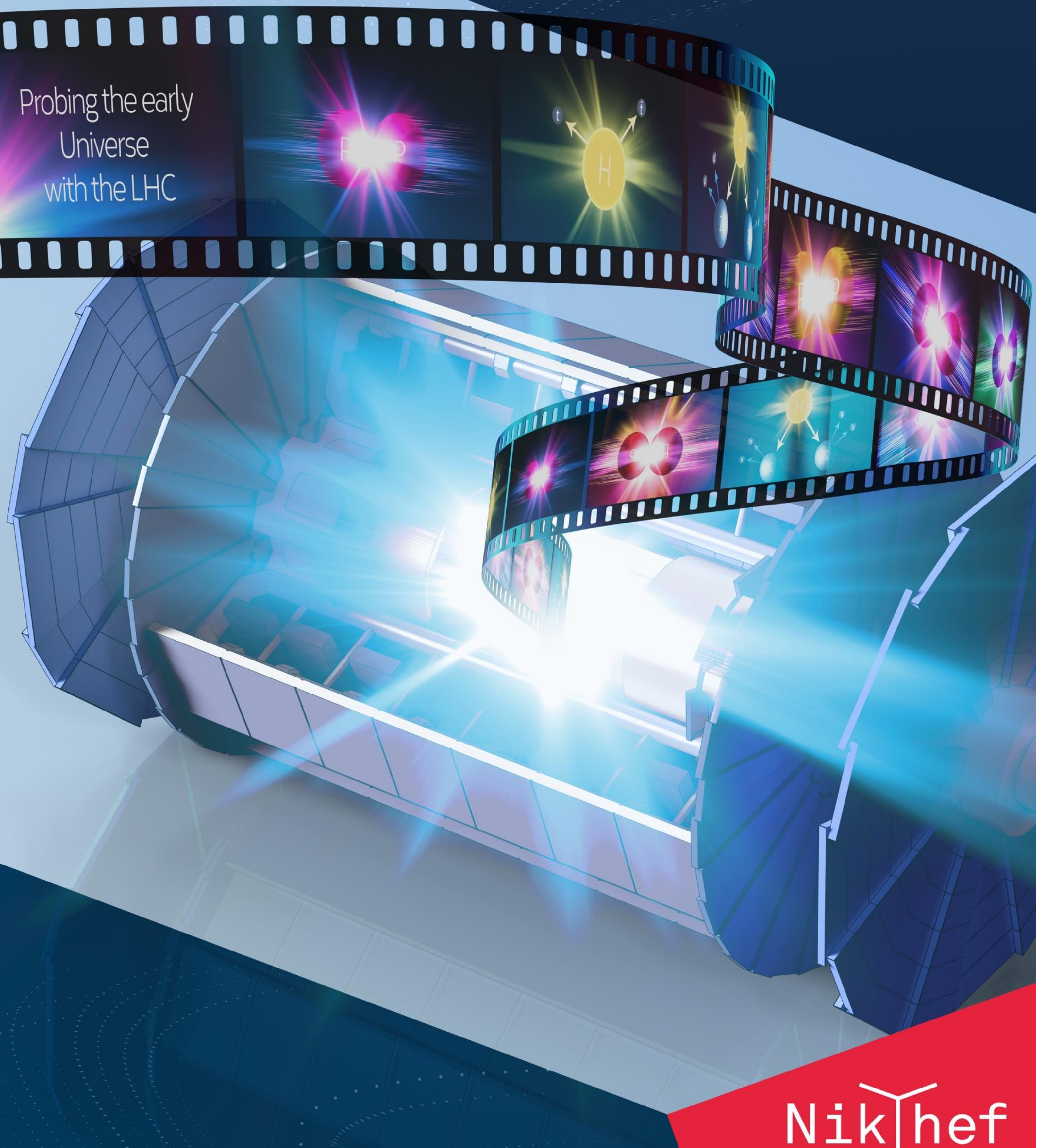
FASTTRACK

Ultra-fast imaging of particle collisions at the LHC



Nikhef

1. General information

Grant application title

FASTTRACK / Ultra-fast imaging of particle collisions at the LHC

Consortium lead and other consortium partners

NWO-I/Nikhef National Institute for Subatomic Physics (**Nikhef**) – responsible institution
Utrecht University (**UU**) – involved institution
University of Amsterdam (**UvA**) – involved institution
Vrije Universiteit Amsterdam (**VU**) – involved institution
Maastricht University (**UM**) – involved institution
Radboud University Nijmegen (**RU**) – involved institution
University of Groningen (**RUG**) – involved institution

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Keywords

Particle physics, particle detectors, tracking systems, fast timing.

Relevant research field(s)

	Code/Field of research:
Main field of research:	12.10.00 Subatomic physics
Other field(s) of research:	12.80.00 Theoretical physics

Relevant Roadmap Domain(s)

☒ Technical and Natural sciences (*100%)*

Abstract

The Large Hadron Collider (LHC) at CERN, Geneva, accelerates particle beams to extremely high energies. At four interaction points, the beams cross and individual beam particles collide, creating thousands of new particles. Dedicated particle detectors, such as ALICE, ATLAS and LHCb, have been built to measure the particles produced. In this way, physical interactions at the highest available energy scales can be studied in a laboratory, deepening our understanding of the formation of matter in the early universe. To enhance the physics programs in the 2030s, the LHC will intensify its beams in the High-Luminosity (HL-LHC) program, which will pose new challenges and offer new opportunities to the experiments. We propose to develop and build innovative detector technologies to fully exploit the intensified-beam program.

Our scientific case is driven by understanding the origin of matter (and the absence of anti-matter), the emergence of nuclear matter, the dynamic explanation of particle mass and the identity of dark matter. The key to unlocking new insights in these topics lies in the study of extremely rare phenomena: accordingly, fully exploiting the LHC by recording unprecedented numbers of collisions is an international priority. To this end, fast-timing instruments are needed to enable the LHC experiments to study particle collisions at a rate up to fifty times faster. The FASTTRACK consortium leverages the expertise of the Dutch community to realize such ultra-fast timing detectors for ALICE, ATLAS and LHCb.

For each beam crossing at the HL-LHC, up to 200 quasi-simultaneous collisions occur in less than a billionth of a second. These collisions produce thousands of particles that traverse the detector, leaving measurable hits in each detection layer. All particles must be tracked through the detector layer-per-layer, and their tracks measured, to enable physics analyses of the collisions. While at present each measured hit has the same timestamp, ultra-fast timing trackers in the HL-LHC era will add picosecond-precise timing information, allowing us to divide the 200 quasi-simultaneous collisions, intractable by present reconstruction algorithms, into time blocks of 40 collisions each, manageable by new reconstruction algorithms.

We will develop fast-timing detectors with novel pixelated silicon sensors and electronics that together will provide unprecedented temporal and spatial resolution. Moreover, we will develop ultralight mechanics and novel cooling technologies to enable stable long-term operation in the harsh environments of the HL-LHC. This will allow us to proceed with a comprehensive and integral approach to implement these technologies in the three experiments.

Our team's 25.5 M€ in personnel cost and 6 M€ for travel and membership fees will be covered by our consortium, while the 21.7 M€ capital investment in materials is requested from this roadmap. The investment will position the Netherlands at the heart of the developments in fast-timing instruments that are of great importance for the international field of particle physics and will put Dutch physicists in a vantage position to assume leading roles in future physics analysis projects, while the developed technologies will also find applications in other scientific and medical fields.

Popular project title and public summary

NL

Ultra-snel afbeelden van botsende deeltjes in de Large Hadron Collider.
Meten is weten, en meer meten is meer weten. Om fundamentele natuurkundemysteries op te lossen, moeten we meer weten over hoe de kleinste deeltjes via fundamentele interacties ons universum vormen. Dit kan door botsingen tussen zulke deeltjes te bestuderen bij de Europese deeltjesversneller LHC op het CERN. Nu de LHC veel meer botsingen gaat genereren, ontwikkelen wij nieuwe technologieën waarmee de detectoren veel sneller beelden kunnen maken, en bijna gelijktijdige botsingen veel beter kunnen onderscheiden. We doen dit op coherente wijze, van technologie-ontwikkeling tot integratie in de analyse van botsingen, om zo nieuwe ontdekkingen mogelijk te maken.

ENG

Ultra-fast imaging of particle collisions at the Large Hadron Collider
The more we measure, the more we know. To solve fundamental physics mysteries, we need to know more about how the smallest particles, through fundamental interactions, form our universe. This is possible by studying collisions between such particles at the European particle accelerator LHC at CERN. With the LHC about to drastically increase its collision rates, we will develop new technologies that enable detectors to take much faster images and record many nearly-simultaneous collisions. We will do so in a coherent way, developing new technologies and integrating them in the analysis of collisions, to pave the way to new discoveries.

2. Large-Scale Research Infrastructure (LSRI)

A bird's-eye view of FASTTRACK

What science will FASTTRACK enable? Particle physics studies particle interactions at the smallest distances and highest energies. These conditions are similar to those of the early universe, when the average energy density was very high. On Earth, such high energies are accessible only at particle accelerators like the Large Hadron Collider (LHC), where particles are accelerated and made to collide to reveal their interactions. Studying these interactions is key to solving the remaining mysteries of our universe. For example, to understand why 80% of the matter in the universe is dark, we must discover the particle nature of dark matter. To understand the dominance of matter over anti-matter, we must discover the tiniest differences between their properties. To understand cosmic inflation, we must discover the dynamics of the Higgs field. To understand the emergence of nuclear matter, we must discover new properties of the quark-gluon plasma. All these discoveries may be waiting for us in the vast amount of data coming from the upcoming High-Luminosity LHC (HL-LHC) program at CERN in the 2030s. The exploration of this data is a top priority for both the European and American strategies for particle physics [1, 2] and requires a concerted effort by multiple experimental programs. For the Netherlands, it is strategic and timely to contribute to this effort and, through FASTTRACK, we can do so in a coherent way.

What is FASTTRACK and why is it needed? The HL-LHC strategy consists in enhancing the discovery process by producing particle collisions at an unprecedented rate. However, to be successful, this strategy must go hand in hand with a coordinated effort to achieve crucial breakthroughs in the enabling detection technologies. We propose to focus on what we (and with us the European Roadmap for Detector R&D [3]) consider most important: the development of large ultra-fast tracking systems, also known as *'4D-tracking'*, with a time resolution of the order of 50 ps (see figs. 5 and 6). These will allow each extremely dense HL-LHC event image, containing on average 200 particle collisions, to be split into manageable sub-images suitable for physics measurements. FASTTRACK will coherently develop, build, and integrate ultra-fast timing detectors into the ALICE, ATLAS and LHCb experiments to keep up with the upcoming high collision rates. Together with complementary components produced by international partners, they will constitute the required 4D tracking systems. Failure to deliver these components will jeopardize the discovery potential of the experiments and therefore the HL-LHC programs at CERN.

How does FASTTRACK fit in the CERN eco-system? The HL-LHC accelerator will be the flagship research facility at CERN in the 2030s. It is fully funded and operated by CERN, while the experiments themselves are funded by the institutions participating (section 4.1). Accordingly, experimental Big Science facilities like ALICE, ATLAS and LHCb depend on large international collaborations. Even the construction of parts of these detectors, such as the envisaged tracking system, will not be realized in a single country, but will be organized internationally. FASTTRACK will account for the expected Dutch contribution to the ALICE, ATLAS and LHCb experiments, which is in the range of 2-4% of the total capital investment of the experiments. In order to optimize the leverage on the Dutch expertise accumulated in the LHC era and to maximize the Dutch impact in the upcoming HL-LHC era, FASTTRACK will coherently focus on only one new detector type, namely the timing detectors in the tracking systems that are at the heart of each of these experiments. The timeline of the FASTTRACK project to develop, build and integrate new ultra-fast timing detectors by the planned accelerator shutdown of 2033-2034 matches the schedule by which the HL-LHC will reach its full performance. In due course, the Dutch share for the operation of the experiments in the 2030s and for the scientific harvesting will be covered by the Nikhef partnership.

Why should the Netherlands fund FASTTRACK? In due time, the Netherlands will be required to contribute to the upgrades of the ALICE, ATLAS and LHCb experiments at a level that matches its size within the international collaborations. Strategically, FASTTRACK envisages a contribution in accordance with the Dutch size, but with a scientific impact that goes well beyond this scale. FASTTRACK not only leverages the recognized Dutch contributions to the current tracking systems of each of these experiments in the LHC era [4-10], but also benefits from successful R&D efforts at Nikhef in the area of fast-timing technologies [11-17]. This will support delivering on time, within budget and with the expected performance, and will secure leading roles in the construction projects. Innovative methods for enhanced exploration of the physics in the particle collisions at the HL-LHC strongly depend on a coherent understanding ranging from detection to reconstruction and data-analysis techniques. With FASTTRACK we embrace such a long-term strategy in the Nikhef consortium. Furthermore, ultra-fast timing detectors are expected to be an essential element in particle physics experiments at any type of future collider. In addition to its main objectives, FASTTRACK represents an impactful stepping stone with a catalyzing effect for future developments.

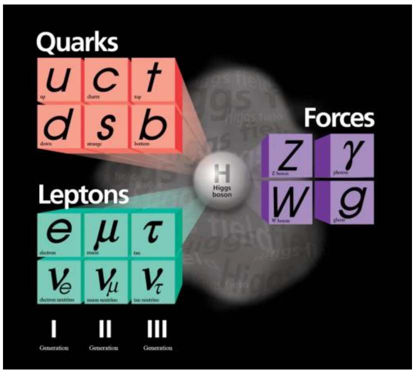
Will FASTTRACK benefit users outside particle physics? Nikhef's innovations in bi-phase CO_2 cooling and in the developments of the Medipix and Timepix chip families have previously led to impactful applications outside particle physics. While the FASTTRACK infrastructure will be integrated into large international facilities for fundamental science at CERN, here too other science domains and society itself will benefit in several ways from the project's scientific and technological breakthroughs (section 3). The ultra-fast timing technology will particularly impact experiments in astroparticle and nuclear physics, and it is an enabling technology for the field of medical imaging.

2.1 General description of the LSRI

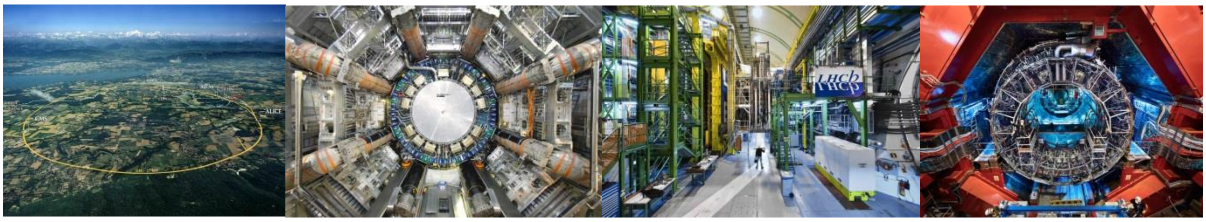
In section 2.1.1, we present our scientific goals and, in section 2.1.2, explain why the High-Luminosity Large Hadron Collider (HL-LHC) is the instrument to achieve them. In section 2.1.3, we show that current tracking systems are inadequate for HL-LHC, and then illustrate, in section 2.1.4, how to overcome this by adding ultra-fast timing capabilities. Finally, in section 2.1.5 we show that, within the lifespan of this proposal, we can develop this technology into next-generation tracking detectors and we present all FASTTRACK components.

2.1.1 Particle physics context and scientific goals

Particle physics – Particle physics is the study of matter at the tiny scales of elementary particles and of the forces that act between these particles. Everything in the universe, from stars and planets, to ourselves, is made from these basic building blocks. All everyday objects that can be touched are ultimately composed of just three elementary particles: the 'up' (*u*) and 'down' (*d*) quarks forming protons and neutrons, and the electron (*e*); a fourth particle, the neutrino (ν_e), comes into play if radioactivity is considered. In the picture to the right, (*u, d*; *e*, ν_e) correspond to the leftmost vertical slice, denoted as *I Generation*. The other two vertical slices, denoted respectively as *II* and *III Generation*, contain particles (*c, s*; μ, ν_μ and *t, b*; τ, ν_τ) that decay too quickly to occur in everyday objects, and are more commonly found in high-energy environments, for example in particle accelerator collisions, or right at the start of the universe just after the Big Bang. This *Standard Model* is a successful model, describing most particle phenomena, but leaving numerous open questions for this to become the *final* theory of fundamental interactions.



Large Hadron Collider – The smallest distance scale that we can access in controlled experiments on earth (*one-thousands of the diameter of a proton*) corresponds to the highest energy scale we can reach, that of the Large Hadron Collider (LHC). Situated in an underground tunnel of 27 km circumference, the LHC accelerates in clock-wise and anti-clock-wise directions two beams of protons or heavy ions. At four collision points, the beams cross and high-energy collision occur, and detector systems observe the particles produced in these collisions. All particle types are copiously produced at the LHC. Figure 1 shows an aerial view of the LHC ring, along with images of the ATLAS, LHCb and ALICE experiments in which the Netherlands participates. Thanks to the extreme beam energies reached by the LHC, thousands of new elementary particles can be produced out of the kinematic energy released in each collision, with the necessary initial conditions for the high-energy physics processes of interest to occur.



(a) ***(b)*** ***(c)*** ***(d)***

***Figure 1**. (a) Aerial view of the Large Hadron Collider at CERN, Geneva, with the 27 km ring outlined. (b) View of the ATLAS experiment. (c) View of the LHCb experiment. (d) View of the Alice experiment. The ATLAS experiment is 43 meters long and more than 20 meters high. The LHCb and ALICE experiments are somewhat smaller in size.*

The past decade – The LHC has fulfilled its promise to be an exceptional facility for groundbreaking discoveries. Highlights include the discovery of the Higgs boson by the ATLAS and CMS experiments in 2012 [18, 19], which was the basis of the 2013 Nobel Prize in physics. This discovery was followed by precision exploration of Higgs boson physics, in particular by the ATLAS collaboration [20], precision measurements of the weak interaction by the LHCb collaboration [21, 22], and precise constraints on the transport properties of the quark gluon plasma by the ALICE collaboration [23]. The Dutch physicists in the FASTTRACK consortium have played a pivotal role in these analyses.

Physics ahead – The physics of fundamental interactions at the smallest distance scales (highest energy scales) is connected to the physics of the largest scales - that of the formation of the universe. The huge volume of data that the LHC collaborations will collect in the high-luminosity era, from 2030 onward, will be the driver of a groundbreaking program of physics measurements and potential discoveries. By unlocking and measuring at the LHC rare fundamental interactions that have to date been experimentally inaccessible, we can study the physics of several phase transitions that appeared in the early universe: the spontaneous breaking of the electroweak symmetry; the breaking of the matter-antimatter symmetry; the transition from quark-gluon plasma to the normal confined hadronic matter (such as protons and neutrons).

The Dutch program to probe the phase transitions in the early universe at the LHC

Addressing the physics of these phase transitions through measurements at the LHC requires a **coherent and unified program**, since scientific breakthroughs may emerge in the interplay of interpreting multiple measurements together. The Dutch particle physics community will continue to embrace this synergistic strategy.

- **Spontaneous symmetry-breaking phase transition and the origin of mass –** The bulk of the mass of an atom originates from the binding energy of the quarks inside neutrons and protons. However, the electron and the quarks, to the best of our current knowledge, are point-like particles without internal structure; their mass follows from a much more exotic mechanism: coupling to a special scalar field that permeates the universe, the Higgs field. Many key aspects of the Higgs field as origin of the elementary particle mass are currently untested: we have not yet seen all particles interact with the Higgs boson, nor found direct evidence of the Higgs potential, which activates this field in the vacuum of the universe. Experimental evidence for many of the untested parts of Higgs mechanism is within reach of the **ATLAS** experiment in the next decade.
- **Phase transition to a matter-antimatter asymmetry and the weak interaction –** All particle physics experiments to date show that particles and anti-particles are produced in pairs; yet somehow in the early universe this balance was broken. The solution to this apparent contradiction, one of the great open question in physics, is believed to be related to the special properties of the weak interaction, to date the only known mechanism that can treat particles and anti-particles differently. Its study can shed further light on the physics behind the disappearance of anti-matter, in connection with a phase transition in the early universe. The ultra-high statistics studies of bound states of particle-antiparticle pairs of all three generations of matter carried out by the LHCb experiment will provide a precise study of the difference between matter and anti-matter.
- **Strong-force phase transition and the quark-gluon plasma –** While the strong force is nowadays only felt within the size of the nucleon, its role in the early universe was much wider. Shortly after the big bang, well before the universe cooled down sufficiently to form protons, neutrons and eventually atoms, the entire universe was filled with a *'quark-gluon'* plasma, whose properties were crucial in the formation of the universe as we observe it today. By colliding lead ions, the LHC can recreate such a plasma in sufficiently large amount that the **ALICE** experiment can study the properties of the hot charged quark-gluon plasma that filled the early universe, as well as how it behaves when it cools down to temperatures at which bound states of quarks, are formed.

2.1.2 The High-Luminosity Large Hadron Collider (HL-LHC) program

The study of the extremely rare processes that occur in LHC collisions will be made possible by the *High-Luminosity LHC* (HL-LHC, InfoBox 1). The HL-LHC is an approved project, funded by CERN, that will lead to a giant leap in the data delivery rate of the LHC, which in turn is pivotal to drastically increase the potential for discoveries and realize the ultimate physics program of the LHC. It is the top priority of the European Strategy for Particle Physics [1].

InfoBox 1 – Interaction probabilities and particle densities: a collider luminosity primer

In most proton-proton collisions nothing interesting happens. The probability for something to happen is expressed through the *cross-section*, a quantity with a tiny value of 10^{-25} cm^2; rare processes like the production of a Higgs boson have cross sections a billion times smaller. To offset these small probabilities, the HL-LHC will manage the incredible feat of colliding clouds (*bunches*) of 200 billions of protons squeezed into a transversal area of one thousandth of 1 mm^2, corresponding to proton densities of 2×10^{27} cm^{-2}. Multiplying this density by the revolution frequency (a proton traveling at the speed of light goes 11,245 times per second around the 27 km LHC ring) and by the number of 2700 bunches per beam, results in a *"luminosity"* of 5×10^{34} cm^{-2} s^{-1}. At this luminosity, each time bunches cross each other, roughly 200 proton-proton interactions take place, while the remaining protons in the bunch continue undisturbed.

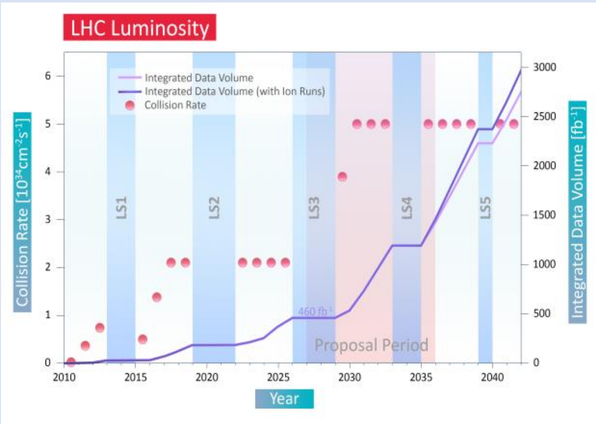


***Figure 2**: LHC collision rate and integrated data volume.*

To appreciate the leap implied by the HL-LHC, consider the following: the first 5% of the total expected data volume of the ATLAS experiment was delivered over a period of eight years (2010-2018); the next 10% is being delivered now in just four years (2022-2026); the remaining 85% is expected to be delivered by the HL-LHC (2030-2041). The installation and commissioning of new accelerator components will take place during a three-year shutdown from 2026 onwards, after which the accelerator will start ramping up toward full performance. Analogous considerations can be made about the size of the increased data volume at LHCb and in the heavy-ion program of ALICE.

2.1.3 Particle tracking at the LHC - current state of the art and challenges

Particles accelerated and collided by the LHC are protons or heavy ions. These have a complex internal structure and each collision results in numerous particles emitted in all directions. State-of-the-art multi-layered detectors have been constructed by the LHC collaborations to reconstruct with high precision the rare and exotic particles buried among the thousands of background particles from the proton remnant. Close to the interaction point, all LHC experiments feature an inner detector that acts as a *tracking system*, measuring the precise location of all charged particles and determining their point of origin (vertex) and their momentum (from the curvature of the trajectory in a magnetic field), as shown schematically in fig. 3a. The tracking system is at the heart of a particle detector; the achievable vertex and momentum resolution are key parameters for the discovery potential of the experiment.

InfoBox 2 – Tracking at particles colliders

Most of the particles produced in each LHC collision decay into other particles. Some, such as the Higgs boson, decay very quickly. Others (not shown in the visualization below), such as those containing third-generation bottom quarks, live long enough to travel up to millimeters away from the collision point.

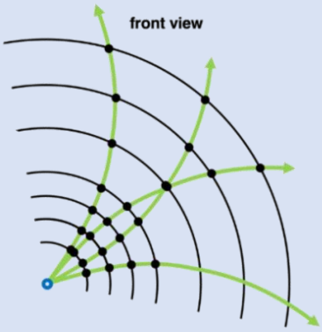


Figure 3a: *Schematic view of particle tracking*

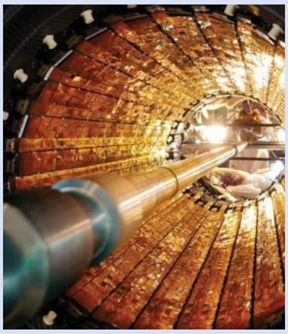


Figure 3b: *ALICE inner tracking system [24]*

A charged particle passing through a tracking detector layer will result in a measured particle **hit** (the black points). Tracking systems consist of multiple detection layers, with sufficient spatial resolution, and positioned close enough to the beam line, to measure enough hits for reconstruction algorithms to connect the hits into **tracks** (the green lines). Tracks can then be extrapolated back to the beam axis to determine if they meet at the positions of the proton-proton (or heavy ion) collision points, the **primary vertices** (the open blue circle).

The Dutch scientific community has been at the heart of tracking system development in the past decade and we have been involved (see section 2.4) in the construction of the current ATLAS inner tracker, the LHCb Vertex Locator and the ALICE Inner Tracking System. To achieve a highly granular design with excellent resolution, the tracking systems of ALICE, ATLAS and LHCb *all deploy a common technology* at the heart of the detector: pixelated silicon-based detectors. The key design parameters, determining vertex and momentum resolution, are: the spatial resolution; the distance from the interaction region; the measurement lever arm; the number of layers; the material budget and the radiation tolerance. The relative importance of these parameters varies from experiment to experiment: ALICE (fig. 3b) emphasizes precise tracking down to low momentum particles and thus sets very tight material budget limits and requires ultra-thin detectors with the ultimate spatial resolution; LHCb and ATLAS require a higher radiation hardness and data-rate capabilities and a substantial increase in the ability to resolve collisions that will eventually become so closely spaced that they can no longer be resolved using spatial information only.

Overall challenge – With the start of the High-Luminosity LHC in 2030, the number of interactions happening each time bunches cross each other will go up dramatically and none of the present silicon pixel detectors at the heart of each experiment will be able to perform at the required level. A new generation of pixel detectors must therefore be developed and built, with all technological advances necessary to overcome a number of challenges (see below).

Challenge 1: Connect tracks with their primary vertex (fig. 4a) – The ability to connect particle tracks back to the primary vertex (fig. 3a) where these particles were produced, is essential for physics analysis. At the HL-LHC, this will be severely compromised due to the *increase in the number of nearly simultaneous interactions per bunch crossing* (InfoBox 1). Tracks and vertices reconstruction in the environment of fig. 4a is beyond the capability of current detection technology: with up to 200 vertices occurring along a 5-cm long section of the beam line, the average distance between proton-proton collision points is less than 1 millimeter, and the spatial resolution of reconstructed tracks extrapolated back to the beamline is no longer good enough to perform an unambiguous assignment of each track to the correct vertex. This effect becomes dramatic for tracks flying at small angles with the beam axis, for which dozens of collision vertices will be within the extrapolation uncertainty. For this reason, the HL-LHC tracking challenge is particularly pressing for the forward-looking LHCb detector, and for this same reason ATLAS plans to install fast-timing detectors in the forward region.

Challenge 2: Reconstruct low-momentum tracks (fig. 4b) – To achieve the physics goals of the ALICE collaboration, the new ALICE detector must be able to reconstruct and identify low-momentum tracks, down to a transverse momentum of about 40 MeV/c for electrons. These low-momentum particles confront the tracking system with an additional issue: due to the relatively high magnetic field (B ∼1 T), these particles follow helicoidal *'looper'* trajectories, as shown in fig. 4b, which represent an extreme challenge for reconstruction algorithms.

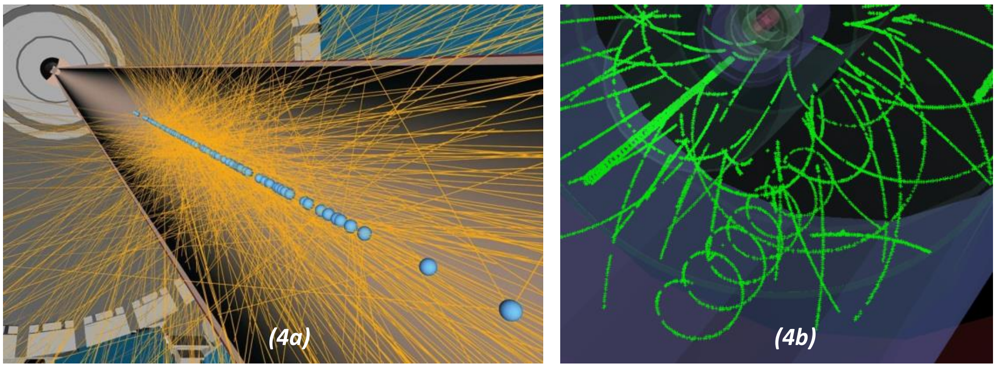


Figure 4. *Visualization of the challenges posed by the huge HL-LHC track density.* ***(a)*** *View along the beamline of a simulated ATLAS event with 200 proton-proton interactions; the yellow lines are tracks reconstructed and extrapolated back to the 200 proton-proton vertices denoted by the blue balls.* ***(b)*** *ALICE lead-lead collisions, with low-momentum tracks "captured" by the strong magnetic field in spiraling trajectories.*

Challenge 3: Integrate new detector technologies in the harsh HL-LHC environment – To implement new technologies into actual detector systems for ALICE, ATLAS, LHCb, we need major developments in a number of *integration* topics, including detector mechanics, cooling systems, and computing. Here, the challenges stem from the radiation environment, the huge data throughput, the tight budget constraints of detector material, the heat generated by densely packed detector layers and the need to realize efficient and affordable computing platforms.

2.1.4 Proposed technology breakthrough: 4D fast-timing detectors

Overall objective – To overcome these challenges and therefore unlock the full potential of the HL-LHC physics program, we request funding to develop, build, and integrate the novel 'fast-timing' detector concept into ALICE, ATLAS and LHCb. The central principle of this concept is to add a timestamp to the three spatial coordinates of each measured hit in the tracking layers with a precision of about 50 ps. This will allow to develop new '4D tracking' algorithms that disentangle in time the otherwise overlapping proton-proton (or heavy ion) collisions.

Disentangling simultaneous interactions (fig. 5) – When observed with a picosecond level time resolution, the proton-proton collisions in each LHC bunch-bunch crossing are no longer observed as simultaneous, but rather as spaced in time, with a few picoseconds between interactions. Detection of the time of passage of all particles, in addition to the hit position, will thus allow to significantly reduce the effective track density, by only considering particle hits that lie within narrow detection time windows, as visualized in fig. 5. Our studies show that with a time resolution of the order of 50 ps the particle density is sufficiently reduced to again obtain a good association of tracks to closely spaced vertices.

Ultra-fast Time-of-Flight (fig. 6) – Sufficiently precise time measurements allow the determination of the velocity of low momentum particles, and thus their mass and identity. Furthermore, timing information allows to distinguish detector hits generated from different cycles of 'looper' tracks, significantly aiding the ability to reconstruct these.

Pico-second-level timing resolution in silicon tracking detectors – Challenges

- The primary signal of a charged particle passing through a thin silicon detector is so tiny, that the small number of electron-hole pairs created results in stochastic uncertainties in any timing measurement that easily exceed the target resolution of 50 ps.
- The on-detector electronics must be small and radiation-hard, and have a low power consumption. It typically measures the so-called *time-over-threshold*, i.e. the time interval over which the signal exceeds a certain detection threshold, and not its complete time profile. This makes it more sensitive to instrumental effects, like jitter noise and *'time-walk'* (larger signals cross a threshold earlier than smaller ones), that deteriorate the resolution.
- Ultimately, even after all mitigation techniques for the previous two issues have been put in place, to achieve the target resolution of 50 ps, one still has to devise and deploy a detailed strategy to achieve a high-precision calibration. Such calibrations are non-trivial, as they consist of multiple steps that have to be applied to each channel, and pixel detectors may have up to billions of channels.

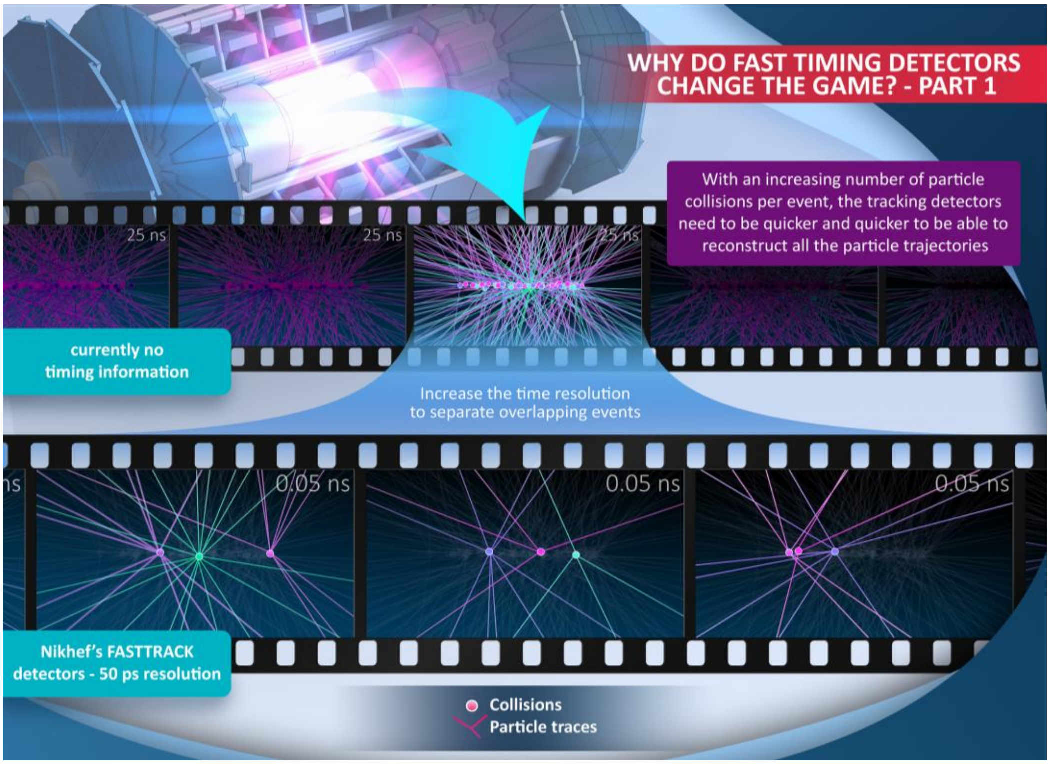


__Figure 5.__ While multiple interactions in a bunch-bunch crossing appear simultaneous on the nanosecond scale, when looked at in "slow motion", they reveal a simpler structure with fewer vertices and less tracks.

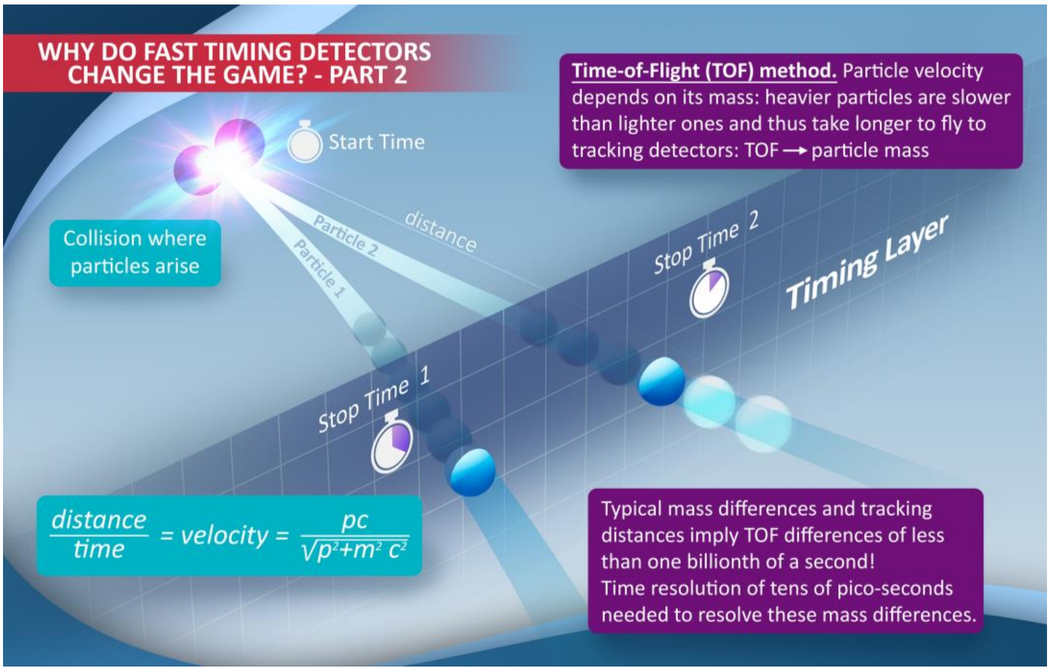


__Figure 6.__ Particles with the same momentum but different masses can be "separated" in velocity, provided that time can be measured precisely enough to detect tiny time-of-flight differences.

At present, there is no combination of sensors and on-detector electronics that can directly be used in FASTTRACK to build detectors with the resolution of 50 ps. However, there are several projects in the R&D phase that have achieved timing resolutions between 30 ps and 180 ps [25, 26, 27]. Nikhef has been a leader in the construction of the current generation of tracking detectors and has initiated key technology [11-17, 28, 29] for fast timing with pixel detectors. A research program on *Fast sensors and Algorithms for Space-time Tracking and Event Reconstruction (FASTER)*, funded under the NWO-ENW Open Competition XL program [30], is well underway, addressing the fundamental challenges of the fast-timing technology, and paving the way toward the FASTTRACK implementation into complete tracking detectors.

Technology objective – The overarching theme of FASTTRACK is to finalize the development of a new generation of sensor technology providing fast signals, with sufficiently fast signal processing, usable for the construction of new timing-enabled tracking detectors for the ALICE, ATLAS and LHCb experiments.

2.1.5 The FASTTRACK LSRI

We request funding for the Dutch contribution to the science program of the HL-LHC. FASTTRACK will enable the construction, by 2034, of a new fast-timing vertex detector for LHCb, of a new ultra-thin fast-timing inner tracking detector for ALICE, and of a forward fast-timing layer in the ATLAS experiment. It will also lead to an R&D program towards an upgrade of the ATLAS inner tracking layers beyond 2036, for which no technology exists yet that can meet all specifications. The following components are coherently integrated into FASTTRACK:

- **Tracker modules**: ultra-fast timing sensors (***WP1***) and fast signal-processing circuitry (***WP2***);
- **Readout**: high-speed/high-throughput data transmission and data acquisition (***WP3***);
- **Support and Interface to services**: modular mechanics based on ultra-light material structures (***WP4***);
- **Event filtering**: real-time computing solutions based on heterogeneous technologies (FPGAs, GPUs) (***WP5***).

The complete construction of the tracking systems will be carried out by an international consortium of institutes within the ATLAS, LHCb and ALICE collaborations, as a coherent effort regulated by agreements specifying the contribution of each partner. The *'WP'* labels denote the FASTTRACK work packages and illustrate our approach: thanks to the unique scientific and technological portfolio of the Nikhef consortium, we will deliver an *"integral package"* of technological developments encompassing all project aspects and a significant fraction of all hardware components (see section 4.1). Through this approach, it is our ambition to have ***leading roles*** in the construction projects and a vantage point in the science harvesting.

Fast timing detectors in ALICE – The future ALICE3 detector, shown in fig. 7, is designed to have a large angular acceptance ($|\eta|<4$, where η is the so-called *pseudorapidity*, a spatial coordinate describing the angle of a particle relative to the beam axis) and a large momentum range ($p_T \geq 40$ MeV/c, where p_T is the component of momentum transverse to the beam line). The tracking and the particle identification systems will be enclosed in a radius of 110 cm from the beam axis. Nikhef will contribute to the construction of the inner tracker, in particular the tracking and timing layers enclosed in the radial region 0.5 cm ≤ r ≤ 19 cm, in which six layers and five disks are foreseen [31]. The three innermost layers and two disks are placed in vacuum, forming the so-called *'IRIS'* retractable vertex tracker; the remaining layers and disks will surround the beam pipe. The layer at r = 19 cm is required to have timing capabilities, with a resolution of about 50 ps, in order to perform time-of-flight measurements at low transverse momentum. The in-vacuum layers are required to have an unprecedented intrinsic spatial precision, made possible by an ultra-low material budget (0.1% of a *radiation length* X_0) and a small pixel *pitch* (see Infobox 3) of about 10 µm. Such a configuration will allow for a pointing resolution to the vertex of a single track of the order of 3 µm at a transverse momentum of 1 GeV/c.

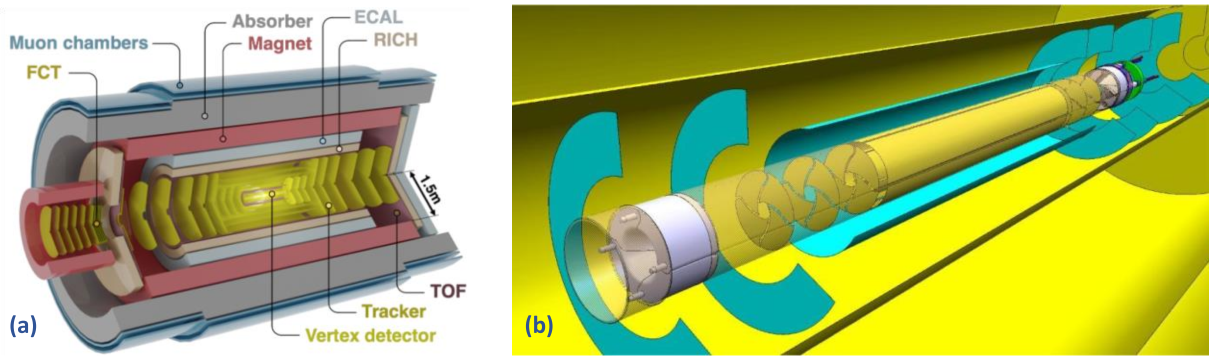


***Figure 7: (a)** Overview of the ALICE3 detector, with the indicated location of the different sub-detectors **(b)** Close-up view of the ALICE3 Vertex detector in closed position.*

Fast timing detectors in ATLAS – In 2029, the ATLAS collaboration will install an all-silicon Inner Tracker (ITk) system, consisting of a cylindrical *barrel* and two *end-caps*, together providing good angular acceptance ($|\eta| < 4$). These are complemented by a high-granularity timing detector (HGTD) covering the forward region. Due to the increasingly extreme HL-LHC operating conditions and resulting radiation damage, the innermost ring of the HGTD sensors will already need to be replaced during the LHC shutdown LS4 starting in 2034. The goal of FASTTRACK is to contribute to the design, construction and installation of these new HGTD sensors with improved radiation-hardness, able to last for the remainder of the HL-LHC foreseen lifetime.

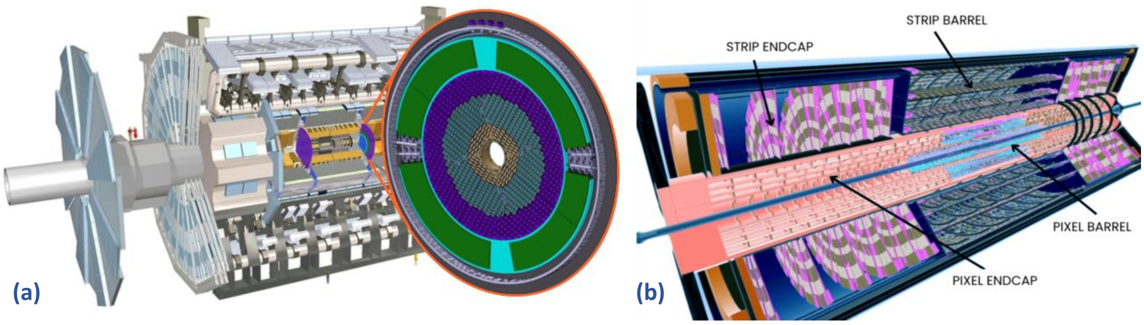


Figure 8: ***(a)*** *Overview of the ATLAS detector, with the indicated location of the High Granularity Timing detector.* ***(b)*** *Closeup view of the ATLAS Inner Tracker (ITk) detector that sits at the heart of the ATLAS detector, with labeling of the end-cap, barrel components, and location of the pixel and strip layers.*

Beyond LS4, the planned replacement of the innermost pixel layers of the ITk barrel will provide an opportunity to adopt new pixel detectors capable of fast-timing measurements. In the second half of the next decade this will enhance the ATLAS science performance at the highest data-taking rates formidably; most notably, this additional timing information in the central region can reduce, up to a factor four, backgrounds due to mis-identification of essential objects in the flag-ship measurement of Higgs self-coupling. At present, no sensor exists suited for a fast-timing detector fulfilling the combined requirements on radiation hardness, power consumption, and time and spatial resolution. FASTTRACK aims to play a leading role in the development of such novel sensors.

Fast timing detectors in LHCb – The Dutch contribution will be focused on the **VErtex LOcator** (VELO), the heart of the LHCb spectrometer. The VELO is a silicon pixel detector that serves to measure the production and the decay point of the unstable beauty and charm particles and of their decay products. To attain the highest measurement precision, it will be positioned as close as possible to the collision point, inside the LHC beam vacuum. The VELO will then be exposed to the highest particle flux, which sets stringent requirements on the radiation tolerance of the sensors as well as on the data throughput of the on-detector electronics. To unravel beauty and charm particle decays amidst the abundant other particles produced in the same collision, the sensors have to provide ultra-precise spatial as well as temporal measurements. A spatial resolution of 10 µm and a temporal resolution of 50 ps will enable the VELO to efficiently reconstruct all proton-proton collision points and to measure the decay length of the unstable beauty and charm particles from their production point to their decay point. Nikhef will play a leading role in the VELO project, focusing on the development of fast timing sensors and of a novel ASIC realized with a 28 nm semiconductor manufacturing process, the design and production of the detector modules, and the engineering and construction of the mechanical interface.

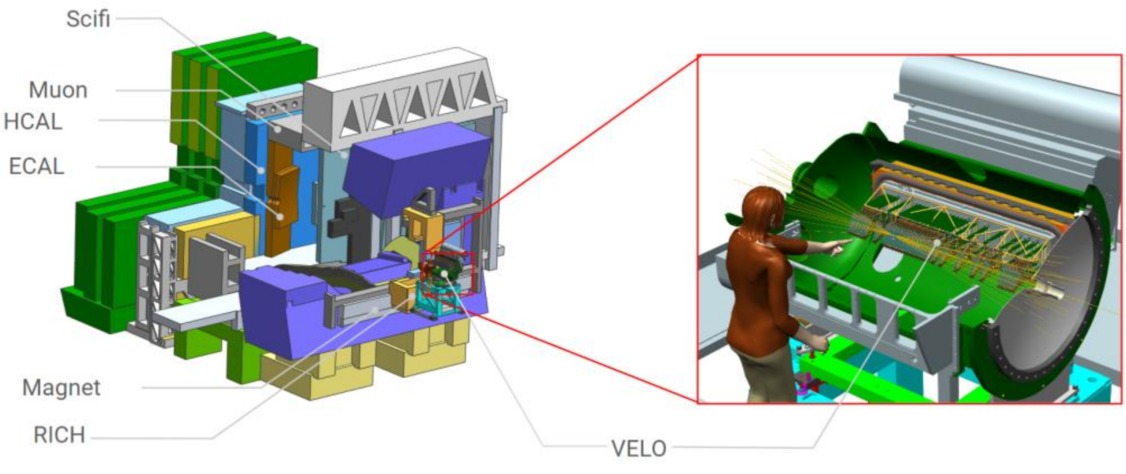
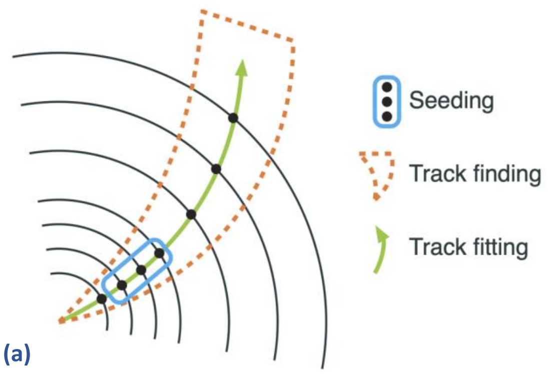


Figure 9: *Side view of the LHCb spectrometer with an exploded-view of the VELO.*

Common computing for track reconstruction with fast timing tracking detectors – Particle trajectories are reconstructed from the collection of detected hits in three steps, as shown in fig. 10a: first, initial 'seeds' of close-by detector hits are established, which give an approximate initial travel direction for each particle; next, a ***track finding algorithm***, based on the traditional Kalman filtering approach, iteratively extends a road traversing the full detector volume, collecting all hits that are assumed to originate from the same particle; finally, a parameterized trajectory model is fit to the collection of hits-on-track, to obtain the best possible measurement of its path. The computation is dominated by the second track-finding step, with processing times typically increasing cubically with the number of hits: with the expected 7-fold increase of the number of hits at the HL-LHC, the computation time will increase by a factor of 350. When one combines this dramatic increase in the complexity of individual collision events with the expected order-of-magnitude increase in the data volume shown in fig. 10b, one realizes that our present processing technology is simply not sustainable and that we necessitate **a paradigm change** in the computational approach to reconstructing particle trajectories.



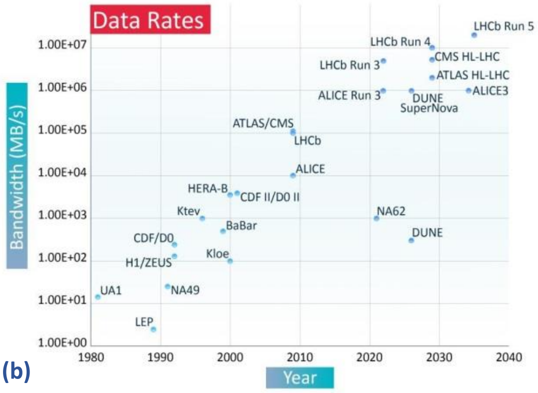


***Figure 10: (a)** Track-reconstruction steps: seeding, track finding and track fitting. **(b)** Order-of-magnitude increase in data volume that our field has experienced in the last decades (data compiled by A. Cerri – Univ. of Sussex).*

We will pursue a multi-pronged approach. The first key factor is the **availability of precise timing information**, which allows to reduce the complexity of the track finding (see fig. 5): only hits with a time stamp close to that of track seeds will have to be considered, thus reducing the effective number of hits on which the computation time critically depends. The second key aspect is the rapid pace of development in hybrid computing architectures and in machine learning algorithms. We will focus on the **adaptation of modern computing hardware**, i.e. processors equipped with specialized co-processors such as Graphics Processing Units (GPUs), Field Programmable Gate Arrays (FPGAs) and AI inference engines, as the strongest growth in computing power in new hardware occurs almost exclusively in these platforms. Efficient use of hybrid hardware requires significant changes to track-finding algorithms to exploit its massive parallel-computing power. We will invest in an accelerator validation facility to investigate the integration of (future) computing accelerators in applications, frameworks and infrastructures. The third key aspect are advances in **deep-learning AI models**. Newly developed AI network architectures (notably the attention-based transformer models at the core of large language models such as ChatGPT) are naturally suited to finding the 'next hit' on a track and may replace the time-consuming Kalman filter step, with large potential gains in computation time, and opportunities for massively parallel track finding executable on hybrid computing hardware.
As tracking software deals only with hits and trajectories, it is not tied to a specific detector or experiment; therefore, the activities described above will represent a joint effort that will lead to ***common computing tools*** for efficient 4D tracking in ALICE, ATLAS and LHCb.

2.2 Expected scientific innovation and breakthroughs

Over the coming decades, the HL-LHC will be the leading scientific instrument in particle physics. Once we have produced fundamental particles, we can study their behavior to find out why the universe is made the way it is. Are the laws of physics we currently know truly *fundamental*, i.e. can they describe physics at *all* energy and distance scales? Can we explain the universe as we see it today, without anti-matter and with nearly no space-time curvature, but with large amounts of dark matter that have shaped the distribution of galaxies and stars, as the natural result of the Big Bang and a concise set of physics laws that have governed its evolution since the start of time? The high-energy collisions at the LHC are energetic enough to turn the clock back to just after the Big Bang. As such, the LHC is the best facility available on Earth for controlled studies of the physics processes that are hypothesized to have governed these universe-shaping transitions shortly after the Big Bang. As highlighted in section 2.1.1, the Dutch LHC community will focus on three main aspects of this physics program: on the Higgs boson within ATLAS, on the matter-antimatter asymmetry within LHCb, and on the properties of the quark-gluon plasma that populated the universe in the first microsecond within ALICE. In next subsections, we will give concrete examples of innovative research questions, that can be addressed with the proposed next-generation detectors and show how these can accelerate scientific breakthroughs.

2.2.1 Innovative research and potential breakthroughs in ATLAS with fast timing

Our physics program in the High-Luminosity phase of ATLAS [32] has three scientific breakthrough **[SB]** areas related to the physics of the early universe that will greatly benefit from the FASTTRACK advances (see fig. 11).

- **Measuring the shape of the Higgs potential [SB1.1] –** The Higgs field plays a central role in the electroweak phase transition (Nobel prize 2013) in the early universe. The precise shape of the Higgs potential is a crucial ingredient to the physics of this transition. The shape of this potential is so far unmeasured. In order to probe it, it is essential to, first, observe and, later, precisely measure the properties of the *collisions in which two Higgs bosons are produced*. This yet-unobserved process, a 1000-times rarer than single Higgs boson production, is only possible if the Higgs boson exhibits a property known as ’self-coupling’. The breakthrough observation of self-coupling would be experimental evidence of the existence of the Higgs potential, and can later help to constrain the potential shape. As Higgs bosons predominantly decay to pairs of so-called ’b-quark jets’, the main way to identify double-Higgs events is through the observation of four b-quark jets (fig. 11(a)). As a consequence, the rate at which collisions with two Higgs bosons can be identified scales with the fourth power of the efficiency with which a single b-quark jet can be identified. Identification of b-quark jets occurs primarily through the identification of a secondary decay vertex that is extremely close to the primary collision point and is therefore completely dependent on the excellent performance of the tracking detectors. An increase of this identification efficiency from 65% to 85%, which is estimated to be feasible by including fast-timing information of both the Inner Tracker upgrade and the HGTD, will *double the discovery significance of two-Higgs events* decaying to four b-quark jets [33].

- **Discovery of new fundamental physics in Higgs boson interactions [SB1.2]** – Signatures of such new hypothetical physics would primarily manifest themselves in the *high-energy tails of single Higgs boson production*. The production process with the cleanest and highest reach in energy to observe such tail effects is the Vector-Boson-Fusion (VBF) process. First experimental signatures, the ’tagging jets’ shown in blue in fig. 11(b), primarily occur in the very forward region. The newly installed ITk tracker, combined with the HGTD forward timing detector and augmented with the additional timing information from a new timing layer in the inner layers of the ITk, can cut by half the otherwise irreducible background [33] and therefore significantly enhance the discovery potential.
- **Observation of long-lived particles [SB1.3] –** Many theories of Nature that aim to extend the theory to the energy scales of the early universe introduce new fundamental interactions or new elementary particles. Such particles may have significantly higher masses than the ones currently known or relatively long decay times, due to their feeble interaction with known particles. The most promising searches of such invisible *long-lived particles* are based on the observation of *’displaced vertices’*, as visualized in fig. 11(c). Therefore, the tracking upgrades presented in this proposal can lead to a breakthrough in the search for such particles, as the additional timing information of the ITk will tremendously suppress, up to a factor 100, the backgrounds in these searches due to the dense track environment of the HL-LHC [33].

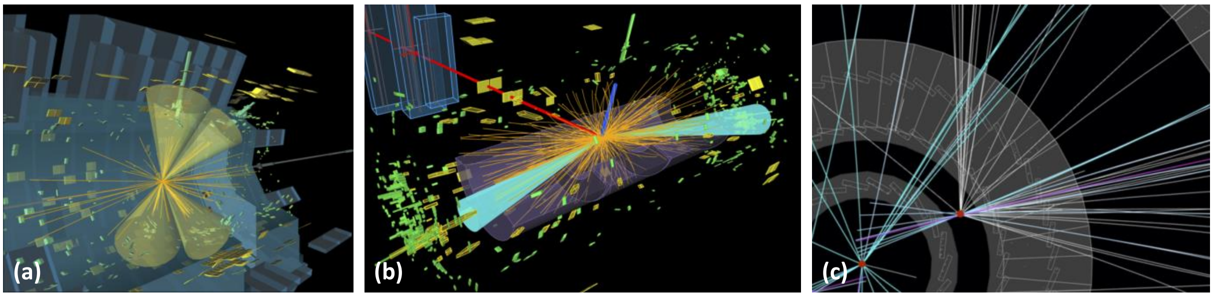


Figure 11: *Visualization of three types of collisions that are key to the ATLAS HL-LHC physics program.*
(a) *Production of two Higgs bosons, decaying into four b-quark jets (yellow cones).* ***(b)*** *Production of a highly energetic Higgs boson through the Vector-Boson-Production process, with its two characteristic ‘tagging jets’ in the forward region (blue cones).* ***(c)*** *Simulated event with a displaced vertex caused by the decay products of a hypothetical long-lived new particle.*

2.2.2 Innovative research and potential breakthroughs in LHCb with fast timing

FASTTRACK will enable LHCb to sustain a jump of almost an order of magnitude in luminosity and will allow to fully exploit the unprecedented data volume that the HL-LHC will deliver. This, in turn, will lead to an unrivalled program of precision searches. Precision measurements open the way to breakthroughs in particle physics [34], as, through quantum effects, they provide us with sensitivity to hypothetical new particles with masses that are orders of magnitude higher than the energy of the colliding particle beams. We plan to exploit this to push the precision frontier in two main research areas: particle-antiparticle asymmetry and rare particle decays. These will result in world-leading measurements, unchallenged by other experiments. Our strategic choice to focus the Dutch hardware contribution on the VELO detector must also be seen in this context: *the precise determination of all particle production and decay points* provided by the VELO is the main ingredient of all decay measurements. Failure to deliver the required VELO performance will render impossible the measurements below; therefore, FASTTRACK is essential for the LHCb science program.

- **Investigating particle-antiparticle asymmetry beyond the CKM paradigm [SB2.1] –** An explanation of the observation that our universe contains matter, but not antimatter, requires violation of a symmetry between particles and antiparticles, known as ’CP violation’. The current CKM theory of the weak nuclear interaction, by

Cabbibo and Kobayashi & Maskawa (Nobel prize 2008), is insufficient to model the violation required to explain the cosmological absence of antimatter. The key to further understand this aspect of the physics of the early universe is an experimental program of precision studies making use of the matter-to-antimatter *'oscillations'* shown in fig. 12(a). This process is extremely sensitive to matter-antimatter differences. As the particles in fig. 12(a) decay after only traveling approximately 7 mm from their production point, an outstanding vertex position resolution is essential for a precision physics program. FASTTRACK will make possible decay-time measurement to the percent level, enabling this precision physics program. We will pursue the following breakthroughs:

1) ***CKM angle γ:*** Consistency of the CKM mechanism relates CP violation in different *B* meson decay modes, resulting in a single value of the so-called CKM decay angle γ for all decay modes. LHCb holds the world-best measurement, with a precision better than 3 degrees. With the HL-LHC data, we will improve this precision almost tenfold, down to 0.35°, allowing us to uncover new sources of CP violation inconsistent with the CKM mechanism.

2) ***CKM mixing parameter ϕ_s:*** An important parameter in the description of the oscillation process of fig 12(a) is the mixing angle ϕ_s, which is very small and precisely predicted: ϕ_s = 34 ± 1 mrad. With FASTTRACK and the HL-LHC data we will be able to reach an experimental precision of O(1 mrad) allowing us to detect new minute differences between matter and anti-matter processes.

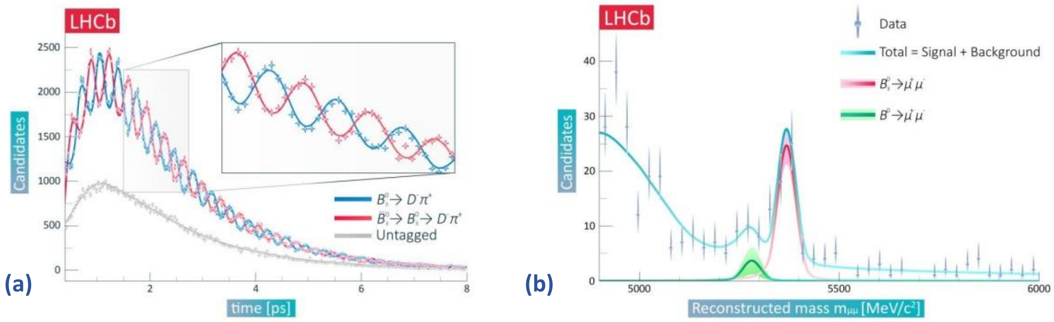


Figure 12: (a) *Quantum oscillations due to B^0_s to anti- B^0_s transitions before decay.* ***(b)*** *The rarest decay process observed to date at the LHC: the highly suppressed decay of B^0_s mesons into a pair of muon particles. The data points are from [22]. The green line denotes the potential signal of the even rarer decay of B^0 mesons to two muons.*

- **Observing the rarest decays [SB2.2] –** We will study some of the rarest particle decays observed in Nature, that of a B^0 or B^0_s decaying to a pair of leptons (electrons, muons or tau's). This is one of the most stringent quantum tests possible: in highly suppressed decays, the sensitivity for the existence of new particles with very high masses, or new forces that occur at very high energy, are greatly enhanced. We will study the decays to all three generations of leptons, as eventual discrepancies among these would be a direct sign of new physics. The FASTTRACK advances will allow us to efficiently isolate these extremely rare events even at the highest LHC beam intensity:

  1) ***Decays to muons:*** Beyond LHCb's observation of $B^0_s \rightarrow \mu\mu$, with a probability of only a three in a billion, FASTTRACK will allow to measure the thirty times rarer $B^0 \rightarrow \mu\mu$ decay (fig. 12(b)) and improve the relative uncertainty on the ratio of these two decays from the present 90% to 10%.

  2) ***Decays to electrons:*** The use of ultralight materials in the VELO detector developed by FASTTRACK will reduce the energy loss of electrons in the detector material; this will allow to significantly increase the electron reconstruction efficiency and enhance the precision of the electron momentum measurement, unlocking the observation of the $B^0_s \rightarrow ee$ decay.

  3) ***Decays to τ leptons:*** Not accessible at present, the $B_s \rightarrow \tau\tau$ decay may come within reach in the HL-LHC era enabled by FASTTRACK, or in any case we will be able to set a tenfold stronger limit on its probability.

2.2.3 Innovative research and potential breakthroughs in ALICE with fast timing

The new ALICE3 detector, with a FASTTRACK ultra-thin fast-timing inner tracker at its heart, will allow unprecedented precision measurements of the quark-gluon plasma, a hot and dense state of matter which we believe permeated the early universe. Breakthroughs on important fundamental physics questions are within reach in the next decade:

- **Unlocking chiral symmetry breaking to explain the emergence of nucleon mass [SB3.1] –** The mass of neutrons and protons vastly exceeds the mass of its constituent particles, the up- and down quarks. This additional mass, which amounts to 99% of the proton and neutron mass, is predicted to arise from a mechanism known as 'chiral symmetry breaking'. The restoration of chiral symmetry in the special form of matter that is the quark-gluon plasma (QGP), allows to study this symmetry breaking at the LHC through high-precision, multi-differential measurements of electromagnetic radiation emitted from the quark–gluon plasma that is created in ion-ion collisions. A key measurement is that of lepton pair production from the QGP, as shown in fig. 13(a), in the low-mass range of the ρ particle and its chiral partner, the a_1 particle. In the presence of chiral symmetry restoration, ρ–a_1 chiral mixing enhances the yield by about 25% with respect to elementary collisions. ALICE3, offering experimental accuracy of 5% is expected to be able to observe this phenomenon, if present [31].

- **Investigation of hadron formation [SB3.2] –** The properties of the formation process of hadrons, e.g. protons and neutrons, in the plasma and its dependence of formation properties on the ambient environment, can be studied by ALICE by specifically looking at the production of hadrons in ion collisions that contain one or more heavy quarks from the second generation of matter. A breakthrough measurement of the production of such hadrons with heavy ’charm quarks’ requires precision measurements of several hadron species, including yield measurements of multi-charm baryons such as Ξ^{++}_{cc} and Ω^{+}_{cc}. Fig. 13(b) shows an overview of capability of ALICE3 to observe multi-charm hadrons in heavy-ion collisions, including several new observations. The observed yield of these particles is expected to be significantly different from their production yield in elementary collisions and this will allow us to determine how composite particles are formed. With a precision of the order of 5-10%, depending on momentum, these measurements allow to set unprecedented constrains on theoretical models [31].
- **Constraining early universe models from measured QGP properties [SB3.3] –** The dense strongly interacting quark-gluon plasma significantly alters the ways in which quarks and gluons can move around inside that medium, compared to the movement of quarks and gluons in vacuum. An important open question is: how do these transport properties arise from the theory of strong interactions, quantum chromodynamics? The transport of quarks and gluons in the QGP medium can be experimentally probed with measurements of heavy hadrons, containing a quark from the 2nd and 3rd generation of matter, which are emitted by the QGP generated in LHC ion-ion collisions. ALICE3 will offer the unique opportunity to investigate the production rate and azimuthal angle of heavy hadrons in heavy ion collisions with precision ranging from few per mill to about 5%, depending on momentum range and hadron species, allowing to firmly constrain theoretical models [31].

The unprecedented capabilities of the ALICE3 detector, in particular in the identification and reconstruction of low-momentum particles and suppression of ’looper track’ backgrounds as shown in fig. 4 and fig. 13(a), will be crucial to the success of the physics breakthrough program. The realization of these new capabilities is contingent on the realization of the novel sensors that will developed and built in the FASTTRACK program.

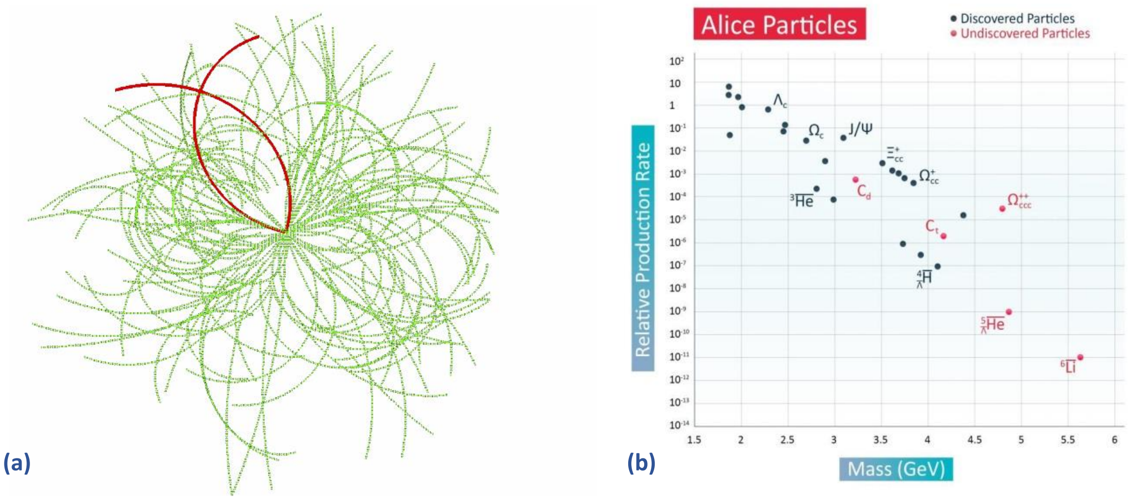


Figure 13: (a) *Visualization of a reconstructed heavy-ion collision emitting a low-energy electron pair (red tracks), the key ingredient to studying chiral symmetry restauration.* ***(b)*** *Rare particles becoming accessible with ALICE 3, possibly including yet-undiscovered nuclei with a nucleon replaced by a charmed baryon (super-nuclei).*

2.3 Coherence of LSRI components

Coherence with HL-LHC common goals – The trackers that will be developed as part of FASTTRACK perform an essential task within the HL-LHC experimental program, and as such are a coherent part of its common goals. This is borne out by the fact that the realization of the tracking systems is part of a coherent international effort, regulated by *Memoranda of Understanding* (section 4.1), in which the contribution of each partner is clearly specified. The Dutch contributions mirror the deliverables of FASTTRACK, targeting essential components of the ALICE, ATLAS and LHCb trackers, without which the science goals presented in the previous sections cannot be achieved. All FASTTRACK milestones (section 4.1.1) are tailored to match the global developments of the HL-LHC project and of the individual experiments.

Coherence of components – FASTTRACK entails developing all components needed for a tracking system: new sensor concepts with fast signal processing circuitry; lightweight mechanical and cooling solutions to assure optimal sensor operation; novel reconstruction algorithms on heterogeneous computing architectures to extract from the data the maximum potential for physics analysis. Failure to deliver on any of these components may lead to global failure of the project. Moreover, the high level of integration of the components implies that the design and production of one impact greatly on others, in terms of schedule and performance. This is why, rather than concentrating on a single component, FASTTRACK will deploy an ***integral approach*** to maximize our control and impact on the overall project. FASTTRACK forms an essential part of not one but three experiments at the HL-LHC, as reflected in experiment-overarching specifications. This will strengthen the overall coherence, as the large community relying on the outcomes of FASTTRACK will open possibilities for joint R&D to overcome common challenges (fast signals, light and radiation-resistance structures, high-speed data transmission, etc.), joint investments in test set-ups (laser beams, particle telescopes, read-out systems, data analysis software) and the sharing of knowledge and resources among local groups. By way of example, all experiments need beam tests that rely on very precise particle telescopes (fig. 14).

Figure 14: *Beam test of VELO pixel modules.*

Coherence with Nikhef portfolio – We have tailored the Dutch contribution proposed in FASTTRACK to optimally exploit Nikhef's scientific and technological portfolio, which encompasses state-of-the art sensor test facilities, Application-Specific Integrated Circuit (ASIC) design, mechanical structure design and engineering (fig. 15), pioneering work on CO_2 cooling systems, forefront research on hybrid computing, etc. The coherence is further strengthened by the unique collaborative organizational structure of Nikhef (see section 4.1) in which the Dutch ALICE, ATLAS and LHCb groups are organized in three national research programs. This enables more than just efficient sharing of know-how: scientists from individual groups work together on technology projects and develop solutions with common utility for all LHC experiments; engineers and technicians work in a matrix structure ensuring a flexible approach for efficient resource sharing.

Figure 15*: Nikhef engineer inspecting the VELO before installation.*

Added value beyond individual components – FASTTRACK enables *4D tracking* at HL-LHC experiments–and in addition gives the Dutch research community a strategic head-start in exploring and exploiting emerging technologies that will be crucial for experiments at future colliders like the FCC [35, 36] (see section 3.2) and in other areas of science.

2.4 Applying consortium, researchers, research groups and other partners involved

Particle physics research is international. The Netherlands (as most European countries) is simply too small a country to be able to completely fund experiments at particle colliders, like ALICE, ATLAS and LHCb, which can be categorized as Big Science projects. Even sub-detector construction projects, like tracking systems, are too challenging to be realized in a single country, and are organized in international collaborations. FASTTRACK must therefore be seen in this international context. All our consortium members, without exception, work in a strongly international environment and have developed strong international reputations, networks and collaborations. Our consortium consists of scientists who have expertise in fundamental physics research at particle colliders and master the workings of the experimental apparatuses. In the next subsections, we will outline how the FASTTRACK team has the expertise to build and commission large-scale infrastructures for particle detection, the demonstrated ability to manage teams, and the scientific quality to realize the expected science breakthroughs.

The Nikhef collaboration – The FASTTRACK consortium gathers expertise from six Dutch universities and institutes: NWO-I Nikhef, UvA, VU, UU, UM, RUG, and RU. It is embedded in the existing Nikhef collaborative structure (section 4.1). Through Nikhef, the consortium members participate in three international LHC experiments: ALICE, ATLAS and LHCb. The consortium builds on and extends Nikhef's organizational principle: development of common detector technologies for LHC experiments is performed jointly. Similarly, research on advanced physics data processing technology is performed jointly with the experts that have built the Dutch Tier-1 data processing center, and with AI and quantum algorithm experts at Dutch universities. Corroborating the benefits of the consortium's organizational model, the 2024 independent review of Nikhef concluded [37] that *"... the tight collaboration between Nikhef and the universities enables an impact which is greater than the sum of its parts, driven by the vision for the Nikhef strategy and the opportunities that can be provided by the central grouping of expertise and infrastructure. Other countries look to the Netherlands as setting an example in terms of what can be achieved with this model."*

Consortium members – The FASTTRACK co-applicants are a subset of the wider Dutch LHC community (about 100 scientists). As can be seen from table 1, they have specific expertise in all the areas relevant to realize FASTTRACK (detector mechanics, sensors, electronics and ASICs, data acquisition systems, reconstruction algorithms and computing) and to harvest the science from the ensuing physics program. In the table, we have singled out the top expertise and the main role for each contributor, but we would like to point out that members of our community typically contribute to the building of the facility, as well as to the data taking and analysis.

Table 1: *Scientists who will contribute to the realization of FASTTRACK. The labels 'WP' and 'SB' denote the contributions to work packages and scientific breakthroughs, respectively.*

Name/gender/affiliation	Expertise & contribution to FASTTRACK
Roel Aaij (m; Nikhef)	Computing accelerator hardware and algorithms (WP5.1,5.2)
Kazu Akiba (m; Nikhef)	Pixel sensors, cooling, detector construction (SB2.1,2.2; WP1.1,4.1,4.2)
Niels van Bakel (m; Nikhef)	Program Leader R&D, sensors & electronics (WP2.1,2.2)
Stan Bentvelsen (m; Nikhef)	Senior Advisor
Martin van Beuzekom (m; Nikhef)	Pixel sensors, read-out chip development and cooling (WP1.1,2.1,3.1)
Kristof de Bruijn (m; RUG)	Data Acquisition, electronics and physics analysis (SB2.1,2.2; WP3.2)
Sascha Caron (m; RU)	Machine Learning algorithms for particle tracking (SB1.1,1.2,1.3; WP5.2)
Panos Christakoglou (m; UM)	Computing and reconstruction algorithms (SB3.1,3.2,3.3)
Elena Dall'Occo (f; Nikhef)	Pixel sensors, electronics, detector construction (SB3.1,3.2,3.3; WP1.3,2.2)
Jorgen D'Hondt (m; Nikhef)	Consortium PI and Nikhef director
Frank Filthaut (m; RU)	ATLAS Program Leader, sensors, physics analysis (SB1.1,1.2,1.3; WP1.2)
Martin Fransen (m; Nikhef)	Pixel sensors, electronics (WP1.2,2.1)
Alessandro Grelli (m; UU)	Pixel sensors, cooling, detector construction (SB1.1,1.2,1.3; WP4.1,4.2)
David Groep (m; Nikhef,UM)	Program Leader PDP, computing infrastructure (WP5.1,5.2)
Wouter Hulsbergen (m; Nikhef,VU)	Detector construction, tracking & vertexing algorithms (SB2.1,2.2; WP4.3)
Marco van Leeuwen (m; Nikhef)	Spokesperson ALICE experiment (SB3.1,3.2,3.3)
Marcel Merk (m; UM,Nikhef)	Detector design, reconstruction algorithms (SB2.1,2.2; WP5.2)
Clara Nellist (f; UvA)	Pixel sensors, Outreach (SB1.1,1.2,1.3; WP1.2)
Antonio Pellegrino (m; Nikhef,RUG)	Electronics, DAQ, Mechanics, project management (WP3.1,3.2)
Ann-Katrin Perrevoort (f; RUG)	DAQ, physics analysis (SB2.1,2.2; WP3.2)
Tristan du Pree (m; Nikhef,UT)	Future accelerators, physics analysis (SB1.1,1.2,1.3)
Gerhard Raven (m; VU)	Real-time analysis software, physics analysis (SB2.1,2.2; WP5.1)
Mara Senghi Soares (f; VU)	Program Leader LHCb, physics analysis (SB2.1,2.2)
Raimond Snellings (m; UU)	Program Leader ALICE, MAPS sensors, physics analysis (SB3.1,3.2,3.3)
Hella Snoek (f; UvA)	Pixel sensors, physics analysis (SB1.1,1.2,1.3; WP1.2)
Jory Sonneveld (f; UvA)	Pixel sensors (WP1.3,2.2)
Niels Tuning (m; Nikhef)	Deputy Program Leader LHCb, project management (SB2.1,2.2)
Wouter Verkerke (m; Nikhef,UvA)	ATLAS Program Leader, physics analysis (SB1.1,1.2,1.3)
Marta Verweij (f; UU)	Deputy Program Leader ALICE, physics analysis (SB3.1,3.2,3.3)
Marcel Vreeswijk (m; UvA)	Mechanics & cooling, project management (SB1.1,1.2,1.3; WP4.2,4.3)
Jacco de Vries (m; UM)	Machine learning algorithms, physics analysis (SB2.1,2.2; WP5.2)
Mengqing Wu (f; RU)	DAQ, physics analysis (SB1.1,1.2,1.3; WP1.2,3.2)

The more senior members have a 25-year record of successfully leading major projects for the construction of particle detectors as well as data processing and computing infrastructure, while junior members bring in new expertise of state-of-the-art technology. Several members of the consortium have already made major contributions to the construction of the current detector systems of ATLAS, LHCb and ALICE, funded by previous roadmap investments. Prominent examples built in the Netherlands by scientists of the consortium are:

- ✓ **ALICE**: the Silicon Strip Detector [4] and MAPS-based Inner Tracking System [5].

- ✓ **ATLAS:** the Barrel Outer Layer muon drift chambers [38, 7], the SemiConductor Tracker End Cap [6, 7] and the FELIX readout system [39, 40].
- ✓ **LHCb**: the silicon-strips VELO [8], the straw-tubes Outer Tracker [10], the silicon-pixels VELO and the scintillating fibers tracker [9].
- ✓ **Computing**: the realization of the Dutch TIER-1 computing center based on the GRID model, and the implementation of GPU accelerators for event filtering [41].

These large-scale infrastructures have resulted in a wealth of scientific discoveries (see section 2.1.1). Their realization would not have been possible without the Dutch expertise and investments. In these footsteps, the implementation of 4D particle-tracking systems for the high-luminosity phase of the LHC collider necessitates the unique Nikhef portfolio of scientific knowledge and technical facilities.

Connection to scientific breakthroughs – In section 2.2 we introduced three lines of breakthrough research enabled by FASTTRACK, corresponding to the three experiments at the LHC. The FASTTRACK consortium covers all three experiments: Nikhef and UU participate in ALICE; Nikhef, UvA and RU participate in ATLAS; and Nikhef, VU, RuG and UM participate in LHCb.

Diversity and inclusion – The institute affiliations are approximately uniformly distributed over the Nikhef institute and the university partners, indicating the geographical spread of the consortium. In addition, the consortium reflects the average gender balance of our field. At the junior to mid-career level (up to 17 years after PhD), the consortium is close to gender parity, thanks to Nikhef's staff hiring practices. Diversity and inclusiveness are also high on the agenda of Nikhef as well as in our international collaborations, who have formalized a code of conduct [42]. At this international level, we promote the same goals, through membership of diversity & inclusion teams as well as early-career scientists board panels that are now in place in all international collaborations.

2.5 Strategy and embedding

Within the Dutch scientific landscape, all Dutch activities at CERN are unified and federated in Nikhef, the National Institute for (Astro)particle Physics. Nikhef's mission is to study the interactions and structure of all elementary particles and fields at the smallest distance scale and the highest attainable energy. Aligned with the principles of Big Science, the strength of the Nikhef partnership lies in the close cooperation among its partners and its careful selection of joint research programs: *"Nikhef has a strong and coherent organisation that allows the institute to take a visible place in the international landscape. Nikhef's reputation is outstanding and Nikhef is welcomed in all European high-level committees for oversight and steering of the research. The institute is very visible on the international landscape, much more than the size may suggest. Nikhef has been on the vanguard of introducing new technologies and continues to do so by carefully selecting topics. The scientific impact is evident in the distinction of the academic staff."* – International Strategic Evaluation Panel 2024 [37].

The embedding in Nikhef ensures that all activities efficiently use the available resources and are focused toward common goals such as to maximize the impact of the Dutch groups in the very large international LHC collaborations, well beyond the relative monetary Dutch contribution (see section 4.2).

National strategy and prioritization – National collaborations are established with the center of excellence for Gravitation and Astroparticle Physics (GRAPPA) at the University of Amsterdam, the Institute for Mathematics, Astrophysics and Particle Physics (IMAPP) at Radboud University, the institute for Gravitational and Subatomic Physics (GRASP) at Utrecht University, the institute for Gravitational Wave and Fundamental Physics (GWFP) at the University of Maastricht, and the Fundamentals of the Universe (FotU) research theme at the University of Groningen. Nikhef is well positioned in the national e-Infrastructure as coordinated by SURF and works together with the NWO institute ASTRON in data-intensive computing. Nikhef has close contacts with a large number of companies and has set up industrial research collaborations via start-up companies as e.g. Amsterdam Scientific Instruments.

In the Nikhef strategy for the period 2023-2028 [43], the exploitation of the HL-LHC is listed as the first priority of the partnership. At the national level, the Dutch Research Agenda (NWA) identified *"building blocks of matter and foundations of space and time"* as an important scientific route [44]. The importance of the HL-LHC program is reflected in the fact that about half of the scientific staff of the Nikhef partnership will be involved in it, including people in the ATLAS, LHCb, ALICE, Physics Data Processing (PDP), R&D, and theory programs. Nikhef is optimally positioned to realize such challenging experimental projects, due to the recognized quality of its technical groups: *"The real backbone of the success of Nikhef comes from the excellent mechanical, vacuum, and electronics labs, both in the teams and the technical capabilities."* – International Strategic Evaluation Panel 2024 [37].

The FASTTRACK technology developments fit well into the National Technology Strategy, as a number of the selected 10 crucial technologies feature strongly within our research program. Section 3.2 illustrates how we will transfer knowledge and technology such that the FASTTRACK know-how finds its way to other applications beyond our field, and how our efforts in the domain of the development of key-enabling technologies can impact the Dutch society and economy. Here it is worth mentioning that some of FASTTRACK developments will occur in the domains labeled as critical in the Knowledge and Innovation Agenda (KIA) with a focus on Key Enabling Technologies (*sleuteltechnologieën*) published as part of the Knowledge and Innovation Covenant (KIC 2024-2027). A key example is the healthcare sector, which is already benefiting for decades from advances in our field of radiation imaging.

International strategy and embedding – In the context of the broader international strategy for particle physics research, the Dutch particle physics community provides input to the European Strategy for Particle Physics (ESPP) [45]. The ESPP serves as the cornerstone of Europe's decision-making process for the long-term future of the field. Based on the input of the community at large, the strategy takes into account the worldwide particle physics landscape and developments in related fields to coordinate activities across a large, international and fast-moving community with the aim to maximize scientific returns. The exploitation of the HL-LHC and its experiments are the top priority for the next decade [1]. The LHC also appears as a landmark project in the most recent 2021 ESFRI Roadmap [46]. The development of the 4D-tracking infrastructure such as proposed in FASTTRACK is considered an essential part of the European roadmap for detector R&D [3] mandated by the ESPP [45].

In summary, the development of the 4D-tracking infrastructure is extremely challenging as it pushes the limits of what is technically feasible. The FASTTRACK consortium has the expertise and track record to realize it. Doing so will provide an excellent opportunity to advance our capabilities and will benefit a broad range of Dutch research groups. This will enable the Netherlands to retain and expand its leadership position in particle physics for the next decades.

3. Impact

With FASTTRACK targeting the international collaborations carrying out fundamental research at the HL-LHC, it will address these user groups and exploit their access policies and the capacity of the most powerful particle accelerator ever built. In this chapter we outline the various impacts FASTTRACK will have. Its main users will be the multidisciplinary and international LHC user community (section 3.1). The impact of the proposed work on fundamental physics research (section 3.2) is particularly deep: the work is a crucial part of the HL-LHC program that is needed to fully realize the discovery potential of the LHC experiments. It will also give Dutch scientists in ALICE, ATLAS and LHCb the needed visibility to play leading roles in international construction projects and in the science harvesting of the HL-LHC. Finally, the hard- and software developed in the project will also have impact on other scientific fields, on society, and on high-tech industry (section 3.3).

3.1 User groups, access policy, and capacity

User groups – More than 5000 scientists from about 200 institutes and universities world-wide participate in the LHC experiments ALICE, ATLAS and LHCb. This user group includes all Dutch groups who are interested in the fundamental physics goals of the LHC experiments, schematically shown in section 2.4, covering all universities engaged in experimental particle physics in the Netherlands. All Dutch groups participating in the ALICE, ATLAS and LHCb experiments are represented in this proposal.

Access policy – The Dutch groups have an open policy: any Dutch scientist can become a member. At the international level, to participate in an LHC experiment, a research organization has to apply to acquire membership to the collaboration. A special board in the collaboration organization reviews each membership application, to verify that the applying group has sufficient resources to be able to effectively contribute. Members of an LHC collaboration are automatically granted full access to the CERN facilities with the status of unpaid scientific associates, under the terms of a *CERN user contract*.

The policies and terms of use of the experiments are defined in a constitution document (see e.g. ref. [47]) for each experiment. All LHC collaborations recognize that their success is bound by individual commitment to physics and the prospect of exciting new results that can only be achieved with a complete and coherent collaborative effort. All groups collaborating in the experiments are therefore directly involved in the decision-making processes. Membership of a collaboration requires a fee from each group, proportional to the number of academic staff members holding a PhD. The membership fee accounts for the maintenance and operation of the experiment, while the investments of all participating groups for the construction of the detectors are specified in Memoranda of Understanding. The LHC experiment governance is described in section 4.1.

Notably, PhD candidates and students are exempt of membership fees, as a way to support the education and training of young scientists. This implies that students have free access to do exciting projects with state-of-the-art instrumentation and with the data collected by the experiments. They are also allowed access to the CERN facilities and to all events (collaboration meetings, workshops and international conferences). A number of opportunities for financial support are offered to students, for example via the CERN *Doctoral Student Program* and *Technical Student Program*, and several *Summer Student Programs* offered by various institutions.

All members of the collaboration have full access to all data and they represent their collaboration during scientific presentations of analysis results at international workshop and conferences. Any output from the LHC experiments is shared by all members of the collaboration, and subject to rigorous review and fact-checking before being made public. Data collected by the LHC experiments are subject to a CERN-wide ***Open Data Policy*** [48], (section 3.2.4).

Capacity – It is unlikely that the user demand will exceed the capacity of the LSRI for which funding is requested. This is in part because there is no competition for the usage of the LHC beam time: it is exclusively allocated to the LHC experiments, while a careful design of the so-called *bunch structure* (see section 2.1) allows data to be collected simultaneously at all collision points; in that sense, there is no issue with the LSRI capacity. The LHC experiments continuously attract new groups interested in fundamental physics research, who bring in new extra resources and know-how. LHC has proven it can meet this increased user demand by accepting new member groups.

3.2 Services to scientific users and impact on the field

The scientific breakthroughs expected from the LHC experiments in the HL-LHC era will provide ground-breaking new results that will have major impact on a number of fundamental physics questions, as has been illustrated in section 2.2. The prominent role of these facilities is recognized in all relevant national and international bodies. This is exemplified by the top priority given to the HL-LHC by the European government agencies for scientific funding, following a strategy report [1] by the European Strategy for Particle Physics [45], and by the U.S. Department of Energy [49], following a strategy report by the Particle Physics Project Prioritization Panel (*P5*) [2]. Below we outline the specific contribution of the LSRI to the overarching impact.

3.2.1 Services to scientific users

As an enabling technology within the larger context of the HL-LHC, the research infrastructure does not provide an isolated service to users. Instead, the proposed fast-timing instruments will enable all scientists in the LHC experimental collaborations to study particle collisions at unprecedented rates, providing them with the precision they need to address problems beyond today's frontiers of particle physics and to uncover new rare physics phenomena.

3.2.2 Global scientific impact

The central role played by the LSRI proposed here, 4D tracking systems with ultra-fast silicon detectors, i.e. tracking systems able to concurrently precisely measure the spatial and temporal coordinates, has been recognized by the European Committee for Future Accelerators in their roadmap document [3]. There is consensus that the LSRI proposed here will have a deep impact on the field of particle physics: the installation of tracking detectors with advanced fast-timing technologies in the ALICE, ATLAS and LHCb experiments, is essential for the success of the experiments and to enable world-class scientific research that will lead to the ground-breaking results illustrated in section 2.2 on fundamental scientific questions, such as on the origin of particle mass, the absence of anti-matter, the emergence of nuclear matter etc. As such, the success of FASTTRACK *will have impact on the experimental program as a whole, and are crucial to achieve the global science impact of the HL-LHC*.

Beyond the direct deliverables, it is the knowledge gained along the way that will constitute a crucial asset for the whole field. The emerging field of silicon sensors for 4D tracking is very young and the capabilities of present technologies have not yet been fully exploited; the interplay between sensors and electronics in timing applications is not fully studied; beside the sheer time resolution, several other parameters (e.g. material budget, power, rates, area, radiation tolerance) have to be reckoned with in determining the overall architecture. *The wealth of knowledge accumulated during FASTTRACK will have the highest impact on the future of the field*.

Last but not least, the impact of FASTTRACK *will stretch well beyond the LHC experiments*. In fact, the level of timing accuracy needed by future experiments will only grow: 4D tracking at the FCC-hh [36], at the foreseen 1000 multiple interactions per beam crossing, will require 10 ps; a similar resolution will be demanded by Time-of-Flight systems at FCC-ee [35] and other Higgs/Electroweak/Top factories. In this sense, FASTTRACK represents ***a long-term investment and stepping stone whose impact cannot be overestimated***.

3.2.3 National scientific impact

The global scientific impact described above will also be felt by the Dutch scientific community. Below we discuss additional scientific impacts for the Netherlands associated with FASTTRACK.

On the FASTTRACK consortium – The technologies and the expertise that will be acquired during the realization of the hardware and the software for the 4D tracking systems of FASTTRACK will become part of the DNA of the Nikhef partnership as a whole, and constitute a tremendous asset for its scientific portfolio, easily spendable in other areas of research beyond and beside the LHC. In addition, there are multiple indirect impacts to be expected:

- ✓ Although the science roles are not directly tied to hardware, experience shows that countries with important hardware contributions have key positions in the collaborations; therefore, the prominent role that the funding requested here will give us in the construction projects guarantees a high return beyond the scale of the investment (see section 4.2.2): it will help members of the Dutch groups in ALICE, ATLAS and LHCb occupy leadership positions in the international tracking projects and, more in general, leading positions in the collaborations;
- ✓ Mastering the technologies used in the construction of the readout systems (*WP3.1, 3.2*), of the modular detector units (*WP4.1*) and of the detector infrastructure (*WP4.2, 4.3*) will enable the Dutch groups to play visible roles in the optimal operation of the experimental facilities;

- ✓ Direct knowledge of the key features of the sensors (*WP1.1, 1.2, 1.3*), of the on-sensor signal processing logic (*WP2.1, 2.2*) and of the track-reconstruction software (*WP5.1, 5.2*) will prove crucial for the analysis of the physics data, which, in turn, will give the Dutch groups an advantage in the science harvest;
- ✓ The strategic choice to focus the Dutch contribution to all three experiments at LHC on one shared technology will give further coherence to the three communities of ALICE, ATLAS and LHCb in the Netherlands, enhancing their relative weight and strengthening their impact in the three international collaborations;
- ✓ It will provide Master and PhD students direct access to state-of-the-art detection technologies, making Nikhef and the partner universities more attractive education centers.

On the Dutch theory community – There is a large theory community in the Netherlands carrying out research in several areas of physics, including particle physics, organized as a cooperation between the theoretical physics groups of six Dutch universities and of the NWO Institute Nikhef [50]. The science harvest resulting from the integration of the FASTTRACK infrastructure in the ALICE, ATLAS and LHCb detectors will enable members of the theory community to carry out the most sensitive tests of several hypothesized or postulated fundamental aspects of particle interactions, with the clear advantage of having a direct link with the Dutch community engaged in the experimental collaborations. To exemplify, the possibility to access tracking information will enable precise calculations of the substructure of *'jets'* (sprays of particles flying out from high-energy particle collisions) and boost the research program of Dr. W.J. Waalewijn on track-based jet algorithms (*'track functions'*) [51]. Another example is the impact on the work of Dr. M. van Beekveld on final-state *'parton showers'*, an essential tool for predicting strong-force effects at colliders [52].

On future research at Nikhef – Finally, the realization of the FASTTRACK infrastructure will have a strong impact on the future of the Nikhef partnership. The additional technological portfolio built up through this project will be a stepping stone toward future research programs in collider physics, in astro-particle physics, and in gravitational wave physics, either through the direct application of 4D tracking detector technologies or through the expertise in mechanics, cooling, electronics, readout systems and computing. Furthermore, it will further strengthen Nikhef's position as the place to be for young talents in frontier research, as well as make Nikhef more attractive for skilled engineers.

3.2.4 Data management and open data policy

The ultra-fast timing tracking detectors of FASTTRACK will produce data that will be recorded and processed together with those of the other detector components in ALICE, ATLAS and LHCb. The format of the tracking data necessary to reconstruct particle trajectories in ultra-dense particle environments will be defined by each experiment and will be tailored to long-term use, reuse and preservation. The data of all LHC collaborations will be managed by CERN and the *Worldwide LHC Computing Grid* (WLCG) [53] (see also section 5.2). Calibrated reconstructed data with the level of detail useful for algorithmic, performance and physics studies is accessible to all members of an LHC collaboration; in practice, due to the data samples sheer size and complexities, re-using the data in a meaningful way requires appropriate data processing capabilities as well as the concurrent release of appropriate simulated data samples, software, reproducible example analysis workflows, and documentation, all of which are centrally provided by the collaborations to all members.

Being part of the ALICE, ATLAS and LHCb data, FASTTRACK data are subject to a CERN-wide ***Open Data Policy*** [48] that foresees use cases such as reinterpretation and reanalysis of physics results, education and outreach, data analysis for technical and algorithmic developments and physics research. This policy distinguishes four levels of complexity of data, three of which are publicly accessible. The fourth one – raw data – is accessible to the LHC collaborations only, as it is practically not usable in a meaningful way outside the collaborations due to the size and the complexity of the data, metadata and software, and due to the required knowledge of the detector itself and of the reconstruction methods. The FASTTRACK data will be released through the CERN Open Data Portal [54] that will be supported by CERN for the lifetime of the data.

To reward the countries/institutes which have enabled the experiments, the CERN Open Data policy follows the common practice of granting collaboration members ***preferred access to the data during a proprietary period***: public data releases occur periodically, following an appropriate latency period to allow thorough understanding of the data, the reconstruction and calibrations, as well as to allow time for the scientific exploitation of the data by the collaboration; the aim is to commence data releases within five years of the conclusion of the run period and to make full datasets available at the end of the collaborative project.

Through their participation in the LHC collaborations and in the WLCG, the Dutch community has access to all data (including provenance metadata, simulated data samples, software and analysis workflows) and to the processing capabilities required to analyze them. Additional assets for the Dutch particle physics community are the Dutch National E-Infrastructure services that are coordinated by and hosted at SURF [55] (itself a WLCG partner) and partly at Nikhef, as well as the support provided by the FuSE Fundamental Sciences E-Infrastructure [56]: these give our community an advantage in effectively and timely handling these data volumes and re-using them for tracking and detector studies.

3.3 Impact on other scientific fields and societal and economic impact

3.3.1 Expected impacts on other scientific fields

The FASTTRACK infrastructure is primarily targeted at collider experiments. However, the technological advances and the expertise that will be acquired during the project have a high potential for applications and impact in research fields beyond this primary focus. Below, we provide a few examples to substantiate this, based on our experiences in long-term collaborations with industrial and medical partners (see also ref. [43]).

On collider development – All advances in sensor and ASIC technologies, as well as in electronics, mechanics and cooling, as part of FASTTRACK will be essential for the development of experiments at any possible future collider, as recognized in the roadmap [3] of the European Committee for Future Accelerators [57]: the International Linear Collider (ILC) [58], the Future Circular Collider (FCC) [35, 36], or future muon colliders [59].

On astro-particle physics – The impact on astro-particle physics of these same technological advances in pixel sensors and readout is more than conceivable. In the Nikhef partnership, we have a strong connection with the Dutch groups engaged in astro-particle physics research, for example in the Deep Underground Neutrino Experiment (DUNE) [60]. It is thanks to readout pixels like those developed for collider experiments that the DUNE '*near detector*' can produce full 3D imaging of tracks; the option of pixel readout is also being considered for a future '*far detector'.* One of the outstanding questions in fundamental physics is the asymmetry between neutrino and anti-neutrino interactions (the so-called *leptonic CP violation*). To resolve this question, it is necessary to *tag* high-intensity neutrino beams, i.e. to implement an identifier of neutrinos and their anti-particles, anti-neutrinos, as close as possible to the beam production point, before they *oscillate* into other neutrino flavors. To drastically reduce the systematic uncertainties in this procedure (due to neutrino flux, cross-section, and energy estimates), the nuTag project has recently proposed a novel experimental technique [61, 62] based on projected advances in silicon pixel technology, most notably ultra-fast timing technologies coupled to high-rate readout and high radiation tolerance. The unprecedented 50 ps timing precision provided by FASTTRACK 4D trackers will allow the reconstruction of the neutrino properties from the initial particle decays in which the neutrino beams are produced and to tag the produced neutrinos. This can have a large impact and the Dutch groups in neutrino-beam experiments can benefit from this knowledge transfer to push the nuTag approach.

On material science – Time-of-flight (TOF) techniques are widely used in many scientific fields. Key to investigation of nuclear reactions is spectroscopy of the neutron energies produced in such reactions; fast-neutron spectroscopy relies on TOF measurements. The Timepix [28,29] chip, designed by Nikhef in cooperation with CERN, has already been successfully employed in this field [63, 64, 65]. Velocity-map-imaging spectrometry [66] and neutron diffraction techniques [67] also use TOF techniques and Timepix chips to study the microstructure of polycrystalline materials. These scientific fields, therefore, will directly profit from the FASTTRACK breakthrough in fast-timing measurements.

On cooling technology – Cooling innovation in FASTTRACK is based on Nikhef's pioneering role in developing bi-phase CO_2 cooling [68]. This cooling approach has become the preferred choice, over fluorocarbon or other greenhouse cooling liquids, for thermal management in particle physics trackers (see e.g. [69]). Cooling will remain a central topic for all future detectors: it is essential for long operation of silicon sensors and ASICs in harsh radiation environments and, for some applications, scaling up current cooling systems will not work. Therefore, the innovations brought by FASTTRACK on cooling microchannels etched into silicon sensors and on sublimation cooling (*WP 4.2*, see section 5.1.4) are expected to have a significant impact for detectors at future collider experiments [3] and in space stations [70]. Beyond the academic realm, these innovations may reverberate in fields like spray chilling for food, pharmaceutical products and cryopreservation.

On medical technologies – The chips that will be developed in FASTTRACK trace their origin to the family of Medipix [71] and Timepix [28, 29] chips. Both have long histories of applications in the medical field:

- The work of the **Medipix** collaboration [71], of which the Nikhef 's Detector R&D group is a founding partner, has led to the development of color X-ray tomography [72], which produces clearer and more accurate pictures that should help doctors give their patients more accurate diagnoses. At present, the *Flexray* project [73], in collaboration with Nikhef's sister institute Centrum voor Wiskunde & Informatica (CWI), with the Nikhef spin-off company ***Amsterdam Scientific Instruments (ASI)*** [74] and ***Tescan XRE*** based in Ghent (Belgium), is exploiting the advantages of the Medipix3 chip to realize a system capable, through advanced algorithms, of online adaption of the data-taking strategy thereby limiting the required dose; e.g. studies in collaboration with the University of Utrecht are verifying whether this could provide an early indication of whether a person suffers from osteoporosis. The Dutch company ***Malvern Panalytical*** [75] uses the single-photon counting capabilities of Medipix3 for their cutting-edge X-ray diffractometers, used for a myriad of purposes such as the characterization of pharmaceuticals, the evaluation and synthesis of new materials and the detection of counterfeit drugs.

- **Timepix** chips (fig. 16) also have a long history of applications in medical imaging [76, 77], as well as in space dosimetry and education. These innovations continue today; a noteworthy example in the Netherlands is in the domain of clinical diagnostics of high-throughput single-cell molecular imaging technologies in the Maastricht MultiModal Molecular Imaging Institute (M4i) [78], where state-of-the-art matrix-assisted laser desorption/ ionization (MALDI) mass spectrometry and secondary-ion mass spectrometry (SIMS) are targeted to the integration of metabolic and proteomic images with cellular resolution into digital pathology.

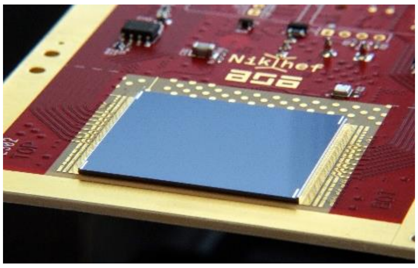


Figure 16: *Timepix4 chip with sensor.*

Therefore, based on our past experience, we believe that FASTTRACK will impact the field of medical technology. We expect the most direct impact on imaging techniques, since Time-of-Flight instrumentation and methods like those that will be developed in FASTTRACK play a crucial role in determining the resolution and mass accuracy of these techniques; e.g. FASTTRACK advances in high-precision fast timing detection will directly impact the development of MALDI and SIMS technologies.

On data science – FASTTRACK also offers opportunities for knowledge utilization in data science. This is due to the FASTTRACK data being subject to a CERN-wide Open Data Policy [48] and released through the CERN Open Data Portal [54]. This will extend the impact of the data beyond the typical use case of physics studies to reinterpret published results: e.g. it will render possible their re-use for algorithmic studies in the machine-learning domain and beyond, to which, at the discretion of each experiment, even subsets of raw data can be released; it will maximize their impact on education and outreach, through dedicated re-usable data subsets, selected and formatted in simplified, portable and self-contained ways, containing physics quantities that are suitable for independent analysis, for educational and public-understanding purposes.

3.3.2 Impact on industry

Nikhef has a proud history of transferring its innovations to industry. For example, the Timepix family of ASICs [28, 29] was triggered by an idea of Nikhef scientists, who designed its timing circuitry. ***ASI*** [74] started up in 2011 from the Nikhef R&D group based on a license of the first Timepix; in 2017, ASI acquired a license for the Timepix3 technology and currently they have a Timepix4 (fig. 16) R&D license (in preparation for a commercial one that should become available towards the end of 2024). These efforts have since then led to many industrial applications becoming a core component for ASI's next generation hybrid pixel cameras for X-ray or electron microscopy; as a by-product, the SPIDR [79] read-out system for Timepix4 was developed in close collaboration with ASI to ensure a smooth transition to a marketable product. Another example, dating back to the early 2000s and still very lively, is the cooperation with ***Malvern Panalytical*** [75], which still relies on Nikhef staff and facilities for part of their detector supply chain and is currently verifying the potential of Timepix4 [29] for their application domain. Timepix is also being exploited for radiation monitoring in NASA's Orion spacecraft and at the International Space Station. Other success stories are linked to the deep-tech venture builder ***HighTechXL*** [80], which continues to reach out to Nikhef for support with other start-ups that could benefit from our knowledge or facilities: ***Incooling*** [81] worked with Nikhef on chip cooling, closed a 3.5 M€ investment round with the Germany-based Pierburg Pump Technology (part of the Sensors and Actuators Division of Rheinmetall AG), and is now an established company; ***Inphocal*** [82] applies a commercial license for the structured laser beam invented at CERN to various laser-marking applications, in which cutting-edge laser systems replace more polluting inkjets; ***Aircision*** [83] develops free space optics systems as a wireless alternative for backhaul communication networks. As in these successful examples, we foresee similar opportunities to collaborate with industrial and scientific partners throughout FASTTRACK.

3.3.3 Impact on the economy

A direct impact on the economy will result from the FASTTRACK construction process itself, as Dutch high-tech companies will be involved in providing materials and services to the project. We have a long history of co-developing technical solutions or outsourcing them to Dutch industrial partners; among others: ***Oceanz*** provided precision 3D-printed parts for the scintillating fiber tracker of LHCb; ***Airborne*** was involved in building composite parts for the new ATLAS inner tracker; ***Capable*** provided complex cabling solutions for several projects. FASTTRACK will stay on this track, supported by our Industrial Liaison Officers who are well connected to the Dutch industrial domain. Concrete examples of possible synergies are: 3D-printing processes like those in use at *Oceanz* and associate companies can be further developed to realize the microchannel cooling structures necessary for the work described in *WP4.1* and *4.2* (section 5.1.4); and lightweight structures like those realized at *Airborne* can bring the solution to the requirements of *WP4.3* (section 5.1.4).

3.3.4 Measures to support impact

Knowledge and technology transfer – To facilitate knowledge utilization, FASTTRACK can rely on the infrastructure that Nikhef has created for knowledge and technology transfer to industry, society and the general public, which is an integral part of Nikhef's mission. Knowledge transfer is spearheaded by Industrial Liaison Officers (ILOs), who make connections with companies and promote collaborations. In the Netherlands, Nikhef plays a leading role in ***BigScience.NL***, the Dutch ILO network [84]. This network acts as an intermediary between the Dutch supplier business/industry and big science-organizations for matters related to procurement, innovation and tech-transfer opportunities. It also connects to many high-tech companies who meet regularly to further their involvement in the domain of Big Science. Over the past decade, BigScience.NL has observed a growth in the number of Dutch companies active on the market of large research infrastructures – a strong signal for the relevance of Big Science for science and innovation. The BigScience.NL network, in turn, is integrated into the Pan-European Research Infrastructure ILO Association (PERIIA) [85], of which Nikhef staff member Dr. J. Visser is a board member. The importance of ILO networks has been recognized by the Dutch Minister of Economic Affairs and Climate (EZK) who, in 2023, made funding available to enable multi-year planning (870 k€ for four years). With the aim of finding applications for the technologies developed in large-scale particle physics infrastructures, the CERN knowledge-transfer group reaches out to member states through direct discussions with large companies and through the CERN Venture Connect program [86]. This program, with a strong focus on start-ups, has been developed with significant input from HighTechXL [80], established on the Eindhoven High Tech Campus. Through Nikhef, there has been a close link between CERN and HighTechXL since 2018, which has led to the incorporation of a number of companies inspired by CERN technologies (see below).

Figure 17: *Nikhef ILO opening a meeting with Dutch industry on HTSM's strategic program on Advanced Instrumentation, which challenges researchers and companies to jointly develop knowledge for technological breakthroughs and innovative applications.*

Outreach and communication – Where did all the antimatter go after the Big Bang? Do all particles get their mass through the Higgs mechanism? Why are there exactly three generations of elementary particles? How can we explain the remaining 80% of the mass of the universe, whimsically referred to as dark matter? FASTTRACK is part of the global efforts to answer these questions that fascinate the general public. Nikhef and the partner universities have historically been very active in science dissemination: the Nikhef Science communication department is staffed with four people and headed by M. van Calmthout, for thirty years a leading science journalist in the Netherlands; various schools for higher professional education (*hoger beroepsonderwijs, HBO*) are connected via internships; several Nikhef members have continuing outreach connections with primary and secondary schools and societal clubs and associations; Dr. Clara Nellist engages with audiences on various social media platforms, sharing informative videos on particle physics [87]; Dr. I. van Vulpen has a special professor appointment in Science Communication at the University of Leiden.

The University of Amsterdam initiated the *'Researcher in the Classroom'* program, in which PhD candidates talk about their daily work as researchers to generate enthusiasm about science among young high-school pupils (fig. 18). By preferably targeting schools with large numbers of pupils from groups traditionally underrepresented in science, the program aims to increase diversity in the environment of particle physics research. Moreover, short research projects (*'profielwerkstukken'*) are offered to high-school students, allowing them for example to take measurements of cosmic ray particles with particle detectors or to analyze samples of collected LHC data especially prepared for outreach and education purposes.

Figure 18. *(Left) Early-career researcher visiting a high school to engage on 12-18 year old children. (Right) Popular science books by Nikhef researchers.*

During every national *'Weekend van de wetenschap'* (weekend of science), Nikhef organizes an open day, during which the institute is open to the public. Visitors can learn about the physics and the technology developed at Nikhef and get a taste of the atmosphere and of how it is to work in this field, through a series of organized activities: simple physics experiments; mini lectures including questions and answers sessions; demonstrations of technologies used in particle detectors; hands-on classes in which young children can build a piece of electronics; virtual-reality 'tours' through a particle detector. FASTTRACK will contribute to all aspects of this effort, and more specifically to the development of online educational material on 4D timing devices usable for university lectures and hands-on courses.

Human capital development – FASTTRACK and the collaborations with internationally highly ranked partners in ALICE, ATLAS and LHCb provide an excellent environment for human capital development. The development of technical, software and scientific capabilities in the Netherlands is strengthened by experience in world-class projects in an international context. The mere gain of experience working in a large-scale international project with different parties, different methodologies, cultures and methods is the main driver of economic benefits, as a company survey and interview series with suppliers in the frame of the LHC project revealed [90]. A detailed social cost-benefit analysis [91] studying the social value of persons that have been formed in the LHC program as students or early-stage researchers shows that the value of training represents up to 40% of total benefits.

The PhD students participating in FASTTRACK activities will gain experiences in international scientific research and in high-tech development that will benefit their future career within and outside academia. In the Nikhef partnership, every year about 25 PhD students graduate, most of whom take their experience into industry. We can confidently say that they are sought after and their international experience in state-of-the-art software and technology domains is a widely valued attribute. Furthermore, we strongly believe that we have a responsibility to facilitate the role of science in society, specifically by educating the next generation of public sector leaders: politicians and public administrators with a science, technology, engineering, and mathematics background can look through a different lens at policy problems, with unique insights into the future implications of new scientific and technological developments. In that, we share the goal of the *'Bèta in Bestuur & Beleid'* (BiBB) initiative of the Dutch Physics Council [88]: improve the flow of our human capital into the public sector, stimulating PhD students and graduates interested in policy making to consider a career in these fields.

3.3.5 Discovery, monitoring and response to emerging opportunities for impact

Underlying the FASTTRACK effort there is the wish to understand our universe in fundamental terms (elementary particles and forces) by means of measurements and of interpretation of data through comparison with theory. In this sense, FASTTRACK can be framed within a typical curiosity-driven research cycle: a fundamental question sparks research activities from which scientific insights emerge that shift the state-of-the-art and inspires new fundamental questions, so that the cycle starts all over again. However, in this cycle, technological innovations, separate from the main scientific mission, are developed and diffused, which creates opportunities for societally beneficial goals.

To capitalize on these emerging opportunities to create impact, in FASTTRACK we will follow the best practices indicated in a comprehensive report of the Organisation for Economic Cooperation and Development (OECD) [89], dedicated to the specific case of large international research facility, like the LHC.
Some opportunities emerge quite spontaneously and the measures to support impact set up in section 3.3.4 are sufficient to lead to commercial products. Other opportunities are more *discretionary*, in the sense that they can become external impacts only with significant modifications; to capitalize also on these, we will ensure sufficient communication to discuss them within the organization and the flexibility to use Nikhef budgetary or personpower resources to pursue them, when desirable. The Nikhef ILO, Dr. J. Visser, will be directly involved in this process and dedicate to it a significant fraction of his time; his long-standing experience in the world of co-development and knowledge transfer will ensure that potential for impact is recognized and, through the BigScience.NL network, channeled to the right partners.

4. Organisational and financial aspects

Organizationally, FASTTRACK is embedded within Nikhef and the international LHC community. In section 4.1, we describe how the national organization of the Dutch LHC community is structured and how it is aligned with the international governance of CERN and the LHC experiments. Our governance aims to maximize efficiency, minimize delays and risks, and guarantee the sustainable operational use of the infrastructures. In section 4.2, the costs of the work packages are detailed, resulting in a total funding request of 21.7 M€.

4.1 Organisation and Governance

International context – While FASTTRACK will locally be embedded in the Nikhef partnership, it must be seen in the broader context of the Dutch participation to the LHC experiments at CERN. The organization of the experimental work is founded on the recognition that the only way to realize such challenging projects, both financially and in terms of human capital, and to maximize their scientific output is through international collaboration. The success of the LHC experiments relies on the coordination of the efforts of research teams located at CERN and at member universities and laboratories worldwide. In this section, we briefly describe the organization and governance of the LHC experiment collaborations and of the Nikhef partnership.

LHC – The LHC falls under the responsibilities of CERN, one of the world's largest center for scientific research, of which the Netherlands is a founding member. CERN is currently run by 24 Member States. The *CERN Council* determines the organization's policy in scientific, technical and administrative matters, defines its strategic programs, sets and follows up its annual goals, and approves its budget. The Netherlands are represented in the CERN Council by the Ministry of Education, Culture and Science and by Nikhef.

The LHC experiments are collaborations of physicists, engineers, technicians, students and support staff from around the world. They represent one of the largest collaborative efforts ever realized in science: as an example, ATLAS has more than 5500 members and almost 3000 scientific authors on each publication. The organization and governance of the collaborations is the product of more than 25 years of scientific collaboration, covering periods of construction and of scientific exploitation. All participating institutes in each experiment are represented in the *Collaboration Board*; day-to-day management is entrusted to the *Management Team*, headed by the spokesperson; the construction of each sub-detector is organized as a *project*, headed by a project leader (see e.g. the organizational chart of the ATLAS collaboration in ref. [92]). The commitments of the partners in the projects are ruled by multilateral *Memoranda of Understanding* (MoUs). Project progress, risks and financial aspects are monitored by a *Resources Review Board* (RRB), that comprises, in addition to the managements of CERN and of each Collaboration, the representatives of each experiment's Funding Agencies (the Nikhef director represents the Netherlands).

Nikhef – The Nikhef partnership was established in 1975, and currently consists of six Dutch universities (University of Amsterdam, Vrije Universiteit Amsterdam, Radboud University, Utrecht University, University of Groningen and Maastricht University) and the NWO-I Nikhef, the National Institute for Subatomic Physics. Nikhef's research activities are organized in *Scientific Programs*, with program leaders appointed by the director, as shown in fig. 19. All activities in FASTTRACK can be mapped onto the following scientific programs: ATLAS, LHCb, ALICE, detector R&D and Physics Data Processing. As the Netherlands' contribution for which funding is requested here falls under the responsibility of Nikhef, the PI of the FASTTRACK project will by default be the Nikhef director, who will delegate the responsibilities for the work itself.

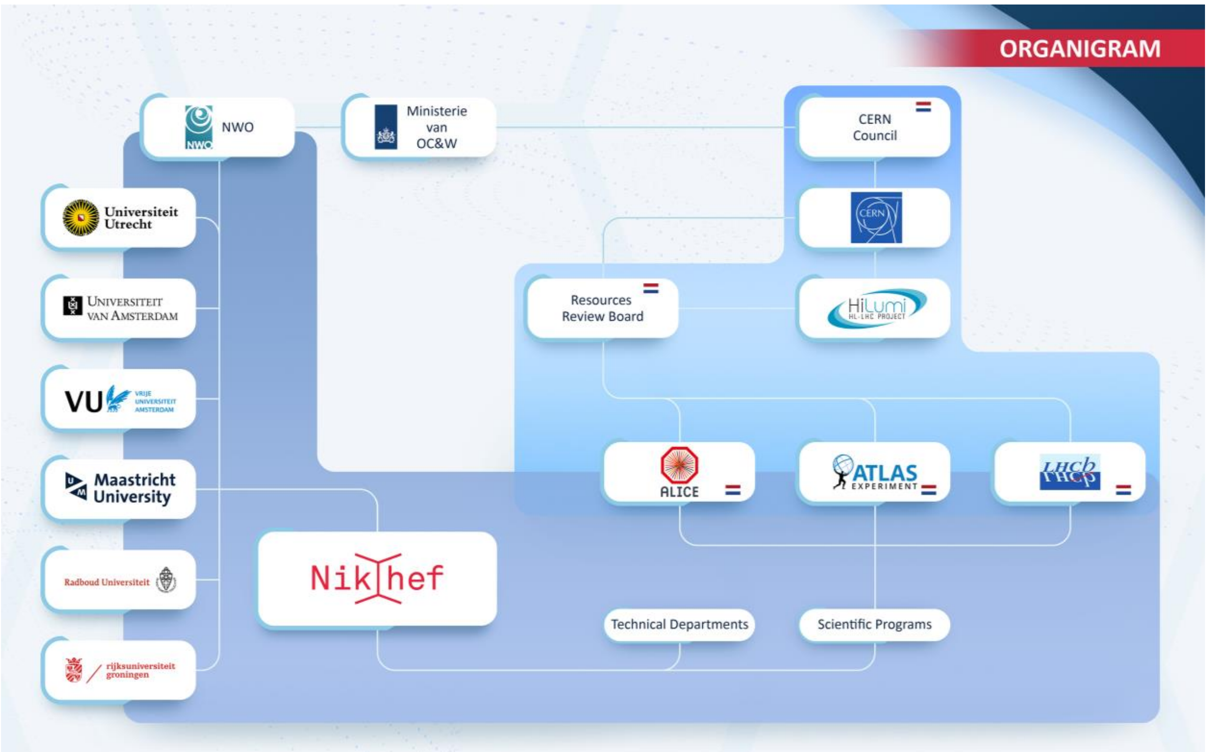


Figure 19: Organizational chart of the Nikhef partnership among six universities and the NWO-I institute Nikhef, schematically indicating the relation with CERN and the LHC experiments.

Work packages – The work proposed in FASTTRACK is organized in work packages (WPs), shown in fig. 20, grouped in broader detector development lines. As the teams carrying out the WPs are embedded in the Dutch LHC community, a *Scientific Coordination Board*, whose members are the Nikhef program leaders, will link local activities with those at the LHC-experiments level; the program leaders have the authority in the early phases of the project to negotiate the scope of the Dutch contributions.

Industry liaison – To connect with Dutch industry, FASTTRACK can rely on Nikhef's *Industrial Liaison Officer* (ILO) and the Dutch BigScience.NL network [84]. These connections will be important for matters related to procurement, innovation and technology-transfer opportunities. They will help ensure that, on the one hand, the proposed work is sufficiently informed by the Dutch industrial knowledge and ambitions and, on the other hand, the relevant findings by the development teams will find use in the national ecosystem.

Project management – The project management will benefit from Nikhef's extensive experience in leading international consortia developing cutting-edge instrumentation, and from the resulting project management practices implemented at Nikhef to achieve optimal *capacity planning*. The project leaders will, in close discussion with their group members, define the project plan, including financial and person-power requirements, deliverables and milestones. To prevent projects running into roadblocks, every six weeks Nikhef-wide *'Overleg Project Plannen'* (OPP) meetings will be held, during which the project progress is monitored and issues with human capital, materials, space and time are tackled, and provisions are taken to deal with eventual budget and time overruns. Project priority will be assigned by the Nikhef director, advised by the WAR council (an internal scientific advisory council), the SAC (the external scientific advisory council), staff meetings, and scientific coordination meetings of all program leaders. The planned project activities will be realized within an *Agile Project Management* approach, with iterations of increasing maturity.

Procurement – Procurement of components will be done through Nikhef, complying with NWO and European procurement regulations. No commercial activities are foreseen. Components must comply with EU laws and regulations. Technical designs will be published in open literature, and no particular IP issues are foreseen.

Education and training – We put great effort into inspiring and preparing the ***next generation*** of scientists. PhD students participating in the development of FASTTRACK will be enrolled in the OSAF (*'Onderzoekschool Subatomaire Fysica'*) graduate school [93]. Working alongside scientists in FASTTRACK, they will gain hands-on experience on the workings of state-of-the-art detectors and train to become the future operators of the infrastructure and the leading scientists at the heart of the exciting HL-LHC science (for FASTTRACK impact on human capital development see section 3.3.4).

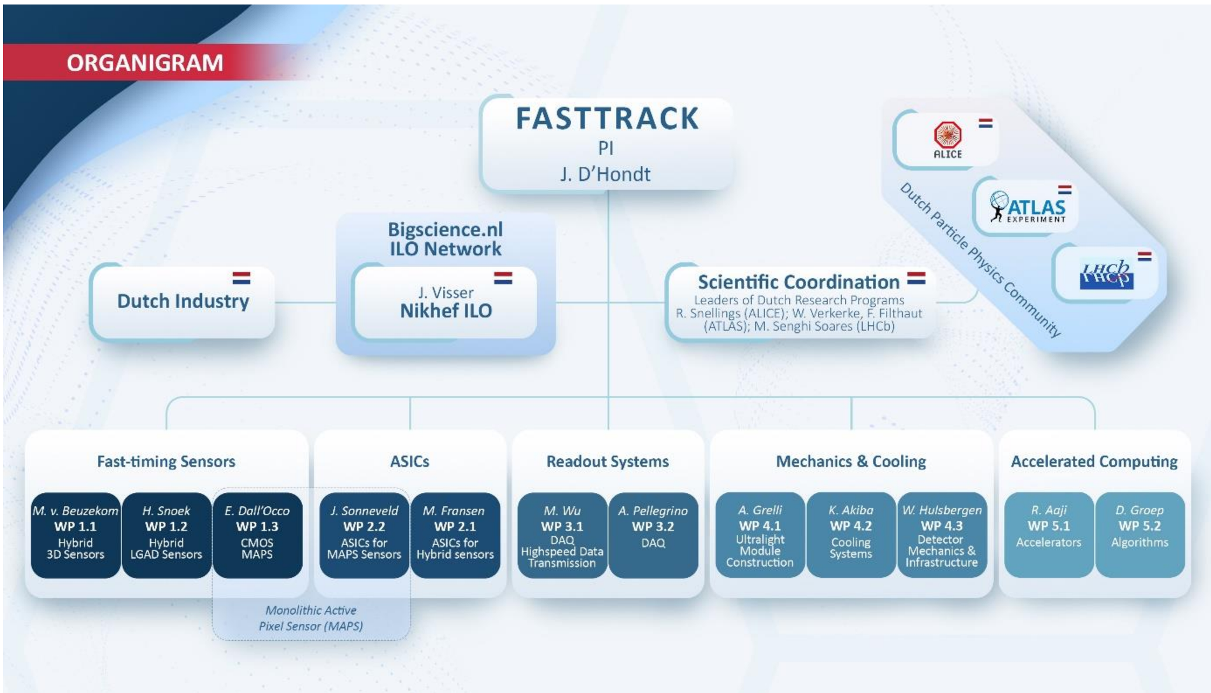


Figure 20: *FASTTRACK organization structure. The work packages are connected to five broader development lines. The organization connects with the Dutch research community as well as with the governance of the LHC experiments through the Scientific Program leaders, and with the Dutch industrial community through the BigScience.NL network of Industrial Liaison Officers [84].*

4.1.1 Key Performance Indicators, milestones, deliverables

FASTTRACK is part of a larger whole and the local activities summarized in the WPs in fig. 20 are mirrored into international projects for the construction of novel ultra-fast-timing tracking detectors, with their own schedule and milestones, embedded in the organization of the LHC experiments. The development phases of our local activities are presented in the Gantt chart of fig. 21; at the top of the Gantt chart, are shown the most relevant system-level milestones of the LHC experiments in which our local activities must be framed, followed by a bird's-eye view of the key performance indicators of this proposal: deliverables, milestones and regular monitoring of the technical and financial realization of the project.

Deliverables and Key Performance Indicators – Ultimately, FASTTRACK provides a crucial contribution to the overarching deliverable of next-generation tracking detectors with ultra-fast timing capabilities for the ALICE, ATLAS and LHCb experiments; the key performance indicator here will be the capability of such detectors to perform tracking at the HL-LHC and collect the unprecedented amount of data necessary to make new discoveries. Within that larger context, the WPs of FASTTRACK aim to deliver the following components: sensor pixels capable of measuring position and time with unprecedented resolution *(WP 1.1, 1.2 and 1.3)*; Application-Specific Integrated Circuits (ASICs) that enable per-pixel signal processing and readout logic *(WP 2.1 and 2.2)*; radiation-tolerant high-speed links in combination with a high-throughput data-acquisition system *(WP 3.1 and 3.2)*; modular structures integrating sensors, ASICs and services (cooling, power etc.), with tight specifications (e.g. material budget, temperature stability, etc.) to ensure high performance and robustness *(WP 4.1, 4.2 and 4.3)*; powerful tracking data processing, guaranteed by a dedicated IT-infrastructure based on computer accelerators and deep-learning-based algorithms *(WP 5.1 and 5.2)*.

The corresponding deliverables of the technical activities are summarized below per work package, with the respective key performance indicators:

WP1.1: fully validated hybrid 3D sensors with 50 ps time resolution and non-uniform radiation profile

WP1.2: fully validated LGAD sensors with 50 ps time resolution and improved radiation tolerance

WP1.3: fully validated CMOS MAPS architecture, with 2.5 µm space resolution and 50 ps time resolution

WP2.1: ASIC design for hybrid sensors towards full ASIC production, meeting the extreme radiation requirement of 1.2 Grad, capable of sustaining data rates above 80 Gbit/s/cm^2 and of achieving time-stamping with a target resolution of 35 ps

WP2.2: final design of the logic circuitry for CMOS MAPS for full production, capable of achieving time-stamping with 50 ps resolution, sustaining a hit rate of 35 MHz cm^{-2} and a per-link data rate of 14 Gbit/s and with a power consumption below 100 mW cm^{-2}

WP3.1: fully validated fast link hardware capable of speeds in excess of 10.24 Gb/s

WP3.2: hardware and firmware of state-of-the-art FPGA boards for control, data acquisition and processing, capable of sustaining the throughput of up to 48 fast data links and a total throughput of 480 Gbit/s

WP4.1: fully completed modular structures integrating sensors/ASIC with state-of-the-art cooling substrates, like 3D-printed titanium, aluminum, ceramic, or printed silicon carbide

WP4.2: last-generation cooling systems ready to be integrated in the operating detectors, capable of reaching stable temperatures below −40 °C

WP4.3: the components of the detector mechanical infrastructure, ready for the final assembly at the experimental site, with minimal material (less than 0.07% of a radiation length) between the beam line and the detector, and novel solutions for powering scheme (serial or optical powering)

WP5.1: facility (8 host servers connected through a fast network) to validate and scale up data-processing pipelines that integrate commercial GPU and FPGA accelerator boards with AI inference engines

WP5.2: deep-learning-based pattern recognition algorithms optimized to run on computing on large accelerator systems integrated in the experiments processing pipelines

Milestones – The most relevant milestones to realize the deliverables of the project are shown in the Gantt chart in fig. 21. They have been matched to the overall project schedules for the realization of the ALICE, ATLAS and LHCb tracking systems, shown at the top of the Gantt chart. The overall LHC schedule alternates data-taking periods and long shutdowns to increase the luminosity. The LHC is currently in a data-taking period, with two long shutdowns planned for 2026-2028 and 2033-2034, respectively. In the first shutdown, the new ATLAS inner tracking system (ITk) and the HGTD detector will be installed; in the second shutdown, the innermost ring of HGTD sensors will be replaced and the new LHCb and ALICE tracking systems will be installed. The harvesting of physics results will continue until 2041.

Monitoring – The development phases of the WPs will be monitored through the Nikhef system for the management of technical projects, previously described; in particular, the OPP will provide a regular platform for communicating, reporting, and resolving technical issues, as well as issues with person-power, materials, space, and time (milestones). The PI will oversee and monitor all technical and financial realizations of the project in close contact with the scientific coordinators of the Dutch LHC research programs. These coordinators will also provide a link with the international bodies monitoring all LHC experimental activities. This system-level monitoring is carried out through the international project management structures foreseen in the organization of each LHC experiment and is supervised by the LHC Committee (LHCC), an independent international panel that meets regularly to review the construction, installation and commissioning of all experiments and R&D programs and provides written reports with recommendations to the CERN Research Board. As mentioned in section 4.1, financial risks are monitored and resolved through the Resources Review Board (RRB).

This in-depth review process (see e.g. [94]) is built into the organization of each LHC collaboration; every project is punctuated by a series of reviews: first, detailed Technical Design Reports (TDR) for each detector sub-system (e.g. tracking) are reviewed; then, for each work package, a Preliminary Design Review (PDR) is held, followed by an Engineering Design Review (EDR) and finally a Production Readiness Review (PRR), in which the results of the proto-typing and pre-production phases are evaluated before the full production of the work package deliverables is launched. The relevance of these reviews is such that in practice they constitute most of the project milestones and are the focus of the LHCC and of the RRB monitoring. The WP schedule presented in fig. 21 fully reckons with the various phases of this review process.

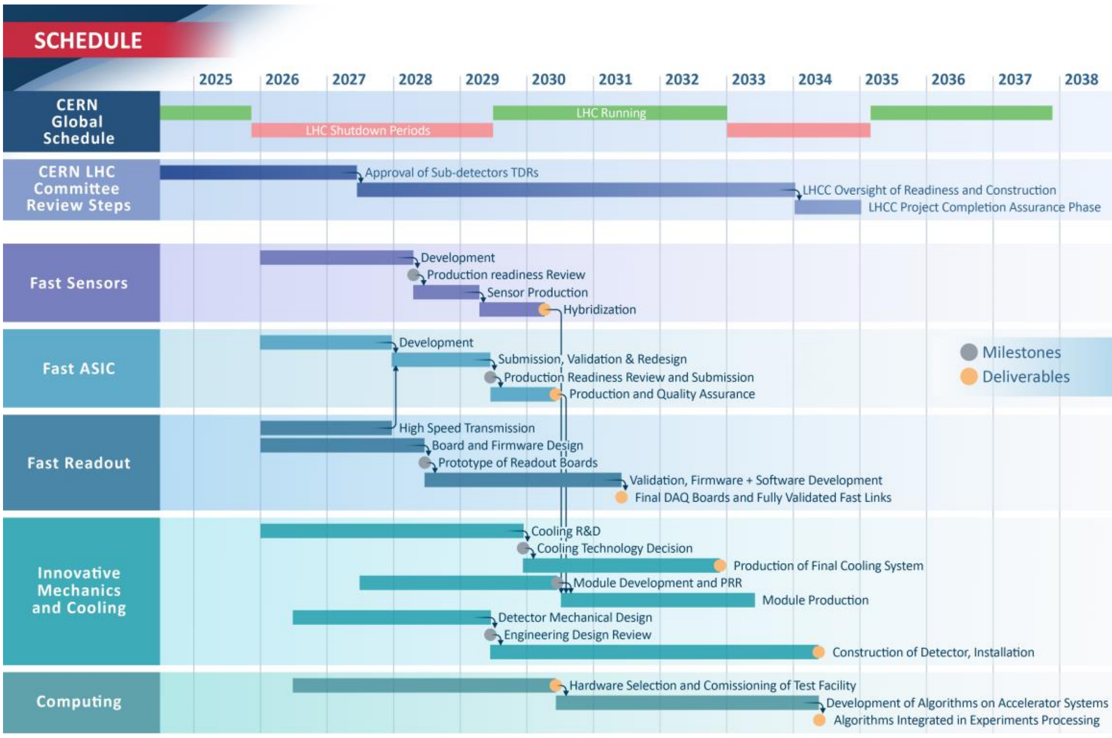


Figure 21: *FASTTRACK Gantt chart. At the top, a "system-level" view of the LHC and of the experiments schedule. Below, the schedule of the FASTTRACK work packages.*

4.2 Financial aspects

The only way to fund experimental facilities like ALICE, ATLAS and LHCb, which can be categorized as Big Science projects, is through large international collaborations. They demand technologies well beyond the state-of-the-art, like FASTTRACK, that require several years to be established from conception to application. Funding requests have the same cadence. The last comparable request by the Dutch particle physics community was awarded in 2013 and the FASTTRACK funding will also span a period of 10 years.

4.2.1. Financial overview of the project

FASTTRACK must be seen in the broader context of the Dutch participation to the HL-LHC, which has received top priority in the European and American strategy for particle physics [1, 2]. The costs to realize the High-Luminosity LHC are fully carried by CERN, one of the world's largest centers for scientific research, of which the Netherlands is a founding member, contributing to capital and operating costs. ALICE, ATLAS and LHCb are large international collaborations with their own objectives, structure and governance; the costs incurred by these collaborations to build and operate the detectors are shared among the participating institutes. Ultra-fast-timing trackers are an essential part of the ALICE, ATLAS and LHCb detectors, mirrored into international projects with their own schedules and milestones. For the Netherlands, contributing to the detector construction through FASTTRACK is strategic and timely in order to get the most out of the large capital investments made in HL-LHC. Tracking systems are not only the heart of the detectors, but they also account for a major fraction (roughly one third) of the *core costs* incurred by the LHC collaborations. The Dutch particle physics community has strategically decided to *concentrate our contribution* on the construction of novel ultra-fast-timing tracking detectors. In this way, our fractional contribution to tracking systems will be *proportionally much more significant* than our fractional contribution to the overall costs, and, correspondingly, we expect our impact and our return to be much higher.

Total project costs

The funding requested in this proposal is based on the additional expenses that the Nikhef partnership will incur to contribute to the fast-timing trackers of ALICE, ATLAS and LHCb. This entails both hardware costs and personnel costs. All costs are based on estimates provided by the ALICE, ATLAS and LHCb collaborations and on preliminary internal agreements about the sharing of responsibilities and costs. The overview of the requested budgets is given in the tables below. The Dutch contribution consists of 27.8 M€ for materials and other cash expenses, and 25.5 M€ for personnel. Of the total 53.3 M€ (see table 2), we request in this proposal an NWO contribution of 21.7 M€.

Table 2: *Total project costs to the Netherlands.*

Total project costs (€)			
	Capital investment (€)	**Running costs (€)**	**Total (€)**
Requested NWO contribution	21,737,333	0	**21,737,333**
In kind contribution consortium	*26,053,474*	*5,500,000*	***31,553,474***
Cash contribution consortium	*0*	*0*	***0***
Total contribution consortium	26,053,474	5,500,000	**31,553,474**
Total project costs	47,790,807	5,500,000	**53,290,807**

Personnel costs

In table 3, the FTE costs are specified per Work Package; the yearly costs are listed in the corresponding Excel multiyear budget form. All personnel costs for the proposal will be covered by the Nikhef consortium and will be the bulk of its in-kind contribution. Given the time scale of FASTTRACK, all these costs are capital investments. Since FASTTRACK consists of items requiring development, production and verification, and the number of units to be delivered is significant, more than half of the total LSRI project consists of personnel costs. Given the very specialized nature of the work, and since a very significant fraction of modelling, designing, production and integration will be performed in-house, experienced technicians (MBO-educated) and engineers (HBO/WO-educated) from the Nikhef consortium are required; additional hiring of experts will also be needed to obtain the required FTE level. The total effort will roughly correspond to 230 FTE years (see annexed multiyear spreadsheet). We expect also staff physicists, postdocs and PhD students to dedicate significant fractions of time to the FASTTRACK development and construction. The exact extent of this effort is difficult to quantify and we did not include these personnel costs in table 3.

Table 3: *Overview of the Netherlands' share of personnel costs, split by work packages.*
All costs are capital investments (no running costs), contributed by Nikhef.

Personnel costs (€)					
Description	**Contributor**	**Capital investment (€)**	**Running costs (€)**	**Total (€)**	**Year(s)**
WP1.1 3D Hybrids	*Nikhef*	*709,062*	*0*	*709,062*	*2026-2035*
WP1.2 LGAD Hybrids	*Nikhef*	*164,898*	*0*	*164,898*	*2026-2035*
WP1.3 Monolithic	*Nikhef*	*205,573*	*0*	*205,573*	*2026-2035*
WP2.1 Hybrid ASICs	*Nikhef*	*2,663,377*	*0*	*2,663,377*	*2026-2035*
WP2.2 Monolithic	*Nikhef*	*199,253*	*0*	*199,253*	*2026-2035*
WP3.1 High-Speed Transmission	*Nikhef*	*3,134,490*	*0*	*3,134,490*	*2026-2035*
WP3.2 Data Acquisition	*Nikhef*	*2,522,372*	*0*	*2,522,372*	*2026-2035*
WP4.1 Module Construction	*Nikhef*	*3,861,094*	*0*	*3,861,094*	*2026-2035*
WP4.2 Cooling	*Nikhef*	*1,799,630*	*0*	*1,799,630*	*2026-2035*
WP4.3 Mechanics & Infrastructure	*Nikhef*	*8,467,720*	*0*	*8,467,720*	*2026-2035*
WP5.1 Accelerators	*Nikhef*	*664,708*	*0*	*664,708*	*2026-2035*
WP5.2 Algorithms	*Nikhef*	*1,137,297*	*0*	*1,137,297*	*2026-2035*
	Total contribution NWO	0	0	**0**	
	Total contribution Nikhef	25,529,474	0	**25,529,474**	
	Total personnel costs	25,529,474	0	**25,529,474**	

Non-personnel costs

Material costs are defined as all non-personnel costs. The FASTTRACK deliverables will be the Dutch contributions to enabling ultra-fast timing in ALICE, ATLAS and LHCb. This will be formalized through Memoranda of Understanding (MoU) between the Nikhef consortium and the LHC experiments.

Table 4 includes also membership fees, with which each collaboration covers Maintenance & Operation (M&O) costs (category A for general costs and category B for detector maintenance) and which we have labelled as running costs. The Dutch share of ALICE, ATLAS and LHCb M&O cat. A costs is based on the size of the Dutch research groups, while the share of M&O cat. B costs is based on the size of the Dutch contribution to the detector. Both are estimated at the collaboration level and agreed in MoU's.

Table 4: *Overview of the Netherlands' share of material costs, split by work packages.*

Non-personnel costs (€)					
Description	**Contributor**	**Capital investment (€)**	**Running costs (€)**	**Total (€)**	**Year(s)**
WP1.1 3D Hybrids	*NWO*	*2,230,000*	*0*	*2,230,000*	*2026-2035*
WP1.2 LGAD Hybrids	*NWO*	*1,000,000*	*0*	*1,000,000*	*2026-2035*
WP1.3 Monolithic	*NWO*	*2,400,000*	*0*	*2,400,000*	*2026-2035*
WP2.1 Hybrid ASICs	*NWO*	*3,460,000*	*0*	*3,460,000*	*2026-2035*
WP2.2 Monolithic	*NWO*	*600,000*	*0*	*600,000*	*2026-2035*
WP3.1 High-Speed Trans.	*NWO*	*1,000,000*	*0*	*1,000,000*	*2026-2035*
WP3.2 Data Acquisition	*NWO*	*1,740,000*	*0*	*1,740,000*	*2026-2035*
WP4.1 Module Construction	*NWO*	*1,838,000*	*0*	*1,838,000*	*2026-2035*
WP4.2 Cooling	*NWO*	*1,050,000*	*0*	*1,050,000*	*2026-2035*
WP4.3 Mechanics & Infrastruct.	*NWO*	*2,780,000*	*0*	*2,780,000*	*2026-2035*
WP5.1 Accelerators	*NWO*	*3,139,333*	*0*	*3,139,333*	*2026-2035*
WP5.2 Algorithms	*NWO*	*500,000*	*0*	*500,000*	*2026-2035*
Travel costs	*Nikhef*	*524,000*	*0*	*524,000*	*2026-2035*
Membership fees (M&O cat. A)	*Nikhef*	*0*	*3,500,000*	*3,500,000*	*2026-2035*
Membership fees (M&O cat. B)	*Nikhef*	*0*	*2,000,000*	*2,000,000*	*2026-2035*
Total contribution NWO		21,737,333	0	**21,737,333**	2026-2035
Total contribution Nikhef		524,000	0	**6,024,000**	2026-2035
Total material costs		22,261,333	5,500,000	**27,761,333**	2026-2035

4.2.2. Financial feasibility and sustainability

In the broader context of the HL-HLC, it must be considered that the exploitation of FASTTRACK extends beyond the 10-year horizon of this funding request. The estimated costs for the entire lifespan of FASTTRACK are listed in table 5. The sustainability of this extended financial and scientific effort beyond the 10-year horizon of this funding request is guaranteed by the long-term scientific commitment of the members of the Nikhef consortium and by the stability of the Nikhef mission budget committed to the experiments hosted at CERN. The cost for the science harvesting in which Dutch physicists and their PhD students will take part has not been included in table 5.

Table 5: *Estimated costs for the entire FASTTRACK lifespan (science harvesting costs are not included).*

Lifespan cost (k€)					
Description	**Contributor**	**Yr 1-10 (k€)**	**Yr 11-16 (k€)**	**Yr 17 (k€)**	**Total (k€)**
Overview of all costs to the Netherlands for the entire lifespan of ALICE/ATLAS/LHCb					
FASTTRACK material costs	*NWO*	*21,737*			***21,737***
FASTTRACK personnel costs	*Nikhef*	*25,530*			***25,530***
FASTTRACK travel costs	*Nikhef*	*524*	*122*		***646***
FASTTRACK maintenance costs	*Nikhef*		*1,200*		***1,200***
FASTTRACK dismantling costs	*Nikhef*			*47*	***47***
Membership fees ALICE/ATLAS/LHCb	*Nikhef*	*5,500*	*3,300*		***8,800***
Total costs to the Netherlands		53,291	4,622	47	**57,960**
Core costs for ALICE/ATLAS/LHCb upgrade - does not include personnel, travel and membership fees					
Material costs to upgrade ALICE/ATLAS/LHCb for the HL-LHC	All ATLAS/ALICE/ LHCb institutions	570,000			**570,000**

FASTTRACK is part of a larger effort. The HL-LHC accelerator will be the flagship research facility at CERN in the 2030s. It is fully funded and operated by CERN, while the experiments themselves are funded by the participating institutions. Accordingly, experimental Big Science facilities like ALICE, ATLAS and LHCb depend on international funding. As shown in table 5, ALICE, ATLAS and LHCb have estimated a total '*core cost'* of 570 M€ to enable the detectors to operate at the HL-LHC (resp. 140 M€ for ALICE, 270 M€ for ATLAS and 160 M€ for LHCb). These are material costs; personnel, travel and membership fees are not included. The international community adheres to a fair-share distribution of the total cost among the participating countries. Funding in all participating countries will be secured and ratified in MoUs for the entire lifespan of the LSRI. Our 21.7 M€ capital investment in materials (table 4) is nearly 4% of the total 570 M€ core cost. Roughly half of this amount will appear in MoU's as the Dutch contribution to the ALICE, ATLAS and LHCb core costs. The other half will cover the development and prototyping costs necessary for the hardware to meet the requirements to be integrated in ALICE, ATLAS and LHCb.

Strategically, FASTTRACK is a coherent contribution across three experiments that, leveraging on previous experiences, envisages a fair share of the cost in accordance with the Dutch size, but with a scientific impact that goes well beyond this fair share.

5. Technical aspects

*Tracking devices for high-luminosity colliders are based on silicon sensors with a spatial resolution of the order of 10 µm, and able to withstand harsh radiation environments. FASTTRACK aims to bring the spatial resolution down to about 5 µm, and add very precise time measurements to the sensing elements. This effectively corresponds to adding a **fourth dimension** to the three spatial dimensions already used for the reconstruction of particle trajectories. In this chapter, we will demonstrate that **4D fast-timing** pixel detectors can be realized with timing resolution better than 50 ps. This innovative technology will cause a **paradigm shift** in the field of particle tracking with silicon sensors. To implement FASTTRACK, we will deploy an **integral approach**. In section 5.1 we discuss the project's feasibility, in section 5.2, our plan concerning the IT aspects, and finally in section 5.3 our risk mitigation strategy.*

5.1 Technical feasibility of an integral 4D fast-timing approach

To realize 4D fast-timing tracking systems for ALICE, ATLAS and LHCb, we will deploy an ***approach encompassing all aspects***: new sensor concepts with fast signal processing circuitry; lightweight mechanical and cooling solutions to assure optimal operation of these sensors; novel reconstruction algorithms on heterogeneous computing architectures to extract more information from the data. Since the challenges for the three LHC experiments are very comparable, the feasibility is discussed per technical topic rather than per experiment. As shown in fig. 20, all activities are organized in *work packages (WPs)*, grouped in five broader detector development lines.

In **section 5.1.1**, the technical implementation of the sensors is described, followed in **section 5.1.2** by the development of the accompanying on-sensor electronics. They will be designed to withstand the increased collision rates of the HL-LHC, and to provide sufficiently fast electrical signals, which are subsequently amplified and digitized by specially designed Application Specific Integrated Circuits (ASICs). The basic terminology is introduced in InfoBox 3; a primer on the three sensor technologies that we will investigate can be found in InfoBox 4. In **section 5.1.3**, we describe our readout solutions to deal with a ten-fold increase in particle multiplicity, together with the additional information of the time measurements, which results in a total data rate increase of more than an order of magnitude. This research will deliver low-power, high-speed data transmission links (above 10 Gbits/s) and the corresponding high-performance and robust readout systems. In **section 5.1.4**, we discuss the assembly and integration of the full infrastructure, comprising thousands of sensors, grouped in modular mechanical structures attached to a frame distributing power, readout and cooling lines, while remaining lightweight. In **section 5.1.5** we discuss how we will achieve the required accelerated computing capabilities to deal with orders of magnitude more data and exploit the additional fast time information.

InfoBox 3 – Sensor & ASIC terminology

Pixel pitch refers to the distance between the centers of two adjacent pixels. The sensor spatial resolution can be estimated as pitch/√12; a better resolution can be achieved with on-pixel charge-weighted measurements. **ASICs** refer to custom integrated circuits, designed for the processing of the sensor signals. For hybrid detectors, the ASIC is produced separately and then *bonded* to the sensor; for Monolithic Active Pixel Sensors (MAPS), ASIC and sensor are integrated and produced in the same process. **65 (28) nm technology** refers to a specific ASIC manufacturing process and its design rules; the number 65 (28) nm refers to the size of the smallest structures in the ASIC, indicative for how much functionality can be included per mm^2. Particle type- and energy-dependent radiation damage is expressed in **1 MeV n_{eq}/cm^2**, the damage caused by a 1 MeV neutron [95].

5.1.1 Fast-Timing Sensors (WP1)

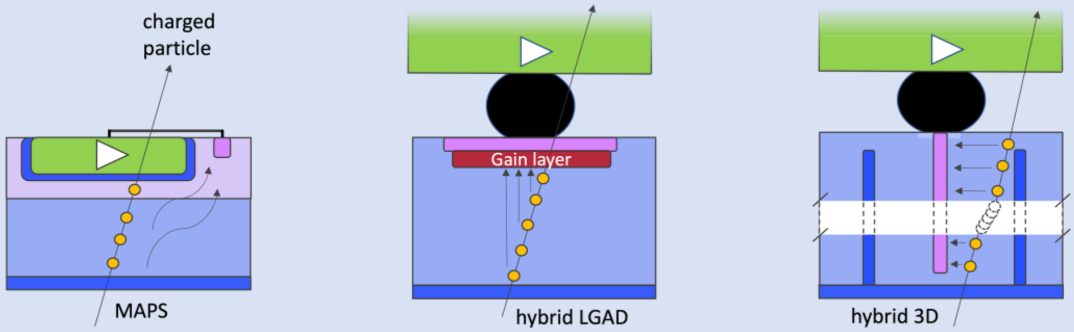
We aim *at developing pixel sensors with a high spatial precision, capable of detecting the tiny signals generated by interacting particles, while keeping the sensor's contribution to the time resolution below 50 ps*.

Three technologies will be pursued since they have distinct advantages in terms of material budget and radiation hardness: Monolithic Active Pixel Sensors (MAPS), because of their extremely low material footprint, which is essential for the inner tracking layers of the ALICE experiment; hybrid LGAD sensors are the ideal candidates for the future ATLAS needs of improved radiation hardness; hybrid 3D detector structures, because of their fast signals and extreme radiation tolerance [96], provide the baseline technology for the LHCb VELO detector. Novel sensor designs will be simulated and fabricated in these three technologies, with prototypes manufactured in collaboration with industrial and scientific partners, and subjected to extensive characterization at beam facilities and in laboratory setups. We will also evaluate potentially radiation-resistant sensor materials such as silicon carbide. Developing these diverse technologies in parallel, we both facilitate cross fertilization and mitigate risks associated with the implementation in the final detector.

WP1.1: Development of hybrid 3D sensors These 3D sensors are the technology of choice for the LHCb VELO detector (see InfoBox 4). The LHCb physics goals require spatial measurements with precision of 10 µm or better, and excellent radiation hardness, above 2.5 × 10^{16} 1 MeV n_{eq}/cm^2. The timing measurement must have precision better than 50 ps per detection plane, which is estimated to yield the desired average time resolution of 20 ps per track.

InfoBox 4 – Primer on silicon pixel sensors

The picture below shows cross-sections of the three main sensor technologies developed in this proposal. For hybrid (LGAD or 3D), the electrode (purple) of the Si sensor (blue) is connected to the readout electronics (green) via little solder balls (black) of order 10 µm diameter. For MAPS, the readout electronics is integrated into the sensor. The thickness of the sensor layer ranges from about 20 µm (for MAPS) to about 200 µm (for 3D sensors). If a charged particle passes through the sensor, it ionizes the silicon, producing electron-hole pairs. The movement of the electrons (shown) and holes (not shown), under influence of the externally applied electric field, induces signals in the pixel readout electrode (purple), which are integrated by the readout electronics. When the integrated charge crosses a threshold, the time is registered, together with the position of the pixel in the matrix and the amount of charge. A time measurement precision (time resolution) better than 50 ps is required for the sensor and electronics combined.



A good time resolution can be obtained with a combination of factors, of which the most important ones are a large amount of charge, a short drift distance, and low pixel capacitance, implying a small readout electrode. The different sensor technologies are optimized for a subset of these factors. MAPS [27] are thin and hence provide little charge, but also have a low capacitance and short drift distance. LGADs [97, 98] increase the charge by a factor of O(10) because of the (avalanche) gain layer, but have larger capacitance with respect to MAPS. Finally, 3D sensors [96] also provide a large signal because they can be thick without increasing the drift distance, but have even more capacitance. Further experiment-specific criteria include radiation hardness, amount of material in the sensor and readout rate.

The sensitive elements of the LHCb VELO will consist of silicon pixel sensors bonded to ASICs, with a pixel pitch of 55 µm or even 48 µm. 3D structures at these scales provide fast signals due to the short charge collection distance, while providing a large signal (proportional to thickness). However, they have high capacitance and relatively high production costs. 3D sensors have demonstrated extreme radiation resistance and impressive time resolutions, below 20 ps at room temperature and moderate bias voltage [99]. Timing tests mostly have been conducted on single pixel prototypes, using high-speed, high-power, discrete-component electronics. It is thus necessary to test large-area devices that can be used for FASTTRACK, e.g. with 256×256 pixels, with realistic ASICs. In this sense, ASIC development is strongly intertwined with sensor development and requires a coordinated effort. For usage in LHCb, operation with a non-uniform fluence across the sensor needs to be proven, and also improvements in spatial resolution are required. Since spatial resolution is directly proportional to the pixel pitch, sensors with smaller pixel sizes, such as 48×48 $µm^2$, need to be investigated. Currently, we are investigating 3D sensor designs (fig. 22), including structures with an intrinsic charge multiplication mechanism (*gain*). A 3D sensor with internal gain would provide a highly efficient fast-timing detector with excellent spatial resolution, with applications extending beyond the VELO; e.g. for the replacement of the inner layers of the ATLAS vertex tracker. The feasibility of novel designs is under discussion with several industrial partners (FBK, CNM, SINTEF, HPK).

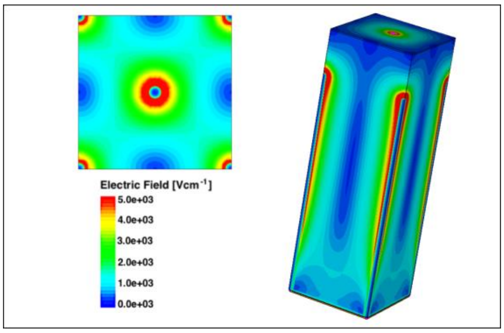


***Figure 22:** TCAD simulation of the electric field in a 55 µm cell, to optimize efficiency and capacitance by adjusting the column diameter.*

The main WP1.1 **deliverable** is the production of sensors for the LHCb VELO detector. In total, 700 sensors are needed. The production schedule takes into account that sensors must be ready in an early phase of the project, in time to be installed in the modular mechanical structures (see section 5.1.4). An important **milestone** of WP1.1 is the sensor Production Readiness Review (PRR) expected by the end of 2026.

WP1.2: Low-Gain Avalanche Detectors LGADs are planar silicon sensors with an internal amplification layer. An additional doping layer is integrated close to the connection to the readout (see InfoBox 4), to amplify the signal within the sensor through an avalanche process. This amplification improves the time resolution with respect to planar sensors.

The ATLAS Collaboration will install the High-Granularity Timing Detector (HGTD) in 2028. This detector will allow for track time measurements with a precision on the order of 30-50 ps by using LGADs segmented into relatively coarse pads of size 1.3 mm × 1.3 mm. Finer segmented LGADs are under investigation by the Nikhef R&D group. Radiation damage severely reduces the HGTD operability above a fluence of 2.5×10^{15} 1 MeV n_{eq}/cm^2. For this reason, the innermost sensors will need to be replaced every three years (each 1000 fb^{-1}) during LHC Long Shutdown periods. The main WP1.2 **deliverable** is new LGAD sensors with improved radiation tolerance that are suitable for the first and second replacement of the inner detector rings of the HGTD to be installed in 2033-2034. In total, 2000 sensors are needed, but this number could become significantly higher depending on the running scenario, i.e. if a larger fraction of the HGTD has to be replaced.

WP1.3: Monolithic Active Pixel Sensors A MAPS implemented in Complementary Metal-Oxide Semiconductor (CMOS) technology has its sensing elements and the readout circuits in the same substrate, which permits thinner detectors (30-50 µm). Furthermore, the single production process reduces the overall cost, an especially important point for trackers covering large areas.

The future ALICE3 detector requires sensors with a spatial resolution at the level of 2.5 µm for the layers closest to the LHC interaction point. This implies that the pixel pitch should be about 10 µm for the in-vacuum layers (see fig. 24), and a less stringent requirement of 50 µm for the out-of-vacuum layers. With the deployment of the ALICE ITS2 tracker in 2020, MAPS technology proved to be a solution yielding a resolution of 5 µm, and a radiation hardness of the order of 10^{13} 1 MeV n_{eq}/cm^2 [5], with a material budget of about 0.3% of X_0 per tracker layer. Nikhef is co-developing the technology in the 65 nm node, and recent beam tests proved the new sensors to have radiation hardness on the order of 10^{15} 1 MeV n_{eq}/cm^2 [100], a value close to the specifications of the envisioned ALICE3 detector.

While MAPS have proven excellent spatial resolution, low power consumption, and sufficient radiation hardness, they still need to prove their time resolution capabilities in the picosecond range. The limiting factor for the time resolution is the relatively small depletion region combined with the non-uniformity of the electric field at the pixel edges. Further R&D is necessary to obtain a sensor readout architecture that will assure a time resolution of the order of 50 ps while keeping the overall power consumption close to the 100 mW/cm^2 required by the ALICE3 tracker. At present, Nikhef in collaboration with CERN is investigating the feasibility of an asynchronous readout architecture. The first test structure is currently under characterization in our labs. The first WP1.3 **milestone** is to improve the production process of the sensors, focusing on the electric field and charge collection time. The second WP1.3 **milestone** is the sensor PRR expected by the end of 2027. The main WP1.3 **deliverable** is a fully validated fast-timing MAPS detector. The amount of sensors to be produced will depend on the technical choices, and is at present estimated to be about 700.

5.1.2 Application-Specific Integrated Circuits for Fast-Timing (WP2)

We aim at *developing integrated circuits that provide per-pixel timing and high-speed readout chain.* ASICs in state-of-the-art technologies, such as a 28 nm CMOS process for hybrid detectors or a 65 nm imaging process for MAPS, enable the development of fine pitch detectors with time-to-digital conversion per pixel with a precision at the level of tens of picoseconds. The emphasis is on novel low-power, high-rate architectures for the time-measuring circuitry, and system-level aspects such as clock distribution with low jitter. Further challenges include time calibration and on-the-fly time correction, necessitating the implementation of dedicated circuits. Pre-processing tasks such as time ordering and clustering should preferentially be performed in the ASIC, to reduce the costs of the subsequent stages of the data acquisition system.

WP2.1: ASICs for hybrid sensors Hybrid pixel detector ASICs need to match the requirement of future detectors such as the LHCb VELO or the ATLAS HGTD. The ASICs will be designed in a 28 nm CMOS technology, which has proven to meet the required radiation resistance of ∼1.2 Grad [101]. This technology allows to integrate up to an order of magnitude more logic gates, and thus higher processing power, than the chips currently in use [102]. Since the particle rate is as high ∼3.5 GHz cm^{-2}, on-chip data reduction algorithms are under investigation to lower the data transmission bandwidth. Even with reduction, the ASIC will have to sustain an unprecedented data rate above 80 Gbit cm^{-2} s^{-1}. This data rate requires the development of dedicated high speed serial links, which is a long-standing expertise of the Nikhef electronics group. Similar links are required for the readout of MAPS sensors, hence the specialized equipment needed for the characterization of such links will be shared between WP2.1 and WP2.2. Currently, Nikhef and CERN participate in prototyping a test ASIC as a proof-of-concept to achieve time-stamping with a target resolution of 35 ps. The main **milestone** of WP2.1 is the ASIC design submission by early 2027. After a full validation and irradiation campaign, the final ASIC, which is the WP2.1 **deliverable**, will be produced by 2028.

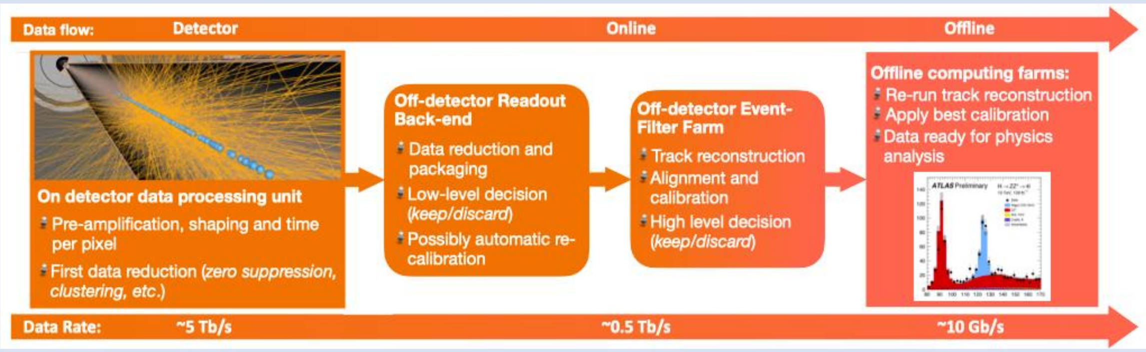
WP2.2: ASICs for MAPS sensors The ASICs will be designed in a 65 nm imaging CMOS technology node, which has the radiation hardness required by the ALICE3 detector. Recently, Nikhef and CERN prototyped the Monolithic Stitched Sensor with Timing (MOST) sensor, a wafer-size sensor designed to reach sub-nanosecond timing. The R&D continues to reach the goal of 50 ps time resolution. The sensors in the most exposed region of the ALICE vertex detector, located in vacuum at 5 mm from the interaction point, must read out an average hit rate of 35 MHz cm^{-2}. To minimize the amount of material of the cooling interfaces, the power consumption of the sensors targets a level of 100 mW cm^{-2} or below. The main **milestone** of WP2.2 is the submission of the ASIC by the beginning of 2027. After a full validation and irradiation campaign, the final ASICs will be produced by 2028. This is the WP2.2 **deliverable**.

5.1.3 Readout Systems (WP3)

To process the enormous data rates produced by the ASICs, further developments in *high-speed data transmission and data acquisition (DAQ) architectures* are necessary (see InfoBox 5). We focus on the transmission of data at unprecedentedly high rates from the on-detector ASIC to the first stage of off-detector processing, which is typically based on Field Programmable Gate Arrays (FPGAs). Subsequent data processing, involving the execution of more elaborate algorithms that require data from the entire detector, is discussed in section 5.1.5.

InfoBox 5 – Why is research on readout systems essential?

Detectors generate an enormous amount of data per second that must be reduced, while interesting events have to be kept. For this, powerful data acquisition systems are needed that can deal with data rates of tens of Tbit/s. The first data reduction is done in the on-detector ASICs, after which the data are transmitted via high-speed links to the off-detector readout back-end equipped with FPGA boards. FPGAs offer flexibility for data reduction and packaging while preserving fixed low *latency* (time elapsed between when data are acquired and when are made available). At this stage also the more elaborate time correction and calibration algorithms are applied.



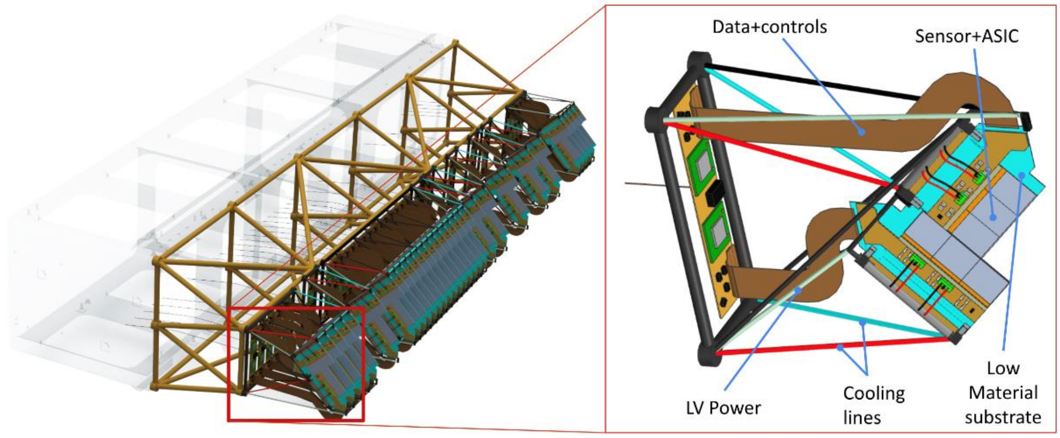
Further in the processing chain GPUs offer parallel-processing capabilities ideal for reconstructing many tracks in parallel, and making event selections. The offline infrastructure to effectively process and analyze data will be based on heterogeneous computing architectures and is discussed in section 5.1.5.

WP3.1: High-speed data transmission The ASICs will produce data at an extremely high rate, requiring low-loss transmission lines, each of them able to cope with up to tens of Gbit/s. To limit the number of *serializers* (circuits in the ASIC dedicated to serialize and transmit the data) per chip, a very high bandwidth per serializer is needed. Commercial off-the-shelf solutions are not suitable due to our special requirements (radiation and power). Multi-level signaling options such as PAM-4 [103] will be assessed as alternative to high-frequency binary transmission. At elevated frequencies, dielectric losses become predominant in transmission lines, prompting exploration of air or vacuum-filled transmission lines to extend the rate limit of the high-speed links. Additionally, the feasibility of implementing electro-optic conversion close to the ASIC (in present inner tracking systems this is typically carried out a few meters from the ASIC), using devices like Mach Zehnder Modulators in silicon photonics, will be investigated. Developments for ATLAS, ALICE and LHCb are, in this respect, very similar. Hence, a joint approach for the design, and the sharing of advanced test equipment is anticipated. The WP3.1 **deliverable** is a fully validated fast link hardware capable of speeds in excess of 10 Gb/s.

WP3.2: Data acquisition The task of the Data Acquisition (DAQ) system is to receive the data from the front-end ASICs over optical fibers, order, compress and reduce it, and finally redistribute the data to the GPU based processing stage. A small fraction of this functionality might be covered by the pixel ASICs described in section 5.1.2, but the majority of these tasks has to be performed by powerful FPGAs which are placed at a distance of over 100 meters from the front-end ASICs, in the radiation-free zone. Compared to the current generation DAQ systems, the new system has to execute additional tasks such as the on-the-fly correction of the time measurements, while at the same time the data rates have increased more than an order or magnitude. Besides processing of the data, the DAQ also plays an important role in the time calibration of the detector and the monitoring thereof, because the sensors and hence their time calibration changes over time due to the accumulated radiation damage. The **deliverable** of WP3.2 consists of the boards hosting the FPGAs and of the FPGA firmware that does the actual data processing. Challenges lie in the development of the high frequency hardware, and in the efficient algorithms that will make the DAQ a reasonably sized, and thereby affordable, system.

5.1.4 Detector Mechanics and Cooling (WP4)

In large tracking systems, the monolithic or hybrid sensors need to be integrated with support mechanics and interfaced to various services, such as cooling, power and transmission lines. These items represent significant engineering challenges and need extensive prototyping; designing them with minimal mass requires the usage of advanced materials. FASTTRACK trackers for ALICE, ATLAS and LHCb will consist of numerous basic mechanical units, called ***modules***. A module combines sensors, ASICs and support structures with interfaces to services. Modules are then integrated in a lightweight frame that constitutes the backbone of the final silicon tracker. Advanced manufacturing techniques, as well as stringent quality control measures, are paramount to ensure optimal performance, reliability, accuracy and stability of each module during years of operation.



(a) Support structure (in yellow) with 32 stations per side (b) Station design with two modules

Figure 23: *VELO mechanical design. A lightweight structure supports 32 'stations' per side. Each station comprises two 'modules', interfaced to cooling, power and a readout unit placed on the station foot.*

WP4.1: Ultralight module construction and interconnect technologies Modules with a low material footprint are the key component of the mechanical part of the infrastructure we propose to build. Nikhef has a long-standing tradition in the realization of modular detector structures, from the design stage all the way to mass production. The most recent examples of which are the modules for the present LHCb VELO and SciFi trackers [104, 105] and for the ALICE inner tracker [106].

LHCb will be built using lightweight substrates on which sensor-ASIC assemblies are mounted. The choice of substrate, which also serves as a cooling interface (see also section 5.1.4) is key, as it has impact on the module design and ease of manufacturing. New cooling-substrate materials and adhesives must be as radiation hard as the sensors and ASICs. Moreover, the adhesives should also have a suitable coefficient of thermal expansion (CTE) to reduce thermally induced stress between ASIC and substrate. Our main goal will be to minimize the material budget without sacrificing the mechanical stability; we will focus on 3D-printed titanium, aluminum and ceramics technologies, which are rapidly evolving in industry.

Very similar considerations apply to the ALICE tracker, which presents additional challenges, as it consists partly of sensing layers inside and partly of layers outside the LHC vacuum enclosure. For the layers outside the vacuum enclosure, the challenge is to cover the large area with light material that at the same time assures extreme mechanical stability. In FASTTRACK, full prototype modules will be designed and tested before mass production is launched. The main **milestones** of WP4.1 are: i) choice of the best performing designs, and start of a pre-production phase during which production methods, testing and quality assurance are developed; ii) module production readiness review. The principal WP4.1 **deliverable** is the full set of completed modules.

WP4.2: Cooling systems Cooling is fundamental to keep sensors and electronics stably operating at the design temperature, as deviations can adversely affect detector efficiency and could even lead to irreversible degradation of the silicon sensors. Cooling design includes research on refrigeration systems, thermal interfaces and transfer/distribution lines. Thermal management within the detector must be integrated into the sensor/module design and, tying in with the requirement to minimize material budget, is one of the biggest challenges for tracking detectors. In addition, colder operating temperatures could potentially allow for higher power dissipation, but may introduce mechanical stresses due to differences in CTE and therefore require different substrates and connections.
Nikhef has a ***long-standing tradition in cooling techniques***, and pioneered bi-phase CO_2 cooling [68], nowadays the preferred choice for tracking systems [69, 70]. FASTTRACK will further develop active cooling systems with low-temperature CO_2 as main coolant, where it will circulate in mini/micro channels in lightweight cold plates. Preliminary thermal simulations performed for the ALICE3 IRIS tracker indicate that such a design, assuming a CO_2 temperature of −30 °C, allows the operation of the silicon sensors at −25 °C with a temperature spread across the surface below 5 °C [31]. An alternative approach allowing even lower temperatures is actively pursued in a joint effort by Nikhef and TU Twente researchers, exploiting the solid-to-gas phase transitions of CO_2 [107]. Colder temperatures could move cooling services further away from the sensors. Based on our experience with CO_2 evaporative systems, we believe that it is feasible to validate this novel approach on the timescale for usage in HL-LHC experiments. The primary **milestone** in WP4.2 is to determine the choice between sublimation and evaporation-based CO_2 cooling. The **deliverable** for WP4.2 is the design and production of a fully operational cooling solution.

WP4.3: Detector Mechanics and Infrastructure The three experiments have strong commonalities in mechanics and infrastructure. The resulting technologies can also be applied to other trackers, e.g. for a possible replacement of the ATLAS pixel detector or for detectors at future accelerators beyond the scope of FASTTRACK. Both the LHCb VELO and the ALICE3 vertex tracker must be protected against electromagnetic interference from the LHC beams by a metal shield, as thin as possible. Hence they are placed in a secondary vacuum enclosure to avoid any differential pressure across this shield. For LHCb *RF shield* the expected thickness is below 75 µm of Al. It will be positioned at 3.5 mm from the LHC beams during data taking but must retract by 30 mm for safe beam injection. This operation needs to be controlled by an automatic, precise, radiation-hard positioning system. Similarly to the LHCb VELO, the IRIS tracker, shown in fig. 24, is designed to be lightweight (about 0.05% X_0 per layer) and retractable: the distance between first sensor layer and interaction point increases from 5 mm in the closed position to 16 mm during injection. The IRIS requires additional attention due to its hermeticity. We will develop the vacuum system, the monitoring of the differential pressure between the LHC primary and detector vacuum, the cooling system, and design a system allowing extraction and replacement if detectors become inoperable due to radiation damage. The in-air layers are shown in orange in fig. 24. Their mechanics consists of modules and support elements as main building blocks. Research will be carried out to choose optimal materials and design for the support frame. The service infrastructure, such as low voltage power cables, contributes a significant amount of material that disturbs particle trajectories. We will exploit serial powering schemes to reduce the number of cables within the sensitive volume. A novel approach based on optical powering will also be investigated, which could provide an alternative for the ATLAS vertex tracker.

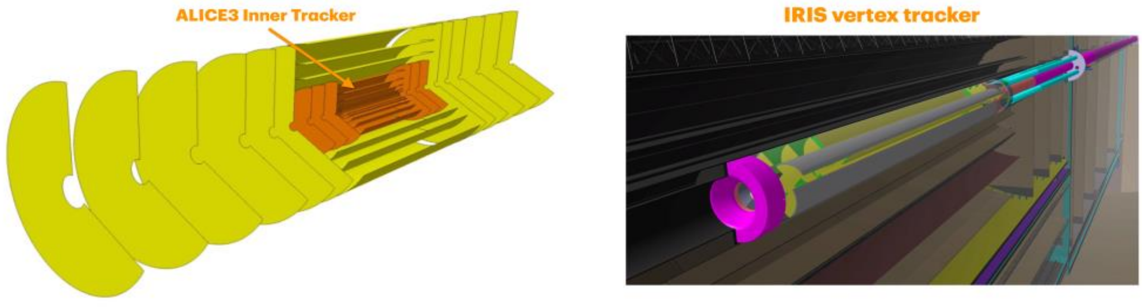


Figure 24: *ALICE3 Inner tracker. In orange is depicted the in-air part (five layers and six disks) enclosing the in-vacuum region of the IRIS tracker (three layers and six disks).*

The main WP4.3 **deliverable** is the complete production of the detector mechanics and infrastructure systems ready for the final integration at each of the experiments. The **milestones** will be the technological choices following the engineering and prototyping phase, the review of the final design, and the launch of the production phase.

5.1.5 Accelerated Computing (WP5)

The FASTTRACK detectors will produce raw data that will exceed by orders of magnitude the long-term storage capabilities of ALICE, ATLAS and LHCb. All experiments, therefore, will need real-time data filters to determine which data to keep and which data to discard, applying the following strategy: for each beam crossing, reconstruct all particles traversing the detector from the raw data; use the reconstructed particles to infer the underlying physics process; decide whether the latter is sufficiently interesting to keep the data. All three experiments will implement this strategy as large *event-filter* farms running real-time data filters (ALICE and ATLAS will also re-run the reconstruction algorithms on stored data).

WP5.1: Accelerator Validation Facility The increased volume and complexity of the data produced by the FASTTRACK detectors will require significantly more compute power than currently available in the LHC collaborations.

Parallel architectures such as GPUs and AI inference engines are today's best performing computer hardware, in terms of both low power consumption and high number of events processed per euro spent. They clearly constitute the path toward affordable computing for HL-LHC experiments.

The FASTTRACK data-processing chain spans multiple applications that communicate with each other inside servers or through networks and utilize systems such as remote storage, and compute accelerators. To achieve good performance and to discover and mitigate bottlenecks, all of these applications and systems need to be designed with an overall approach and validated through global system tests. The main **deliverable** of WP5.1 will be an accelerator validation facility, that will consist of approximately 8 host servers, each housing a number of (future) compute accelerators, connected through a fast network. The goal of the facility is to help us pick workflows that target accelerators and to validate that they can scale up to what will be needed for production, i.e. to close the gap between running a few jobs for a few hours on a single server and running hundreds of thousands of jobs for days on the grid. To stay abreast of developments in available hardware over the duration of the project, we intend to purchase and install hardware in two phases. The WP5.1 **milestones** are the selection and procurement of the phase-1 and phase-2 hardwares at the end of 2026 and 2030, respectively, and their installation and commissioning by the end of 2027 and 2031, respectively.

WP5.2: Tracking with Machine Learning Traditional tracking methods such as modified Kalman filters [108, 109], have been foundational in particle tracking. However, as the density of hits grows, the time required to reconstruct all tracks dramatically increases, making it very difficult to distinguish between overlapping tracks. Exploiting the FASTTRACK breakthrough presented in section 2.1.4, we will develop and implement deep learning-based tracking algorithms incorporating the fast-time information that are optimized for compute accelerators.

Graph Neural Networks (GNNs) [110] represent an innovative approach, modelling the relationships between tracked particles as nodes and edges in a graph; GNNs can effectively handle multi-particle tracking scenarios, but require significant resources for training and inference. We will therefore focus on a transformer-based architecture, for which our pilot studies have shown extremely encouraging results. These models use attention mechanisms to capture long-range dependencies and interactions between tracked particles to improve the accuracy, track-finding capabilities and data throughput of tracking systems [111]. Once proof-of-concept algorithms have been developed, we will improve the scalability of our models and reduce their computational load and memory requirements. Finally we will develop hybrid models that combine the strengths of transformers and GNNs with existing techniques such as Kalman filters, and with physics insight.

The central WP5.2 **deliverable** is a set of fully optimized and integrated deep-learning based algorithms ready to be used for the track reconstruction of FASTTRACK detectors by the end of 2034. The first WP5.2 **milestone** will be to design and implement prototype (hybrid) algorithms based on GNNs, transformers and potentially other promising deep-learning techniques by the end of 2028. The second **milestone**, at the end of 2031, will be a demonstration of the integration of the newly designed algorithms with existing pattern recognition frameworks and pipelines.

5.2 IT-infrastructure including data and software

Processing infrastructure The experiments in FASTTRACK are amongst the largest scientific data producers in the world, and the LHC experiments have established a globally-distributed processing infrastructure, coordinated by CERN, to deal with the collaborative nature of the infrastructure and the volume and complexity of data. This *Worldwide LHC Computing Grid* (WLCG) [53] comprises data centers hosted by over 170 institutions in more than 40 countries, with "Tier-1" centers ensuring long-term data preservation and guaranteed transport links to ensure measured data is safely stored. The Netherlands is one of the 12 countries providing such Tier-1 services and the only one to do so *'as a service'* through its national e-infrastructure federation (SURF in the Netherlands [55]). In 2024 the NL-T1 provides over 77 million CPU cores, 17.3 petabyte of on-line disk storage and almost 48 petabyte of managed near-line storage. This is distributed over facilities at Nikhef and SURF, and coordinated by SURF, the collaborative organization for IT in Dutch education and research [55].

The distribution and capacity of the WLCG is based on international agreements, following a review process within each experiment, followed by independent expert scrutiny in the WLCG collaboration, and endorsed by the LHC Resources Review Board. The national shares are derived from the thus-validated experiment requirements, but obviously constrained by available resources. To tackle the increased data volume and complexity from FASTTRACK detectors, significantly more computing power is required. In section 5.1.5, we addressed the required developments in analysis and system instrumentation: computing accelerators, GPU and AI inference methods, and improved tracking with machine learning. These advancements are foundational to lower the investment cost for computing hardware, but also to make it more energy efficient. The latter is critical not only because of budget constraints and environmental considerations, but also because the energy grid has reached its capacity limits.

Funding The funding for the operational infrastructure for the WLCG collaboration, i.e. the mass processing of measured data and validation simulations, intermediate storage and archival facilities, is provided from a variety of sources including institutional-, national-, and collaborative 'joint infrastructure' projects, and is not part of FASTTRACK. The FASTTRACK budget solely includes the IT costs that are required to develop and validate the next generation of data processing systems: the accelerator validation facility and the engineering to improve tracking with machine learning and AI inference, with staged acquisition to support a continuous improvement methodology. Providing only the foundational model and empirical validation of the data processing of the FASTTRACK detectors, it can never aspire to deal with the operational data volumes coming from the HL-LHC. It is intentionally not designed for that purpose.

It is therefore imperative that the advances of FASTTRACK are embedded in the future Dutch National e-Infrastructure coordinated by SURF. As one of the most advanced and coordinated infrastructures in Europe, SURF enables close collaboration in all three innovation horizons: in terms of futuring (5+ years), where the advancements in FASTTRACK align with the technology trends that SURF identified in consultation with national expert groups, but, importantly, also in the innovation flow towards national technology demonstrators in the SURF innovation zones and in the big data science innovation collaborations between SURF, Nikhef, and peer research organizations with similar processing needs. As a result of these collaborations, it has been agreed with SURF to facilitate integration of their federated services into the validation facility to explore horizontal scaling to other facilities such as SURF's Experimental Technologies Platform [55]. By the time that the HL-LHC data is fully operational, the national e-infrastructure will then be ready to process the experimental data, both from the FASTTRACK detectors but also from other research disciplines, on a next generation national High Throughput (HTC) and High Performance (HPC) infrastructure. To this end, Nikhef already co-develops the benchmarks and (where feasible) jointly procures with SURF the next generation high-performance networks and HTC and HPC systems. FASTTRACK strengthens this national collaboration, and the advances in accelerated computing (section 5.1.5) will be embedded in the national e-infrastructure innovation agenda.

Software Algorithms and software developed in FASTTRACK are designed to exploit new hardware and use new tracking models. The FASTTRACK software follows well-defined and open engineering practices, as the FASTTRACK enhancements need to become part of standard libraries and software toolkits for high-energy physics that have an operational lifetime of decades. Their applicability often extends to other experiments and adjacent disciplines, and for this reason codes also consistently use open-source licenses (to permit wide re-use) and appropriate open- source development methodology, sharing results early in public and openly accessible code repositories. CERN, with its tradition and consistent advocacy of Open Access publishing and open data policies [48, 54], ensures the availability of code and documentation. Joint work with the Netherlands e-Science Center on accelerated computing supports embedding in both the national and European software community.

FAIR data principles The data collected through FASTTRACK fall into two categories: the data collected with the next-generation detectors by the HL-LHC are by definition part of the data of the experimental collaborations, and will be processed on the global WLCG infrastructure. The Open Data Policies of CERN and the experiments [48] align fully with the FAIR principles, and ensure re-use of both existing and new HL-LHC data. The data collected as part of the FASTTRACK detector R&D process, including characterization and validation, are a critical component of the technical design publications of the experiments, and have to remain available for as long as the FASTTRACK detectors are operational, and some will have applicability beyond just these detectors. Data will be collected, indexed, annotated, and archived in alignment with FAIR criteria at CERN (either in the open data repository [54] or in Zenodo). For data that have a more local scope, the Nikhef Institutional Repository will handle persistent identifier assignment, accessibility, annotation, and availability for re-use (of course subject to confidentiality requirements and export regulations). Domain data management experts ensure that the choice of repository maximizes impact of the data publication and re-use opportunities.

5.3 Risk analysis and mitigation strategy

The final design and construction of the detector components of the fast-timing tracking systems are essential parts of the LHC experiments at CERN, and their delivery and planning will be embedded in the LHC collaborations. In these projects, timely achievement of milestones will be followed in detail in regular project meetings and reviews. All collaborations have implemented a Technical Board, which reviews major technical and planning issues and proposes possible solutions. The collaborations have much experience in dealing with unforeseen problems. In general, major projects in both the LEP and LHC eras have been successfully completed, within time and budget envelopes (with modest exceptions in individual projects).

The risks specific to FASTTRACK are listed in table 6. Generally speaking, technical risks imply that some specifications may not be fully reached; our overall approach of sensors, electronics, read-out, mechanics and computing allows performance slightly below specifications in one WP to be compensated in another.

***Table 6:** Risks and mitigation strategy.*

Risk	Likelihood	Effect	Mitigation
Technical risks			
Not achieving time resolution specification	Moderate	Moderate	We can increase computing power, operate at slightly lower intensity or implement additional measurement layers. In case of major issues with one technology, we can consider switching to another technology.
Not achieving the required radiation tolerance	Low	Low	The radiation hardness is extensively tested by experts in the consortium and in the field. A first mitigating action would be operating the sensors at lower temperatures. If needed, either partial replacement or operation at reduced luminosity can also be considered.
Not achieving the data transmission speed	Moderate	Low	We can either operate at lower LHC luminosity or invest in a larger number of data links.
Not achieving specifications for cooling or lightweight support	High	Low	Our R&D on both topics is high-risk, high-gain. We can use more conservative technologies that serve as a back-up, at the cost of slightly reduced detector performance.
Financial risks (see also section 4.2)			
Costs overrun	Moderate	Low	The long-term budget planning of Nikhef includes an allocation for cost overruns (not included in the budget for this LSRI proposal), at a level of 20%, which is the standard practice for particle physics projects.
Unforeseen extension of engineering or production phase	Moderate	Low	Can be mitigated by re-scheduling in the Nikhef project-structure or by adding person power to make up for delays. Hiring temporary technical support staff from the 20% funding overhead could also be considered.
Scheduling risks (see also section 4.1)			
Delays in the HL-LHC schedule	Moderate	Moderate	We can adapt the FASTTRACK construction schedule to such delays. We consider the consequent delay in the beginning of the science harvesting to have moderate impact, since the HL-LHC physics potential is not challenged by competition in the near future.

6. LITERATURE AND OTHER RELEVANT INFORMATION

Literature references

[1] 2020 Update of Eur Strat for part phys, **[2]** Part Phys PPP 2023, **[3]** ECFA R&D Roadmap, **[4]** P Kuijer *et al* 2000 *NIM-A* **447** 1 P251, **[5]** B Abelev *et al* 2014 JPhys G **41** P087002, **[6]** A Abdesselam *et al* 2008 *JINST* **3** P05002, **[7]** G Aad *et al* 2008 *JINST* **3** S08003, **[8]** R Aaij *et al* 2014 *JINST* **9** P09007, **[9]** R Aaij *et al* 2024 *JINST* **19** P05065, **[10]** R Arink *et al* 2014 *JINST* **9** P01002, **[11]** G Aglieri Rinella *et al* 2024 *arXiv 2407.18528*, **[12]** GA Rinella *et al* 2023 *NIM-A* **1056** P168589, **[13]** K Ma *et al* 2024 *NIM-A* **1063** P169237, **[14]** S Ali *et al* 2023 *JINST* **18** 5 P05005, **[15]** J Ballabriga *et al* 2023 *NIM-A* **1045** P167489, **[16]** K Heijhoff et al 2021 JINST 16 P08009, **[17]** R Geertsema *et al* 2022 *JINST* 17 P02023, **[18]** G Aad *et al* 2012 *Phys Lett B* **716** P1, **[19]** S Chatrchyan *et al* 2012 *Phys Lett B* **716** P30, **[20]** G Aad *et al* 2022 *Nature* **607** P52, **[21]** R Aaij *et al* 2023 *PRL* **131** P051803, **[22]** R Aaij *et al* 2022 *PRL* **128** P041801, **[23]** S Archarya *et al* 2024 *EPJ-C* **84** 813, **[24]** CERN courier July/Aug 2021, **[25]** HFW Sadrozinski *et al* 2017 *RPP* **81** P026101, **[26]** L Diehl *et al* 2024 *NIM-A* **1065** P169517, **[27]** G Iacobucci *et al* 2019 *JINST* **14** P11008, **[28]** T Poikela *et al* 2014 *JINST* **9** C05013, **[29]** X Llopart *et al* 2022 *JINST* **17** C01044, **[30]** HL Snoek *et al* FASTER, **[31]** ALICE Coll 2022 *CERN-LHCC-2022-009*, **[32]** ATLAS coll 2022 *ATL-PHYS-PUB-2022-018*, **[33]** ATLAS Coll 2023 *ATL-PHYS-PUB-2023-023*, **[34]** I Bediaga *et al* 2018 *arXiv 1808.08865*, **[35]** A Abada *et al* 2019 *EPJ-ST* **228** P261, **[36]** A Abada *et al* 2019 *EPJ-ST* **228** P755, **[37]** Nikhef SEP 2023, **[38]** H van der Graaf *et al* 1998 *NIM-A* **419** P336, **[39]** J Anderson *et al* 2015 JP Conf Ser **664** 8 P082050, **[40]** G Aad *et al* 2024 *JINST* **19** P05063, **[41]** R Aaij *et al* 2022 *CS Big Sci* **6** 1, **[42]** CERN Code of Conduct, **[43]** Nikhef Strategy 2023-2028, **[44]** NWA route, **[45]** Euro Strat for Particle Phys, **[46]** ESFRI RM 2021, **[47]** LHCb org 2024, **[48]** CERN Data Policy, **[49]** HEPAP, **[50]** DRSTP school, **[51]** K Lee *et al* 2023 *arXiv* 2308.00028, **[52]** M van Beekveld *et al* 2024 *arXiv* 2406.02661, **[53]** WLCG, **[54]** CERN OpenData 2024, **[55]** about SURF, **[56]** FuSE, **[57]** ECFA org, **[58]** ILC, **[59]** C Accettura *et al* 2023 *EPJ-C* **83** 864, **[60]** DUNE exp, **[61]** M Perrin-Terrin 2022 EPJ C 82 P465, **[62]** A Baratto-Roldán *et al* 2024 *arXiv* 2401.17068, **[63]** B Bergmann *et al* 2014 *JINST* **9** C05048, **[64]** C Lynde *et al* 2020 *NIM-A* **954** P161373, **[65]** J Vallerga *et al* 2011 *JINST* **6** C01049, **[66]** H Bromberger *et al* 2022 *JP-B* **55** 14 P144001, **[67]** A Cereser *et al* 2017 *Sci Rep* **7** P9561, **[68]** B Verlaat *et al CERN-2008-008.328*, **[69]** JH Arling *et al* 2022 *NIM-A* **1038** 1 P166953, **[70]** G Ambrosi *et al* 2023 *ATE* **230** P120738, **[71]** Medipix Coll **[72]** Medipix colour Xray CT, **[73]** S Coban *et al* 2020 *JofImaging* **6** 4, **[74]** ASI, **[75]** Malvern Panalytical, **[76]** K Gwosch *et al* 2013 *Phys Med Biol* **58** P3755, **[77]** AM Reinhart *et al* 2017 *Phys Med Biol* **62** P4884, **[78]** M4i res inst, **[79]** J Visser *et al* 2015 *JINST* **10** C12028, **[80]** HighTechXL, **[81]** Incooling, **[82]** Inphocal, **[83]** Aircision, **[84]** Bigscience.nl, **[85]** PERIIA, **[86]** CERN Venture Connect, **[87]** C Nellist ParticleClara, **[88]** DPC BiBB, **[89]** OECD Tech rep 2014, **[90]** M

Florio et al 2018 Indust and Corp change 27 P915, **[91]** A Bastianin, M Florio *2018 CERN-ACC-2018-0014*, **[92]** ATLAS org 2024, **[93]** OSAF school, **[94]** LHC exp comm *CERN-LHCC-2022-012*, **[95]** M Huhtinen *et al* 1993 *NIM-A* **335.3** P580, **[96]** G Kramberger *et al* 2019 *NIM-A* **934** P26, **[97]** K Ma *et al* 2024 *NIM-A* **1063** P169237, **[98]** M Carulla *et al* 2019 *NIM-A* **924** P373, **[99]** F Borgato *et al* 2024 Front Phys **12** P1393019, **[100]** GA Rinella *et al* 2023 *NIM-A* **1056** P168589, **[101]** F Resta *et al* 2018 *Integr* **63** P306, **[102]** HJ Barnaby 2006 *IEEE ToNS* **53** 6 P3103, **[103]** J Wei *et al* 2015 *IEEE ECOC* P1, **[104]** K Akiba *et al* 2024 *JINST* **19** P06023, **[105]** P Hopchev 2017 *arXiv* 1710.08325, **[106]** S Acharya *et al* 2024 *JINST* **19** P05062, **[107]** AS Purandare *et al* 2023 Int Comm HMR **148** P107042, **[108]** RE Kalman 1960 *J Basic Eng* **82** P35, **[109]** M Aaboud *et al* 2017 EPJ C **77** 673, **[110]** J Shlomi *et al* 2020 *Mach Learn Sci Tech* **2** P021001, **[111]** S Caron *et al* 2024 *arXiv* 2407.07179.

Relevant key publications

Roel Aaij R Aaij *et al* "Test of Lepton Universality in $b\to s\ell^+\ell^-$ Decays" 2023 *PRL* **131** P015803 ❖ R Aaij *et al* "Allen: A High-Level Trigger on GPUs for LHCb" 2020 *Comput Softw Big Sci* **4** 7 / **Kazu Akiba** K Akiba *et al* "The LHCb VELO Upgrade module construction" 2024 *JINST* **19** P06023 ❖ R Geertsema *et al* "Charge and temporal characterisation of silicon sensors using a two-photon absorption laser" 2022 *JINST* 17 P02023 ❖ E Dall'Occo *et al* "Temporal characterisation of silicon sensors on Timepix3 ASICs" 2021 *JINST* **16** P07035 **/ Stan Bentvelsen** G Aad *et al* "Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC" 2012 *Phys Lett B* **716** P1 ❖ G Aad *et al* "The ATLAS Experiment at the CERN Large Hadron Collider" 2008 *JINST* **3** S08003 ❖ G Aad *et al* "Top quark-pair production cross section with ATLAS in pp collisions at sqrt(s) is 7 TeV" 2011 EPJ C **71** 1577 / **Martin van Beuzekom** J Ballabriga *et al* "The Timepix4 analog front-end design" 2023 *NIM-A* **1045** P167489 ❖ K Heijhoff et al "Timing measurements with a 3D silicon sensor on Timepix3 in a 180 GeV/c hadron beam" JINST 16 P08009 ❖ R Geertsema et al "Charge and temporal characterisation of silicon sensors using a two-photon absorption laser" 2022 JINST 17 P02023 / **Jorgen D'Hondt** J de Blas *et al* 2020 "Higgs Boson studies at future particle colliders" *JHEP* **1** 139 ❖ CMS collaboration "The Phase-2 Upgrade of the CMS Tracker" CERN-LHCC-2017-009 ❖ AM Sirunyan *et al* "Identification of heavy-flavour jets with the CMS detector" 2018 *JINST* **13** P05011 / **Frank Filthaut** G Aad *et al* "Observation of a new particle in the search for the Standard Model Higgs boson" 2012 *Phys Lett B* **716** P1 ❖ G Aad *et al* "A detailed map of Higgs boson interactions by the ATLAS experiment ten years after the discovery" 2022 *Nature* **607** P52 ❖ ATLAS collaboration "A High-Granularity Timing Detector for the ATLAS Phase-II Upgrade" 2020 CERN-LHCC-2020-007 / **Martin Fransen** G Aglieri Rinella *et al* "Time performance of Analog Pixel Test Structures with in-chip operational amplifier implemented in 65 nm CMOS" 2024 *arXiv 2407.18528* ❖ M Voschezang, M Fransen "Optimizations of a Generic Holographic Projection Model for GPU's" 2021 *CS ICCS* **part IV** V12745 / **Alessandro Grelli** ALICE ITS project "First demonstration of in-beam performance of bent Monolithic Active Pixel Sensors" 2022 *NIM-A* **1028** P166280 ❖ B Abelev *et al* "The Upgrade of the ALICE Inner Tracking System" 2014 JPhys G **41** P087002 ❖ ALICE Collaboration "Letter of intent for ALICE 3" 2022 *CERN-LHCC-2022-00* / **David Groep** EC DG RI, K Wierenga *et al* "Report from the EOSC Executive Board WG Architecture AAI TF" *EOSC Authent. & Author. Infra – EOSC EB WG Architecture AAI TF* ❖ D L Groep and D Bonacorsi "20th International Conference on Computing in High Energy and Nuclear Physics (CHEP2013)" 2014 *J Phys Conf Ser* **513** 001001 / **Wouter Hulsbergen** R Aaij *et al* "Test of Lepton Universality in $b\to s\ell^+\ell^-$ Decays" 2023 *PRL* **131** P015803 ❖ R Aaij *et al* "The LHCb Upgrade I" 2024 *JINST* **19** P05065 ❖ R Aaij *et al* "Improved measurement of CP violation parameters in $B^0_s\to J/\psi K^+K^-$ decays in the vicinity of the $\phi(1020)$ resonance" *Phys Rev Lett* **132** P051802 / **Marcel Merk** R Aaij *et al* "Analysis of Neutral *B*-Meson Decays into Two Muons" 2022 *PRL* **128** P041801 ❖ R Aaij *et al* "The LHCb Upgrade I" 2024 *JINST* **19** P05065 ❖ I Bediaga *et al* "Physics case for an LHCb Upgrade II" 2018 *arXiv 1808.08865* **/ Elena Dall'Occo** R Geertsema *et al* "Charge collection properties of prototype sensors for the LHCb VELO upgrade" 2021 *JINST* **16** P02029 ❖ E Dall'Occo *et al* "Temporal characterisation of silicon sensors on Timepix3 ASICs" 2021 *JINST* **16** P07035 ❖ K Akiba *et al* "Reconstruction of charged tracks with Timepix4 ASICs" 2023 *JINST* **18** P02011 / **Antonio Pellegrino** R Aaij *et al* "Analysis of Neutral *B*-Meson Decays into Two Muons" 2022 *PRL* **128** P041801 ❖ R Aaij *et al* "The LHCb Upgrade I" 2024 *JINST* **19** P05065 ❖R Arink *et al* "Performance of the LHCb Outer Tracker" 2014 *JINST* **9** P01002 / **Raimond Snellings** S Archarya *et al* "The ALICE experiment: a journey through QCD" 2024 *EPJ-C* **84** 813 ❖ G Nijs *et al* "Transverse Momentum Differential Global Analysis of Heavy-Ion Collisions" *PRL* **126** P202301 ❖ U Heinz, R Snellings "Collective Flow and Viscosity in Relativistic Heavy-Ion Collisions" 2013 *Ann Rev Nucl Part Sci* **63** 123 / **Hella Snoek** R Geertsema *et al* "Charge and temporal characterisation of silicon sensors using a two-photon absorption laser" 2022 *JINST* 17 P02023 ❖ ATLAS collaboration "Evidence of off-shell Higgs boson production from *ZZ* leptonic decay channels and constraints on its total width" *Phys Lett B* **846** P138223 / **Mara Senghi Soares** R Aaij *et al* "Test of Lepton Universality in $b\to s\ell^+\ell^-$ Decays" 2023 *PRL* **131** P015803 ❖ S Chatrchyan *et al* "Observation of a new boson at a mass of 125 GeV" 2012 *Phys Lett B* **716** P30 ❖ CMS "Top-quark pole mass and strong coupling constant from the t t-bar production cross section in pp collisions at sqrt(s) = 7 TeV" 2013 Phys Lett B **728** 496 / **Jory Sonneveld** GA Rinella *et al* "Digital pixel test structures implemented in a 65 nm CMOS process" 2023 *NIM-A* **1056** P168589 ❖J Debevc *et al* Time resolution of the RD50-MPW2 DMAPS prototype using TCT and ^{90}Sr" 2024 *JINST* **19** P05068 ❖ M Benoit *et al* "Simulating radiation effects and signal response in silicon sensors" 2021 CERN-2021-001 P123 / **Wouter Verkerke** G Aad *et al* "Observation of a new particle in the search for the Standard Model Higgs boson" 2012 *Phys Lett B* **716** P1 ❖ G Aad *et al* "A detailed map of Higgs boson interactions ten years after the discovery" 2022 *Nature* **607** P52 ❖ G Aad *et al* "The Higgs boson production and decay rates and constraints on its couplings from a combined ATLAS and CMS analysis" 2016 JHEP **8** 45 / **Mengqing Wu** M Wu *et al* "A High-Granularity Timing Detector for the ATLAS Phase-II Upgrade" 2024 *JPS ConfProc* **42** P011026 ❖ Y Liu *et al* "EUDAQ2—A flexible data acquisition software framework for common test beams" 2019 *JINST* **14** P10033 ❖ J Brau *et al* "Lycoris - A large-area, high resolution beam telescope" 2021 *JINST* **16** P10023.

Number of pages

The number of pages of Sections 1 to 6 of this grant application is: 40 pages *(max. 40 pages).*

7. DATAMANAGEMENT

1. Will this project involve re-using existing research data?
   - ☒ Yes: Are there any constraints on its re-use?
   - ☐ No: Have you considered re-using existing data but discarded the possibility? Why?

The construction and upgrades of FASTTRACK are embedded in the LHC experiments, and built upon research and development data, materials detector characterization results, and operational data of the existing detectors that are part of the LHC detector data. These data are freely accessible to the members of the LHC collaborations and are also FAIR and openly accessible within the constraints of protection of intellectual property, applicable non-disclosure agreements with suppliers, while being mindful of dual-use controls and export regulations that could apply to parts of the re-used data. The LHC collaborations in whose context the FASTTRACK construction will take place will ensure that the existing data necessary for the infrastructure are available.

2. Will data be collected or generated that are suitable for reuse?
   - ☒ Yes: Please answer questions 3 and 4.
   - ☐ No: Please explain why the research will not result in reusable data or in data that cannot be stored or data that for other reasons are not relevant for reuse.

3. After the project has been completed, how will the data be stored for the long-term and made available for the use by third parties? Are there possible restrictions to data sharing or embargo reasons? Please state these here.

The data collected as part of the FASTTRACK upgrades for the LHC will be curated and managed as part of the LHC detector design and operational data for a least as long as the detectors will be operational, which well exceeds the minimum of 10 years and will likely be for an indefinite period of time (at least till 2042). Data that are suitable for re-use (such as for materials studies, characterization) and all data used in publications and other scientific output, will be stored persistently in a managed repository and annotated with appropriate meta-data, including at least the essential meta-data for resource description (‘*Dublin core*’), but where possible and applicable annotated with domain-specific keywords, ontologies, and references. The preferred repository will depend on the data type, with the LHC Open Data repository, Zenodo, and the Nikhef Institutional Data Repository as pre-identified repositories. All these repositories assign persistent identifiers (typically DOIs), whereas individual data files may be assigned Handles (Handle.net) for accessibility. Some data may be access-restricted due to their commercial nature, or to comply with dual-use restrictions and export control regulations.

Note that the data volume collected as part of the R&D for FASTTRACK is of relatively modest size compared to the data volume that will be collected by the LHC program using the entire facility (including the FASTTRACK upgrades and the processing of the LHC experimental data through the novel accelerated analysis and machine learning pipelines). These data are managed by the LHC collaborations under the CERN Open Data Policy for the LHC Experiments (November 2020) framework. This ensures that data associated with published results will be released as open data at the time of publication in accordance with the FAIR principles. The “Reconstructed Data” (also known as “Level 3” data products) are released after a proprietary period and comprise calibrated reconstructed data with the level of detail useful for algorithmic, performance and physics studies. A limited level of support for users of the Level 3 Open Data will be provided on a best-effort basis by the collaborations.
It is not practically possible to make the full raw data-set (already in 2024 this is over 600,000,000 gigabytes of data, not even including the significant increase that FASTTRACK will generate once the HL-LHC is operational) from the LHC experiments usable in a meaningful way outside the collaborations. Access to representative subsets of raw data—useful for example for studies in the machine learning domain and beyond—can be released together with Level-3 formats, at the discretion of each experiment.

4. Will any costs (financial and time) related to data management and sharing/preservation be incurred?
   - ☐ Yes: Then please be sure to specify the associated expenses in the budget table of this application.
   - ☒ No: All the necessary resources (financial and time) to store and prepare data for sharing/preservation are or will be available at no extra cost.

The HL-LHC data itself, i.e. the data generated with the upgraded LHC detectors and facility once it includes the FASTTRACK upgrades, are out of scope for this infrastructure upgrade itself: the funding for the operational infrastructure is arranged by means of the dedicated “Worldwide LHC Computing Grid” collaboration (as discussed in section 5.2): the mass processing of measured data and validation simulations, intermediate storage and archival facilities, is covered by a variety of funding sources including institutional-, national-, and collaborative 'joint infrastructure' projects. This includes facilities for data preservation and access.

The data generated as a result of FASTTRACK itself are of limited size, and the repositories identified above can store and share that data without incurring additional costs.

8. Declarations and signature

Funding elsewhere

Have you requested funding via a grant application for this research infrastructure elsewhere?

☒ No
☐ Yes

Ethical aspects.

	Not applicable	Not yet applied for	Applied for	Received
Approval from a medical ethics review committee	☒			
Approval from an animal experiments committee	☒			
Permission for research with the population screening Act	☒			
Approval from any other recognised ethics review committee(s)	☒			

By submitting this form, I declare that:

☒ I have completed this form truthfully;
☒ I satisfy the nationally and internationally accepted standards for scientific conduct as stated in the Netherlands Code of Conduct for Research Integrity 2018;
☐ I have submitted non-referees (no more than 3 in total);
☒ I have entered all co-applicants in ISAAC;
☐ I endorse and follow the Code Openness Animal Experiments (if applicable);
☐ I endorse and follow the Code Biosecurity (if applicable);
☒ The consortium partners are aware of the NWO Grant Rules and obligatory establishment of an agreement containing IP&P arrangements and will adhere to this if the proposal is awarded.

Initial(s) and surname(s):

Place:

Date: