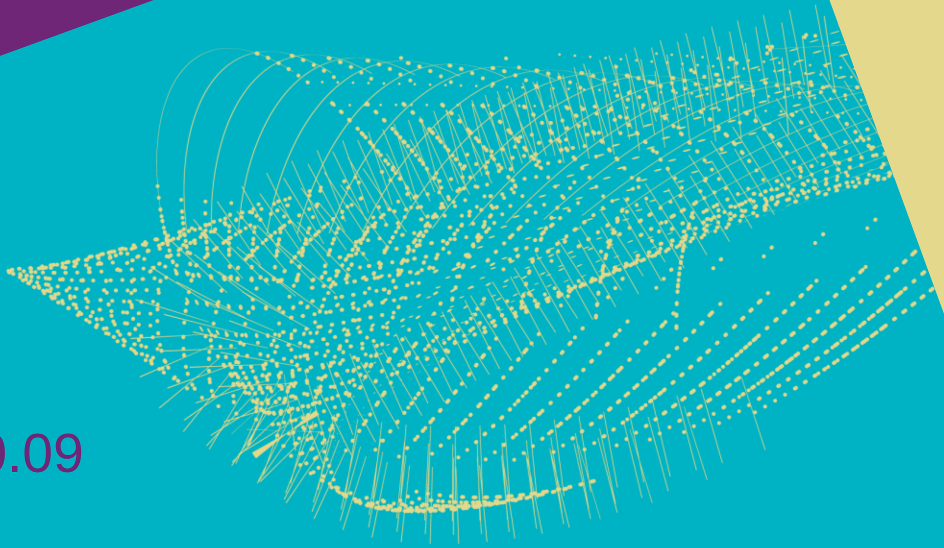
Nikhef



Tuesday 14 September 2021
10.30 – 17.30, WCW room Z0.09

Welcome to the joint Nikhef-QuSoft workshop

QuSoft
Research Center for Quantum Software

Welcome to today's programme!

10.30 .. 12.45	Session 1 *Introduction to the challenges of subatomic physics in HEP and GW* *Introduction to Quantum Computing* *Use case: the case from LHCb and tracking - followed by discussion*	
12.45 .. 14.00	Lunch	in room Z0.10 opposite
14.00 .. 15.30	Session 2 *State of the Art in Quantum Algorithms* *Use case: gravitational waves, 'template matching', and discussion*	
15.30 .. 16.00	Tea	also in room Z0.10
16.00 .. 16.45	Ideas Market: your lightning pitch, and some planning	
16.45 .. 17.30	Drinks, food, networking: building lasting collaboration …	

Nikhef

Nikhef-QuSoft workshop

Computing challenges in HEP and GW for the QC era

David Groep, PDP
September 2021

‘We live and breathe in a quantum world’

What are basic building blocks of matter and space-time?

How are structures formed and
how do they evolve?

And … how can we measure this?

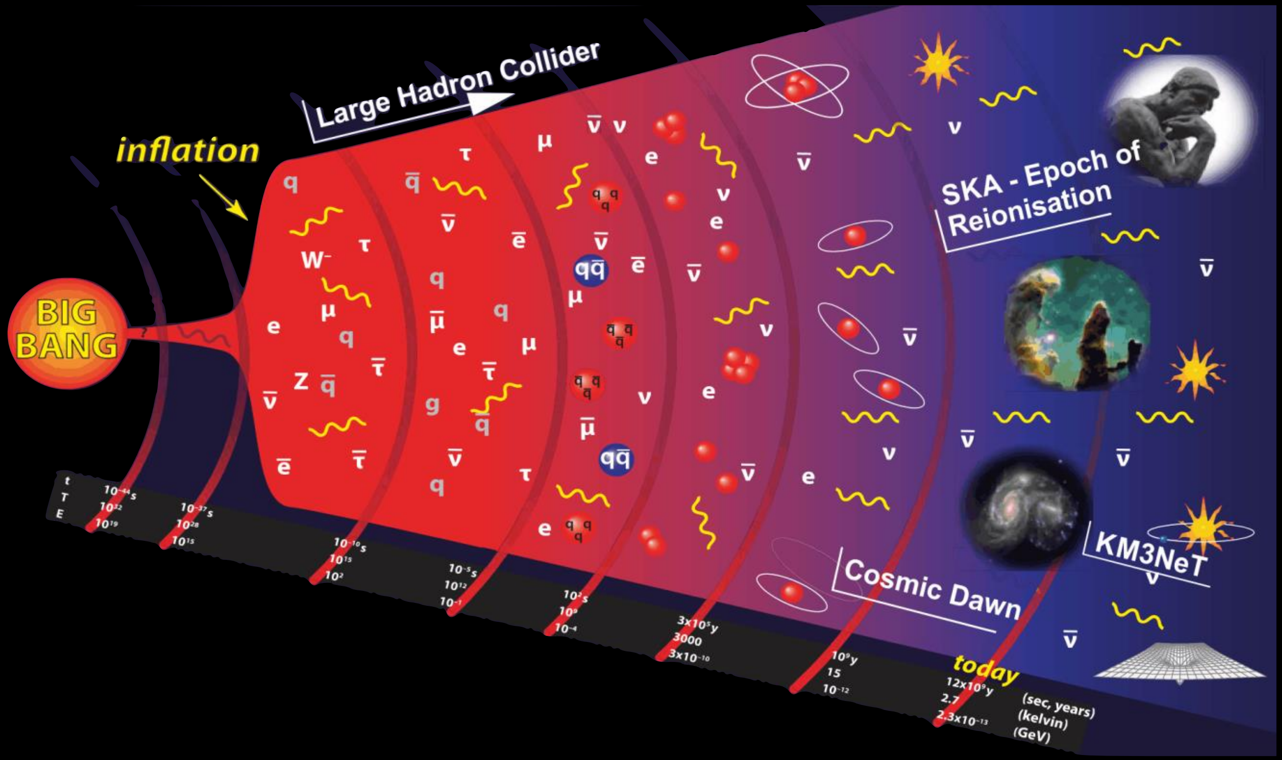
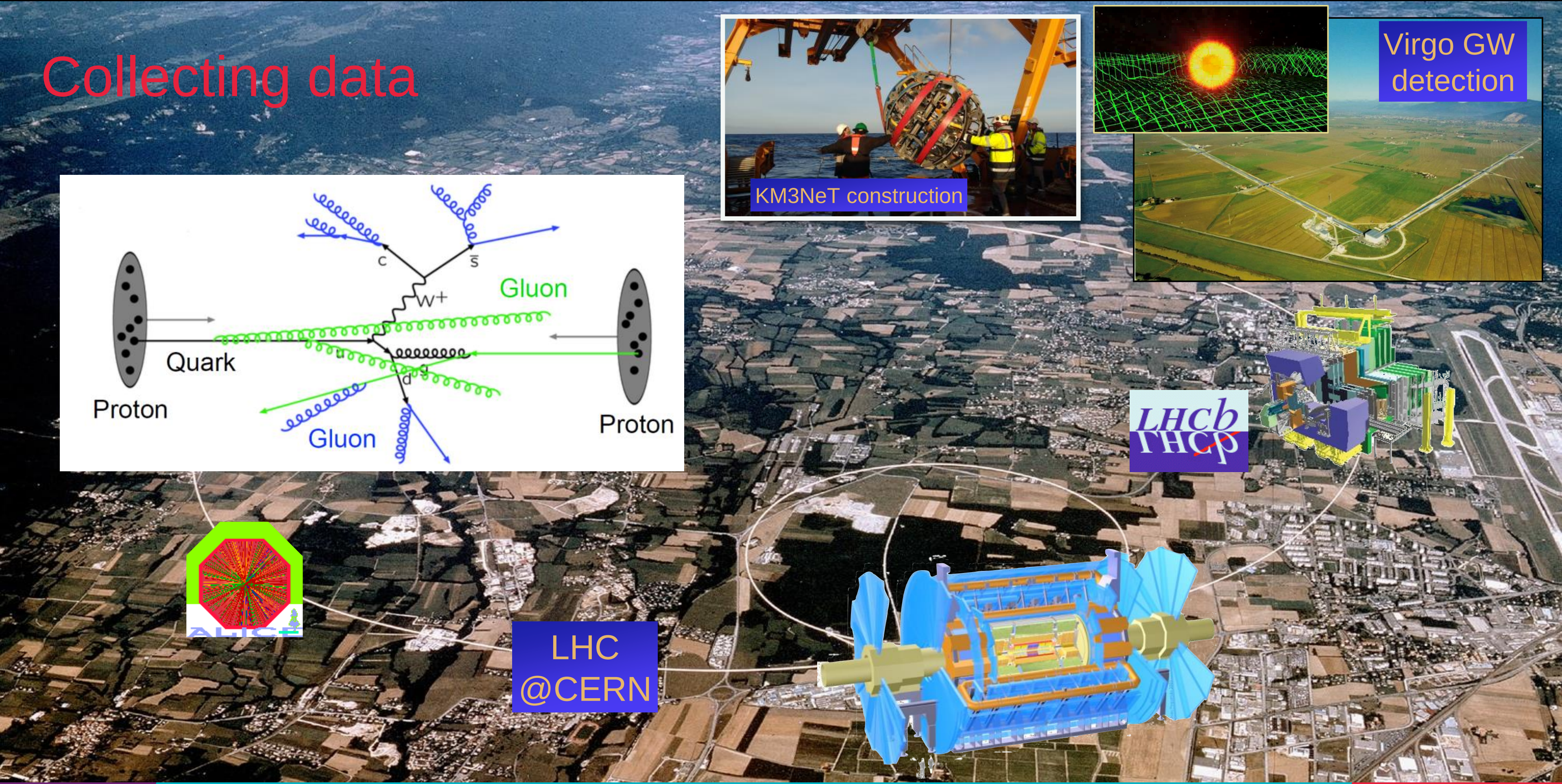


Image adapted from an original by: Kees Huyser, Nikhef

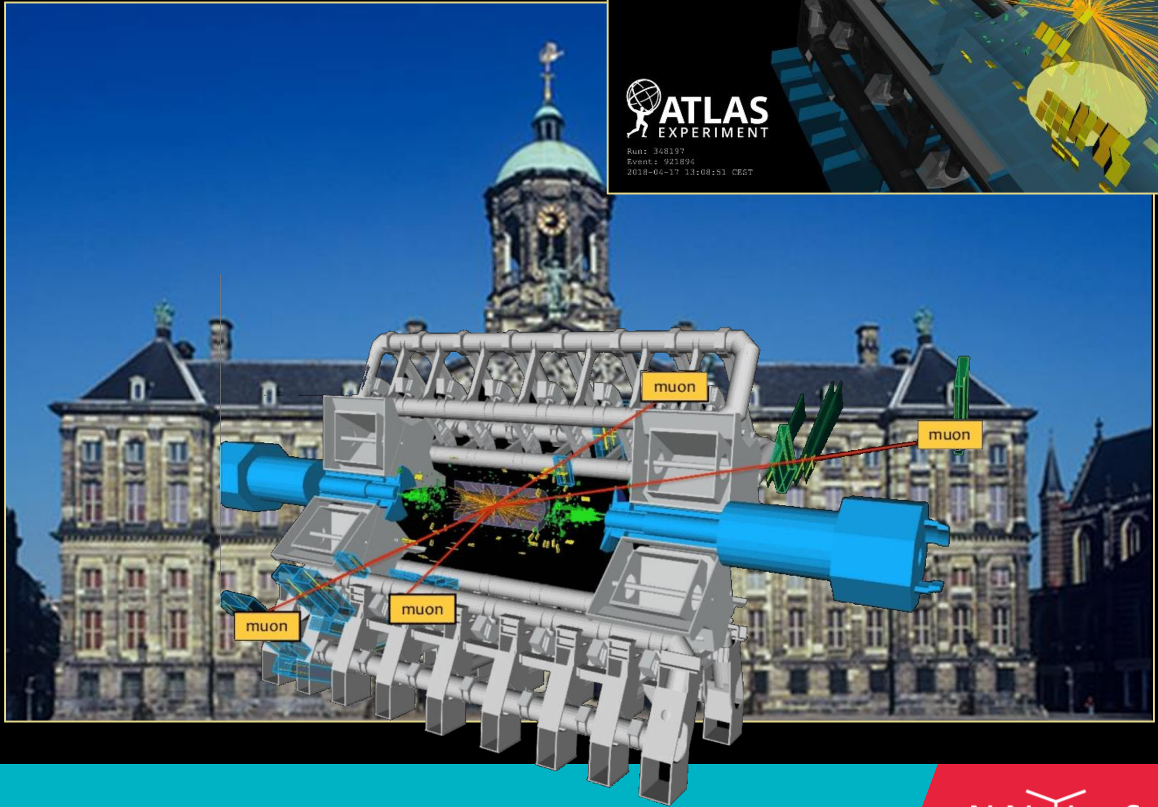
Collecting data

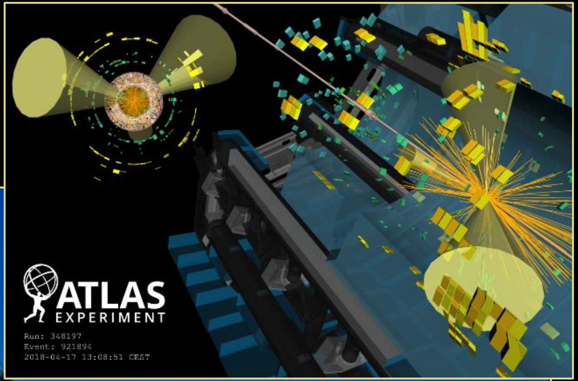


Images: Alice, ATLAS, and LHCb collaborations, CERN, Wikimedia, KM3NeT, Virgo collaboration

LHC data challenges

~ 50 PiB per year collected
180 institutions





Images: ATLAS collaboration, CERN, Wikimedia

Combining the small and large

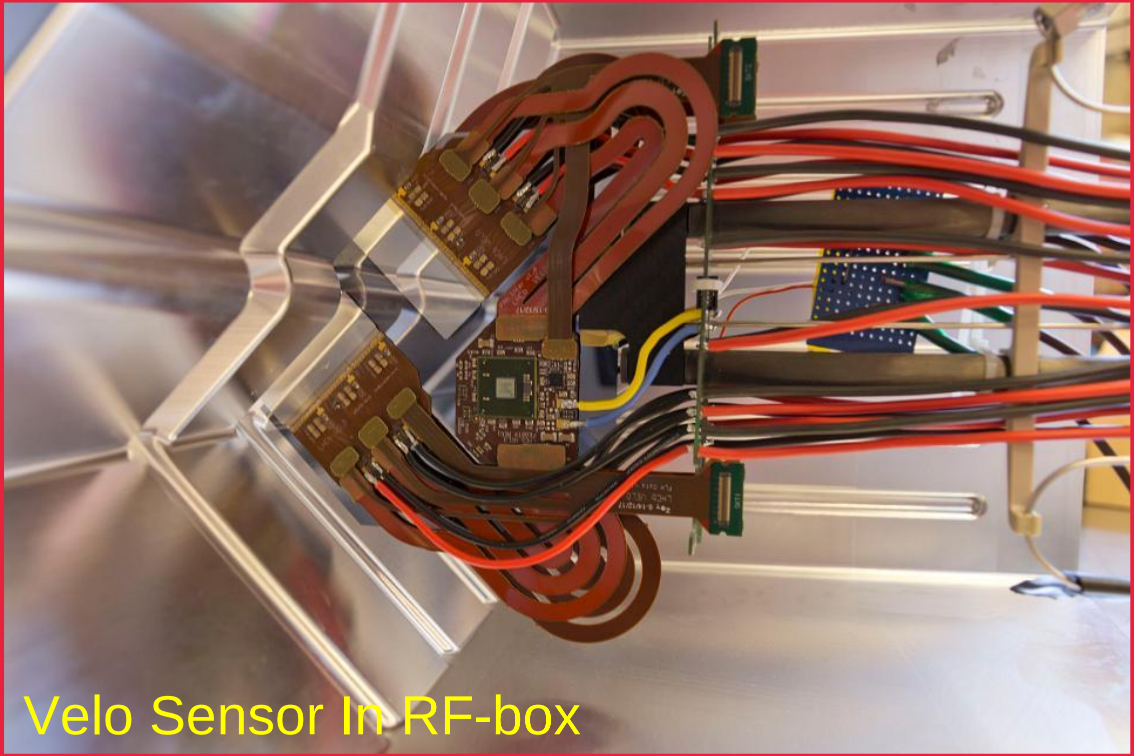
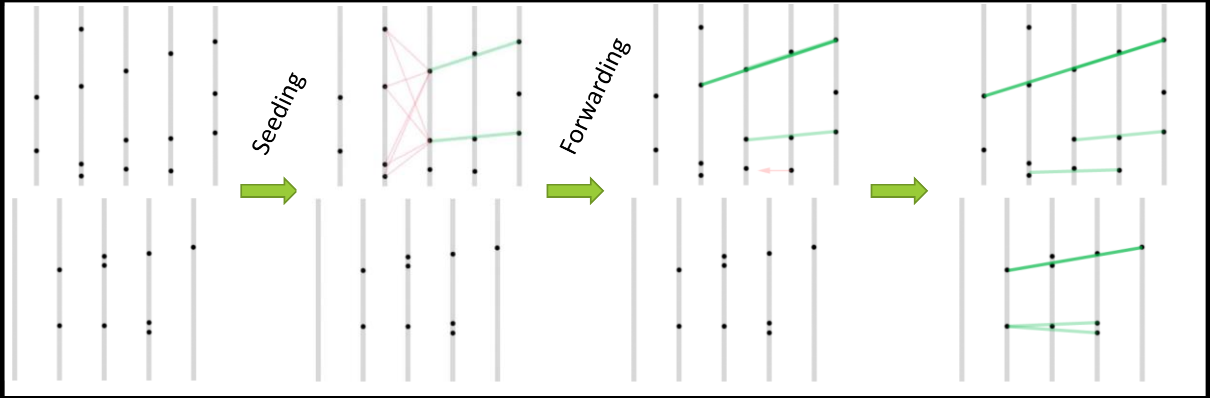


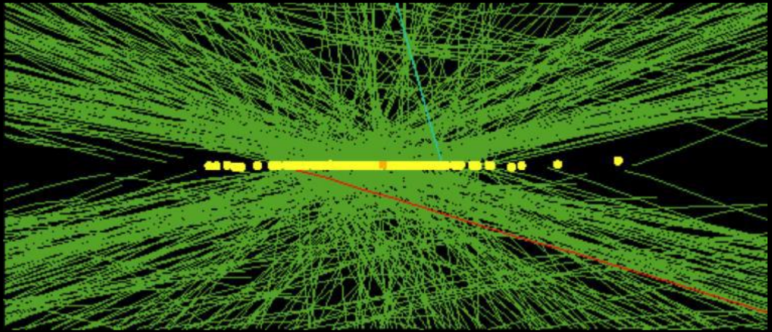
Image: Nikhef, LHCb

Tracking – a single particle is easy …

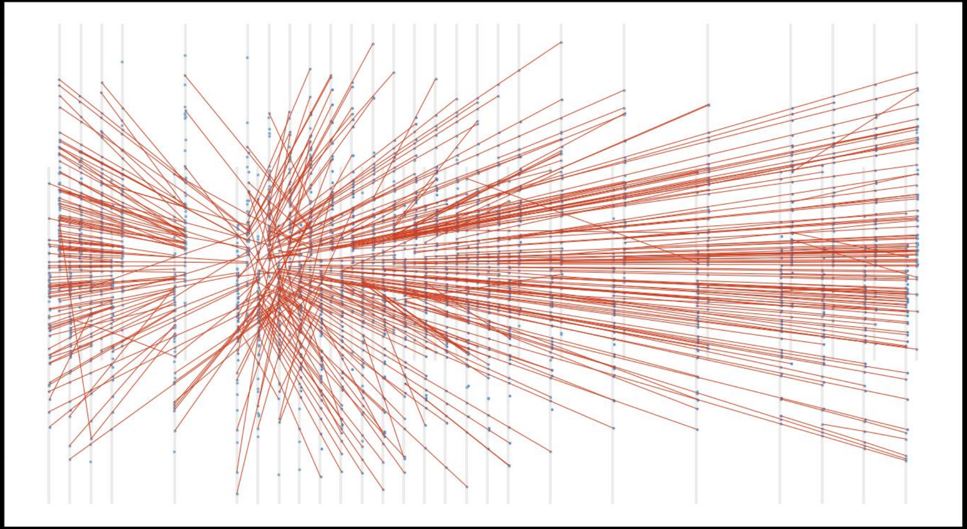


video ATLAS Muon chamber: Frank Linde, Nikhef
tracking image: P. Durante et al. , CERN (LHCb)

Like overlapping photo's



Typically available event information:
~ 90M pixel: (x,y,z), ($x,y,z,$dE), ($x,y,z,t,$dE)



but these contain
'overlapping exposures':
today: ~ 35-40
HL-HLC: > 250

frames: 40 million/sec …
(so you have just 25 ns)

Image from: 2016 J. Phys.: Conf. Ser. 706 022002, B. Schmidt, CERN
High pileup event with 78 reconstructed vertices taken in 2012 by CMS.
Multiplicity numbers from ATLAS: ATL-PHYS-PROC-2018-101, LHCP2018
Tracking image: D. Campora, LHCb, UM & Nikhef

Dealing with both volume and complexity

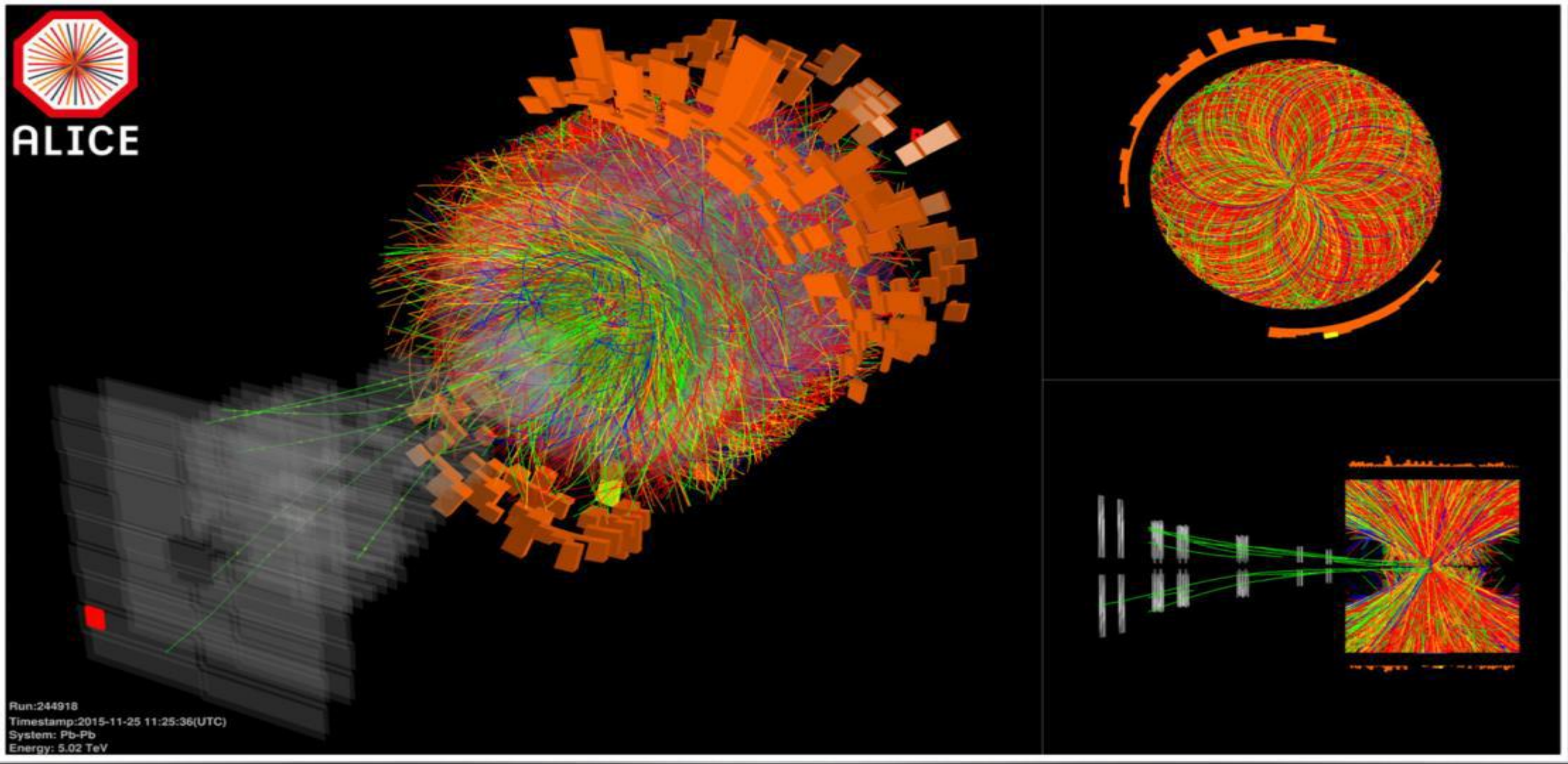
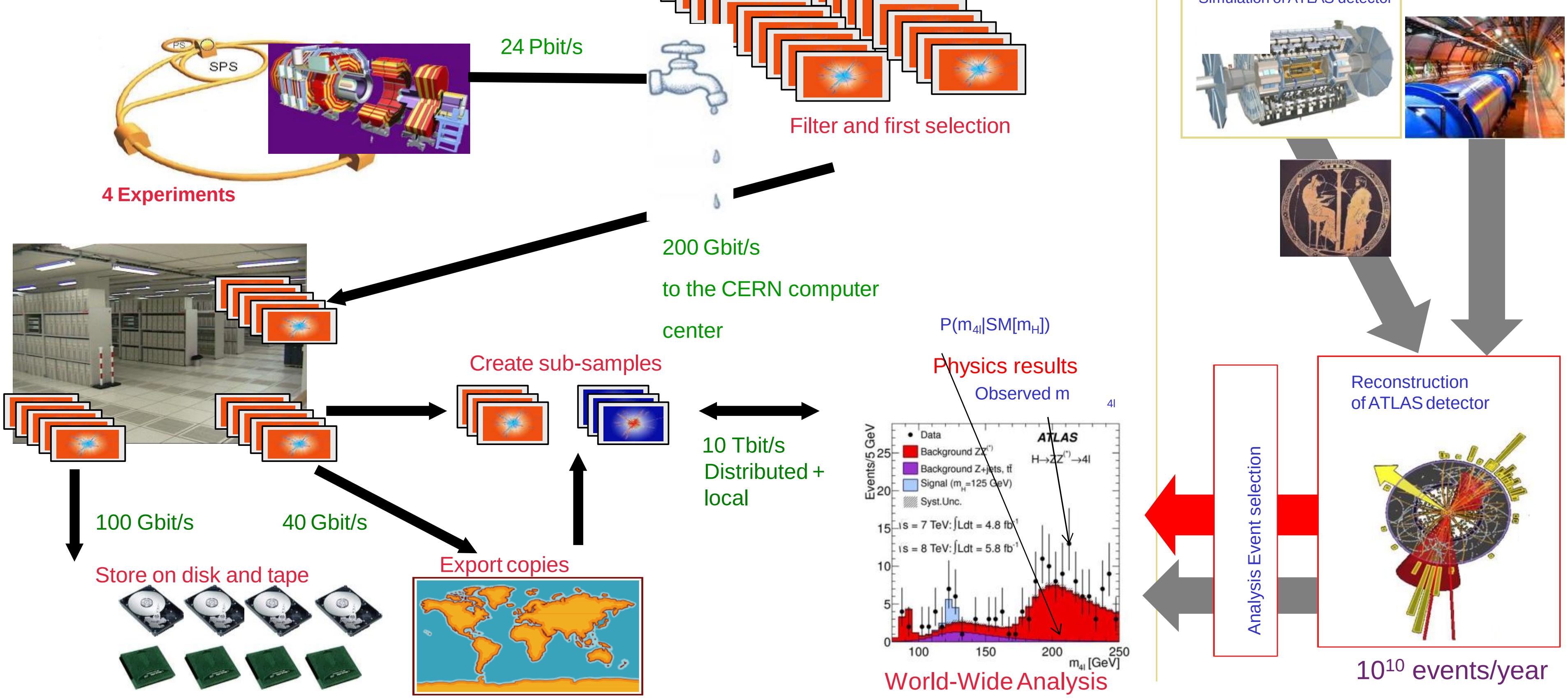


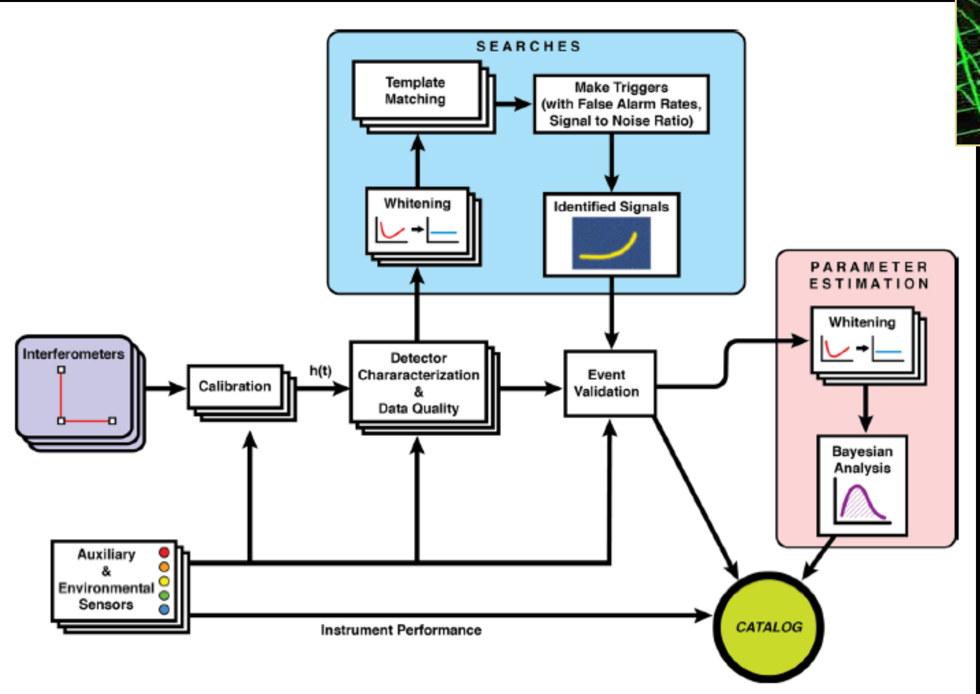
Image: Alice collaboration @LHC

Data flows at the LHC



Graphic elements from: Edoardo Martelli, CERN, for SIG-NGN
Wouter Verkerke, Nikhef
H->ZZ-> 4l plot: ATLAS

And there’s data from gravitational wave events



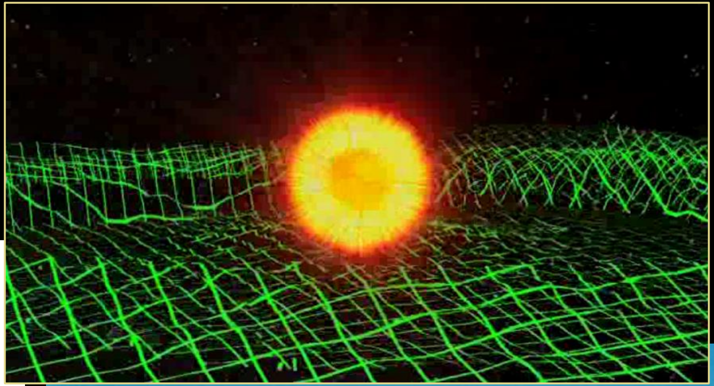
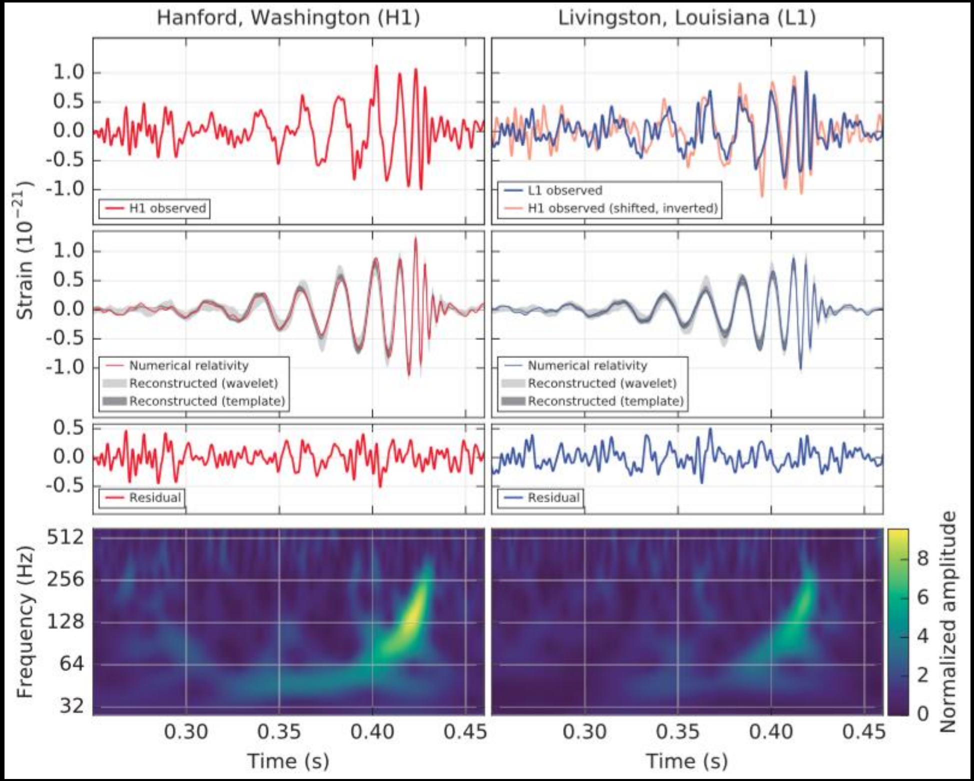
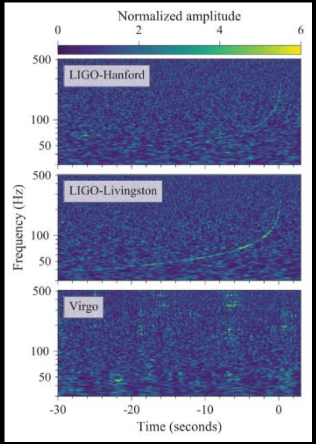


Diagram from: B P Abbott *et al.* 2020 Class. Quantum Grav. 37 055002
Image: Virgo GW detector in Pisa

Thriving on *fast* Fourier transforms …





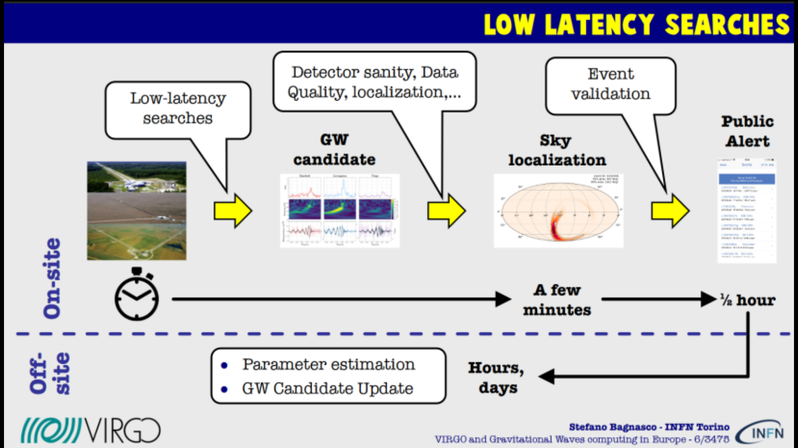
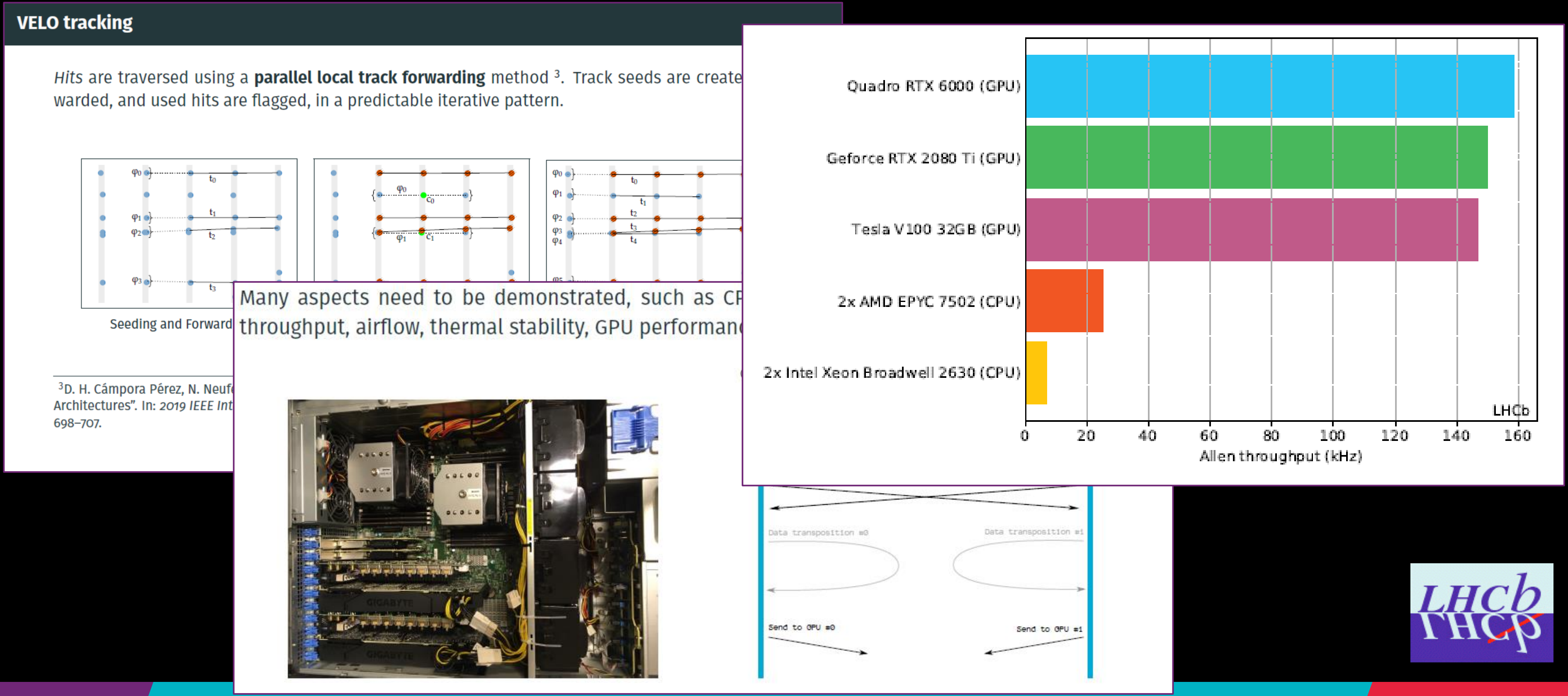


Image: GW150914 (source: LVC) PRL 116 061102
and GW170817. PRL 119 (16) 161101
Low-latency slide: Stefano Bagnasco, INFN Torino and Virgo

Parallelism and GPUs are already making a difference



Source: Daniel Cámpora, UM & Nikhef
and the LHCb *Allen* project

An additional way of dealing with volume

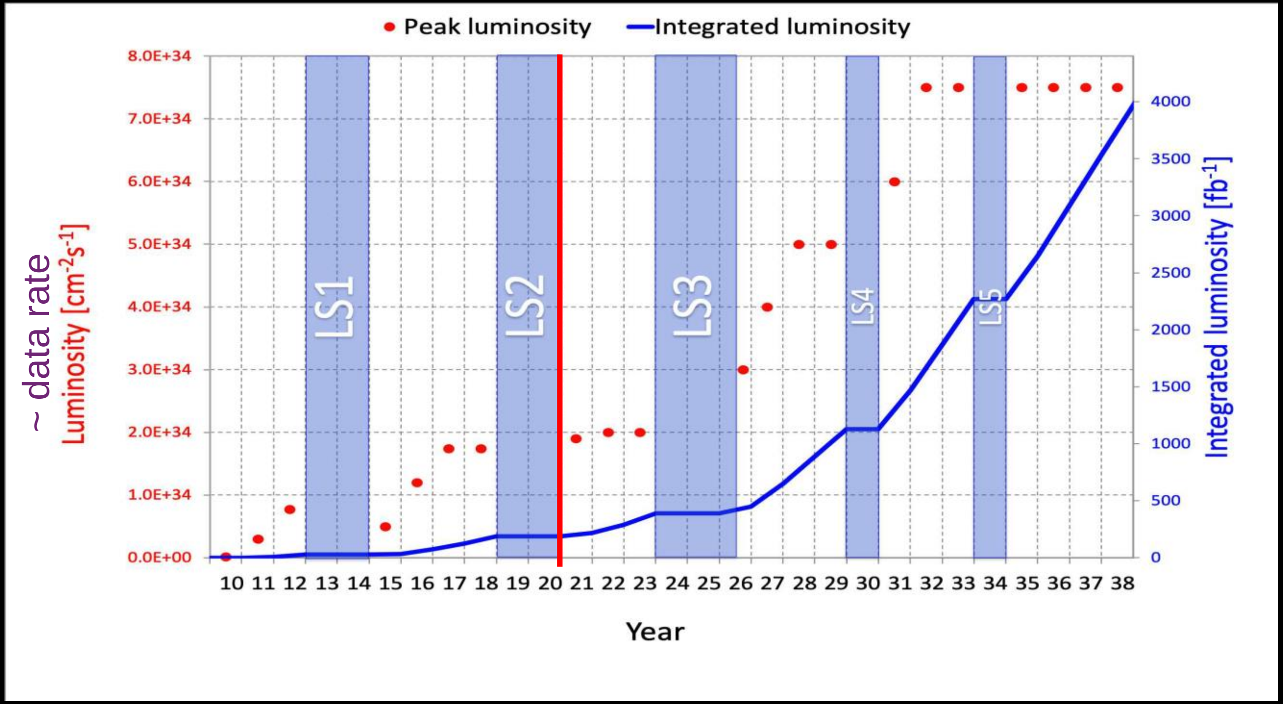
WLCG:
Worldwide LHC Computing Grid

- ~ 180 institutions, with 13 ‘tier-1’ sites (NL-T1)
- ~ 60 countries/regions
- ~ 10 000 daily users

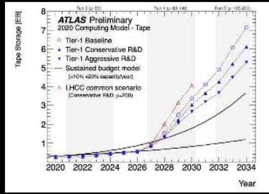
- ~ 600 000 cpu cores
- >>300 PiB mass storage

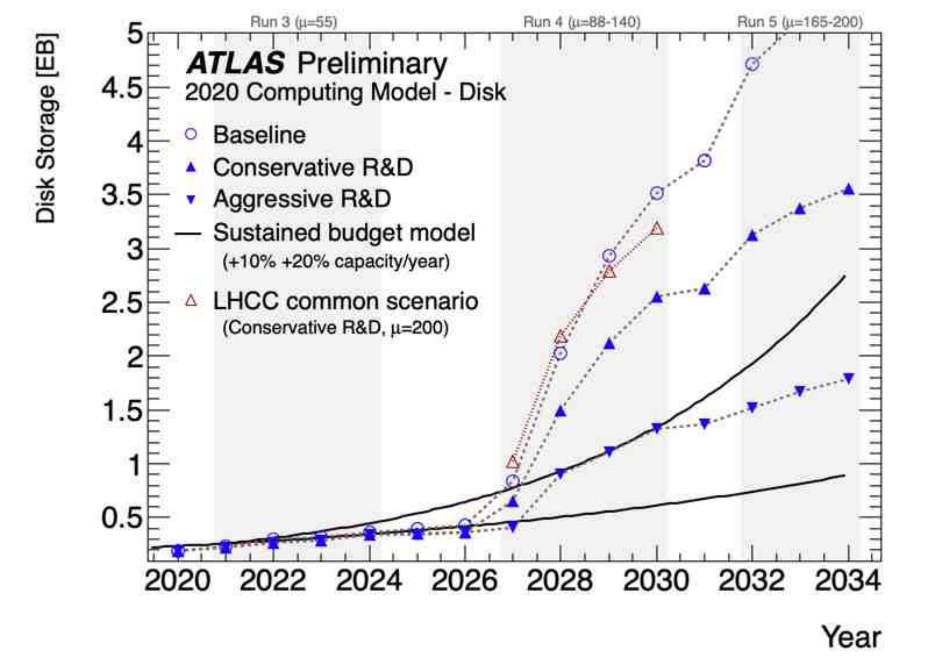
Image sources: CERN OpenLab/SDC, WLCG, Rocío Rama Ballesteros

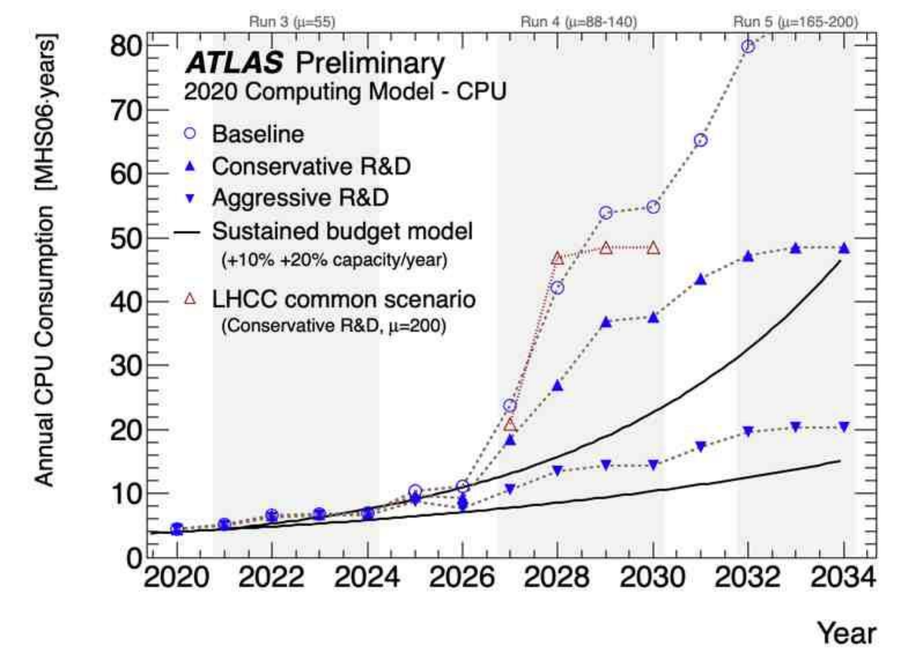
Facing scaling issues for 2030 and beyond



A sizeable amount of data …





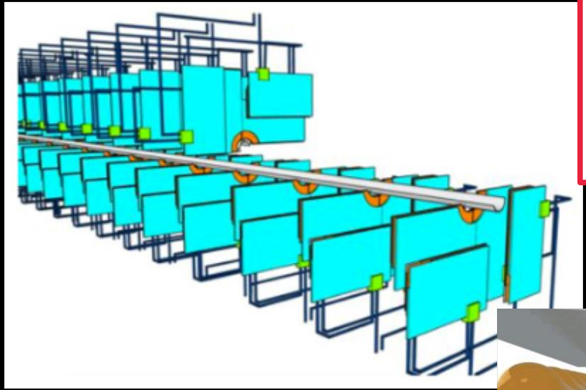


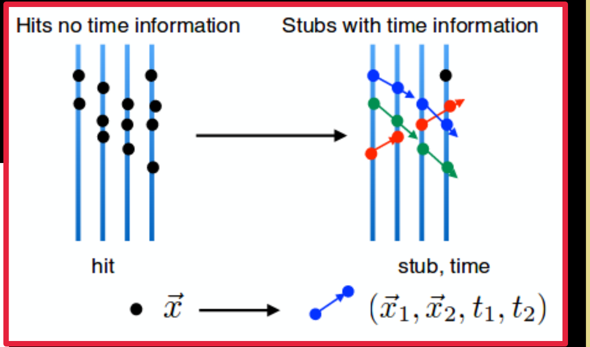
Graphic: ATLAS collaboration
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ComputingandSoftwarePublicResults

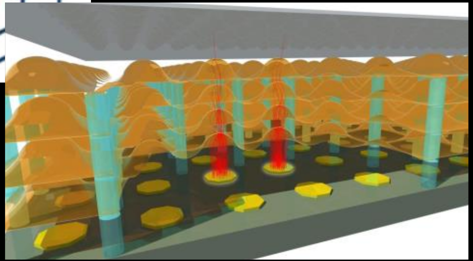
Some cleverness can be done in hardware

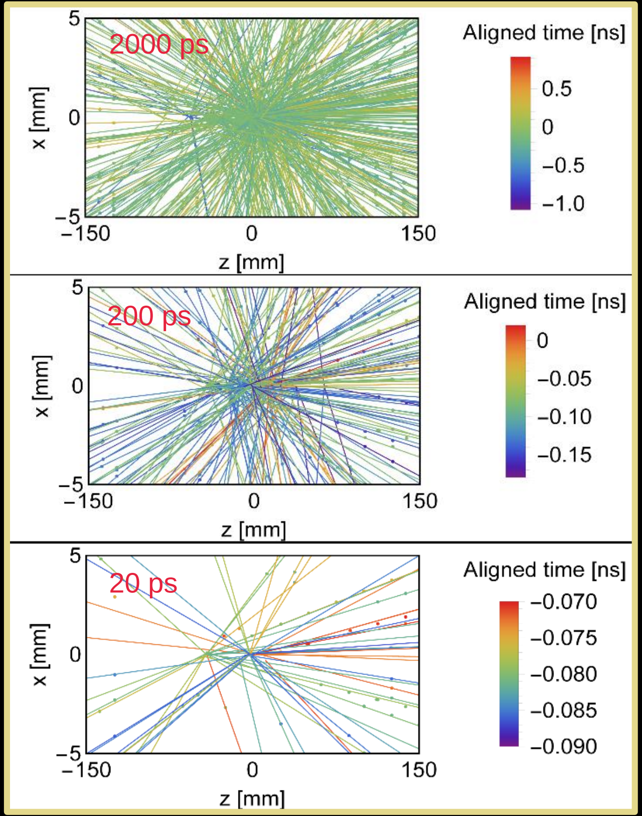
1 ps = 10^{-12}s

adding additional parameters
to improve discriminating power









scheduled for ~2030 (LS4)

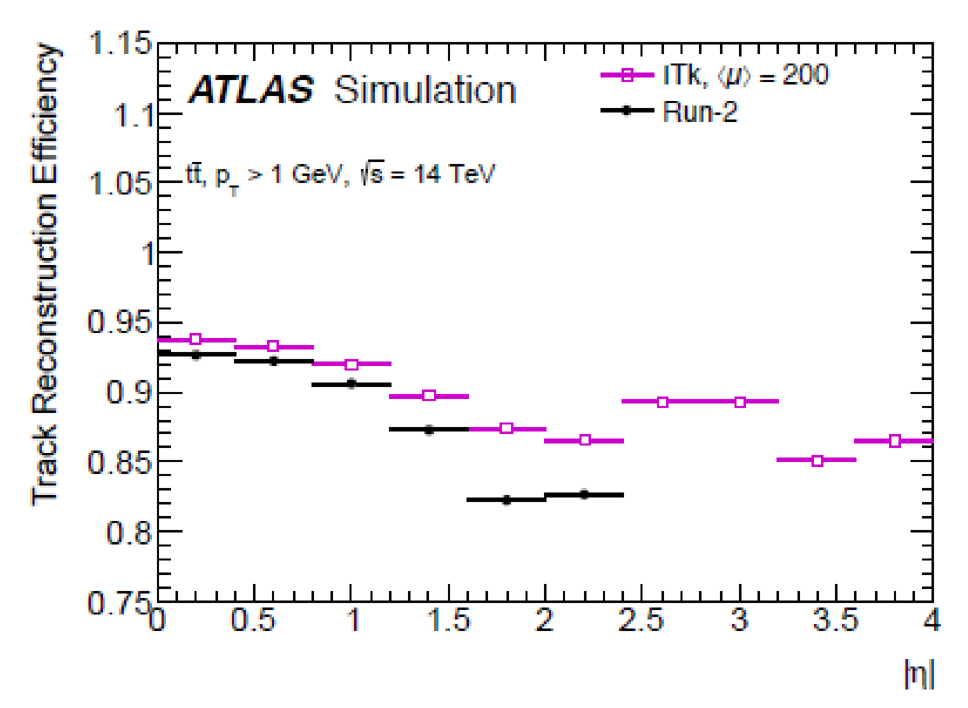
Images: LHCb Velo-3 4D tracking
Marcel Merk, UM & Nikhef

Also we can deal with some inefficiency, *provided* it's quantifiable

efficiency can be determined comparing reconstruction of simulated data to theoretical input

all within limits of course:

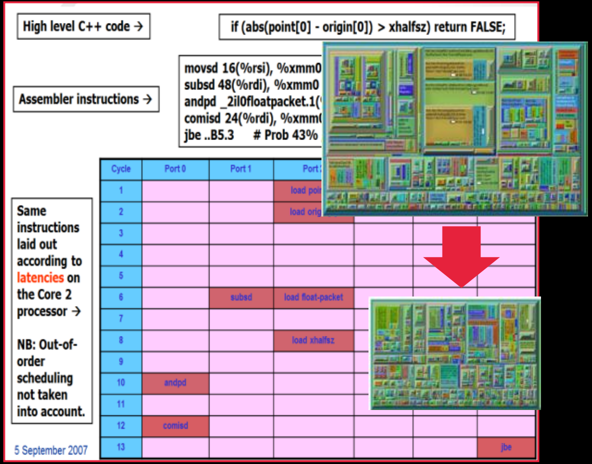
- we need 'most' valid events to 'survive' reconstruction
- and not get 'fake' data out …

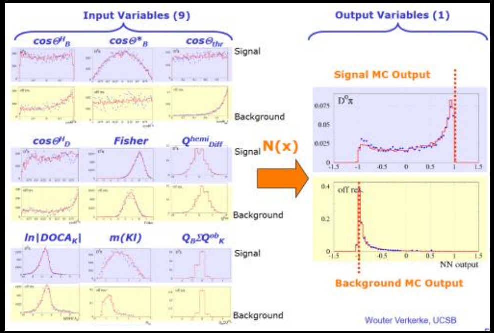


Example of an efficiency plot: Liza Mijovic, LHCP2018, ATL-PHYS-PROC-2018-101

Time to get inspired

Improving parallelism and pipelining





Machine Learning (NNs, BDTs, …)

Accelerators: GPUs, DPUs

and we see very interesting ideas coming for QC …

2007 Core2 efficientcy: Sverre Jarp, CHEP2007
RECO improvements 2012-2015: Gerhard Raven, Nikhef
Learning: Wouter Verkerke Practical Statistics –part I
GPU node: plofkip.nikhef.nl

Nikhef

Get inspired by early work ... much of it on simulations

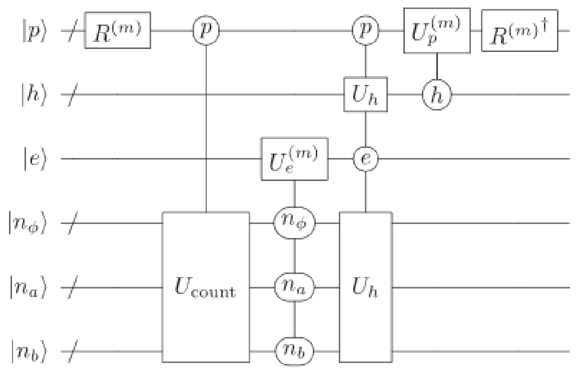
PHYSICAL REVIEW LETTERS **126,** 062001 (2021)

Quantum Algorithm for High Energy Physics Simulations

Benjamin Nachman,[1,*] Davide Provasoli,[1,†] Wibe A. de Jong,[2,§] and Christian W
[1]*Physics Division, Lawrence Berkeley National Laboratory, Berkeley, California 9472*
[2]*Computational Research Division, Lawrence Berkeley National Laboratory, Berkeley, Califor*

(Received 14 September 2020; revised 2 December 2020; accepted 17 December 2020; publishe

Simulating quantum field theories is a flagship application of quantum computing. However, experimentally relevant high energy scattering amplitudes entirely on a quantum computer is p difficult. It is well known that such high energy scattering processes can be factored into pieces



The circuit calls for six registers, which are detailed in the Supplemental Material [27] and summarized in Tables I and II. The initial state of $|p\rangle$ consists of n_I particles (which can be fermions or bosons) in the f...

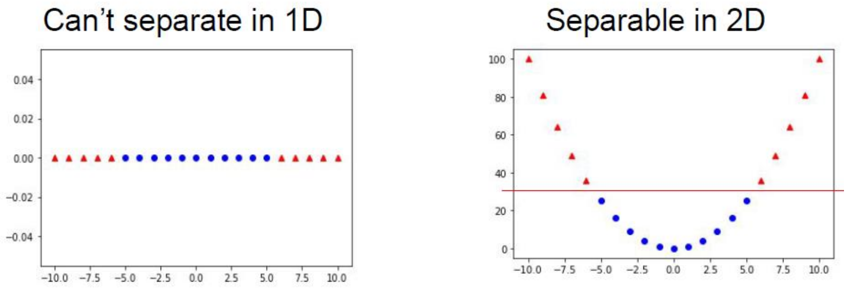
Mostly simulated,
with some early experimental results

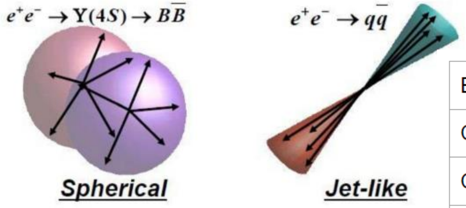
Nachman *et al.*, 10.1103/PhysRevLett.126.062001

Nikhef

Distinguishing events

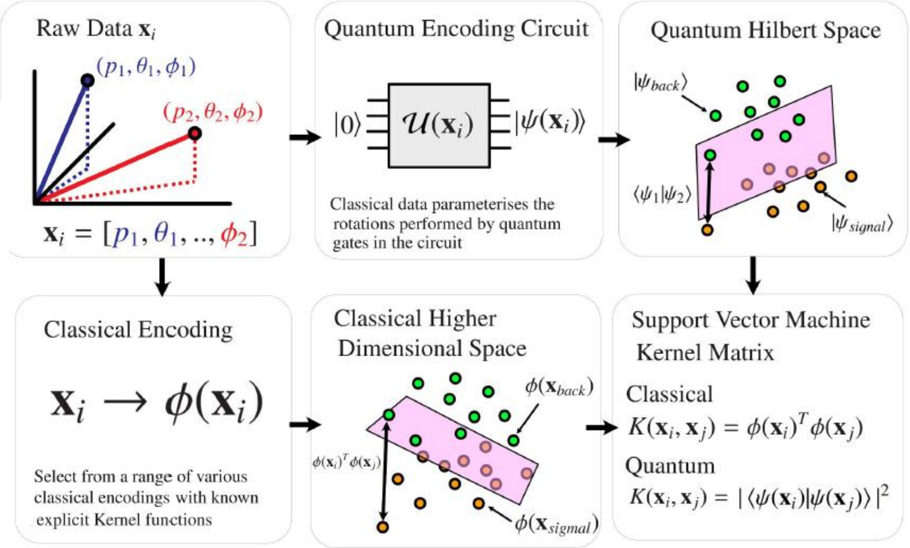
- Support Vector Machines classify events
- QSVM (in simulations) works quite well – comparable to best classic models





Encoding Circuit (70,000 events)	AUC
Combinatorial Encoding	0.827
Combinatorial Multi-qubit	0.845
Separate Particle	0.853
Simple Bloch	0.861
Separate Particle + Bloch Sphere	0.877

Classical Algorithm (70,000 events)	AUC
XGBoost	0.648
RBF Kernel SVM	0.865



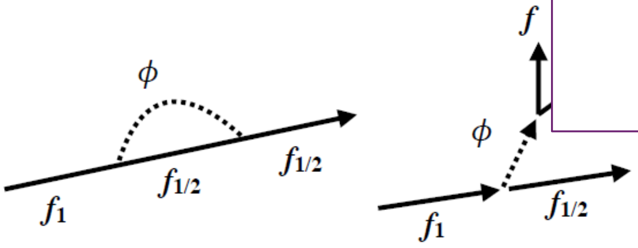
Images from: Jamie Heredge, et al. UMelbourne, in vCHEP2021 https://indico.cern.ch/event/vchep2021 https://arxiv.org/abs/2103.12257

Optimizing algorithms (in this case for ‘parton shower’ sim)

C. W. Bauer, B. Nachman *et al.*
Phys. Rev. Lett. 126, 062001 (2021)

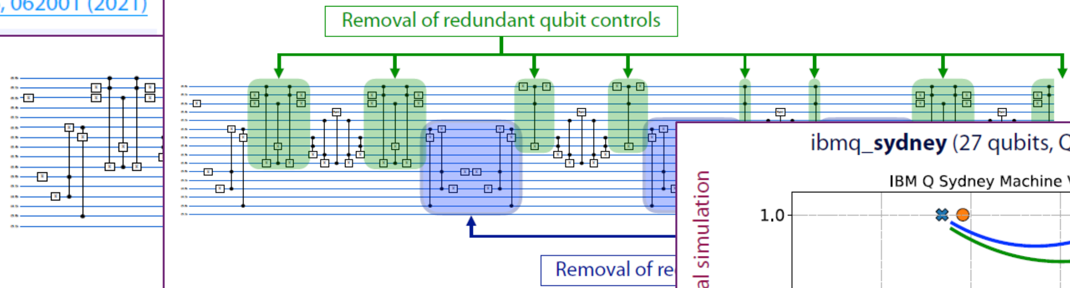
Quantum parton shower model:

- Consider a system composed of boson ϕ ar
- Emission of ϕ-boson ($f \rightarrow f\phi$) and splitting
- Interference due to two fermion flavors $\{f_1,$ intermediate states

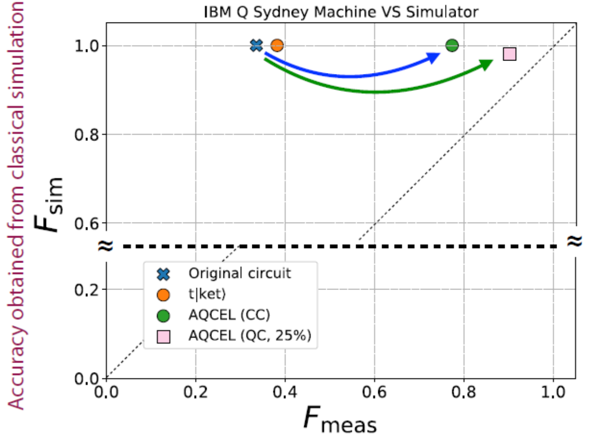


Developed a novel optimization protocol called **AQCEL** :

- Removal of redundant qubit controls by identifying zero- or low-amplitude basis states
- Removal of redundant gates



Actual circuit contains >1200 gates (after just for 2 branching steps in showering…



From: W. Jang et al (UTokyo, ICEPP, and LBL)
vCHEP21: *Quantum Circuit Optimization*
AQCEL optimization protocol, arXiv:2102.10008

Nikhef

Many challenges in volume and complexity – and quantum computing could help us here!

Current Nikhef focus for *accelerator-based* experiments at the LHC

- track reconstruction
- event classification

and in *gravitational waves observation* and analysis

- time-to-frequency domain conversion, filtering of data
- template matching (‘waveform fitting’) to understand GW sources
- and possibly also ... solving the many differential equations

We start from here!

Nikhef

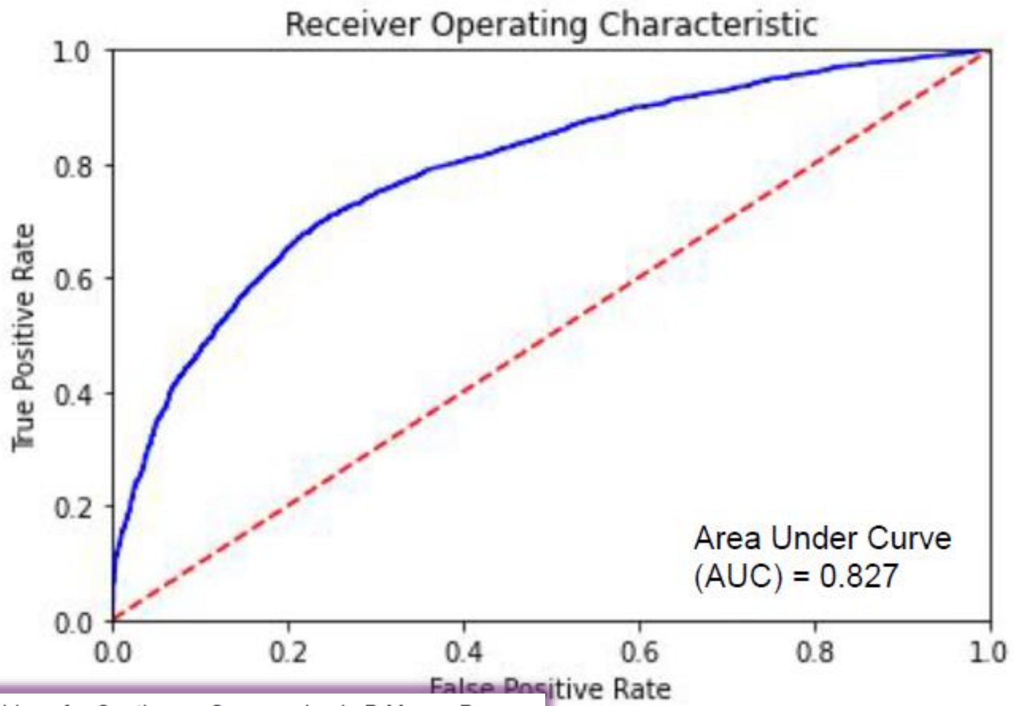
David Groep
davidg@nikhef.nl
https://www.nikhef.nl/~davidg/presentations/
https://orcid.org/0000-0003-1026-6606

Background slides from vCHEP21

Results - Combinatorial Encoding

Encoding Circuit (70,000 events)	Test AUC
QSVM Combinatorial	0.827

Algorithm (70,000 events)	Test AUC
XGBoost	0.648
RBF kernel	0.866



J. Heredge et al, Quantum Support Vector Machines for Continuum Suppression in B Meson Decays
https://arxiv.org/abs/2103.12257

Belle II

Kernel Matrix for All Events

THE UNIVERSITY OF MELBOURNE

Quantum encoding

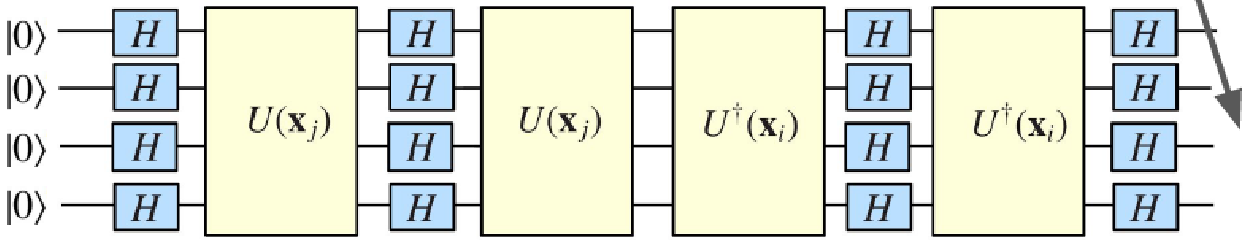
$$|\psi(\mathbf{x})\rangle = \mathcal{U}(\mathbf{x})\,|0\rangle^{\otimes n} = U(\mathbf{x})H^{\otimes n}U(\mathbf{x})H^{\otimes n}\,|0\rangle^{\otimes n}$$

Kernel Estimation

$$|\langle\psi(\mathbf{x}_i)|\psi(\mathbf{x}_j)\rangle|^2 = |\langle 0^{\otimes}|\mathcal{U}^{\dagger}(\mathbf{x}_i)|\mathcal{U}(\mathbf{x}_j)|0^{\otimes}\rangle|^2$$

Proportion of 0000 counts measured over many shots = Kernel Value

Repeat for each event against every other event = Full Kernel Matrix



to Classical SVM

J. Heredge et al, Quantum Support Vector Machines for Continuum Suppression in B Meson Decays
https://arxiv.org/abs/2103.12257