

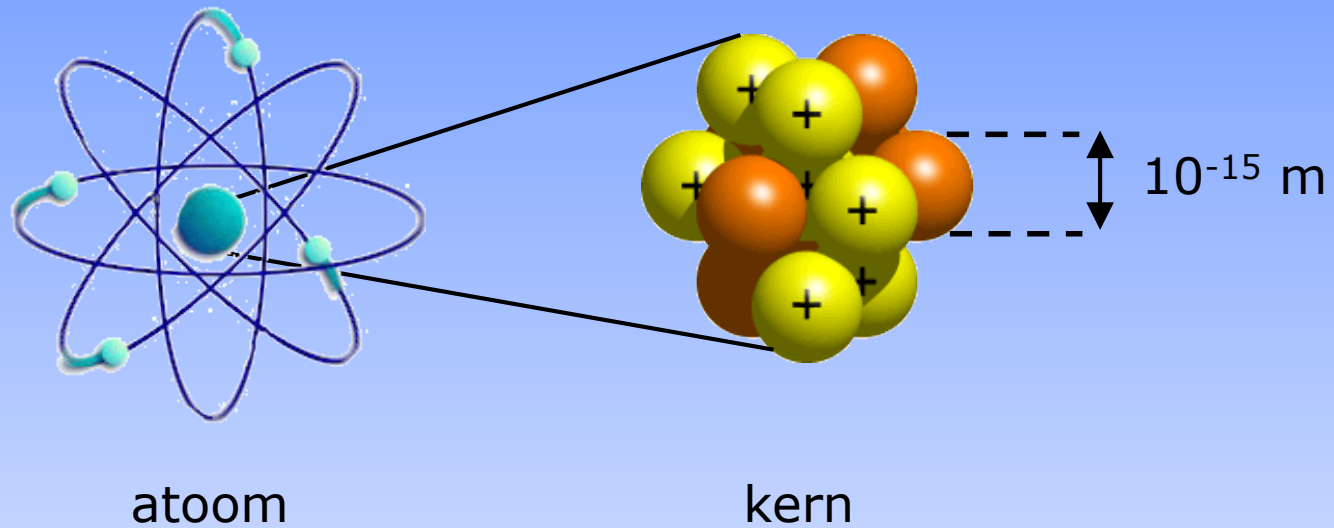
Zoektocht naar de elementaire
bouwstenen van de natuur

Resultaten uit 1^e jaar van de LHC

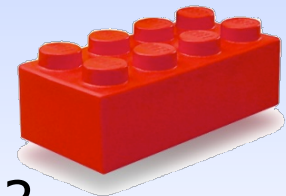


Ivo van Vulpen

Deeltjesfysica



Wat zijn de bouwstenen van de dingen om ons heen ?



De stand van zaken in april 2010



[http:// pdg.lbl.gov](http://pdg.lbl.gov)

De elementaire deeltjes



up

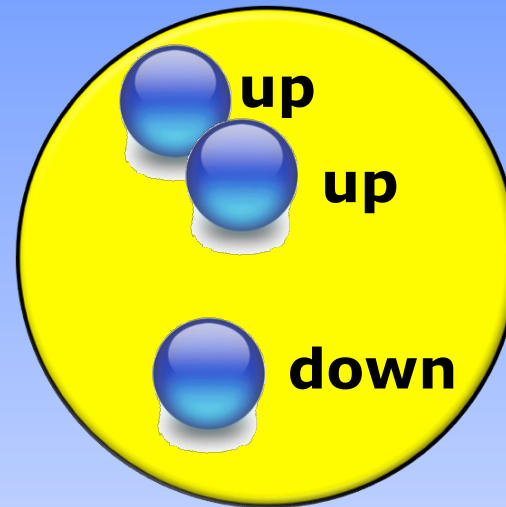


down

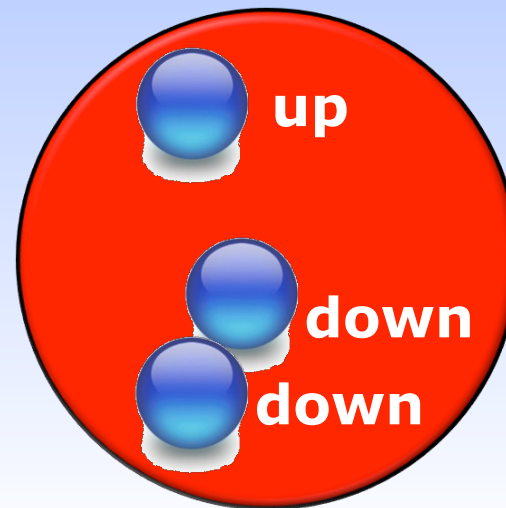


elektron

+ 4 natuurkrachten



Proton



Neutron

Deeltjes

Krachten

Quarks

Leptons

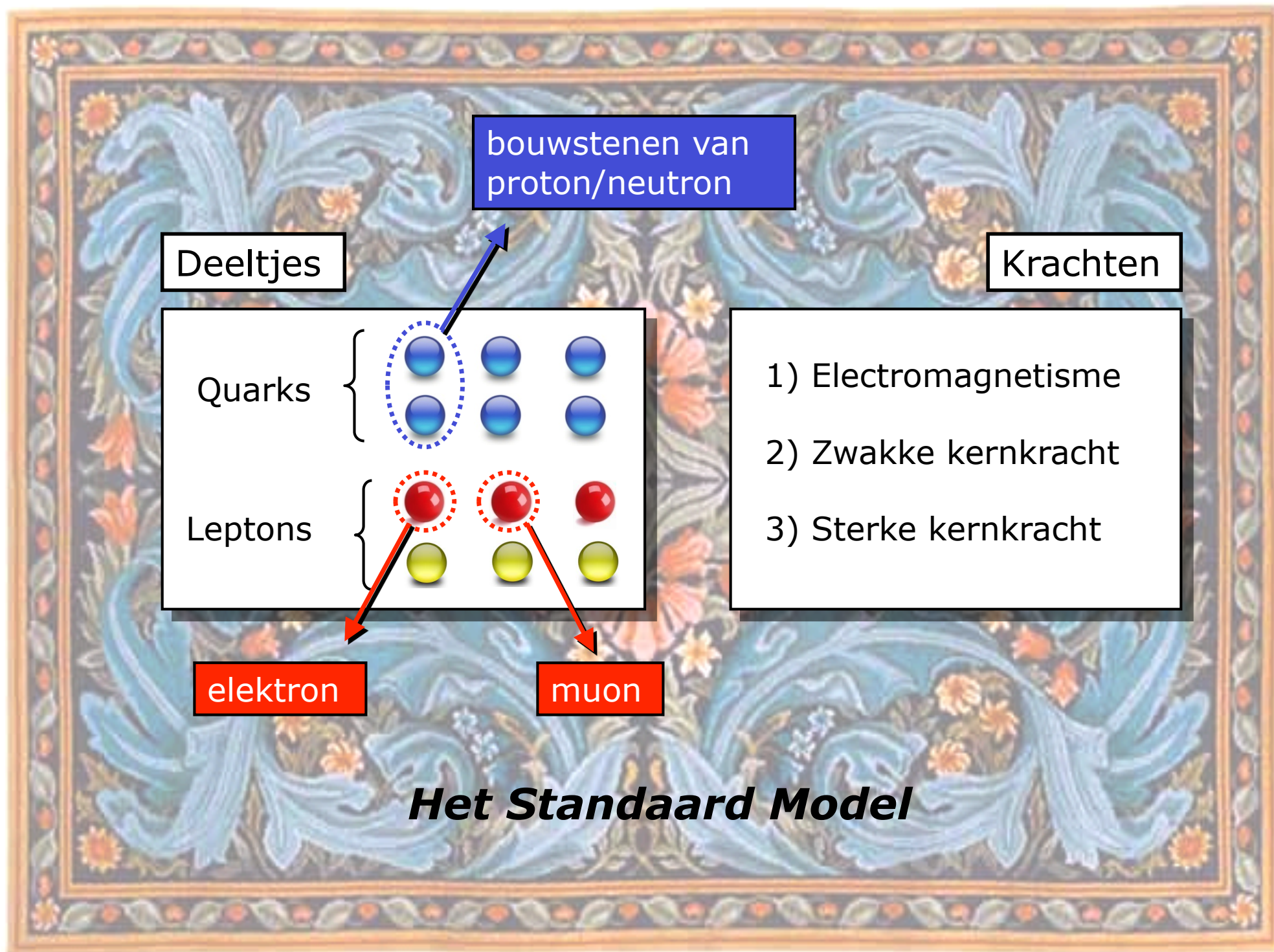
bouwstenen van
proton/neutron

elektron

muon

- 1) Electromagnetisme
- 2) Zwakke kernkracht
- 3) Sterke kernkracht

Het Standaard Model



Ontdekkingsreis

[A] Waarom valt het electron niet op de kern ?

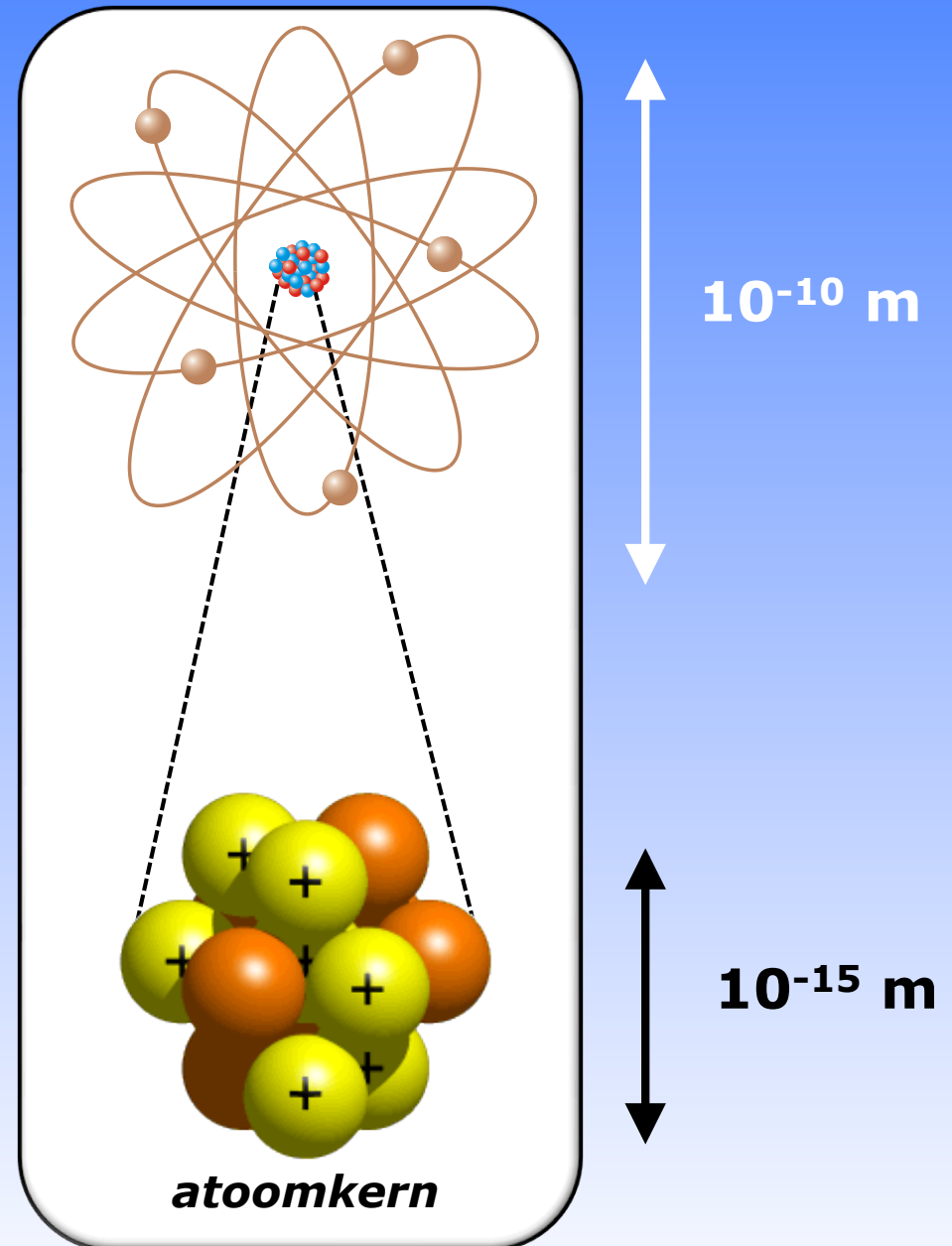
2 nieuwe concepten:

- quantummechanica
- relativiteitstheorie

[B] Wat houdt de kerndeeltjes bij elkaar ?

2 nieuwe natuurkrachten:

- zwakke kernkracht
- sterke kernkracht



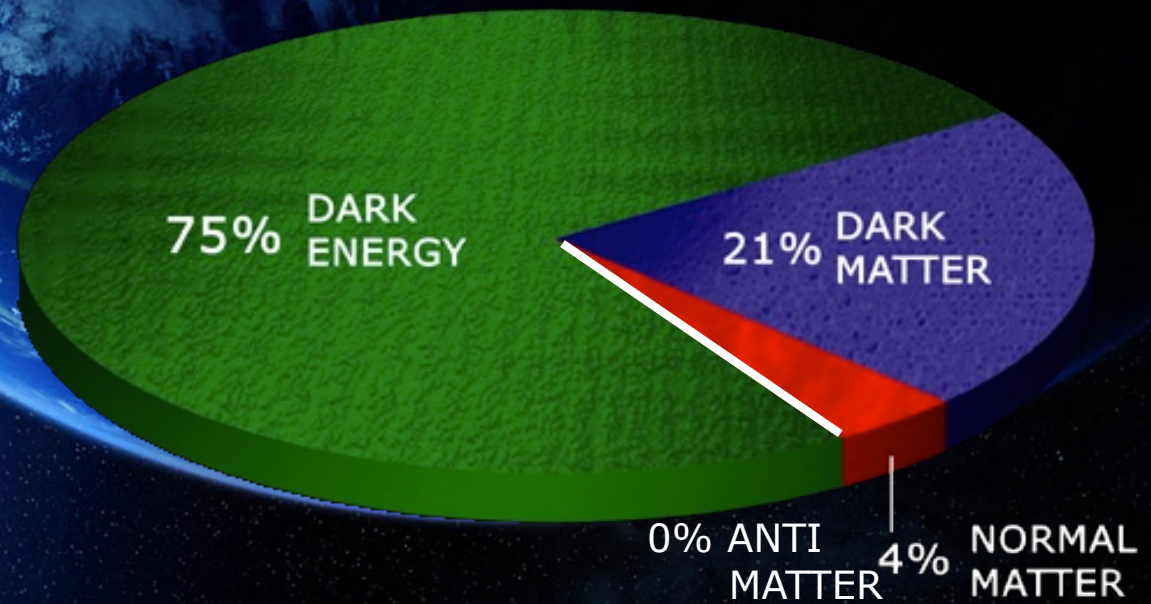
Wat snappen we nog niet:





Revolutie in kosmologie laatste paar jaar
Structuur van het heelal

Waar bestaat het heelal uit?



Paar 'kleine' dingetjes:

1

96% van de materie in het heelal is onbekend
→ donkere materie

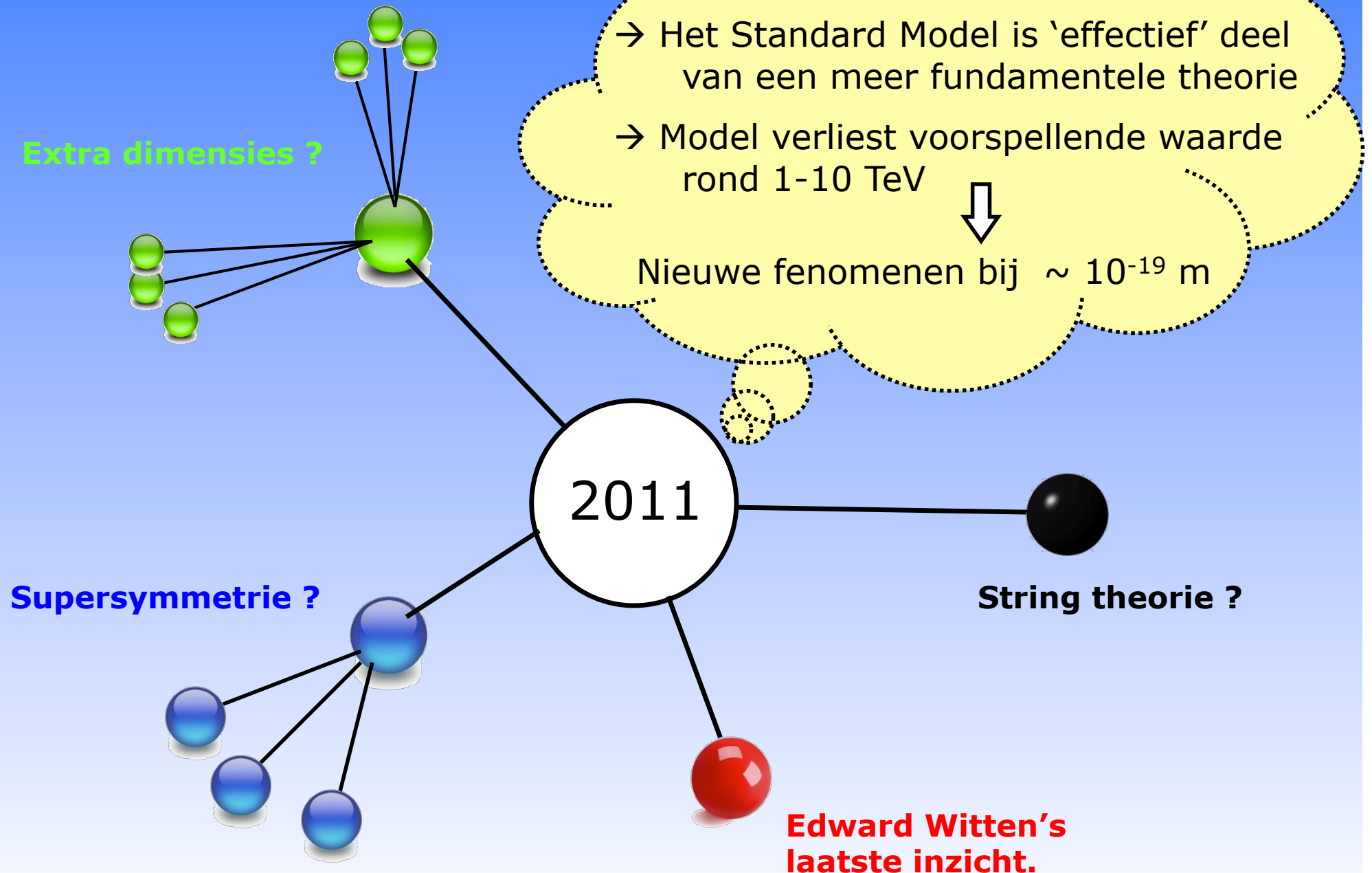
2

Waar is alle anti-materie gebleven ?

3

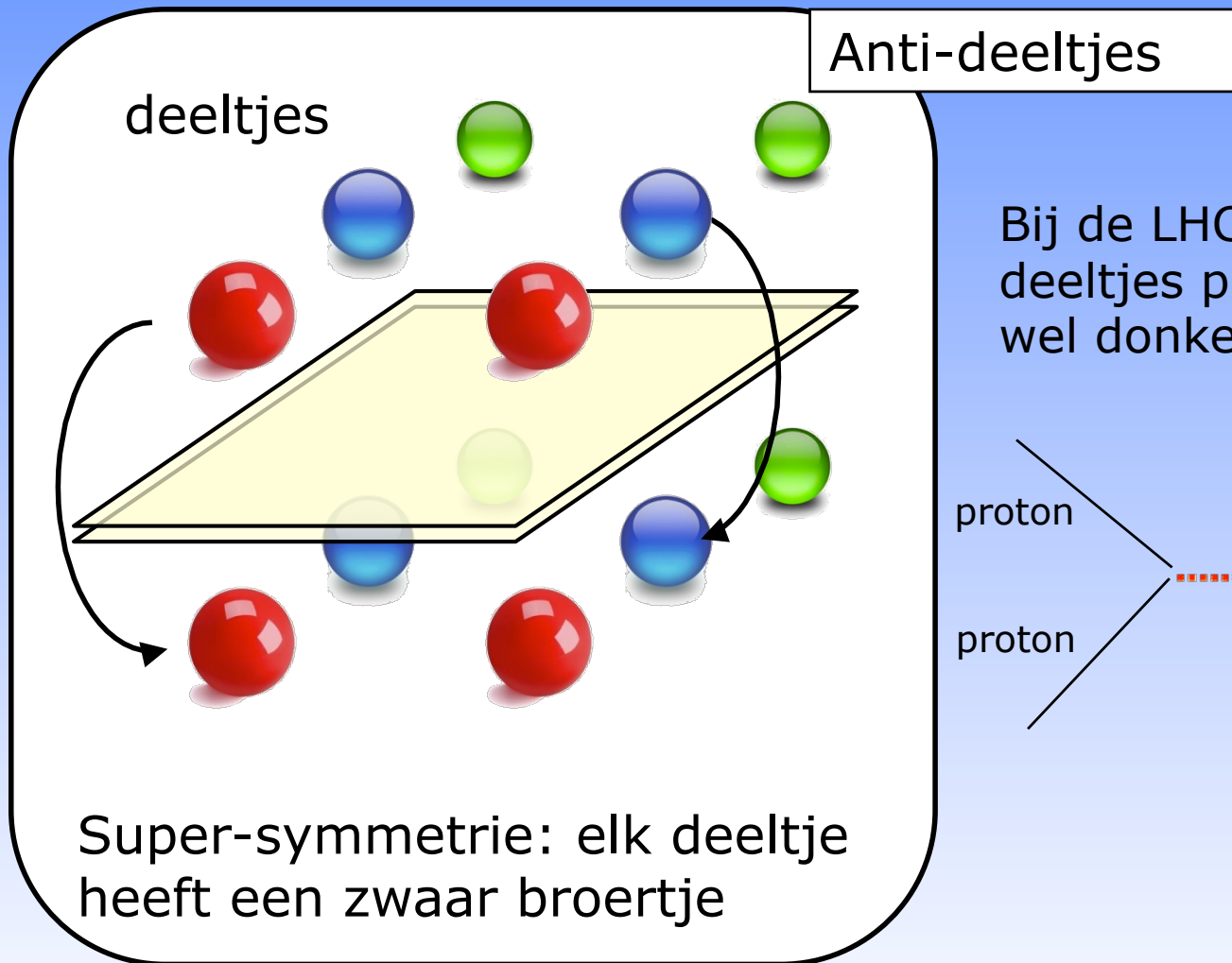
Higgs boson

- waarom past gravitatie niet in SM, extra dimensies, waarom 3 families, fermionen fundamentele deeltjes, supersymmetrie, protonen stabiel, quantisatie elektrische lading, exploderende quantumcorrecties, kleine neutrino massa's, string theorie, ...

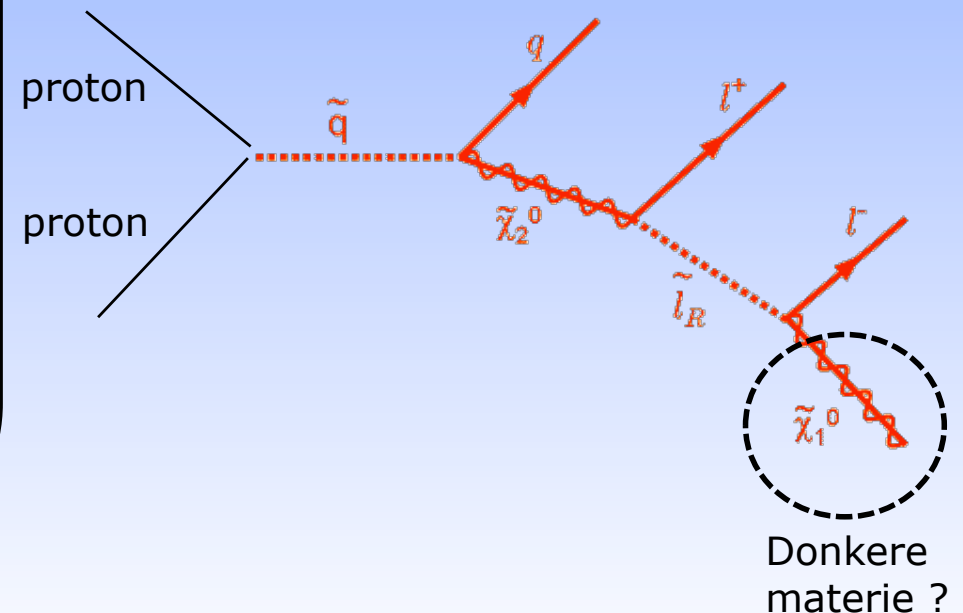


Donkere Materie

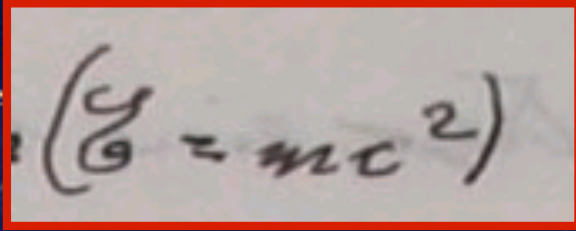
Theoretisch idee: Supersymmetrie:

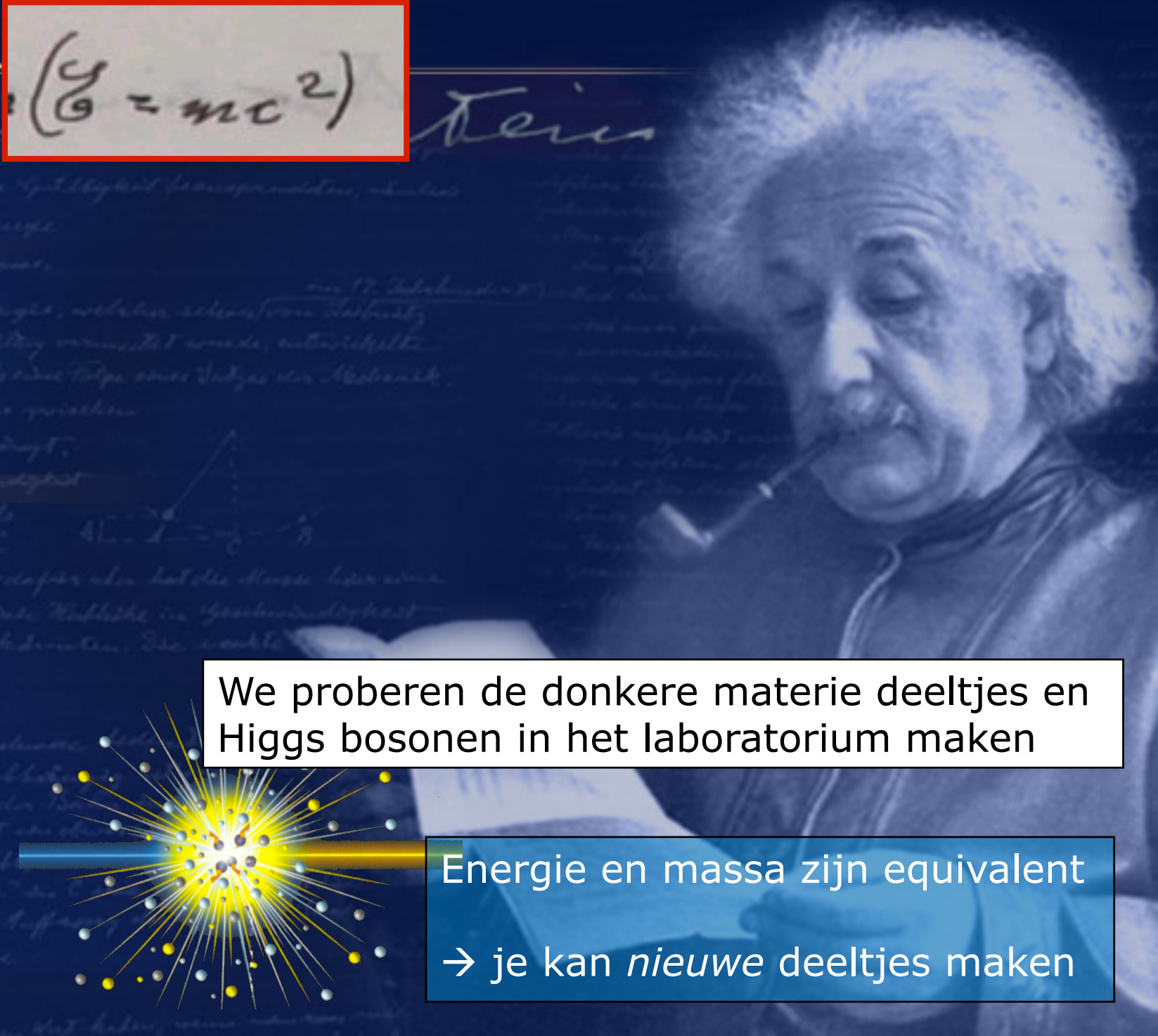


Bij de LHC kunnen we deze super-deeltjes produceren. En misschien wel donkere materie maken.



Albert Einstein


$$E = mc^2$$



We proberen de donkere materie deeltjes en Higgs bosonen in het laboratorium maken



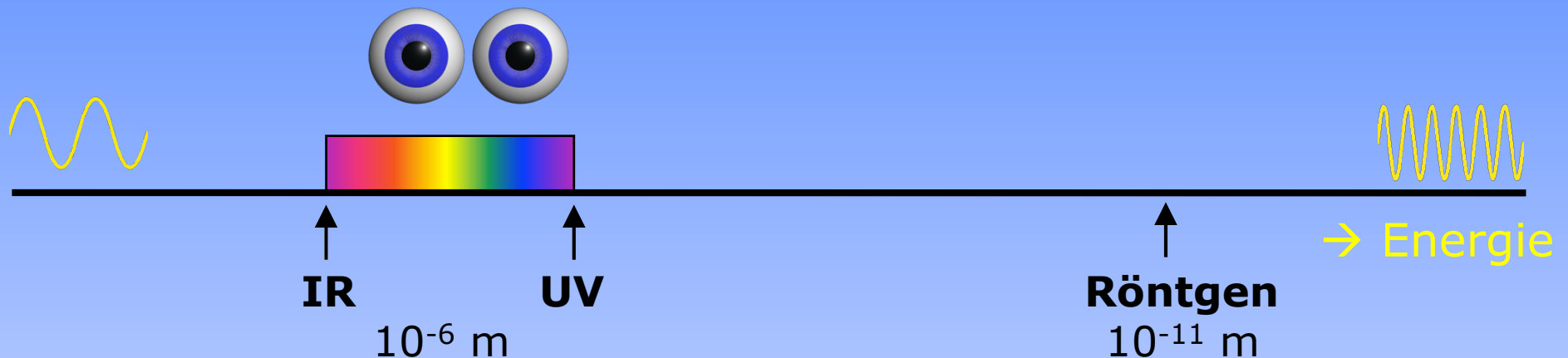
Energie en massa zijn equivalent
→ je kan *nieuwe* deeltjes maken

kijken zonder je ogen te gebruiken



1] Kijken met licht

Licht verstrooit aan objecten die groter zijn dan de golflengte van het licht

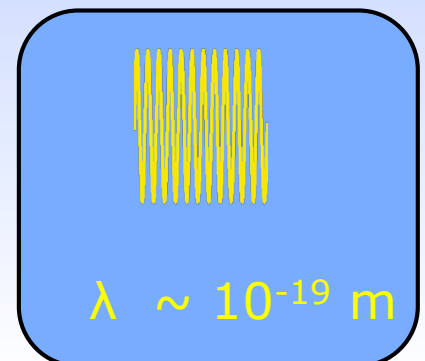


2] Kijken met deeltjes

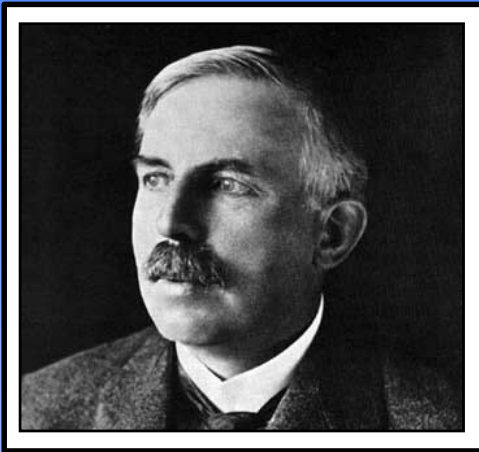
Quantummechanica: deeltjes zijn golven

→ microscoop voor zeer kleine afstanden:

- klein: elektronen microscoop
- kleinst: protonen micsoscoop
Large Hadron Collider

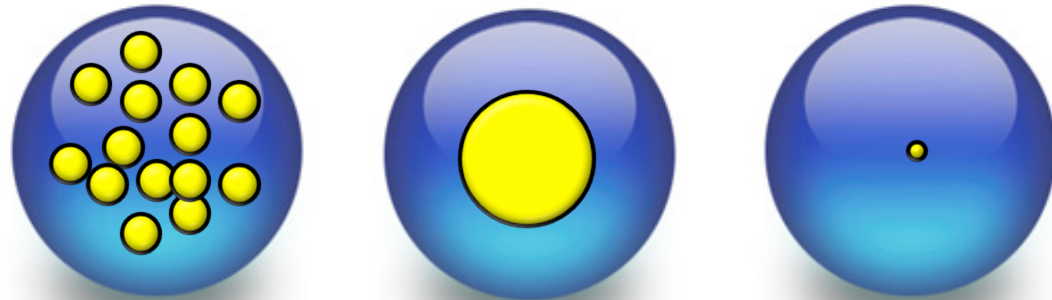


Het atoom

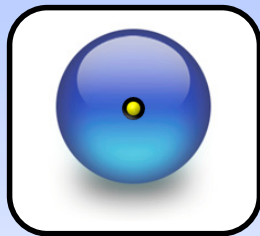


Rutherford

Thomson



Hypothese:



en

$$F \propto \frac{1}{r^2}$$

$$\frac{d\sigma}{d\Omega}(\theta) = \left(\frac{ZZ'}{4E} \right)^2 \frac{1}{\sin^4(\frac{\theta}{2})}$$

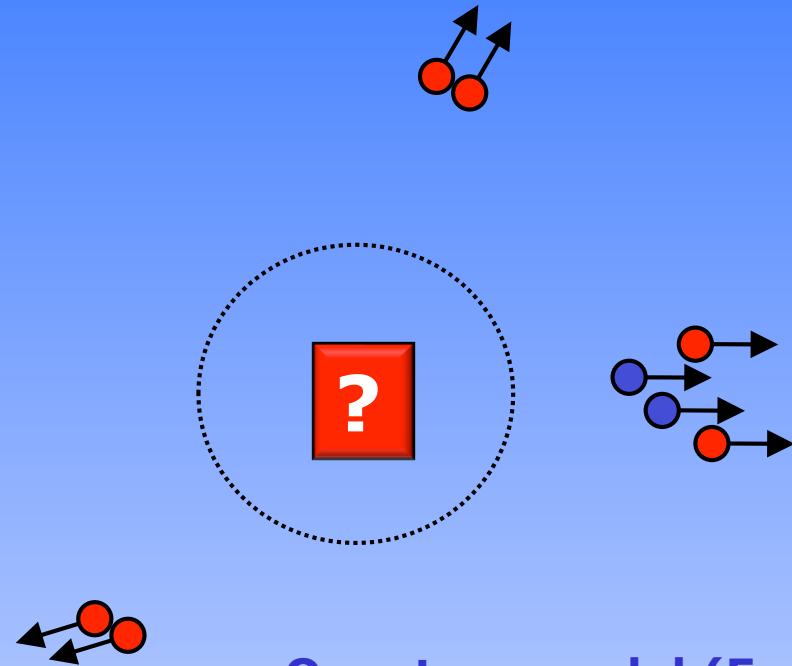
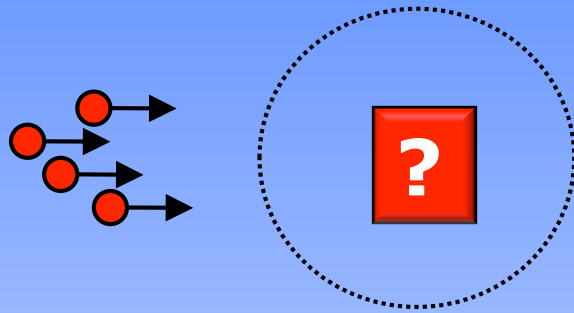
Meting:

Scattering of α and β Particles by Matter.

681

Metal.	Atomic weight.	z .	$z/A^{3/2}$.
Lead	207	62	208
Gold	197	67	242
Platinum	195	63	232
Tin	119	34	226
Silver	108	27	241
Copper	64	14.5	225
Iron	56	10.2	250
Aluminium ...	27	3.4	243
Average			233

Deeltjesfysica experiment

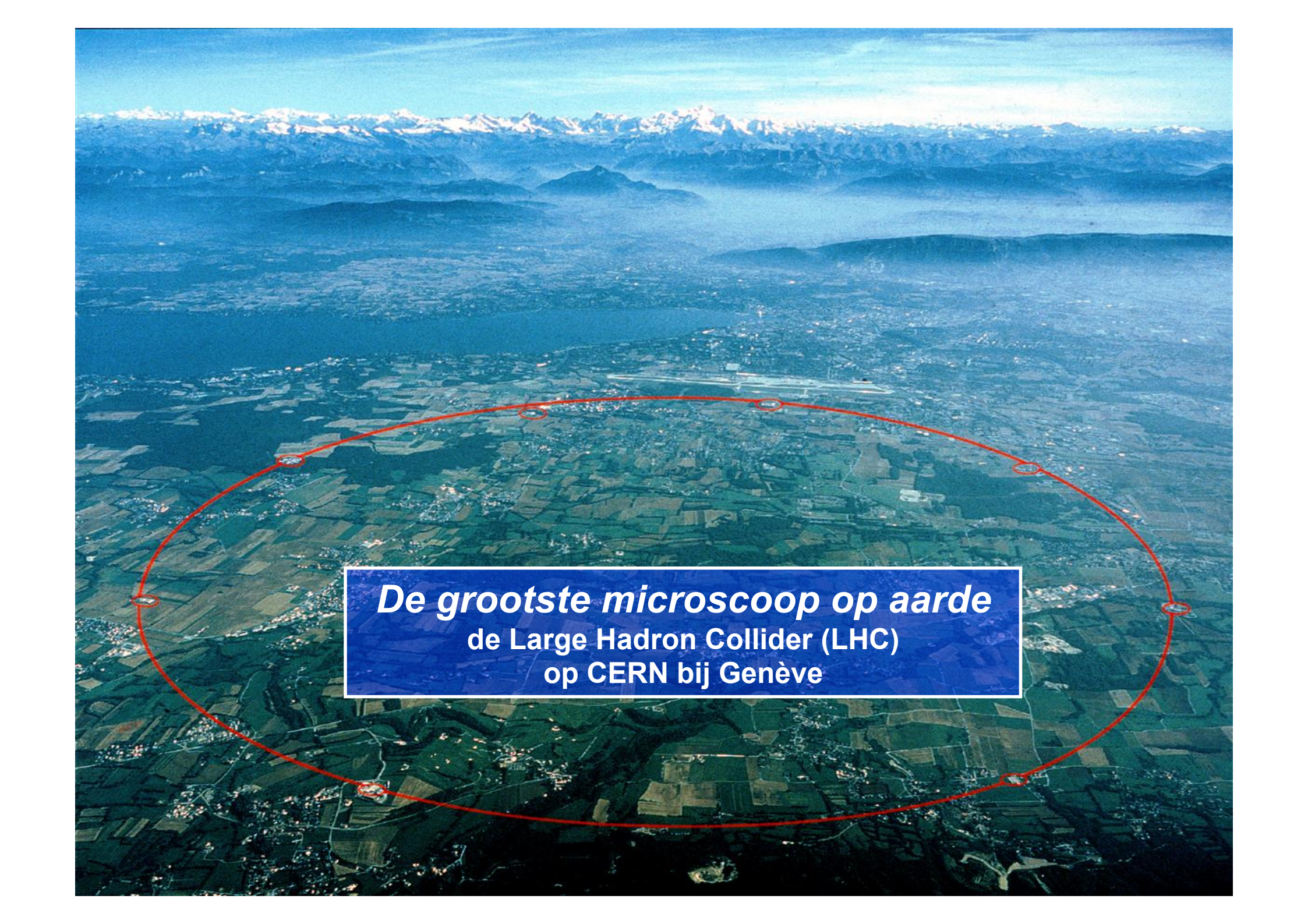


Quantum-model ($E=mc^2$)
→ *nieuwe deeltjes*

‘Kijken’ naar sub-atomaire structuren:

- 1) Kleine deeltjes maken:
- 2) Berekenen wat je verwacht voor een hypothese:
- 3) Verstrooide deeltjes kunnen bekijken:

Deeltjesversneller
Theorie
Detector

An aerial photograph of the CERN facility near Geneva, Switzerland. A large red oval is drawn over the landscape, representing the path of the Large Hadron Collider (LHC) tunnel. The landscape is a patchwork of green fields and some buildings. In the background, a large body of water (Lake Geneva) is visible, followed by a range of mountains with significant snow cover under a clear blue sky.

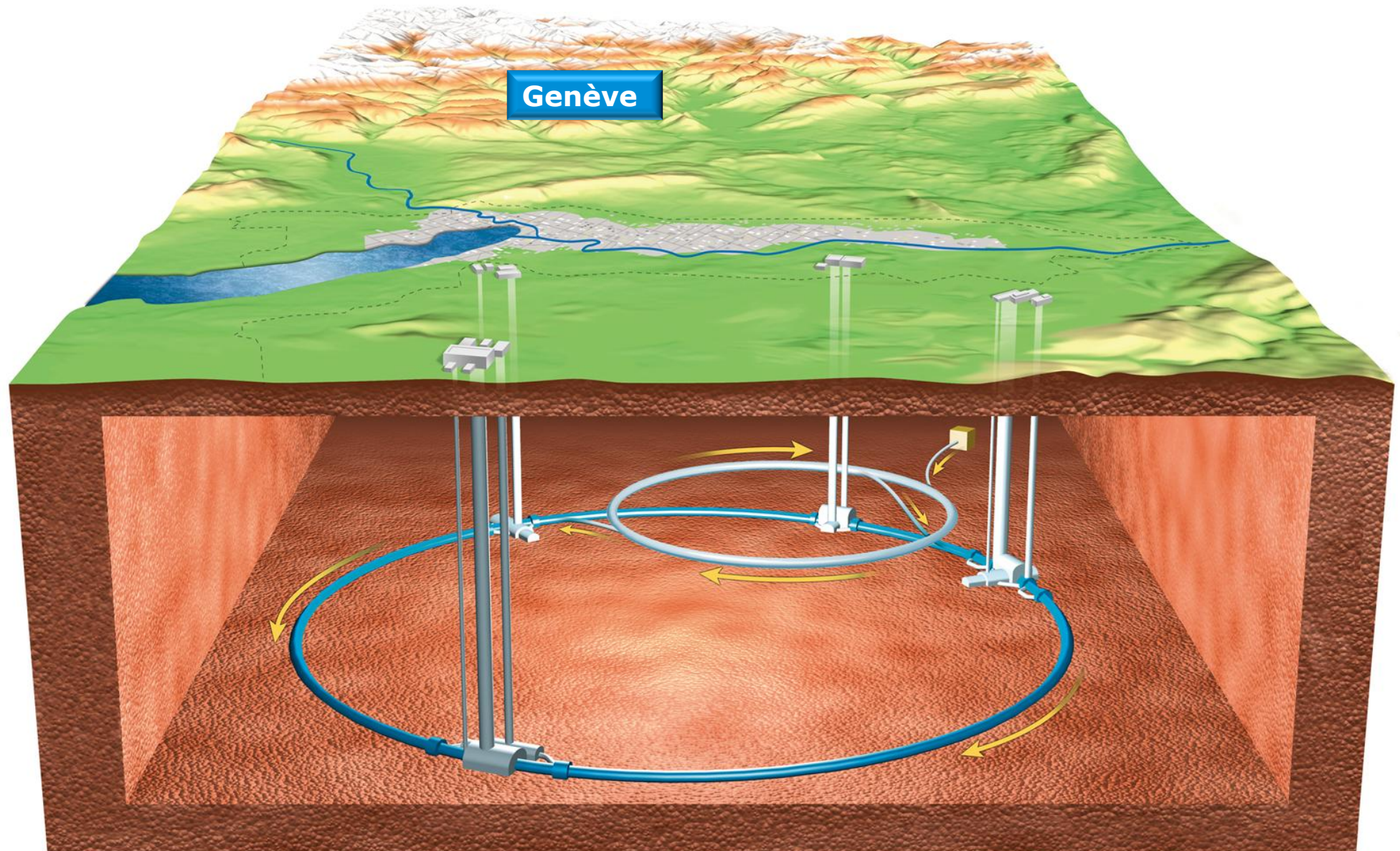
De grootste microscoop op aarde
de Large Hadron Collider (LHC)
op CERN bij Genève

De Large Hadron Collider

LHC: 27 km



De LHC deeltjesversneller



De LHC machine

Versnellen is een eitje



Hoge energie: 14 TeV

Energie begrensd door sterkte van de 1232
dipool magneten, met $B = 8.4 \text{ T}$ bij 1.9 K

→ *Mogelijke productie zware deeltjes (tot 4 TeV)*

→ 7 x Tevatron

20 goud atomen

Hoge intensiteit: $10^{33/34} \text{ cm}^{-2}\text{s}^{-1}$ (40 M bots/sec)

→ *Zoeken naar zeldzame gebeurtenissen*

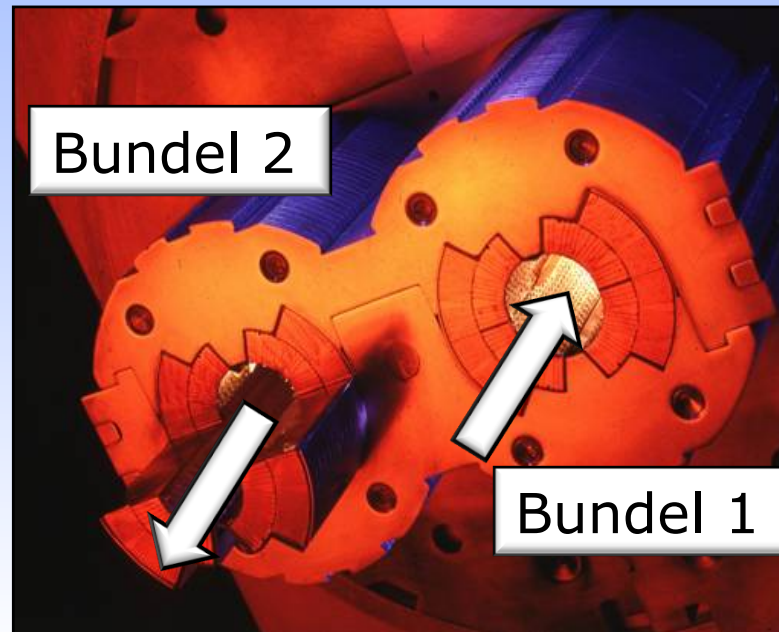
→ 100 x LEP &
Tevatron

Energie 1 proton (LHC)



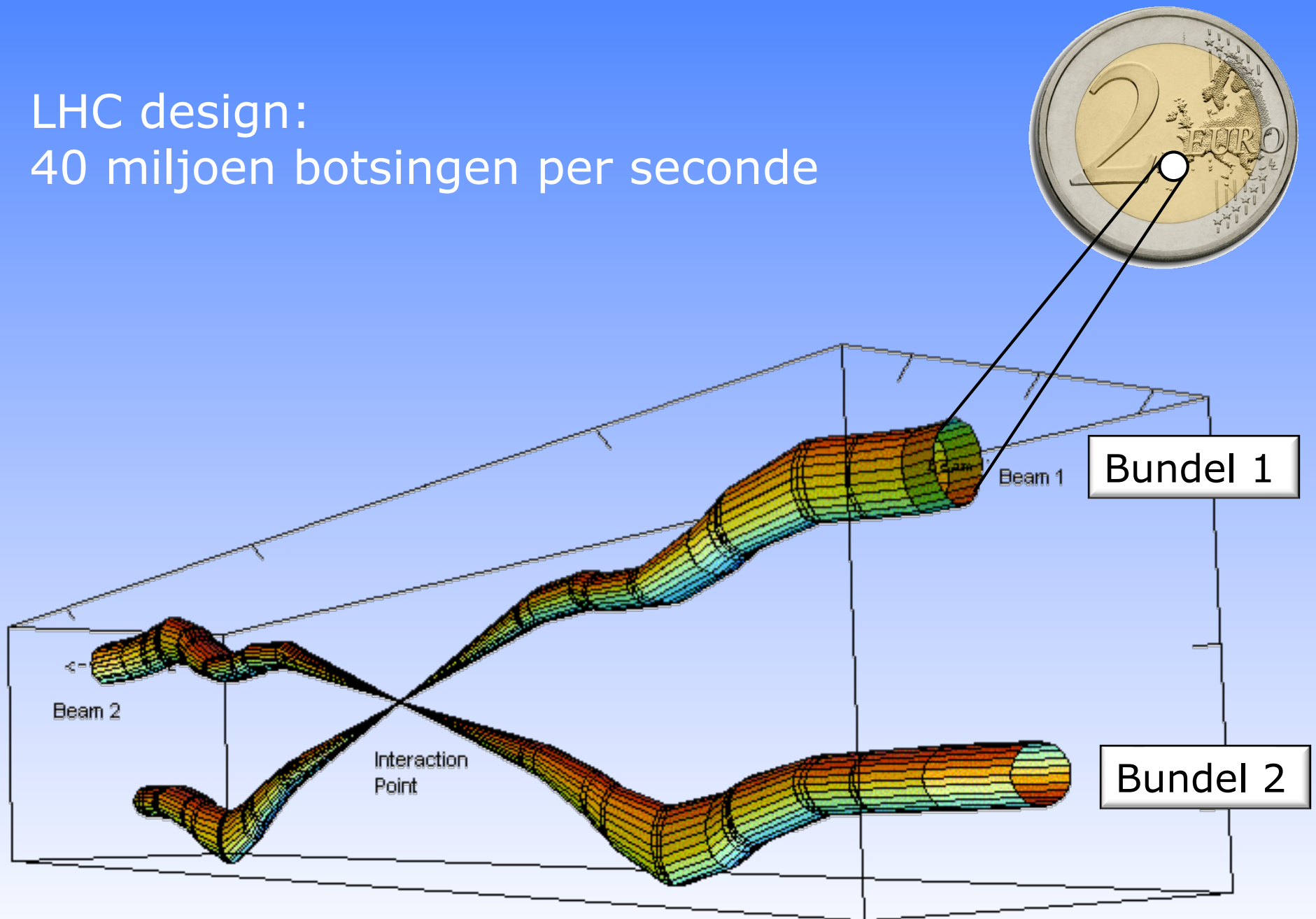
Energie LHC bundel

$3000 \times 100.000.000.000$ protonen

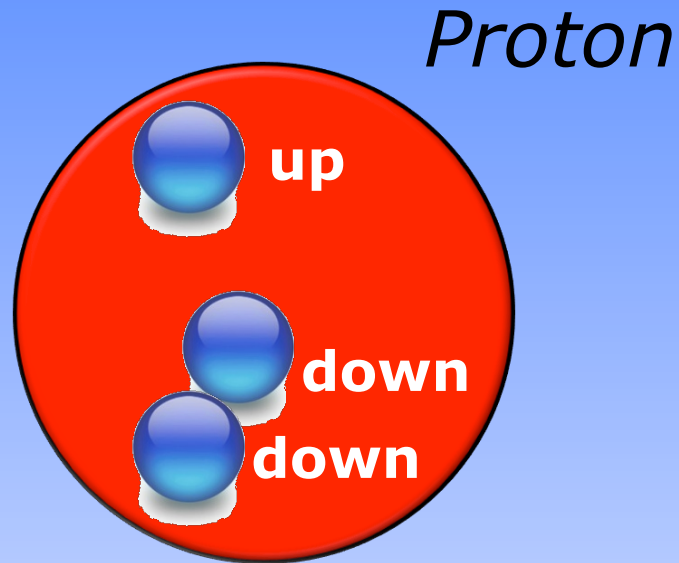


*Doorsnede LHC
bundelpijp*

LHC design:
40 miljoen botsingen per seconde

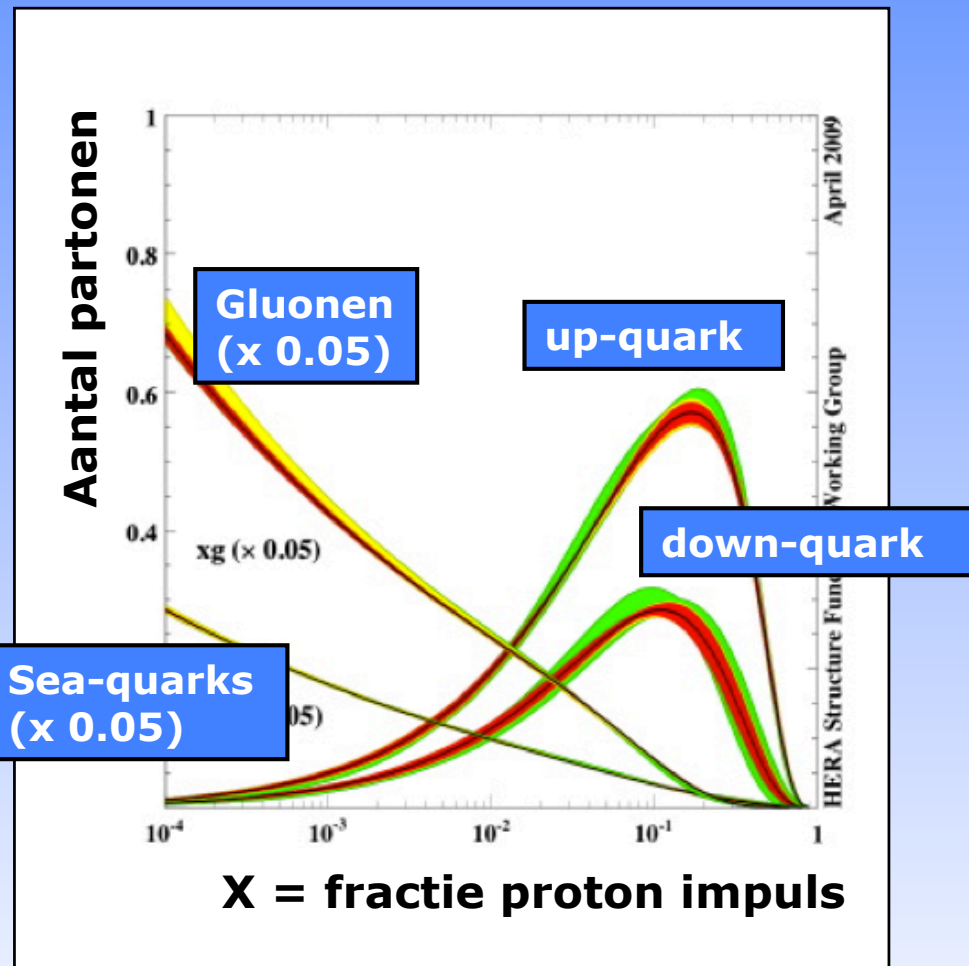


Wat botst er nou eigenlijk ?



Proton bestaat uit een grote
kluwe quarks en gluonen

... voornamelijk gluonen!





Klassiek botsen

Quantummechanisch botsen



Wat verwacht je ?

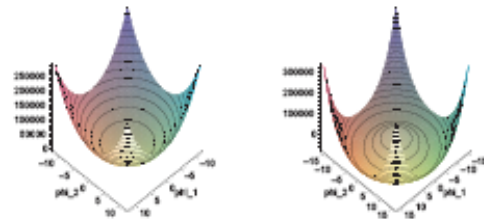


FIG. 1: The potential $V(\phi)$ ($\phi = \phi_1 + i\phi_2$) plotted for an arbitrary positive value of λ and for an arbitrary positive (right) or negative (left) value of μ^2 .

broken, and new interesting features emerge. To be more specific, let's pick the following ϕ_0 minimum (along the direction of the real part of ϕ , as traditional) and shift the ϕ field accordingly:

$$\phi_0 = \left(-\frac{\mu^2}{2\lambda}\right)^{1/2} = \frac{v}{\sqrt{2}} \rightarrow \phi(x) = \phi_0 + \frac{1}{\sqrt{2}}(\phi_1(x) + i\phi_2(x)) . \quad (5)$$

The Lagrangian in Eq. (3) can then be rearranged as follows:

$$\mathcal{L} = \underbrace{-\frac{1}{4}F^{\mu\nu}F_{\mu\nu}}_{\text{massive vector field}} + \underbrace{\frac{1}{2}g^2v^2A_\mu^2 + \frac{1}{2}(\partial^\mu\phi_1)^2 + \mu^2\phi_1^2}_{\text{massive scalar field}} + \underbrace{\frac{1}{2}(\partial^\mu\phi_2)^2 + gvA_\mu\partial^\mu\phi_2}_{\text{Goldstone boson}} + \dots \quad (6)$$

and now contains the correct terms to describe a massive vector field A^μ with mass $m_A^2 = g^2v^2$ (originating from the kinetic term of $\mathcal{L}_\phi$), a massive real scalar field ϕ_1 with mass $m_{\phi_1} = -2\mu^2$, that will become a *Higgs boson*, and a massless scalar field ϕ_2 , a so called *Goldstone boson* which couples to the gauge vector boson A^μ . The terms omitted contain couplings between the ϕ_1 and ϕ_2 fields irrelevant to this discussion. The gauge symmetry of the theory allows us to make the particle content more transparent. Indeed, if we parameterize the complex scalar field ϕ as:

$$\phi(x) = \frac{e^{i\chi(x)}}{\sqrt{2}}(v + H(x)) \xrightarrow{U(1)} \frac{1}{\sqrt{2}}(v + H(x)) , \quad (7)$$

the χ degree of freedom can be *rotated away*, as indicated in Eq. (7), by enforcing the $U(1)$ gauge invariance of the original Lagrangian. With this gauge choice, known as *unitary gauge* or *unitarity gauge*, the Lagrangian becomes:

$$\mathcal{L} = \mathcal{L}_A + \frac{g^2v^2}{2}A_\mu^2 + \frac{1}{2}(g^\mu H\partial_\mu H + 2\mu^2 H^2) + \dots \quad (8)$$

a factor of two, making therefore almost a factor of four at the rate level. All other mass corrections, in the matrix element and phase space entering the calculation of the $H \rightarrow Q\bar{Q}$ decay rate, can in first approximation be safely neglected.

4. Loop induced Higgs boson decays: $H \rightarrow \gamma\gamma, \gamma Z, gg$

At the lowest order the decay rate for $H \rightarrow \gamma\gamma$ can be written

$$\Gamma(H \rightarrow \gamma\gamma) = \frac{G_F \alpha^2 M_H^4}{128\sqrt{2}\pi^3} \left| \sum_f N_f^2 Q_f^2 A_f^H(\tau_f) + A_W^H(\tau_W) \right|^2 , \quad (102)$$

where $f = l, q$ respectively), Q_f is the charge of the f fermion species, and A_f^H is defined as:

$$f(\tau) = \begin{cases} \arcsin^2 \frac{1}{\sqrt{\tau}} & \tau \geq 1 \\ -\frac{1}{4} \left[\ln \frac{1+\sqrt{1-\tau}}{1-\sqrt{1-\tau}} - i\pi \right]^2 & \tau < 1 , \end{cases} \quad (103)$$

and A_W^H are given by:

$$A_f^H = 2\tau[1 + (1-\tau)f(\tau)] , \quad (104)$$

$$A_W^H(\tau) = -[2 + 3\tau + 3\tau(2-\tau)f(\tau)] .$$

The decay rate for $H \rightarrow \gamma Z$ is given by:

$$\Gamma(H \rightarrow \gamma Z) = \frac{M_W^2 \alpha M_H^4}{64\pi^4} \left(1 - \frac{M_Z^2}{M_H^2}\right)^2 \left| \sum_f A_f^H(\tau_f, \lambda_f) + A_W^H(\tau_W, \lambda_W) \right|^2 , \quad (105)$$

with $\lambda_i = 4M_i^2/M_H^2$ ($i = f, W$), and the form factors $A_f^H(\tau, \lambda)$ and

$$= 2N_f^2 \frac{Q_f(I_{3f} - 2Q_f \sin^2 \theta_W)}{\cos \theta_W} [I_1(\tau, \lambda) - I_2(\tau, \lambda)] , \quad (106)$$

$$= \cos \theta_W \left\{ \left[\left(1 + \frac{2}{\tau}\right) \tan^2 \theta_W - \left(5 + \frac{2}{\tau}\right) \right] I_1(\tau, \lambda) + 4(3 - \tan^2 \theta_W) I_2(\tau, \lambda) \right\} , \quad (107)$$

defined after Eq. (102), and I_2^f is the weak isospin of the f fermion

$$\frac{\tau\lambda}{(\tau-\lambda)} + \frac{\tau^2\lambda^2}{2(\tau-\lambda)^2}[f(\tau) - f(\lambda)] + \frac{\tau^2\lambda}{(\tau-\lambda)^2}[g(\tau) - g(\lambda)] ,$$

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$$\frac{\tau\lambda}{(\tau-\lambda)} + \frac{\tau^2\lambda^2}{2(\tau-\lambda)^2}[f(\tau) - f(\lambda)] + \frac{\tau^2\lambda}{(\tau-\lambda)^2}[g(\tau) - g(\lambda)] ,$$

Klopt het ?

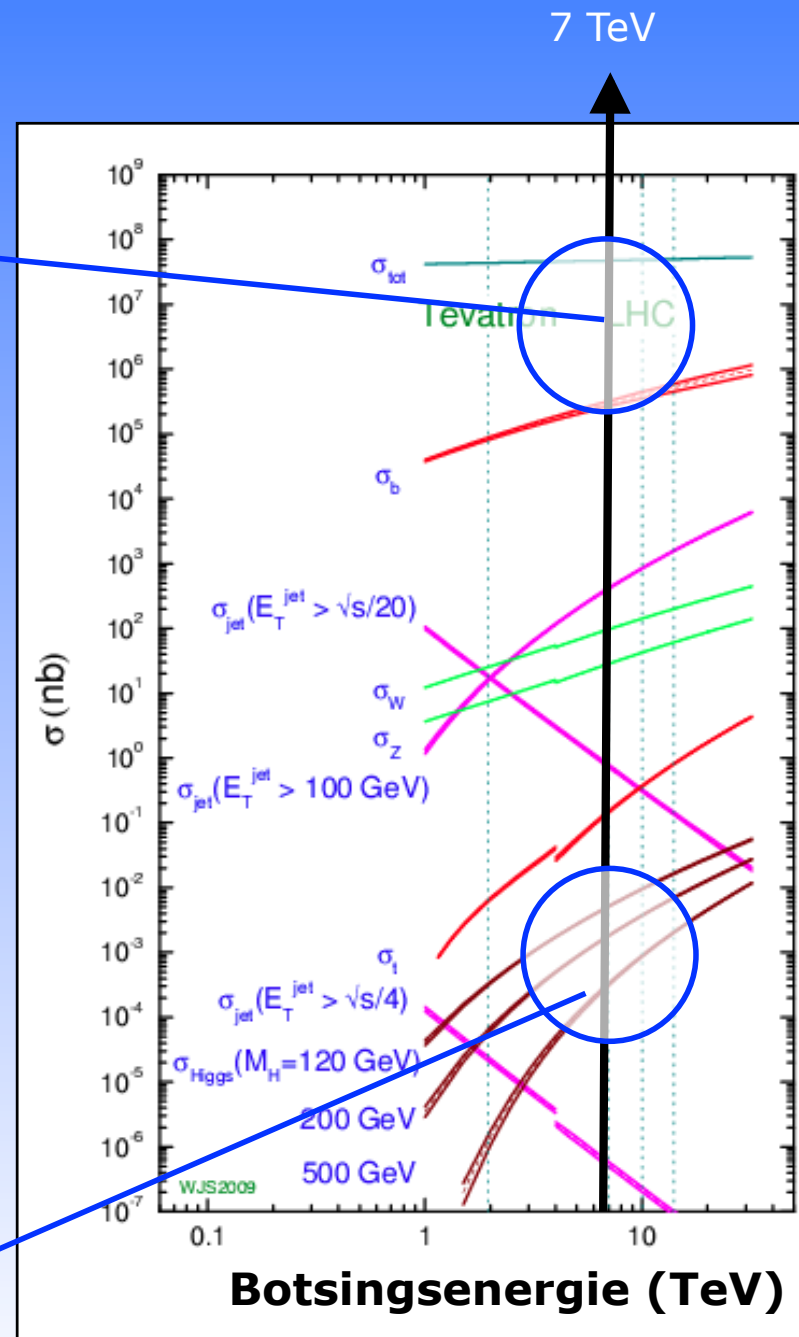
Inderdaad nieuwe deeltjes ?

Deeltjes productie kansen

Heel veel 'gewone' dingen

b-quark	10^5
Hoge energie jet	10^3
W-boson	10^2
Z-boson	10^1
top quark	10^{-1}
Higgs boson	$10^{-4} / 10^{-7}$
Supersymmetrie	$\varepsilon / 0 ?$

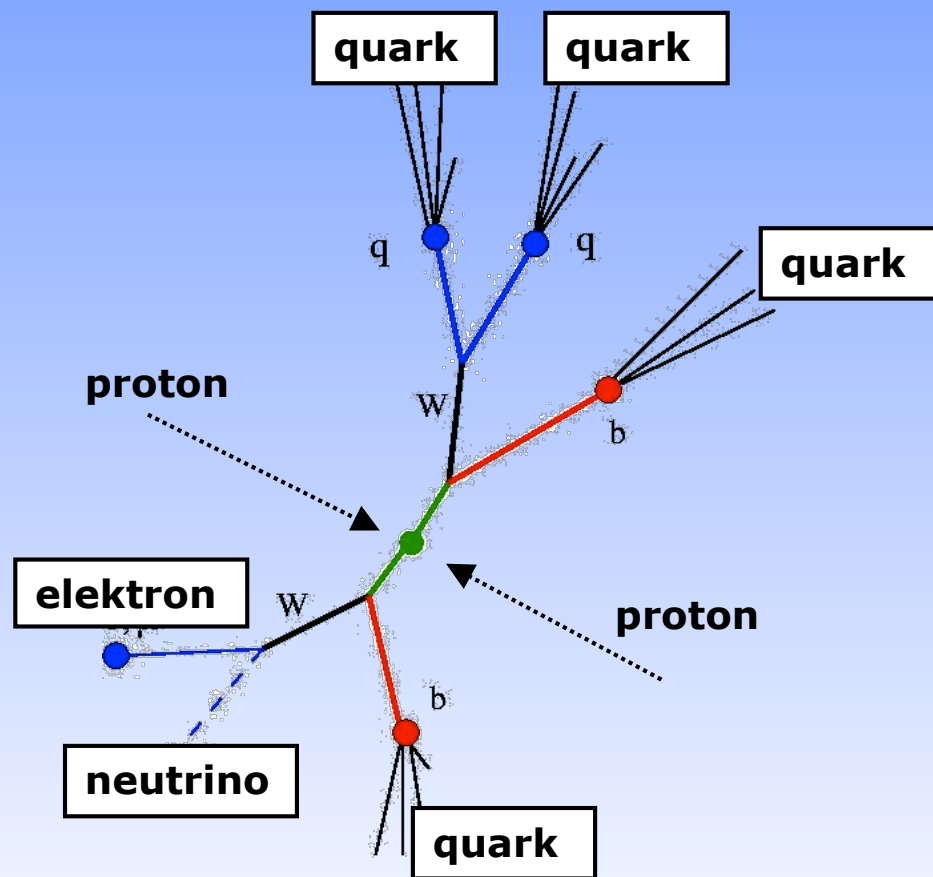
Heel weinig Higgs bosonen



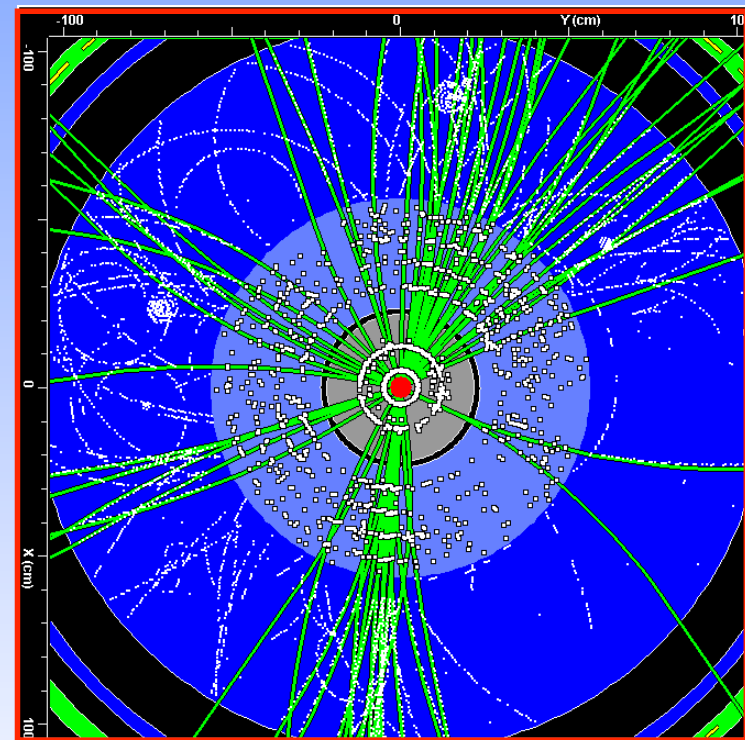
... wel al een hand vol gemaakt dit jaar

Hoe zien die botsingen er nou uit ?

Top quarks bijvoorbeeld



Simulatie top quark productie

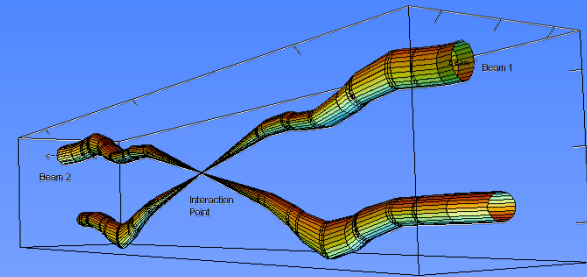


Luminosity

'effectief aantal botsingen per tijdseenheid'

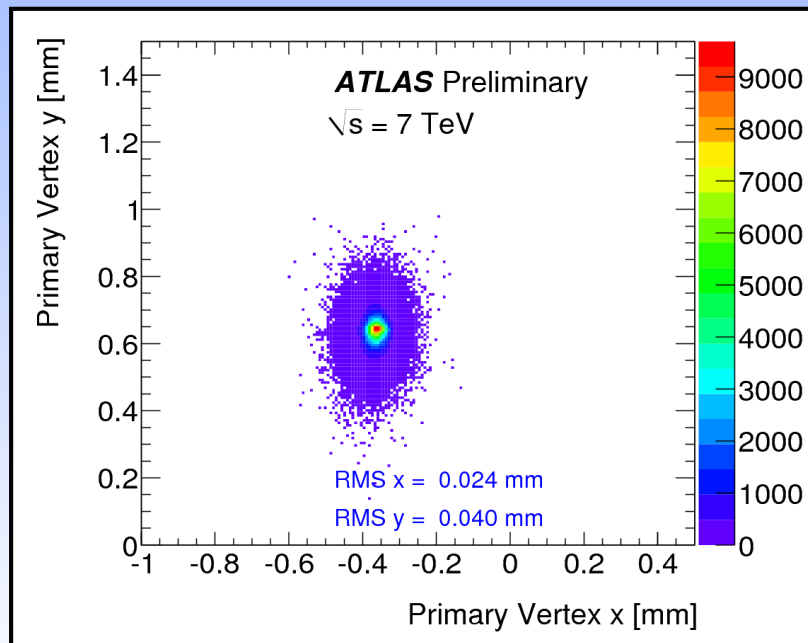
$$L \propto \frac{n_1 n_2}{\sigma_x \sigma_y}$$

Vergroot intensiteit



Kleinere bundeloverlap

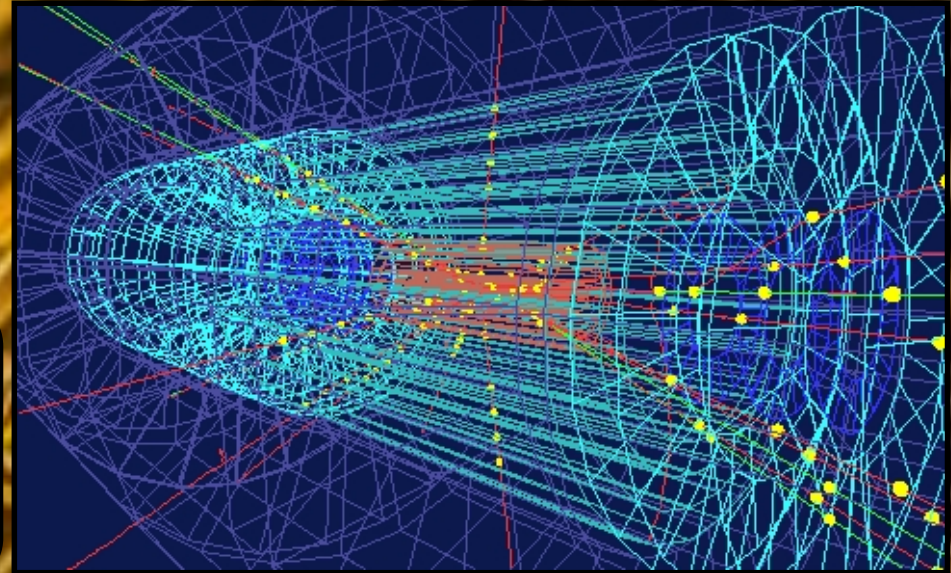
Meer protonen per bundel
... of meer bundels



200 days (seconds)	17280000
N colliding bunches	2808
revolution frequency	1.12×10^4
protons per bunch	1×10^{11}
Beam size (micron)	15 x 20
Peak Luminosity ($\text{cm}^{-2}\text{s}^{-1}$)	1×10^{34}
Hubner factor	0.3
Integrated (fb^{-1}) per year	50

Fotootjes kijken

40 miljoen botsingen per seconde
mag maar 200 per seconde opslaan



1 naald in 40 miljoen hooibergen
..... per seconde !



ongeveer 1 Higgs boson per dag

Wist je dat je maar 200 botsingen per seconde op kan slaan ?



... dat is nl. al 6 PetaByte per jaar
(6000 Tb = 100.000 DVD's)

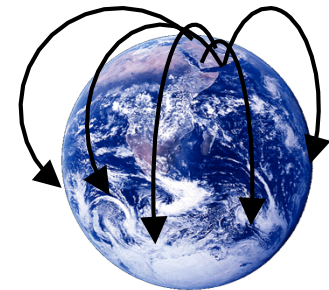
... je moet dus 99.9995 % van de foto's
weggooien ... elke seconde weer

☒ YES

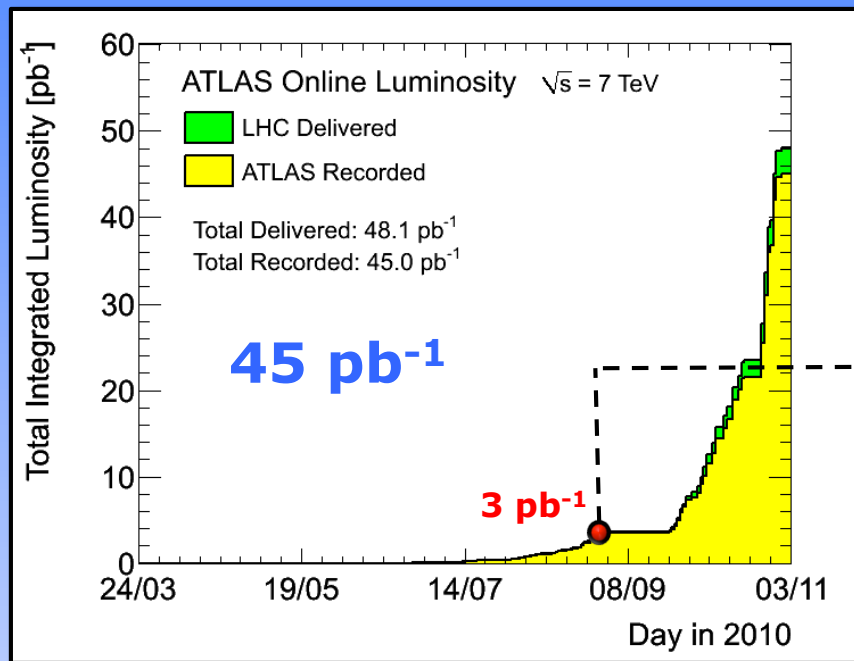
☐ NO

☐ Cancel

De data wordt verspreid over de hele wereld
Ook naar SARA/Nikhef (Amsterdam)



LHC start-up programme



Komend jaar 100x meer data

0

Understand ATLAS
Testbeam/cosmics

1

Understand SM+ATLAS
in *simple* topologies

W/Z

2

Understand SM+ATLAS
in *complex* topologies

Top quark pairs

3

Look for *new physics*
in ATLAS at 14 TeV

Higgs/SUSY

LHC startup

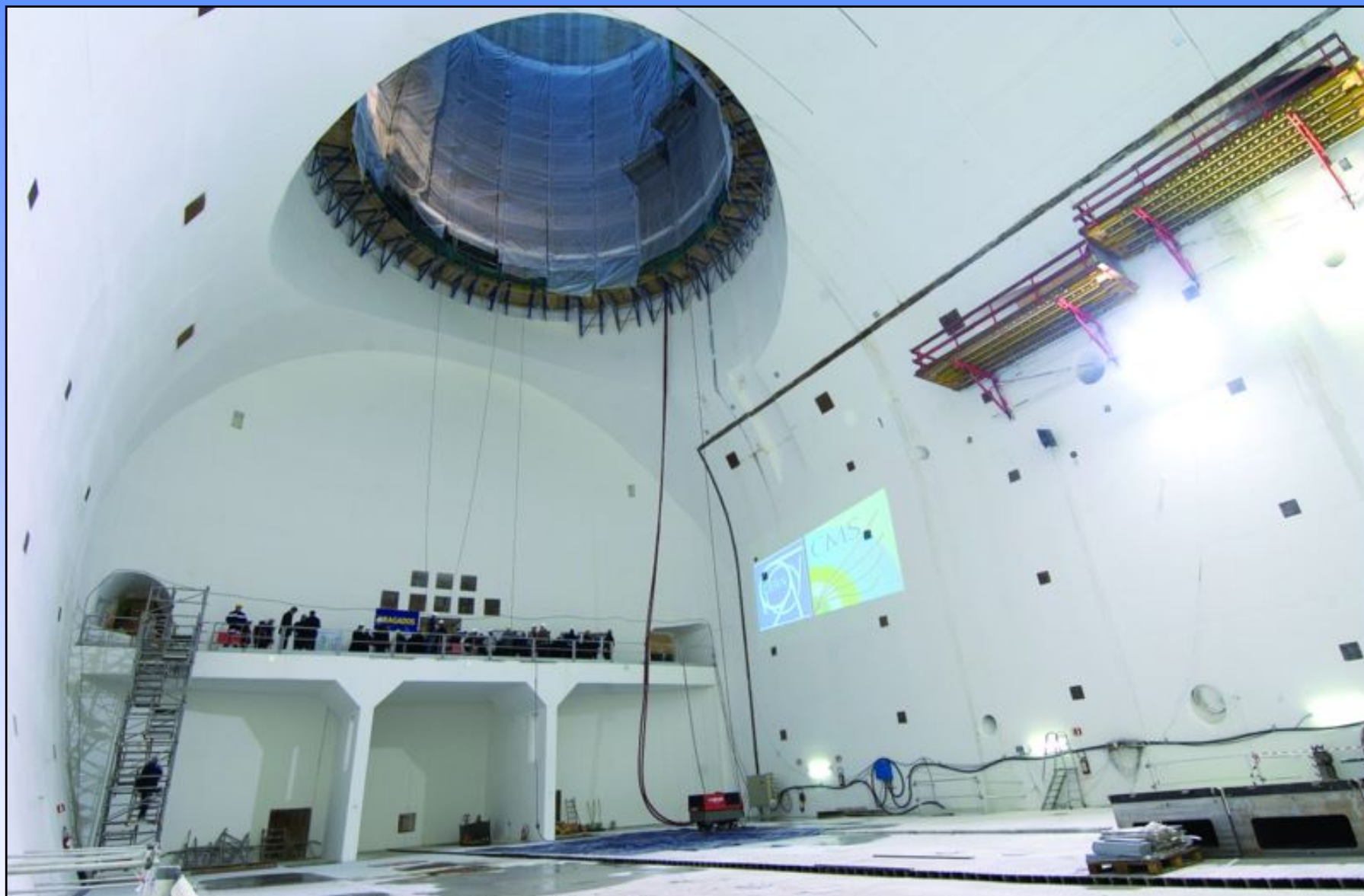
Andreas Hoecker

Time



Op 100 meter diep een grote grot maken





1

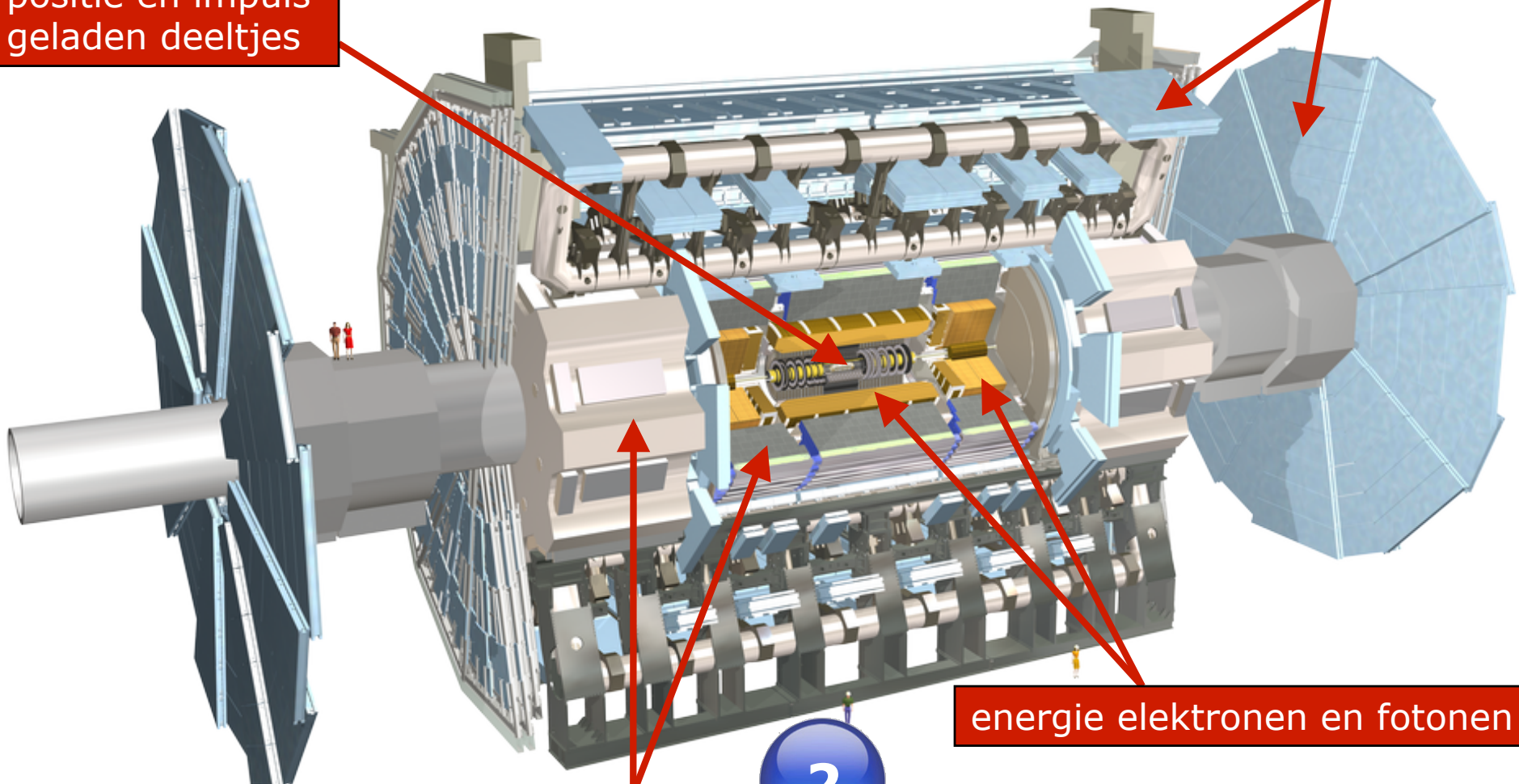
De Atlas detector

het grootste fototoestel op aarde

3

positie en impuls
geladen deeltjes

muon detector

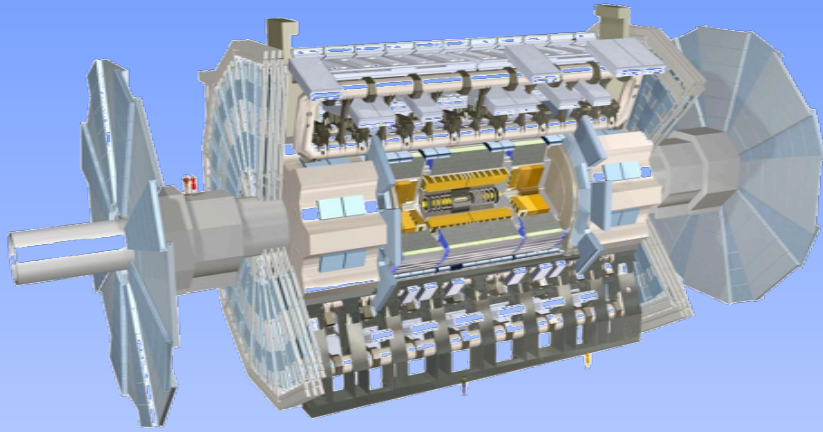


energie elektronen en fotonen

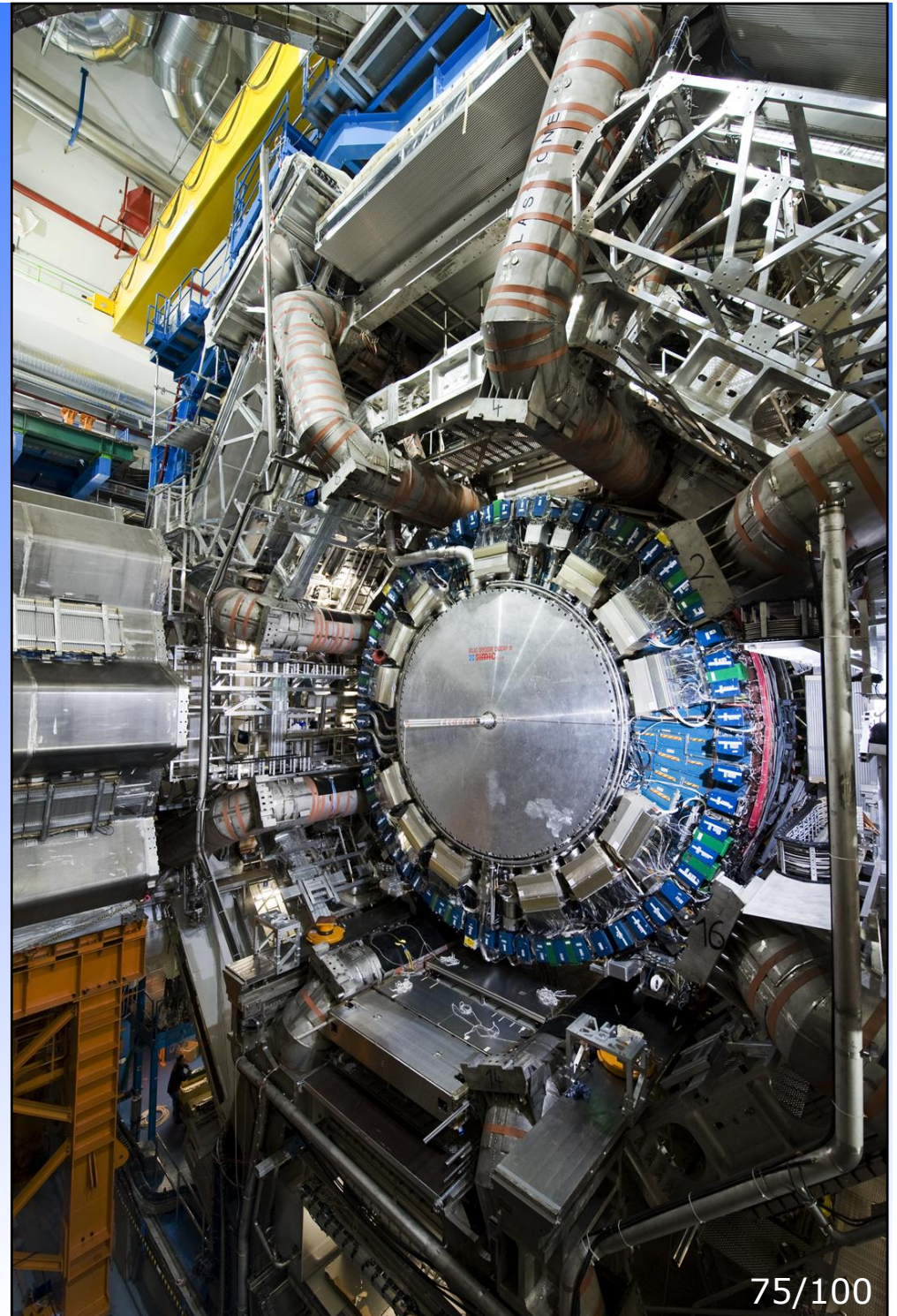
energie quark-deeltjes

2

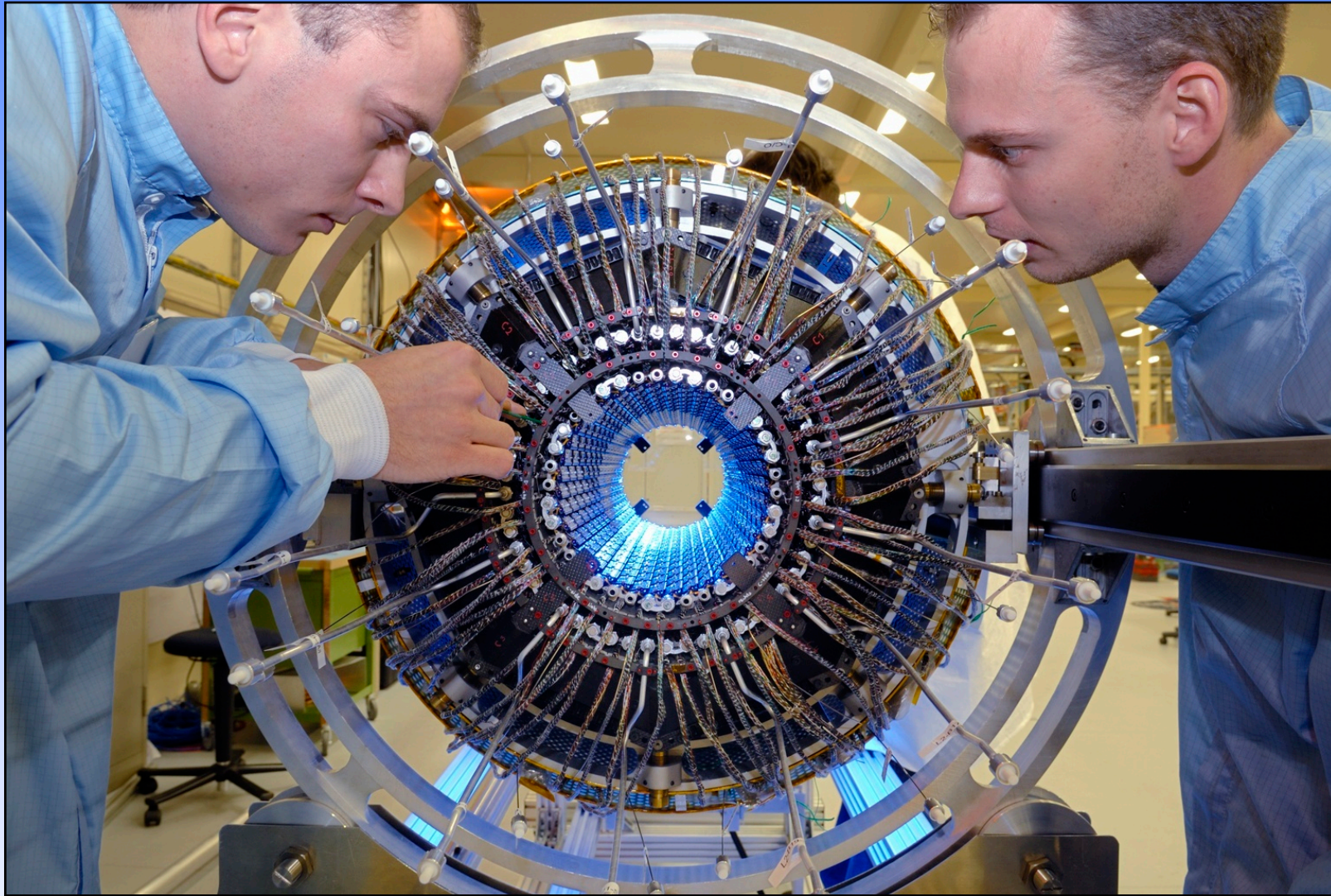
De ATLAS detector



45 m lang, 25 m hoog, 7000 ton



De Atlas pixel detector



80 MegaPixel camera 40.000.000 foto's per seconde

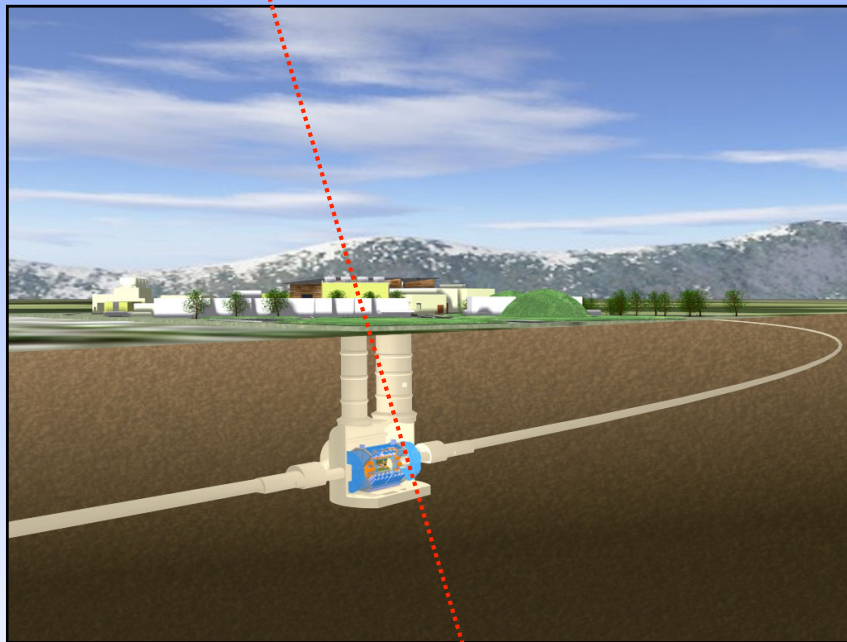
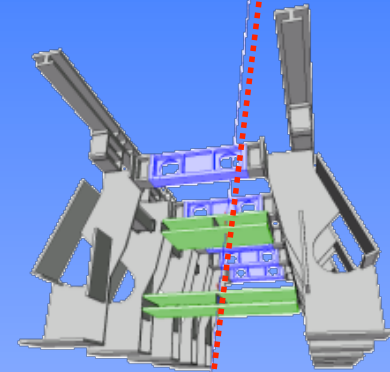
De Atlas SCT detector



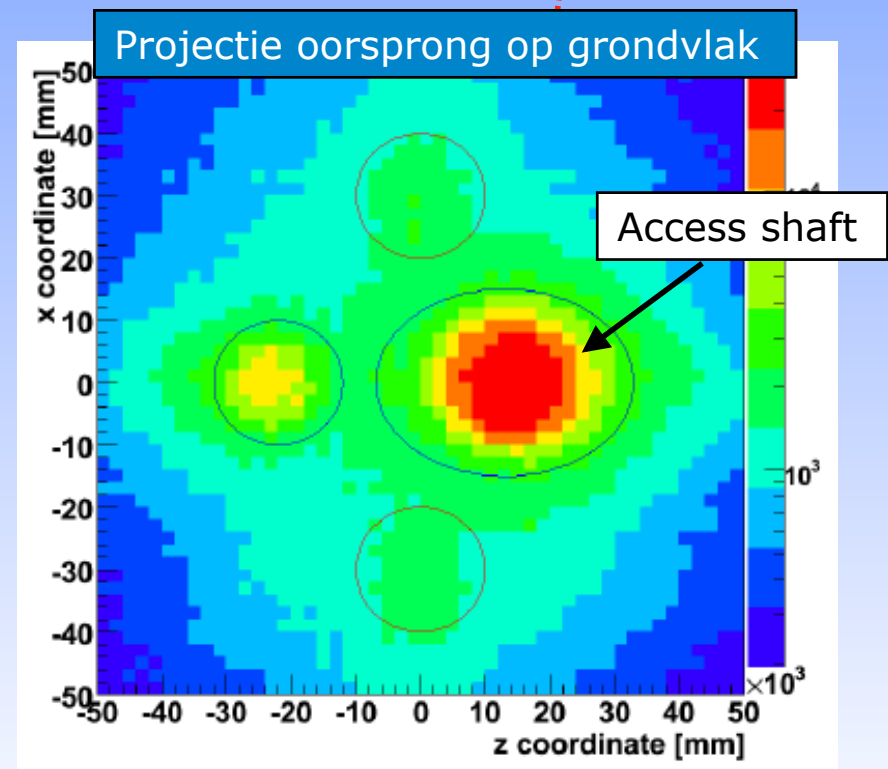
Foto in de cleanroom op het Nikhef (Amsterdam)

Atmosferische muonen in ATLAS

~25 Hz atmosferische muonen in ATLAS detector
500 miljoen events, 1.2 Pb ruwe data



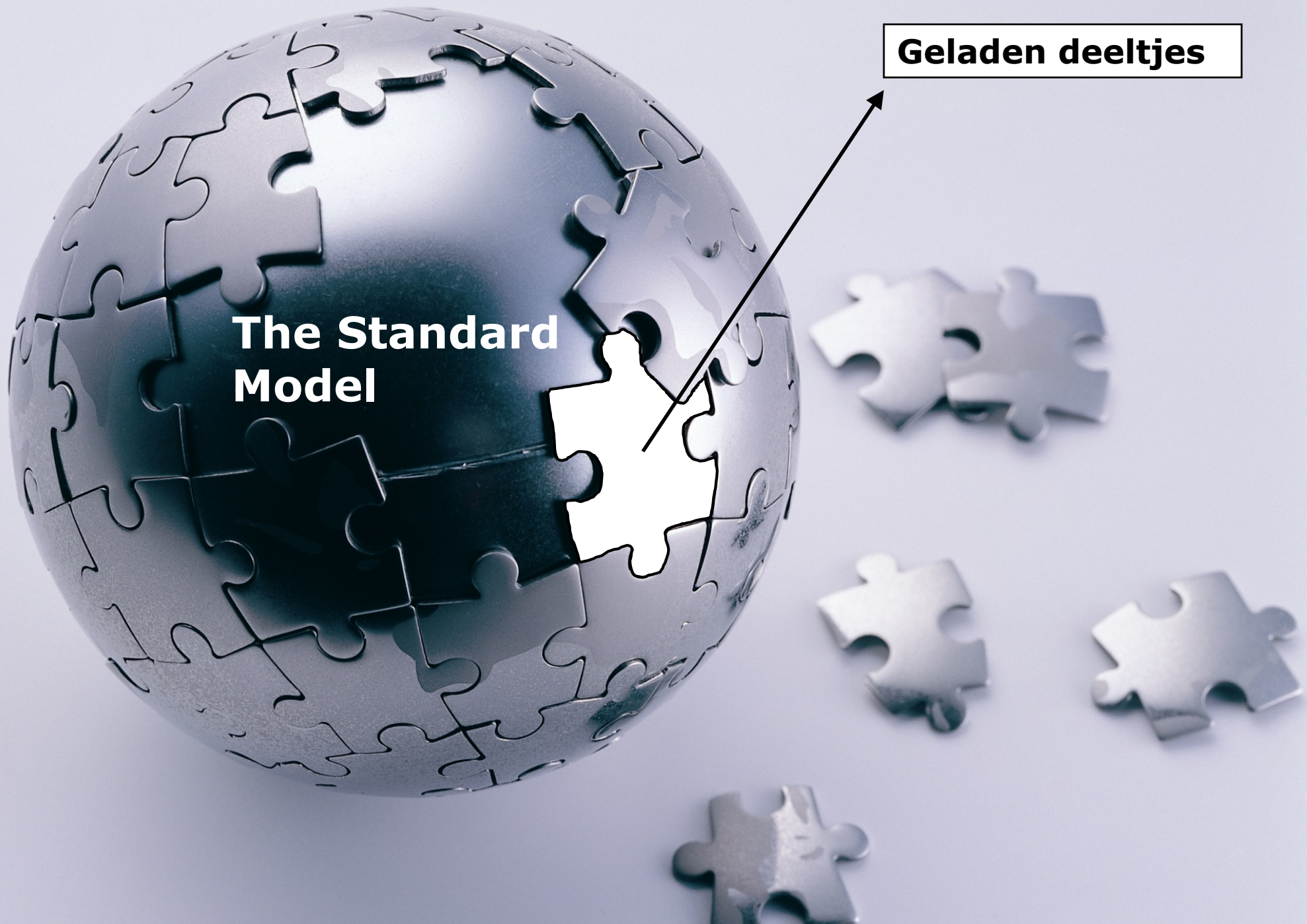
muon



ATLAS detector operation

Subdetector	# channels	Operational	
Pixels	80 M	97.3 %	<i>Tracking</i>
SCT Silicon Strips	6.3 M	99.2 %	
TRT Transition Radiation Tracker	350 k	97.1 %	
Lar EM Calorimeter	170 k	97.9%	<i>Calorimeter</i>
Tile Calormeter	9800	96.8 %	
Hadronic Endcap LAr calorimeter	5600	99.9 %	
Forward LAr Calorimeter	3500	100 %	
L1 Calo trigger	7160	99.9 %	<i>Trigger</i>
LVL1 Muon RPC trigger	370 k	99.5 %	
LVL1 Muon TGC trigger	320 k	100 %	
LVL1 Muon Drift Tubes	350 k	99.5 %	
CSC cathode strip chambers	31 k	98.5 %	
RPC Barrel Muon Chambers	370 k	97.0 %	
TGC Endcap Muon Chambers	320 k	98.4 %	

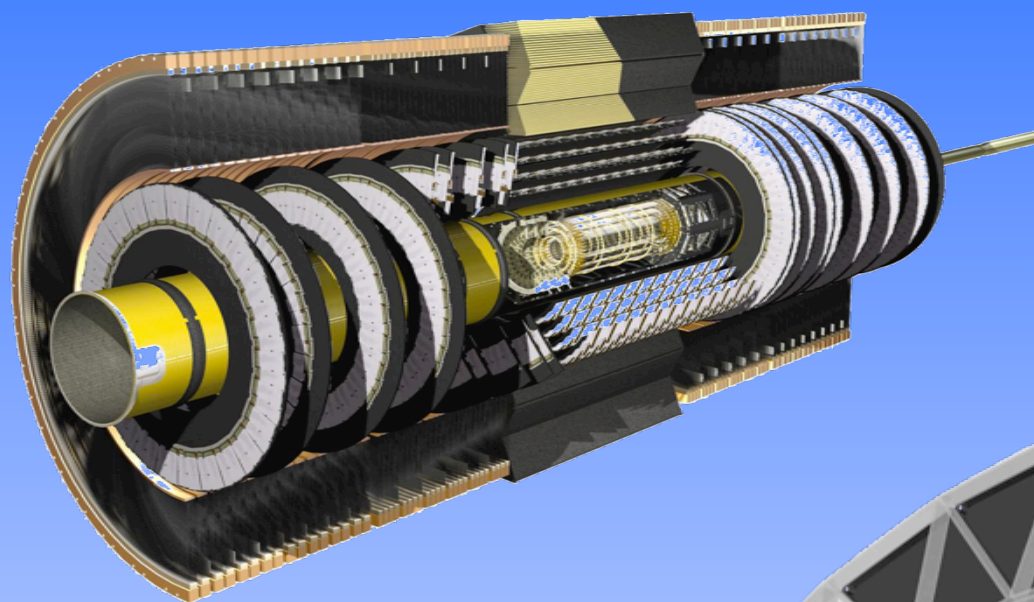
→ *de detector doet het fenomenaar*

A conceptual image of a globe constructed from dark grey puzzle pieces. One piece is missing, revealing a white background. Several other puzzle pieces are scattered on the light blue surface to the right of the globe. An arrow points from a text box to the missing piece.

The Standard Model

Geladen deeltjes

Inner detector



ATLAS inner detector

Transition Radiation Tracker

barrel: ≥ 30 straws

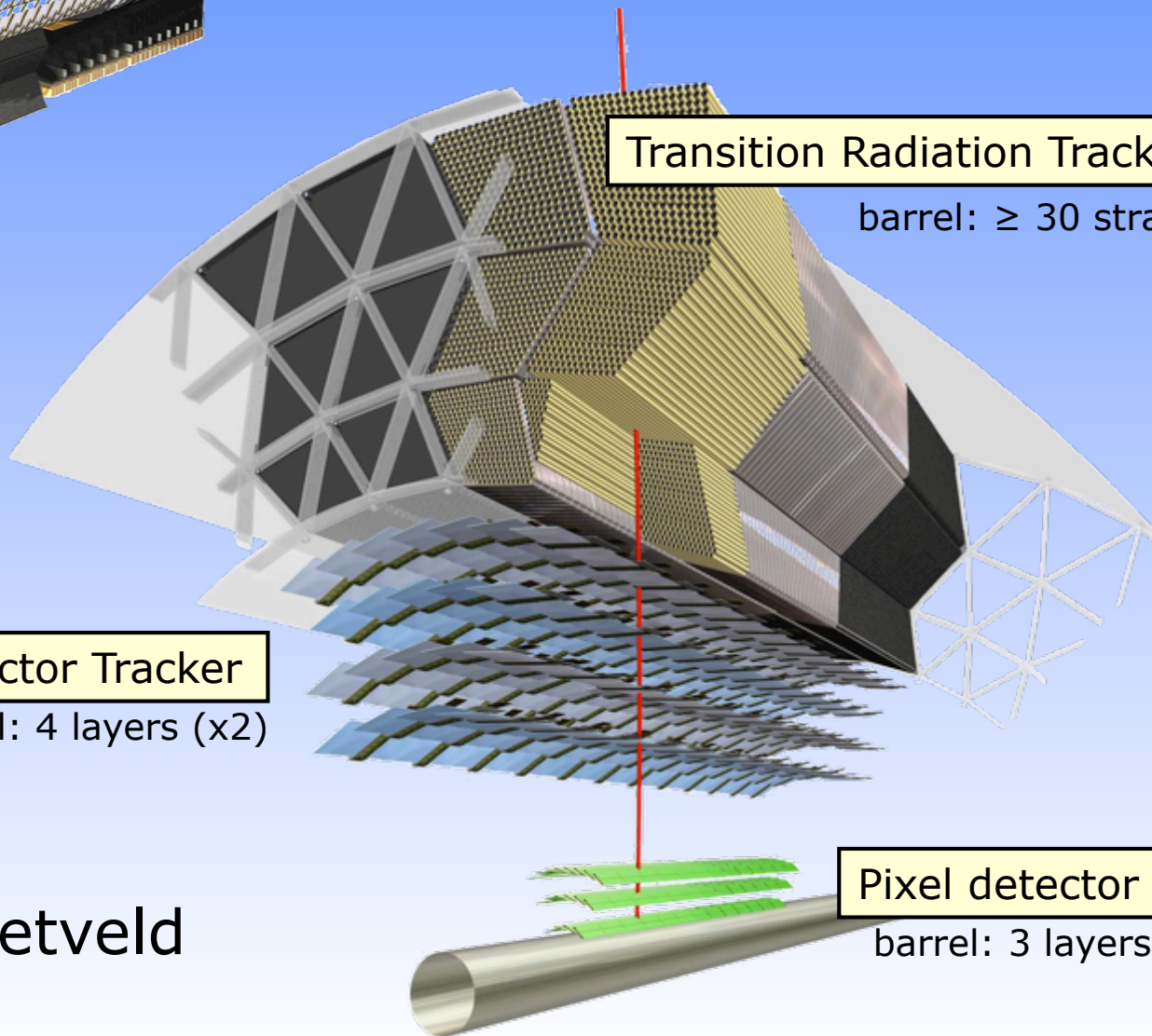
SemiConductor Tracker

barrel: 4 layers (x2)

In 2 Tesla magneetveld

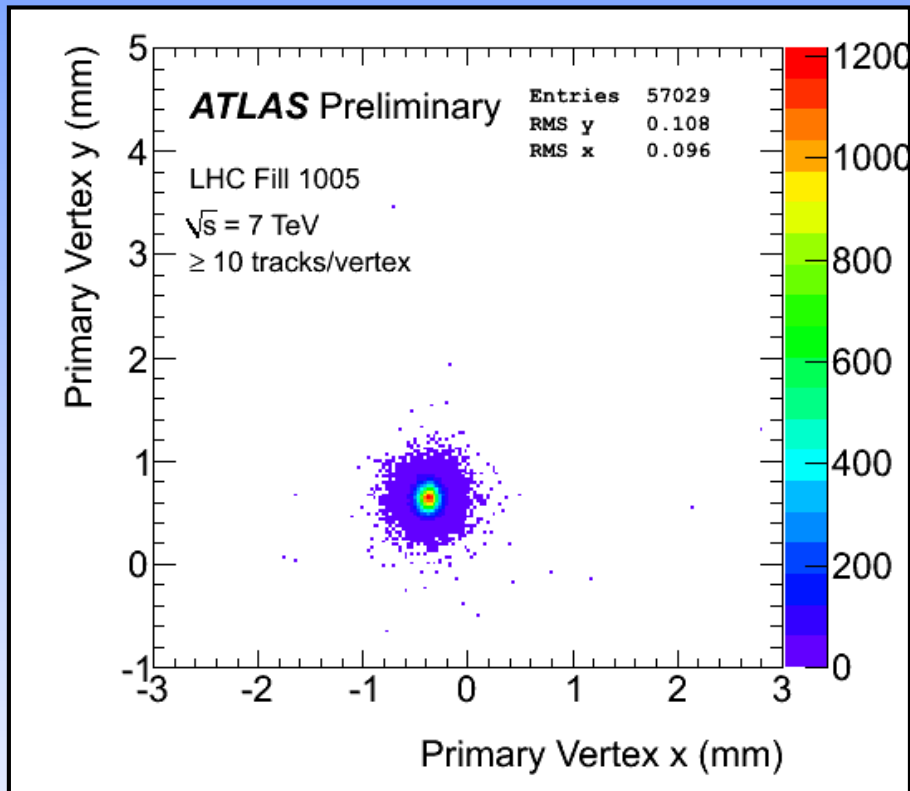
Pixel detector

barrel: 3 layers



Vertexing

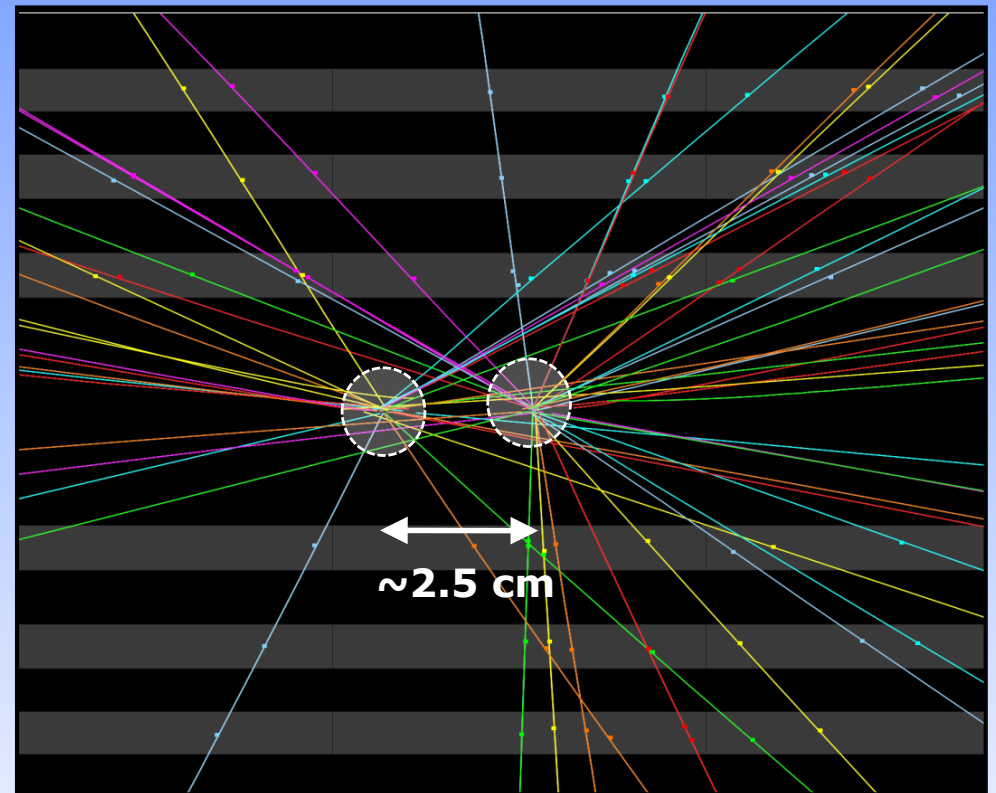
Primary vertices



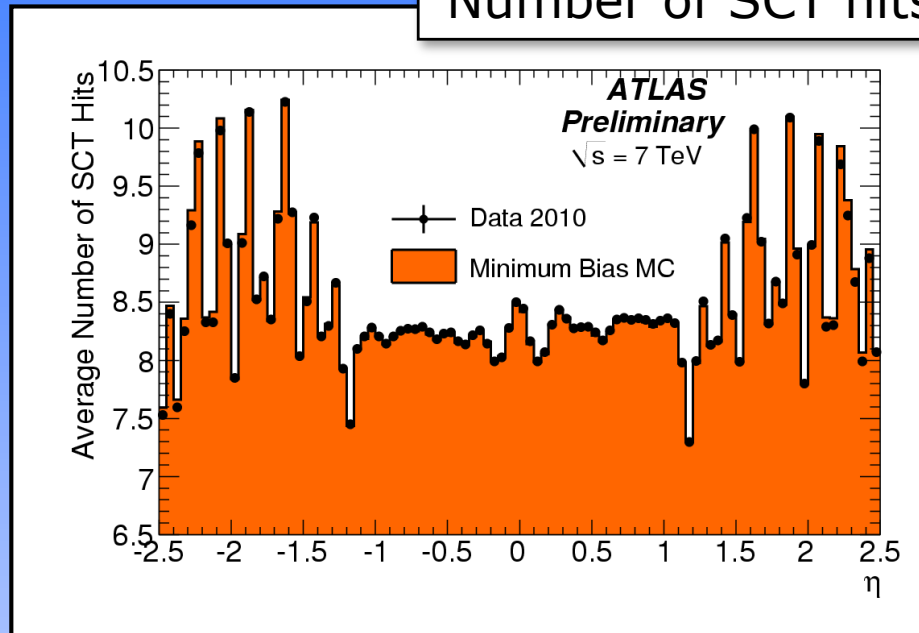
Luminous region: $\sigma_x = 45 \mu\text{m}$, $\sigma_y = 70 \mu\text{m}$

Vertex resolution $\sim 75 \mu\text{m}$

Pile-up event

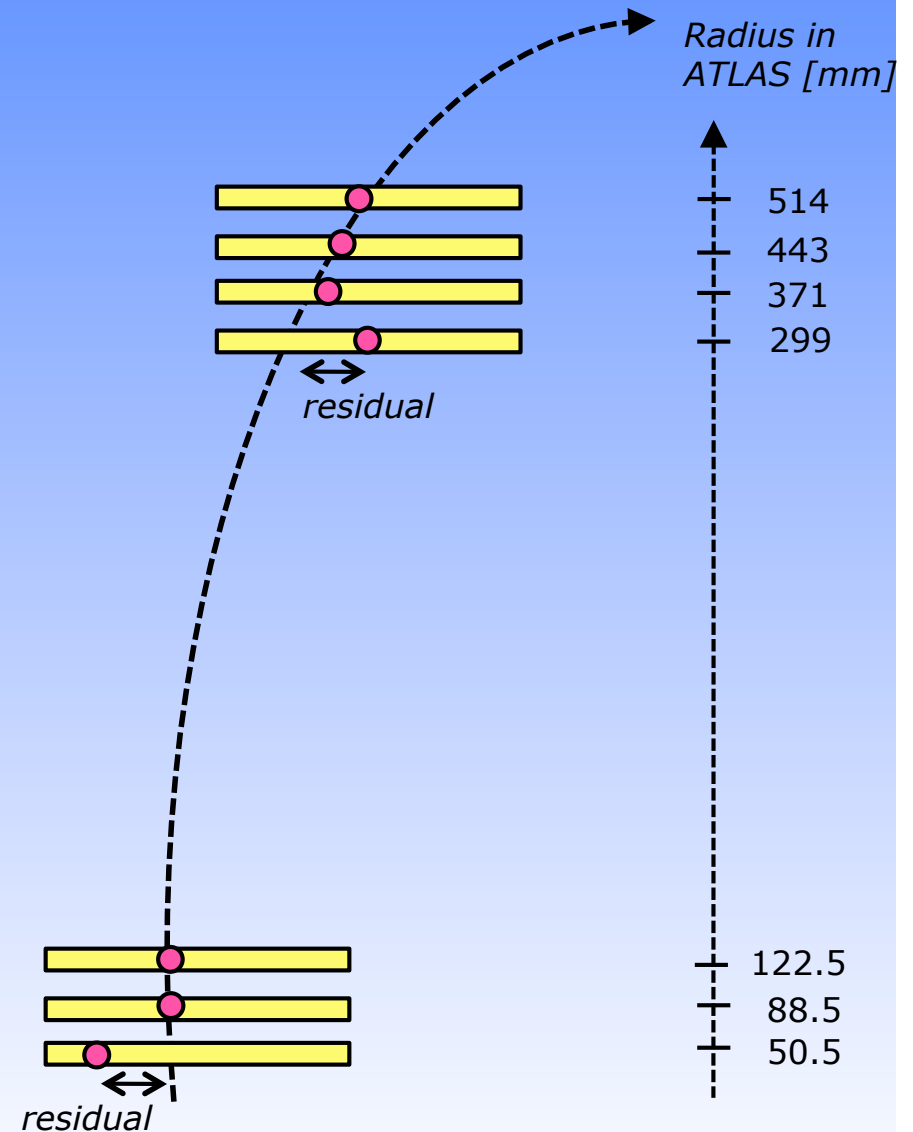
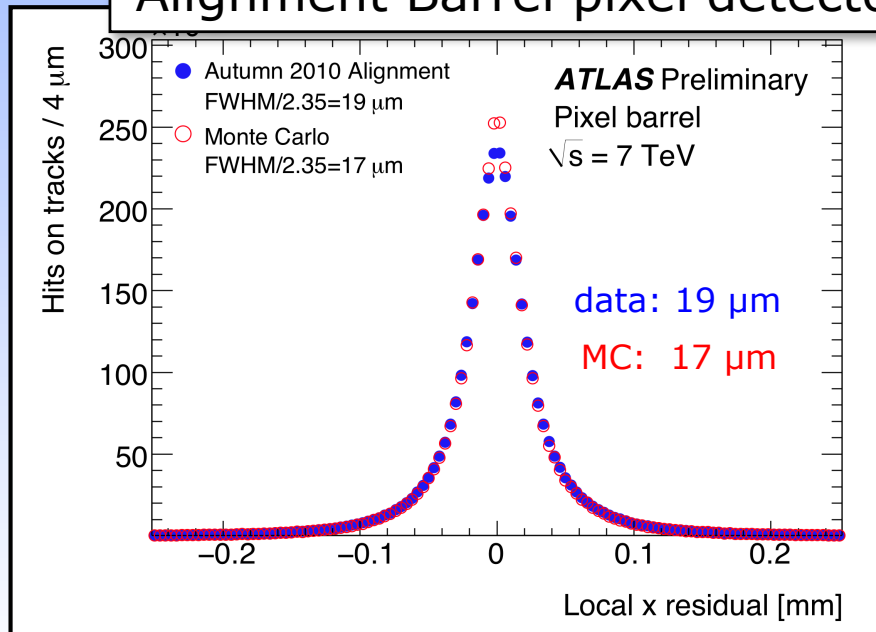


Number of SCT hits



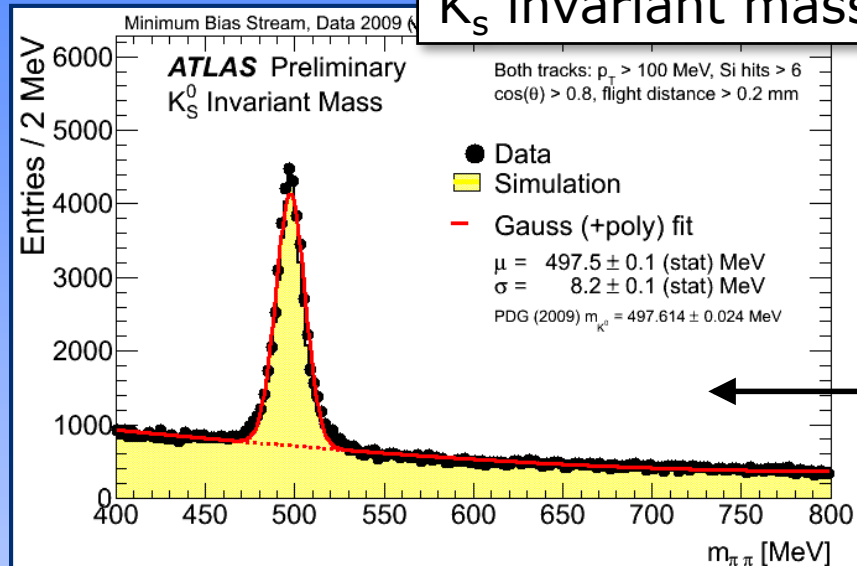
Tracking detectoren

Alignment Barrel pixel detector

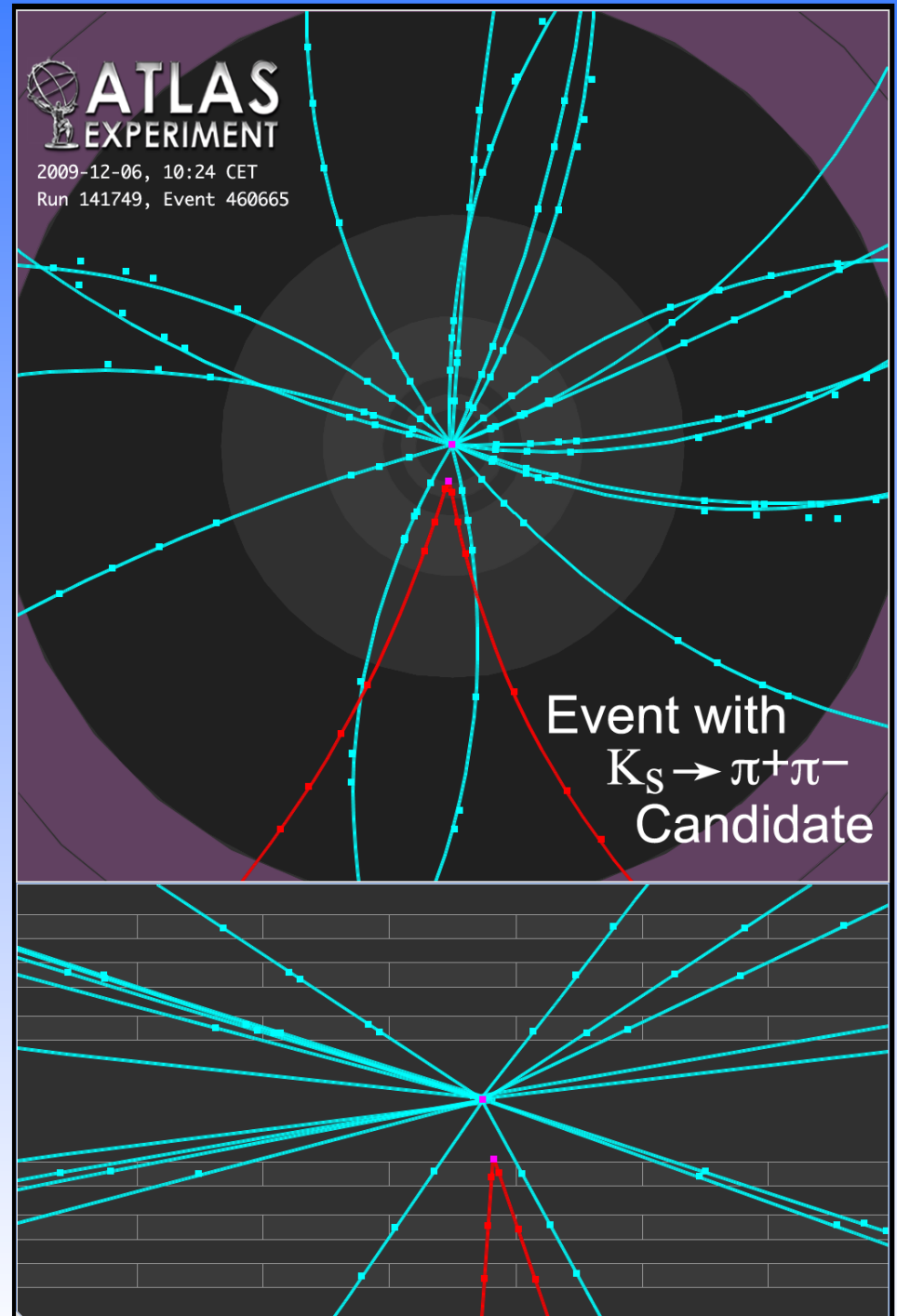
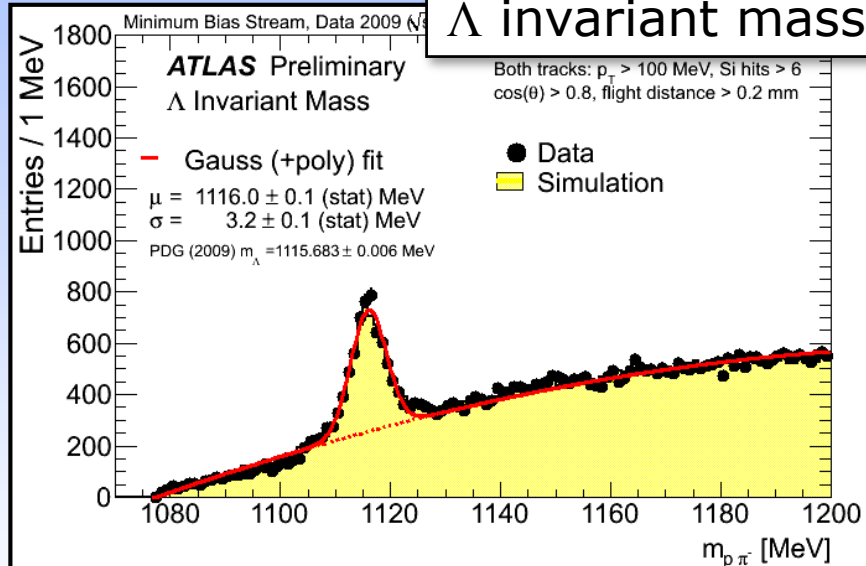


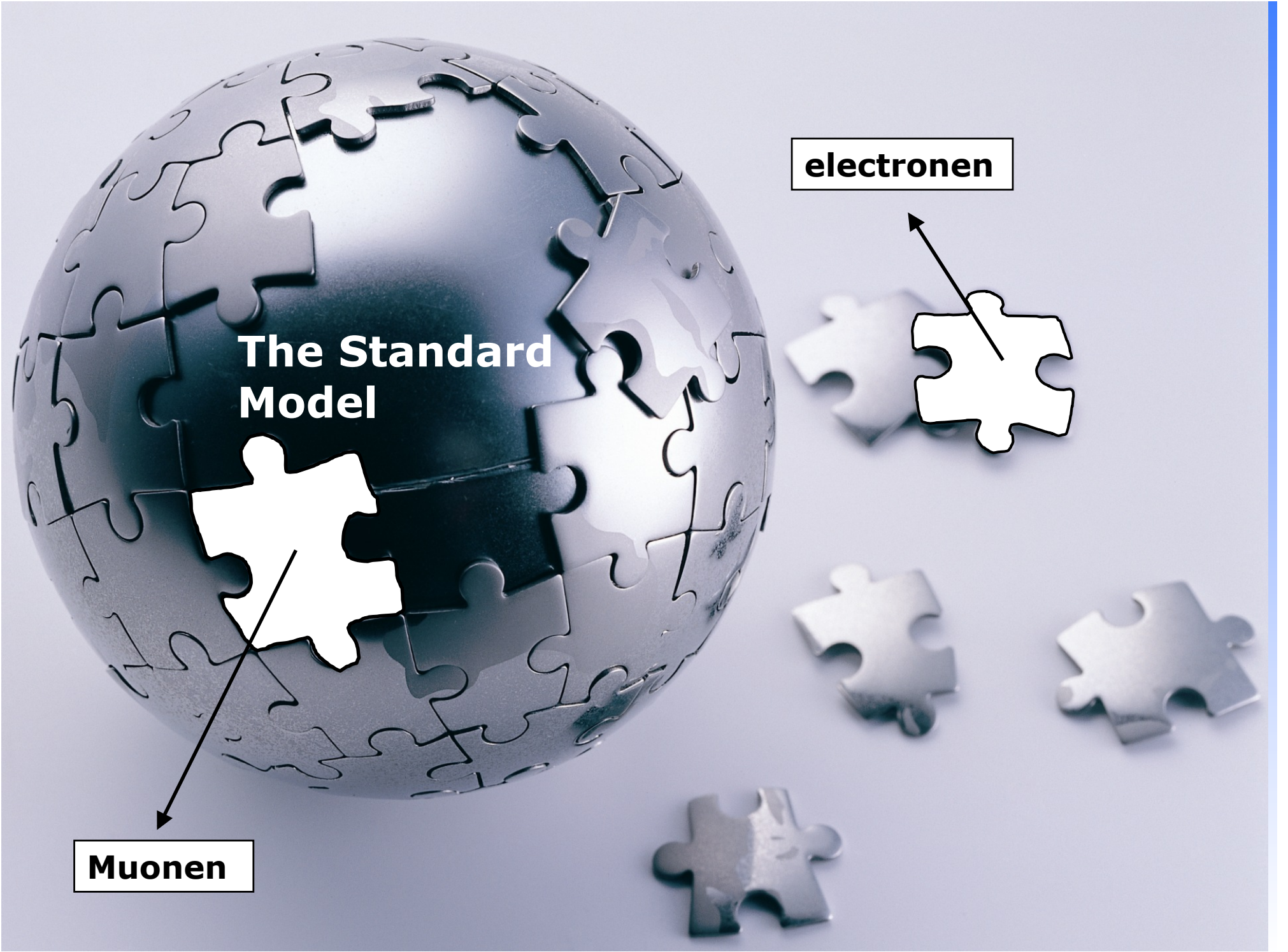
'Lang' levende deeltjes

K_S invariant mass



Λ invariant mass



A conceptual image showing a globe constructed from dark grey puzzle pieces. Two pieces are missing, creating white gaps. An arrow points from the label 'Muonen' to one of these gaps. To the right of the globe, several individual puzzle pieces are scattered on a light blue surface. One of these pieces is highlighted with a white fill and a black outline. An arrow points from the label 'electronen' to this highlighted piece. The text 'The Standard Model' is centered on the globe.

The Standard Model

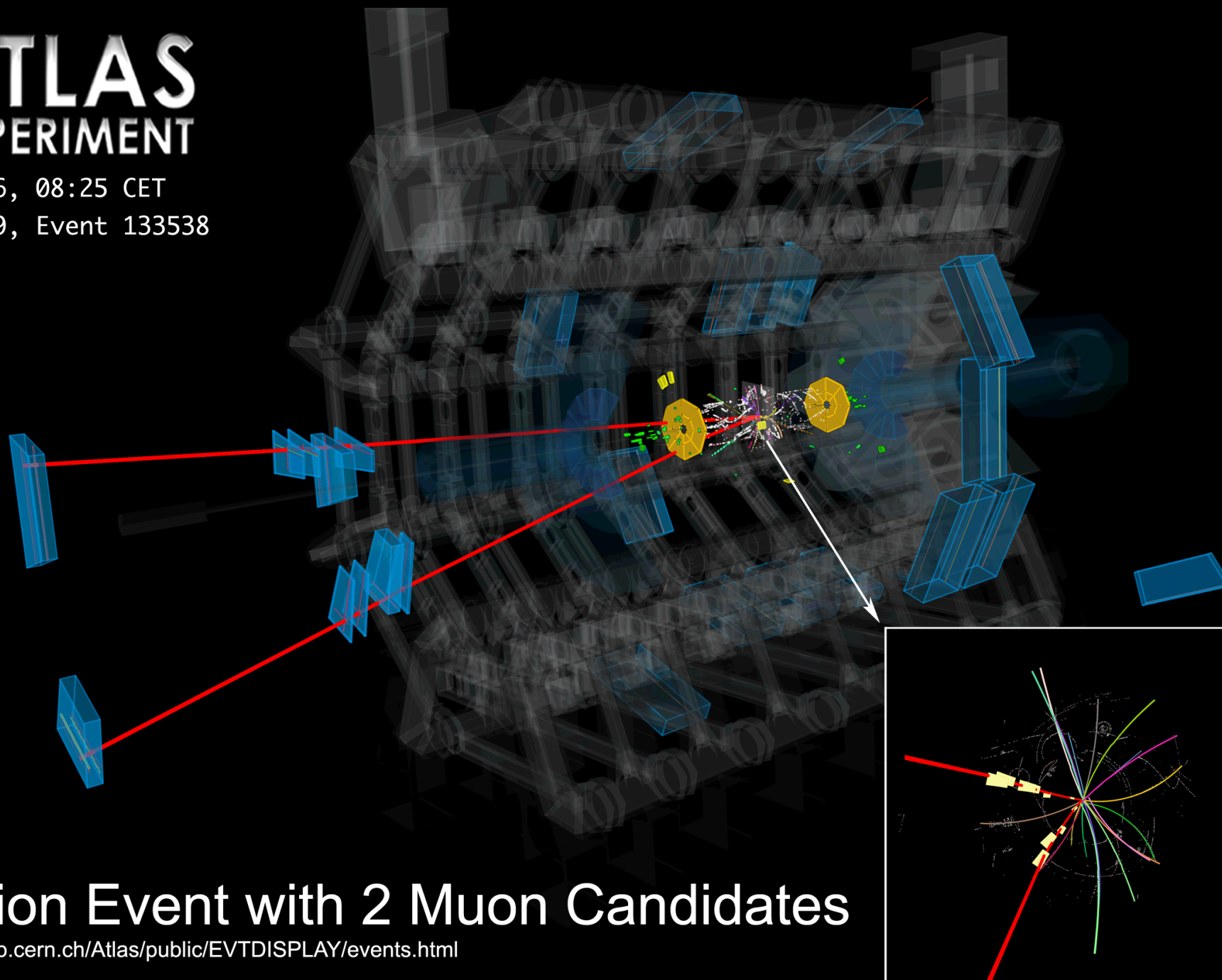
Muonen

electronen



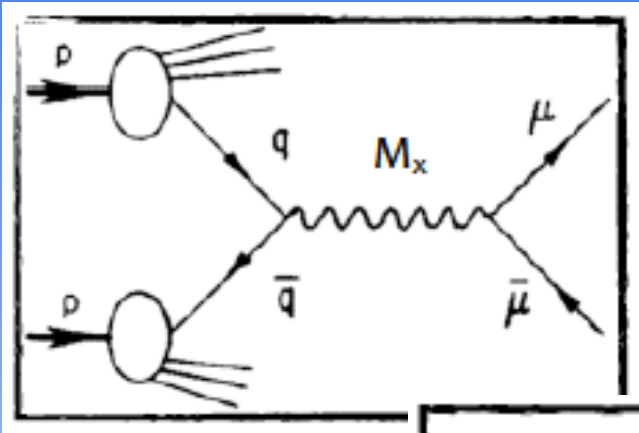
2009-12-06, 08:25 CET

Run 141749, Event 133538



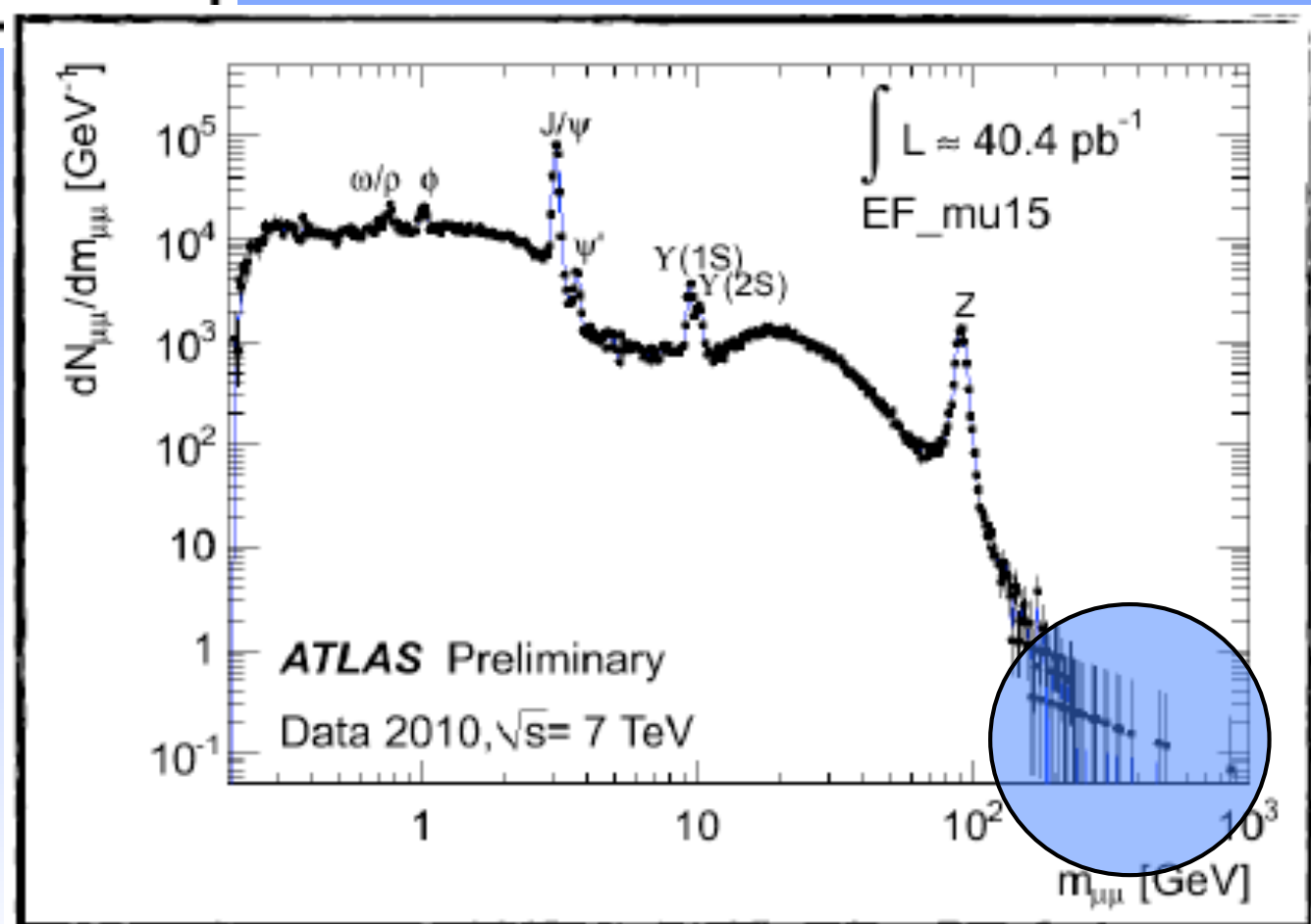
Collision Event with 2 Muon Candidates

<http://atlas.web.cern.ch/Atlas/public/EVTDISPLAY/events.html>



2 muonen in een event

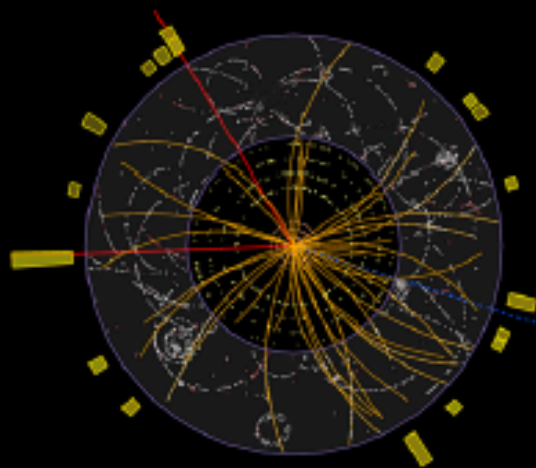
NB: Het mooiste Higgs boson verval is $H \rightarrow 4$ muonen



?

 **ATLAS**
EXPERIMENT

Candidate Event with a $Z \rightarrow \mu\mu$ and missing E_T



Run 167776, Event 129360643
Time 2010-10-28 10:41:18 CET

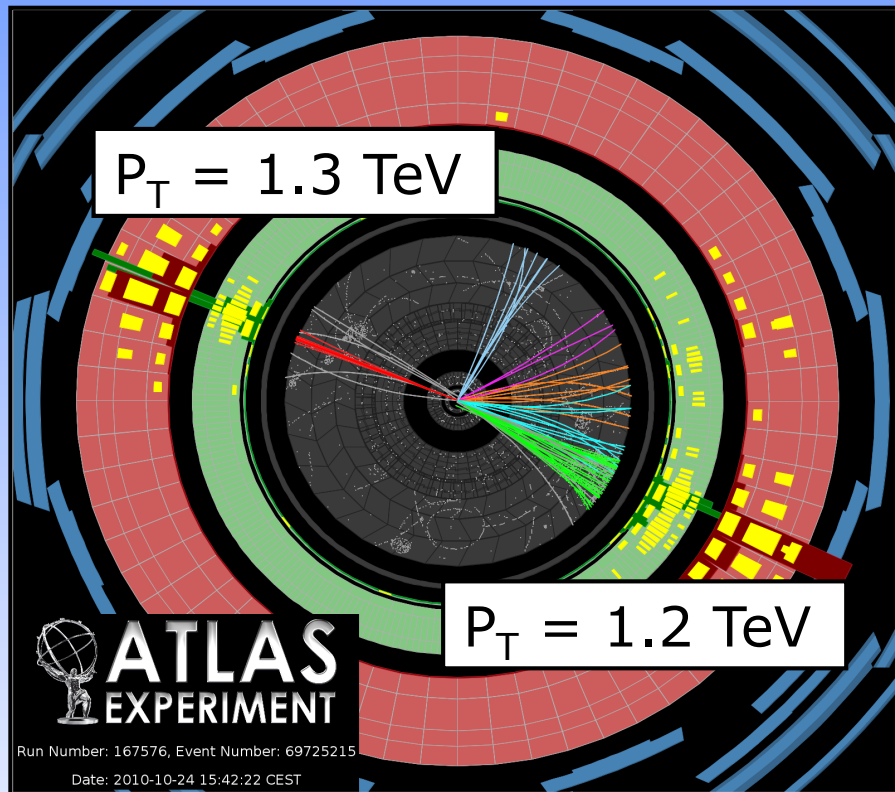


Jets

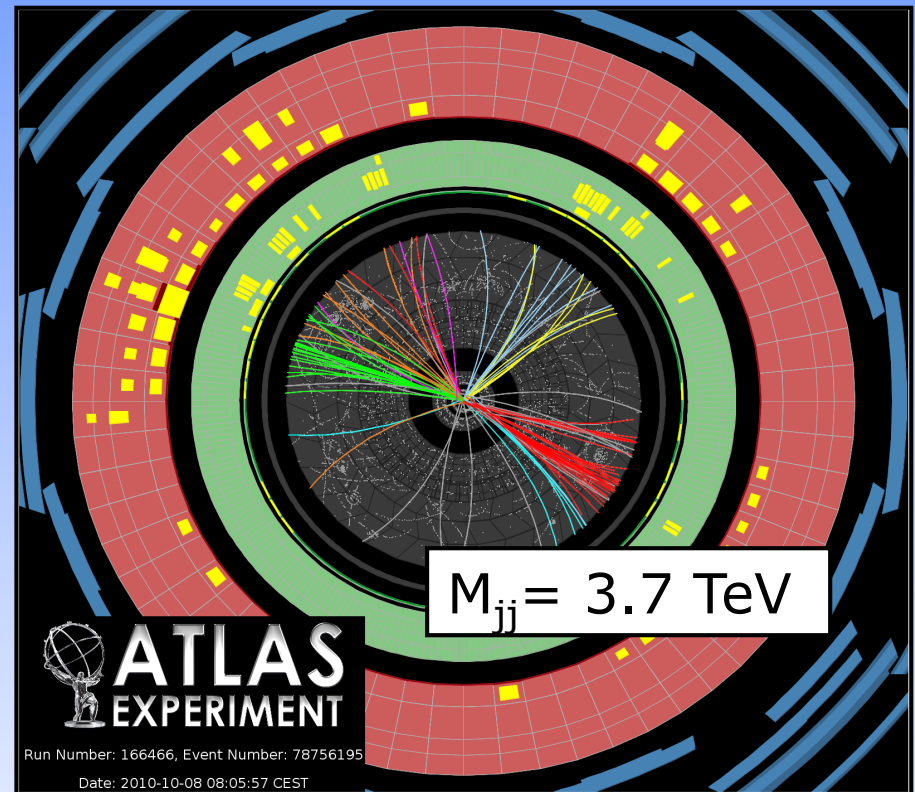
**The Standard
Model**

Jets:

overblijfselen van gluon of quark fragmentatie



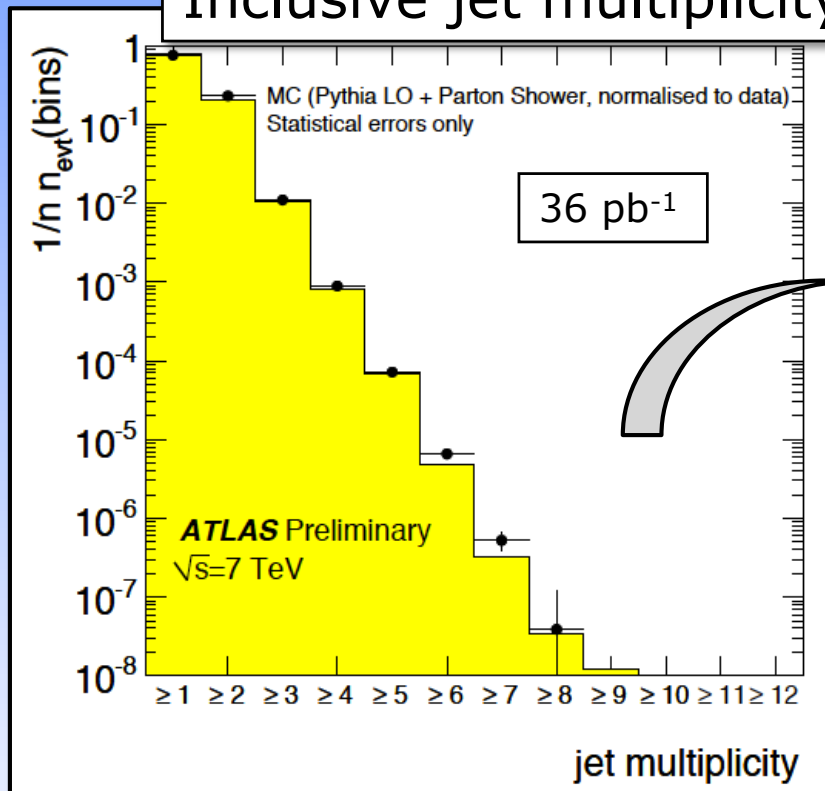
Highest transverse momentum



Highest invariant mass

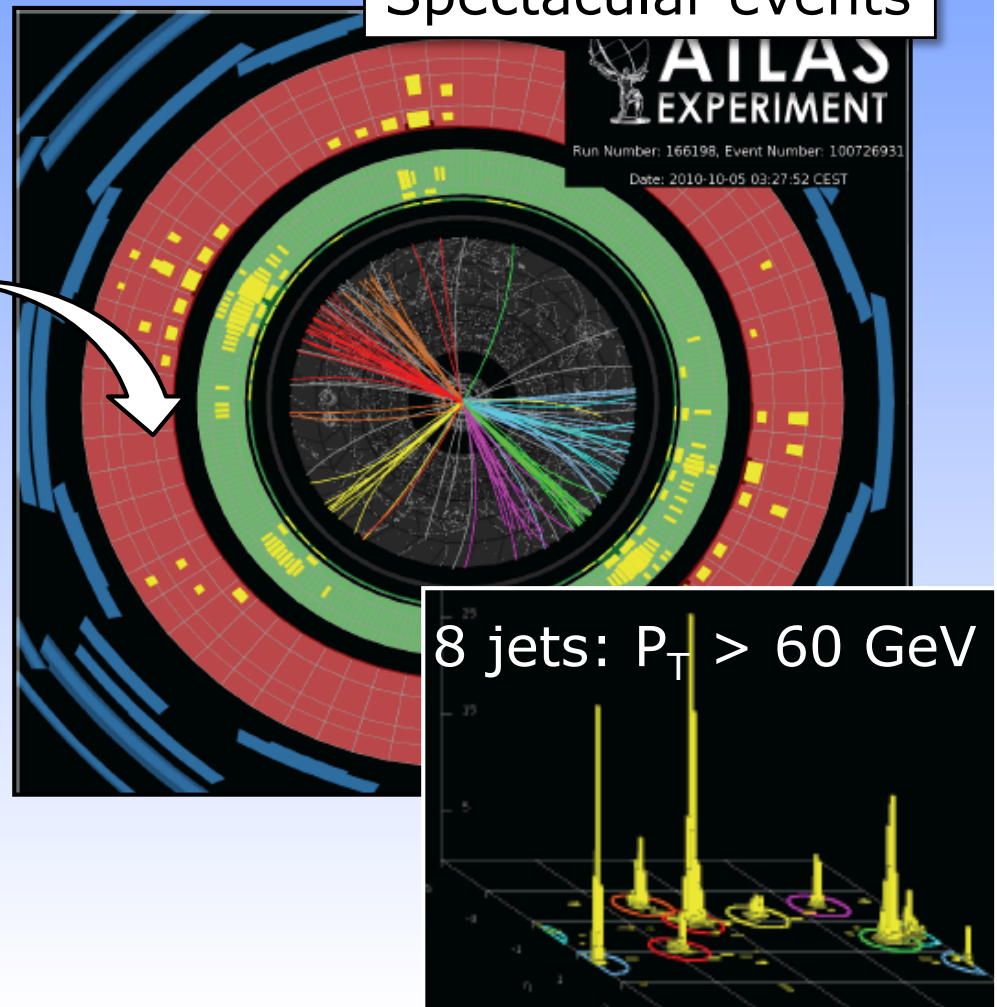
Differential jet distributions

Inclusive jet multiplicity



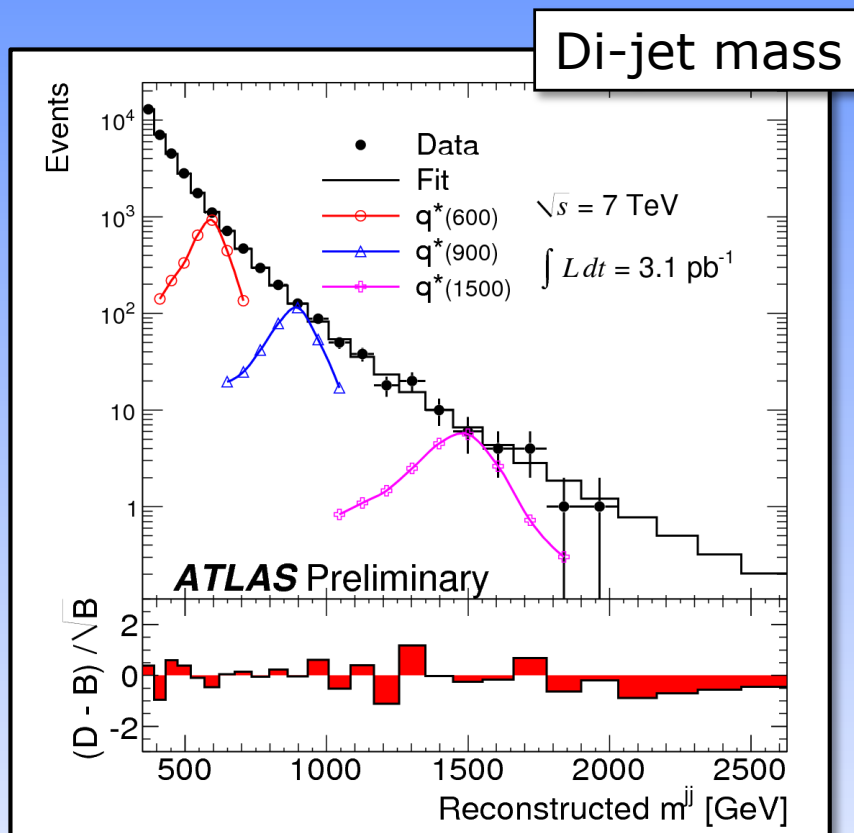
Jets with $P_T > 60$ GeV

Spectacular events



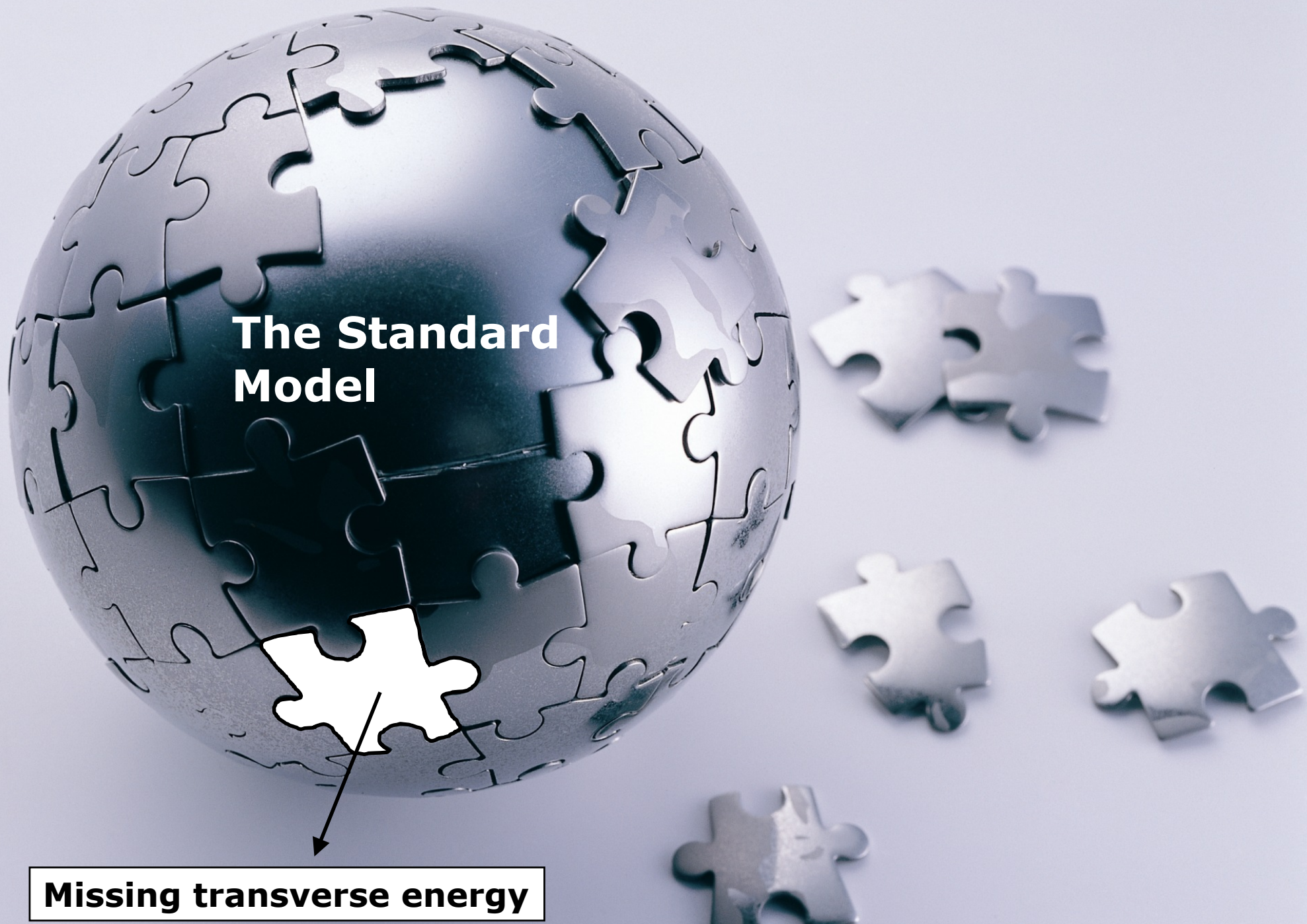
Differential jet distributions

New physics: di-jet resonances & correlations



ATLAS: $500 \text{ GeV} < M_{q^*} < 1.53 \text{ TeV}$

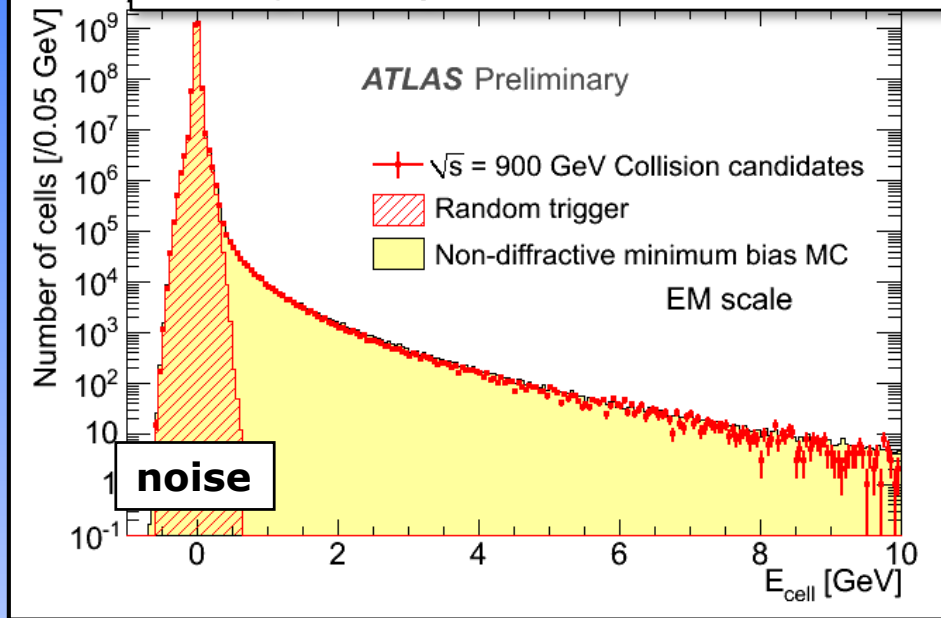
CDF: $260 \text{ GeV} < M_{q^*} < 870 \text{ GeV}$

A conceptual image showing a globe constructed from dark grey puzzle pieces. One piece is missing from the lower-left quadrant, revealing a white background. Several other puzzle pieces are scattered on the light blue-grey surface to the right of the globe. The text 'The Standard Model' is centered on the globe's surface.

The Standard Model

Missing transverse energy

Energie depositie in Calorimeter

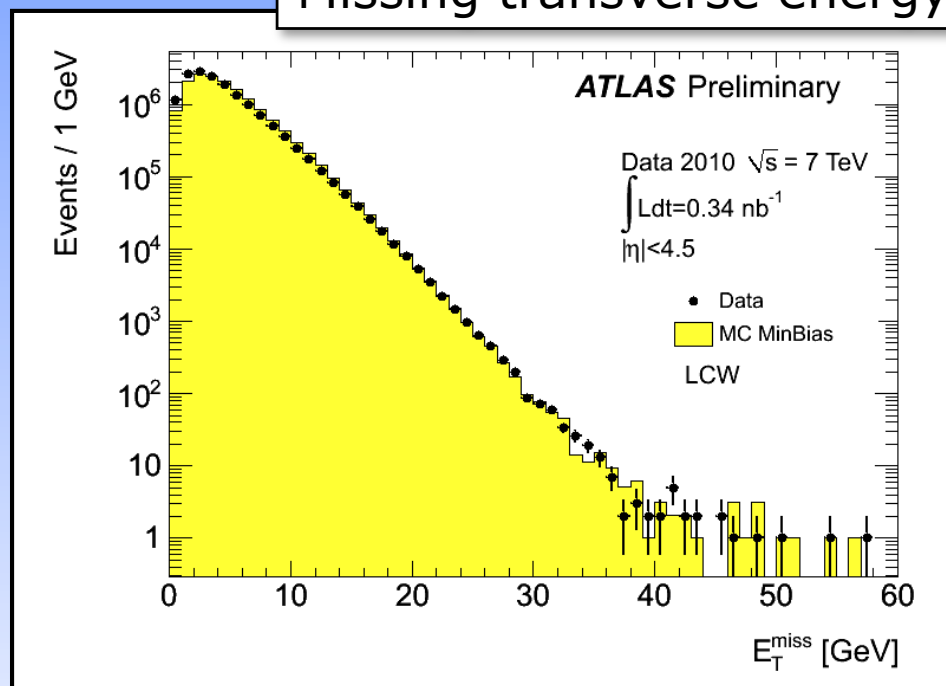


Impuls/energie behoud in xy-vlak. Inbalans wijst op:

- 1) 'ruis' van bekende effecten: materiaal, resolutie etc etc.
- 2) Een deeltje dat niet met materie interageert is ontsnapt: neutrino ... of donkere materie deeltje
- 3) ... of je detector doet het niet

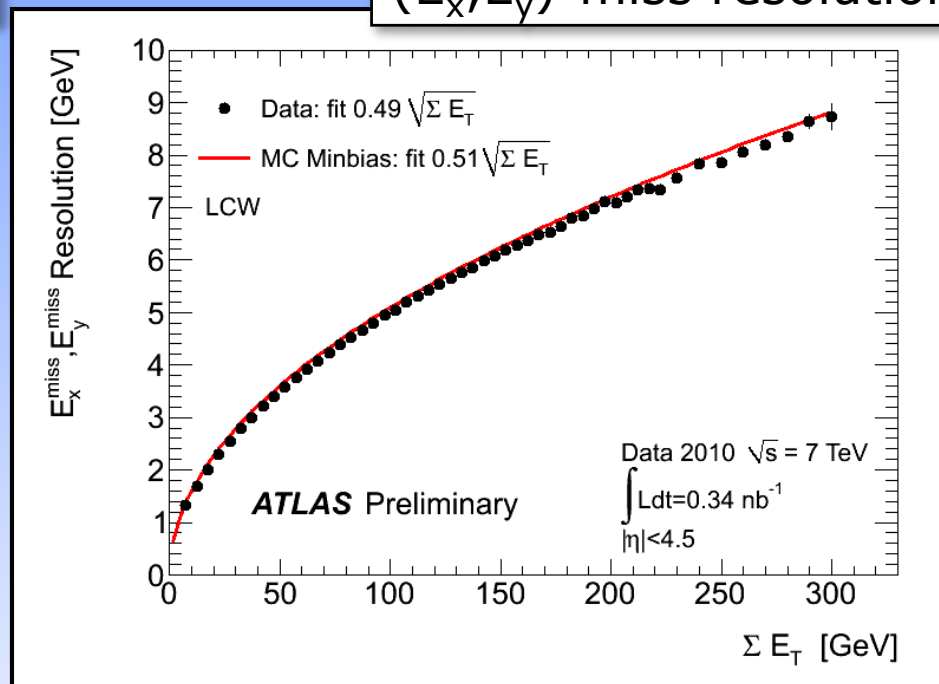
Missing transverse energy

Missing transverse energy



Tails under control

(E_x, E_y) -miss resolution



Resolution as expected

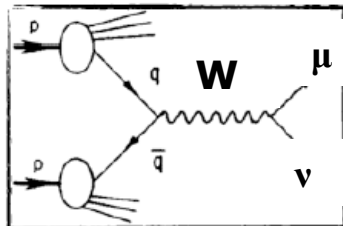
Run: 152845, Event: 3338173
Date: 2010-04-12 16:56:44 CEST



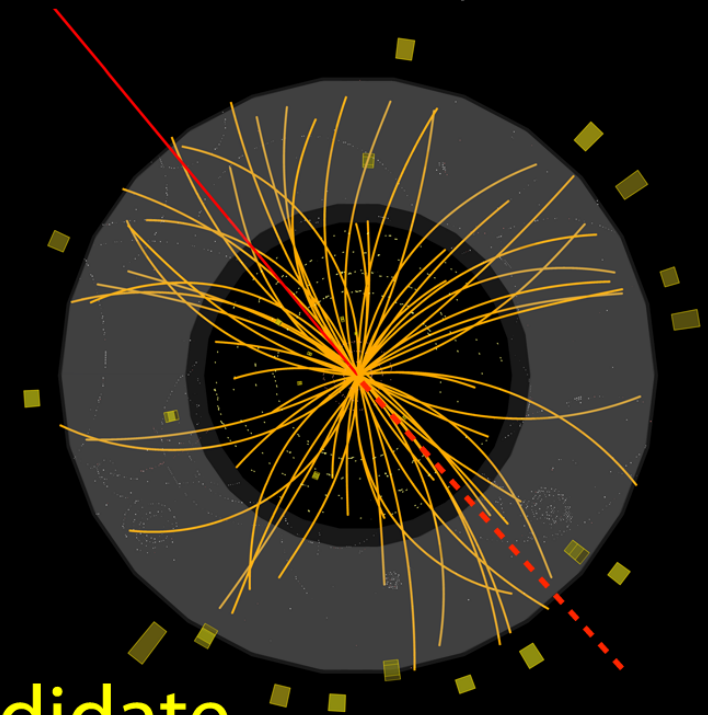
ATLAS EXPERIMENT

$p_T(\mu^-) = 40 \text{ GeV}$
 $\eta(\mu^-) = 2.0$
 $E_T^{\text{miss}} = 41 \text{ GeV}$
 $M_T = 83 \text{ GeV}$

W bosonen:

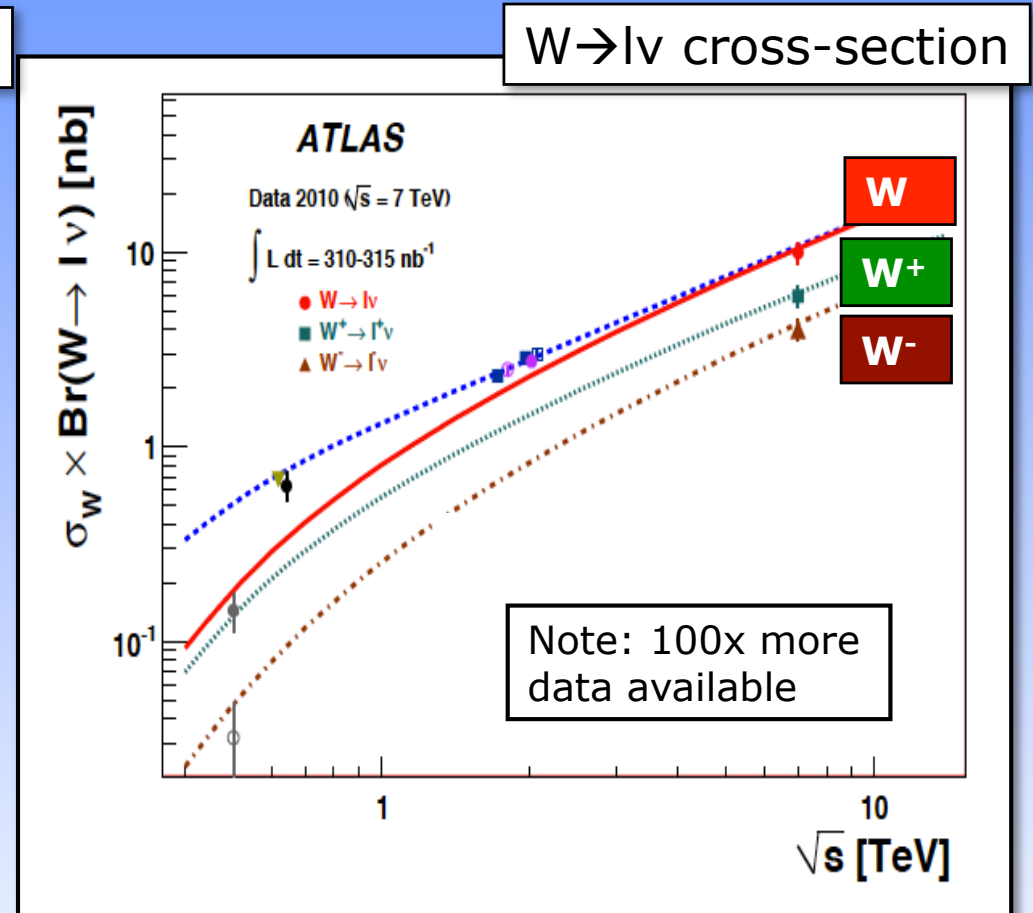
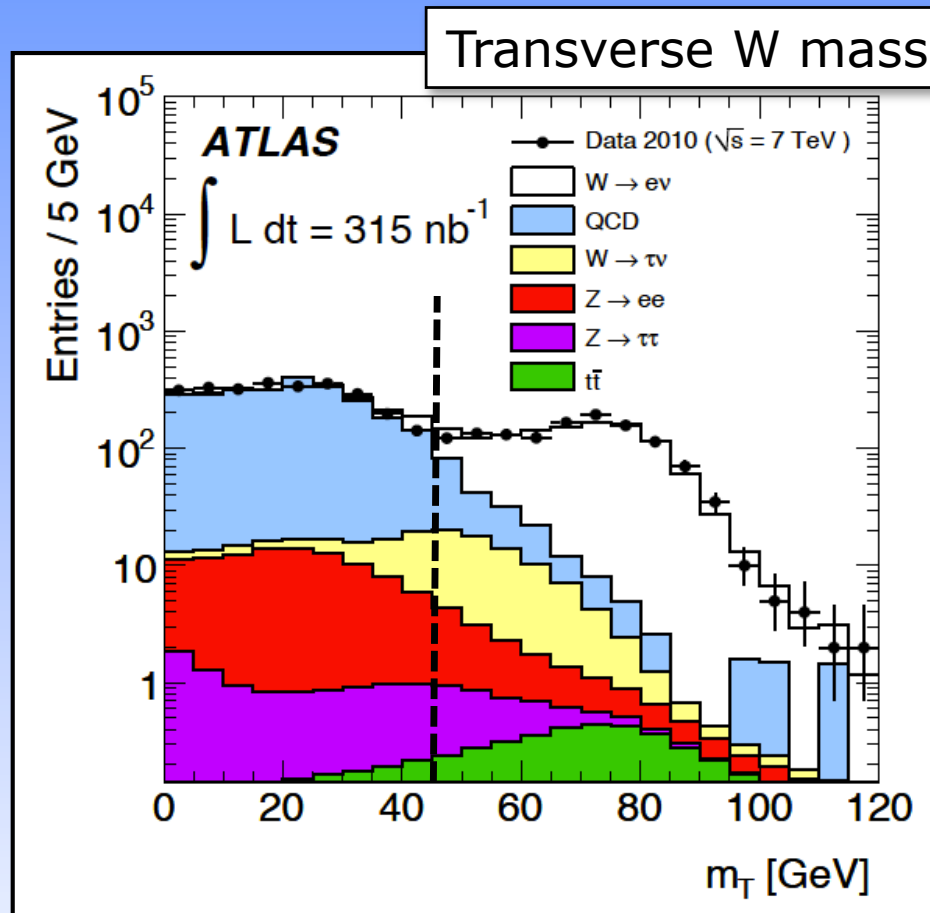


**$W \rightarrow \mu\nu$ candidate
in 7 TeV collisions**



Selecting leptonic W-boson decays:

Lepton + missing energy (neutrino)

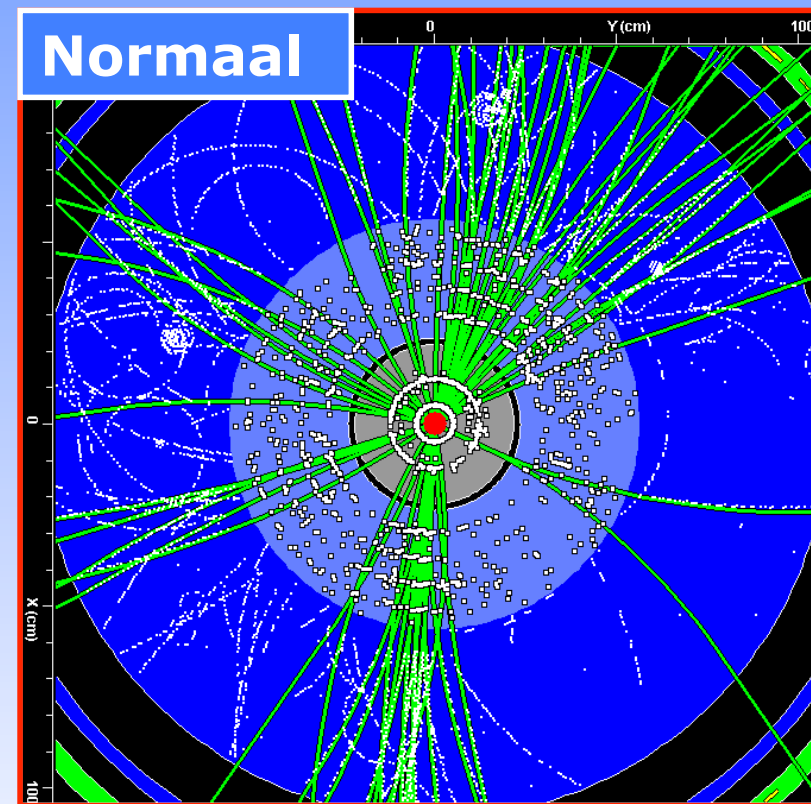
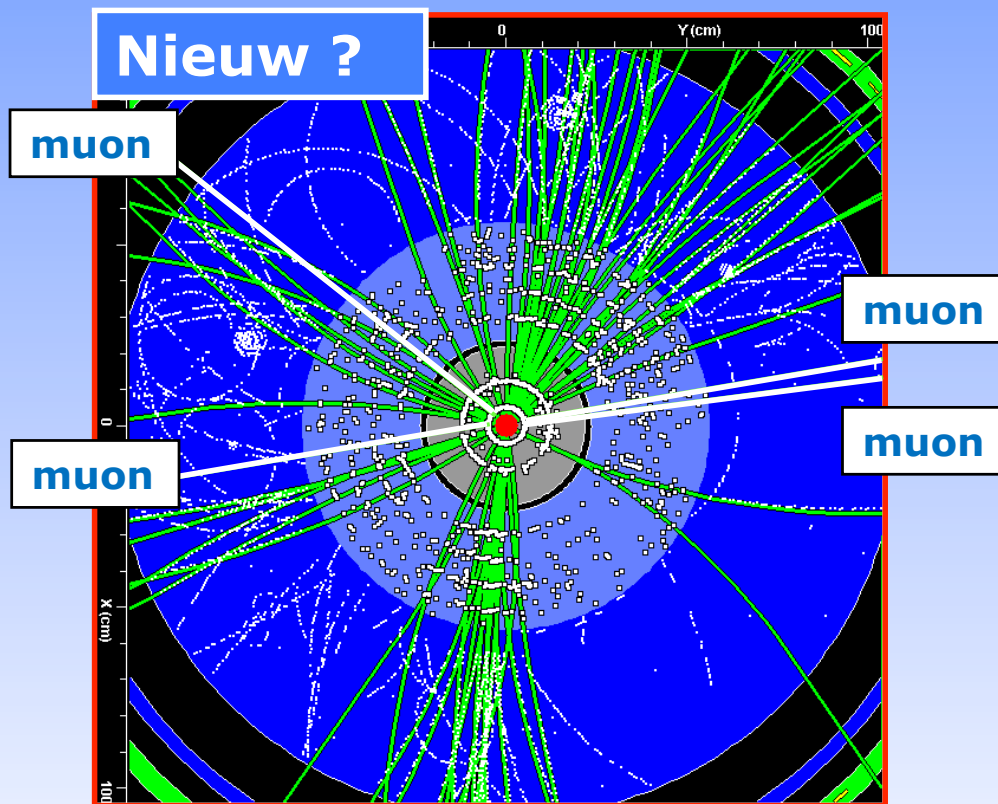


$$\sigma_W^{\text{tot}} \cdot \text{Br}(W \rightarrow l\nu) = 9.96 \pm 0.23(\text{stat}) \pm 0.50(\text{syst}) \pm 1.10(\text{lumi}) \text{ nb}$$

Nieuwe fysica

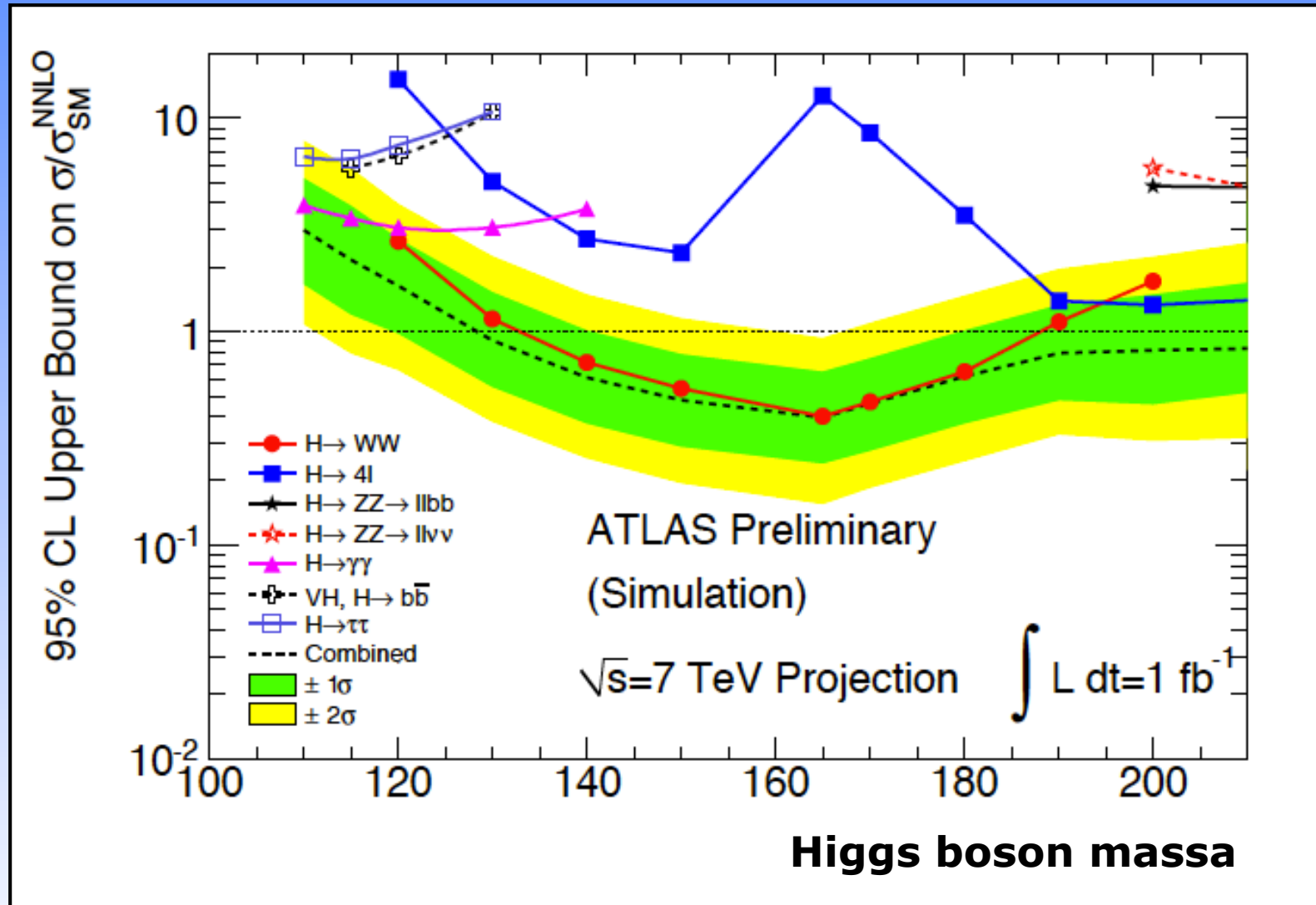
Hoe ontdek je nou nieuwe dingen: Higgs boson

Nieuwe afstandschaal EN nieuwe detector



Ja ... Higgs is het wel

Higgs boson: wat kunnen we dit jaar verwachten



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The ATLAS collaboration



The Standard Model

De ATLAS detector doet het fantastisch

Stortvloed SM metingen

Op zoek naar rare dingen in 2011