

Zoektocht naar de elementaire bouwstenen van de natuur



Volksuniversiteit Soest, 14 februari 2012

Ivo van Vulpen

CERN



Mijn oude huis

ATLAS detector

Anti-materie

Vergaderen

- Waarom deeltjesfysica en grote versnellers
 - Wat weten we al
 - Wat willen we nog meer weten
- CERN & de LHC
 - Wat komt er bij kijken
 - Wat hopen we te vinden

Het grootste en het kleinste

... volgens mijn dochter van 3

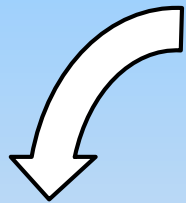
... volgens haar vader



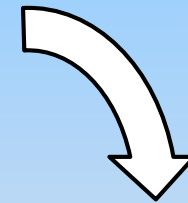
Olifant



Klein muisje



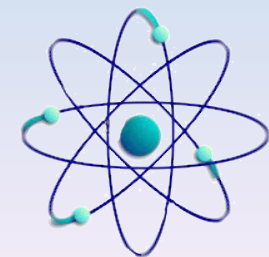
Grootst



Kleinst



10^{+22} m

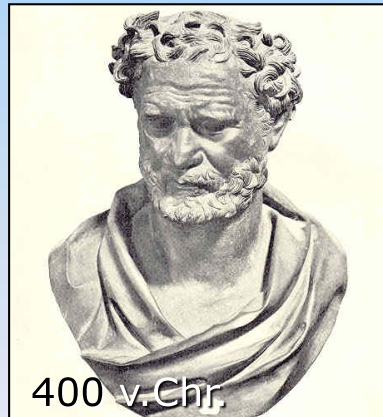


10^{-9} m

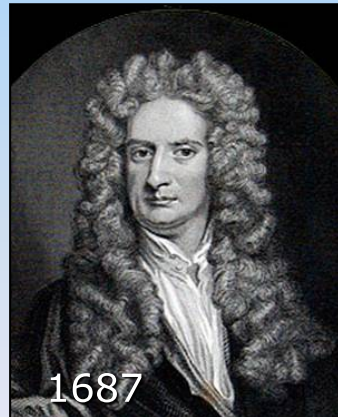
Elementaire deeltjes fysica

Vragen die de mensheid al 2000 jaar bezighouden:

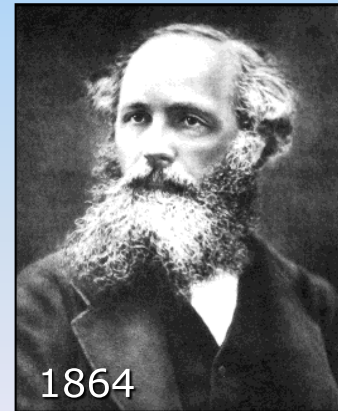
- Wat zijn de bouwstenen van de materie ?
- Welke krachten werken op deze bouwstenen ?



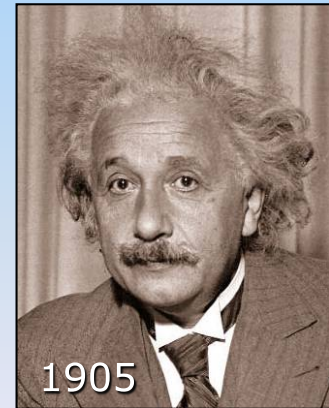
Demokritos
atoom



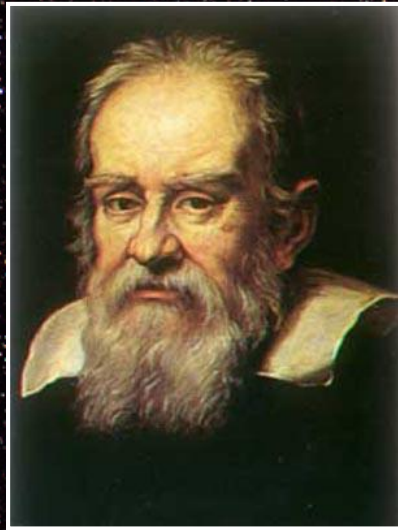
Newton
krachten



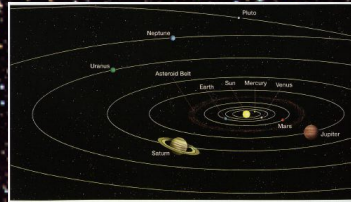
Maxwell
electromagnetisme



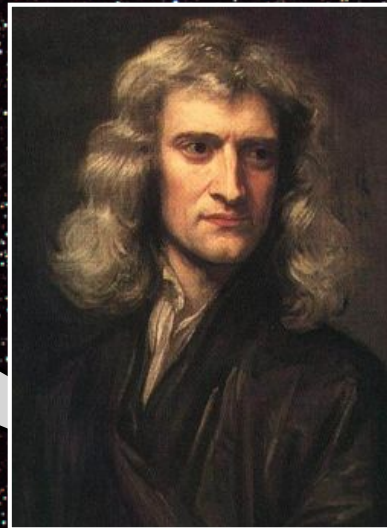
Einstein
van alles...



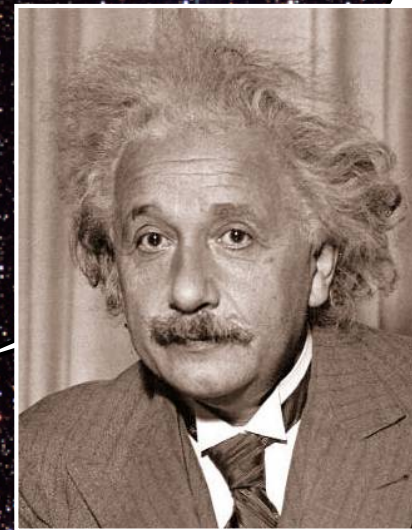
Galileo



Het heelal



Newton

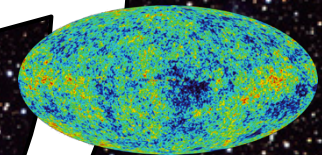


Einstein

$$E=mc^2$$

Albert Einstein, 1905.

Verlinde



Klassieke mechanica ... hoe werkt de natuur

1) Lagrangiaan

$$L = T - V$$

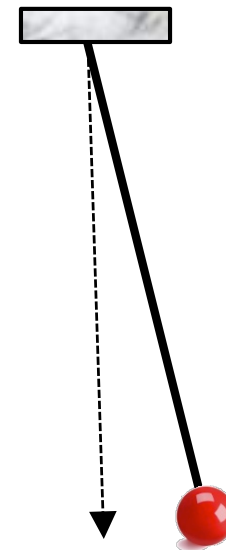
2) Euler-Lagrange vergelijking

$$\frac{d}{dt} \frac{\partial L}{\partial \dot{q}_i} - \frac{\partial L}{\partial q_i} = 0$$

→ bewegingsvergelijking

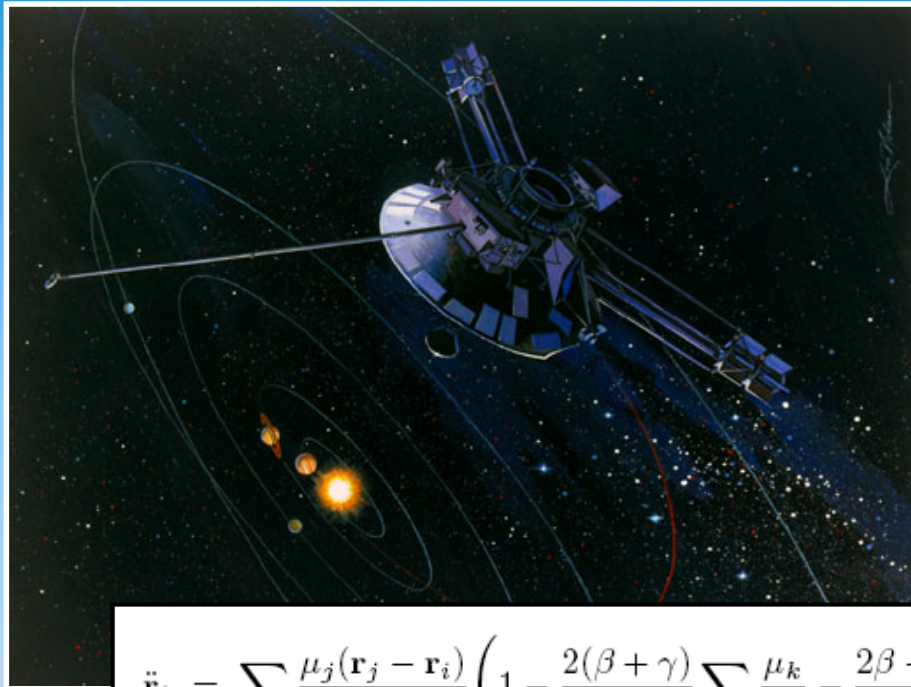
$$T = \frac{1}{2} m (l \dot{\theta})^2$$
$$V = -mgl \cos(\theta)$$

$$\ddot{\theta} - \left(\frac{g}{l}\right) \sin(\theta) = 0$$



de slinger

Klassieke mechanica ... moeilijk zat !



Pioneer ruimtevaartuig

$$\ddot{\mathbf{r}}_i = \sum_{j \neq i} \frac{\mu_j (\mathbf{r}_j - \mathbf{r}_i)}{r_{ij}^3} \left(1 - \frac{2(\beta + \gamma)}{c^2} \sum_{k \neq i} \frac{\mu_k}{r_{ik}} - \frac{2\beta - 1}{c^2} \sum_{k \neq j} \frac{\mu_k}{r_{jk}} - \frac{3}{2c^2} \left[\frac{(\mathbf{r}_j - \mathbf{r}_i) \dot{\mathbf{r}}_j}{r_{ij}} \right]^2 + \frac{1}{2c^2} (\mathbf{r}_j - \mathbf{r}_i) \ddot{\mathbf{r}}_j - \frac{2(1 + \gamma)}{c^2} \dot{\mathbf{r}}_i \dot{\mathbf{r}}_j + \right. \\ \left. + \gamma \left(\frac{v_i}{c} \right)^2 + (1 + \gamma) \left(\frac{v_j}{c} \right)^2 \right) + \frac{1}{c^2} \sum_{j \neq i} \frac{\mu_j}{r_{ij}^3} \left([\mathbf{r}_i - \mathbf{r}_j] \cdot [(2 + 2\gamma) \dot{\mathbf{r}}_i - (1 + 2\gamma) \dot{\mathbf{r}}_j] \right) (\dot{\mathbf{r}}_i - \dot{\mathbf{r}}_j) + \frac{3 + 4\gamma}{2c^2} \sum_{j \neq i} \frac{\mu_j \ddot{\mathbf{r}}_j}{r_{ij}} \quad (3)$$

*Lastige wiskunde en veel rekenen niet belangrijk
.....**inzicht** in de natuurwetten, daar gaat het om!*



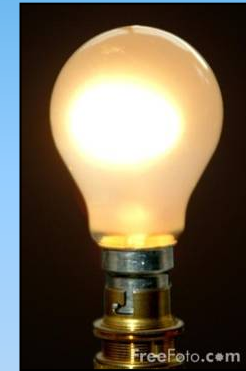
Waarom is de lucht blauw ?

Hoe (lang) brandt de zon ?

Het nut van fundamenteel onderzoek?



"Oneindig veel toegepast onderzoek aan de kaars zou ons nooit het elektrische licht hebben gebracht."

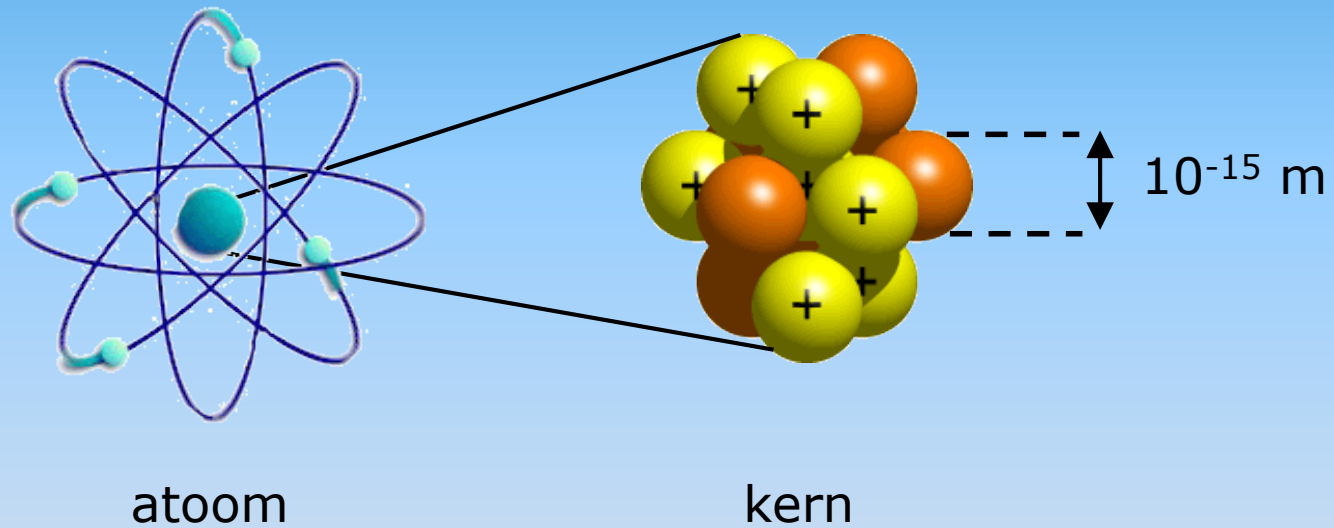


Heeeeeeeel snelle stoomtrein

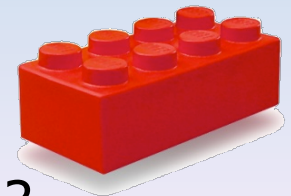


Bugatti Veyron

Deeltjesfysica

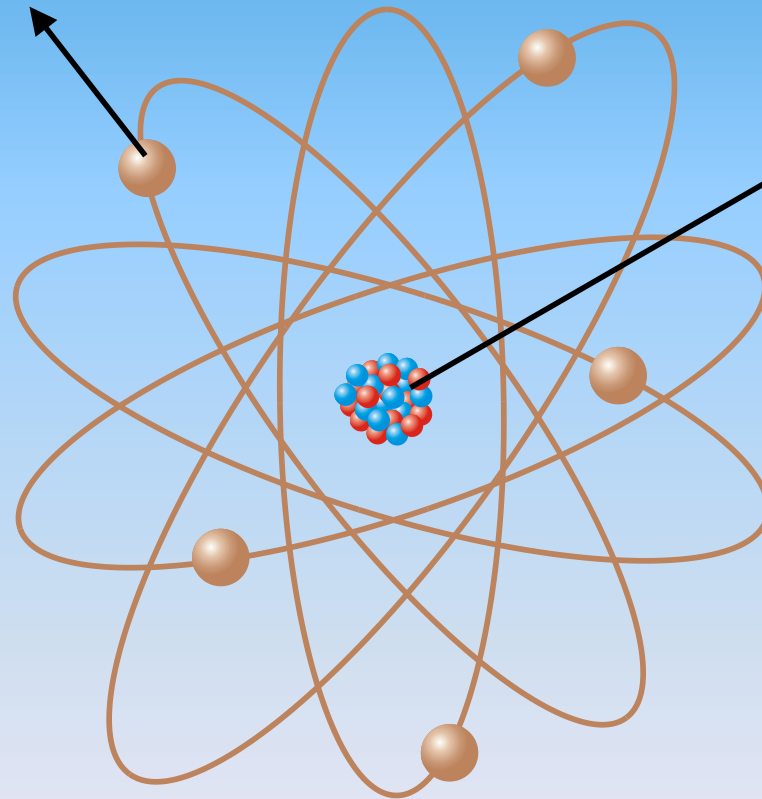


Wat zijn de bouwstenen van de dingen om ons heen ?



Wat waren de problemen 100 jaar geleden ?

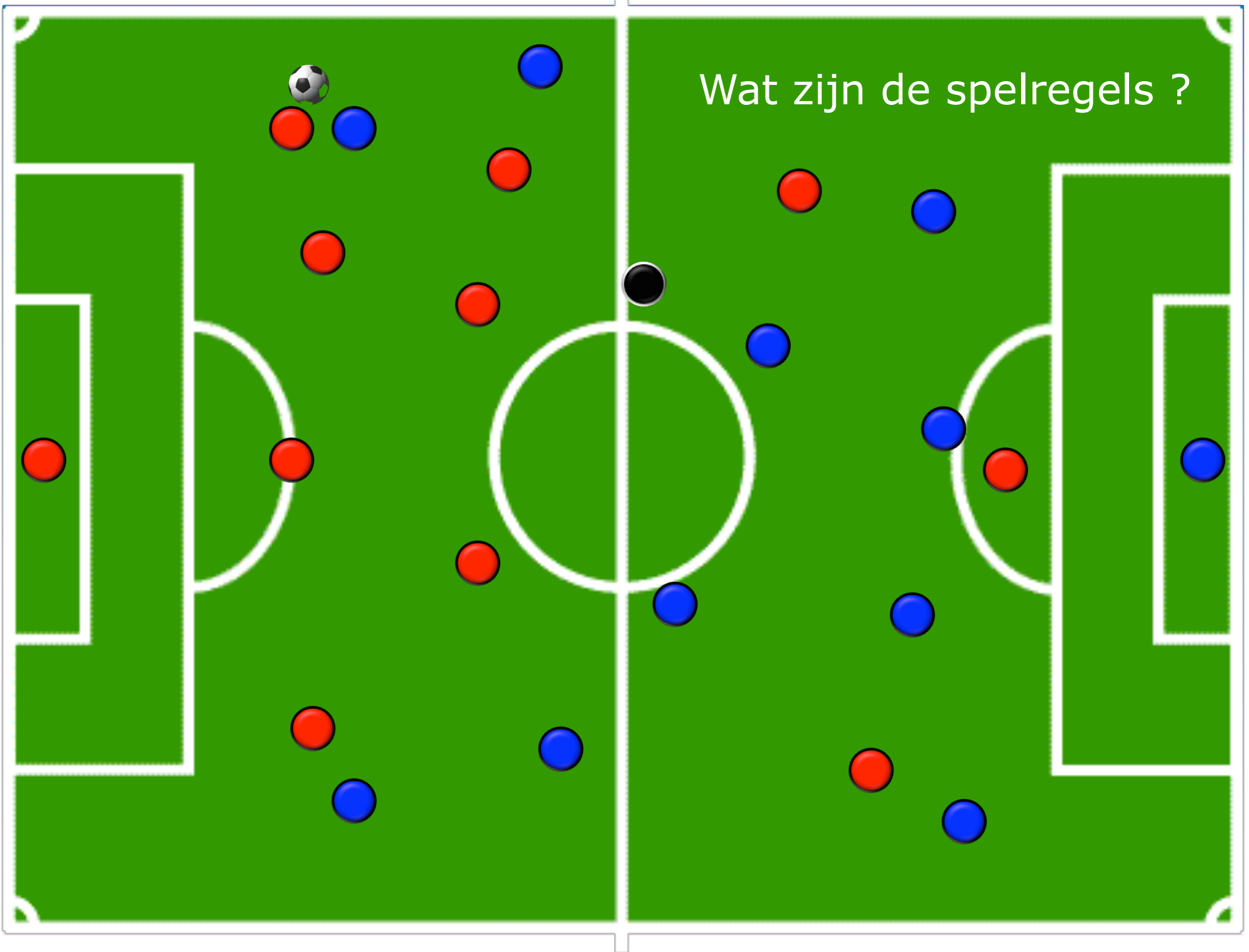
elektron:lading -1



proton:lading +1

Waarom valt het elektron niet op de kern ?

Wat zijn de spelregels ?

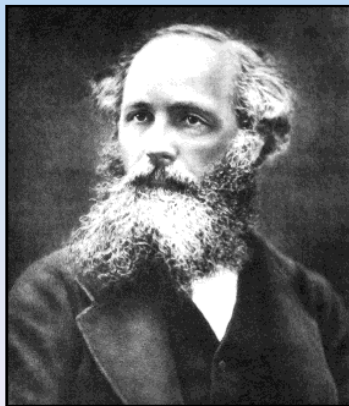


Zwaartekracht en Electromagnetisme

“zelfde krachten ... nieuwe modellen”



Newton



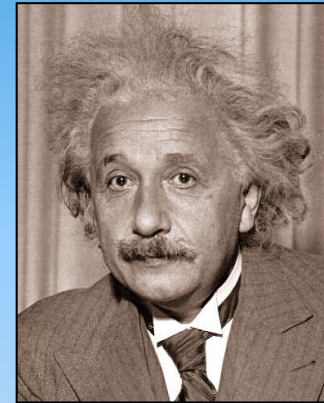
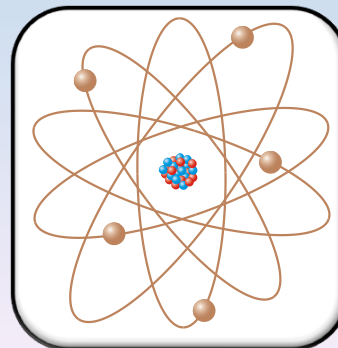
Maxwell



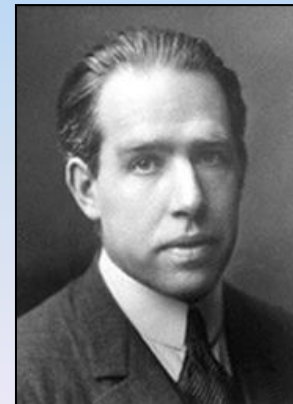
Relativiteitstheorie



Quantummechanica



Einstein



Bohr

Quantummechanica ... nuttig ?

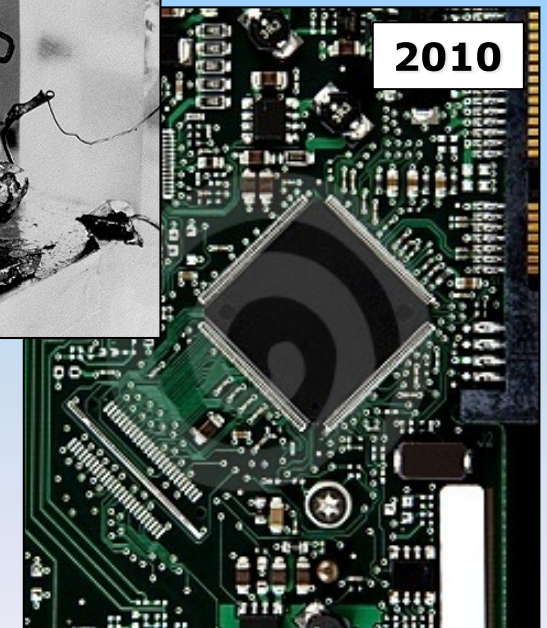
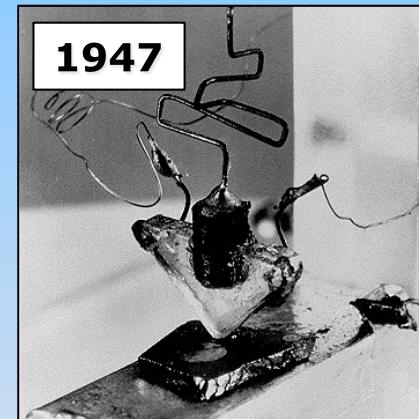
Quantum mechanica ?



Niels Bohr

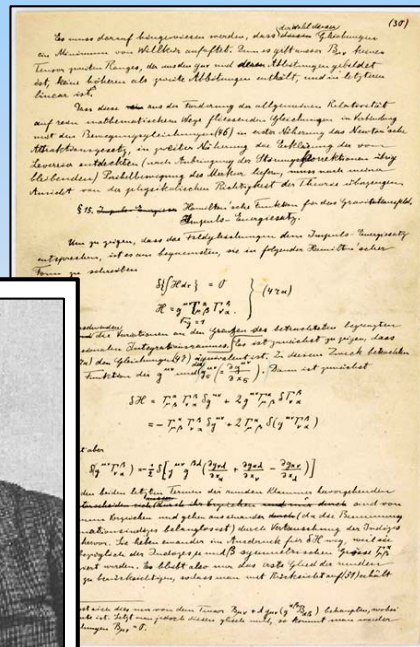
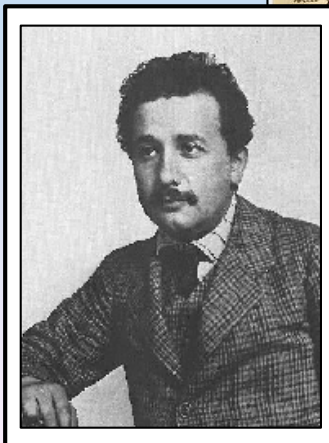


"Quantum mechanica en begrip van atomen cruciaal voor transitors."



Relativiteitstheorie ... nuttig ?

Relativiteitstheorie ?



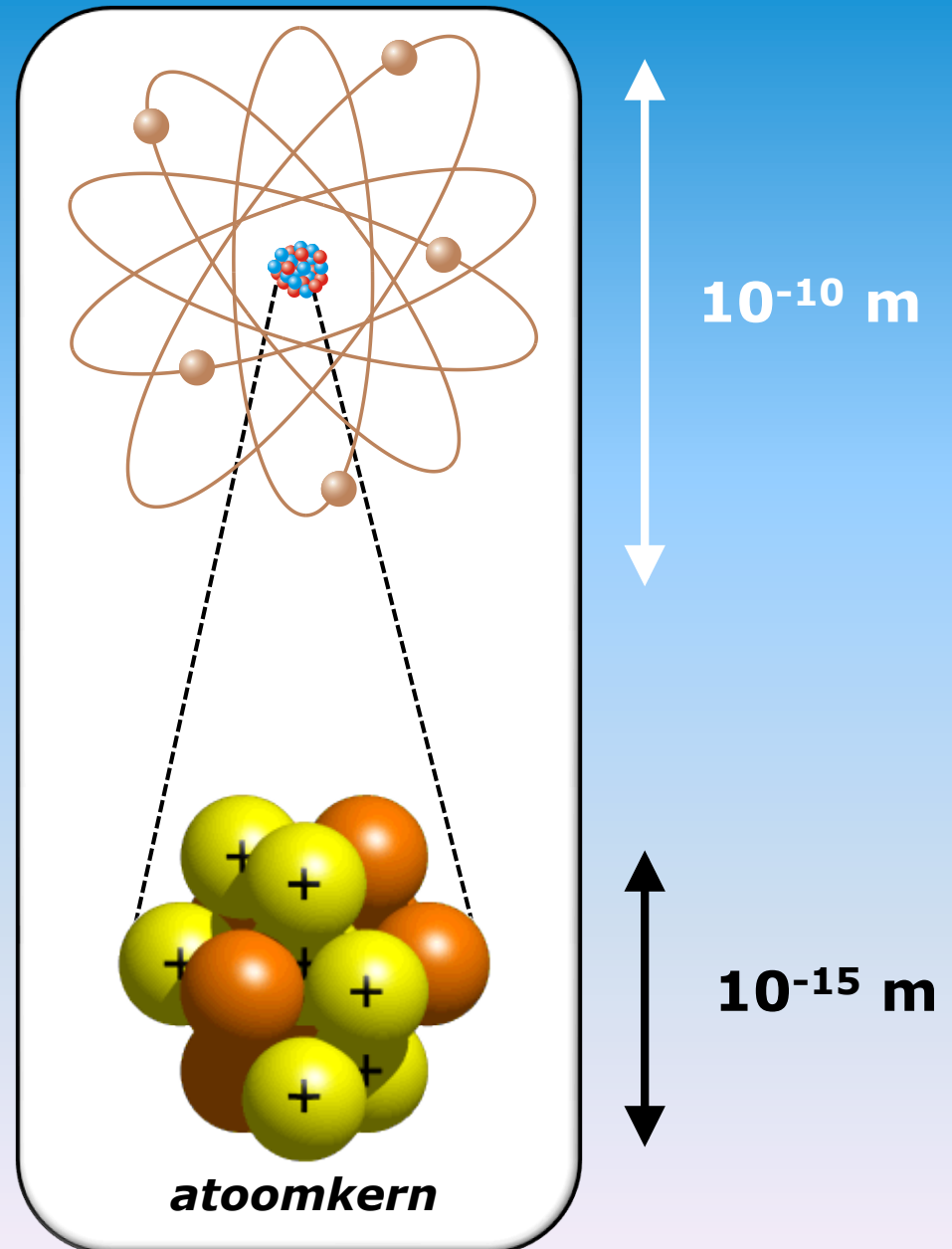
"Zonder relativiteitstheorie zit de GPS er 10 km per dag naast!"

De kernkrachten

- 1] Positieve deeltjes stoten elkaar toch af ?
- 2] Wat houdt de neutrale deeltjes bij elkaar ?

2 nieuwe natuurkrachten:

- zwakke kernkracht
- sterke kernkracht





[1] Wow, mooi ! ... fascinerende complexe patronen !

[2] Gewoon 4 gekleurde draadjes en simpel symmetrisch patroon

De stand van zaken in februari 2012



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

De elementaire deeltjes



up

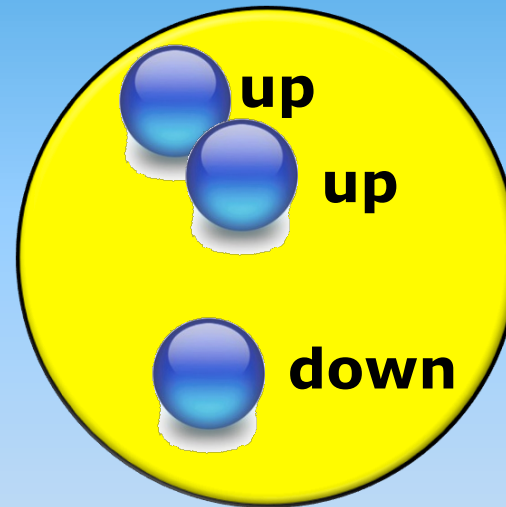


down

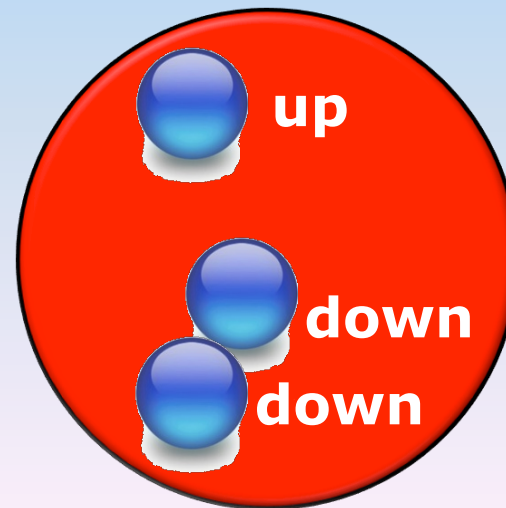


elektron

+ 4 natuurkrachten



Proton



Neutron

Wat kan je maken met deze 3 bouwstenen ?

*periodiek systeem
van Mendeleev*

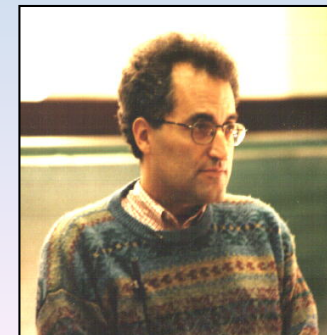
1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	71 Lu	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	103 Lr	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt									
57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb				
89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No				



Alles!



Alles wat we nodig hebben !



Edward Witten

Deeltjes

Krachten

bouwstenen van
proton/neutron

Quarks

Leptons

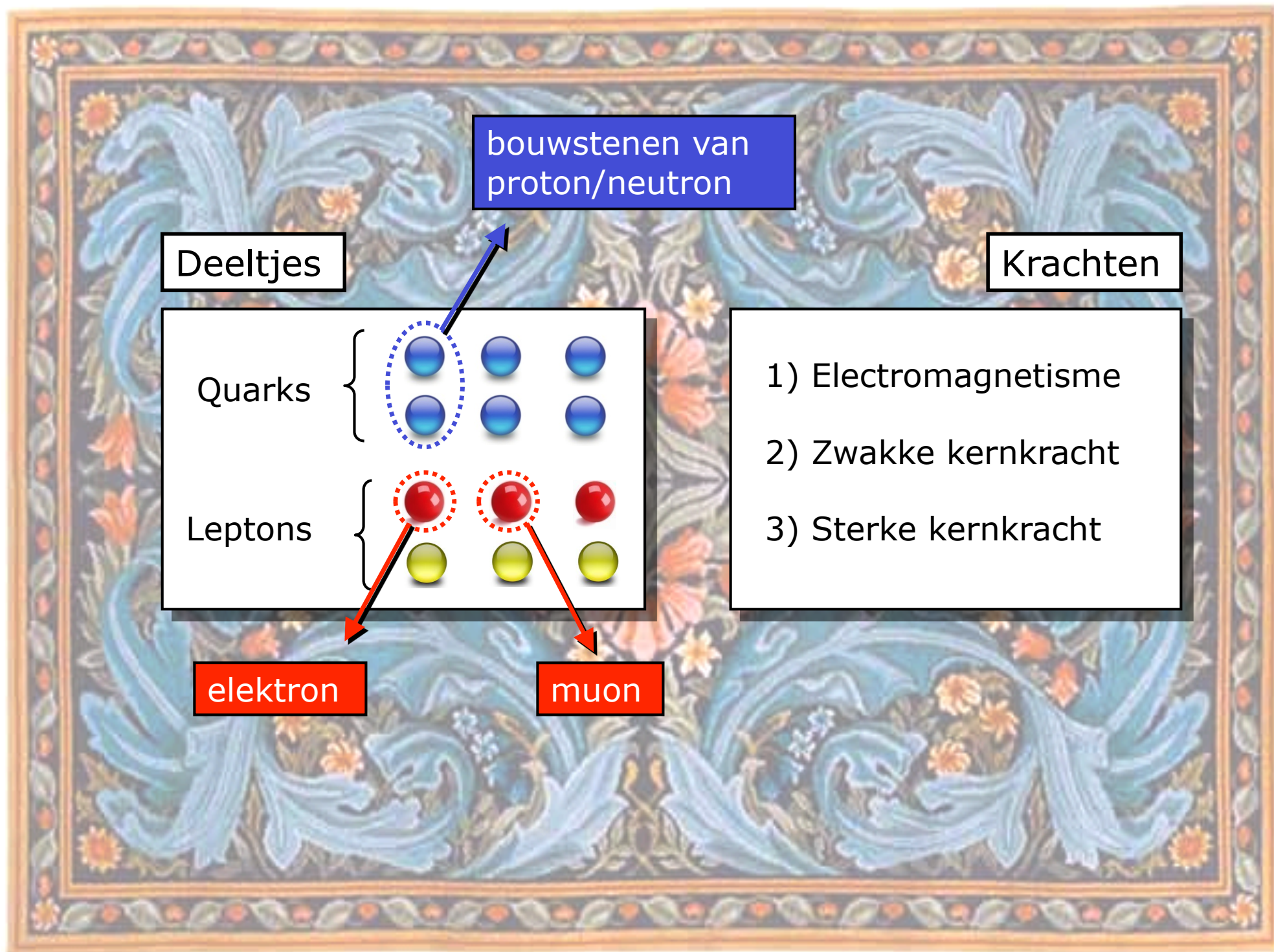
1) Electromagnetisme

2) Zwakke kernkracht

3) Sterke kernkracht

elektron

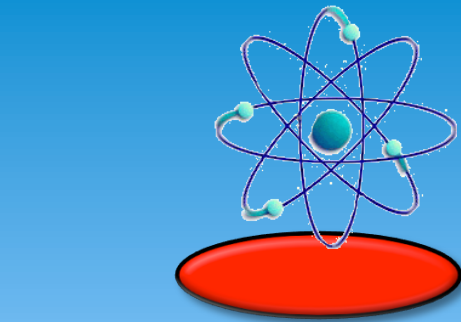
muon



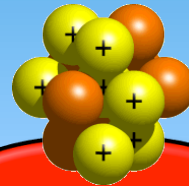
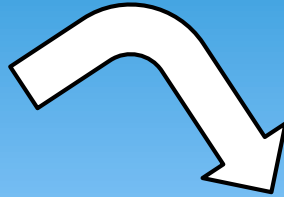
Waar bestaat het heelal uit?



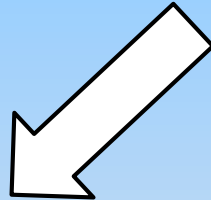
De zoektocht naar de bouwstenen



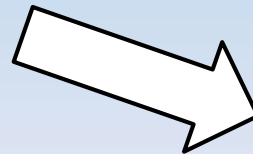
Atoom 10^{-10} m



Atoomkern: 10^{-14} m



Nucleon: 10^{-15} m



10^{-19} m

De Large Hadron Collider

Wat snappen we nog niet:







Revolutie in kosmologie laatste paar jaar
Structuur van het heelal

**Is het volume van heelal eindig en
hoe kan het ooit ontstaan zijn ?**

Is de tijd ooit begonnen ?

... gaan we vandaag niet oplossen



<http://www.shatters.net/celestia/>

"Google earth voor het heelal"

Paar 'kleine' dingetjes:

1

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

2

Waar is alle anti-materie gebleven ?

3

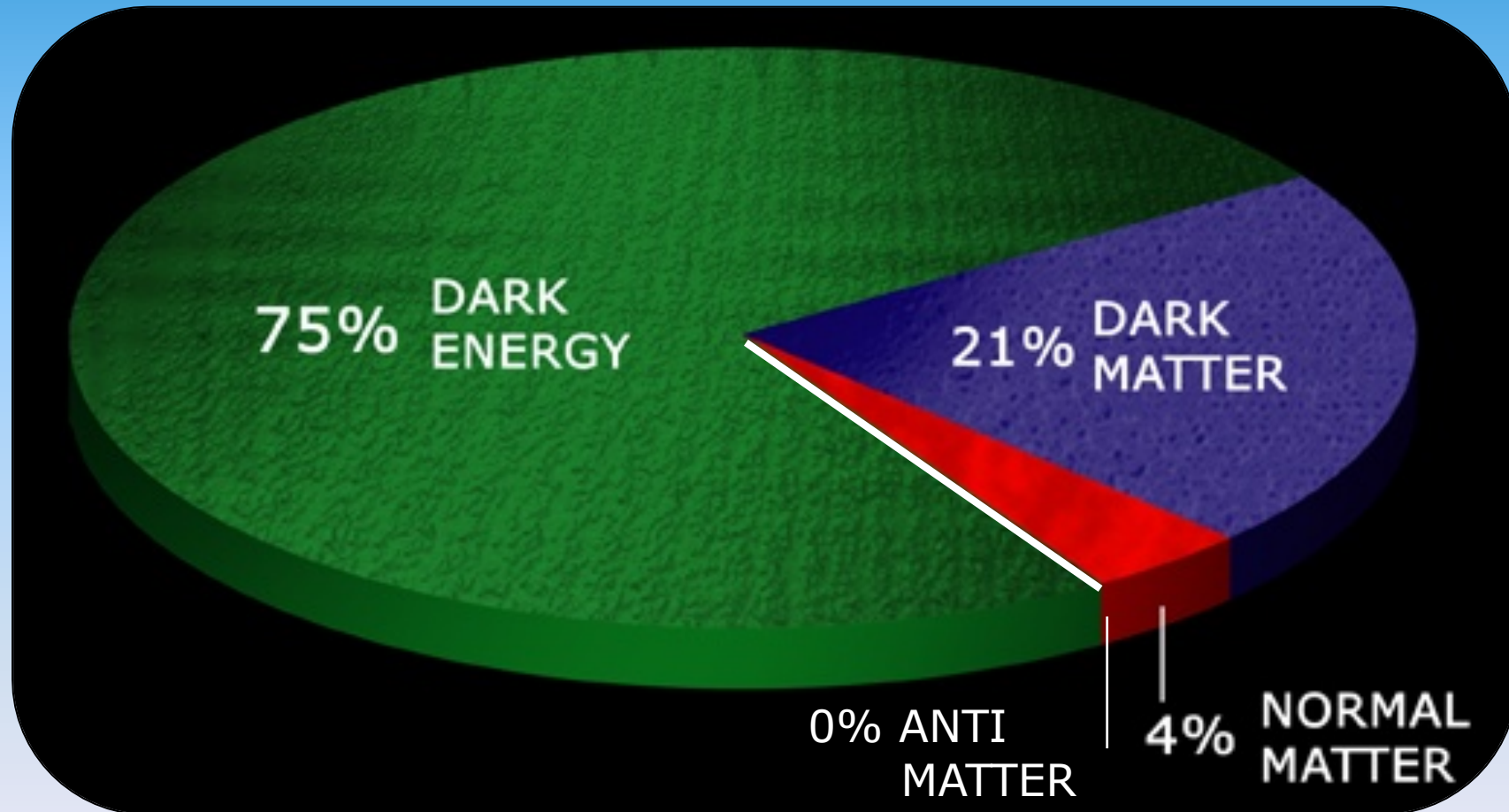
Higgs boson

- 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, ...

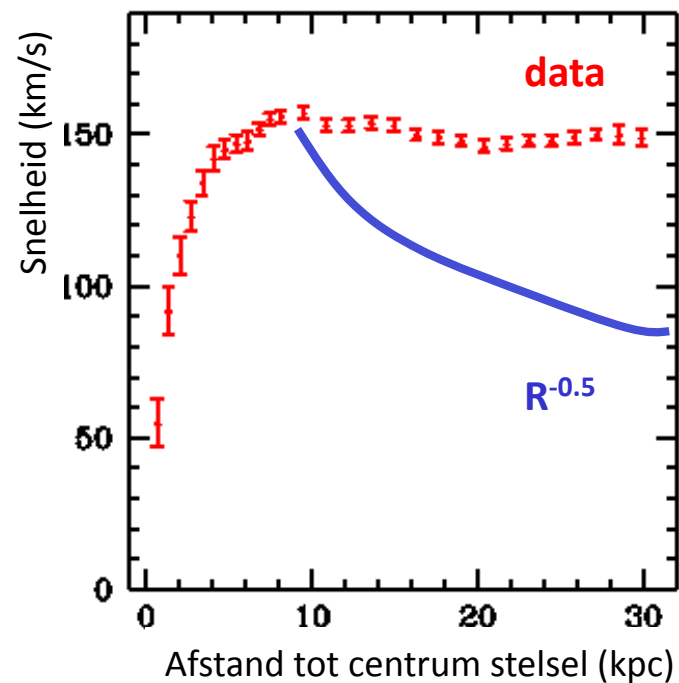
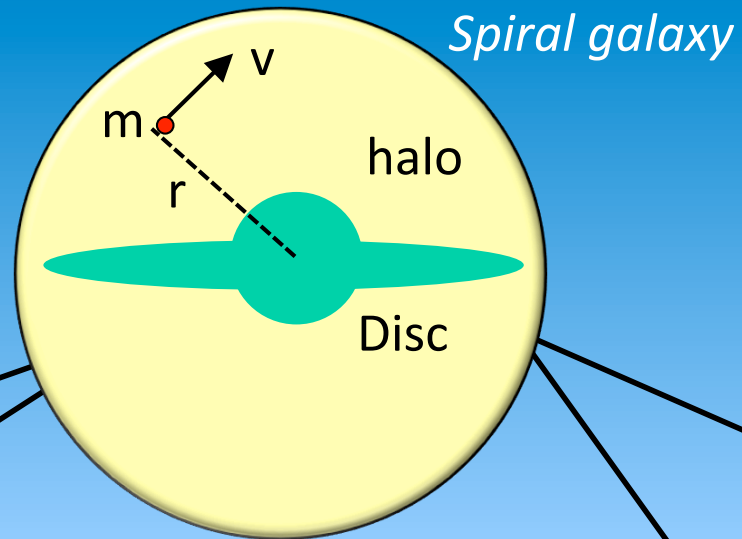
1

Donkere-materie

Waar bestaat het heelal uit?



Slechts 4% is normale materie...



Rotatie

Gravitatie vs centrifugale kracht:

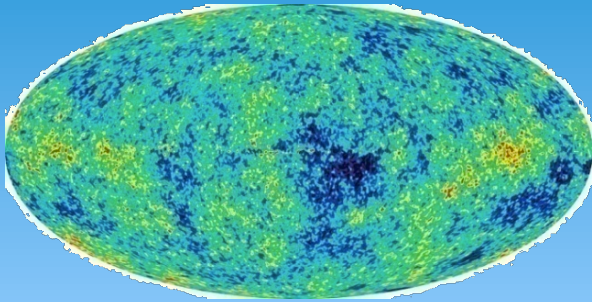
$$\frac{mv^2}{R} = G \frac{mM(R)}{R^2}$$

$$v = \sqrt{\frac{GM(R)}{R}}$$

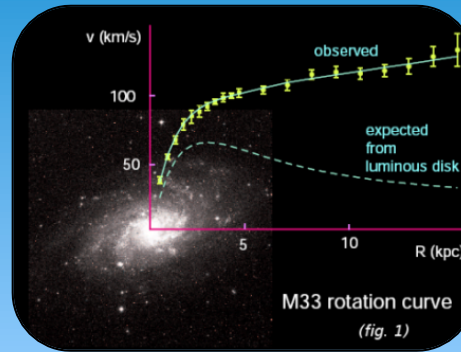
Er is dus meer massa dan we kunnen zien ... donkere materie deeltjes ?

1

Donkere-materie



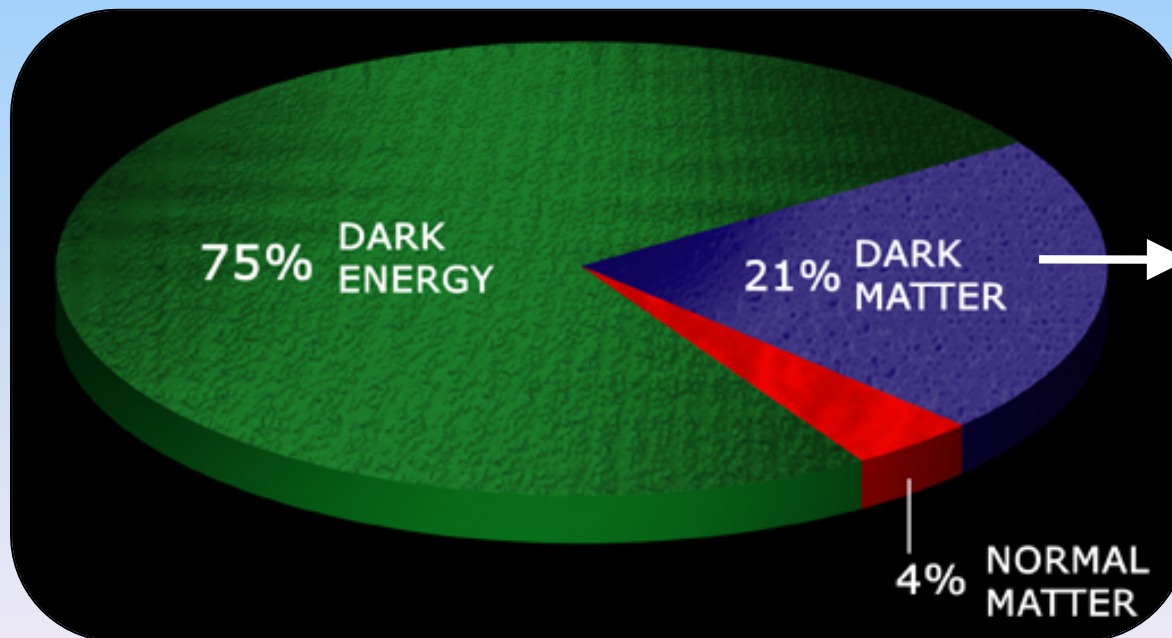
Temperatuurfluctuaties
structuur van het heelal



Rotatie-curves



Cluster formaties &
gravitationele lens



Wat is de
donkere materie ?

We hebben al die tijd maar 4% van het heelal bestudeerd!

2

Anti-materie: waar is het gebleven ?

Nieuwe fenomenen: anti-materie



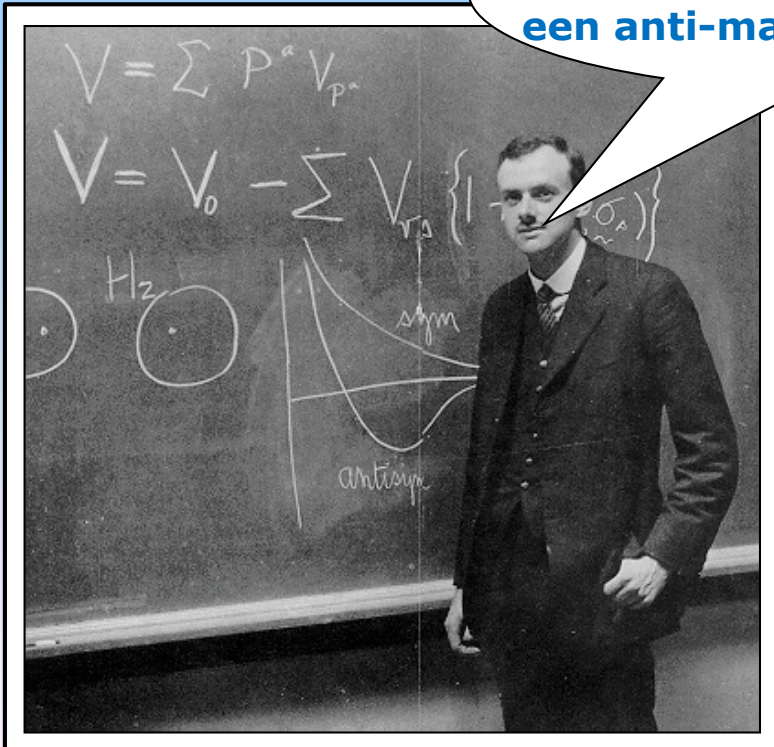
Mooie een-twee'tje theorie-experiment

- Revoluties begin vorige eeuw:
Relativiteitstheorie & Quantum Mechanica
- Paul Dirac (1928):
Relativistische quantum theorie!

Dirac vergelijking

$$(i\gamma_\mu \partial^\mu - m) \psi = 0$$

**Voor elk materiedeeltje bestaat
een anti-materiedeeltje!**



Anti-materie deeltje:

- Zelfde massa
- Tegenovergestelde lading

Materie



up



down



elektron



Anti-materie



anti-up

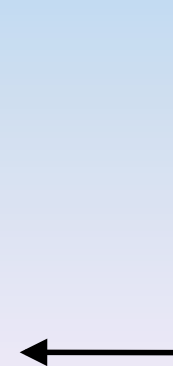


anti-down



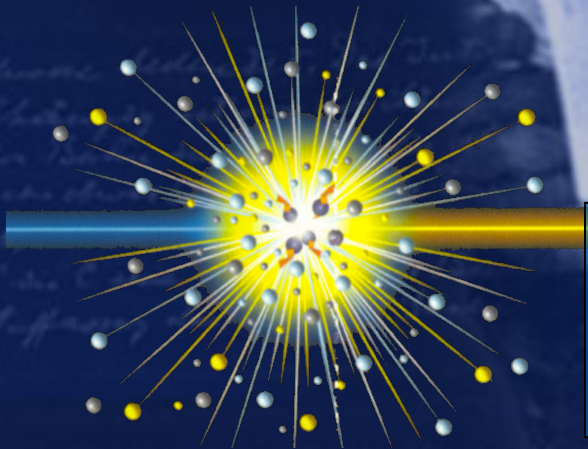
positron

Voorspelling: anti-elektron



Albert Einstein

$$E = mc^2$$



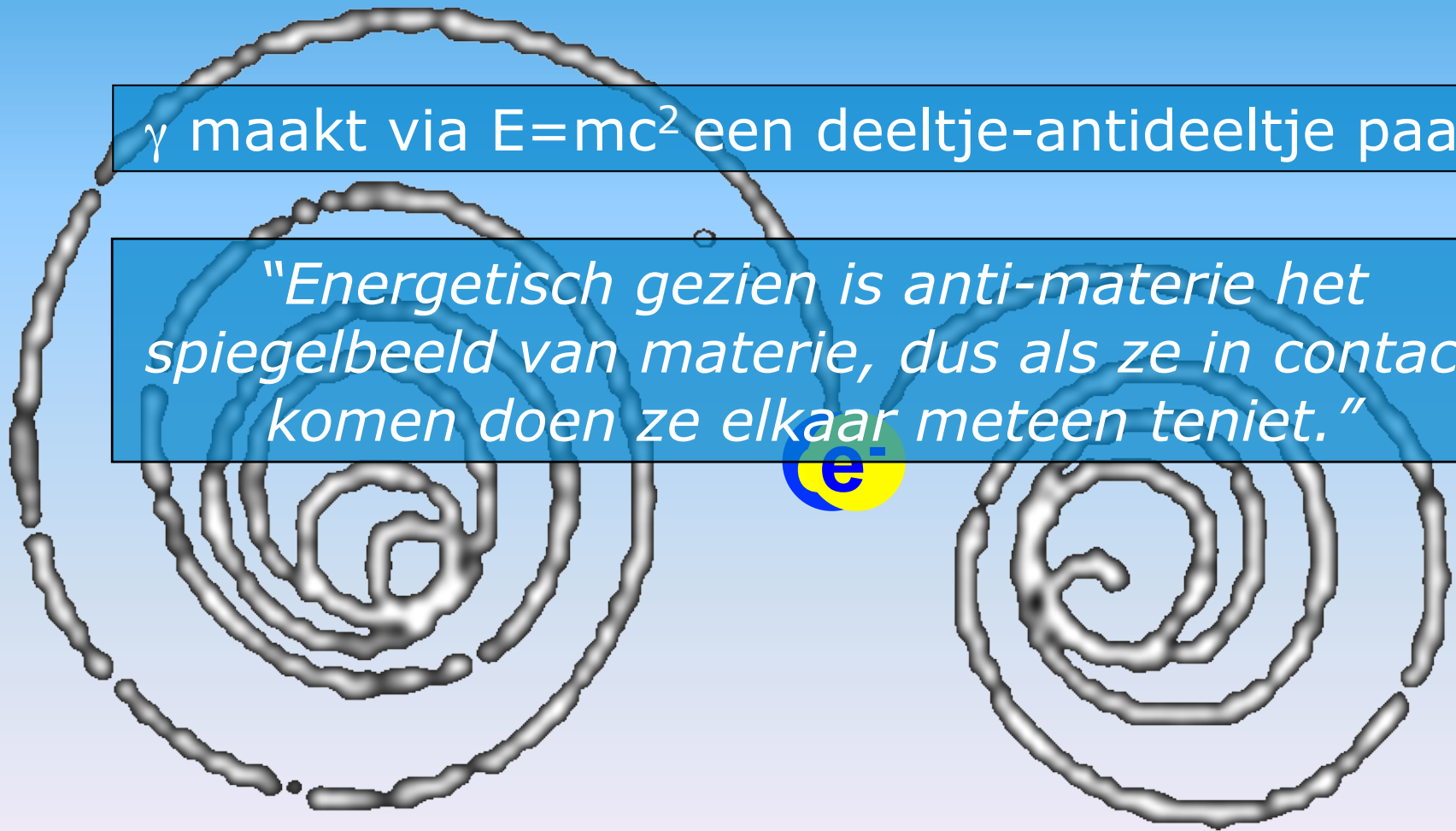
Energie en massa zijn equivalent
→ je kan *nieuwe* deeltjes maken

Anti-materie: $\gamma \rightarrow e^+e^-$



γ maakt via $E=mc^2$ een deeltje-antideeltje paar

"Energetisch gezien is anti-materie het spiegelbeeld van materie, dus als ze in contact komen doen ze elkaar meteen teniet."



Anti-materie: $\gamma \rightarrow e^+e^-$

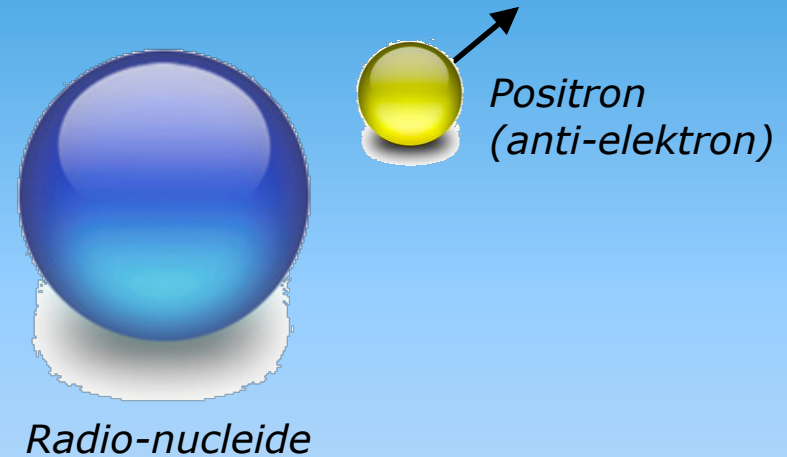


Deeltje-antideeltje paar maakt via $E=mc^2$ een γ

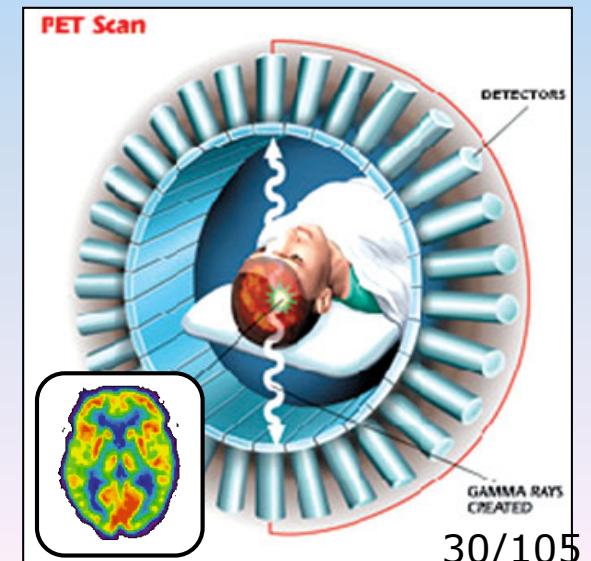
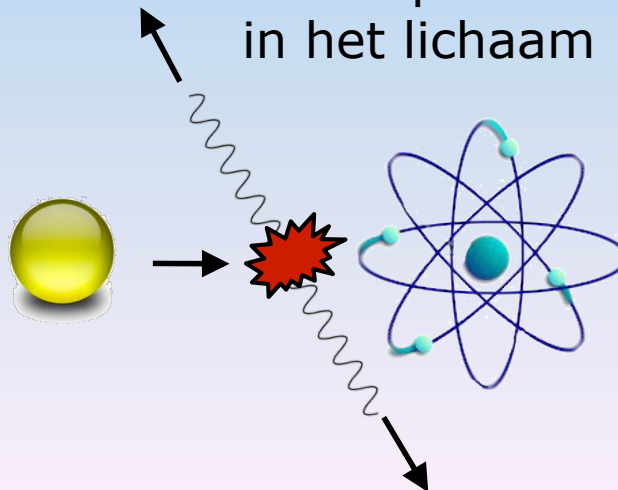


Anti-materie in het ziekenhuis: de PET scan

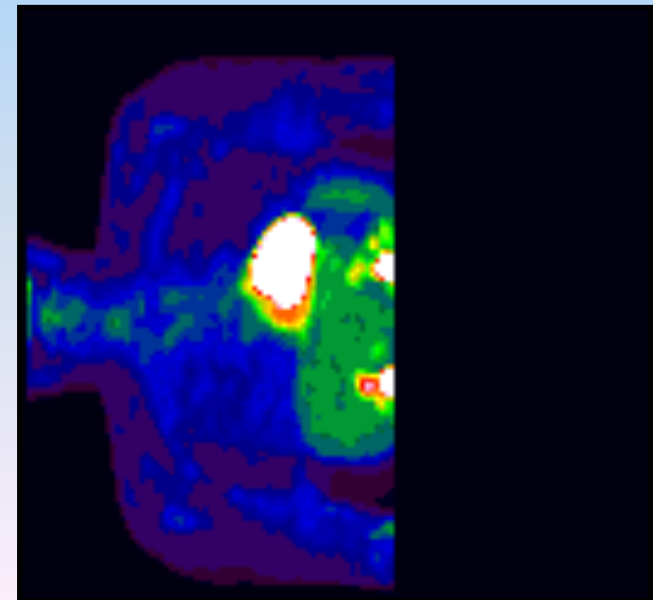
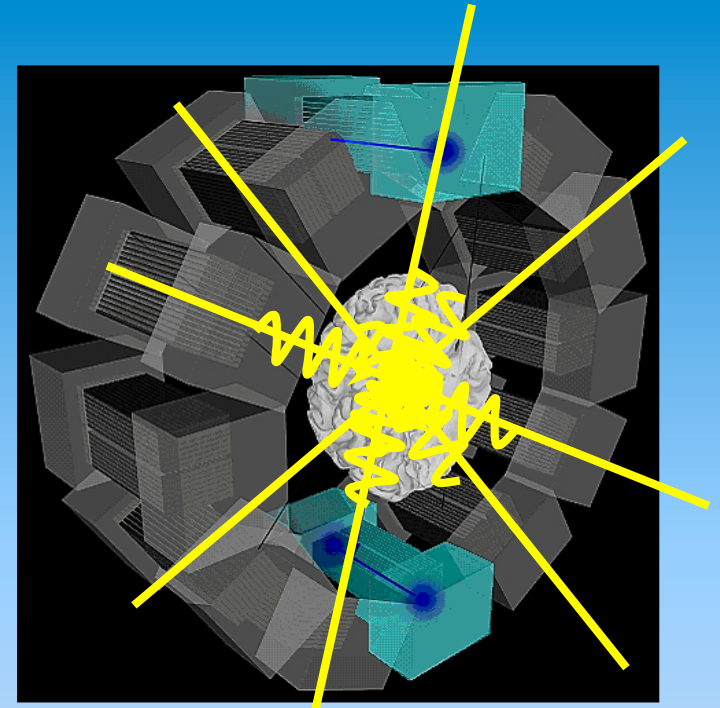
- 1) Injectie met radio-nuclide stof
→ zendt positronen uit



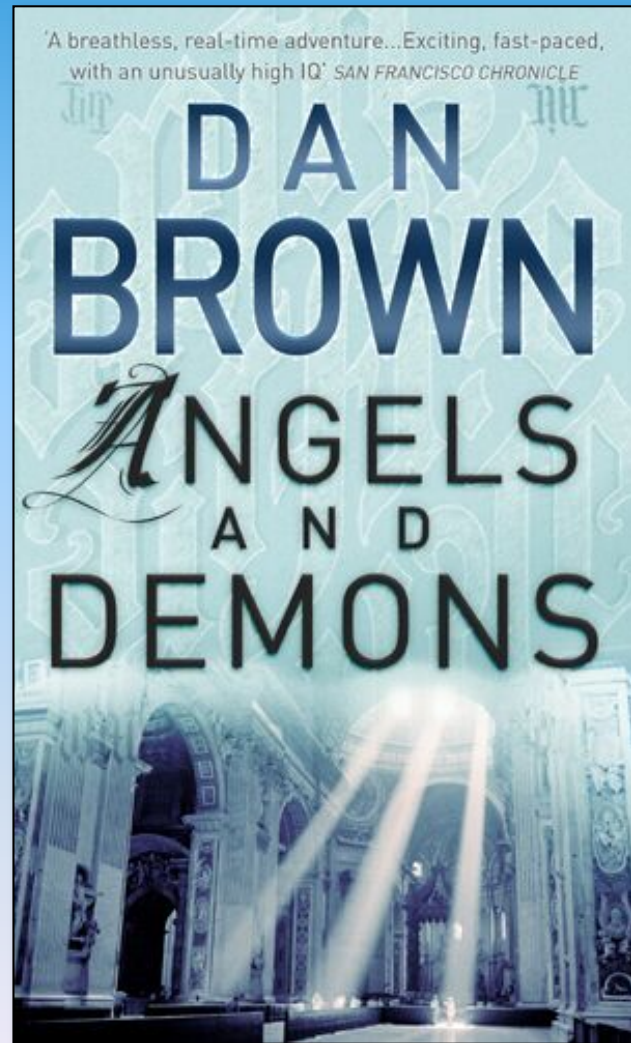
- 2) positron
botst op elektron van atoom
in het lichaam → 2 fotonen



Positron Emissie Tomografie



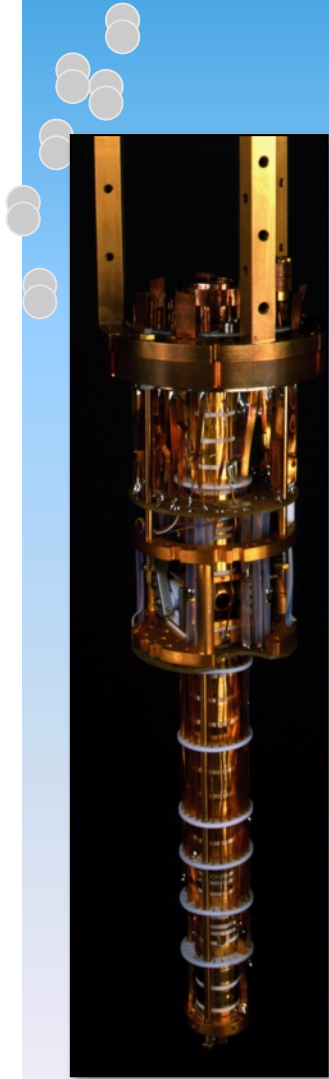
Dan Brown



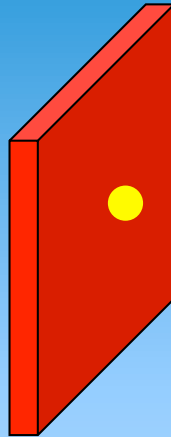
1/4 gram anti-protonen van CERN gestolen

Gebruik om het Vaticaan op te blazen

Productie van anti-waterstof: CERN vs Angels&Demons



CERN

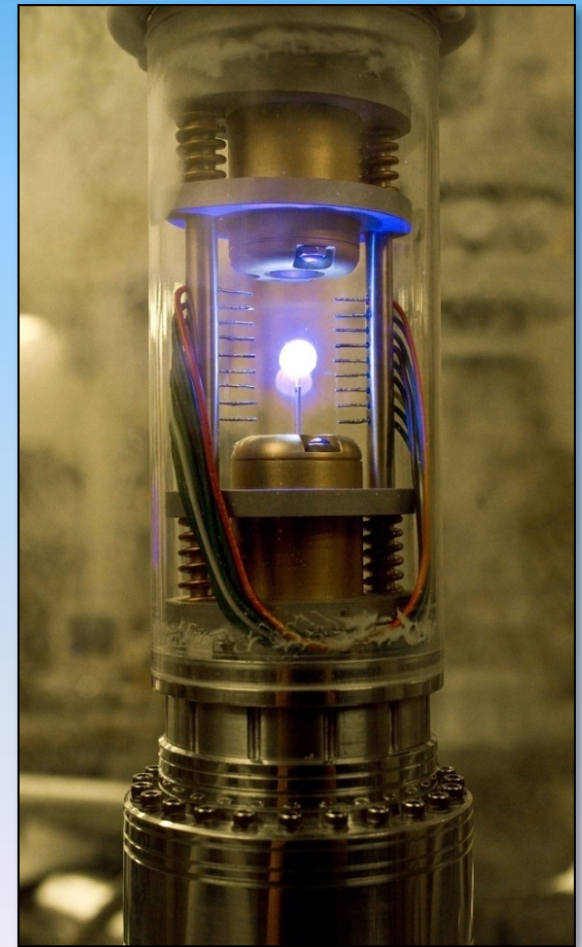


CERN kan 10 miljoen anti-protonen per seconde maken!

1 gram protonen ~
602,214,150,000,000,000,000,000

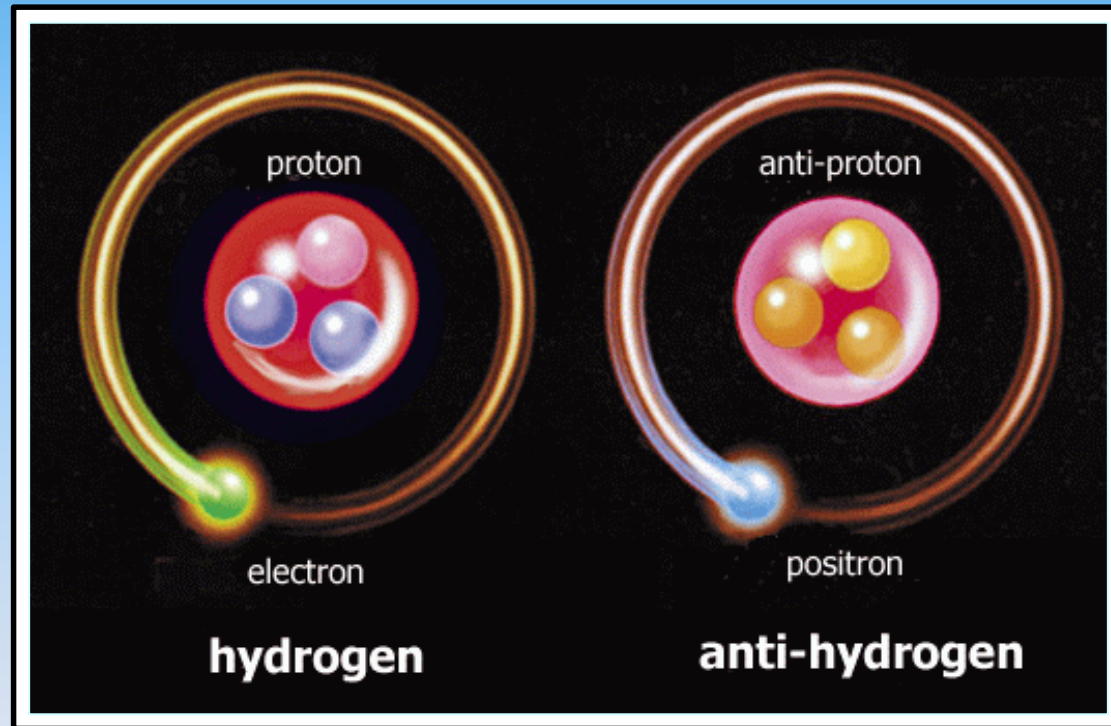
Hoe lang duurt het om $\frac{1}{4}$ gram anti-protonen te maken ?

~ $\frac{1}{2}$ miljard jaar !



Dan Brown

Van anti-deeltjes naar anti-materie → anti-waterstof



1995: Eerste anti-waterstof geproduceerd op CERN

2002: Duizenden anti-atomen geproduceerd op CERN en Fermilab

De elementaire deeltjes



up



charm



top



down



strange



bottom



elektron



muon



tau



neutrino



neutrino



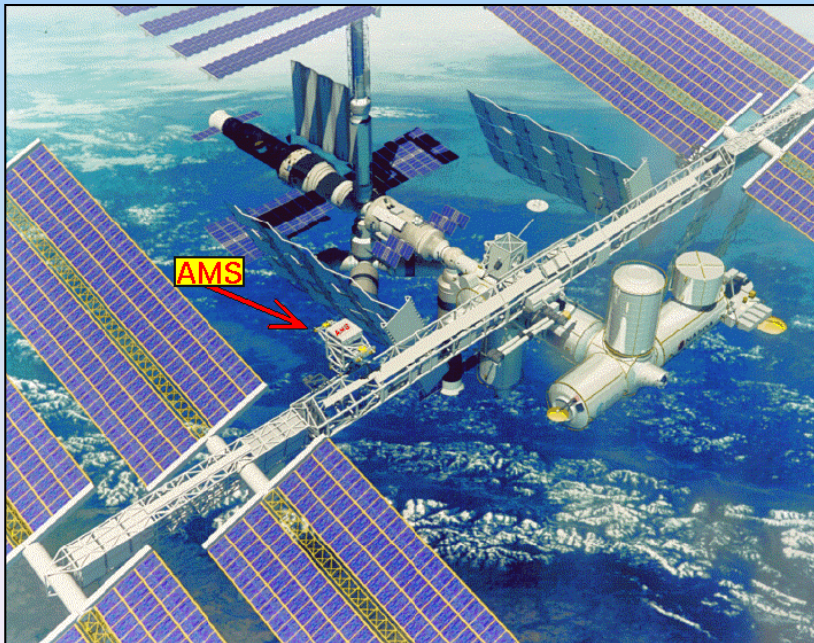
neutrino

2

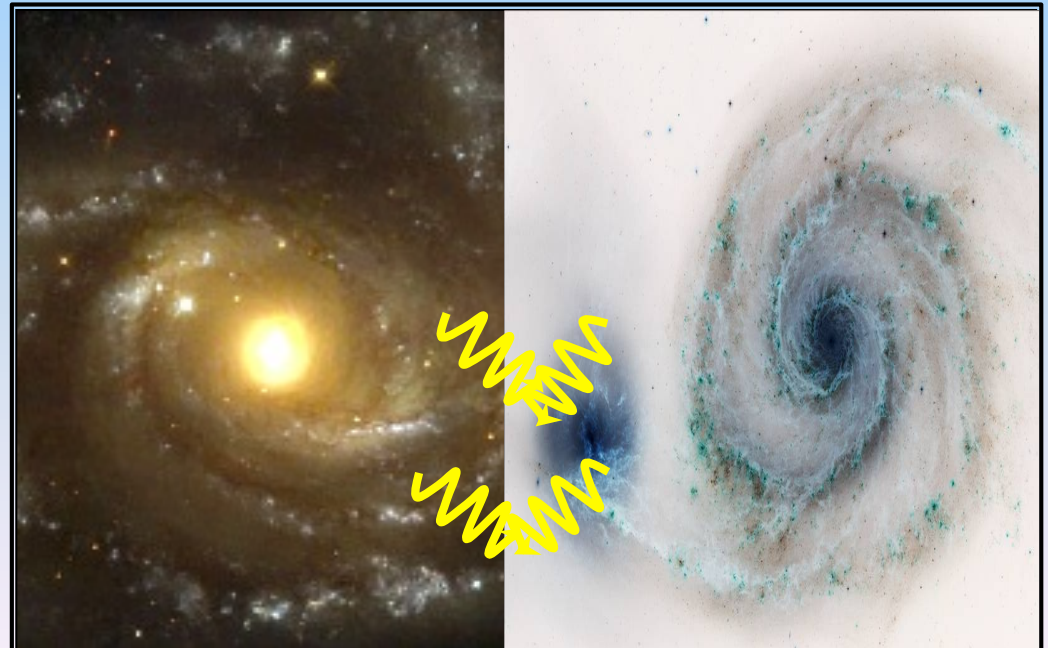
Anti-materie: waar is het gebleven ?

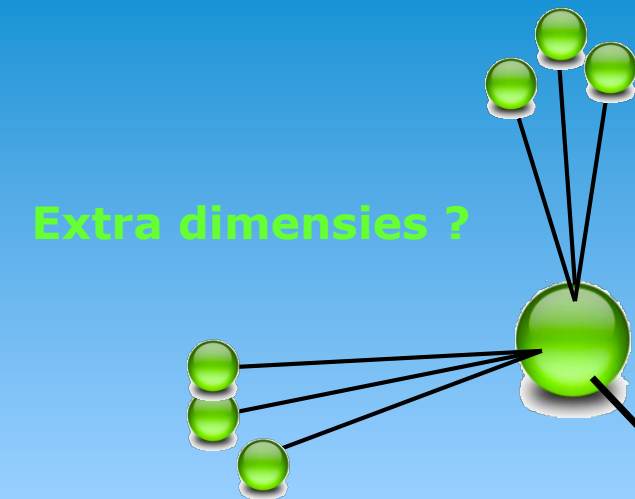
Theorie: materie en anti-materie zijn 'gelijk'

Geen anti-materie in satellieten



Geen anti-materie sterrenstelsels



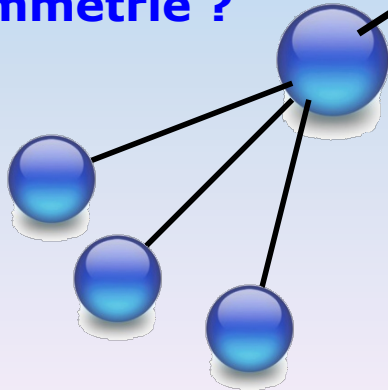


- Het Standard Model is 'effectief' deel van een meer fundamentele theorie
- Model verliest voorspellende waarde rond 1-10 TeV



Nieuwe fenomenen bij $\sim 10^{-19}$ m

Supersymmetrie ?

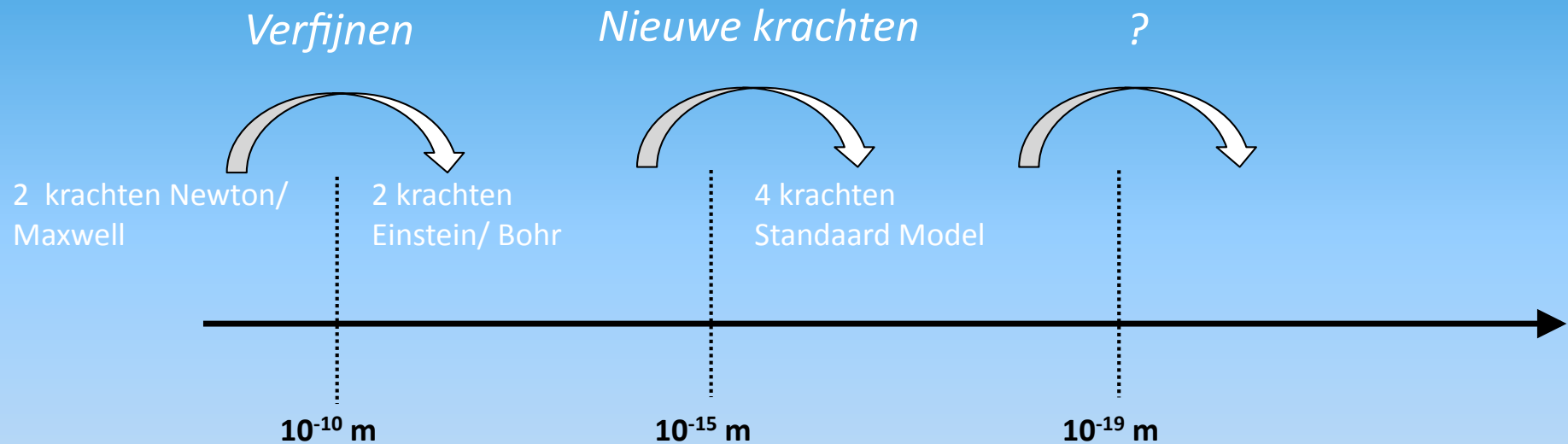


2012

String theorie ?

Edward Witten's
laatste inzicht.

Nieuwe modellen, nieuwe krachten ??



We gaan kijken wat de natuur voor ons in petto heeft

... en wiens model werkt

E. Verlinde



L. Randall



R. Dijkgraaf



E. Witten



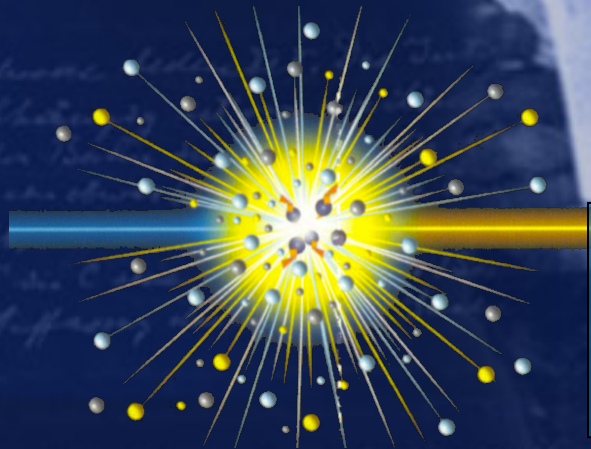


Revolutie in kosmologie laatste paar jaar
Structuur van het heelal

We proberen de donkere materie deeltjes
in het laboratorium maken

Albert Einstein

$$E = mc^2$$



Energie en massa zijn equivalent

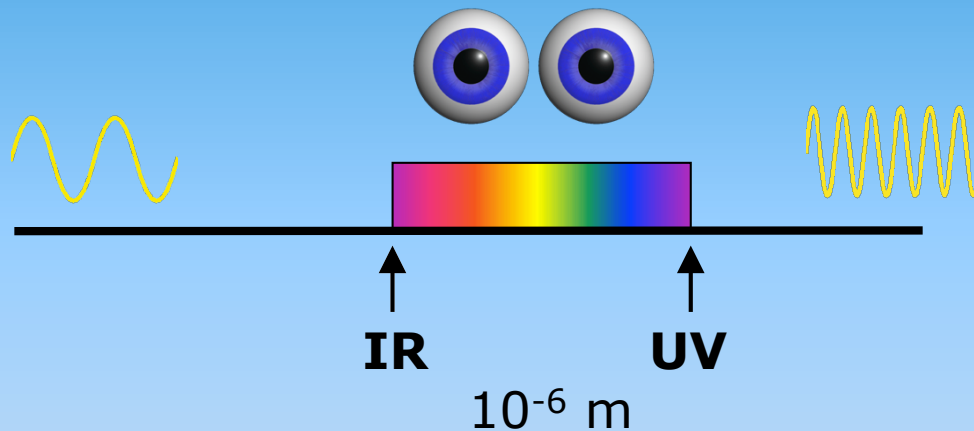
→ je kan *nieuwe* deeltjes maken

kijken zonder je ogen te gebruiken



1] Kijken met licht

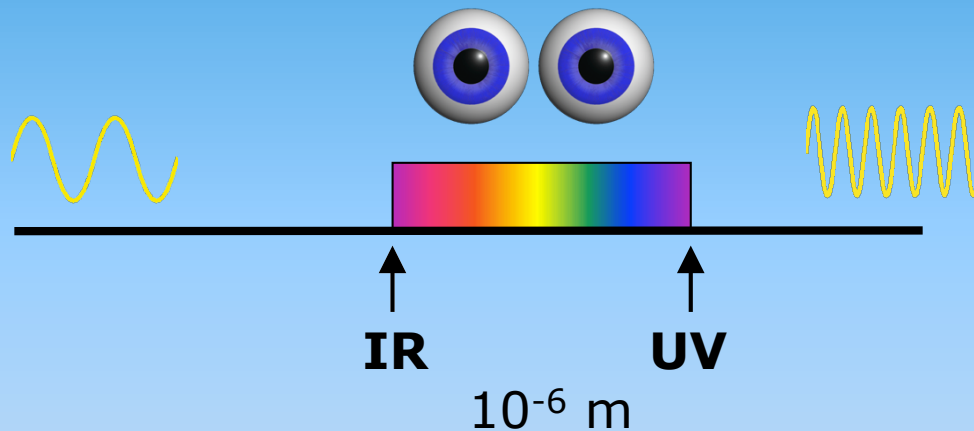
Licht verstrooit aan objecten die groter zijn dan zijn golflengte



Met je oog kan je niks zien
dat kleiner is dan 10^{-6} m

1] Kijken met licht

Licht verstrooit aan objecten die groter zijn dan zijn golflengte



Met je oog kan je niks zien dat kleiner is dan 10^{-6} m

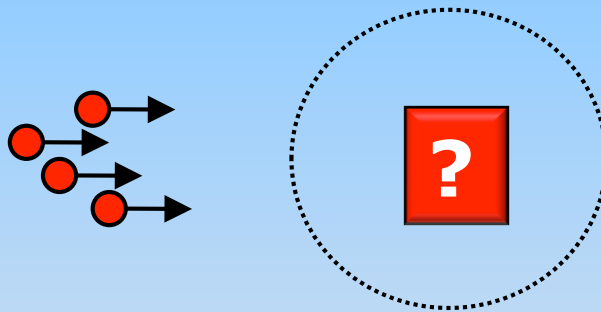
2] Kijken met deeltjes

Idee: laat kleine deeltjes afketsen van het object

- deeltjes-microscoop:
- klein: elektronen microscoop
 - kleinst: protonen microscoop (LHC)

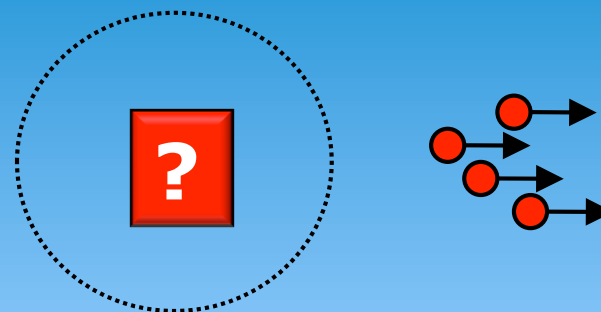
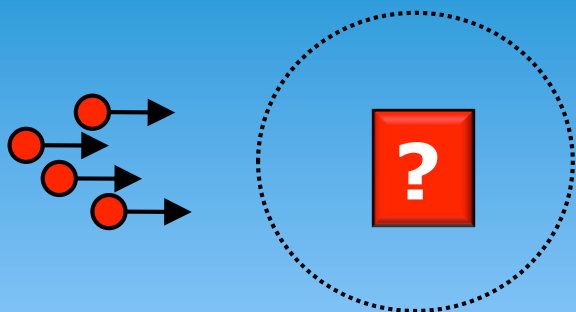
onbekend voorwerp achter een gordijn
... en 100 kogeltjes

bovenaanzicht

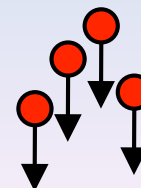
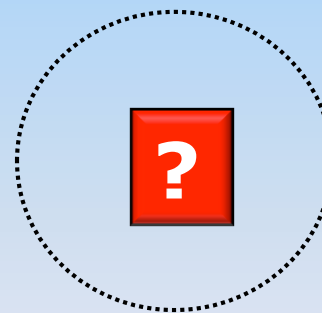
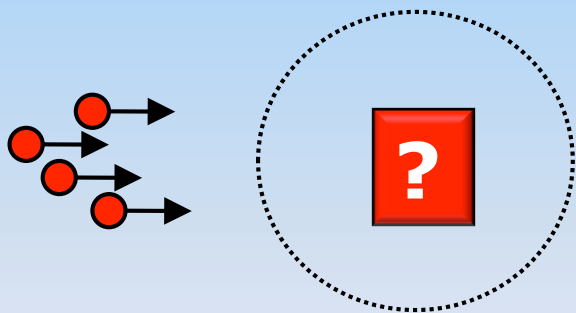


Hoe ketsen de kogels af ?

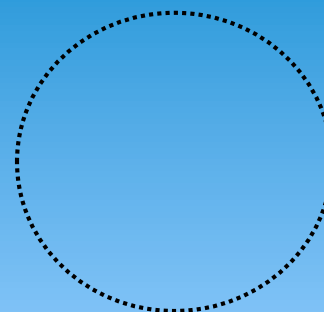
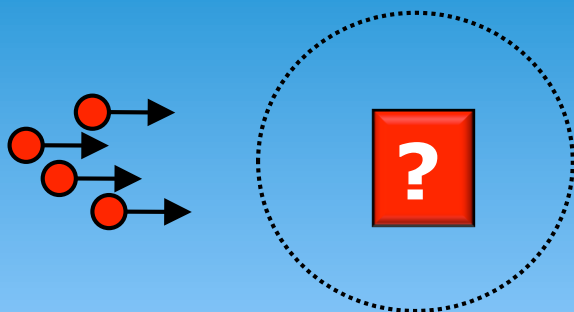
Experiment 1



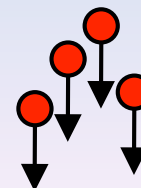
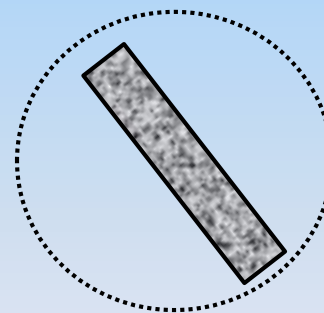
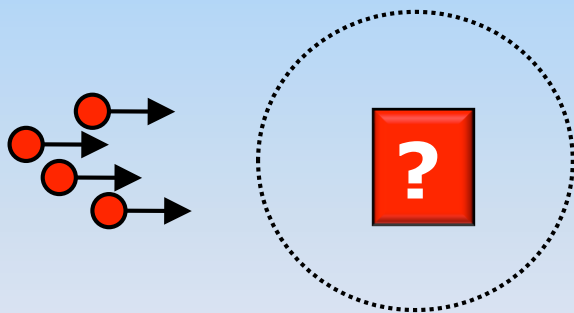
Experiment 2



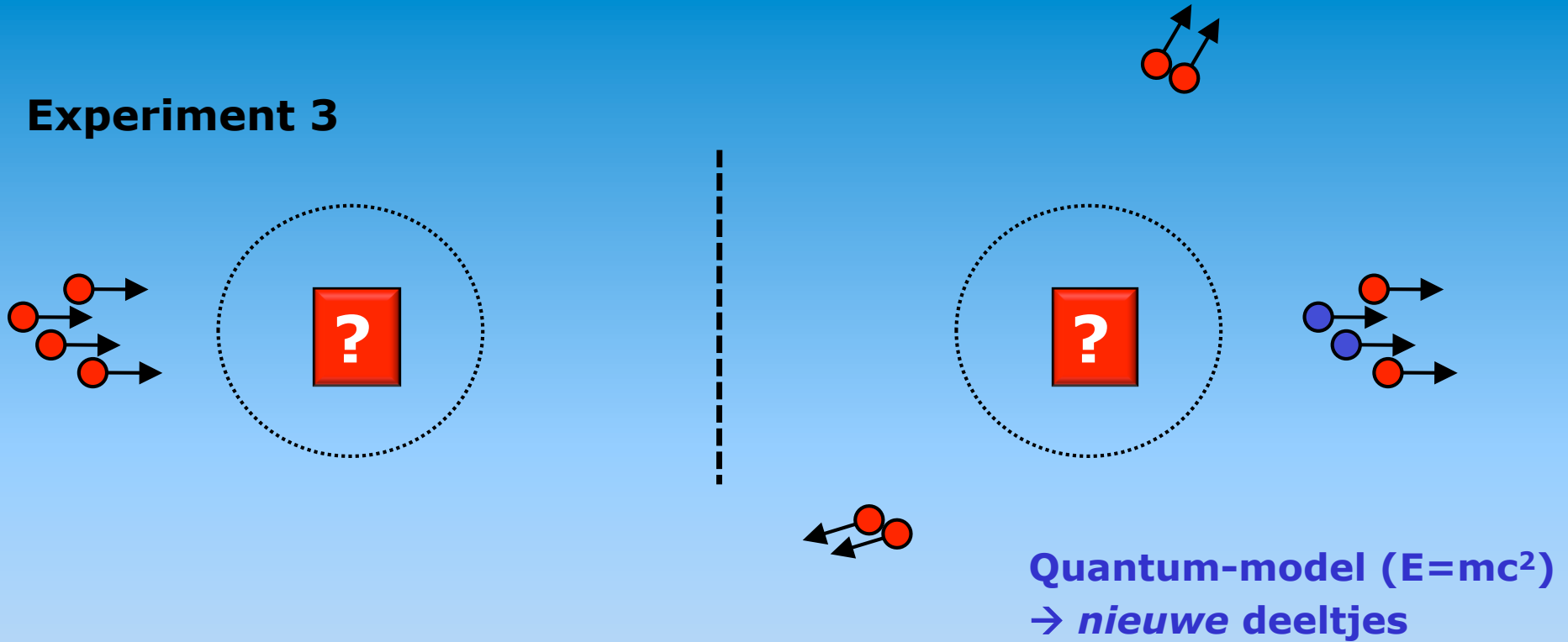
Experiment 1



Experiment 2



Experiment 3

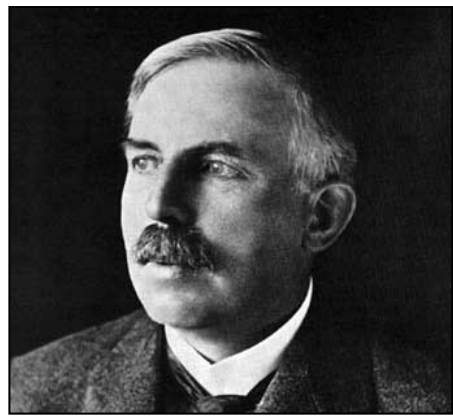


'Kijken' naar sub-atomaire structuren:

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

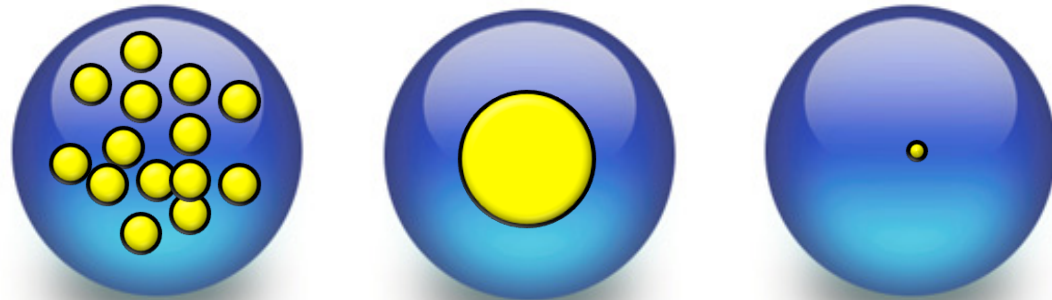
Deeltjesversneller
Theorie
Detector

Het atoom

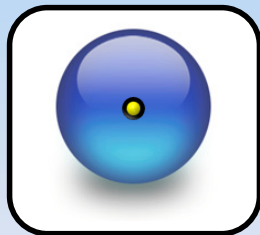


Rutherford

Thomson



Hypothese:



en

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

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

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

Het zichtbaar maken van afgeketste of nieuwe deeltjes

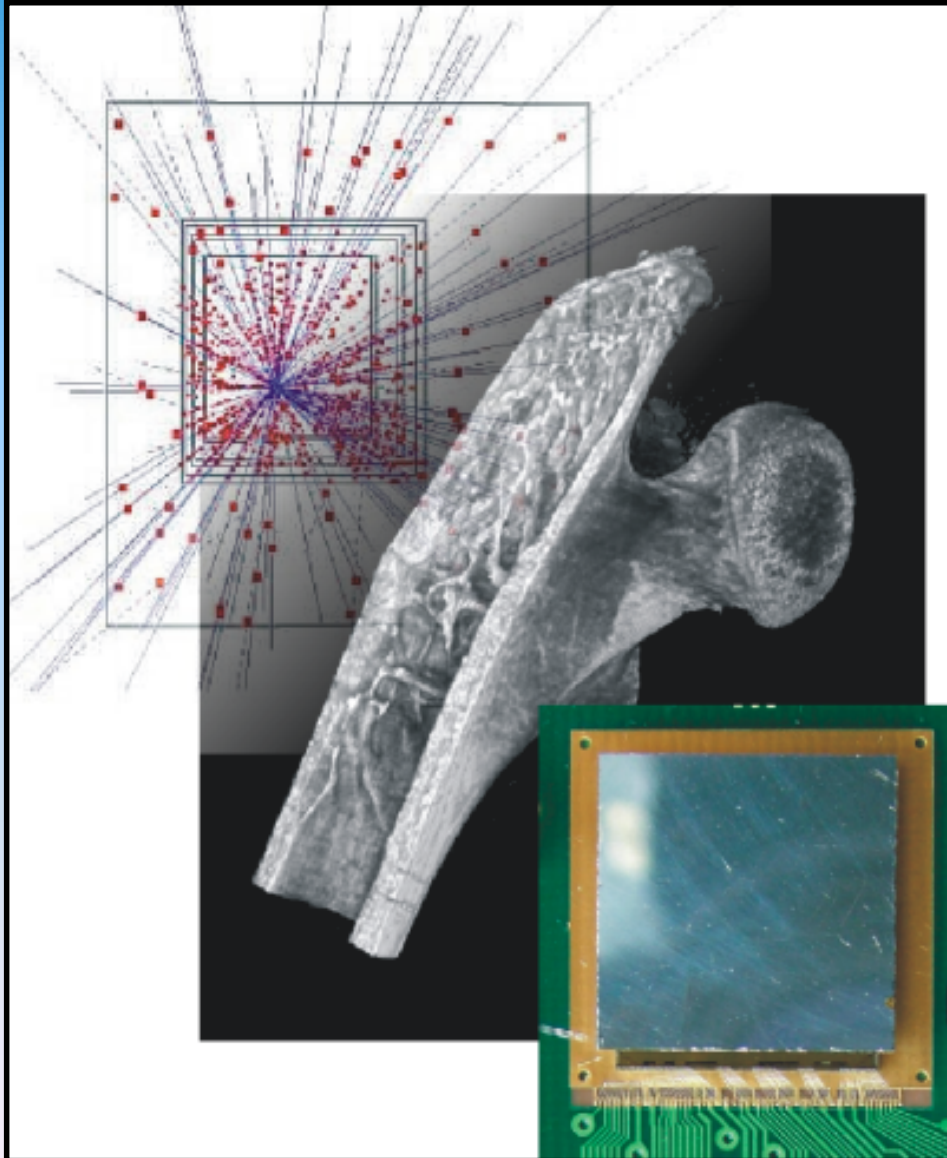
Rontgen foto



PET scan



Detectietechnieken: Medipix



Minder dosis
Hogere resolutie

TUSSENDOORTJE

Grote inbreng Nederland (Nikhef)

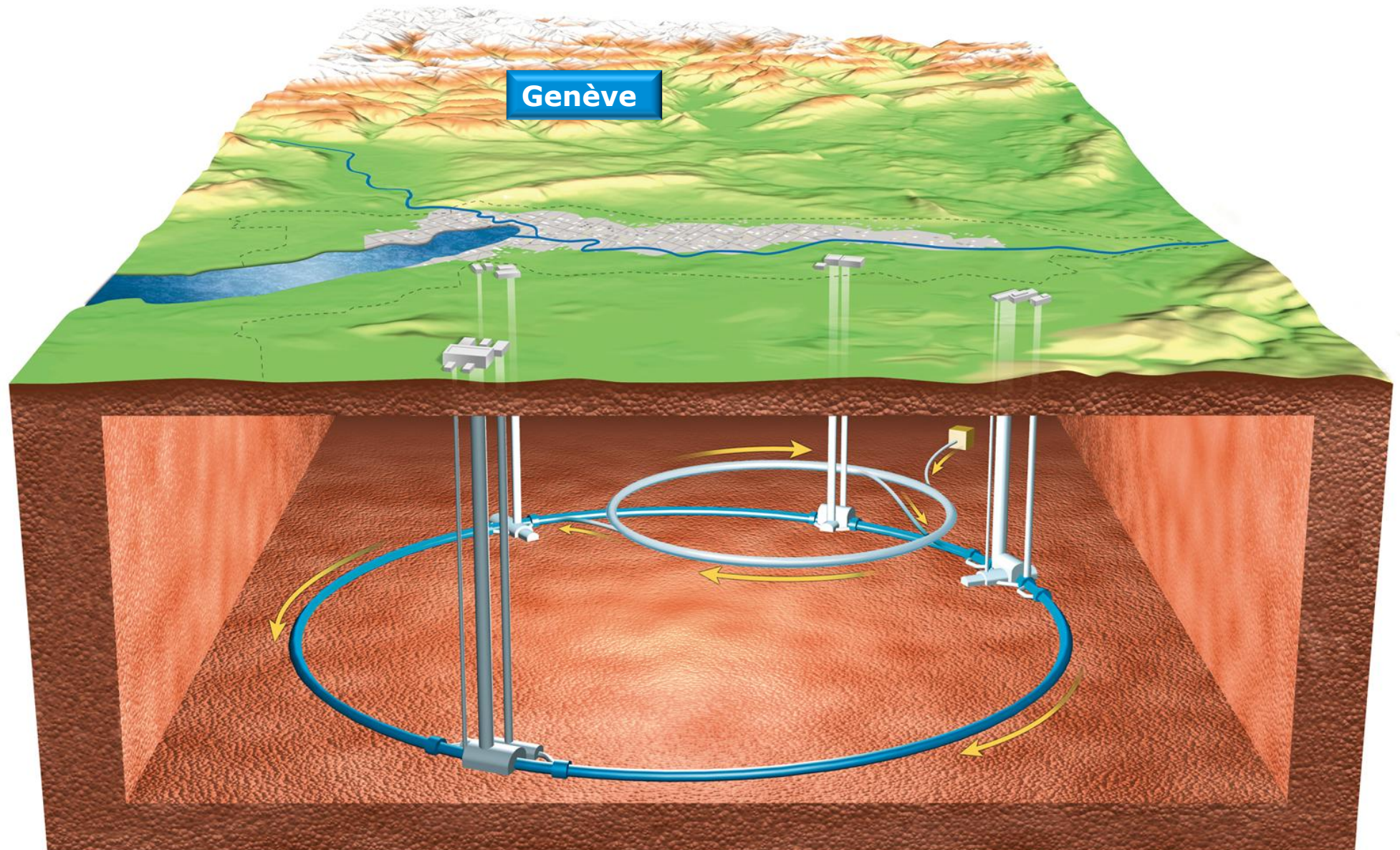


MRI scan knie

An aerial photograph of the CERN facility near Geneva, Switzerland. A large red oval is superimposed on the image, representing the circular path of the Large Hadron Collider (LHC) tunnel. The landscape below is a patchwork of green fields and some urban areas. In the far distance, a range of snow-capped mountains is visible under a clear blue sky. The text is centered within a blue rectangular box with a white border.

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

De LHC deeltjesversneller



LHC: 27 km



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

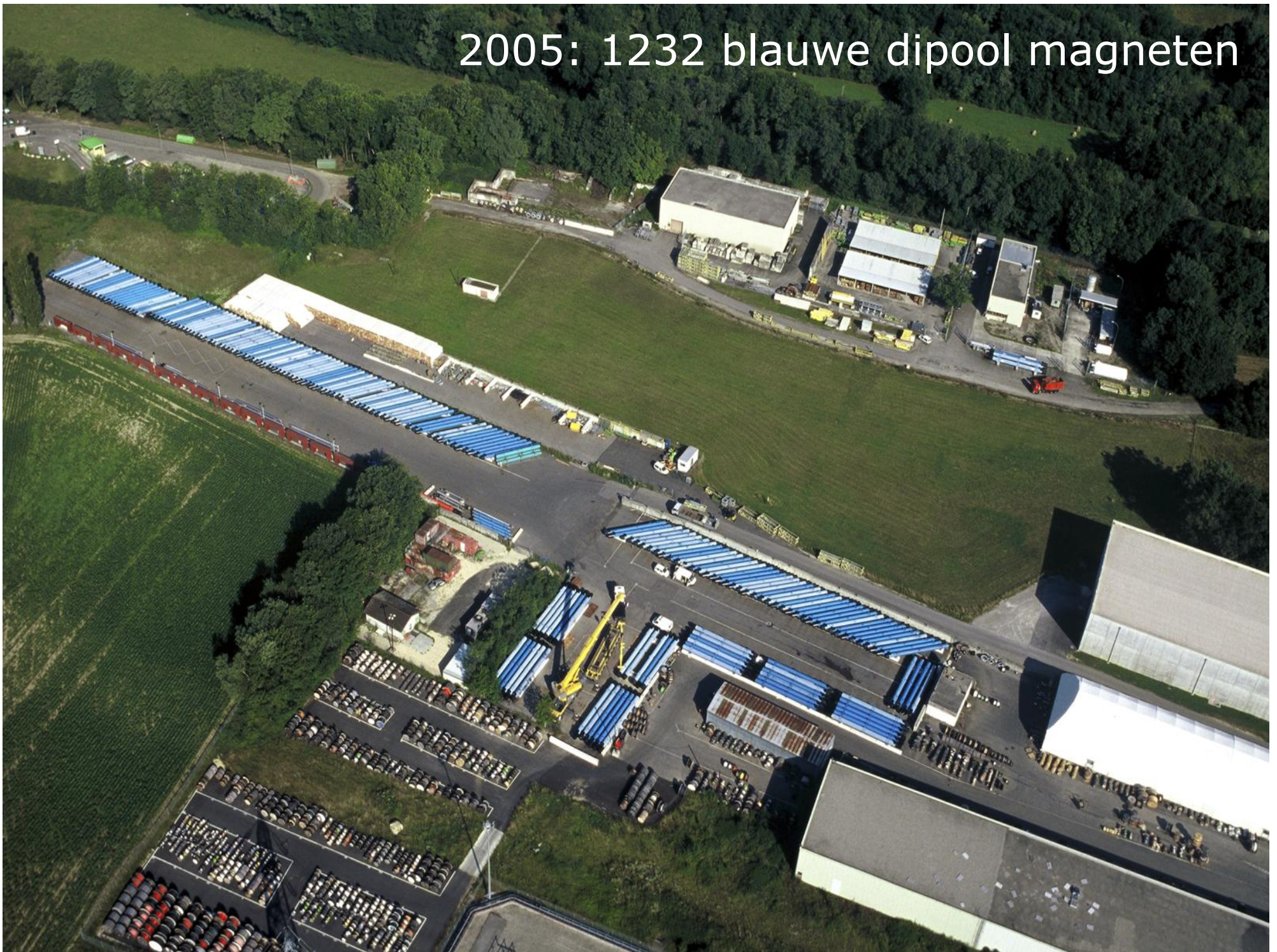
20 goud atomen

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

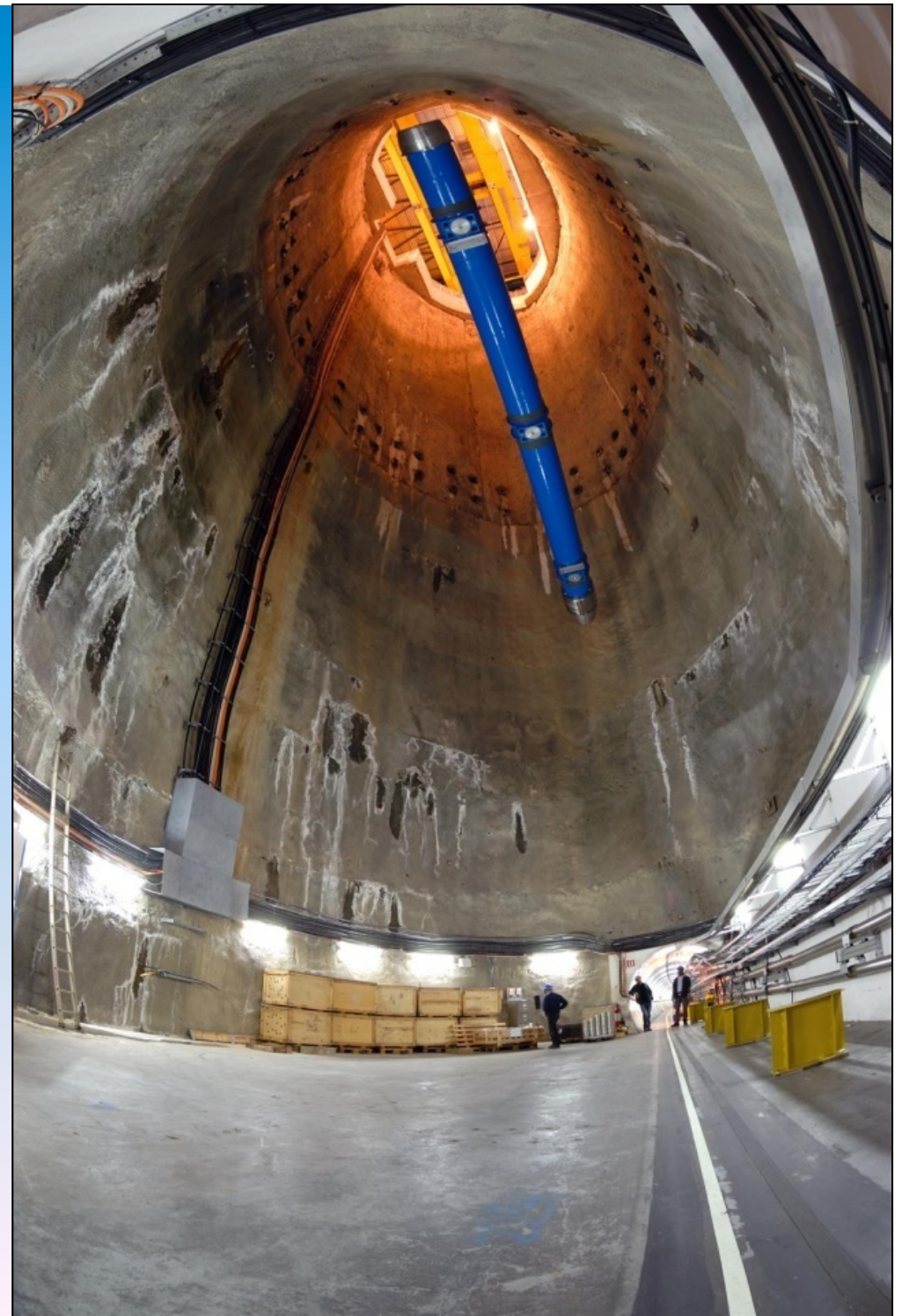
→ *Zoeken naar zeldzame gebeurtenissen*

→ 100 x LEP & Tevatron

2005: 1232 blauwe dipool magneten

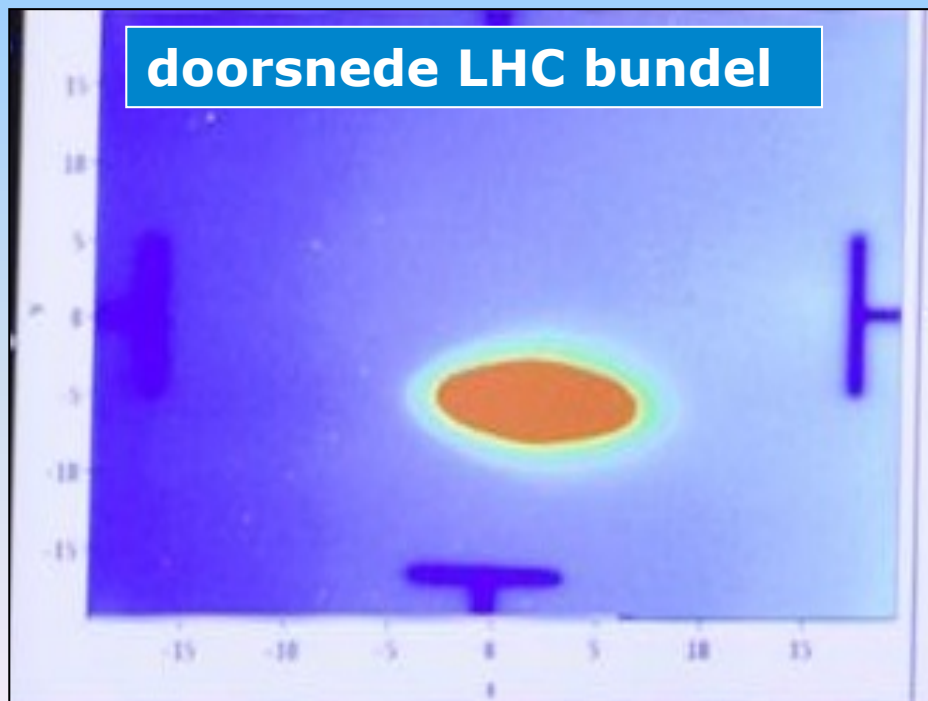


Logistieke nachtmerrie
maar gelukt



De LHC is rond !

“Op 10 september 2008 hebben bundels protonen een rondje in LHC gemaakt”

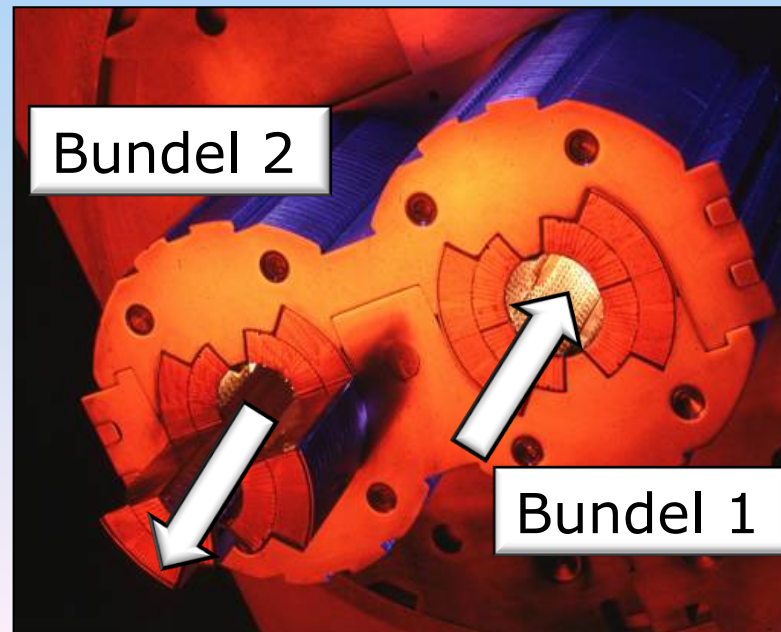


Energie 1 proton (LHC)



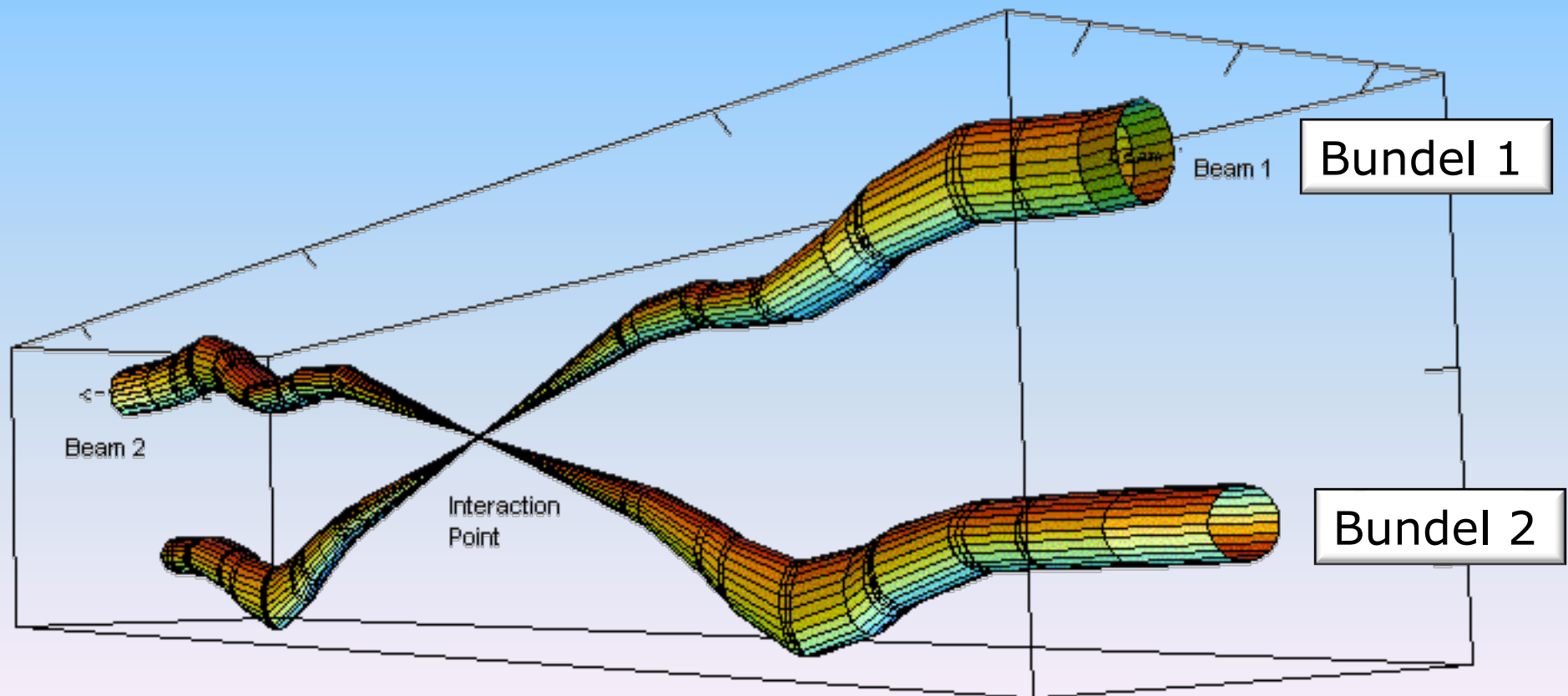
Energie LHC bundel

$3000 \times 100.000.000.000$ protonen



*Doorsnede LHC
bundelpijp*

40 miljoen botsingen per seconde





Klassiek botsen

Quantummechanisch botsen



Wat verwacht je ?

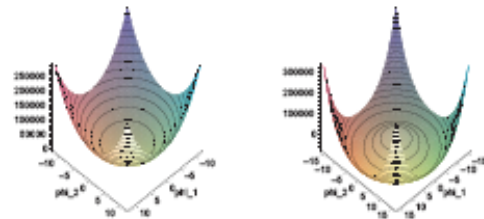


FIG. 1: The potential $V(\phi)$ ($\phi = \phi_1 + i\phi_2$) plotted for an arbitrary positive value of λ and for an arbitrary positive (right) or negative (left) value of μ^2 .

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:

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

and now contains the correct terms to describe a massive vector field A^μ with mass $m_A^2 = g^2 v^2$ (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:

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

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 l, q respectively), Q_f is the charge of the f fermion species, and A_f^H are given by:

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

and A_W^H are given by:

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

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

At the lowest order the decay rate for $H \rightarrow \gamma Z$ is given by:

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

where $\lambda_i = 4M_i^2/M_Z^2$ ($i = f, W$), 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

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

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 l, q respectively), Q_f is the charge of the f fermion species, and A_f^H are given by:

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

and A_W^H are given by:

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

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

At the lowest order the decay rate for $H \rightarrow \gamma Z$ is given by:

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

where $\lambda_i = 4M_i^2/M_Z^2$ ($i = f, W$), 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

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

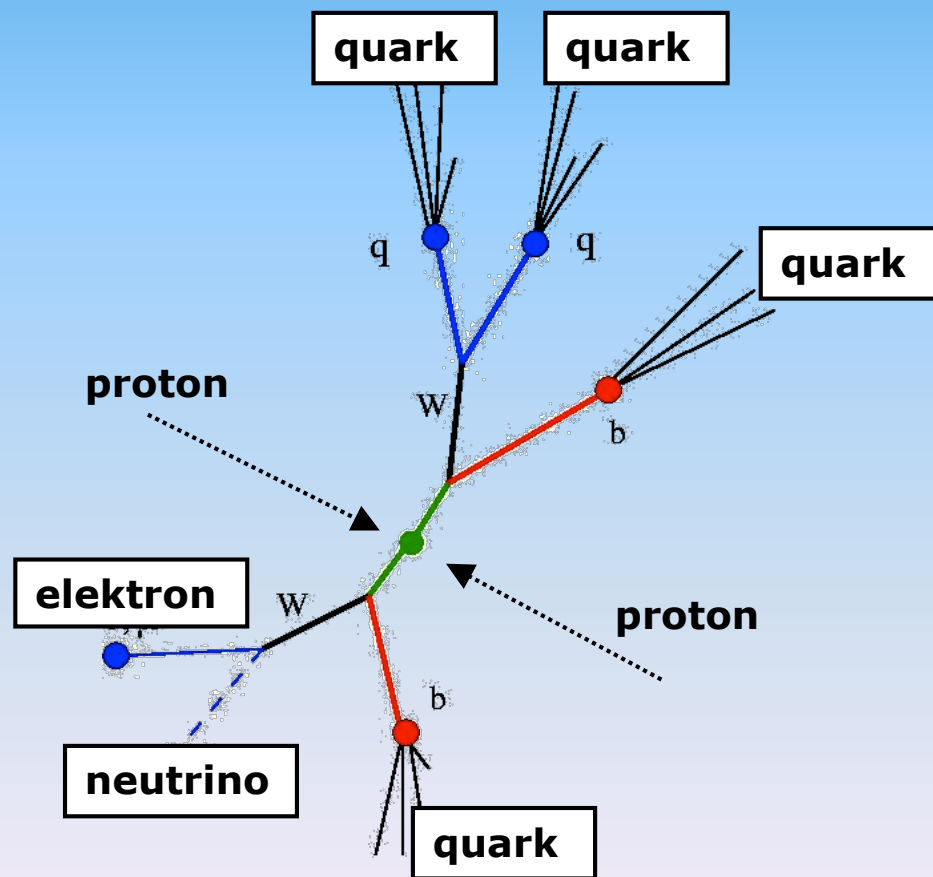
Klopt het ?

Inderdaad nieuwe deeltjes ?

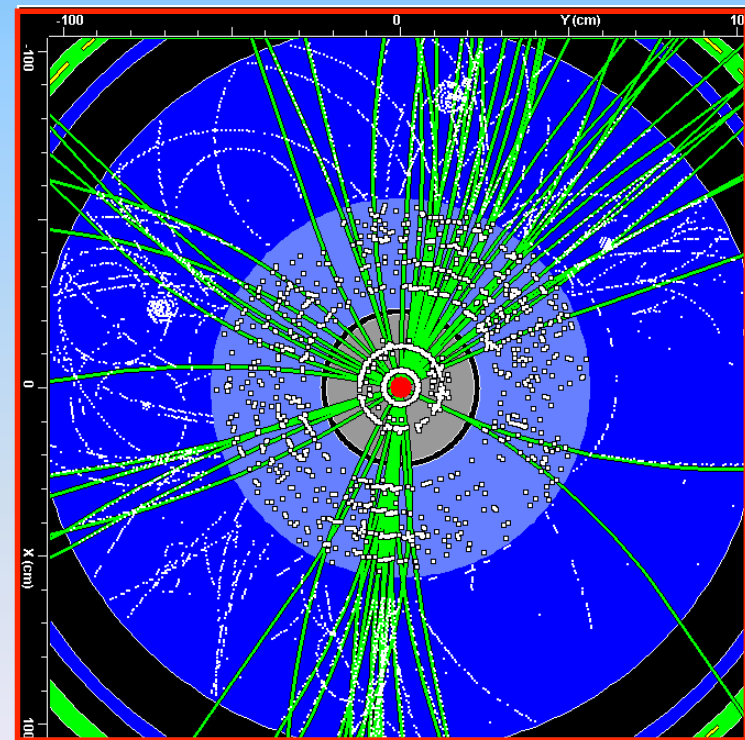


Heel vaak botsen

Hoe zien die botsingen er nou uit ?



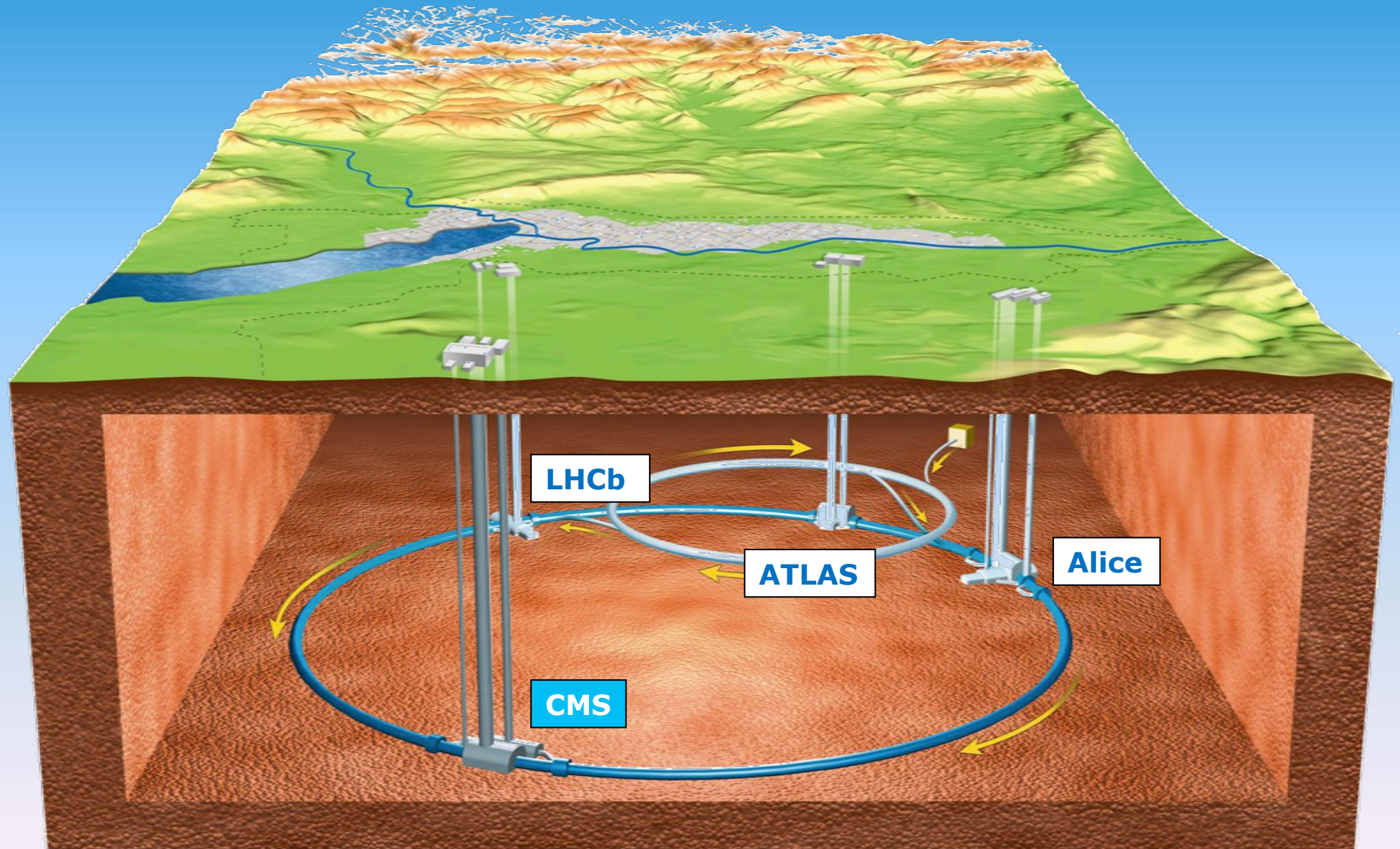
Simulatie top quark productie



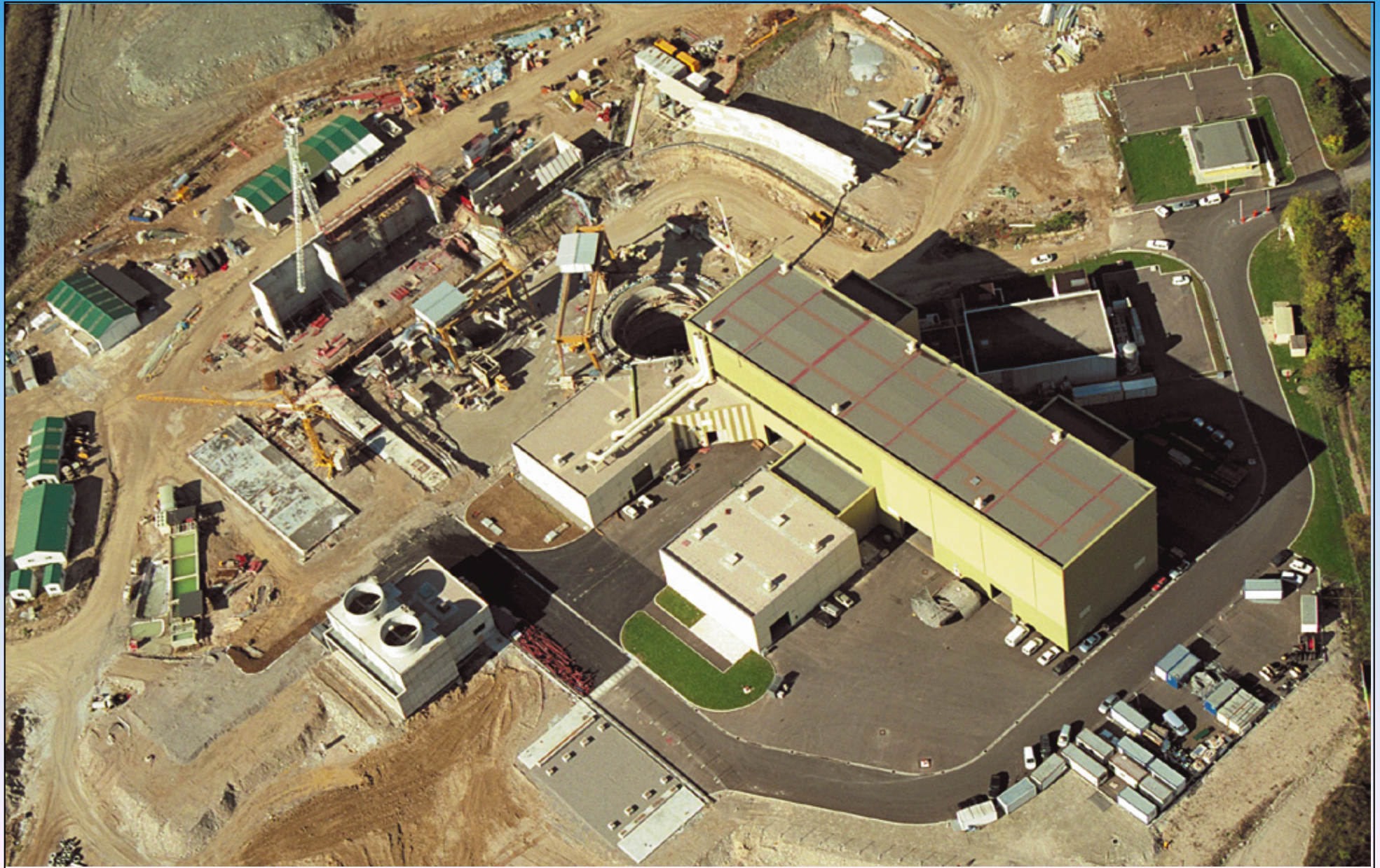
Onze 'fototoestellen'



De vier experimenten



Een gat in de grond ... ongeveer 100 meter diep

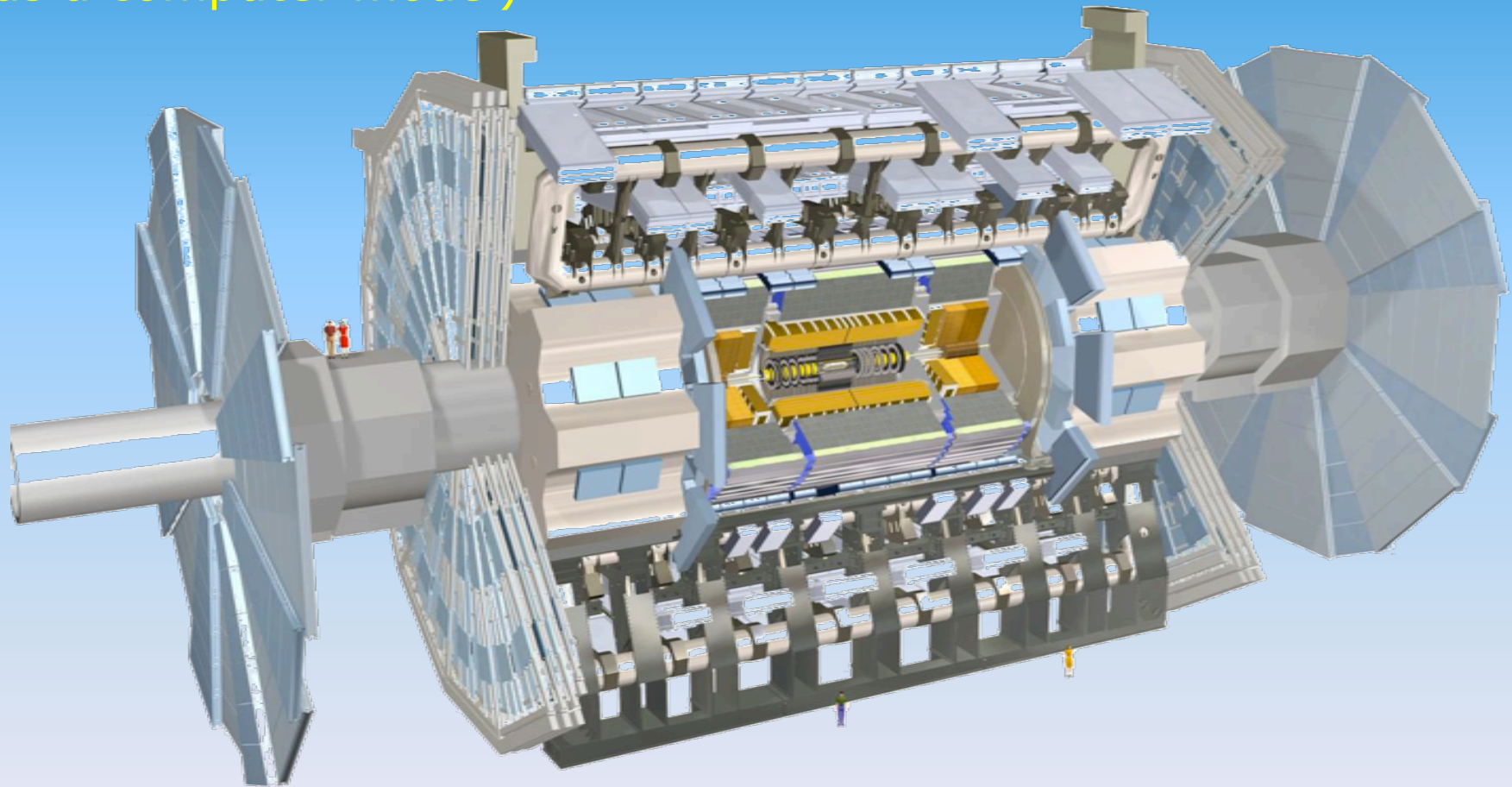


Op 100 meter diep een grote grot maken



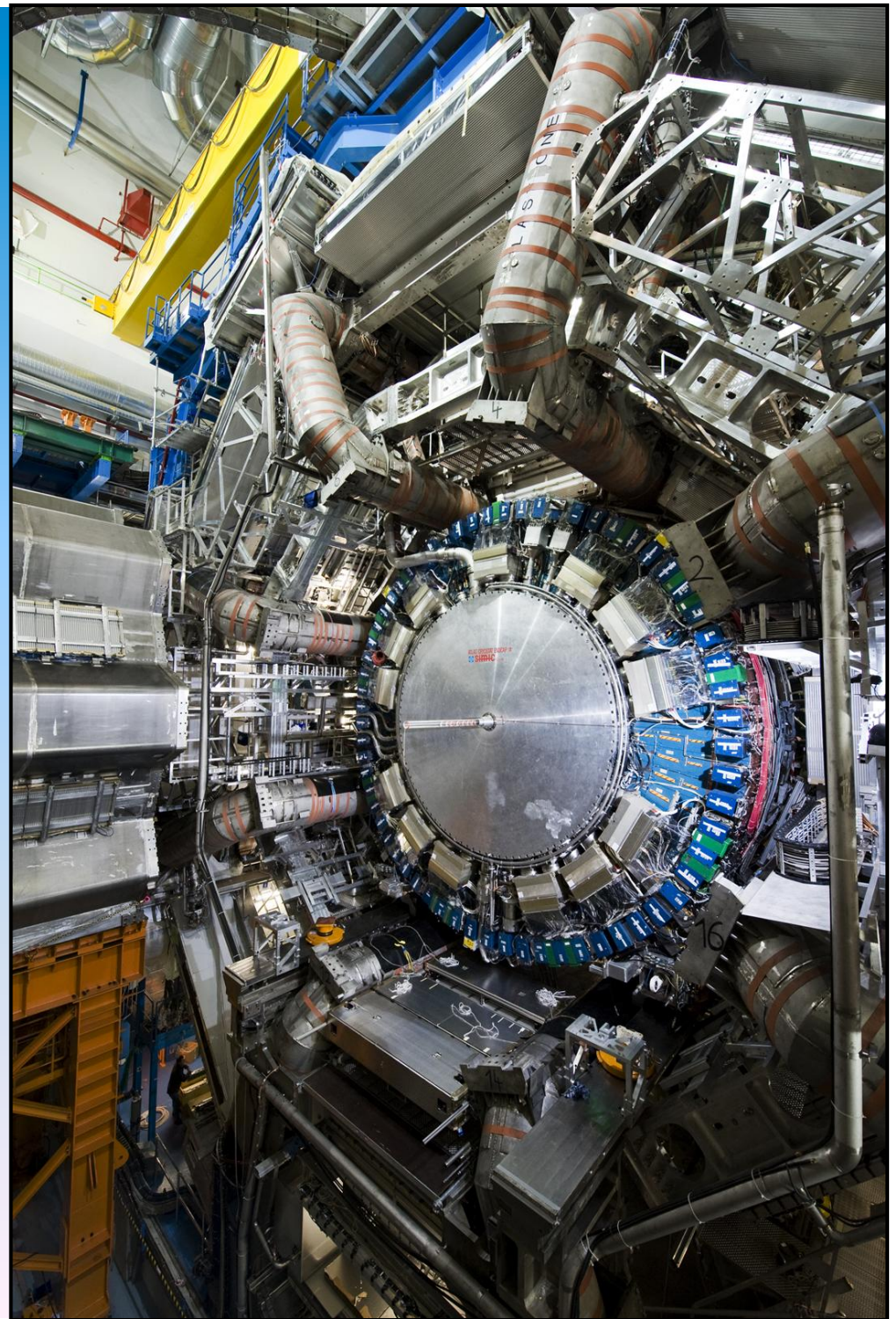
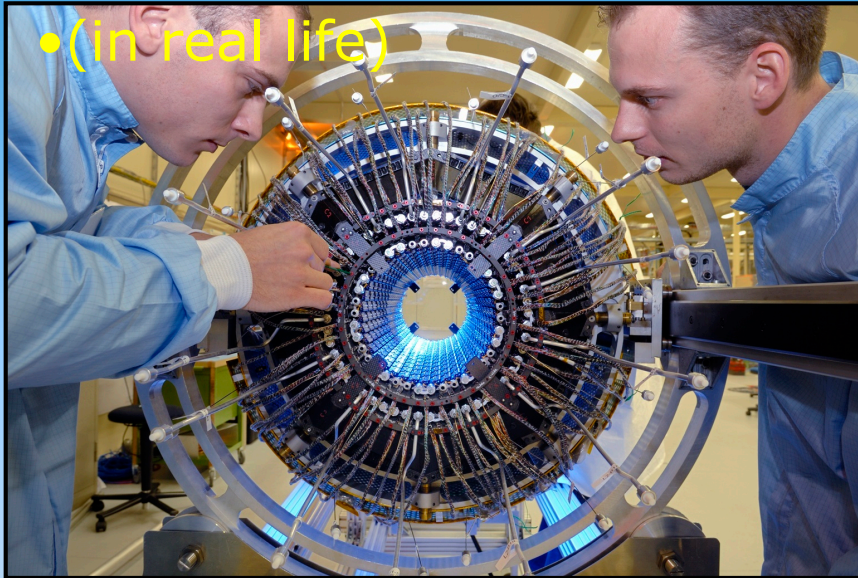


- The ATLAS detector
(as a computer model)



- The ATLAS detector

- (in real life)

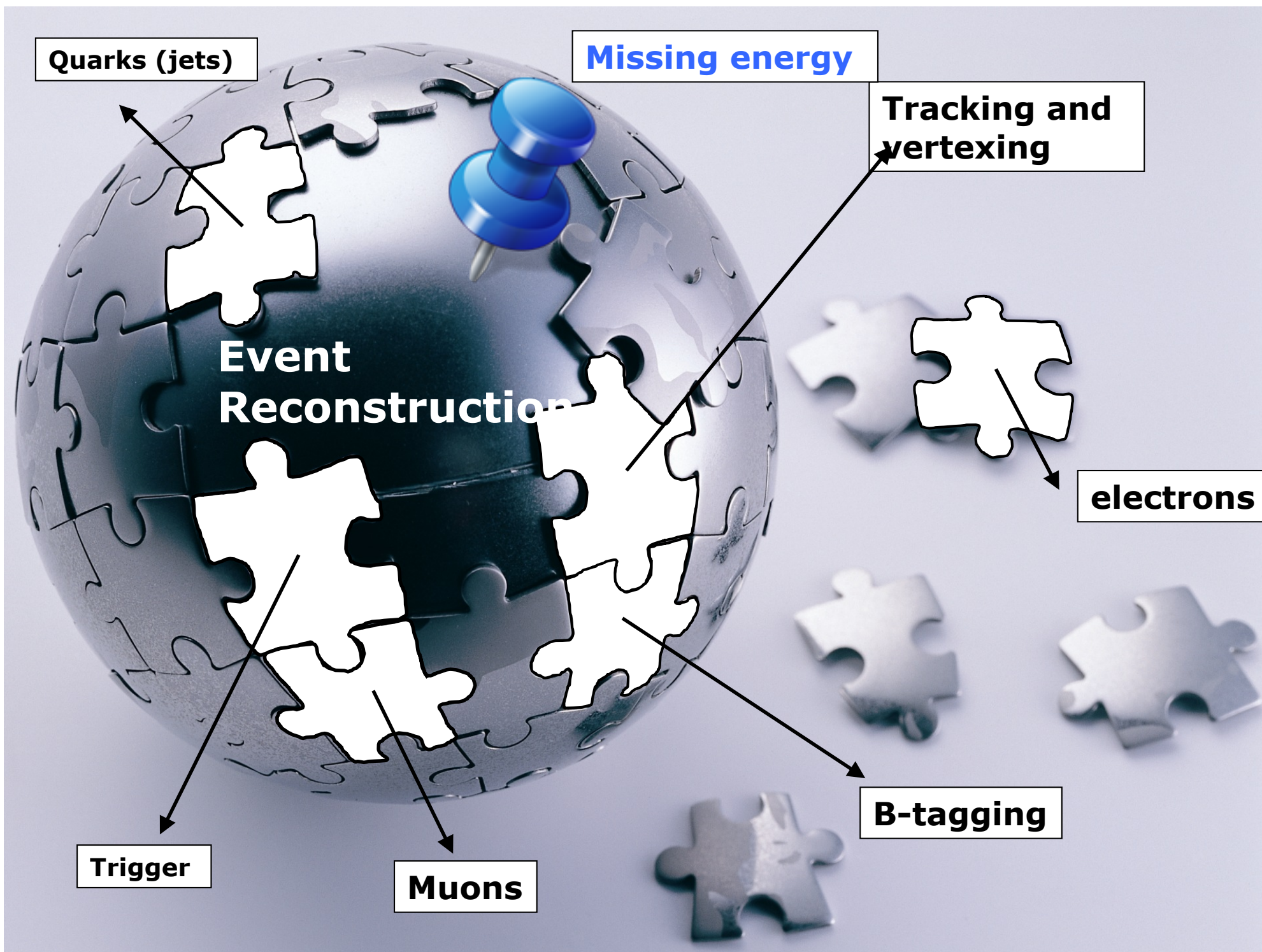


De Atlas detector bestaat echt

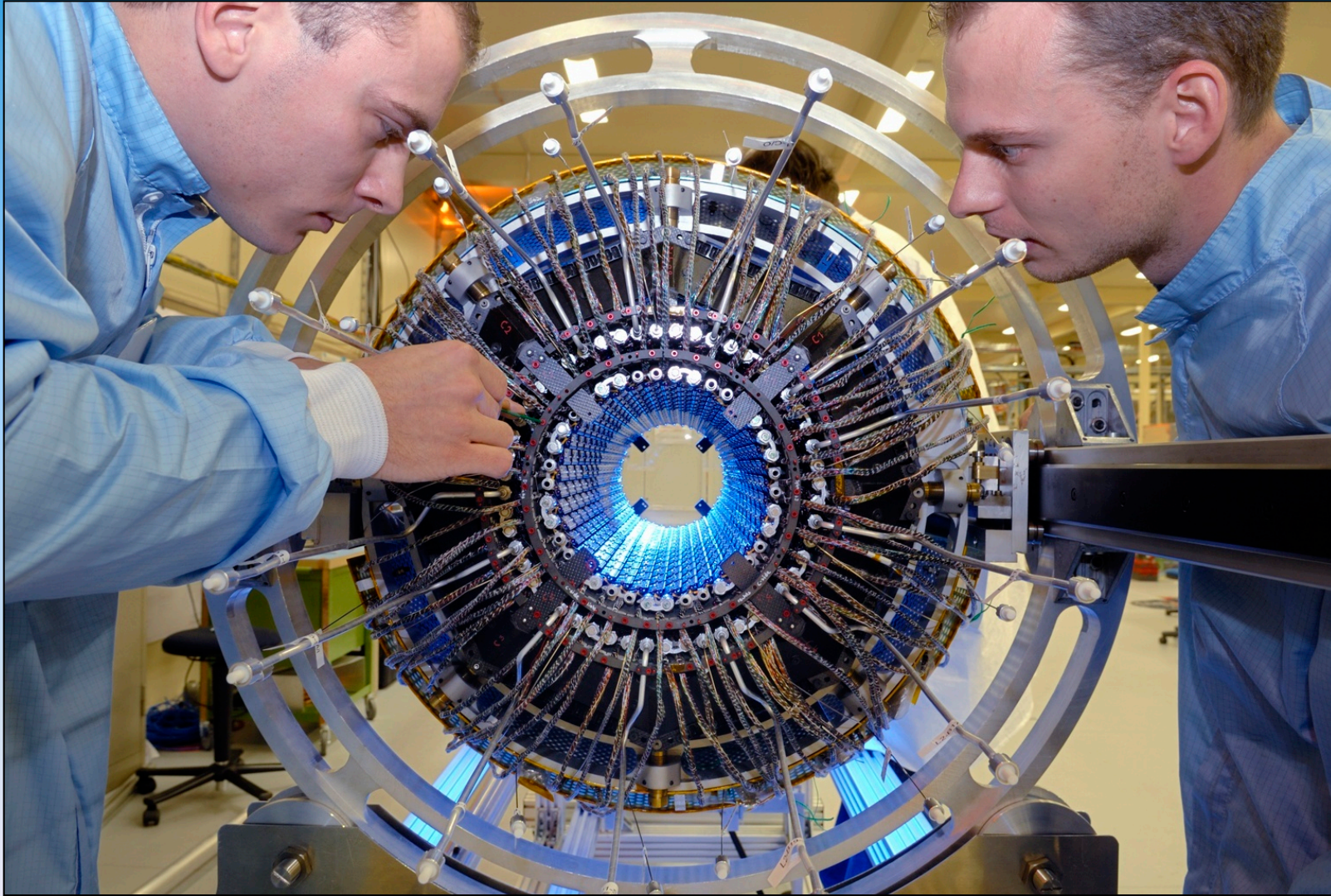


nieuwe baas

oude baas



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)

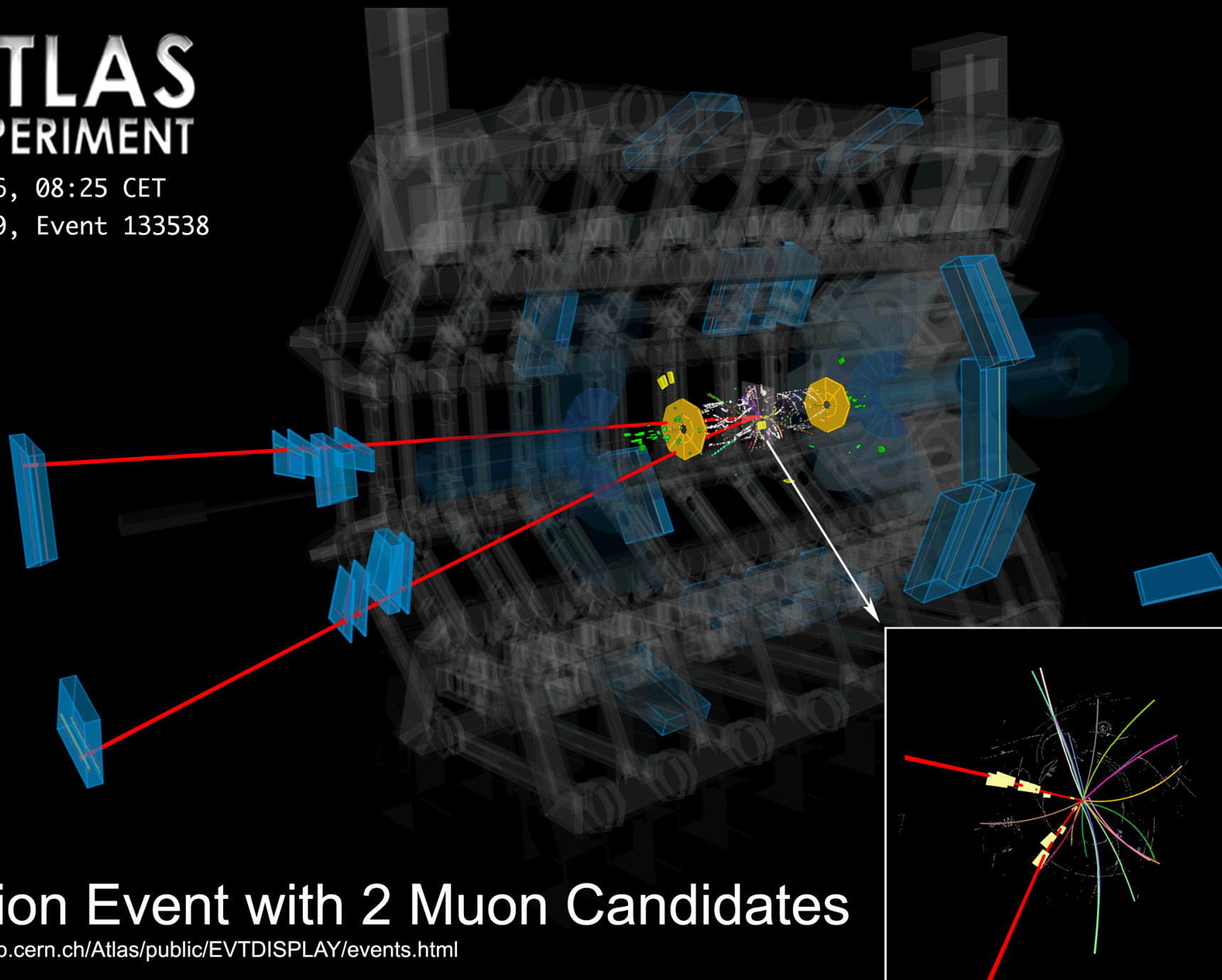
Puzzelen voor gevorderden





2009-12-06, 08:25 CET

Run 141749, Event 133538



Collision Event with 2 Muon Candidates

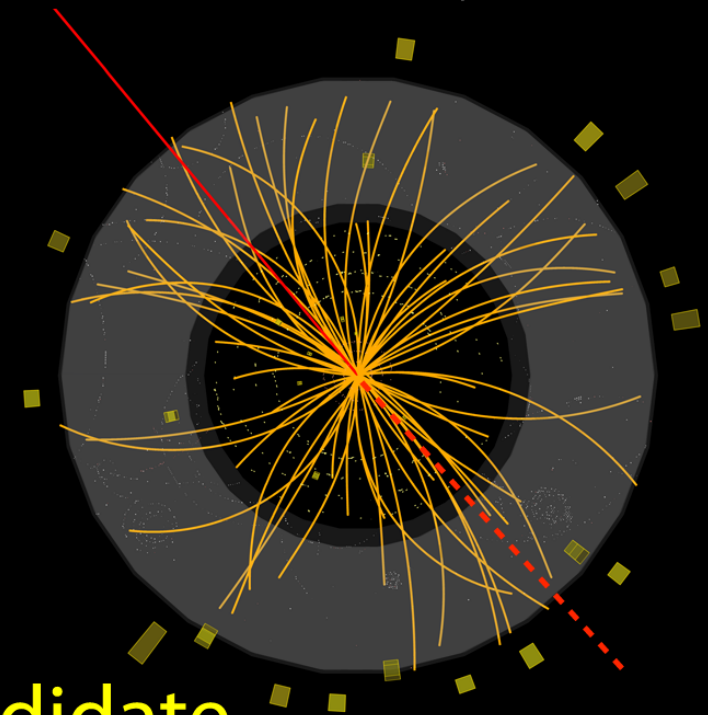
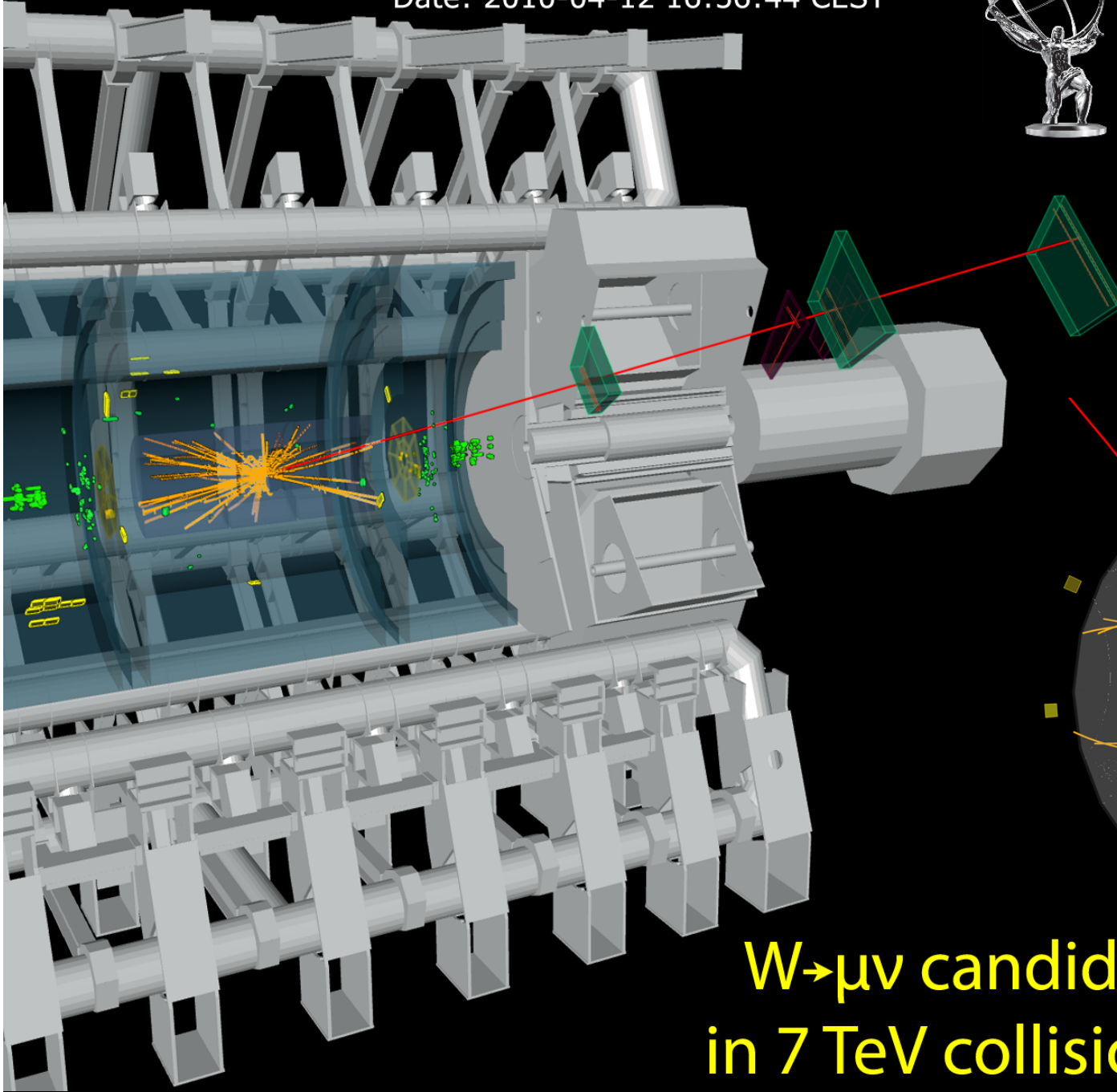
<http://atlas.web.cern.ch/Atlas/public/EVTDISPLAY/events.html>

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



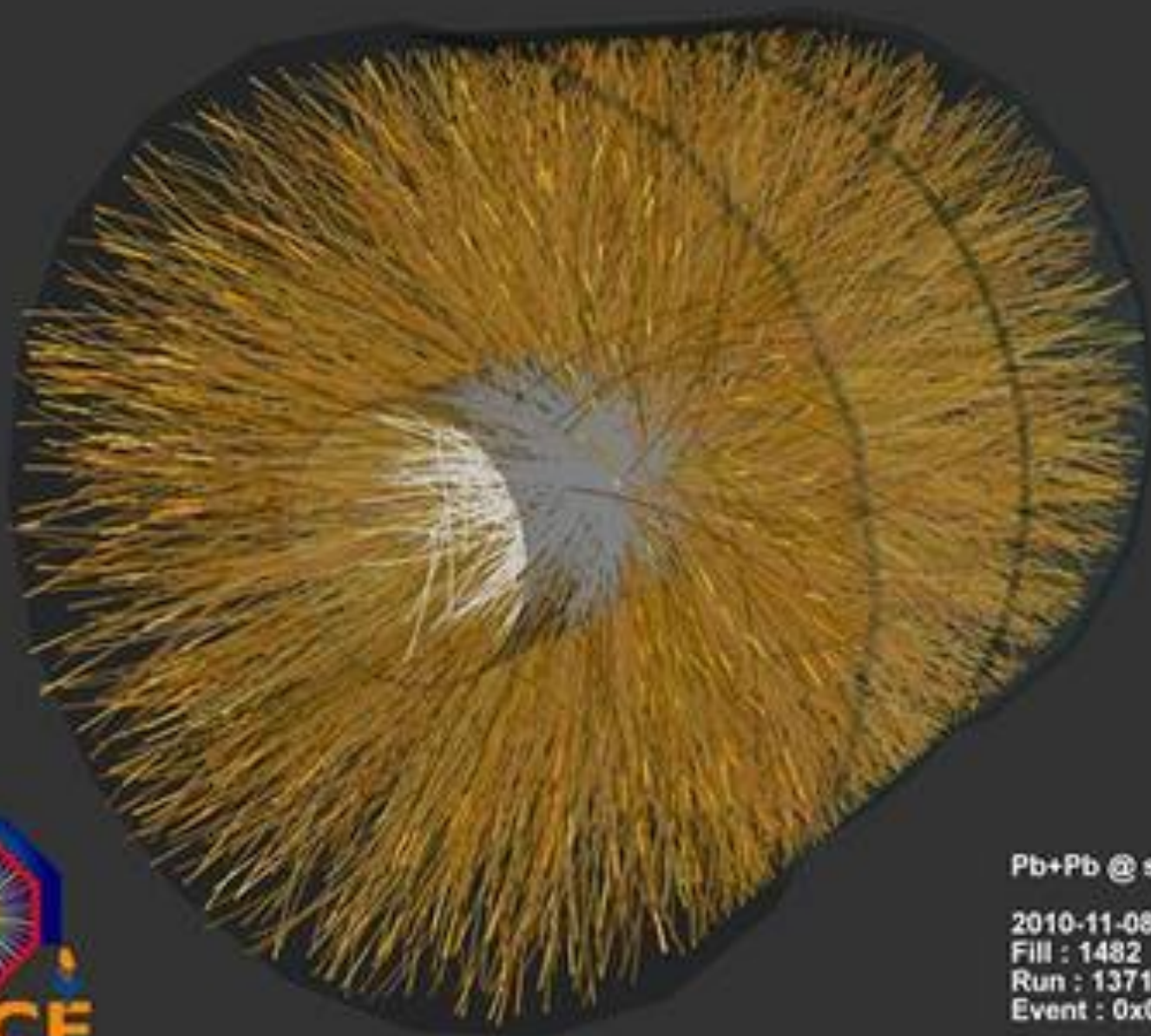
ATLAS EXPERIMENT

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



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

ALICE experiment



Pb+Pb @ $\sqrt{s} = 2.76$ ATeV

2010-11-08 11:30:46

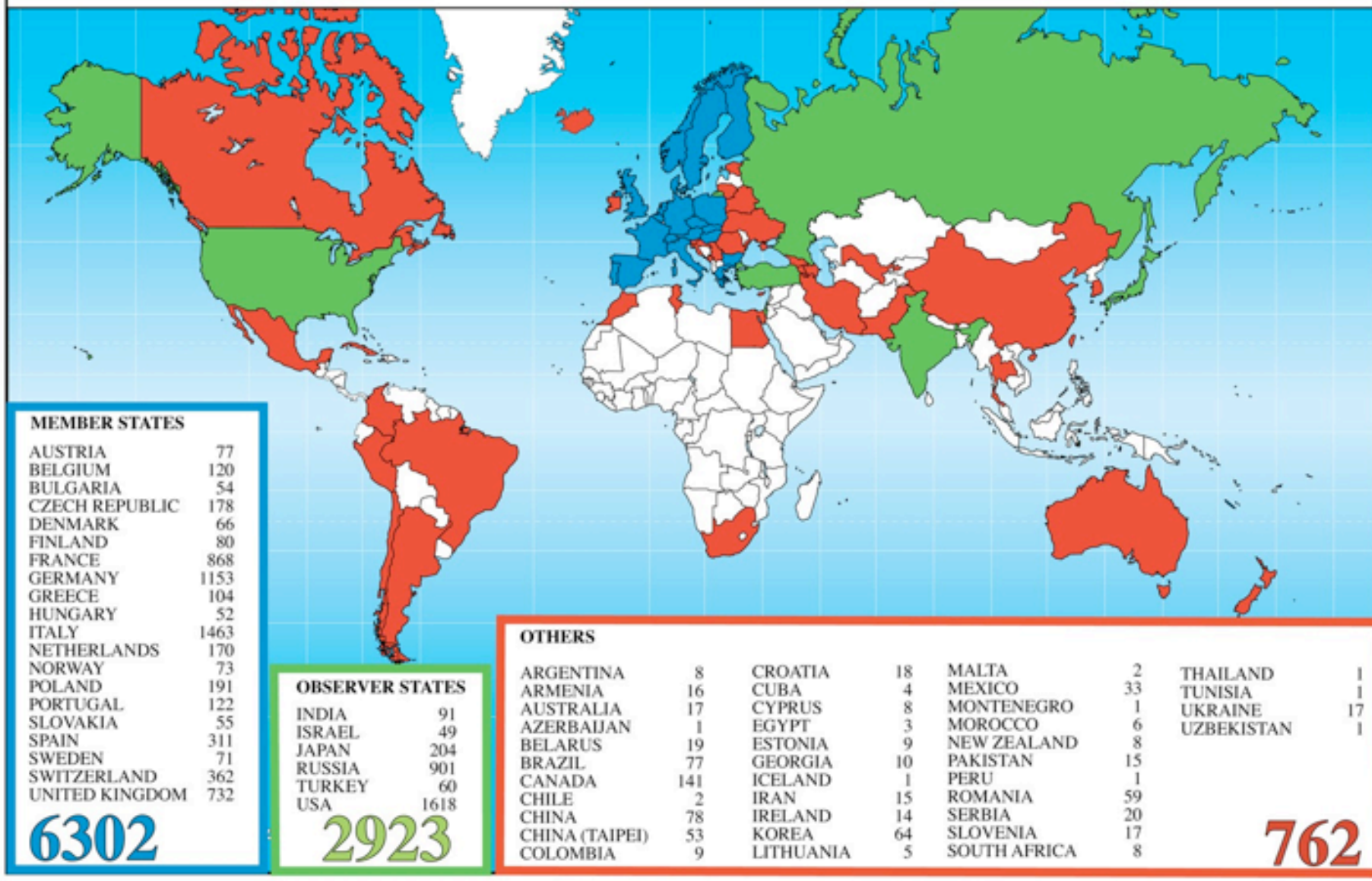
Fill : 1482

Run : 137124

Event : 0x00000000D3BBE693

Cern gebruikers

Distribution of All CERN Users by Nation of Institute on 20 January 2010



G. Aad¹⁴⁸, B. Abbott¹¹¹, J. Abdallah<sup>111, A. A. Abdelalim⁴⁰, A. Abdeneken¹¹⁸, O. Abdurro¹⁰, B. Abi¹¹²
 G. Abolmawad¹¹⁸, M. Abolmawad¹¹⁸, A. Abou¹⁰, B.S. Acharya^{164,166}, M. Adam¹⁰, A. Adams²,
 T.N. Adye¹⁶, J. Adelman¹⁷⁰, M. Aderholz¹⁰, S. Adomec¹⁶⁸, P. Adragna¹⁷⁰, T. Adye¹⁶, S. Aefsky²²,
 J.A. Aguilar-Saavedra^{124b}, M. Aharouch⁸¹, S.P. Ahlen¹⁶⁷, F. Ahles⁴⁸, T. Ahm¹⁴⁸, M. Ahsan⁶,
 G. Aielli^{132,133b}, T. Akdogan¹⁴⁸, T.P.A. Åkesson⁹⁰, G. Akimoto¹⁰⁵, A.V. Akimov⁹⁴, M.S. Alam¹, M.A. Alam⁶,
 S. Albani¹⁰, M. Alekso²⁰, I.N. Alekseyev⁶⁰, M. Alekseyev^{10,30b}, F. Alessandri¹⁰, G. Alexee²⁴, G. Alexander¹⁰³</sup>

G. Alexandre⁴⁰, T. Allen⁴¹, P. Alpari⁴², S. E. Alfaro⁴³, M.P. Alvares⁴⁴, J. Almeida⁴⁵, K. O. Akir^{2a}, P. Calafura¹⁴, G. Calderini¹⁸, P. Califfay³⁶, R. Calkins¹⁰⁶, L.P. Calob^{22a}, R. Calvo⁴², S. Calvez⁴³, A. Camard¹⁸, P. Camara^{132a,132b}, M. Cambiaggi^{110a,110b}, D. Camarero^{22a}, M. Campanelli¹⁷, V. Canak^{102a,102b}, F. Canelli³⁰, A. Canepa^{10a}, J. Canter¹⁰, M.M. Capenas Garrido⁹, I. Capriotti^{2a}, M. Caprin^{2a}, D. Capriotti^{2a}, M. Capua^{30a}, S. Caracciolo^{22a}, R. Cardarelli¹², T. Car¹⁰, S. Carino¹⁰, L. Carminar^{30a,30b}, B. Carlini³⁰, A. Antonelli⁴⁶, M. Anton⁴⁷, R. Anelli¹¹⁸, G. Arabi¹¹⁹, O. Cakir^{2a}, P. Calafura¹⁴, G. Calderini¹⁸, P. Califfay³⁶, R. Calkins¹⁰⁶, L.P. Calob^{22a}, R. Calvo⁴², S. Calvez⁴³, A. Camard¹⁸, P. Camara^{132a,132b}, M. Cambiaggi^{110a,110b}, D. Camarero^{22a}, M. Campanelli¹⁷, V. Canak^{102a,102b}, F. Canelli³⁰, A. Canepa^{10a}, J. Canter¹⁰, M.M. Capenas Garrido⁹, I. Capriotti^{2a}, M. Caprin^{2a}, D. Capriotti^{2a}, M. Capua^{30a}, S. Caracciolo^{22a}, R. Cardarelli¹², T. Car¹⁰, S. Carino¹⁰, L. Carminar^{30a,30b}, B. Carlini³⁰, A. Antonelli⁴⁶, M. Anton⁴⁷, R. Anelli¹¹⁸, G. Arabi¹¹⁹, O. Cakir^{2a}, P. Calafura¹⁴, G. Calderini¹⁸, P. Califfay³⁶, R. Calkins¹⁰⁶, L.P. Calob^{22a}, R. Calvo⁴², S. Calvez⁴³, A. Camard¹⁸, P. Camara^{132a,132b}, M. Cambiaggi^{110a,110b}, D. Camarero^{22a}, M. Campanelli¹⁷, V. Canak^{102a,102b}, F. Canelli³⁰, A. Canepa^{10a}, J. Canter¹⁰, M.M. Capenas Garrido⁹, I. Capriotti^{2a}, M. Caprin^{2a}, D. Capriotti^{2a}, M. Capua^{30a}, S. Caracciolo^{22a}, R. Cardarelli¹², T. Car¹⁰, S. Carino¹⁰, L. Carminar^{30a,30b}, B. Carlini³⁰, A. Antonelli⁴⁶, M. Anton⁴⁷, R. Anelli¹¹⁸, G. Arabi¹¹⁹

L.F. Arguán¹¹⁰, E. Erik¹¹¹,
C. Arnau¹¹², A. Arjón¹¹³,
S. Ask¹⁷, B. Asman^{146a},
B. Aubert¹⁴, B. Auerbach¹⁴,
C. Ay¹⁴, G. Azzurro¹⁰²,
H. Bachacou³⁶, K. Badi¹,
Y. Bai¹²², D.C. Bailey¹,
E. Baktaneh-Mirzadeh¹⁷²,
J.R. Batstone¹¹, V. Batta-
rini¹¹, C. Basso¹¹, M. Cavig-
li-Mazzoni¹¹, A. Cattaui¹¹,
A. Cerni¹, L. Cerrito¹⁰,
K. Chan¹, B. Chapiro¹,
S. Cheshmian¹, S. Chelak-
hian¹⁷², S. Cheng¹⁷²,
N. Ellis²⁹, J. Elmsheuser⁵⁶, M. Elsing²⁹, R. Ely¹,
A. Eppig⁸⁷, J. Erdmann⁸⁴, A. Erodutalo¹⁶, C. Es-
tève¹⁶⁵, E. Ertef⁸¹, M. Escalier¹¹⁸, C. Exco-
let¹¹⁸, A. Etiennev¹³⁶, E. Etzion¹⁴³, D. Evyangelakou⁸⁴, R.M. Fakhrudin¹⁰, S. Falciano¹²³, A.C. Far-
ley¹⁴⁷, L. T. Faraouqe¹⁸⁸, S.M. Farrington¹¹⁸,
B. Fathollahzadeh¹⁸⁸

E. Banaś²⁸, P. Banerjee²⁹
S.P. Baranov³⁰, A. Barni³¹
M. Barbiero³², D.Y. Bar
R.M. Barnett³³, A. Bar
R. Barndorff-Nielsen³⁴, A.E. Bar
M. Battistin³⁵, G. Battis
R. Beccherle³⁶, P. Bec
E. Bied³⁷, S.L. Cheung³⁸
A. Chilingirian³⁹, F. Chio
A. Christof⁴⁰, D.S. Chrom
R. Cifuentes⁴¹, D. Cinc⁴², V.
M. Cishunskan⁴³, A. Clari
R.W. Cif⁴⁴, J. Coudan
J. Coggeshall⁴⁵, E. Cogge
N. Collins⁴⁶, C. C-lyde
I. Fedorko⁴⁷, W. Fedor
E.J. Feng⁴⁸, A.B. Feny
S. Ferrag⁴⁹, J. Ferrando
D. Ferrere⁵⁰, C. Ferret
P. Filthaut⁵¹, M. Finck
M.J. Fishes⁵², S.M. Fi
S. Fleischmann⁵³, T. Fl
J.C. Hill⁵⁴, N. Hill⁵⁵, K.
D. Hirschbuhl⁵⁶, J. H
J. Hoffman⁵⁷, D. Hoffm
J.L. Holzhauser⁵⁸, R.J.
J.Y. Hostachy⁵⁹, T.H.
I. Hristova⁶⁰, J. Hrivis
F. Huisman⁶¹, F. Hui

[illegible]

R.M. Hanchard,¹ M. Bissu
A. Bingu¹, L.C. Bini¹²⁵
G. Blanchot,²⁰ C. Bloche
V.B. Bobrovnikov¹⁰⁷, A.
J.A. Bogerts,²⁰ A. Bog
M. Boonchachan,² G. B.
A. Borison,¹²⁸ G. Borise
M. Boudry,¹²⁹ A. Boudry
A. Da Rocha Guedali,¹⁶ M.
C. Daliapour,¹⁰³, S.J. Dal
R. Danlers,¹⁰⁸, D. Danhe
W. Davey,¹² T. David,¹²
J.W. Dawood,¹⁰⁰, R.K. Day
L. De Groot¹⁰⁴, P. de Jon
L. De Noij¹⁰⁰, M. De Olie
H. De Smet,¹³⁴, H. De Smet
L. Gauthier,¹³⁵ L.I. Gav
Ch. Geich-Gimbel¹⁰⁰, S.
C. George,⁷⁶, P. Gerlach
B. Gincabov,¹⁰⁴, S. Gier
A. Gibson¹²⁸, S.M. Gils
V. Gilevsky¹⁰¹, D. Gills
F.M. Giorgio,¹⁰, P. Giov
C. Glaser,¹⁰⁶, I. Chav
W. Ji¹³¹, Y. Jiang,¹³², J.
L.G. Johannesen¹³³, M.J.
K. Jon-And¹⁴⁶, M. Kato
C. Joram¹²⁹, P.M. Joris
M. Kac¹⁴⁷, A. Kaczmarek
S. Kalinin¹³⁴, L.V. Kalin
J. Kazanek¹⁰, B. Kapla

C. Bottenrood¹⁰⁴, D. De Salicis¹⁰⁵, T. Giese¹⁰⁶, T. Giese¹⁰⁷, C. Gierke¹⁰⁸, C. Boursier¹⁰⁹, N. Bo
J. Bracinich¹¹⁰, A. Braem
O. Brandt¹¹¹, U. Bratzke
S. Bresles¹¹², D. Bretton
R. Brock¹¹³, J. D. Brodie
G. Brown¹¹⁴, E. Brubaker
A. Brunel¹¹⁵, C. Brunel¹¹⁶
D. D. Dvordovic¹¹⁷, J. Degen
D. Del Prete¹¹⁸, M. Del
M. Del Maestro¹¹⁹, P. Delpie
B. Demirkhan¹²⁰, J. Deng
P. Dervan¹²¹, K. Desch¹²²
R. Dhulipudi¹²³, A. Di Ci
A. Di Mattia¹²⁴, R. Di Nar
C. Giamfranceschi¹²⁵, C. Giardin
S. N. Golovinski¹²⁶, S. G
S. Gonzalez¹²⁷, S. Gonz
L. Goossens¹²⁸, P. A. Go
A. Gorisek¹²⁹, E. Gornic
M. Gostinik¹³⁰, M. Gou
A. G. Goussous¹³¹, C. G
V. Kartvelishvili¹³², E. Kat
Y. Katsukawa¹³³, E. Kat
M. S. Kaye¹³⁴, V. A. K
G. D. Kekelidze¹³⁵, M. K
B. P. Kerisvan¹³⁶, D. K
A. Khanov¹³⁷, D. Khan
N. Khavchinskii¹³⁸, V. K
K. Kim¹³⁹, S. H. Kim

R.M. Buckingham¹⁸, E.B. Diehl¹⁷, H. Diehl¹⁹, F. Gragnano^{20,21}, S.G.
C. Dionisi^{22,23}, P. Dita²⁴, E. Graziani^{13,24}, O.G.C.
D. Buira-Clark¹⁸, E.J.S. Burles²⁵, M. De Val²⁶, A. Do
P. Dobson²⁷, M. Dobson¹⁶, P. Grenier^{14,23}, E. Griem
I. Dolenc²⁸, Z. Dolzal²⁹, P.L.Y. Ricks^{13,23}, Y.V. Grien
J.M. Butterworth⁷⁷, W. J. Groth-Jensen⁷⁹, M.
A.D. Dixons¹⁰³, A.T. Do
M.D.-2¹⁰, I.C. Doris¹⁰⁴, S. Guindon⁹⁴, H. Güler
A. Gutierrez⁹³, P. Putis
A. Haas^{13,23}, S. Haas²⁰, G.

M. Tris¹, J.G. Drohan¹,
F. Dudak¹¹⁶, M. Dührsen¹,
R. Duxfield¹³⁰, M. Dwumr
K. Edmunds⁸¹, C.A. Edwards
K. Einsweiler¹⁴, E. Eisen

S. Haider²⁰, Z. Hajduk²,
L. Has^{52b}, K. Hanagaki¹,
J.D. Hansen²⁶, P.H. Ha
R.D. Harrington²¹, O.M
A. Harvey²⁵, S. Hasegaw
R. Hauser⁷⁶, M. Havran
D. Hayden⁷⁸, H. Hays
J. Kall⁸⁸, D. Kollar²⁰,
A.I. Kononov⁴⁵, R. K
K. Kordas¹⁵⁴, V. Kore
O. Kortner²⁹, S. Kort
A. Koutsman¹⁰⁹, R. K
V.A. Kramarenko⁹⁷, C
F. Krejci¹²⁷, J. Kretzsch
J. Kugelers²⁰, J. Ks

S. Heim²³, B. Reinemas²³,
C. Helsens¹¹, R.C.W. H.
F. Henry-Couannier²³,
G. Herten⁴⁸, R. Hertel¹,
S. Kuehn⁴⁸, A. Kugel¹,
M. Kunz⁸³, N. Kundu¹,
W. Kuykendall¹²⁸, M.
L. Labarga⁴⁹, J. Labbe¹,
E. Ladygin⁴⁹, R. Lafay¹,
W. Lamp⁴⁸, E. Lanco¹,
A.J. Lankford¹²⁹, F. L.

A.V. Larionov¹²⁸, A.
W. Lavrijsen¹⁴, P. Lay
E. Le Menedeu¹⁵⁶, M.
J.S.H. Lee¹⁶⁰, S.C. Lee

- The ATLAS collaborati

112a, 112b,
17, J. Gammin²⁰,
Capasso^{102a, 102b},
puto¹⁴⁸,
S. Caron⁴⁸,
J. Carvalho^{124a, b},
117

Emeliyanov¹²⁹, R. Engelmann¹⁴⁸, A. Eng¹⁶⁸, B. Epp⁶²
 en^{146a}, J. Ernst¹, M. Ernst²⁴, J. Erzwiese¹³⁶, D. Errede¹⁶⁰,
 Espinal Curall¹¹, B. Esposito⁴⁷, F. Etienne⁶³,
 Evans⁸¹, L. Fabbri^{100,106}, C. Fabre²⁰, K. Facius³⁵,
 Y. Fang¹⁷², M. Fantì^{89,80b}, A. Farbin⁷, A. Farilla^{134a},
 Farthouat³⁹, D. Fasching¹⁷², P. Faesnach²⁰, D. Faesoulotis⁵
 Fe¹³⁷, Fe¹³⁶, Fe¹³¹, Fe¹³¹, Fe¹³¹, Fe¹³¹, Fe¹³¹

Hilker⁴¹, S. Hillert²⁰, S.J. Hillier¹⁷, I. Hinchliffe¹⁴, E. Hines¹²⁰, M. Hiron¹¹⁶, F. Hirsch⁴²,
 43, N. Hod¹⁰³, M.C. Hodgkinson¹²⁰, P. Hodgson¹²⁰, A. Hoedker¹²⁰, M.R. Hoefkamp¹⁰²,
 88, M. Hohlfield¹⁶¹, M. Holder¹⁴¹, A. Holmes¹¹⁵, S.O. Holmgren^{146a}, T. Holy¹²⁷,
 17, Y. Homma⁸⁷, T. Horowitzovska¹²⁷, C. Horn¹⁴³, S. Horner⁴⁸, K. Horton¹¹⁸,
 S. Hoo¹⁸¹, M.A. Houlden¹²⁸, A. Hoommada^{108a}, J. Howarth⁸², D.F. Howell¹¹⁸,
 I. Hruska¹²⁰, T. Hryn'ova⁴, P.J. Hu¹⁷⁰, S.C. Hsu⁴, G.S. Huang¹¹¹, Z. Hubacek¹²⁷,
 6, T. Hui¹²⁷, 118, 119, 120, 121, 122, 123, 124, 125, 126, 127, 128, 129, 130, 131, 132, 133, 134, 135, 136, 137, 138, 139, 140, 141, 142, 143, 144, 145, 146, 147, 148, 149, 150, 151, 152, 153, 154, 155, 156, 157, 158, 159, 160, 161, 162, 163, 164, 165, 166, 167, 168, 169, 170, 171, 172, 173, 174, 175, 176, 177, 178, 179, 180, 181, 182, 183, 184, 185, 186, 187, 188, 189, 190, 191, 192, 193, 194, 195, 196, 197, 198, 199, 200, 201, 202, 203, 204, 205, 206, 207, 208, 209, 210, 211, 212, 213, 214, 215, 216, 217, 218, 219, 220, 221, 222, 223, 224, 225, 226, 227, 228, 229, 230, 231, 232, 233, 234, 235, 236, 237, 238, 239, 240, 241, 242, 243, 244, 245, 246, 247, 248, 249, 250, 251, 252, 253, 254, 255, 256, 257, 258, 259, 260, 261, 262, 263, 264, 265, 266, 267, 268, 269, 270, 271, 272, 273, 274, 275, 276, 277, 278, 279, 280, 281, 282, 283, 284, 285, 286, 287, 288, 289, 290, 291, 292, 293, 294, 295, 296, 297, 298, 299, 300, 301, 302, 303, 304, 305, 306, 307, 308, 309, 310, 311, 312, 313, 314, 315, 316, 317, 318, 319, 320, 321, 322, 323, 324, 325, 326, 327, 328, 329, 330, 331, 332, 333, 334, 335, 336, 337, 338, 339, 340, 341, 342, 343, 344, 345, 346, 347, 348, 349, 350, 351, 352, 353, 354, 355, 356, 357, 358, 359, 360, 361, 362, 363, 364, 365, 366, 367, 368, 369, 370, 371, 372, 373, 374, 375, 376, 377, 378, 379, 380, 381, 382, 383, 384, 385, 386, 387, 388, 389, 390, 391, 392, 393, 394, 395, 396, 397, 398, 399, 400, 401, 402, 403, 404, 405, 406, 407, 408, 409, 410, 411, 412, 413, 414, 415, 416, 417, 418, 419, 420, 421, 422, 423, 424, 425, 426, 427, 428, 429, 430, 431, 432, 433, 434, 435, 436, 437, 438, 439, 440, 441, 442, 443, 444, 445, 446, 447, 448, 449, 450, 451, 452, 453, 454, 455, 456, 457, 458, 459, 460, 461, 462, 463, 464, 465, 466, 467, 468, 469, 470, 471, 472, 473, 474, 475, 476, 477, 478, 479, 480, 481, 482, 483, 484, 485, 486, 487, 488, 489, 490, 491, 492, 493, 494, 495, 496, 497, 498, 499, 500, 501, 502, 503, 504, 505, 506, 507, 508, 509, 510, 511, 512, 513, 514, 515, 516, 517, 518, 519, 520, 521, 522, 523, 524, 525, 526, 527, 528, 529, 530, 531, 532, 533, 534, 535, 536, 537, 538, 539, 540, 541, 542, 543, 544, 545, 546, 547, 548, 549, 550, 551, 552, 553, 554, 555, 556, 557, 558, 559, 560, 561, 562, 563, 564, 565, 566, 567, 568, 569, 570, 571, 572, 573, 574, 575, 576, 577, 578, 579, 580, 581, 582, 583, 584, 585, 586, 587, 588, 589, 590, 591, 592, 593, 594, 595, 596, 597, 598, 599, 600, 601, 602, 603, 604, 605, 606, 607, 608, 609, 610, 611, 612, 613, 614, 615, 616, 617, 618, 619, 620, 621, 622, 623, 624, 625, 626, 627, 628, 629, 630, 631, 632, 633, 634, 635, 636, 637, 638, 639, 640, 641, 642, 643, 644, 645, 646, 647, 648, 649, 650, 651, 652, 653, 654, 655, 656, 657, 658, 659, 660, 661, 662, 663, 664, 665, 666, 667, 668, 669, 670, 671, 672, 673, 674, 675, 676, 677, 678, 679, 680, 681, 682, 683, 684, 685, 686, 687, 688, 689, 690, 691, 692, 693, 694, 695, 696, 697, 698, 699, 700, 701, 702, 703, 704, 705, 706, 707, 708, 709, 710, 711, 712, 713, 714, 715, 716, 717, 718, 719, 720, 721, 722, 723, 724, 725, 726, 727, 728, 729, 730, 731, 732, 733, 734, 735, 736, 737, 738, 739, 740, 741, 742, 743, 744, 745, 746, 747, 748, 749, 750, 751, 752, 753, 754, 755, 756, 757, 758, 759, 760, 761, 762, 763, 764, 765, 766, 767, 768, 769, 770, 771, 772, 773, 774, 775, 776, 777, 778, 779, 780, 781, 782, 783, 784, 785, 786, 787, 788, 789, 790, 791, 792, 793, 794, 795, 796, 797, 798, 799, 800, 801, 802, 803, 804, 805, 806, 807, 808, 809, 810, 811, 812, 813, 814, 815, 816, 817, 818, 819, 820, 821, 822, 823, 824, 825, 826, 827, 828, 829, 830, 831, 832, 833, 834, 835, 836, 837, 838

C. Leggett¹⁴, M. Lehtinen²⁰, G. Lehmann Miotto²⁹, M. Lehto^{35a}, X. Lei^a, M.A.L. Leite^{23c}, D. Lellouch¹⁷¹, J. Lellouch¹⁶⁸, M. Lelchouk³⁴, V. Lendermann^{38a}, K.J.C. Lesauvage^{144b}, T. Li^a, B. Lenzi³⁶, K. Leonhardt⁴³, C. Leroy⁹³, J.R. Lessard¹⁴⁷, J. Lesser¹⁴⁶, G.C. Lester²⁷, A. Le Veque^{33d}, D. Levin³⁷, L.J. Levinson¹²¹, M.S. Levitski¹²⁸, M. Lewandowski²⁶, N. Leyton S.I.^{32b}, X.-L. Li³⁷, Z. Liang²⁰, Z. Liang¹¹⁸, B. Liberti^{133a}, P. Lichtard²⁹, M. Lichtner³⁸, K. R. Lifshitz¹⁰², J.N. Lilley⁷, A. Limosani⁵⁰, M. Limper⁶³, S.C. Lin¹⁸¹, F. Linde¹⁰⁰, J.T. Liu E. Lipides²², L.J. Liu¹²⁰, A. Litke¹²⁰, J.S. M-F. Liu¹⁶⁹, A.M. Liu¹⁶⁹, Y. Liu¹⁶⁹

H. Lühr,¹ J.-F. Lüdtke,¹ M.
E. Lobodzinski¹⁰¹, A. P. I.
A. Logunov¹⁷⁹, C.W. Lu
R.E. Long¹⁷, L. Lopes
M.J. Losy^{180a}, X. Lou
L. Lu³⁹, H.J. Lubatti¹²
P. Fuehring⁶¹, G. Luij
J. Lundberg⁶, J. Luntz
P. Nemethy¹⁰⁸, A.A. Nepomuchenko^{25a}, M. Nemesi³, S.Y. Nesterov¹²¹, R.
R.M. Neves¹⁰⁸, P. Nevski²⁴, P.R. Newman¹⁷, R.B. Nielsen¹¹⁸, R.
F. Niedercomen¹¹⁰, J. Nielsen¹³⁷, T. Niimilä²⁰⁰, A. Nikiforov¹⁸⁵, V. Ni-
kolic¹⁸⁶, K.K. Nikolopoulos²⁴, H. Nilåsen⁶⁶, P. Nilsson¹, Y. Ninomiya¹⁸⁰, A. Ni-
lsson¹⁸⁷, D. Nisenzon¹⁸⁸, B. Nitzsche¹⁸⁹, A. Nizovskiy¹⁹⁰, L. Nolte¹⁹¹,
L. Nordlund¹⁹², M.M. Nomura¹¹⁰, I. Norrmäki¹⁵⁴, H. Nomoto¹⁸³, M. Noo-
O. Norriella Francisco¹¹, P.R. Norton¹²¹, J. Novakovic¹³⁰, M.M. Nomura¹⁹³,
A.-E. Nucio-Quintero²⁰, G. Nunes Hanninger²⁰, T. Nunnenmacher⁹⁸, E. Nuñez
S.W. O'Connell¹⁹⁴, D.C. O'Nell¹⁹⁵, W. Osipow¹⁹⁶, F.G. Otárola¹⁹⁷

H. Ma²⁴, L.L. Ma¹⁷²,
J. Machado Miguens¹²,
T. Maeno²⁴, P. Mitting¹,
C.A. Mazarati¹⁰⁴, Y. Ma¹,
A. Maio^{124a}, S. Majas¹,
F. Male¹⁰⁵, U. Malik¹⁶,
A. Manabe¹⁶, L. Mani¹,
A. Manó³⁴, T.M. Manó¹,
S.W. O'Keefe¹⁰, D.C.
S. Oskada¹⁰, J. Ojier⁴³,
H. Ohashi¹⁴⁰, T.K. Ooi¹,
A.G. Olchevski¹⁶⁰, M. O
J. Olzonowski¹², C. Om
F. Orellana⁴⁰, Y. Oren¹,
B. Oscualt¹⁶⁰, N. Oso
F. Ould-Saada¹¹⁷, A.
B.M. Salvachua Ferrando⁹, D. Salvatore³⁶,
H. Sandaker¹², H.G. Sander¹⁰¹, M.P. Sane
S. Sandvoss¹⁷⁴, D.P.C. Sankey¹²⁹, A. Sar
H. Santos^{124a}, J.G. Saravia^{124a, 1}, T. Sar
O. Sasmal⁶⁶, T. Sasmal⁶⁶, N. Sasmal⁶⁶, L.
V. Sayas²⁴, M. Saxon⁶³, L.P. Sayas¹,
J. Schachurschmidt⁴³, P. Schacht¹⁰

A. Mann ⁶⁰ , J.F. Mann ⁶¹	N. Ozturk ⁷ , A. Pacheco ⁶²	A.G. Schiavon ¹⁰⁷ , V. Scharf ¹⁰⁸	V. V.
L. March ³⁰ , P.M. March ³¹	D. Pallin ²³ , A. Palma ¹²	M. Schoppa ^{260,261} , S. Schönlank ²⁶²	H. T.
A. Marin ^{28(a)} , C.P. Marín ²⁸	S. Panitkin ²⁵ , D. Pante ²⁶	M. Schmitz ²⁶³ , A. Schöning ²⁶⁴	H. T.
S. Marti ^{29(a)} , A. Marti ²⁹	A. Paramonov ²⁷ , S.J. P. P.	C. Schroeder ²⁶⁵ , N. Schroe ²⁶⁶	H. T.
T.A. Martin ¹⁷ , B. Martin ¹⁸	E. Pasquellunich ^{122(a)} , A.	J.W. Schumacher ²⁶⁷ , M. Schuma ²⁶⁸	M. U.
F. Marzano ^{132(a)} , A. Marz ¹³²	J.R. Pater ⁸² , S. Patrio ⁸³	P. Schwenling ¹⁷ , R. Schwiene ¹⁸	F. U.
M. Ma ⁶⁴ , I. Maissa ^{14(a)}	H. Peng ¹⁷² , R. Pengo ²⁷²	E. Segura ¹⁴¹ , S.C. Seidel ¹⁷³	A. S.
P. Matricón ¹¹² , H. Ma ¹¹³	E. Perez Codina ¹¹⁴ , M.J.		

S.J. Maxfield²⁷, E.N. S.P. McKe²⁷, A. McFadyen¹³⁹, H. T.R. McMahon¹⁶, T.J. M. Medinini¹, R. Meislin⁴⁸, B. Meislin⁴⁸, A. Mengual^{106,130}, S. C. Moore¹⁰⁶, P. M. B. Seldén^{140a}, G. Sellers²⁷, M. S. Severini¹¹, M. Servio²⁶, M. Shapiro¹⁴, P.B. Shatalov²⁰, I. A. Shibaeva²⁵, S. Shimizu²⁹, P. Sicho²⁸, A. Sidoti¹⁵, A. Siehl²⁸, D. Silverstein¹⁴³, S.R. Silverstein¹⁴³, P. Sinervo¹⁰⁸, N.B. Sinner¹¹⁴, V. T.B. Sjurksen¹³, L.A. Skinnari¹⁴,

C. Meyer ¹⁷³ , J. F. S. Meyer ¹⁷⁴	V. Polychronakos ¹⁷⁵ , D. G. A. Papenoceno ¹⁷⁶ , D. S. Pospisil ¹⁷⁷ , I. N. Pot	K. Sliva ¹⁶¹ , T. J. Sloan ¹⁶² , J. Slovic ¹⁶³	J. V.
P. Miele ²⁰ , S. Migas ¹⁷⁸ , R. J. Miller ¹⁷⁹ , W. J. Mi	P. Pralavorio ¹⁸³ , S. P. P. M. Prichard ¹⁸⁴ , D. Pr	B. Smith ¹⁶⁷ , D. Smith ¹⁶⁸ , K. M. J. Snow ¹⁶⁹ , J. S. Smuerner ¹⁶⁵ , S. S	M. V.
M. Miñano ¹⁸⁰ , I. M. G. Mirabeli ^{182a} , I. M. V. A. Mitsou ¹⁸⁷ , S. M	X. Prudent ¹⁸⁵ , H. Przytycki ¹⁸⁶ , V. Rajendran ¹⁸⁷ , J. J. R	M. Solarik ¹⁷² , J. Solt ¹⁷² , U. Soldner ¹⁷⁰ , J. Sonderzucker ¹⁷⁴ , N. Sontz ¹⁷⁵ , V. S	M. V.
S. Mood ¹⁷ , S. Moeller	M. Rana ¹⁸⁰ , V. V. Radesi	S. Spagnolo ^{176, 178} , F. Spanio ¹⁷⁴ , M. Spouta ¹²⁶ , T. Spruitzen ¹⁶⁸	M. V.
		E. Srebrny ¹⁶⁹ , J. S. Srebrny ¹⁶⁹	J. von

A.M. Moiseev^{128,*}, R.
S. Montesano^{128,*}, R.
A. Moraes¹²⁸, A. Morai
P. Morettini^{10a}, M. Me
J.D. Morris⁷², H.G. M.
E.J. J.W. Moysa⁸⁴, M. M
A. Muji¹⁰⁵, A. Muir¹⁶
A.G. Mykura¹²⁸, M. F.
E. Stancu¹⁴², H.W. Stancu¹⁴², C.
P. Starovrovtov²⁴, A. Stane¹⁴², F.
I. Stel¹²⁷, B. Stelzer¹⁴², H.J. S.
T. Stockmann²⁹, M.C. Stockman
A. Strasner⁸¹, J. Strandberg¹⁷⁵
P. Strizene^{143b}, R. Ströhmer¹⁷⁵
I. Stur¹⁴², J. Stupak¹⁴⁸, P. S
C. Sahn¹⁰⁶, K. Saita⁸⁷, M. Suk¹

Y. Nakakuma ¹¹⁹ , K. N.	S. Rodier ¹²⁰ , D. Rodrig	K. Suruliza ^{164,165} , S. Sushkov ¹⁶¹	J. We
N.R. Nation ¹²¹ , T. Nat	A. Romanovic ¹⁶⁶ , V.M.	I. Sylora ^{144,144} , T. Sylora ¹²⁶ , B. S	B. S
A. Negri ^{119a,119b} , G. N	M. Rose ¹²⁰ , G.A. Rosen	A. Tapa ¹⁷¹ , N. Taublim ¹⁵¹ , Y. T	S.J. V
	L.P. Rossi ¹⁶¹ , L. Rossi ¹	A. Talyshchev ¹⁰⁷ , M.C. Tammet ²⁴	C. W
	C.R. Royon ¹³⁶ , A. Roz	N. Tannoury ⁸³ , P.P. Tappers ²⁰	D. W
	G. Rudolph ¹⁶² , F. Rühr	P. The ¹²⁶ , M. Tsvetkova ¹²⁹ , E. T	C. W
	K. Runge ¹²⁰ , O. Runolf	G.N. Taylor ⁸⁶ , W. Taylor ^{106b} , A	E. W
		D.K. Tey ¹⁵¹ , Y.D. Tenenbaum	T. W

P. Ruzicki,¹²⁰ Y.F. Ry
A.F. Saavedra¹⁰⁰, I. Sa
G. Salamanna¹⁰⁵, A. S

Correspondence: D.R. Tovey^{1,2*}, D. Traynor^{1,2}, T. S. Trincas-Duvold^{1,2}, T.N. Trinh¹, C. Troncon^{3,4}, M. Trotter-McD¹, P.V. Tsirehchik^{5,6}, D. Tsionon^{1,2}

H. Zhang
S. Zhai
G. Zeng

I. van Vulpen¹⁰⁵

Leitzner¹²⁶
G. Lenzen¹⁷⁴
Book Cheong¹⁷²,
L. Li⁸³, H. Li¹⁷²,
W. Liebzig¹,
Li⁸⁸
Li^{121, 86}

Neubauer¹⁶⁵, A. Neusiedl⁸¹,
 Plaidou¹⁵⁶, L. Nicola¹³⁰, B. Niquevert²⁰,
 Planken¹²⁸, K. Nikolaev⁶⁰, I. Nikolic-Audit⁷⁸,
 132a, T. Nishiyama⁶⁷, R. Nisim⁶⁰,
 50, B. Nordkvist^{146a, 146b},
 M. Nosicka¹¹, I.M. Nugent^{100a},
 77, T. Nyman²⁰, B.J. O'Brien⁴⁰,
 160, L. O'Connell⁷⁵, A. Oishi⁵, S. Oki¹⁸⁰

¹⁴⁹ b. F. Salvatore¹⁴⁹, A. Salzburger¹⁵⁰, D. Samonidisa¹⁰⁴, B.H. Sameset¹¹⁷,
¹⁰⁸ M. Sandhoff¹⁷⁴, P. Sandlin¹⁵¹, T. Sanwald²⁷, R. Sandstrom¹⁰⁸,
¹⁴⁷ G. C. Santamarina-Rios⁹⁸, C. Santoni¹⁵², R. Santonicio^{133a,133b},
¹⁷² E. Sarkisyan-Grinbaum¹, F. Sarri^{126,127b}, G. Sartisohn¹⁷⁴,
unkевич¹⁰⁰, G. Sauvage¹, P. Savary^{108,99}, V. Savinov¹²³, P. Savva⁹,
Sharra^{10a,10b}, A. Shirazi^{10a,10b}, Scallan⁹³, D.A. Scannicchio¹⁶³

¹ Jia²⁹, J.-W. Tsung²⁰, S. Tsuchida⁶⁶, D. Tsybichev⁴⁸, A. Tuz¹³⁸, J.M. Tuggle⁵⁰, M. Turah³⁸, D. Ty
Chakr⁴⁶, E. Turley¹⁰⁵, P.M. Tuttle³⁴, A. Tykhonov⁷⁴, M. Tymal^{146a,146b}, M. Tyndel¹²⁹, D. Tysdal
⁶ G. Tzanakos⁸⁸, K. Uchida²⁰, I. Ueda¹³⁸, R. Ueno³⁸, M. Ugland¹³, M. Uhlenbrock²⁰,
nacher³⁴, F. Takagaki⁶⁶, G. Unal²⁹, D.G. Underwood⁴, A. Undrus²⁴, G. Unel¹⁶³, Y. Uno⁶⁶, D. U
S¹⁵³, P. Urquijo¹⁴⁹, P. Urrejola¹¹⁴, G. Usai⁷, M. Uslenghi^{110a,110b}, L. Vaczargy⁸³, V. Vacko¹²²,
⁸⁵ S. Valassi¹³⁸, C. Vallier¹³⁰, J. Van Driessche^{132a}, S. Valishev^{132a}, S. Valkar^{132a}, S. Valm
Jia²⁹, J.-W. Tsung²⁰, S. Tsuchida⁶⁶, D. Tsybichev⁴⁸, A. Tuz¹³⁸, J.M. Tuggle⁵⁰, M. Turah³⁸, D. Ty
Chakr⁴⁶, E. Turley¹⁰⁵, P.M. Tuttle³⁴, A. Tykhonov⁷⁴, M. Tymal^{146a,146b}, M. Tyndel¹²⁹, D. Tysdal
⁶ G. Tzanakos⁸⁸, K. Uchida²⁰, I. Ueda¹³⁸, R. Ueno³⁸, M. Ugland¹³, M. Uhlenbrock²⁰,
nacher³⁴, F. Takagaki⁶⁶, G. Unal²⁹, D.G. Underwood⁴, A. Undrus²⁴, G. Unel¹⁶³, Y. Uno⁶⁶, D. U
S¹⁵³, P. Urquijo¹⁴⁹, P. Urrejola¹¹⁴, G. Usai⁷, M. Uslenghi^{110a,110b}, L. Vaczargy⁸³, V. Vacko¹²²,
⁸⁵ S. Valassi¹³⁸, C. Vallier¹³⁰, J. Van Driessche^{132a}, S. Valishev^{132a}, S. Valkar^{132a}, S. Valm

¹⁰⁰ J. van der Steep²⁰, B. Van Eijk¹⁰⁸, N. van Eldik⁸⁴, P. van Gemmeren⁸, Z. van Kesteren¹⁰⁰, W. Vandell²⁰, G. Vandoni²⁰, A. Vaniachine¹, P. Vankov⁴¹, F. Vannucci⁷⁸, F. Varela Rolo¹⁰⁰, E. W. Varnes⁶, D. Varouchas¹⁴, A. Vartapetian¹, K.E. Varvell¹⁰⁰, V.I. Vassilikopoulos¹⁶, F. Vassilopoulos^{83a,83b}, J.J. Veillet¹¹⁵, C. Velidris⁶, F. Veloso^{124a}, R. Venes²², S. Veneziano¹²⁴, A. Ventura^{72a,72c}, M. Venturi⁴⁷, M. Verbeke⁴⁸, N. Verbeke¹⁶, W. Verkerke^{112a}, M. Vermaas¹³⁸, M. Vichit¹⁰⁰

¹A. S. Ventura,²M. Venturi,³N. Venturi,⁴V. Vercesi,⁵M. Verdino,⁶V. Vesterke
neulen⁷,⁸A. Vest⁹,M.C. Vetterli^{10,22},J. Viehou¹⁶,T. Vickes^{148,a},G.H.A. Viechhaus¹¹⁸,S.
^{19,126},M. Villaplana Perez¹⁶⁷,E. Vilucchi⁴⁷,M.G. Vincet²⁸,E. Vinek²⁰,V.B. Vinogradov⁶⁵,
Vlasov¹⁵⁶,S. Vitrec³³,J. Virzi¹⁴,A. Vitale^{104,106},O. Vitells¹⁷¹,I. Vivarelli⁴⁵,F. Vives Vaque¹¹,S.
¹²⁷,N. Vlasov²⁰,A. Vogel²⁰,P. Volok¹²⁷,M. Volpi¹,G. Volpin⁶⁵,H. von der Schmitten⁵⁰,
50,H. von Radziewski⁴⁸,E. von Toernow²⁰,V. Vorobel¹²⁶,A.P. Vorobiev¹²⁸,V. Vorwerk¹¹,
20,20,20,V. Wata¹¹⁴,W. Wiedemann¹⁷³,C.W. Wimmer¹³⁸,N. Winkler¹²⁴,M. Winter¹²⁴,V. Winter
124

J.I. Vosses⁹, J.H. Vossebeide¹⁰, A.S. Vovenko¹¹, N. Vranjes¹², M. Vranjes Milosavljevic¹³, V.
twijf¹⁴, T. Vu An¹⁵, R. Vuilleumier²⁰, I. Vukotic¹¹⁸, W. Wagner⁷⁴, P. Wagner¹²⁰, H. Wahlén¹⁷⁴
oyashiki¹⁰¹, J. Wallberndt⁴², S. Walden⁸⁷, J. Walder⁷¹, R. Walker⁶⁸, W. Walkowiak¹⁴¹, R. Wall¹⁷⁵
C. Wang⁴⁴, H. Wang¹⁷², J. Wang¹⁵¹, J. Wang²²⁴, J.C. Wang¹³⁸, S.M. Wang¹⁶¹, A. Warburton
rd⁷², M. Warsinsky⁶⁸, P.M. Watkins¹⁷, A.T. Watson¹²⁷, M.F. Watson¹⁷, G. Watts¹³⁸, S. Watts⁸²
ugh¹⁶⁰, B.M. Waugh⁷⁷, J. Weber⁴², M. Weber¹²⁰, M.S. Weber⁴², P. Weber⁵⁴, A.R. Weidberg¹¹⁸
C.B. Weir¹²⁶, D.S. Weiss¹²⁹, W.E. White⁴⁷, T. White²⁴, S.W. White¹³², T.

[illegible][illegible]

Tomiyama¹, K. Yorita¹, H. Yoshida², C. Young³, S.P. Yousefi⁴, D. Yu⁵, J. Yu⁶, J. Yu⁷, J. Yu⁸, J. Yu⁹, J. Yu¹⁰, J. Yu¹¹, J. Yu¹², J. Yu¹³, J. Yu¹⁴, J. Yu¹⁵, J. Yu¹⁶, J. Yu¹⁷, J. Yu¹⁸, J. Yu¹⁹, J. Yu²⁰, J. Yu²¹, J. Yu²², J. Yu²³, J. Yu²⁴, J. Yu²⁵, J. Yu²⁶, J. Yu²⁷, J. Yu²⁸, J. Yu²⁹, J. Yu³⁰, J. Yu³¹, J. Yu³², J. Yu³³, J. Yu³⁴, J. Yu³⁵, J. Yu³⁶, J. Yu³⁷, J. Yu³⁸, J. Yu³⁹, J. Yu⁴⁰, J. Yu⁴¹, J. Yu⁴², J. Yu⁴³, J. Yu⁴⁴, J. Yu⁴⁵, J. Yu⁴⁶, J. Yu⁴⁷, J. Yu⁴⁸, J. Yu⁴⁹, J. Yu⁵⁰, J. Yu⁵¹, J. Yu⁵², J. Yu⁵³, J. Yu⁵⁴, J. Yu⁵⁵, J. Yu⁵⁶, J. Yu⁵⁷, J. Yu⁵⁸, J. Yu⁵⁹, J. Yu⁶⁰, J. Yu⁶¹, J. Yu⁶², J. Yu⁶³, J. Yu⁶⁴, J. Yu⁶⁵, J. Yu⁶⁶, J. Yu⁶⁷, J. Yu⁶⁸, J. Yu⁶⁹, J. Yu⁷⁰, J. Yu⁷¹, J. Yu⁷², J. Yu⁷³, J. Yu⁷⁴, J. Yu⁷⁵, J. Yu⁷⁶, J. Yu⁷⁷, J. Yu⁷⁸, J. Yu⁷⁹, J. Yu⁸⁰, J. Yu⁸¹, J. Yu⁸², J. Yu⁸³, J. Yu⁸⁴, J. Yu⁸⁵, J. Yu⁸⁶, J. Yu⁸⁷, J. Yu⁸⁸, J. Yu⁸⁹, J. Yu⁹⁰, J. Yu⁹¹, J. Yu⁹², J. Yu⁹³, J. Yu⁹⁴, J. Yu⁹⁵, J. Yu⁹⁶, J. Yu⁹⁷, J. Yu⁹⁸, J. Yu⁹⁹, J. Yu¹⁰⁰, J. Yu¹⁰¹, J. Yu¹⁰², J. Yu¹⁰³, J. Yu¹⁰⁴, J. Yu¹⁰⁵, J. Yu¹⁰⁶, J. Yu¹⁰⁷, J. Yu¹⁰⁸, J. Yu¹⁰⁹, J. Yu¹¹⁰, J. Yu¹¹¹, J. Yu¹¹², J. Yu¹¹³, J. Yu¹¹⁴, J. Yu¹¹⁵, J. Yu¹¹⁶, J. Yu¹¹⁷, J. Yu¹¹⁸, J. Yu¹¹⁹, J. Yu¹²⁰, J. Yu¹²¹, J. Yu¹²², J. Yu¹²³, J. Yu¹²⁴, J. Yu¹²⁵, J. Yu¹²⁶, J. Yu¹²⁷, J. Yu¹²⁸, J. Yu¹²⁹, J. Yu¹³⁰, J. Yu¹³¹, J. Yu¹³², J. Yu¹³³, J. Yu¹³⁴, J. Yu¹³⁵, J. Yu¹³⁶, J. Yu¹³⁷, J. Yu¹³⁸, J. Yu¹³⁹, J. Yu¹⁴⁰, J. Yu¹⁴¹, J. Yu¹⁴², J. Yu¹⁴³, J. Yu¹⁴⁴, J. Yu¹⁴⁵, J. Yu¹⁴⁶, J. Yu¹⁴⁷, J. Yu¹⁴⁸, J. Yu¹⁴⁹, J. Yu¹⁵⁰, J. Yu¹⁵¹, J. Yu¹⁵², J. Yu¹⁵³, J. Yu¹⁵⁴, J. Yu¹⁵⁵, J. Yu¹⁵⁶, J. Yu¹⁵⁷, J. Yu¹⁵⁸, J. Yu¹⁵⁹, J. Yu¹⁶⁰, J. Yu¹⁶¹, J. Yu¹⁶², J. Yu¹⁶³, J. Yu¹⁶⁴, J. Yu¹⁶⁵, J. Yu¹⁶⁶, J. Yu¹⁶⁷, J. Yu¹⁶⁸, J. Yu¹⁶⁹, J. Yu¹⁷⁰, J. Yu¹⁷¹, J. Yu¹⁷², J. Yu¹⁷³, J. Yu¹⁷⁴, J. Yu¹⁷⁵, J. Yu¹⁷⁶, J. Yu¹⁷⁷, J. Yu¹⁷⁸, J. Yu¹⁷⁹, J. Yu¹⁸⁰, J. Yu¹⁸¹, J. Yu¹⁸², J. Yu¹⁸³, J. Yu¹⁸⁴, J. Yu¹⁸⁵, J. Yu¹⁸⁶, J. Yu¹⁸⁷, J. Yu¹⁸⁸, J. Yu¹⁸⁹, J. Yu¹⁹⁰, J. Yu¹⁹¹, J. Yu¹⁹², J. Yu¹⁹³, J. Yu¹⁹⁴, J. Yu¹⁹⁵, J. Yu¹⁹⁶, J. Yu¹⁹⁷, J. Yu¹⁹⁸, J. Yu¹⁹⁹, J. Yu²⁰⁰, J. Yu²⁰¹, J. Yu²⁰², J. Yu²⁰³, J. Yu²⁰⁴, J. Yu²⁰⁵, J. Yu²⁰⁶, J. Yu²⁰⁷, J. Yu²⁰⁸, J. Yu²⁰⁹, J. Yu²¹⁰, J. Yu²¹¹, J. Yu²¹², J. Yu²¹³, J. Yu²¹⁴, J. Yu²¹⁵, J. Yu²¹⁶, J. Yu²¹⁷, J. Yu²¹⁸, J. Yu²¹⁹, J. Yu²²⁰, J. Yu²²¹, J. Yu²²², J. Yu²²³, J. Yu²²⁴, J. Yu²²⁵, J. Yu²²⁶, J. Yu²²⁷, J. Yu²²⁸, J. Yu²²⁹, J. Yu²³⁰, J. Yu²³¹, J. Yu²³², J. Yu²³³, J. Yu²³⁴, J. Yu²³⁵, J. Yu²³⁶, J. Yu²³⁷, J. Yu²³⁸, J. Yu²³⁹, J. Yu²⁴⁰, J. Yu²⁴¹, J. Yu²⁴², J. Yu²⁴³, J. Yu²⁴⁴, J. Yu²⁴⁵, J. Yu²⁴⁶, J. Yu²⁴⁷, J. Yu²⁴⁸, J. Yu²⁴⁹, J. Yu²⁵⁰, J. Yu²⁵¹, J. Yu²⁵², J. Yu²⁵³, J. Yu²⁵⁴, J. Yu²⁵⁵, J. Yu²⁵⁶, J. Yu²⁵⁷, J. Yu²⁵⁸, J. Yu²⁵⁹, J. Yu²⁶⁰, J. Yu²⁶¹, J. Yu²⁶², J. Yu²⁶³, J. Yu²⁶⁴, J. Yu²⁶⁵, J. Yu²⁶⁶, J. Yu²⁶⁷, J. Yu²⁶⁸, J. Yu²⁶⁹, J. Yu²⁷⁰, J. Yu²⁷¹, J. Yu²⁷², J. Yu²⁷³, J. Yu²⁷⁴, J. Yu²⁷⁵, J. Yu²⁷⁶, J. Yu²⁷⁷, J. Yu²⁷⁸, J. Yu²⁷⁹, J. Yu²⁸⁰, J. Yu²⁸¹, J. Yu²⁸², J. Yu²⁸³, J. Yu²⁸⁴, J. Yu²⁸⁵, J. Yu²⁸⁶, J. Yu²⁸⁷, J. Yu²⁸⁸, J. Yu²⁸⁹, J. Yu²⁹⁰, J. Yu²⁹¹, J. Yu²⁹², J. Yu²⁹³, J. Yu²⁹⁴, J. Yu²⁹⁵, J. Yu²⁹⁶, J. Yu²⁹⁷, J. Yu²⁹⁸, J. Yu²⁹⁹, J. Yu³⁰⁰, J. Yu³⁰¹, J. Yu³⁰², J. Yu³⁰³, J. Yu³⁰⁴, J. Yu³⁰⁵, J. Yu³⁰⁶, J. Yu³⁰⁷, J. Yu³⁰⁸, J. Yu³⁰⁹, J. Yu³¹⁰, J. Yu³¹¹, J. Yu³¹², J. Yu³¹³, J. Yu³¹⁴, J. Yu³¹⁵, J. Yu³¹⁶, J. Yu³¹⁷, J. Yu³¹⁸, J. Yu³¹⁹, J. Yu³²⁰, J. Yu³²¹, J. Yu³²², J. Yu³²³, J. Yu³²⁴, J. Yu³²⁵, J. Yu³²⁶, J. Yu³²⁷, J. Yu³²⁸, J. Yu³²⁹, J. Yu³³⁰, J. Yu³³¹, J. Yu³³², J. Yu³³³, J. Yu³³⁴, J. Yu³³⁵, J. Yu³³⁶, J. Yu³³⁷, J. Yu³³⁸, J. Yu³³⁹, J. Yu³⁴⁰, J. Yu³⁴¹, J. Yu³⁴², J. Yu³⁴³, J. Yu³⁴⁴, J. Yu³⁴⁵, J. Yu³⁴⁶, J. Yu³⁴⁷, J. Yu³⁴⁸, J. Yu³⁴⁹

¹Y. Zhu^{1,12}, A. Zhuang¹, V. Zhuraviov¹, D. Ziemanski¹, B. Zilka^{1,12}, R. Zimmermann¹,
ermann²⁰, S. Zimmermann⁴⁸, M. Ziolkowski¹⁴¹, R. Zitoun¹, I. Zivkovic³⁴, V.V. Zmouchen^{128,x},
nig¹⁷², A. Zoccol^{19a,19b}, Y. Zolnierowski⁴, A. Zsenc²⁹, M. zur Nedden¹⁵, V. Zutshi¹⁰⁶, L. Zwalin

I. van Vulpen¹⁰⁵

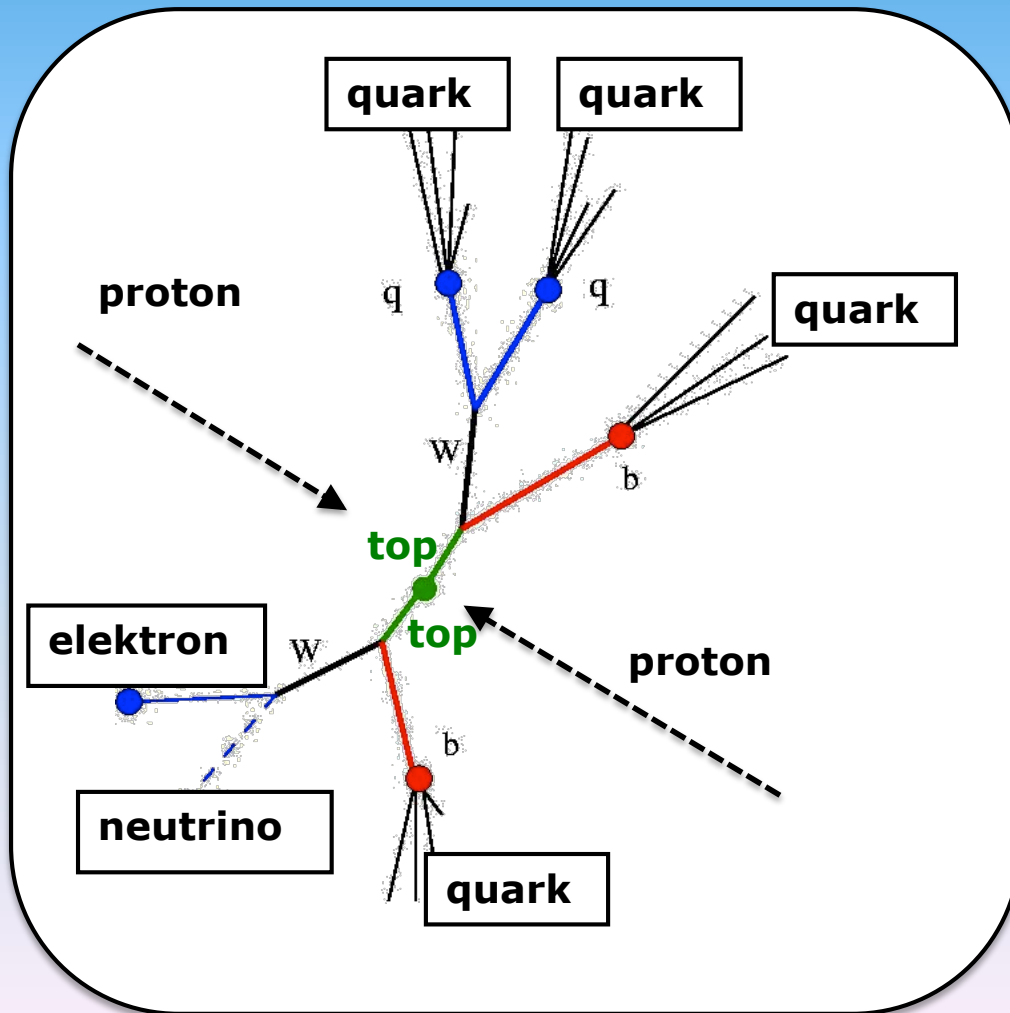
- The ATLAS collaboration

... het echte werk!

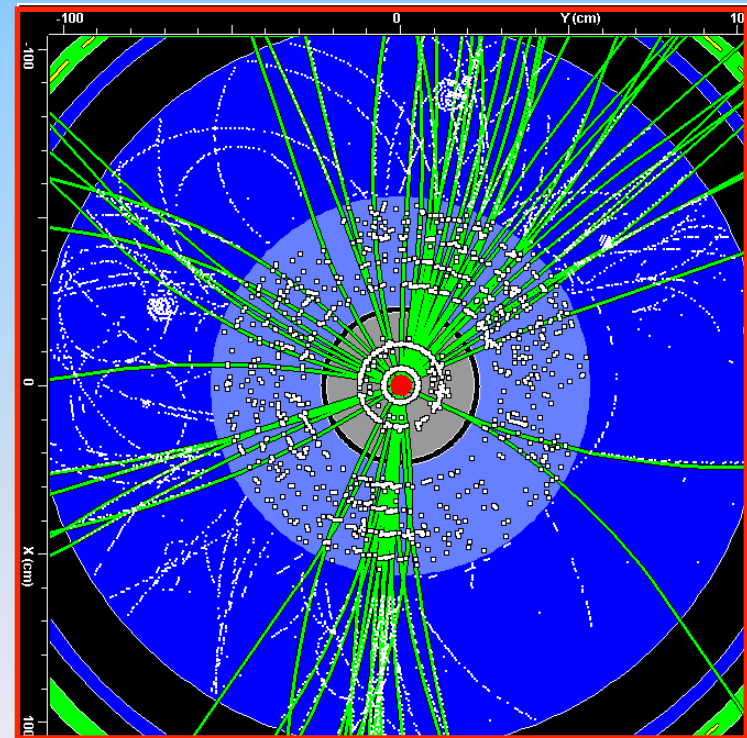


Interpreting LHC events

top quark pair-production



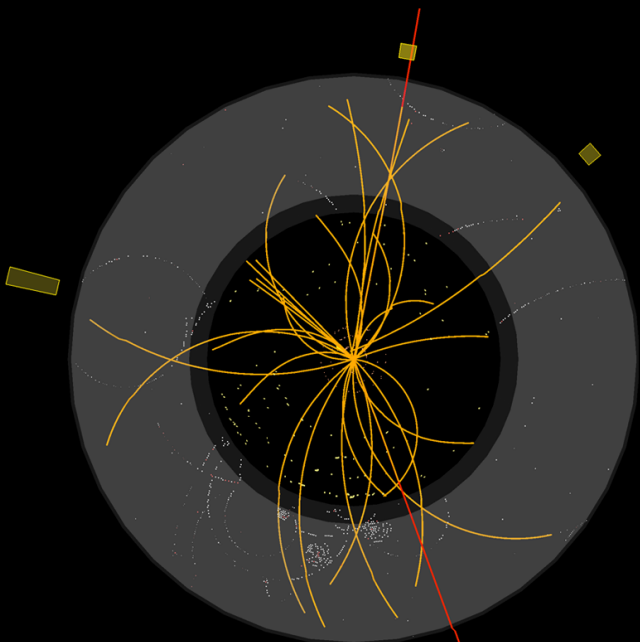
Simulation top quark production





ATLAS EXPERIMENT

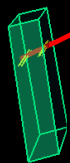
Run: 154822, Event: 14321500
Date: 2010-05-10 02:07:22 CEST



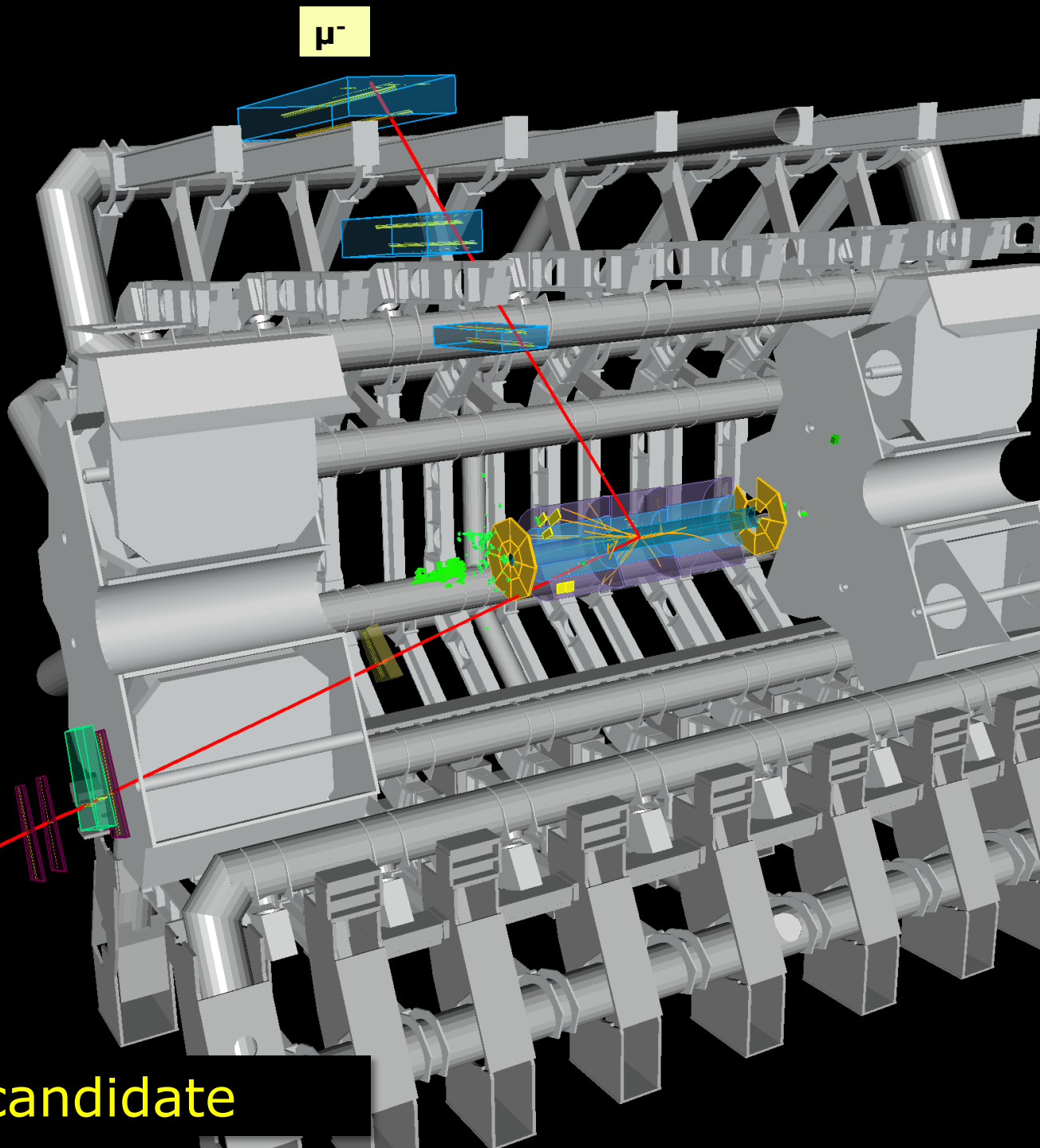
$p_T(\mu^-) = 27 \text{ GeV}$ $\eta(\mu^-) = 0.7$
 $p_T(\mu^+) = 45 \text{ GeV}$ $\eta(\mu^+) = 2.2$

$M_{\mu\mu} = 87 \text{ GeV}$

μ^+

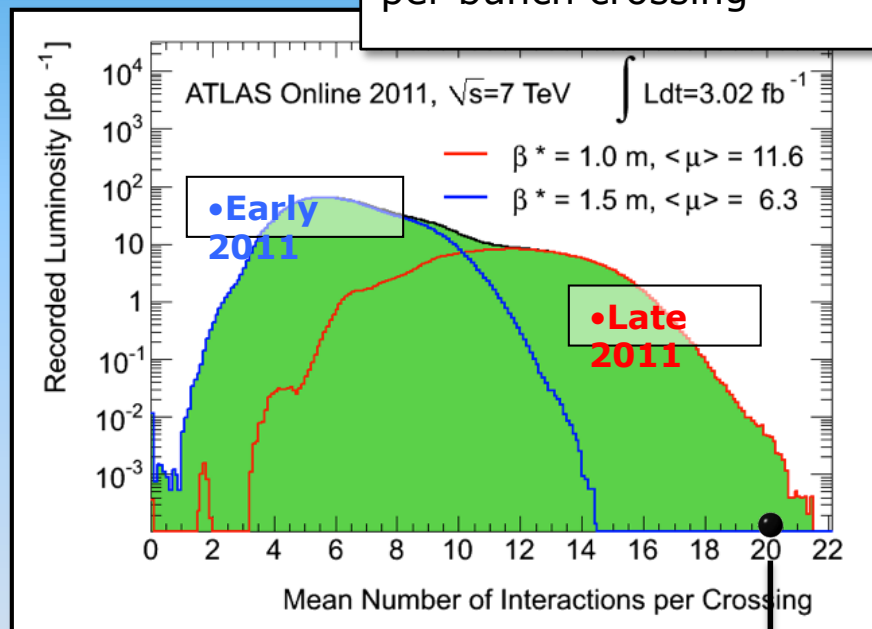


$Z \rightarrow \mu^+\mu^-$ candidate

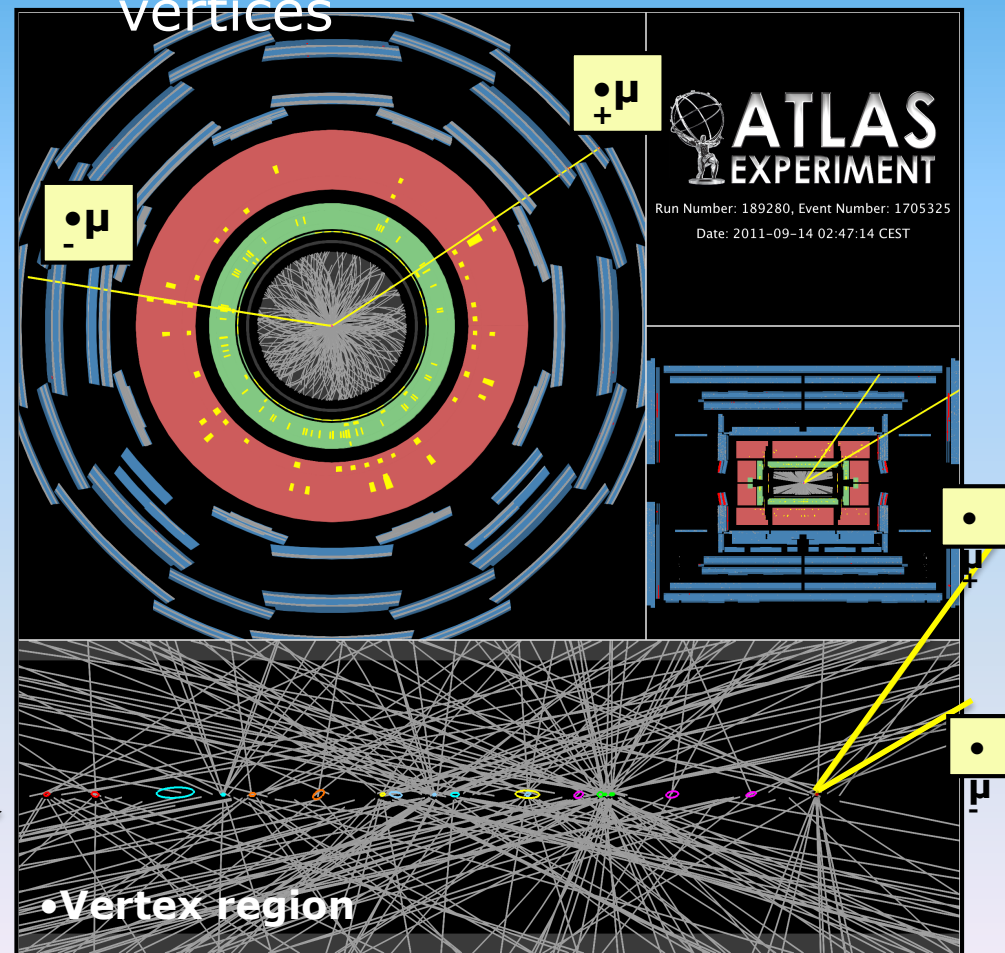


- LHC is not a quiet environment

- Number of interactions per bunch crossing

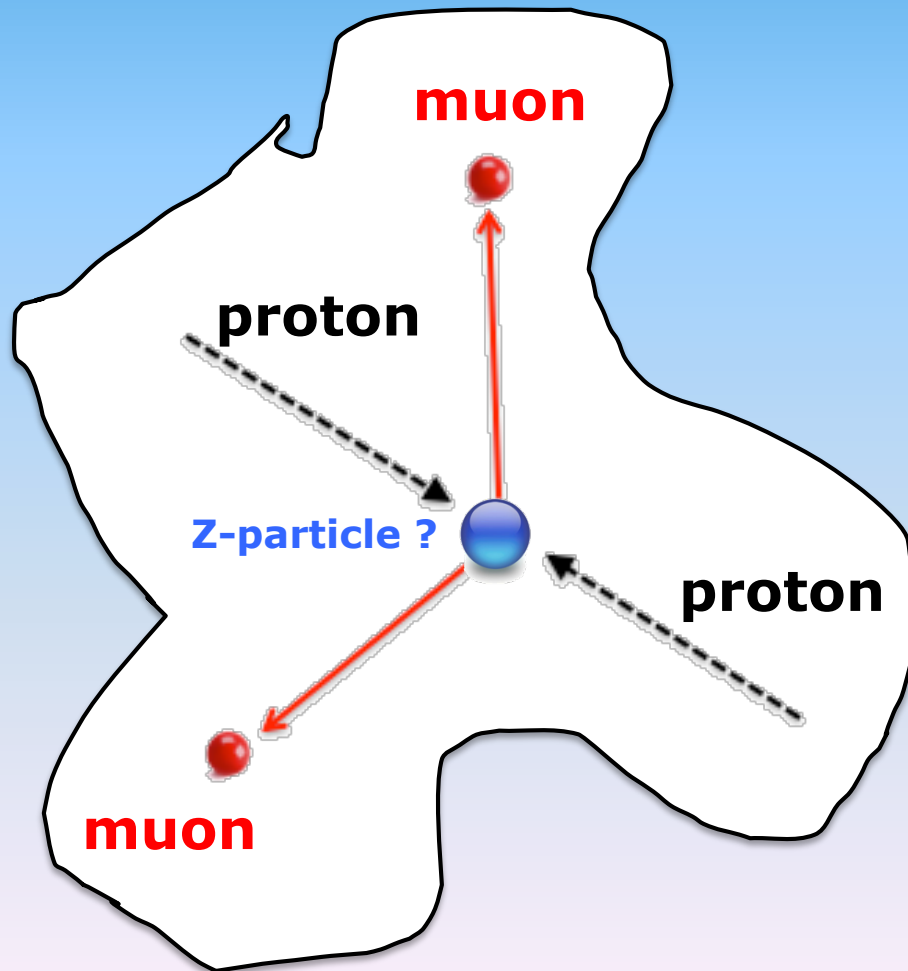


- $Z \rightarrow \mu^+ \mu^-$ event with 20 vertices

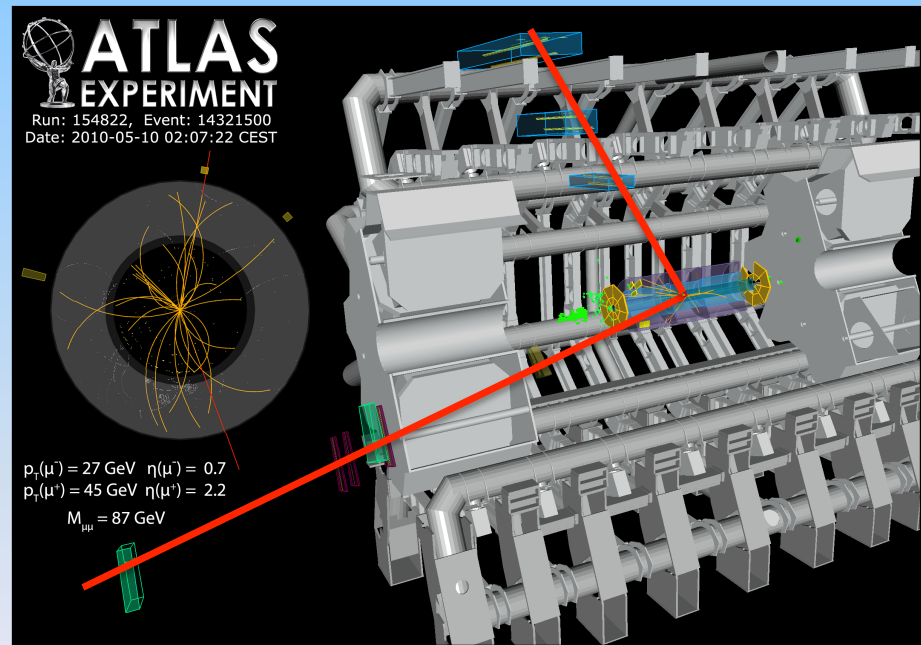


How do you discover a Z particle ?

Deviations from the prediction without a Z boson



2-muons as seen in the ATLAS detector



What is the fingerprint of the Z particle:
→ the di-muon mass

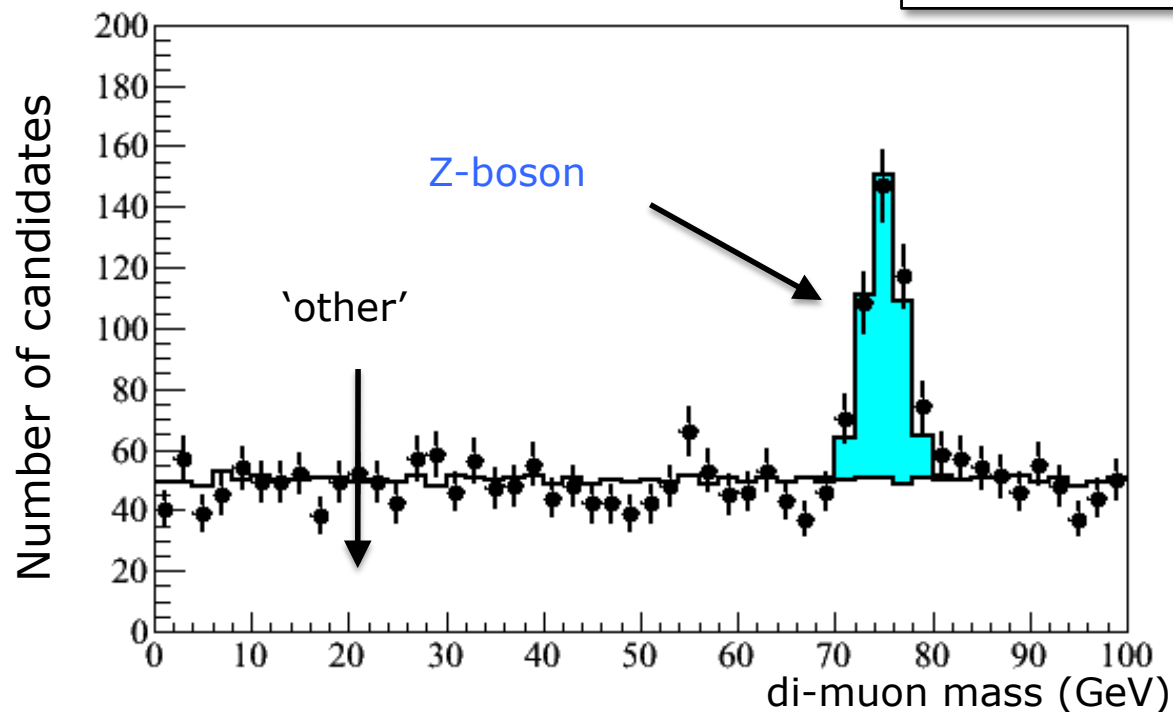
di-muon mass



'other': no preference/structure

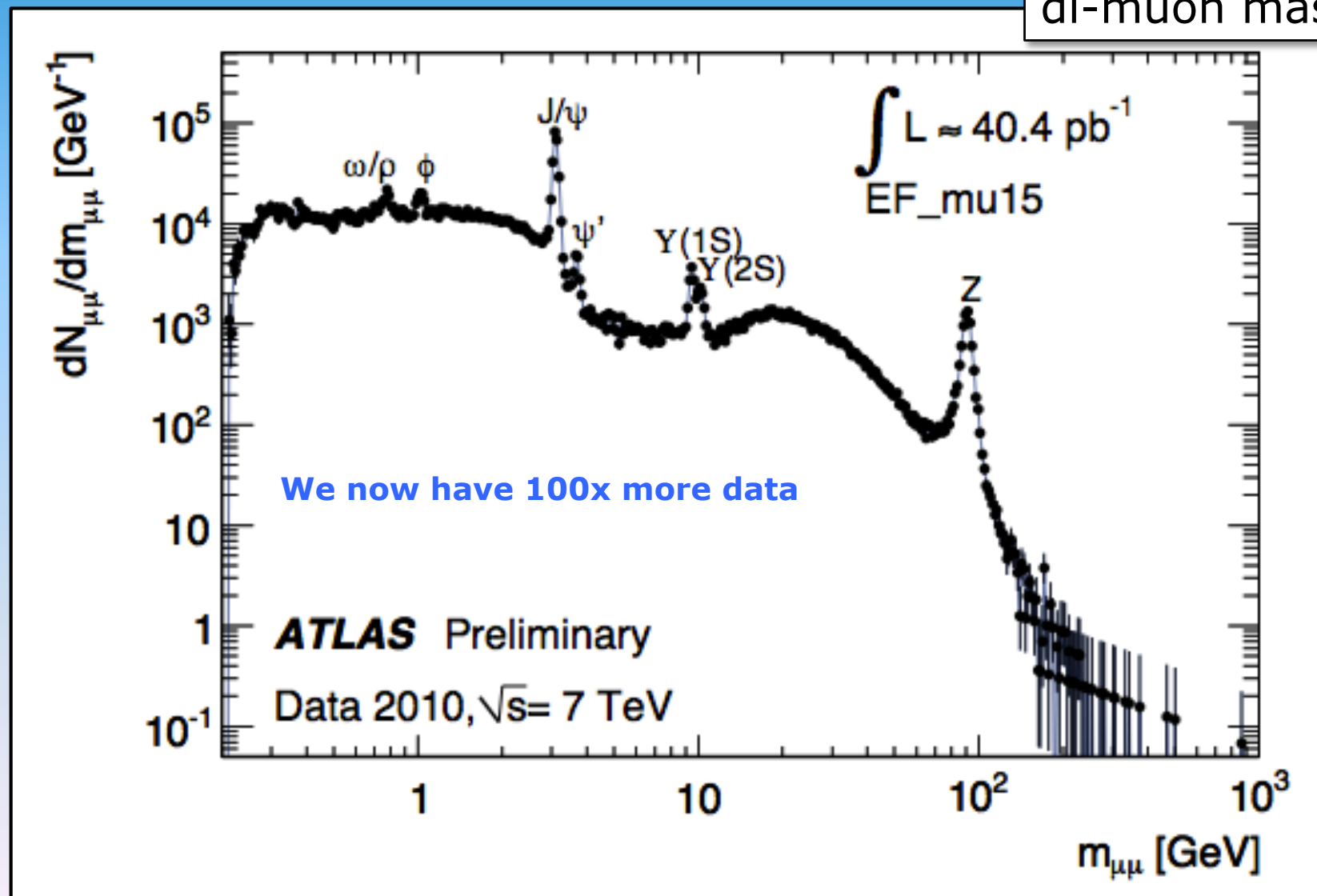
Z-boson: Breit-Wigner $\otimes$ resolution

di-muon mass



Di-muon resonances in proton-proton

di-muon mass



**THE SEARCH FOR THE
HIGGS BOSON**

Het Higgs boson



Laatst missende puzzelstukje

Als hij bestaat: 1 x per miljard botsingen gemaakt
... daarna vervalt hij onmiddellijk in 'normale' deeltjes

(In)famous Higgs boson



The Higgs boson



Paris Hilton

Famous and constantly in the news
... but are they important ?

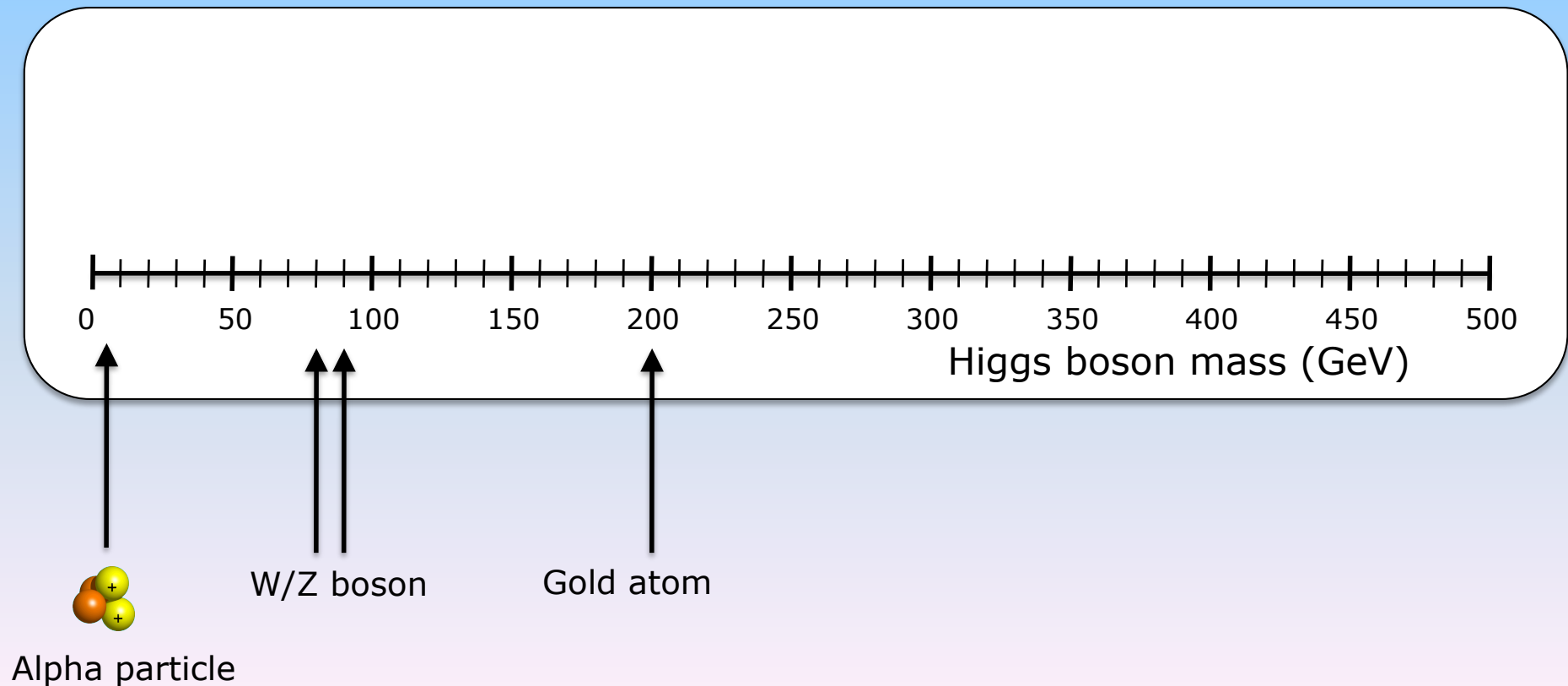
If the Higgs boson is discovered
it will go straight into our history
books



If the Higgs boson is **not** discovered
it will **also** go straight into our history
books

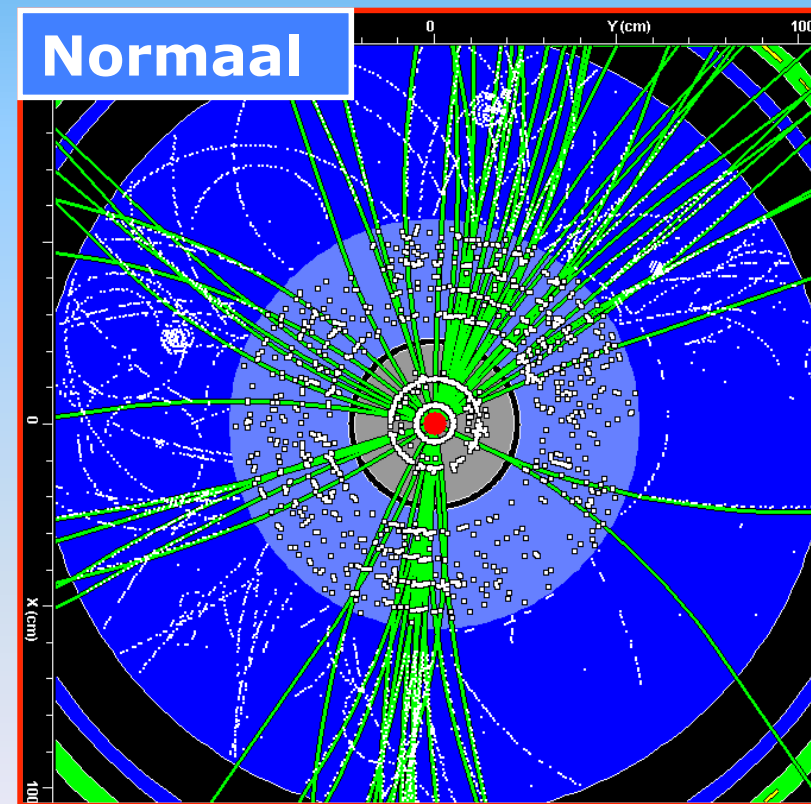
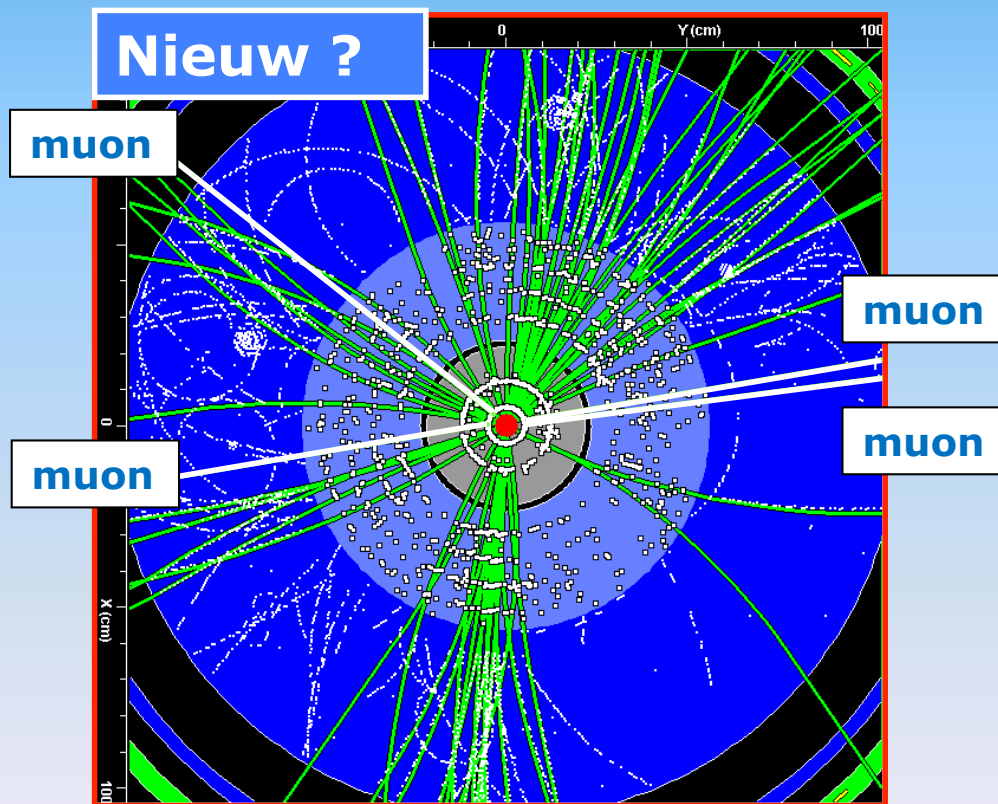


The mass of the Higgs boson



Hoe ontdek je nou nieuwe dingen: Higgs boson

Nieuwe afstandschaal EN nieuwe detector



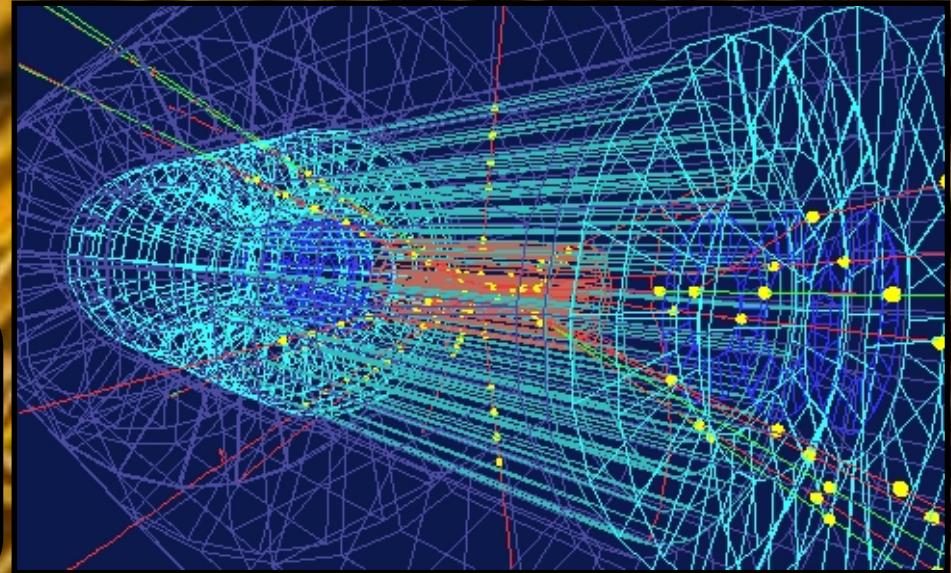
Ja ... Higgs is heel klein wel

... computing ... ook geen eitje



Fotootjes kijken

40 miljoen botsingen per seconde
mag maar 200 per seconde opslaan

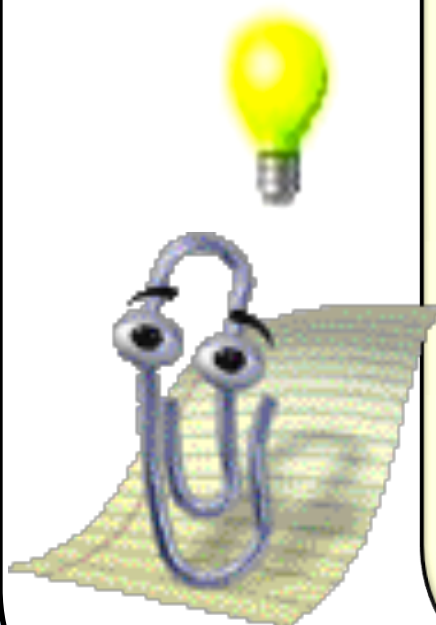


1 naald in 40 miljoen hooibergen
..... per seconde !



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)

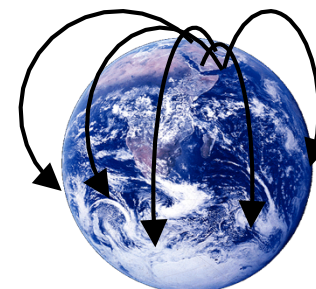
... je moet dus 99.9995 % van de foto's
weggooien ... elke seconde weer

YES

NO

Cancel

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

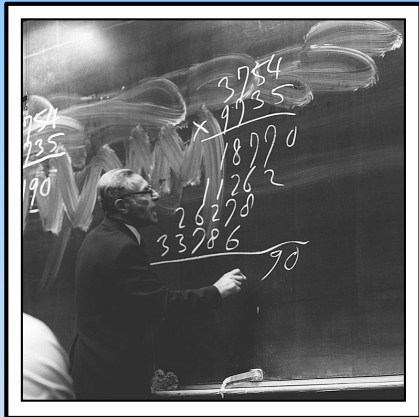


(Grid-) computing

ATLAS: 40 miljoen botsingen/sec

→ 200 Hz op tape

'gewoon' 3000 PC's

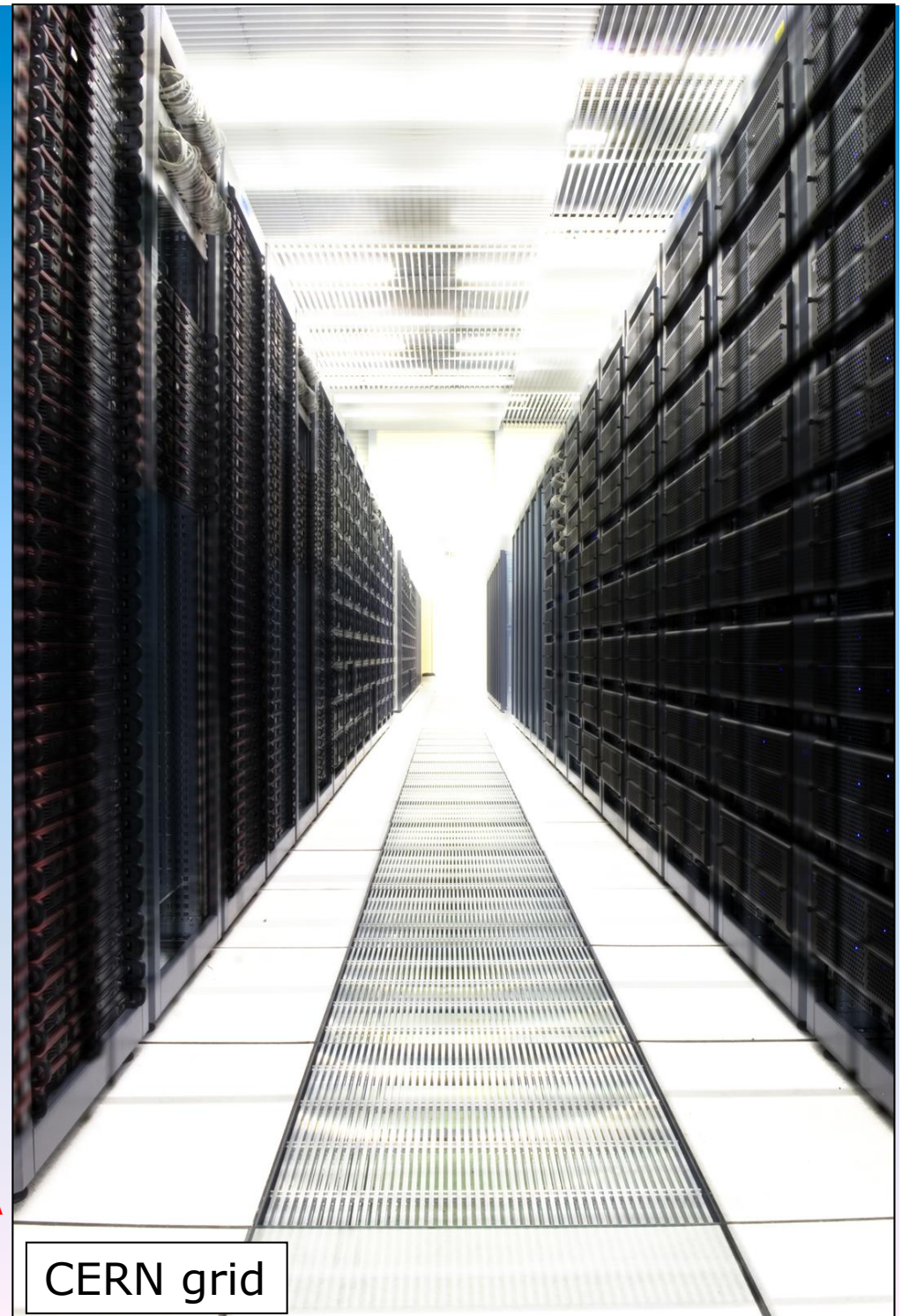


CERN's eerste computer

Wim Klein

Data-storage:

- ATLAS produceert 50 Pb per jaar
- 10 Tier-1 sites, met **Nikhef/SARA**

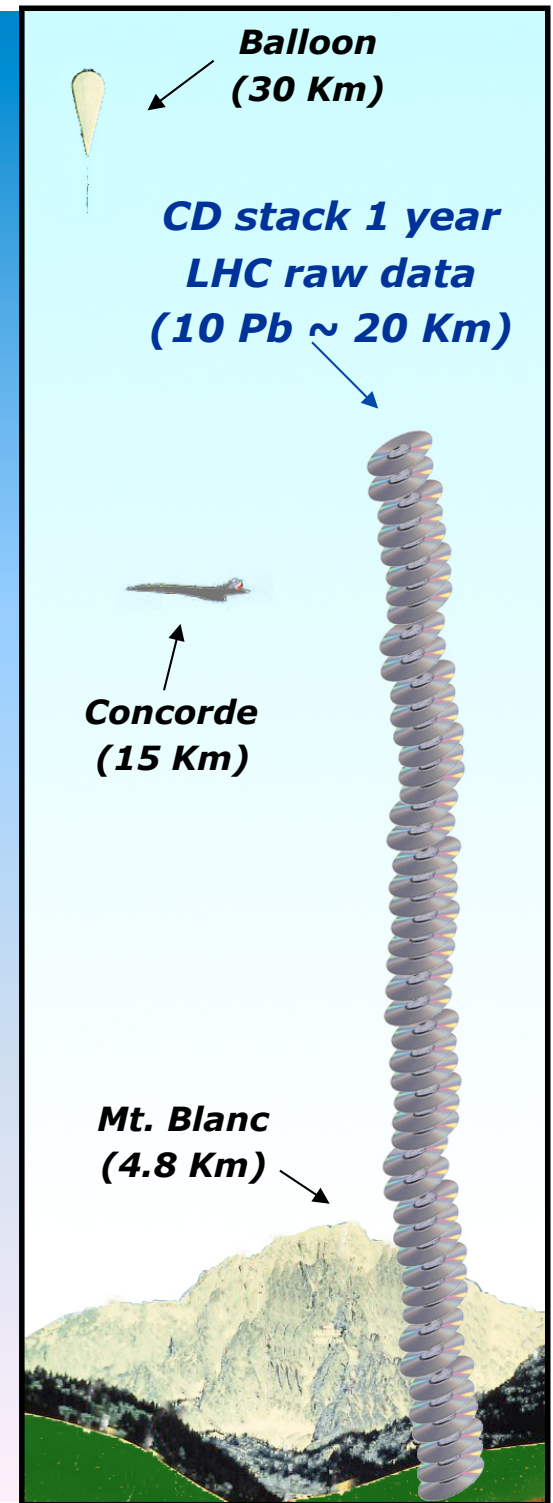


CERN grid

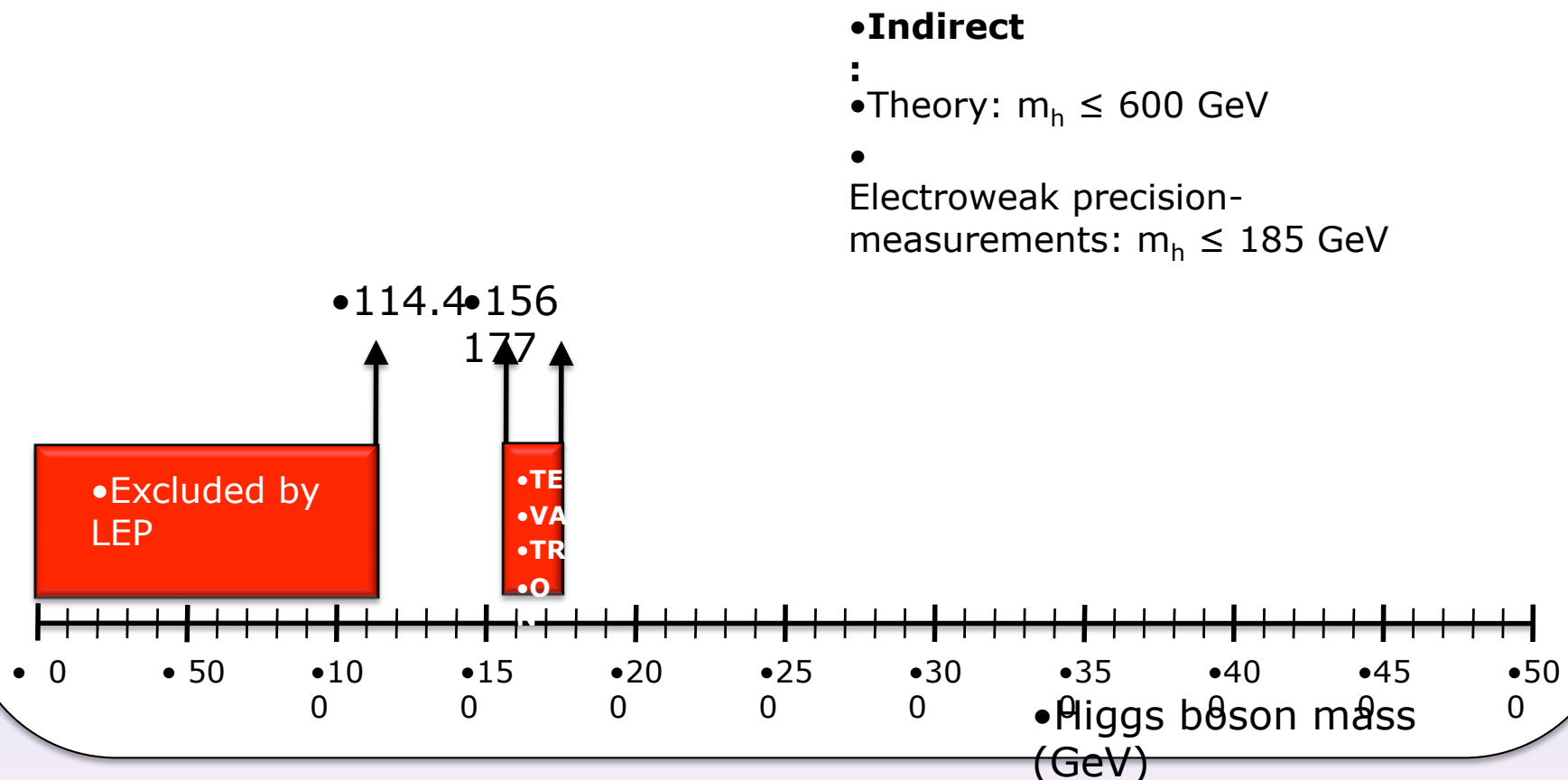
LHC data

... is het nou echt zoveel ?

... ja !



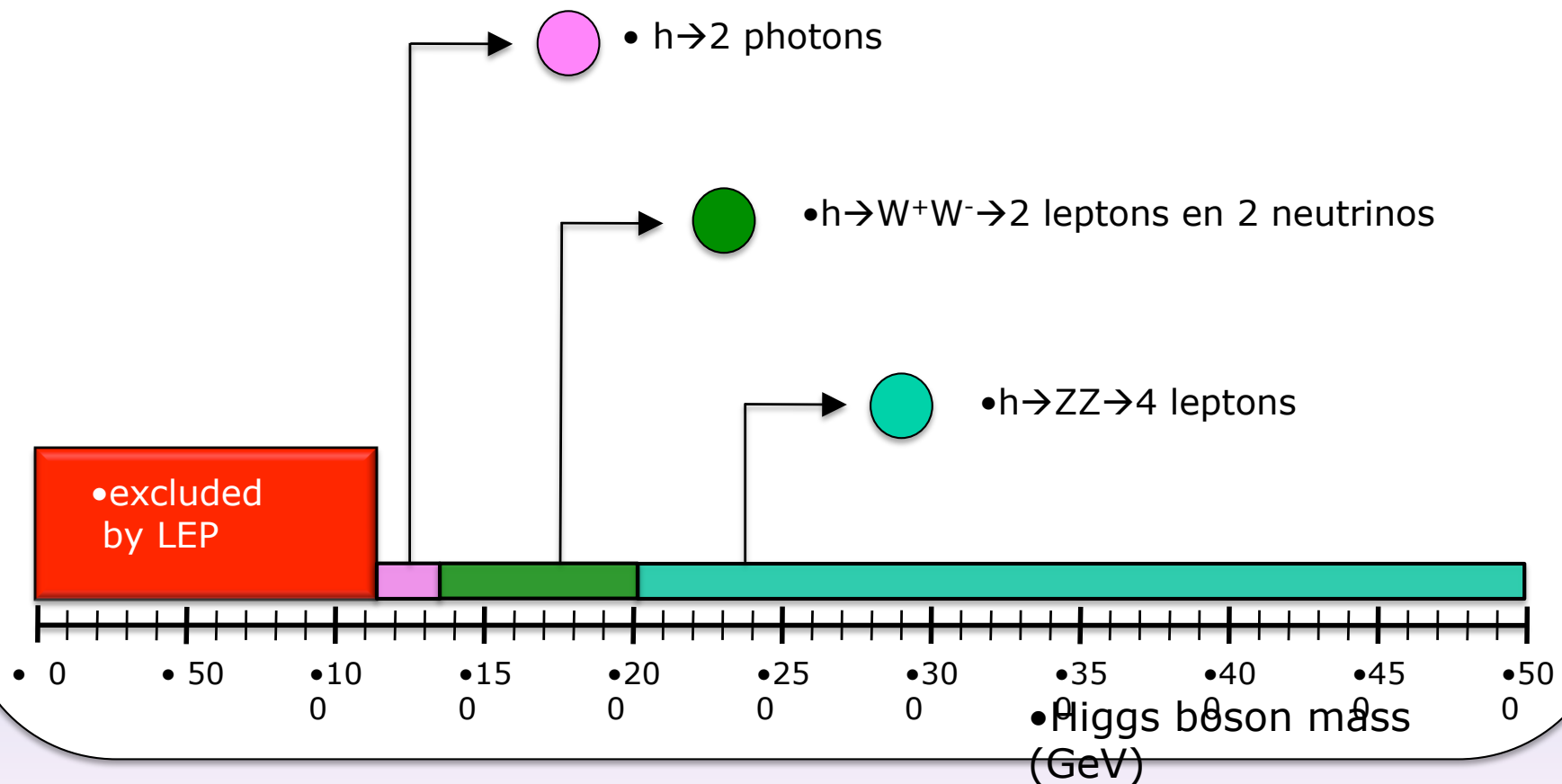
- Status on February 8, 2011



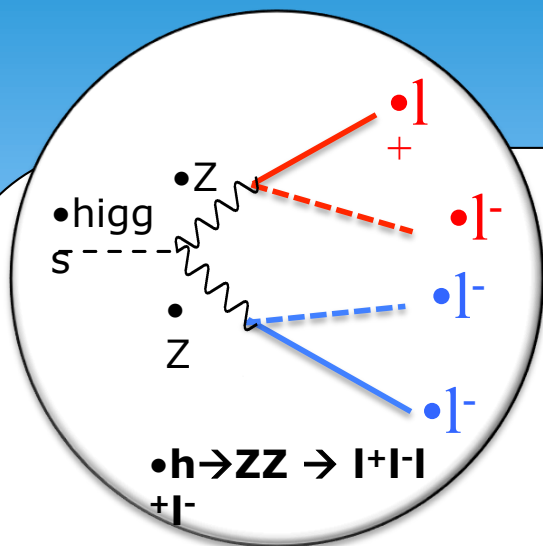
- Experiments at the LHC Sensitive for mass range: 114-1000 GeV

•The clearest fingerprint of the Higgs boson

•For every mass here are multiple channels: these are most sensitive ones



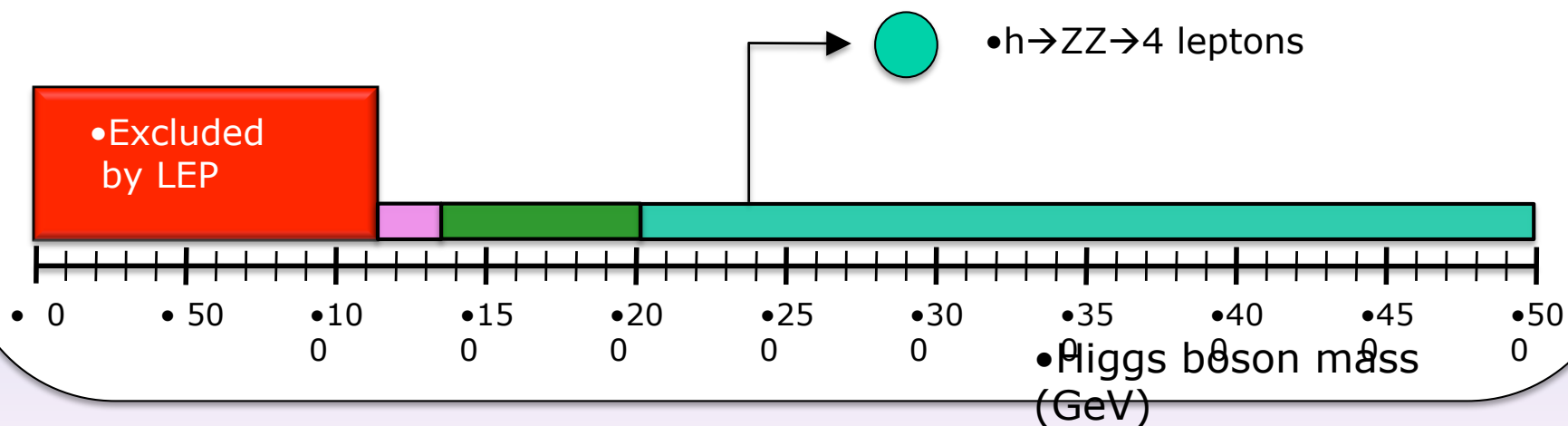
• High mass's: $m_H > 200$ GeV

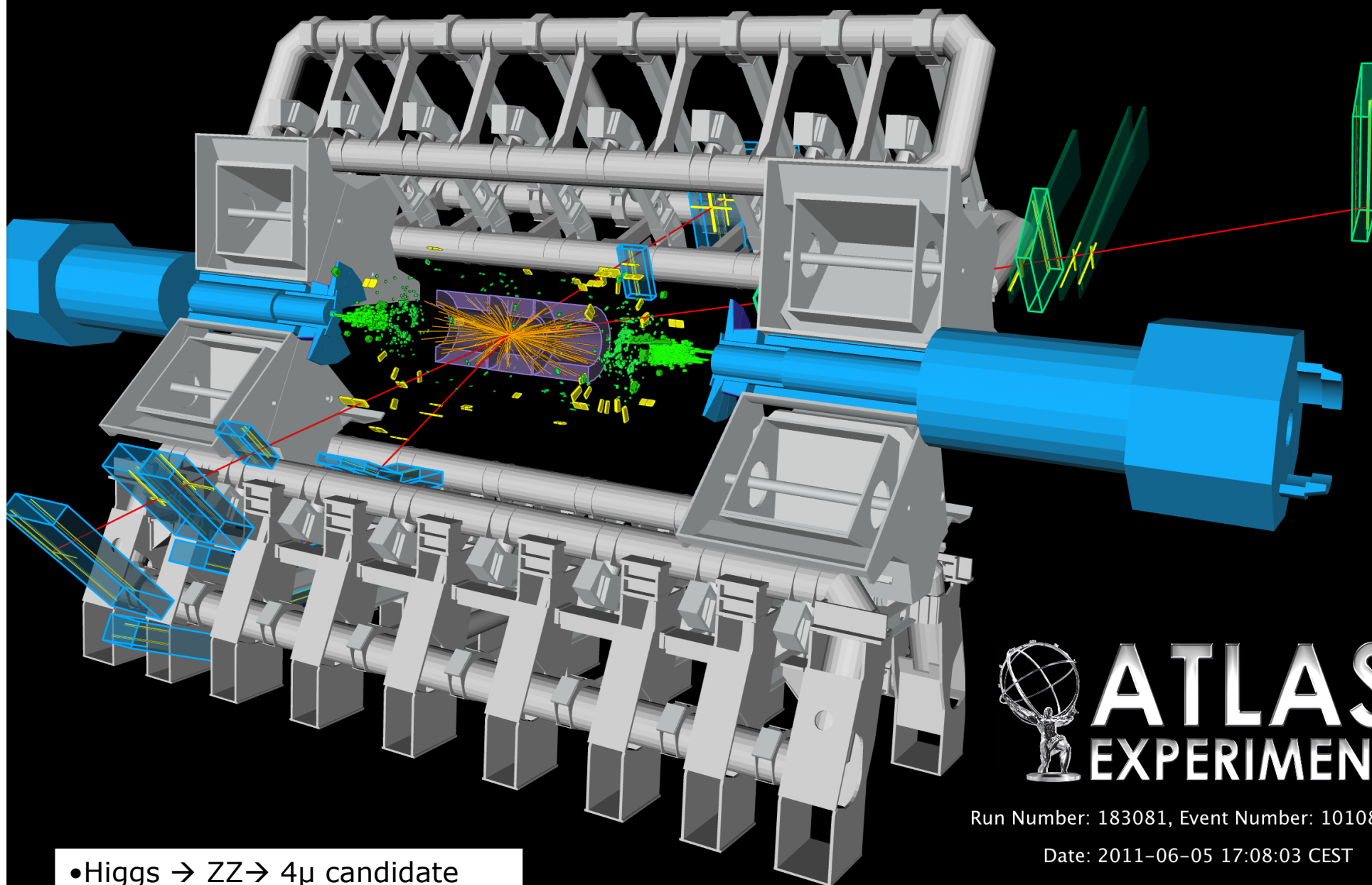


• The golden channel

- - 4 leptons (e/ μ)
- very rare: Higgs of ZZ

• Fingerprint: 4-lepton mass





•Higgs $\rightarrow$ ZZ $\rightarrow$ 4 μ candidate

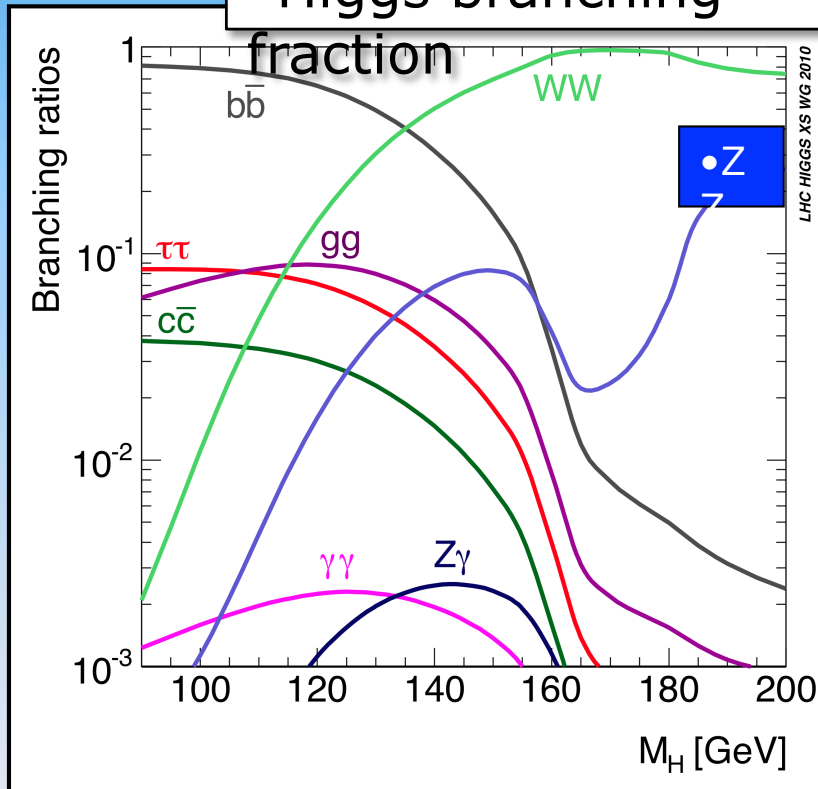
 **ATLAS**
EXPERIMENT

Run Number: 183081, Event Number: 10108572

Date: 2011-06-05 17:08:03 CEST

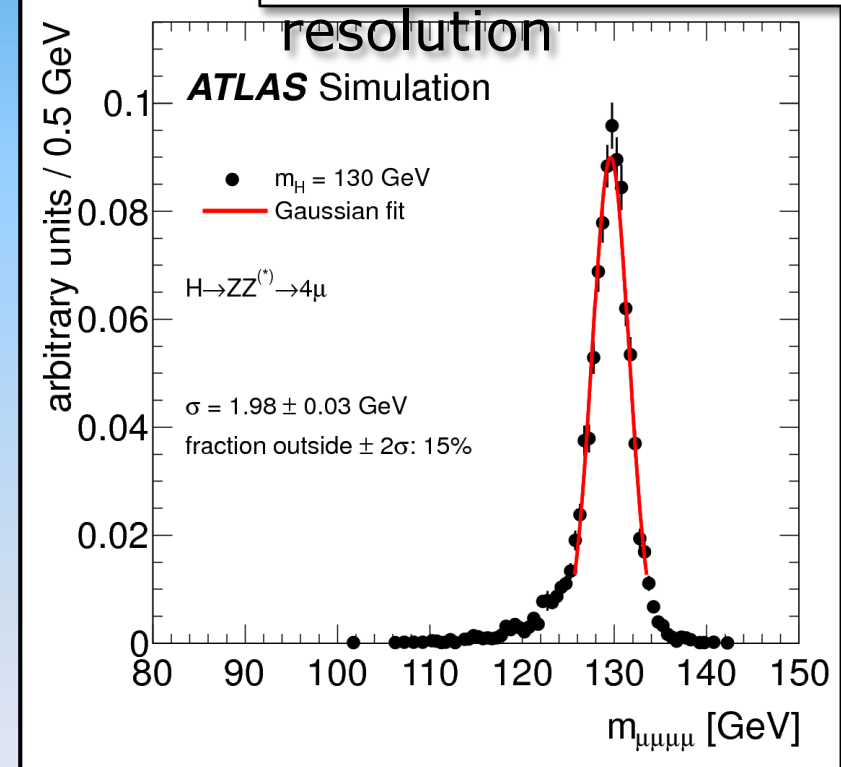
• Higgs $\rightarrow ZZ \rightarrow 4$ leptons
Small number of beautiful collisions

• Higgs branching



• $\Gamma(Z \rightarrow ee) = \Gamma(Z \rightarrow \mu\mu) = 3.36\%$

• 4-muon mass



• Mass resolution ~ 2 GeV

•Higgs $\rightarrow$ ZZ $\rightarrow$ 4 leptons

Small number of beautiful collisions

- 30.000 Higgs bosons

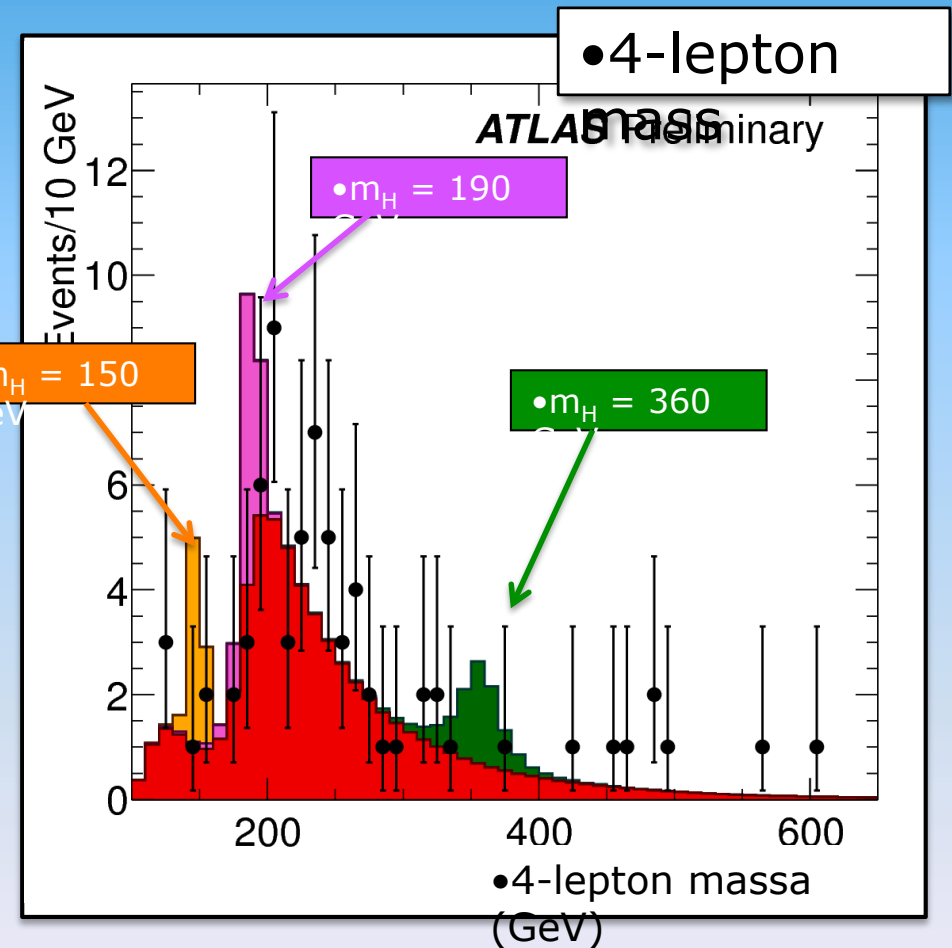


- Only 1 in 1000 Higgs bosons decays to 4 leptons (e/ μ).
- 50% of them are all correctly reconstructed by the ATLAS detector



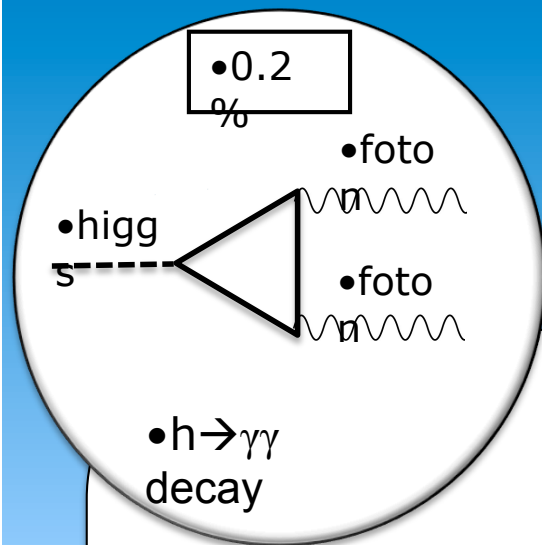
•16 Higgs decays to 4 leptons

- | | |
|--------------|-----------|
| • 'overig' | 52 events |
| • with Higgs | 68 events |



- No clear peak unfortunately
 $\rightarrow m_h < 200$ GeV

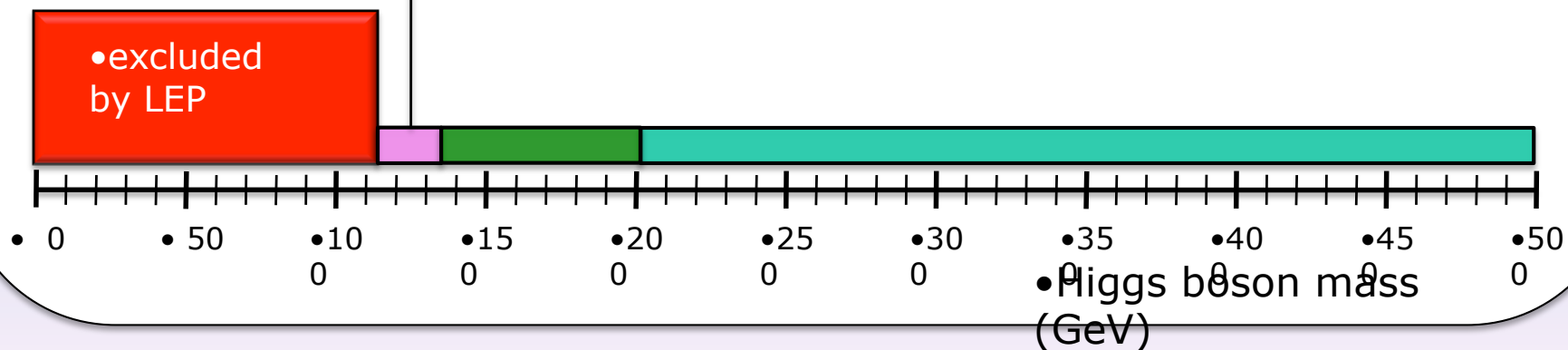
•The low-mass region



• $h \rightarrow 2$ photons

- 2 energetic isolated photons
- detector sensitive for 'fake' signals

•Fingerprint: 2-photon mass

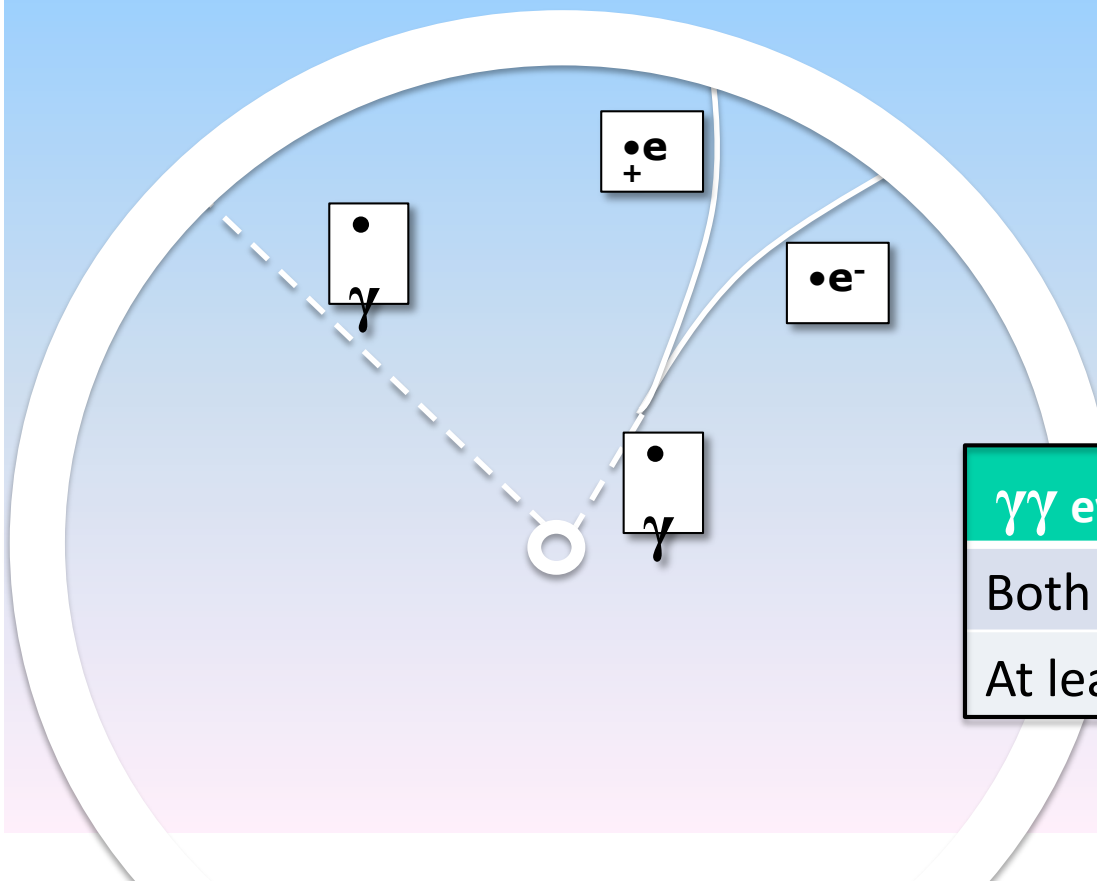


• Photon identification and event selection

- Selection: 2 isolated photons: $P_T > 40$ (25 GeV)
- 39% selection efficiency

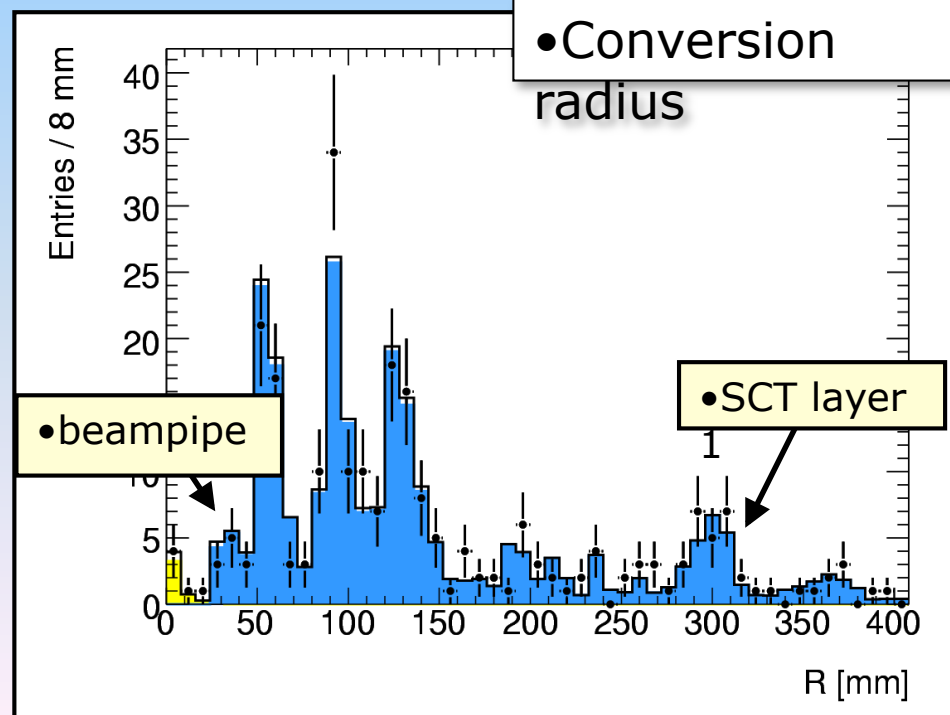
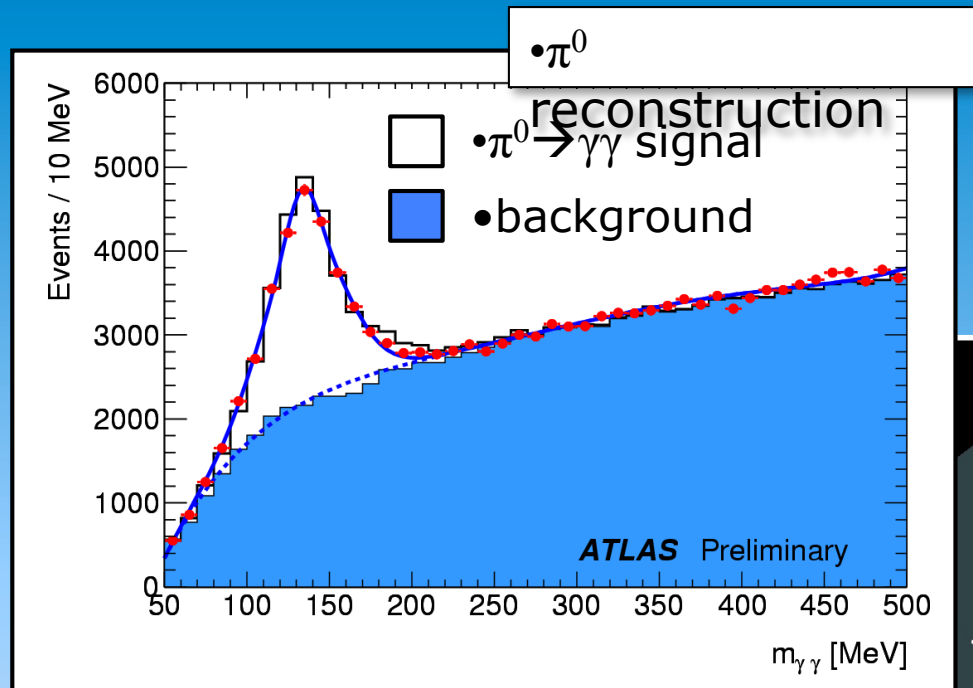


• "Elk nadeel hep z'n voordeel"



$\gamma\gamma$ event classification	Fraction
Both unconverted	36%
At least 1 converted	64%

Photon conversions



• Clean electron sample
Good material description in MC

Event-type	Number of events
------------	------------------

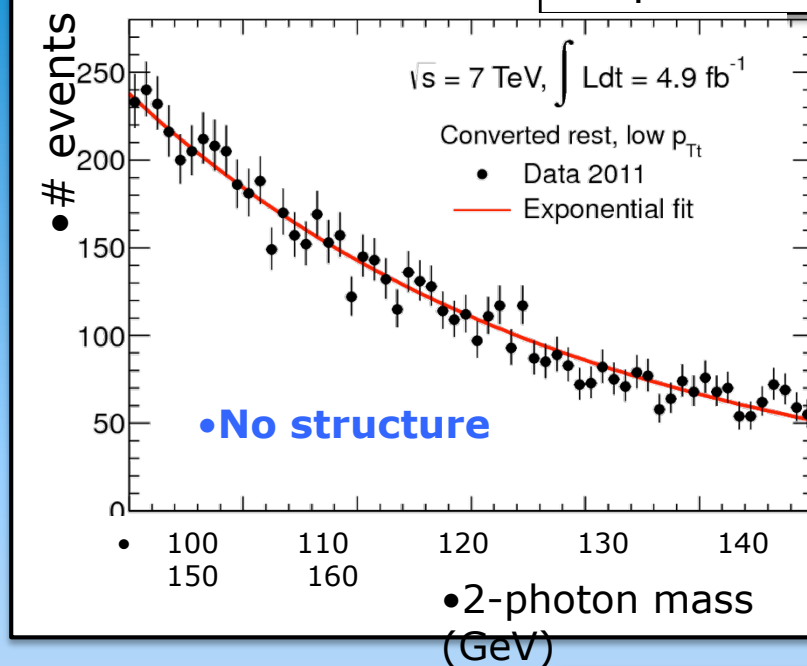
•Other origin

$\gamma\gamma$	3650 ± 100 ± 290
$\gamma + \text{jet}$	1110 ± 60 ± 270
Di-jet	220 ± 20 ± 130
Drell-Yan	86 ± 1 ± 14
'normal'	5066

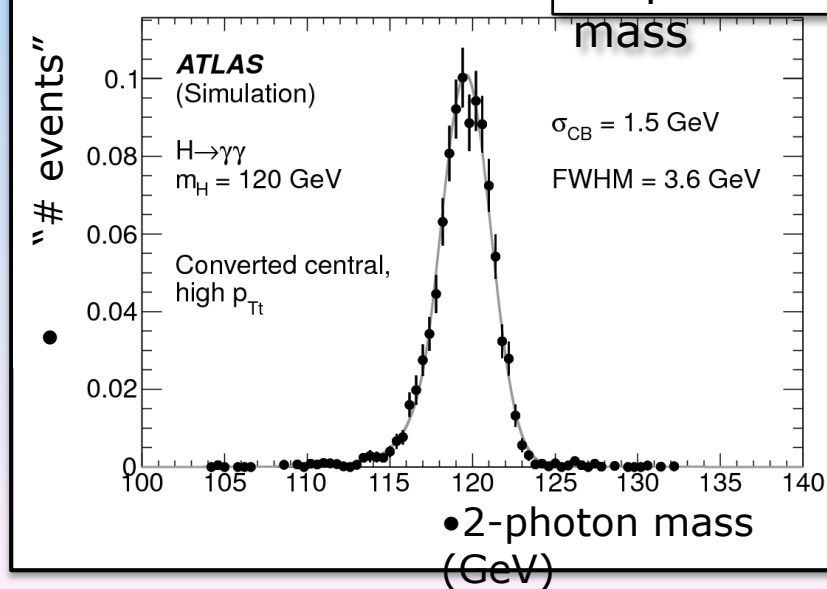
•Higgs

Higgs signal	17.6
--------------	------

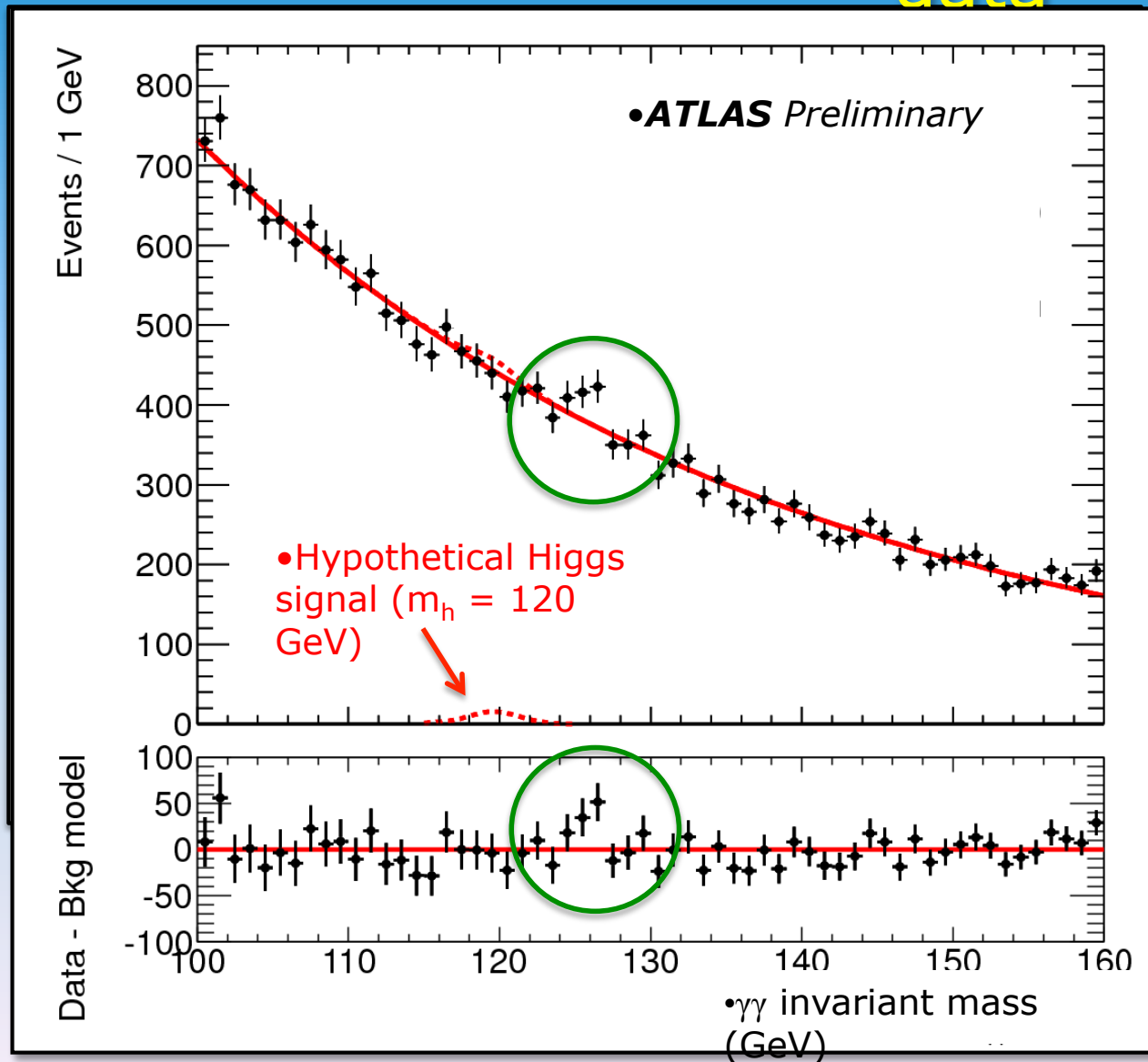
•2-photon



•2-photon mass



- The ATLAS data



- peak ?

• Interpretation excess in ATLAS

- Probability to fluctuate as much as observed or even higher: ~ 1 op 100
- Pure chance of fake dice ?

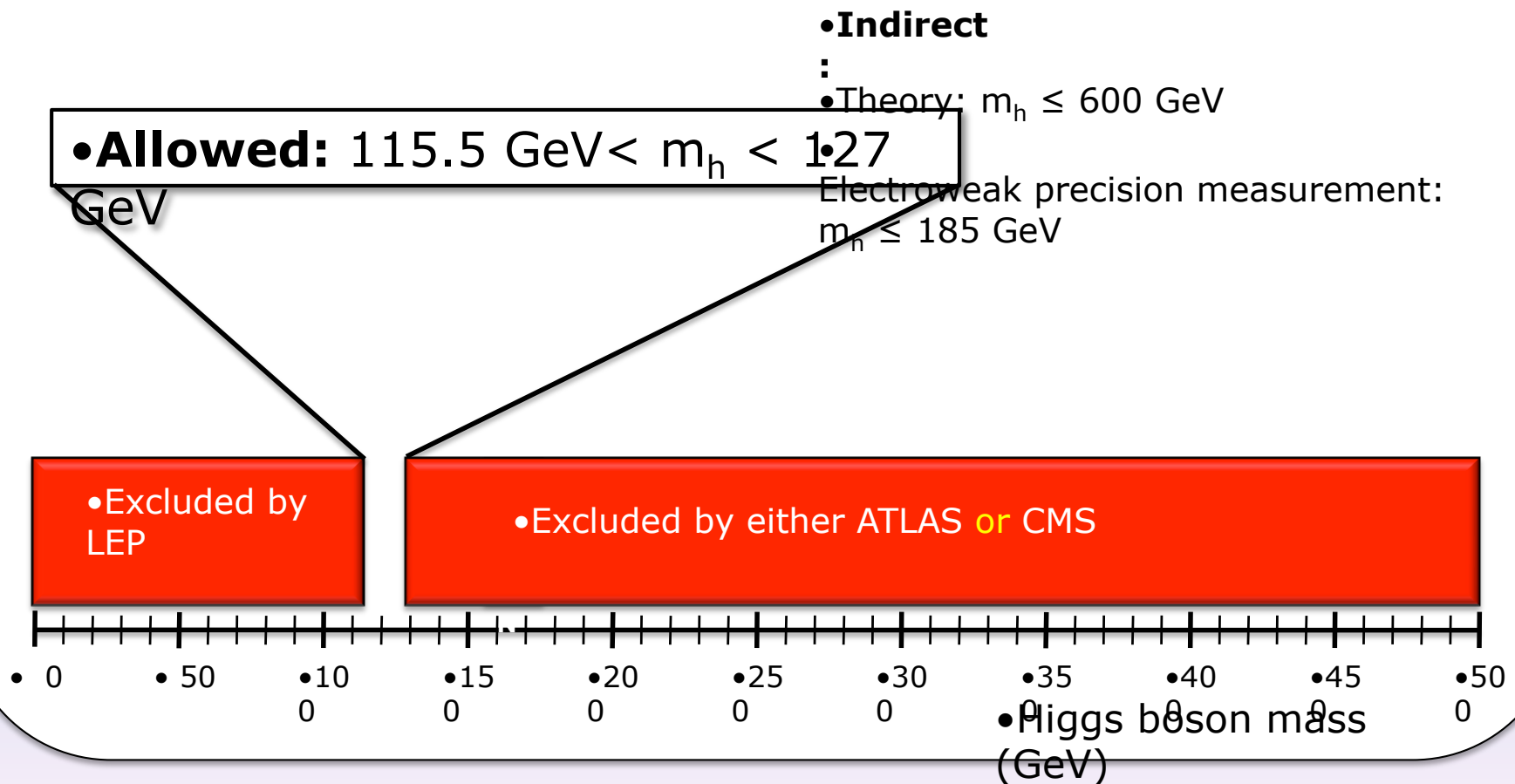


• **Claim discovery if:**

- Probability on such a fluctuation from other processes < 1 on 1,000,000

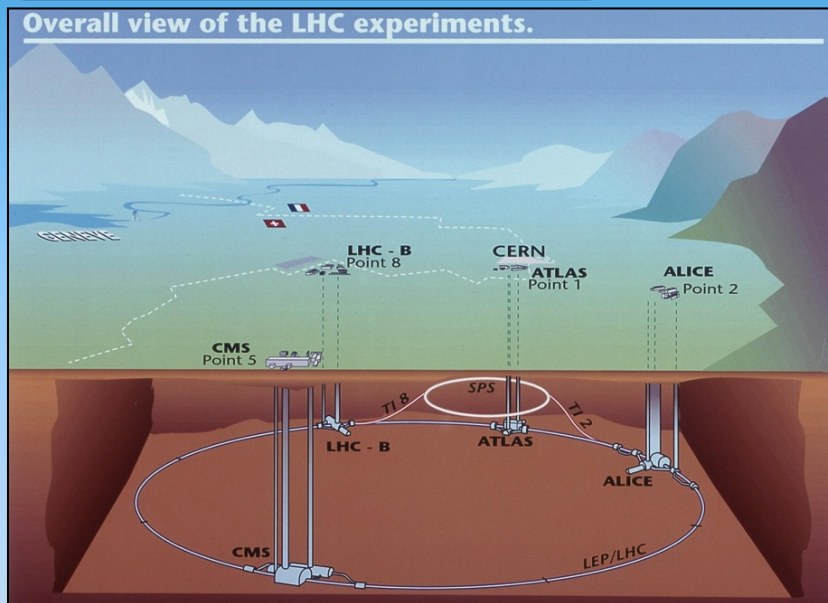
- Throw 8 times 6 in a row
- (need ~ 3 times more data)

- Status on February 8, 2012



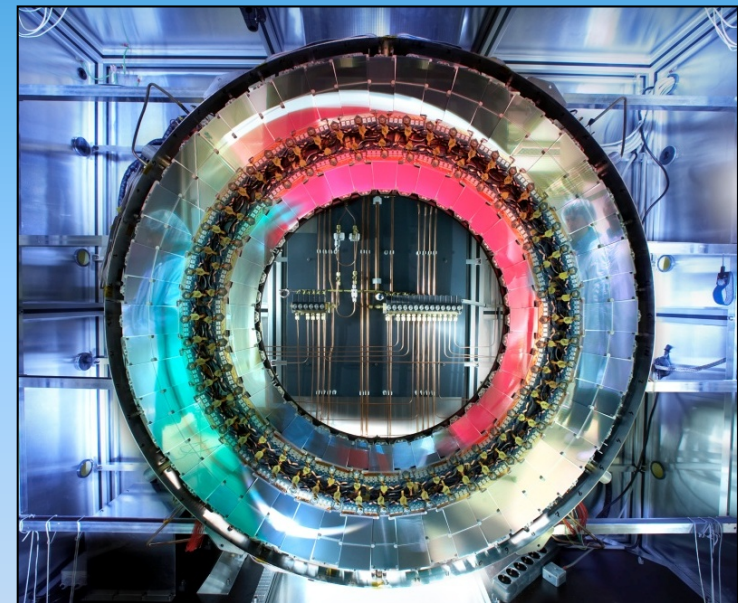
We zijn er klaar voor

LHC versneller

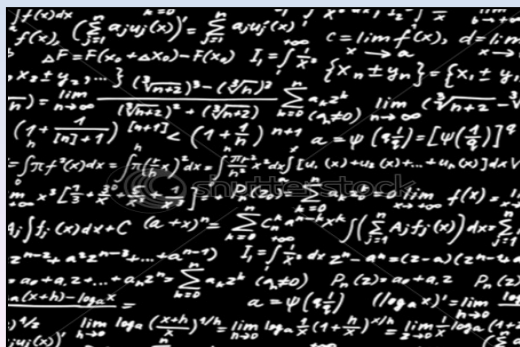


Herstart september 2009

Detectoren



Vier detector zijn klaar



Theorie

Meer dan genoeg vragen
... meer dan genoeg ideeën/oplossingen

Einde

Ivo.van.Vulpen@nikhef.nl

Alle publieke resultaten van het ATLAS experiment

<https://twiki.cern.ch/twiki/bin/view/AtlasPublic>

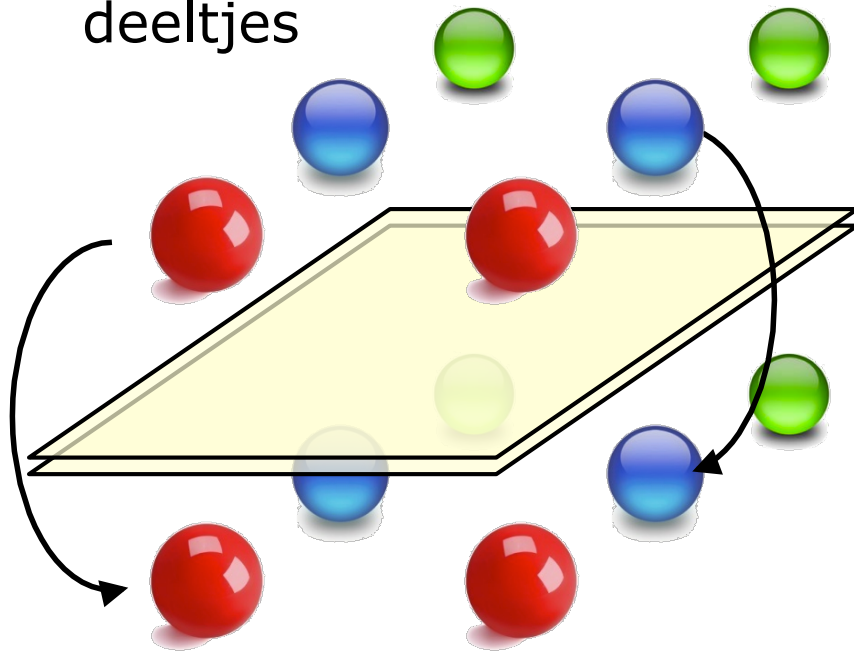
Donkere Materie

Theoretisch idee: Supersymmetrie:



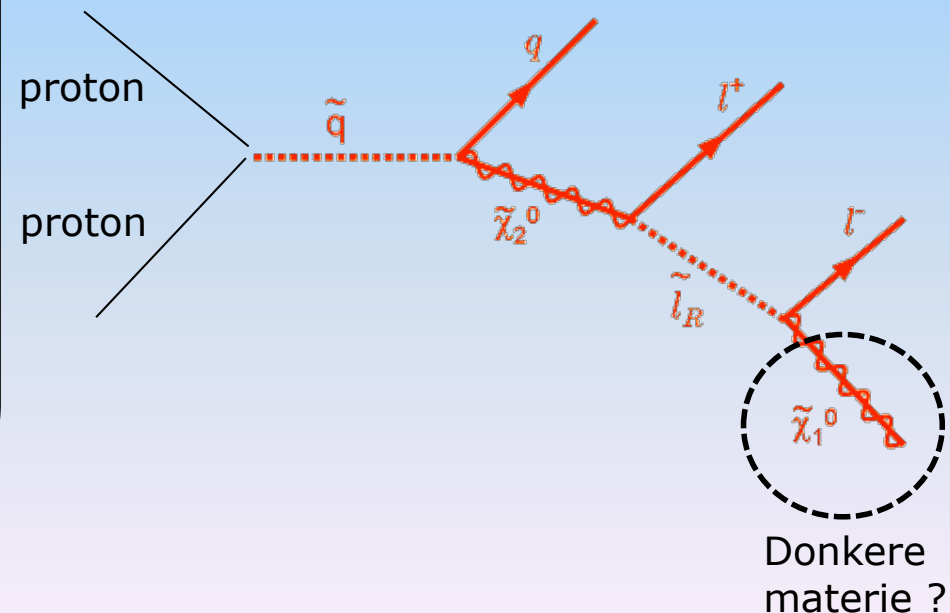
Anti-deeltjes

deeltjes



Super-symmetrie: elk deeltje heeft een zwaar broertje

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

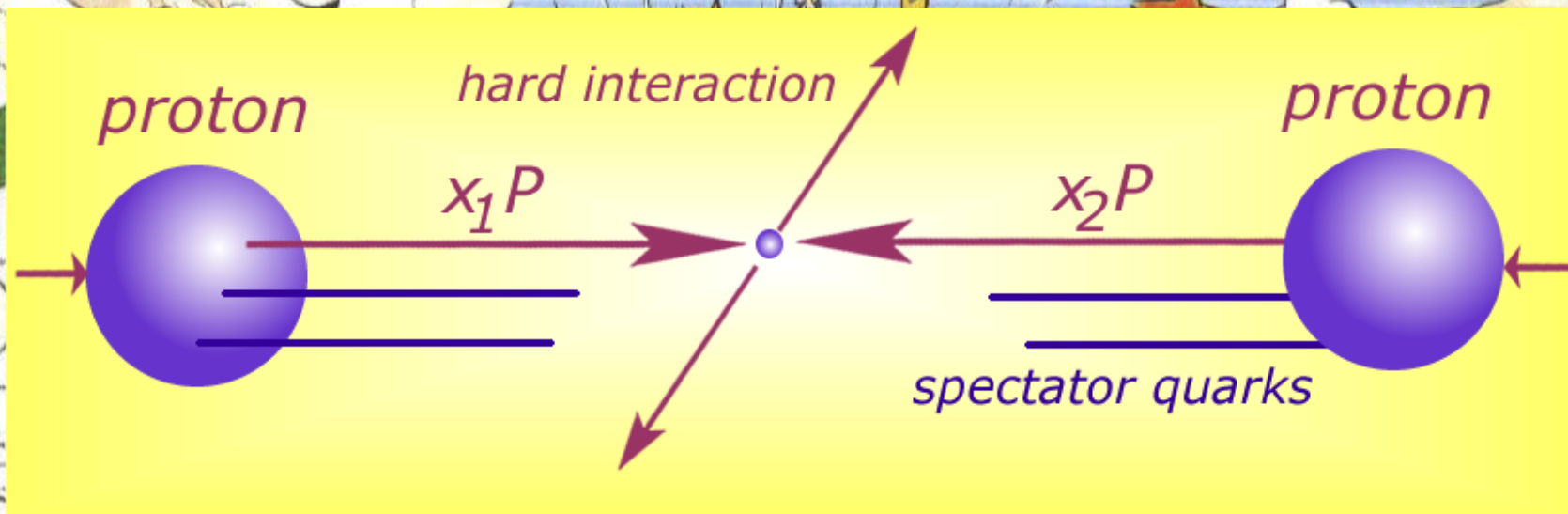


Fenomenologie botsingen

“Alsof je twee wekkers op elkaar knalt...”

‘Harde’ botsingen:

Feitelijk is proton een ‘vuilniszak’ met quarks en gluone



Slechts een gedeelte van de energie van de protonen beschikbaar voor de ‘harde botsing’