

Zoektocht naar de elementaire bouwstenen van de natuur



Leiden honours students, 15 juni 2012

Ivo van Vulpen

CERN



Mijn oude huis

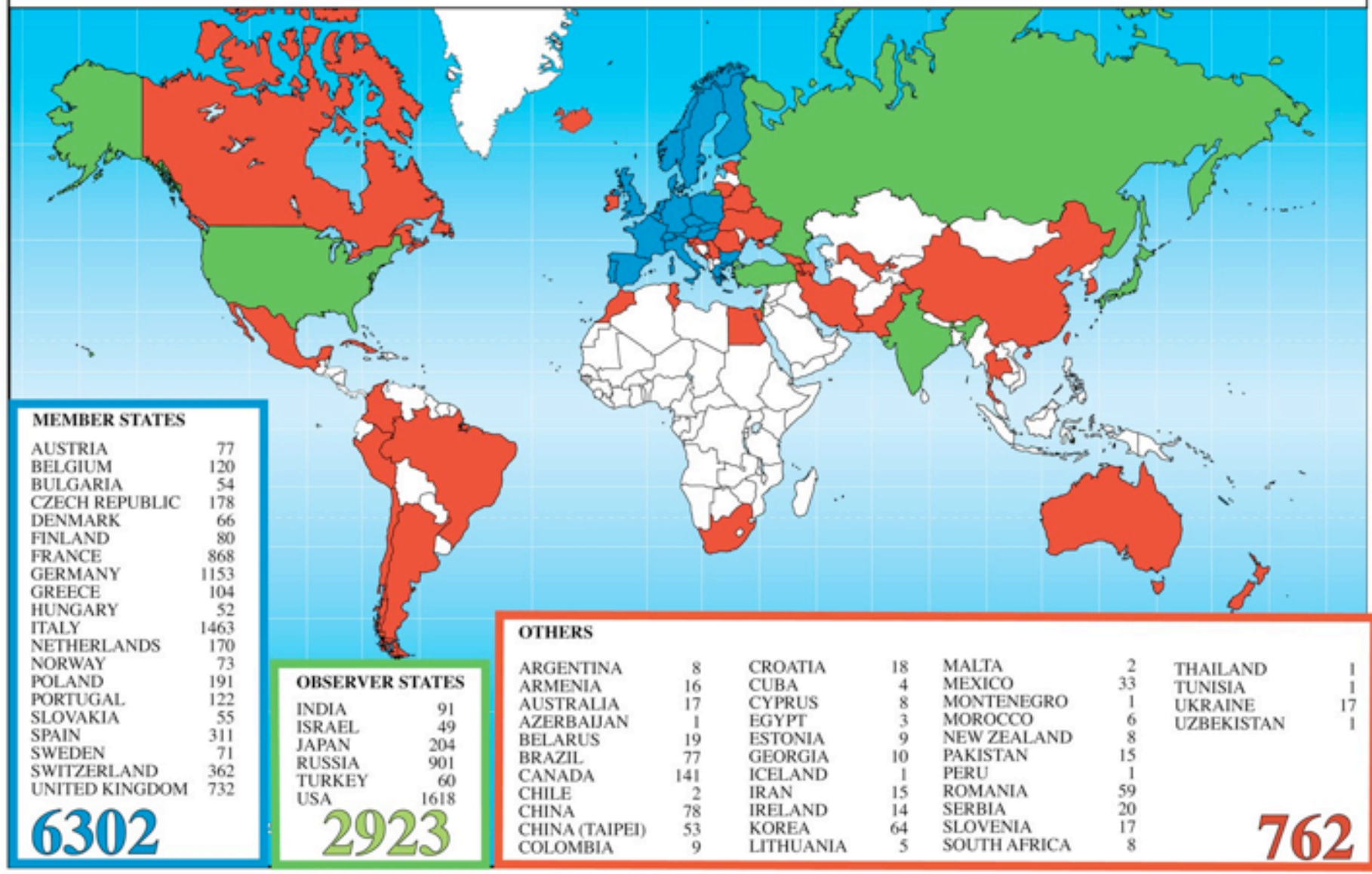
Anti-materie

ATLAS detector

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

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



CERN gebruikers

Het grootste en het kleinste

... volgens mijn dochter van 3

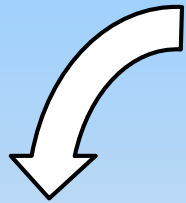
... volgens haar vader



Olifant



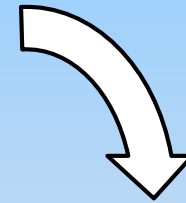
Klein muisje



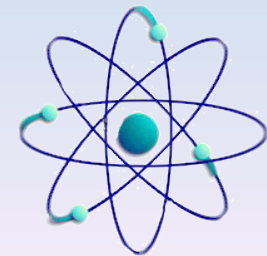
Grootst



10^{+22} m

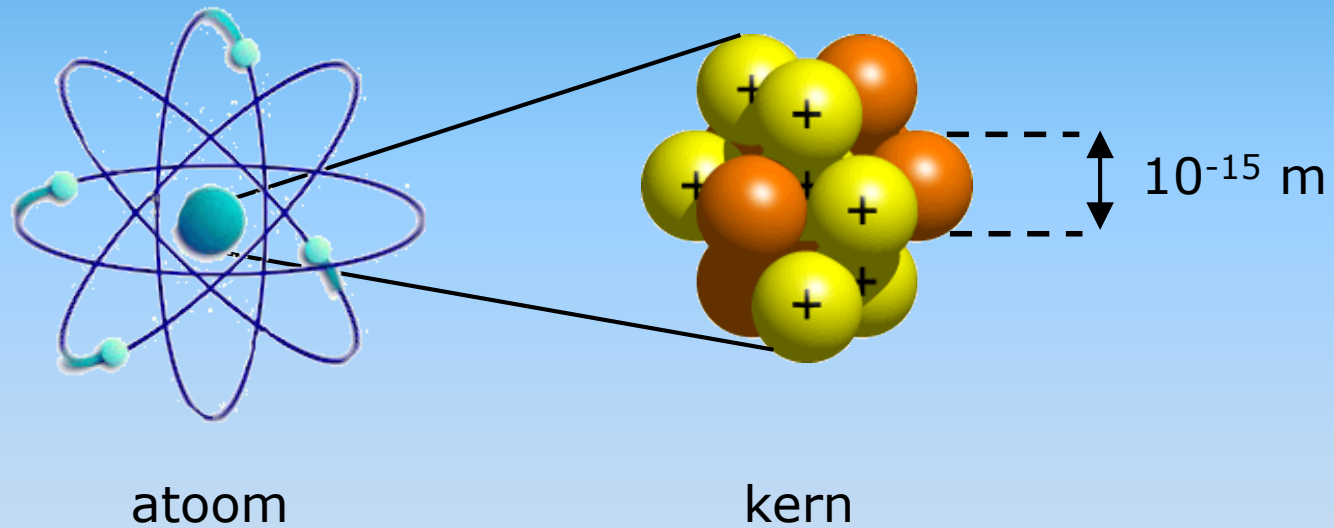


Kleinst

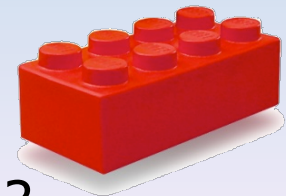


10^{-9} m

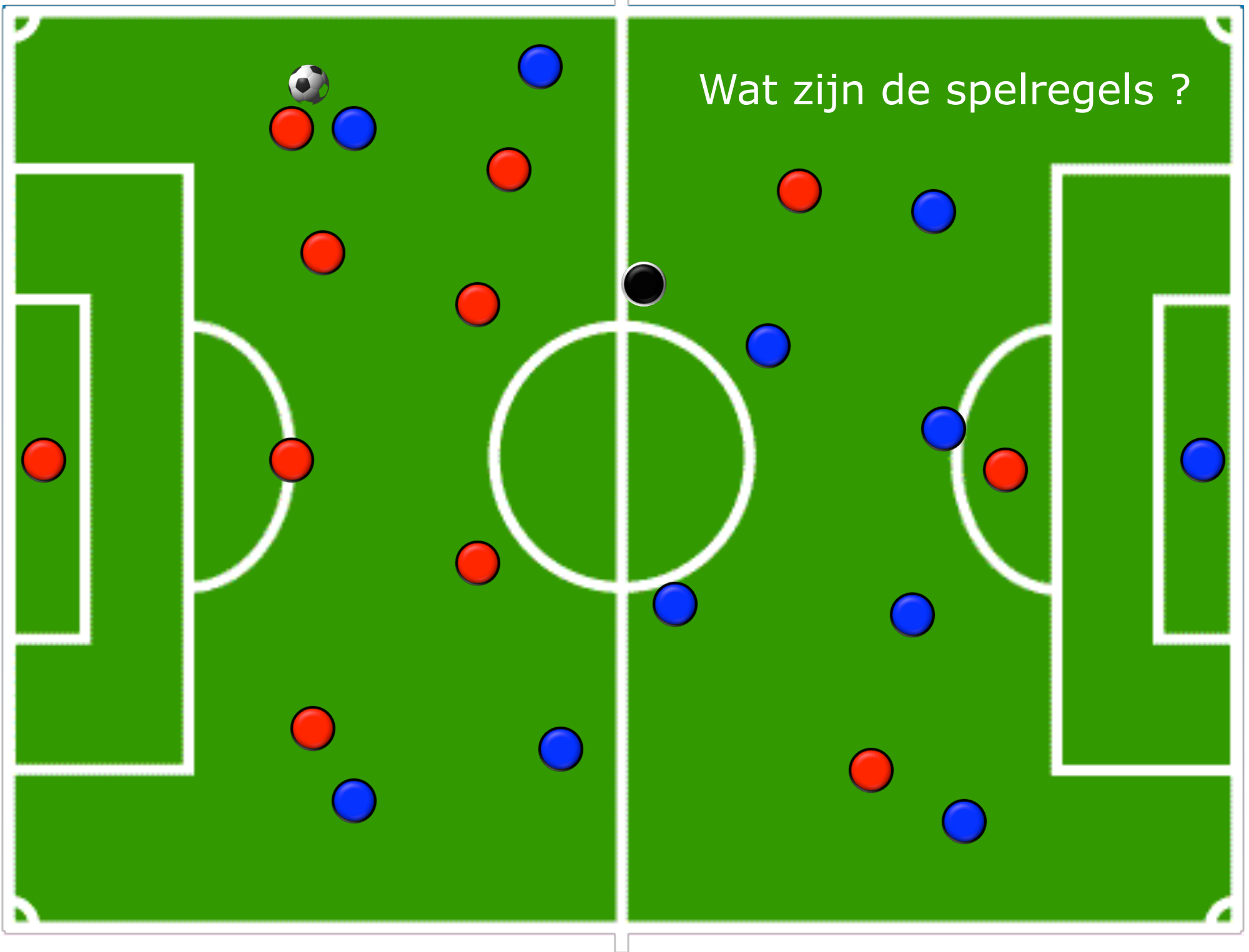
Deeltjesfysica



Wat zijn de bouwstenen van de dingen om ons heen ?

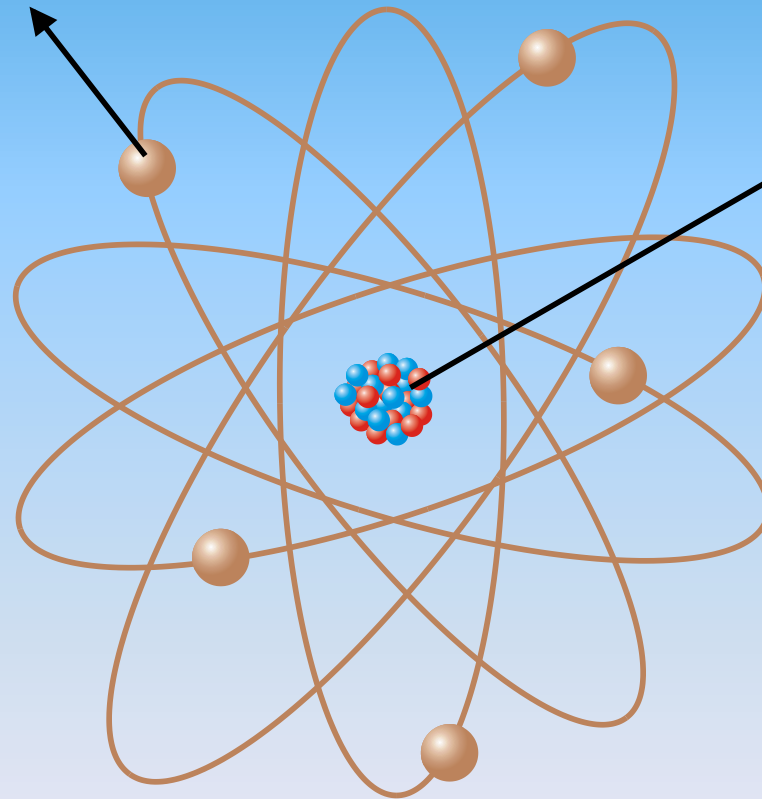


Wat zijn de spelregels ?



Wat waren de problemen 100 jaar geleden ?

elektron:lading -1



proton:lading +1

Waarom valt het elektron niet op de kern ?

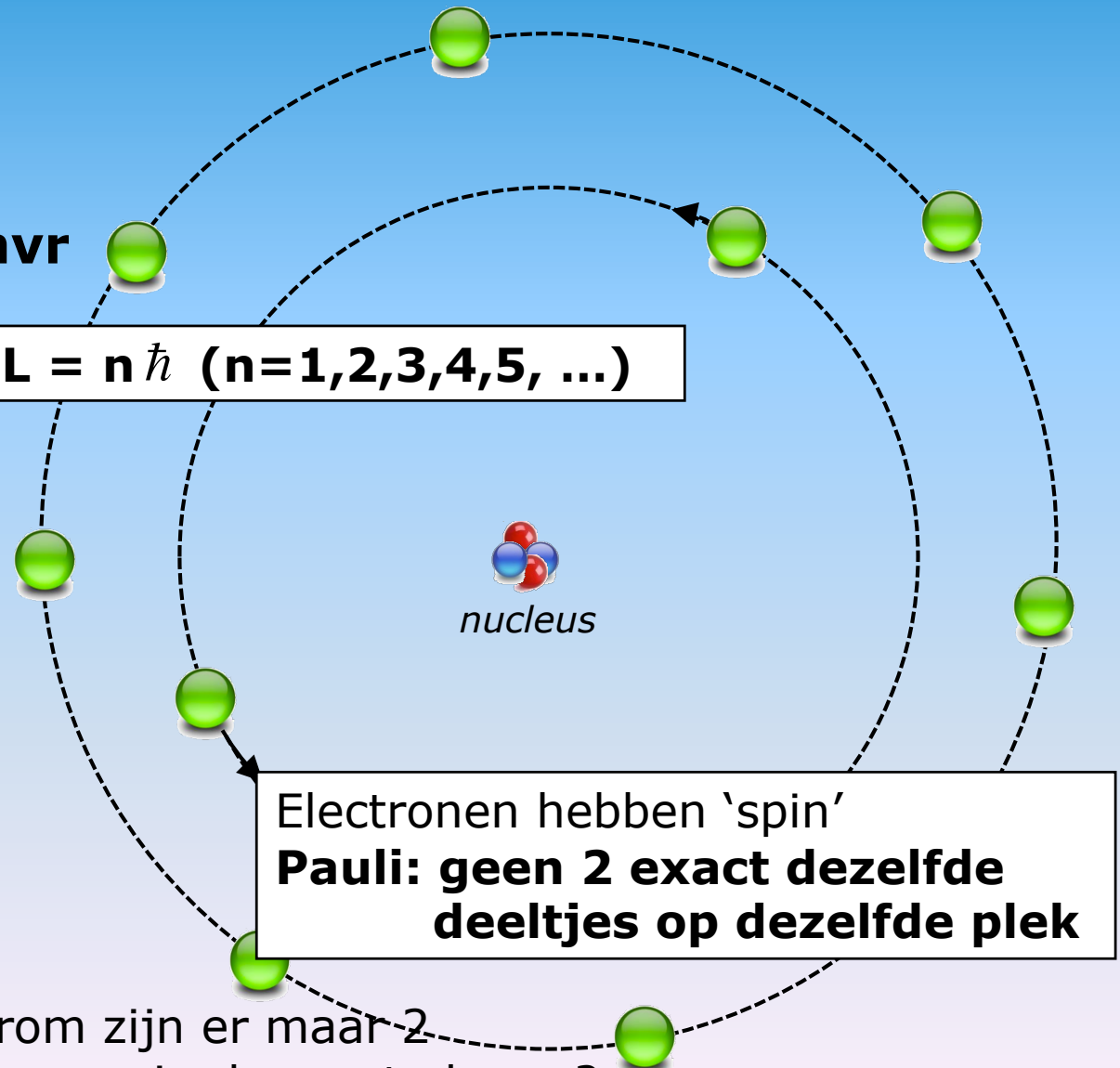
Het atoom

1) Waarom vallen de electronen niet op de kern?

No.	Element	1	2	3	4	5
1	Hydrogen	1				
2	Helium	2				
3	Lithium	2	1			
4	Beryllium	2	2			
5	Boron	2	3			
6	Carbon	2	4			
7	Nitrogen	2	5			
8	Oxygen	2	6			
9	Fluorine	2	7			
10	Neon	2	8			
11	Sodium	2	8	1		
12	Magnesium	2	8	2		
13	Aluminium	2	8	3		
14	Silicon	2	8	4		
15	Phosphorus	2	8	5		
16	Sulfur	2	8	6		
17	Chlorine	2	8	7		
18	Argon	2	8	8		
19	Potassium	2	8	8	1	
20	Calcium	2	8	8	2	
21	Scandium	2	8	9	2	
22	Titanium	2	8	10	2	
23	Vanadium	2	8	11	2	
24	Chromium	2	8	13	1	
25	Manganese	2	8	13	2	

$$L = mvr$$

$$\text{Bohr: } L = n \hbar \quad (n=1,2,3,4,5, \dots)$$



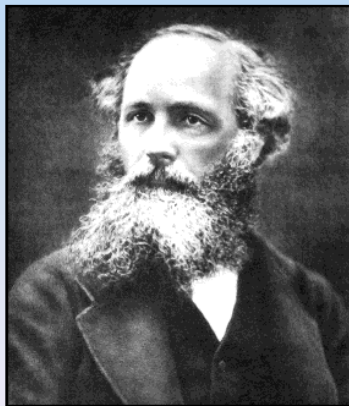
2) Waarom zijn er maar 2 electronen in de eerste baan ?

Zwaartekracht en Electromagnetisme

“zelfde krachten ... nieuwe modellen”



Newton



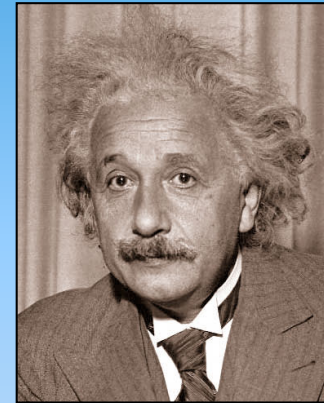
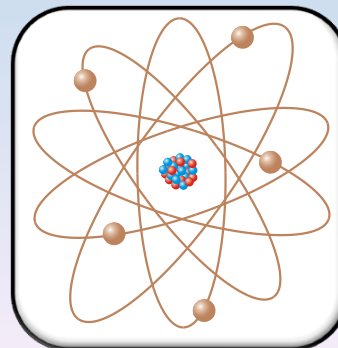
Maxwell



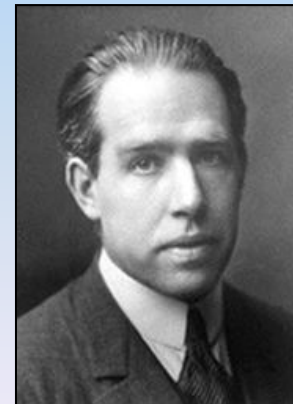
Relativiteitstheorie



Quantummechanica



Einstein



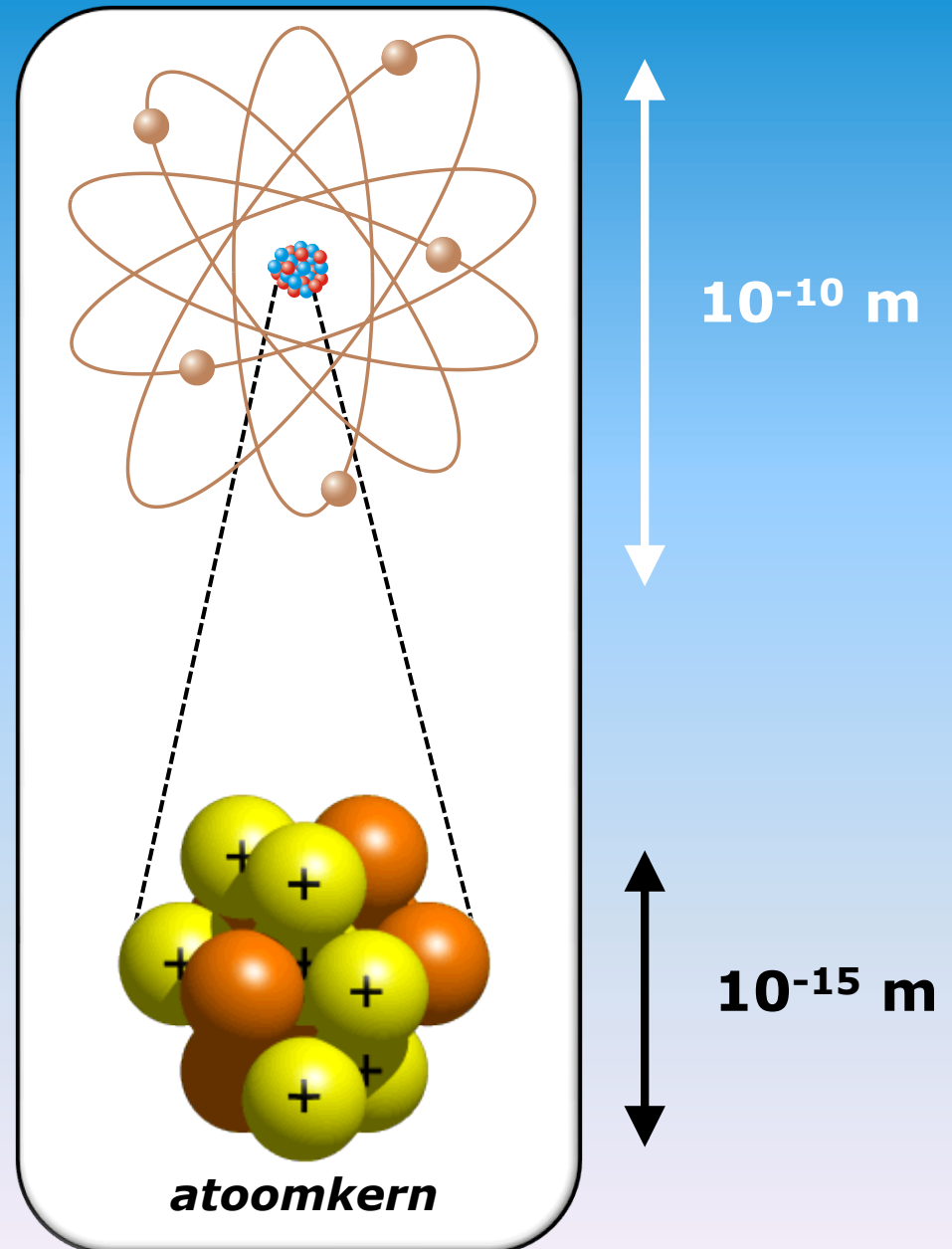
Bohr

De kernkrachten

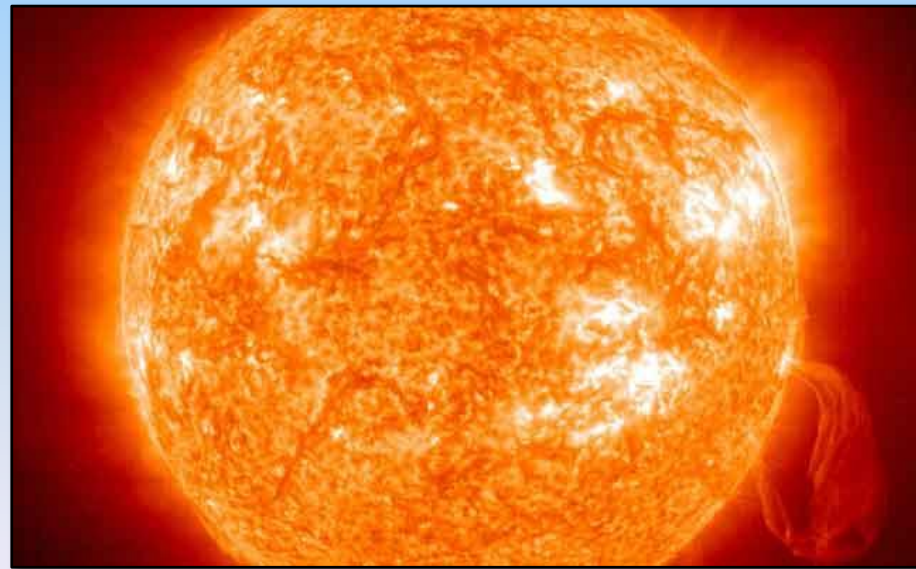
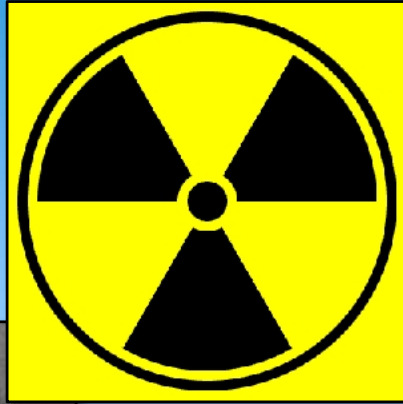
- 1] Positieve deeltjes stoten elkaar toch af ?
- 2] Wat houdt de neutrale deeltjes bij elkaar ?

2 nieuwe natuurkrachten:

- zwakke kernkracht
- sterke kernkracht



Nuclear forces





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

[2] Gewoon 4 gekleurde draadjes en simpel symmetrisch patroon

De stand van zaken op 15 juni 2012



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

De elementaire deeltjes



up

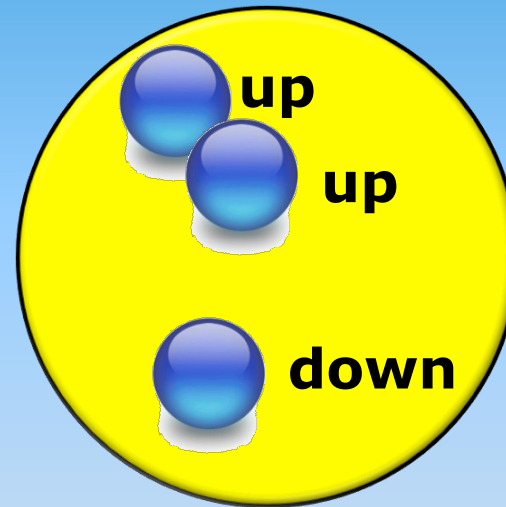


down

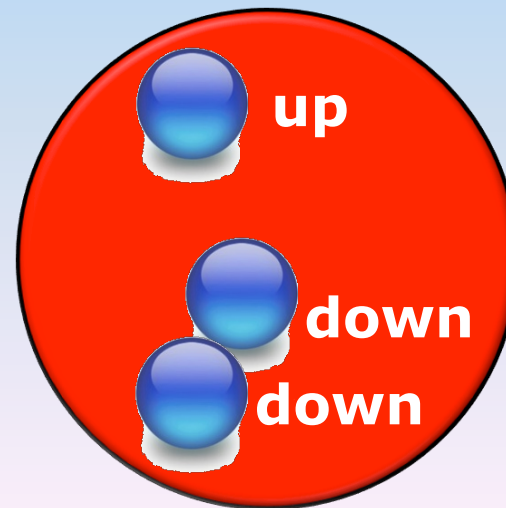


elektron

+ 4 natuurkrachten



Proton



Neutron

Wat kan je maken met deze 3 bouwstenen ?

*periodiek systeem
van Mendeleev*

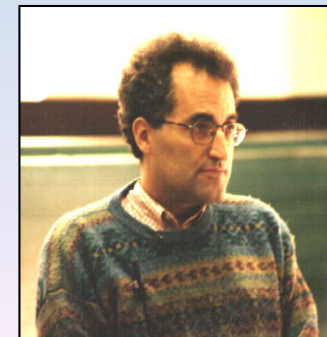
1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 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

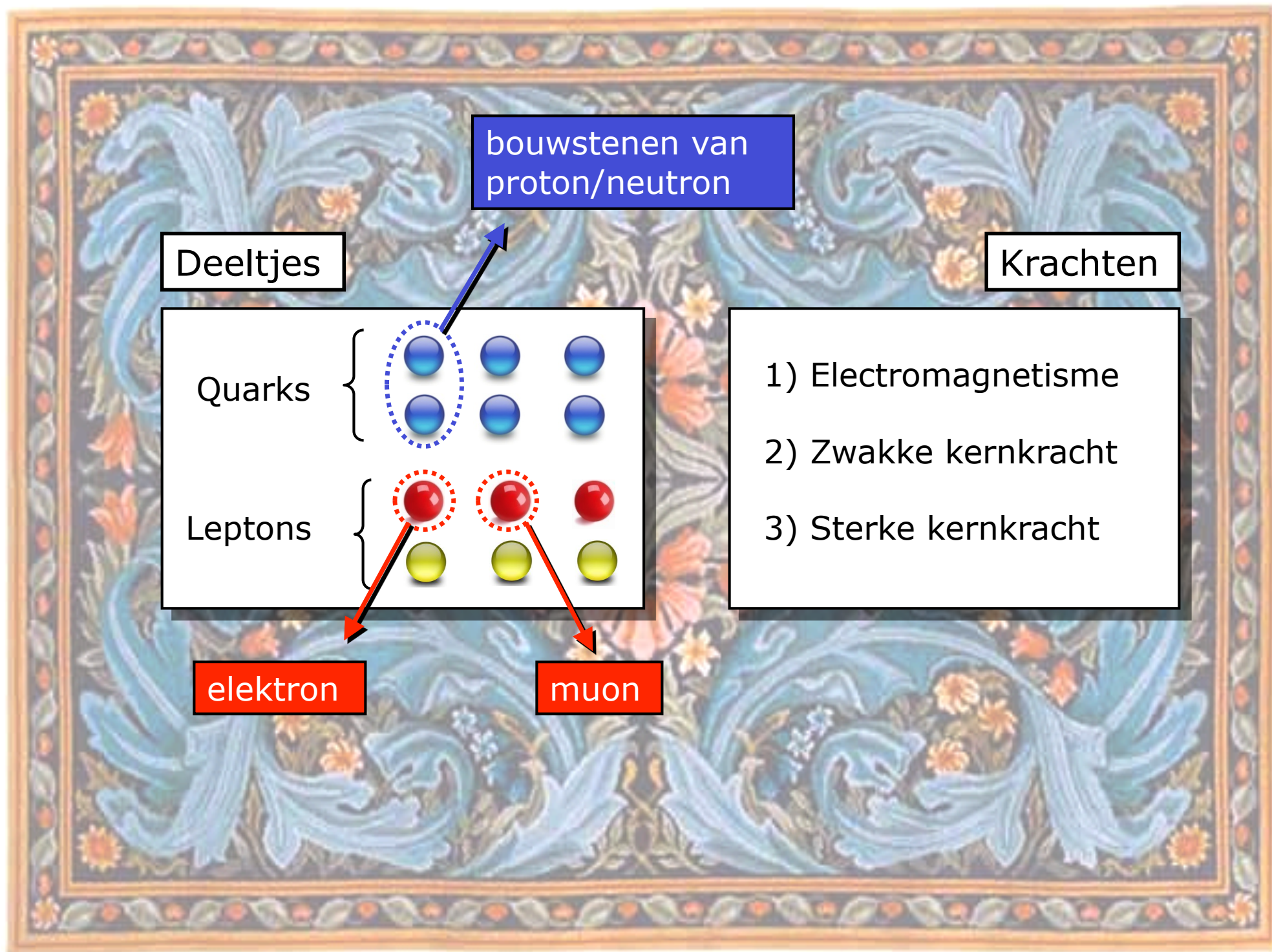
Quarks

Leptons

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

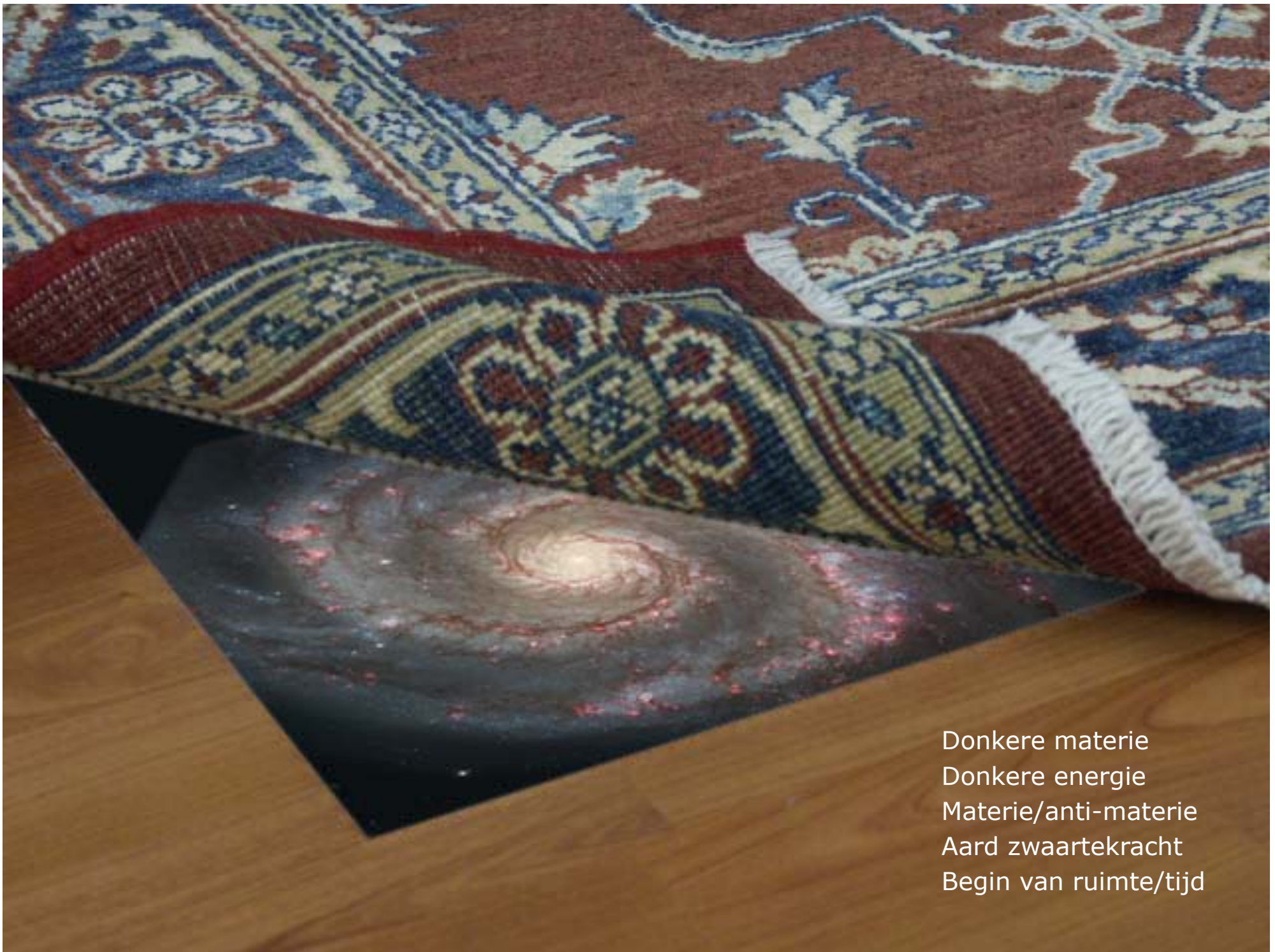
elektron

muon



Wat snappen we nog niet:





Donkere materie
Donkere energie
Materie/anti-materie
Aard zwaartekracht
Begin van ruimte/tijd

A composite image of Earth, the Moon, and the Sun in space. The Earth is a large, curved blue and white sphere on the left. The Moon is a smaller, grey sphere in the upper right. The Sun is a bright, glowing yellow star with lens flare in the lower left. The background is a dark, star-filled space.

Waar bestaat het heelal uit?

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

80% 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, ...

2

Anti-materie: waar is het gebleven ?

Nieuwe fenomenen: anti-materie



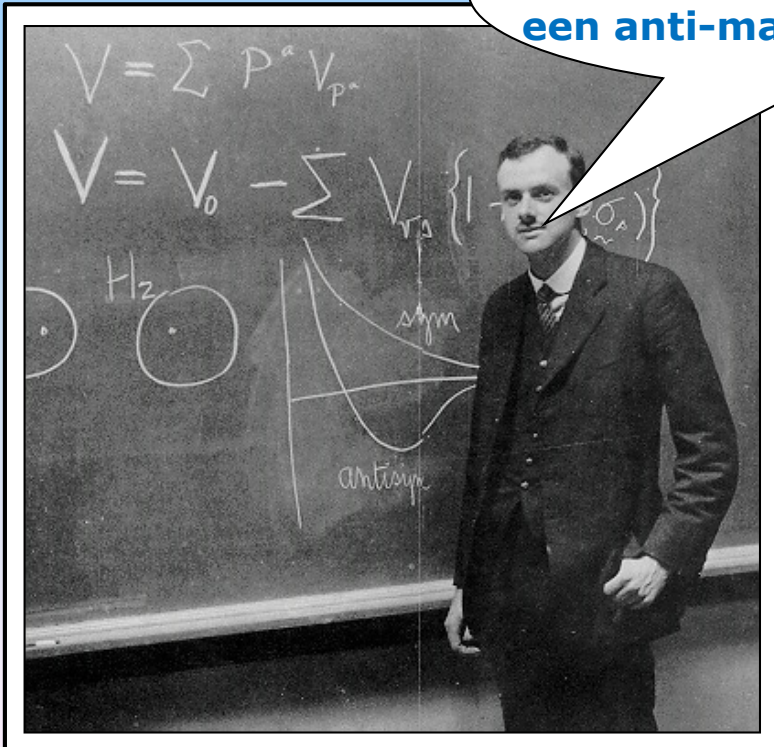
Mooie een-twee'tje theorie-experiment

- 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

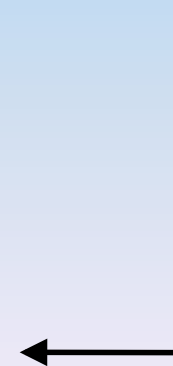


anti-down



positron

Voorspelling: anti-elektron

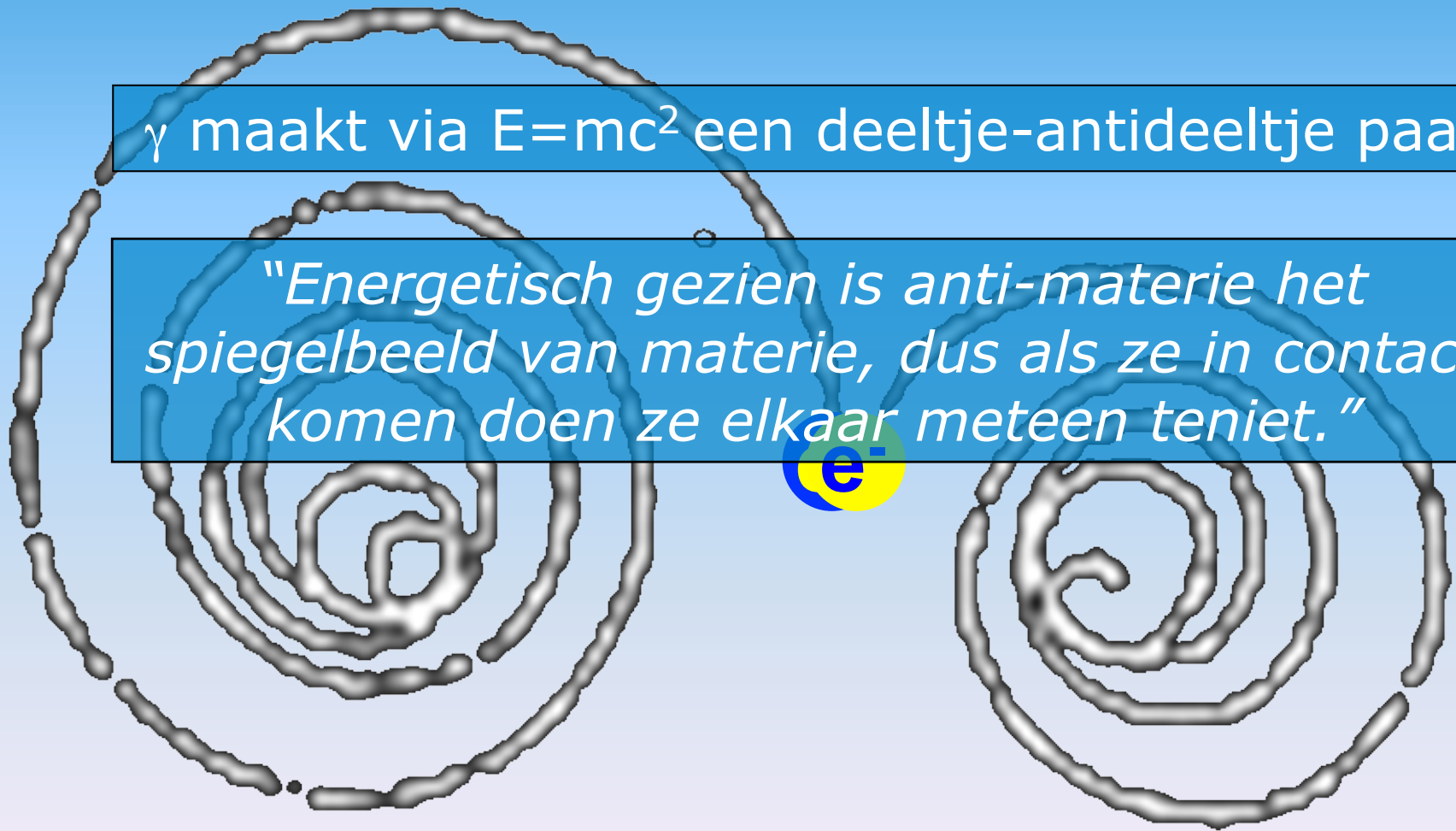


Anti-materie: $\gamma \rightarrow e^+e^-$



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."

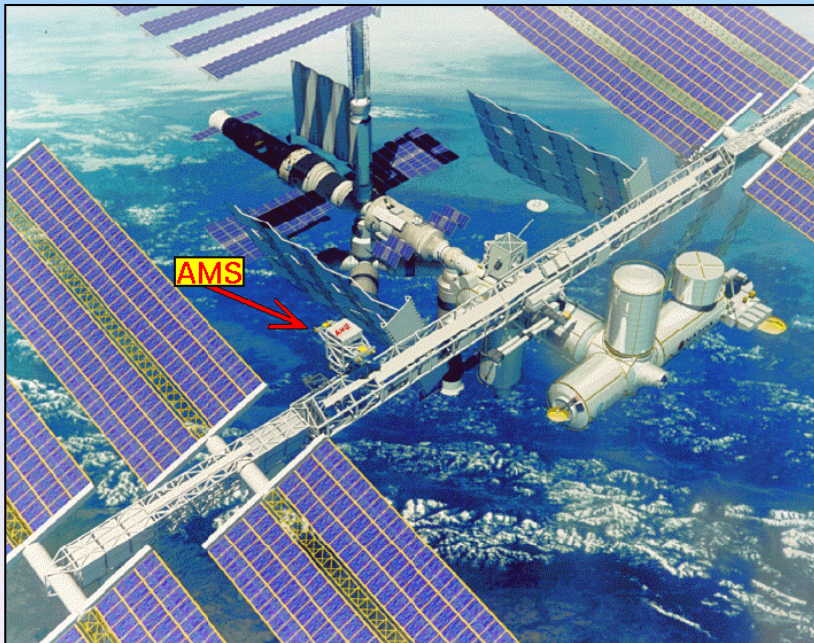


2

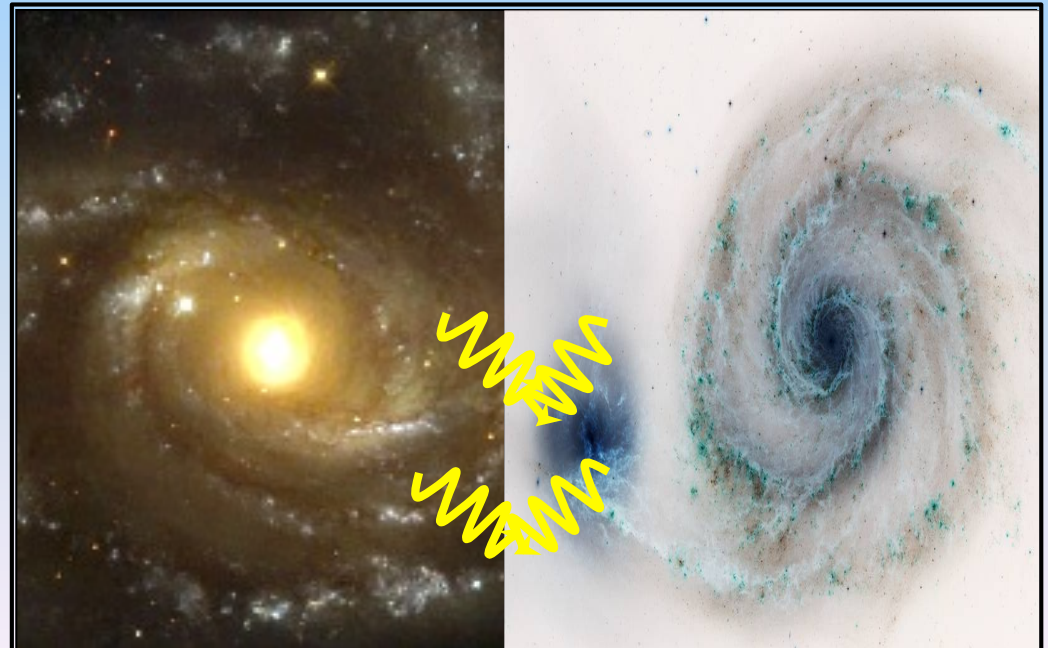
Anti-materie: waar is het gebleven ?

Theorie: materie en anti-materie zijn 'gelijk'

Geen anti-materie in satellieten



Geen anti-materie sterrenstelsels



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

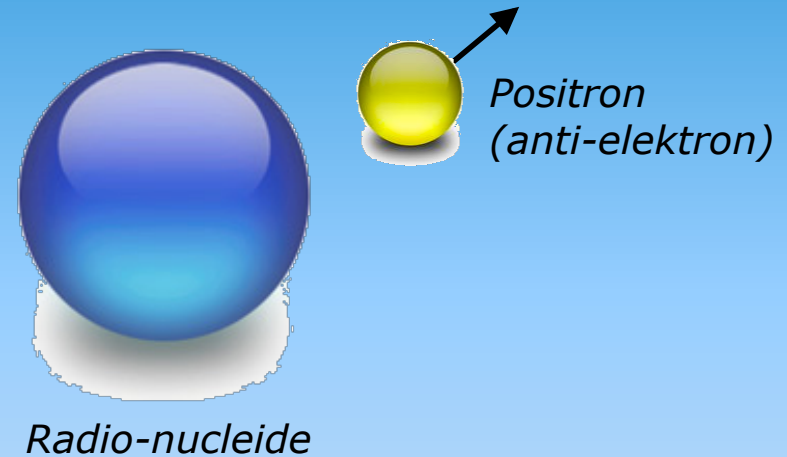


Deeltje-antideeltje paar maakt via $E=mc^2$ een γ

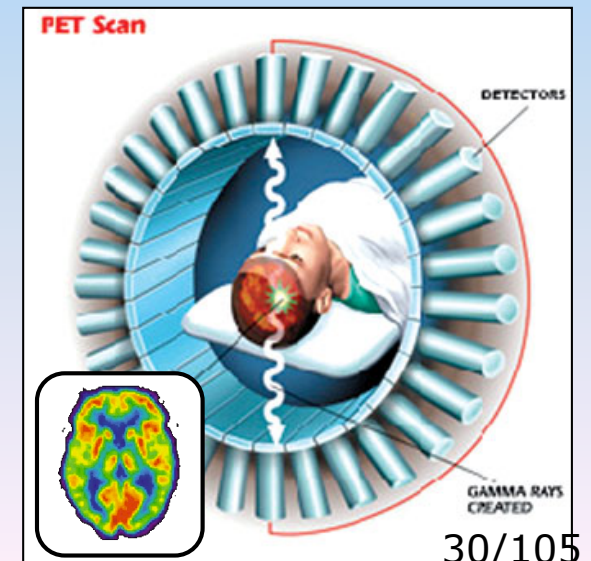
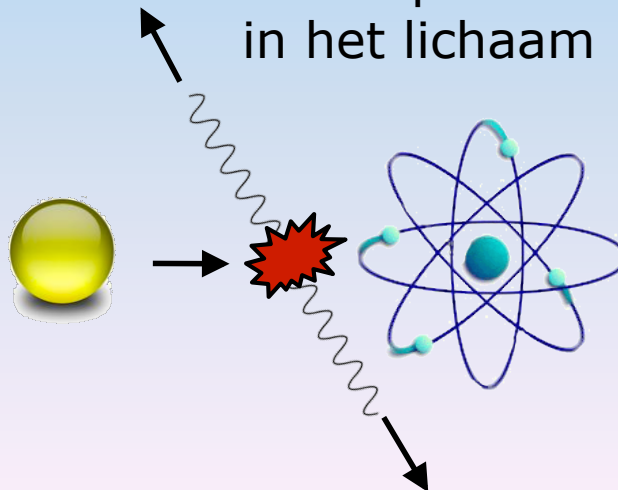


Anti-materie in het ziekenhuis: de PET scan

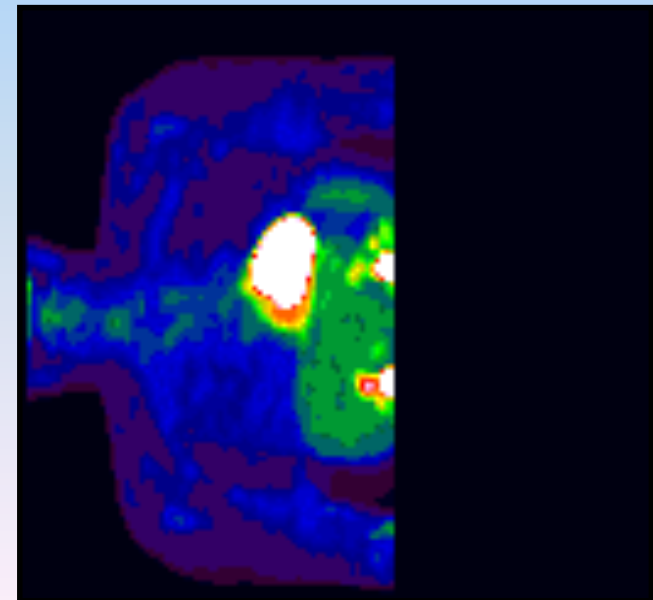
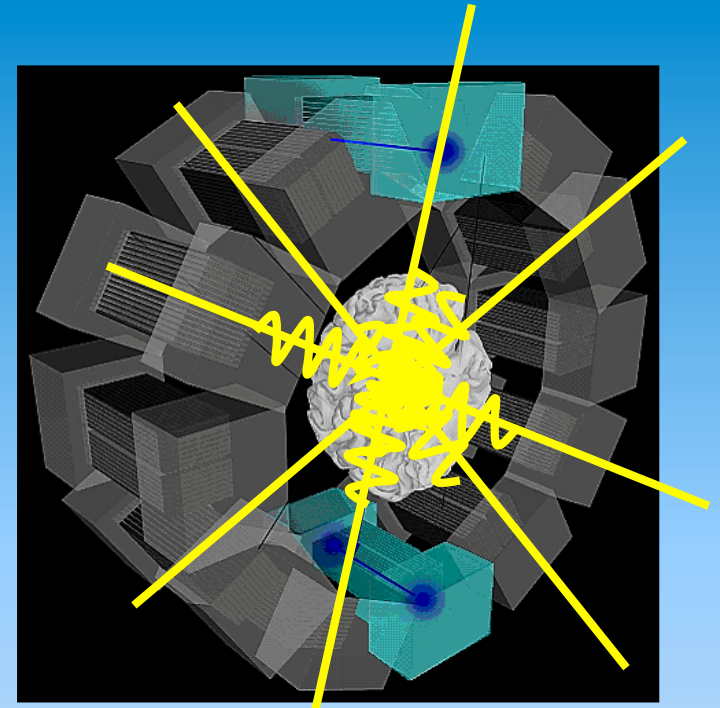
- 1) Injectie met radio-nuclide stof
→ zendt positronen uit



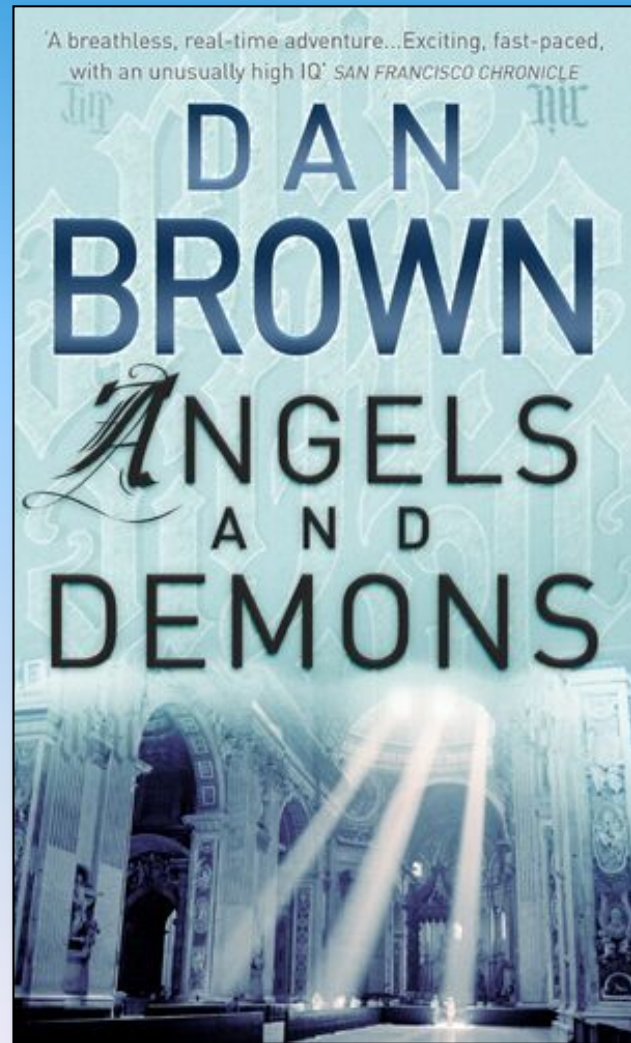
- 2) positron
botst op elektron van atoom
in het lichaam → 2 fotonen



Positron Emissie Tomografie



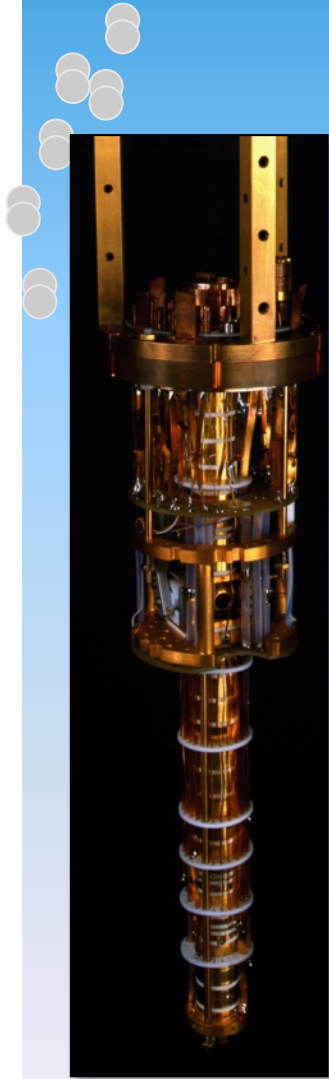
Dan Brown



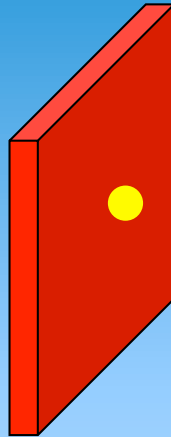
1/4 gram anti-protonen van CERN gestolen

Gebruik om het Vaticaan op te blazen

Productie van anti-waterstof: CERN vs Angels&Demons



CERN

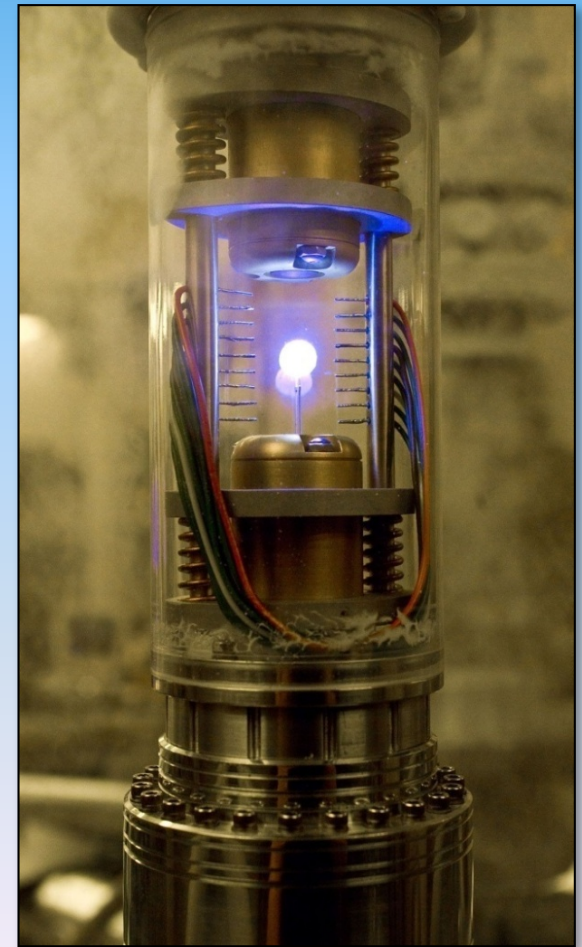


CERN kan 10 miljoen anti-protonen per seconde maken!

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

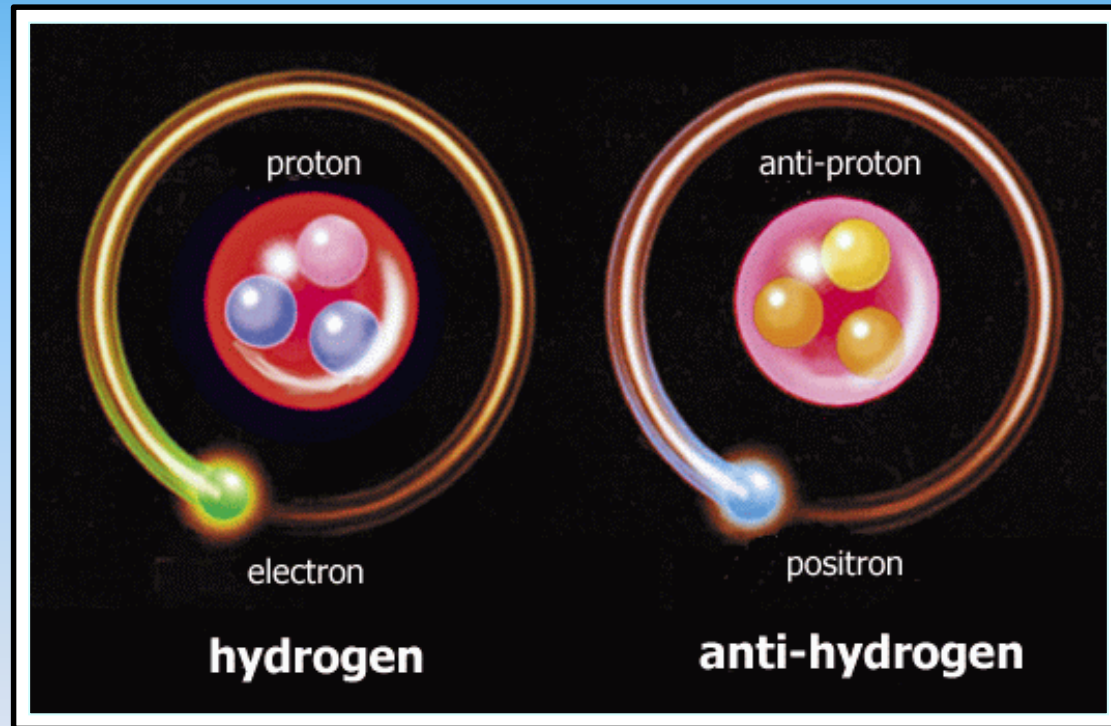
Hoe lang duurt het om $\frac{1}{4}$ gram anti-protonen te maken ?

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



Dan Brown

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



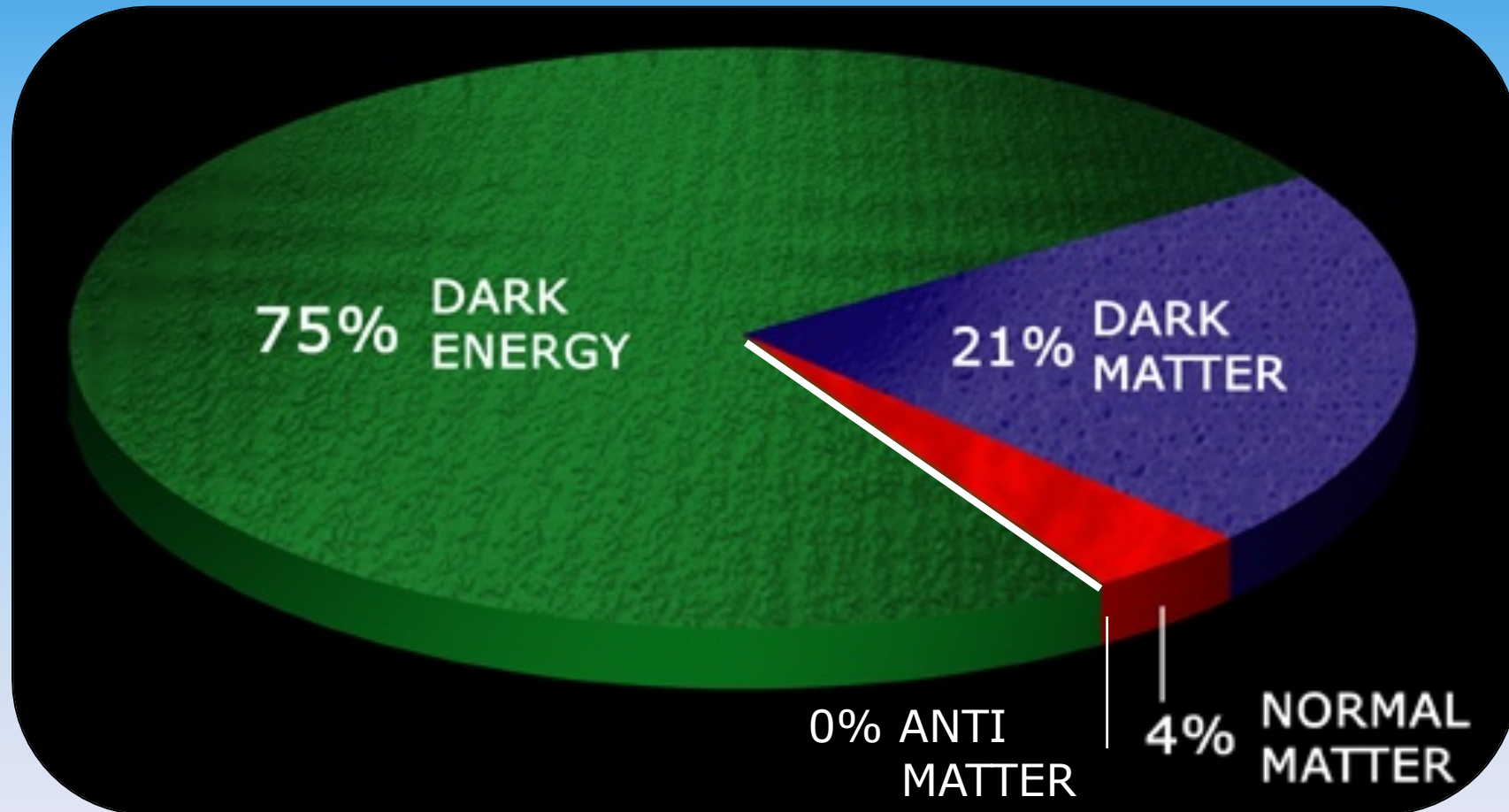
1995: Eerste anti-waterstof geproduceerd op CERN

2002: Duizenden anti-atomen geproduceerd op CERN en Fermilab

1

Donkere-materie

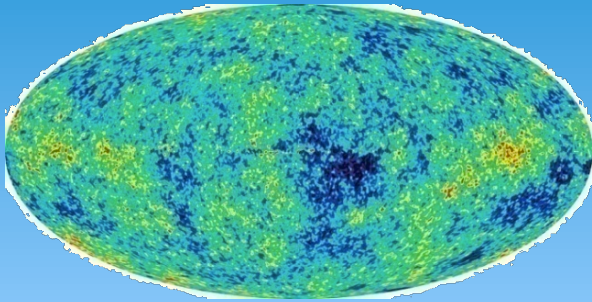
Waar bestaat het heelal uit?



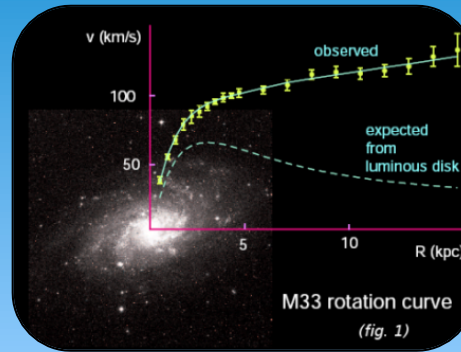
Slechts 4% is normale materie...

1

Donkere-materie



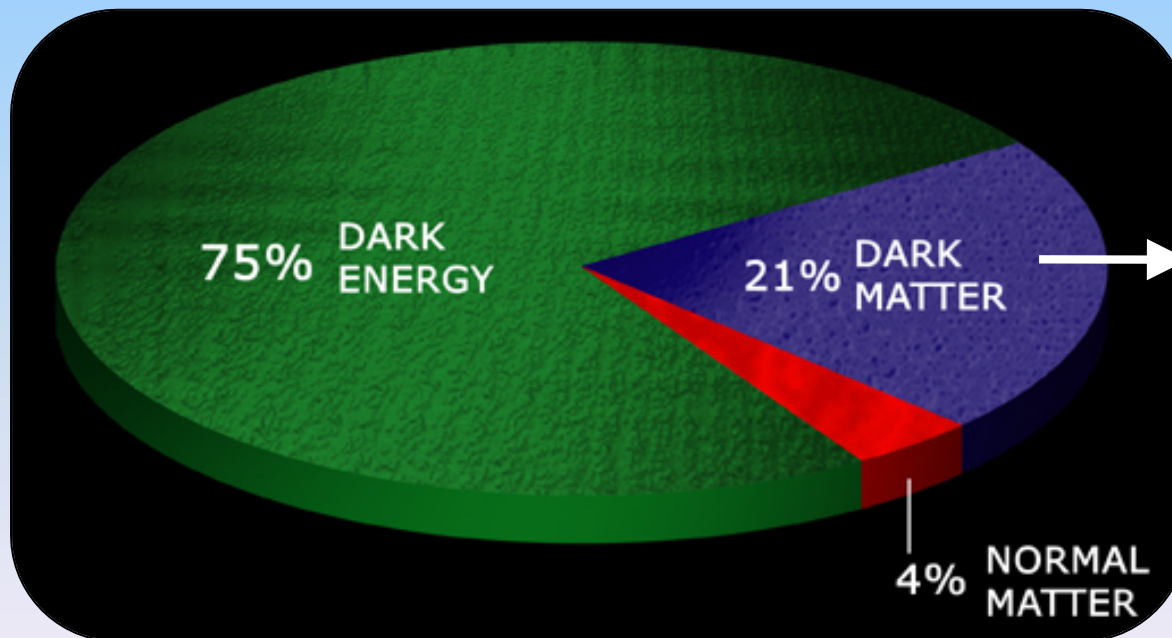
Temperatuurfluctuaties
structuur van het heelal



Rotatie-curves



Cluster formaties &
gravitationele lens



Wat is de
donkere materie ?

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



Revolutie in kosmologie laatste paar jaar
Structuur van het heelal

We proberen de donkere materie deeltjes
in het laboratorium maken

deeltjes

Anti-deeltjes

Bij de LHC
deeltjes pr
wel donker

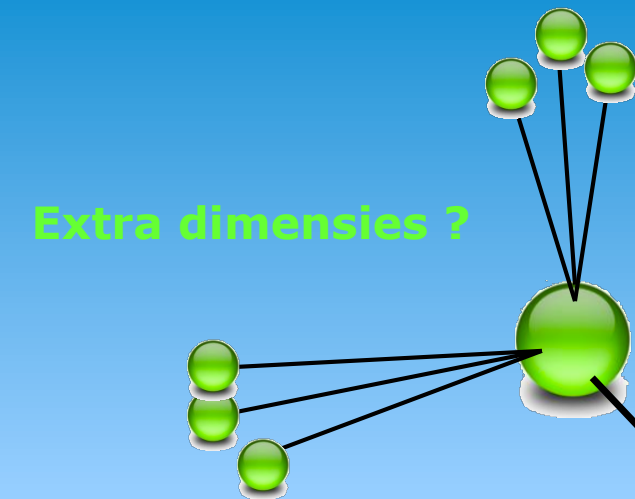
proton

proton

Super-symmetrie: elk deeltje
heeft een zwaar broertje

Diagram illustrating a proton decay process:

- Two incoming protons (p) interact.
- The decay products are: a quark (q), a positron (l^+), an electron (l^-), and two neutralinos ($\tilde{\chi}_2^0$ and $\tilde{\chi}_1^0$).
- The $\tilde{\chi}_1^0$ is circled and labeled "Donkere materie?" (Dark matter?).

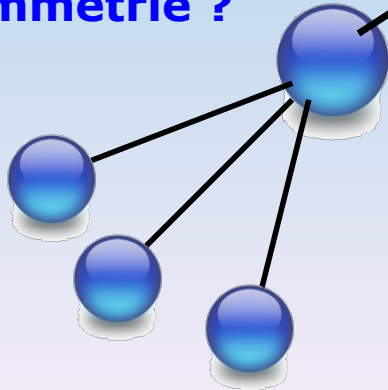


- Het Standard Model is 'effectief' deel van een meer fundamentele theorie
- Model verliest voorspellende waarde rond 1-10 TeV



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

Supersymmetrie ?

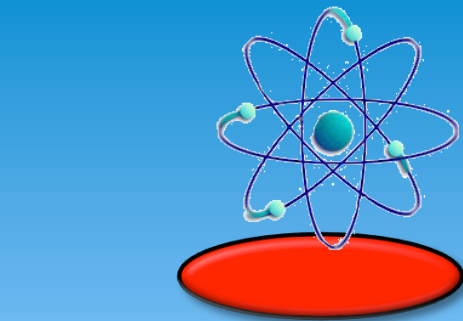


2012

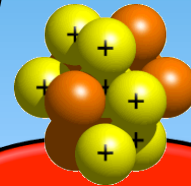
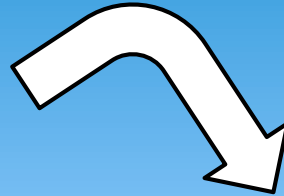
String theorie ?

Edward Witten's
laatste inzicht.

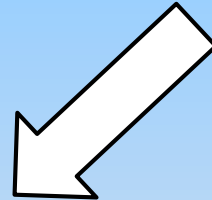
De zoektocht naar de bouwstenen



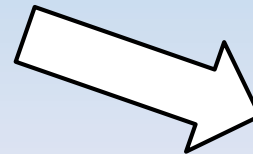
Atoom 10^{-10} m



Atoomkern: 10^{-14} m



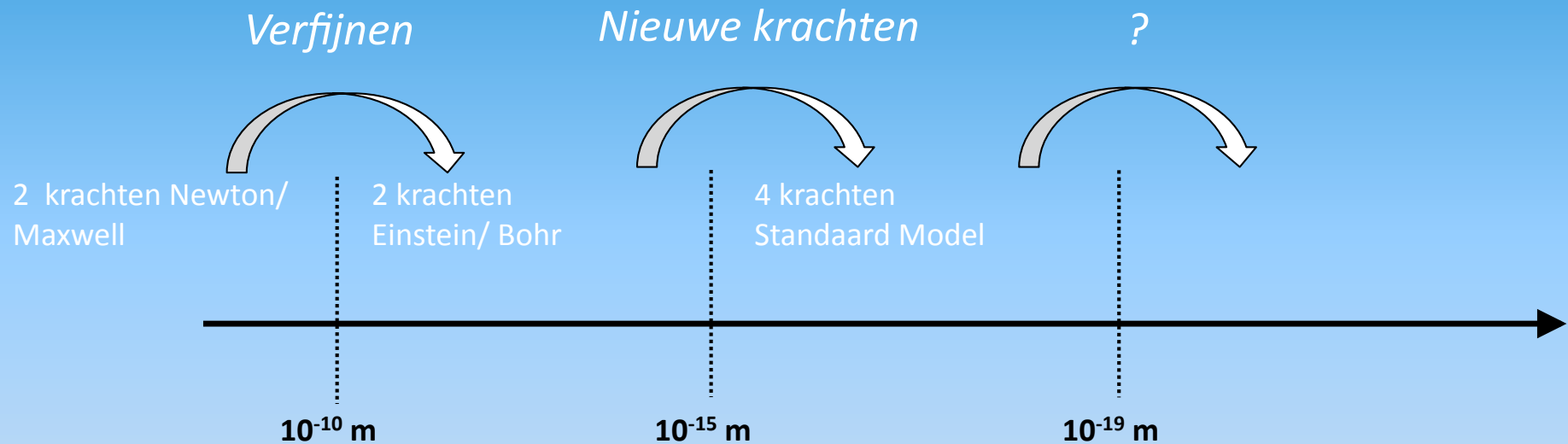
Nucleon: 10^{-15} m



10^{-19} m

De Large Hadron Collider

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

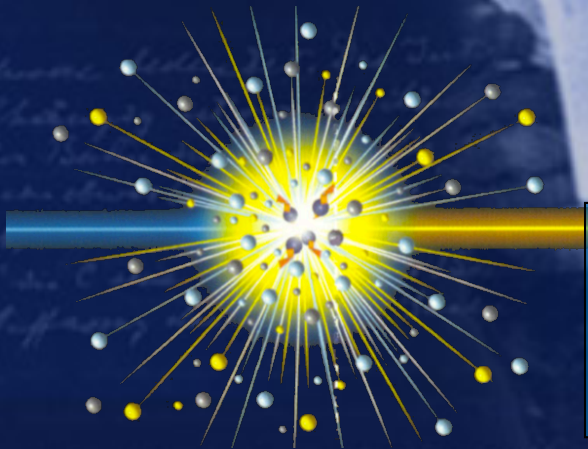


E. Witten



Albert Einstein

$$E = mc^2$$



Energie en massa zijn equivalent

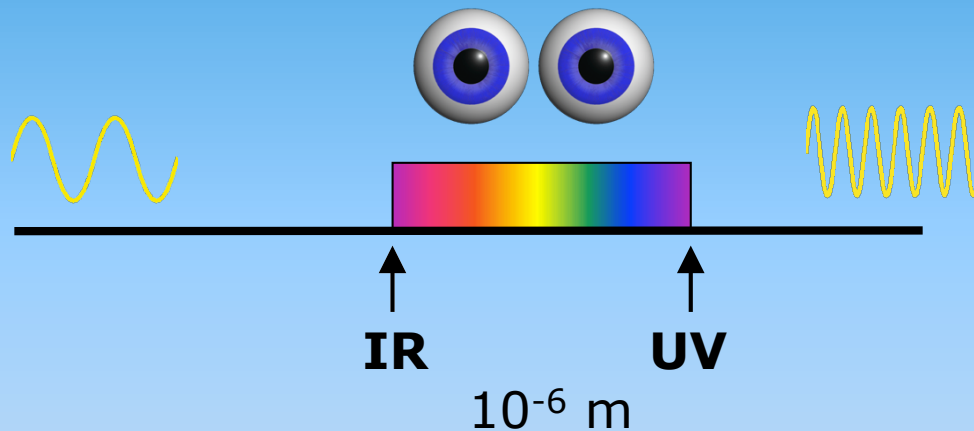
→ je kan *nieuwe* deeltjes maken

kijken zonder je ogen te gebruiken



1] Kijken met licht

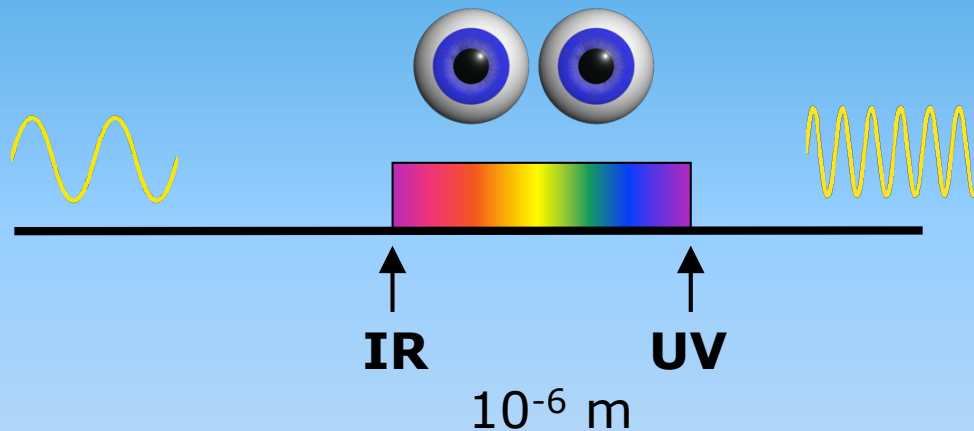
Licht verstrooit aan objecten die groter zijn dan zijn golflengte



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

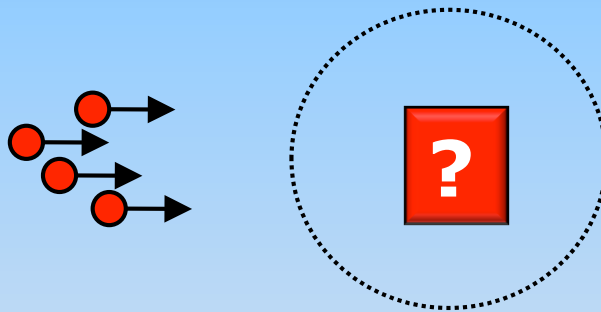
2] Kijken met deeltjes

Idee: laat kleine deeltjes afketsen van het object

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

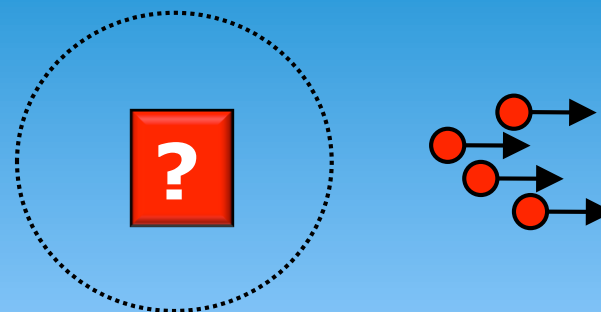
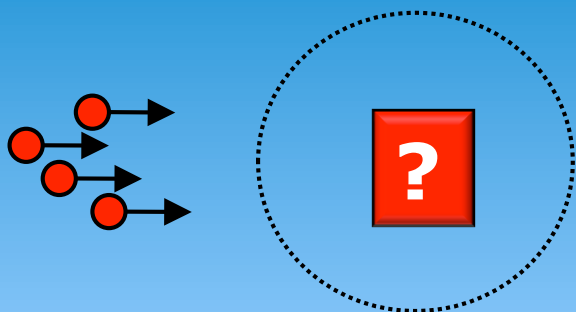
onbekend voorwerp achter een gordijn
... en 100 kogeltjes

bovenaanzicht

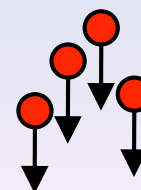
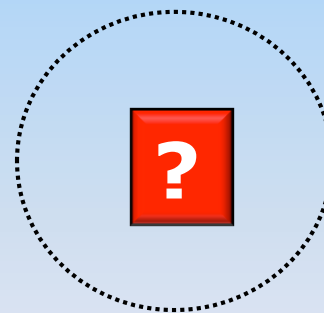
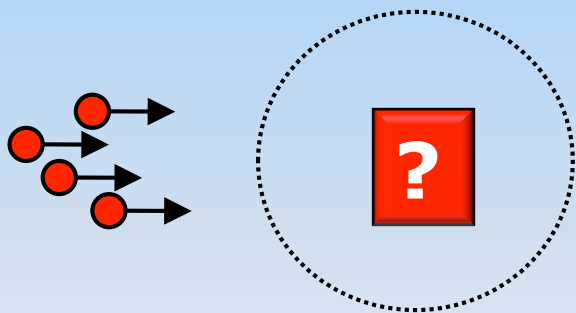


Hoe ketsen de kogels af ?

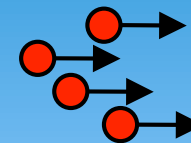
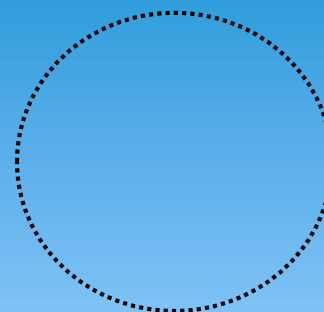
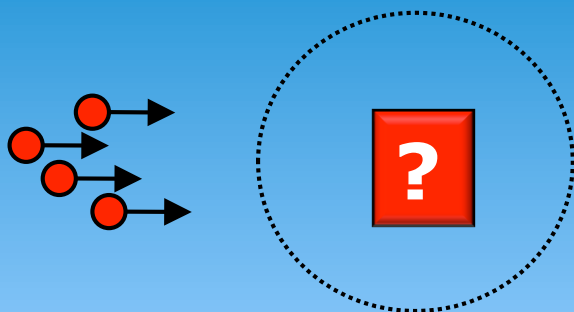
Experiment 1



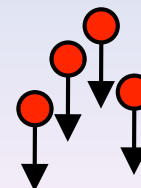
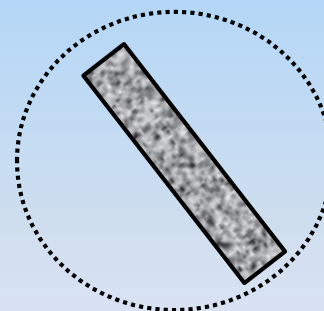
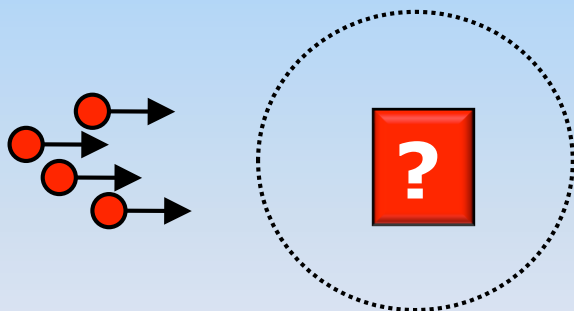
Experiment 2



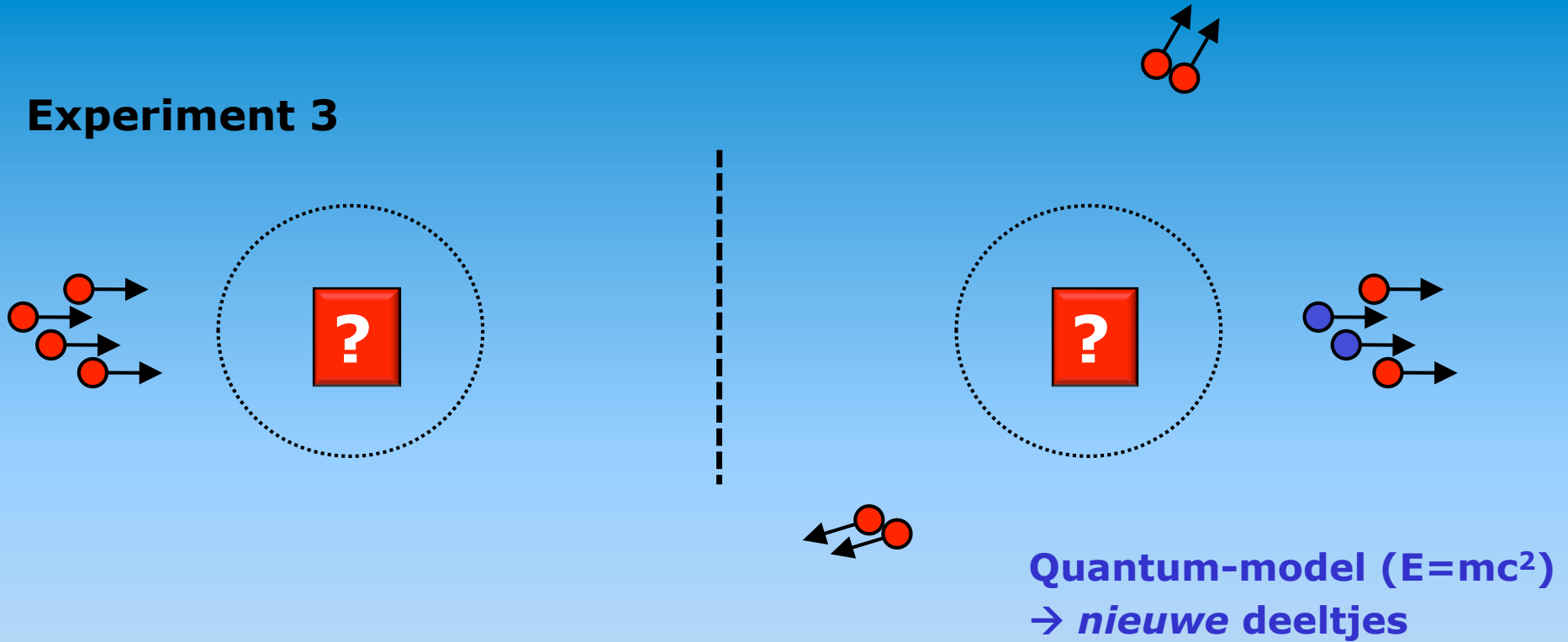
Experiment 1



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 zichtbaar maken van afgeketste of nieuwe deeltjes

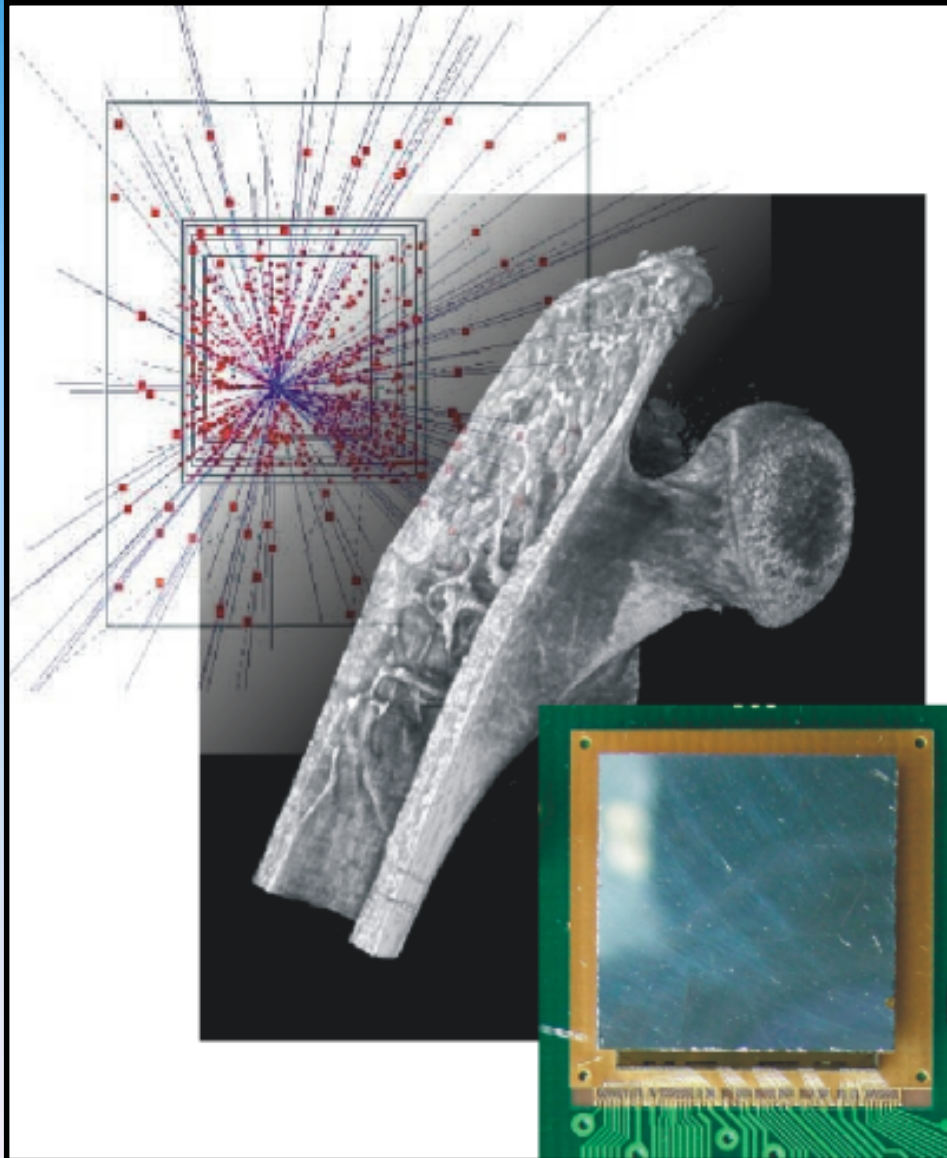
Rontgen foto



PET scan



Detectietechnieken: Medipix



Minder dosis
Hogere resolutie

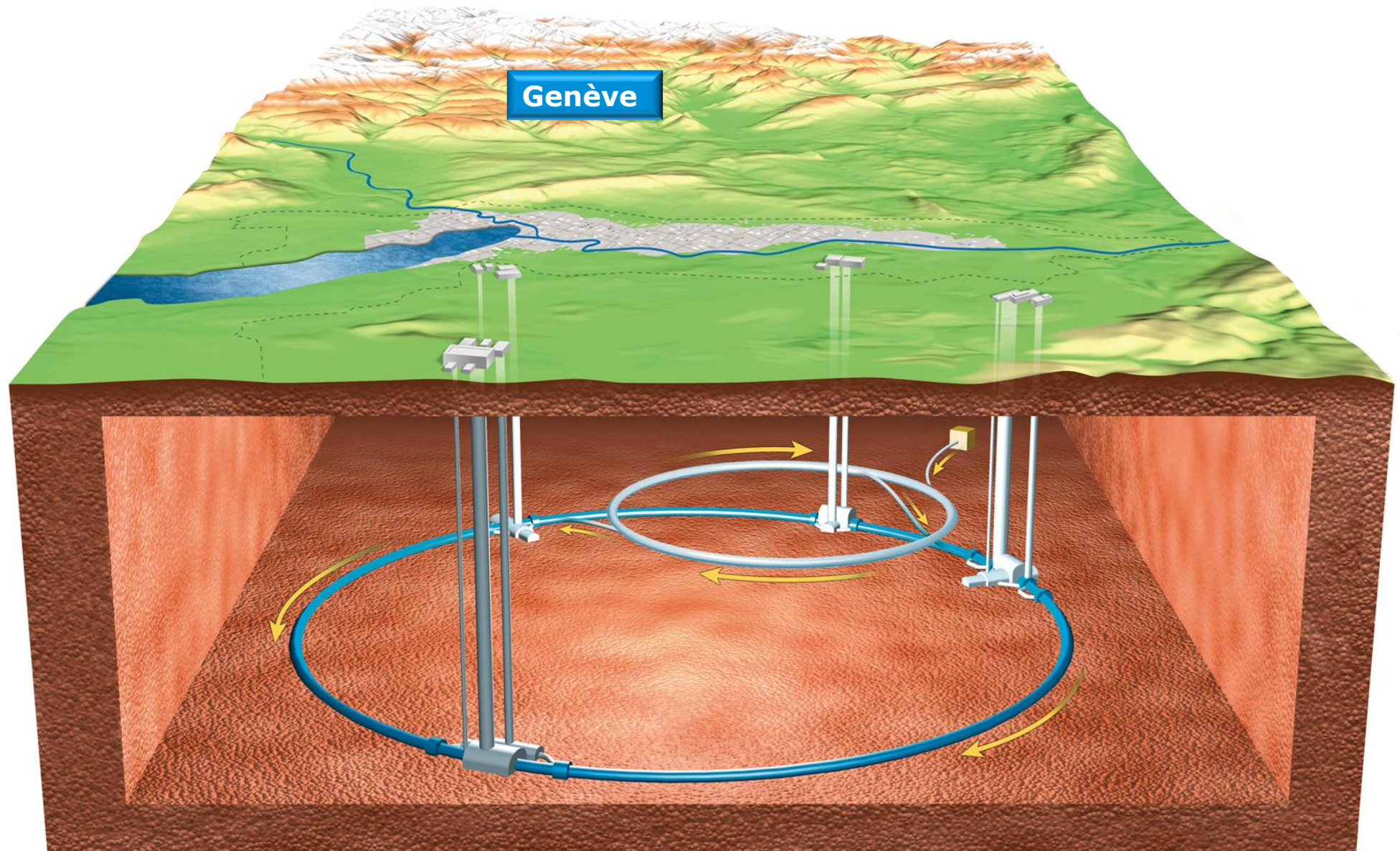
TUSSENDOORTJE

Grote inbreng Nederland (Nikhef)

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



De Large Hadron Collider

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

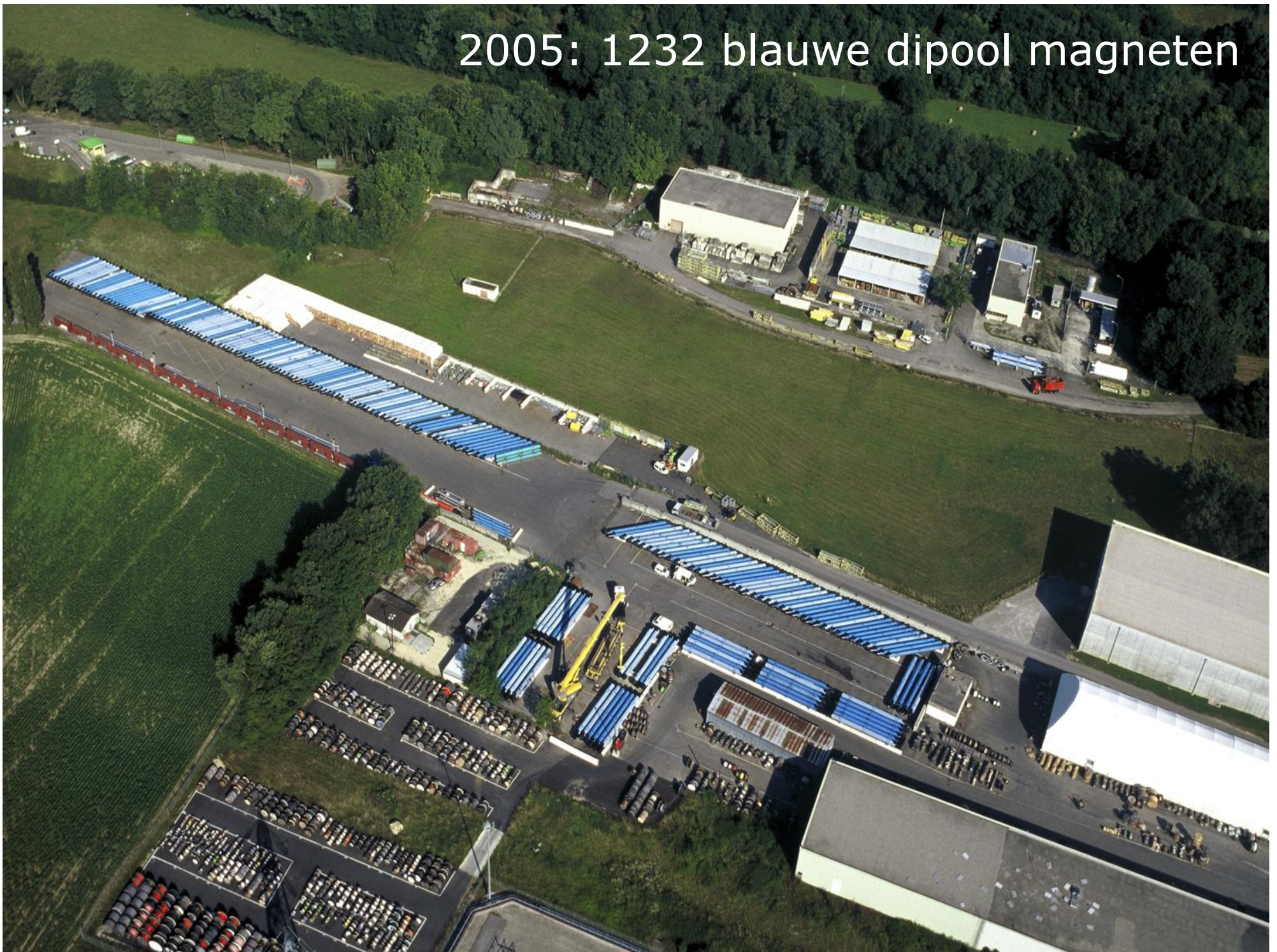
20 goud atomen

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

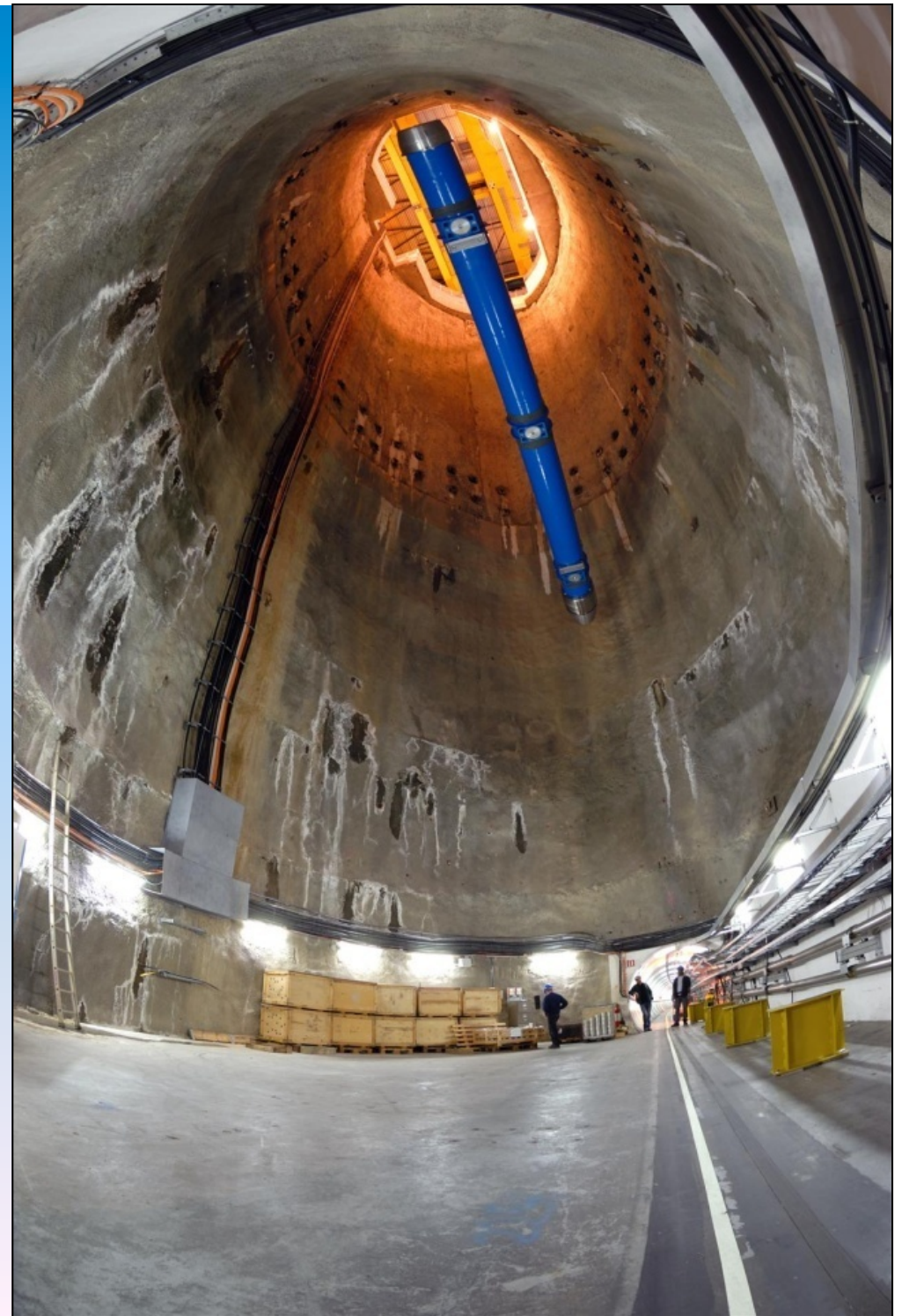
→ *Zoeken naar zeldzame gebeurtenissen*

→ 100 x LEP &
Tevatron

2005: 1232 blauwe dipool magneten

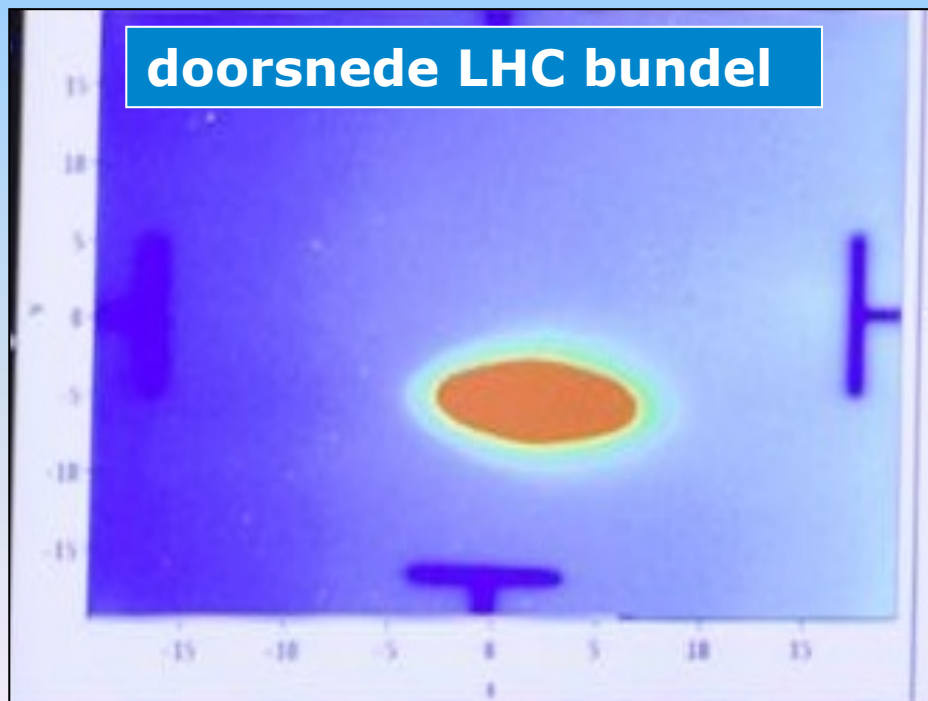


Logistieke nachtmerrie
maar gelukt



De LHC is rond !

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

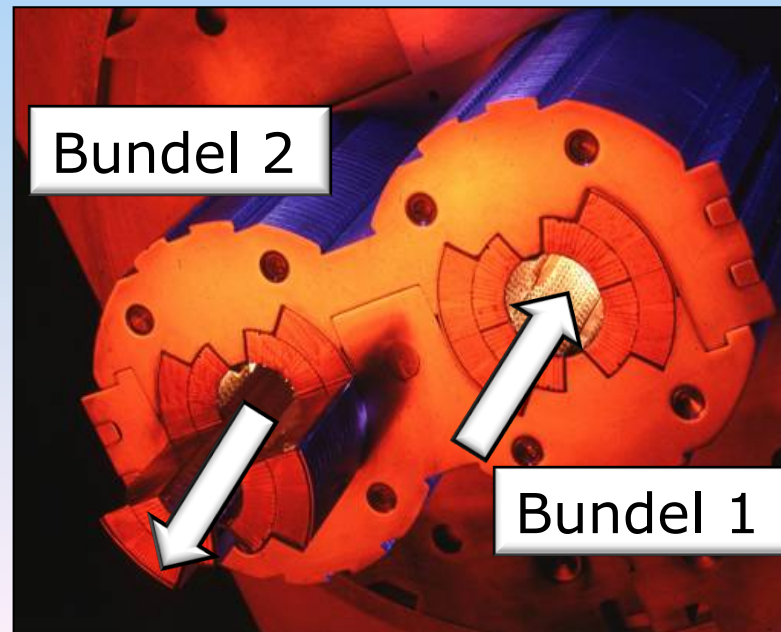


Energie 1 proton (LHC)



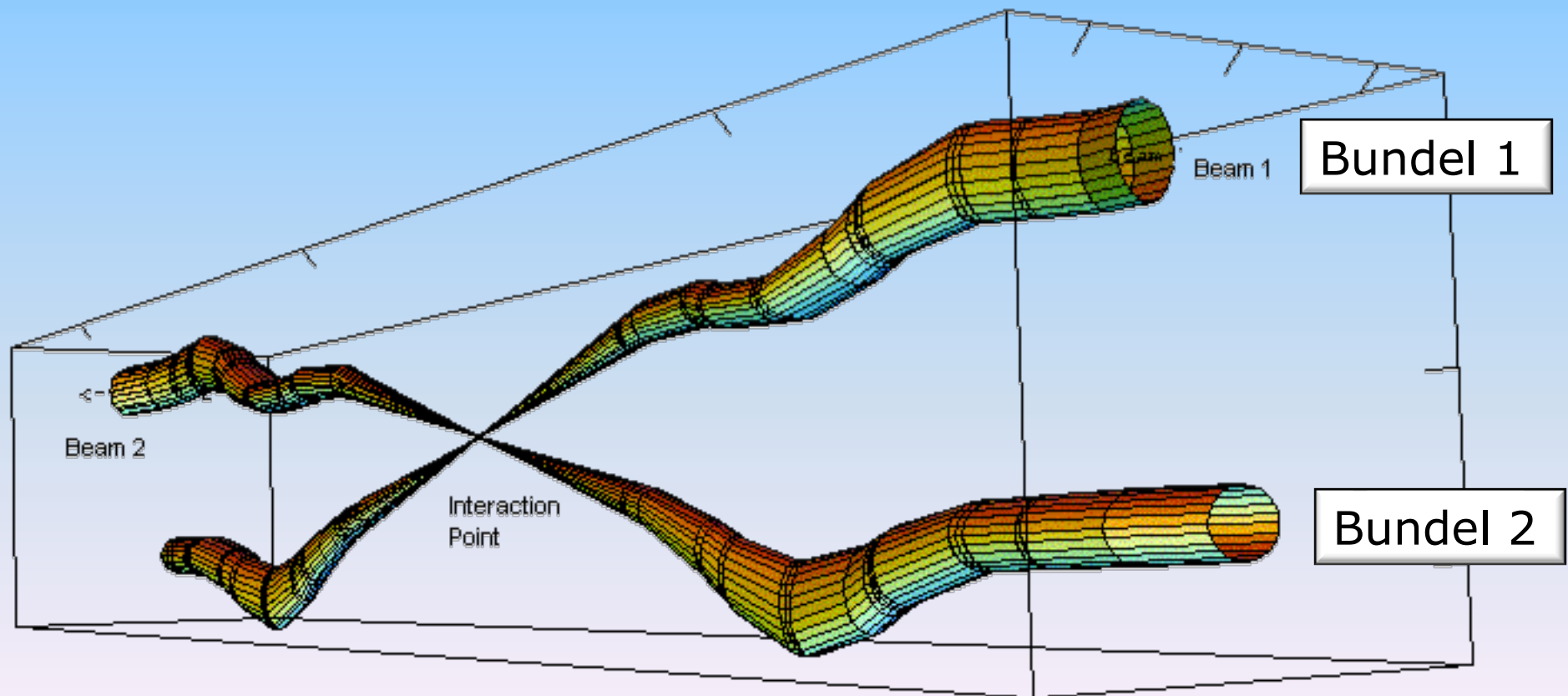
Energie LHC bundel

$3000 \times 100.000.000.000$ protonen



*Doorsnede LHC
bundelpijp*

40 miljoen botsingen per seconde





Klassiek botsen

Quantummechanisch botsen



Wat verwacht je ?

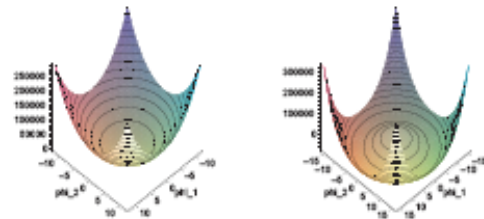


FIG. 1: The potential $V(\phi)$ ($\phi = \phi_1 + i\phi_2$) plotted for an arbitrary positive value of λ and for an arbitrary positive (right) or negative (left) value of μ^2 .

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:

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

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:

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

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:

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

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

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

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: $H \rightarrow \gamma\gamma, \gamma Z, gg$

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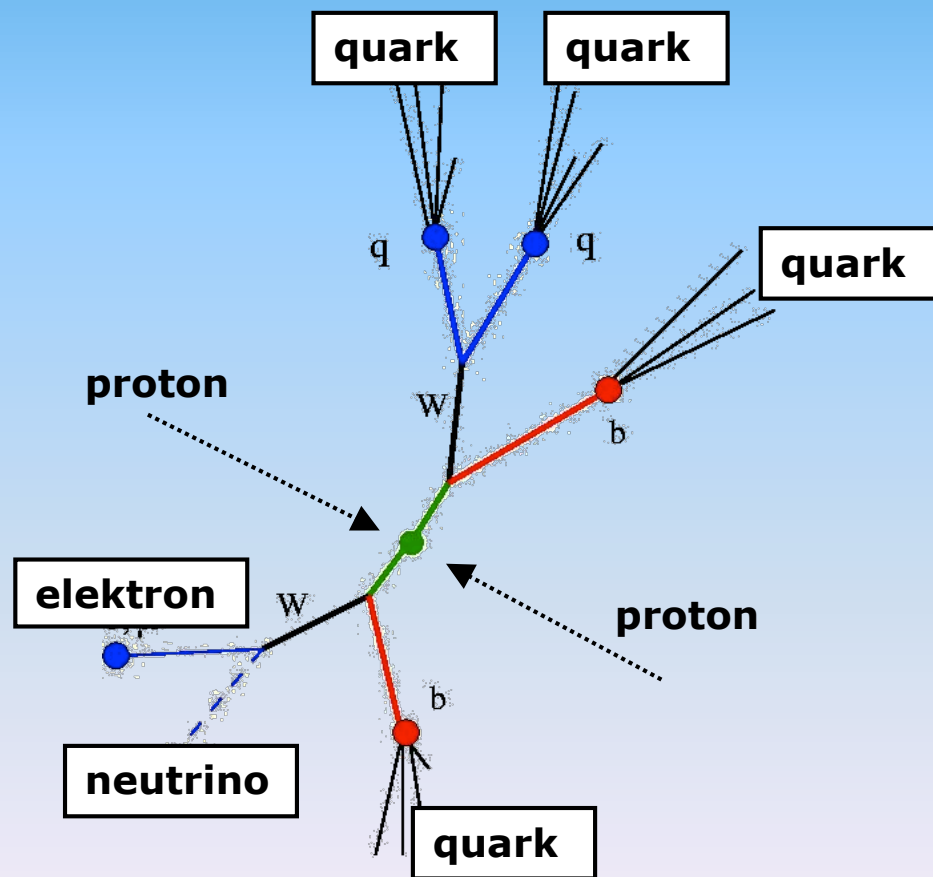
Klopt het ?

Inderdaad nieuwe deeltjes ?

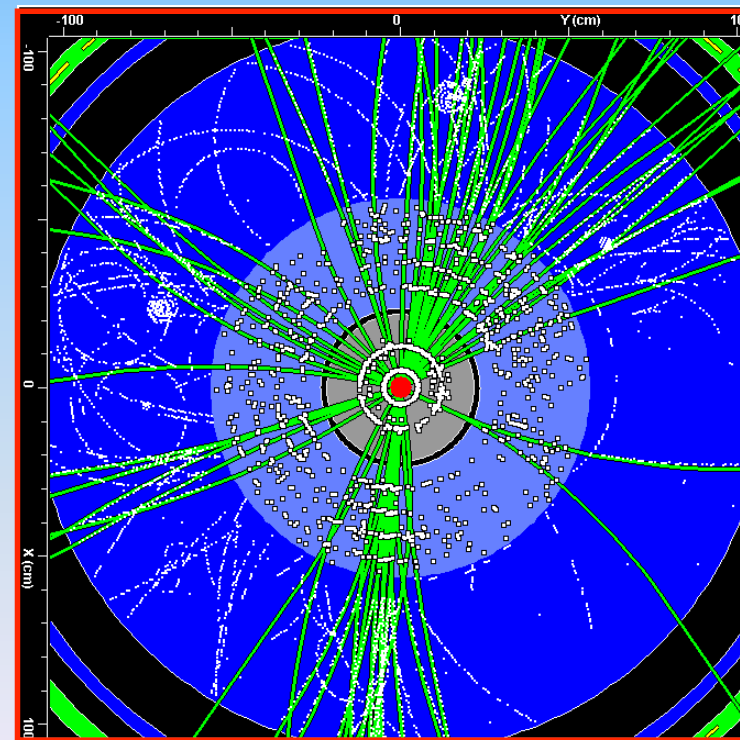


Heel vaak botsen

Hoe zien die botsingen er nou uit ?



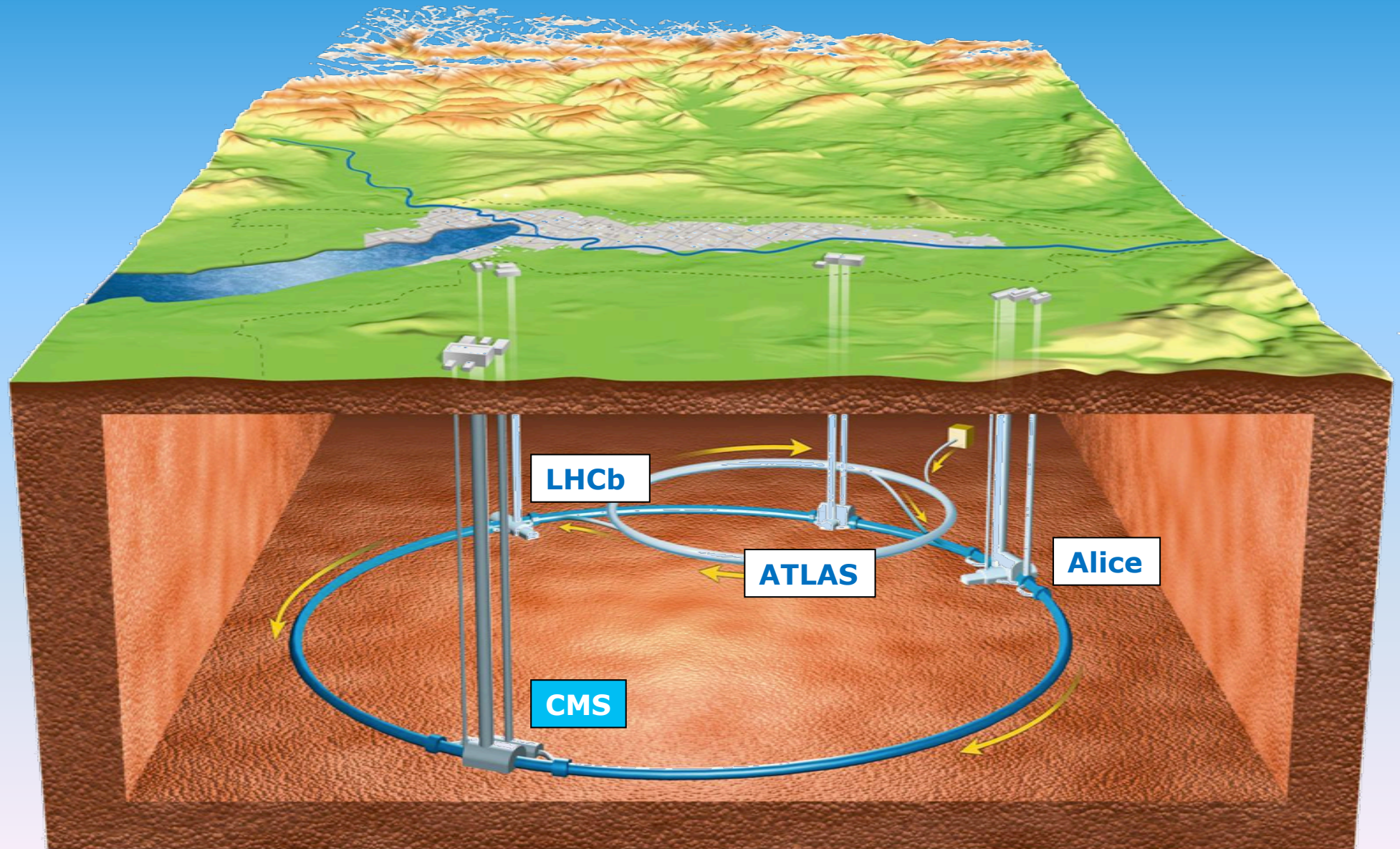
Simulatie top quark productie



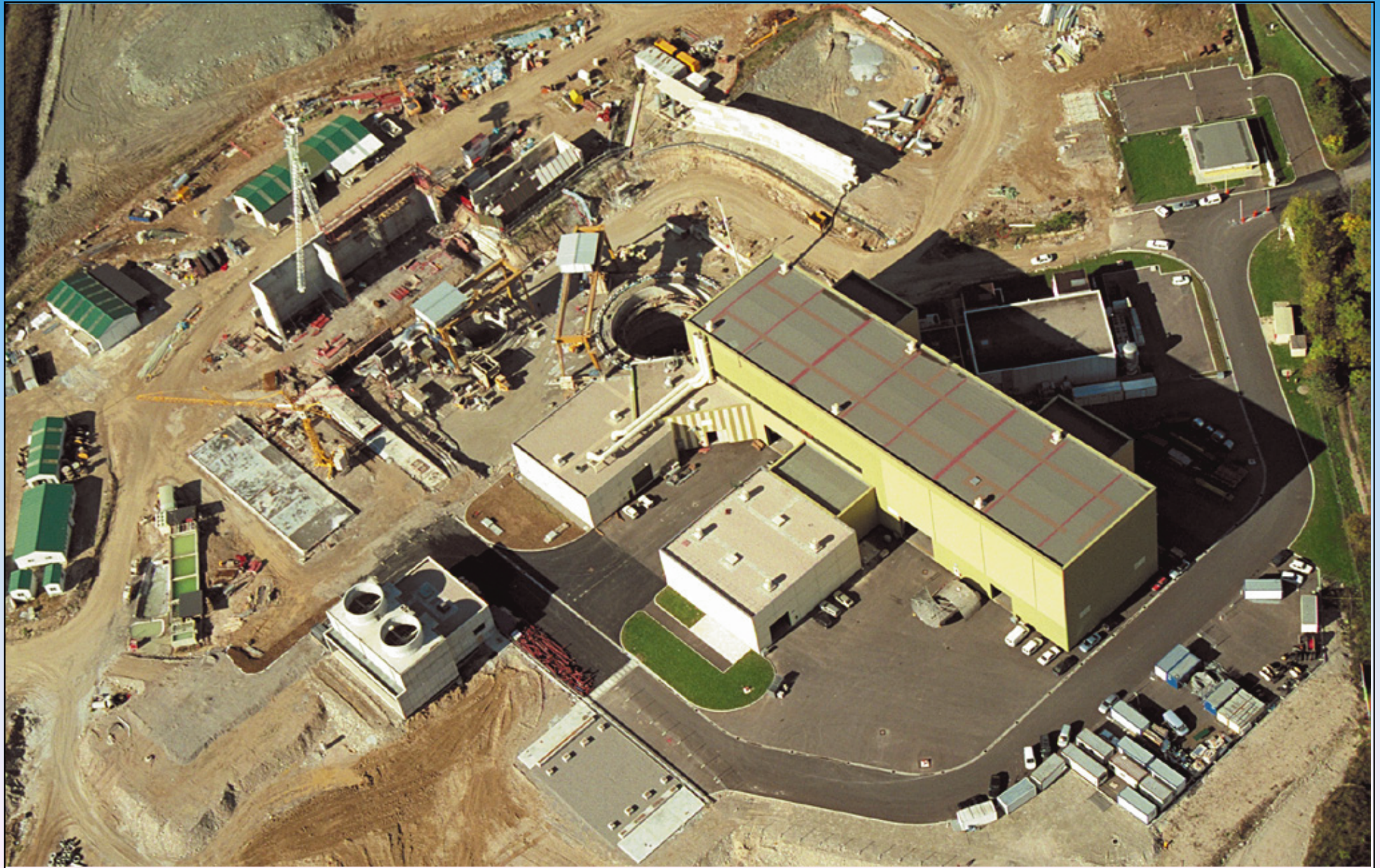
Onze 'fototoestellen'



De vier experimenten

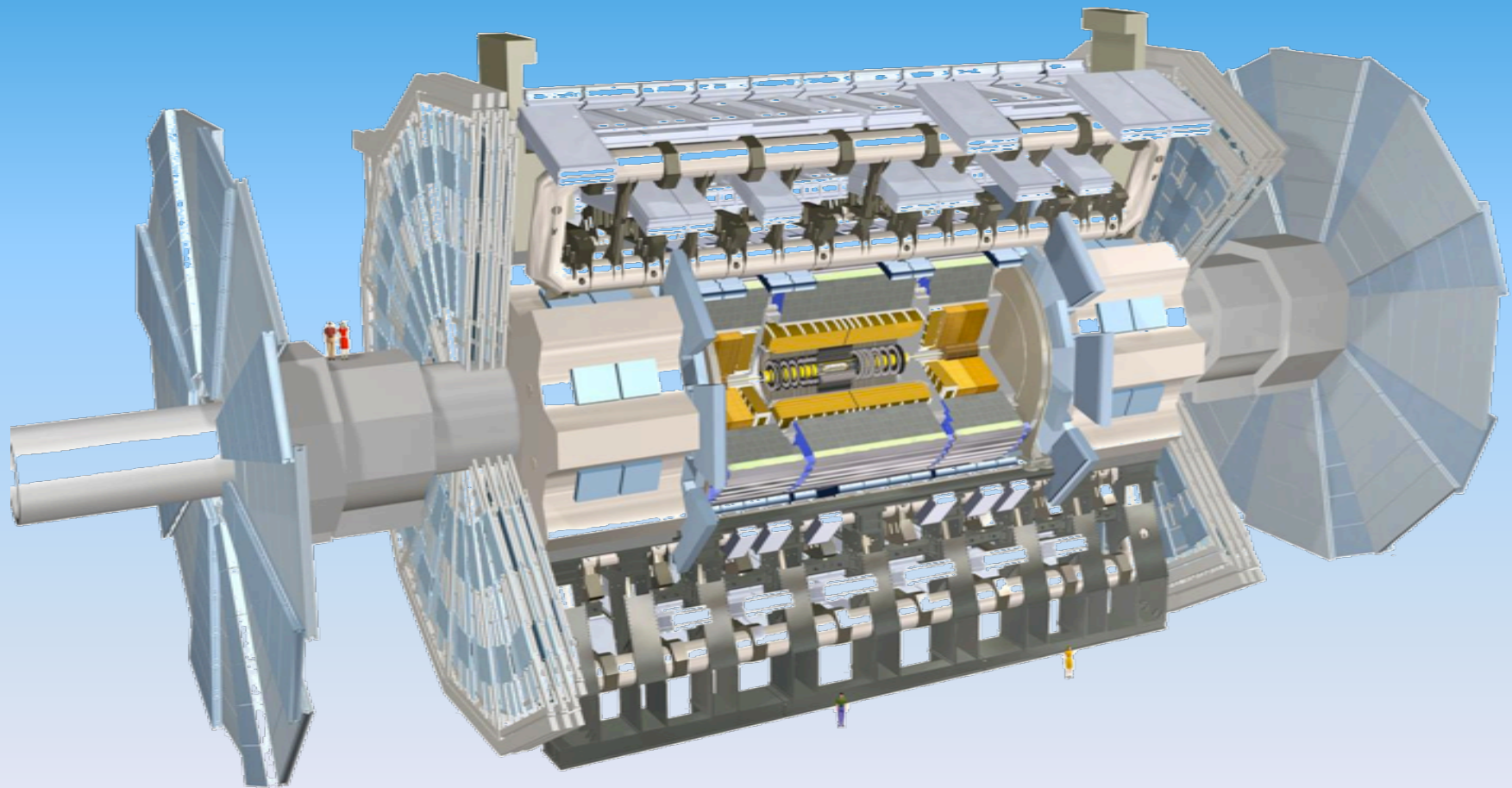


Een gat in de grond ... ongeveer 100 meter diep





De ATLAS detector (als computer model)



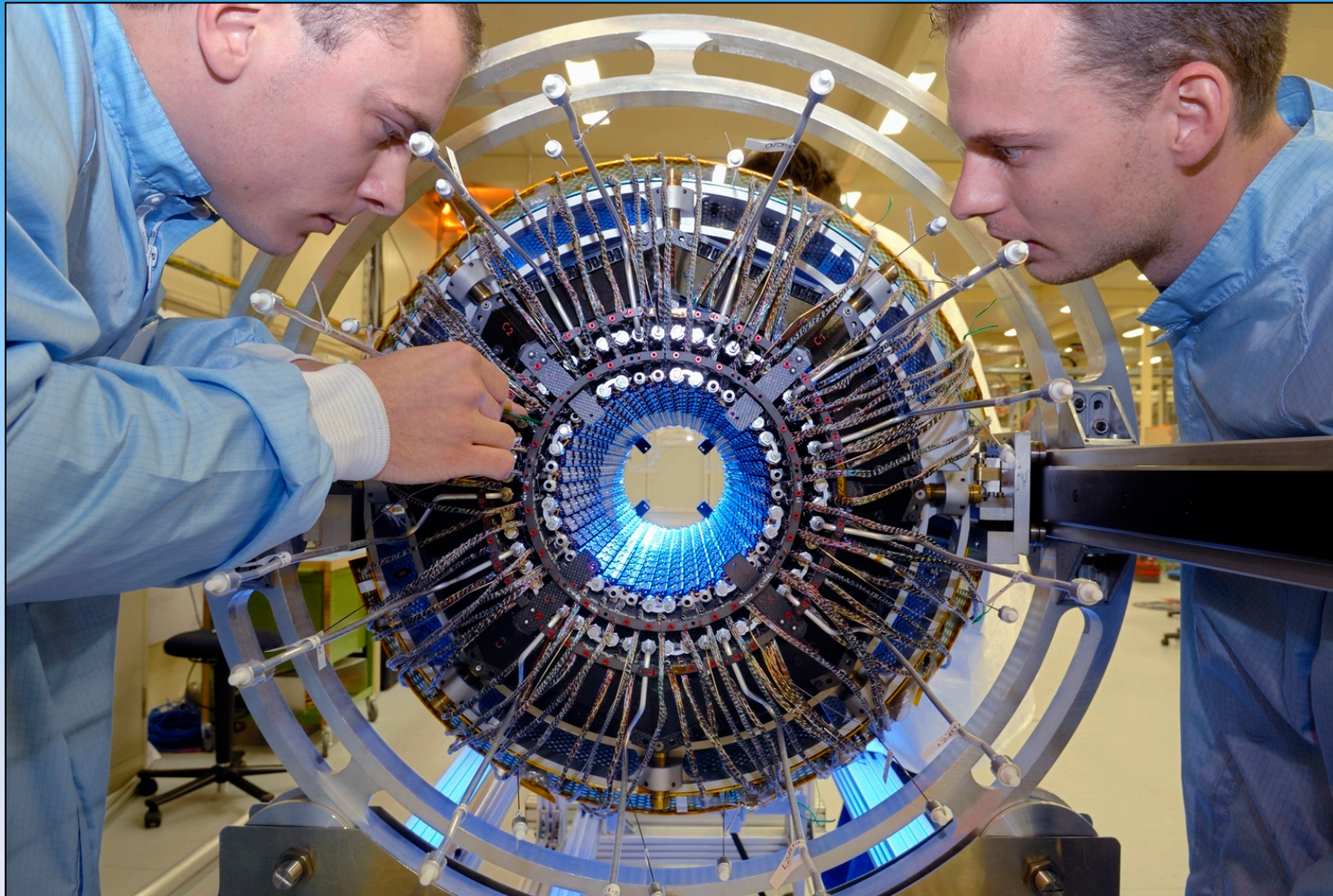
De Atlas detector bestaat echt



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

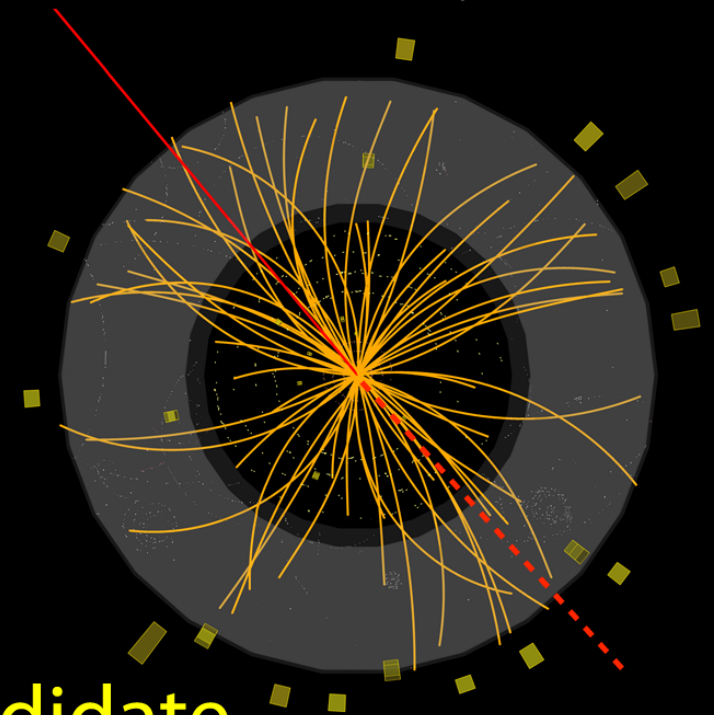
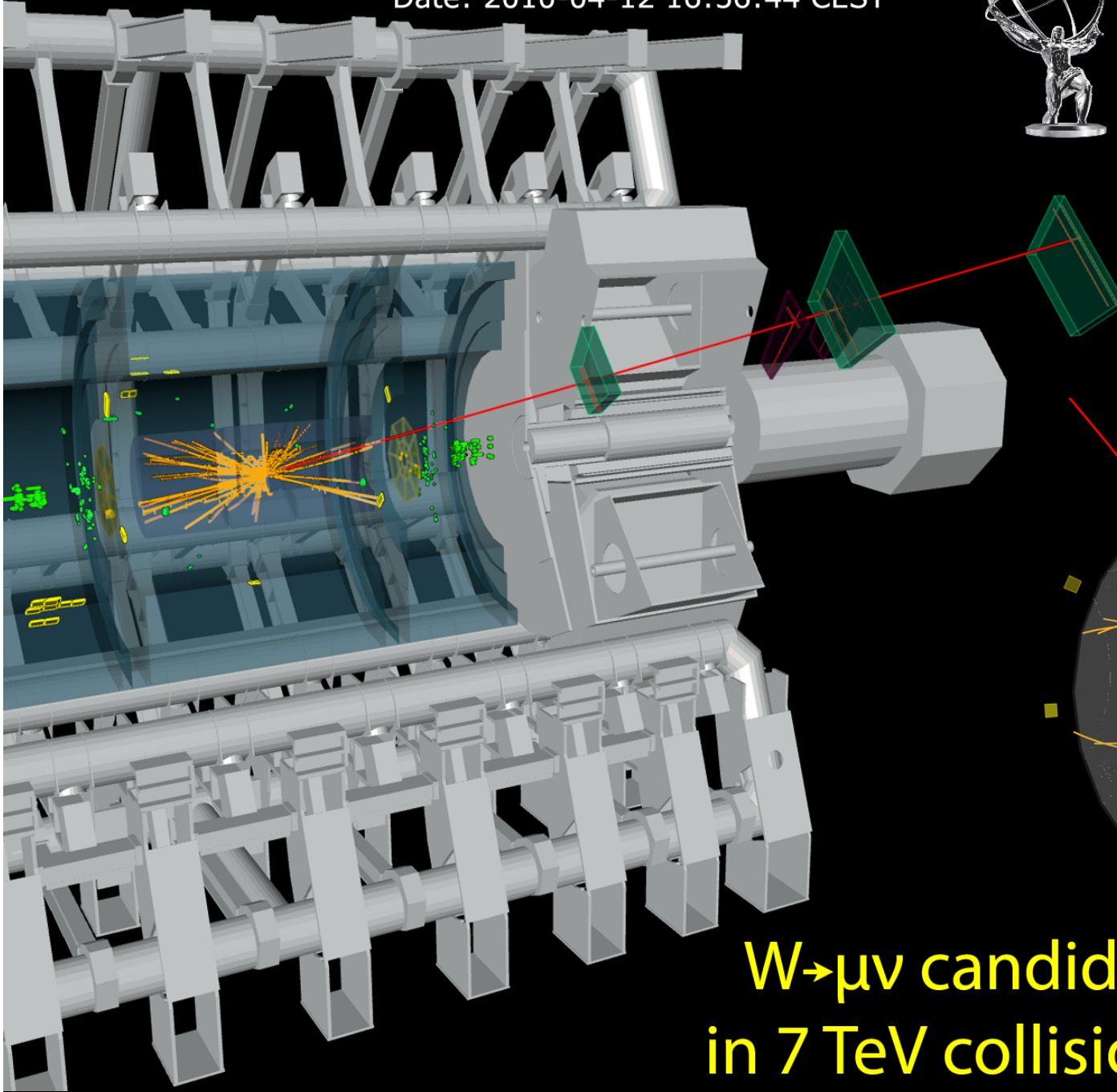


Run: 152845, Event: 3338173
Date: 2010-04-12 16:56:44 CEST



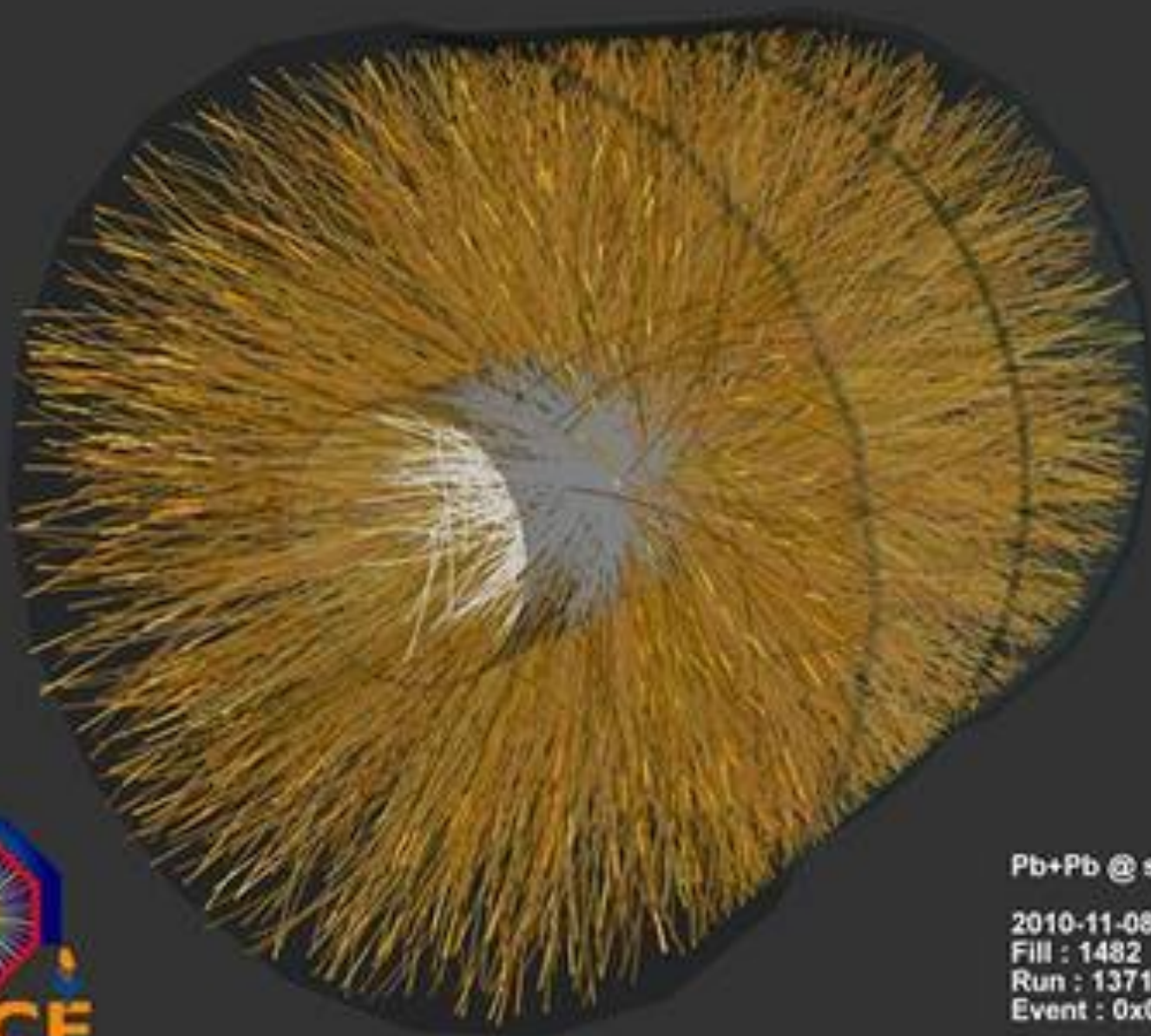
ATLAS EXPERIMENT

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



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

ALICE experiment



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

2010-11-08 11:30:46

Fill : 1482

Run : 137124

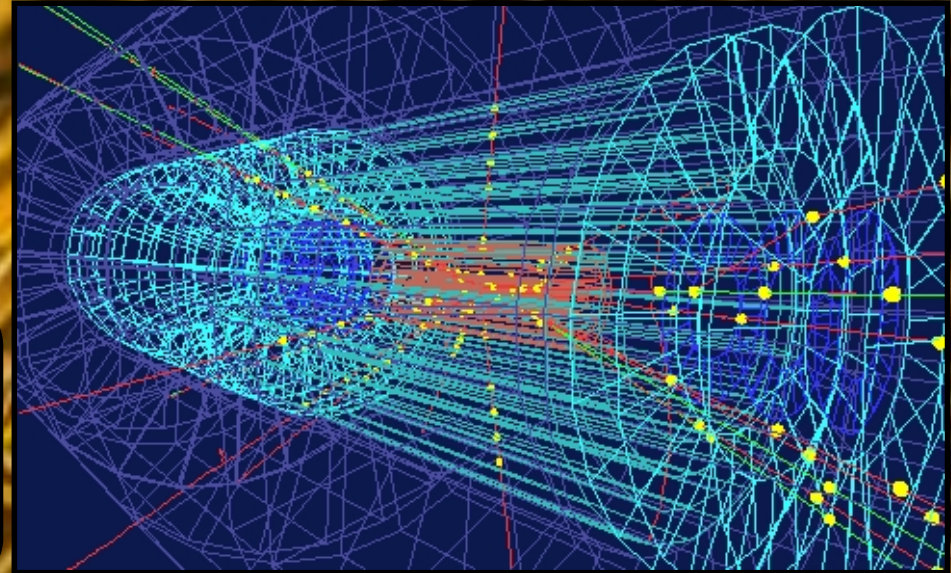
Event : 0x00000000D3BBE693

... 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 !



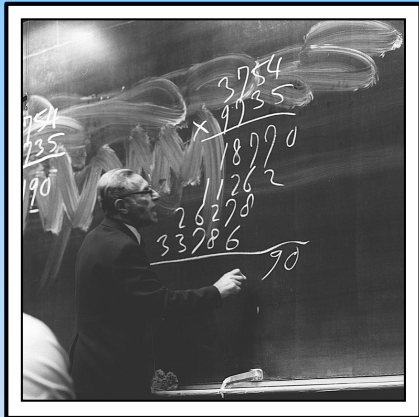
ongeveer 1 Higgs boson per dag

(Grid-) computing

ATLAS: 40 miljoen botsingen/sec

→ 200 Hz op tape

'gewoon' 3000 PC's

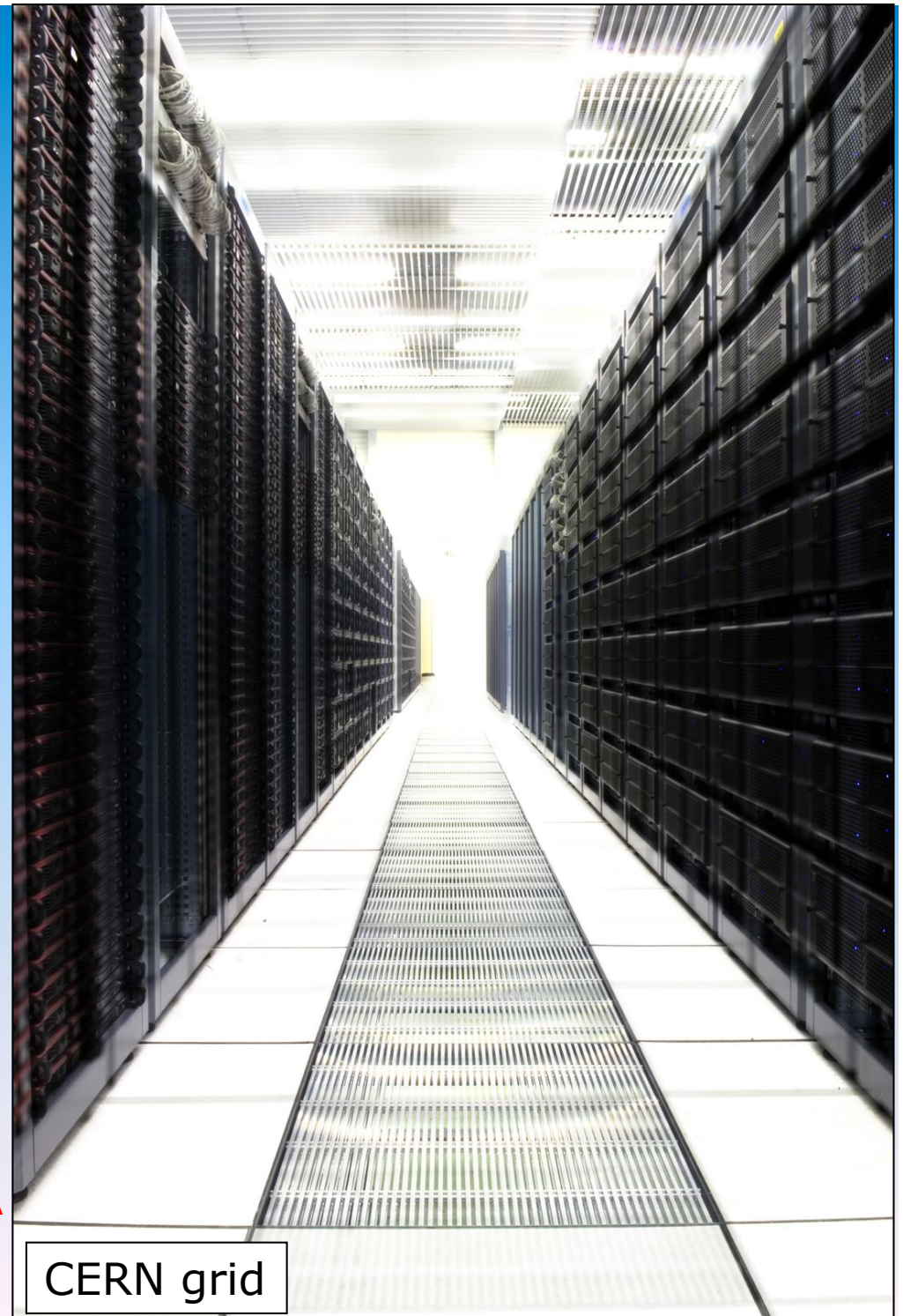


CERN's eerste computer

Wim Klein

Data-storage:

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



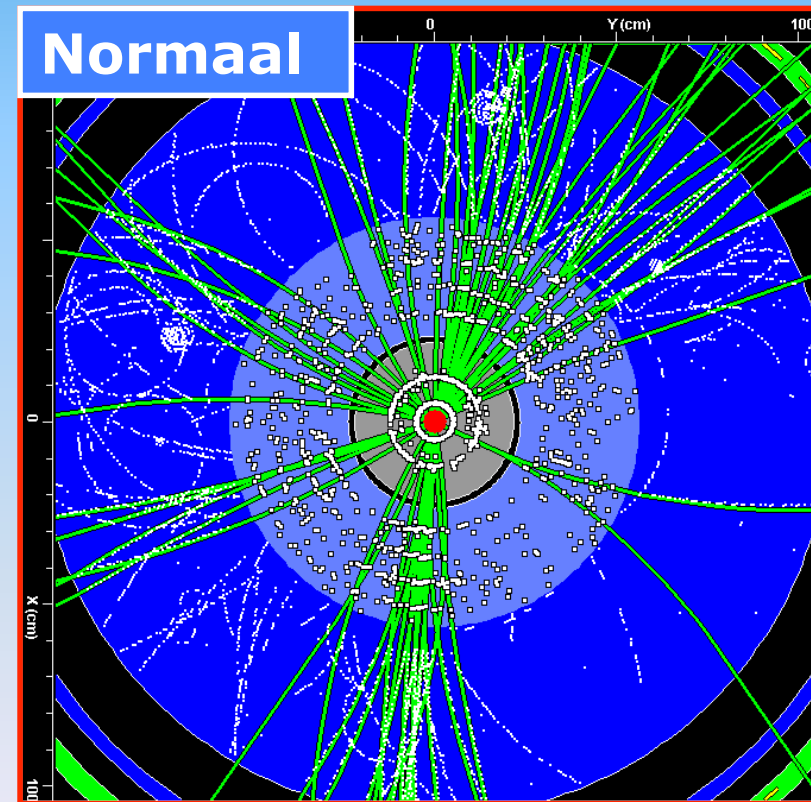
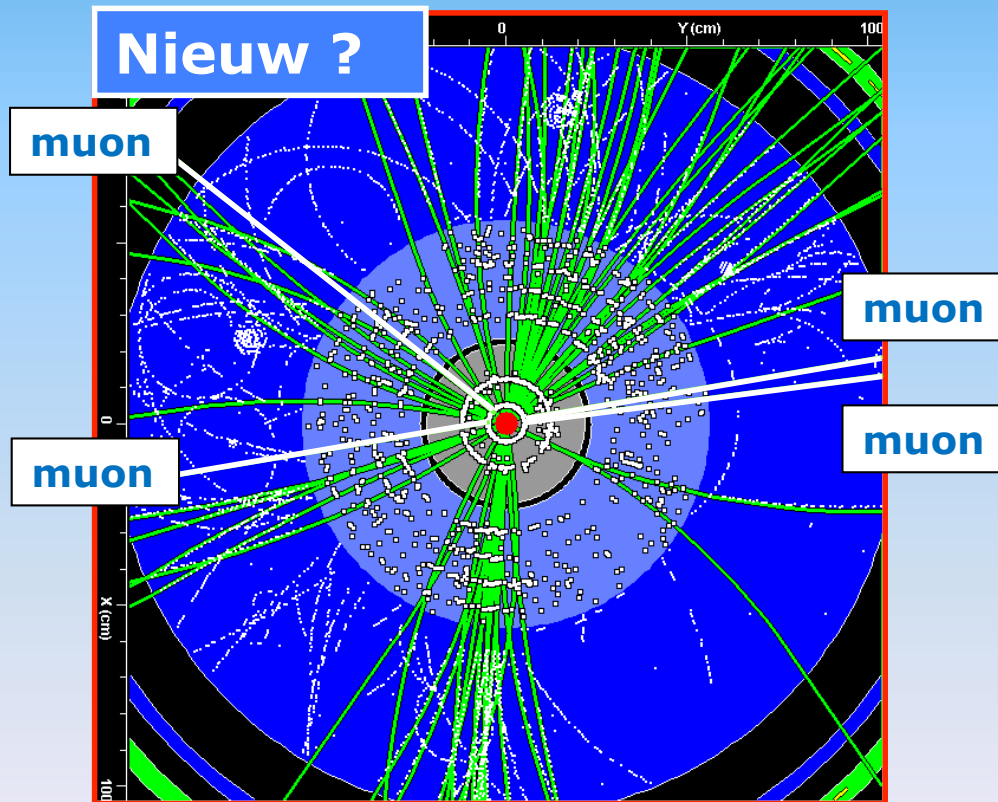
CERN grid

... het echte werk!



Hoe ontdek je nou nieuwe dingen: Higgs boson

Nieuwe afstandschaal EN nieuwe detector



Ja ... Higgs is heel klein wel

G. Aad¹⁴⁸, B. Abbott¹¹¹, J. Abdallah<sup>111, A. A. Abdelalim⁴⁰, A. Abdeneken¹¹⁸, O. Abidin¹⁰, B. Abi¹¹²
 A. Abouhamed¹¹⁸, M. Abouzeid¹¹⁸, A. A. Abouzeid¹⁰, B. S. Acharya^{164, 166}, M. Adam¹⁰, D. L. Adams²,
 T. N. Adye¹⁶⁶, J. Adelman¹⁷⁰, M. Aderholz¹⁰, S. Adomec¹⁶⁸, P. Adragna¹⁷⁰, T. Adye¹⁶⁶, S. Aefsky²²,
 J. Aguilera-Saavedra^{124b}, M. Aharouch⁸¹, S. P. Ahlen¹⁶⁷, F. Ahles⁴⁸, T. Ahm¹⁴⁸, M. Ahsan⁶,
 G. Aielli^{133, 138}, T. Akdogan¹⁴⁸, T. P. A. Akesson¹⁰, G. Akimoto¹⁰⁵, A. V. Akimov⁹⁴, M. S. Alam¹, M. A. Alam⁶,
 S. Albataineh¹⁰, M. Alekseev²⁰, I. N. Alekseyev⁶⁰, M. Alekseyev^{10, 50b}, F. Alkassab¹⁰, G. Alvares²⁴, G. Alexander¹⁰³</sup>

[illegible]

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-
gali¹¹, M. Cavalli-Sforza¹¹, C. Catti
A. Cerni¹, L. Cerri¹⁰¹,
K. Chan¹, B. Chapiro¹,
S. Cheshmian¹, S. Chelkan-
ov¹⁷², X. Chen¹⁷², S. Cheng¹⁷²,
N. Ellis²⁹, J. Elstraesser⁵⁶, M. Elsing²⁹, R. Ely¹,
A. Eppig⁸⁷, J. Erdmann⁸⁴, A. Erodutalo¹⁶, C. Es-
tue¹⁶, S. Errede¹⁶⁵, E. Ertef⁸¹, M. Escalier¹¹⁸, C. Exco-
let¹, A. Etiennev¹³⁶, E. Etzion¹⁴³, D. Evyangelakou⁸⁴, R.M. Fakhrudin¹⁰, E. Falciano¹²³, S. Falciano¹²³, A.C. Far-
ley¹⁴⁷, L. Farooque¹⁸⁸, S.M. Farrington¹⁷²,
B. Fathollahzadeh¹⁸⁸

E. Banaś²⁸, P. Banerjee²⁹
S.P. Baranov³⁰, A. Baran³¹
M. Barbone³², D.Y. Bar
R.M. Barnett³³, A. Bar
R. Barndorff³⁴, A.E. Bar
M. Battistin³⁵, G. Battis
R. Beccherle³⁶, P. Bec
E. Ciesi³⁷, S.L. Cheung³⁸
A. Chilingarov³⁹, J. Chio
A. Christof⁴⁰, D. Chrove
R. Cifuentes⁴¹, D. Cinc⁴², M.
M. Cishunjan⁴³, A. Clari
R.W. Cliff⁴⁴, Y. Coadou
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. Ferretti
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. Holzbauner⁵⁸, R.J.
J.Y. Hostachy⁵⁹, T.H.
I. Hristova⁶⁰, J. Hrivis
F. Huisant⁶¹, F. Hui

V.A. Bodinyakov⁶², C. B. E. Bonaldi⁶³, C. B. Belanger-Champagne⁶⁴, C. Bellonchi¹⁰⁴, A. Bellei⁶⁵, C. Bellomo⁶⁶, M. Beni-El-Mechaieck⁶⁷, J.R. Beninger⁶⁸, K. Berggren⁶⁹, E. Bergin⁷⁰, A. Bertin⁷¹, J. Bertin⁷², J. Bessada⁷³, C. Bhat⁷⁴, C. Bhat⁷⁵, C. Bhat⁷⁶, C. Bhat⁷⁷, C. Bhat⁷⁸, C. Bhat⁷⁹, C. Bhat⁸⁰, C. Bhat⁸¹, C. Bhat⁸², C. Bhat⁸³, C. Bhat⁸⁴, C. Bhat⁸⁵, C. Bhat⁸⁶, C. Bhat⁸⁷, C. Bhat⁸⁸, C. Bhat⁸⁹, C. Bhat⁹⁰, C. Bhat⁹¹, C. Bhat⁹², C. Bhat⁹³, C. Bhat⁹⁴, C. Bhat⁹⁵, C. Bhat⁹⁶, C. Bhat⁹⁷, C. Bhat⁹⁸, C. Bhat⁹⁹, C. Bhat¹⁰⁰, C. Bhat¹⁰¹, C. Bhat¹⁰², C. Bhat¹⁰³, C. Bhat¹⁰⁴, C. Bhat¹⁰⁵, C. Bhat¹⁰⁶, C. Bhat¹⁰⁷, C. Bhat¹⁰⁸, C. Bhat¹⁰⁹, C. Bhat¹¹⁰, C. Bhat¹¹¹, C. Bhat¹¹², C. Bhat¹¹³, C. Bhat¹¹⁴, C. Bhat¹¹⁵, C. Bhat¹¹⁶, C. Bhat¹¹⁷, C. Bhat¹¹⁸, C. Bhat¹¹⁹, C. Bhat¹²⁰, C. Bhat¹²¹, C. Bhat¹²², C. Bhat¹²³, C. Bhat¹²⁴, C. Bhat¹²⁵, C. Bhat¹²⁶, C. Bhat¹²⁷, C. Bhat¹²⁸, C. Bhat¹²⁹, C. Bhat¹³⁰, C. Bhat¹³¹, C. Bhat¹³², C. Bhat¹³³, C. Bhat¹³⁴, C. Bhat¹³⁵, C. Bhat¹³⁶, C. Bhat¹³⁷, C. Bhat¹³⁸, C. Bhat¹³⁹, C. Bhat¹⁴⁰, C. Bhat¹⁴¹, C. Bhat¹⁴², C. Bhat¹⁴³, C. Bhat¹⁴⁴, C. Bhat¹⁴⁵, C. Bhat¹⁴⁶, C. Bhat¹⁴⁷, C. Bhat¹⁴⁸, C. Bhat¹⁴⁹, C. Bhat¹⁵⁰, C. Bhat¹⁵¹, C. Bhat¹⁵², C. Bhat¹⁵³, C. Bhat¹⁵⁴, C. Bhat¹⁵⁵, C. Bhat¹⁵⁶, C. Bhat¹⁵⁷, C. Bhat¹⁵⁸, C. Bhat¹⁵⁹, C. Bhat¹⁶⁰, C. Bhat¹⁶¹, C. Bhat¹⁶², C. Bhat¹⁶³, C. Bhat¹⁶⁴, C. Bhat¹⁶⁵, C. Bhat¹⁶⁶, C. Bhat¹⁶⁷, C. Bhat¹⁶⁸, C. Bhat¹⁶⁹, C. Bhat¹⁷⁰, C. Bhat¹⁷¹, C. Bhat¹⁷², C. Bhat¹⁷³, C. Bhat¹⁷⁴, C. Bhat¹⁷⁵, C. Bhat¹⁷⁶, C. Bhat¹⁷⁷, C. Bhat¹⁷⁸, C. Bhat¹⁷⁹, C. Bhat¹⁸⁰, C. Bhat¹⁸¹, C. Bhat¹⁸², C. Bhat¹⁸³, C. Bhat¹⁸⁴, C. Bhat¹⁸⁵, C. Bhat¹⁸⁶, C. Bhat¹⁸⁷, C. Bhat¹⁸⁸, C. Bhat¹⁸⁹, C. Bhat¹⁹⁰, C. Bhat¹⁹¹, C. Bhat¹⁹², C. Bhat¹⁹³, C. Bhat¹⁹⁴, C. Bhat¹⁹⁵, C. Bhat¹⁹⁶, C. Bhat¹⁹⁷, C. Bhat¹⁹⁸, C. Bhat¹⁹⁹, C. Bhat²⁰⁰, C. Bhat²⁰¹, C. Bhat²⁰², C. Bhat²⁰³, C. Bhat²⁰⁴, C. Bhat²⁰⁵, C. Bhat²⁰⁶, C. Bhat²⁰⁷, C. Bhat²⁰⁸, C. Bhat²⁰⁹, C. Bhat²¹⁰, C. Bhat²¹¹, C. Bhat²¹², C. Bhat²¹³, C. Bhat²¹⁴, C. Bhat²¹⁵, C. Bhat²¹⁶, C. Bhat²¹⁷, C. Bhat²¹⁸, C. Bhat²¹⁹, C. Bhat²²⁰, C. Bhat²²¹, C. Bhat²²², C. Bhat²²³, C. Bhat²²⁴, C. Bhat²²⁵, C. Bhat²²⁶, C. Bhat²²⁷, C. Bhat²²⁸, C. Bhat²²⁹, C. Bhat²³⁰, C. Bhat²³¹, C. Bhat²³², C. Bhat²³³, C. Bhat²³⁴, C. Bhat²³⁵, C. Bhat²³⁶, C. Bhat²³⁷, C. Bhat²³⁸, C. Bhat²³⁹, C. Bhat²⁴⁰, C. Bhat²⁴¹, C. Bhat²⁴², C. Bhat²⁴³, C. Bhat²⁴⁴, C. Bhat²⁴⁵, C. Bhat²⁴⁶, C. Bhat²⁴⁷, C. Bhat²⁴⁸, C. Bhat²⁴⁹, C. Bhat²⁵⁰, C. Bhat²⁵¹, C. Bhat²⁵², C. Bhat²⁵³, C. Bhat²⁵⁴, C. Bhat²⁵⁵, C. Bhat²⁵⁶, C. Bhat²⁵⁷, C. Bhat²⁵⁸, C. Bhat²⁵⁹, C. Bhat²⁶⁰, C. Bhat²⁶¹, C. Bhat²⁶², C. Bhat²⁶³, C. Bhat²⁶⁴, C. Bhat²⁶⁵, C. Bhat²⁶⁶, C. Bhat²⁶⁷, C. Bhat²⁶⁸, C. Bhat²⁶⁹, C. Bhat²⁷⁰, C. Bhat²⁷¹, C. Bhat²⁷², C. Bhat²⁷³, C. Bhat²⁷⁴, C. Bhat²⁷⁵, C. Bhat²⁷⁶, C. Bhat²⁷⁷, C. Bhat²⁷⁸, C. Bhat²⁷⁹, C. Bhat²⁸⁰, C. Bhat²⁸¹, C. Bhat²⁸², C. Bhat²⁸³, C. Bhat²⁸⁴, C. Bhat²⁸⁵, C. Bhat²⁸⁶, C. Bhat²⁸⁷, C. Bhat²⁸⁸, C. Bhat²⁸⁹, C. Bhat²⁹⁰, C. Bhat²⁹¹, C. Bhat²⁹², C. Bhat²⁹³, C. Bhat²⁹⁴, C. Bhat²⁹⁵, C. Bhat²⁹⁶, C. Bhat²⁹⁷, C. Bhat²⁹⁸, C. Bhat²⁹⁹, C. Bhat³⁰⁰, C. Bhat³⁰¹, C. Bhat³⁰², C. Bhat³⁰³, C. Bhat³⁰⁴, C. Bhat³⁰⁵, C. Bhat³⁰⁶, C. Bhat³⁰⁷, C. Bhat³⁰⁸, C. Bhat³⁰⁹, C. Bhat³¹⁰, C. Bhat³¹¹, C. Bhat³¹², C. Bhat³¹³, C. Bhat³¹⁴, C. Bhat³¹⁵, C. Bhat³¹⁶, C. Bhat³¹⁷, C. Bhat³¹⁸, C. Bhat³¹⁹, C. Bhat³²⁰, C. Bhat³²¹, C. Bhat³²², C. Bhat³²³, C. Bhat³²⁴, C. Bhat³²⁵, C. Bhat³²⁶, C. Bhat³²⁷, C. Bhat³²⁸, C. Bhat³²⁹, C. Bhat³³⁰, C. Bhat³³¹, C. Bhat³³², C. Bhat³³³, C. Bhat³³⁴, C. Bhat³³⁵, C. Bhat³³⁶, C. Bhat³³⁷, C. Bhat³³⁸, C. Bhat³³⁹, C. Bhat³⁴⁰, C. Bhat³⁴¹, C. Bhat³⁴², C. Bhat³⁴³, C. Bhat³⁴⁴, C. Bhat³⁴⁵, C. Bhat³⁴⁶, C. Bhat³⁴⁷, C. Bhat³⁴⁸, C. Bhat³⁴⁹, C. Bhat³⁵⁰, C. Bhat³⁵¹, C. Bhat³⁵², C. Bhat³⁵³, C. Bhat³⁵⁴, C. Bhat³⁵⁵, C. Bhat³⁵⁶, C. Bhat³⁵⁷, C. Bhat³⁵⁸, C. Bhat³⁵⁹, C. Bhat³⁶⁰, C. Bhat³⁶¹, C. Bhat³⁶², C. Bhat³⁶³, C. Bhat³⁶⁴, C. Bhat³⁶⁵, C. Bhat³⁶⁶, C. Bhat³⁶⁷, C. Bhat³⁶⁸, C. Bhat³⁶⁹, C. Bhat³⁷⁰, C. Bhat³⁷¹, C. Bhat³⁷², C. Bhat³⁷³, C. Bhat³⁷⁴, C. Bhat³⁷⁵, C. Bhat³⁷⁶, C. Bhat

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A. Borison,¹²⁸ G. Borise
M. Boudry,¹²⁹ A. Boudry
A. Da Rocha Guedali,¹⁶ M.
C. Dalliapour,¹³⁰, S.J. Dal
R. Daners,¹⁰⁸, D. Danne
W. Davey,¹² T. David,¹²
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A. Gibson¹³⁸, S.M. Gills
V. Gilevsky¹⁰¹, D. Gills
F.M. Giorgio¹⁰, P. Giov
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M. Kac¹⁴³, A. Kaczmare
S. Kalinin¹³⁴, L.V. Ka
J. Kazanek¹⁴⁵, B. Kapla

C. Bottenrood¹⁰⁴, D. De Salicrú¹⁰⁵, T. Giese¹⁰⁶, C. Giffard¹⁰⁷, C. Goetz¹⁰⁸, C. Bourdian¹⁰⁹, N. Boj¹¹⁰, J. Bracinich¹¹¹, A. Braem¹¹², O. Brandt¹¹³, U. Bratzke¹¹⁴, S. Bresles¹¹⁵, J. D. Bretton¹¹⁶, R. Brock¹¹⁷, T.J. Brodbeck¹¹⁸, G. Brown¹¹⁹, E. Brubaker¹²⁰, A. Bruijn¹²¹, C. Bruijn¹²², D. Budnik¹²³, D. D. Dvorod¹²⁴, J. Degen¹²⁵, D. Del Prete¹²⁶, M. Delgado¹²⁷, T. Del Maestro¹²⁸, P. A. Delp¹²⁹, B. Demirkhan¹³⁰, J. Deng¹³¹, P. Dervan¹³², K. Desch¹³³, R. Dhulipudi¹³⁴, M. A. Di Cera¹³⁵, A. Di Mattia¹³⁶, R. Di Narzo¹³⁷, C. Giamberini¹³⁸, C. Giardin¹³⁹, S. N. Golovinski¹⁴⁰, S. S. Gonzalez¹⁴¹, S. A. Gonzalez¹⁴², L. Goossens¹⁴³, P. A. Gora¹⁴⁴, A. Gorisek¹⁴⁵, E. Gornic¹⁴⁶, M. Gostinik¹⁴⁷, M. Gou¹⁴⁸, A. G. Goussous¹⁴⁹, C. M. Goussous¹⁵⁰, V. Kartvelishvili¹⁵¹, E. Katkalo¹⁵², Y. Katsukawa¹⁵³, E. Katz¹⁵⁴, M.S. Kaye¹⁵⁵, V.A. Kikvidze¹⁵⁶, G.D. Kikvidze¹⁵⁷, M. Kishimoto¹⁵⁸, B.P. Kiselevan¹⁵⁹, D. Khakhria¹⁶⁰, A. Khamov¹⁶¹, D. Kharin¹⁶², N. Khavchinskii¹⁶³, V. Khavchinskii¹⁶⁴, S. Kim¹⁶⁵

R.M. Buckingham¹⁸, E.B. Diehl¹⁷, H. Diehl¹⁹, F. Gragnano^{20,21}, S.G.
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M.D.-2¹⁰, I.C. Durrant¹⁰⁵, A. Gutierrez⁹³, P. Putis
Hase¹⁰⁶, S. Hase¹⁰⁷, G.

M. Tris¹, J.G. Drohan¹,
F. Dudak¹¹⁶, M. Dührsen¹,
R. Duxfield¹⁹⁰, M. Dwumr
K. Edmunds⁸¹, C.A. Edwards
K. Einsweiler¹⁴, E. Eisen

S. Haider²⁰, Z. Hajduk²,
L. Has⁵²⁶, 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. Kononov⁴⁸, R. K
K. Kordas¹⁵⁴, V. Kore
O. Kortner²⁹, S. Kort
A. Koutseman¹⁰⁹, R. K
V.A. Kramarenko⁹⁷, C
F. Krejci¹²⁷, J. Kretzsch
J. Kugelberg²⁰, J. K

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.
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Hilker⁴¹, S. Hillert²⁰, S.J. Hillier¹⁷, I. Hirschliffé¹⁴, E. Hines¹²⁰, M. Hirzoe¹¹⁶, F. Hirsch⁸²
Hodges⁹⁸, N. Hod¹⁰³, M.C. Hodgkinson¹²⁰, P. Hodgson¹²⁰, A. Hoedeker⁹⁴, M.R. Hoeferkamp¹⁰²,
¹⁴³, M. Hofeldt⁸¹, M. Holder¹⁴¹, A. Holmes¹¹⁵, S.O. Holmgren^{146e}, T. Holy¹²⁷,
Holzer¹⁷, Y. Homma⁹⁷, T. Horowitzovsky^{127c}, C. Horn¹⁴³, S. Horner⁴⁸, K. Horton¹¹⁸,
S. Hos¹⁸¹, M.A. Houlsen⁷⁵, A. Houmouda^{108a}, J. Howarth⁸², D.F. Howell¹¹⁸,
I. Huska¹²⁰, T. Hyryova⁸⁴, P.J. Huo¹⁷⁰, S.-C. Hsu⁸⁴, G.S. Huang¹¹¹, Z. Hubacek^{127d},
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C. Leggett¹⁴, M. Lehtinen²⁰, G. Lehmann Miotto²⁹, M. Lehto^{35a}, X. Lei^a, M.A.L. Leite^{23c}, D. Lellouch¹⁷¹, J. Lellouch¹⁶⁸, M. Lelouchuk³⁴, V. Lendermann^{38a}, K.J.C. Lesauvage^{144b}, T. Li^b, B. Lenzi³⁶, K. Leonhardt⁴³, C. Leroy⁹³, J.R. Lessard¹⁴⁷, J. Lesser¹⁴⁶, G.C. Lester²⁷, A. Lezzeri³³, J. Levayek⁶³, D. Levin³⁷, L.J. Levinson¹²¹, M.S. Levitskiy¹²⁸, M. Lewandowski²⁶, N. Leyton S.I.^{32b}, X.-L. Li³⁷, Z. Liang²⁰, Z. Liang¹¹⁸, ^aB. Liberti^{133a}, ^bP. Richard²⁹, ^cM. Lichtnerer³⁸, K. R. Lifshitz¹⁰², J.N. Lilley⁷, A. Limosani⁵⁰, ^aM. Limper⁶³, ^cS.C. Lin¹⁵¹, ^aF. Linde¹⁰⁰, J.T. Liu¹, E. Lipkin²⁹, L.J. Little¹²⁰, ^aA. Litke¹⁴⁹, ^bT.M.F. Liu¹⁶⁰, ^aX.-M. Liu¹⁴⁹, ^aM. Liu¹⁴⁹

H. Lühr,¹ J. B. Lühr,¹ M. E. Lobodzinski,¹⁴¹ P. L. A. Loguinov,¹⁷⁹ C. W. L. R.E. Long,¹⁷ L. Lopes M.J. Lusty,^{180a}, X. Luo L. Lu,³⁹ J.H. Lubatti,¹⁵ F. Luehring,⁶¹ G. Ljung J. Lundberg,⁶ G. Luijckx,¹⁰⁸ A.A. Nepomuchenko,^{25a}, M. Nemesi,¹⁰ S.Y. Nesterov,¹²¹ R.M. Neveu,¹⁰⁸ P. Nevski,²⁴ P.R. Newman,¹⁷ R.B. Nielsen,¹¹⁸ R. F. Niedercom,¹¹⁰ J. Nielsen,¹³⁷, T. Niimilä,²⁰ A. Nikiforov,¹⁸⁵ V. N. Nikopolenko,²⁴ H. Nilesen,⁶ P. Nilsson,¹ V. Niinimäki,¹⁸⁶ A. Nishida,¹⁸⁷ N. Nishida,¹⁸⁸ M. Nomura,¹¹¹ I. Nomidis,¹⁸⁴, H. Nomoto,¹⁸³, M. O. Norriella Francisco,¹¹ P.R. Norton,¹²² J. Novakovic,¹⁰ M. Nomura,¹⁸⁹ A.-E. Nuncio-Quirós,²⁰ G. Nunes Hanninger,²⁰ T. Nunnenmacher,⁹⁸, E. O. O'Neil,¹⁹⁰ D.C. O'Neil,¹⁹¹ M. Oishi,¹⁹² F.G. Oshchepkov,¹⁹³

H. Ma²⁴, L.L. Ma¹⁷²,
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S. Odaoka¹⁰, J. Ojier⁴³,
H. Ohshita¹⁴⁰, T.K. Oki
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C. Meyer ¹⁷³ , J. F. S. Meyer ¹⁷⁴	V. Polyichronakos ¹⁷⁵ , D. G. A. Papenoceno ¹⁷⁶ , D. S. Pospisil ¹⁷⁷ , I. N. Pot	K. Sliva ¹⁶¹ , T. J. Sloan ¹⁶¹ , J. Slo	J. V.
P. Miele ²⁰ , S. Migas ¹⁷⁸ , R. J. Miller ¹⁷⁹ , W. J. Mi	P. Pralavorio ¹⁸³ , S. Pra	B. Smith ¹⁶⁷ , D. Smith ¹⁴³ , K. M	D. C.
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M. Moed ¹⁷ , S. Moedler	X. Prudent ⁴³ , H. Przy	M. Solarik ¹² , J. Solc ¹²⁷ , U. Sold	M. V.
	Y. Pylychynski ¹¹⁷ , J. R.	J. Sonderzucker ²⁴ , N. Sont ² , V. S.	M. V.
	M. Rana ¹⁰⁰ , V. Radice	S. Spagnolo ^{78,72b} , F. Spanio ⁷⁴	M. V.
		M. Spouta ¹²⁶ , T. Spritzner ¹⁶⁸	J. von
		E. Stenlund ¹²⁶ , P. E. Stenlund ¹²⁶	n.

A.M. Moiseev^{128,*}, R.
S. Montesano^{128,*}, R.
A. Moraes¹²⁵, A. Morai
P. Morettini^{10a}, M. Me
J.D. Morris⁷², H.G. M.
E.J. M'wambi⁸⁴, M. M.
A. Muji¹⁰⁵, A. Muir¹⁶
A.G. Mykura¹²⁸, M. F.
S. Rajagopal²⁴, S. R.
P.N. Ratapan¹⁷¹, F. Raus
G. Redlinger²⁴, R. Ree
D. Reljic¹²⁶, C. Rembe
B. Resend¹³⁶, P. Reza
S. Rickle⁸¹, M. Rijpers
G. Rivetella¹²⁸, M. F.
J.F.M. Robinson⁷⁷, M. F.
E. Stancarevic¹²⁴, H.W. Stancarevic¹²⁴, F.
P. Starovrovtov²⁰, A. Staneic¹²⁴, C.
I. Stel¹²⁷, B. Stelzer¹⁴², H.J. S.
T. Stockmann²⁹, M.C. Stockman
A. Strasner⁸¹, J. Strandberg¹⁷³
P. Strizene^{143b}, R. Ströhmer¹⁷³
I. Stumer¹⁴³, J. Stupak¹⁴⁸, P. S.
C. Suhl¹⁰⁶, K. Suita⁸⁷, M. Suk¹
A.T.

Y. Nakakuma ¹¹⁹ , K. N.	S. Rodier ¹²⁰ , D. Rodrig	K. Suruliza ^{164,165} , S. Sushkov ¹⁶¹	J. We
N.R. Nation ¹²¹ , T. N.	A. Romanovic ¹⁶⁶ , V.M.	I. Saylor ^{144,144} , T. Saylor ¹²⁶ , B. S	B. S
A. Negri ^{119a,119b} , G. Nat	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. Salamann¹⁰⁵, 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. Tsiareschka^{5,6}, D. Tsionou^{1,2}

H. Zhang
S. Zhu
G. Zhang

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. Oishi³, S. Oki¹⁸⁰

¹⁴⁹ b. F. Salvatore¹⁴⁹, A. Salzburger¹⁵⁰, D. Samonidisa¹⁰⁴, B.H. Sameset¹¹⁷,
¹⁰⁸ M. Sandhoff¹⁷⁴, P. Sandlin¹⁵⁸, T. Sandoval²⁷, R. Sandstrom¹⁰⁸,
¹⁴⁷ G. C. Santamarina-Rios⁹⁸, C. Santoni¹⁵⁷, 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,
Sharma^{10a,10b}, A. Shirazi^{10a,10b}, S. Scallan⁹³, D.A. Scannicchio¹⁶³

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¹S. Valsen, ²C. Valderanis, ³J. Valenta, ⁴P. Valente, ⁵S. Valentini, ⁶S. Valsek, ⁷A. Valdes, ⁸M. Valdes, ⁹E. Vallejos, ¹⁰F. Vallero, ¹¹L. Vallero, ¹²G. Vallero, ¹³D. Vallero, ¹⁴H. Vallero, ¹⁵A. Vallero, ¹⁶A. Vallero, ¹⁷A. Vallero, ¹⁸A. Vallero, ¹⁹A. Vallero, ²⁰A. Vallero, ²¹A. Vallero, ²²A. Vallero, ²³A. Vallero, ²⁴A. Vallero, ²⁵A. Vallero, ²⁶A. Vallero, ²⁷A. Vallero, ²⁸A. Vallero, ²⁹A. Vallero, ³⁰A. Vallero, ³¹A. Vallero, ³²A. Vallero, ³³A. Vallero, ³⁴A. Vallero, ³⁵A. Vallero, ³⁶A. Vallero, ³⁷A. Vallero, ³⁸A. Vallero, ³⁹A. Vallero, ⁴⁰A. Vallero, ⁴¹A. Vallero, ⁴²A. Vallero, ⁴³A. Vallero, ⁴⁴A. Vallero, ⁴⁵A. Vallero, ⁴⁶A. Vallero, ⁴⁷A. Vallero, ⁴⁸A. Vallero, ⁴⁹A. Vallero, ⁵⁰A. Vallero, ⁵¹A. Vallero, ⁵²A. Vallero, ⁵³A. Vallero, ⁵⁴A. Vallero, ⁵⁵A. Vallero, ⁵⁶A. Vallero, ⁵⁷A. Vallero, ⁵⁸A. Vallero, ⁵⁹A. Vallero, ⁶⁰A. Vallero, ⁶¹A. Vallero, ⁶²A. Vallero, ⁶³A. Vallero, ⁶⁴A. Vallero, ⁶⁵A. Vallero, ⁶⁶A. Vallero, ⁶⁷A. Vallero, ⁶⁸A. Vallero, ⁶⁹A. Vallero, ⁷⁰A. Vallero, ⁷¹A. Vallero, ⁷²A. Vallero, ⁷³A. Vallero, ⁷⁴A. Vallero, ⁷⁵A. Vallero, ⁷⁶A. Vallero, ⁷⁷A. Vallero, ⁷⁸A. Vallero, ⁷⁹A. Vallero, ⁸⁰A. Vallero, ⁸¹A. Vallero, ⁸²A. Vallero, ⁸³A. Vallero, ⁸⁴A. Vallero, ⁸⁵A. Vallero, ⁸⁶A. Vallero, ⁸⁷A. Vallero, ⁸⁸A. Vallero, ⁸⁹A. Vallero, ⁹⁰A. Vallero, ⁹¹A. Vallero, ⁹²A. Vallero, ⁹³A. Vallero, ⁹⁴A. Vallero, ⁹⁵A. Vallero, ⁹⁶A. Vallero, ⁹⁷A. Vallero, ⁹⁸A. Vallero, ⁹⁹A. Vallero, ¹⁰⁰A. Vallero.

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J.I. Vosses⁹, J.H. Vossebeide¹⁰, A.S. Vovenko¹¹, N. Vranjes¹², M. Vranjes Milosavljevic¹³, V.
twijf¹⁴, T. Vu An¹⁵, R. Vuilleumier²⁹, 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. Weir¹²⁵, D.S. Weiss¹²⁹, W.E. Weir⁴⁷, T.W. Weir²⁴, S.W. Weir¹²³, E.

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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

**THE SEARCH FOR THE
HIGGS BOSON**

(In)famous Higgs boson



The Higgs boson



Paris Hilton

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

Het Higgs boson

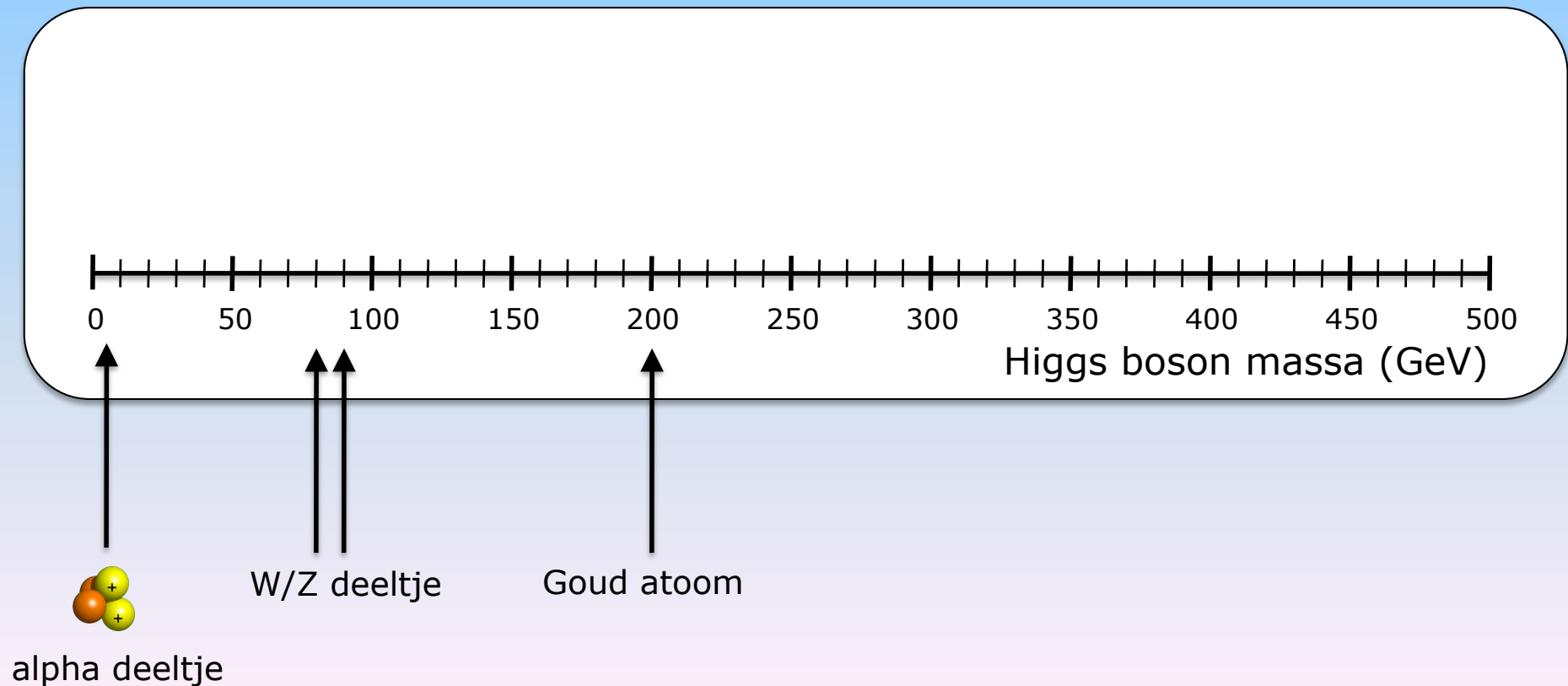


Laatst missende puzzelstukje

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

De massa van het Higgs boson

1 GeV → massa proton = massa Waterstof atoom



- Hoeveel Higgs bosons zijn er geproduceerd in 2011 ?



- Als hij wel

bestaat:

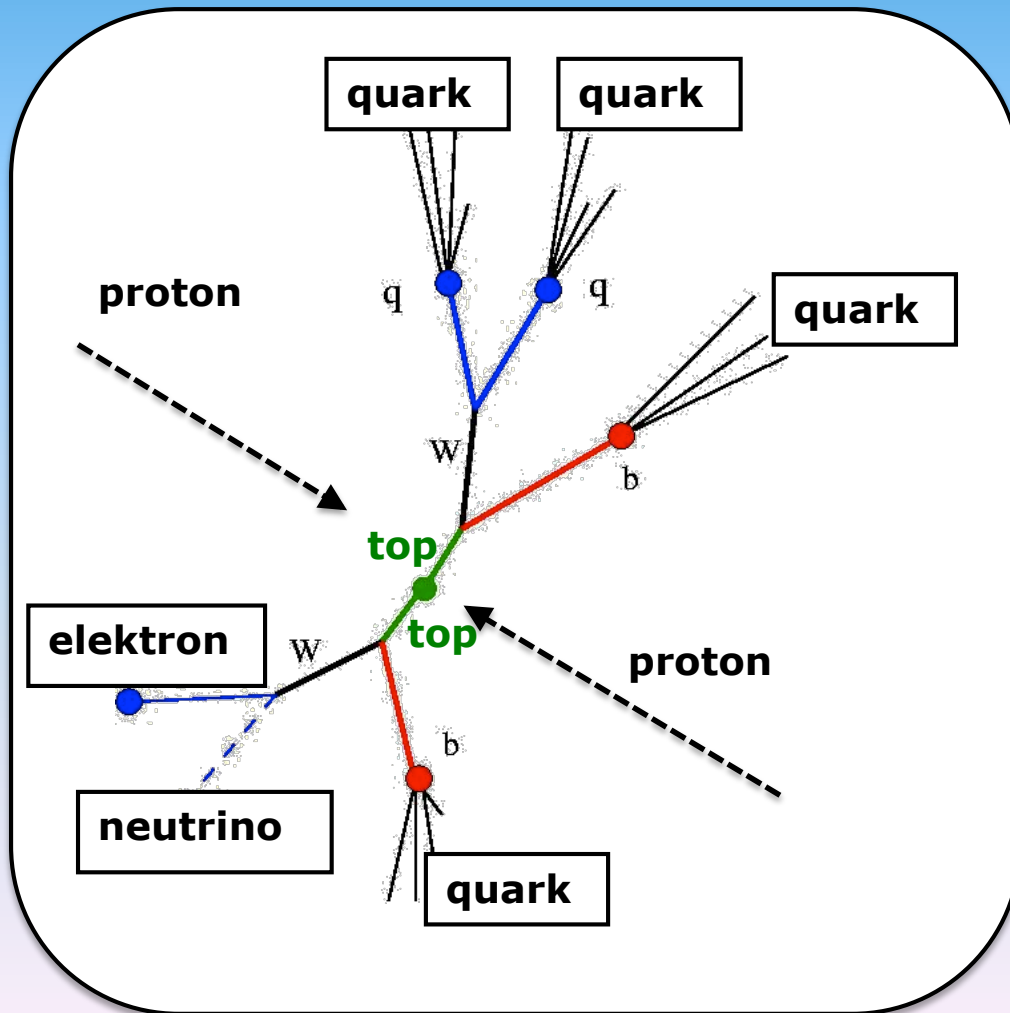
- $m_h = 120 \text{ GeV}$:

- $m_h = 200 \text{ GeV}$:

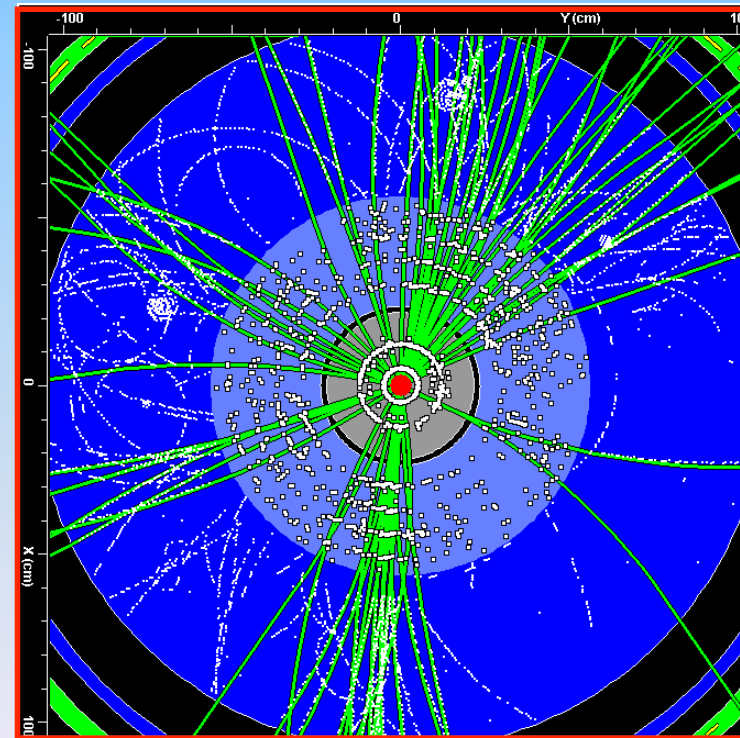
60.000 30.000

Interpreting LHC events

top quark pair-production

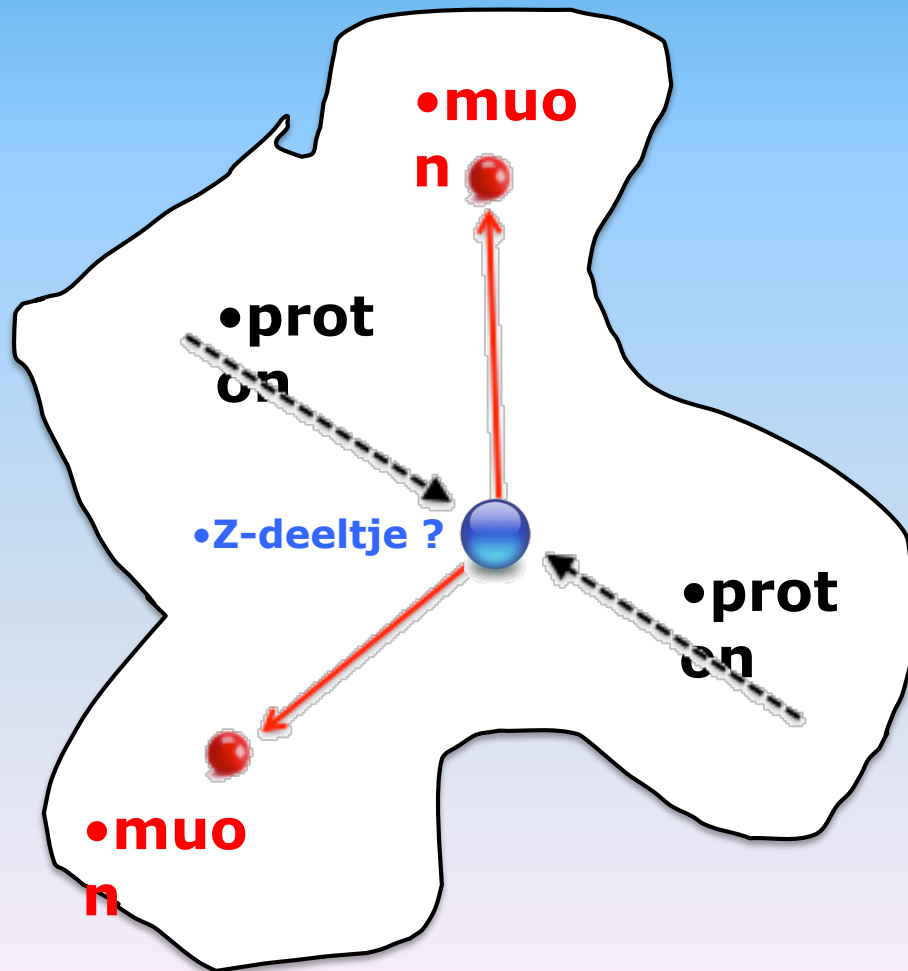


Simulation top quark production

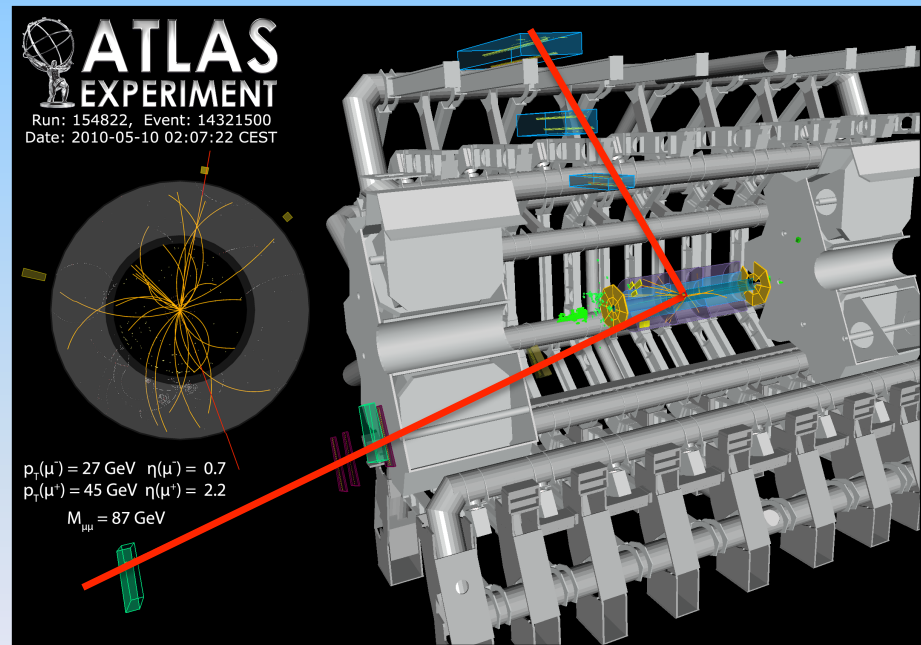


•Hoe ontdek je het Z-deeltje ?

•Afwijkingen van voorspelling zonder Z-boson



•2-muonen gezien in ATLAS



- Wat is de 'vingerafdruk' van het Z-deeltje:
- de massa van het 2-muon systeem

- 2-muon massa



- 'overig':

geen voorkeur, vlak

- Z-deeltje: waarde

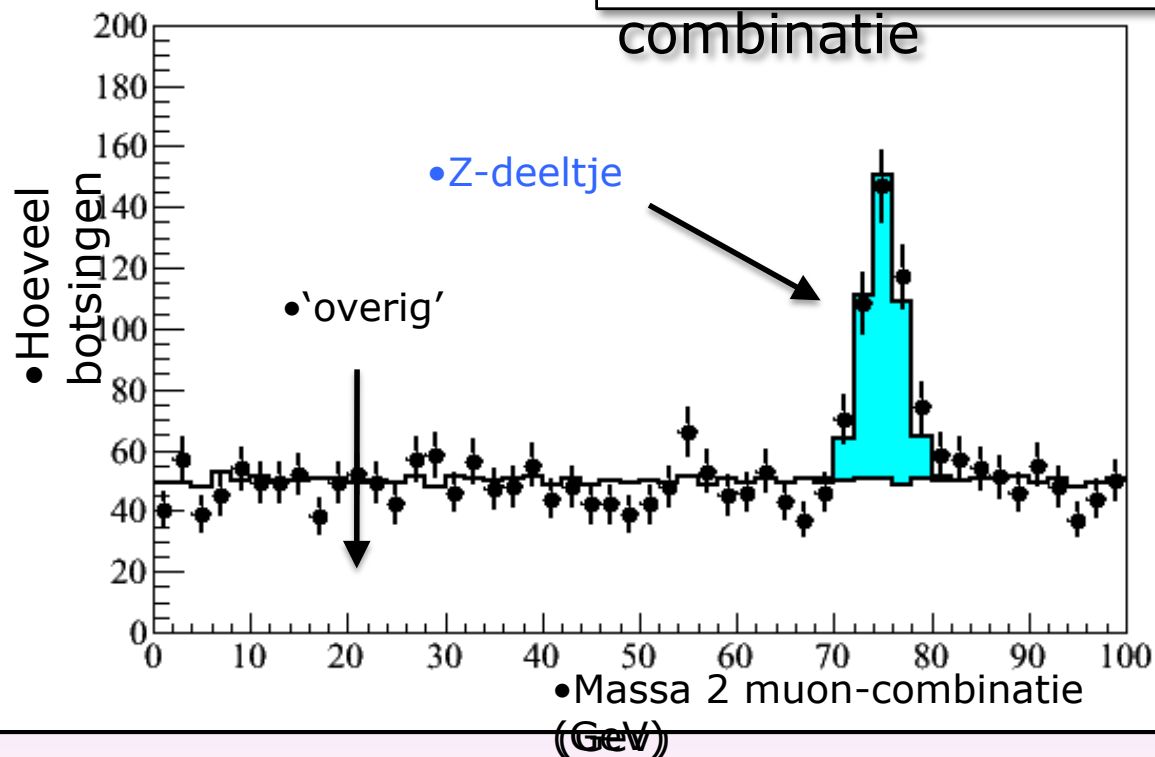
- $E =$ altijd dezelfde

$$mc^2$$

(massa van het Z-deeltje)

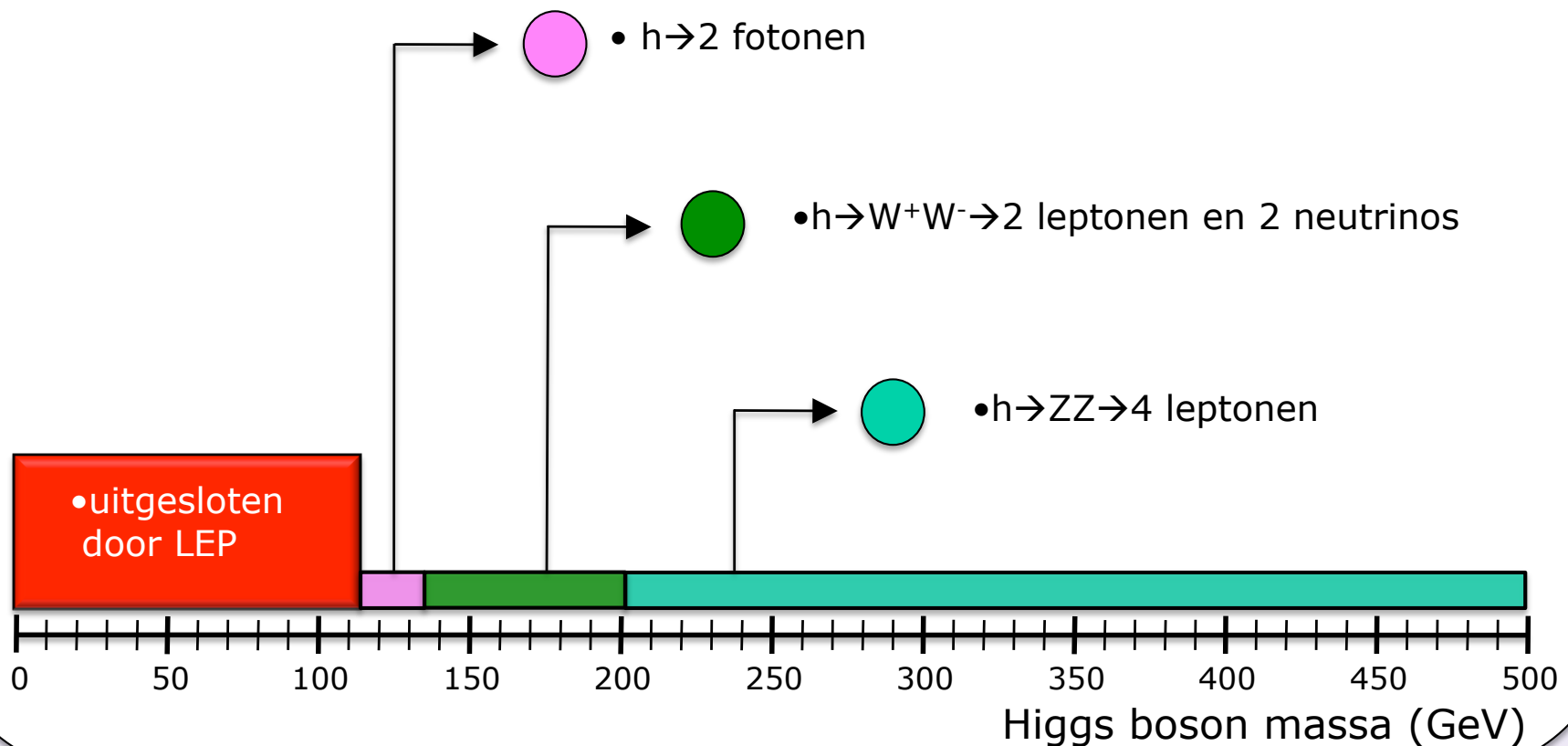
-

- Massa 2 muon-combinatie

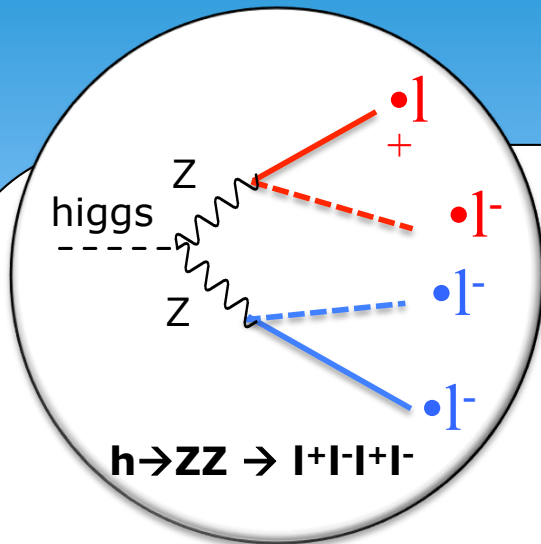


•De duidelijkste vingerafdruk van het Higgs boson

•Voor elke massa zijn er meerdere kanalen: dit zijn de belangrijkste



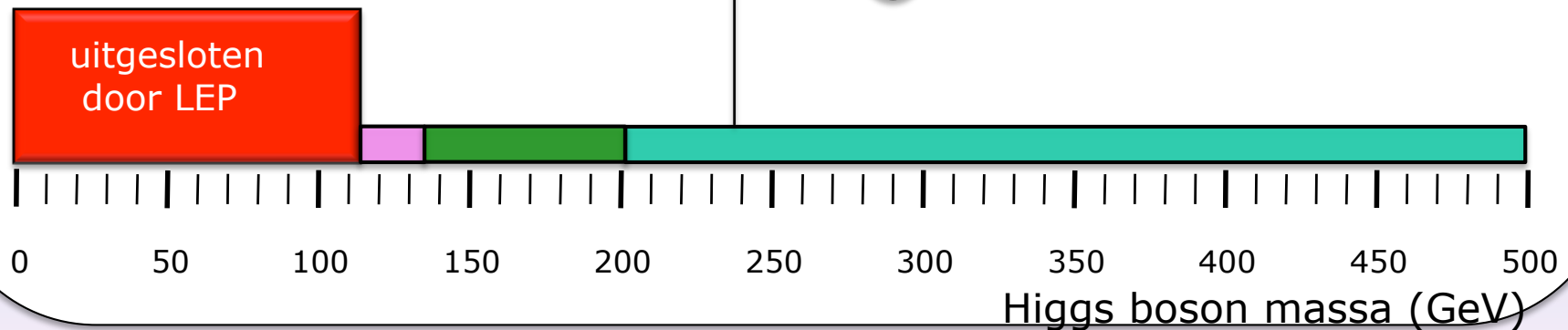
Hoge massa's: $m_H > 200 \text{ GeV}$

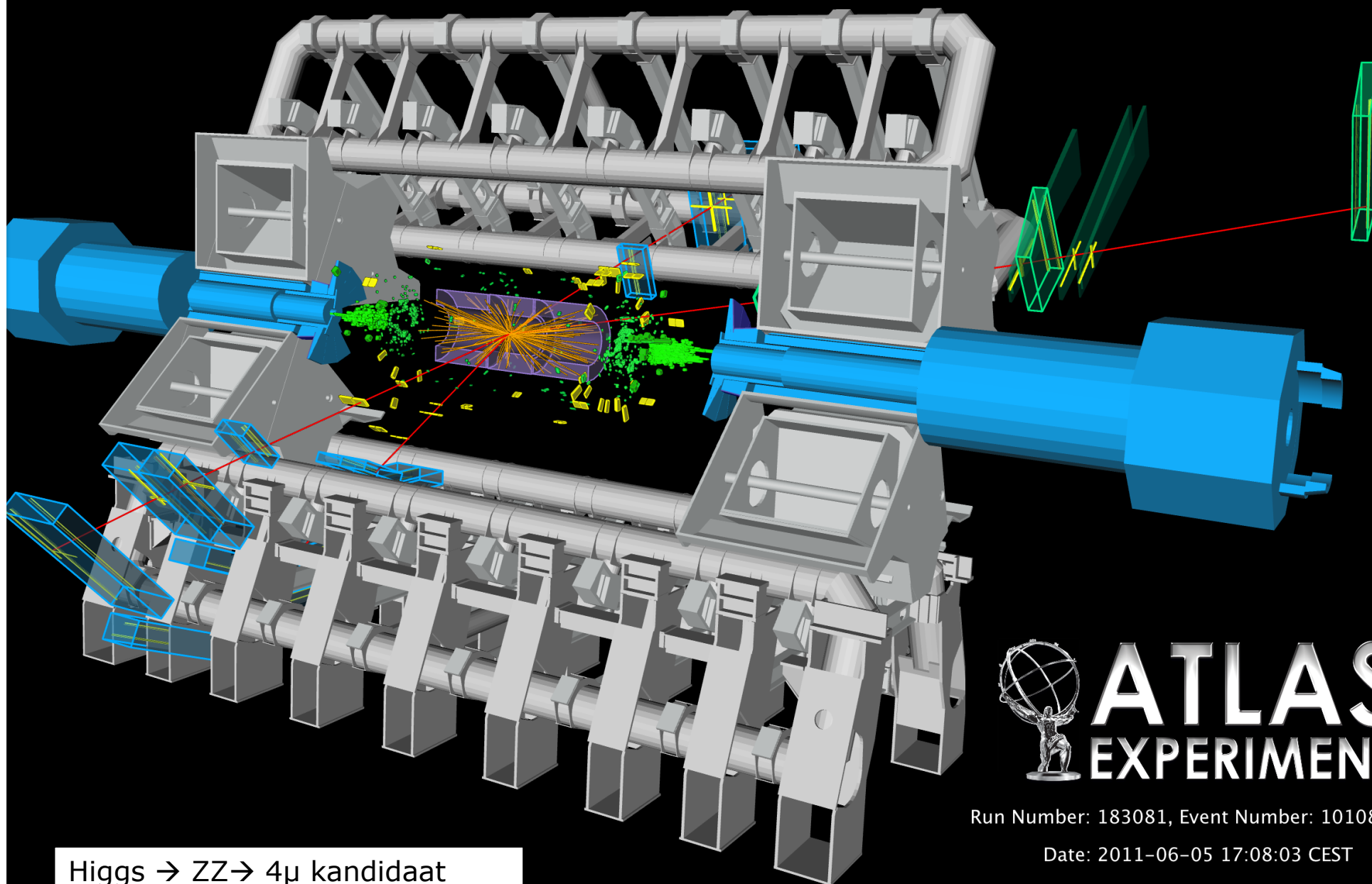


The golden channel

- 4 leptonen (e/μ)
- Erg zeldzaam: Higgs of ZZ

Vingerafdruk: 4-lepton massa





ATLAS
EXPERIMENT

Run Number: 183081, Event Number: 10108572

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

Higgs $\rightarrow$ ZZ $\rightarrow$ 4 leptonen

klein aantal schitterende botsingen

30.000 Higgs bosonen

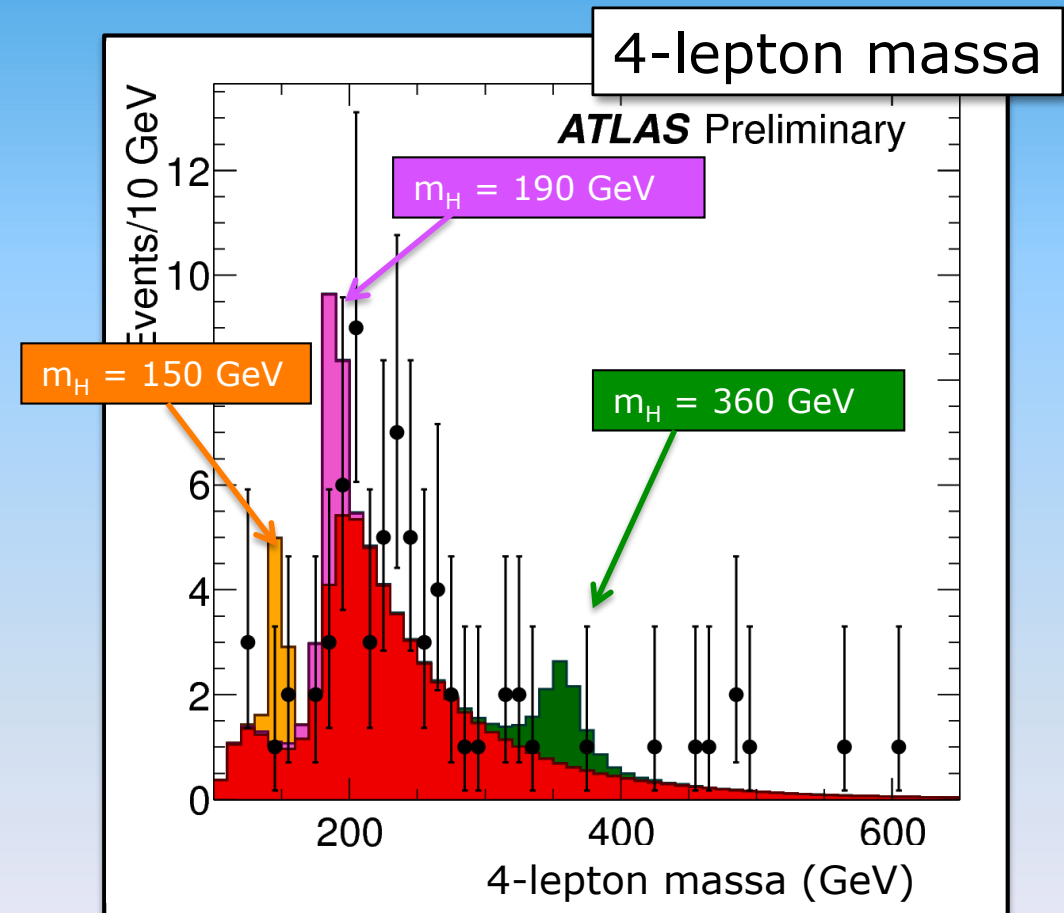


- Maar 1 op de 1000 Higgs bosonen vervalt naar 4 leptonen
- 50% kans dat ATLAS detector ze allemaal goed terugvindt



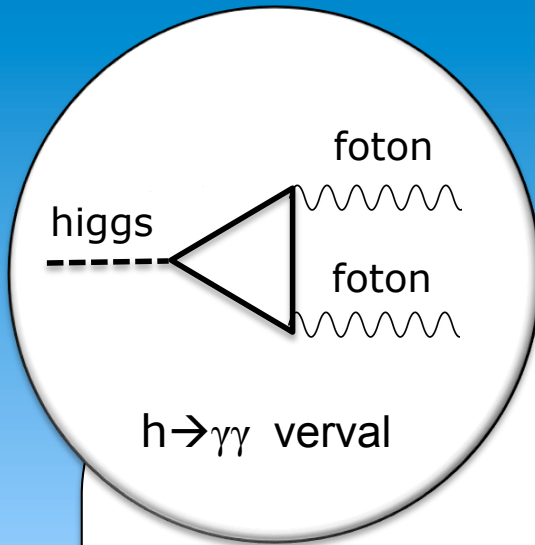
16 Higgs $\rightarrow$ 4 lepton events

'overig'	52 events
Met Higgs	68 events



Geen duidelijk piekje helaas
 $\rightarrow m_h < 200$ GeV

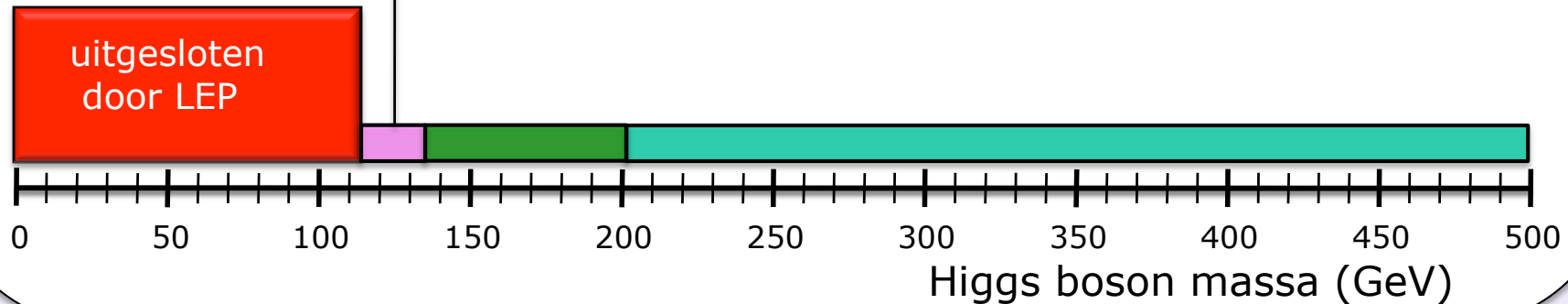
De laagste massa's



$h \rightarrow 2$ fotonen

- 2 energetische geïsoleerde fotonen
- detector gevoelig voor 'valse' signalen

Vingerafdruk: 2-foton massa



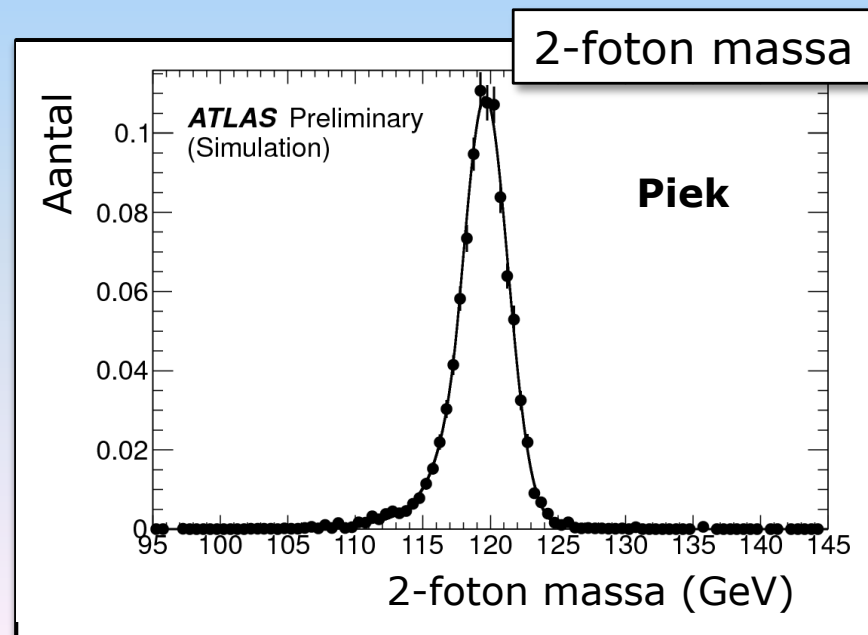
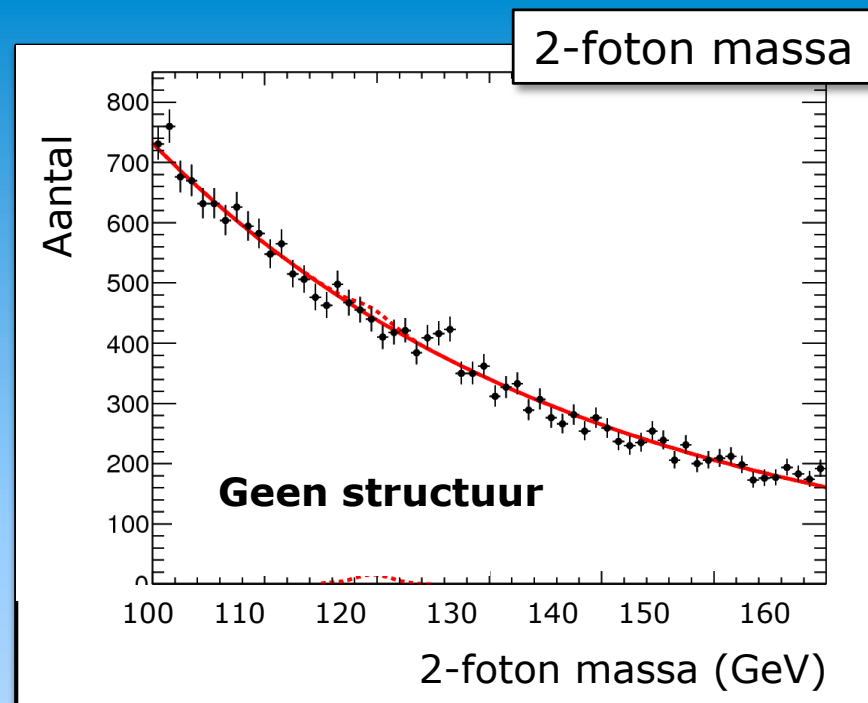
Event-type	Aantal events
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Overig

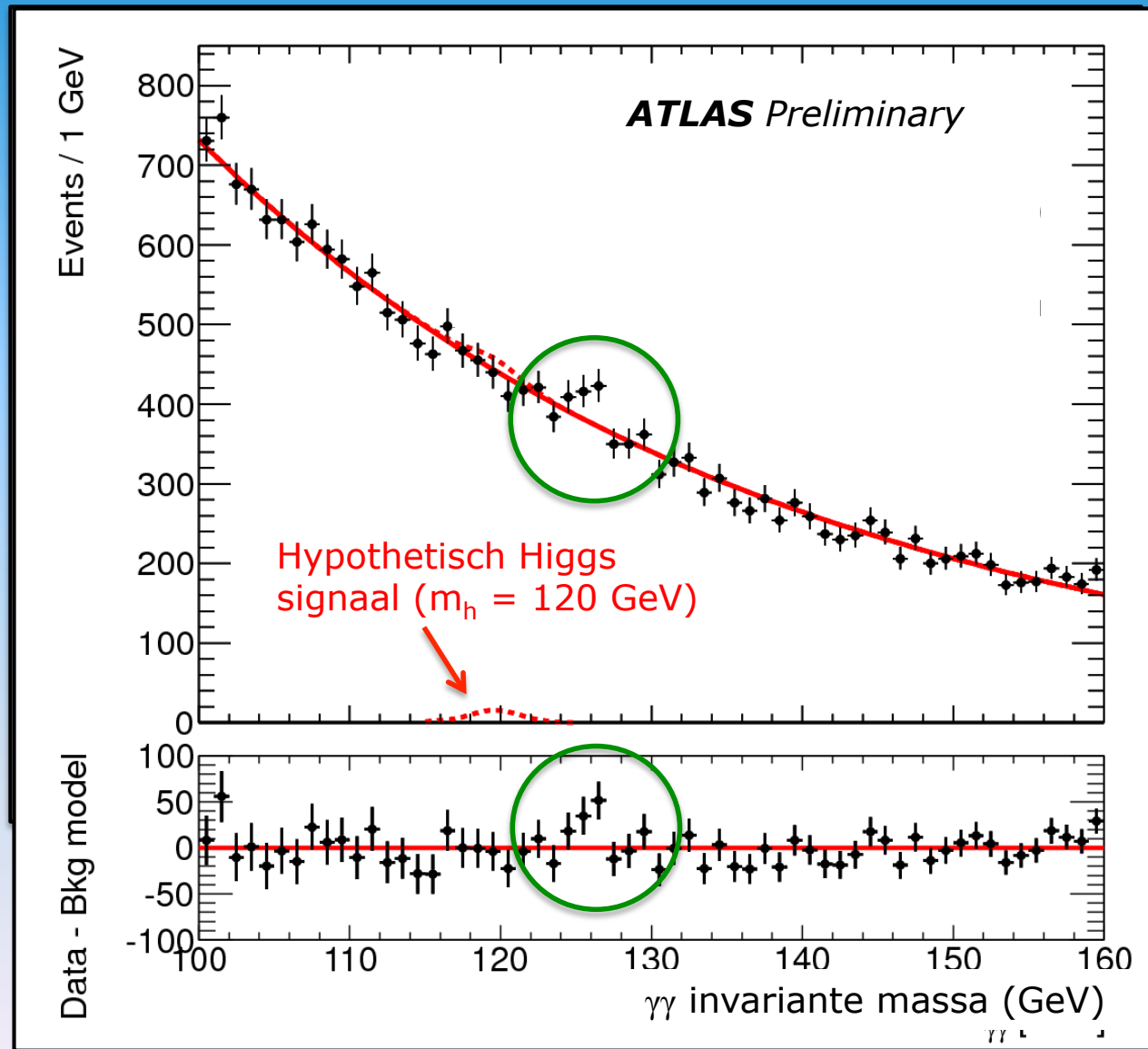
$\gamma\gamma$	3650 ± 100 ± 290
γ + jet	1110 ± 60 ± 270
Di-jet	220 ± 20 ± 130
Drell-Yan	86 ± 1 ± 14
'normaal'	5066

Higgs

Higgs signal	17.6
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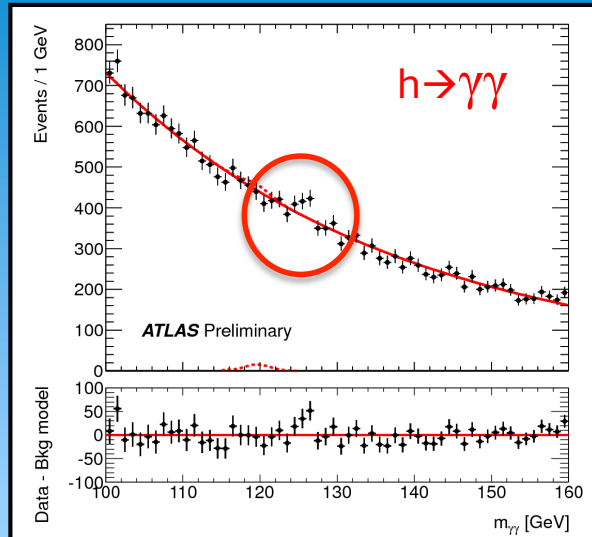


De 'echte' LHC data



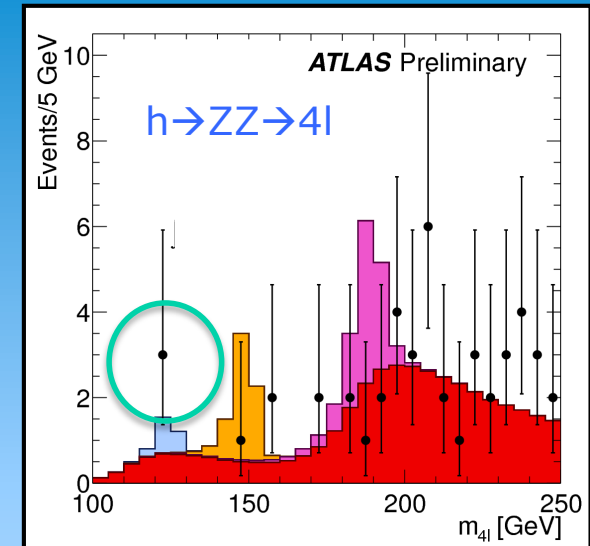
piekje ?

Higgs $\rightarrow$ 2 fotonen

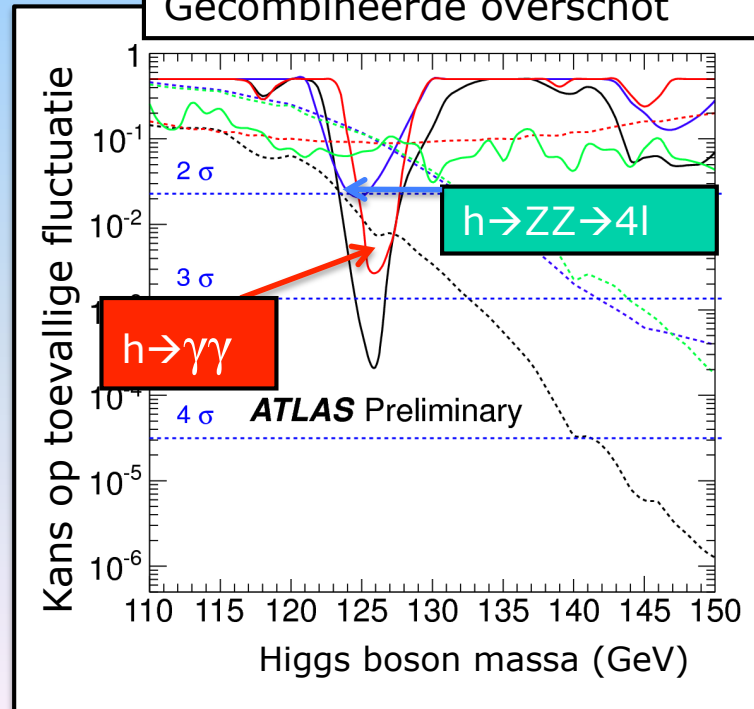


Overschot in twee kanalen zichtbaar

Higgs $\rightarrow$ 4 leptonen



Gecombineerde overschot



Kans $\sim 1/100$ (2.3σ)

Interpretatie overschot in ATLAS

Kans op toevallige fluctuatie zoals
geobserveerd of nog groter:
 ~ 1 op 100

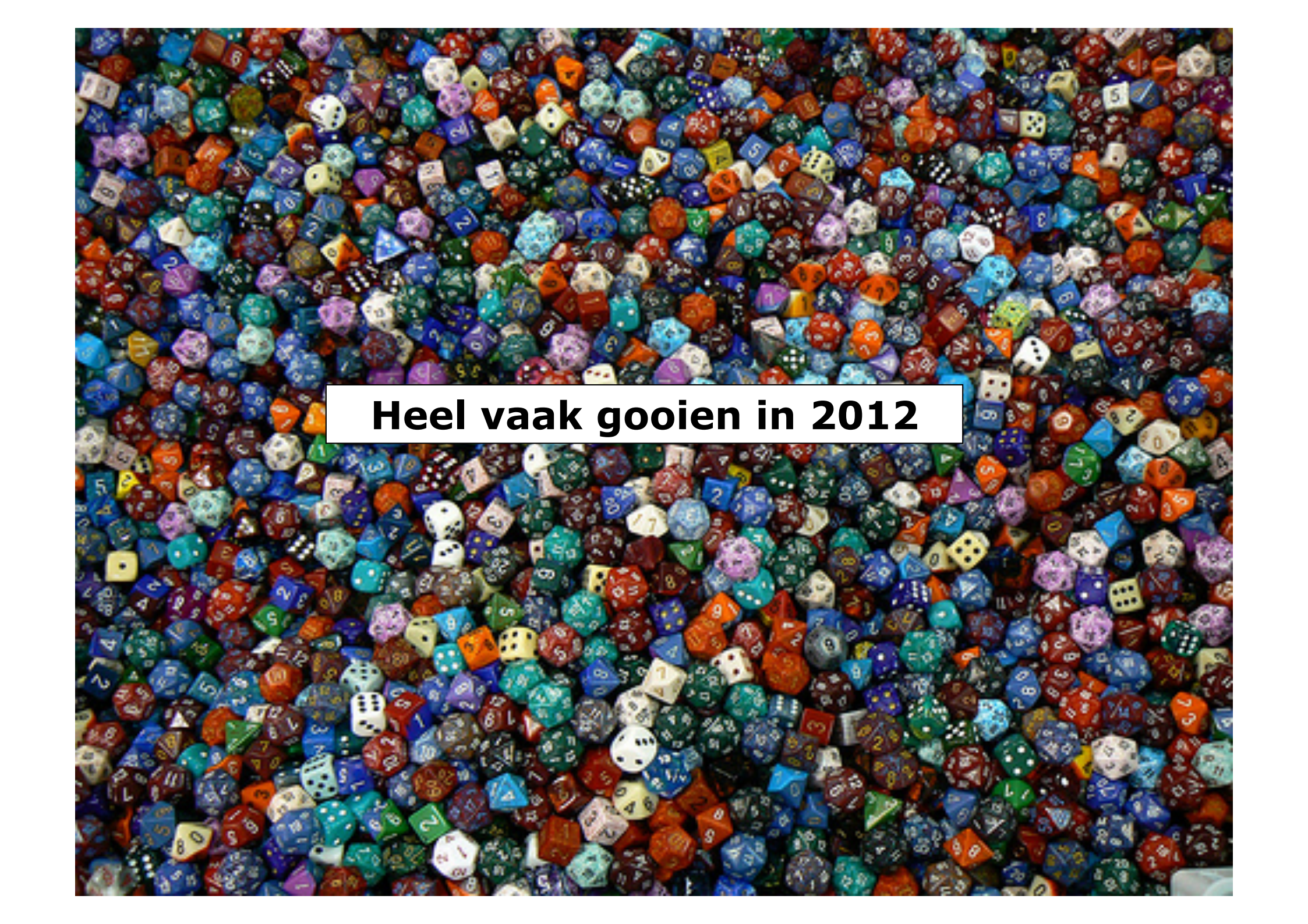
Toeval of valse dobbelsteen ?



Claim pas ontdekking als:

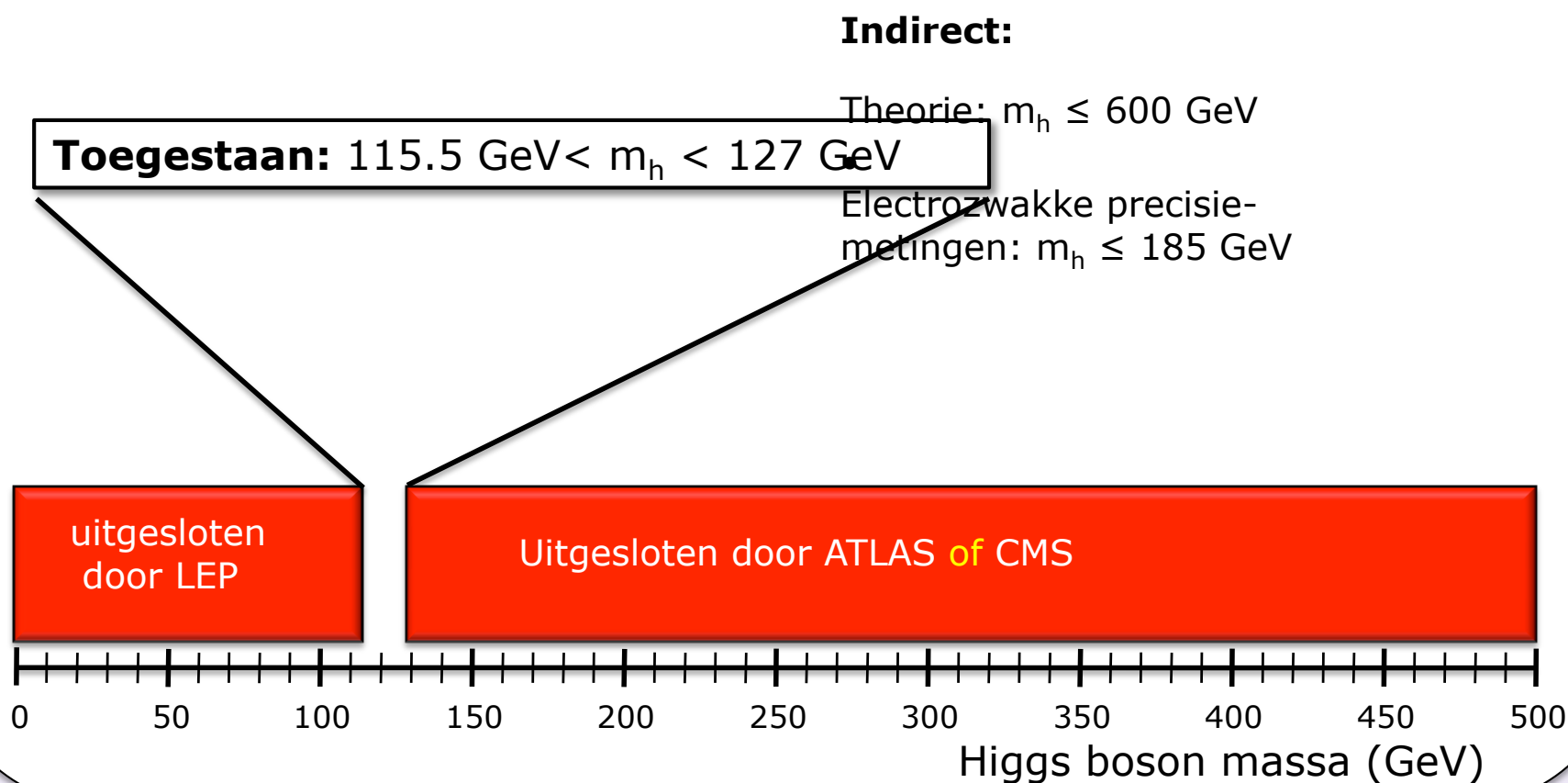
Kans op toevallige fluctuatie zoals ge-
observeerd kleiner dan 1 op 1,000,000

8 keer 6 gooien achter elkaar



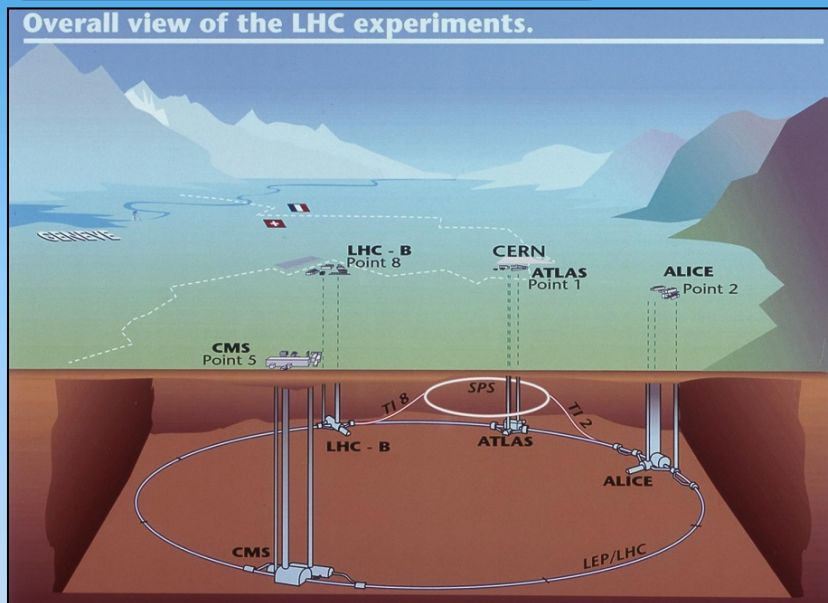
Heel vaak gooien in 2012

Stand van zaken 15 juni 2012



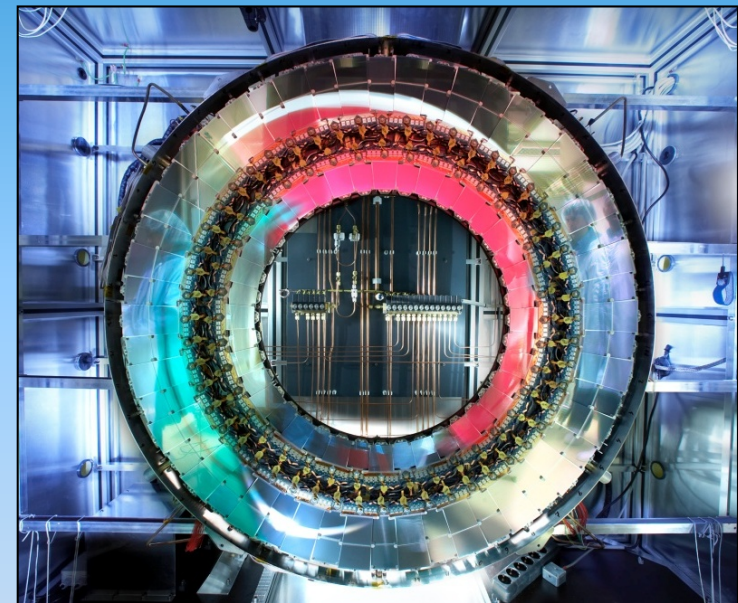
We zijn er klaar voor

LHC versneller

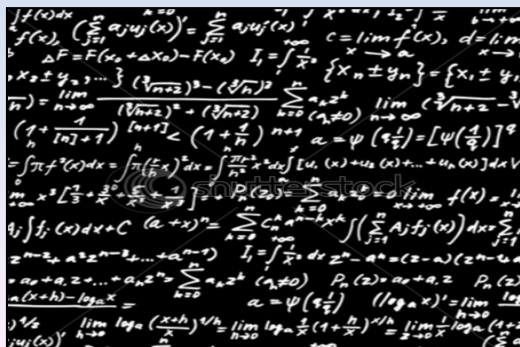


Herstart september 2009

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>