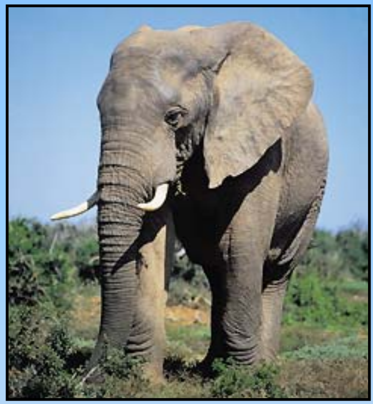
De large hadron collider:
Hoe zien de eerste botsingen eruit ?

Ivo van Vulpen

Het grootste en het kleinste

… volgens mijn dochter van 3

… volgens haar vader



Olifant

Klein muisje

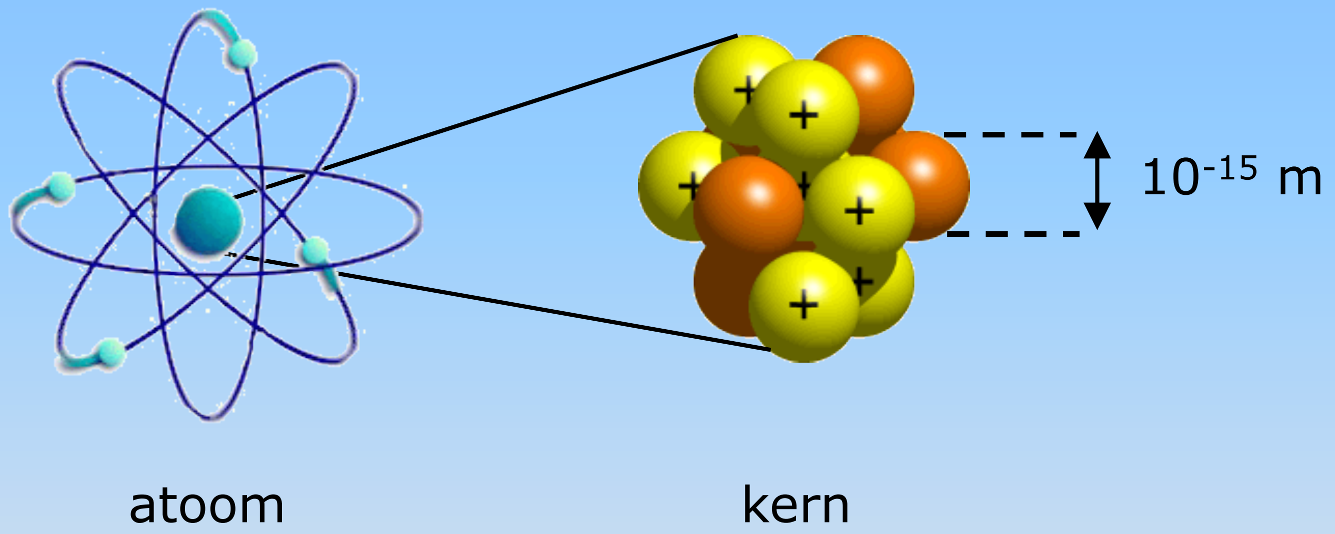
Grootst

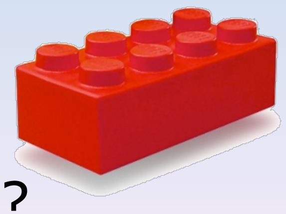
10^{+22} m

Kleinst

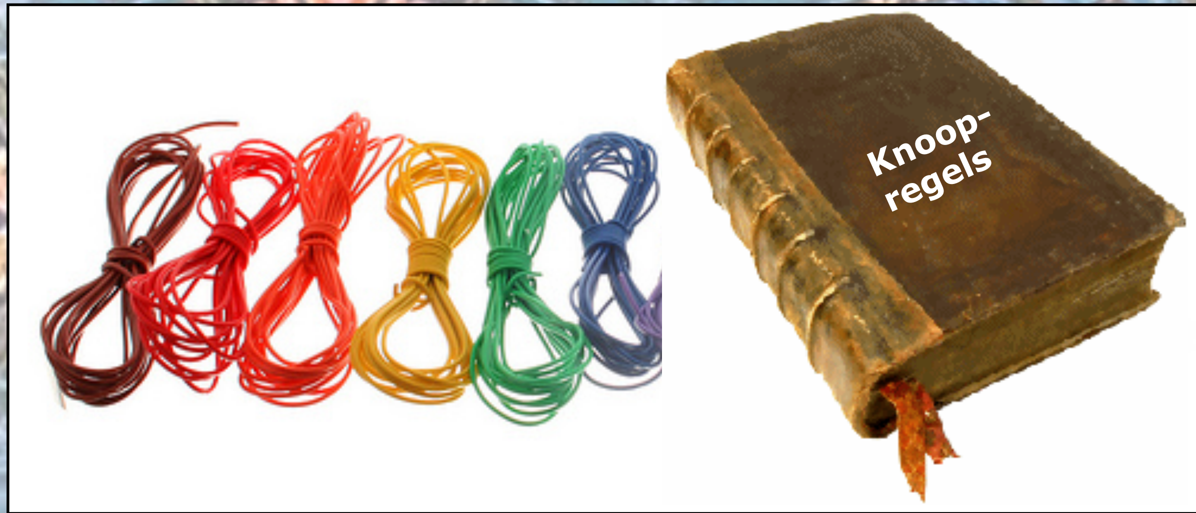
10^{-9} m

Deeltjesfysica





Wat zijn de bouwstenen van de dingen om ons heen ?



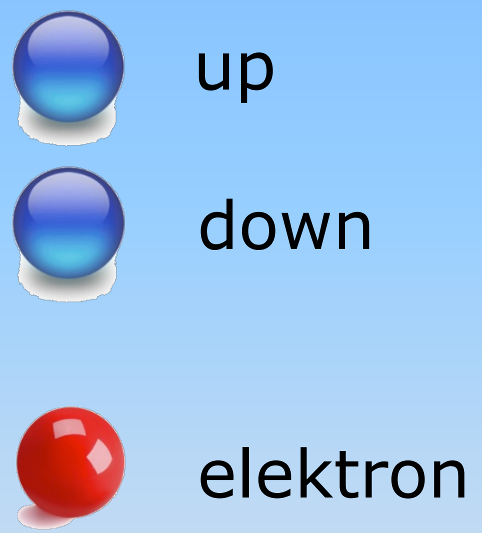
[1] Wow, mooi ! … fascinerende complexe patronen !

[2] Gewoon 4 gekleurde draadjes en simpel symmetrisch patroon

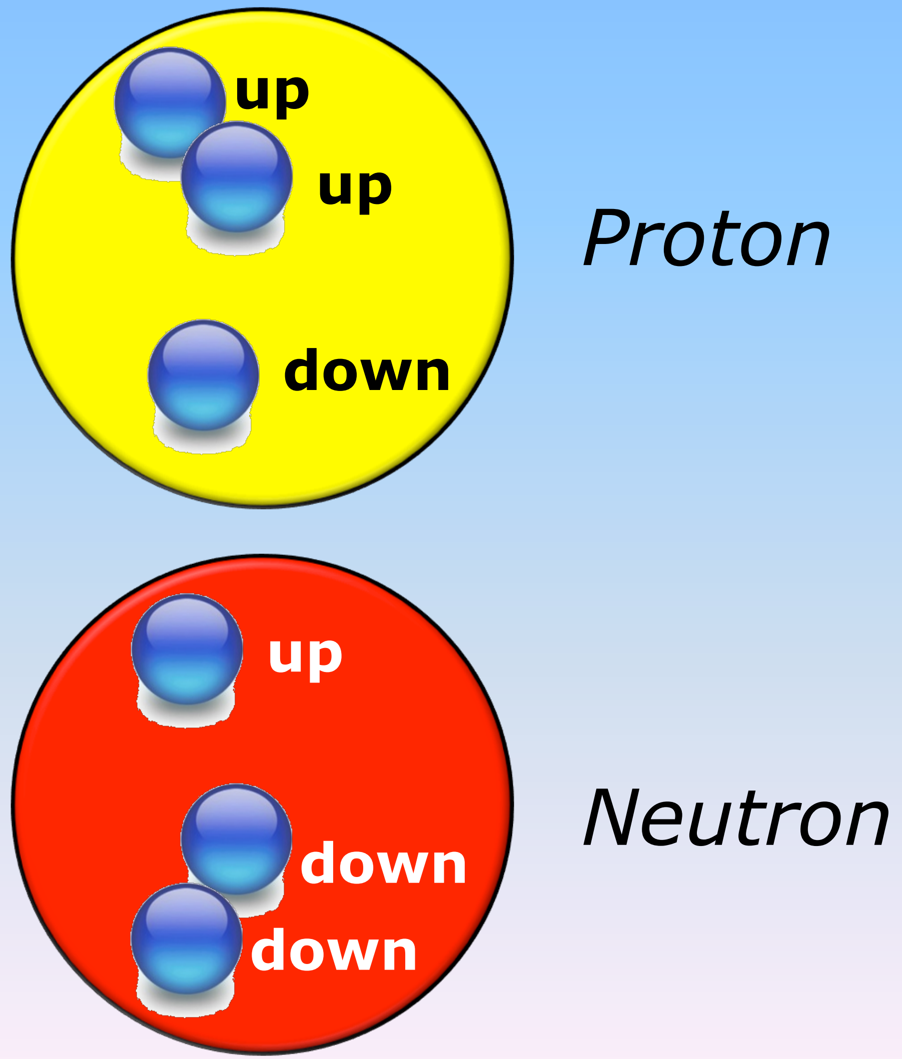
De stand van zaken in oktober 2009

http:// pdg.lbl.gov

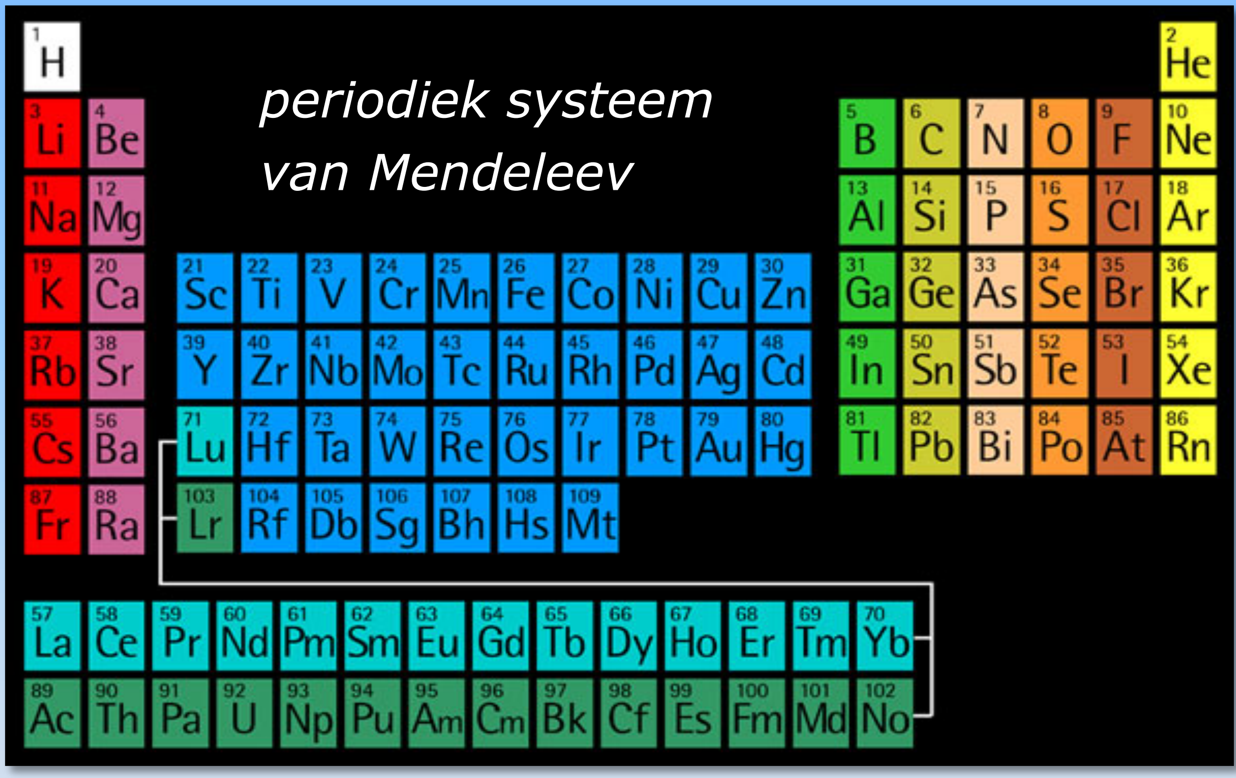
De elementaire deeltjes



+ 4 natuurkrachten



Wat kan je maken met deze 3 bouwstenen ?



Alles!

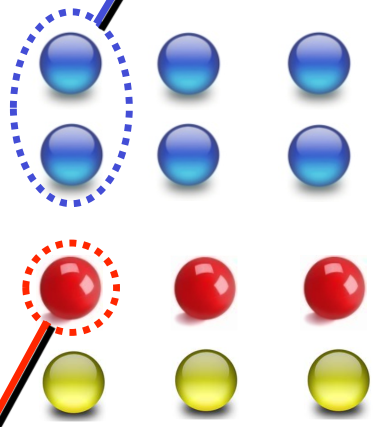
Voorzitter NWO

bouwstenen van proton/neutron

Deeltjes

Quarks

Leptons



elektron

Krachten

1) Electromagnetisme

2) Zwakke kernkracht

3) Sterke kernkracht

Wat snappen we nog niet:

Paar ‘kleine’ dingetjes:

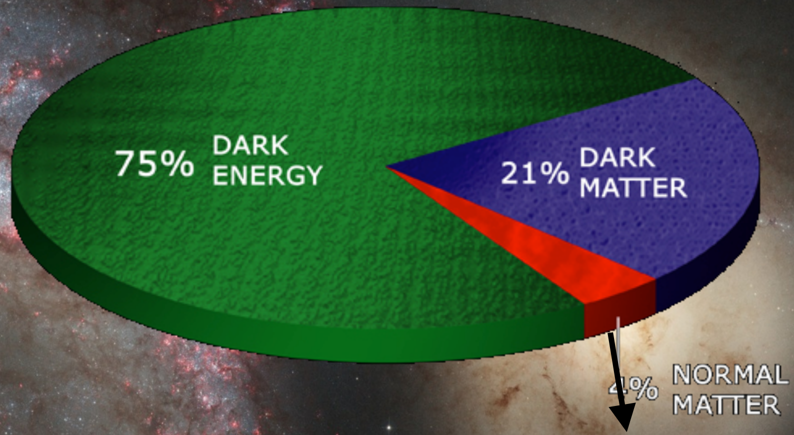
1. 96% van de materie in het heelal is onbekend
   → donkere materie

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 electrische lading, exploderende quantumcorrecties, kleine neutrino massa’s, string theorie, …

1 *Donkere-materie*



Normale materie (4%)

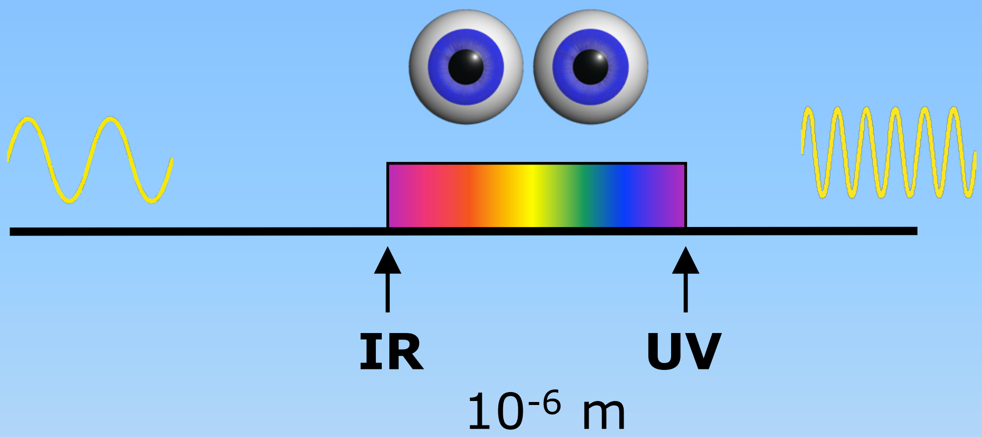
Revolutie in kosmologie laatste paar jaar
Structuur van het heelal:
we hebben al die tijd maar 4% van het heelal bestudeerd

We gaan proberen de donkere materie deeltjes in het laboratorium 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

2] Kijken met deeltjes

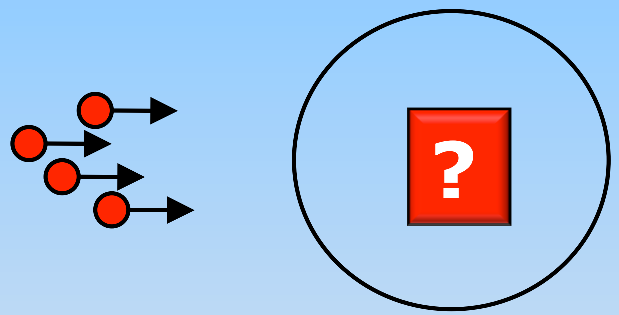
Idee: laat kleine deeltjes afketsen van het object

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

onbekend voorwerp achter een gordijn

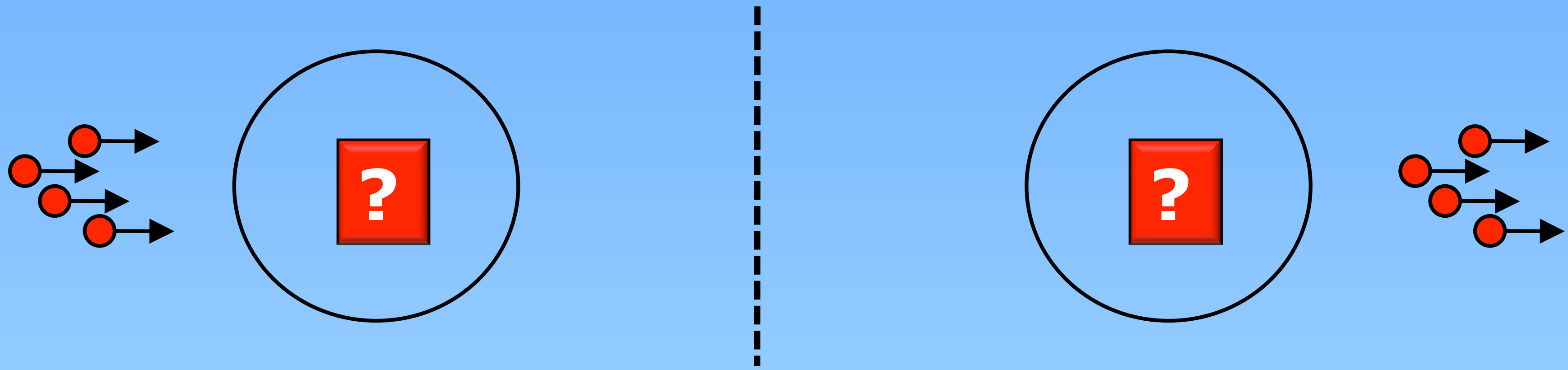
… en 100 kogeltjes

bovenaanzicht

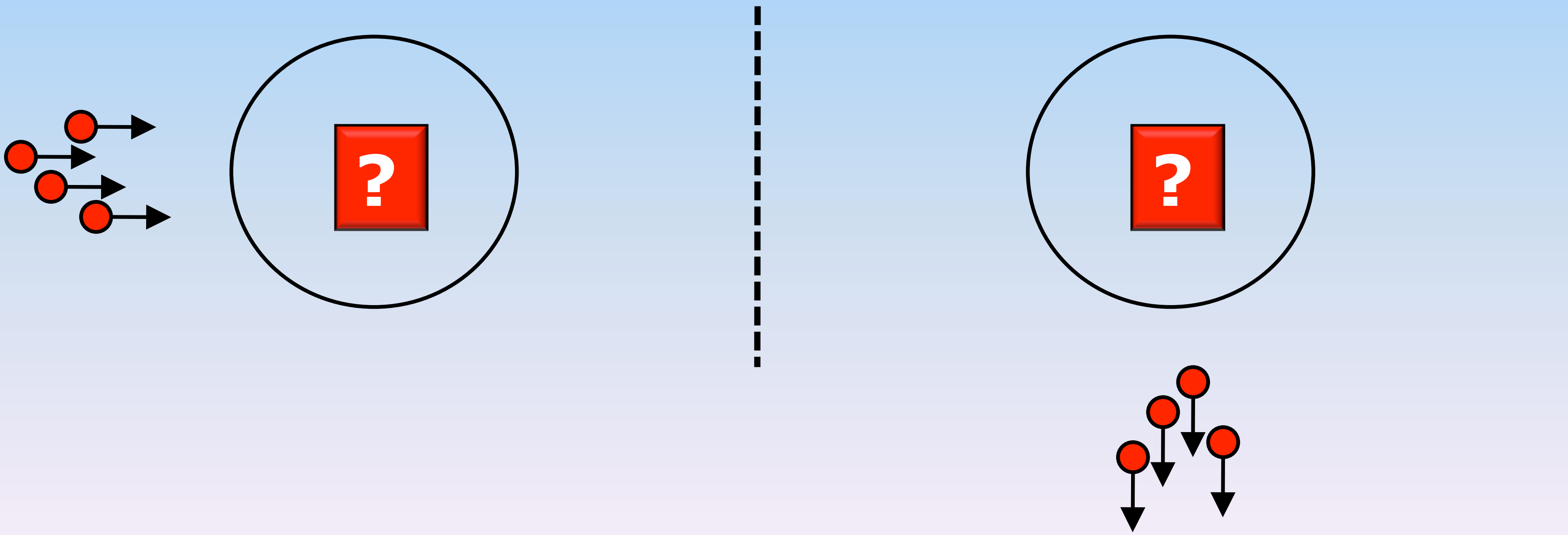


Hoe ketsen de kogels af ?

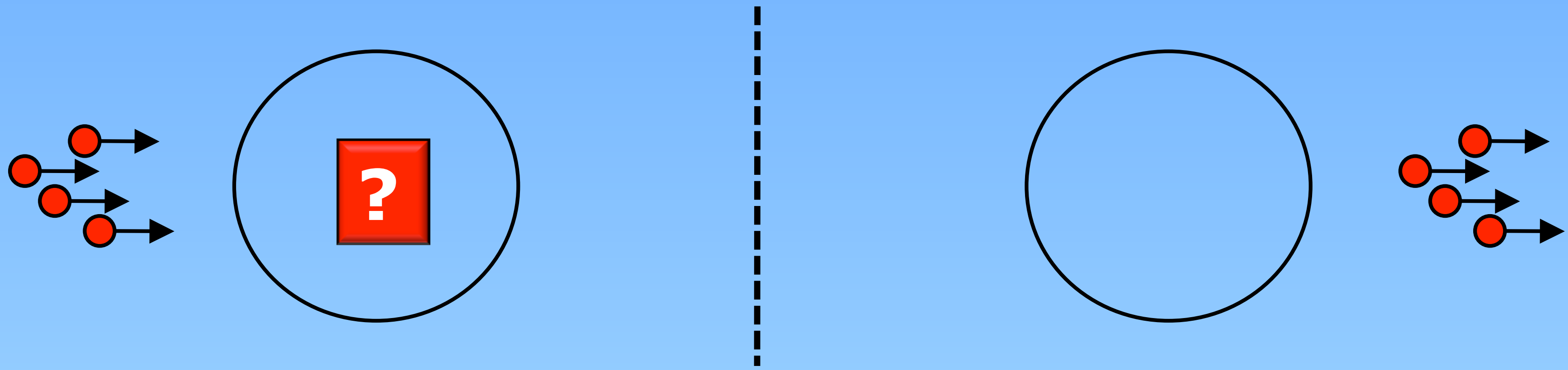
Experiment 1



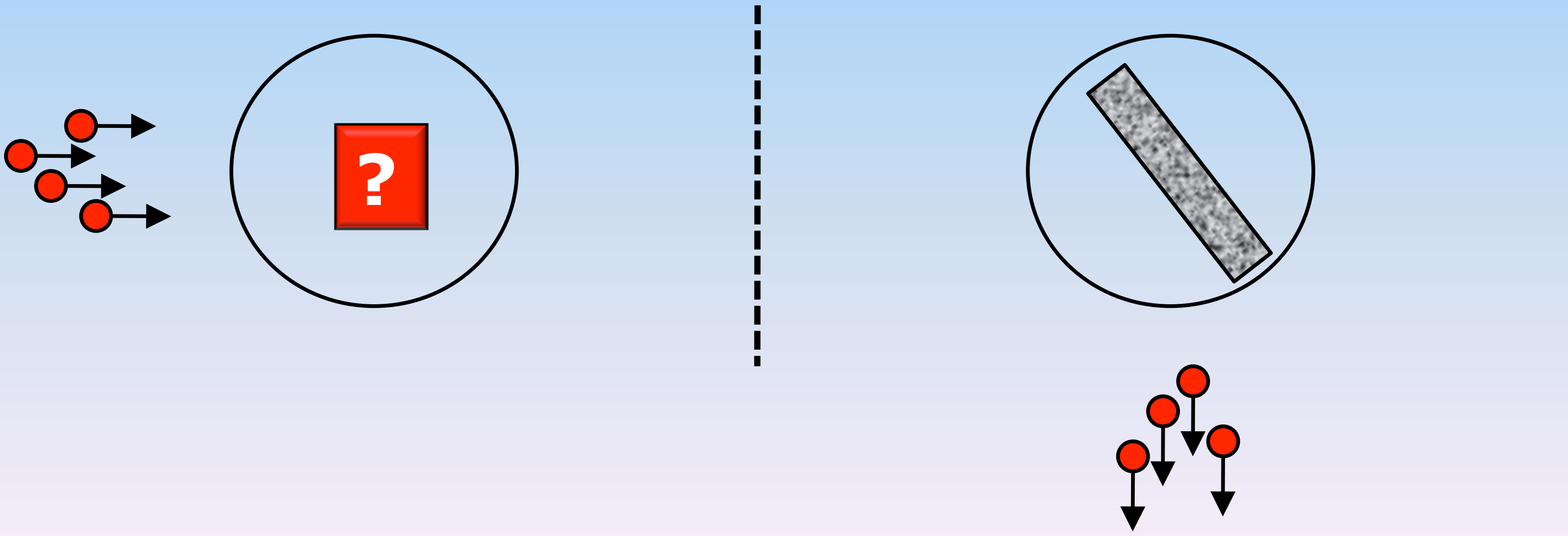
Experiment 2



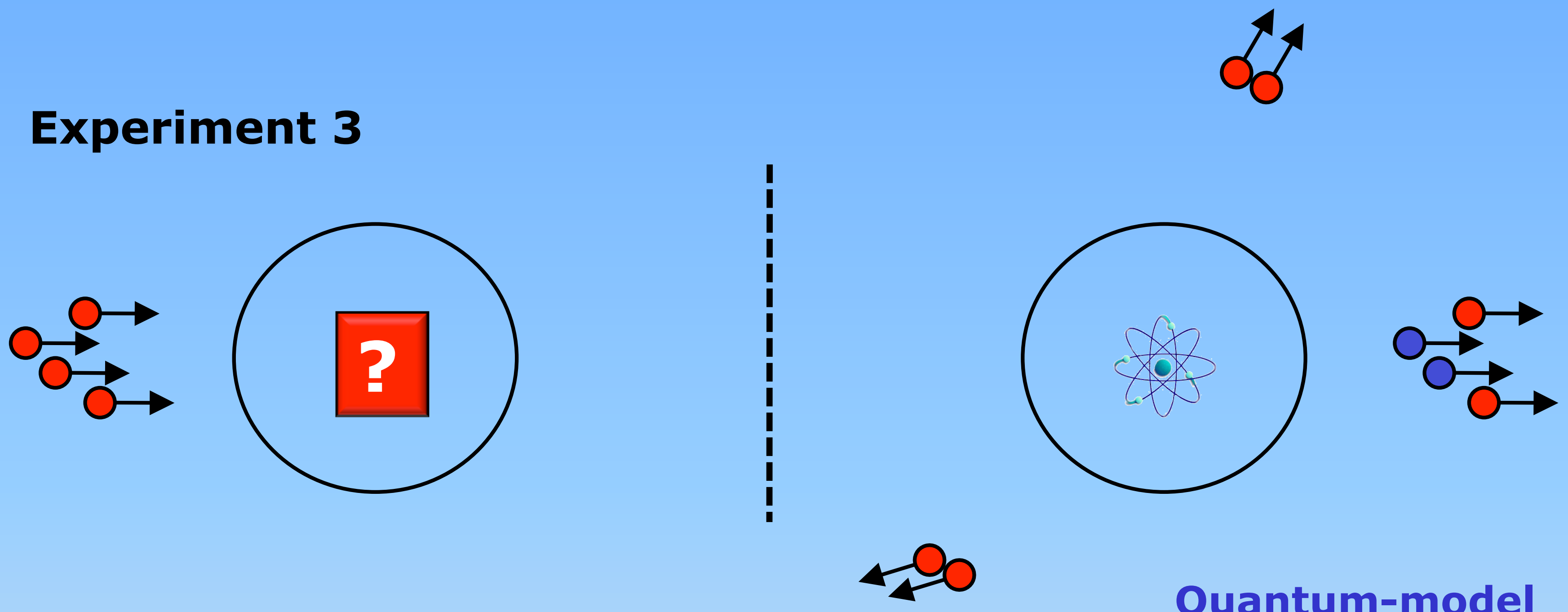
Experiment 1



Experiment 2



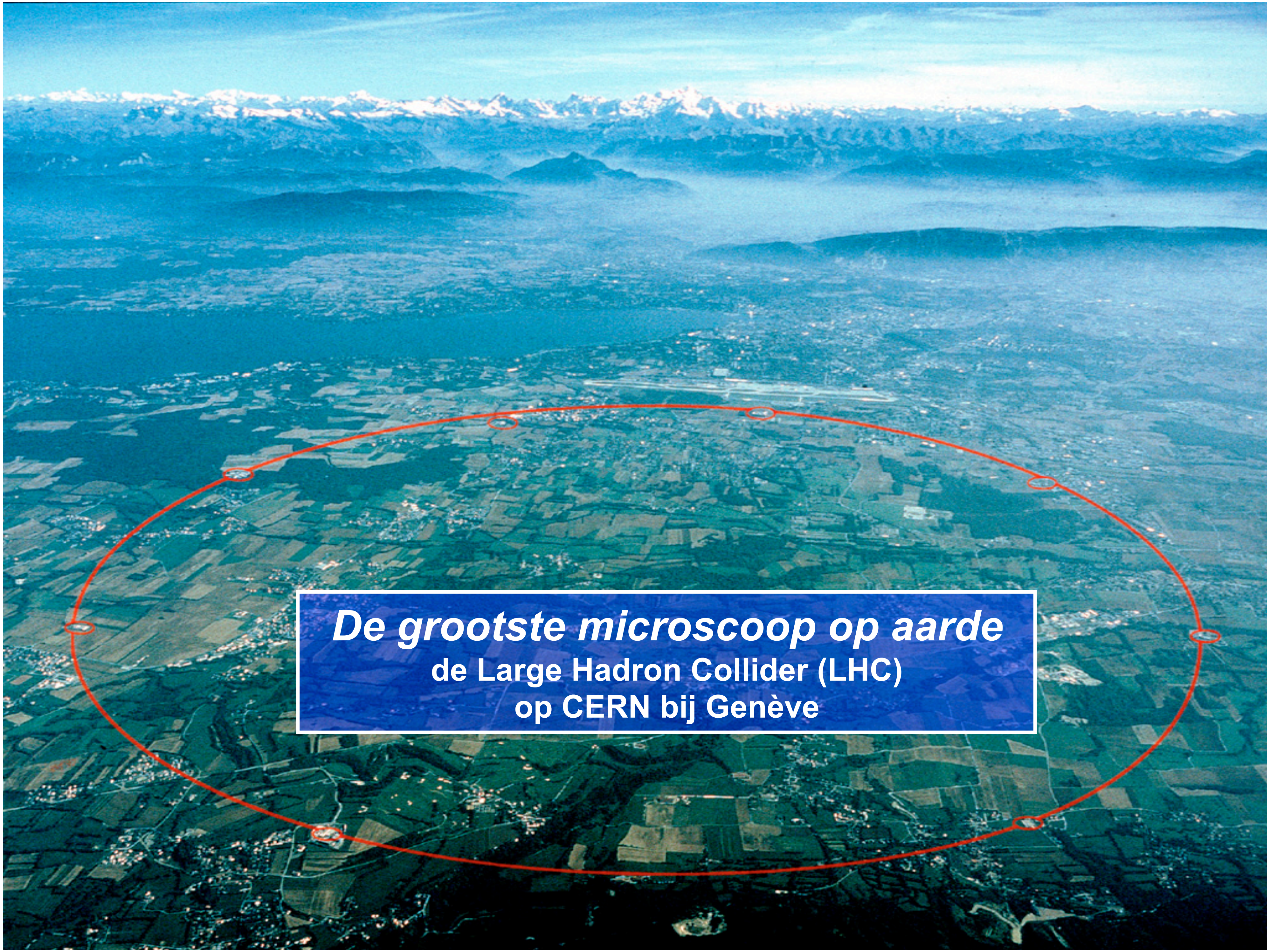
Experiment 3



Quantum-model
Einstein: $E=mc^2$

‘Kijken’ naar sub-atomaire structuren:

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

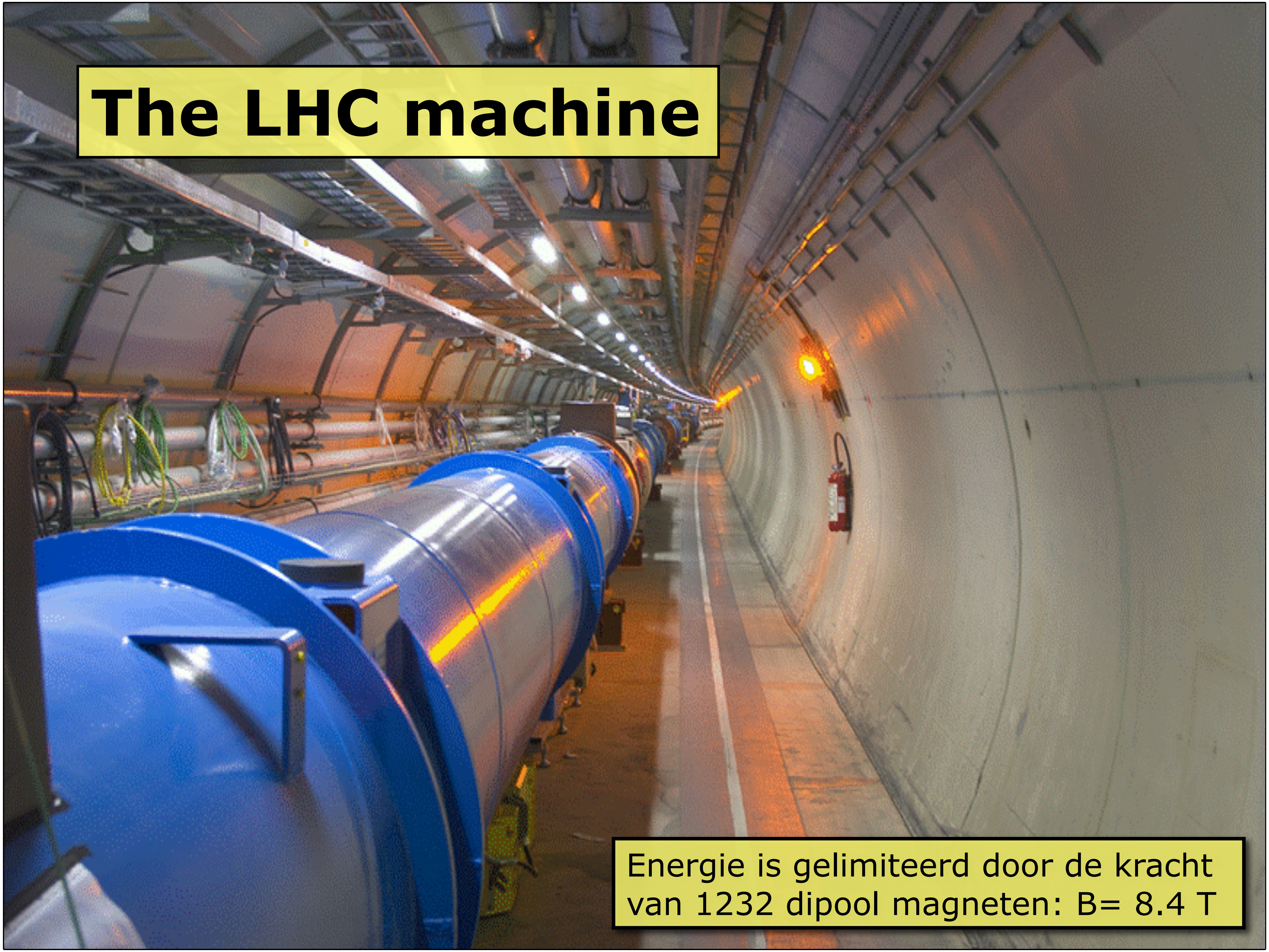

De grootste microscoop op aarde
de Large Hadron Collider (LHC)
op CERN bij Genève

De Large Hadron Collider

LHC: 27 km

A10: 32 km

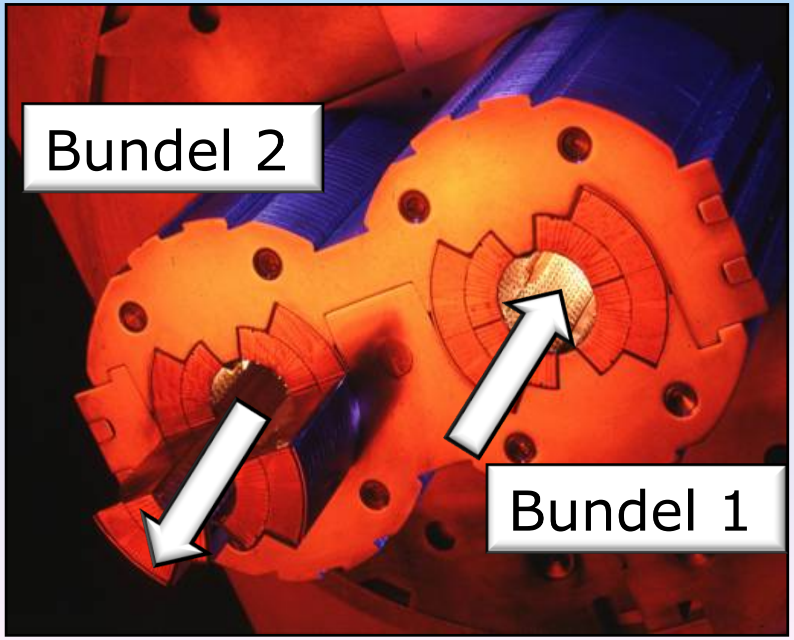
The LHC machine



Energie is gelimiteerd door de kracht van 1232 dipool magneten: B= 8.4 T

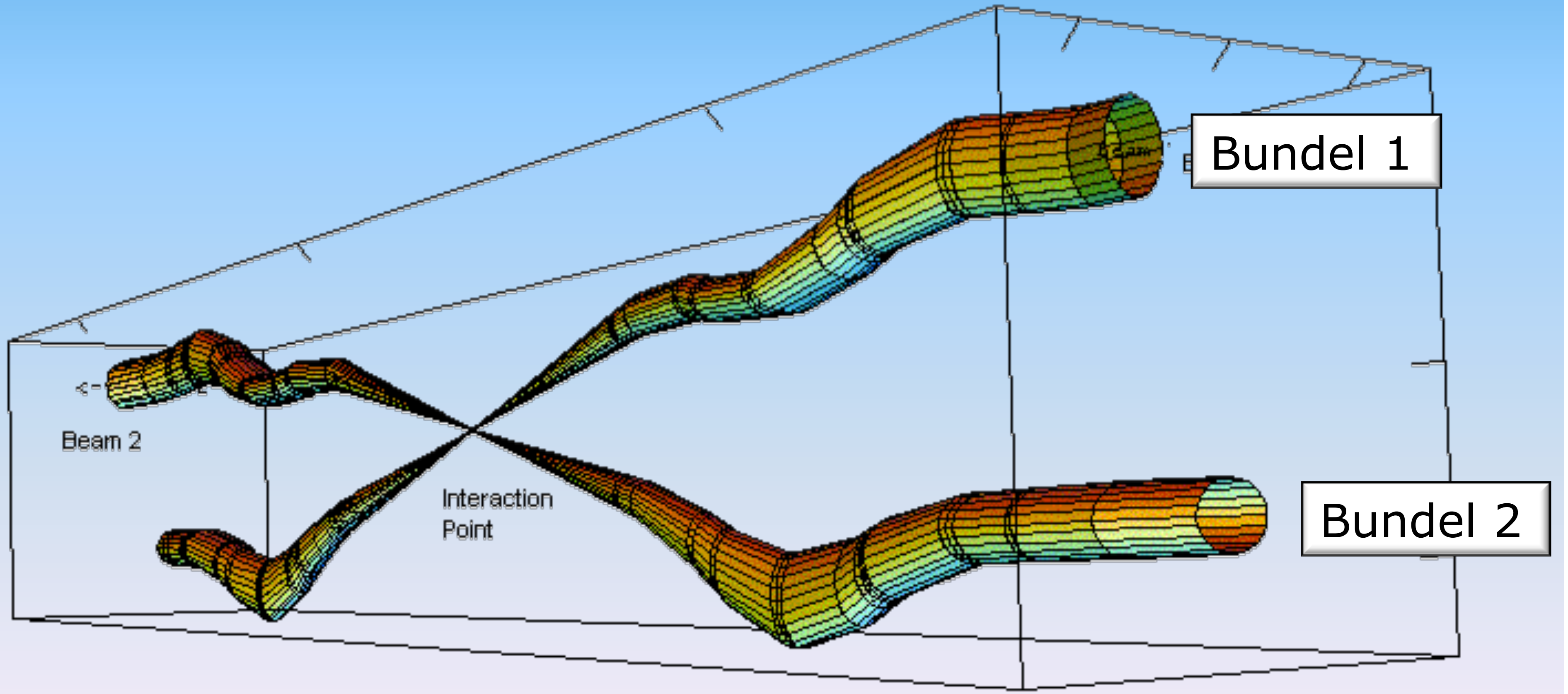
Energie van 1 proton
in de LHC

Energie LHC bundel
3000 x 100.000.000.000 protonen



Doorsnede LHC bundelpijp

40 miljoen botsingen per seconde



Klassiek botsen

Quantummechanisch botsen

Wat verwacht je ?

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 $H \to Q\bar{Q}$ decay rate, can in first approximation be safely neglected.

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

...he $H\gamma\gamma$ and $H\gamma Z$ couplings are induced at one loop via both a ... At the lowest order the decay rate for $H \to \gamma\gamma$ can be written

$$\dots = \frac{G_F\alpha^2 M_H^3}{128\sqrt{2}\pi^3}\left|\sum_f N_c^f Q_f^2 A_f^H(\tau_f) + A_W^H(\tau_W)\right|^2 , \qquad (102)$$

... l, q respectively), Q_f is the charge of the f fermion species, ... $f(\tau)$ is defined as:

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

... A_W^H are given by:

$$A_f^H = 2\tau\left[1+(1-\tau)f(\tau)\right] , \qquad (104)$$
$$A_W^H(\tau) = -\left[2+3\tau+3\tau(2-\tau)f(\tau)\right] .$$

...ay rate for $H \to \gamma Z$ is given by:

$$\dots\frac{\alpha M_H^3}{\dots^4}\left(1-\frac{M_Z^2}{M_H^2}\right)^3\left|\sum_f A_f^H(\tau_f,\lambda_f) + A_W^H(\tau_W,\lambda_W)\right|^2 , \qquad (105)$$

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

$$\dots 2N_c^f\frac{Q_f(I_{3f}-2Q_f\sin^2\theta_W)}{\cos\theta_W}\left[I_1(\tau,\lambda)-I_2(\tau,\lambda)\right] , \qquad (106)$$

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

...ed after Eq. (102), and I_3^f is the weak isospin of the f fermion

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

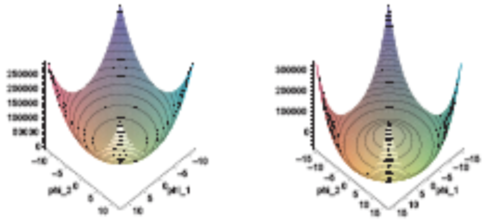


FIG. 1: The potential $V(\phi)$ ($\phi = \phi_1 + i\phi_2$) plotted for an arbitrary positive value of λ and for an arbitrary positive (right) or negative (left) value of μ^2.

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:

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

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

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

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:

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

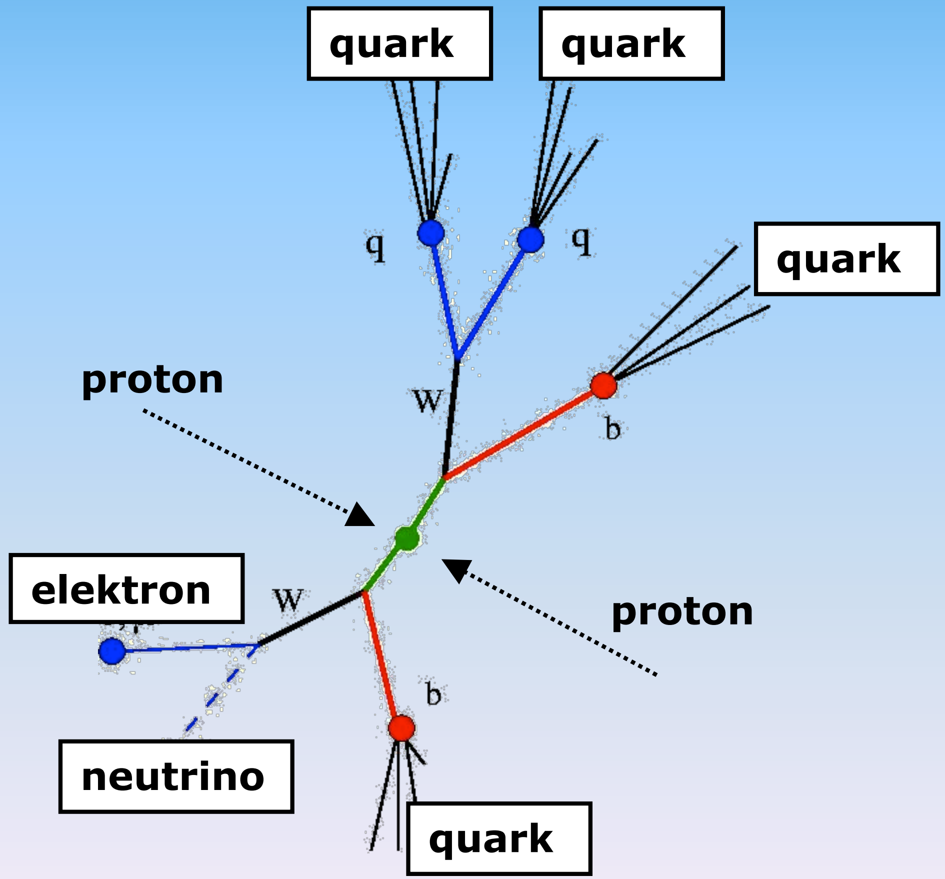
the χ degree of freedom can be *rotated away*, as indicated in Eq. (7), by enforcing the $U(1)$ gauge invariance of the original Lagrangian. With this gauge choice, known as *unitary gauge* or *unitarity gauge*, the Lagrangian becomes:

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

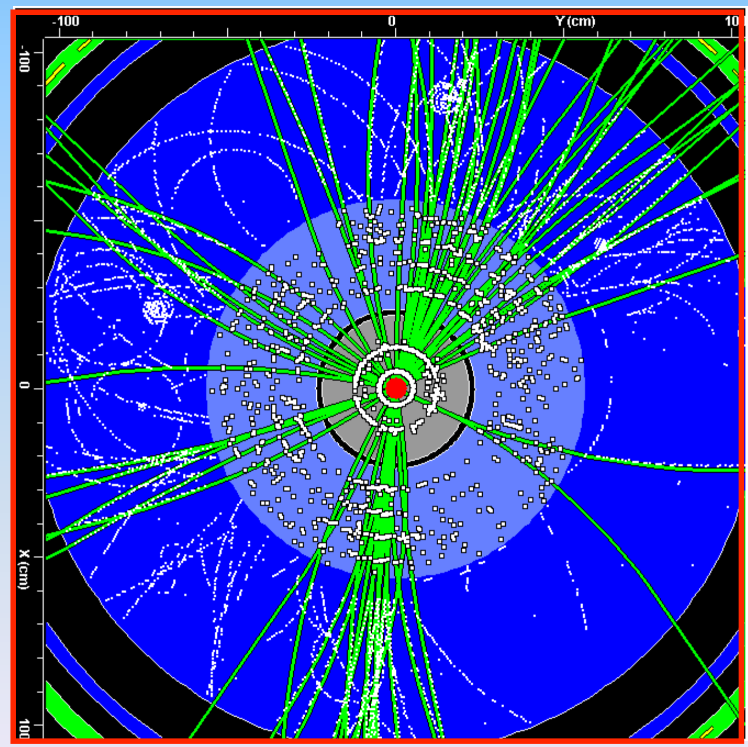
Klopt het ?

Inderdaad nieuwe deeltjes ?

Hoe zien die botsingen er nou uit ?

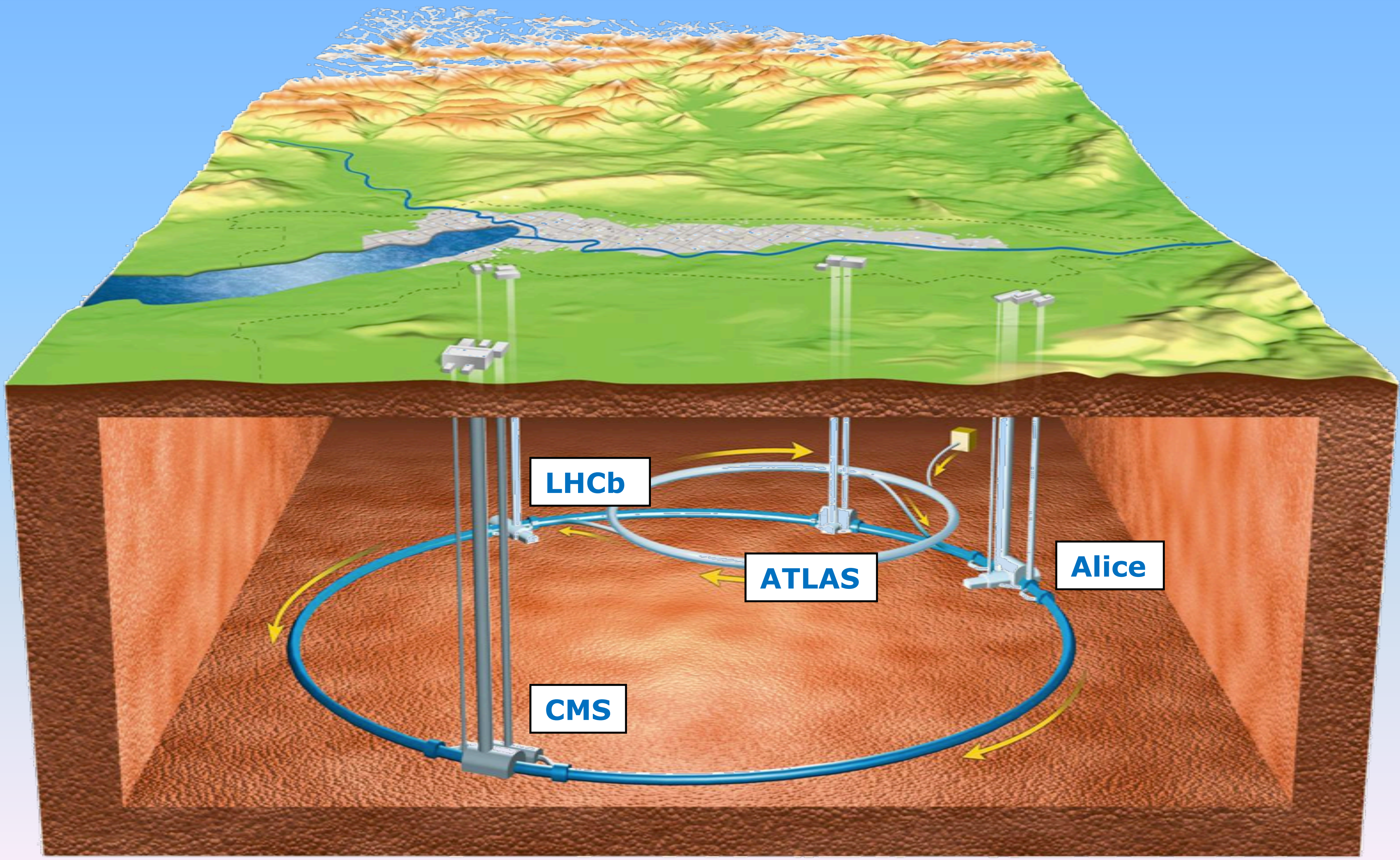


Simulatie top quark productie

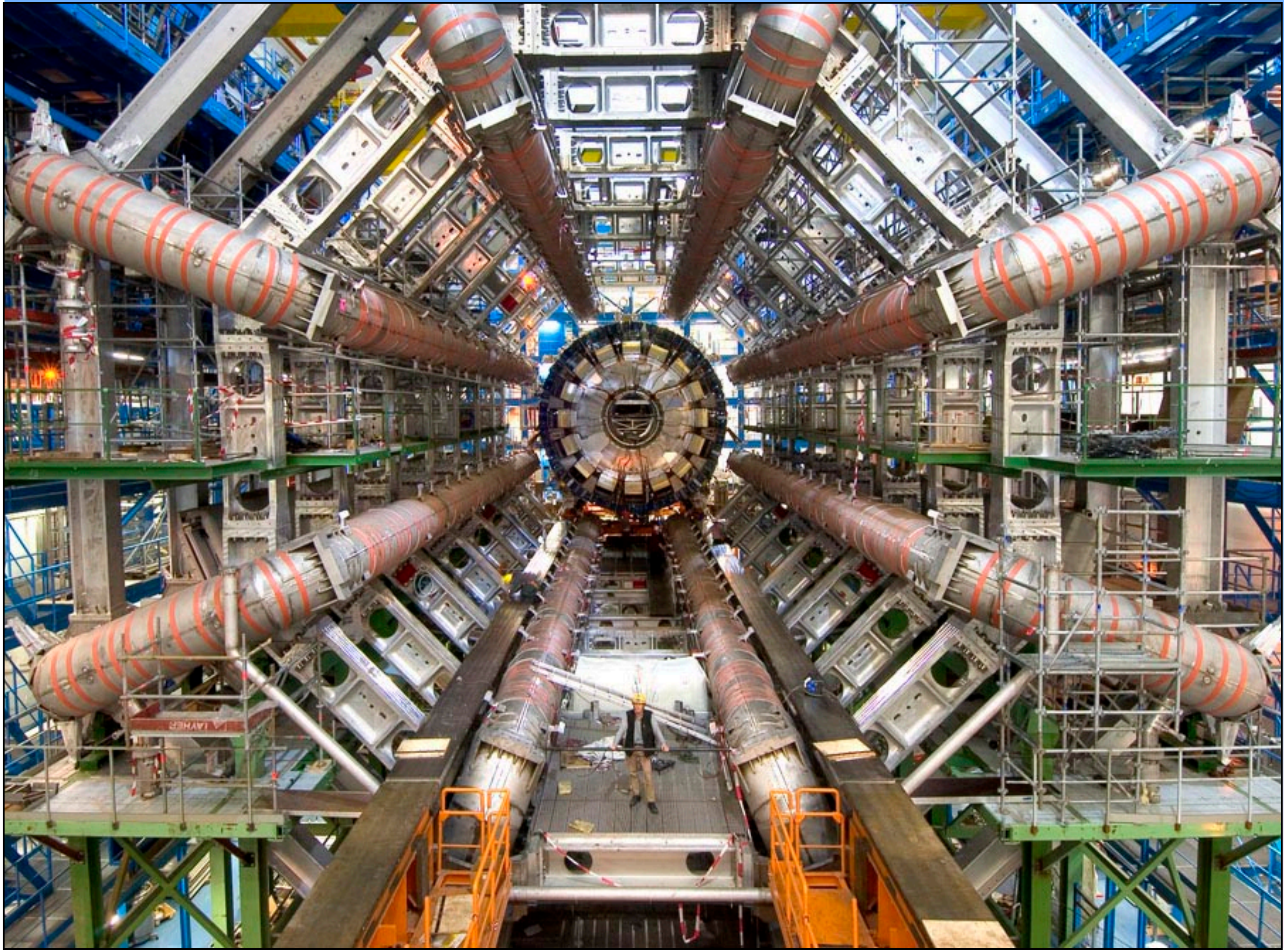


Onze ‘fototoestellen’

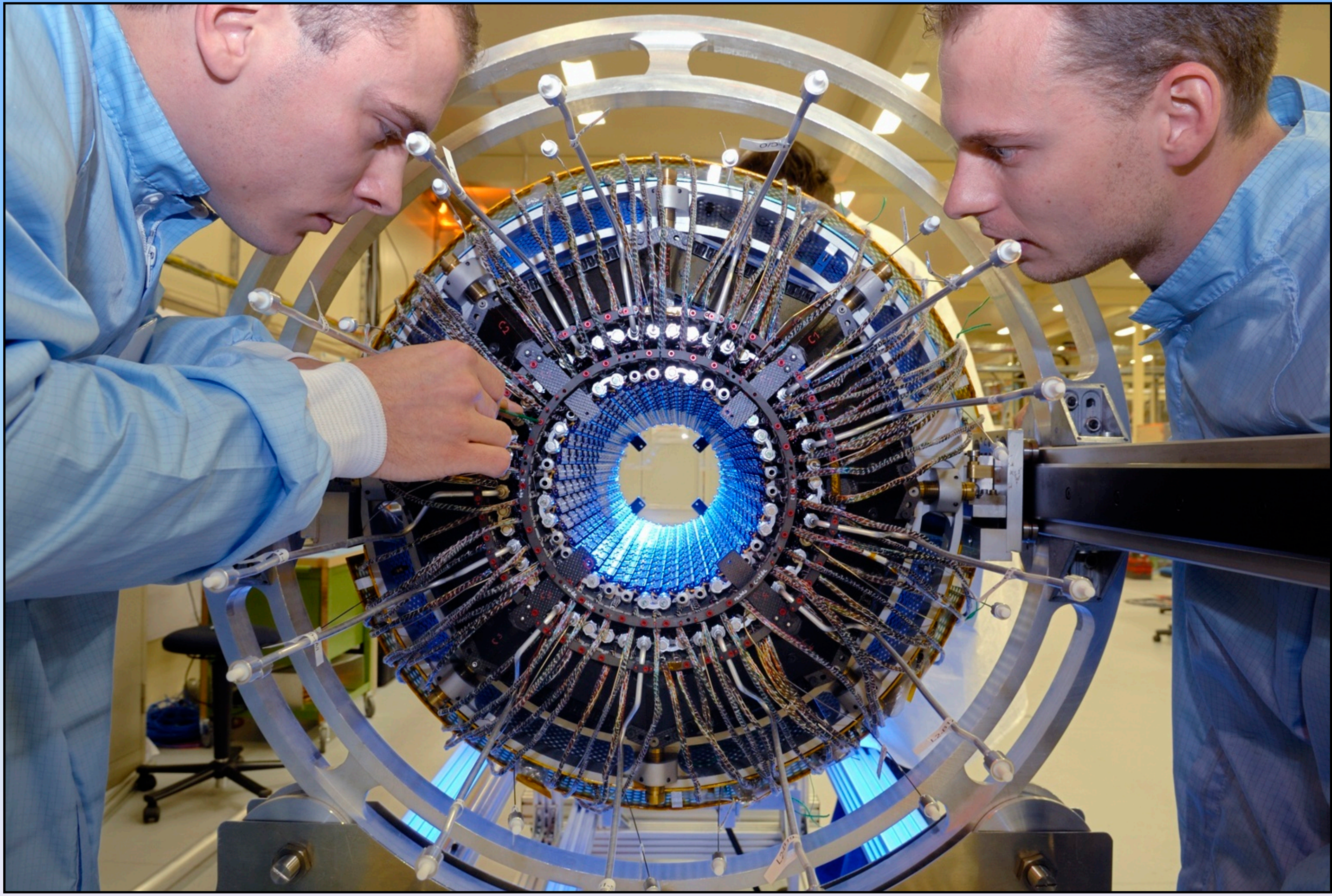
De vier experimenten




CMS



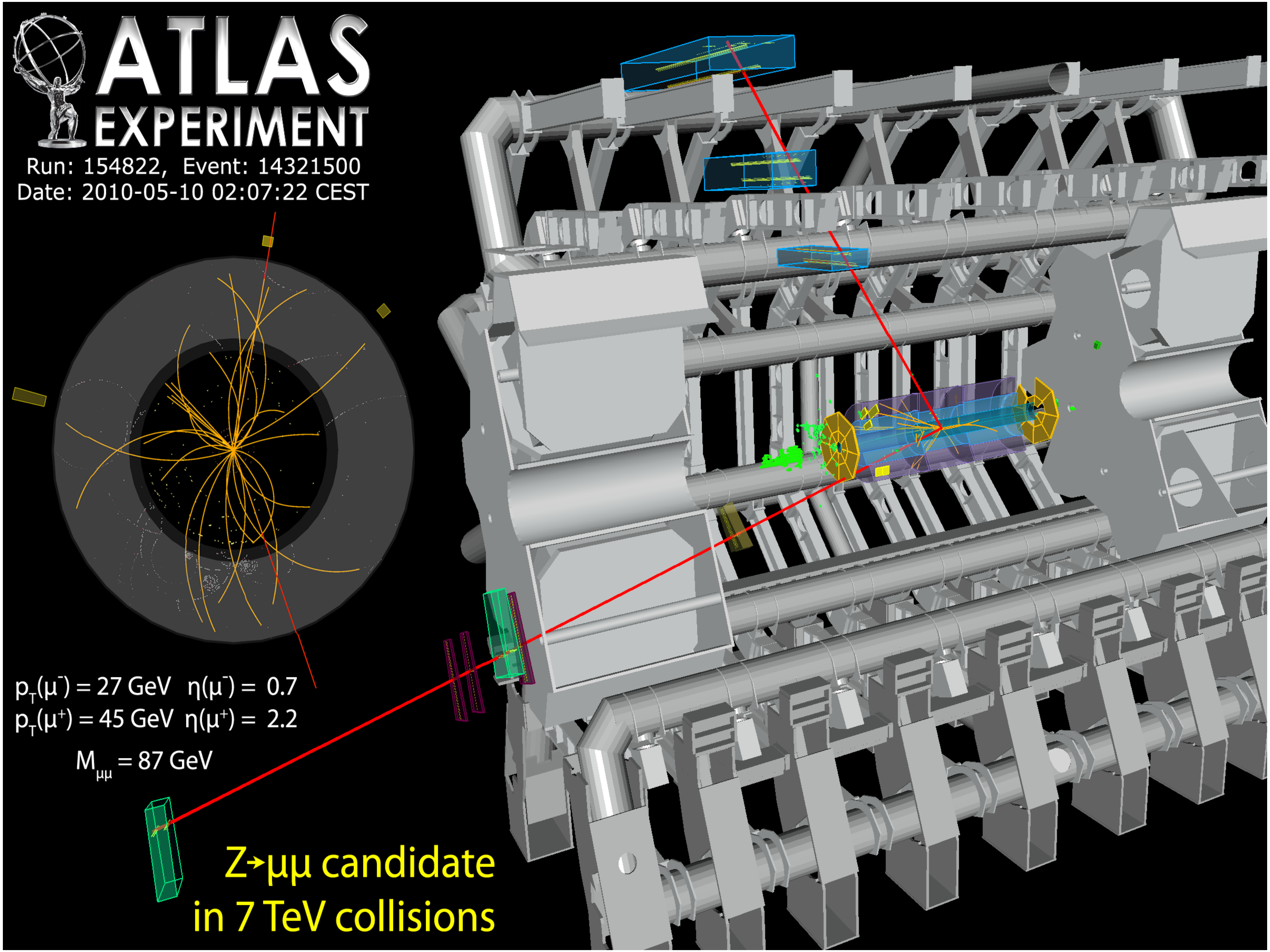
De Atlas pixel detector

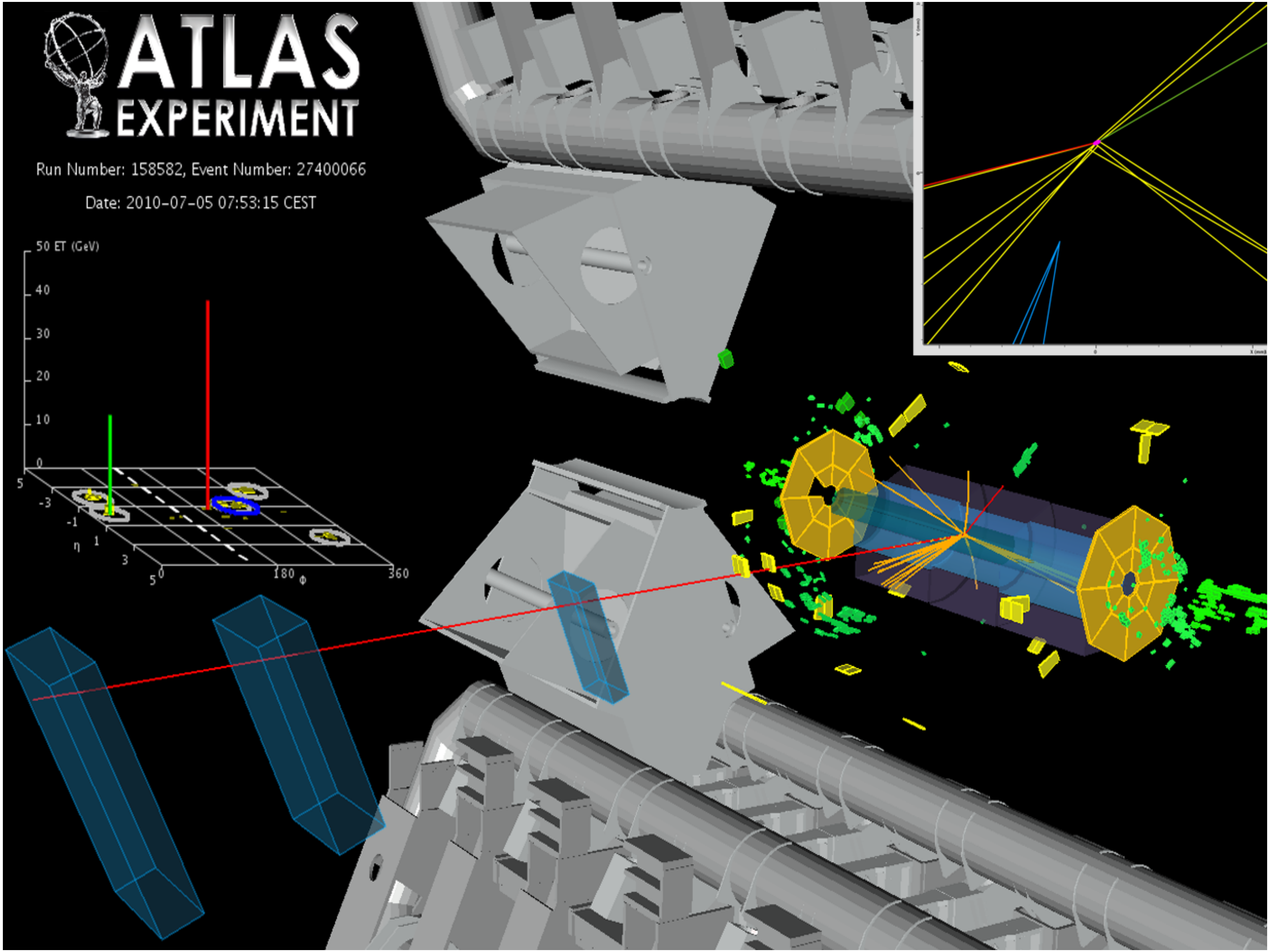


80 MegaPixel camera 40.000.000 foto's per seconde

De Atlas SCT detector

Foto in de cleanroom op het Nikhef (Amsterdam)

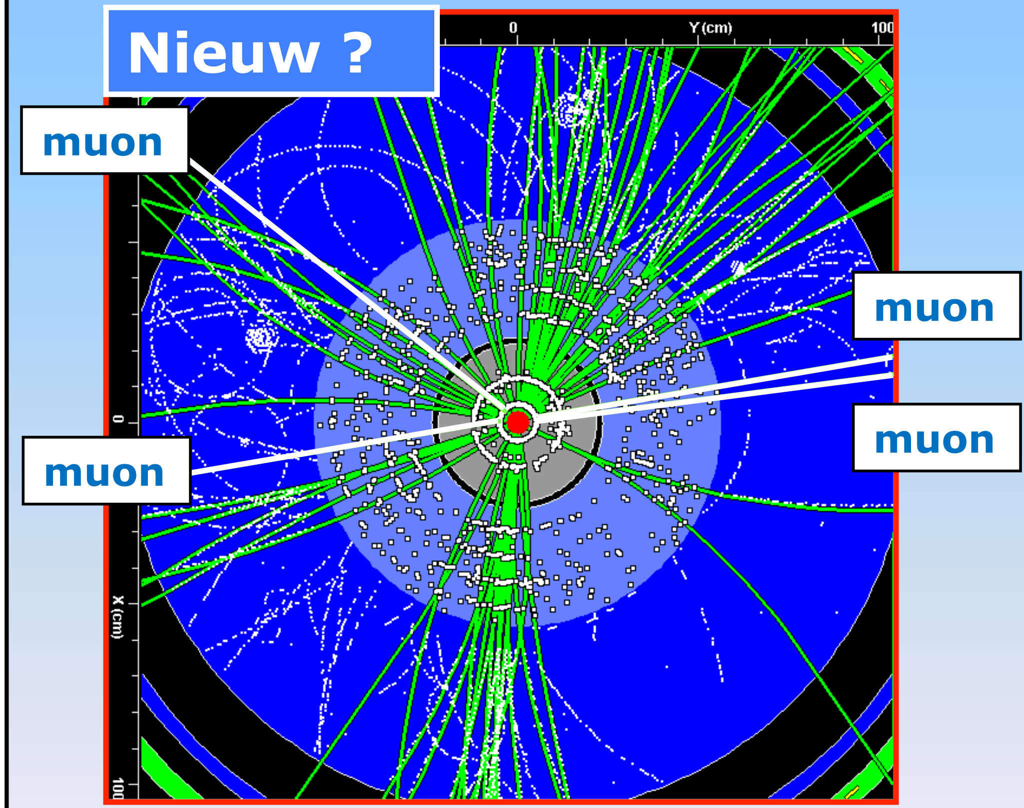

ATLAS EXPERIMENT
Run: 154822, Event: 14321500
Date: 2010-05-10 02:07:22 CEST
$p_T(\mu^-) = 27$ GeV $\eta(\mu^-) = 0.7$
$p_T(\mu^+) = 45$ GeV $\eta(\mu^+) = 2.2$
$M_{\mu\mu} = 87$ GeV
$Z \rightarrow \mu\mu$ candidate
in 7 TeV collisions

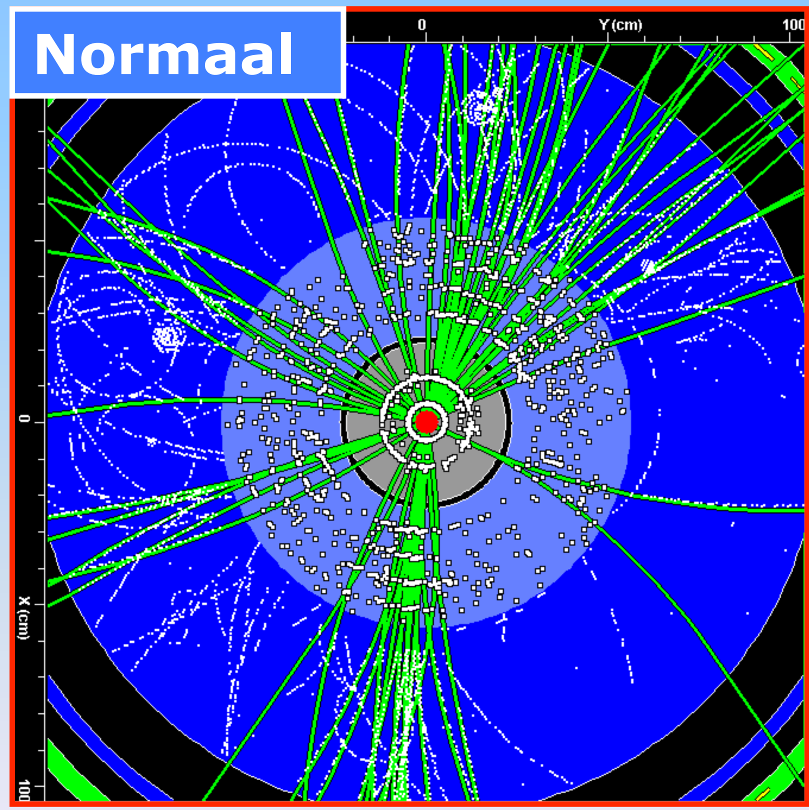

ATLAS
EXPERIMENT
Run Number: 158582, Event Number: 27400066
Date: 2010-07-05 07:53:15 CEST
50 ET (GeV)
40
30
20
10
0
η
φ
0
180
360

… hoe ontdek je nou nieuwe dingen ?

Hoe ontdek je nou nieuwe dingen

Nieuwe afstandschaal EN nieuwe detector

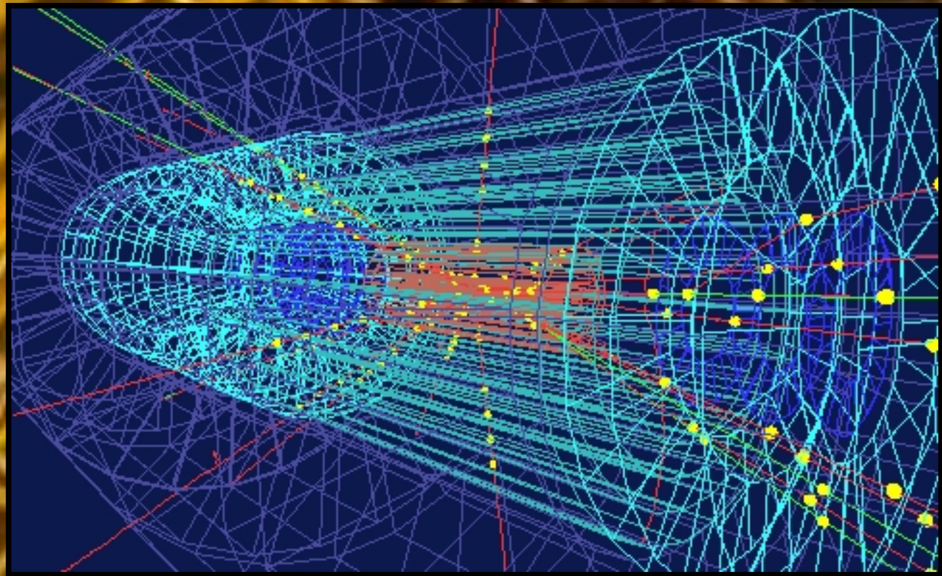




Higgs deeltje?

Ja … waarschijnlijk wel

Fotootjes kijken



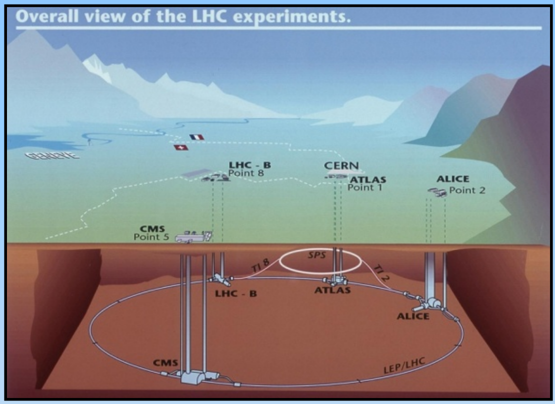
40 miljoen botsingen per seconde

mag maar 200 per seconde opslaan

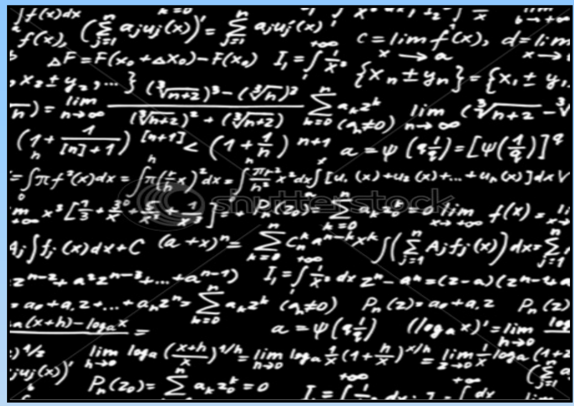
ongeveer 1 Higgs boson per dag

We zijn er klaar voor

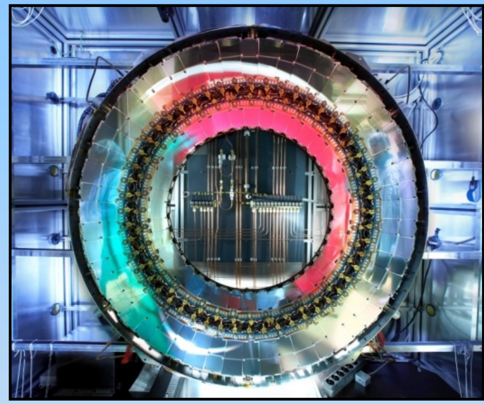
Deeltjesversneller



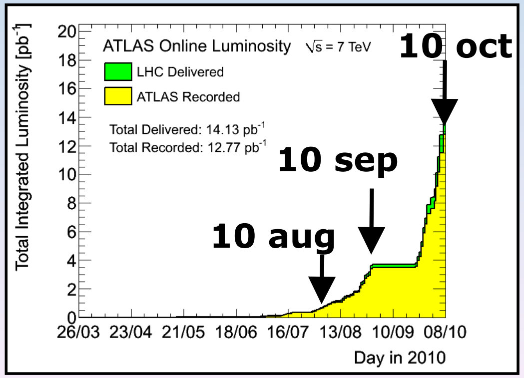
Theorie



Detectoren



Volop aan het runnen



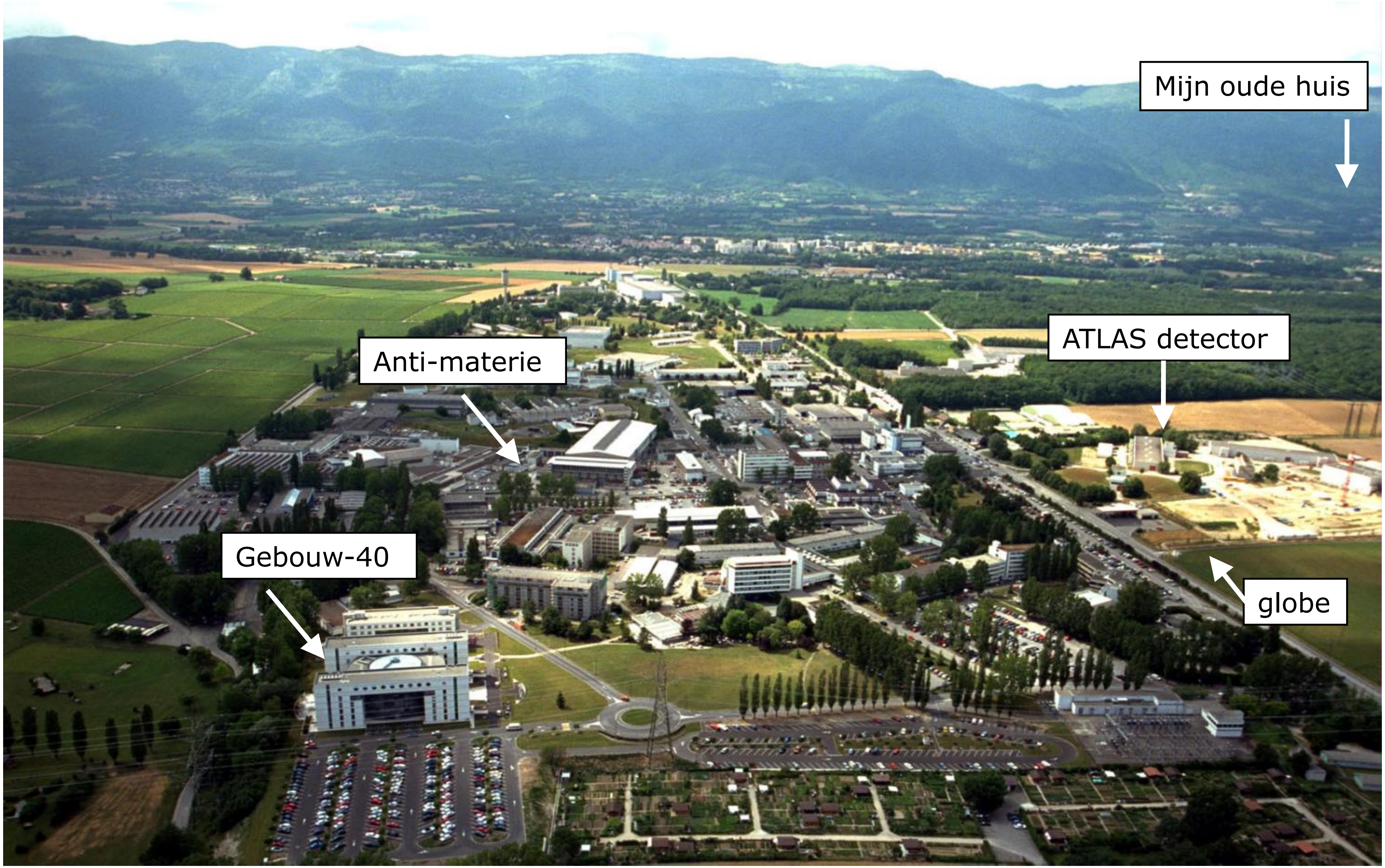
Meer dan genoeg vragen

… meer dan genoeg ideeën

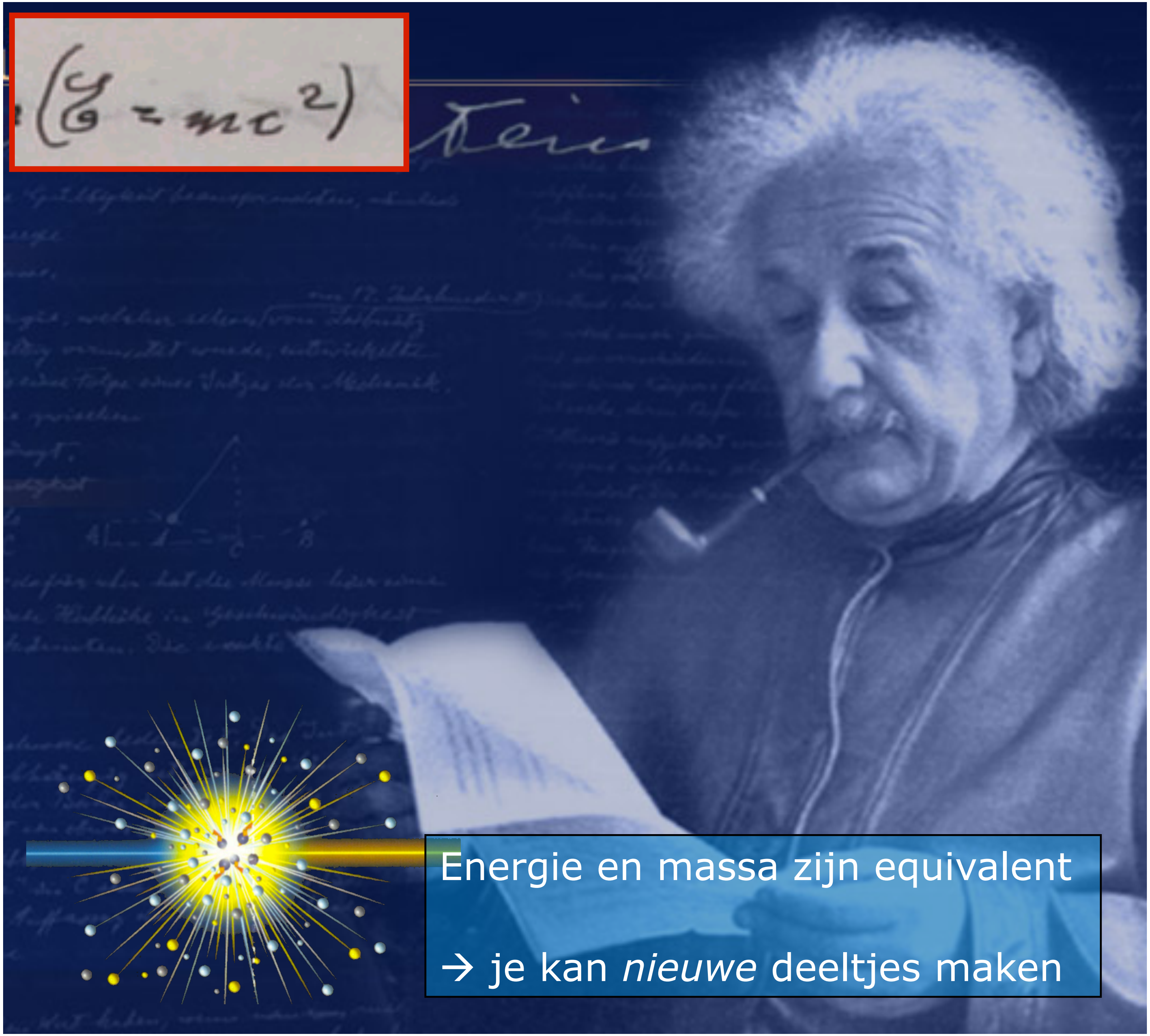
EINDE

Email: Ivo.van.Vulpen@nikhef.nl

CERN



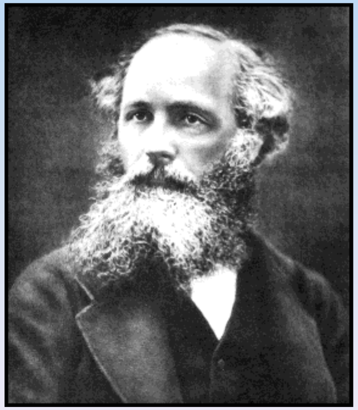
Albert Einstein



Zwaartekracht en Electromagnetisme

"zelfde krachten … nieuwe modellen"

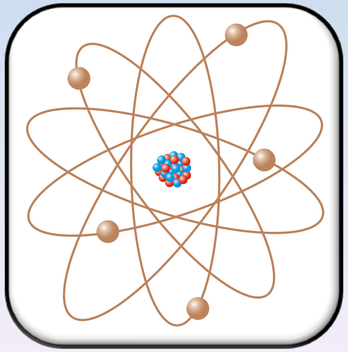
Newton

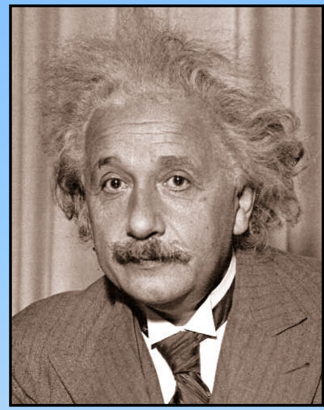


Maxwell

Relativiteitstheorie

Quantummechanica

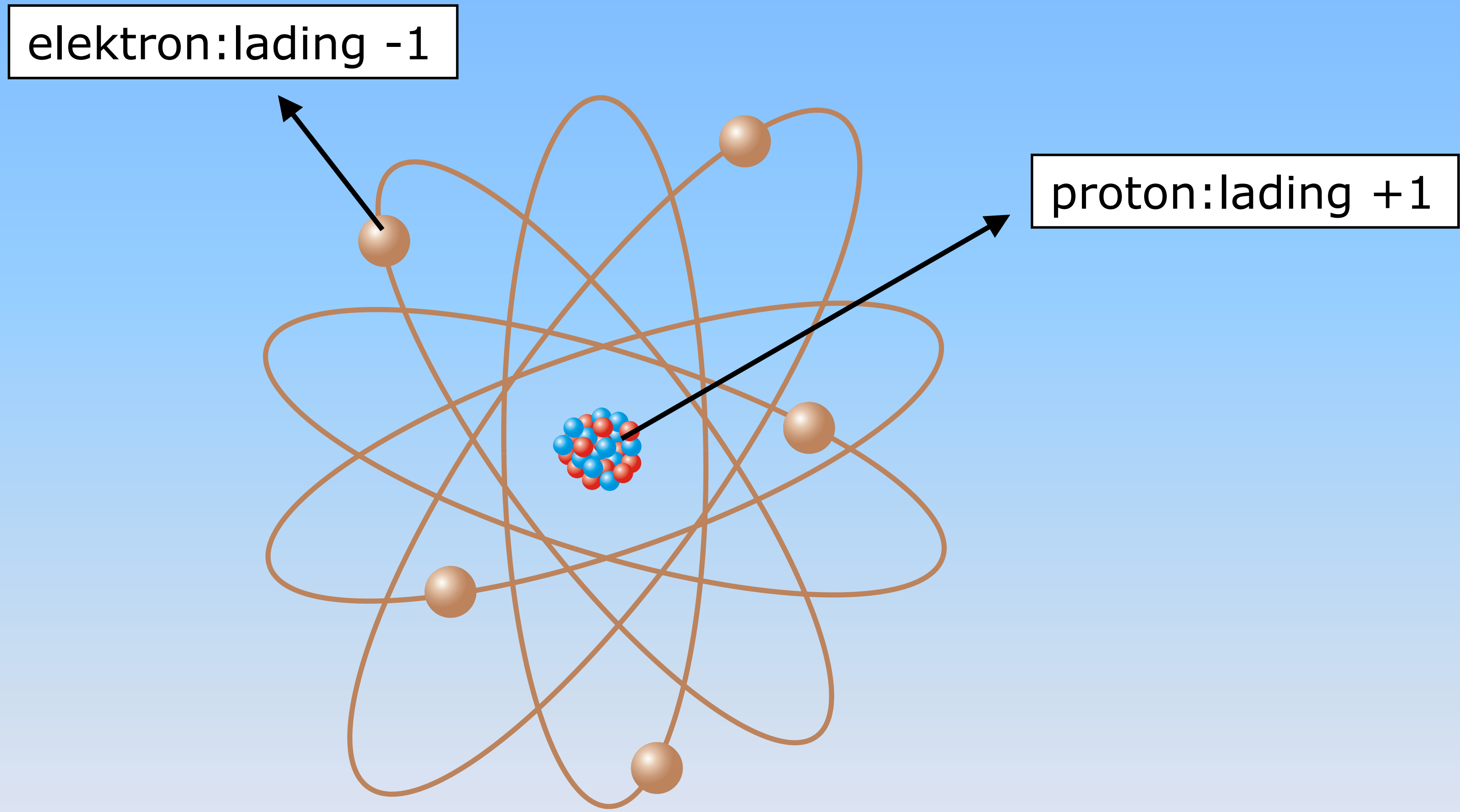




Einstein

Bohr

Wat waren de problemen 100 jaar geleden ?

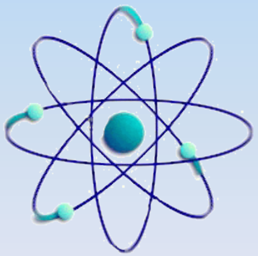


Waarom valt het elektron niet op de kern ?

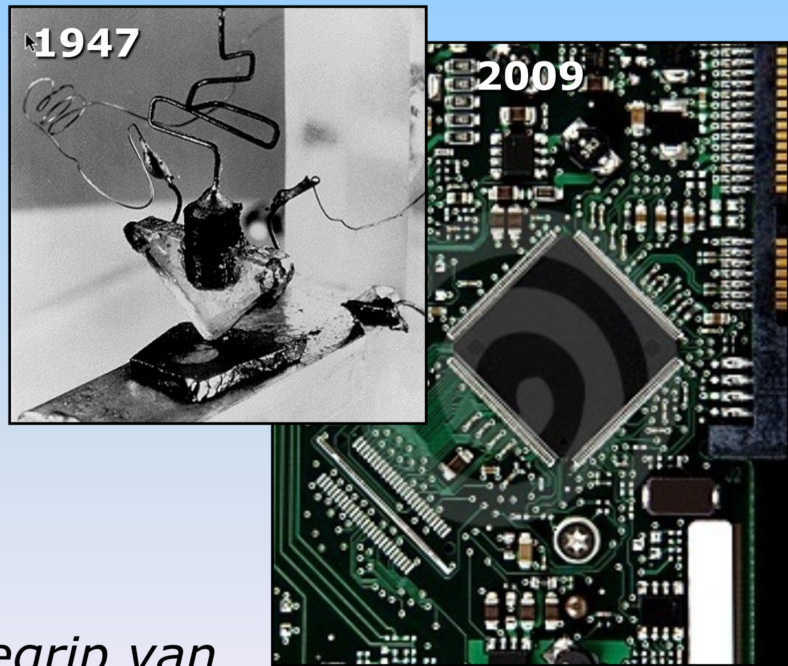
Quantummechanica … nuttig ?

Quantum mechanica ?

Niels Bohr

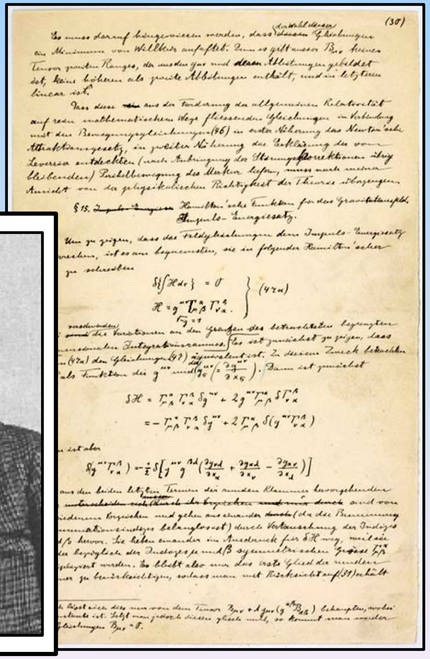


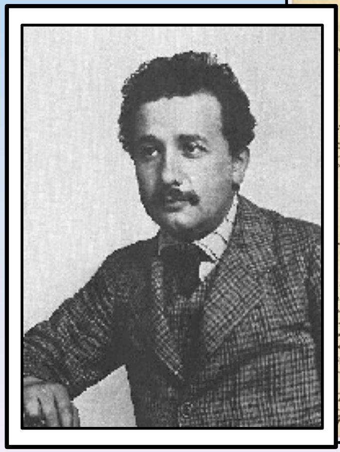
"Quantum mechanica en begrip van atomen cruciaal voor transitors."



Relativiteitstheorie … nuttig ?

Relativiteitstheorie ?





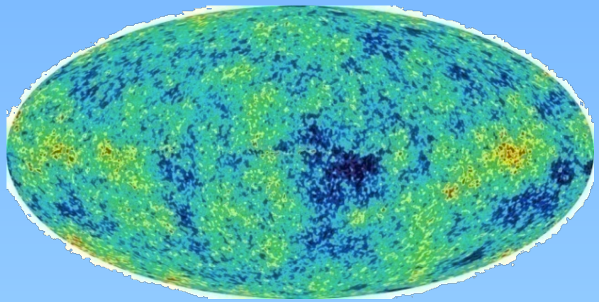
"Zonder relativiteitstheorie zit de GPS er 10 km per dag naast!"

Maan

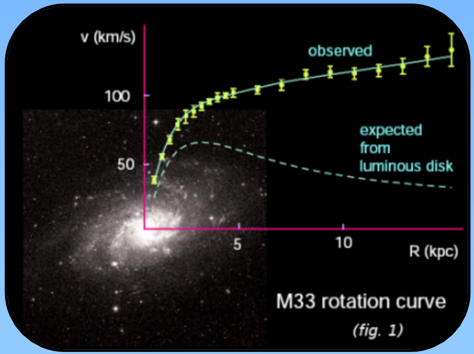
Aarde

Mars

1 *Donkere-materie*



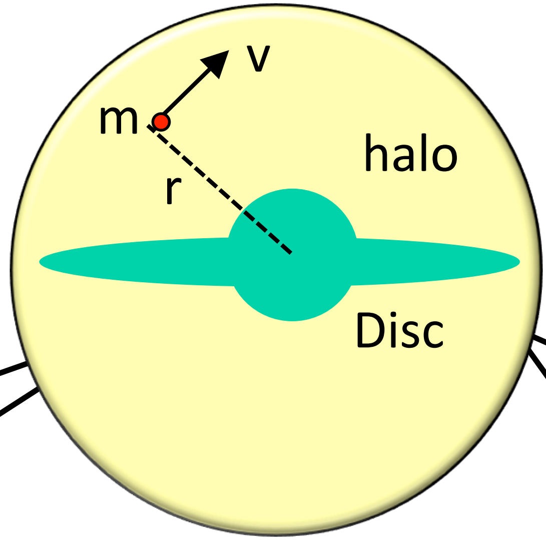
Temperatuurfluctuaties structuur van het heelal

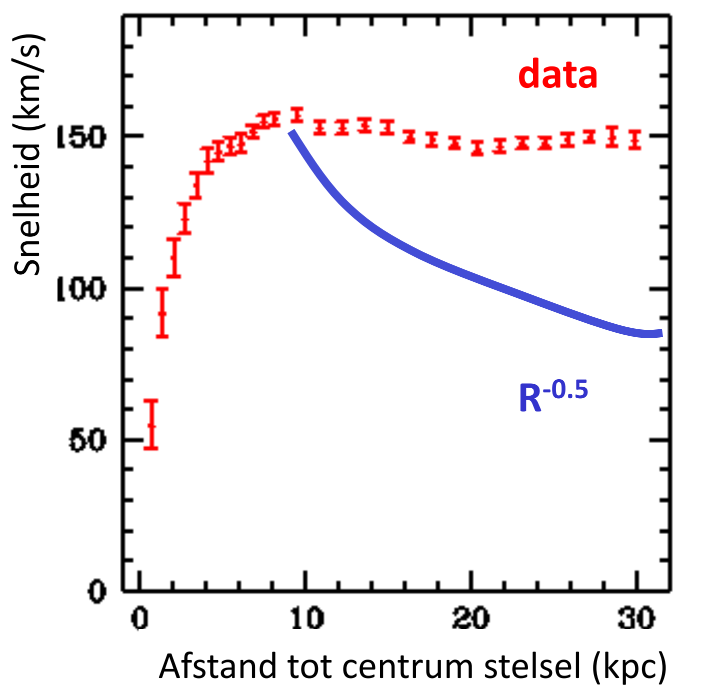


Rotatie-curves

Cluster formaties & gravitationele lens

Er is meer materie dan we kunnen zien





Gravitatie vs centrifugale kracht:

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

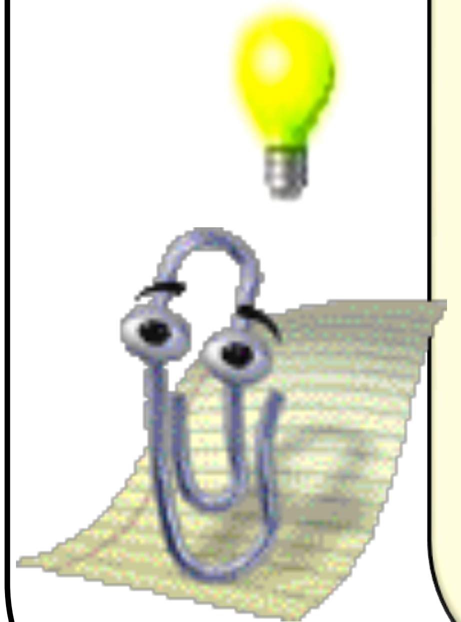
$$v = \sqrt{\frac{GM(R)}{R}}$$

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

De Atlas detector bestaat echt


Gazelle

… computing … ook geen eitje



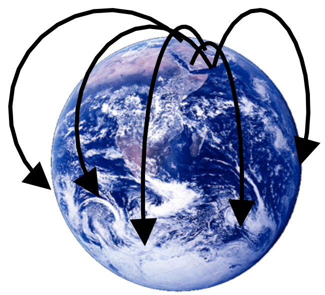
Wist je dat je maar 200 botsingen per seconde op kan slaan ?

… 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

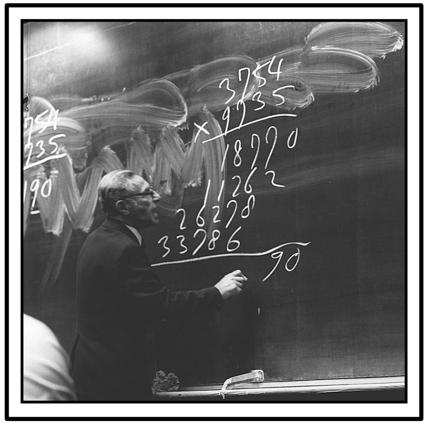
YES NO Cancel

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



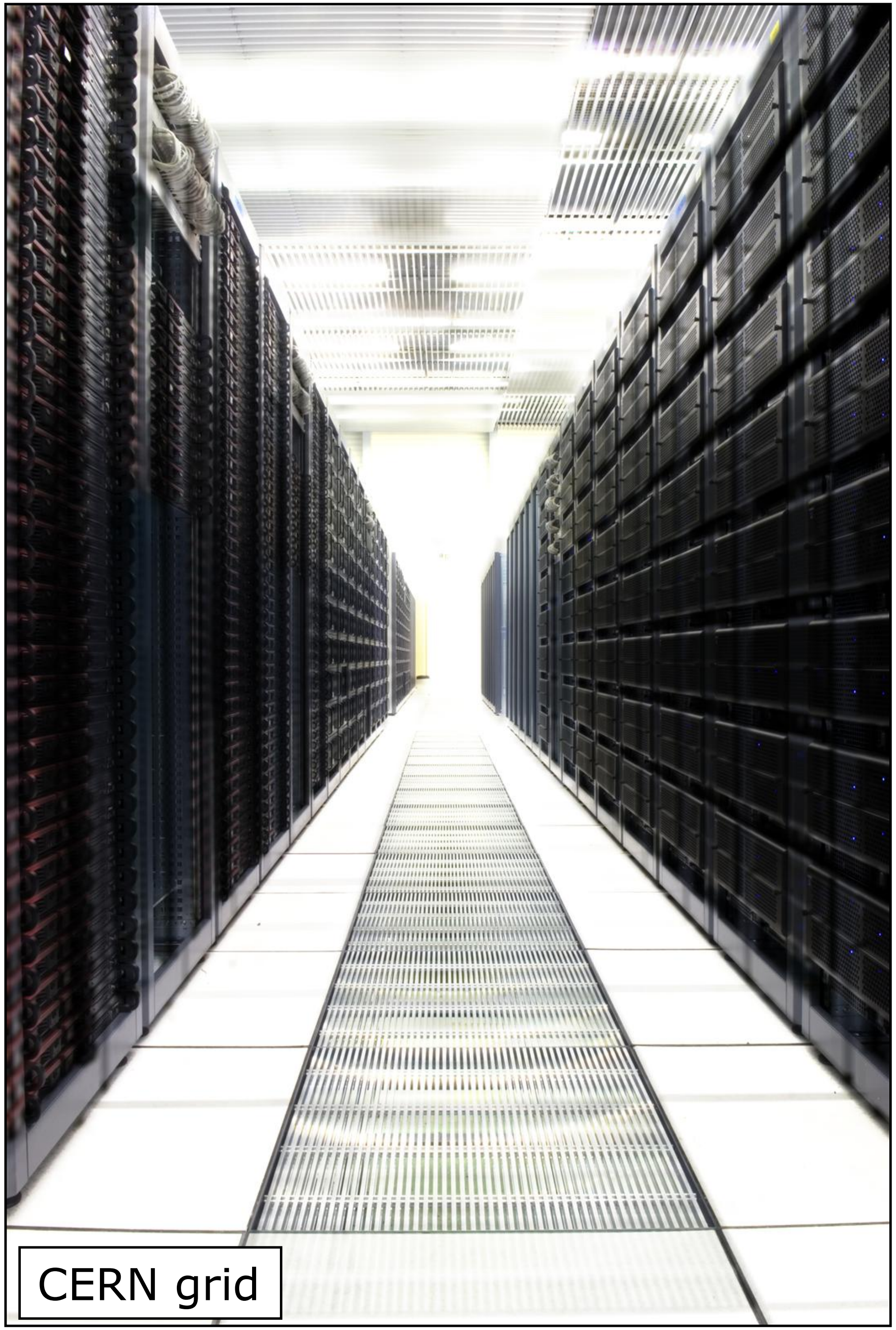
ATLAS: 40 miljoen botsingen/sec
→ 200 Hz op tape

'gewoon' 3000 PC's



CERN's eerste computer

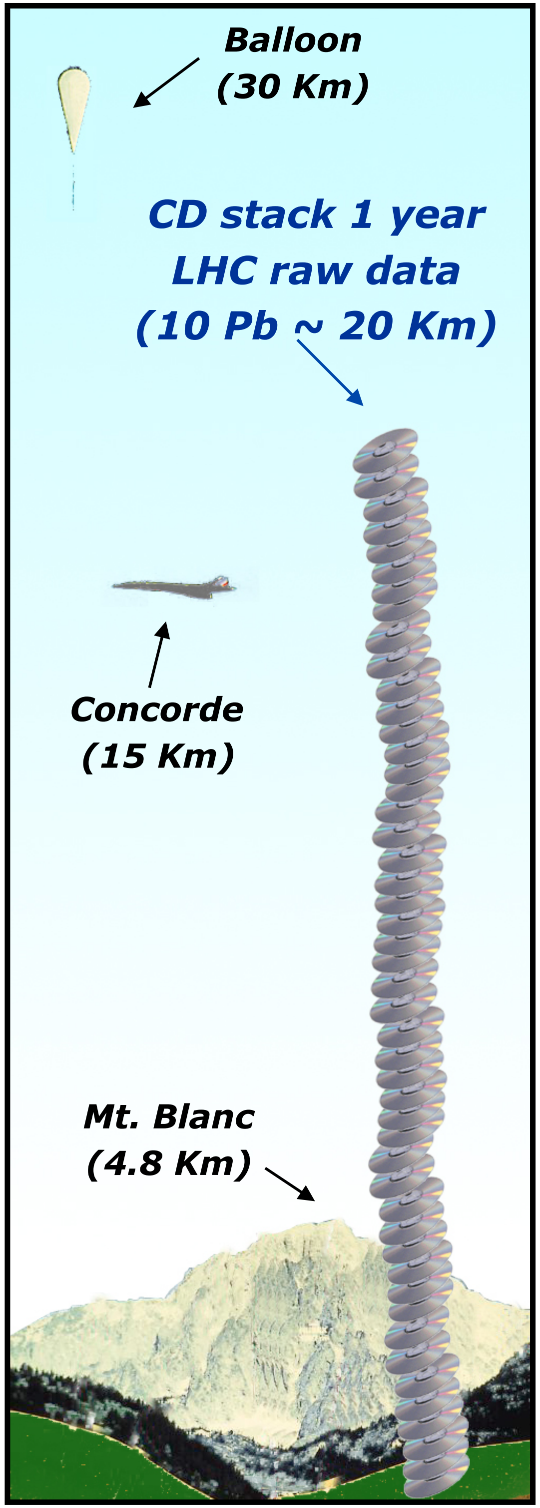
Wim Klein



CERN grid

Data-storage:

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


Balloon
(30 Km)
CD stack 1 year
LHC raw data
(10 Pb ~ 20 Km)
Concorde
(15 Km)
Mt. Blanc
(4.8 Km)