

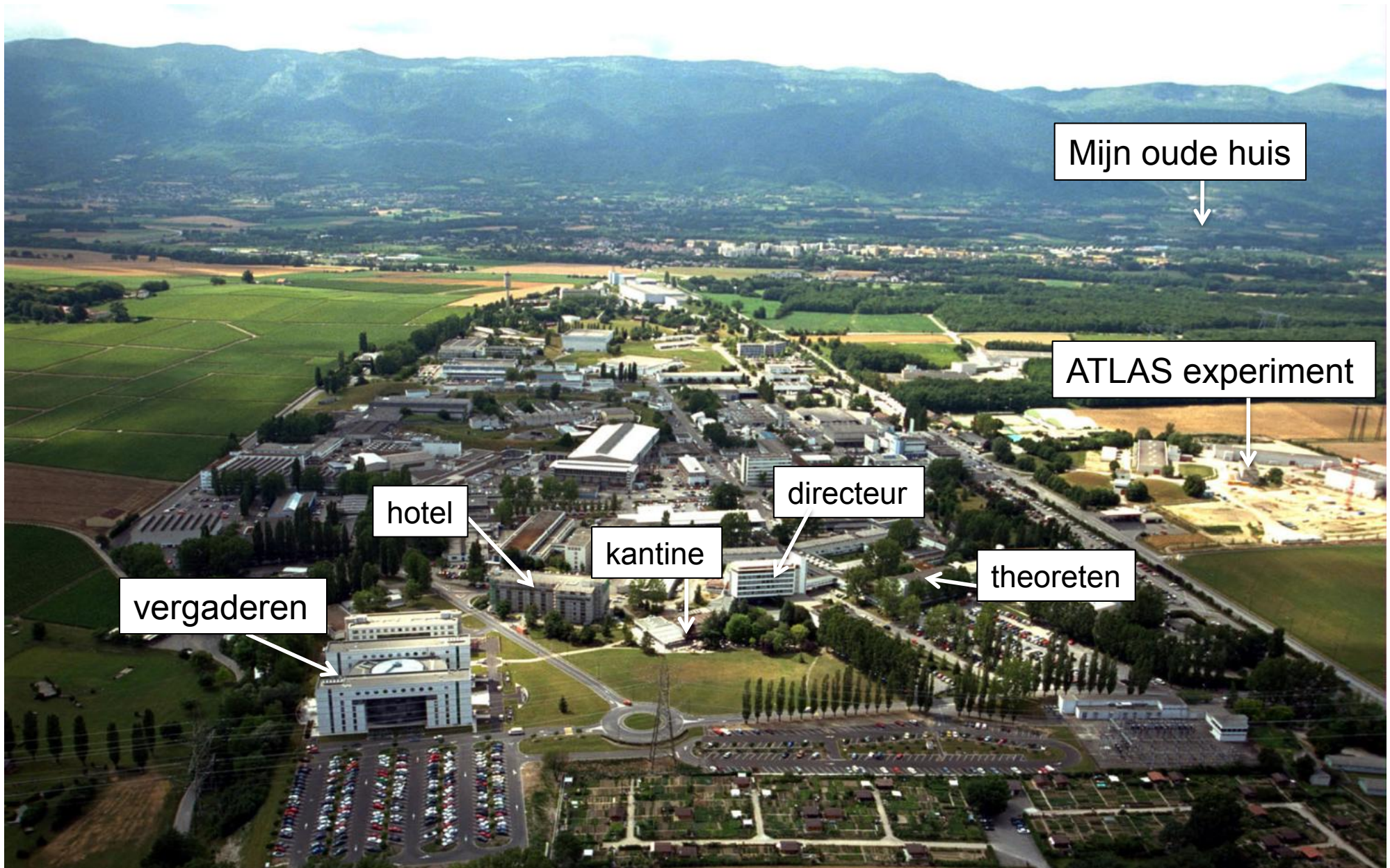
Zoektocht naar de elementaire bouwstenen van de natuur



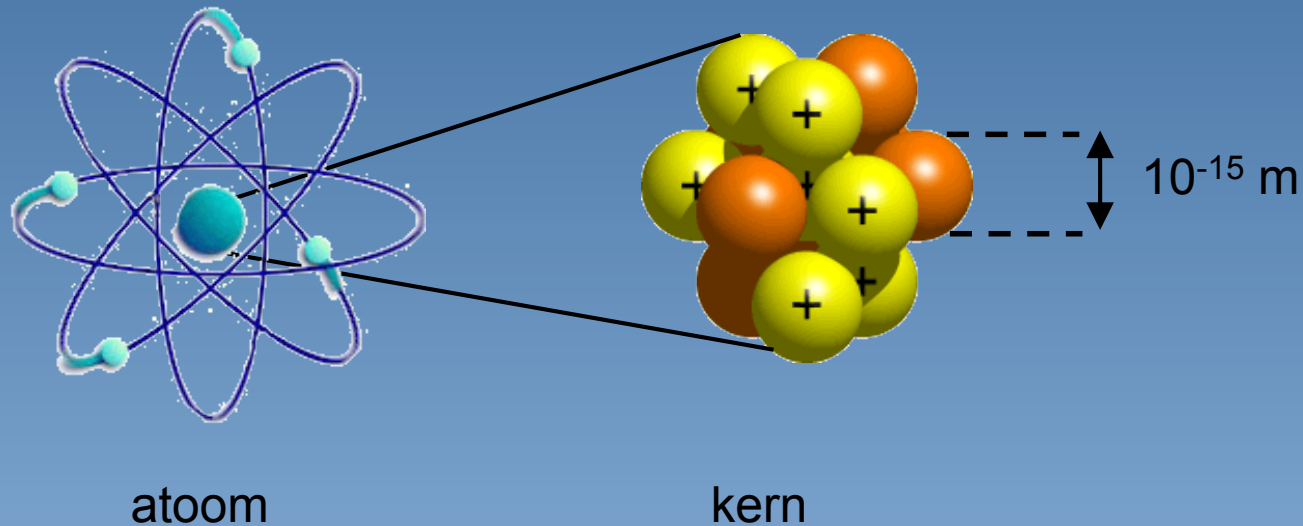
104^e NNGC congres, Leiden, 27 oktober 2012

Ivo van Vulpen

CERN in Genève, Zwitserland

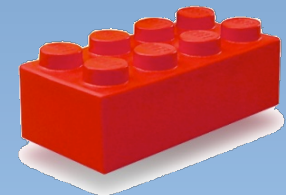


Deeltjesfysica

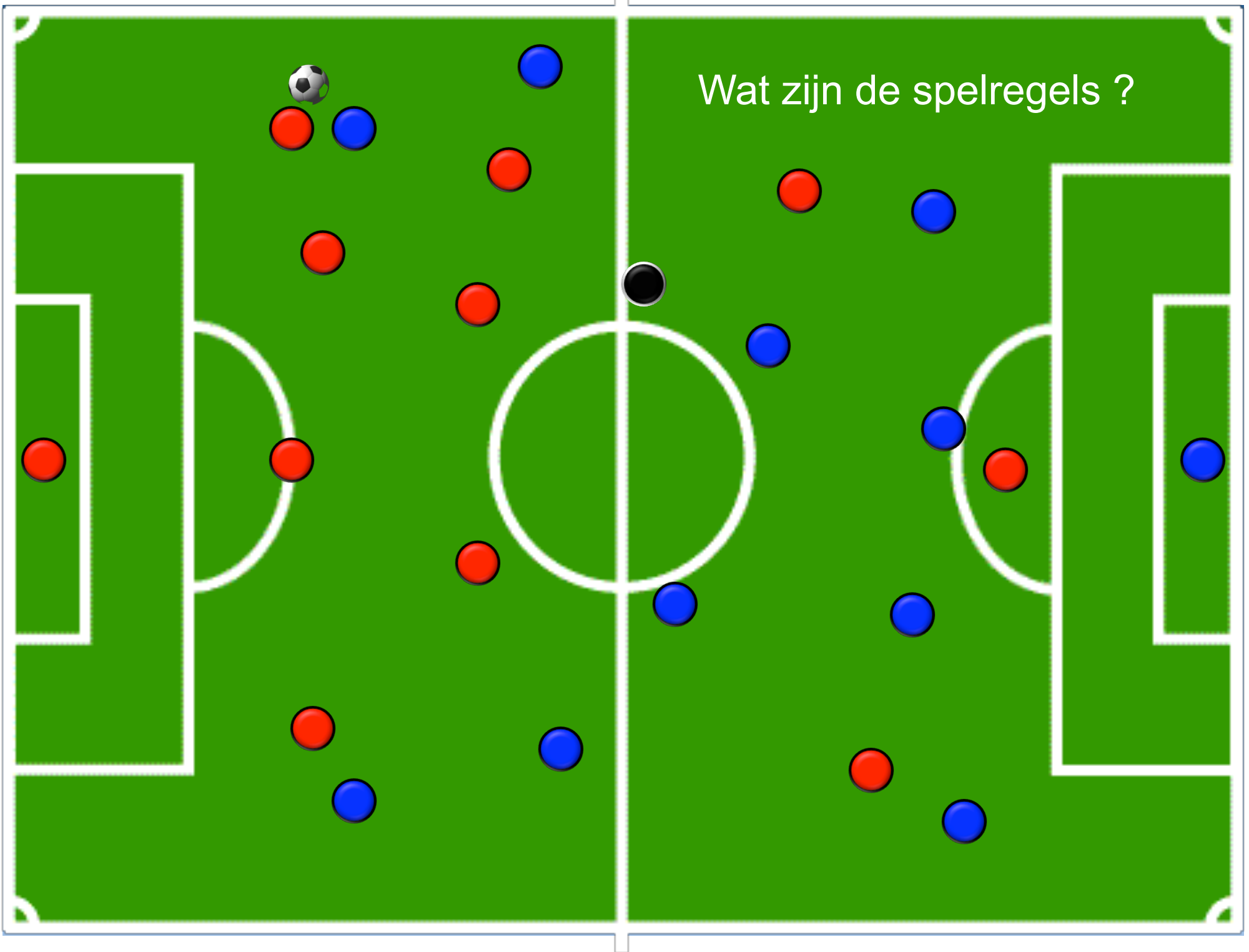


Wat zijn de bouwstenen van de dingen om ons heen ?

Welke krachten beschrijven hun interacties ?



Wat zijn de spelregels ?



Van *wat* naar *hoe*

oogkleur ouders en kind

papa		mama	=	kans op oogkleur baby		
	+		=	 75%	 18.75%	 6.25%
	+		=	 50%	 37.5%	 12.5%
	+		=	 50%	 0%	 50%
	+		=	 <1%	 75%	 25%
	+		=	 0%	 50%	 50%
	+		=	 0%	 1%	 99%

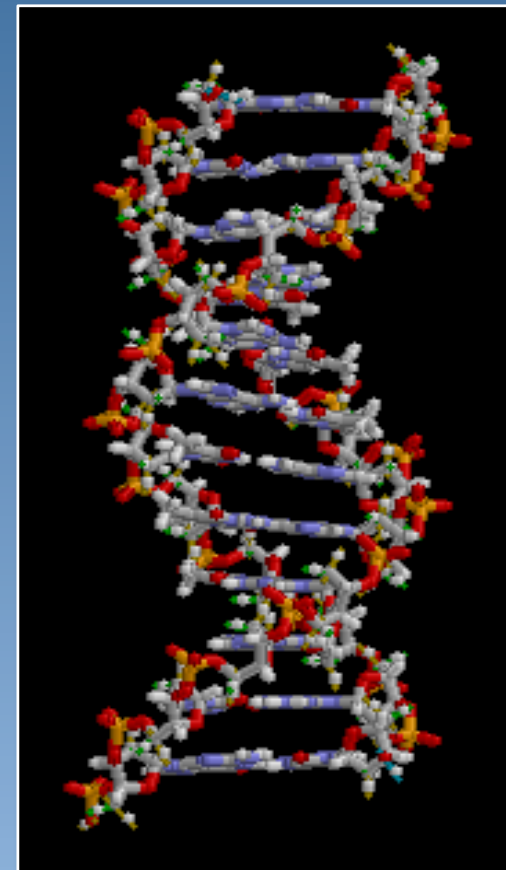


+



=

?



DNA: GTCA-nucleotiden

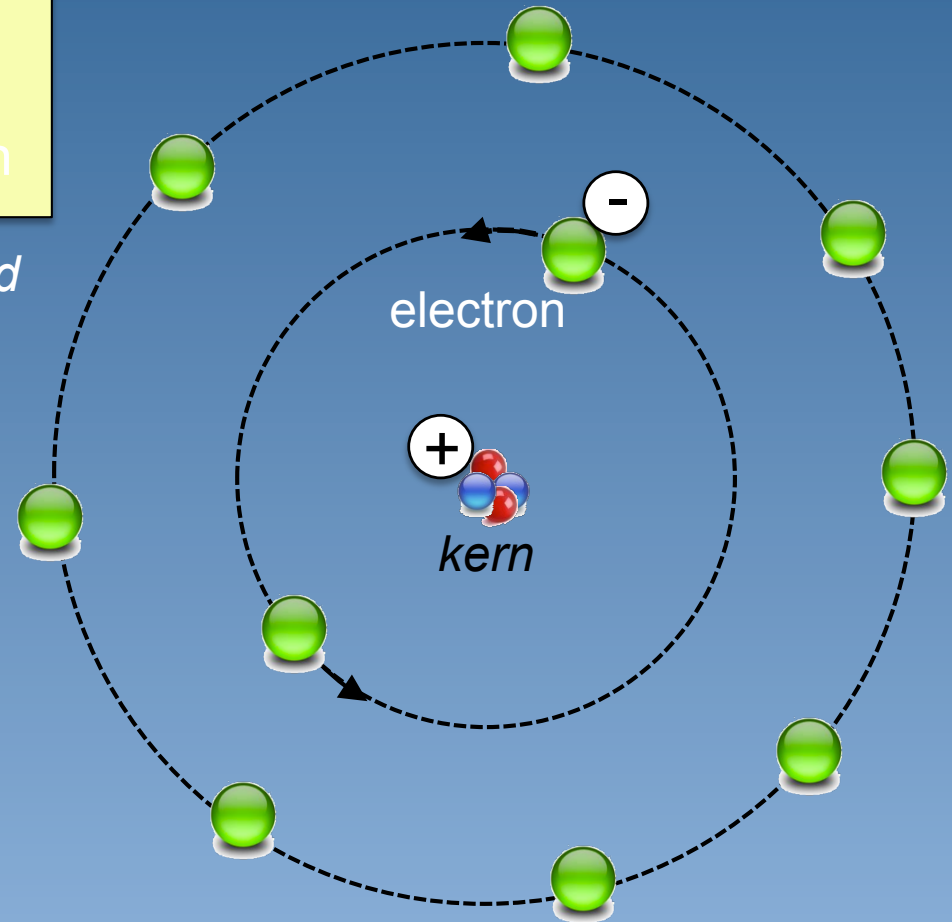
De atoomwereld

1) Het electron valt niet op de kern

→ **Quantummechanica**

... en bracht vele nieuwe inzichten

Niels Bohr poneert extra wetmatigheid

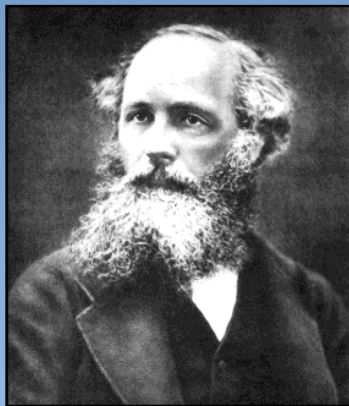


Zwaartekracht en Electromagnetisme

“zelfde krachten ... nieuwe modellen”



Newton



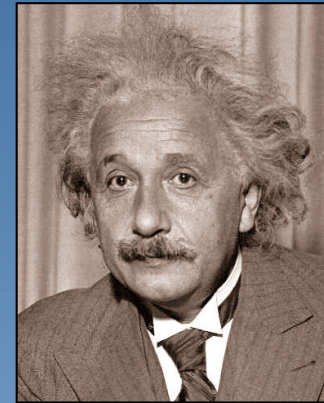
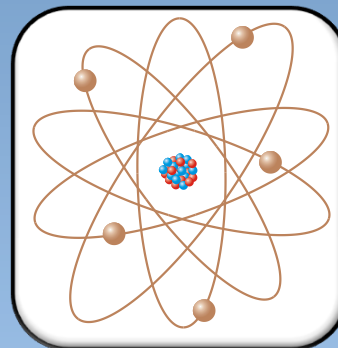
Maxwell



Relativiteitstheorie



Quantummechanica



Einstein



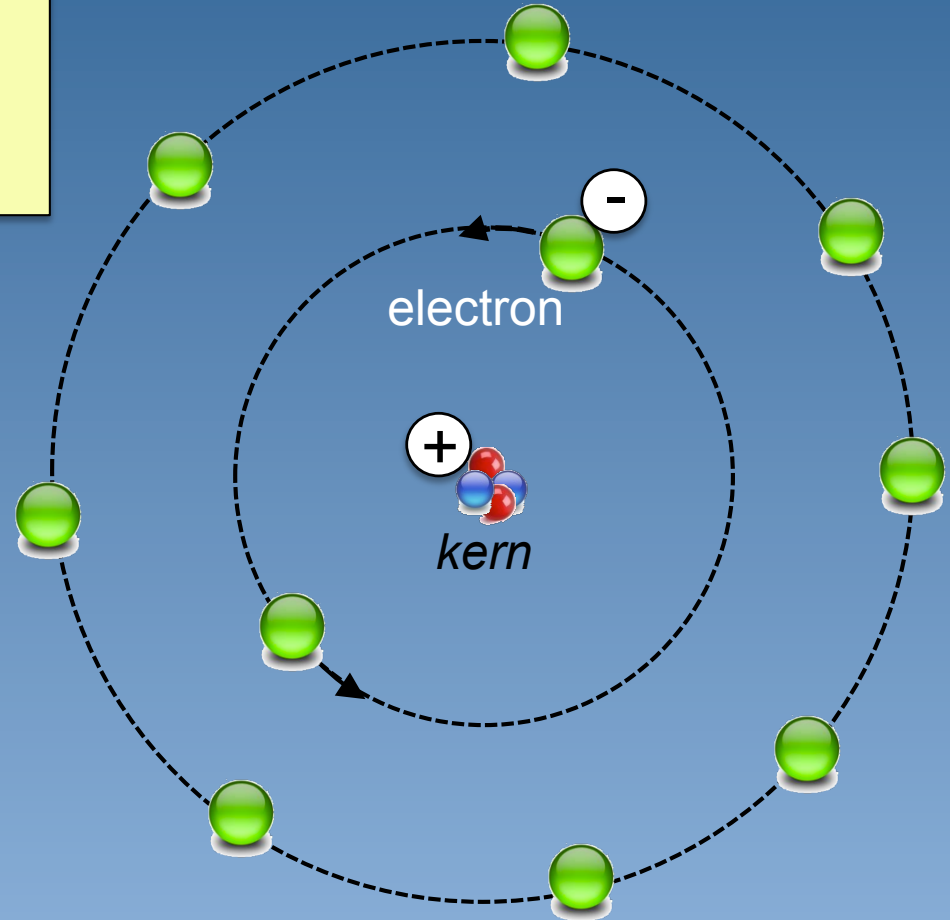
Bohr

De atoomwereld

1) Het electron valt niet op de kern
→ **Quantummechanica**

2) De kerndeeltjes kleven aan elkaar
→ **Zwakke en sterke kernkracht**

3) Dubbel aantal electronen per baan
→ **Nieuwe eigenschappen: spin**



De stand van zaken op 27 oktober 2012



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

De elementaire deeltjes



up

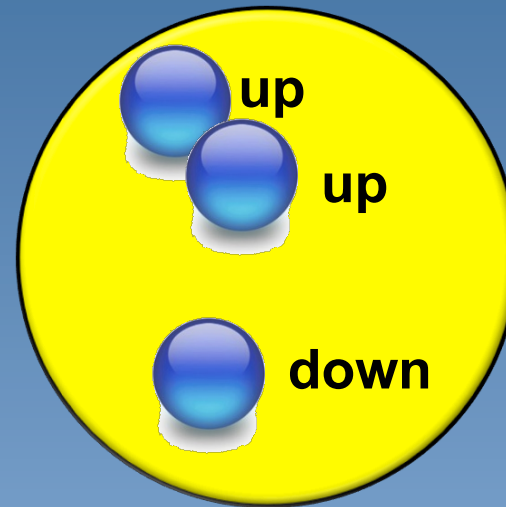


down

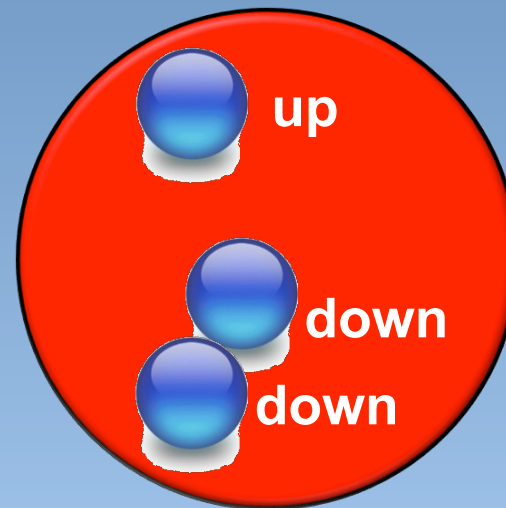


elektron

+ 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!



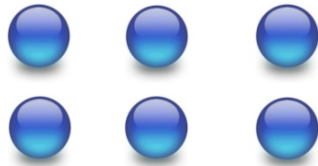
Alles wat we nodig hebben !



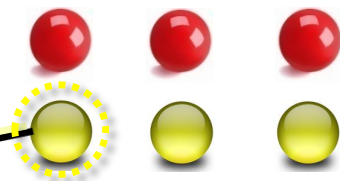
Jos Engelen

Deeltjes

Quarks



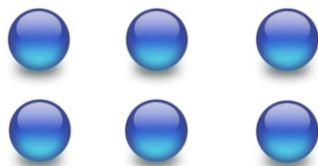
Leptonen



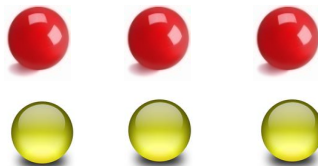
neutrino

Anti-deeltjes

Anti-
Quarks



Anti-
Leptonen



Krachten

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

Abstractie in de wetenschap

Standaard Model Lagrangiaan

$$SU(2)_L \otimes U(1)_Y \otimes SU(3)_C$$

$$\begin{aligned} & -\frac{1}{2}\partial_\nu g_\mu^a \partial_\nu g_\mu^a - g_s f^{abc} \partial_\mu g_\nu^a g_\mu^b g_\nu^c - \frac{1}{4}g_s^2 f^{abc} f^{ade} g_\mu^b g_\nu^c g_\mu^d g_\nu^e + \frac{1}{2}ig_s^2 (\bar{q}_i^\alpha \gamma^\mu q_j^\alpha) g_\mu^a + \\ & G^a \partial^2 G^a + g_s f^{abc} \partial_\mu G^a G^b g_\mu^c - \partial_\mu W_\mu^+ \partial_\nu W_\mu^- - M^2 W_\mu^+ W_\mu^- - \frac{1}{2}\partial_\nu Z_\mu^0 \partial_\nu Z_\mu^0 - \frac{1}{2}M^2 Z_\mu^0 Z_\mu^0 - \\ & \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2}\partial_\mu H \partial_\mu H - \frac{1}{2}m_H^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2 \phi^+ \phi^- - \frac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \\ & \frac{1}{2c_w} M \phi^0 \phi^0 - \beta_h [\frac{2M^2}{g^2} + \frac{2M}{g} H + \frac{1}{2}(H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-)] + \frac{2M^4}{g^2} \alpha_h - ig_{cw} [\partial_\nu Z_\mu^0 (W_\mu^+ W_\nu^- - \\ & W_\mu^- W_\nu^+) - Z_\nu^0 (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + Z_\mu^0 (W_\nu^+ \partial_\nu W_\mu^- - W_\nu^- \partial_\nu W_\mu^+) - ig_{sw} [\partial_\nu A_\mu (W_\mu^+ W_\nu^- - \\ & W_\mu^- W_\nu^+) - A_\nu (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + A_\mu (W_\nu^+ \partial_\nu W_\mu^- - W_\nu^- \partial_\nu W_\mu^+)] - \frac{1}{2}g^2 W_\mu^+ W_\mu^- W_\nu^+ W_\nu^- + \\ & \frac{1}{2}g^2 W_\mu^+ W_\nu^- W_\mu^- W_\nu^+ + g^2 c_w^2 (Z_\mu^0 W_\nu^+ Z_\mu^0 W_\nu^- - Z_\mu^0 W_\nu^+ Z_\mu^0 W_\nu^-) + g^2 s_w^2 (A_\mu W_\nu^+ A_\mu W_\nu^- - \\ & A_\mu A_\nu W_\nu^+ W_\nu^-) + g^2 s_w c_w [A_\mu Z_\mu^0 (W_\nu^+ W_\nu^- - W_\nu^- W_\nu^+) - 2A_\mu Z_\mu^0 W_\nu^+ W_\nu^-] - g\alpha [H^3 + \\ & H \phi^0 \phi^0 + 2H \phi^+ \phi^-] - \frac{1}{8}g^2 \alpha_h [H^4 + (\phi^0)^4 + 4(\phi^+ \phi^-)^2 + 4(\phi^0)^2 \phi^+ \phi^- + 4H^2 \phi^+ \phi^- + \\ & 2(\phi^0)^2 H^2] - g M W_\mu^+ W_\mu^- H - \frac{1}{2}g \frac{M}{c_w} Z_\mu^0 Z_\mu^0 H - \frac{1}{2}ig [W_\mu^+ (\phi^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) - W_\mu^- (\phi^0 \partial_\mu \phi^+ - \\ & \phi^+ \partial_\mu \phi^0)] + \frac{1}{2}g [W_\mu^+ (H \partial_\mu \phi^- - \phi^- \partial_\mu H) - W_\mu^- (H \partial_\mu \phi^+ - \phi^+ \partial_\mu H)] + \frac{1}{2}g \frac{1}{c_w} (Z_\mu^0 (H \partial_\mu \phi^0 - \\ & \phi^0 \partial_\mu H) - ig \frac{s_w}{c_w} M Z_\mu^0 (W_\mu^+ \phi^- - W_\mu^- \phi^+) + ig_{sw} M A_\mu (W_\mu^+ \phi^- - W_\mu^- \phi^+) - ig \frac{1-2c_w^2}{2c_w} Z_\mu^0 (\phi^+ \partial_\mu \phi^- - \\ & \phi^- \partial_\mu \phi^+) + ig_{sw} A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \frac{1}{4}g^2 W_\mu^+ W_\mu^- [H^2 + (\phi^0)^2 + 2\phi^+ \phi^-] - \\ & \frac{1}{4}g^2 \frac{1}{c_w} Z_\mu^0 Z_\mu^0 [H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2 \phi^+ \phi^-] - \frac{1}{2}g^2 \frac{s_w^2}{c_w} Z_\mu^0 \phi^0 (W_\mu^+ \phi^- + W_\mu^- \phi^+) - \\ & \frac{1}{2}ig^2 \frac{s_w^2}{c_w} Z_\mu^0 H (W_\mu^+ \phi^- - W_\mu^- \phi^+) + \frac{1}{2}g^2 s_w A_\mu \phi^0 (W_\mu^+ \phi^- + W_\mu^- \phi^+) + \frac{1}{2}ig^2 s_w A_\mu H (W_\mu^+ \phi^- - \\ & W_\mu^- \phi^+) - g^2 \frac{s_w}{c_w} (2c_w^2 - 1) Z_\mu^0 A_\mu \phi^+ \phi^- - g^1 s_w^2 A_\mu A_\mu \phi^+ \phi^- - e^\lambda (\gamma \partial + m_d^\lambda) e^\lambda - \\ & \bar{\nu}^\lambda \gamma \partial \nu^\lambda - \bar{u}_j^\lambda (\gamma \partial + m_u^\lambda) u_j^\lambda - \bar{d}_j^\lambda (\gamma \partial + m_d^\lambda) d_j^\lambda + ig_{sw} A_\mu [-(e^\lambda \gamma^\mu e^\lambda) + \frac{2}{3}(\bar{u}_j^\lambda \gamma^\mu u_j^\lambda) - \\ & \frac{1}{3}(\bar{d}_j^\lambda \gamma^\mu d_j^\lambda)] + \frac{ig}{4c_w} Z_\mu^0 [(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (e^\lambda \gamma^\mu (4s_w^2 - 1 - \gamma^5) e^\lambda) + (\bar{u}_j^\lambda \gamma^\mu (\frac{4}{3}s_w^2 - \\ & 1 - \gamma^5) u_j^\lambda) + (\bar{d}_j^\lambda \gamma^\mu (1 - \frac{8}{3}s_w^2 - \gamma^5) d_j^\lambda)] + \frac{ig}{2\sqrt{2}} W_\mu^+ [(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) e^\lambda) + (\bar{u}_j^\lambda \gamma^\mu (1 + \\ & \gamma^5) C_{\lambda\kappa} d_j^\kappa)] + \frac{ig}{2\sqrt{2}} W_\mu^- [(\bar{e}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{d}_j^\kappa C_{\lambda\kappa}^\dagger \gamma^\mu (1 + \gamma^5) u_j^\lambda)] + \frac{ig}{2\sqrt{2}} \frac{m_\lambda^2}{M} [-\phi^+ (\bar{\nu}^\lambda (1 - \\ & \gamma^5) e^\lambda) + \phi^- (\bar{e}^\lambda (1 + \gamma^5) \nu^\lambda)] - \frac{g}{2} \frac{m_\lambda^2}{M} [H (\bar{e}^\lambda e^\lambda) + i\phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda)] + \frac{ig}{2M\sqrt{2}} \phi^+ [-m_\lambda^2 (\bar{u}_j^\lambda C_{\lambda\kappa} (1 - \\ & \gamma^5) d_j^\kappa) + m_\lambda^2 (\bar{u}_j^\lambda C_{\lambda\kappa} (1 + \gamma^5) d_j^\kappa) + \frac{ig}{2M\sqrt{2}} \phi^- [m_\lambda^2 (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 + \gamma^5) u_j^\kappa) - m_\lambda^2 (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 - \\ & \gamma^5) u_j^\kappa) - \frac{g}{2} \frac{m_\lambda^2}{M} H (\bar{u}_j^\lambda u_j^\lambda) - \frac{g}{2} \frac{m_\lambda^2}{M} H (\bar{d}_j^\lambda d_j^\lambda) + \frac{ig}{2} \frac{m_\lambda^2}{M} \phi^0 (\bar{u}_j^\lambda \gamma^5 u_j^\lambda) - \frac{ig}{2} \frac{m_\lambda^2}{M} \phi^0 (\bar{d}_j^\lambda \gamma^5 d_j^\lambda) + \\ & \bar{X}^+ (\partial^2 - M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \frac{M^2}{c_w^2}) X^0 + \bar{Y} \partial^2 Y + ig_{cw} W_\mu^+ (\partial_\mu \bar{X}^0 X^- - \\ & \partial_\mu \bar{X}^+ X^0) + ig_{sw} W_\mu^+ (\partial_\mu \bar{Y} X^- - \partial_\mu \bar{X}^+ Y) + ig_{cw} W_\mu^- (\partial_\mu \bar{X}^- X^0 - \partial_\mu \bar{X}^0 X^+) + \\ & ig_{sw} W_\mu^- (\partial_\mu \bar{X}^- Y - \partial_\mu \bar{Y} X^+) + ig_{cw} Z_\mu^0 (\partial_\mu \bar{X}^+ X^- - \partial_\mu \bar{X}^- X^+) + ig_{sw} A_\mu (\partial_\mu \bar{X}^+ X^- + \\ & \partial_\mu \bar{X}^- X^+) - \frac{1}{2}g M [\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w} \bar{X}^0 X^0 H] + \frac{1-2c_w^2}{2c_w} ig M [\bar{X}^+ X^0 \phi^- + \\ & \bar{X}^- X^0 \phi^+] + \frac{1}{2c_w} ig M [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + ig M s_w [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + \\ & \frac{1}{2}ig M [\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0] \end{aligned}$$

Bladmuziek (J.S. Bach)

bladmuziek



Wat snappen we nog niet:



Paar 'kleine' dingetjes die we hopelijk wel gaan beantwoorden:

1

Hoe krijgen (kracht-)deeltjes massa [Higgs boson]

2

80% materie in heelal onbekend [donkere materie]

3

Waar is alle anti-materie gebleven ?

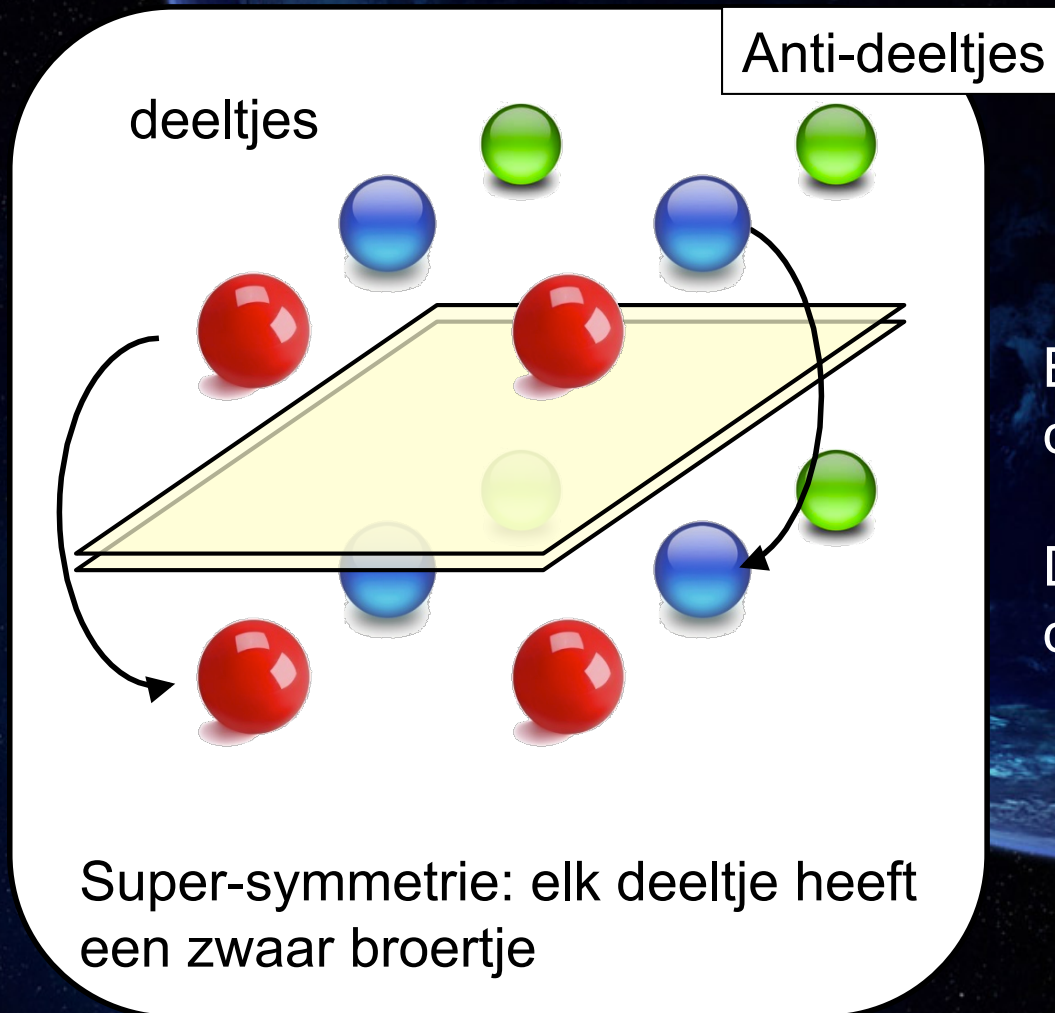
- waarom past gravitatie niet in SM, extra dimensies, waarom 3 families, fermionen fundamentele deeltjes, supersymmetrie, protonen stabiel, quantisatie elektrische lading, exploderende quantumcorrecties, kleine neutrino massa's, string theorie, ...



Het Higgs boson
Stan Bentvelsen

Donkere Materie zelf maken

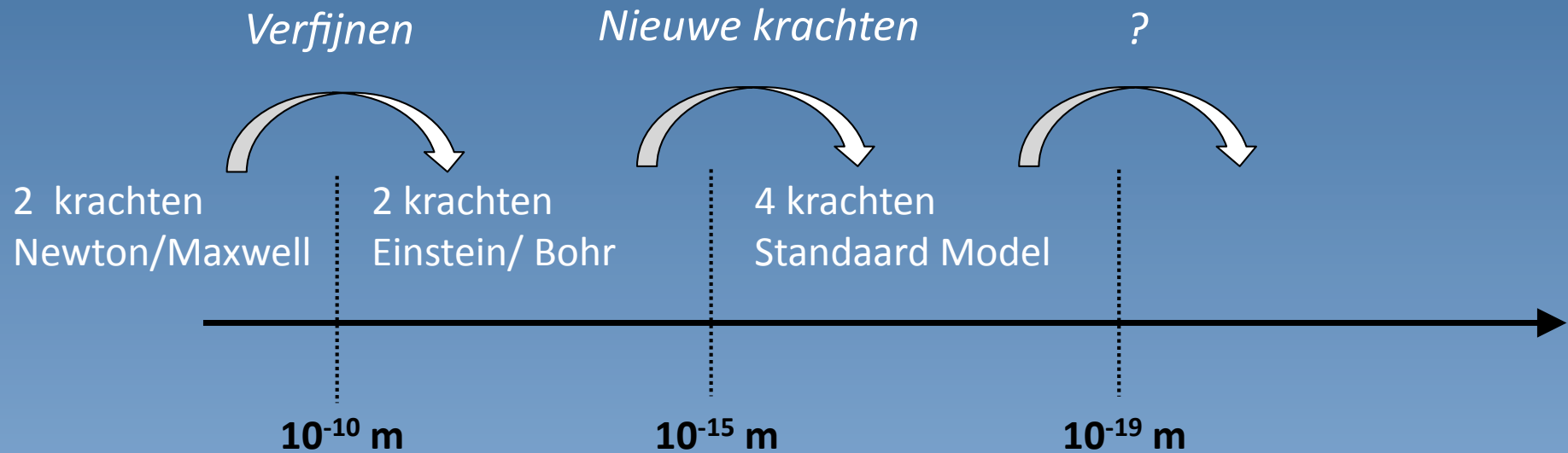
Theoretisch idee: Supersymmetrie:



Bij de LHC kunnen we deze super-deeltjes produceren

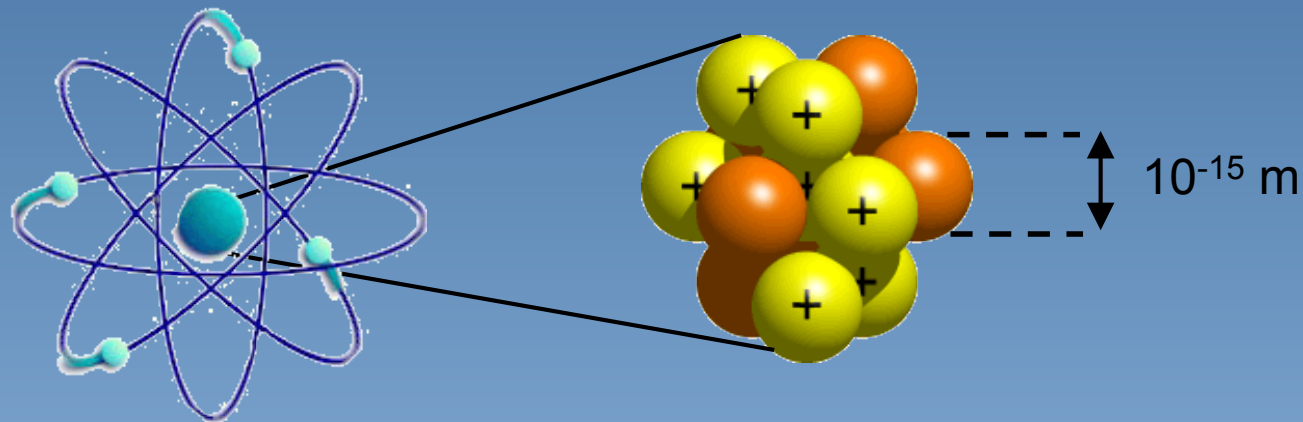
De lichtste is misschien stabiel: donkere materie

Standaard Model slechts een effectieve theorie ?



De Large Hadron Collider: Nieuwe deeltjes, krachten, concepten ? Maar wat ?

Deeltjesfysica



atoom

kern

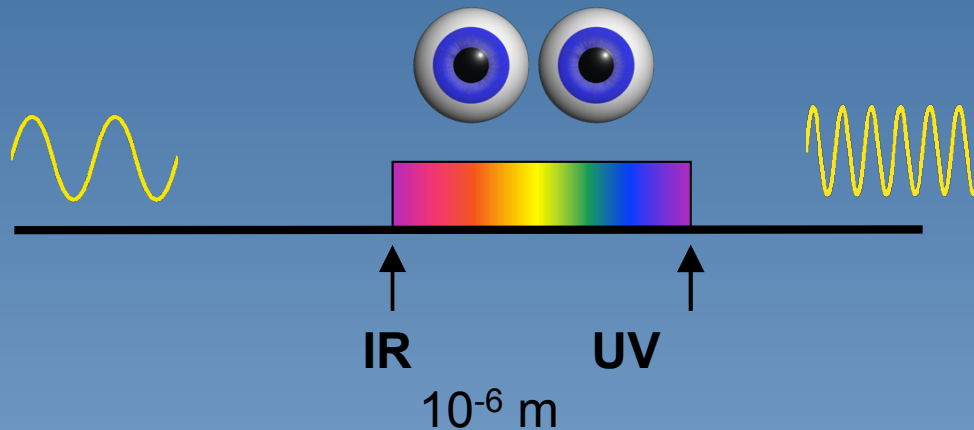
Hoe bekijk je dingen op deze afstanden eigenlijk ?

Kijken zonder je ogen te gebruiken



1] Kijken met licht

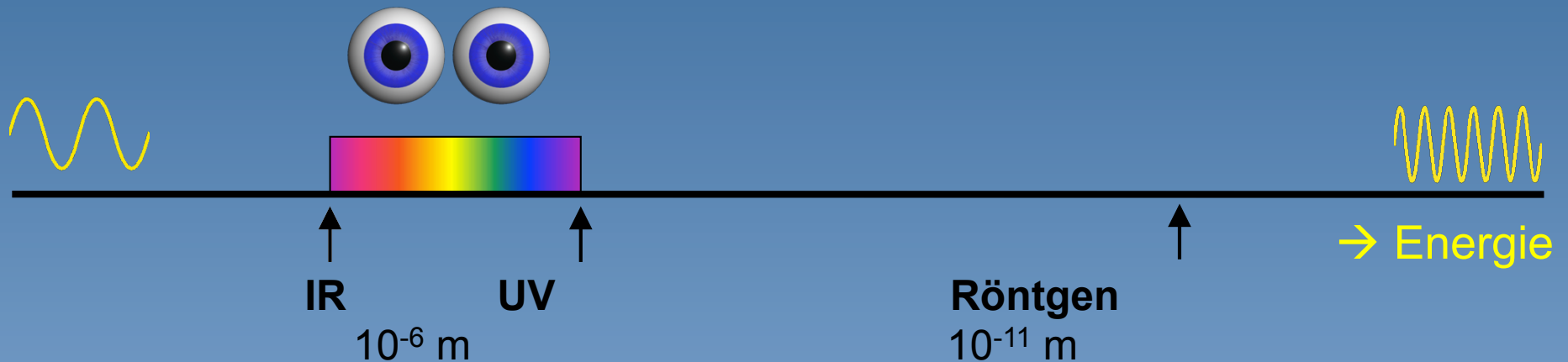
Licht verstrooit aan objecten die groter zijn dan zijn golflengte



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.



2] Kijken met deeltjes

Quantummechanica: deeltjes zijn golven

→ microscoop voor zeer kleine afstanden:

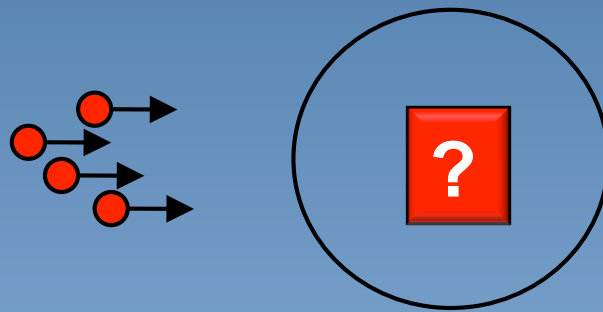
- klein: elektronen microscoop
- kleinst: protonen microscoop

De Broglie:

$$\lambda = \frac{2\pi\hbar}{p} = \frac{2\pi\hbar}{\gamma m v}$$

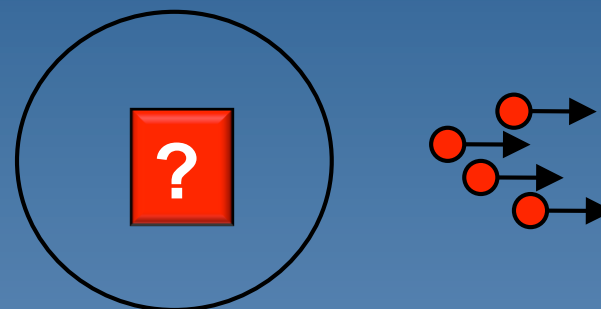
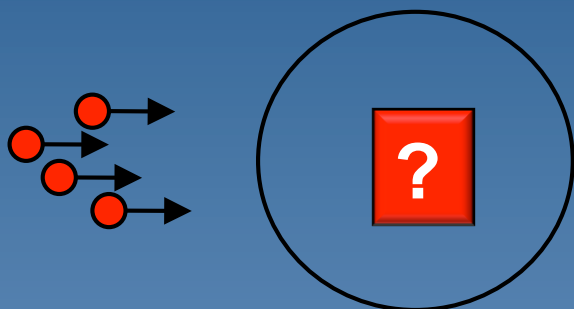
onbekend voorwerp achter een gordijn
... en 100 kogeltjes

bovenaanzicht

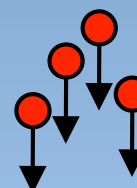
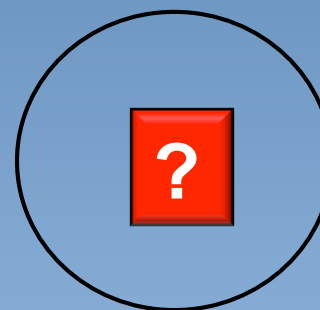
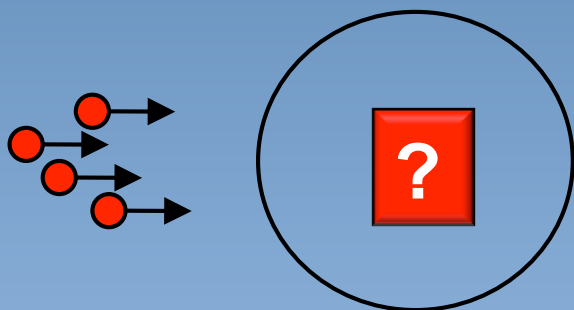


Hoe ketsen de kogels af ?

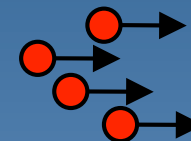
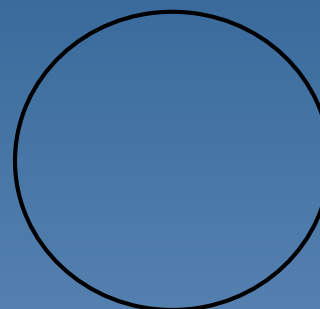
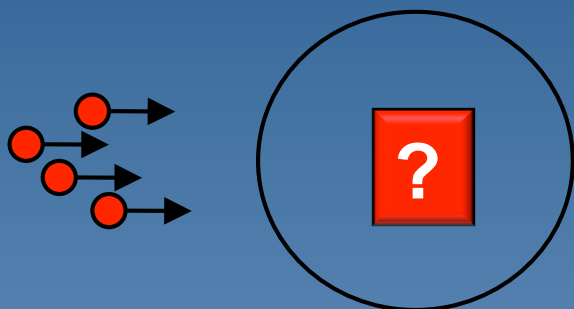
Situatie 1



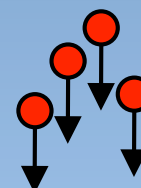
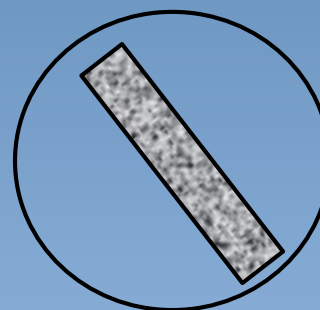
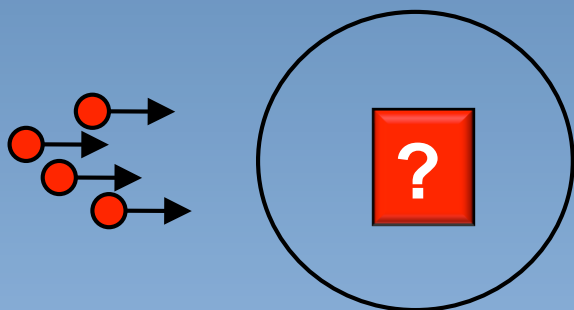
Situatie 2



Situatie 1



Situatie 2



Het zichtbaar maken van (niet-)afgeketste deeltjes

Röntgen foto

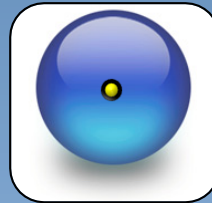


Het atoom: Rutherford scattering



6 MeV alfa deeltje: zeer korte golf

Hypothese:

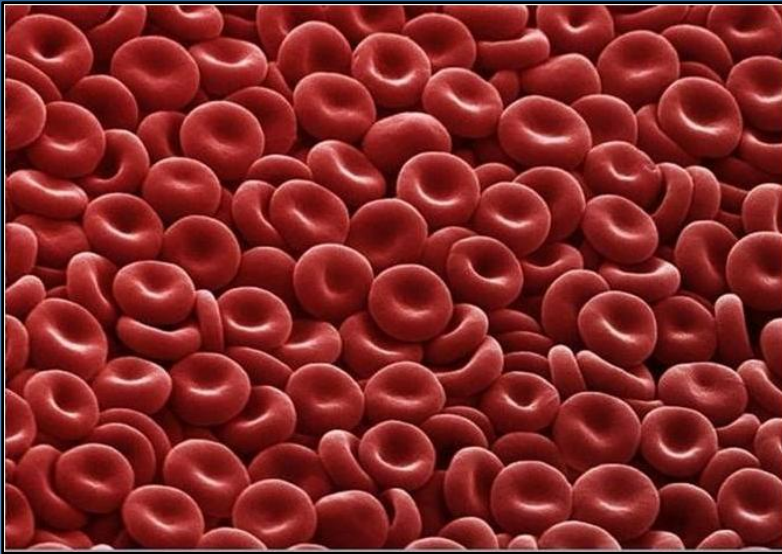


$$V \propto \frac{1}{r}$$

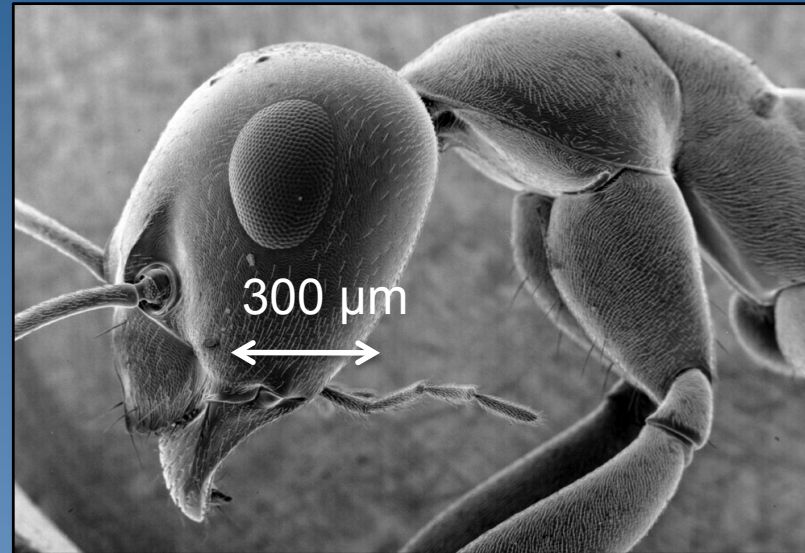
$$\frac{d\sigma}{d\Omega}(\theta) = \left(\frac{ZZ'}{4E} \right)^2 \frac{1}{\sin^4(\theta/2)}$$

dit bleek te kloppen

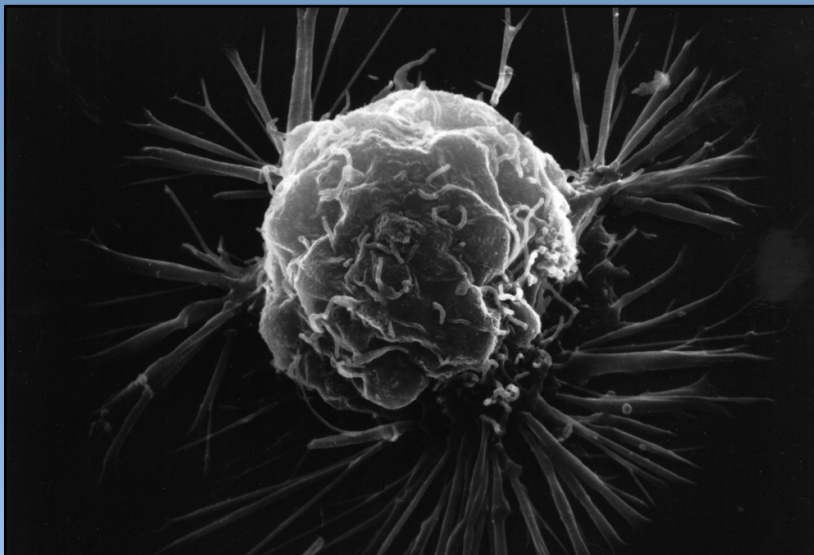
Rode bloedlichaampjes



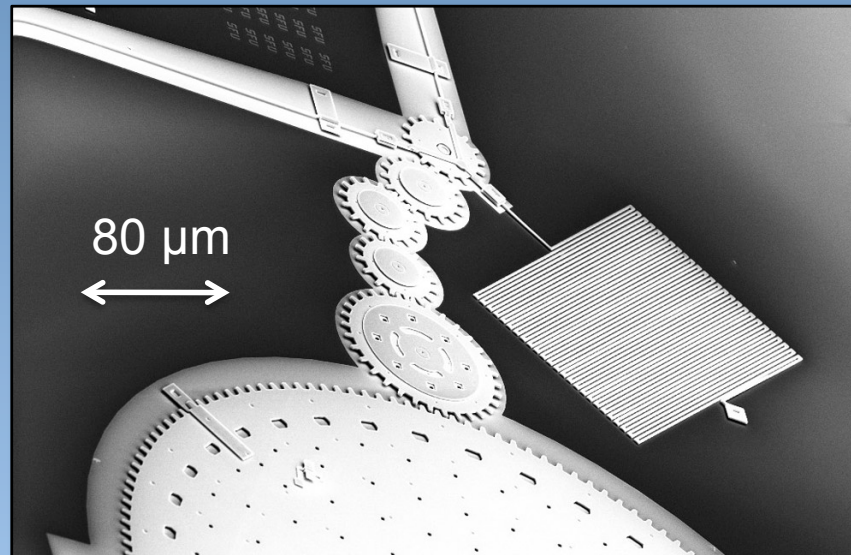
Mier



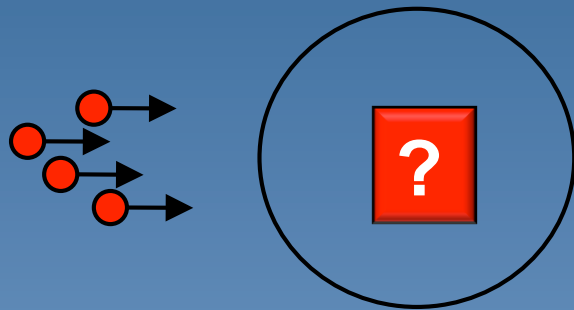
Borstkanker cel



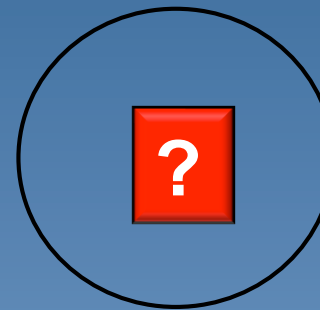
Microelectronisch systeem



Situatie 3



Quantum-model en kernkrachten



*Je kan ook nieuwe
deeltjes maken*

‘Kijken’ naar sub-atomaire structuren:

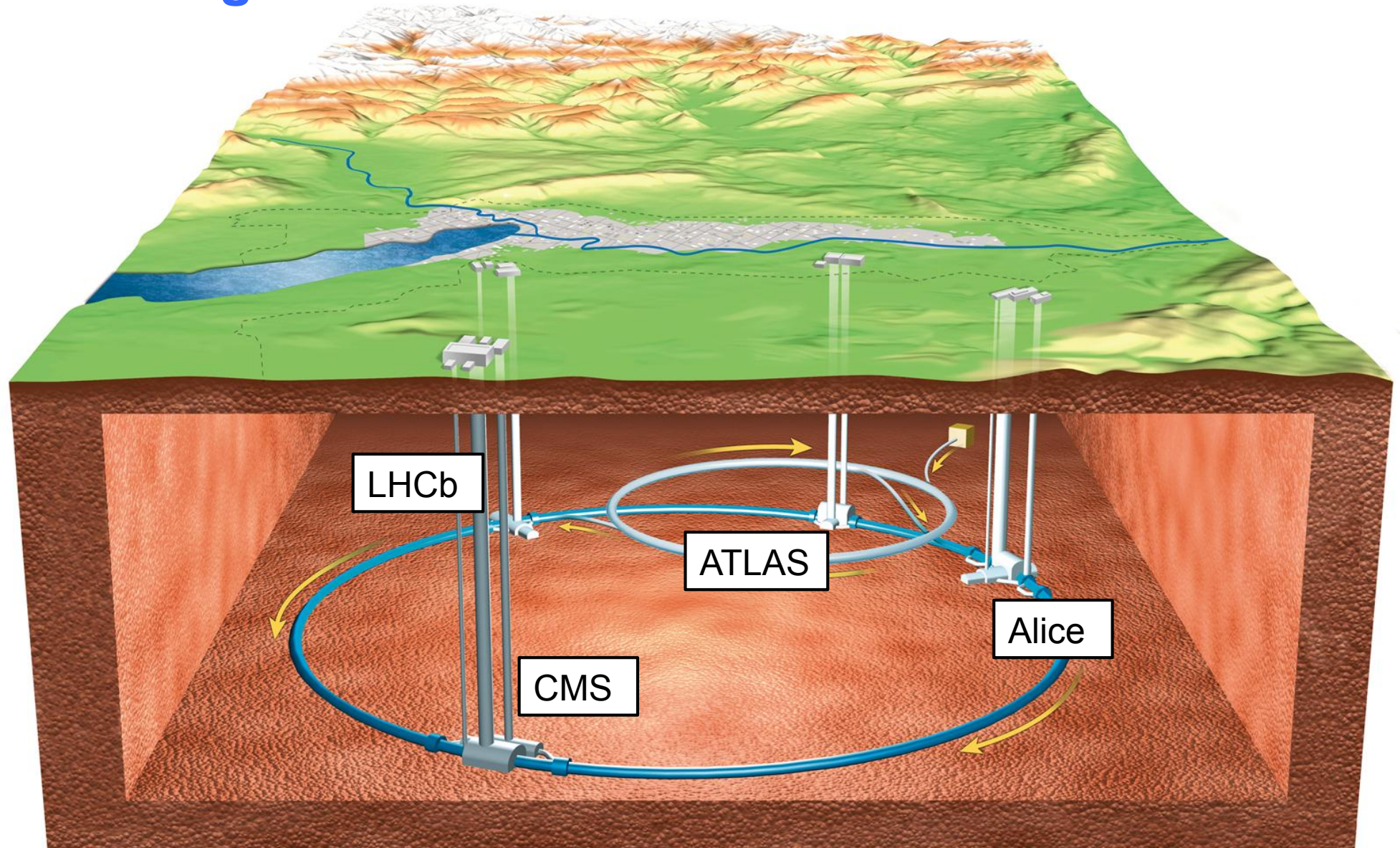
- 1) Kleine kogels maken:
- 2) Berekenen verwachting voor hypothese:
- 3) Afgeketste deeltjes kunnen bekijken:

Deeltjesversneller
Theorie
Detector

An aerial photograph of the CERN facility near Geneva, Switzerland. A large red oval is superimposed on the image, representing the path of the Large Hadron Collider (LHC) tunnel. The oval passes through several small red circles, which are the locations of the LHC's four main interaction points. The landscape below is a patchwork of green fields and some buildings. In the background, a large body of water (Lake Geneva) is visible, followed by a range of mountains with significant snow cover under a clear blue sky.

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

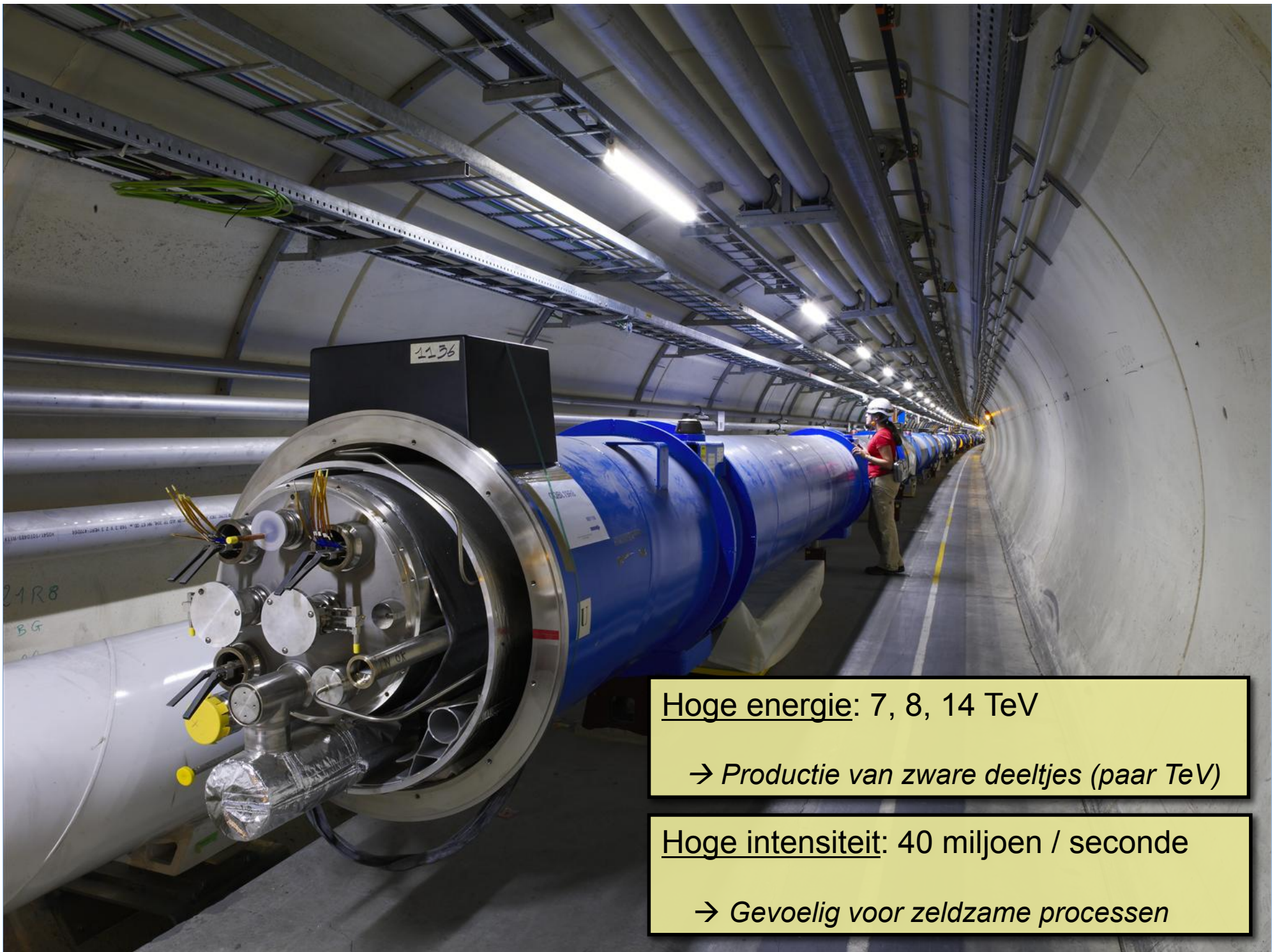
De Large hadron collider



De Large Hadron Collider

LHC: 27 km





Hoge energie: 7, 8, 14 TeV

→ *Productie van zware deeltjes (paar TeV)*

Hoge intensiteit: 40 miljoen / seconde

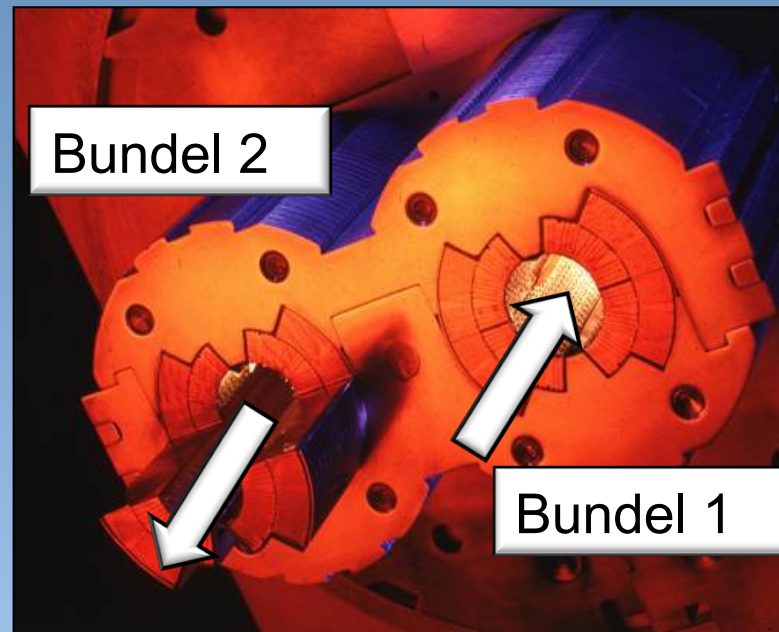
→ *Gevoelig voor zeldzame processen*

Energie 1 proton (LHC)



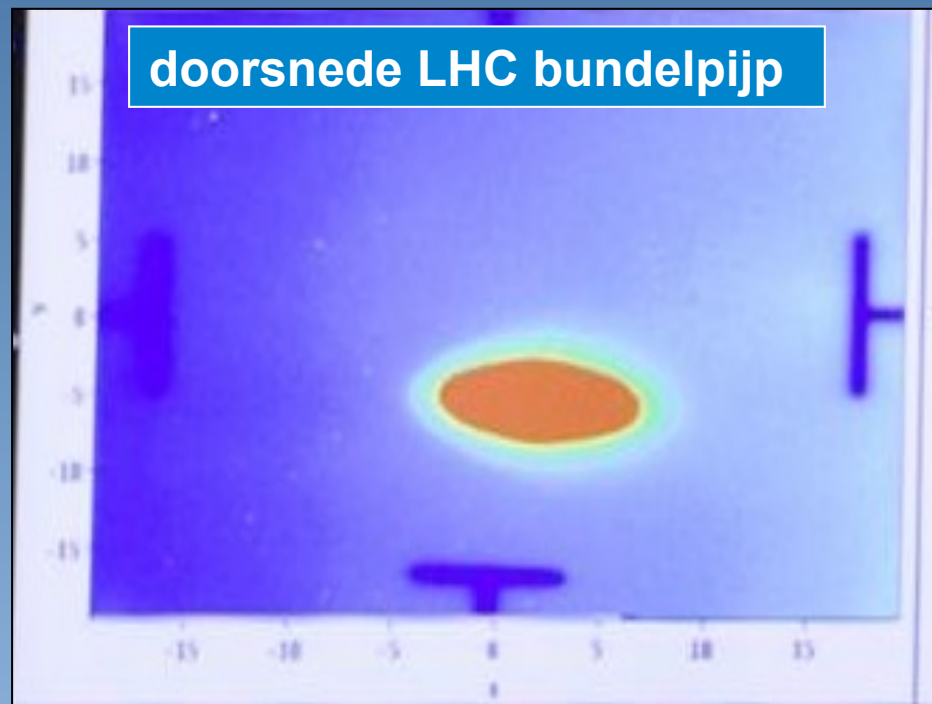
Energie LHC bundel

3000 x 100.000.000.000 protonen



*Doorsnede LHC
bundelpijp*

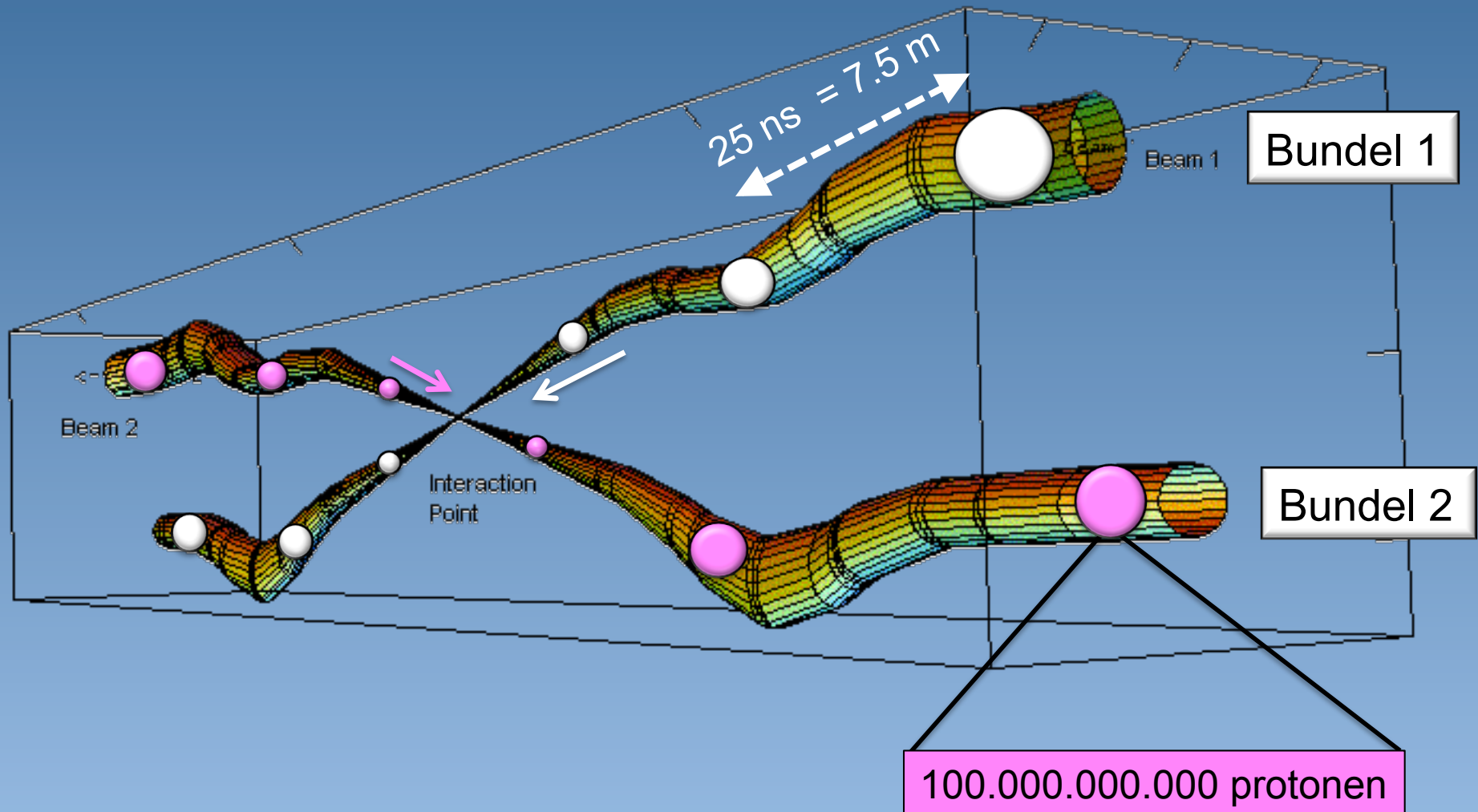
De LHC bundel is zo groot als Spanje op een 2 euro munt



10 september 2008



Botsende bundels: 40 miljoen keer 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 $H \rightarrow Q\bar{Q}$ 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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4. Loop induced Higgs boson decays: $H \rightarrow \gamma\gamma, \gamma Z, gg$

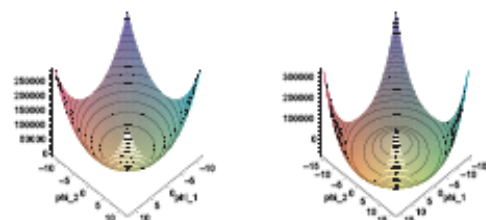


FIG. 1: The potential $V(\phi)$ ($\phi = \phi_1 + i\phi_2$) plotted for an arbitrary positive value of λ and for an arbitrary positive (right) or negative (left) value of μ^2 .

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:

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

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

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

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

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

and A_W^H are given by:

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

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

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

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

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

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

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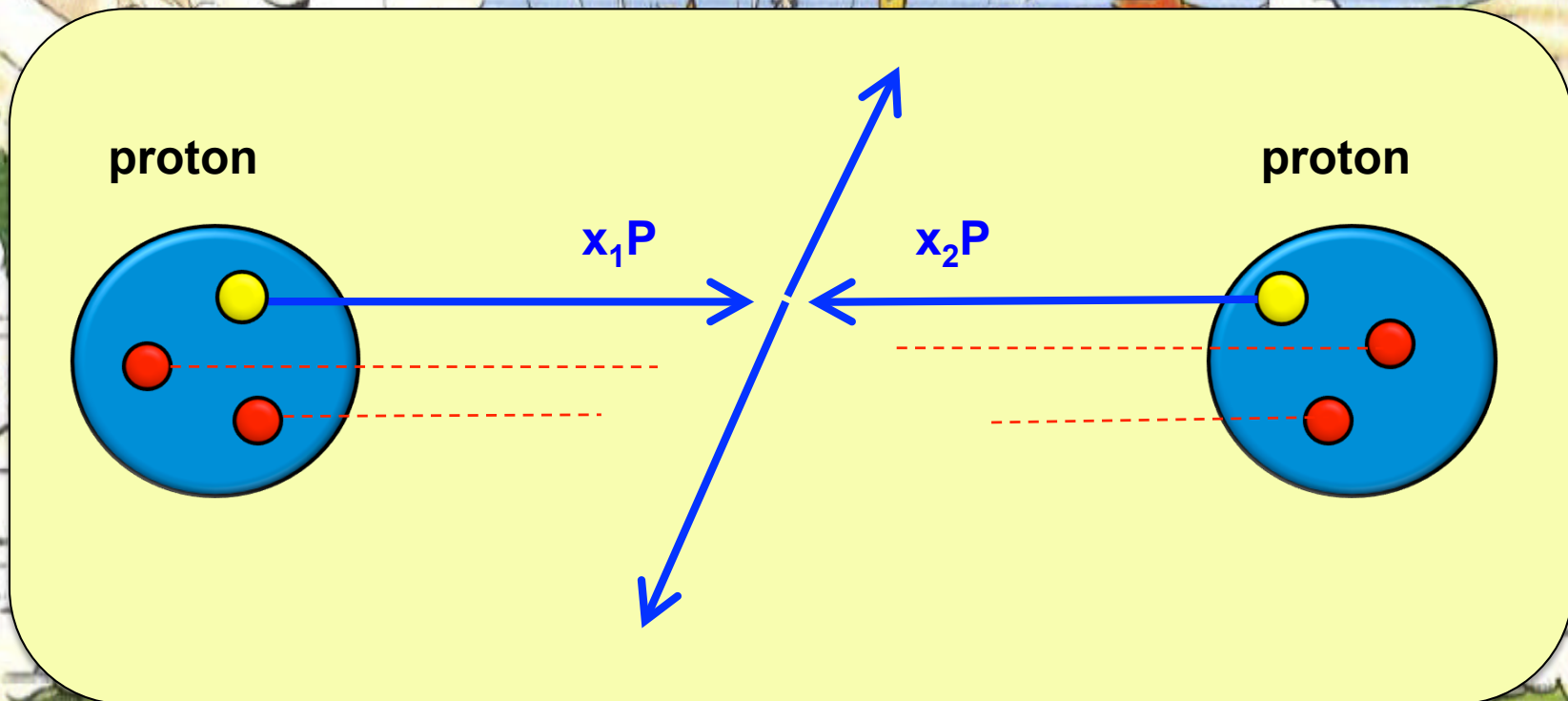
$$\frac{\tau\lambda}{(\tau-\lambda)} + \frac{\tau^2\lambda^2}{2(\tau-\lambda)^2}[f(\tau) - f(\lambda)] + \frac{\tau^2\lambda}{(\tau-\lambda)^2}[g(\tau) - g(\lambda)] ,$$

Klopt het ?

Inderdaad nieuwe deeltjes ?

Fenomenologie botsingen

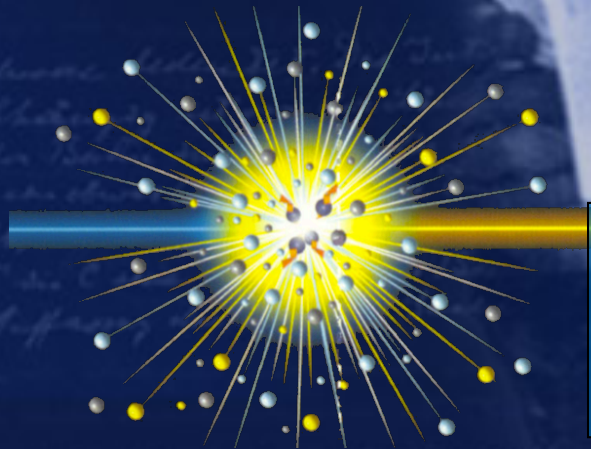
“Proton is als een zak vol met (anti-)quarks en gluonen”



Maar klein deel van de energie beschikbaar voor de harde ('echte') botsing

Albert Einstein

$$E = mc^2$$



Energie en massa zijn equivalent

→ je kan *nieuwe* deeltjes maken

$$E = mc^2$$

Energie omzetten in massa en vice versa

1 gram = 21 kiloton TNT



1 gram = 25 GigaWatt uur

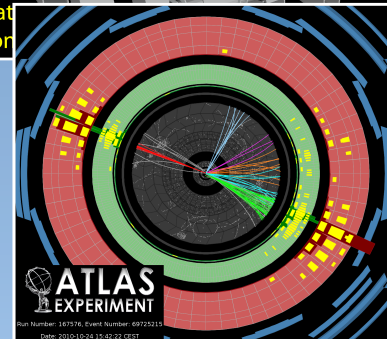
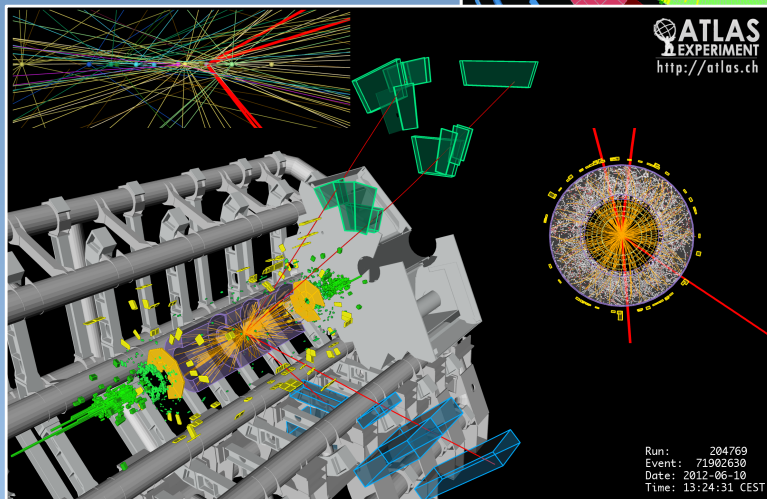
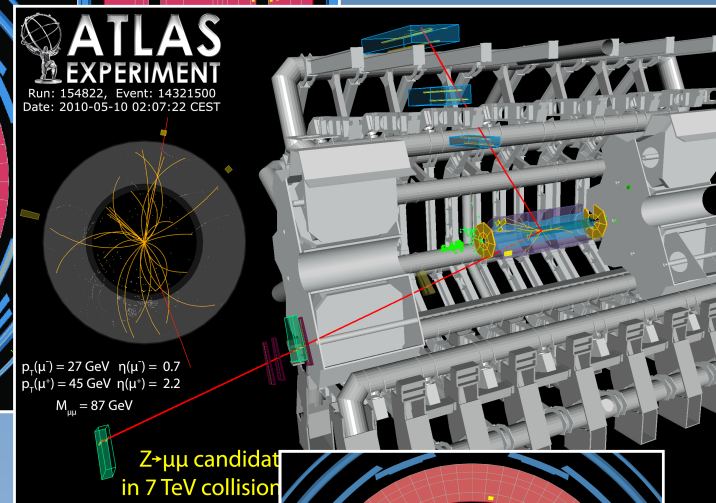
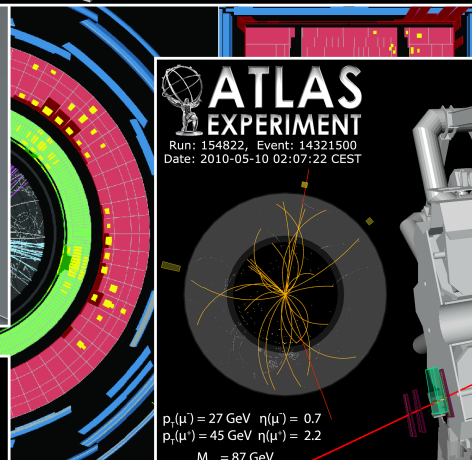
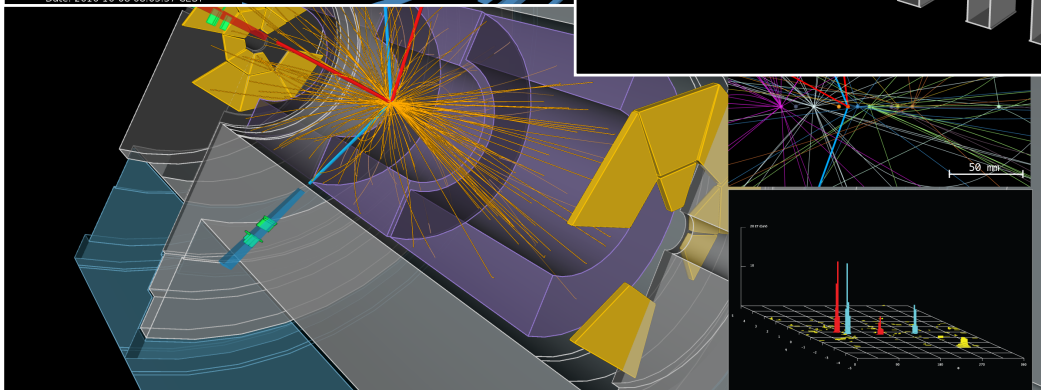
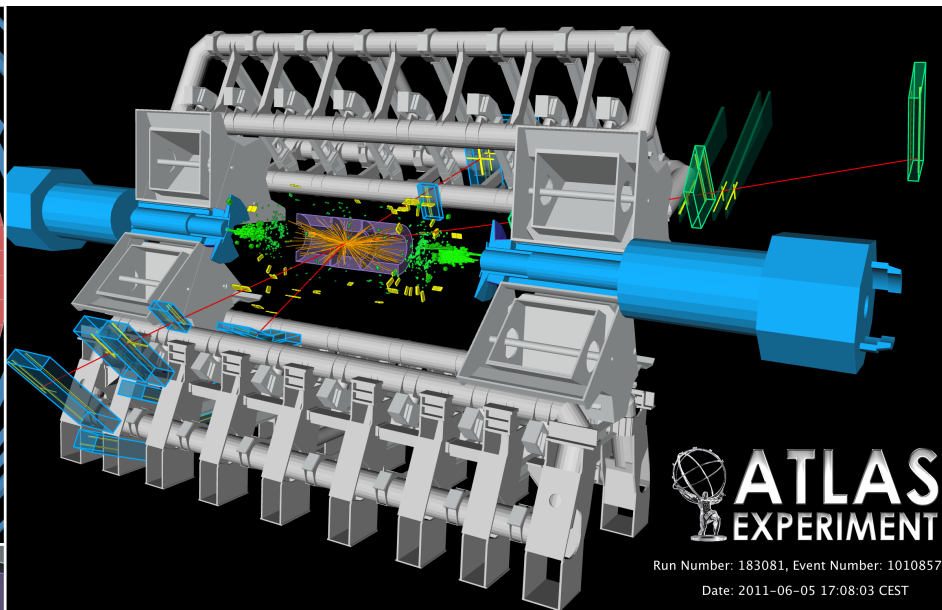
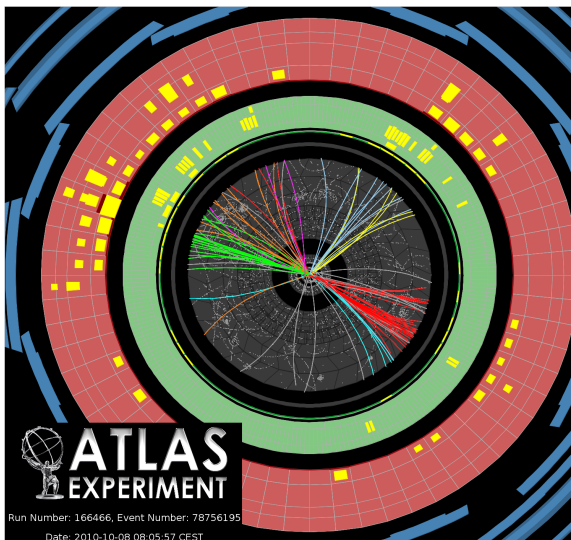


Op CERN doen we het andersom

deeltjes wegen bijna niks: 0.000000000000001 gram → ongevaarlijk



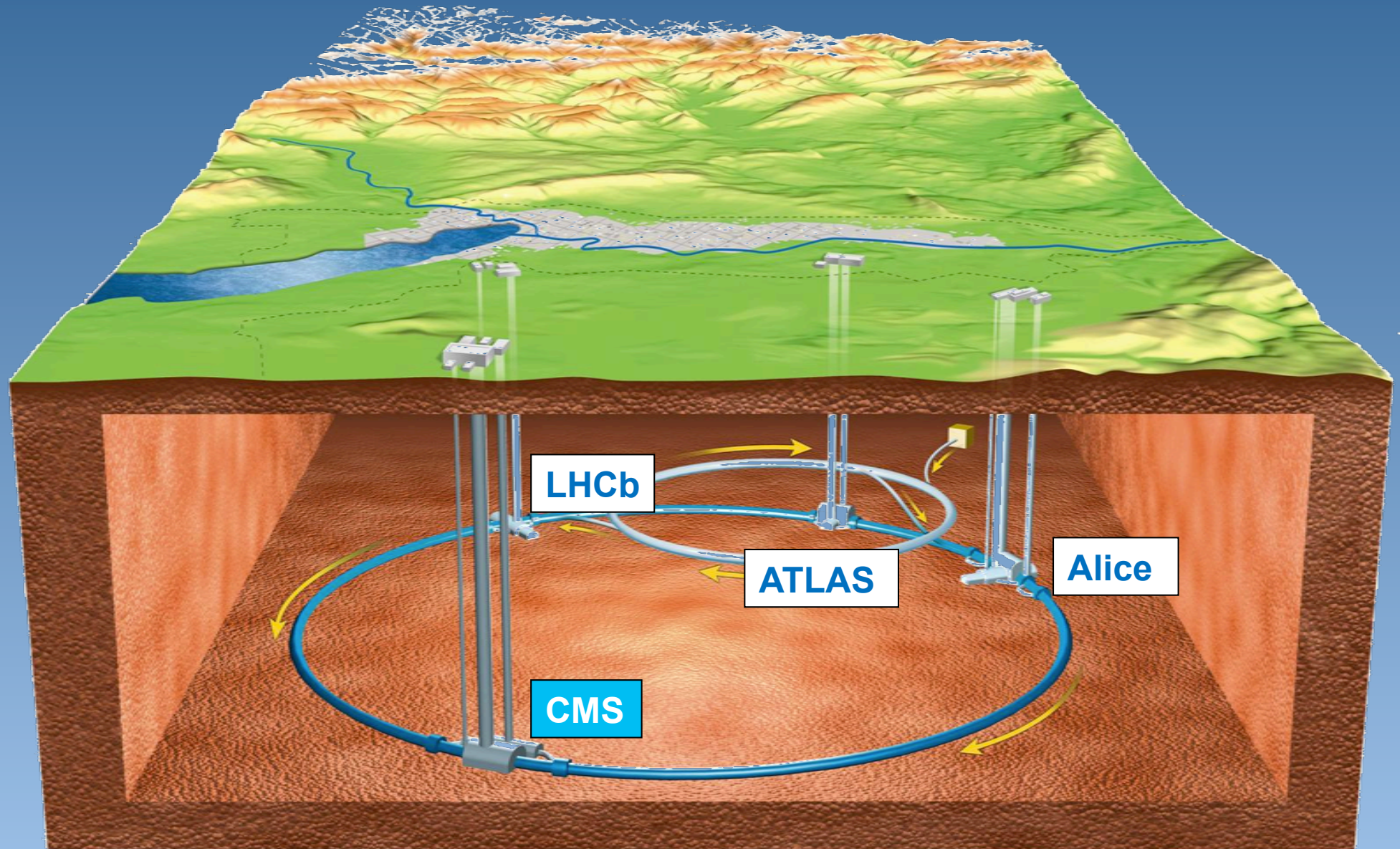
Heel vaak botsen



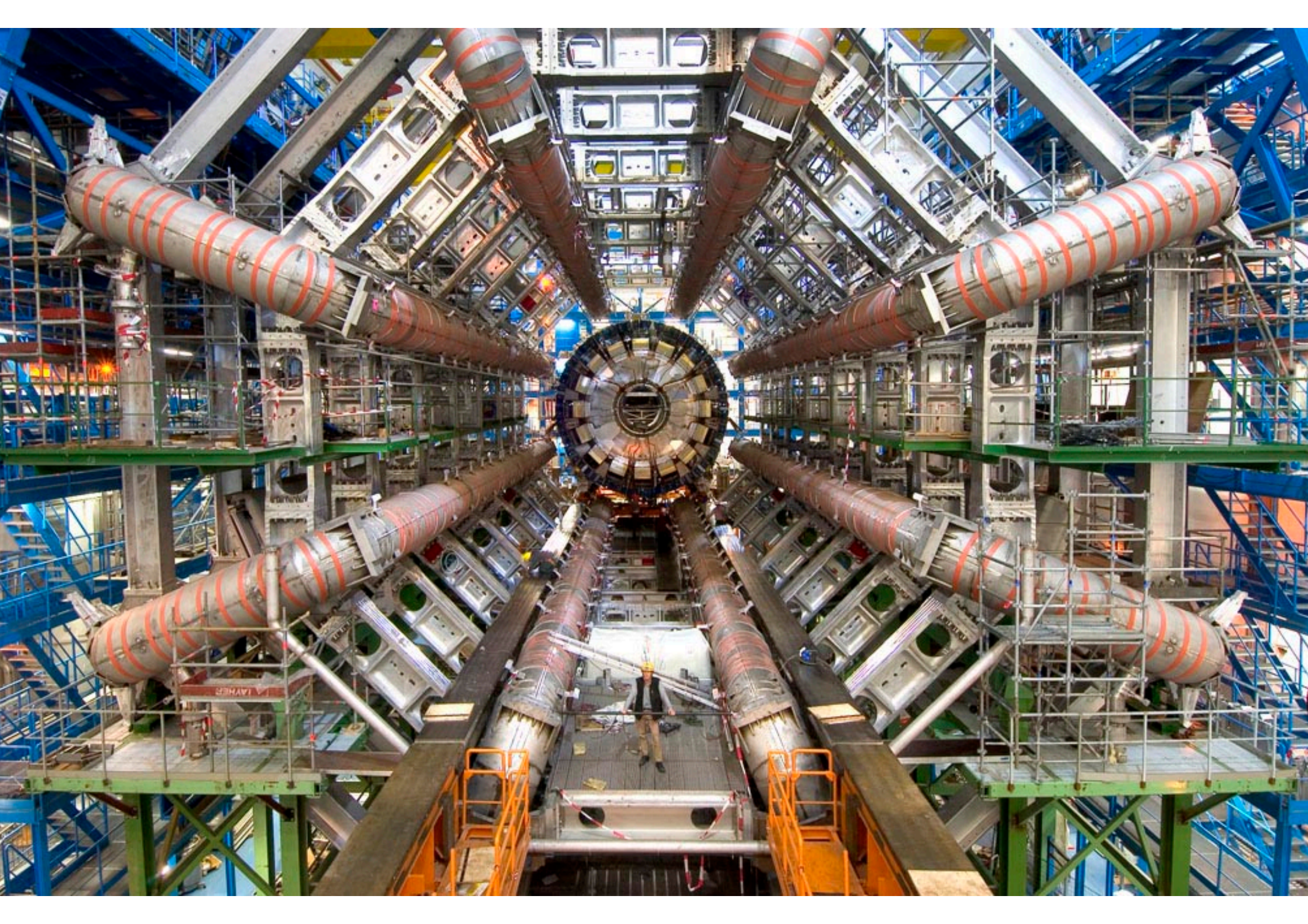
Onze 'fototoestellen'



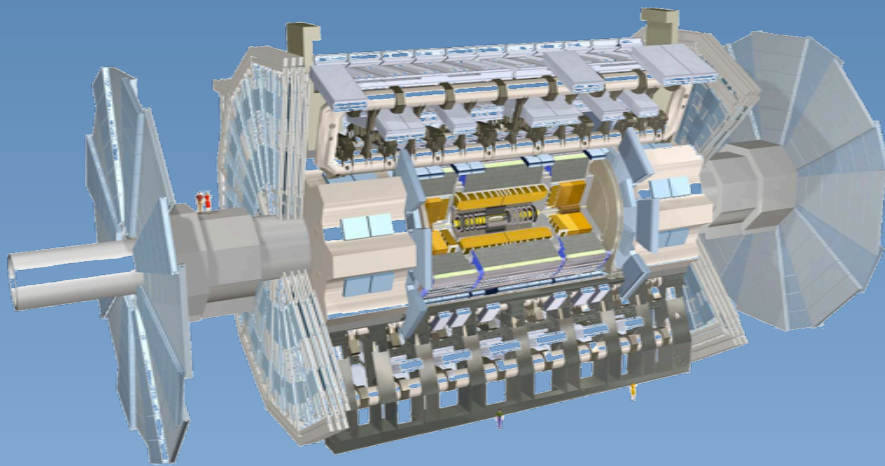
De vier experimenten







ATLAS detector

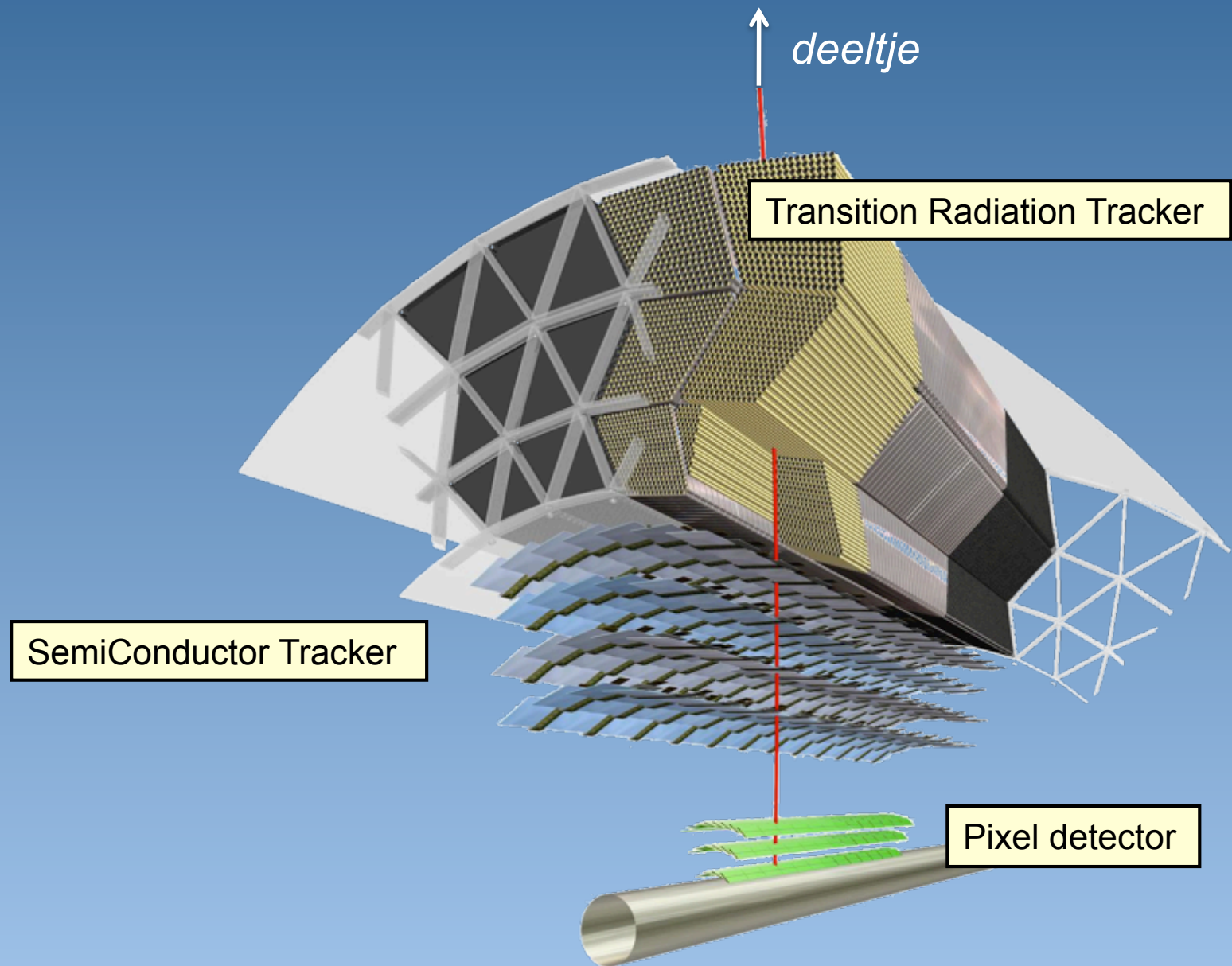


44 x 22 meter, 100 miljoen
electronische kanalen

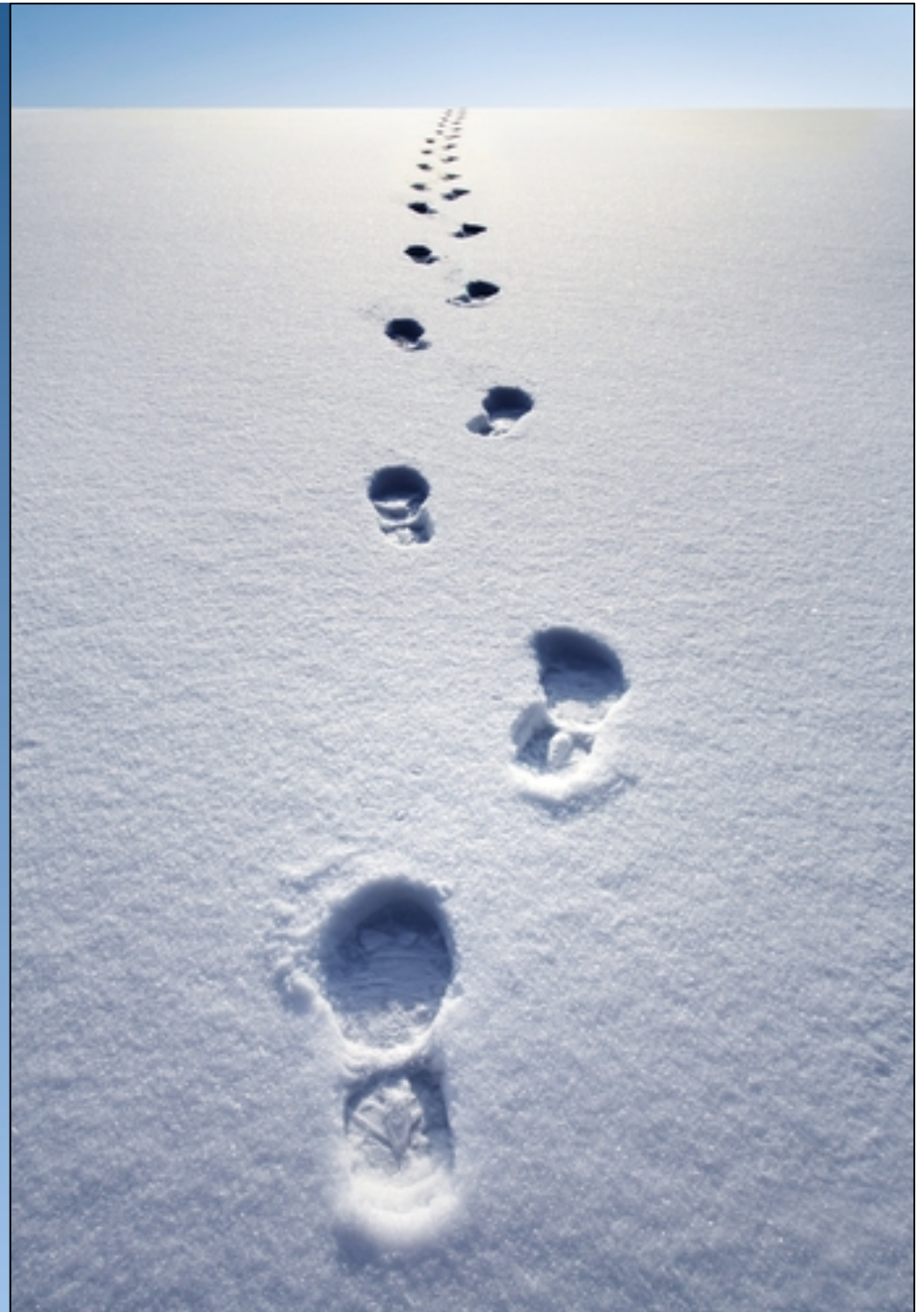


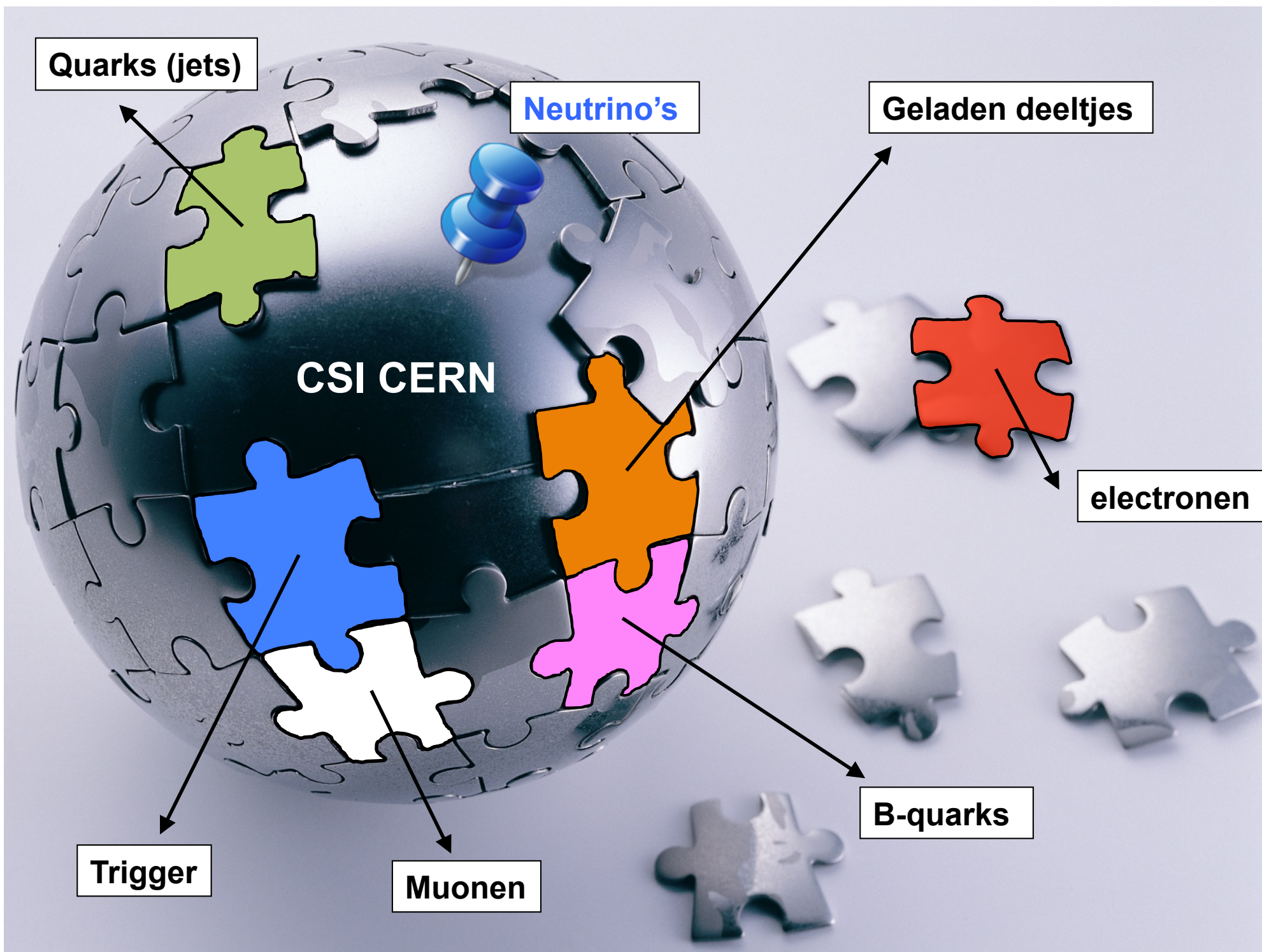
Waarom is die ATLAS detector nou zo complex ?

Het ene deeltje is het andere niet

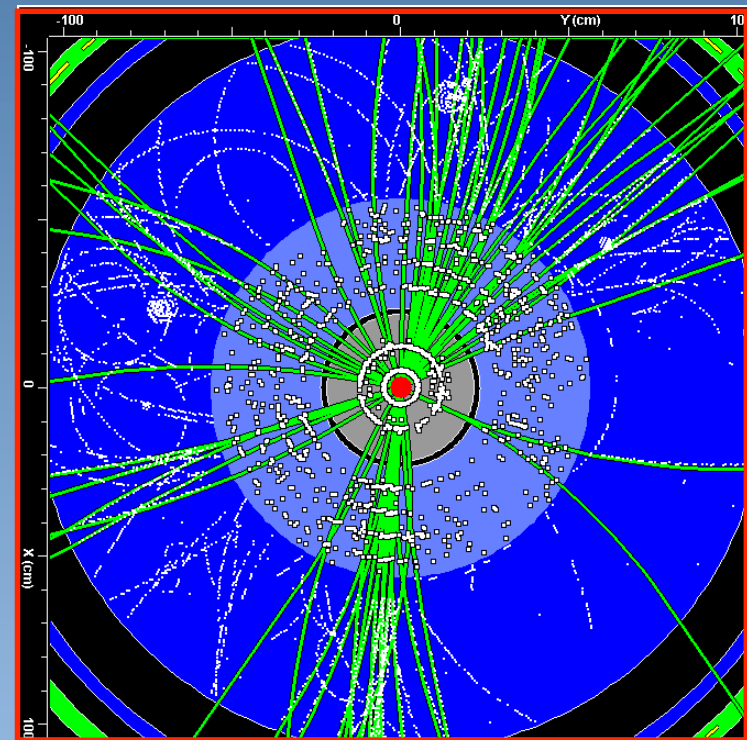
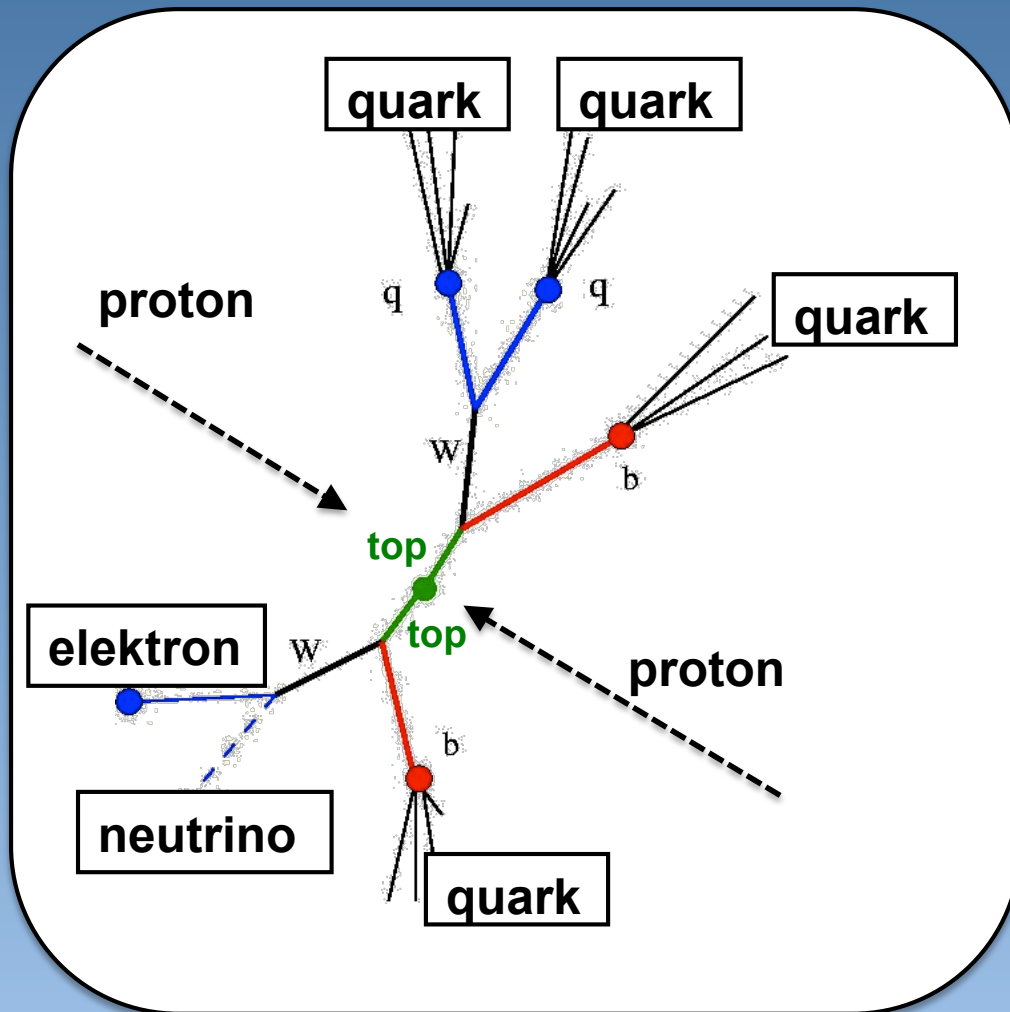


Konijn, auto of mens ?

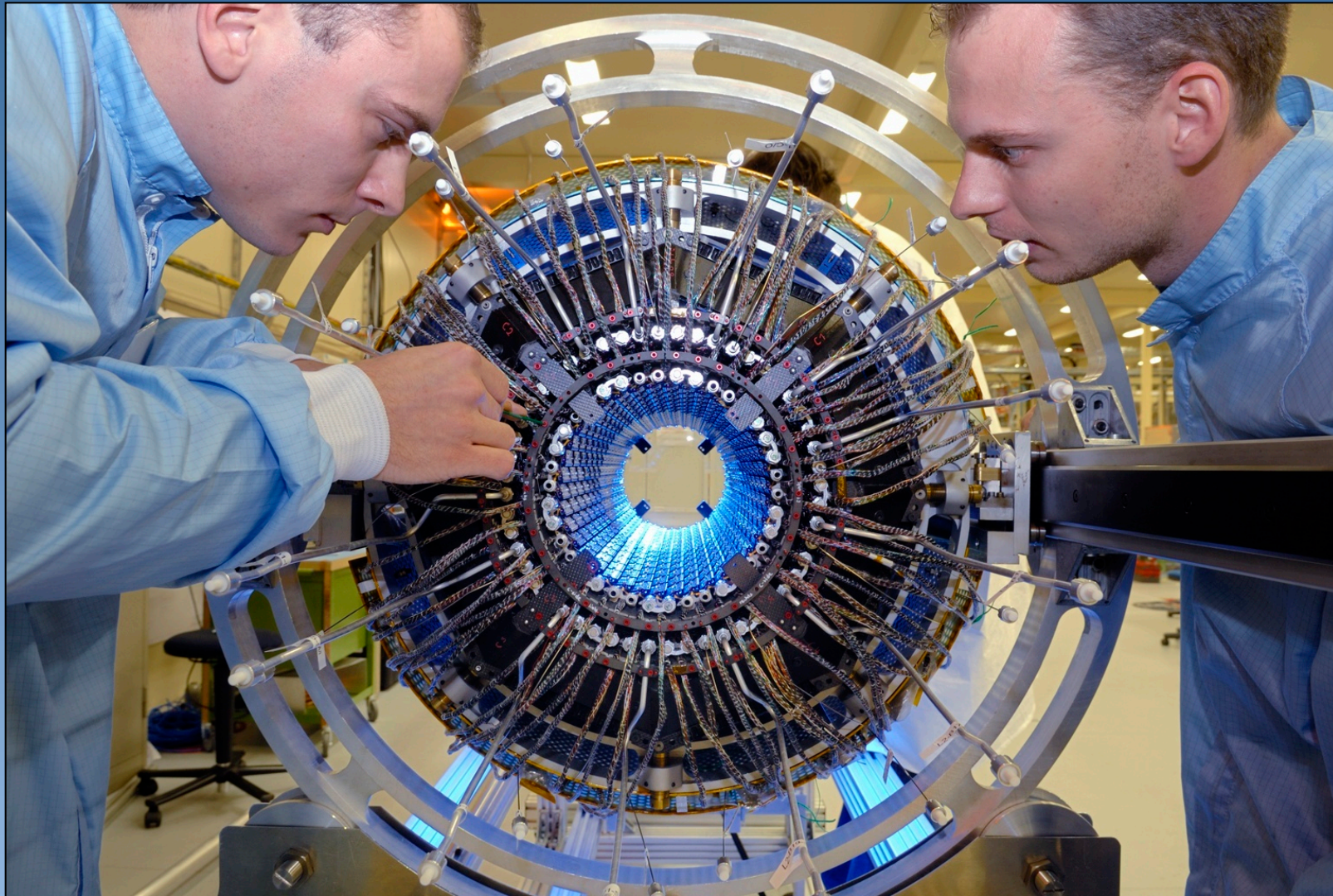




Complexe topologie: top quark paren

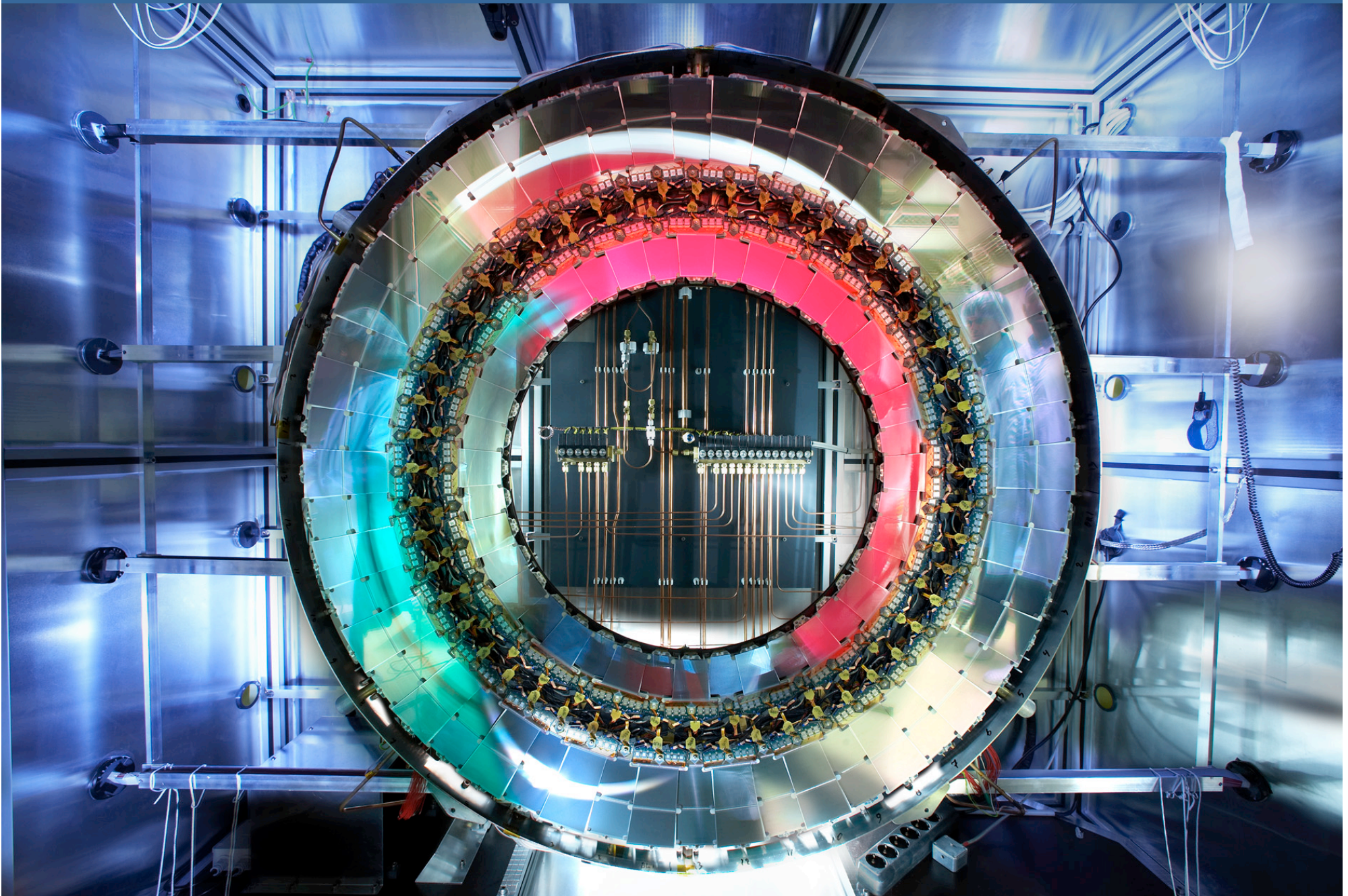


De Atlas pixel detector

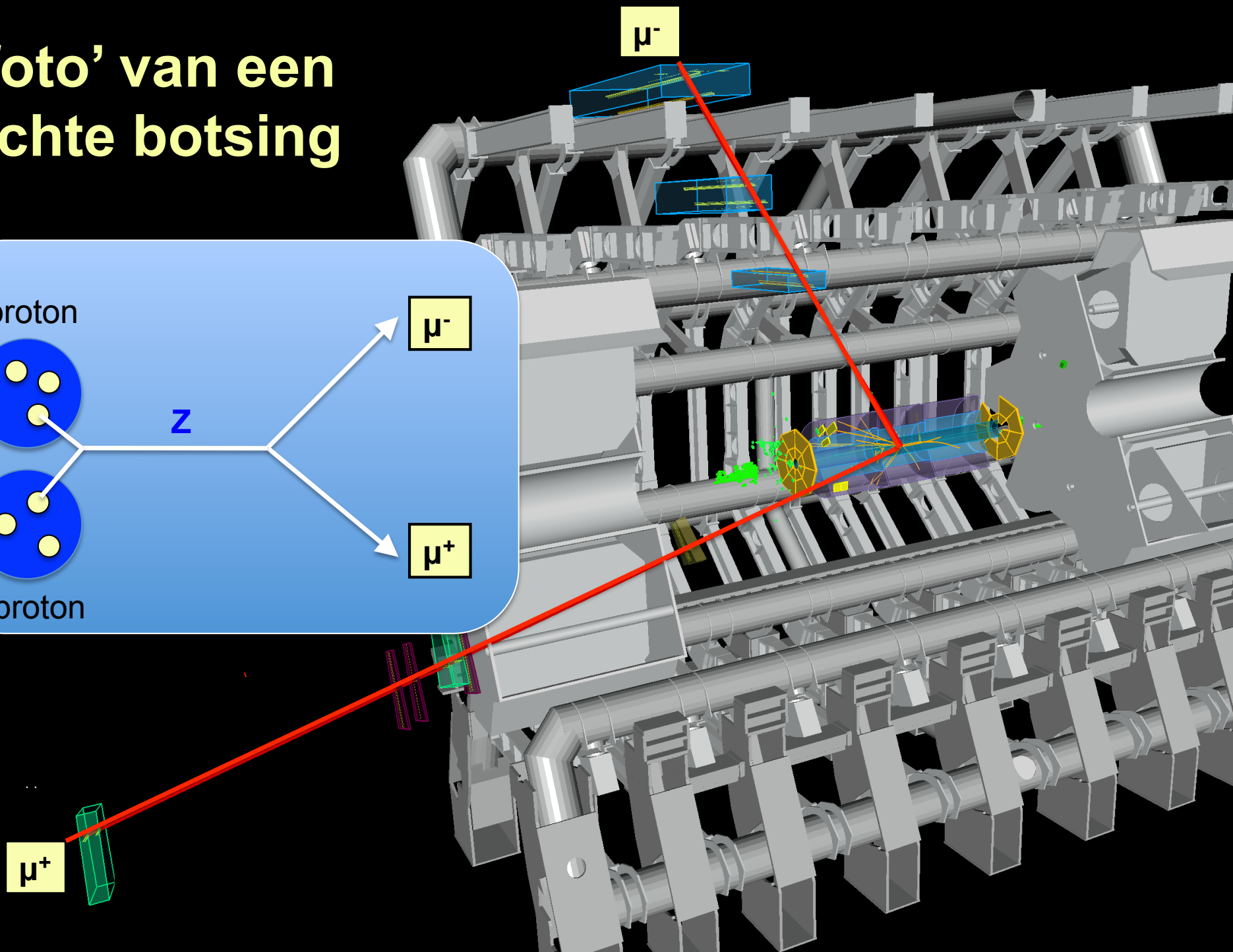
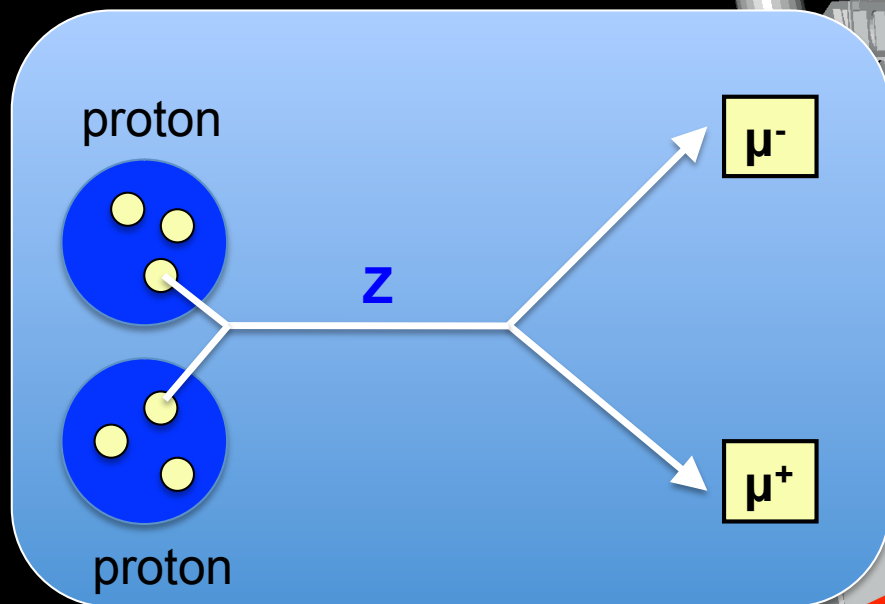


80 MegaPixel camera 40.000.000 foto's per seconde

Deel ATLAS detector is bedacht en gemaakt in Nederland

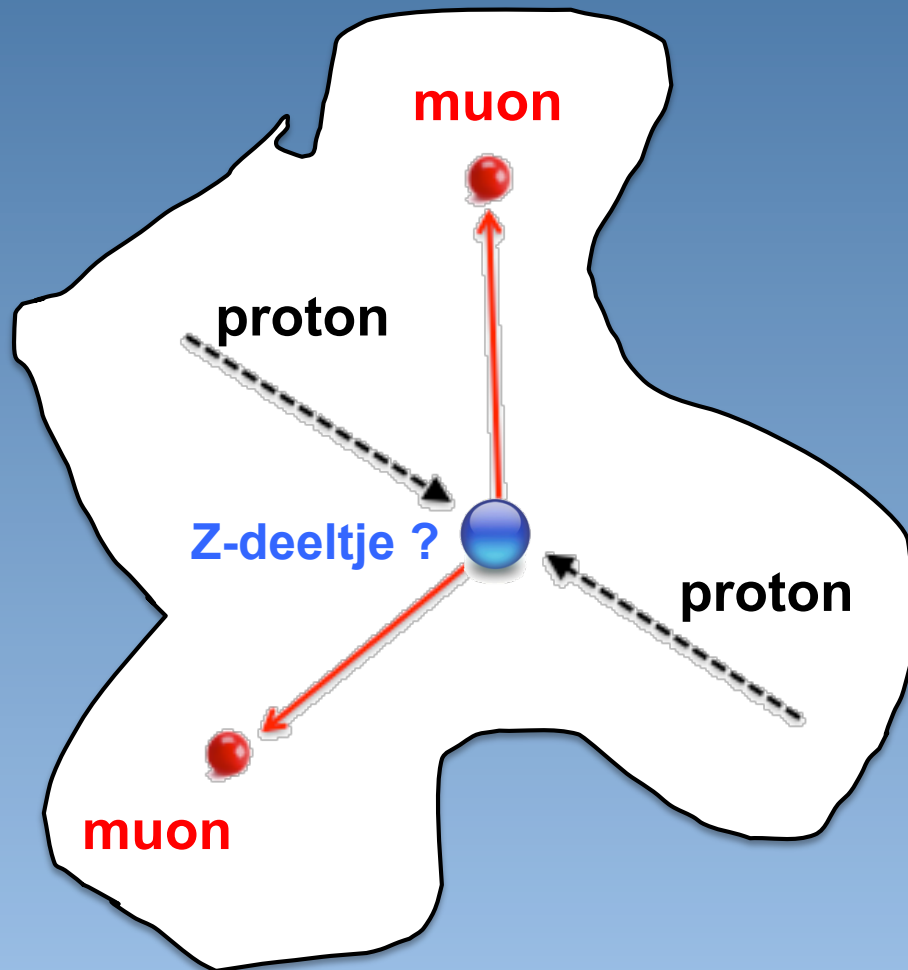


‘foto’ van een echte botsing

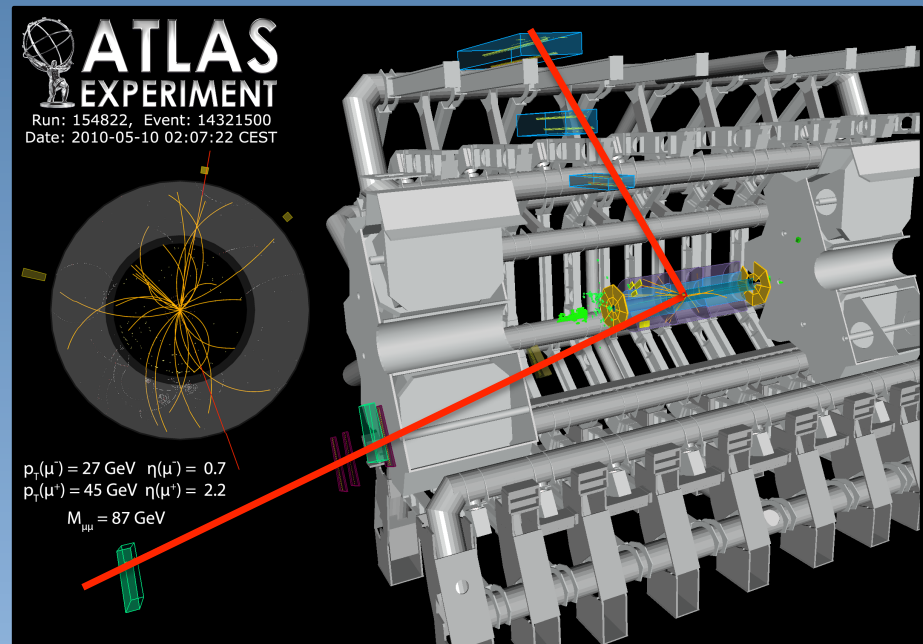


Hoe bewijs je dat er een Z-deeltje bestaat ?

Afwijking van de voorspelling in een model zonder Z-boson



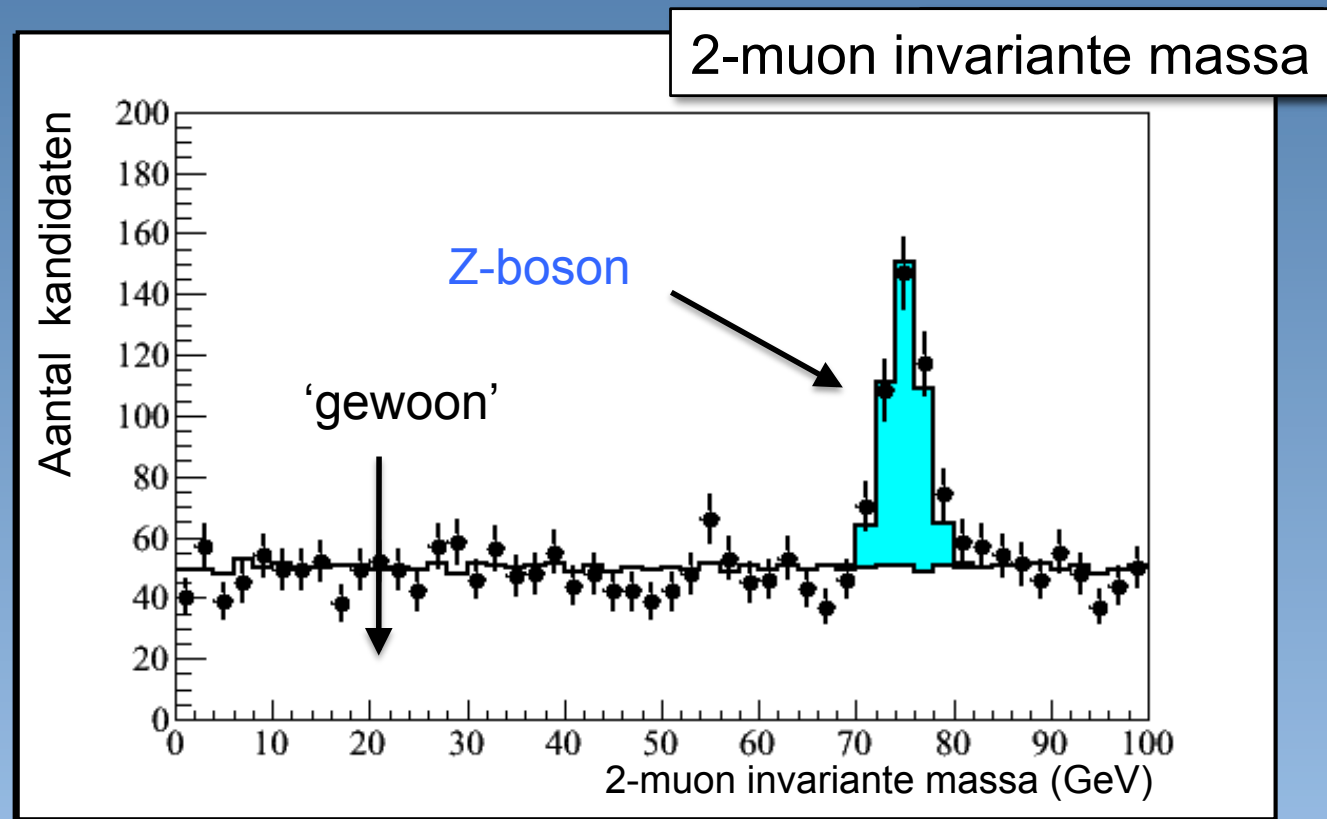
2-muonen gezien in de ATLAS detector



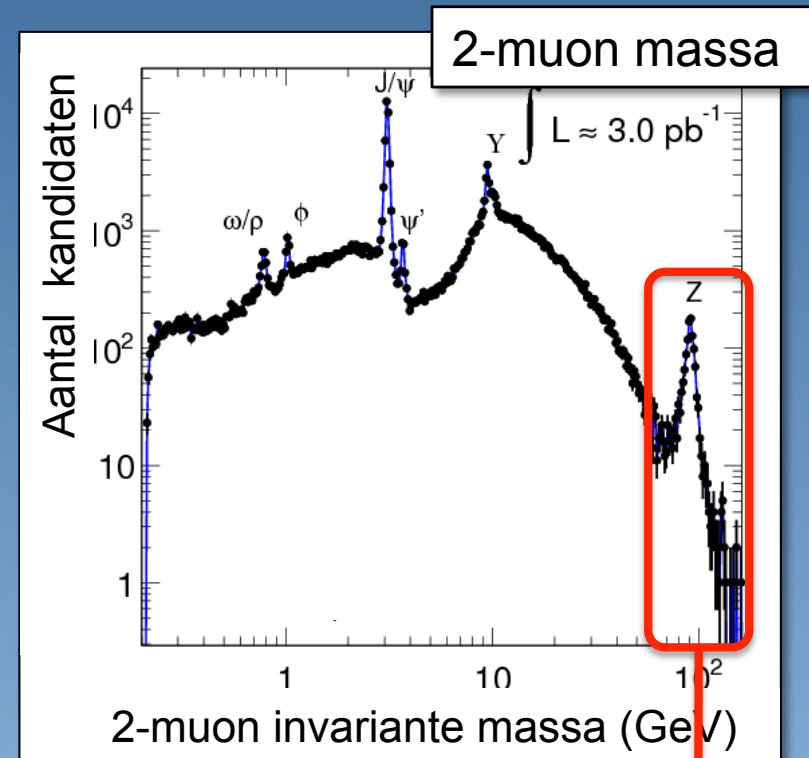
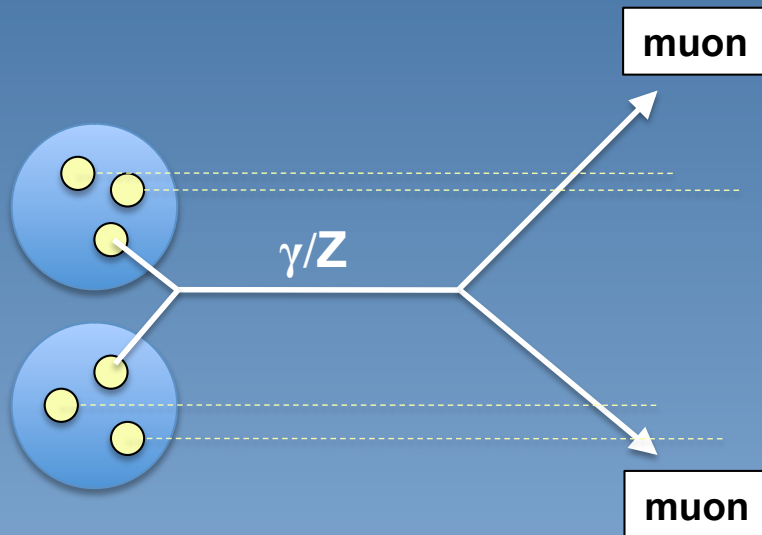
Voorspelling voor muon paren:

→ Ander proces: willekeurige openingshoek

→ Z-boson: karakteristieke (grote) openingshoek



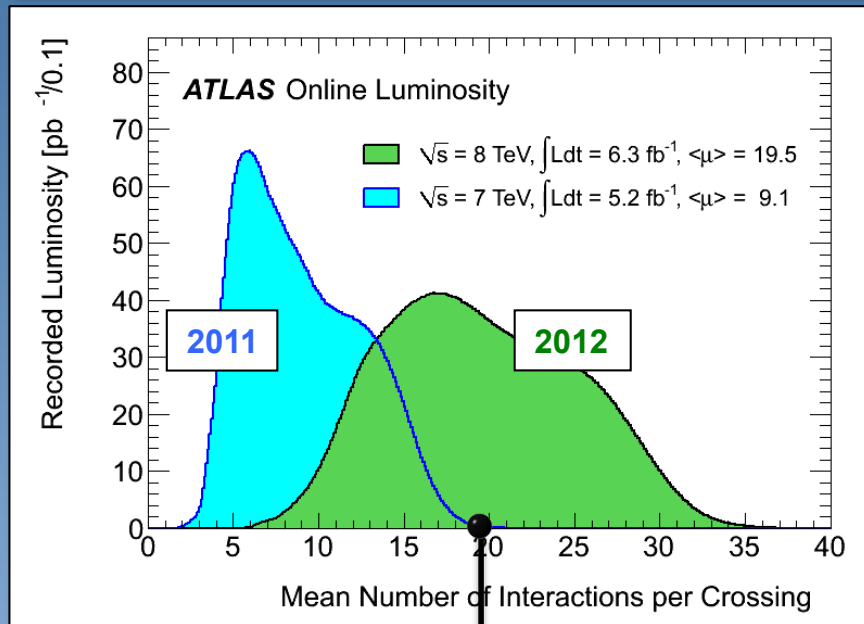
De 'echte' LHC data



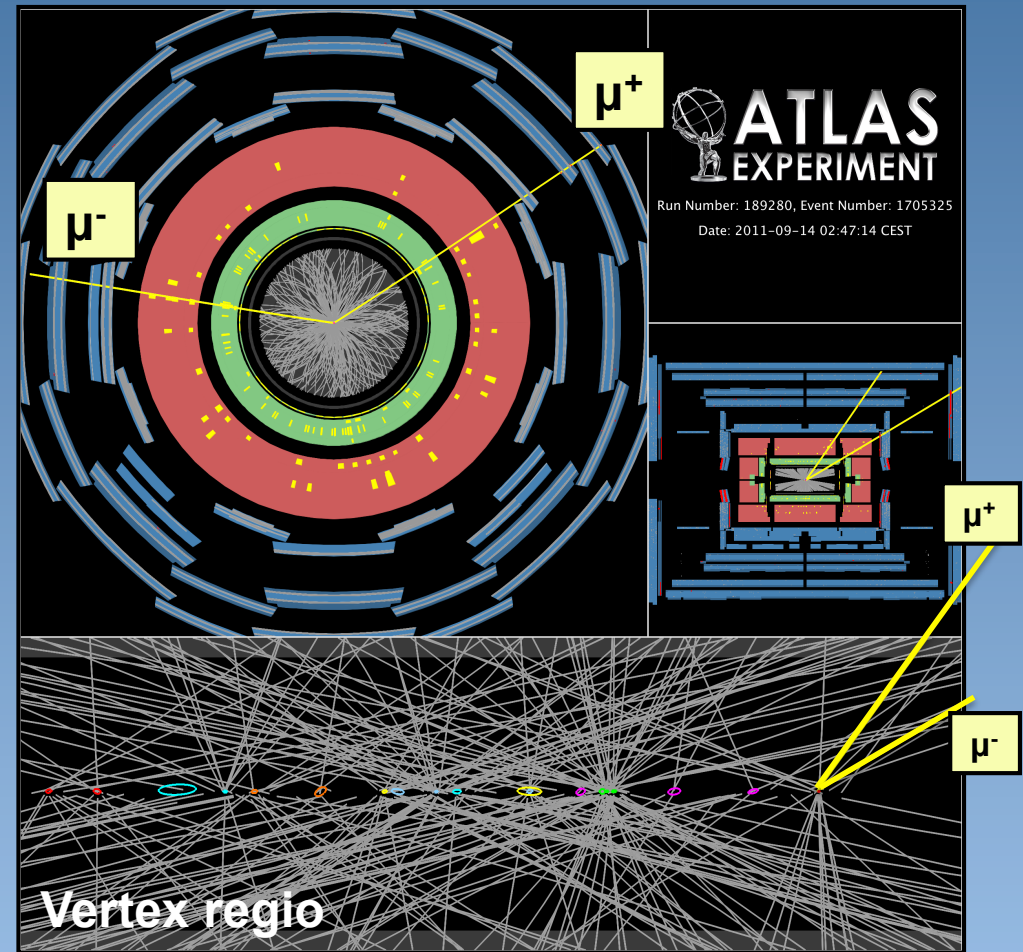
Interne structuur van protonen, eigenschappen van deeltjes en Z-bosonen (de zwakke kernkracht) bij hoge energie (kleinere afstanden)

Uitdagingen (1): LHC is geen rustige omgeving

Aantal interacties per bundelkruising



$Z \rightarrow \mu^+ \mu^-$ botsing met 20 vertices

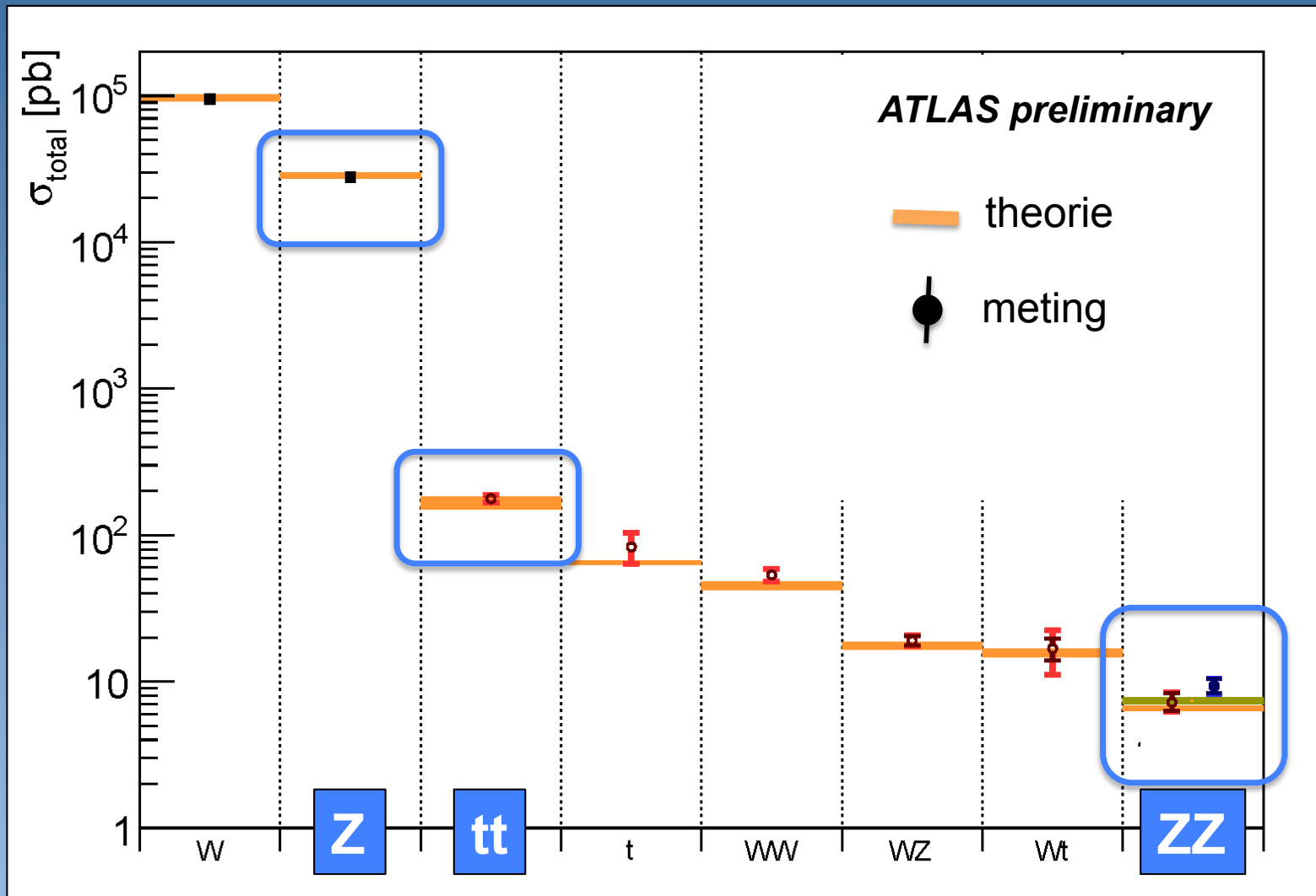


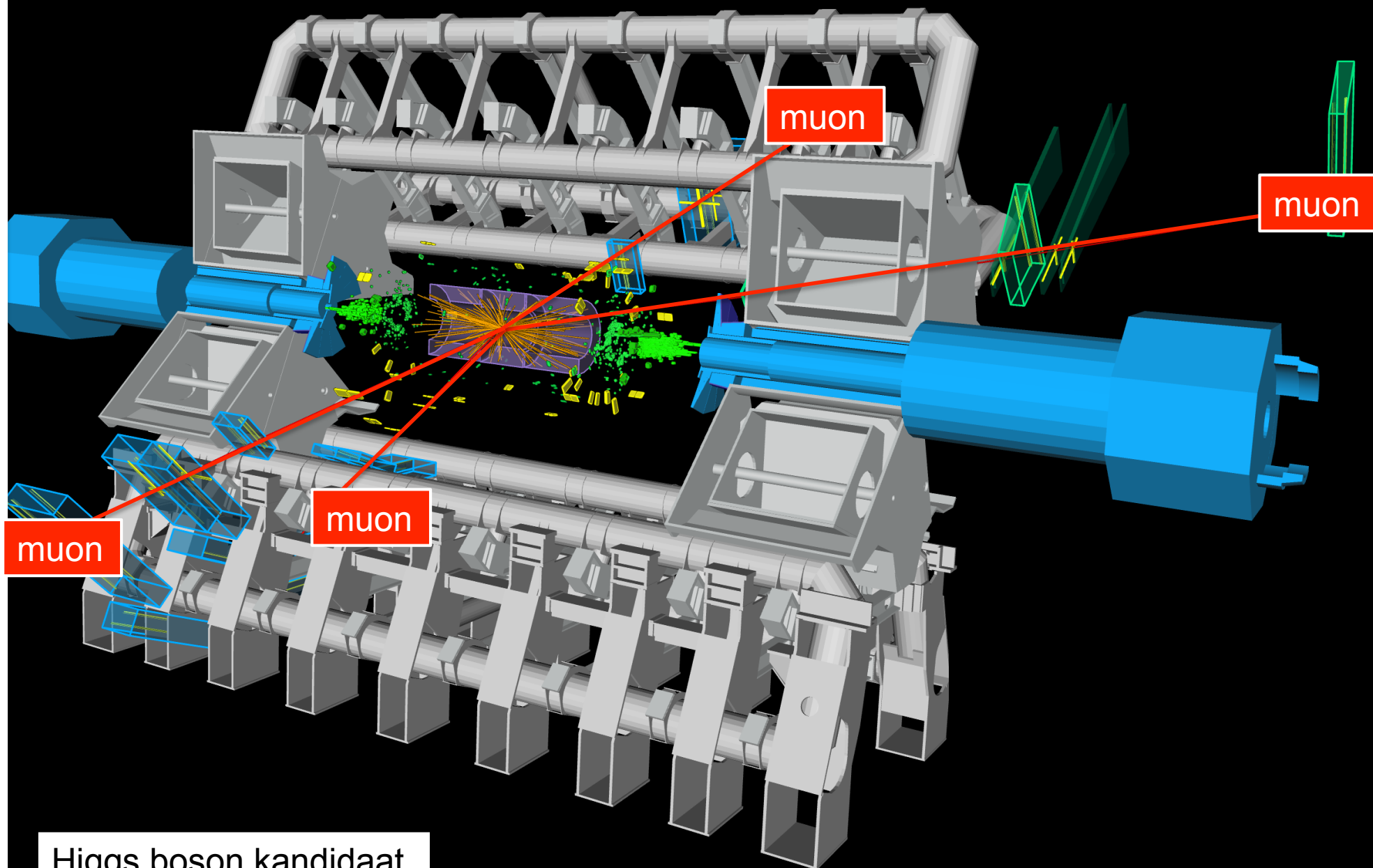
Uitdagingen (2): trigger

40 miljoen botsingen per seconde, maar ...
je kan er maar 300 per seconde bewaren

Heel heel heel lastig irreversibel real-time selectie proces

Productiesnelheid voor verschillende processen





Higgs boson kandidaat

Calce^{132a,132b}
ner¹⁰⁷, I¹¹, J. Cammin²⁰
80, L. Capasso^{102a,102b}
R. Caputo¹⁴⁸
on¹⁰⁶, S. Caron¹⁴⁸
ter¹⁰⁷, J. Carvalho^{132a,132b}
4. D. Emelyanov¹³⁹, R. Engelmann¹⁴⁸, A. Engu¹⁰⁸, B. Epp⁶²
rikova^{146a}, J. Ernst¹, M. Erus²⁴, D. Ervade^{16a},
16a¹⁶⁷, X. Espinal Curull¹¹, B. Esposito⁴⁷, F. Etienne⁸³,
H. Evans⁶¹, L. Fabbri^{10a,10b}, C. Fabre²⁰, K. Fadic³³,
ou¹¹⁰, Y. Fang¹⁷², M. Fan^{20a,20b}, A. Farbin⁷, A. Farilla^{134a},
P. Farthouat¹⁰², D. Faeschig¹⁷², P. Fassenhag¹⁰², D. Fassoulou⁸³
C.H. Hiller⁴¹, S. Hiller¹⁰⁷, S.J. Hillier¹⁷, I. Hinchliffe¹⁴, E. Hines¹²⁰, M. Hirose¹¹⁶, F. Hirsch^{47,102},
Hilke¹⁴⁹, N. Hod¹⁰³, M.C. Hodgkinson¹³⁰, P. Hodgson¹³⁰, A. Hoecker¹²⁹, M.R. Hoefcker¹⁰²,
Homes⁸³, M. Hohlhoff¹⁶⁰, M. Holder¹⁴¹, A. Holmes¹¹², S.O. Holmgren^{146a}, T. Holey¹²⁷
Homer¹⁷, Y. Homma⁶⁷, T. Horawadsky¹²⁷, C. Horn¹⁴³, S. Horner⁴⁸, K. Horton¹¹⁸
100¹⁰⁹, S. Hou¹¹, M.A. Houlden⁷⁵, A. Housmadda^{130a}, J. Howarth⁸², D.F. Howell¹¹⁸
114, I. Hruska¹²⁰, T. Hryn'ova⁶⁴, P.J. Han¹⁴, S.C. Hsu¹⁴, G.S. Huang¹¹¹, Z. Hubacek¹²⁷
C. Leggett¹¹⁴, L. Lehmann²⁰, G. Lehmann Miotto²⁰, M. Lelito³⁰, X. Les⁴, M.A.L. I.
D. Lellouch¹⁷¹, J. Lellouch¹⁸, M. Lelschou¹⁷, V. Lendermann¹⁰⁶, K.C. Jency¹⁰⁶,
A. Legnini¹⁰, K. Lehnhardt⁴⁵, C. Leroy⁴⁹, J.R. Lessard¹⁶⁰, J. Lesser^{160a}, C.G. Lester²⁷
J. Leveque⁸³, D. Levin⁸⁷, L.J. Levinson¹⁷¹, M.S. Levitzki¹²⁸, M. Lewandowska²¹, M. Li
S.^{132b}, X. Li⁸⁷, Z. Liang²⁰, Z. Liang^{189a}, B. Libert^{133a}, P. Lichard¹²⁰, M. Lichtnecker
R. Lifshitz¹⁰², J.N. Lilley¹⁷, A. Limosani⁸⁶, M. Limper⁴⁵, S.C. Lin^{101a}, A. F. Linder¹⁰²
E. Lipielez¹²⁰, L. Lippman¹²⁰, T. Lippman¹²⁰, A. Lippman¹²⁰, A. Lippman¹²⁰, A. Lippman¹²⁰
H. Liu⁸⁷, J.B. Liu⁸⁷, M. Ljubic¹⁰²
E. Lobodinskii¹⁰²
A. Logez¹⁰², J.N. Lolley¹⁷, C.W. Loo¹⁷
R.E. Long¹⁷, L. Lopes¹⁰²
M.J. Lorty^{102a}, X. Los¹⁰²
L. Lu⁸⁹, H.J. Lubatti¹⁷
P. Luchering⁶¹, G. Luij¹⁷
J. Lundberg¹⁷, J. Lusa¹⁰²
M. Ma¹²⁴, L.M. Ma¹²⁴
J. Machado¹⁰², P. Magagnoli¹⁰²
T. Masenc²⁴, P. Mättig¹⁰²
C.A. Magrath¹⁰⁴, Y. Ma¹⁰²
A. Maior^{24a,24b}, S. Maj¹⁰²
F. Malek⁸³, U. Mallik⁴⁶
A. Manabe¹⁷, L. Mane¹⁰²
S. Manal¹⁰², P.M. Manal¹⁰²
L. March⁸⁰, J.F. Mar¹⁰²
A. Marin²¹, C.P. Mar¹⁰²
S. Marti-Garcia¹⁰⁷, A.
T.A. Martin¹⁷, B. Mar¹⁰²
P. Nemethy¹⁰⁸, A.A. Nepomuceno^{20a}, M. Nemi²⁰, S.Y. Nester
R.M. Neves¹⁰⁸, P. Nevski²⁴, P.R. Newman¹⁷, R.B. Nickerson¹⁷
P. Niedercon¹¹⁰, J. Nielsen¹²⁷, T. Niinikoski²⁰, A. Nikiforov¹⁰²
K. Nikopolou²⁴, H. Nilisen¹²⁷, P. Nilsson¹⁷, Y. Ninomiya¹¹⁰
I. Nodulman¹⁰⁶, M. Nomachi¹¹⁶, I. Nomidis¹⁰⁴, H. Nomoto¹⁰²
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Wat weten we **wel**

De natuur zit vol vreemde spelregels

De LHC werkt!

Het Standaard Model werkt prima!

Hoe krijgen (kracht-) deeltjes massa

Wat weten we nog **niet**

Waarom de spreiding in massa's ?

Waar is donkere materie van gemaakt ?

Waarom is gravitatie zo anders ?

Waar is alle anti-materie gebleven ?

Schitterend avontuur de komende jaren!