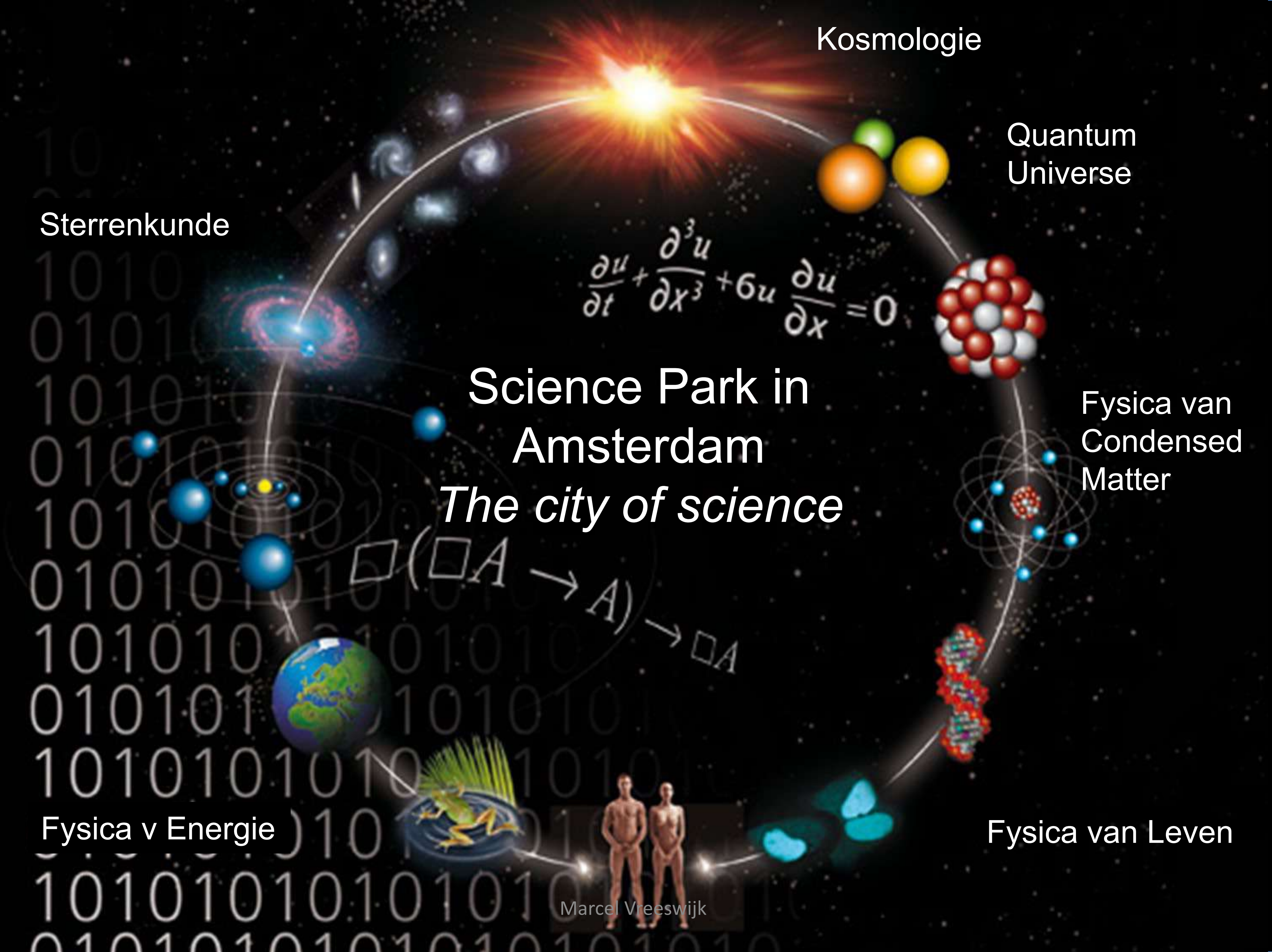
Een zoektocht naar de bouwstenen van de natuur.

Inhoud
- Intro Natuurkunde en Deeltjesfysica
- Rol van het Higgs deeltje
- Detectie Higgs deeltje met de LHC
- OK, en nu?

Marcel Vreeswijk

Amsterdam Science Park – Viva Fysica 2020

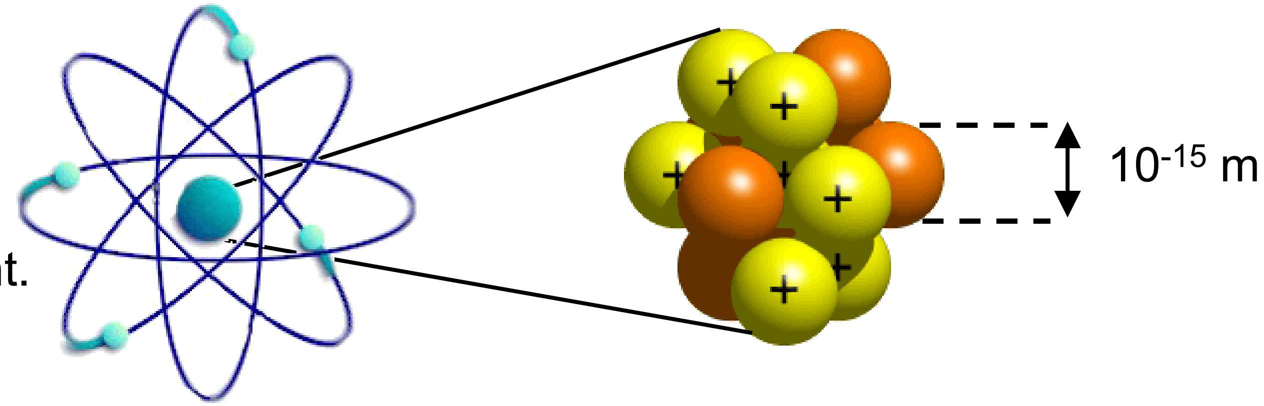
Science Park in Amsterdam
The city of science



Quantum Universe: het atoom en haar bouwstenen

Elektronen
lading -1

Elektron is elementair
''voelt'' elektrische kracht.

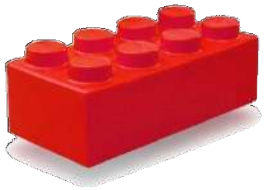


Kern is samengesteld:
protonen (lading +1)
en neutronen

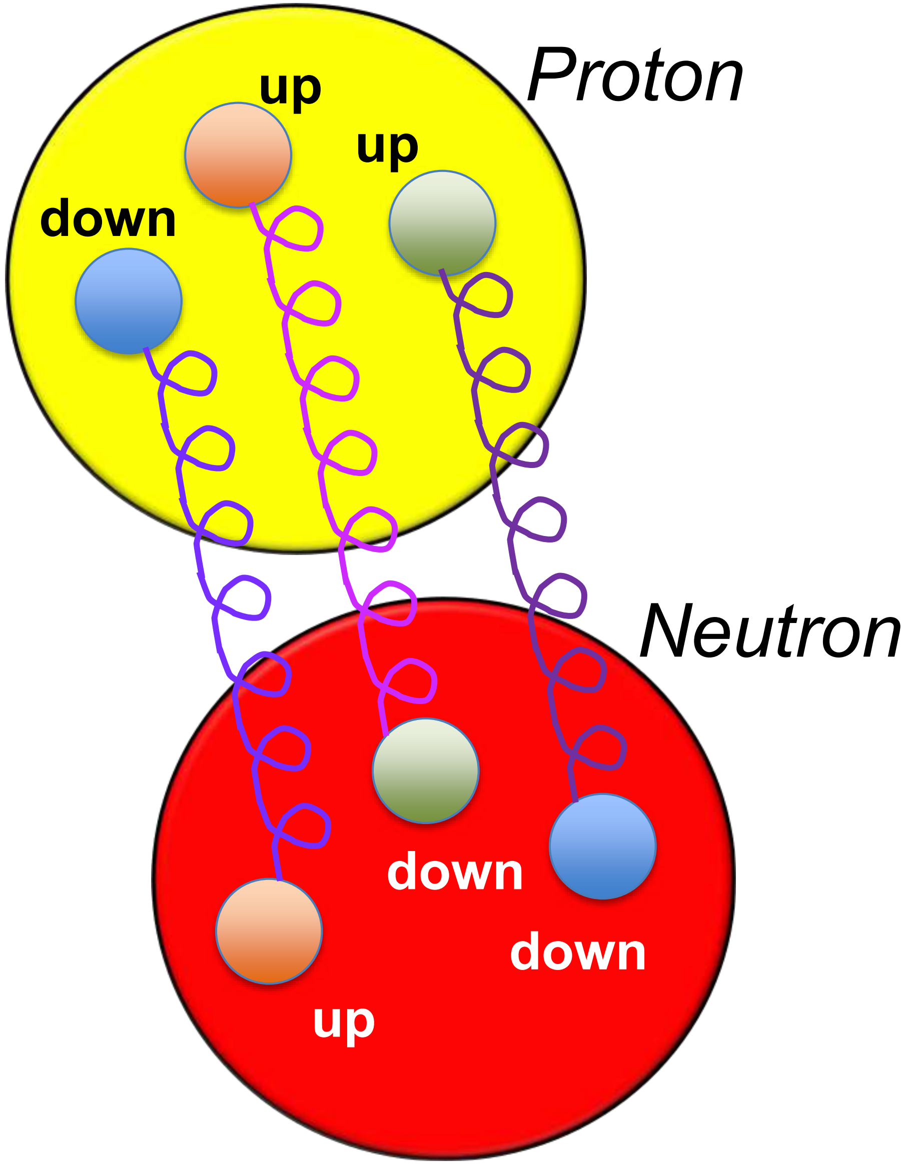
klopt dit beeld wel?

Wat zijn de bouwstenen van de dingen om ons heen ?

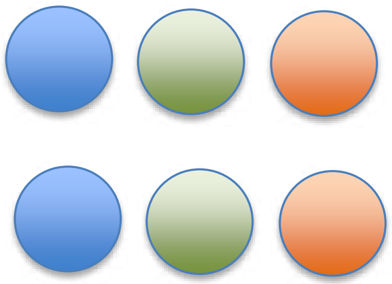
Welke krachten beschrijven hun interacties ?



Quarks en gluonen



Elementaire deeltjes



Up (3)

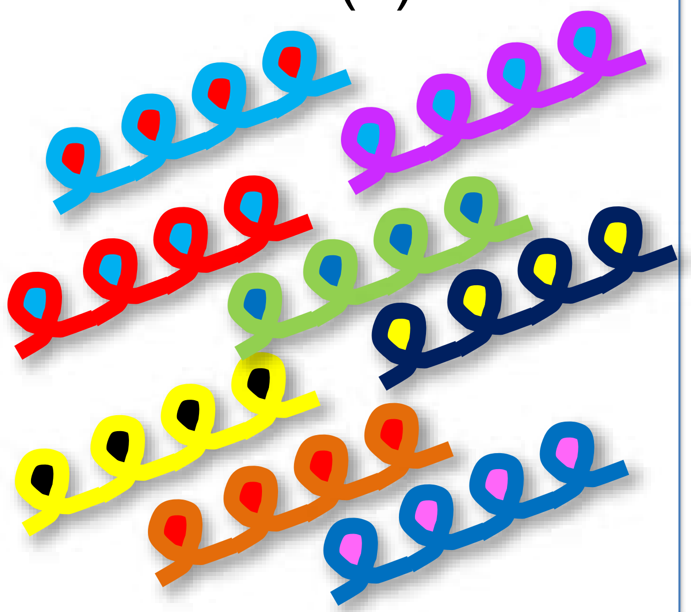
Down (3)

We hadden ook al:

elektron

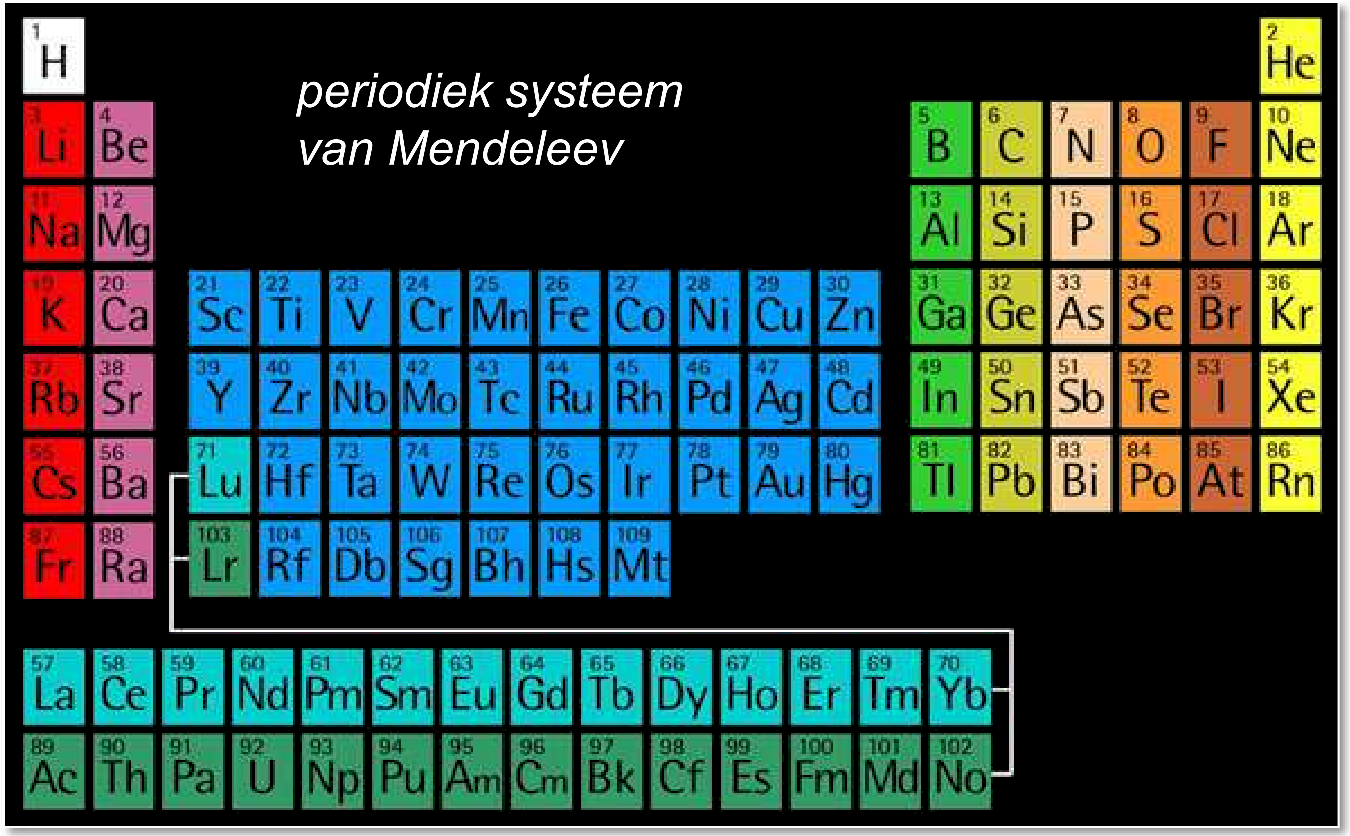
Elementaire kracht

Gluonen (8)



Elementaire deeltjes: Up-, Down quark en het elektron

Wat kan je maken met deze 3 bouwstenen?
(en hun elementaire krachten)



Alles!

Wat zijn krachten (interacties) nou eigenlijk precies?

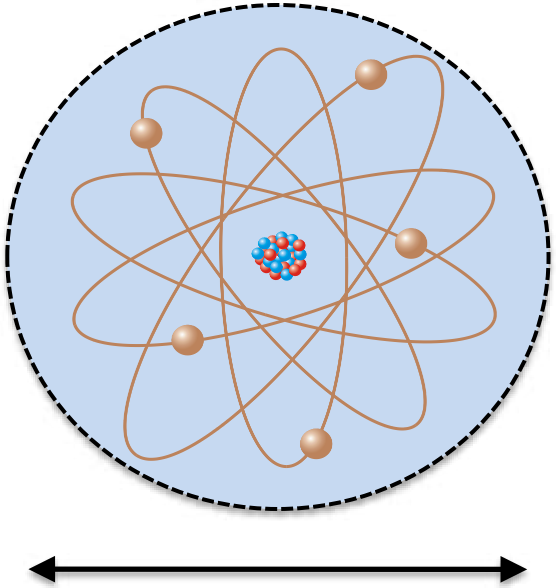
Elektrische kracht

(Klassiek E-veld,
macroscopische
samenhang met B veld.)

1 [m]

Elektrische kracht

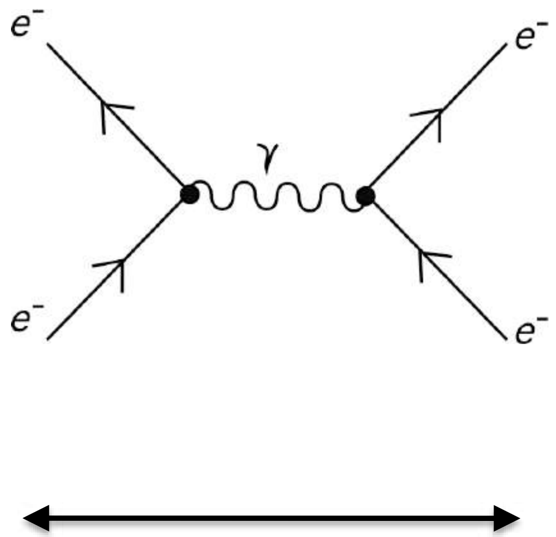
(Quantummechanica
Kleine afstanden, deeltjes
worden golven → vaste
waarden ‘spin’.)



0.0000000001[m]

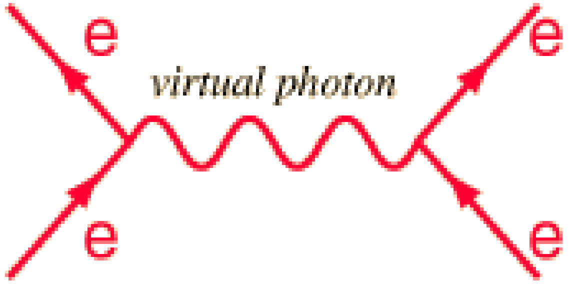
Elektrische kracht

Deeltjesfysica, uitwisseling
krachtendeeltjes.
Wiskundige Symmetrien →
behoudswetten

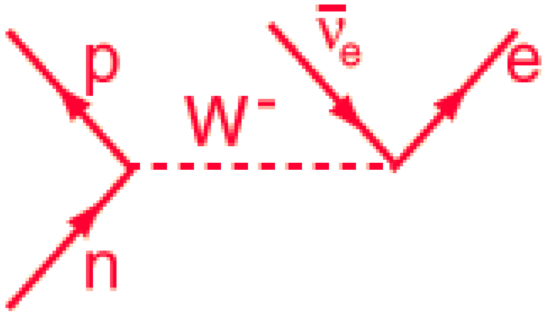


<< 0.0000000001 [m]
Veel energie per deeltje

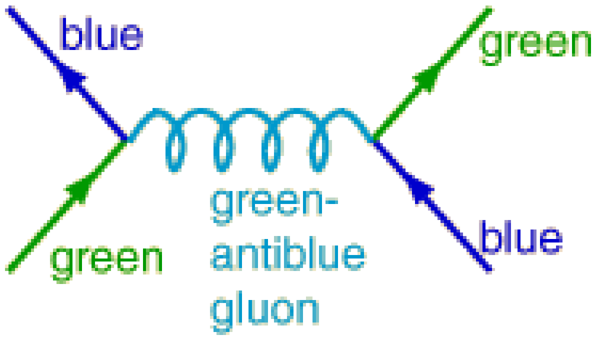
Fundamentele interacties



Electromagnetisme:
uitwisseling fotonen



Zwakke kracht:
uitwisseling W, Z deeltjes



Sterke kracht:
uitwisseling gluonen

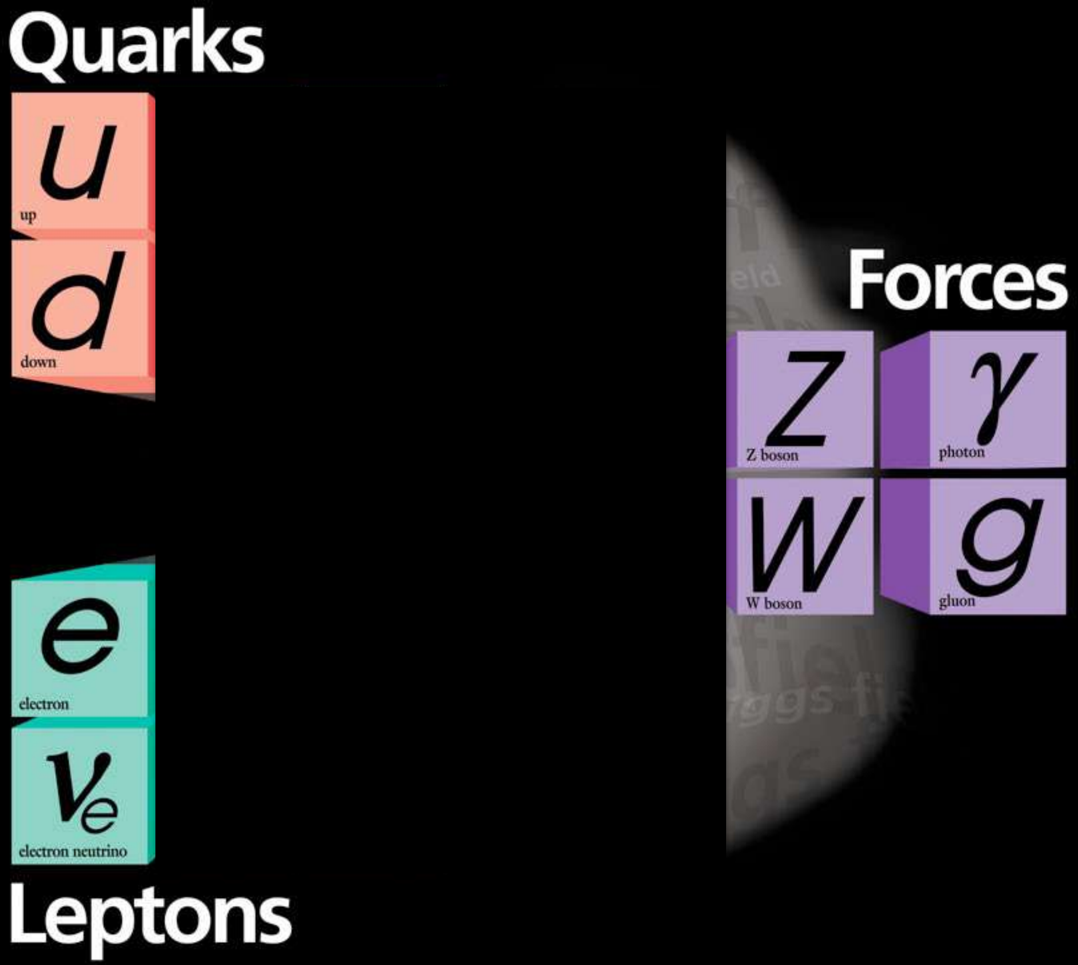
Zwaartekracht:

Uitwisseling gravitonen?

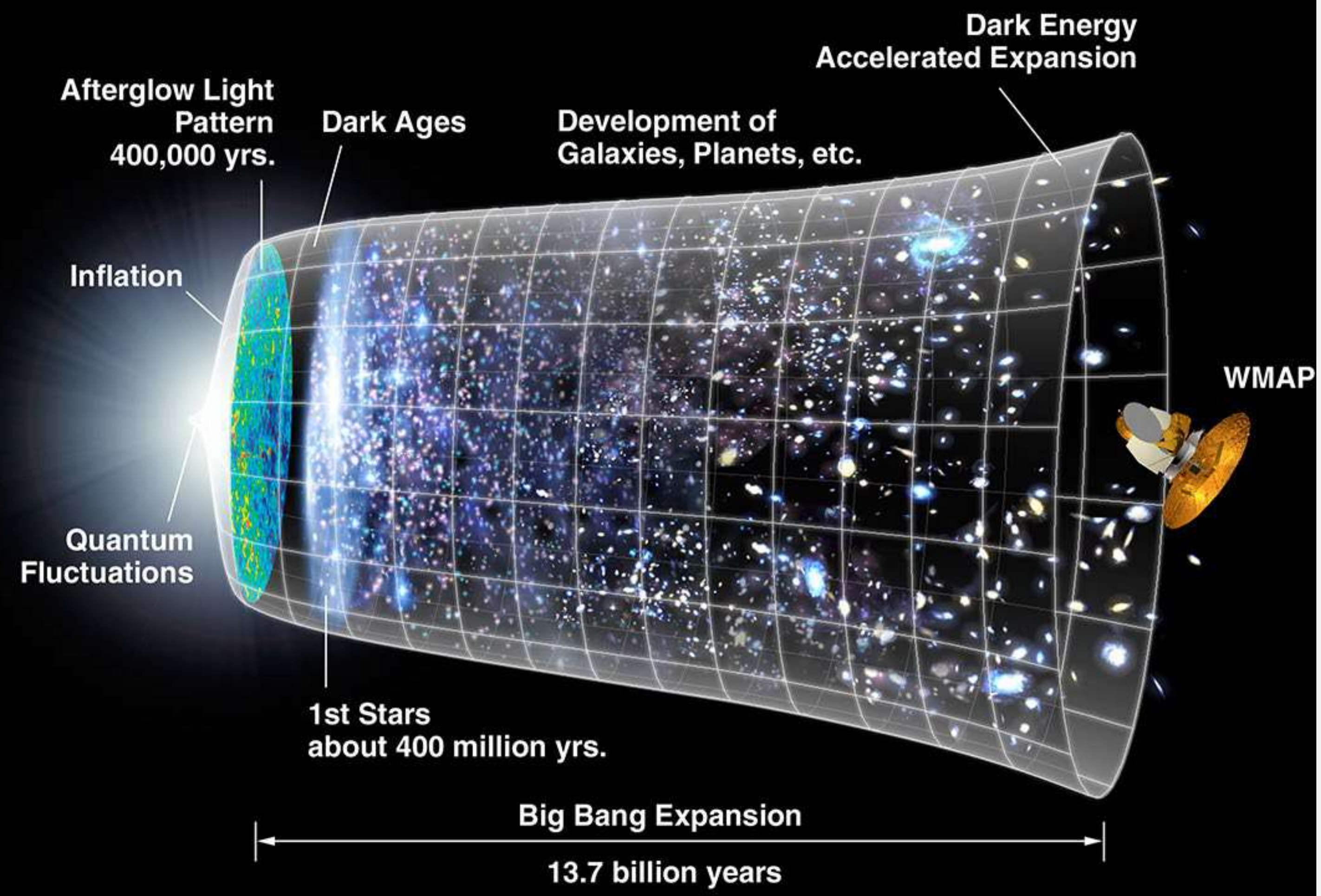
0.000000000000000000000
00000000000000000000001
x zo klein als de Elektrische
kracht

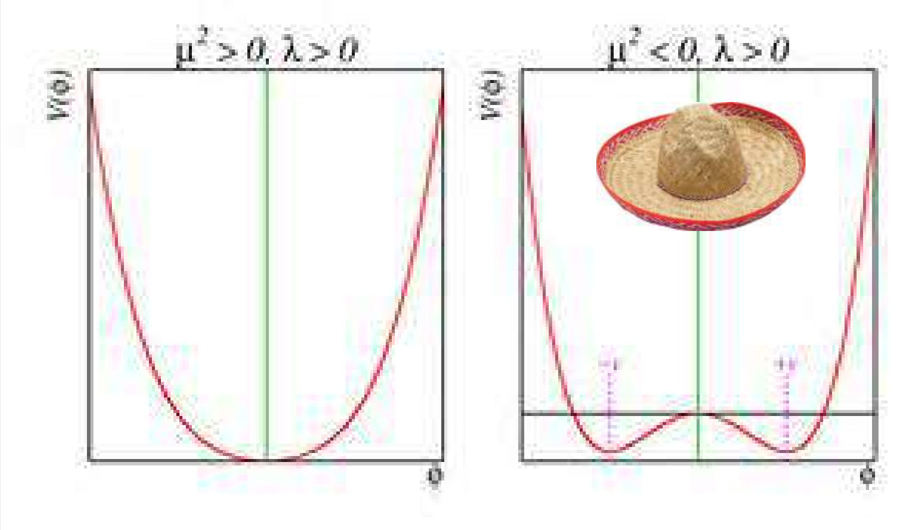
Massa blijft een mysterie…

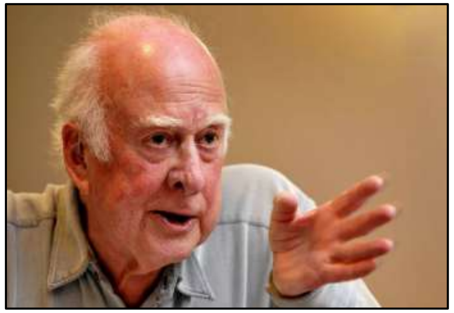
Standaardmodel - Compleet



Higgs mechanisme







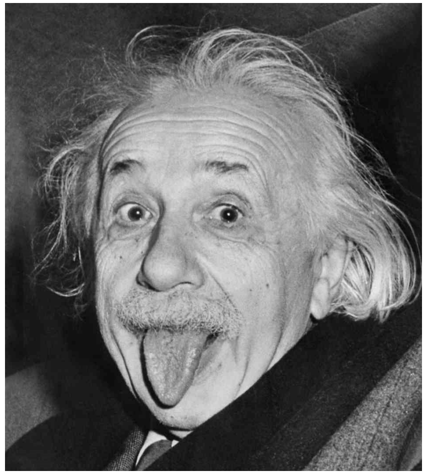
Peter Higgs: er is een scalair veld dat andere deeltjes massa geeft. (Een Veld bestaat uit virtuele deeltjes.)

Standaard Model Lagrangiaan

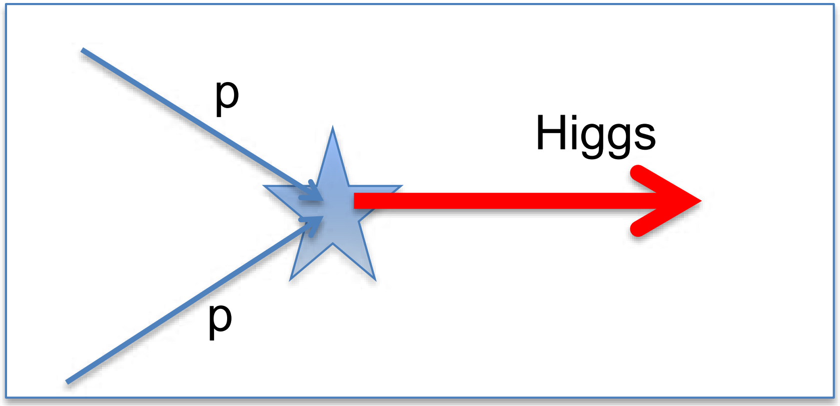
$$SU(2)_L \otimes U(1)_Y \otimes SU(3)_C$$

$$-\frac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \frac{1}{4}g_s^2 f^{abc}f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \frac{1}{2}ig_s^2(\bar{q}^\sigma_i \gamma^\mu q^\sigma_j)g^a_\mu +$$
$$\bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - M^2 W^+_\mu W^-_\mu - \frac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \frac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu -$$
$$\frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2}\partial_\mu H \partial_\mu H - \frac{1}{2}m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2 \phi^+\phi^- - \frac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 -$$
$$\frac{1}{2c_w^2}M\phi^0\phi^0 - \beta_h\left[\frac{2M^2}{g^2} + \frac{2M}{g}H + \frac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)\right] + \frac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu -$$
$$W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu(W^+_\mu W^-_\nu -$$
$$W^+_\nu W^-_\mu) - A_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + A_\mu(W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)] - \frac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu +$$
$$\frac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu -$$
$$A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w[A_\mu Z^0_\nu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 +$$
$$H\phi^0\phi^0 + 2H\phi^+\phi^-] - \frac{1}{8}g^2\alpha_h[H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- +$$
$$2(\phi^0)^2H^2] - gMW^+_\mu W^-_\mu H - \frac{1}{2}g\frac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \frac{1}{2}ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ -$$
$$\phi^+\partial_\mu\phi^0)] + \frac{1}{2}g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)] + \frac{1}{2}g\frac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 -$$
$$\phi^0\partial_\mu H) - ig\frac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + igs_w MA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\frac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- -$$
$$\phi^-\partial_\mu\phi^+) + igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \frac{1}{4}g^2 W^+_\mu W^-_\mu[H^2 + (\phi^0)^2 + 2\phi^+\phi^-] -$$
$$\frac{1}{4}g^2\frac{1}{c_w^2}Z^0_\mu Z^0_\mu[H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2\phi^+\phi^-] - \frac{1}{2}g^2\frac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) -$$
$$\frac{1}{2}ig^2\frac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \frac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) + \frac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- -$$
$$W^-_\mu\phi^+) - g^2\frac{s_w}{c_w}(2c_w^2 - 1)Z^0_\mu A_\mu\phi^+\phi^- - g^1 s_w^2 A_\mu A_\mu\phi^+\phi^- - \bar{e}^\lambda(\gamma\partial + m_e^\lambda)e^\lambda -$$
$$\bar{\nu}^\lambda\gamma\partial\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + m_u^\lambda)u^\lambda_j - \bar{d}^\lambda_j(\gamma\partial + m_d^\lambda)d^\lambda_j + igs_w A_\mu[-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \frac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) -$$
$$\frac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)] + \frac{ig}{4c_w}Z^0_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2 - 1 - \gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(\frac{4}{3}s_w^2 -$$
$$1 - \gamma^5)u^\lambda_j) + (\bar{d}^\lambda_j\gamma^\mu(1 - \frac{8}{3}s_w^2 - \gamma^5)d^\lambda_j)] + \frac{ig}{2\sqrt{2}}W^+_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(1 +$$
$$\gamma^5)C_{\lambda\kappa}d^\kappa_j)] + \frac{ig}{2\sqrt{2}}W^-_\mu[(\bar{e}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\lambda\kappa}\gamma^\mu(1+\gamma^5)u^\lambda_j)] + \frac{ig}{2\sqrt{2}}\frac{m_e^\lambda}{M}[-\phi^+(\bar{\nu}^\lambda(1-$$
$$\gamma^5)e^\lambda) + \phi^-(\bar{e}^\lambda(1+\gamma^5)\nu^\lambda)] - \frac{g}{2}\frac{m_e^\lambda}{M}[H(\bar{e}^\lambda e^\lambda) + i\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda)] + \frac{ig}{2M\sqrt{2}}\phi^+[-m_d^\kappa(\bar{u}^\lambda_j C_{\lambda\kappa}(1-$$
$$\gamma^5)d^\kappa_j) + m_u^\lambda(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j] + \frac{ig}{2M\sqrt{2}}\phi^-[m_d^\lambda(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m_u^\kappa(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1-$$
$$\gamma^5)u^\kappa_j] - \frac{g}{2}\frac{m_u^\lambda}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \frac{g}{2}\frac{m_d^\lambda}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \frac{ig}{2}\frac{m_u^\lambda}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) - \frac{ig}{2}\frac{m_d^\lambda}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) +$$
$$\bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 - \frac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2 Y + igc_w W^+_\mu(\partial_\mu\bar{X}^0 X^- -$$
$$\partial_\mu\bar{X}^+ X^0) + igs_w W^+_\mu(\partial_\mu\bar{Y}X^- - \partial_\mu\bar{X}^+ Y) + igc_w W^-_\mu(\partial_\mu\bar{X}^- X^0 - \partial_\mu\bar{X}^0 X^+) +$$
$$igs_w W^-_\mu(\partial_\mu\bar{X}^- Y - \partial_\mu\bar{Y}X^+) + igc_w Z^0_\mu(\partial_\mu\bar{X}^+ X^+ - \partial_\mu\bar{X}^- X^-) + igs_w A_\mu(\partial_\mu\bar{X}^+ X^+ -$$
$$\partial_\mu\bar{X}^- X^-) - \frac{1}{2}gM[\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w^2}\bar{X}^0 X^0 H] + \frac{1-2c_w^2}{2c_w}igM[\bar{X}^+ X^0\phi^+ -$$
$$\bar{X}^- X^0\phi^-] + \frac{1}{2c_w}igM[\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-] + igMs_w[\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-] +$$
$$\frac{1}{2}igM[\bar{X}^+ X^+\phi^0 - \bar{X}^- X^-\phi^0]$$

Hoe maak je een zwaar deeltje?



$$E = mc^2$$



Nodig:

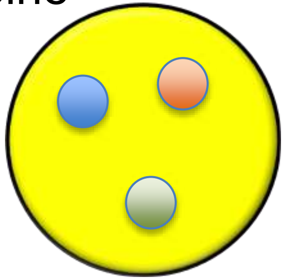
Deeltjes-botser
+
Deeltjes-detector
=
CERN LHC+ATLAS

LHC versneller:
protonenergie 7000GeV
ATLAS detector:
State-of-the-art detection

Massa Higgs deeltje 125 GeV
Massa proton 1 GeV

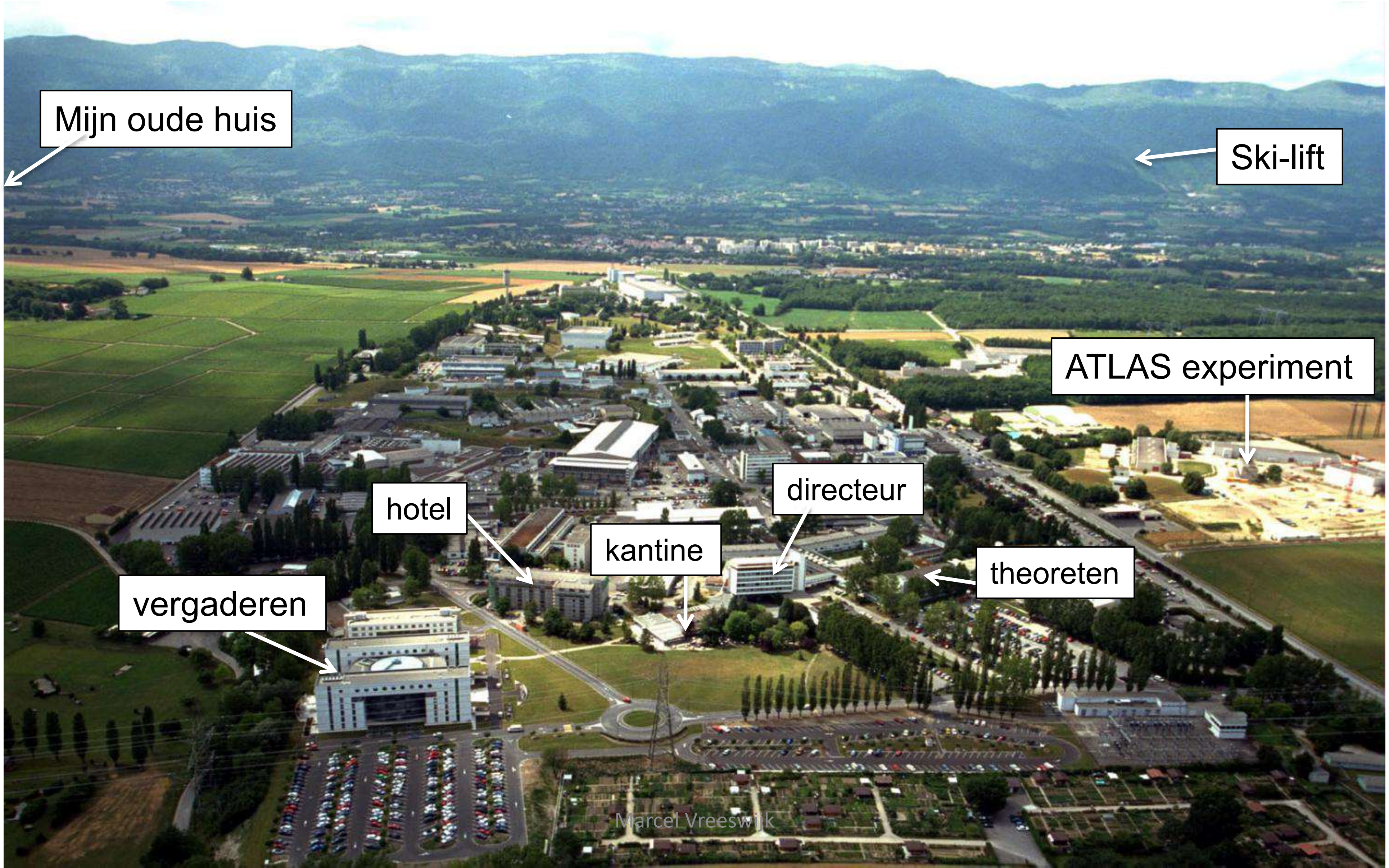
Energie per proton E=7000 GeV
Beschikbaar 2E=14000GeV (14TeV)

Toch niet makkelijk:
Quarks dragen maar kleine fractie *x* van de energie

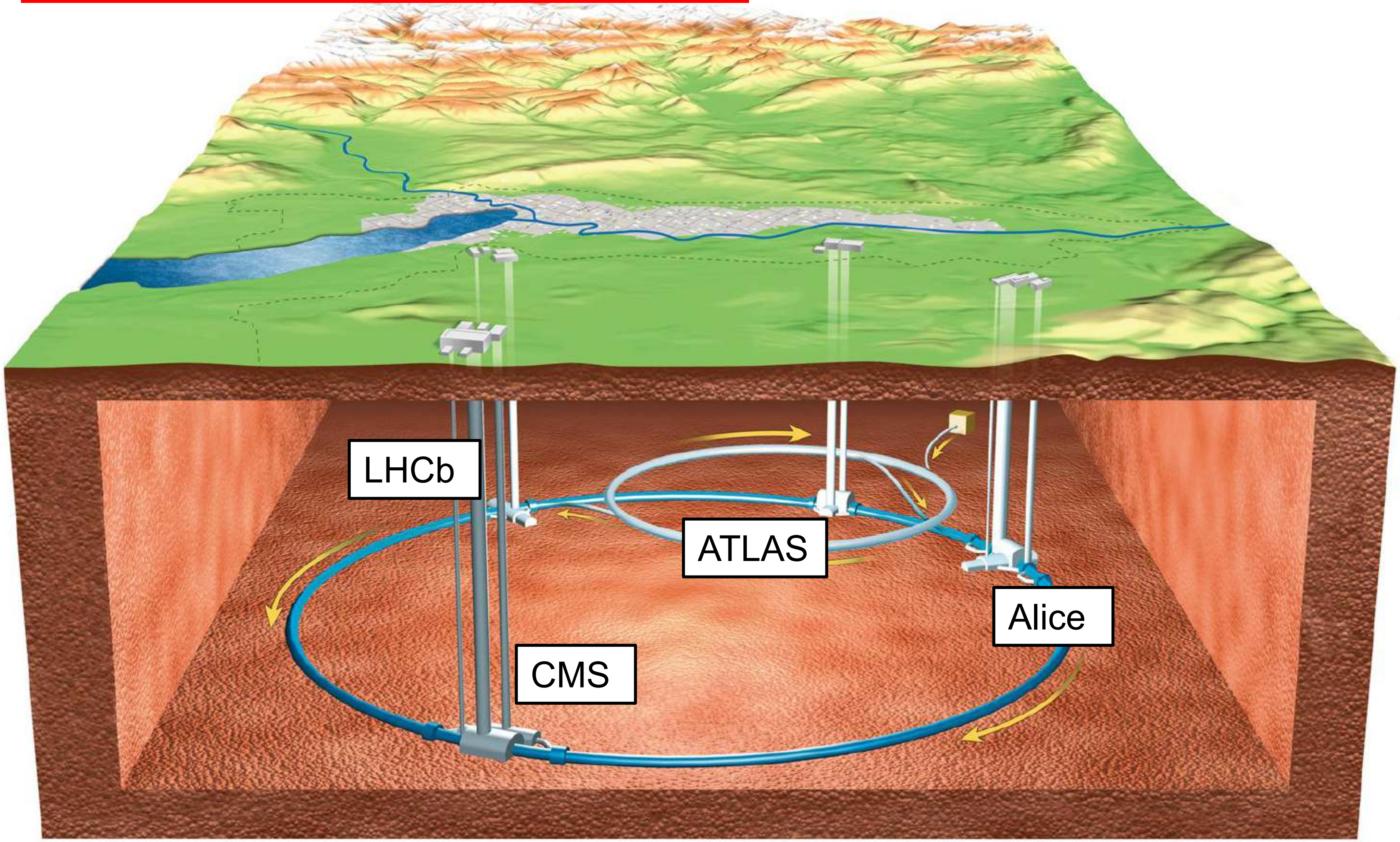


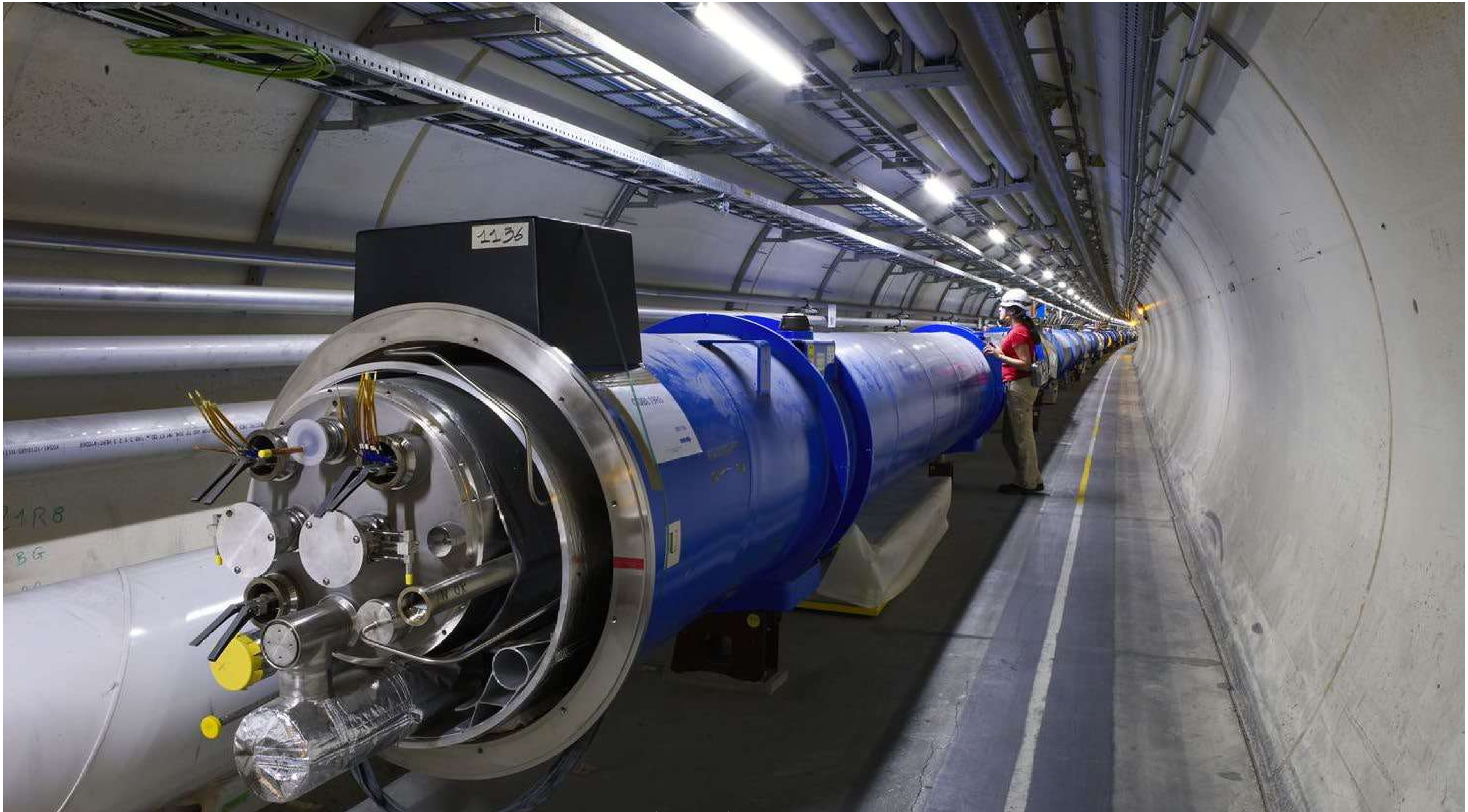
Beschikbare energie *x2E* met *x*~0.01

CERN in Genève, Zwitserland



De Large hadron collider





Marcel Vreeswijk

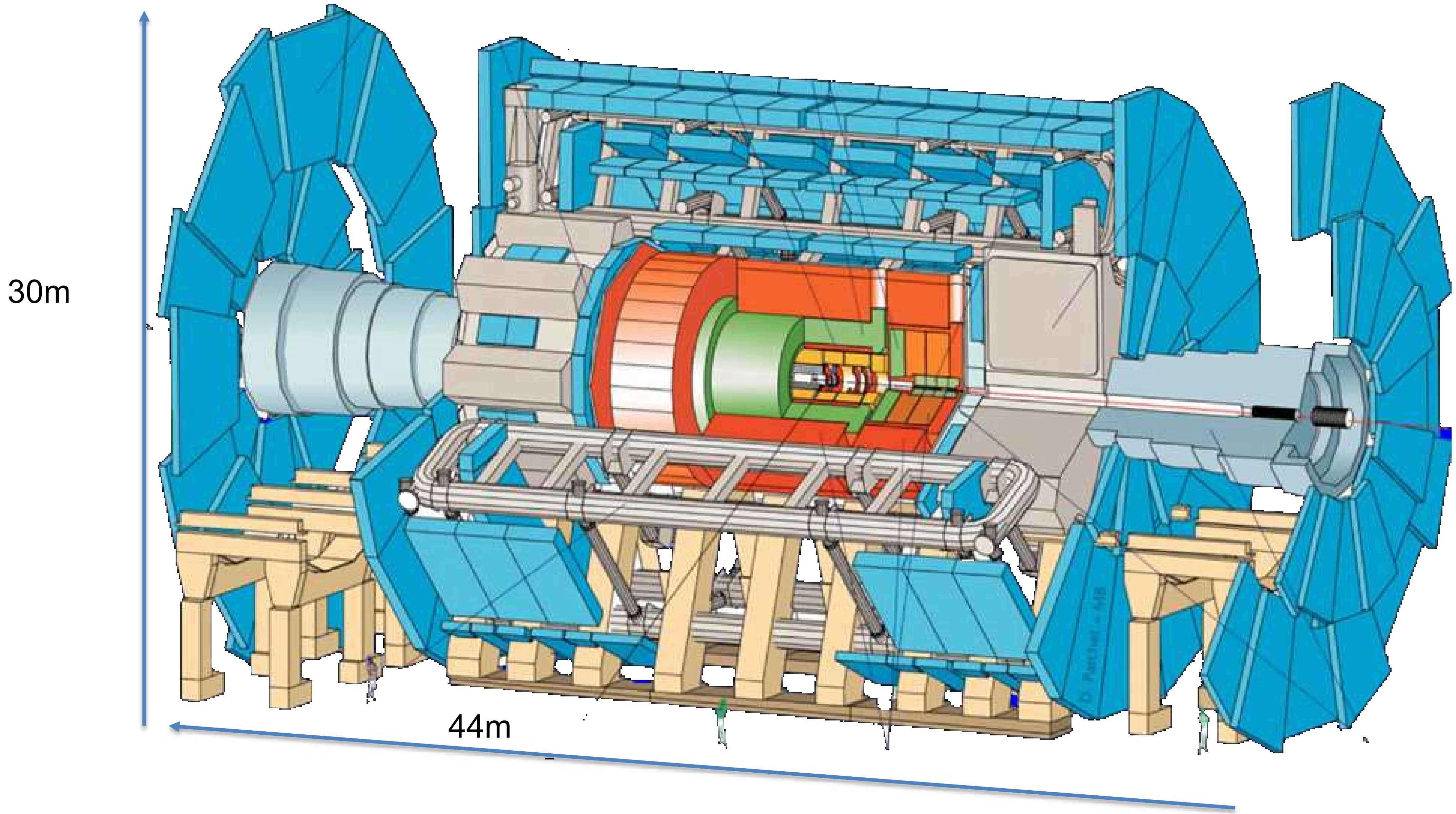
De Large Hadron Collider

Check: proton massa 1 GeV, Energie 7000GeV → v=0.99999 c
11000 rondjes per seconde

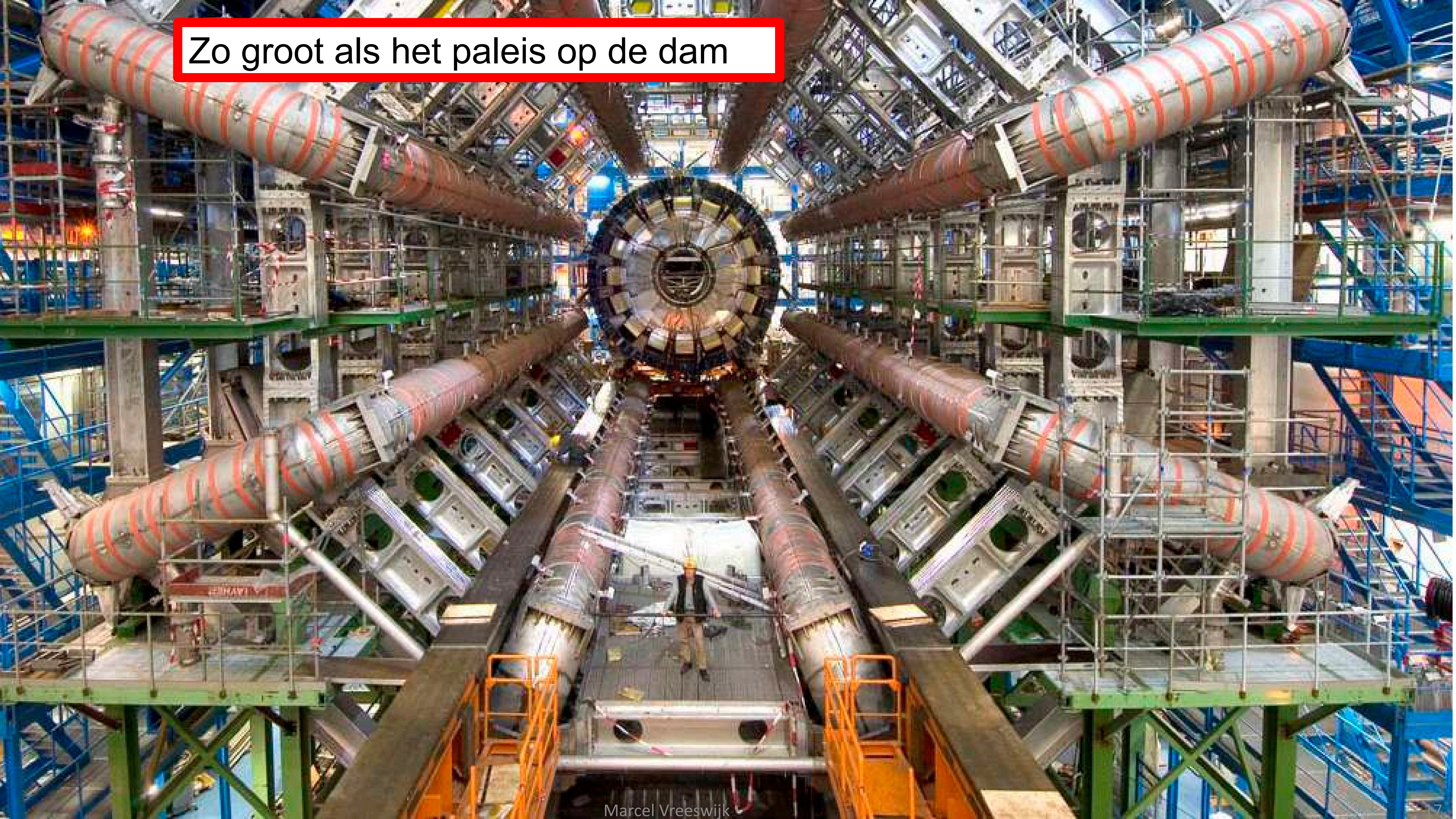
LHC: 27 km

A10: 32 km

ATLAS

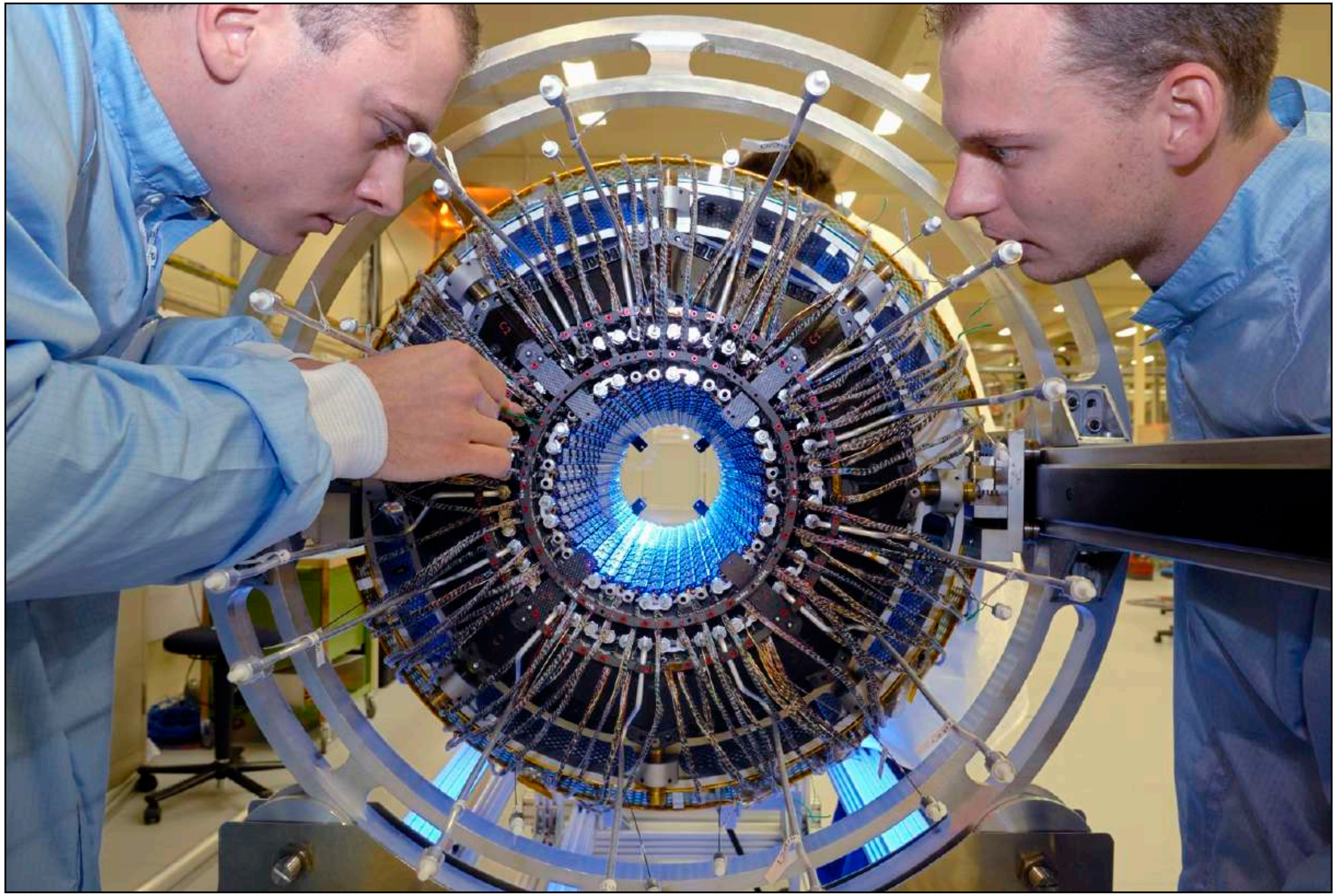


Zo groot als het paleis op de dam



Marcel Vreeswijk

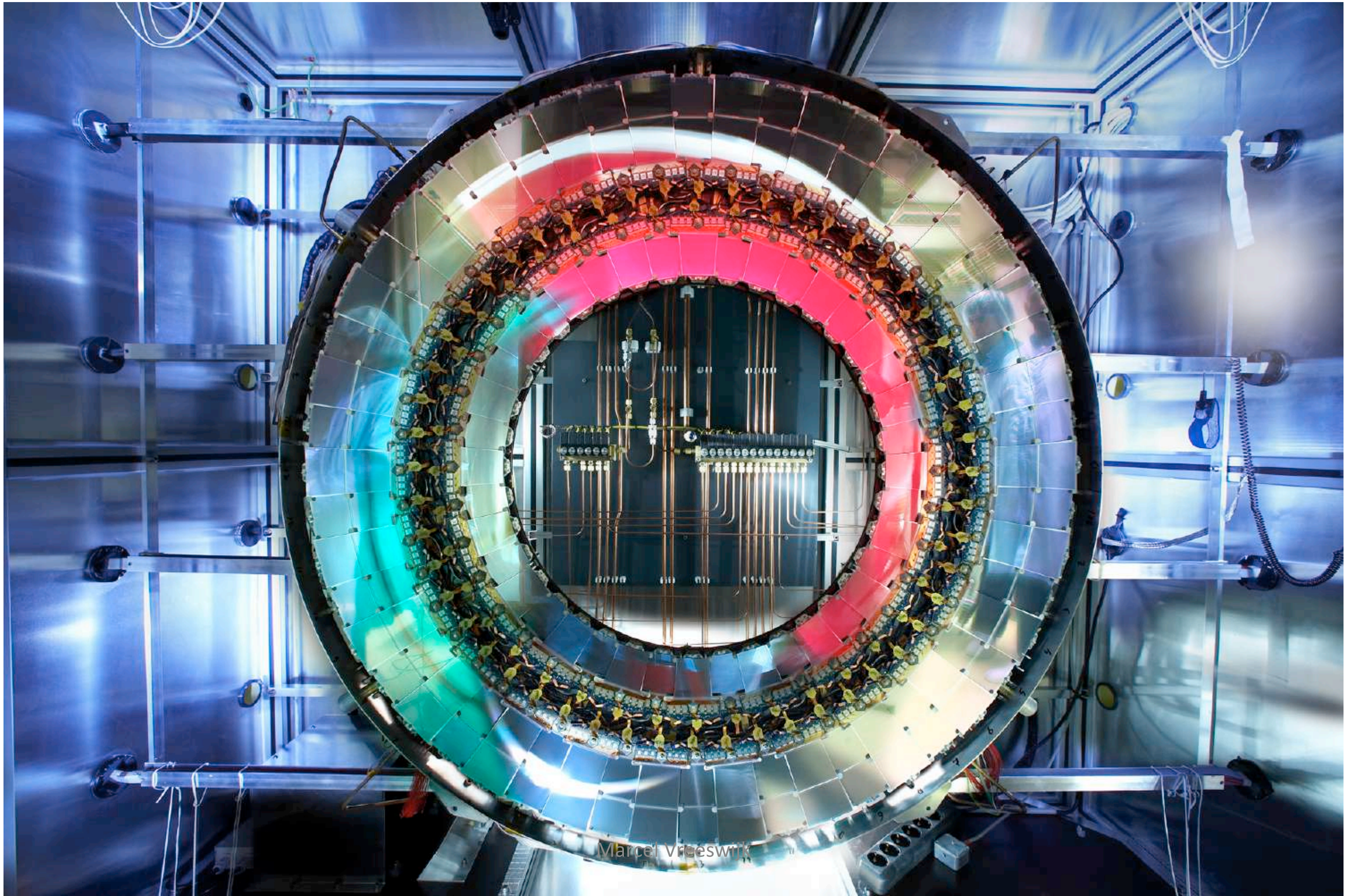
De Atlas pixel detector



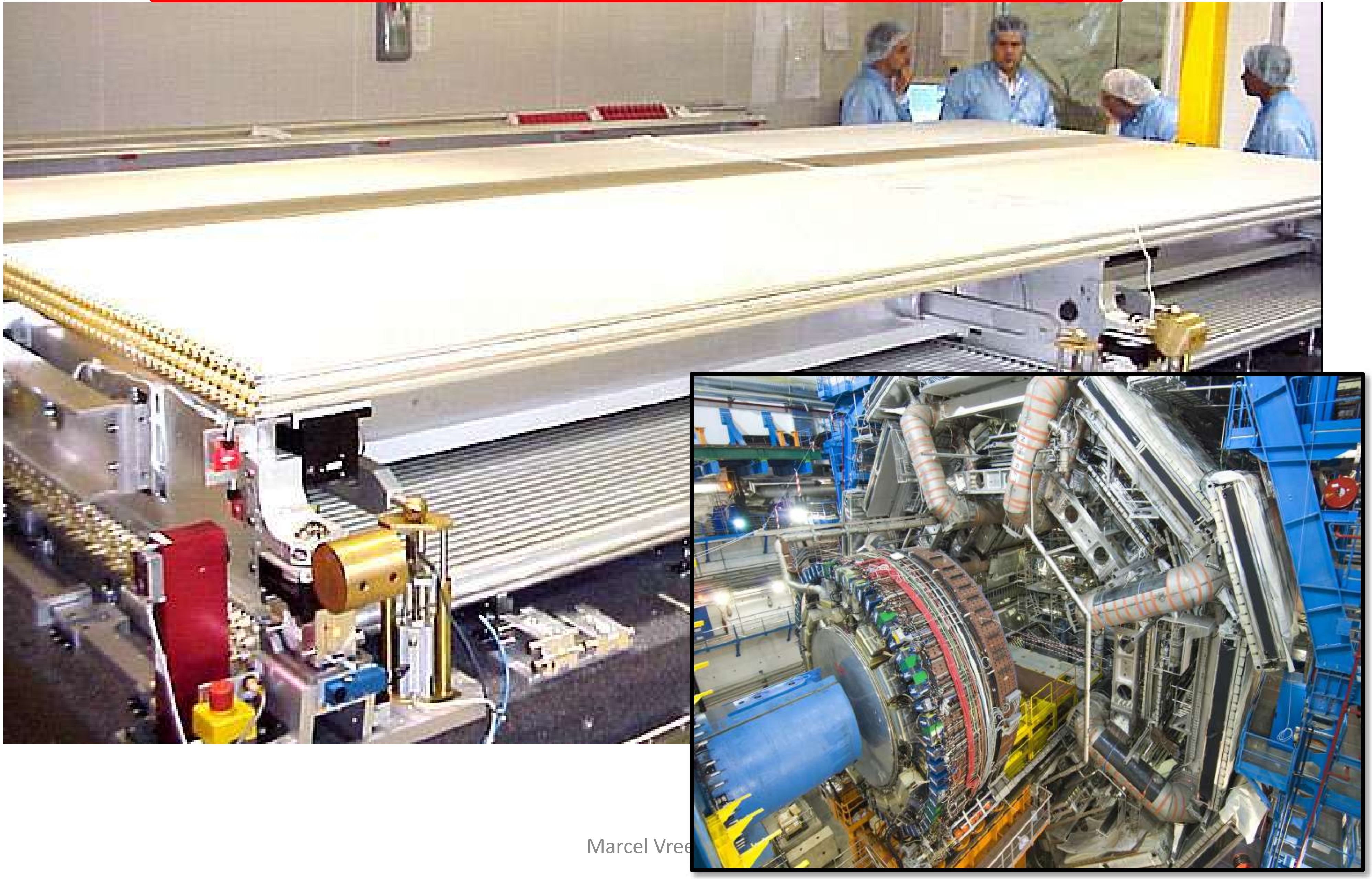
80 MegaPixel camera 40.000.000 foto's per seconde

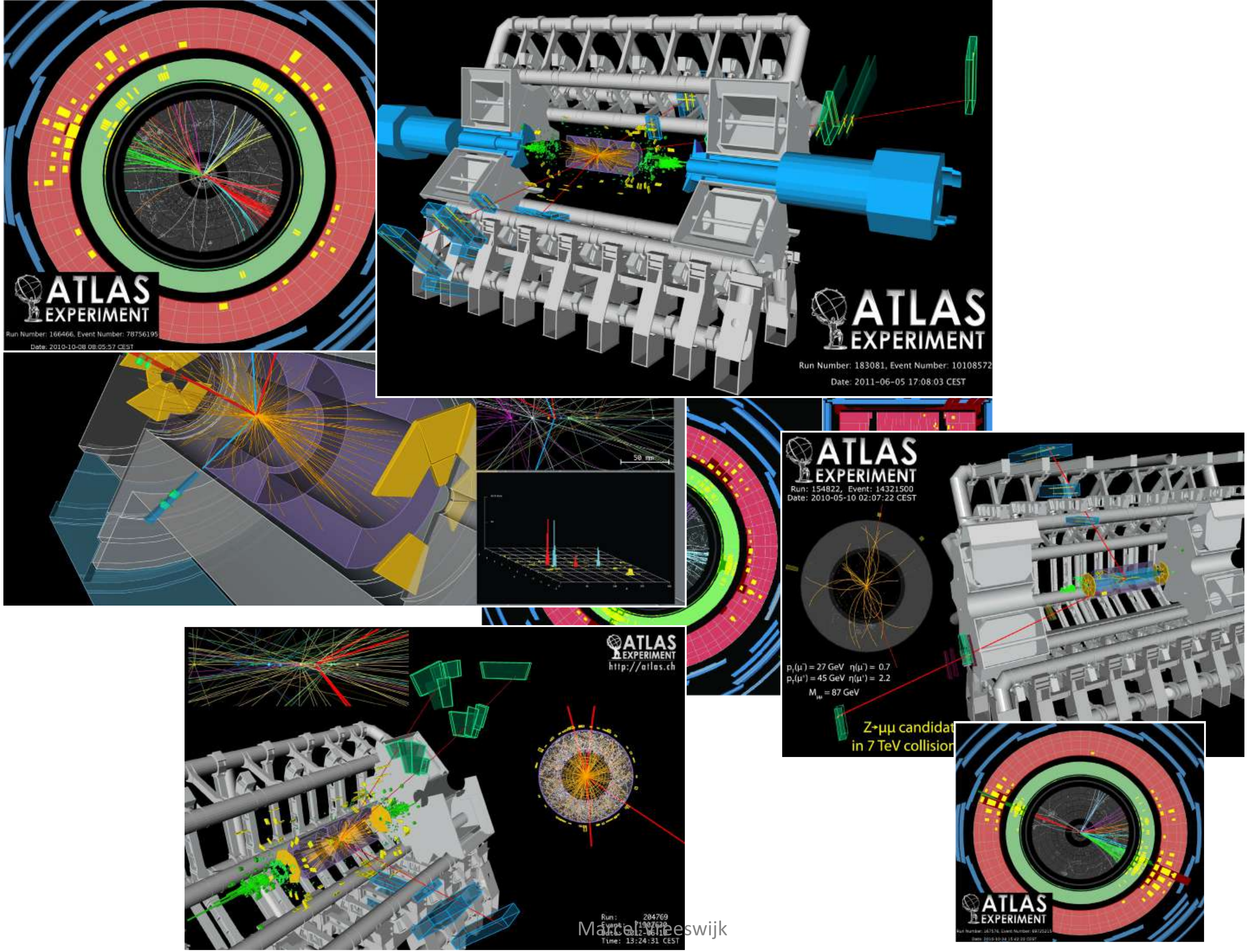
Deel ATLAS detector is gemaakt in o.a. Nederland

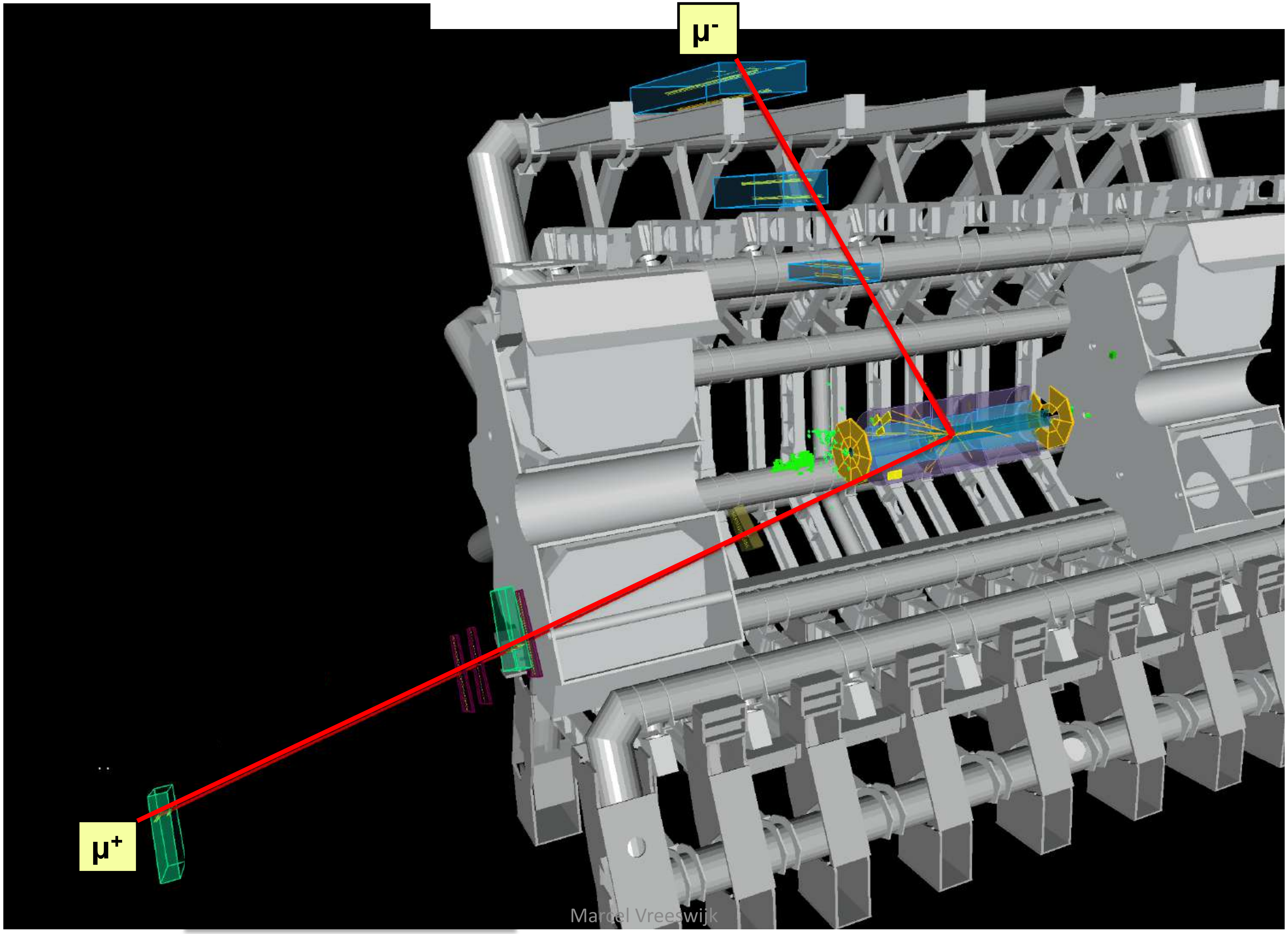
Deel ATLAS detector is bedacht en gemaakt in Nederland



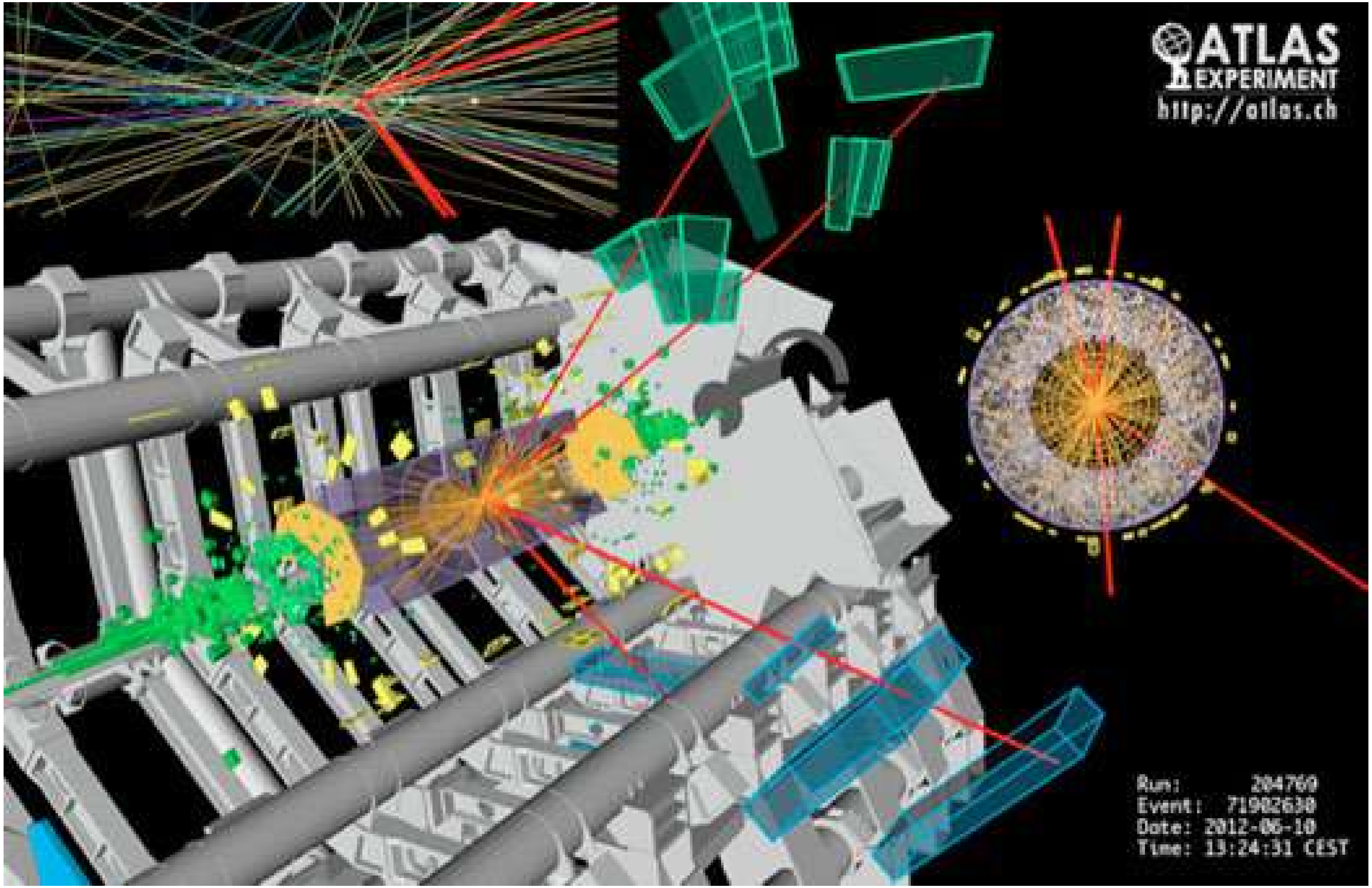
De ATLAS muon detectoren zijn in NL gemaakt!

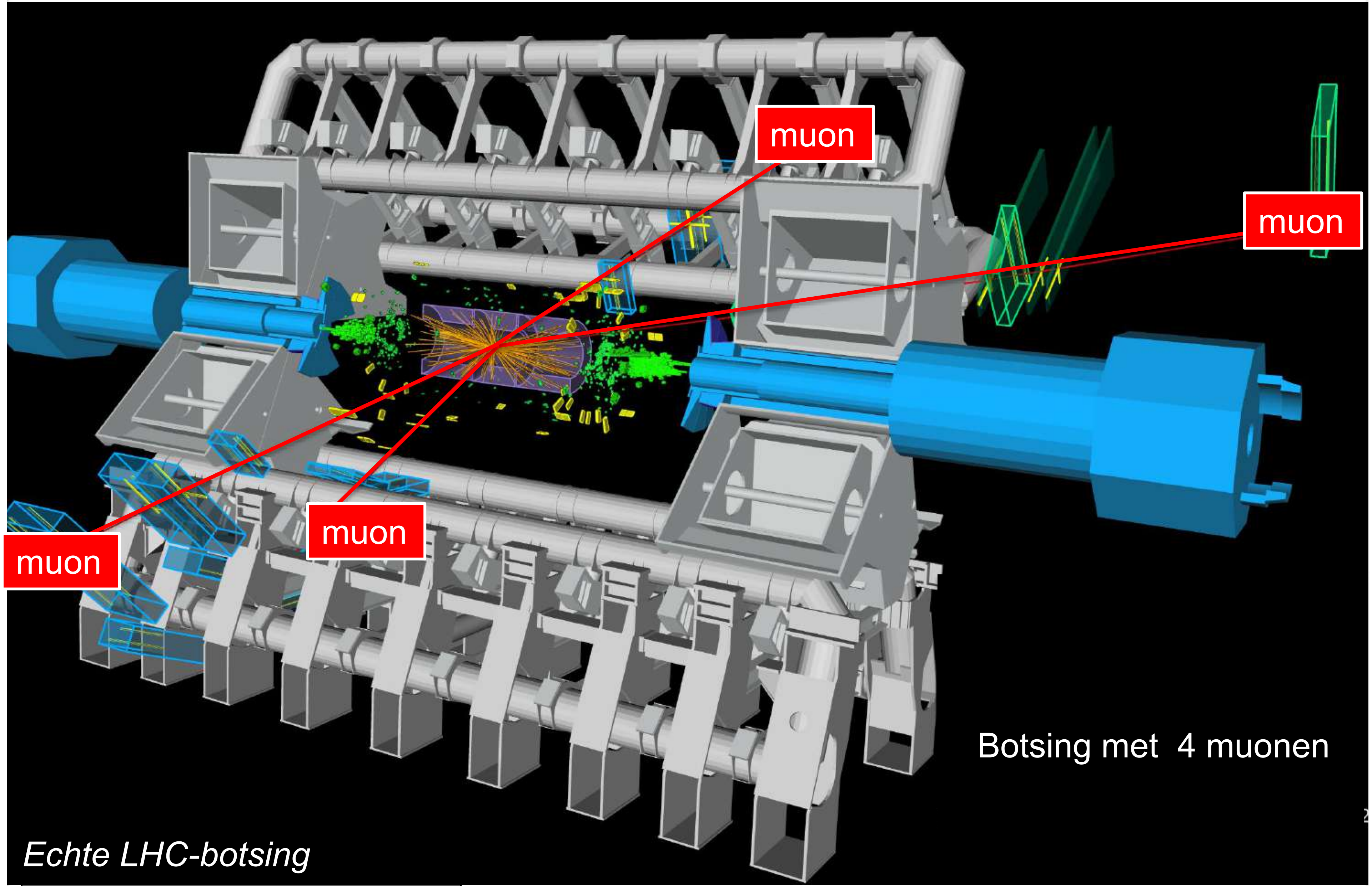



ATLAS EXPERIMENT
Run Number: 166466, Event Number: 78756195
Date: 2010-10-08 08:05:57 CEST
ATLAS EXPERIMENT
Run Number: 183081, Event Number: 10108572
Date: 2011-06-05 17:08:03 CEST
ATLAS EXPERIMENT
Run: 154822, Event: 14321500
Date: 2010-05-10 02:07:22 CEST
$p_T(\mu^-) = 27$ GeV $\eta(\mu^-) = 0.7$
$p_T(\mu^+) = 45$ GeV $\eta(\mu^+) = 2.2$
$M_{\mu\mu} = 87$ GeV
Z→μμ candidat
in 7 TeV collision
ATLAS EXPERIMENT
http://atlas.ch
Run: 204769
Time: 13:24:31 CEST
ATLAS EXPERIMENT



μ-
μ+

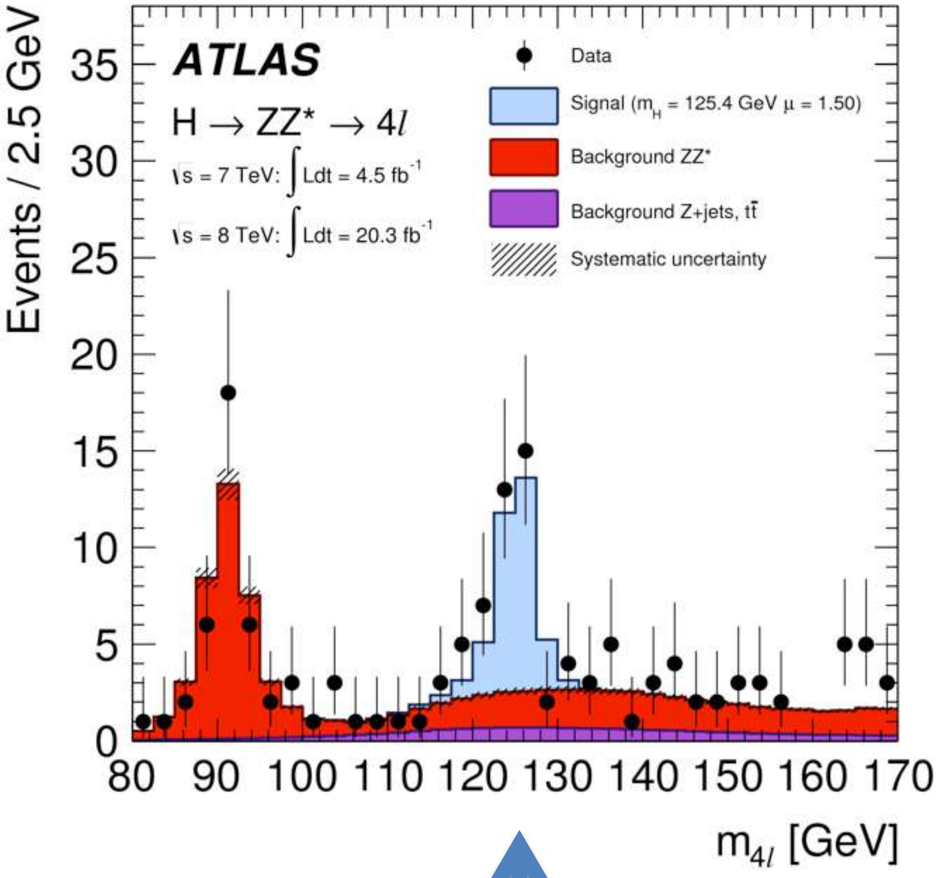

ATLAS
EXPERIMENT
http://atlas.ch
Run: 204769
Event: 71902630
Date: 2012-06-10
Time: 13:24:31 CEST



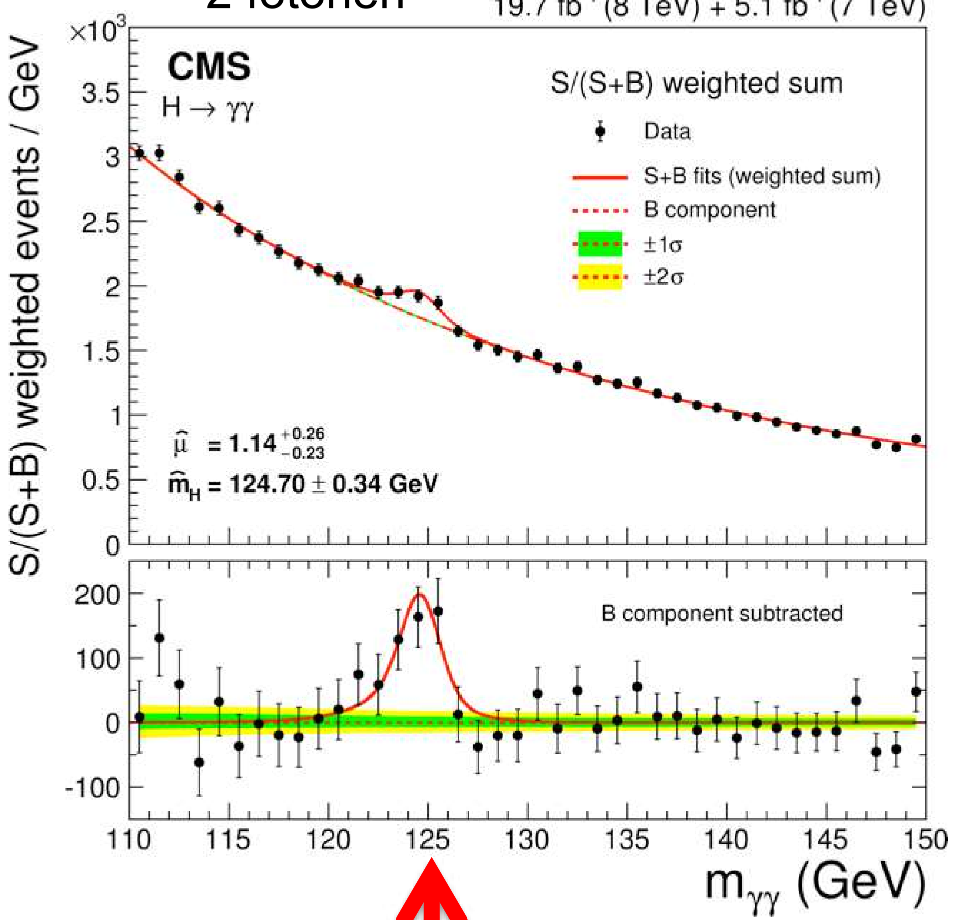
Higgs boson kandidaat

Een heleboel botsingen in een grafiek

4 muonen



2 fotonen

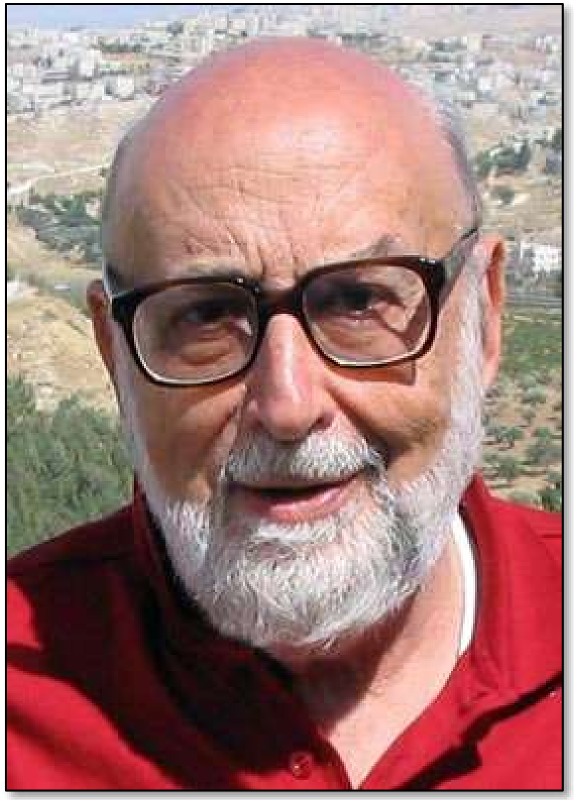


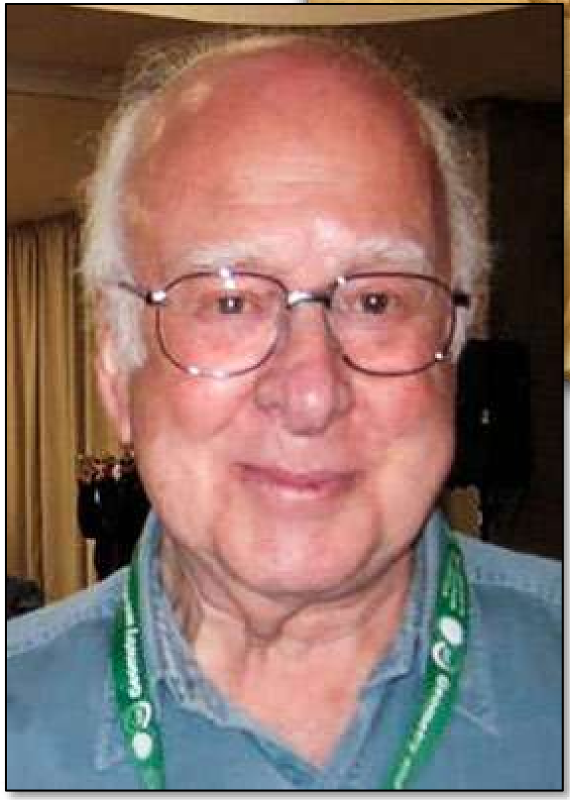
MH = 125.09 ± 0.24 GeV [±0.21 (stat.) ±0.11(syst.)]

4 juli 2012: “Ladies and Gentlemen, we got him”

Nobelprijs natuurkunde 2013

“Er is een Higgs veld in het vacuum”

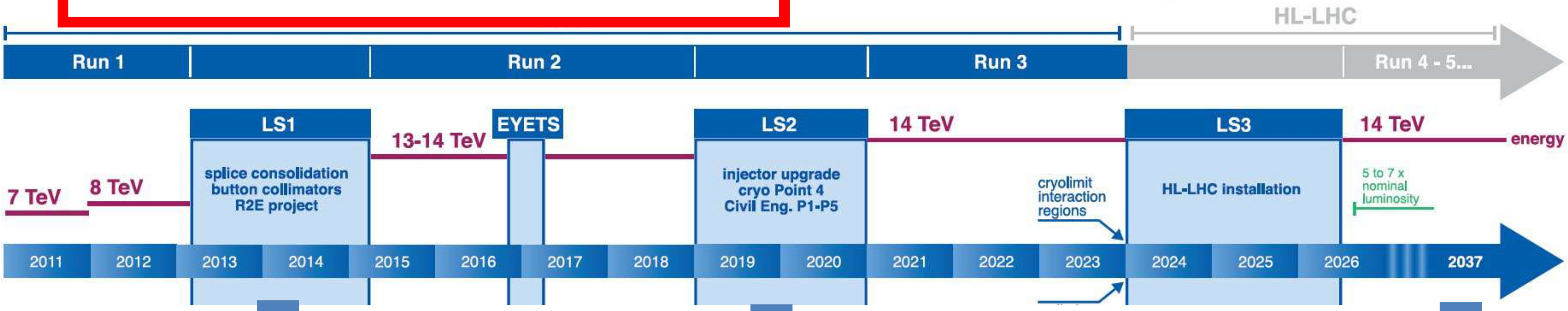




Problemen:

- Standaard Model bij hele hoge energie toevallig stabiel?
- Waar is alle anti-materie (gebleven) sinds de oerknal?
- Wat is zwaartekracht? Zijn er meer dan 3(+1) dimensies?
- Wat is de mysterieuze donkere energie en donkere materie?

LARGE HADRON COLLIDER



LHC HIGGS GEVONDEN

~30 fb^{-1}

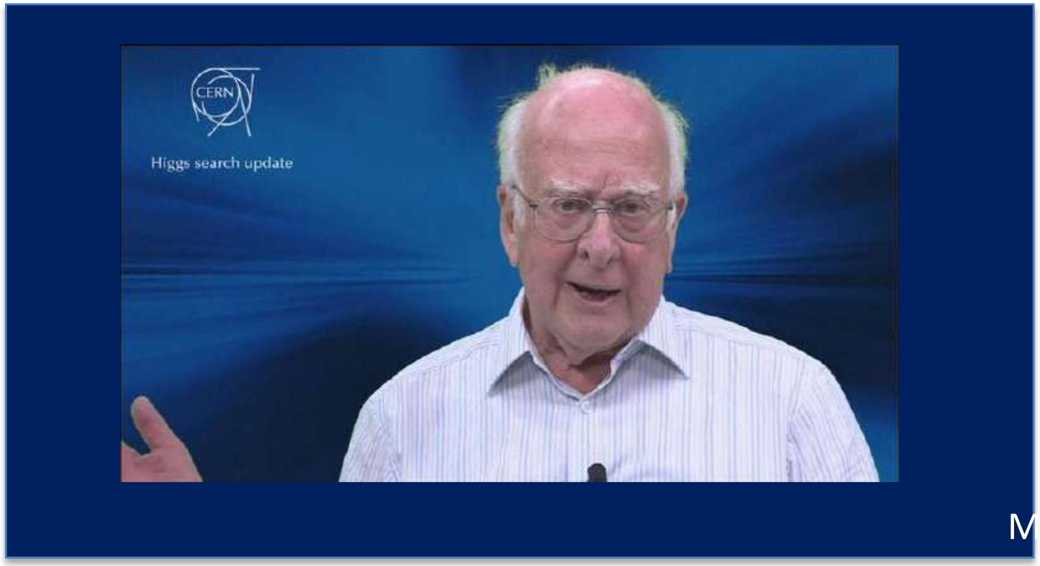
LHC VANDAAG

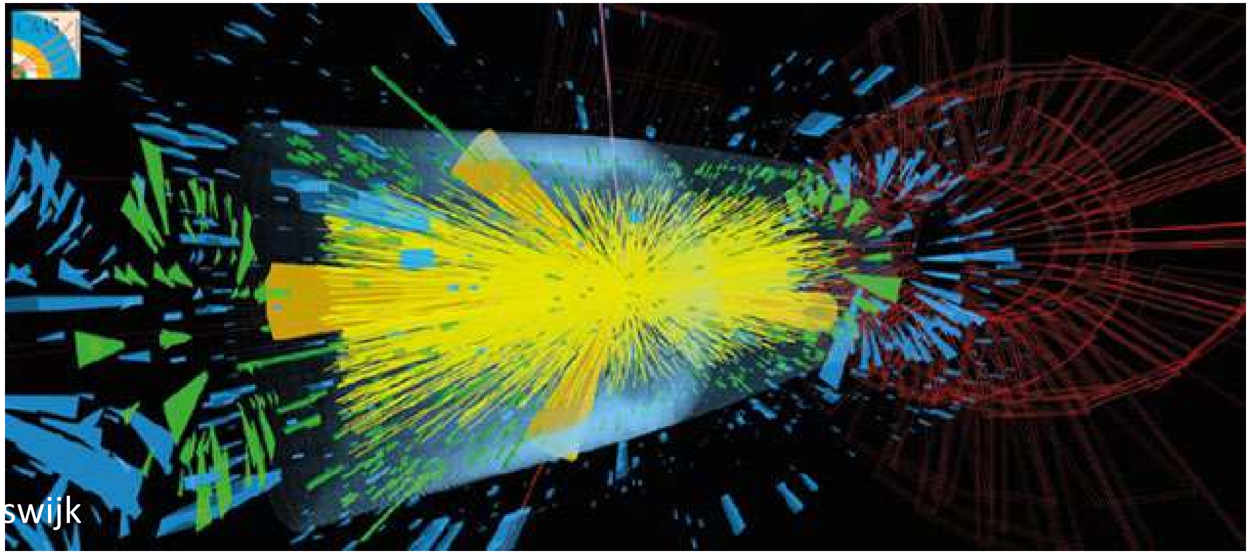
~150 fb^{-1}

Uitdaging: vele deeltjes, overlappende botsingen

HL-LHC

~3000 fb^{-1}

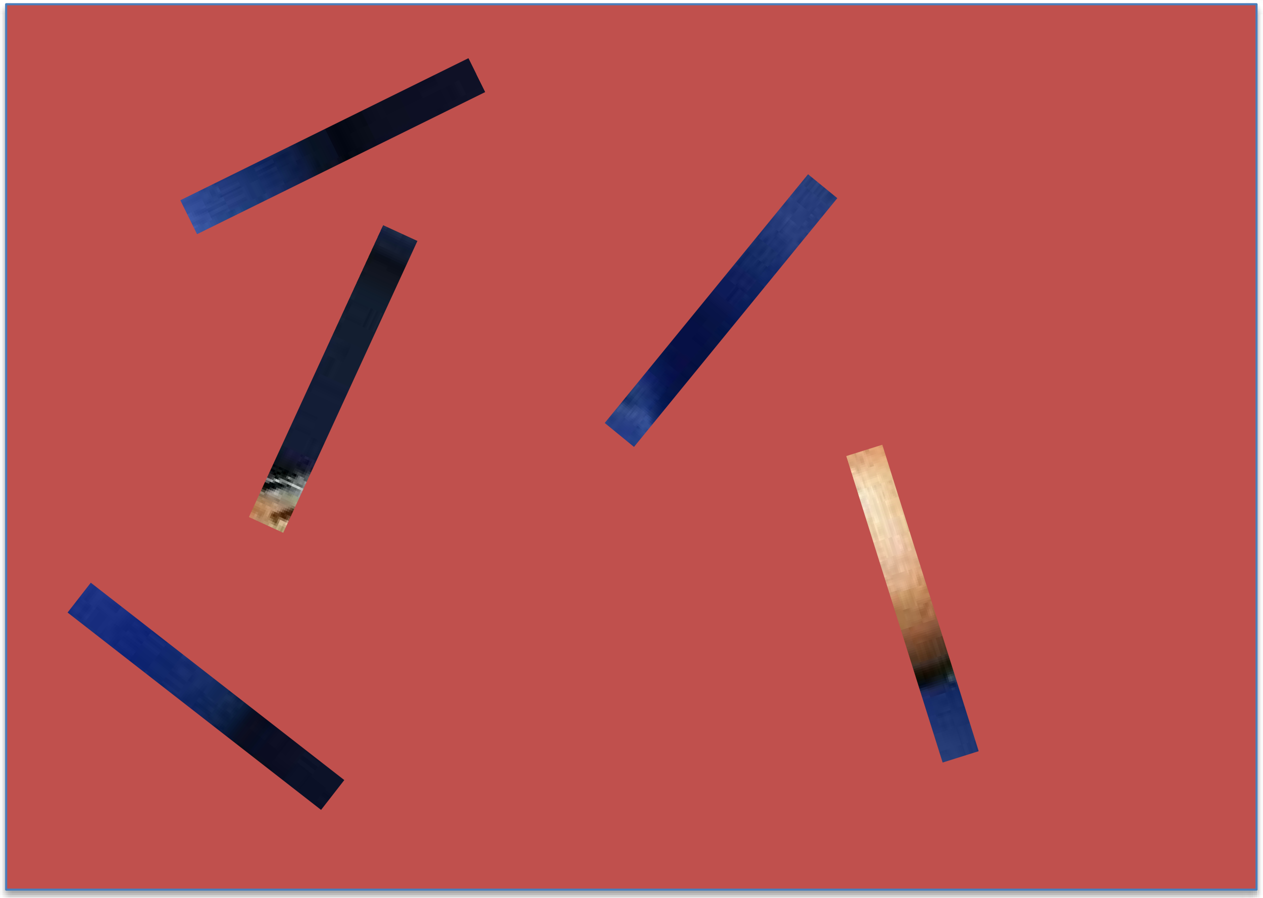




WE HAVE SEEN ONLY <5% OF ALL STATISTICS YET

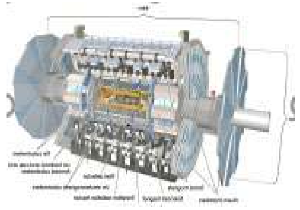
LHC 5%

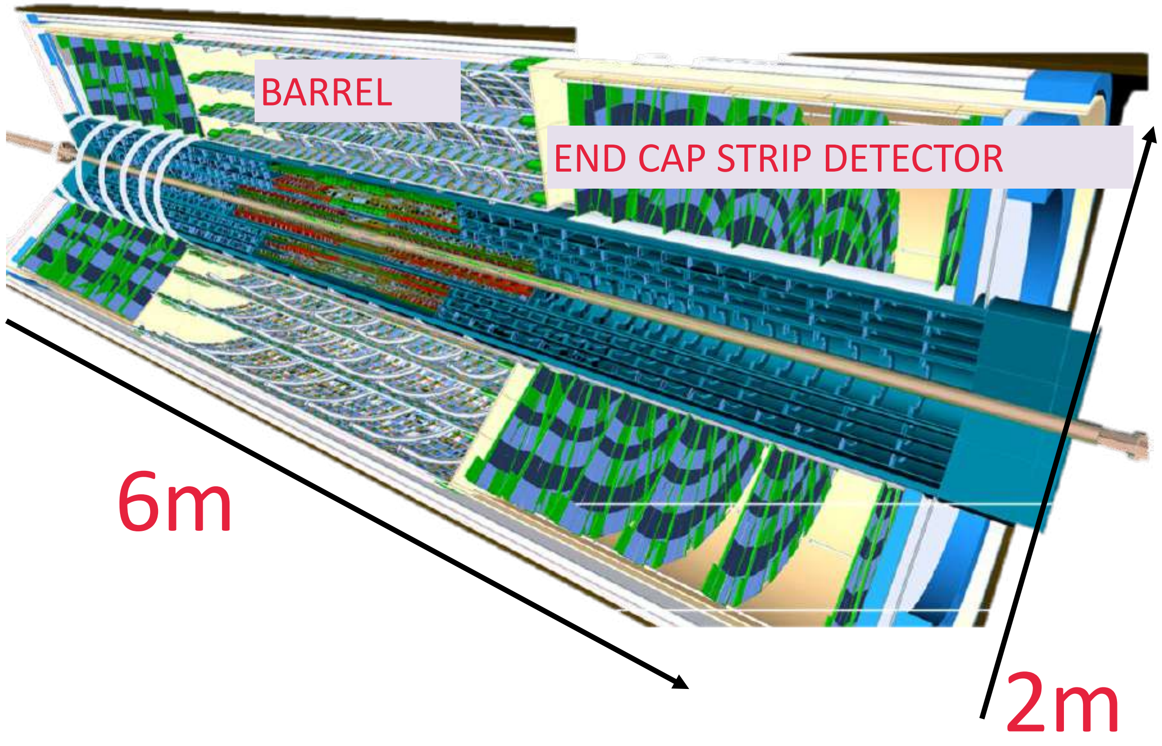
HL-LHC 100%



Veel statistiek betekent extreme precisie met HL-LHC

HL-LHC → UPGRADES NEEDED





At Nikhef:
two EC strip detectors

"SHORT" PROTOTYPE

- PROGRAMMA'S VOOR DOCENTEN EN SCHOLIEREN:

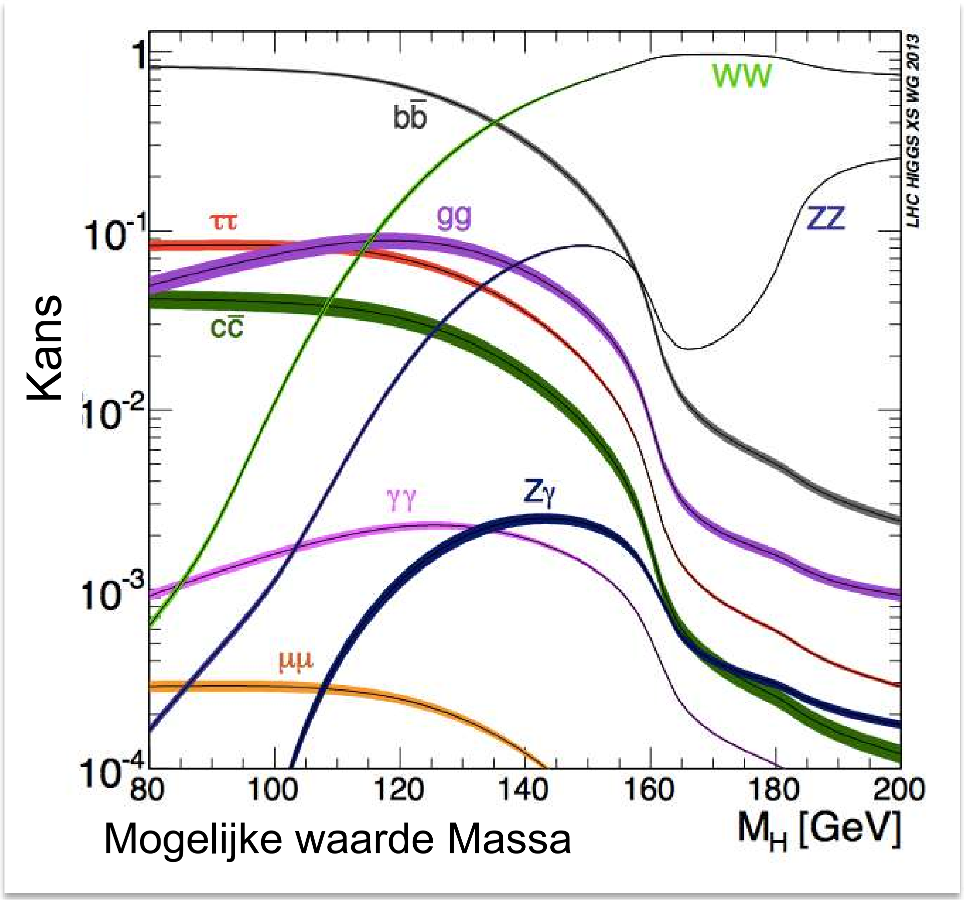
- Voor natuurkundedocenten bovenbouw havo/vwo
- Bezoek CERN
- 23 t/m 27 december 2020
- www.nikhef.nl/docenten

- Voor leerlingen bovenbouw vwo
- Lezingen en zelf aan de slag met échte onderzoeksdata
- Op Nikhef (Amsterdam)
- 26 maart 2020
- www.nikhef.nl/leerlingen

Samenvatting

De natuur zit vol vreemde spelregels
Er zijn nog vele vragen
De LHC gaat binnenkort weer van start

Schitterend avontuur de komende jaren!



1 op de
10000000000
botsingen

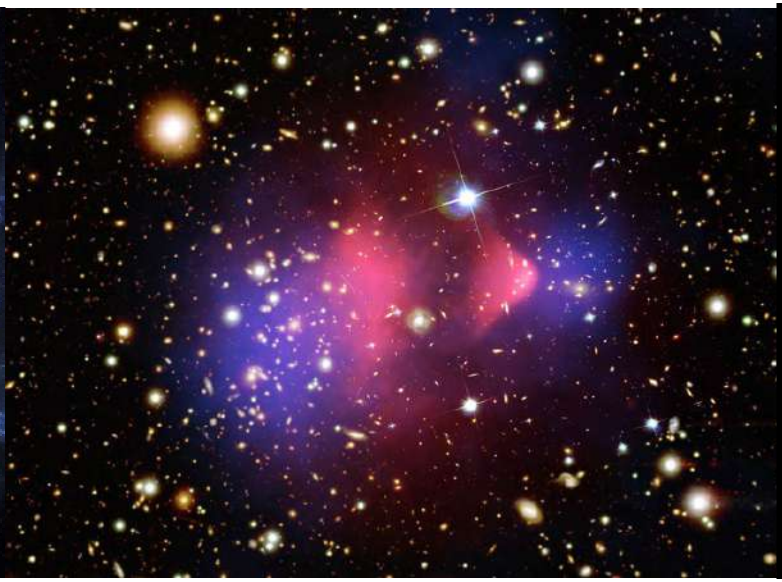
Essentie:

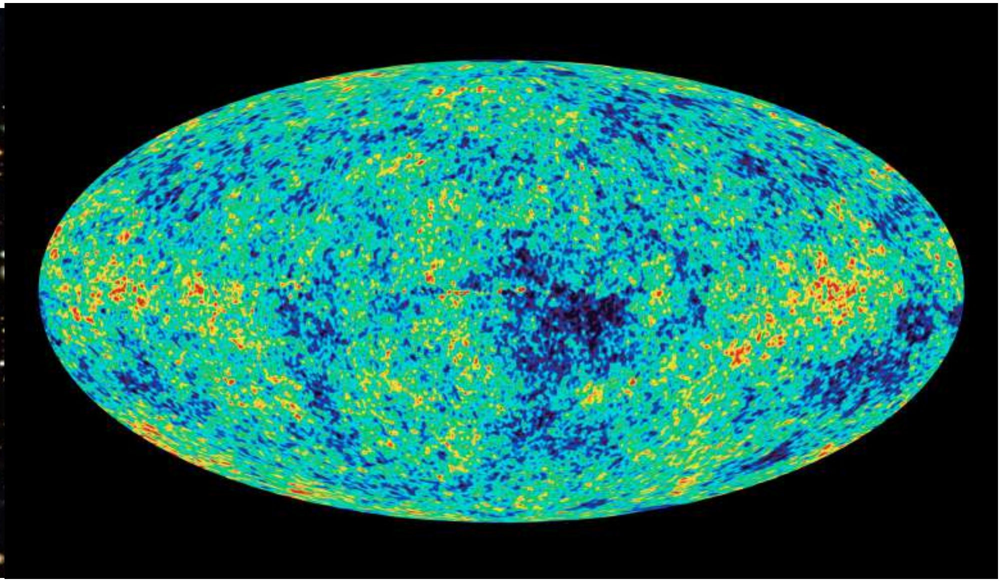
- specifieke signatuur in de dectector door een Higgs verval (decay)
- Reconstrueer Massa v/d Higgs uit vervalsproducten: 1 vaste waarde

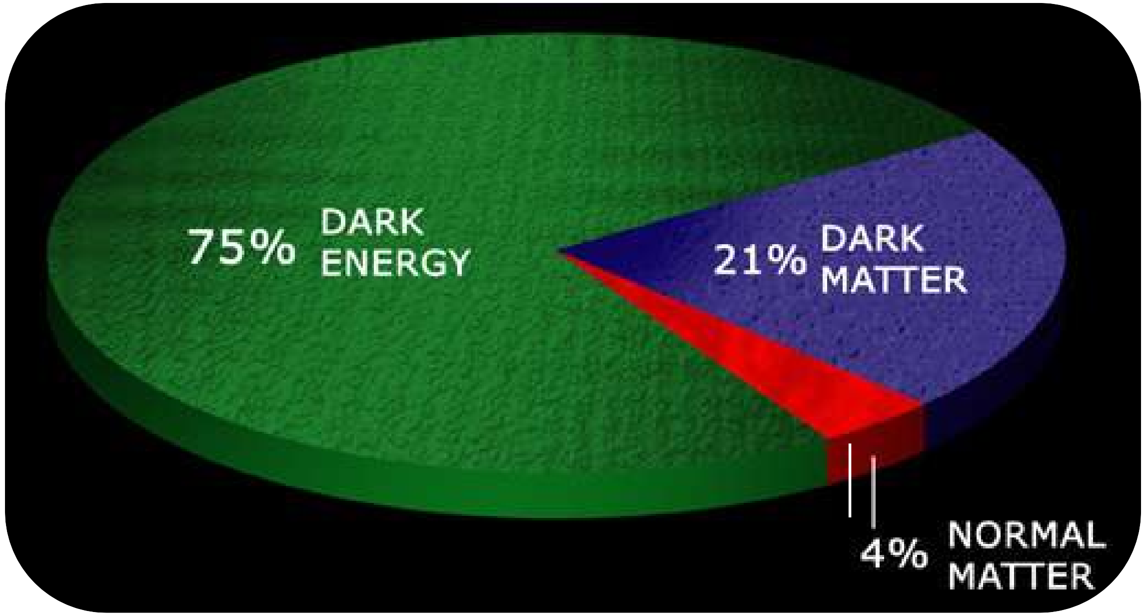
Gouden kanalen (weinig achtergrond):

- Higgs naar 4 muonen
- Higgs naar 2 fotonen

Vele ‘experimentele’ bewijzen voor Dark energy & Matter





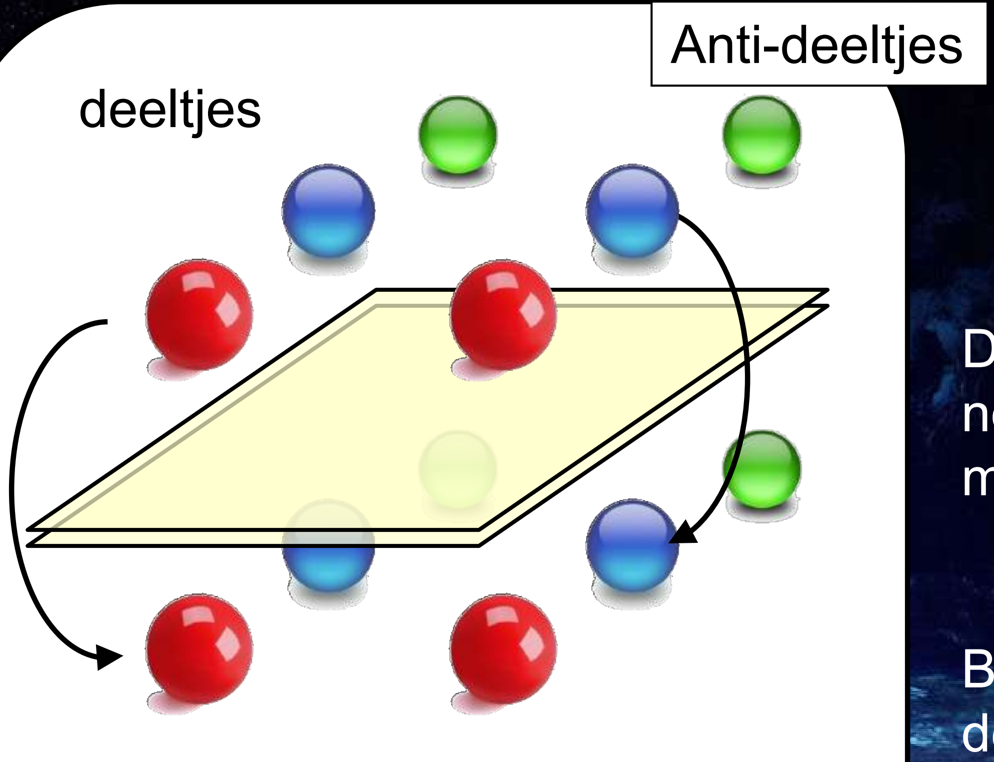


Om ons heen zit dus donkere materie, donkere energie, een Higgs veld. en heel veel deeltjes die we wel kennen.

Slechts 4% is normale materie????

Donkere Materie zelf maken

Theoretisch idee: Supersymmetrie:



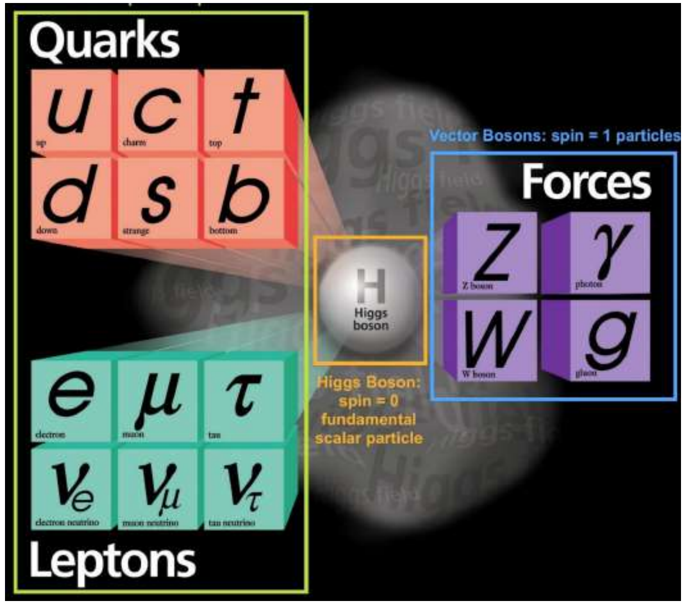
Super-symmetrie: elk deeltje heeft een zwaar broertje

De lichtste is misschien stabiel: nog onbekend ‘zwaar’ donkere materie deeltje

Bij de LHC kunnen we deze super-deeltjes produceren → DOEL van de volgende Run2.

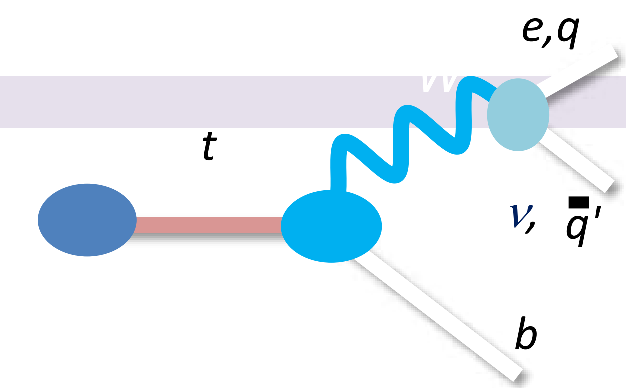
• Top quark in the Standard Model

- Extremely high mass 173 GeV (Yukawa coupling $\sqrt{2}\, m_t / v \cong 1$)
- Mass is around the Electroweak symmetry breaking scale → new physics
- Decays ($<10^{-24}$s) before it hadronizes → only naked quark



Produced in pairs or single

SM top decay:
- $t \rightarrow Wb$ (~100%)



W decay:
- *W* leptonic (~33%)
  $e+\nu_e$, $\mu+\nu_\mu$, $(\tau+\nu_\tau)$
- hadronic (~66%)
  $q, \bar{q}'$