

# LHCb

**Wat doen wij?**



Niels Tuning – 25 nov 2022

**Vrijdag 25 nov. 2022**



**Nederland 17.00 Ecuador**



**Groep A**

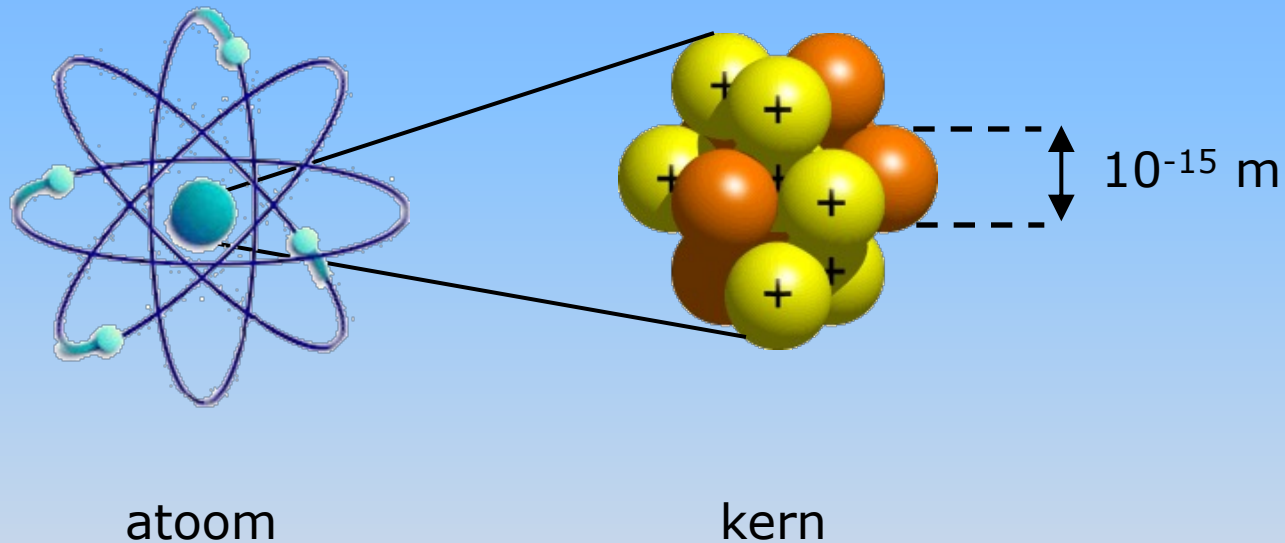
**WK2022-QATAR.NL**

# LHCb

- Waarom deeltjesfysica?
- Waarom LHCb?
- Resultaten
- Higgs en LHCb

# Deeltjesfysica

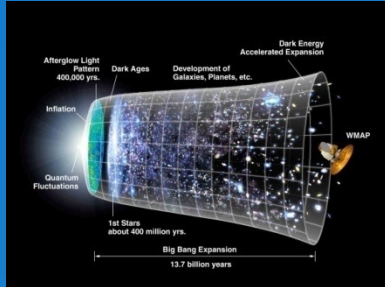
Bestudeert de natuur op afstanden  $< 10^{-15}$  m



Quantum theorie beschrijft alle metingen tot  $10^{-18}$  m  
(Ter vergelijik:  $10^{+18}$  m = 100 lichtjaar)



# Machten van tien ...



Heelal  
 $10^{26}$  m



Melkweg  
 $10^{21}$  m



Zonnestelsel  
 $10^{13}$  m

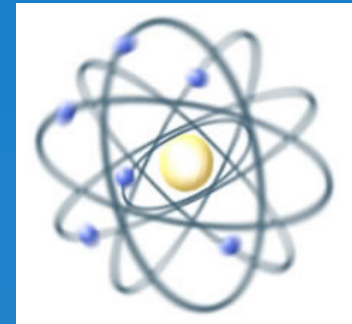


Aarde  
 $10^7$  m

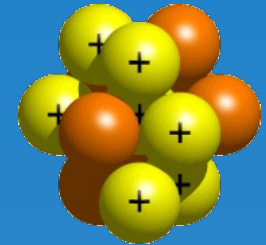
Spin  
 $10^{-2}$  m



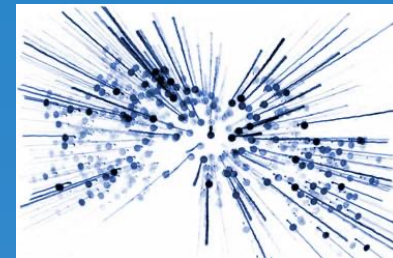
Atoom  
 $10^{-10}$  m



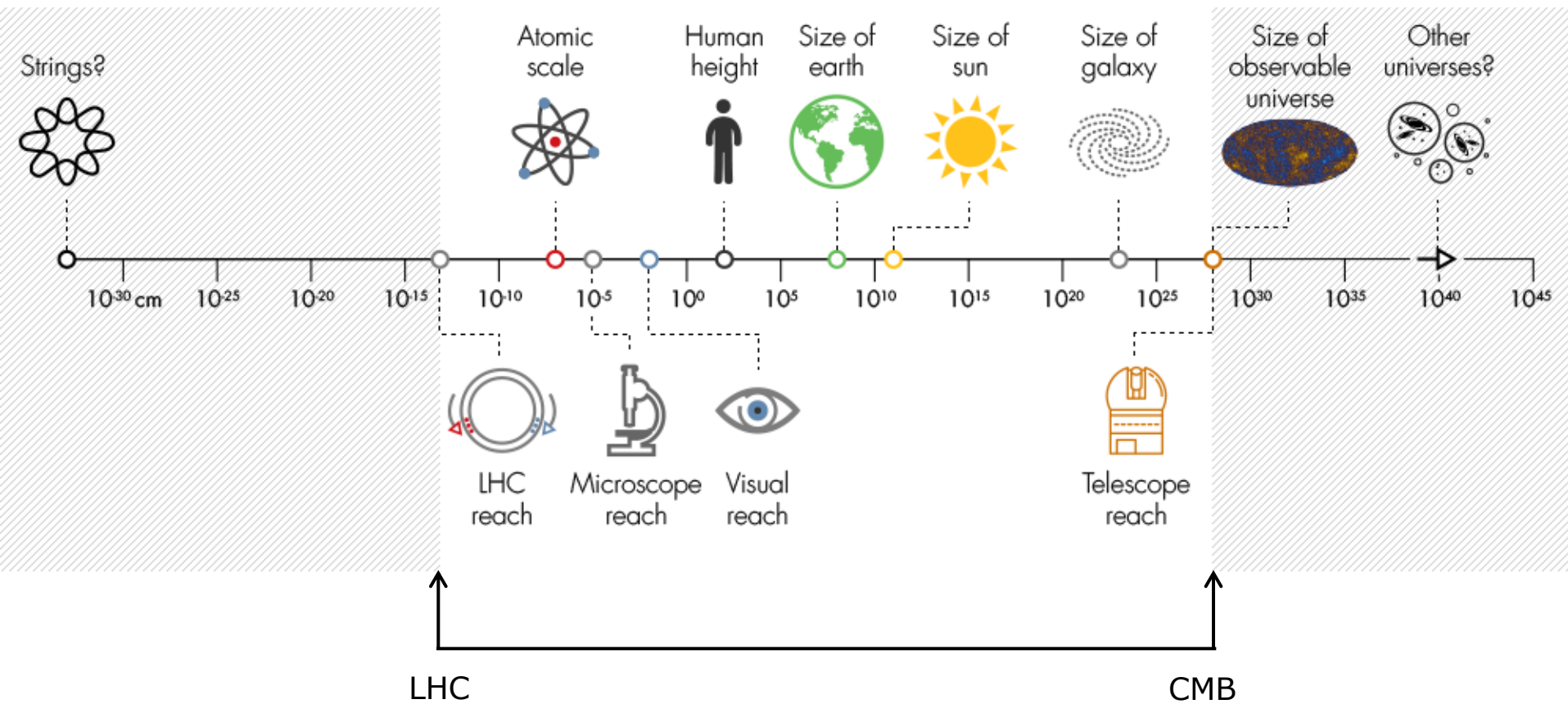
Kern  
 $10^{-15}$  m



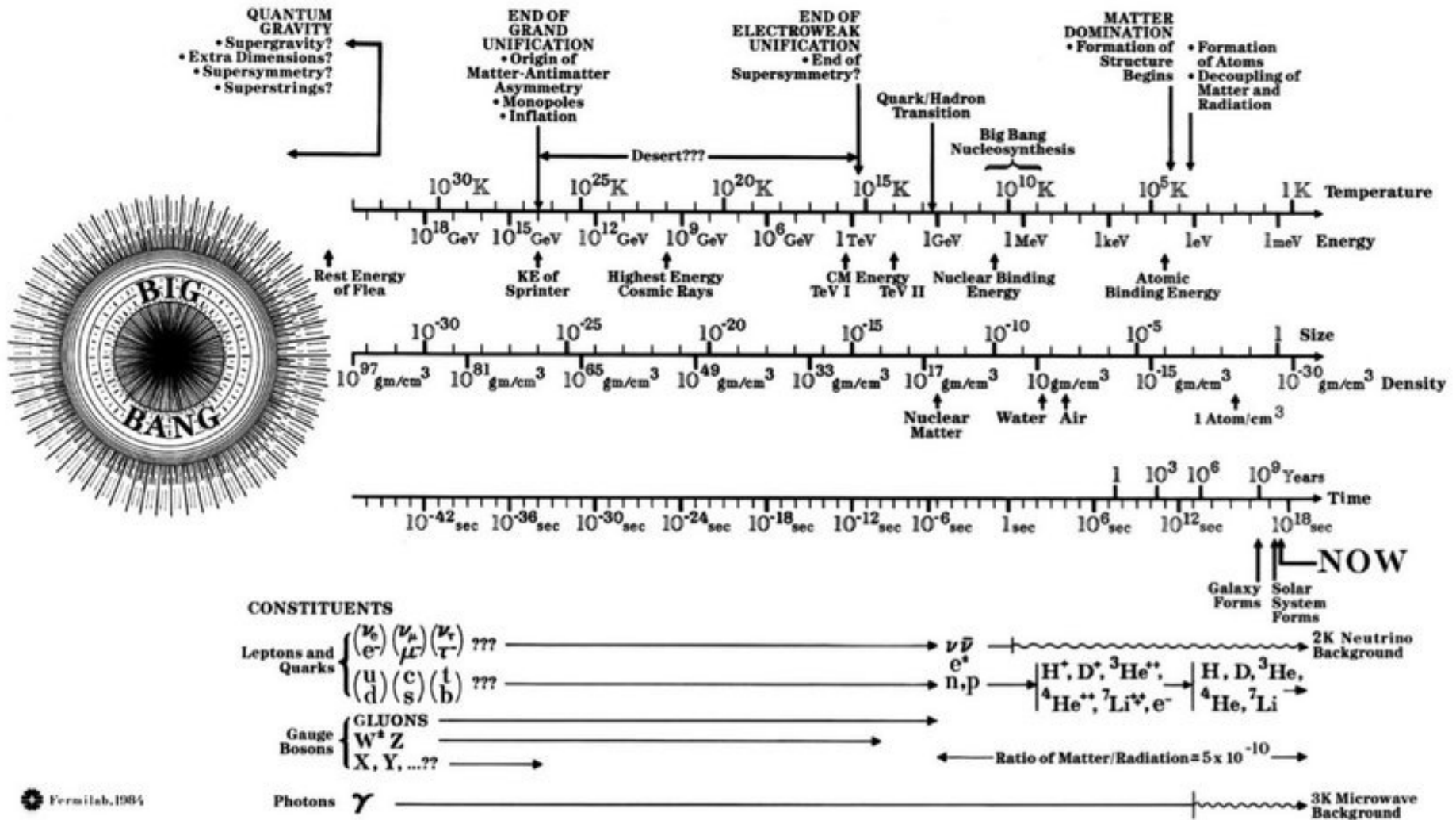
Botsingen  
 $10^{-18}$  m



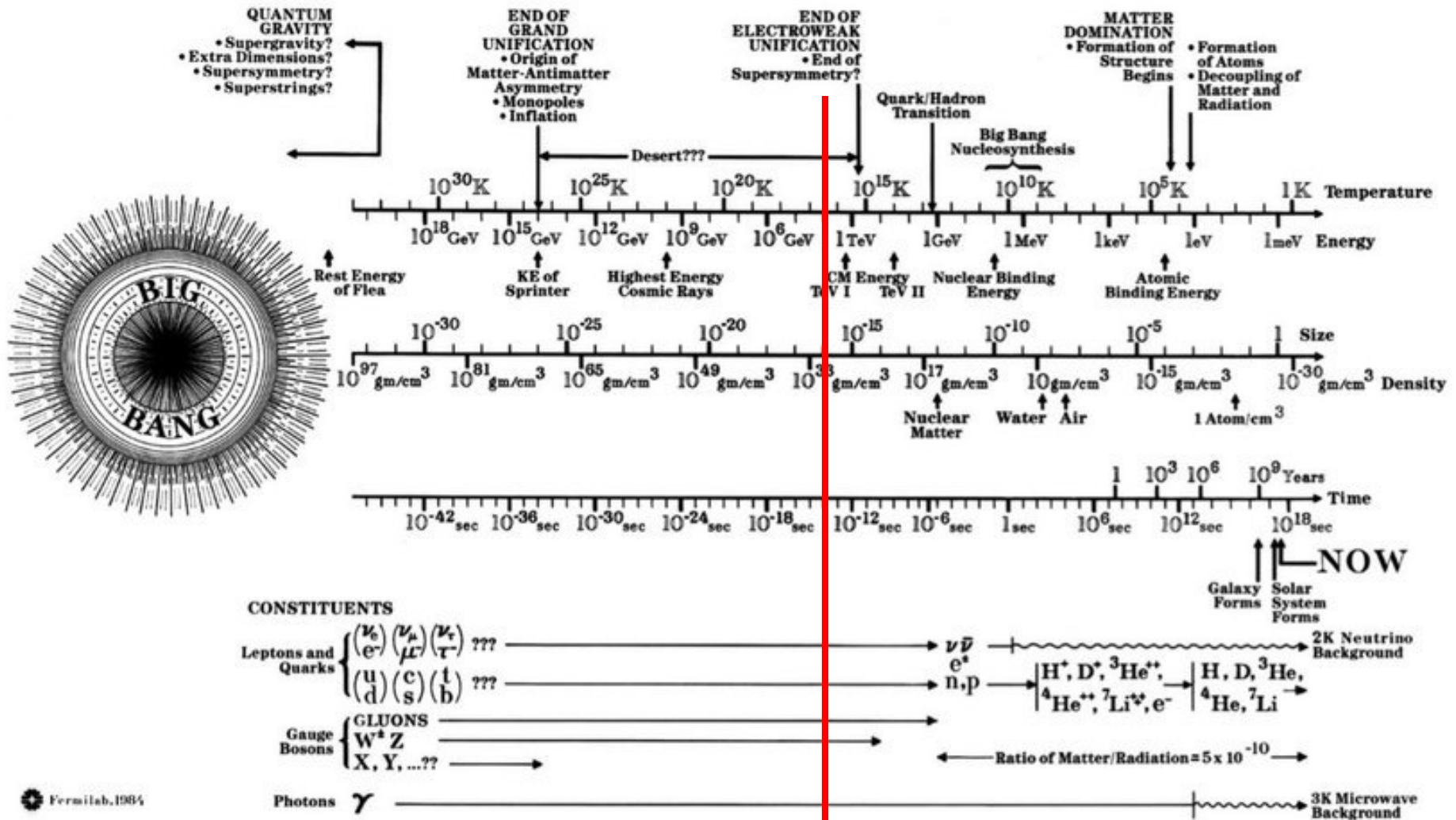
# Schaal



# Complete History of the Universe



# Complete History of the Universe



**U bent hier:  $\blacklozenge$   $10^{-16} \text{ m}$ ,  $10^{-14} \text{ s}$ ,  $10^{16} \text{ K}$**

# De stand van zaken in 2022



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



# De elementaire deeltjes



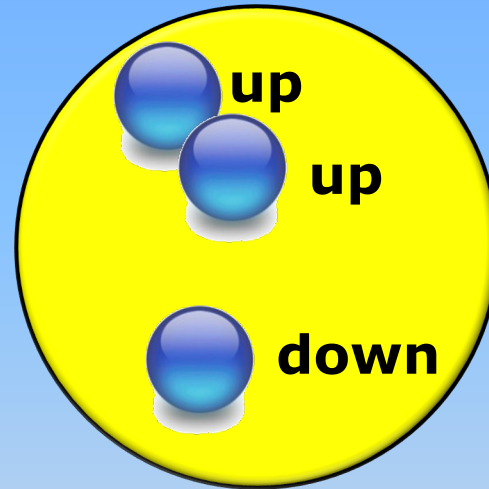
up



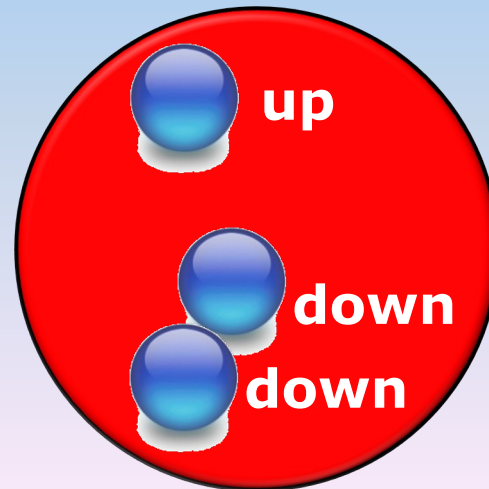
down



elektron

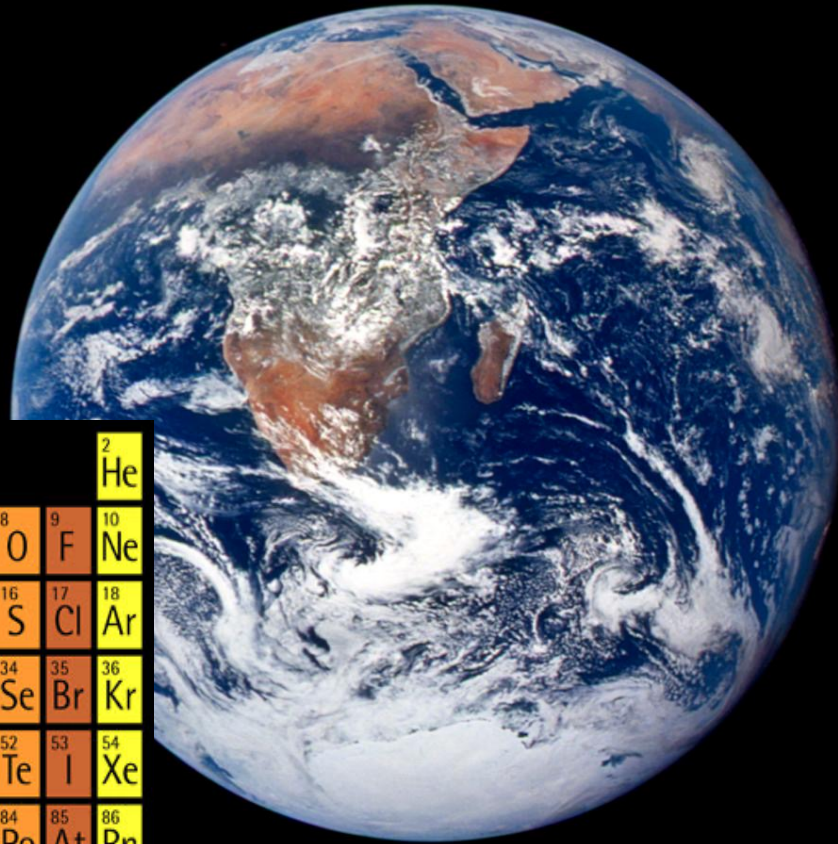
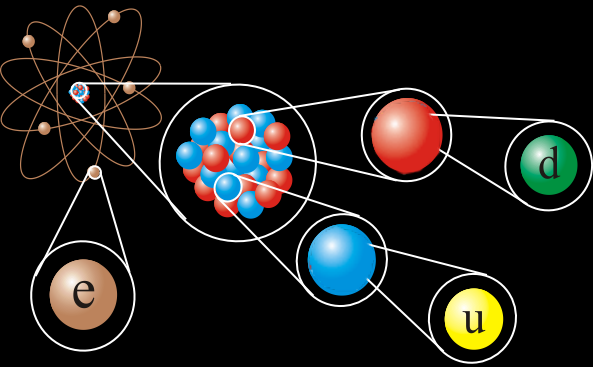


*Proton*



*Neutron*

# Wat kan je maken van deze 3 bouwstenen?



periodiek systeem  
van Mendeleev

1

H

3

Li

4

Be

11

Na

12

Mg

19

K

20

Ca

37

Rb

38

Sr

55

Cs

56

Ba

87

Fr

88

Ra

21

Sc

22

Ti

23

V

24

Cr

25

Mn

26

Fe

27

Co

28

Ni

29

Cu

30

Zn

39

Y

40

Zr

41

Nb

42

Mo

43

Tc

44

Ru

45

Rh

46

Pd

47

Ag

48

Cd

71

Lu

72

Hf

73

Ta

74

W

75

Re

76

Os

77

Ir

78

Pt

79

Au

80

Hg

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

5

B

6

C

7

N

8

O

9

F

13

Al

14

Si

15

P

16

S

17

Cl

31

Ga

32

Ge

33

As

34

Se

35

Br

49

In

50

Sn

51

Sb

52

Te

53

I

81

Tl

82

Pb

83

Bi

84

Po

85

At

101

Md

102

No

2

He

10

Ne

18

Ar

36

Kr

54

Xe

86

Rn

periodiek systeem

van Mendeleev

Alles!

# De elementaire deeltjes

Niet één serie, maar drie!

I

II

III

quarks

**u**

**c**

**t**

(1976)

(1995)

**d**

**s**

**b**

(1947)

(1978)

leptons

**e**

**$\mu$**

**$\tau$**

(1895)

(1936)

(1973)

**$\nu_e$**

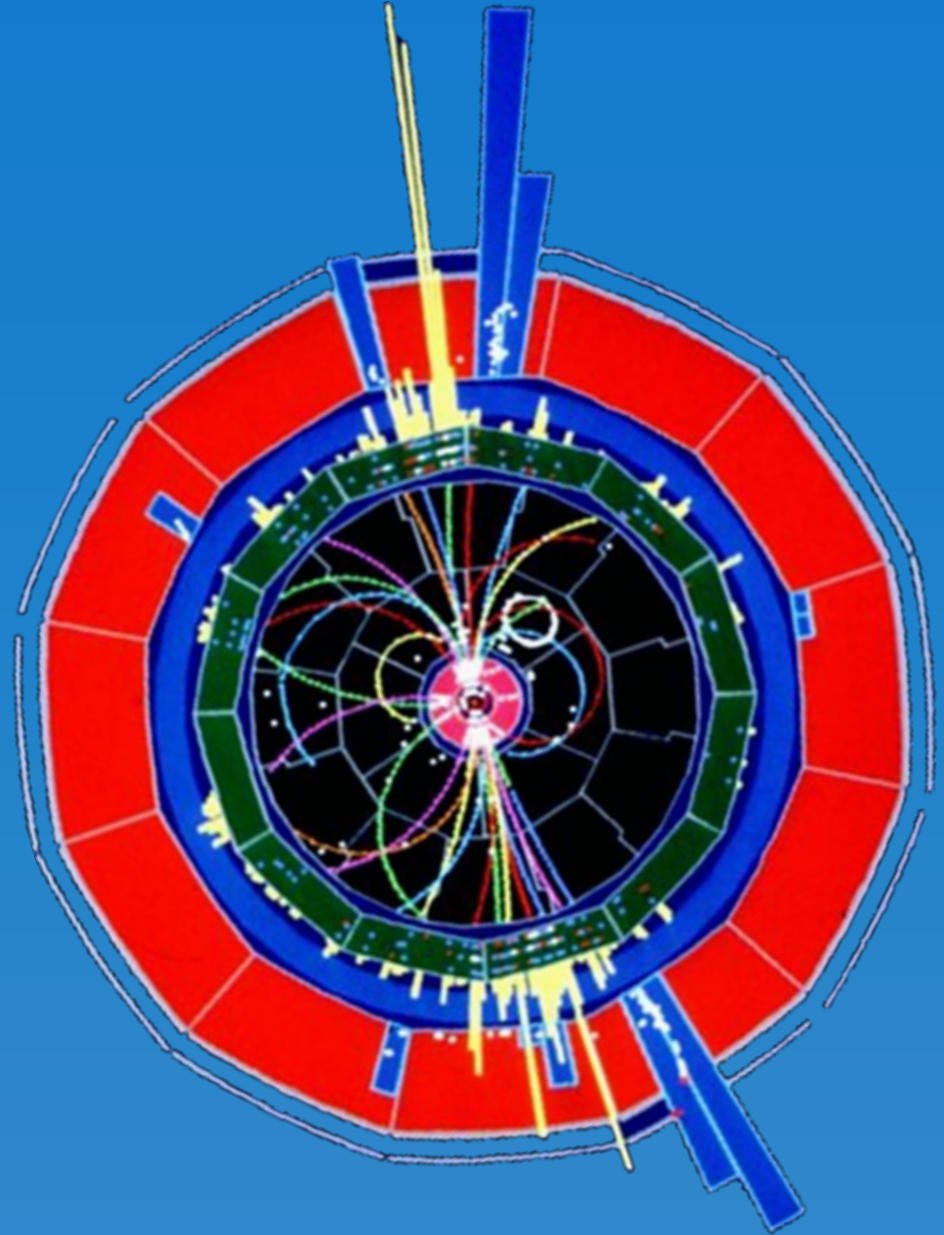
**$\nu_\mu$**

**$\nu_\tau$**

(1956)

(1963)

(2000)





# De elementaire deeltjes

Generatie:

I

II

III

Lading

quarks

**u**

**c**

**t**

$+2/3 e$

(1976)

(1995)

**d**

**s**

**b**

$-1/3 e$

(1947)

(1978)

leptons

**e**

**$\mu$**

**$\tau$**

$-1 e$

(1895)

(1936)

(1973)

**$\nu_e$**

**$\nu_\mu$**

**$\nu_\tau$**

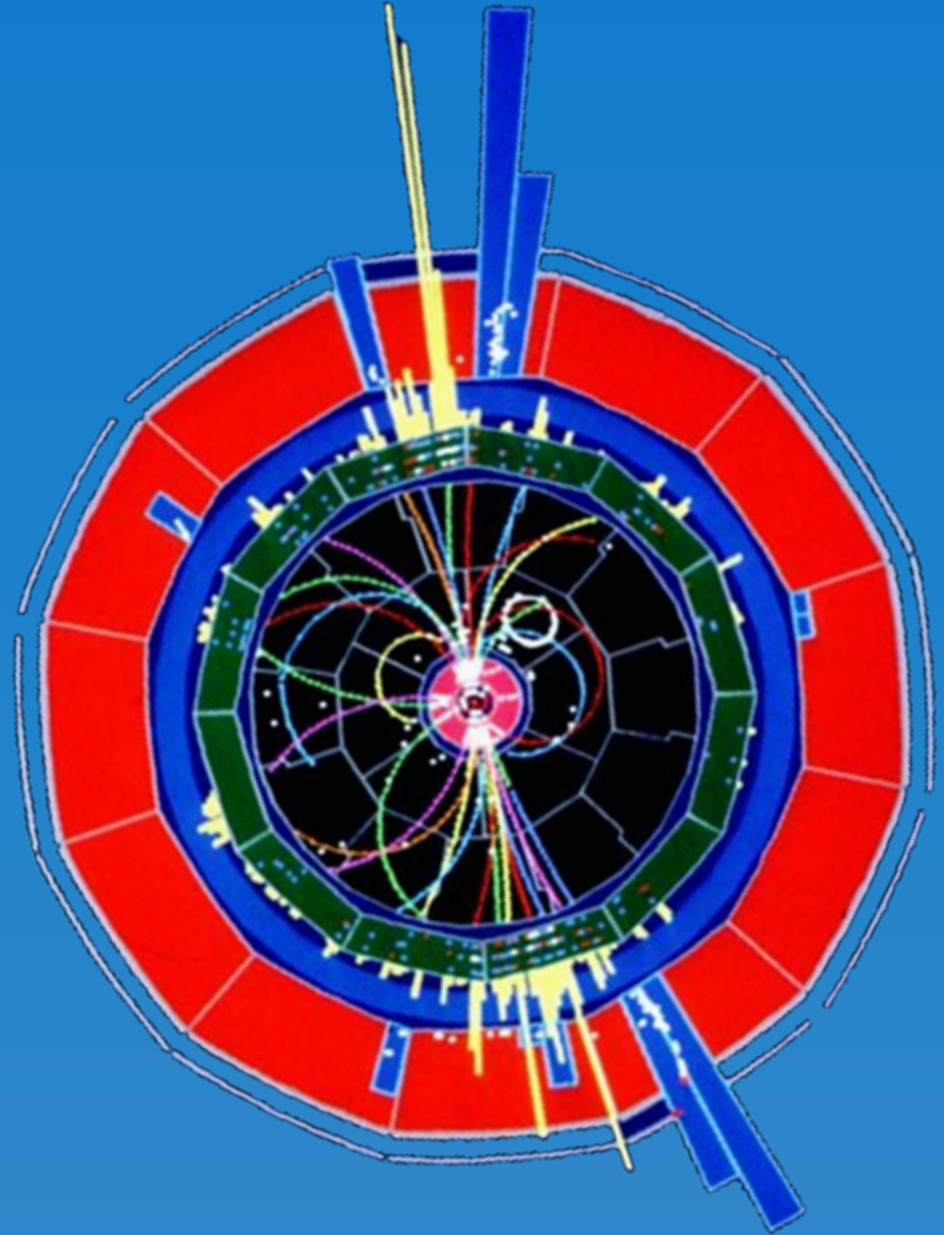
$0 e$

(1956)

(1963)

(2000)

Materie



# Is dit alles?

Generatie:

I

II

III

Lading

quarks

**u**

**c**

**t**

+2/3 e

(1976)

(1995)

**d**

**s**

**b**

-1/3 e

(1947)

(1978)

leptons

**e**

**$\mu$**

**$\tau$**

-1 e

(1895)

(1936)

(1973)

**$\nu_e$**

**$\nu_\mu$**

**$\nu_\tau$**

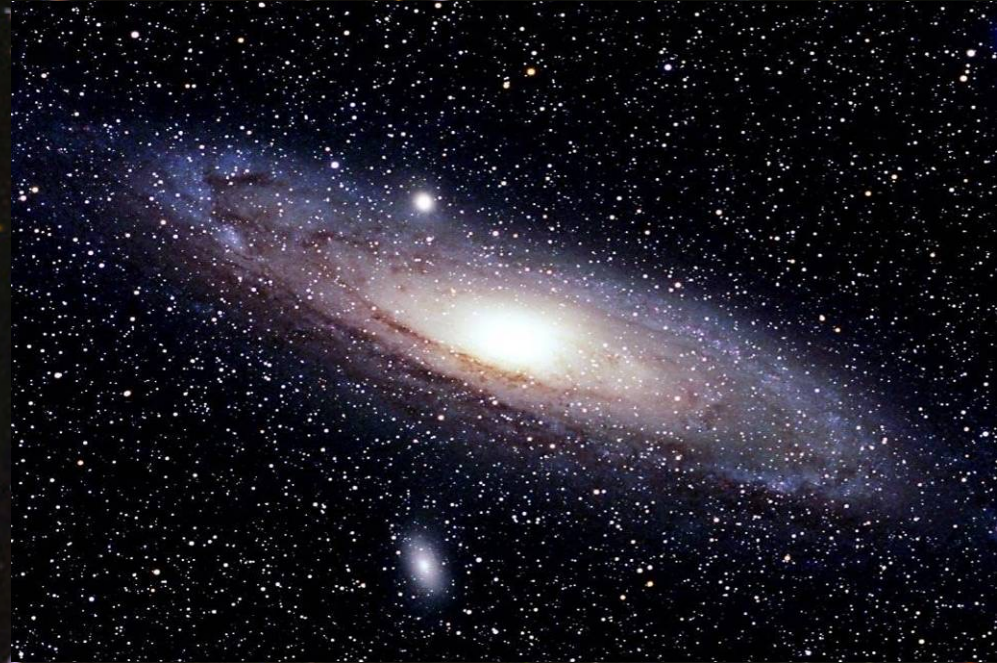
0 e

(1956)

(1963)

(2000)

Materie





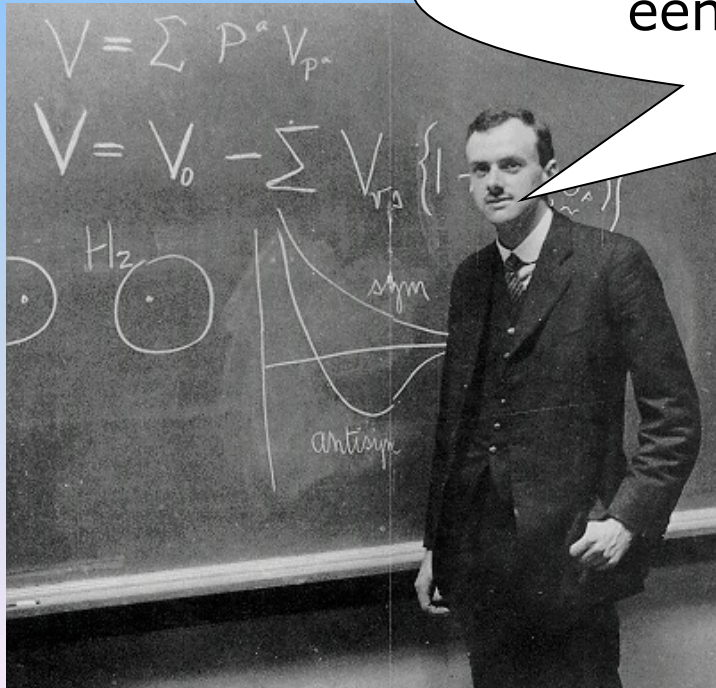
# Anti-materie

Revoluties begin vorige eeuw:

- Relativiteitstheorie
- Quantum Mechanica

Paul Dirac (1928): relativistische quantum theorie!

Voor elk materiedeeltje bestaat een anti-materiedeeltje!



Anti-materie deeltje:

- Zelfde massa
- Tegenovergestelde lading

# De elementaire deeltjes

	I	II	III	<u>Lading</u>
quarks	<b>u</b>	<b>c</b> (1976)	<b>t</b> (1995)	$+2/3 e$
	<b>d</b>	<b>s</b> (1947)	<b>b</b> (1978)	$-1/3 e$
leptons	<b>e</b> (1895)	<b><math>\mu</math></b> (1936)	<b><math>\tau</math></b> (1973)	$-1 e$
	<b><math>\nu_e</math></b> (1956)	<b><math>\nu_\mu</math></b> (1963)	<b><math>\nu_\tau</math></b> (2000)	$0 e$

Materie

# De elementaire deeltjes

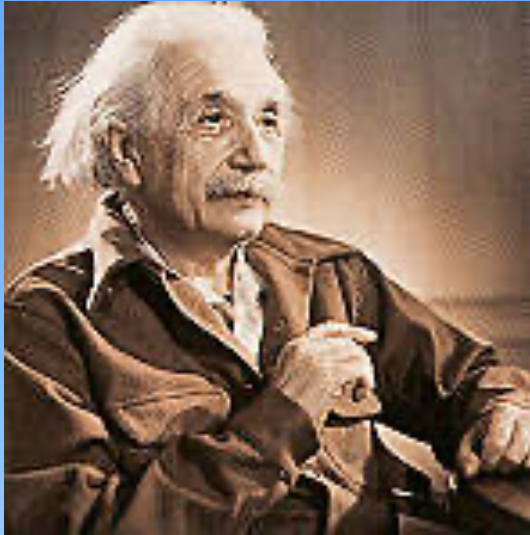
	I	II	III	<u>Lading</u>
quarks	<b>u</b>	<b>c</b> (1976)	<b>t</b> (1995)	+2/3 e
	<b>d</b>	<b>s</b> (1947)	<b>b</b> (1978)	-1/3 e
leptons	<b>e</b> (1895)	<b>μ</b> (1936)	<b>τ</b> (1973)	-1 e
	<b>ν<sub>e</sub></b> (1956)	<b>ν<sub>μ</sub></b> (1963)	<b>ν<sub>τ</sub></b> (2000)	0 e

Materie

<u>Lading</u>	I	II	III
-2/3 e	<b><math>\bar{u}</math></b>	<b><math>\bar{c}</math></b>	<b><math>\bar{t}</math></b>
+1/3 e	<b><math>\bar{d}</math></b>	<b><math>\bar{s}</math></b>	<b><math>\bar{b}</math></b>
+1 e	<b><math>\bar{e}</math></b>	<b><math>\bar{\mu}</math></b>	<b><math>\bar{\tau}</math></b>
0 e	<b><math>\bar{\nu}_e</math></b>	<b><math>\bar{\nu}_\mu</math></b>	<b><math>\bar{\nu}_\tau</math></b>

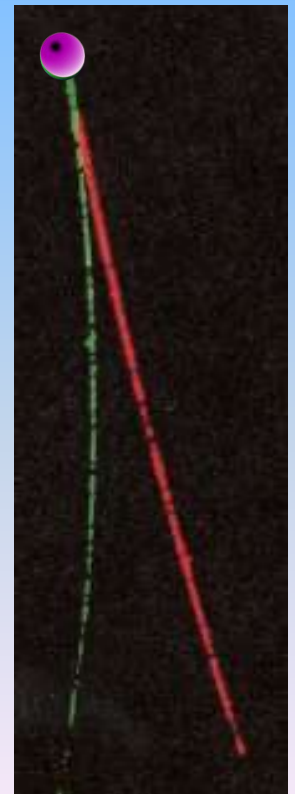
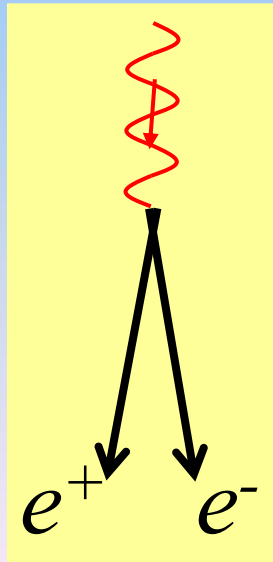
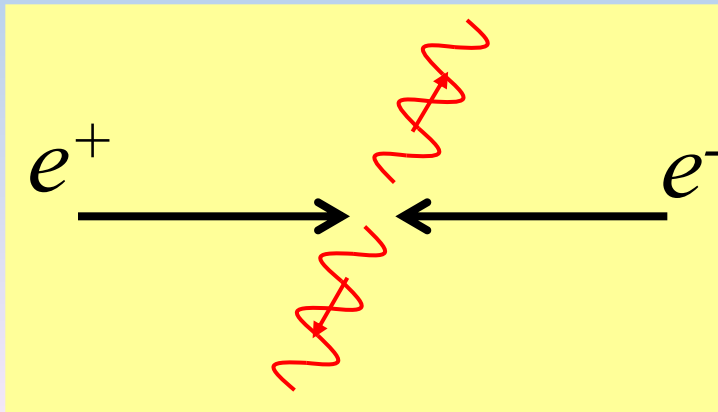
Anti-materie

# Hoe maak je anti-materie??

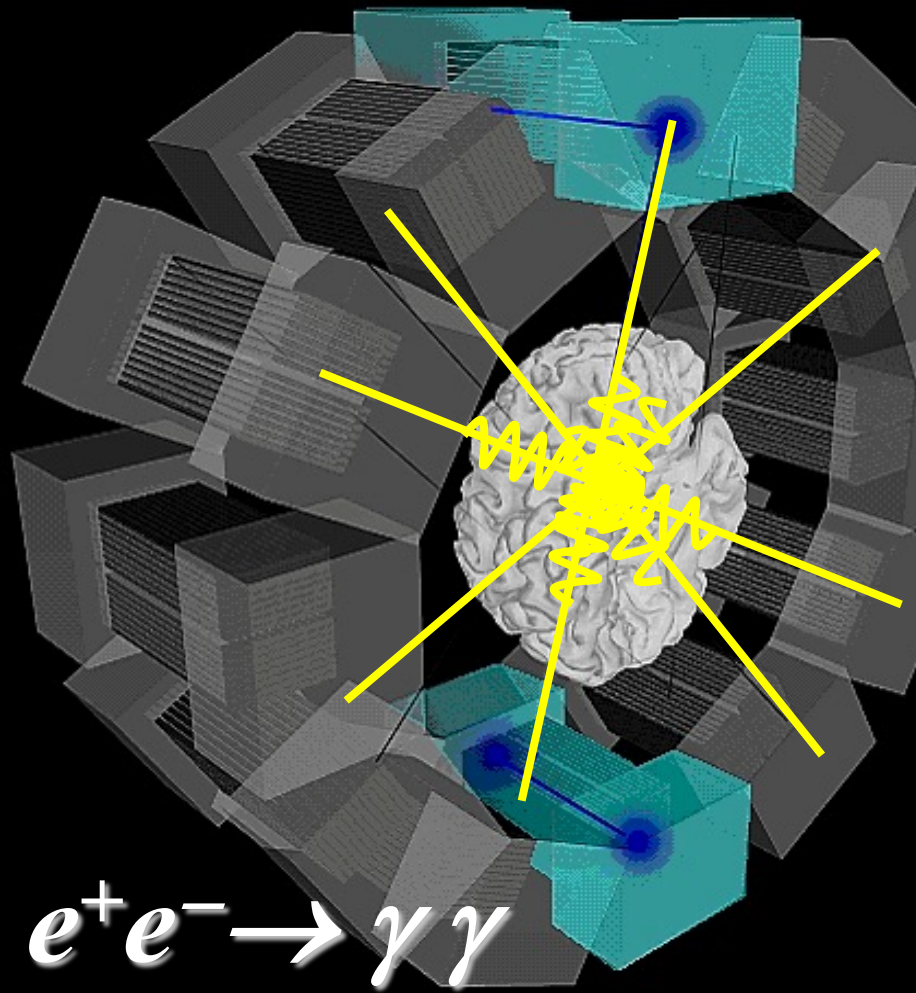
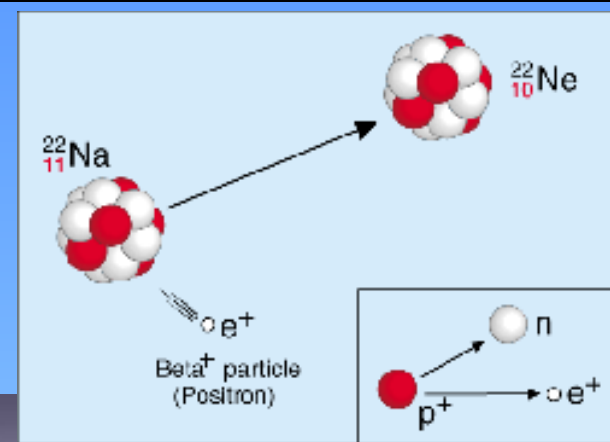


Albert Einstein:  
 $E=mc^2$

materie + antimaterie = licht !  
(en vice versa)



# Anti-materie in ziekenhuizen: de PET-scan



**Wat snappen we nog niet:**

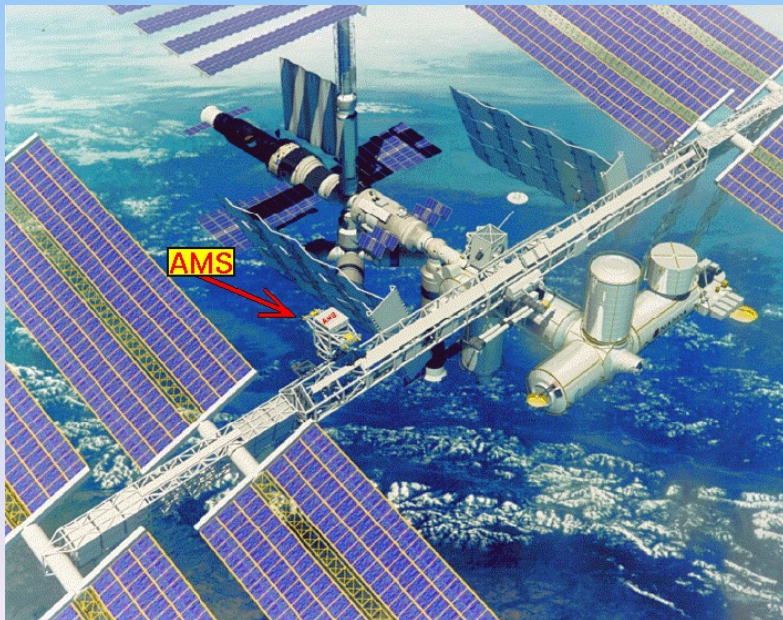




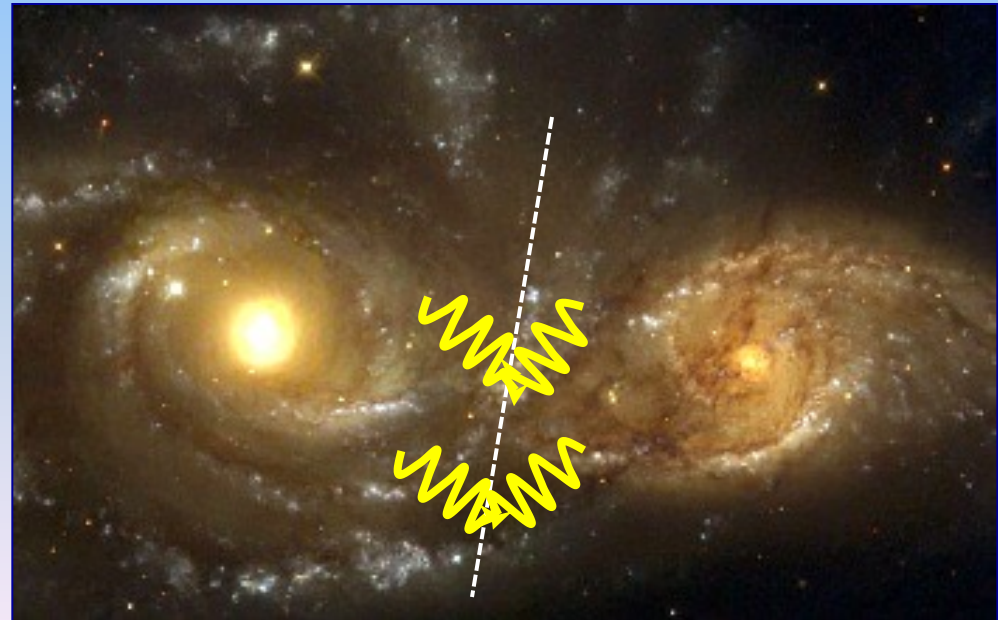
# I. Wat snappen we nog niet? “*Anti-materie*”

Waar is de anti-materie gebleven?

*Geen anti-materie  
met satellieten*



*Geen anti-materie  
sterrenstelsels*



## II. Wat snappen we nog niet? “Higgs”

(Gedeeltelijk beantwoord op 4 juli 2012 !)

### Massa van deeltjes



### Bijzondere voorspelling:

#### Het Higgs boson:

zorgt ervoor dat deeltjes massa kunnen hebben in de theorie

Neutrino's

• Elektron

• Muon

• Tau

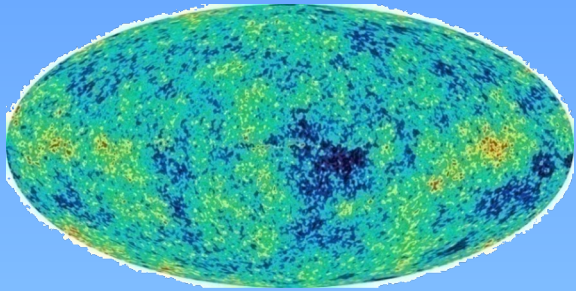
• up, down, strange

• charm

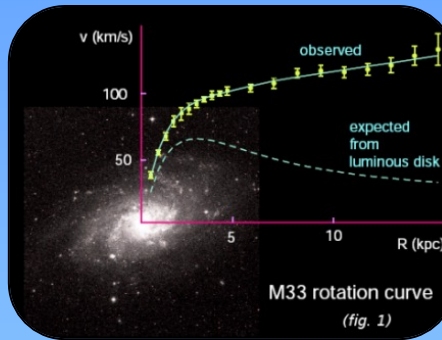
Top quark

• bottom

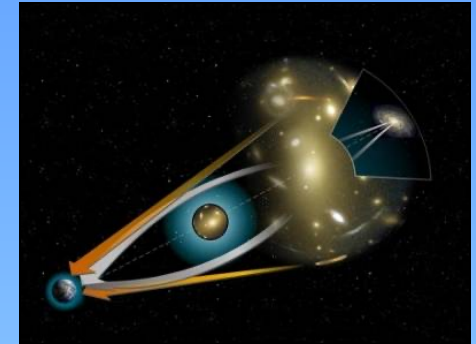
### III. Wat snappen we nog niet? “Donkere materie”



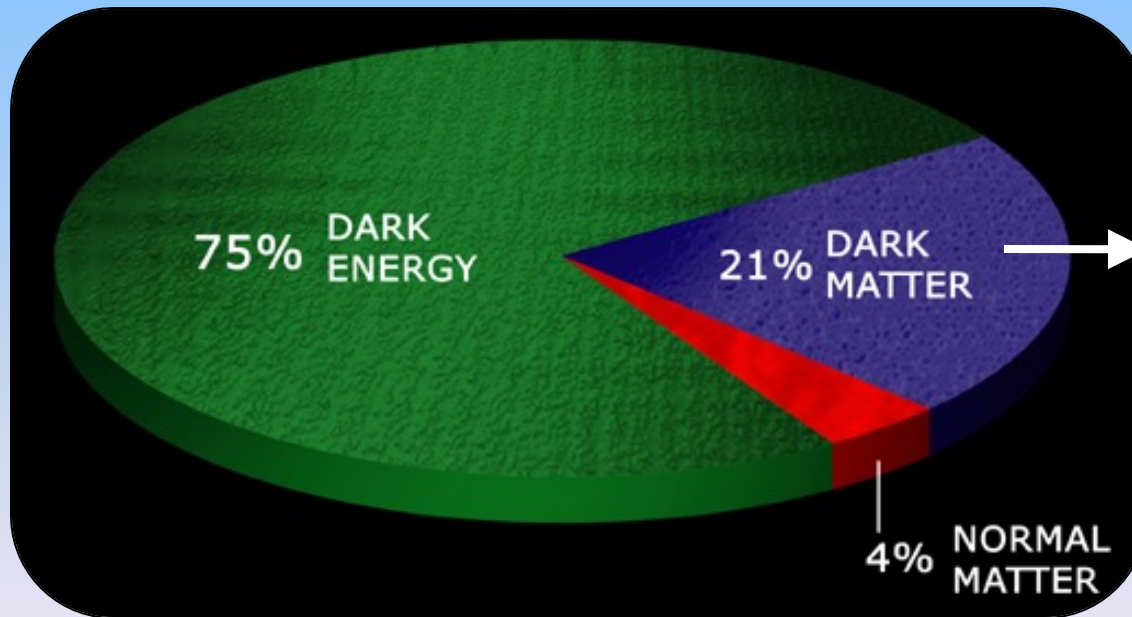
Temperatuurfluctuaties  
structuur van het heelal



Rotatie-curves



Gravitationele lens

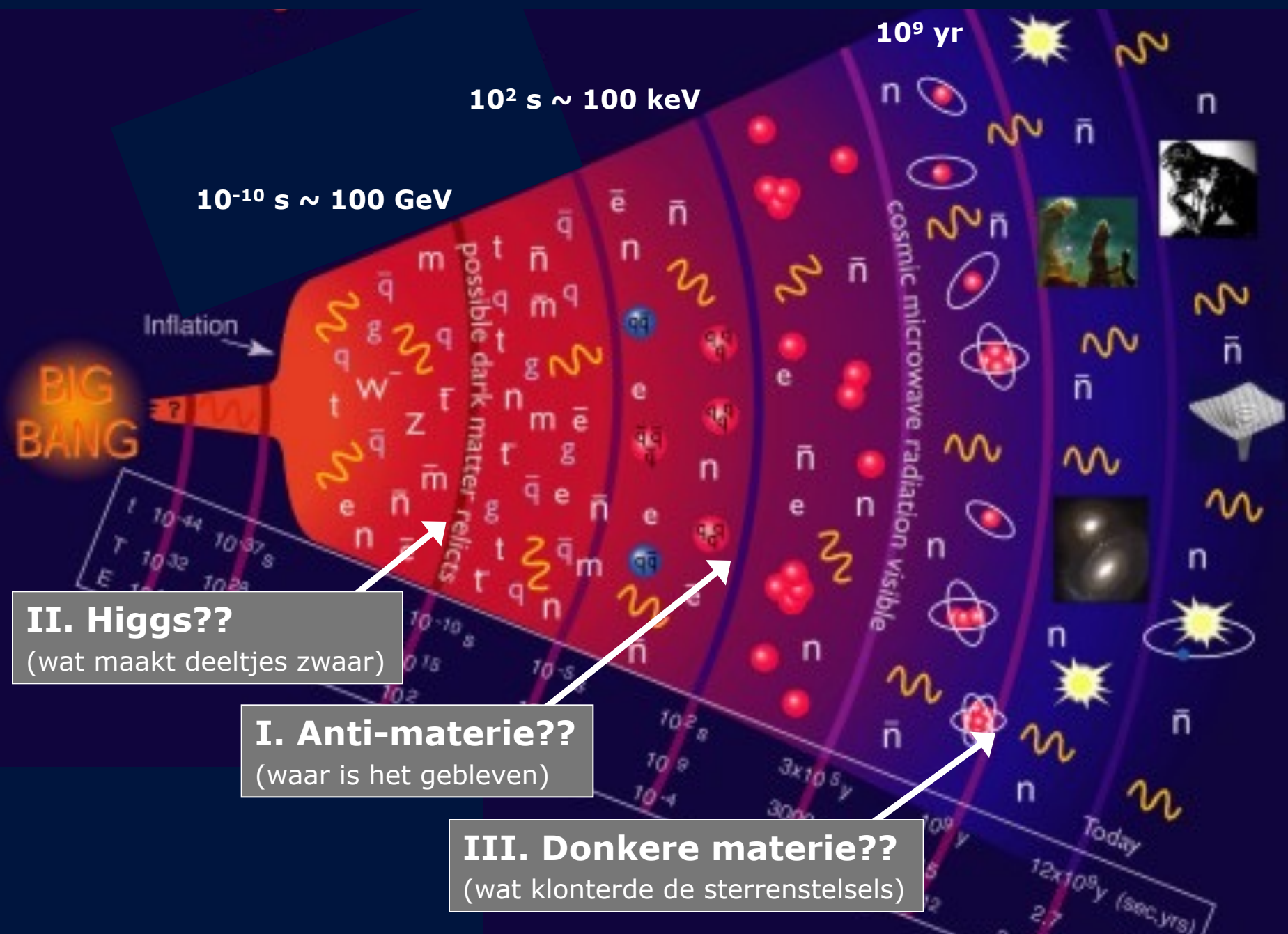


Wat is de  
donkere materie ?

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



# Wat snappen we niet? Drie Grote Vragen





Astronomie

Deeltjes  
fysica

Fundamenteel  
(nieuwsgierigheid gedreven)  
onderzoek







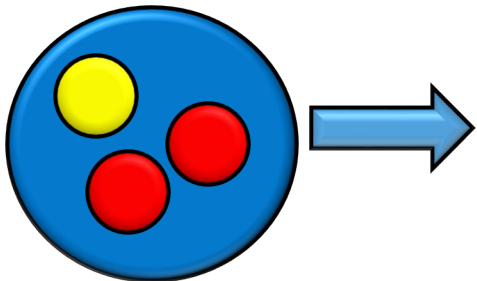




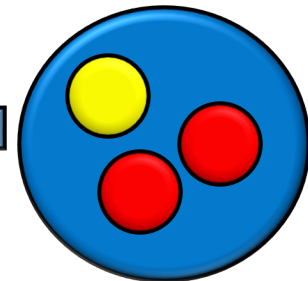
## Klassiek botsen

## Quantummechanisch botsen

proton



proton

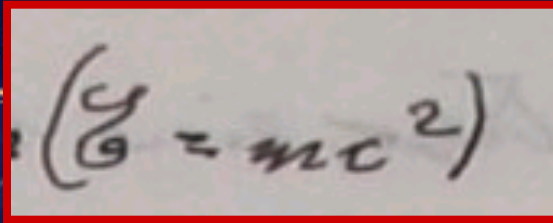


# Wat verwacht je ?

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

Al 40 jaar bestaan er precieze  
wiskundige voorspellingen!

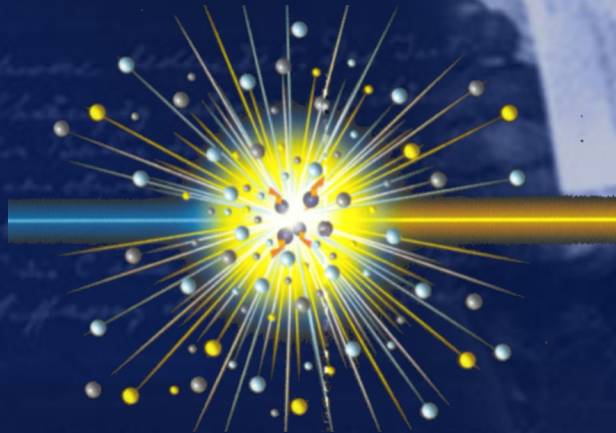


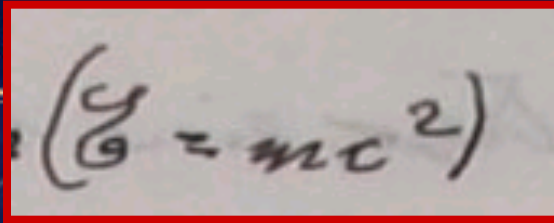

$$E = mc^2$$

# Hoe ontdekken we nieuwe deeltjes?

Bij de LHC op Cern:

1) Verander energie in materie!

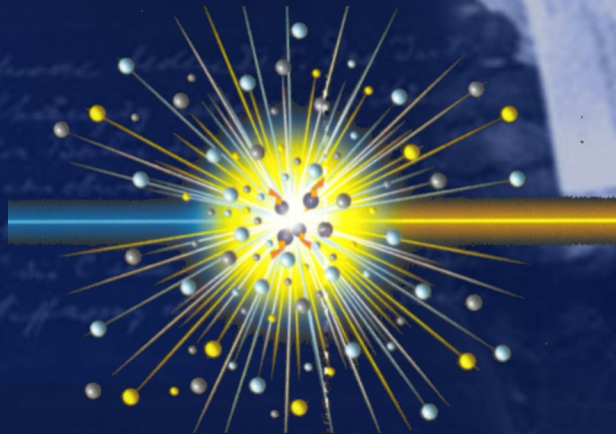



$$E = mc^2$$

# Hoe ontdekken we nieuwe deeltjes?

Bij de LHC op Cern:

- 1) Verander energie in materie!
- 2) Nieuwe deeltjes veranderen voorspellingen







*LHCb*

*ATLAS*

*CMS*

*ALICE*





2) Nieuwe deeltjes  
veranderen voorspellingen

The image is an aerial photograph of a landscape in Switzerland, showing a patchwork of green and brown fields. A large red oval is superimposed on the image, representing the LHC tunnel. Two blue boxes with white text are placed on the oval: 'LHCb' on the left and 'ATLAS' on the right. Two blue dots are also on the oval, one near the 'LHCb' box and one near the 'ATLAS' box. Two text boxes are positioned above the oval: '2) Nieuwe deeltjes veranderen voorspellingen' on the left and '1) Verander energie in materie' on the right. In the background, there are blue mountains and a clear blue sky.

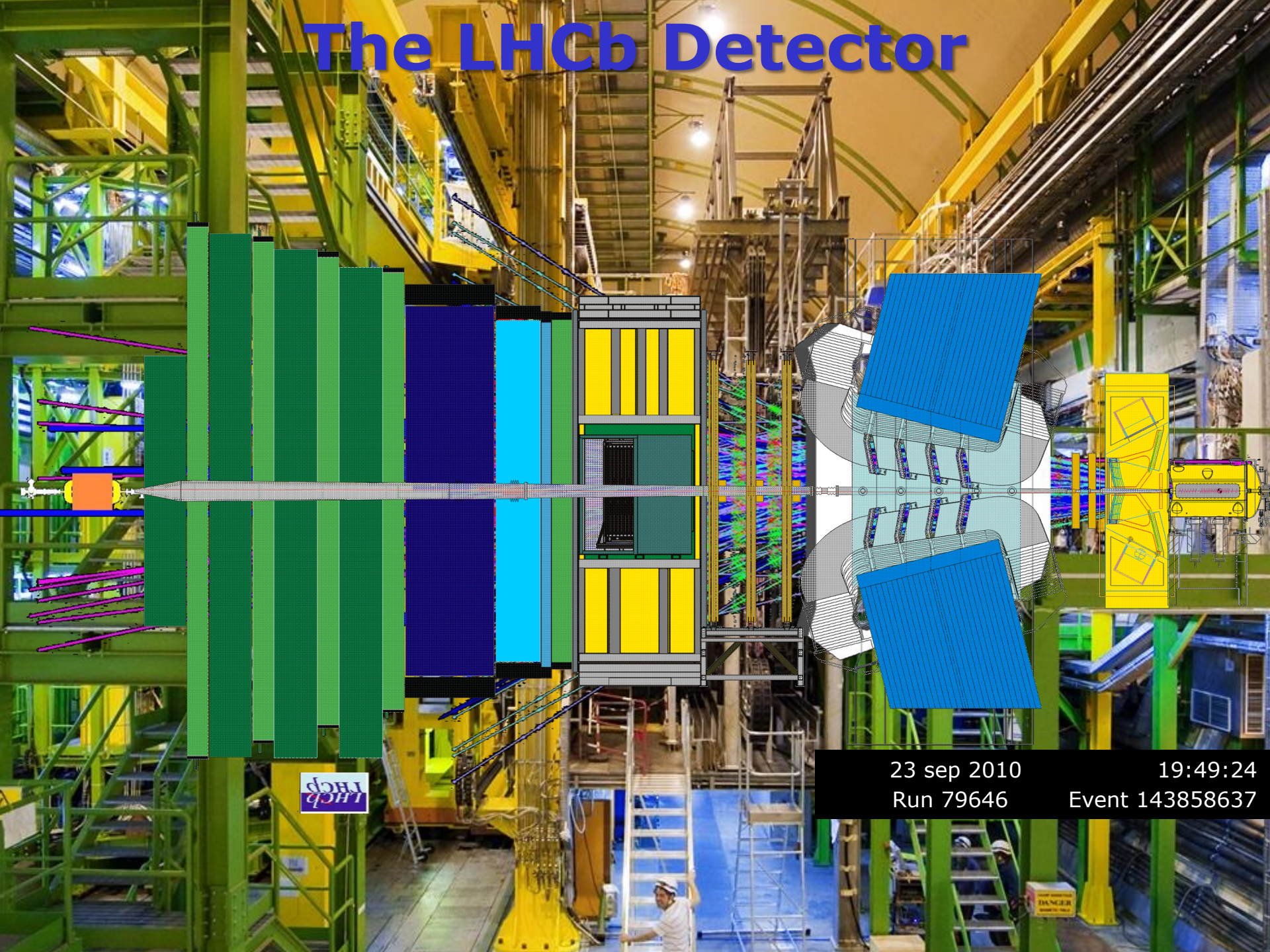
1) Verander energie in  
materie

*LHCb*

*ATLAS*



# The LHCb Detector



LHCb

23 sep 2010  
Run 79646

19:49:24  
Event 143858637

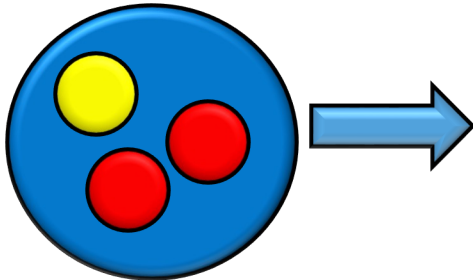
DANGER



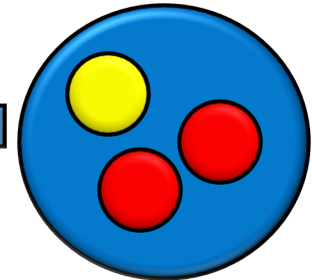
$$\begin{aligned}
& -\frac{1}{2}\partial_\nu g_\mu^a \partial_\nu g_\mu^a - g_s f^{abc} \partial_\mu g_\nu^a g_\mu^b g_\nu^c - \frac{1}{2}g_s^2 f^{abc} f^{ade} g_\mu^b g_\nu^c g_\mu^d g_\nu^e + \\
& \frac{1}{2}ig_s^2 (\bar{q}^c \gamma^\mu q^c) g_\mu^a + G^a \partial^2 G^a + g_s f^{abc} \partial_\mu G^a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

# Quantummechanisch botsen

proton



proton



# LHCb in getallen

**120,000 B events per sec**

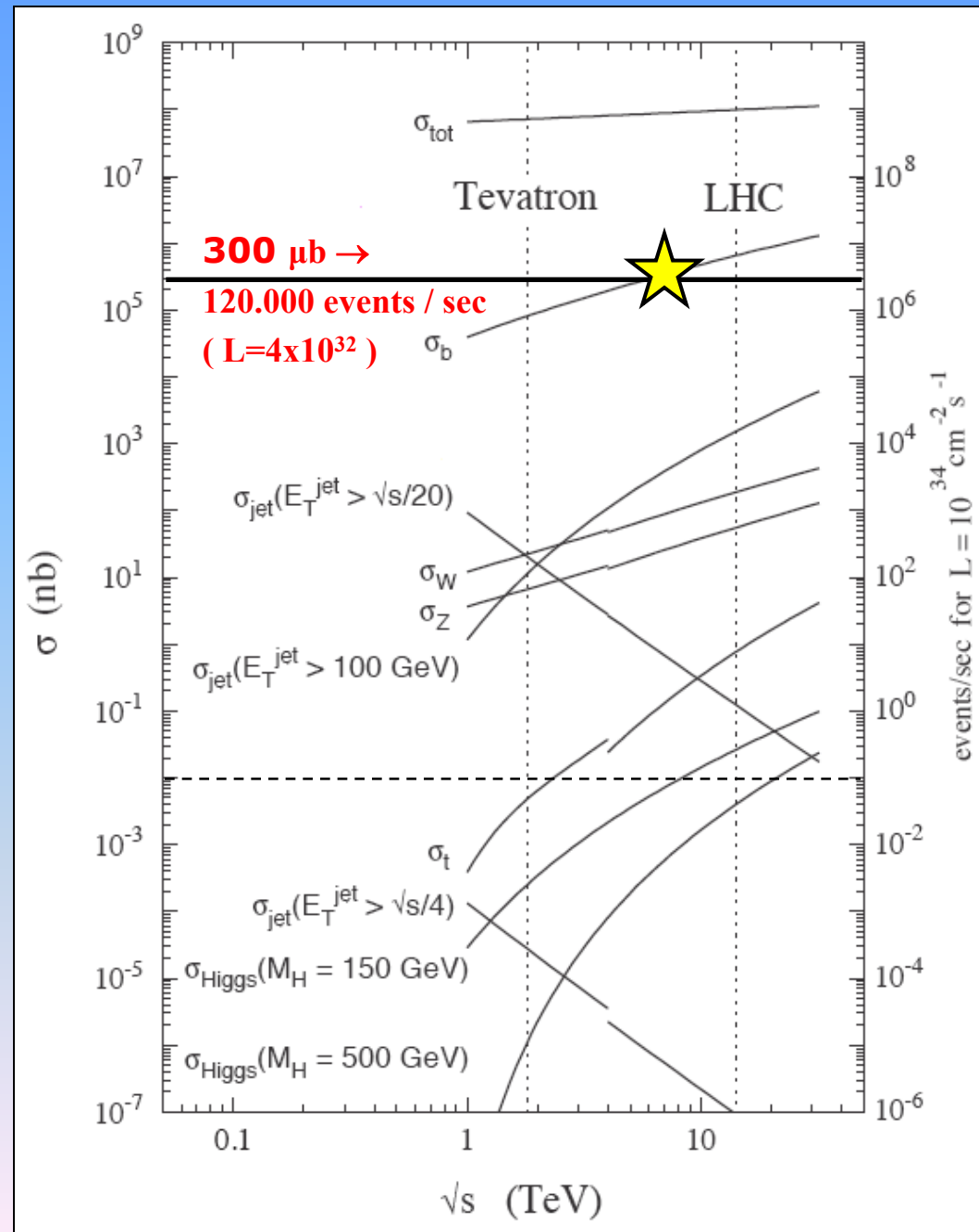
(ter vergelijik: in ATLAS : 1 Higgs in 100 sec)

**$10^{12}$  B events in 2022**

(ter vergelijik: Babar heeft in totaal  $10^9$  B events)

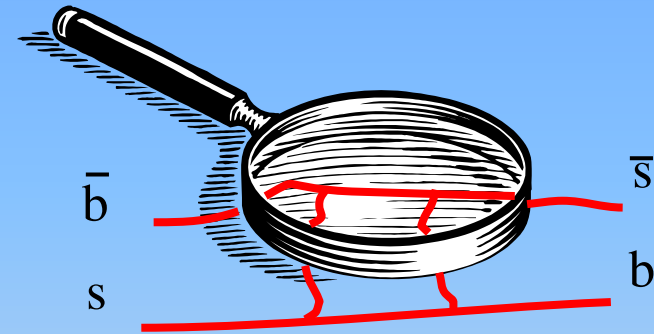
**5 kHz naar tape**

(ter vergelijik: ATLAS schrijft 200 Hz weg)

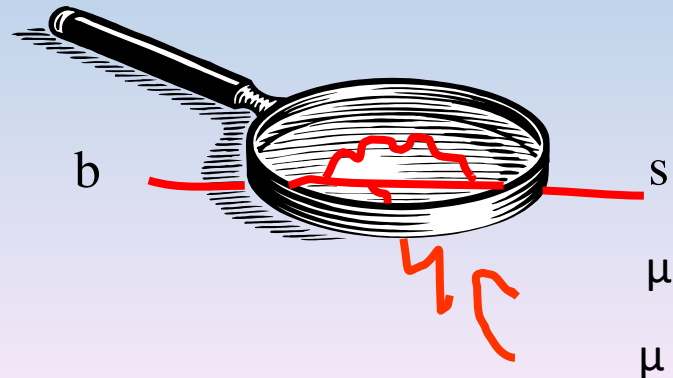


# LHCb: bestuderen van $B$ deeltje

1) Vind verschillen tussen materie en anti-materie

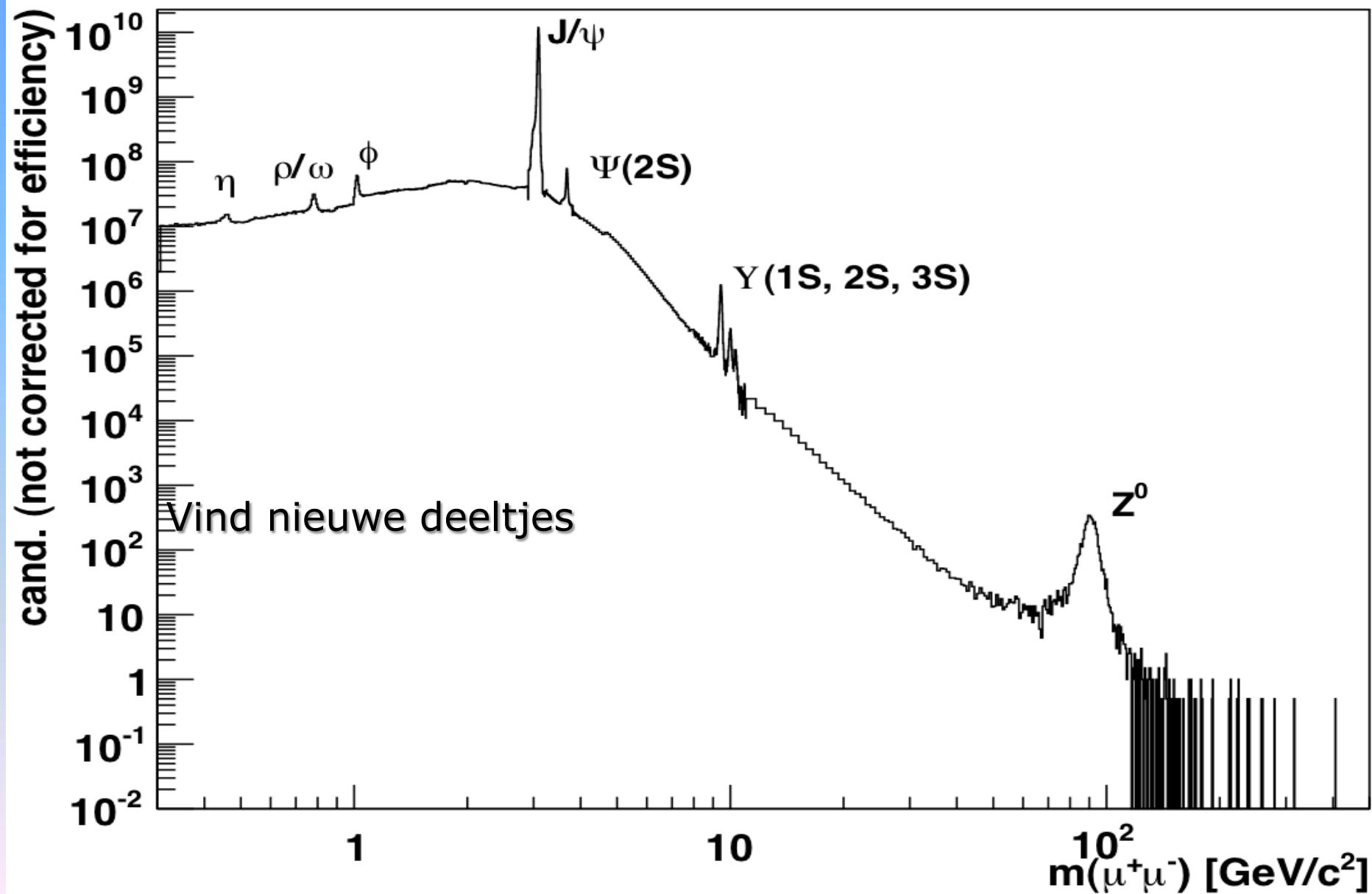


2) Vind nieuwe deeltjes

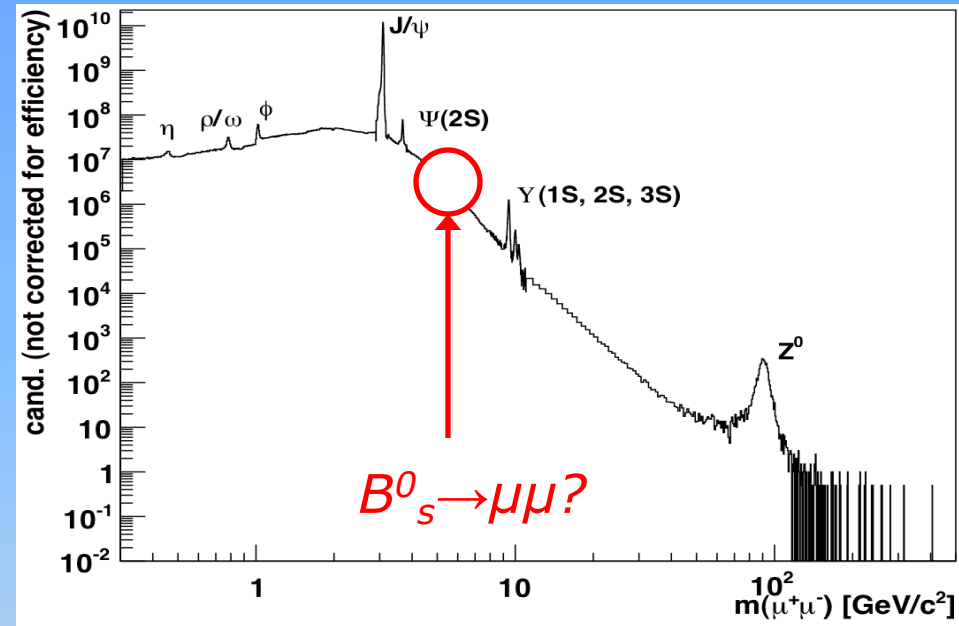




# LHCb: bestuderen van $B$ deeltje

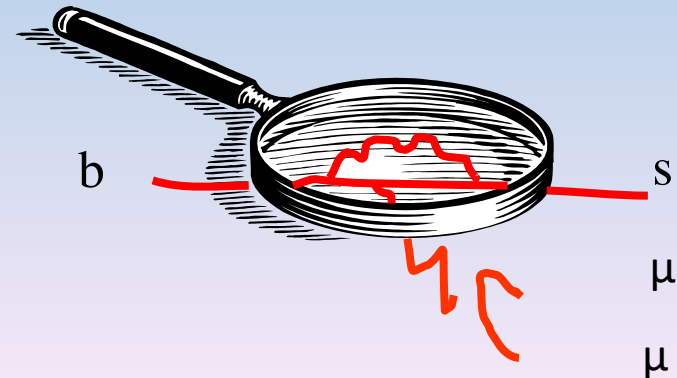
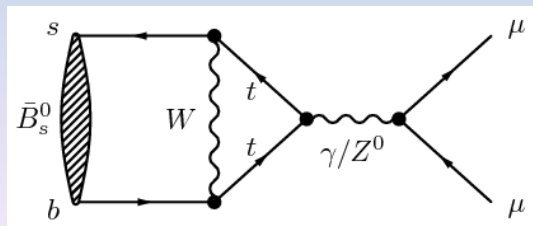


# LHCb: bestuderen van $B$ deeltje

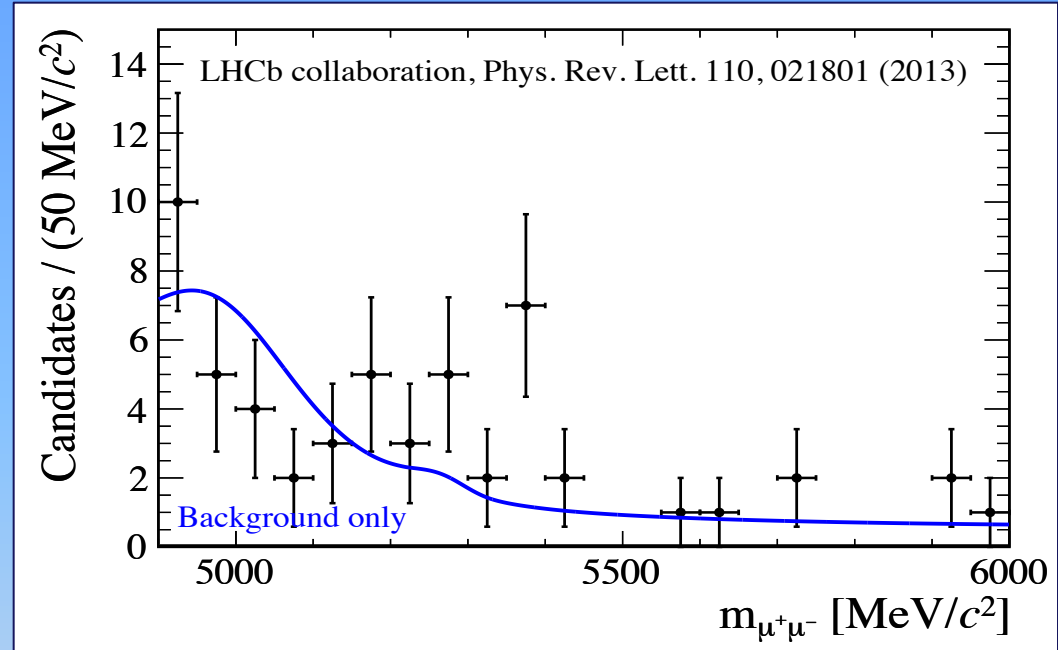


## 2) Vind nieuwe deeltjes

$$B^0_s \rightarrow \mu\mu$$

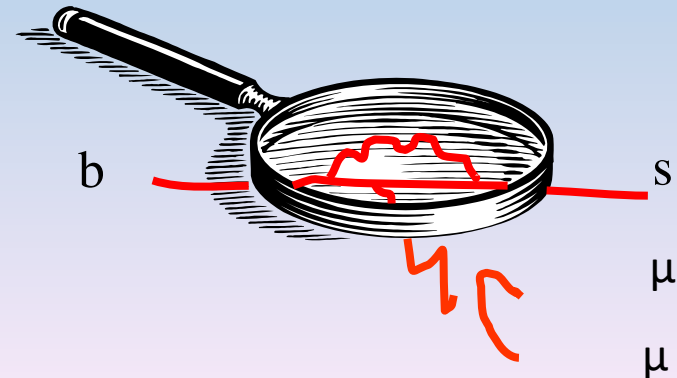


# LHCb: bestuderen van $B$ deeltje

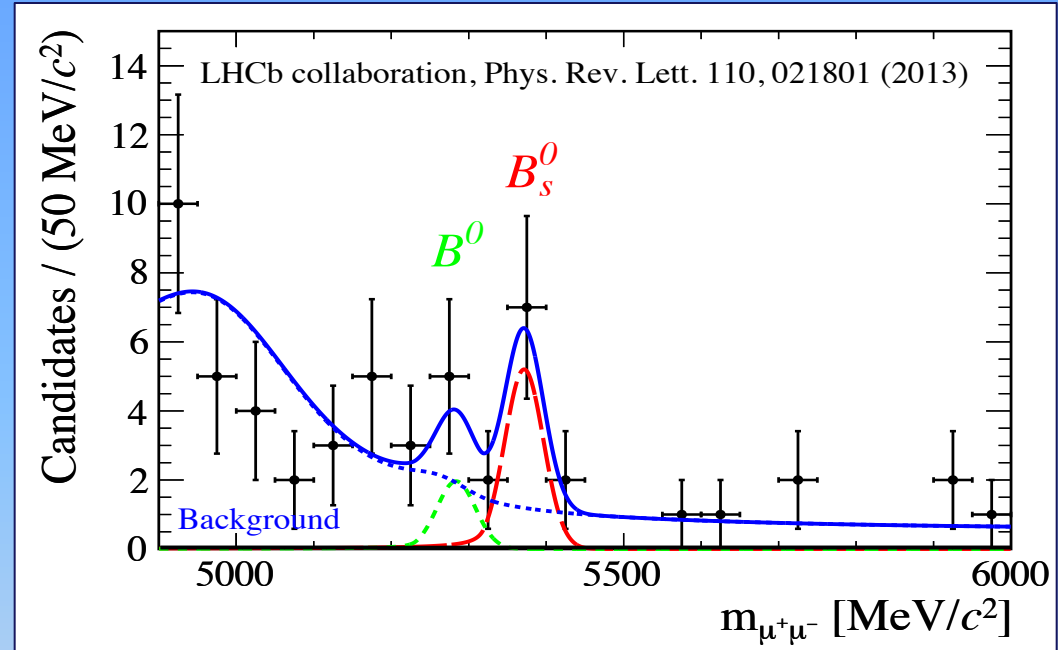


Slechts 3 op de miljard  $B$  deeltjes vervalst naar 2 muonen

Bestaan er nieuwe deeltjes?

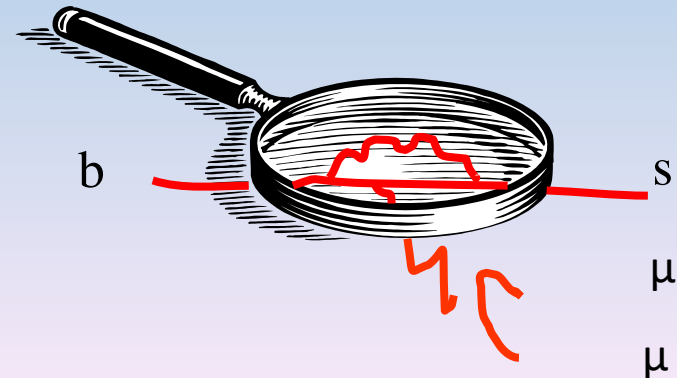


# LHCb: bestuderen van $B$ deeltje

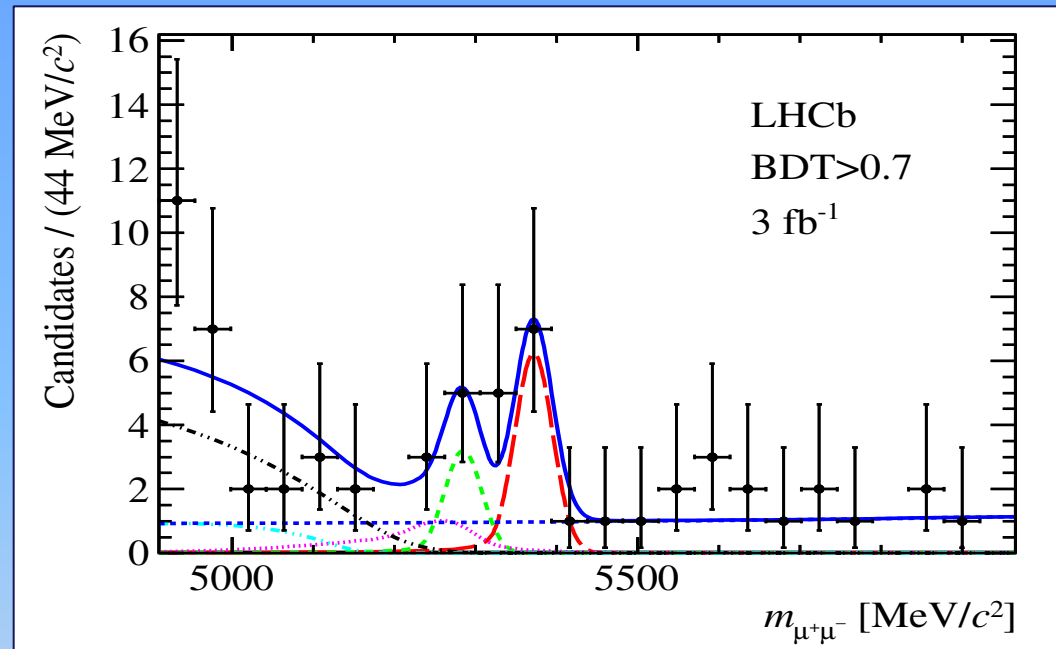


Slechts 3 op de miljard  $B$  deeltjes vervalst naar 2 muonen

Bestaan er nieuwe deeltjes?

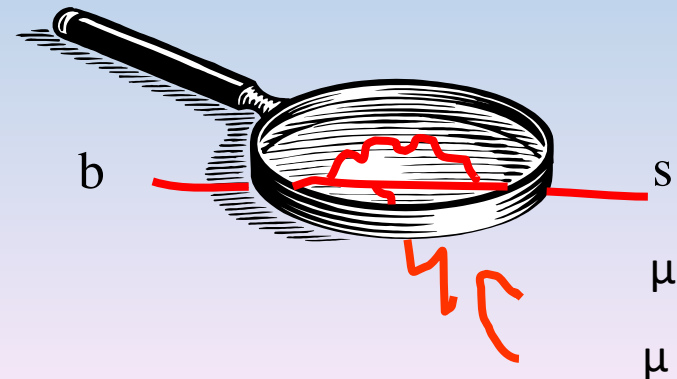


# LHCb: bestuderen van $B$ deeltje



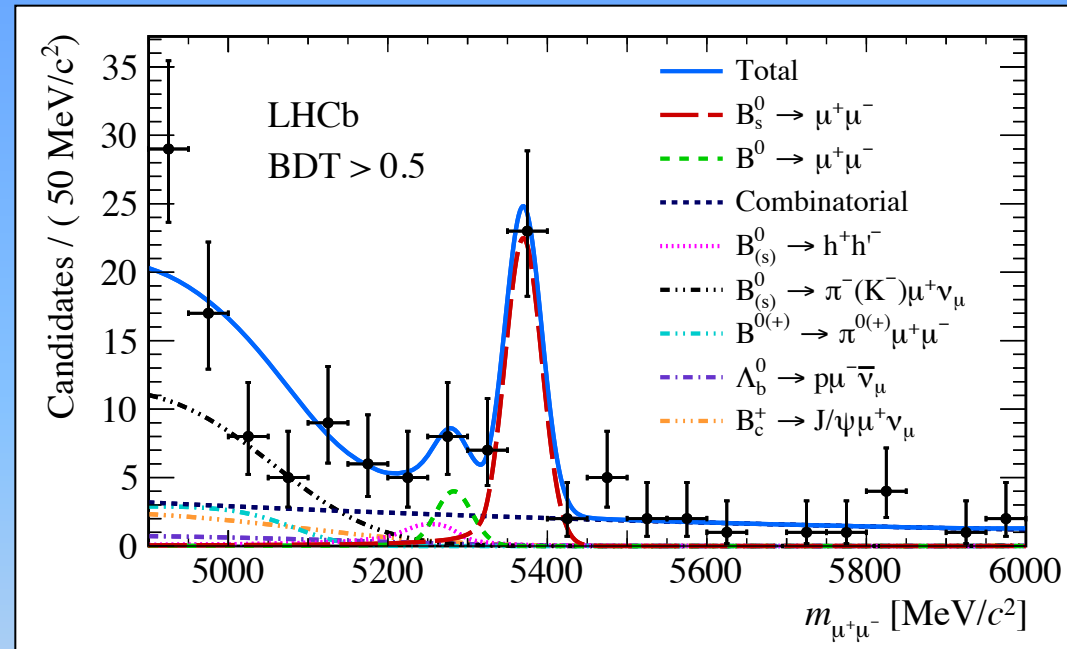
Slechts 3 op de miljard  $B$  deeltjes vervalst naar 2 muonen

Bestaan er nieuwe deeltjes?



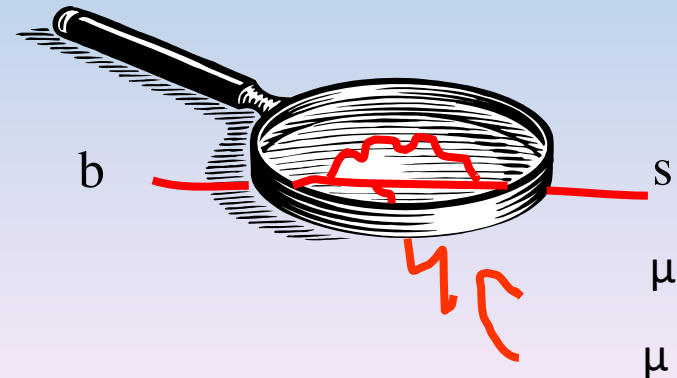


# LHCb: bestuderen van $B$ deeltje

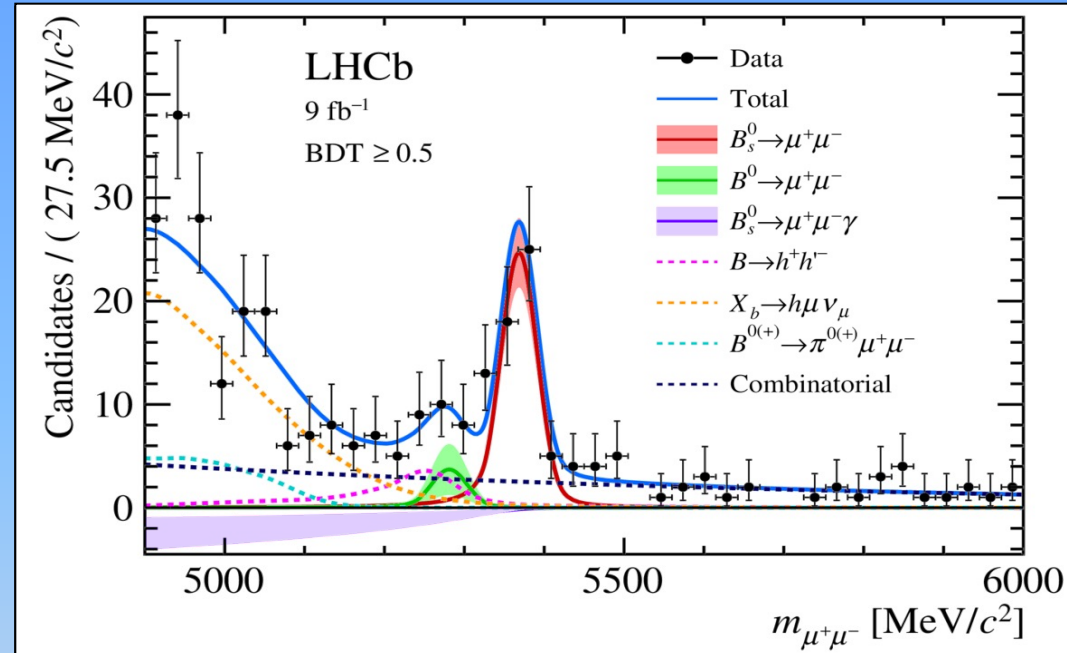


Slechts 3 op de miljard  $B$  deeltjes vervalst naar 2 muonen

Bestaan er nieuwe deeltjes?



# LHCb: bestuderen van $B$ deeltje



Phys. Rev. Lett. 128, (2022) 041801

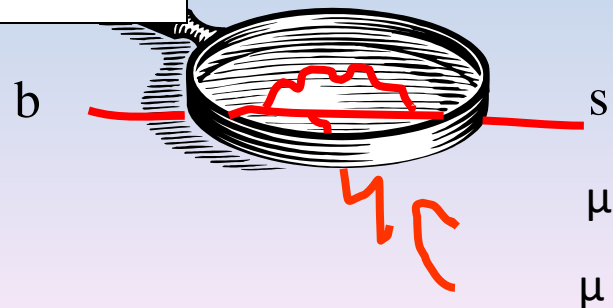
$$\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-) = (3.09^{+0.46+0.15}_{-0.43-0.11}) \times 10^{-9}$$

$$\mathcal{B}(B^0 \rightarrow \mu^+\mu^-) = (1.2^{+0.8}_{-0.7} \pm 0.1) \times 10^{-10}$$

Theory:

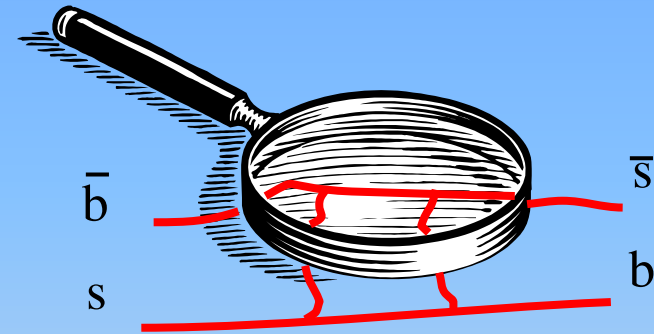
$$\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-) = (3.65 \pm 0.23) \times 10^{-9}$$

$$\mathcal{B}(B^0 \rightarrow \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$$

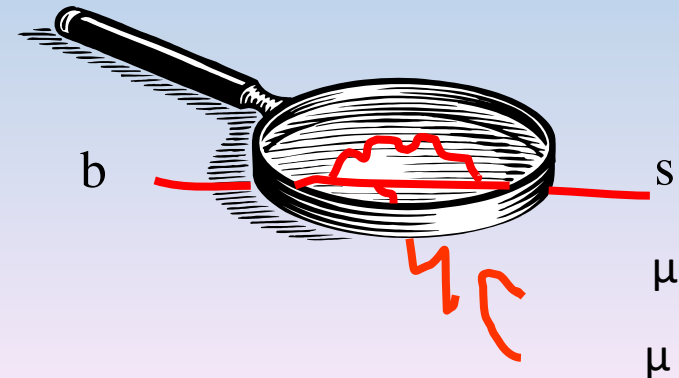


# LHCb: bestuderen van $B$ deeltje

1) Vind verschillen tussen materie en anti-materie



2) Vind nieuwe deeltjes



# LHCb: highlights

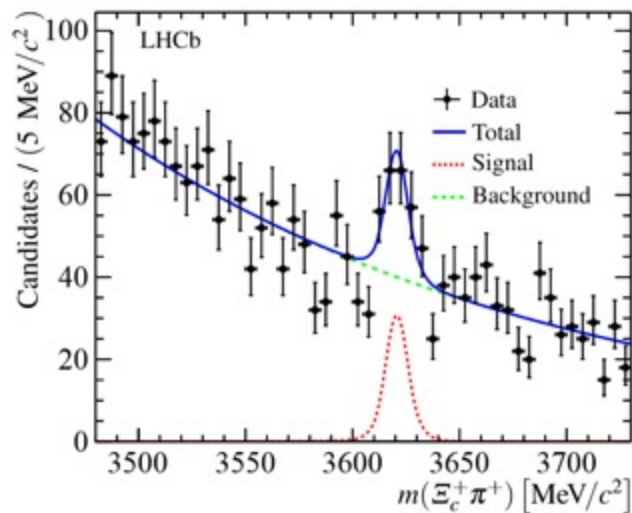
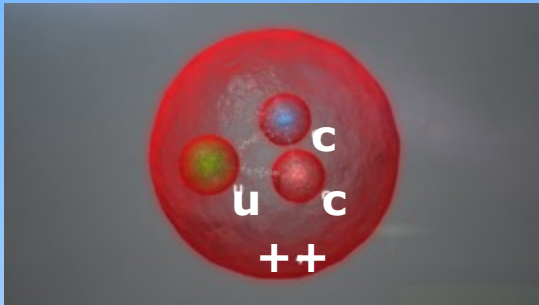
- 1) Nieuwe 'gewone' hadronen
- 2) Nieuwe 'exotische' hadronen: Tetraquark en pentaquark
- 3) Ontdekking 'CP schending'  $B_s$
- 4) Ontdekking 'CP schending' charm

## Hot topic:

- 5) Verschil electron, muon, tau??

# LHCb: nieuwe 'gewone' hadronen

(ccu):  $\Xi_{cc}^{++}$



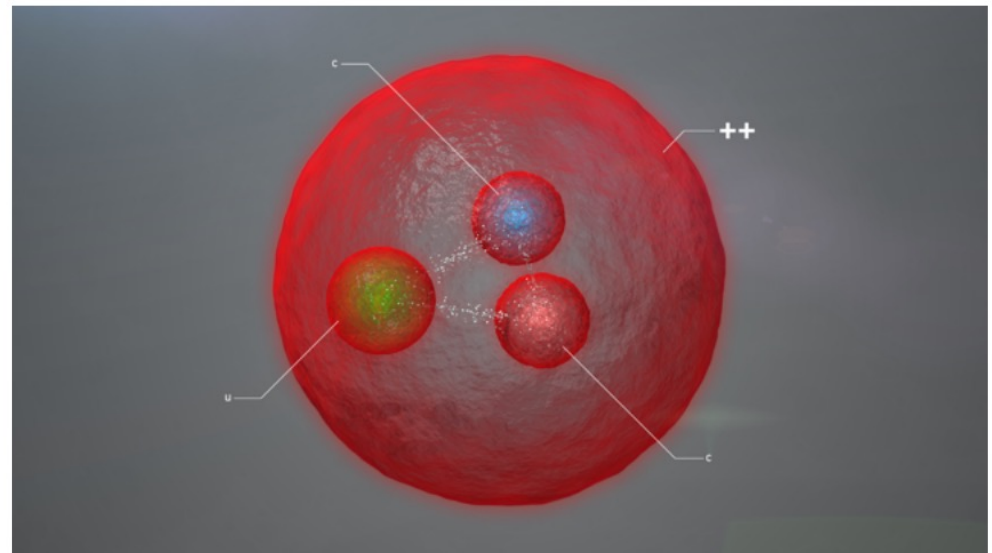
**NewScientist**  
IDEEËN DIE DE WERELD VERANDEREN

## Nieuw zwaar deeltje legt sterke kernkracht op de pijnbank

12 juli 2017



Jacob Aron en Leah Crane

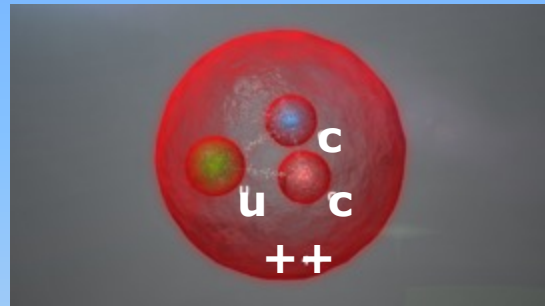


Het nieuwe deeltje bevat twee charm-quarks in het midden en een up-quark daaromheen. Beeld: Daniel Dominguez/CERN.



# LHCb: nieuwe 'gewone' hadronen

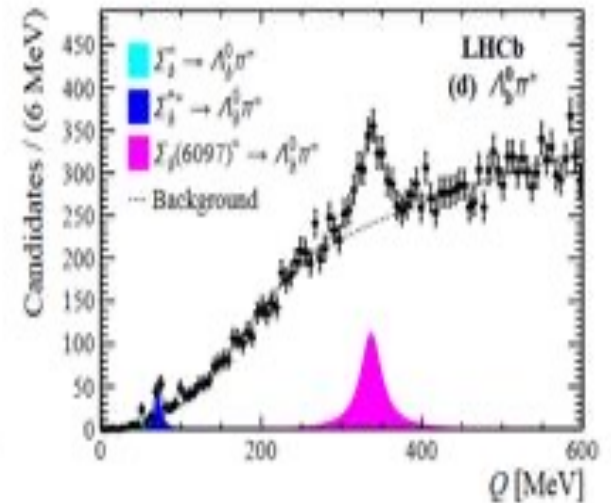
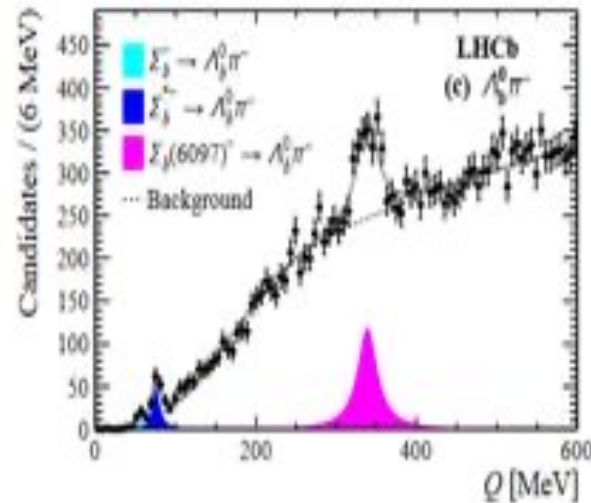
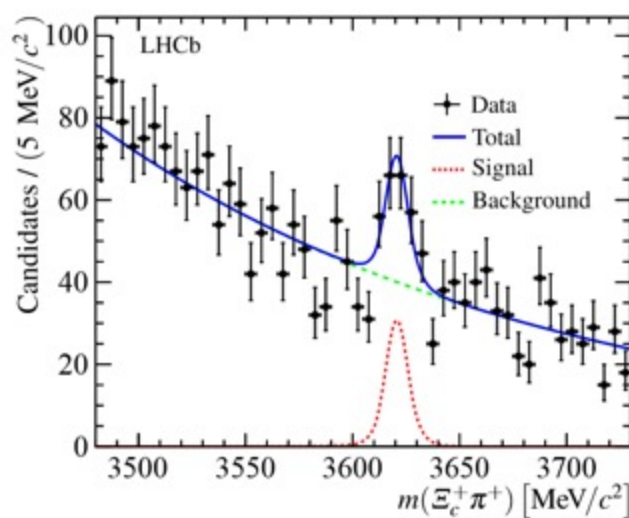
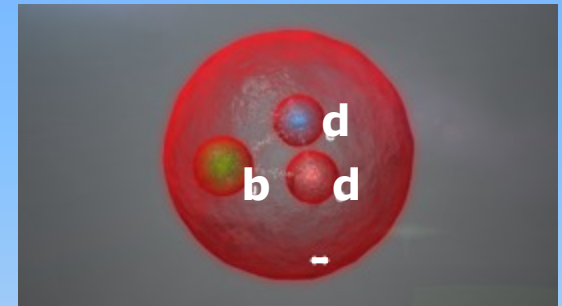
(ccu):  $\Xi_{cc}^{++}$



(buu):  $\Sigma_b(6097)^+$

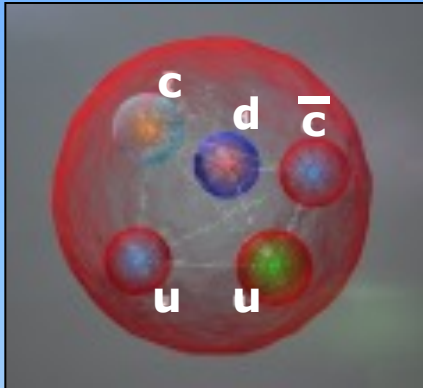


(bdd):  $\Sigma_b(6097)^-$

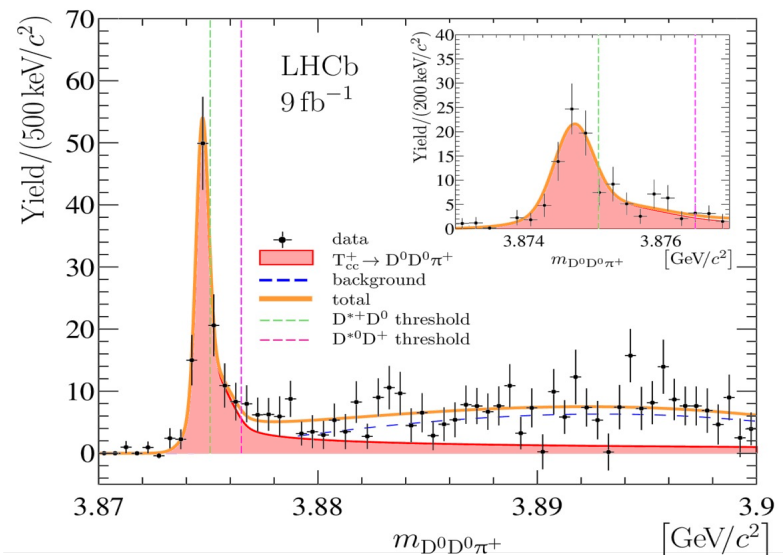
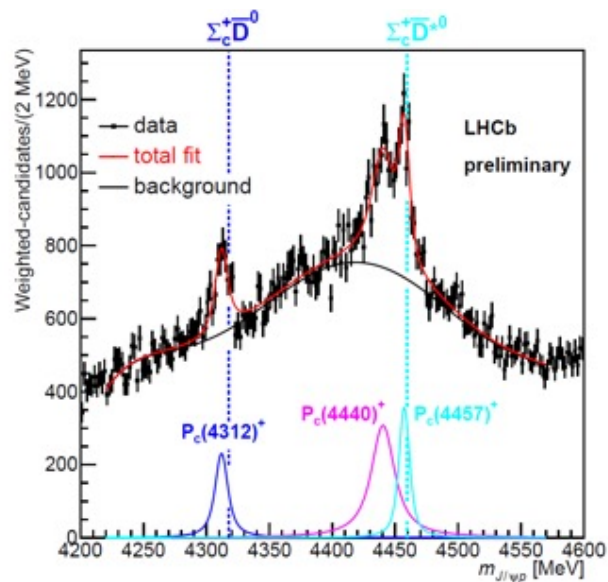
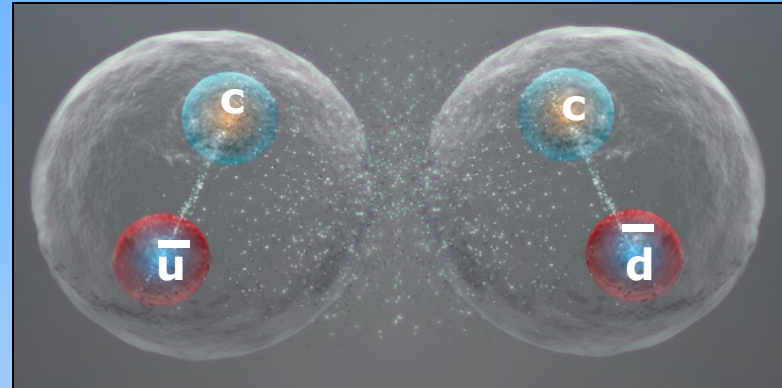


# LHCb: nieuwe 'exotische' hadronen

$(c\bar{c}duu): \mathbf{P}_c(\mathbf{4312})^+$

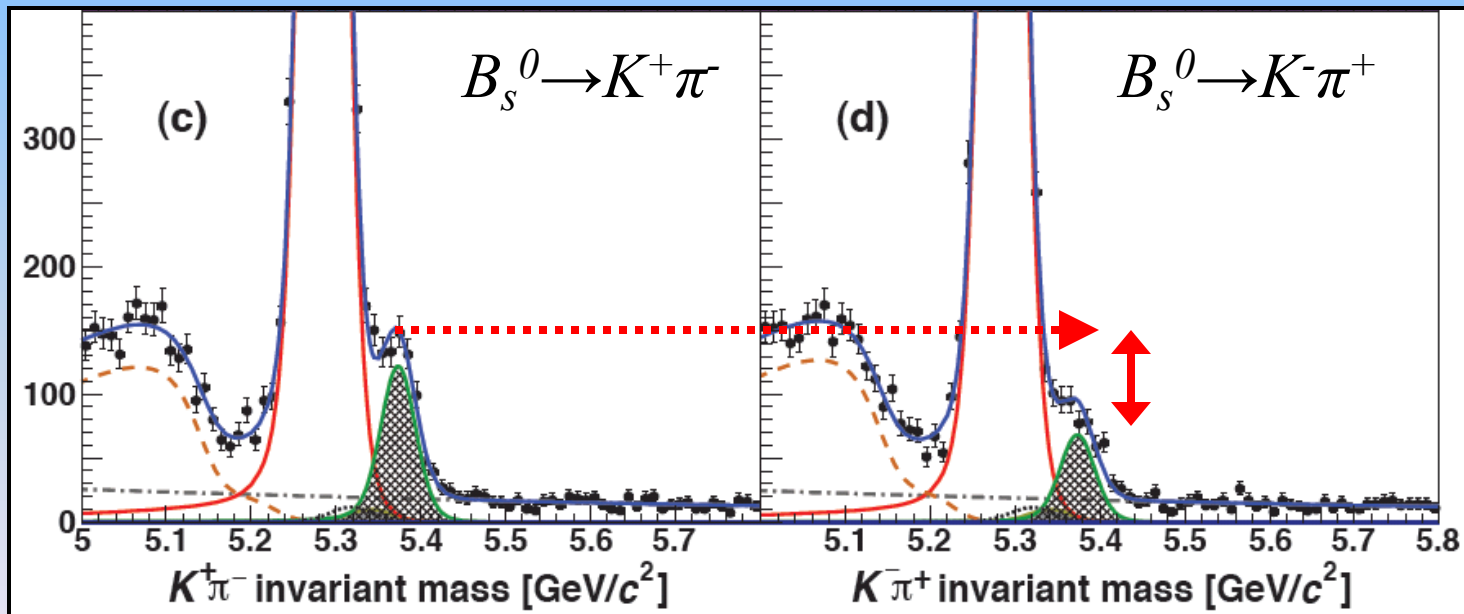
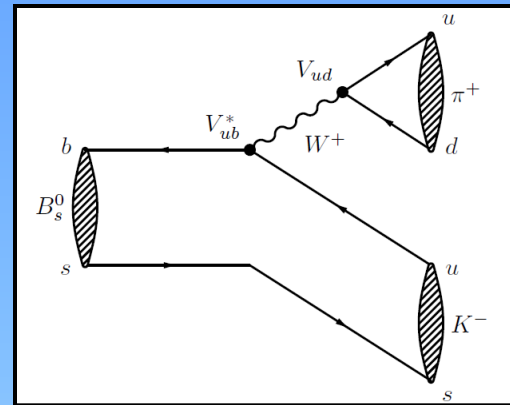


$(c\bar{u} \ c\bar{d}): \mathbf{T}_{cc}^+(\mathbf{3875})$



# LHCb: antimaterie verschil in $B_s^0$

CP schending in  $B_s^0$





# LHCb: antimaterie verschil in charm

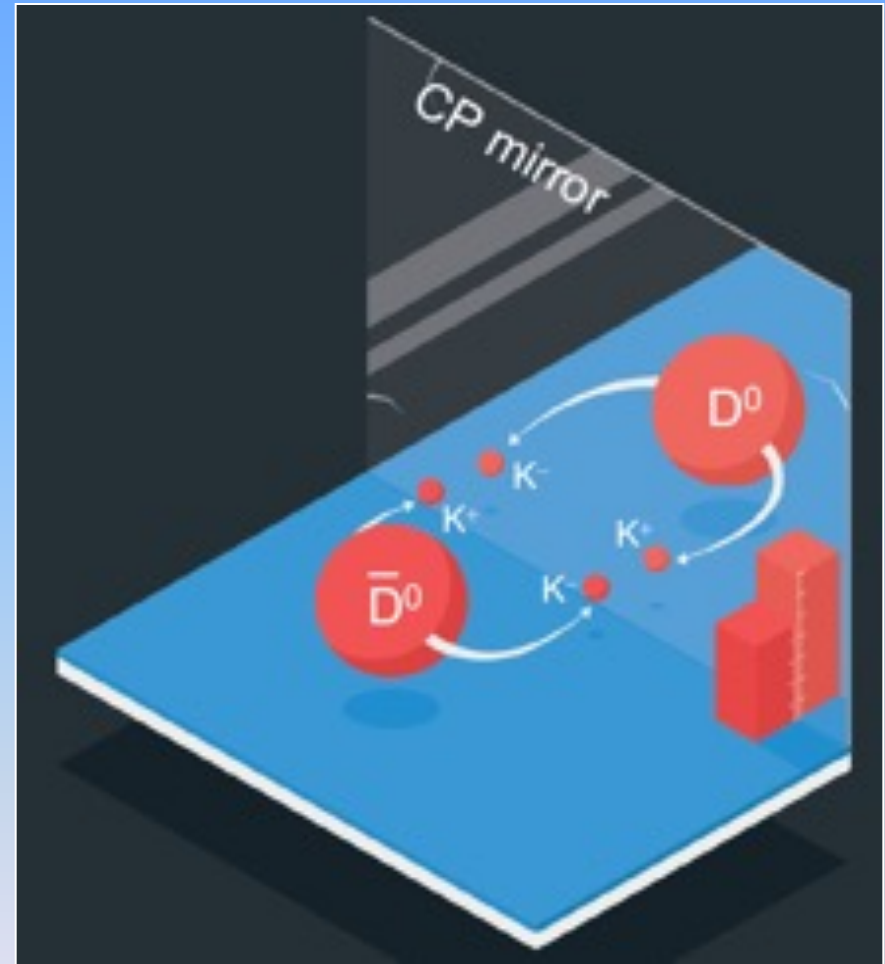
“CP schending”

$D^0 \rightarrow K^+ K^-$  same as

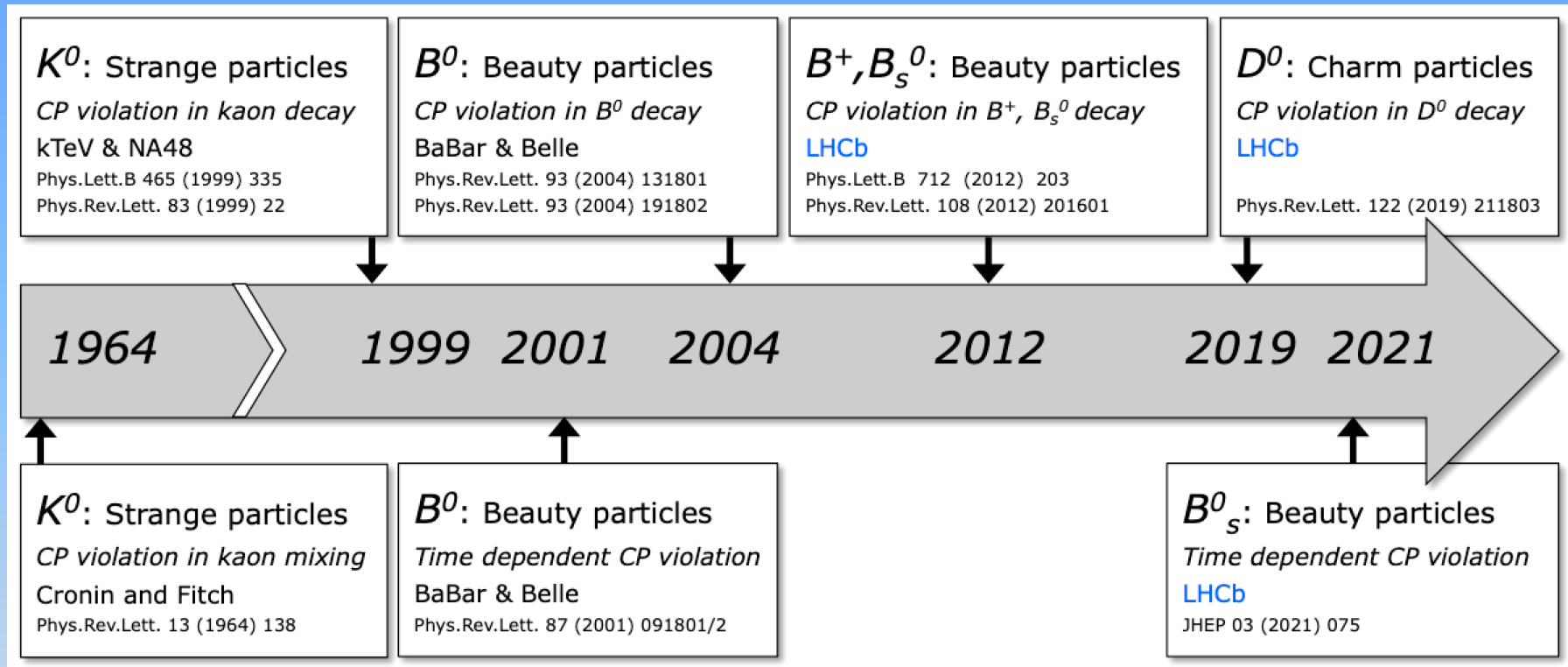
$\bar{D}^0 \rightarrow K^+ K^-$  ??

at least it is different compared to  
 $D^0 \rightarrow \pi^+ \pi^-$  ...:

$$\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}$$



# LHCb: antimaterie verschillen



- |      |  |                   |
|------|--|-------------------|
| (ds) | <b>1964</b> : CP schending met $K^0$   | (Nobelprijs 1980) |
| (bd) | <b>2000</b> : CP schending met $B^0$   | (Nobelprijs 2008) |
| (bs) | <b>2012</b> : CP schending met $B_s^0$ | (LHCb)            |
| (cu) | <b>2019</b> : CP schending met $D^0$   | (LHCb)            |

# LHCb: highlights

- 1) Nieuwe 'gewone' hadronen
- 2) Nieuwe 'exotische' hadronen: Tetraquark en pentaquark
- 3) Ontdekking 'CP schending'  $B_s$
- 4) Ontdekking 'CP schending' charm

## Hot topic:

- 5) Verschil electron, muon, tau??



# LHCb: hot topic

**NewScientist**  
IDEEËN DIE DE WERELD VERANDEREN

## Cern vindt nieuwe hint voor scheurtjes in standaardmodel

19 april 2017



George van Hal



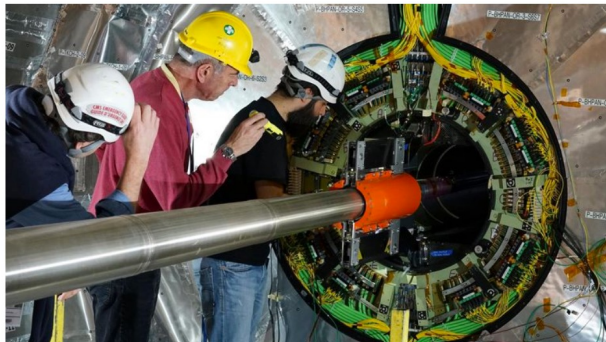
mogelijke hint dat er meer is dan alleen het standaardmodel. Beeld: Cern.

**de Volkskrant**

## CERN is 'voorzichtig opgewonden' over subtiel verschillen in deeltjeswereld

Een gevoel van 'voorzichtige opwindning' heeft zich meester gemaakt van deeltjesfysici van CERN in Genève. Dinsdag maakte de LHCb-detector daar bekend subtiel verschillen te zien tussen bepaalde deeltjes. De gangbare deeltjestheorie neemt aan dat deeltjes in essentie identiek zijn.

Martijn van Calmthout 19 april 2017, 21:29



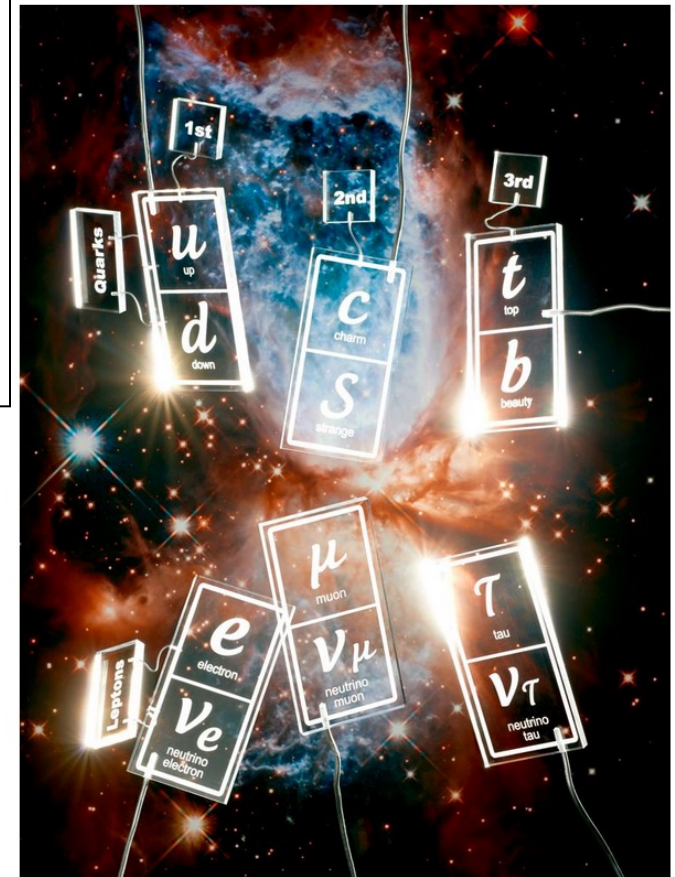
Wellicht is de deeltjeswereld niet zo democratisch als vooraf gedacht werd. Beeld: epa

**de Volkskrant**

## Moeder aller deeltjes: de zoektocht naar de leptoquark

Is het fundamenteelste deeltje in het universum altijd over het hoofd gezien? Komende week kan de wereld opgeschud worden, als natuurkundigen in Seoul hun resultaten bekendmaken. Leptoquark, onthoud dat woord.

Martijn van Calmthout 29 juni 2018, 11:25



Beeld: Rein Janssen

# LHCb: hot topic

deVolkskrant

## Moeder aller deeltjes: de zoektocht naar de leptoquark

Is het fundamenteelste deeltje in het universum altijd over het hoofd gezien? Komende week kan de wereld opgeschud worden, als natuurkundigen in Seoul hun resultaten bekendmaken. Leptoquark, onthoud dat woord.

Martijn van Calmthout 29 juni 2018, 11:25

Maar de LHCb-metingen geven al jaren kleine hints dat er iets mis is met deze keurige lepton-universaliteit. En dat elektronen en muonen ergens diep van binnen toch net iets anders met quarks omgaan.



Beeld Rein Janssen



$$t \rightarrow W^+ b$$

$$BR(t \rightarrow Wb) = \frac{\Gamma(t \rightarrow Wb)}{\Gamma(t \rightarrow Wb) + \Gamma(t \rightarrow Wc) + \Gamma(t \rightarrow Ws)}$$

$$= \frac{|V_{tb}|^2}{|V_{tb}|^2 + |V_{ts}|^2 + |V_{td}|^2}$$

$$\approx \frac{(0.9945)^2}{(0.9945)^2 + (0.0079)^2 + (0.004)^2}$$

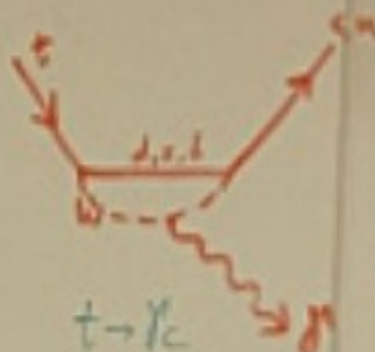
$$= 99.82\%$$

but F.C.N.C...



$$t \rightarrow Zc$$

$$t \rightarrow Zb$$



$$t \rightarrow \gamma c$$

$$t \rightarrow \gamma b$$

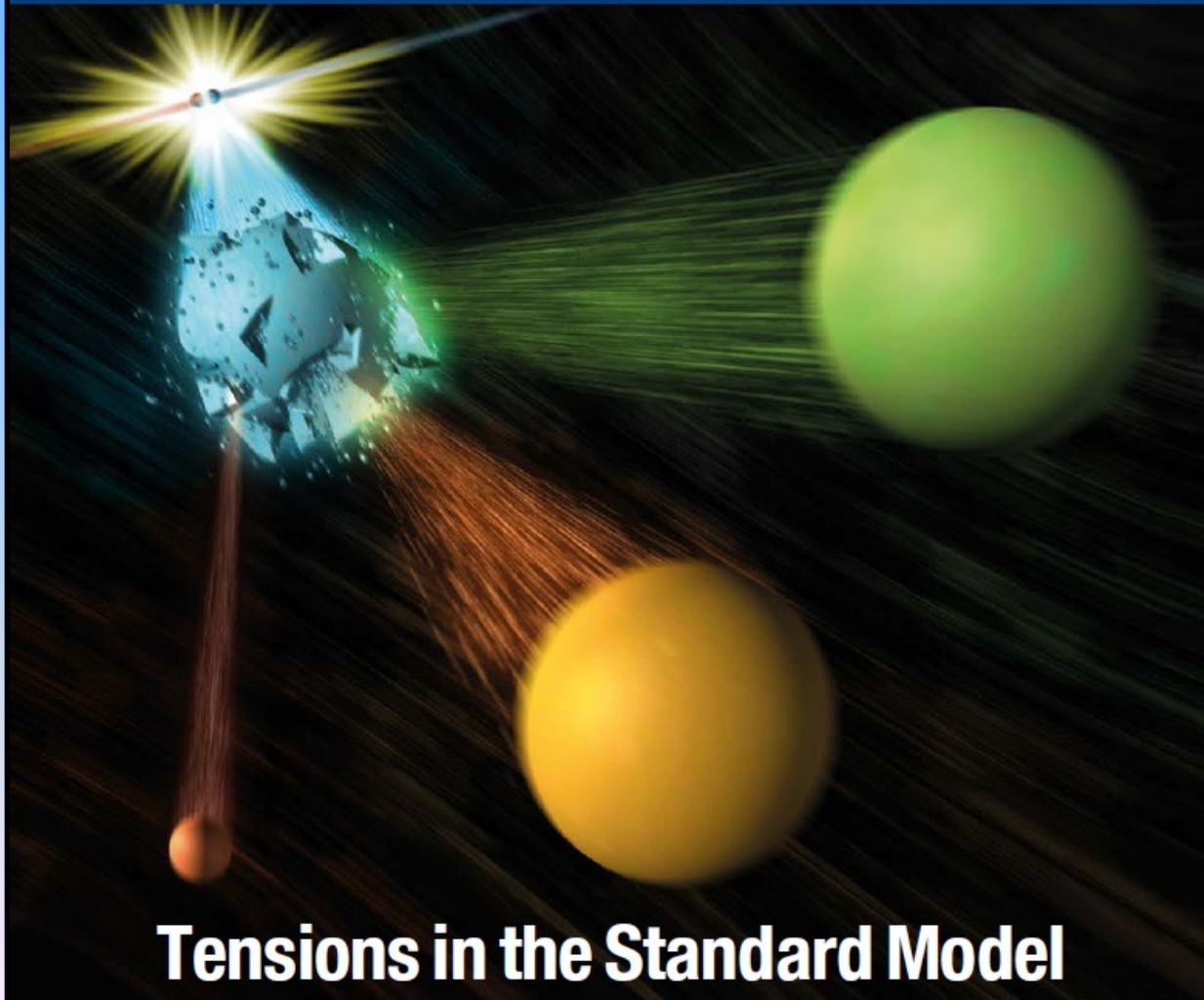
$$U_{CKM} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{13} - c_{12}s_{23}s_{\delta} & c_{12}c_{23} & s_{23}e^{-i\delta} \\ s_{12}s_{13} - c_{12}s_{23}c_{\delta} & -s_{23}c_{13} & c_{23}e^{-i\delta} \end{pmatrix}$$



INTERNATIONAL JOURNAL OF HIGH-ENERGY PHYSICS

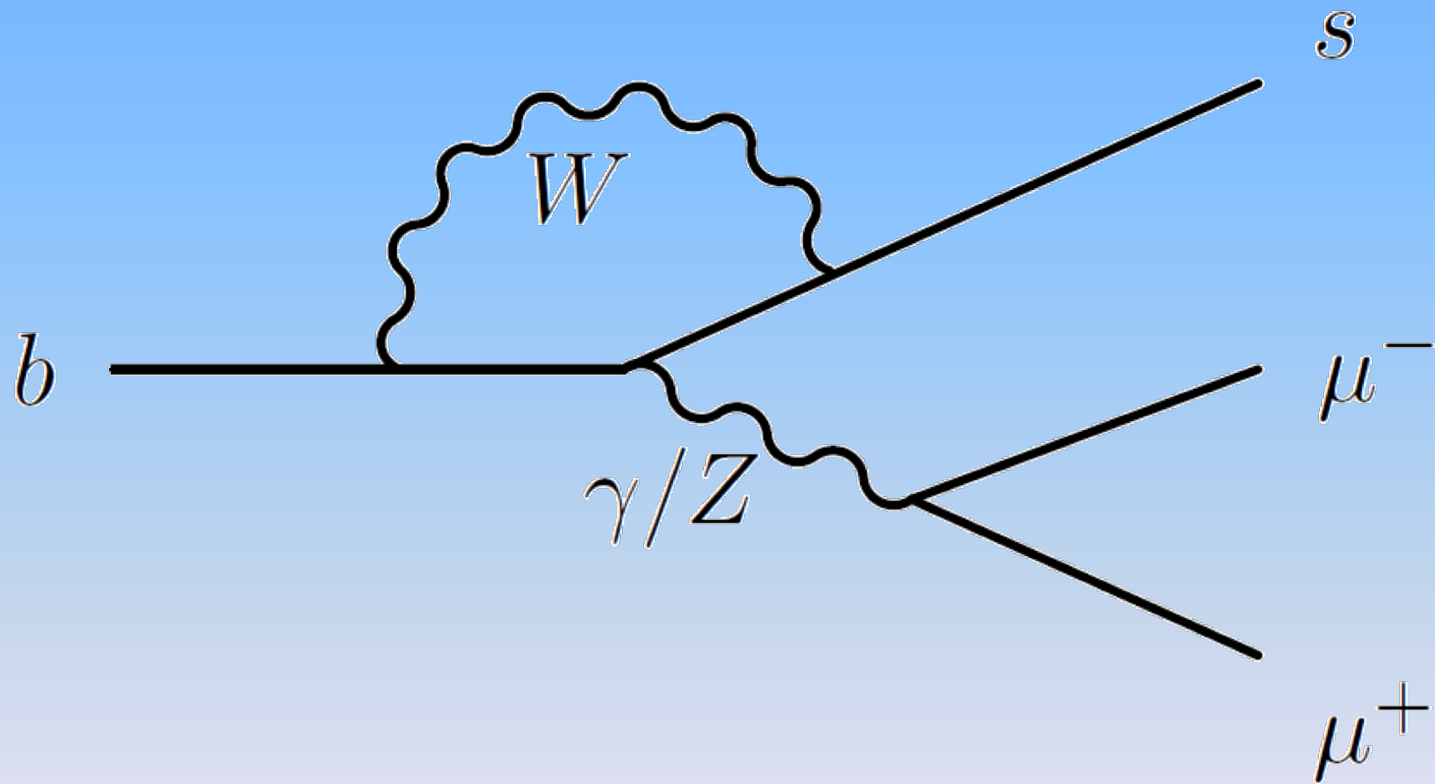
# CERN COURIER

VOLUME 55 NUMBER 9 NOVEMBER 2015

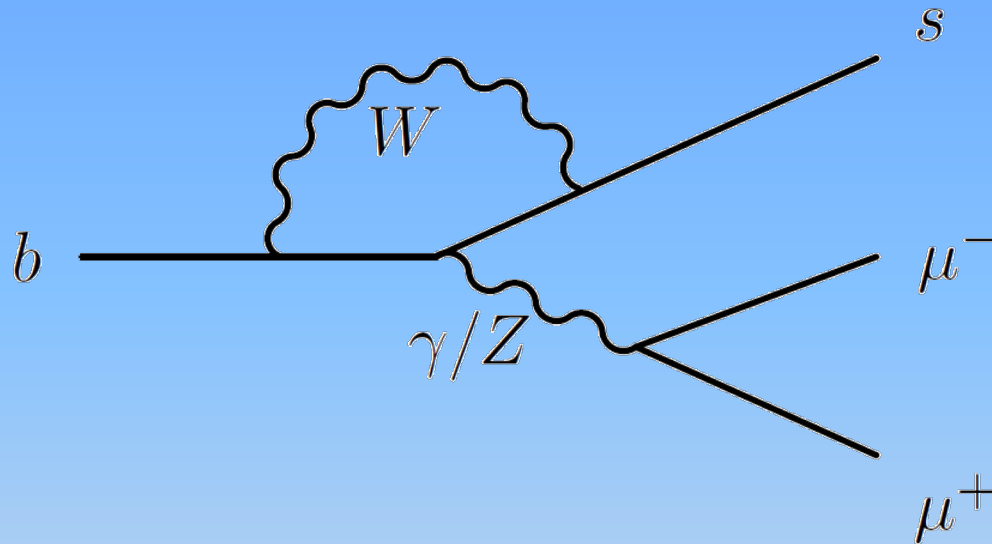


**Tensions in the Standard Model**

# LHCb: hot topic



# LHCb: hot topic

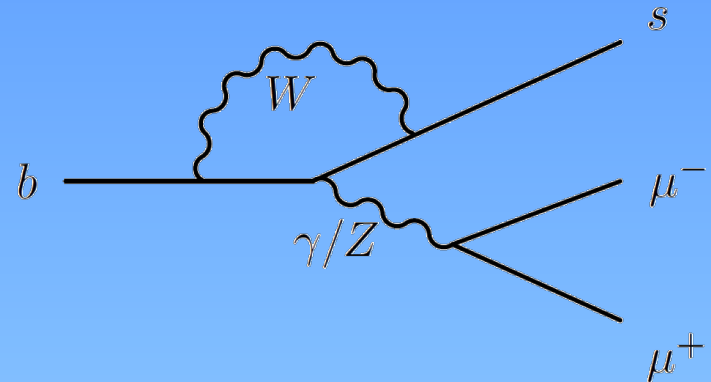


Flavour changing neutral current electroweak penguin

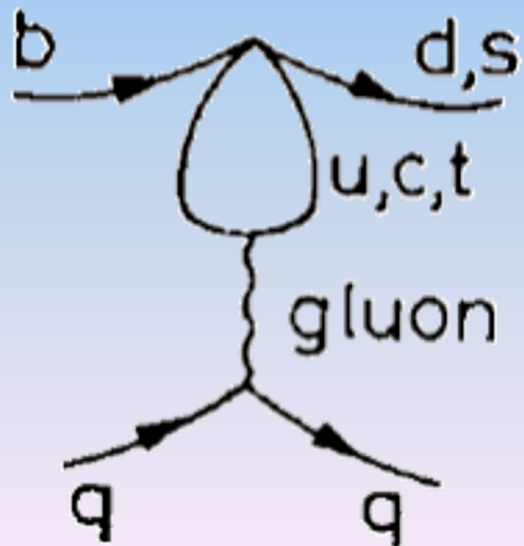
FCNC EWP



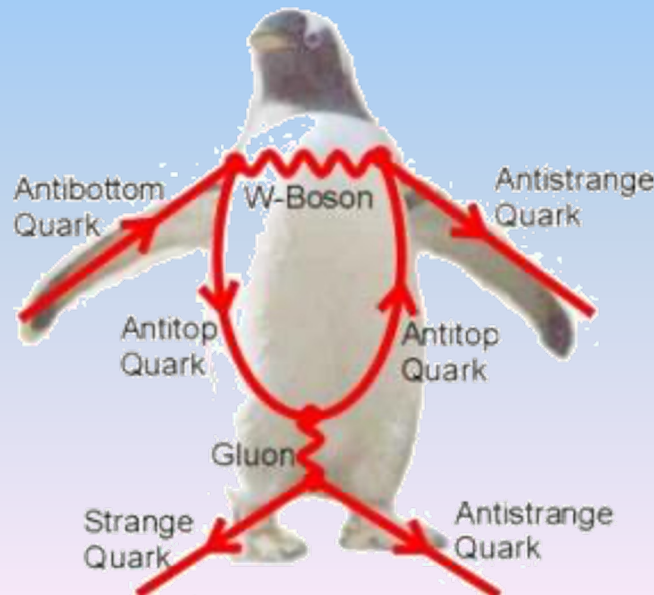
# LHCb: hot topic



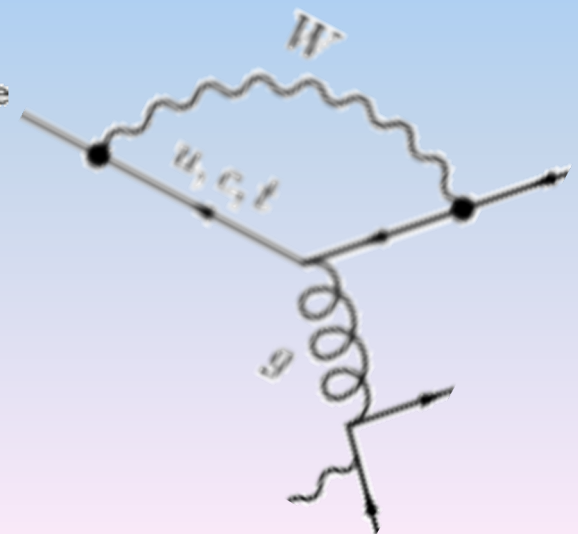
*The original penguin:*



*A real penguin:*

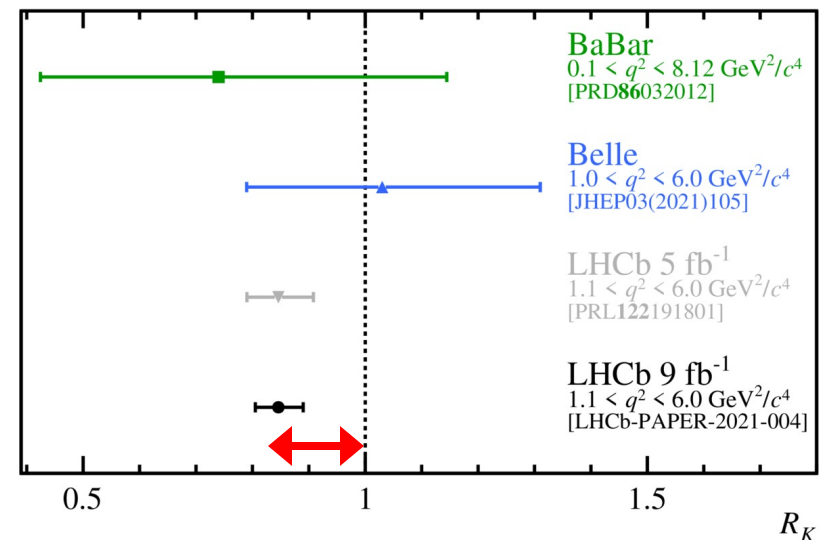
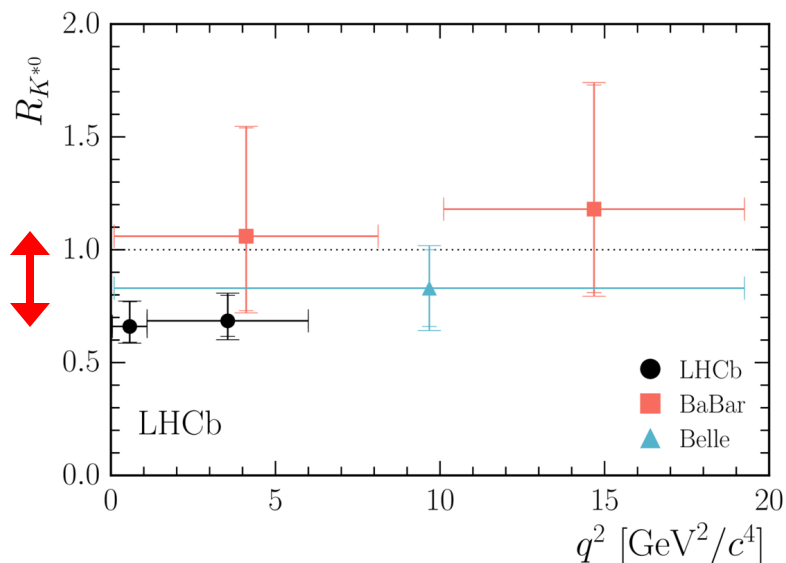
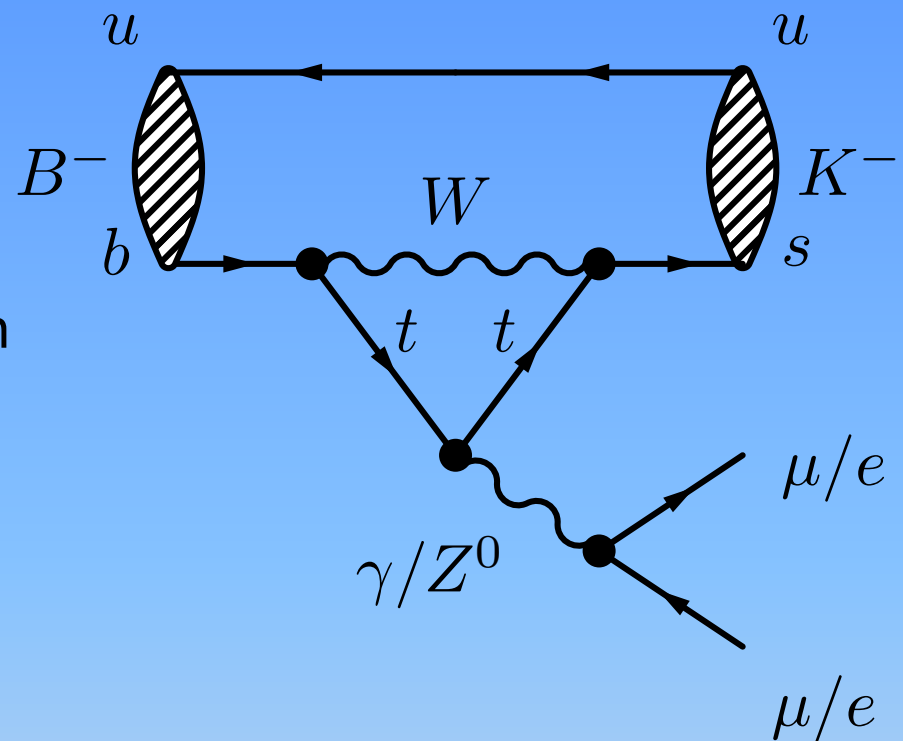


*Our penguin:*



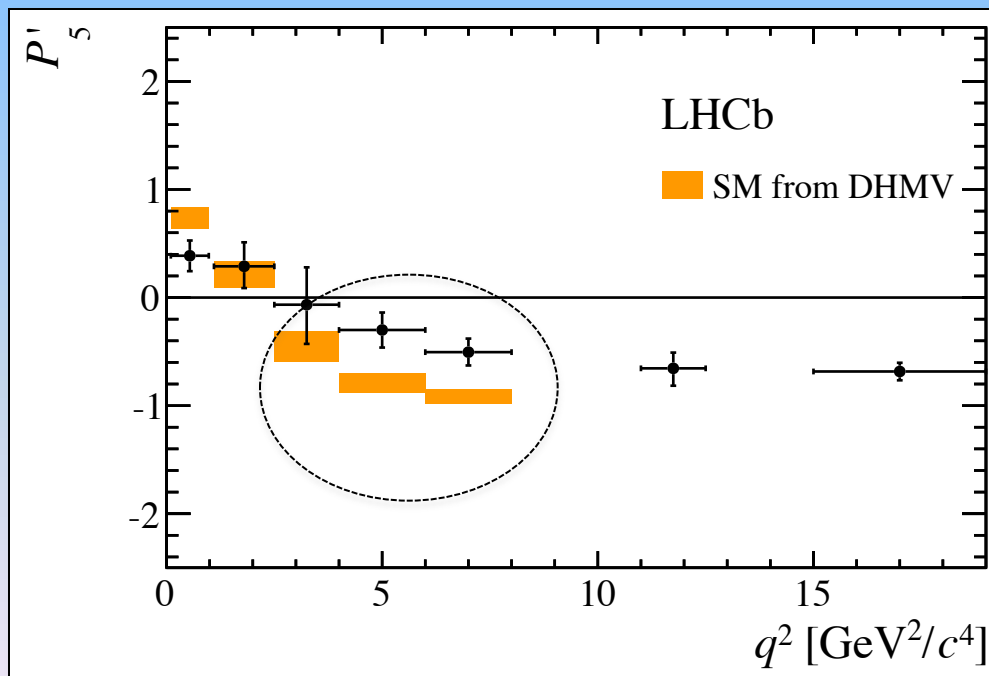
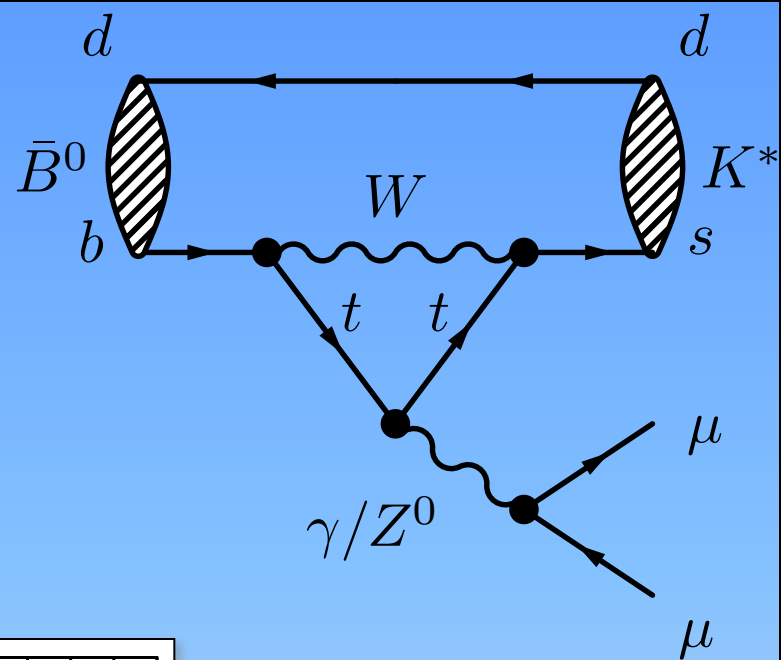
# LHCb: hot topic

Electronen en muonen gedragen zich anders?



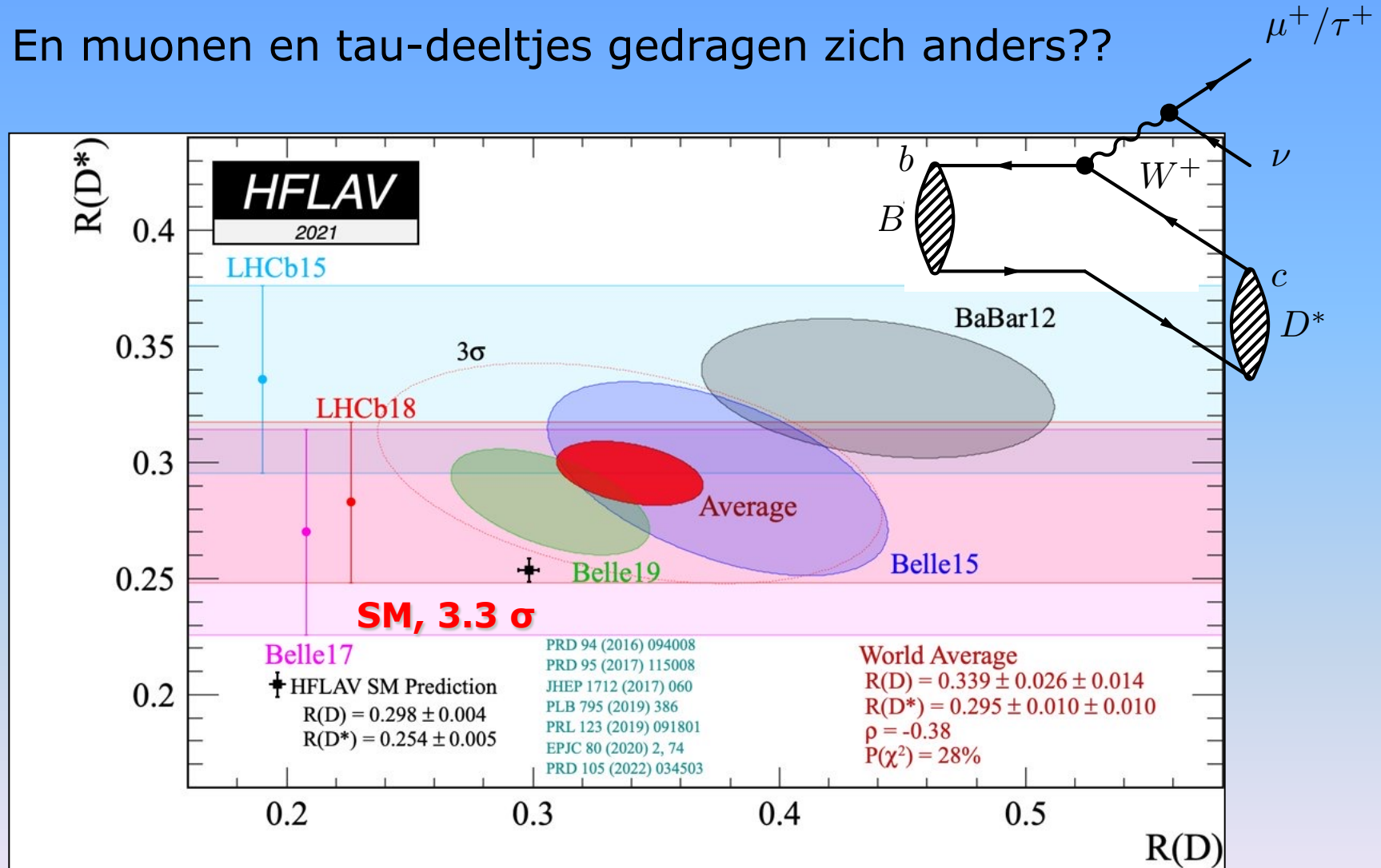
# LHCb: hot topic

Ook hoekverdeling is anders...



# LHCb: hot topic

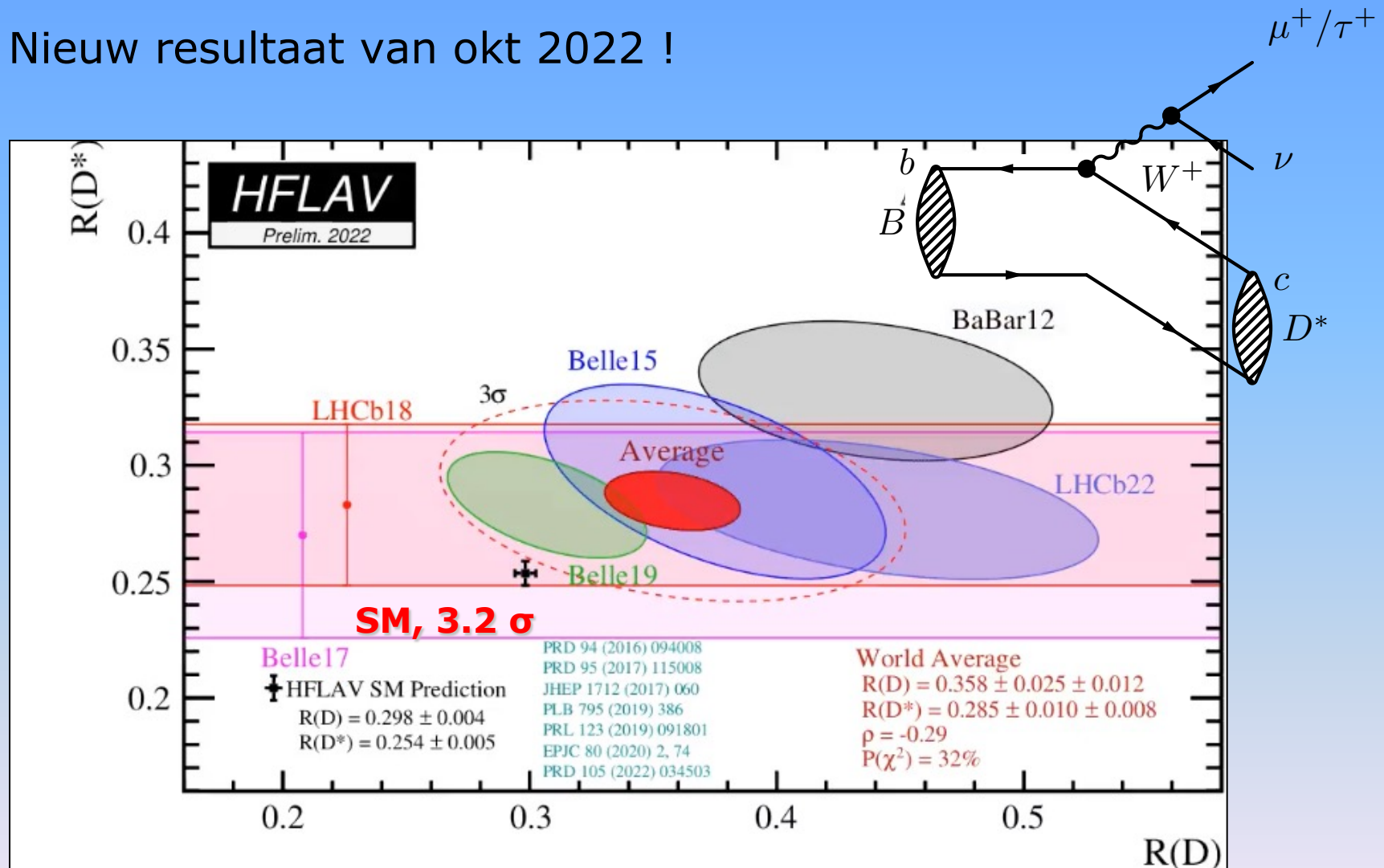
En muonen en tau-deeltjes gedragen zich anders??





# LHCb: hot topic

Nieuw resultaat van okt 2022 !



# LHCb: wat kan het zijn?

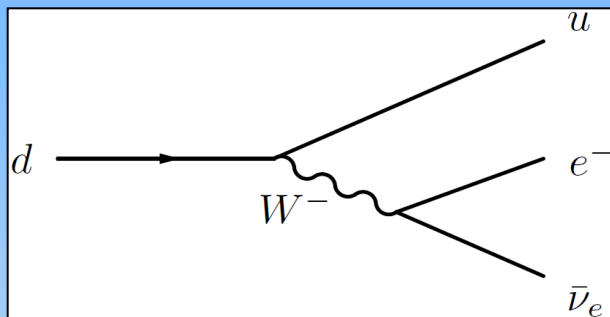
deVolkskrant

## Moeder aller deeltjes: de zoektocht naar de leptoquark

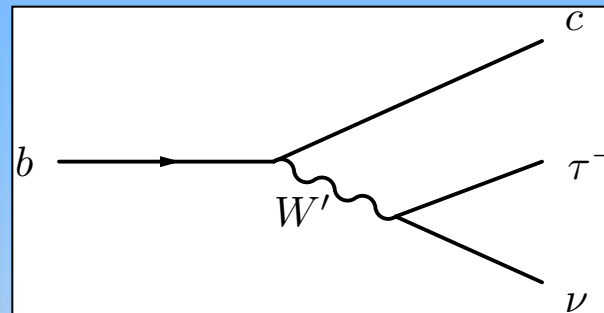
Is het fundamenteelste deeltje in het universum altijd over het hoofd gezien? Komende week kan de wereld opgeschud worden, als natuurkundigen in Seoul hun resultaten bekendmaken. Leptoquark, onthoud dat woord.

Martijn van Calmthout 29 juni 2018, 11:25

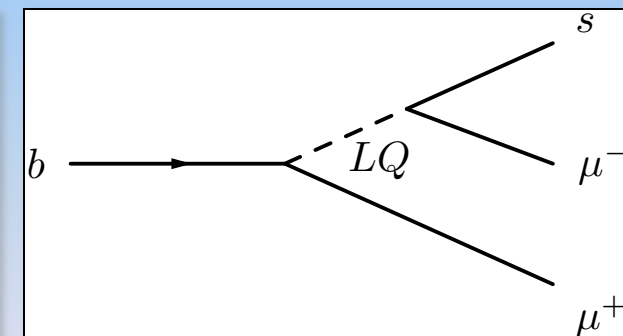
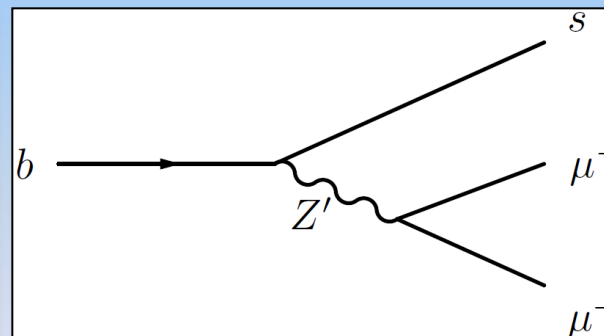
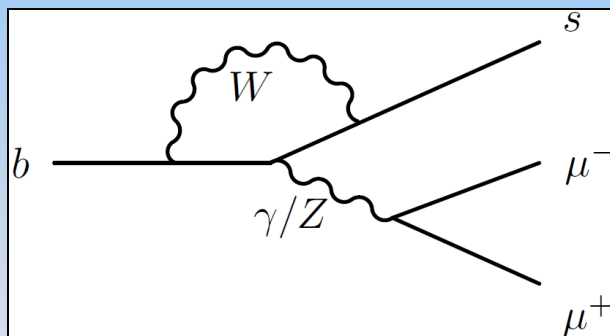
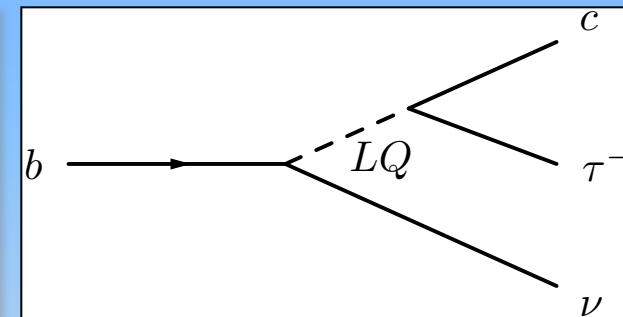
SM



SU(2)'



Leptoquark



Leptoquark, onthoud dat woord.

M. Van Calmthout

# LHCb zoekt naar nieuwe deeltjes om antwoorden te zoeken op grote vragen

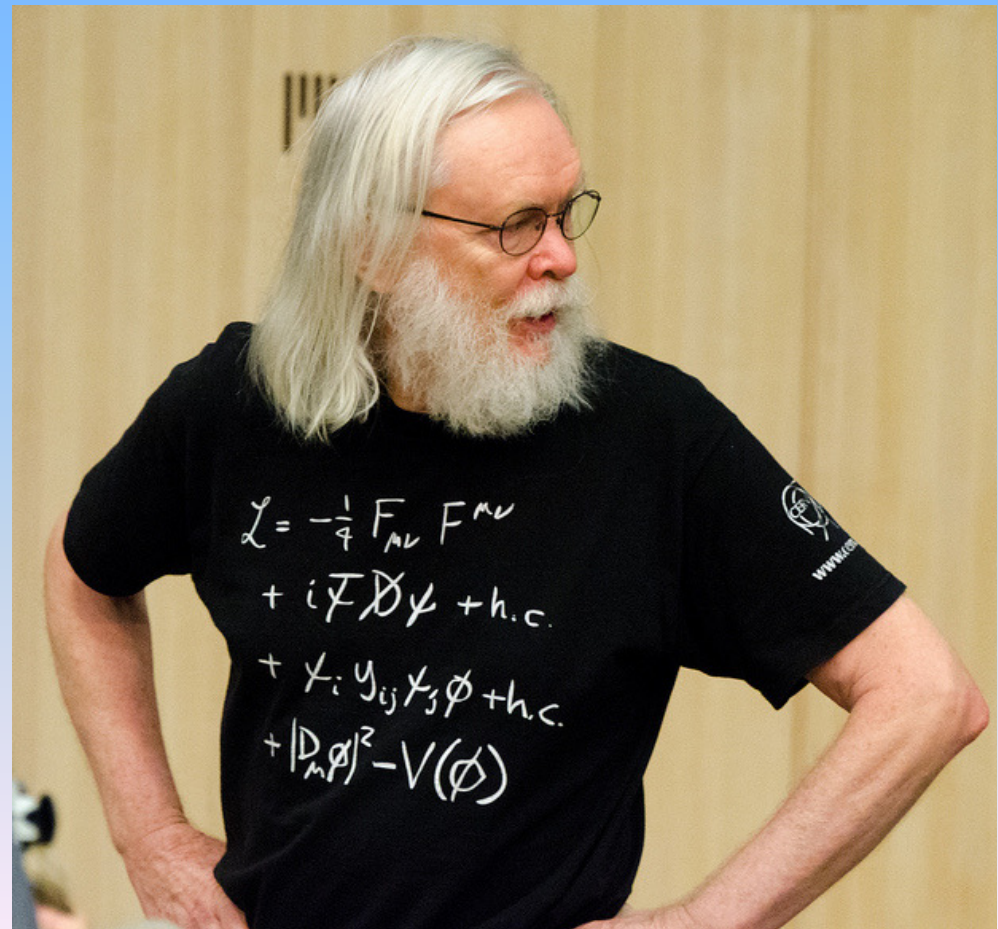


**Dank!**

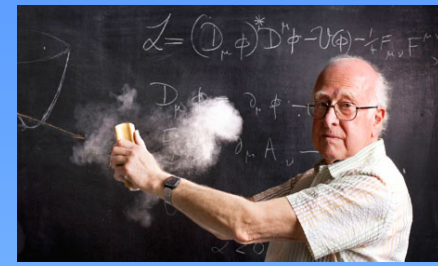


# Higgs en LHCb

# Waarom is de Higgs zo bijzonder?



# Waarom is de Higgs zo bijzonder?



Higgs heeft unieke rol in de wereld van elementaire deeltjes

$\psi$ : "normale" deeltjes

$\phi$ : Higgs

De helft van het T-shirt gaat over Higgs!

$$\begin{aligned}\mathcal{L} = & -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \\ & + i \bar{\psi} \not{D} \psi \\ & + \bar{\psi}_i y_{ij} \psi_j \phi \\ & + |D_\mu \phi|^2 - V(\phi)\end{aligned}$$

Quarks	$u$ up	$c$ charm	$t$ top
	$d$ down	$s$ strange	$b$ bottom

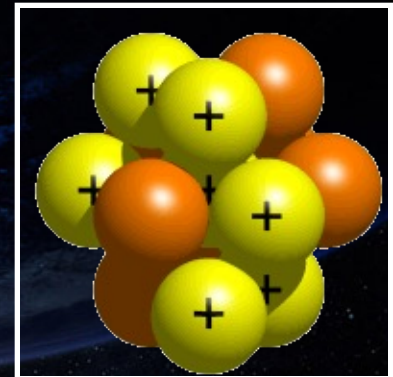
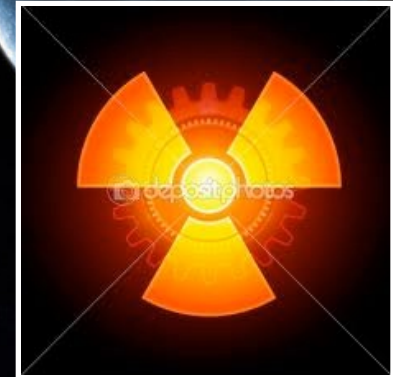
Leptons	$\nu_e$ electron neutrino	$\nu_\mu$ muon neutrino	$\nu_\tau$ tau neutrino
	$e$ electron	$\mu$ muon	$\tau$ tau

$\gamma$ photon	Force carriers
$Z$ Z boson	
$W$ W boson	
$g$ gluon	

12 deeltjes

4 krachten

+ Higgs

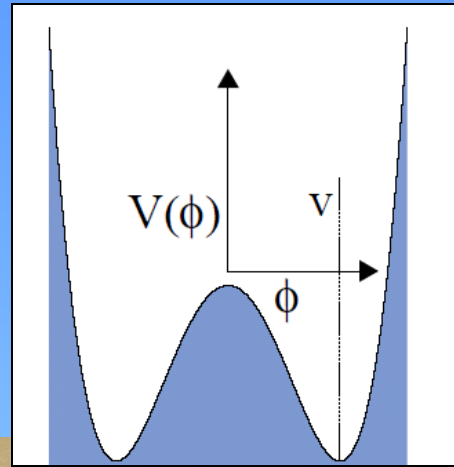




# Higgs en LHCb?

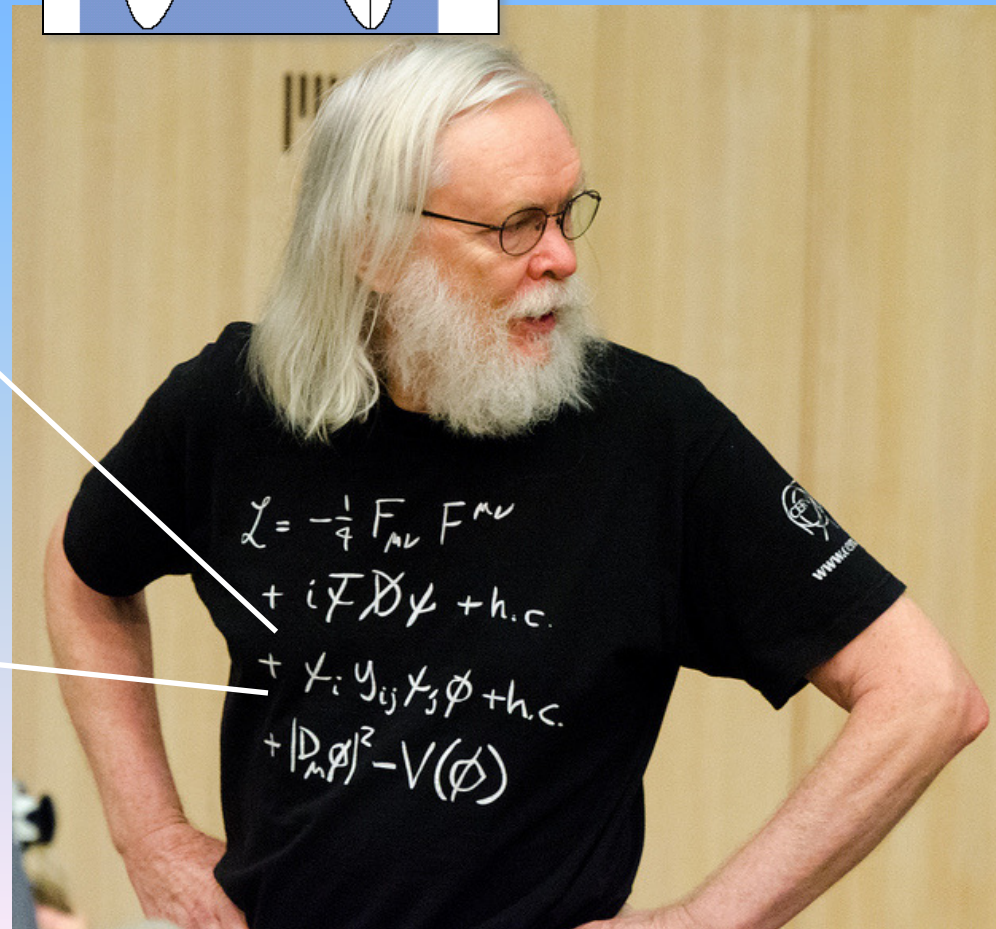
$$Y_{ij} \psi_i \psi_j \phi \rightarrow \underbrace{Y_{ij} \psi_i \psi_j}_{\text{m: } Y_{ij} v} (v + H) / \sqrt{2}$$

$$\text{m: } Y_{ij} v$$



$$\phi = \frac{v + h}{\sqrt{2}} e^{i\chi/v}$$

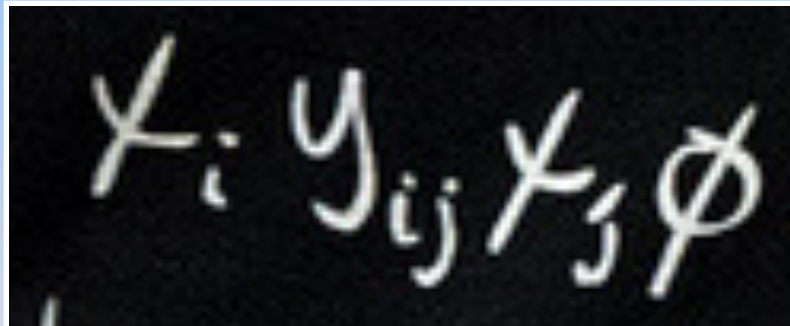
$$\mathcal{L} = y_{ij} \psi_i \psi_j \phi$$

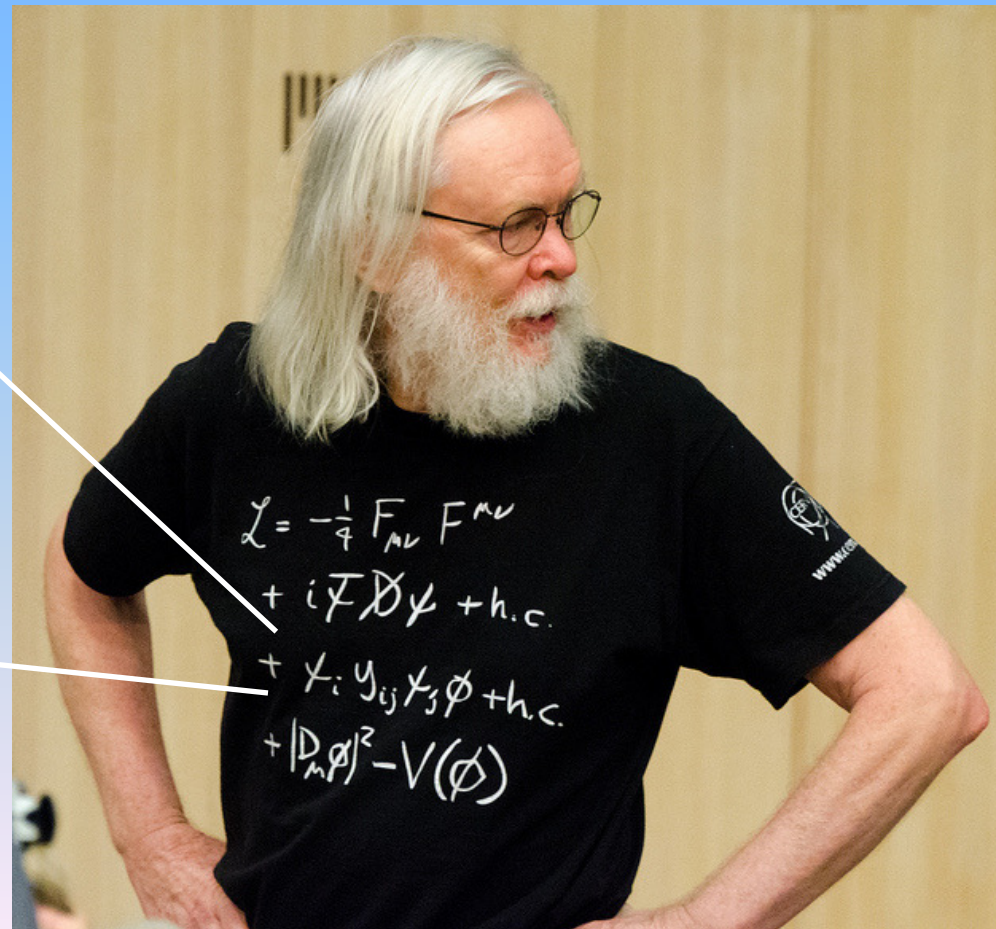


# Higgs en LHCb?

$\psi$ : quarks

$Y_{ij}$ : koppeling tussen verschillende quarks  $i, j$

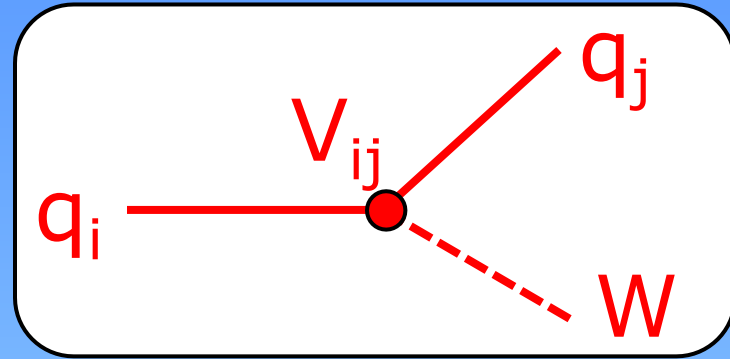

$$\psi_i Y_{ij} \psi_j \phi$$



# Higgs en LHCb?

$\psi$ : quarks

$Y_{ij}$ : koppeling tussen verschillende quarks  $i, j$



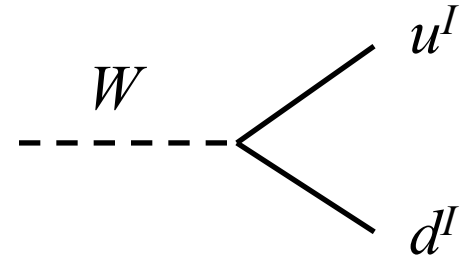
$\chi, y_{ij}, \chi, \phi$



$$\mathcal{L}_{SM} = \mathcal{L}_{Kinetic} + \mathcal{L}_{Higgs} + \mathcal{L}_{Yukawa}$$

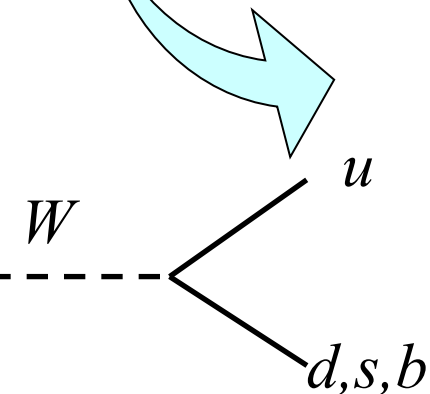
$$-\mathcal{L}_{Yuk} = \mathbf{Y}_{ij}^d (\overline{u}_L^I, \overline{d}_L^I)_i \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} d_{Rj}^I + \dots$$

$$\mathcal{L}_{Kinetic} = \frac{g}{\sqrt{2}} \overline{u}_{Li}^I \gamma^\mu W_\mu^- d_{Li}^I + \frac{g}{\sqrt{2}} \overline{d}_{Li}^I \gamma^\mu W_\mu^+ u_{Li}^I + \dots$$



- Diagonalize Yukawa matrix  $\mathbf{Y}_{ij}$ 
  - Mass terms
  - Quarks rotate
  - Off diagonal terms in charged current couplings

$$\begin{pmatrix} d^I \\ s^I \\ b^I \end{pmatrix} \rightarrow V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$



$$-\mathcal{L}_{Mass} = (\overline{d}, \overline{s}, \overline{b})_L \cdot \begin{pmatrix} m_d & & \\ & m_s & \\ & & m_b \end{pmatrix} \cdot \begin{pmatrix} d \\ s \\ b \end{pmatrix}_R + (\overline{u}, \overline{c}, \overline{t})_L \cdot \begin{pmatrix} m_u & & \\ & m_c & \\ & & m_t \end{pmatrix} \cdot \begin{pmatrix} u \\ c \\ t \end{pmatrix}_R + \dots$$

$$\mathcal{L}_{CKM} = \frac{g}{\sqrt{2}} \overline{u}_i \gamma^\mu W_\mu^- \mathbf{V}_{ij} (1 - \gamma^5) d_j + \frac{g}{\sqrt{2}} \overline{d}_j \gamma^\mu W_\mu^+ \mathbf{V}_{ij}^* (1 - \gamma^5) u_i + \dots$$

$$\mathcal{L}_{SM} = \mathcal{L}_{CKM} + \mathcal{L}_{Higgs} + \mathcal{L}_{Mass}$$

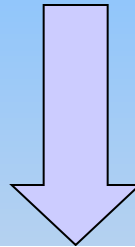


# What do we know about the CKM matrix?

Magnitudes of elements have been measured over time

- Result of a *large* number of measurements and calculations

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

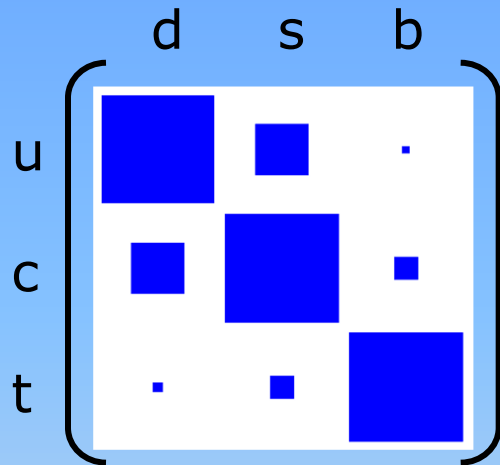


$$\begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{pmatrix} = \begin{pmatrix} 0.97419 & 0.2257 & 0.00359 \\ 0.2256 & 0.97334 & 0.0415 \\ 0.00874 & 0.0407 & 0.999133 \end{pmatrix} \pm \begin{pmatrix} 0.00022 & 0.0010 & 0.00016 \\ 0.0010 & 0.00023 & 0.0011 \\ 0.00037 & 0.0010 & 0.000044 \end{pmatrix}$$

• **Magnitude of elements shown only, no information of phase**

# Higgs en LHCb?

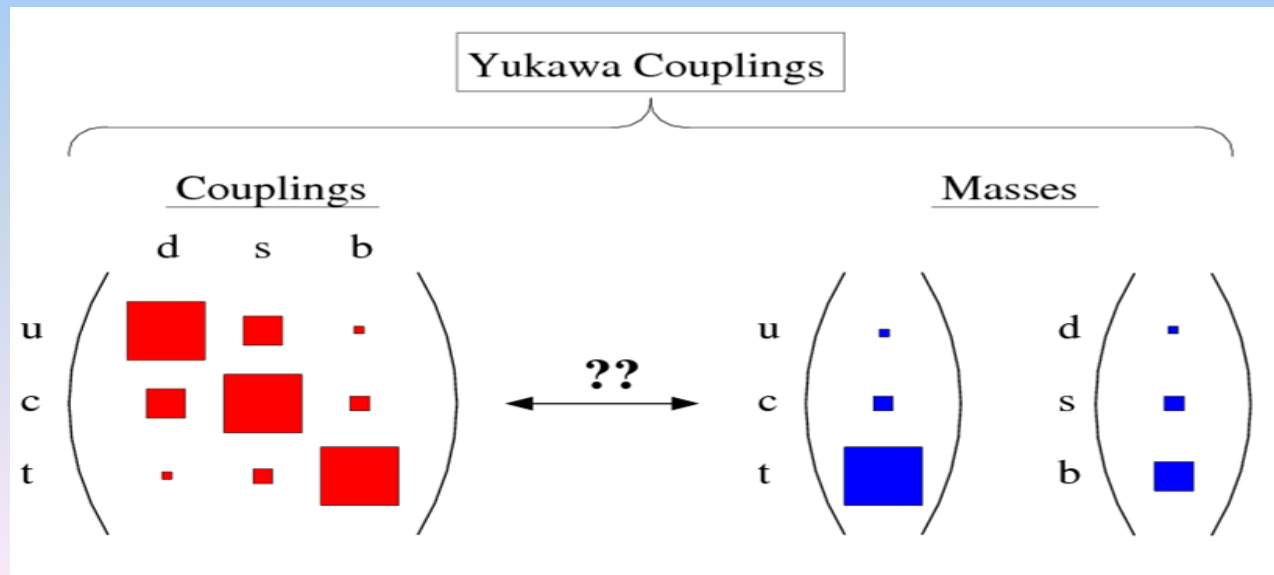
Quark koppelingen:



Waarom dit patroon in quark koppelingen?

Waarom dit patroon in quark massa's?

→ **Is er een verband?**



# Intermezzo: How about the leptons?

the equivalent of the CKM matrix

– Pontecorvo-Maki-Nakagawa-Sakata matrix

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix} \quad \bullet \text{vs} \quad \begin{bmatrix} |d'\rangle \\ |s'\rangle \\ |b'\rangle \end{bmatrix} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} |d\rangle \\ |s\rangle \\ |b\rangle \end{bmatrix}.$$

a completely different hierarchy!

$$U_{MNSP} \approx \begin{pmatrix} 0.85 & 0.53 & 0 \\ -0.37 & 0.60 & 0.71 \\ -0.37 & 0.60 & -0.71 \end{pmatrix}$$

$$V_{CKM} = \begin{pmatrix} 0.97428 & 0.2253 & 0.00347 \\ 0.2252 & 0.97345 & 0.0410 \\ 0.00862 & 0.0403 & 0.999152 \end{pmatrix}$$

# Intermezzo: How about the leptons?

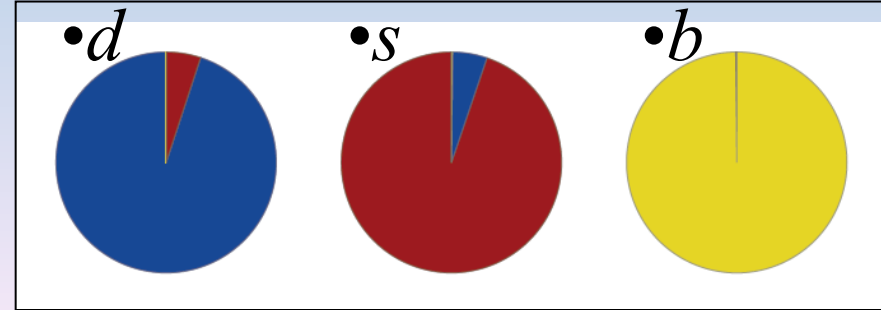
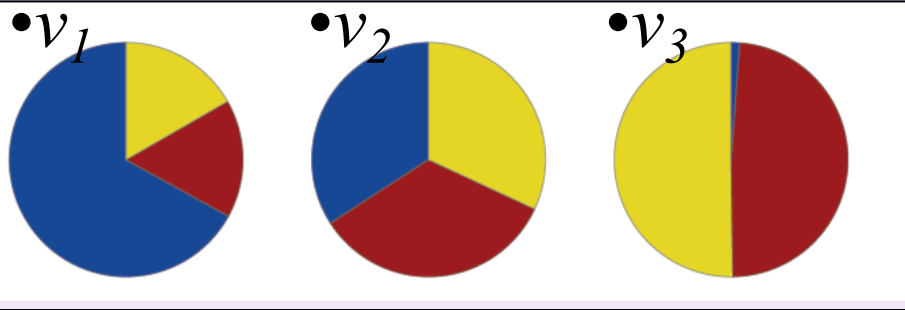
the equivalent of the CKM matrix

– Pontecorvo-Maki-Nakagawa-Sakata matrix

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix} \quad \bullet \text{vs} \quad \begin{bmatrix} |d'\rangle \\ |s'\rangle \\ |b'\rangle \end{bmatrix} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} |d\rangle \\ |s\rangle \\ |b\rangle \end{bmatrix}.$$

a completely different hi

$$\begin{pmatrix} |U_{e1}|^2 & |U_{e2}|^2 & |U_{e3}|^2 \\ |U_{\mu1}|^2 & |U_{\mu2}|^2 & |U_{\mu3}|^2 \\ |U_{\tau1}|^2 & |U_{\tau2}|^2 & |U_{\tau3}|^2 \end{pmatrix} \approx \begin{pmatrix} \frac{2}{3} & \frac{1}{3} & 0 \\ \frac{1}{6} & \frac{1}{3} & \frac{1}{2} \\ \frac{1}{6} & \frac{1}{3} & \frac{1}{2} \end{pmatrix}$$

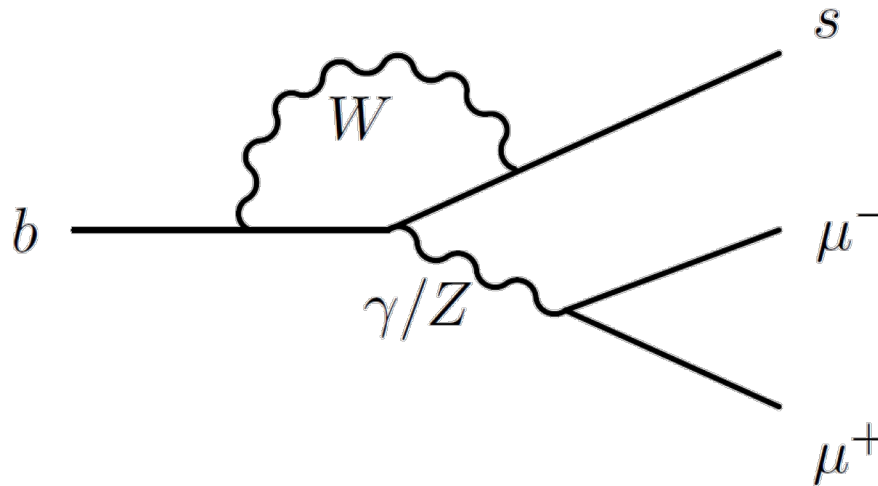


• See eg. *PhD thesis R. de Adelhart Toorop* (Niels Tuning (78))



# Take home message

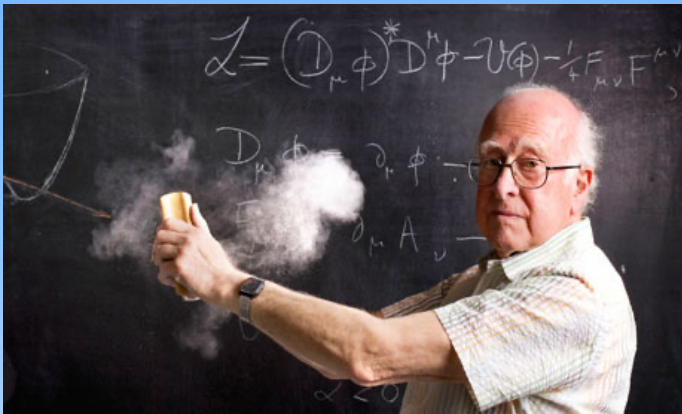
- 1) LHCb zoekt verschillen tussen materie en antimaterie
- 2) LHCb kan zeer zware deeltjes vinden (maar alleen *virtueel*)
- 3) Nieuwe deeltjes helpen om grote vragen te beantwoorden



**Einde**

# Wat snappen we nog niet?

## Massa van deeltjes



## Bijzondere voorspelling:

### Het Higgs boson:

zorgt ervoor dat deeltjes massa kunnen hebben in de theorie

Neutrino's

• Elektron

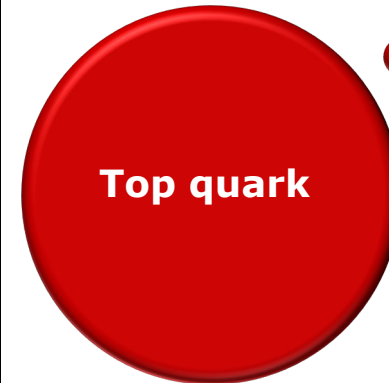
• Muon

• Tau



up,down, strange

• charm



Top quark



bottom

# Wat is massa ?? Anno 1687

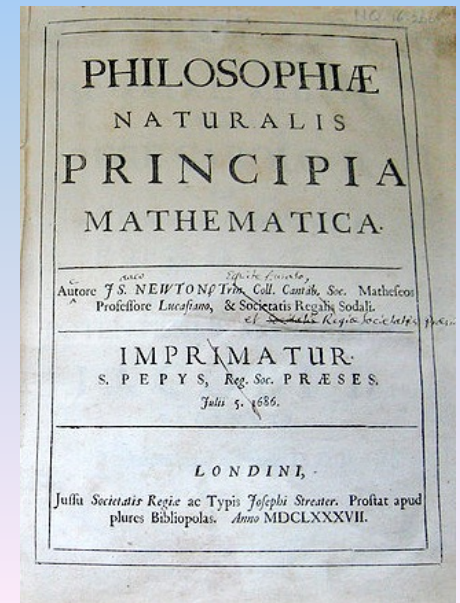
Massa is de 'wisselkoers' tussen kracht en versnelling:

$$F = m \times a$$

Beschrijft niet wat massa **is** ...



**Newton**





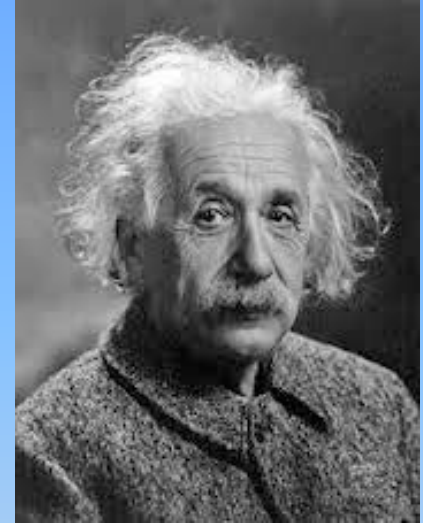
# Wat is massa ?? Anno 1905

Massa is energie

$$E = m \times c^2$$

Beschrijft wel wat massa **is** !

Maar niet waar het vandaan komt ...



**Einstein**

## 13. Ist die Trägheit eines Körpers von seinem Energieinhalt abhängig? von A. Einstein.

Die Resultate einer jüngst in diesen Annalen von mir publizierten elektrodynamischen Untersuchung<sup>1)</sup> führen zu einer sehr interessanten Folgerung, die hier abgeleitet werden soll.

Ich legte dort die Maxwell-Hertz'schen Gleichungen für den leeren Raum nebst dem Maxwellschen Ausdruck für die elektromagnetische Energie des Raumes zugrunde und außerdem das Prinzip:

Die Gesetze, nach denen sich die Zustände der physikalischen Systeme ändern, sind unabhängig davon, auf welches von zwei relativ zueinander in gleichförmiger Parallel-Translationsbewegung befindlichen Koordinatensystemen diese Zustandsänderungen bezogen werden (Relativitätsprinzip).

Gestützt auf diese Grundlagen<sup>2)</sup> leitete ich unter anderem das nachfolgende Resultat ab (l. c. § 8):

Ein System von ebenen Lichtwellen besitze, auf das Koordinatensystem  $(x, y, z)$  bezogen, die Energie  $l$ ; die Strahlrichtung (Wellennormale) bilde den Winkel  $\varphi$  mit der  $x$ -Achse des Systems. Führt man ein neues, gegen das System  $(x, y, z)$  in gleichförmiger Paralleltranslation begriffenes Koordinatensystem  $(\xi, \eta, \zeta)$  ein, dessen Ursprung sich mit der Geschwindigkeit  $v$  längs der  $x$ -Achse bewegt, so besitzt die genannte Lichtmenge — im System  $(\xi, \eta, \zeta)$  gemessen — die Energie:

$$l' = l \frac{1 - \frac{v}{V} \cos \varphi}{\sqrt{1 - \left(\frac{v}{V}\right)^2}}$$

wobei  $V$  die Lichtgeschwindigkeit bedeutet. Von diesem Resultat machen wir im folgenden Gebrauch.

1) A. Einstein, Ann. d. Phys. 17. p. 891. 1905.

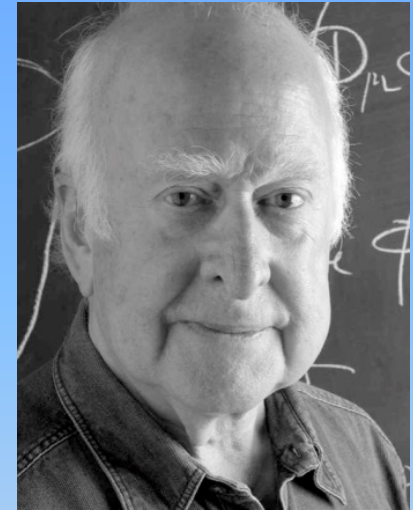
2) Das dort benutzte Prinzip der Konstanz der Lichtgeschwindigkeit ist natürlich in den Maxwellschen Gleichungen enthalten.

# Wat is massa ?? Anno 1964

Massa van elementaire deeltjes komt door  
“wrijving” met alomtegenwoordig ‘Higgs veld’

$$m: \psi\psi H$$

Huh?



Higgs



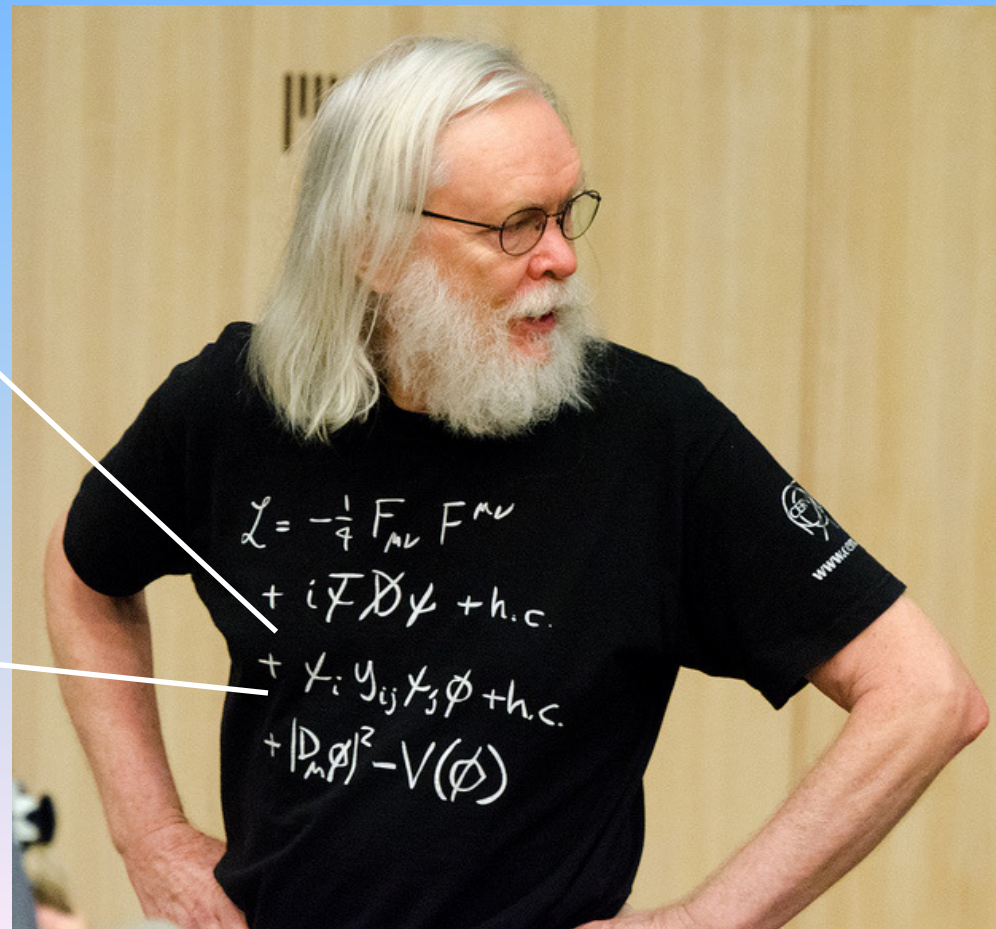
# Wat is massa ?? Anno 1964

Massa van elementaire deeltjes komt door  
“wrijving” met alomtegenwoordig ‘Higgs veld’

$$m: \psi\psi H$$



$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\psi}\not{D}\psi + h.c. + \chi_i y_{ij} \chi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$



Nee, dit is niet Pierre, dit is John Ellis

# Modelleren van interactie

## Standaard Model Lagrangiaan

$$\begin{aligned}
 & -\frac{1}{2}\partial_\nu g_\mu^a \partial_\nu g_\mu^a - g_s f^{abc} \partial_\mu g_\mu^a g_\mu^b g_\mu^c - \frac{1}{4}g_s^2 f^{abc} f^{ade} g_\mu^a g_\mu^b g_\mu^c g_\mu^d g_\mu^e + \frac{1}{2}ig_2^2 (\bar{q}_i^c \gamma^\mu q_j^c) g_\mu^a + \\
 & \bar{G}^a \partial^2 G^a + g_s f^{abc} \partial_\mu \bar{G}^a G^b g_\mu^c - \partial_\mu W_\mu^+ 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^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^2}{g^2} \alpha_h - ig_{cw} [\partial_\nu Z_\mu^0 (W_\mu^+ W_\nu^- - \\
 & W_\mu^- W_\nu^+) - Z_\mu^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_\nu (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_\nu^+ W_\mu^- + g^2 c_w^2 (Z_\mu^0 W_\mu^+ Z_\mu^0 W_\nu^- - Z_\mu^0 Z_\mu^0 W_\mu^+ W_\nu^-) + g^2 s_w^2 (A_\mu W_\mu^+ A_\nu W_\nu^- - \\
 & A_\mu A_\nu W_\mu^+ W_\nu^-) + g^2 s_w c_w [A_\mu Z_\mu^0 (W_\mu^+ W_\nu^- - W_\mu^- W_\nu^+) - 2A_\nu Z_\mu^0 W_\mu^+ 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_\nu^- H - \frac{1}{2}g \frac{M}{c_w} Z_\mu^0 Z_\nu^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_\nu^- [H^2 + (\phi^0)^2 + 2\phi^+ \phi^-] - \\
 & \frac{1}{4}g^2 \frac{1}{c_w^2} Z_\mu^0 Z_\nu^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^2} Z_\mu^0 \phi^0 (W_\mu^+ \phi^- + W_\mu^- \phi^+) - \\
 & \frac{1}{2}ig^2 \frac{s_w^2}{c_w^2} 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_\nu 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^2 s_w^2 A_\mu A_\nu \phi^+ \phi^- - e^2 (\gamma \partial + m_\phi^2) e^\lambda - \\
 & \bar{\nu}^\lambda \gamma \partial \nu^\lambda - \bar{u}_j^2 (\gamma \partial + m_\phi^2) u_j^2 - \bar{d}_j^2 (\gamma \partial + m_\phi^2) d_j^2 + ig_{sw} A_\mu [-(e^\lambda \gamma^\mu e^\lambda) + \frac{2}{3}(\bar{u}_j^2 \gamma^\mu u_j^2) - \\
 & \frac{1}{3}(\bar{d}_j^2 \gamma^\mu d_j^2)] + \frac{ig}{4c_w} Z_\mu^0 [(\bar{\nu}^\lambda \gamma^\mu \nu^\lambda) + (e^\lambda \gamma^\mu e^\lambda) + (4s_w^2 - 1 - \gamma^5) e^\lambda] + (\bar{u}_j^2 \gamma^\mu (\frac{2}{3}s_w^2 - \\
 & 1 - \gamma^5) u_j^2) + (\bar{d}_j^2 \gamma^\mu (1 - \frac{2}{3}s_w^2 - \gamma^5) d_j^2)] + \frac{ig}{2\sqrt{2}} W_\mu^+ [(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) e^\lambda) + (\bar{u}_j^2 \gamma^\mu (1 + \\
 & \gamma^5) C_{\lambda\kappa} d_j^2)] + \frac{ig}{2\sqrt{2}} W_\mu^- [(\bar{e}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{d}_j^2 C_{\lambda\kappa}^* \gamma^\mu (1 + \gamma^5) u_j^2)] + \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^2 C_{\lambda\kappa} (1 - \\
 & \gamma^5) d_j^2) + m_\lambda^2 (\bar{u}_j^2 C_{\lambda\kappa} (1 + \gamma^5) u_j^2)] + \frac{ig}{2M\sqrt{2}} \phi^- [m_\lambda^2 (\bar{d}_j^2 C_{\lambda\kappa}^* (1 + \gamma^5) u_j^2) - m_\lambda^2 (\bar{d}_j^2 C_{\lambda\kappa}^* (1 - \\
 & \gamma^5) u_j^2)] - \frac{g}{2} \frac{m_\lambda^2}{M} H (\bar{u}_j^2 u_j^2) - \frac{g}{2} \frac{m_\lambda^2}{M} H (\bar{d}_j^2 d_j^2) + \frac{ig}{2} \frac{m_\lambda^2}{M} \phi^0 (\bar{u}_j^2 \gamma^5 u_j^2) - \frac{ig}{2} \frac{m_\lambda^2}{M} \phi^0 (\bar{d}_j^2 \gamma^5 d_j^2) + \\
 & \bar{X} + (\partial^2 - M^2) X + \bar{X} - (\partial^2 - M^2) X - X^0 (\partial^2 - \frac{M^2}{2}) X^0 + 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} X^0 - \partial_\mu \bar{X}^0 X) + ig_{cw} Z_\mu^0 (\partial_\mu \bar{X} X^0 - \partial_\mu \bar{X}^0 X) + ig_{sw} A_\mu (\partial_\mu \bar{X} X^0 - \\
 & \partial_\mu \bar{X} X^0) - \frac{1}{2}g M [\bar{X} X^0 + H + \bar{X} X^0 - H + \frac{1}{2} \bar{X} 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} X^0 \phi^+ - \bar{X} X^0 \phi^-] + ig M s_w [\bar{X} X^0 \phi^+ - \bar{X} X^0 \phi^-] + \\
 & \frac{1}{2}ig M [\bar{X} X^0 \phi^+ - \bar{X} X^0 \phi^-]
 \end{aligned}$$

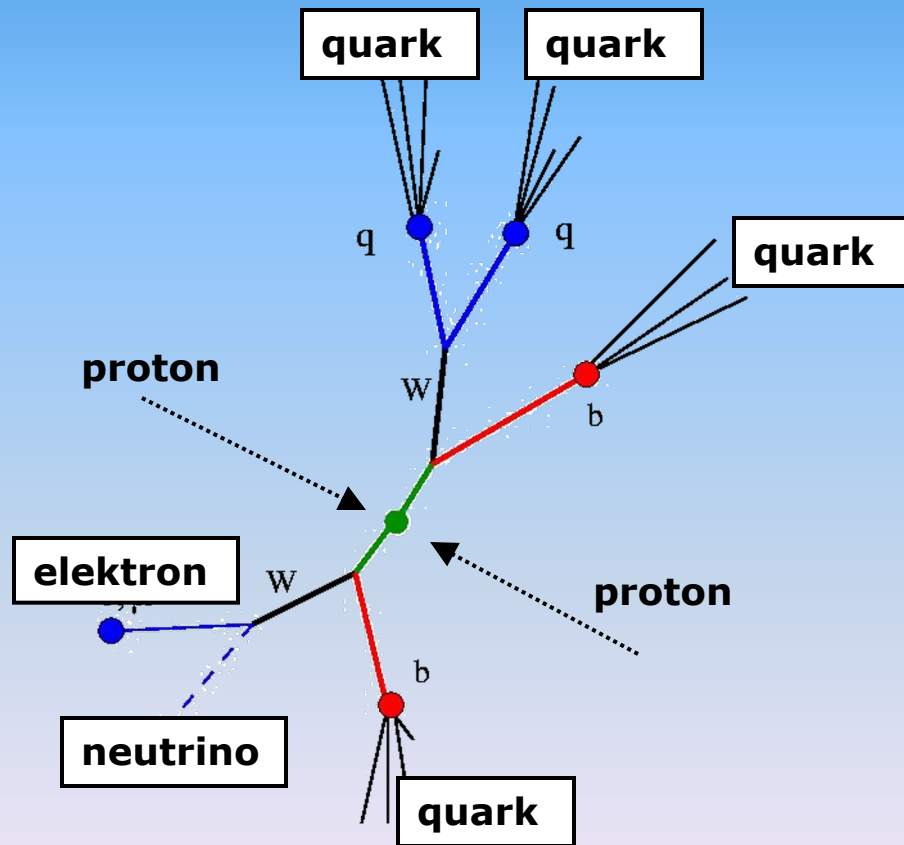
## Bladmuziek (J.S. Bach)

bladmuziek

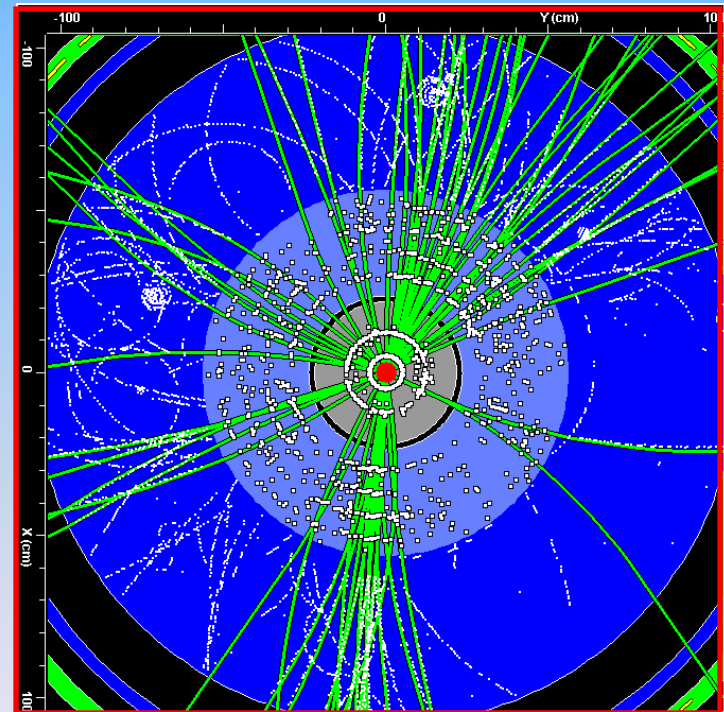




# Hoe zien die botsingen er nou uit ?



## Simulatie top quark productie



# Hoe ontdek je nou nieuwe dingen

*Nieuwe afstandschaal EN nieuwe detector*

**Nieuw ?**

muon

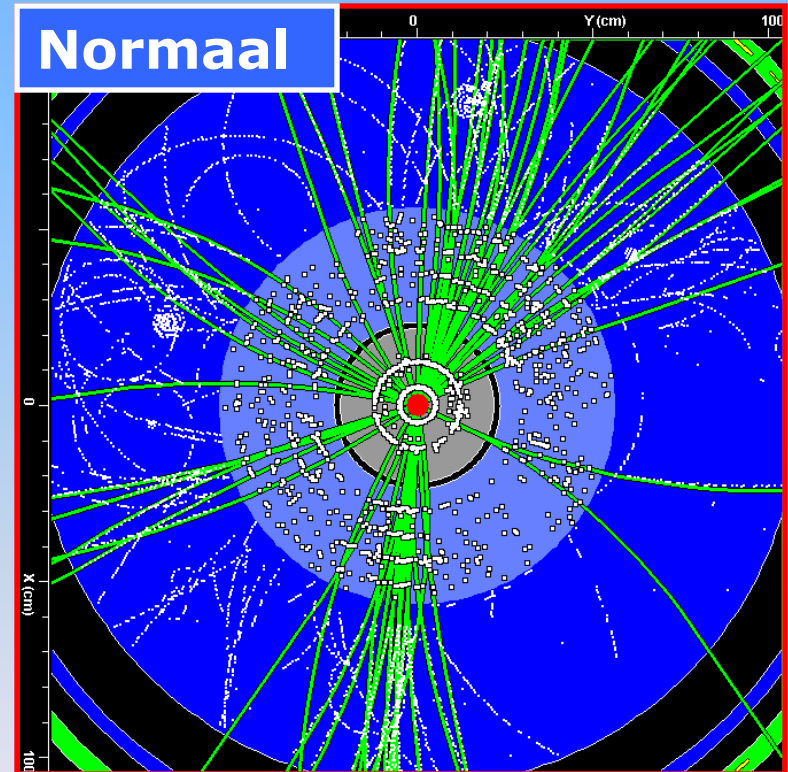
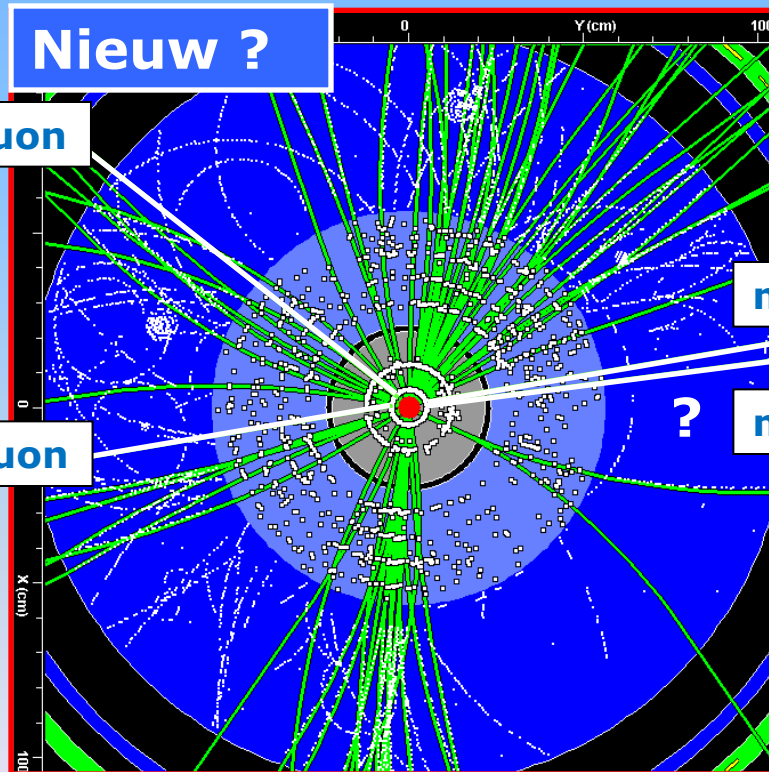
muon

muon

muon

?

**Normaal**



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

*klein aantal schitterende botsingen*

120.000 Higgs bosonen

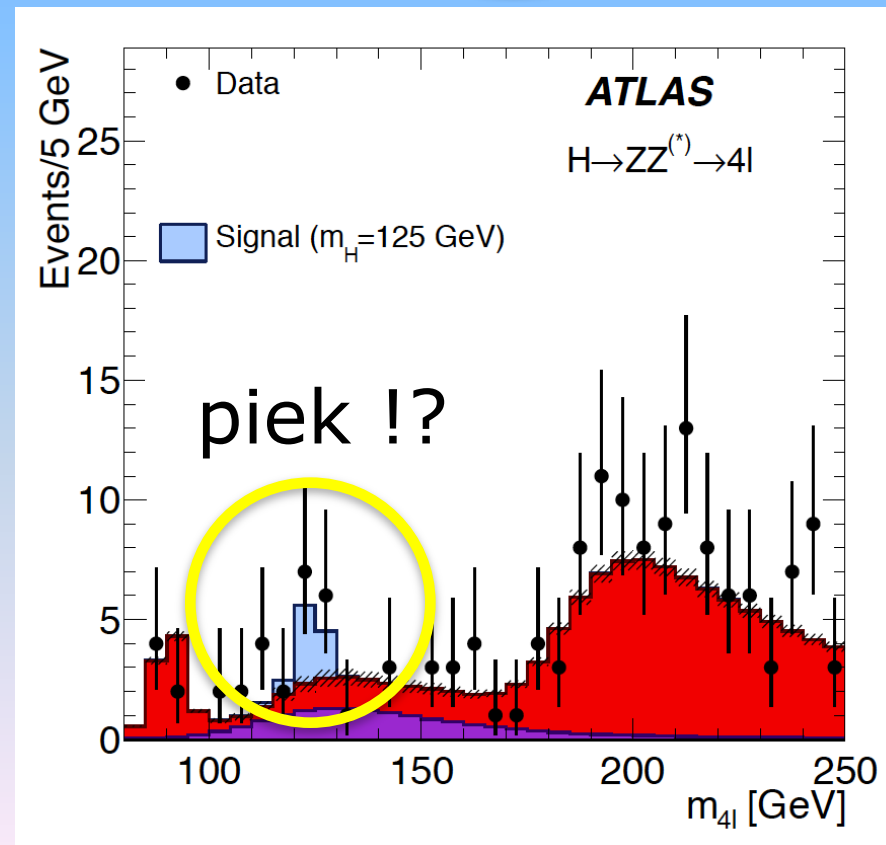
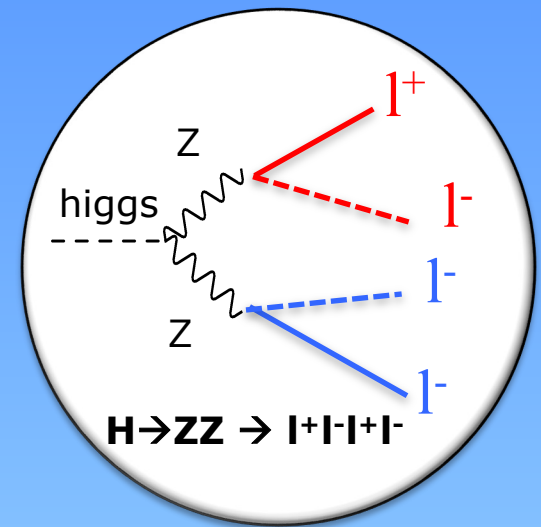


- Maar 1 op de 1000 Higgs bosonen vervalt naar 4 leptonen
- 50% kans dat ATLAS detector ze allemaal goed terugvindt



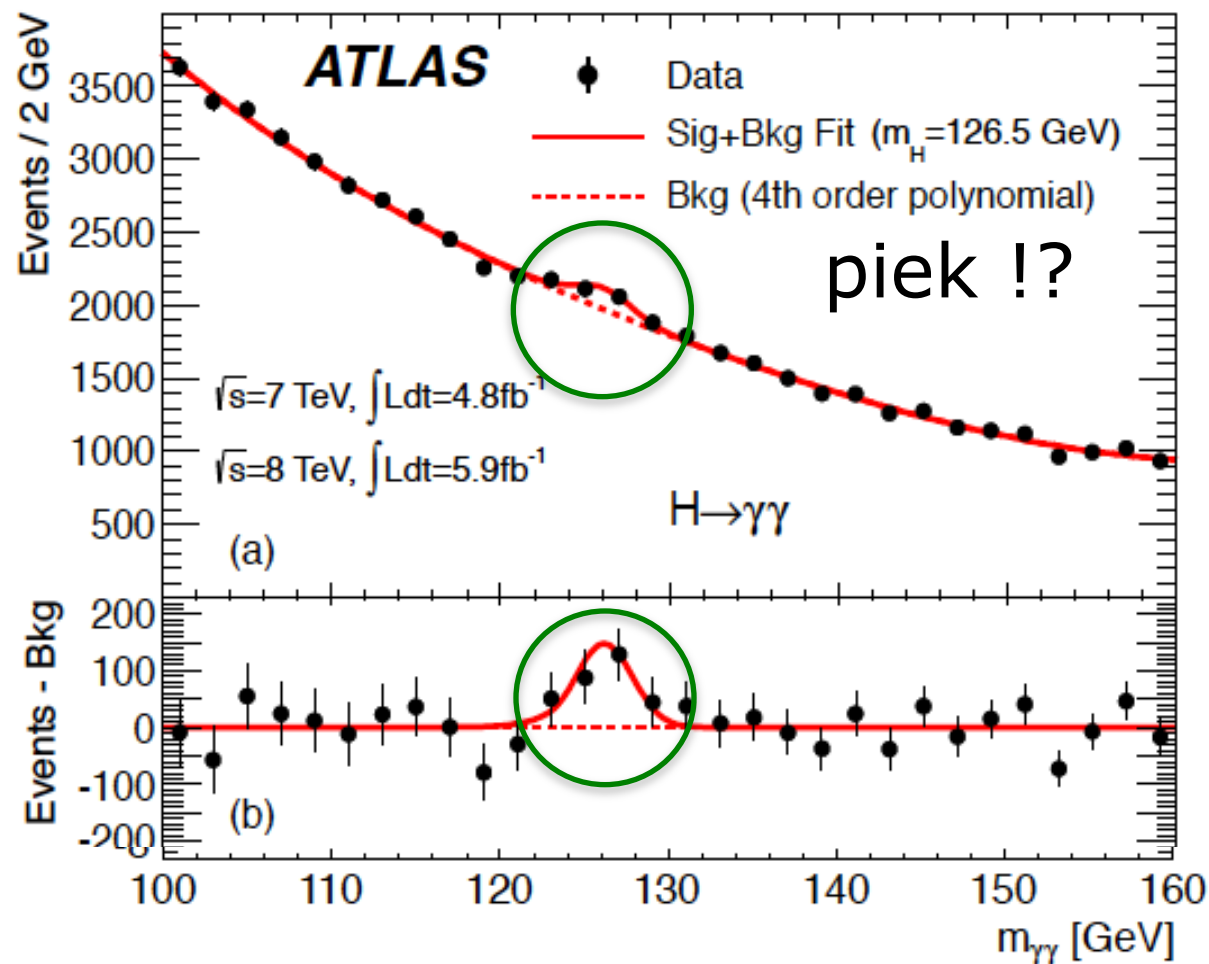
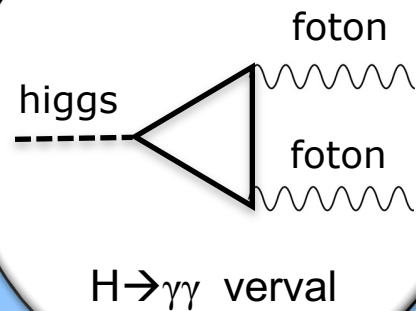
60 (Higgs  $\rightarrow$  4 lepton) events

'overig'	52 events
Met Higgs	68 events



# Higgs $\rightarrow$ 2 fotonen

foton





# Interpretatie overschot in ATLAS



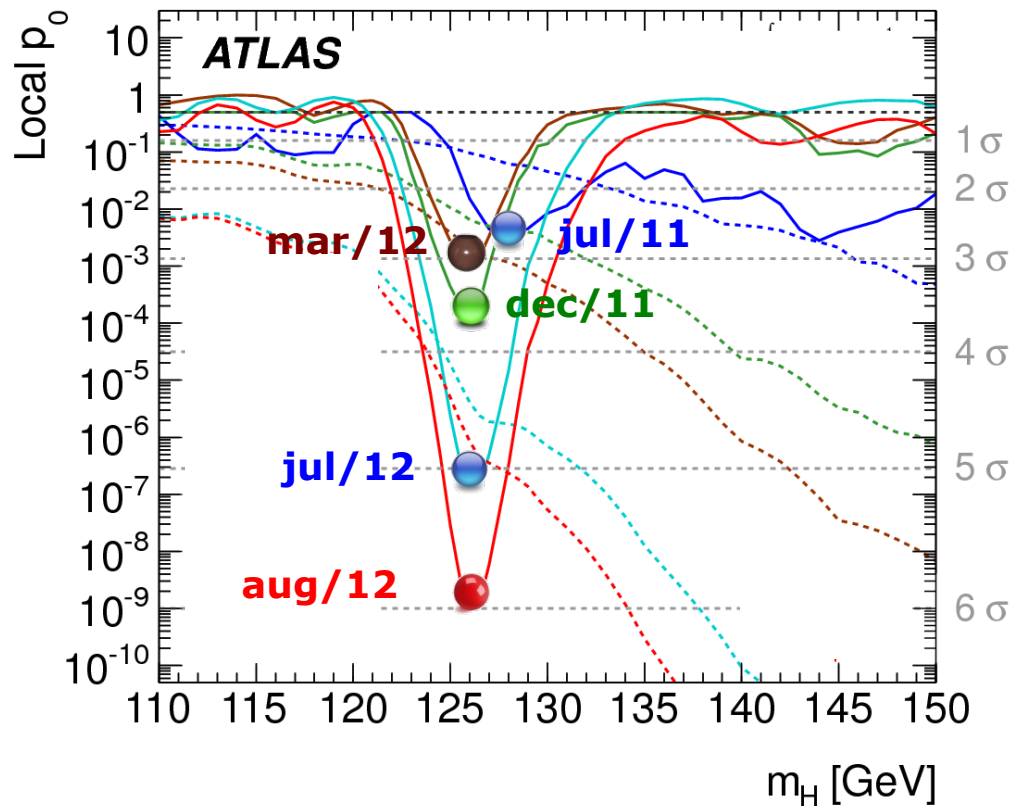
## **Claim pas ontdekking als:**

Kans op toevallige fluctuatie zoals geobserveerd kleiner dan 1 op 1 miljoen

*8 keer 6 gooien achter elkaar*

# Een ontdekking in slow-motion

Time-line higgs ontdekking



EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)



CERN-PH-EP-2012-218  
Accepted by: Physics Letters B

## Observation of a New Particle in the Search for the Standard Model Higgs Boson with the ATLAS Detector at the LHC

The ATLAS Collaboration

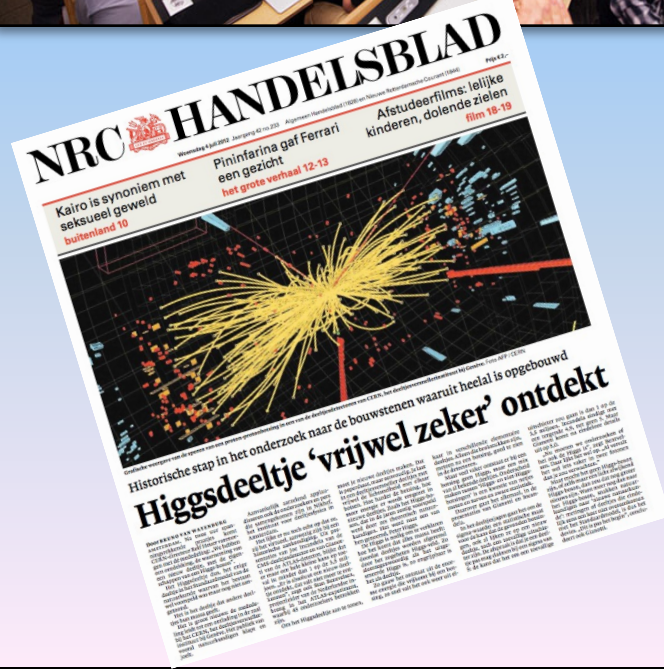
This paper is dedicated to the memory of our ATLAS colleagues who did not live to see the full impact and significance of their contributions to the experiment.

### Abstract

A search for the Standard Model Higgs boson in proton-proton collisions with the ATLAS detector at the LHC is presented. The datasets used correspond to integrated luminosities of approximately  $4.8 \text{ fb}^{-1}$  collected at  $\sqrt{s} = 7 \text{ TeV}$  in 2011 and  $5.8 \text{ fb}^{-1}$  at  $\sqrt{s} = 8 \text{ TeV}$  in 2012. Individual searches in the channels  $H \rightarrow ZZ^{(0)} \rightarrow 4\ell$ ,  $H \rightarrow \gamma\gamma$  and  $H \rightarrow WW^{(0)} \rightarrow \ell\nu\ell\nu$  in the 8 TeV data are combined with previously published results of searches for  $H \rightarrow ZZ^{(0)}$ ,  $WW^{(0)}$ ,  $b\bar{b}$  and  $\tau^+\tau^-$  in the 7 TeV data and results from improved analyses of the  $H \rightarrow ZZ^{(0)} \rightarrow 4\ell$  and  $H \rightarrow \gamma\gamma$  channels in the 7 TeV data. Clear evidence for the production of a neutral boson with a measured mass of  $126.0 \pm 0.4 (\text{stat}) \pm 0.4 (\text{sys}) \text{ GeV}$  is presented. This observation, which has a significance of 5.9 standard deviations, corresponding to a background fluctuation probability of  $1.7 \times 10^{-4}$ , is compatible with the production and decay of the Standard Model Higgs boson.

arXiv:1207.7214v2 [hep-ex] 31 Aug 2012

# Ontdekking van het Higgs deeltje op 4 juli 2012





# Nog een paar 'kleine' dingetjes:

**1**

Waar is alle anti-materie gebleven ?

**2**

80% van de materie in het heelal is onbekend  
→ donkere materie

**3**

Higgs boson en quark koppelingen?  
(wat is het verband) ?

- 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, ...

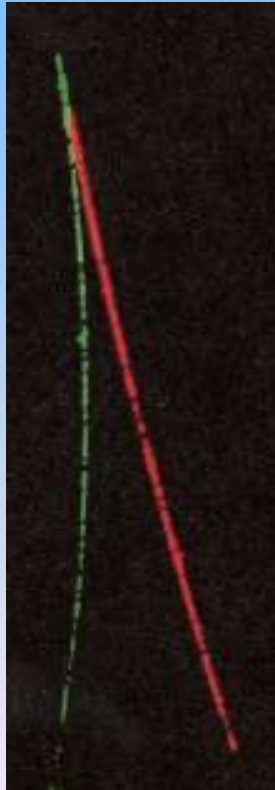
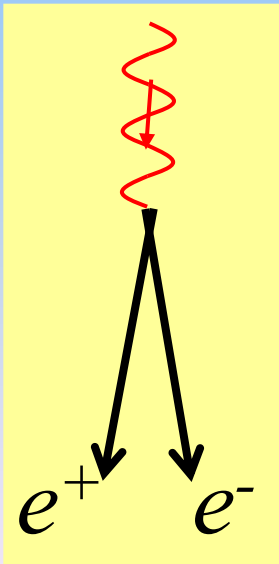


# Higgs en het Universum

# Higgs: Deeltje? Veld?

## Deeltje

Foton (lichtdeeltje)



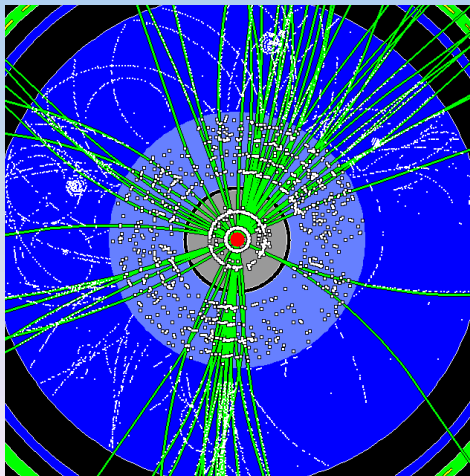
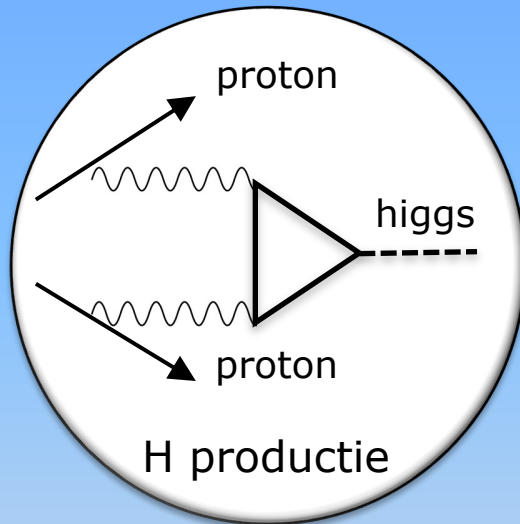
## Veld

Elektrisch veld

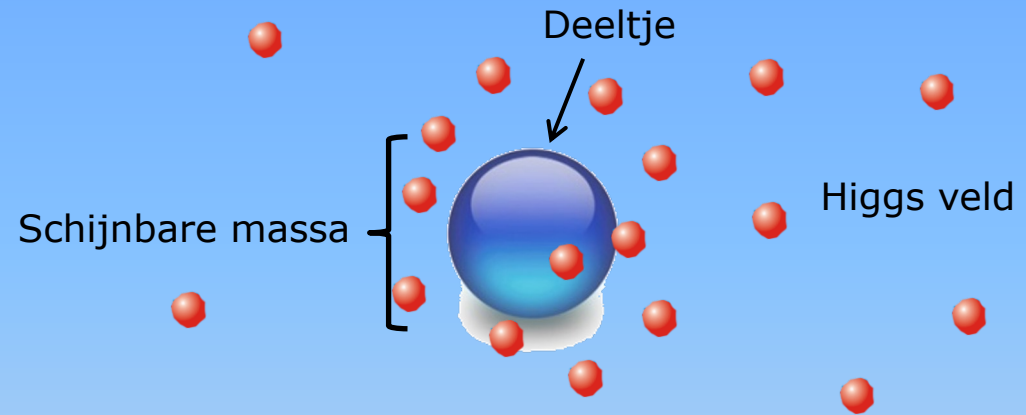


# Waarom is de Higgs zo bijzonder?

## Deeltje



## Veld



Alsof de vis het water heeft ontdekt...

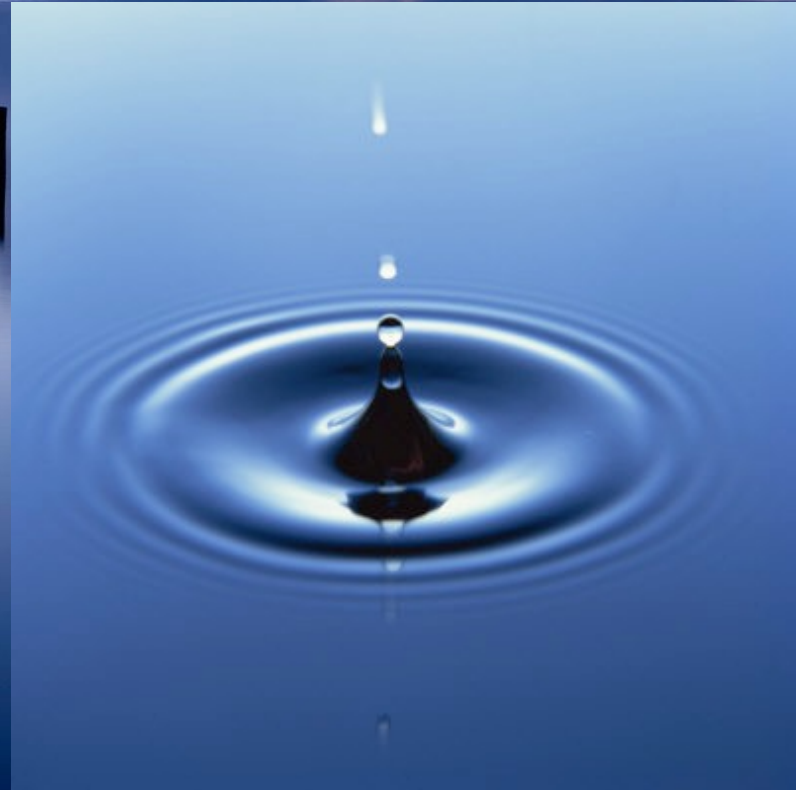
# Het Higgs veld – kun je het zien?

Het Higgs veld is uniform – als het meer in deze foto

Het maken van een Higgs deeltje is als een rimpeling op het meer

## De theorie van Higgs:

als het veld bestaat is er  
ook een bijbehorend deeltje





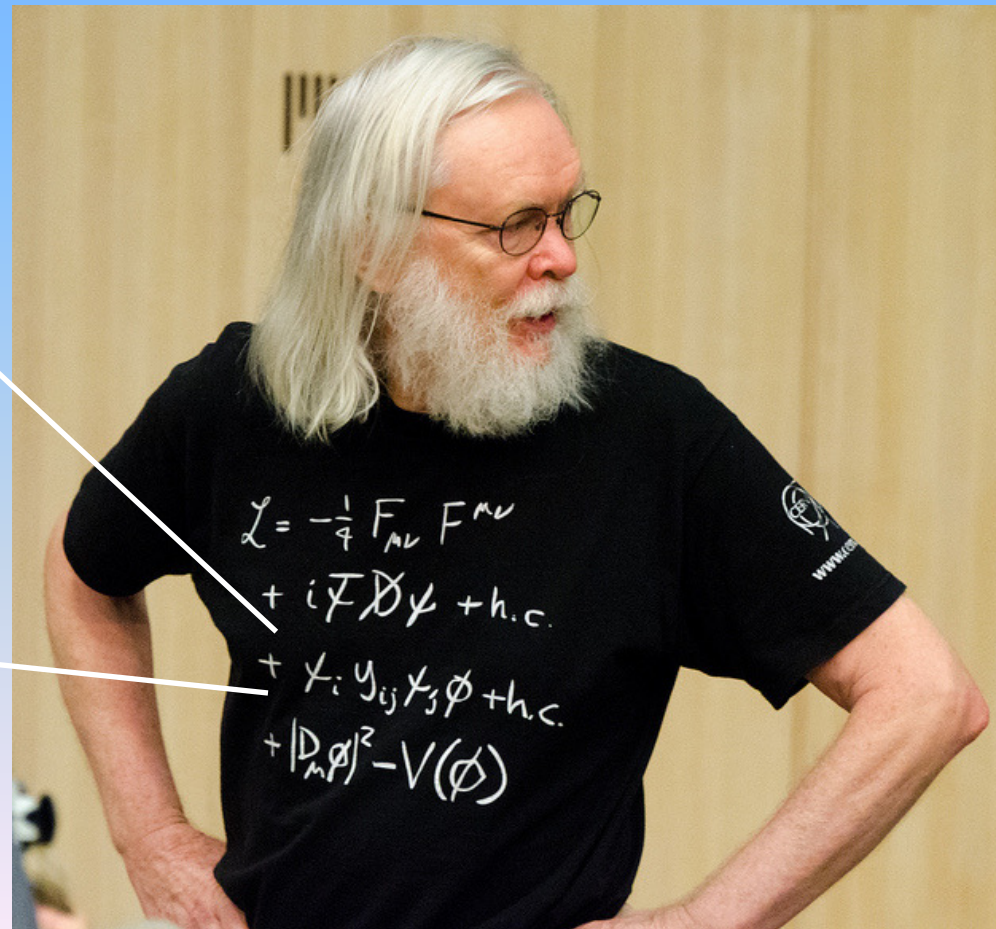
# Wat is massa ?? Anno 1964

Massa van elementaire deeltjes komt door  
“wrijving” met alomtegenwoordig ‘Higgs veld’

$$m: \psi\psi H$$



$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\psi}\not{D}\psi + h.c. + \psi_i \gamma_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$



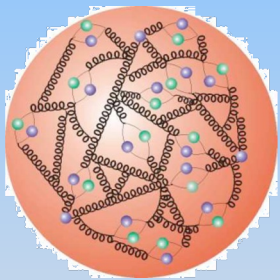
Nee, dit is niet Pierre, dit is John Ellis

# Wat is massa ?

Massa van elementaire deeltjes komt door  
“wrijving” met alomtegenwoordig ‘Higgs veld’

## Einstein:

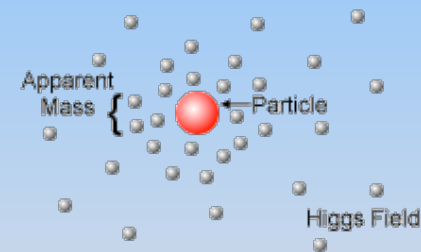
proton massa =  
bindings energie



Elementair deeltje  
in lege ruimte:  
geen rust-energie=  
**geen massa**

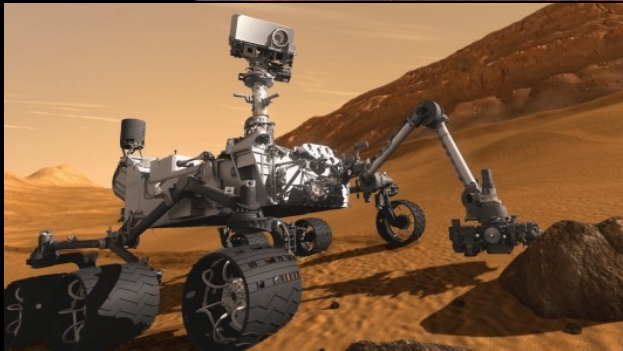


Elementair deeltje  
in Higgs veld:  
rust energie =  
interactie met Higgs veld  
**= massa**



Revolutionair – met spectaculaire consequenties :  
de ruimte is *niet* leeg, maar gevuld met soort ‘ether’

Als de marslander  
leven vindt ...

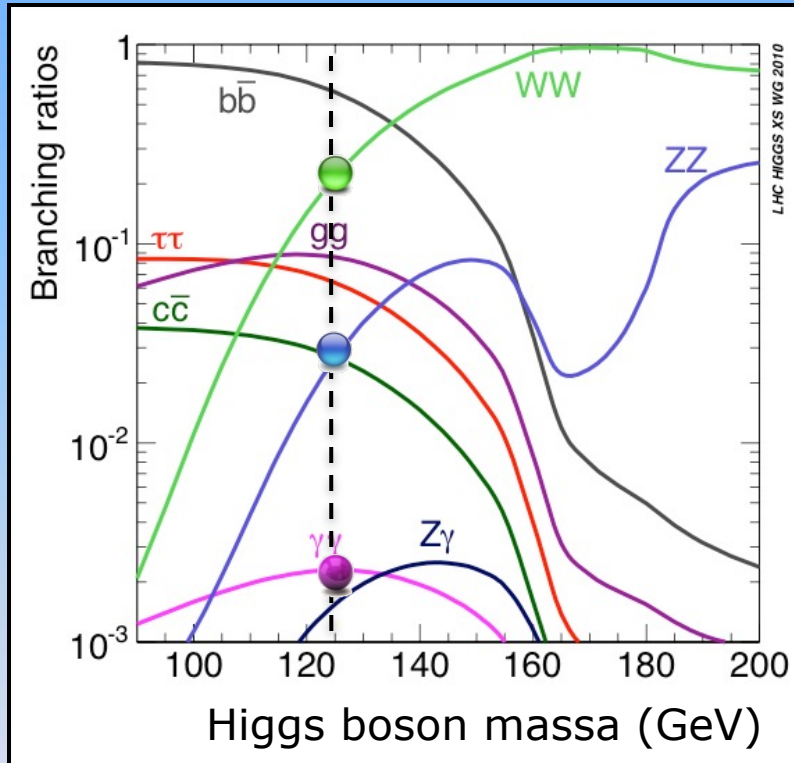


... heb je 1000  
nieuwe vragen



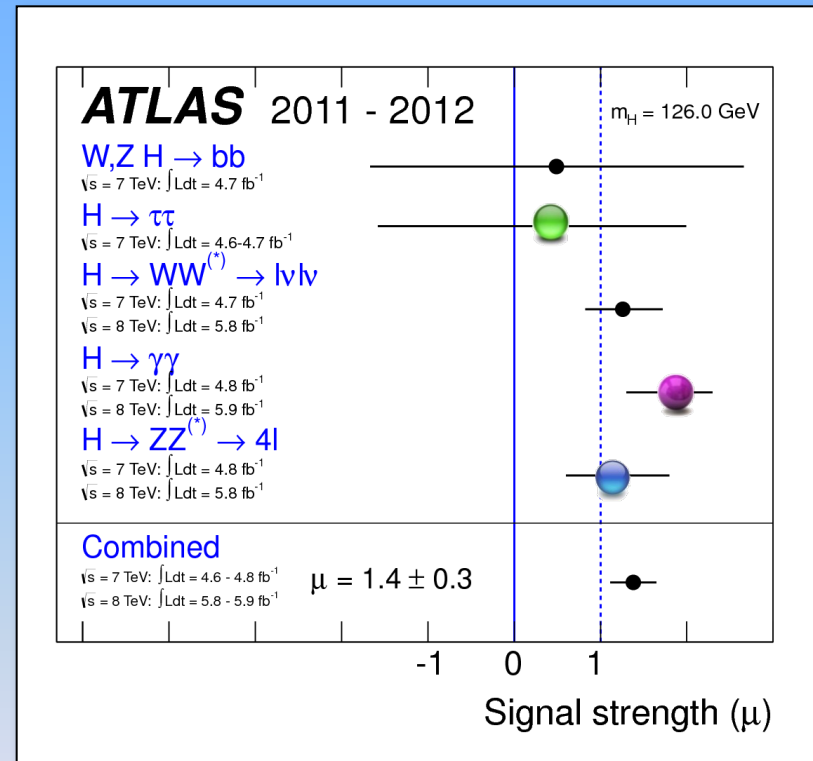
# Kloppen Higgs' eigenschappen ?

$m_h = 125 \text{ GeV}$



*voorspelling*

Standaard Model



*meting*



# Kloppen Higgs' eigenschappen ?

Zijn er nog meer soorten Higgs deeltjes ?

$$\begin{aligned}\mathcal{L}_{\text{susy}} = & -\frac{g^2}{8}(H_u^\dagger \sigma^a H_u + H_d^\dagger \sigma^a H_d)^2 - \frac{g'^2}{8}(H_u^\dagger H_u - H_d^\dagger H_d)^2 \\ & + \lambda_{ij}^u H_u^T \epsilon \bar{u}_i q_j - \lambda_{ij}^d H_d^T \epsilon \bar{d}_i q_j - \lambda_{ij}^e H_e^T \epsilon \bar{e}_i \ell_j \\ & - \frac{H_u^\dagger}{\sqrt{2}}(g\sigma^a \bar{W}^a + g'\bar{B})\bar{H}_u - \frac{H_d^\dagger}{\sqrt{2}}(g\sigma^a \bar{W}^a - g'\bar{B})\bar{H}_d + \text{h.c.}\end{aligned}$$

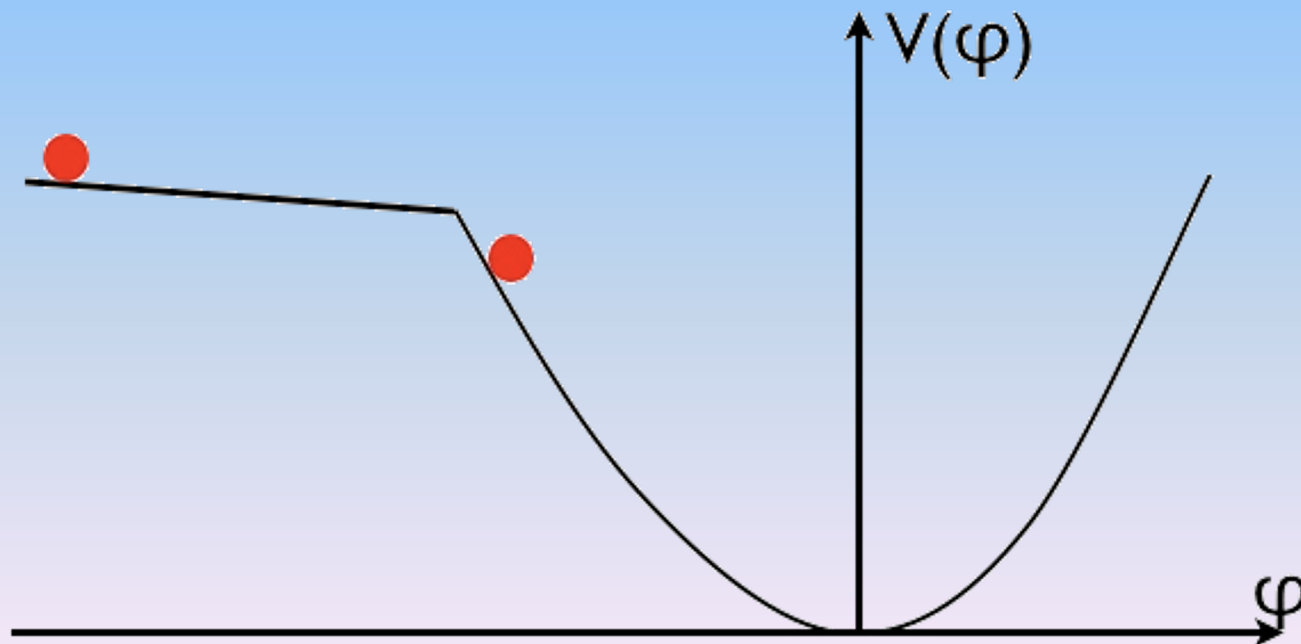
**Een stap verder...**



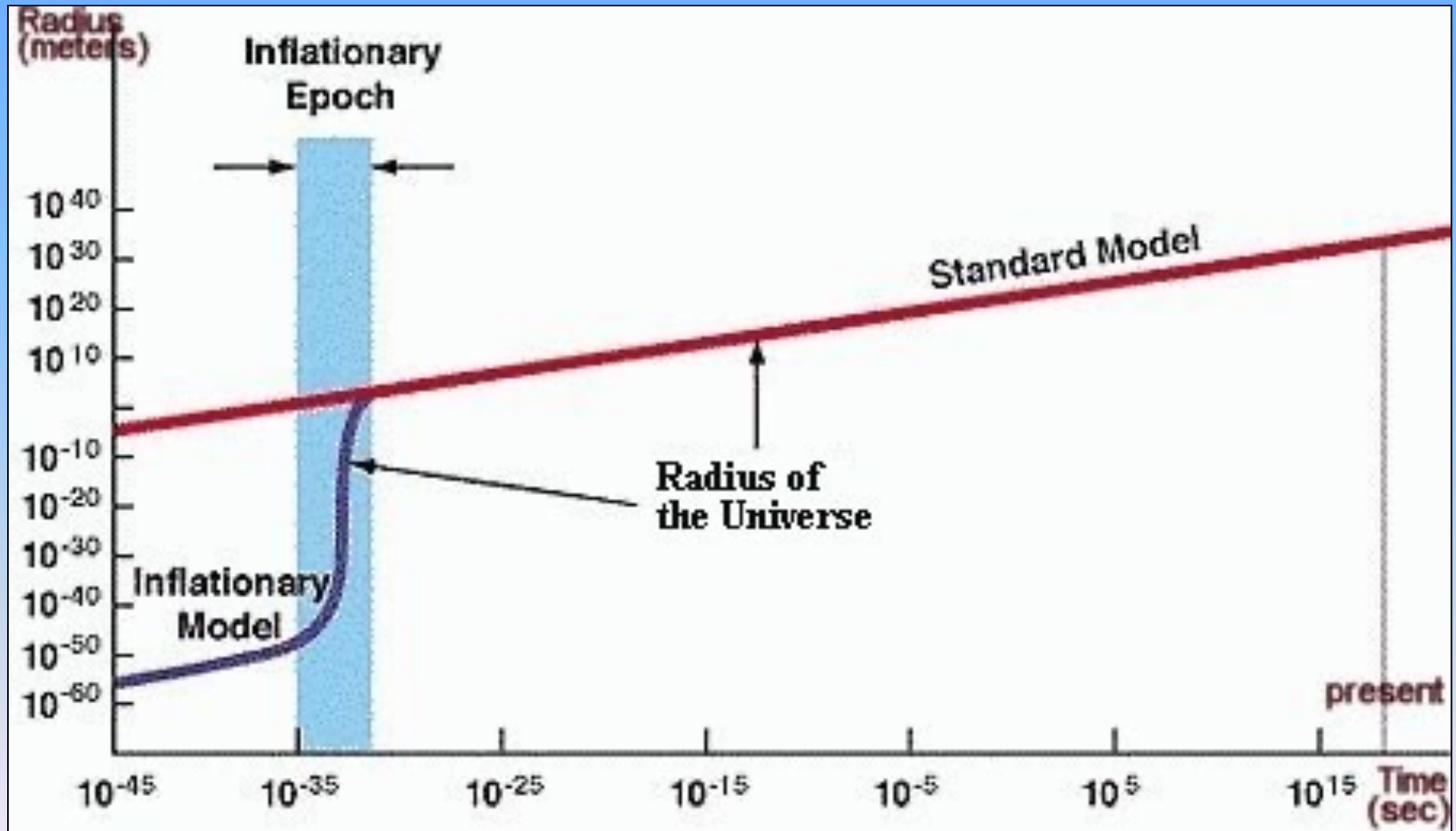
# Een ander veld: de Big Bang

Een van Higgs' eigenschappen komt overeen met een ander veld...

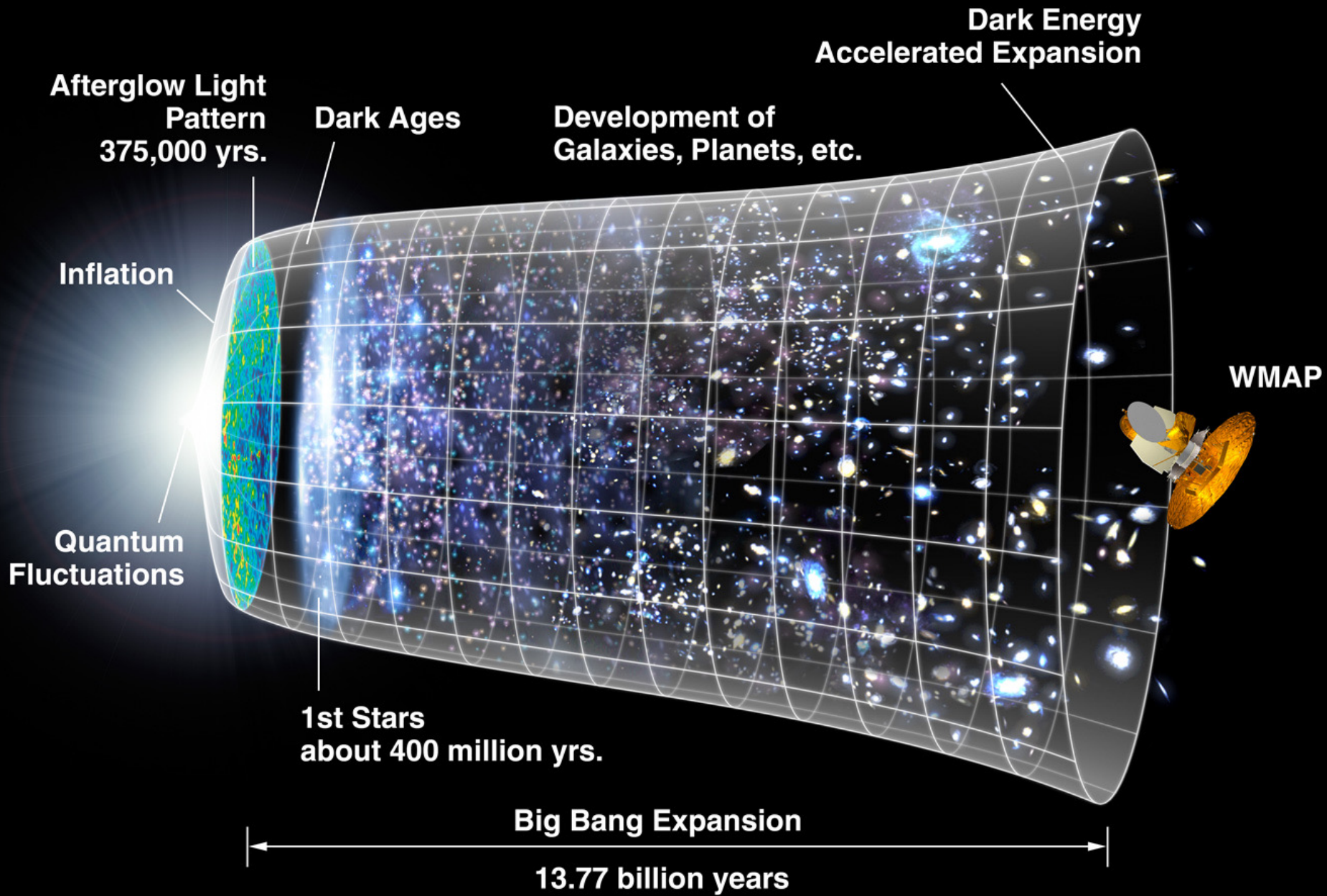
Het *inflaton* dat de het heelal opblies tussen  $10^{-33}$  en  $10^{-32}$  seconde na de Big Bang



# Een ander veld: de Big Bang







# Higgs:

**1**

Een Higgs deeltje gevonden in Geneve

**2**

Heelal gevuld met Higgs veld

**3**

Kloppen zijn eigenschappen?



# Nog een paar 'kleine' dingetjes:

4

80% van de materie in het heelal is onbekend  
→ donkere materie

5

Waar is alle anti-materie gebleven ?

6

Higgs boson (hoe krijgen deeltjes massa) ?

- 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, ...

**EINDE**



# Wat is het nut van dit onderzoek?

## Fundamenteel onderzoek

- Kan leiden tot verrassingen,
  - Soms zelfs nuttig...
  - Maar per definitie van te voren onbekend



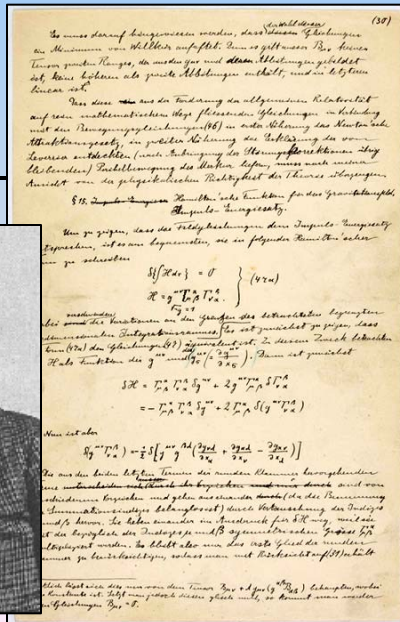
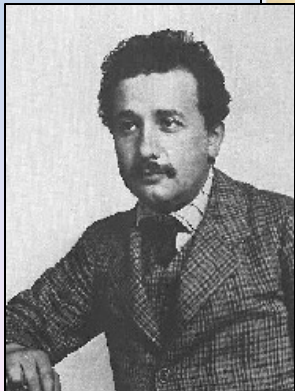
*“Oneindig veel toegepast onderzoek aan de kaars zou ons nooit het elektrische licht hebben gebracht.”*



# Wat is het nut van dit onderzoek?

## Fundamenteel onderzoek

- Kan leiden tot verrassingen,
  - Soms zelfs nuttig...
  - Maar per definitie van te voren onbekend



“Zonder relativiteitstheorie zit de GPS er 10km/dag naast!”



# Wat is het nut van dit onderzoek?

## Fundamenteel onderzoek

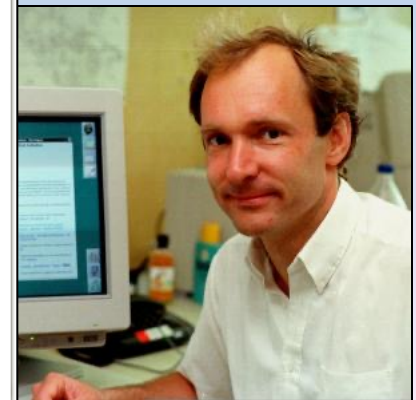
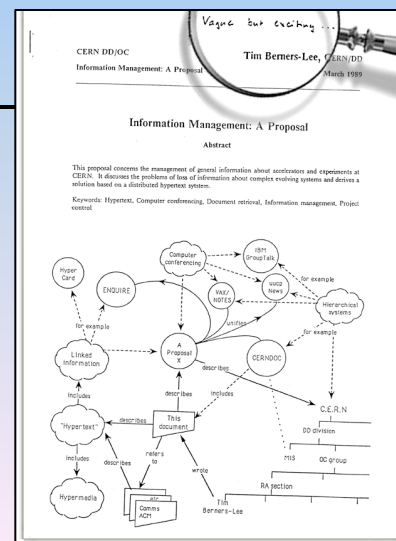
### – Heeft nuttige bij-effecten

- Medische toepassingen
- Internet
- Opleiden van onderzoekers voor de maatschappij (Philips, ASML, etc, etc)

PET scan

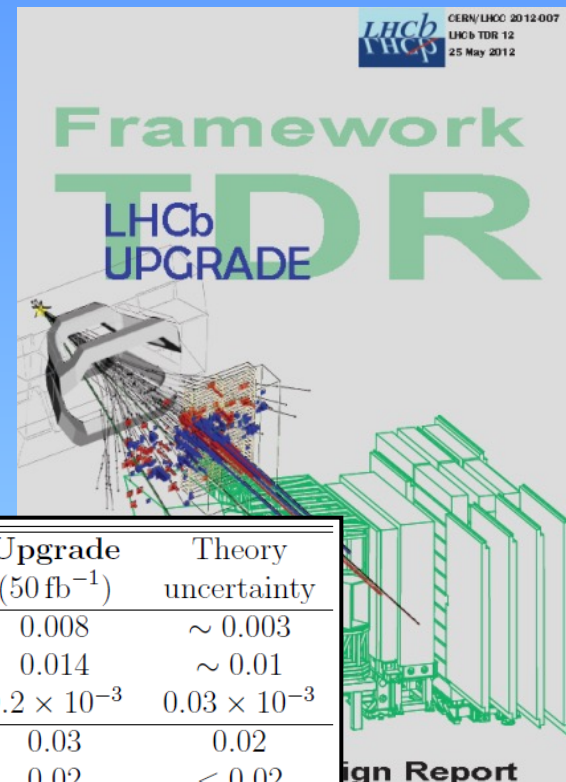


WWW



# LHCb: Hoe verder?

- Preciezer! → Upgrade (2018)



Type	Observable	Current precision	LHCb 2018	Upgrade (50 fb <sup>-1</sup> )	Theory uncertainty
$B_s^0$ mixing	$2\beta_s (B_s^0 \rightarrow J/\psi \phi)$	0.10 [30]	0.025	0.008	$\sim 0.003$
	$2\beta_s (B_s^0 \rightarrow J/\psi f_0(980))$	0.17 [32]	0.045	0.014	$\sim 0.01$
	$a_{sl}^s$	$6.4 \times 10^{-3}$ [63]	$0.6 \times 10^{-3}$	$0.2 \times 10^{-3}$	$0.03 \times 10^{-3}$
Gluonic penguins	$2\beta_s^{\text{eff}} (B_s^0 \rightarrow \phi \phi)$	—	0.17	0.03	0.02
	$2\beta_s^{\text{eff}} (B_s^0 \rightarrow K^{*0} \bar{K}^{*0})$	—	0.13	0.02	$< 0.02$
	$2\beta_s^{\text{eff}} (B^0 \rightarrow \phi K_S^0)$	0.17 [63]	0.30	0.05	0.02
Right-handed currents	$2\beta_s^{\text{eff}} (B_s^0 \rightarrow \phi \gamma)$	—	0.09	0.02	$< 0.01$
	$\tau^{\text{eff}} (B_s^0 \rightarrow \phi \gamma) / \tau_{B_s^0}$	—	5 %	1 %	0.2 %
Electroweak penguins	$S_3(B^0 \rightarrow K^{*0} \mu^+ \mu^-; 1 < q^2 < 6 \text{ GeV}^2/c^4)$	0.08 [64]	0.025	0.008	0.02
	$s_0 A_{\text{FB}}(B^0 \rightarrow K^{*0} \mu^+ \mu^-)$	25 % [64]	6 %	2 %	7 %
	$A_I(K \mu^+ \mu^-; 1 < q^2 < 6 \text{ GeV}^2/c^4)$	0.25 [9]	0.08	0.025	$\sim 0.02$
	$\mathcal{B}(B^+ \rightarrow \pi^+ \mu^+ \mu^-) / \mathcal{B}(B^+ \rightarrow K^+ \mu^+ \mu^-)$	25 % [29]	8 %	2.5 %	$\sim 10 \%$
Higgs penguins	$\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-)$	$1.5 \times 10^{-9}$ [4]	$0.5 \times 10^{-9}$	$0.15 \times 10^{-9}$	$0.3 \times 10^{-9}$
	$\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) / \mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-)$	—	$\sim 100 \%$	$\sim 35 \%$	$\sim 5 \%$
Unitarity triangle angles	$\gamma (B \rightarrow D^{(*)} K^{(*)})$	$\sim 10\text{--}12^\circ$ [40, 41]	$4^\circ$	$0.9^\circ$	negligible
	$\gamma (B_s^0 \rightarrow D_s K)$	—	$11^\circ$	$2.0^\circ$	negligible
	$\beta (B^0 \rightarrow J/\psi K_S^0)$	$0.8^\circ$ [63]	$0.6^\circ$	$0.2^\circ$	negligible
Charm	$A_\Gamma$	$2.3 \times 10^{-3}$ [63]	$0.40 \times 10^{-3}$	$0.07 \times 10^{-3}$	—
CP violation	$\Delta A_{CP}$	$2.1 \times 10^{-3}$ [8]	$0.65 \times 10^{-3}$	$0.12 \times 10^{-3}$	—



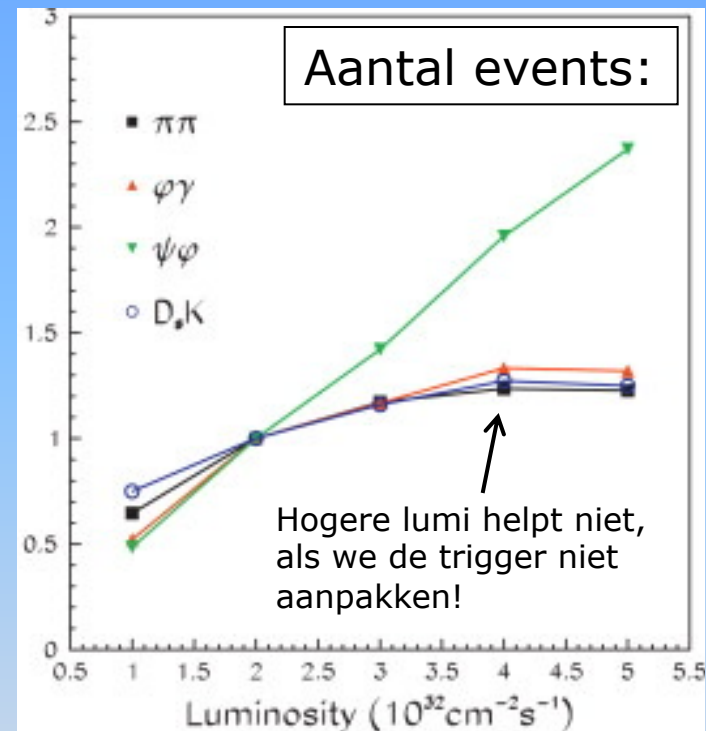
# LHCb: Upgrade - Trigger

- Precisie meting → Meer luminositeit
- Meer luminositeit → ~~Hogere trigger rate~~
- Meer luminositeit → Hogere threshold
- Hogere threshold → ~~Minder events ...~~

## Oplossing:

Slimmere trigger → *alle* events naar CPU farm:

➤ Readout @40 MHz, niet 1 MHz ...

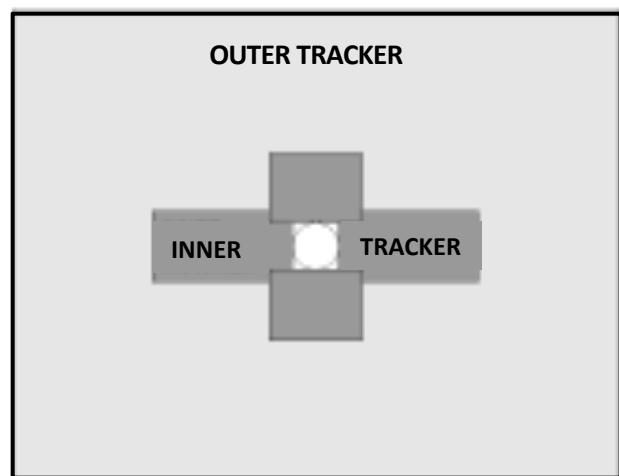
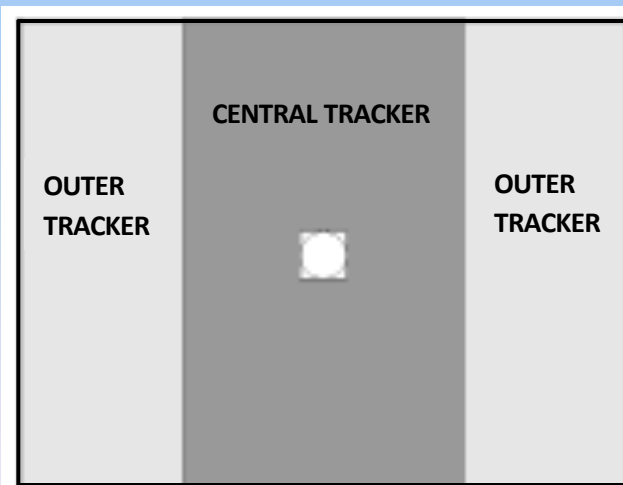


# LHCb: Upgrade - Detectors

- Precisie meting → Meer luminositeit
- Meer luminositeit → Hogere particle rate
- Hogere particle rate → **Occupancy te hoog** in de Outer Tracker

➤ 2 opties:

*Beslissing in 2013*



**1) Inner Tracker wordt Scintil. Fiber,  
Outer Tracker wordt minder**

**2) Inner Tracker wordt groter,  
Outer Tracker wordt kleiner**



# Schrödinger

Klassiek verband tussen E and p:

$$E = \frac{\vec{p}^2}{2m}$$

Quantum mechanische substitutie:  
(operator acting on wave function  $\psi$ )

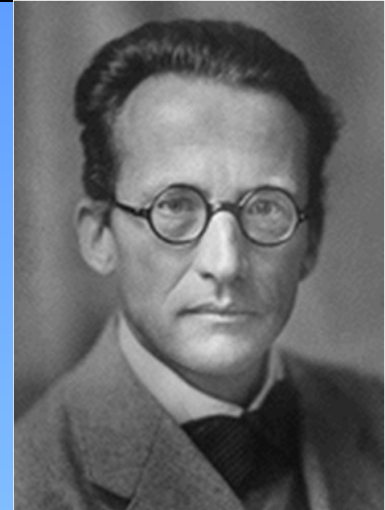
$$E \rightarrow i \frac{\partial}{\partial t} \quad \text{and} \quad \vec{p} \rightarrow -i \vec{\nabla}$$

Schrodinger vergelijking:

$$i \frac{\partial}{\partial t} \psi = \frac{-1}{2m} \nabla^2 \psi$$

Oplossing:

$$\psi = N e^{i(\vec{p}\vec{x} - Et)}$$



•(show it is a solution)



# Klein-Gordon

Relativistisch verband tussen E and p:

$$E^2 = \vec{p}^2 + m^2$$

Quantum mechanische substitutie:  
(operator acting on wave function  $\psi$ )

$$E \rightarrow i \frac{\partial}{\partial t} \quad \text{and} \quad \vec{p} \rightarrow -i \vec{\nabla}$$

Klein Gordon vergelijking:

$$-\frac{\partial^2}{\partial t^2} \phi = -\nabla^2 \phi + m^2 \phi$$

or :

$$(\square + m^2) \phi(x) = 0$$

$$\text{or : } (\partial_\mu \partial^\mu + m^2) \phi(x) = 0$$

Oplossing:

$$\phi(x) = N e^{-ip_\mu x^\mu}$$

$$E^2 = \vec{p}^2 + m^2$$

*Maar: negatieve energie oplossing?*

$$E = \pm \sqrt{\vec{p}^2 + m^2}$$



# Dirac



Paul Dirac zocht een vergelijking, die

- relativistisch correct is,
- Maar lineair in  $d/dt$  om negatieve energie te vermijden
- (en lineair in  $d/dx$  (or  $\nabla$ ) vanwege Lorentz covariantie)

Hij vond een vergelijking, die

- spin-1/2 deeltjes bleek te beschrijven en
- het bestaan van anti-deeltjes voorspelde

# Dirac

➤ How to find that relativistic, linear equation ??

Write Hamiltonian in general form,

$$H\psi = (\vec{\alpha} \cdot \vec{p} + \beta m) \psi$$

but when squared, it must satisfy:

$$H^2\psi = (\vec{p}^2 + m^2) \psi$$

Let's find  $\alpha_i$  and  $\beta$  !

$$\begin{aligned} H^2\psi &= (\alpha_i p_i + \beta m)^2 \psi \quad \text{with : } i = 1, 2, 3 \\ &= \left( \underbrace{\alpha_i^2}_{=1} p_i^2 + \underbrace{(\alpha_i \alpha_j + \alpha_j \alpha_i)}_{=0 \quad i>j} p_i p_j + \underbrace{(\alpha_i \beta + \beta \alpha_i)}_{=0} p_i m + \underbrace{\beta^2}_{=1} m^2 \right) \psi \end{aligned}$$

So,  $\alpha_i$  and  $\beta$  must satisfy:

- $\alpha_1^2 = \alpha_2^2 = \alpha_3^2 = \beta^2$
- $\alpha_1, \alpha_2, \alpha_3, \beta$  anti-commute with each other
- (not a unique choice!)

# Dirac

$$H\psi = (\vec{\alpha} \cdot \vec{p} + \beta m) \psi$$

## ➤ What are $\alpha$ and $\beta$ ??

- The lowest dimensional matrix that has the desired behaviour is 4x4 !?

$$\vec{\alpha} = \begin{pmatrix} 0 & \vec{\sigma} \\ \vec{\sigma} & 0 \end{pmatrix} \quad ; \quad \beta = \begin{pmatrix} I & 0 \\ 0 & -I \end{pmatrix}$$

- Often used
- Pauli-Dirac representation:

- with: 
$$\sigma_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \quad ; \quad \sigma_2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix} \quad ; \quad \sigma_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

So,  $\alpha_i$  and  $\beta$  must satisfy:

- $\alpha_1^2 = \alpha_2^2 = \alpha_3^2 = \beta^2$
- $\alpha_1, \alpha_2, \alpha_3, \beta$  anti-commute with each other
- (not a unique choice!)



# Dirac

$$H\psi = (\vec{\alpha} \cdot \vec{p} + \beta m) \psi$$

Usual substitution:

$$H \rightarrow i\frac{\partial}{\partial t}, \vec{p} \rightarrow -i\vec{\nabla}$$

Leads to:

$$i\frac{\partial}{\partial t}\psi = (-i\vec{\alpha} \cdot \vec{\nabla} + \beta m) \psi$$

Multiply by  $\beta$ :

$$\left( i\beta\frac{\partial}{\partial t}\psi + i\beta\alpha_1\frac{\partial}{\partial x} + i\beta\alpha_2\frac{\partial}{\partial y} + i\beta\alpha_3\frac{\partial}{\partial z} \right) \psi - m\psi = 0 \quad \bullet(\beta^2=1)$$

Gives the famous Dirac equation:

$$(i\gamma^\mu\partial_\mu - m) \psi = 0$$

with :  $\gamma^\mu = (\beta, \beta\vec{\alpha}) \equiv$  Dirac  $\gamma$ -matrices

$$\text{for each } j=1,2,3,4 : \sum_{k=1}^4 \left[ \sum_{\mu=0}^3 i(\gamma^\mu)_{jk} \partial_\mu - m\delta_{jk} \right] (\psi_k) = 0$$

# Dirac

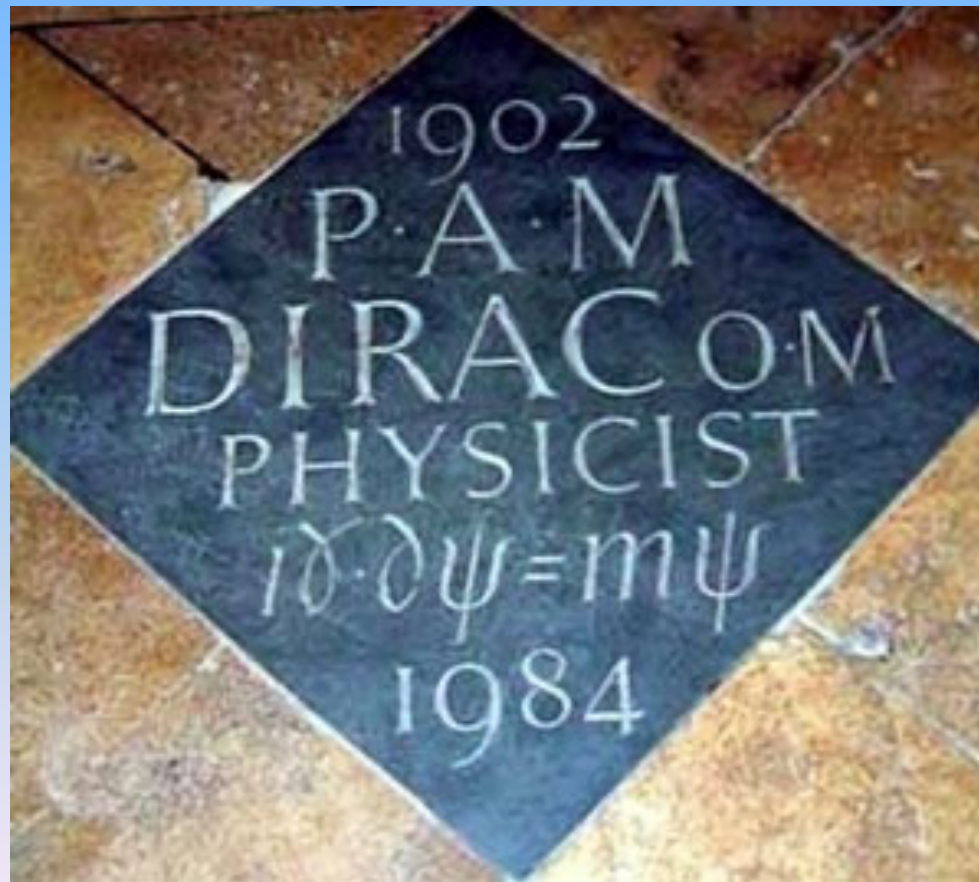
$$H\psi = (\vec{\alpha} \cdot \vec{p} + \beta m) \psi$$

The famous Dirac equation:

$$(i\gamma^\mu \partial_\mu - m) \psi = 0$$

with :  $\gamma^\mu = (\beta, \beta\vec{\alpha}) \equiv$  Dirac  $\gamma$ -matrices

R.I.P. :



# Dirac vergelijking

## Schrödinger equation

- Time-dependence of wave function

$$E = \frac{\vec{p}^2}{2m}$$

$$i \frac{\partial}{\partial t} \psi = \frac{-1}{2m} \nabla^2 \psi$$

## Klein-Gordon equation

- Relativistic equation of motion of scalar particles

$$E^2 = \vec{p}^2 + m^2$$

$$-\frac{\partial^2}{\partial t^2} \phi = -\nabla^2 \phi + m^2 \phi$$

## Dirac equation

- Relativistically correct, and linear
- Equation of motion for spin-1/2 particles
- Prediction of anti-matter

$$(i\gamma^\mu \partial_\mu - m) \psi = 0$$



$$\psi = \begin{pmatrix} \psi_1 \\ \psi_2 \\ \psi_3 \\ \psi_4 \end{pmatrix}$$