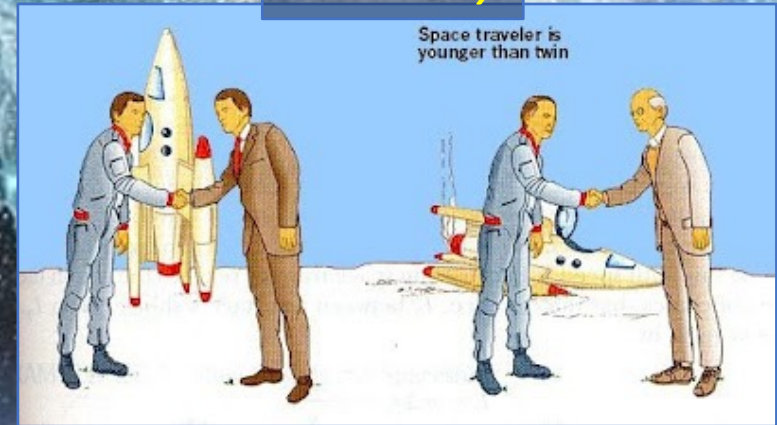


The Relativistic Quantum World

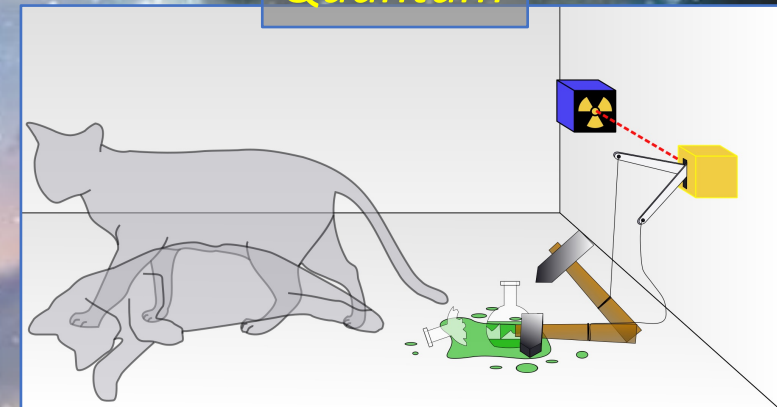
A lecture series on
Relativity Theory and Quantum Mechanics

Marcel Merk
Studium Generale Maastricht
Nov 1 – Nov 29, 2023

Relativity



Quantum



Relativity

Nov. 1:

Lecture 1: The Principle of Relativity and the Speed of Light
Lecture 2: Time Dilation and Lorentz Contraction

Nov. 8:

Lecture 3: The Lorentz Transformation and Paradoxes
Lecture 4: General Relativity and Gravitational Waves

Quantum Mechanics

Nov. 15:

Lecture 5: The Early Quantum Theory
Lecture 6: Feynman's Double Slit Experiment

Nov 22:

Lecture 7: Wheeler's Delayed Choice and Schrodinger's Cat
Lecture 8: Quantum Reality and the EPR Paradox

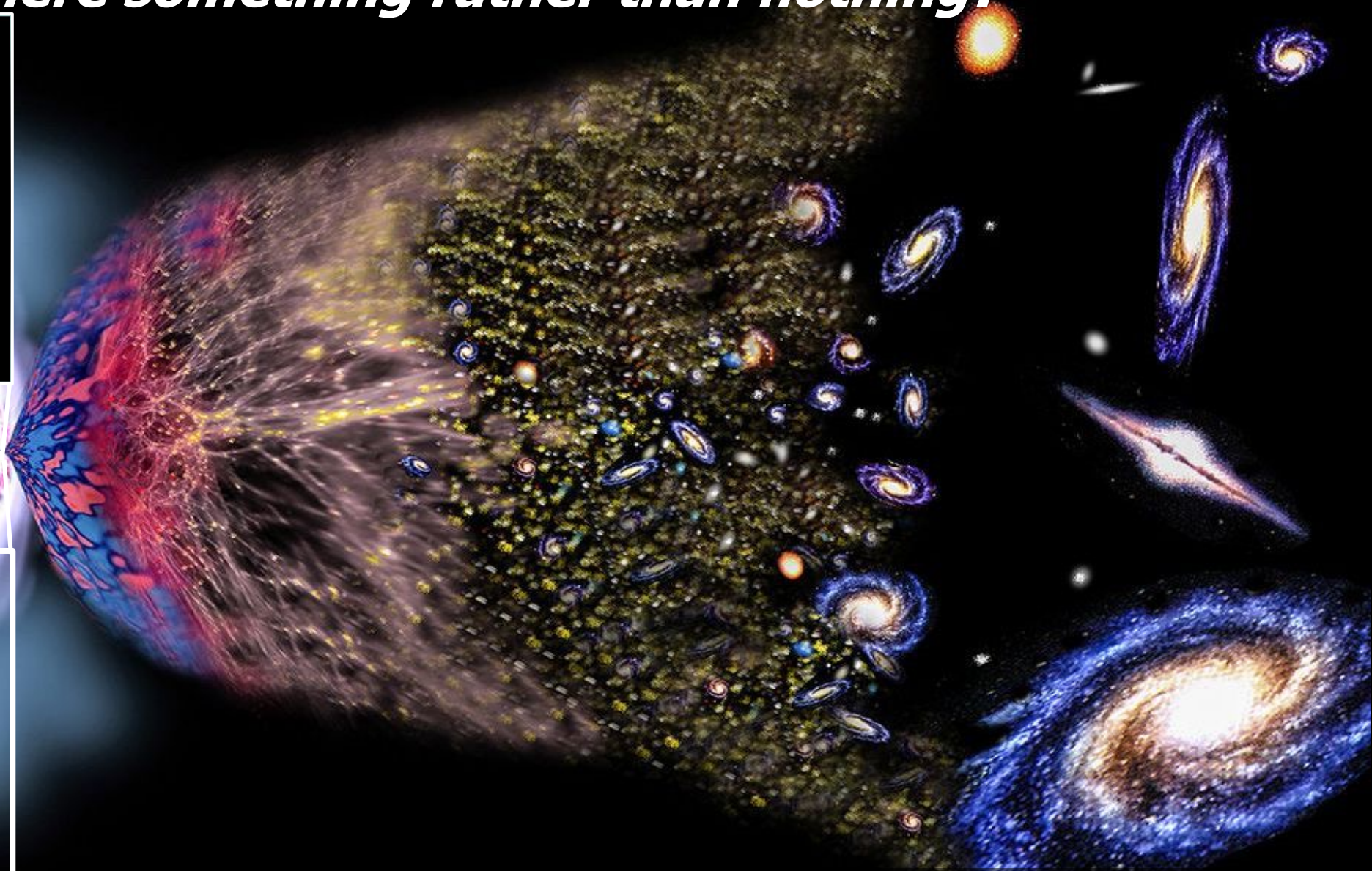
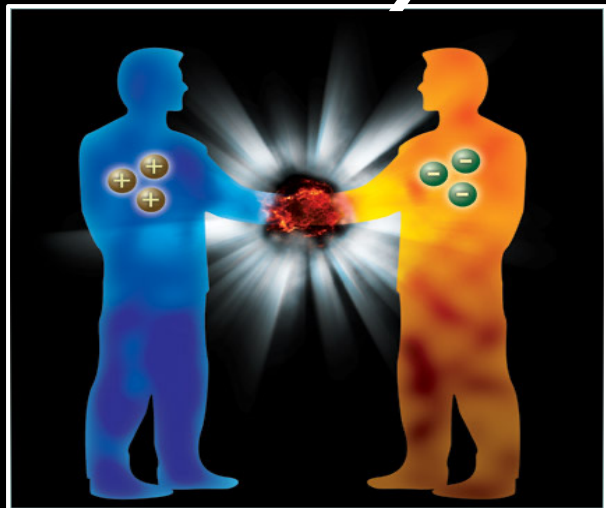
Standard Model

Nov. 29:

Lecture 9: The Standard Model and Antimatter
Lecture 10: Why is there something rather than nothing?

Lecture notes, written for this course, are available: www.nikhef.nl/~i93/Teaching/
Prerequisite for the course: High school level physics & mathematics.

Why is there something rather than nothing?



Fermionen: spin=1/2 deeltjes

Quarks			H	Krachten	
1	2	3		Z	γ
u	c	t	W	g	
d	s	b			
ν_e	ν_μ	ν_τ			
e	μ	τ			

Leptonen

"Flavor" puzzle: why are there three generations of fundamental particles?

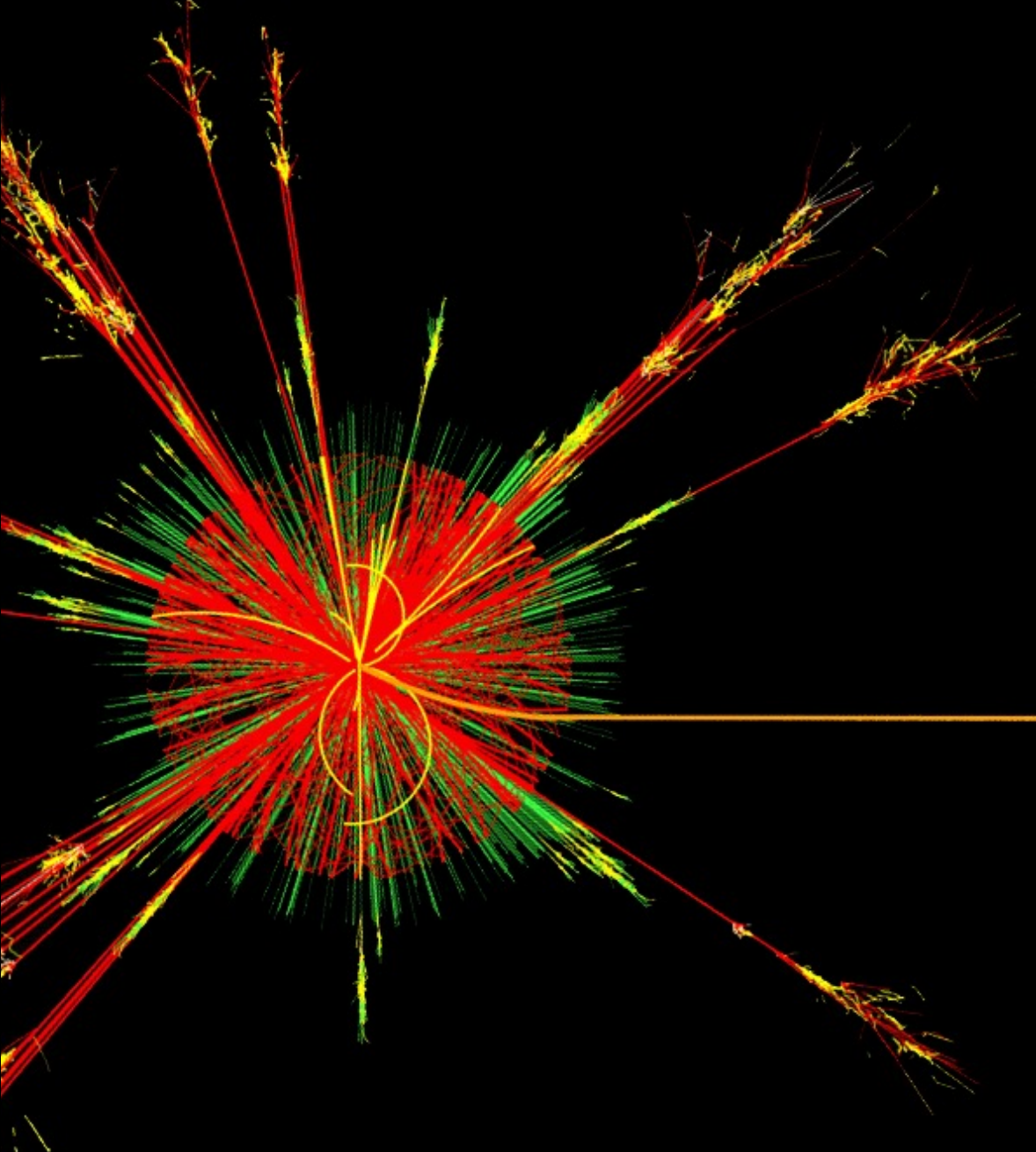


Lecture 10: Why is there something rather than nothing?

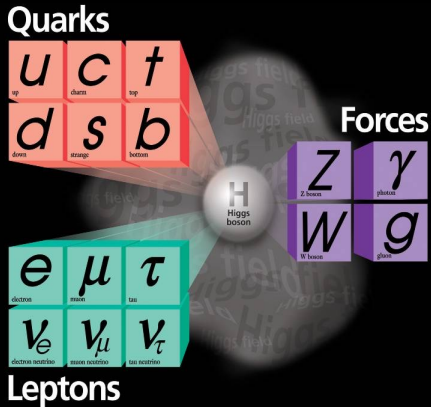
1: Discovery of the Higgs boson

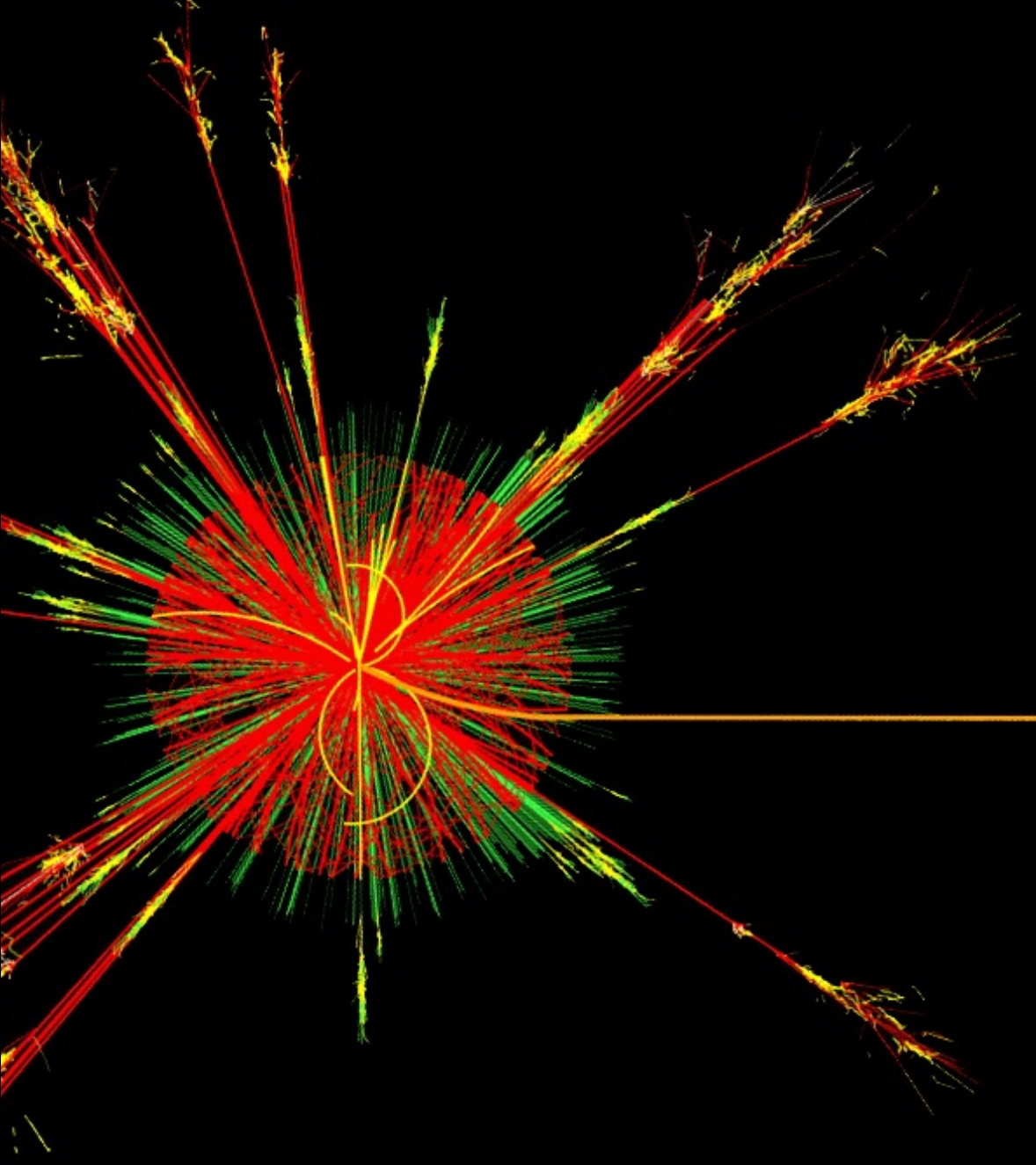
2: Symmetry between Matter and Antimatter?

3: A new force of Nature?

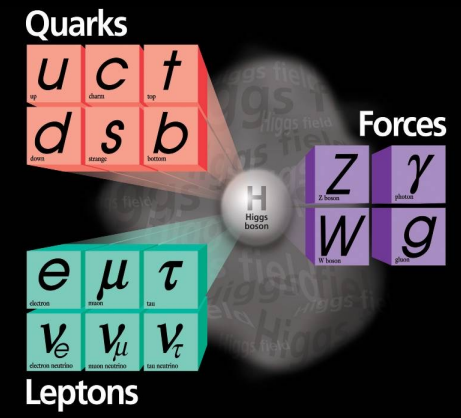


1: Discovery of the Higgs boson

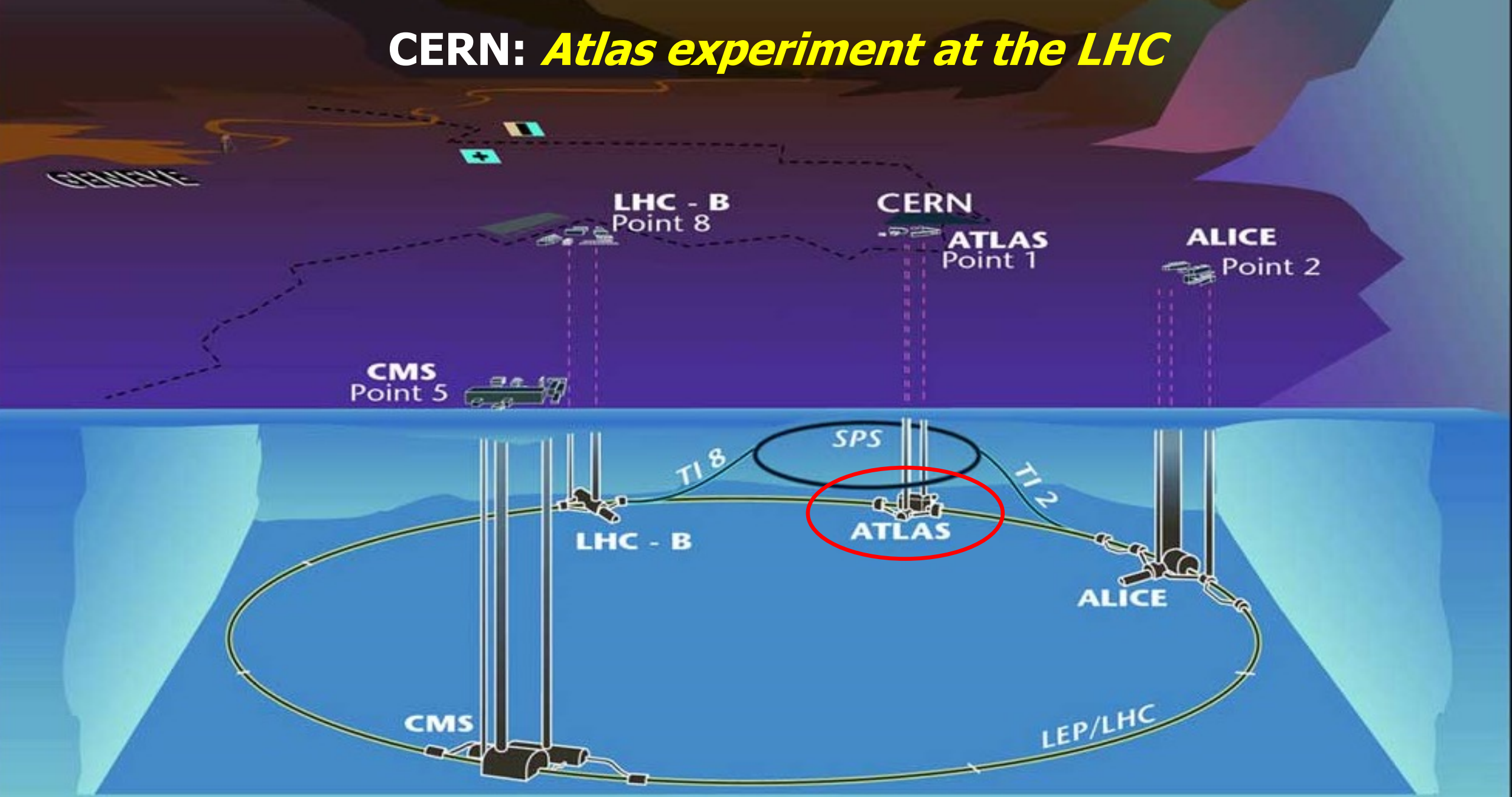




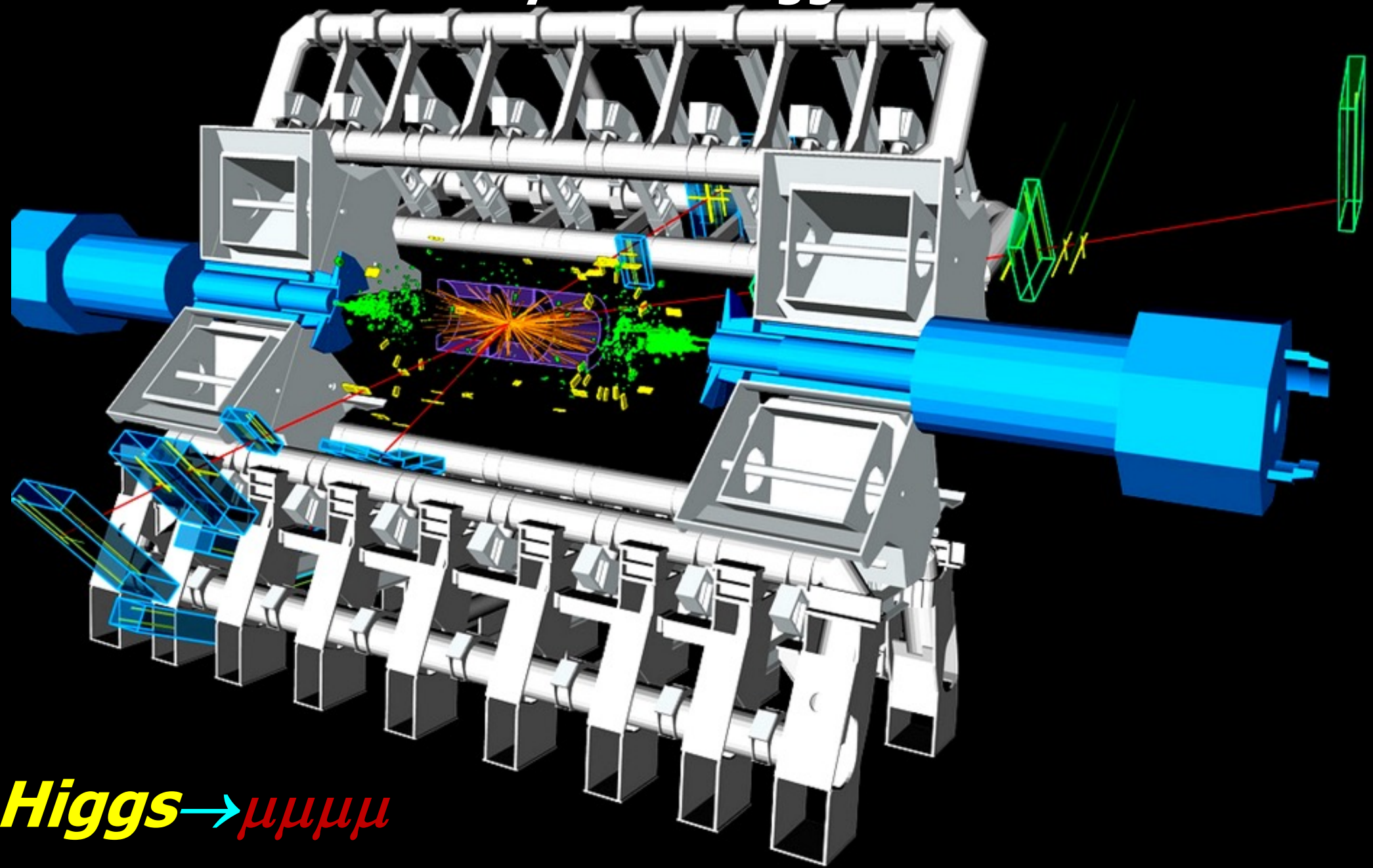
1: Discovery of the Higgs boson



CERN: *Atlas experiment at the LHC*

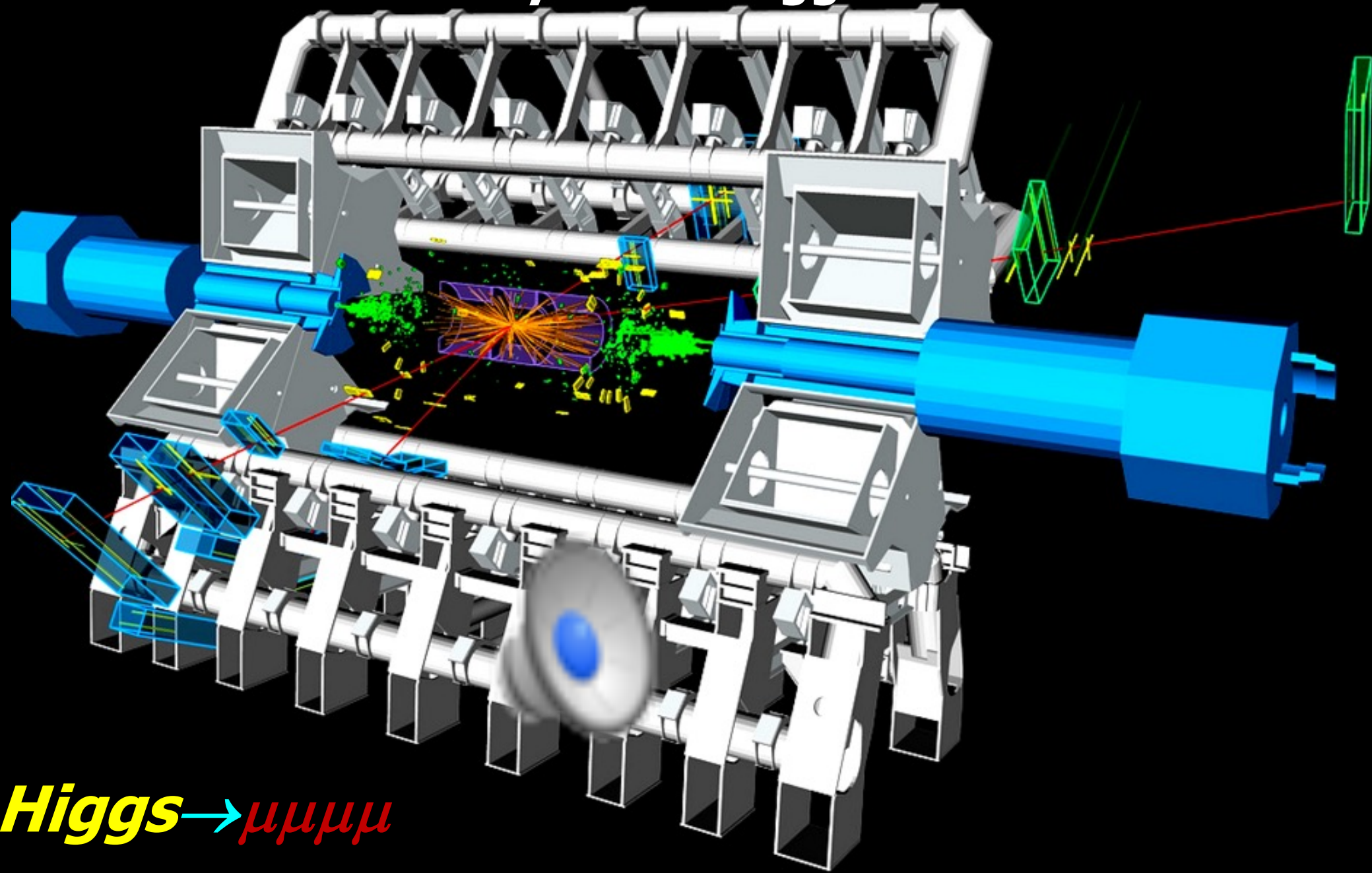


Discovery of the Higgs boson



$pp \rightarrow Higgs \rightarrow \mu\mu\mu\mu$

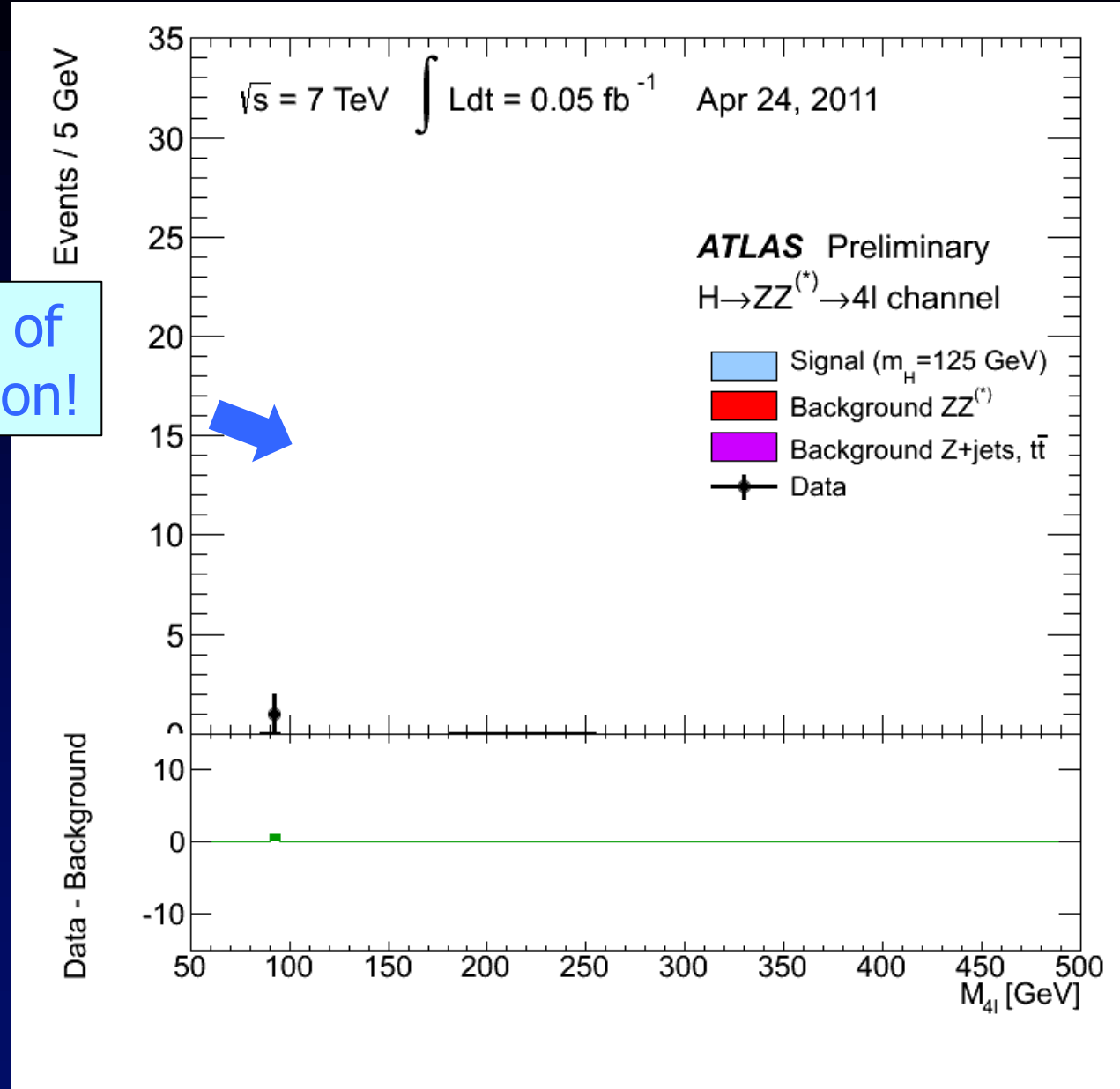
Discovery of the Higgs boson



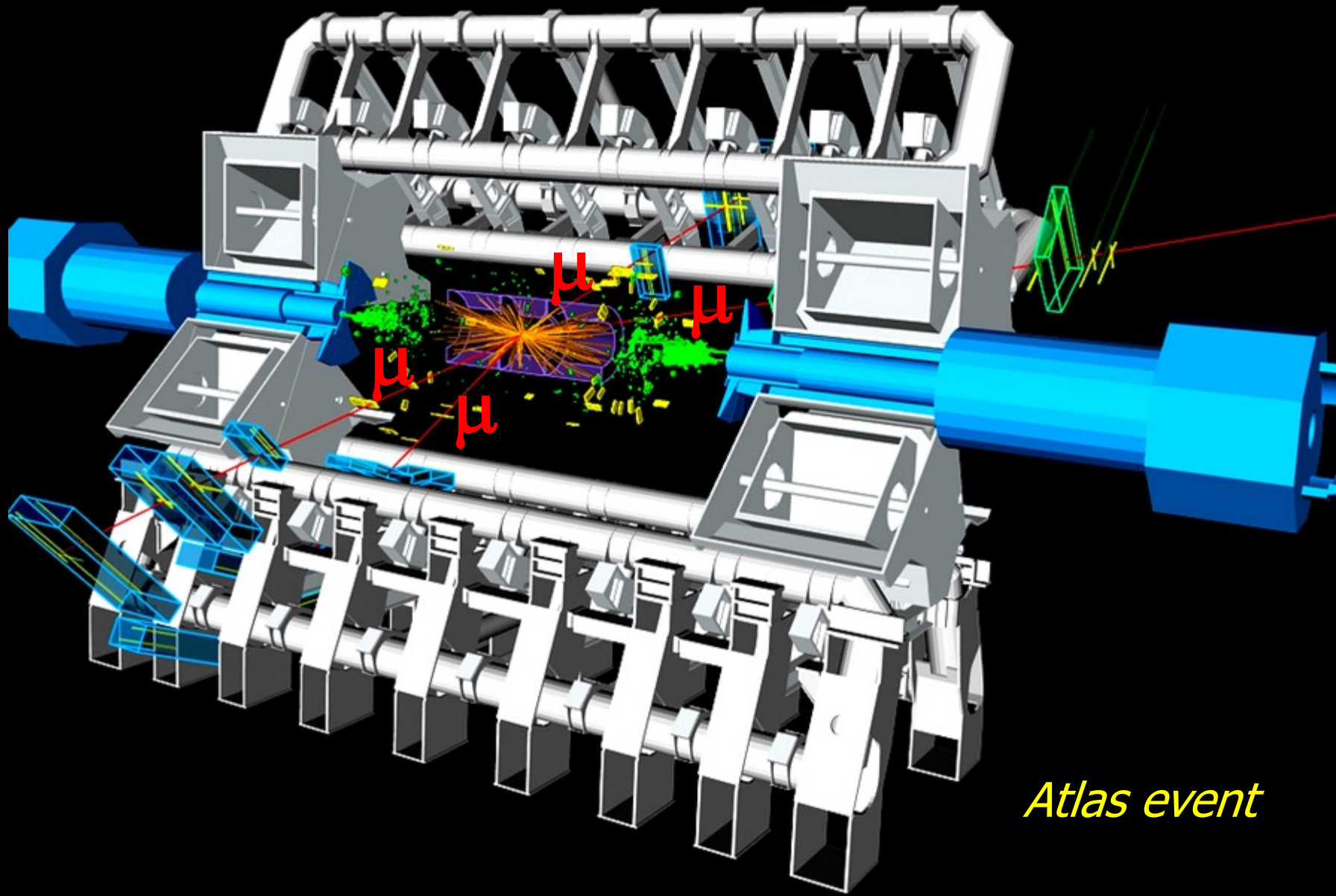
$pp \rightarrow Higgs \rightarrow \mu\mu\mu\mu$

Higgs: collecting data and testing theory

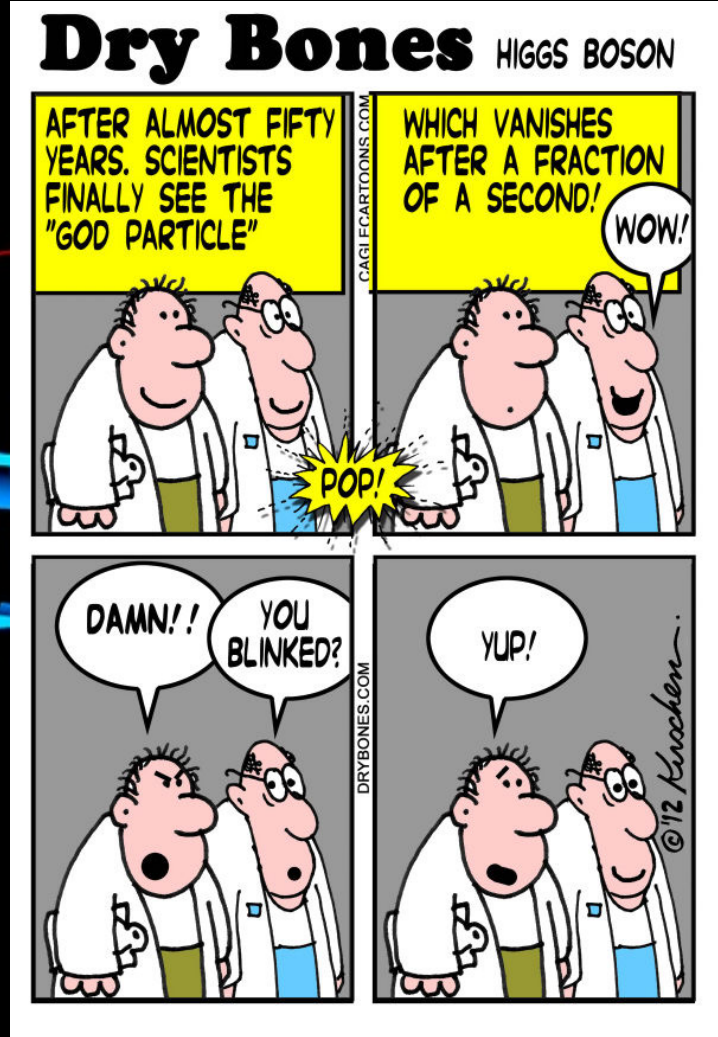
Discovery of Higgs boson!



$$pp \rightarrow Higgs \rightarrow \mu\mu\mu\mu$$



Atlas event



4 July 2012

Announcement Higgs discovery



2013 Nobel prize in Physics



Robert Brout

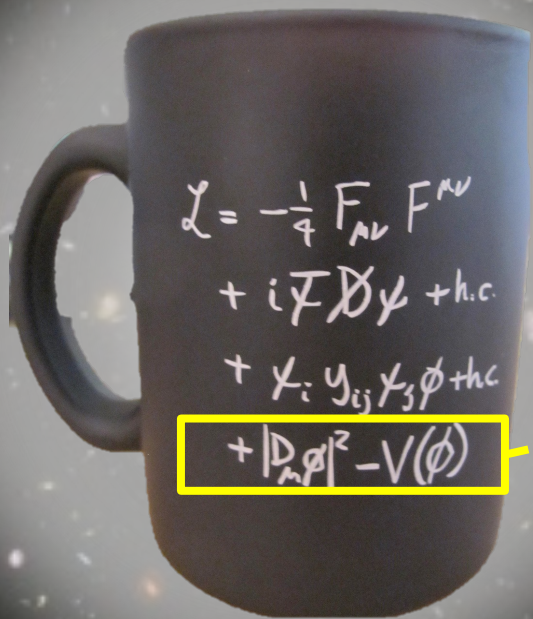


Francois Englert

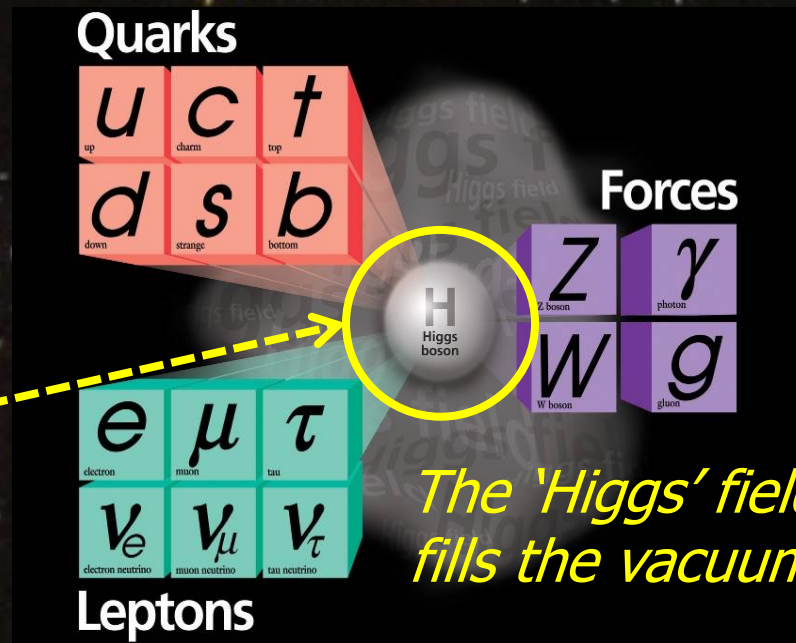
Peter Higgs

What did we discover?

"The formula"



"The building blocks"



Higgs Field ϕ and Particle H

- Higgs field is uniform, hard to see
- Higgs boson particle is “wave” of the field
- Mass results from interaction of matter particles with the Higgs field

- Compare:
 - A photon is a quantum of electromagnetic field
 - Water wave

ϕ

Higgs field



H

Higgs particle
a “field-quantum”



July 4, 2012: The Vacuum



HORSEY
©2002
LOS ANGELES
TIMES

"PHYSICISTS HAVE JUST CONFIRMED THERE'S
A 'GOD PARTICLE' -- THE HIGGS BOSON--
THAT BINDS THE UNIVERSE TOGETHER
AND MAKES ALL THINGS
POSSIBLE!!"



PERSPECTIVE IS EVERYTHING.

1897



Electron, e

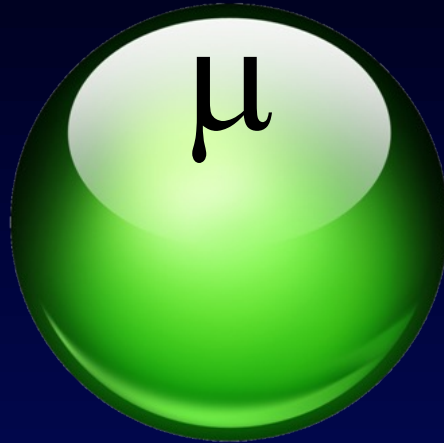
Spin $\frac{1}{2}$

Charge -1

Lifetime ∞

Mass .511 MeV

1937



Muon, μ

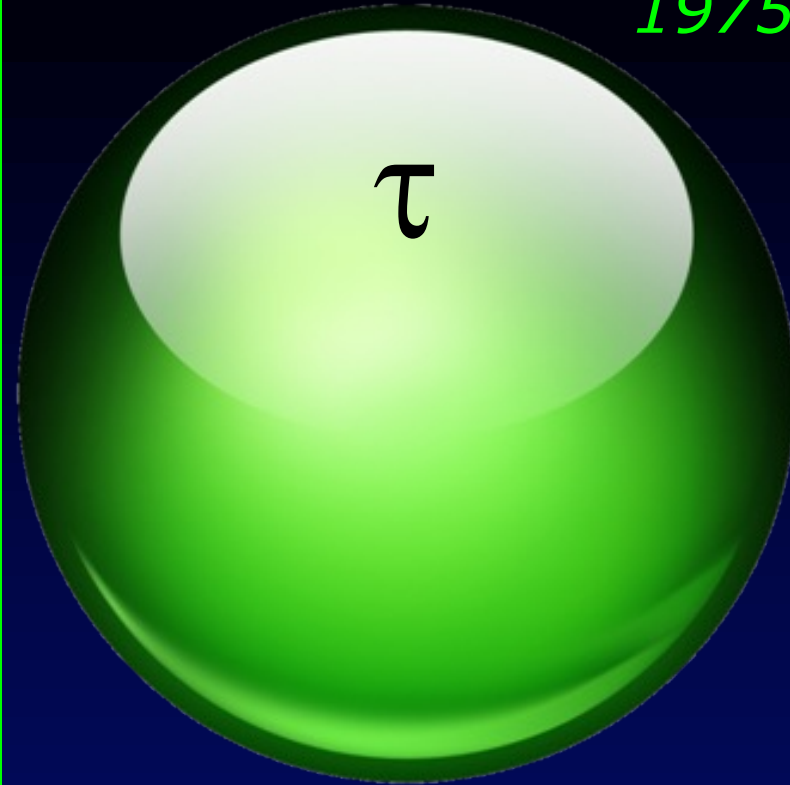
Spin $\frac{1}{2}$

Charge -1

Lifetime $2.2 \mu\text{s}$

Mass 106 MeV

1975



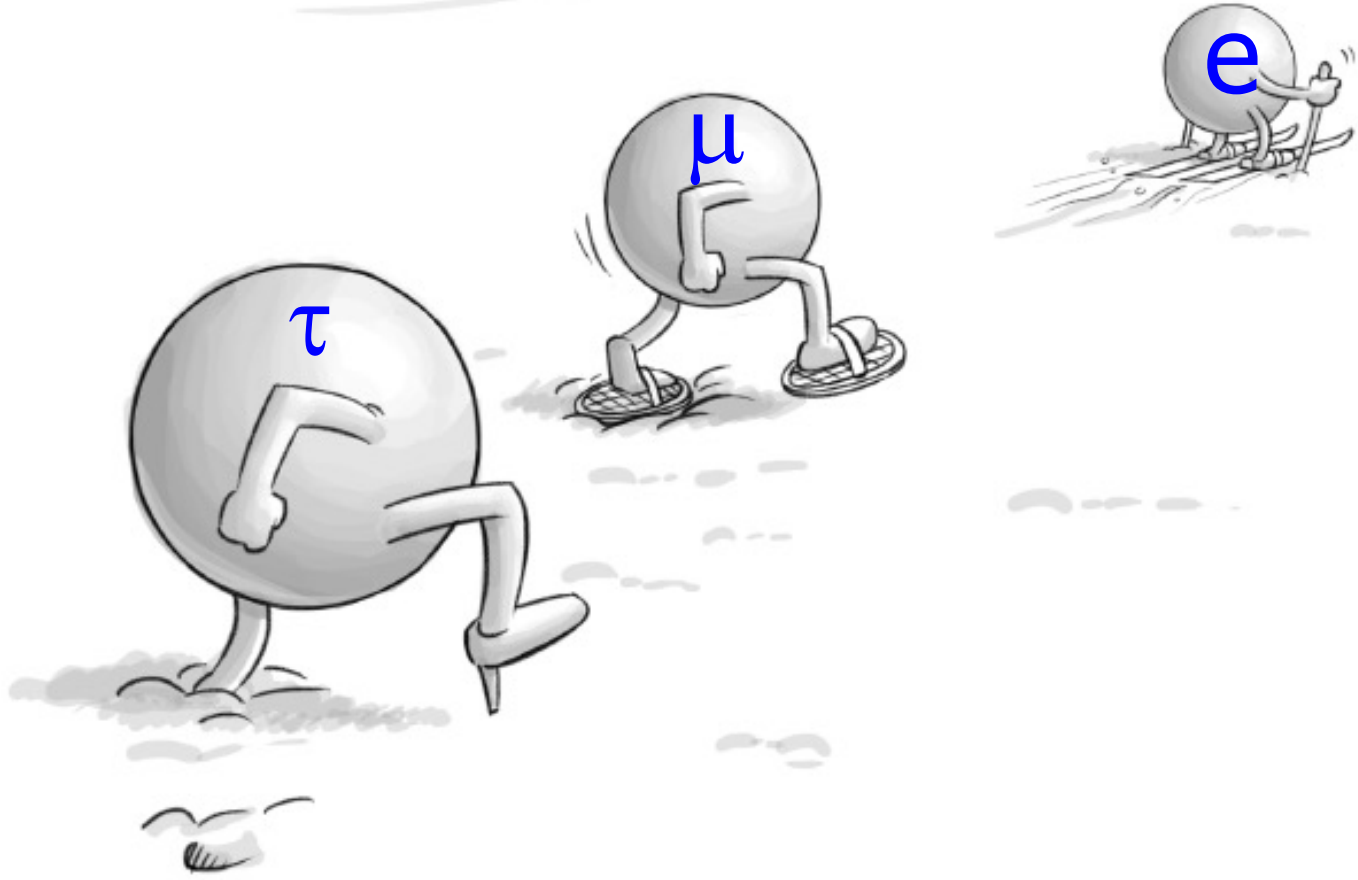
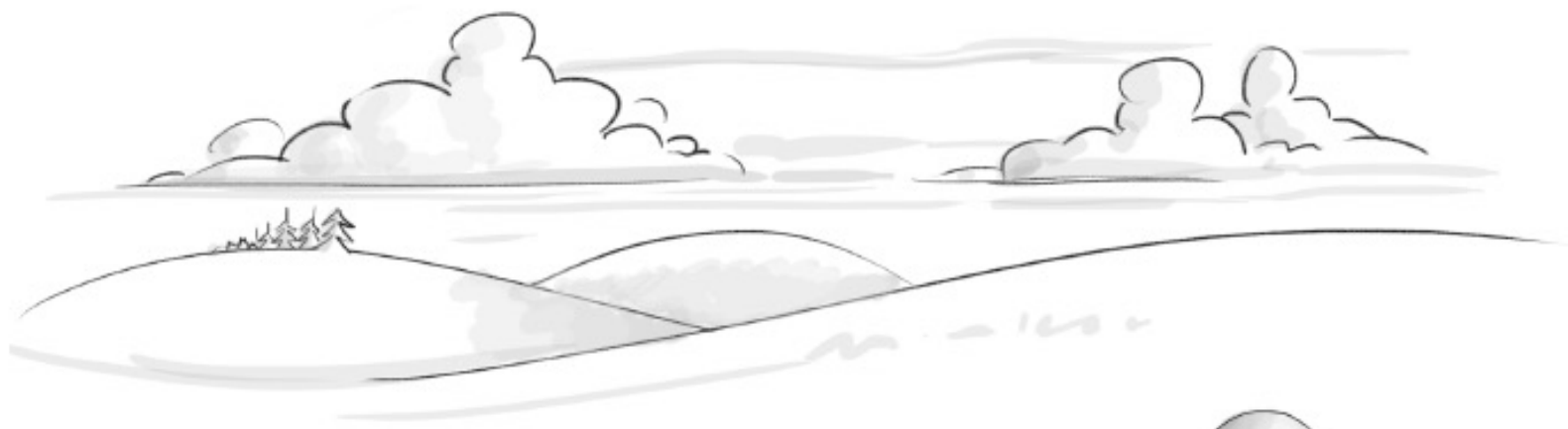
Tau, τ

Spin $\frac{1}{2}$

Charge -1

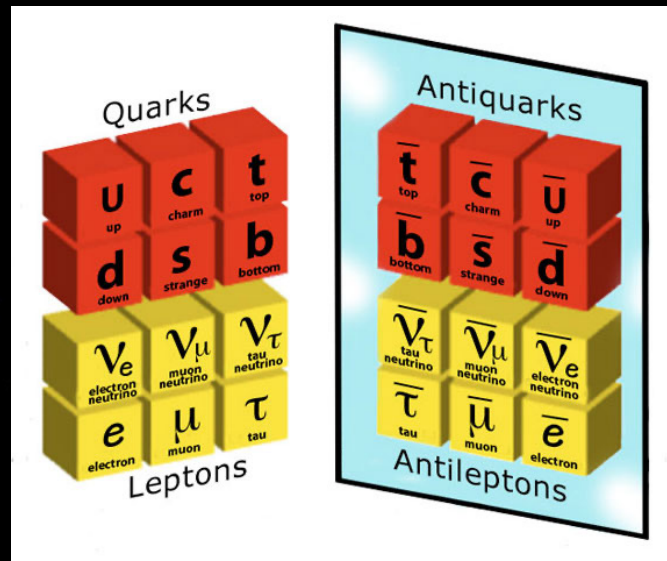
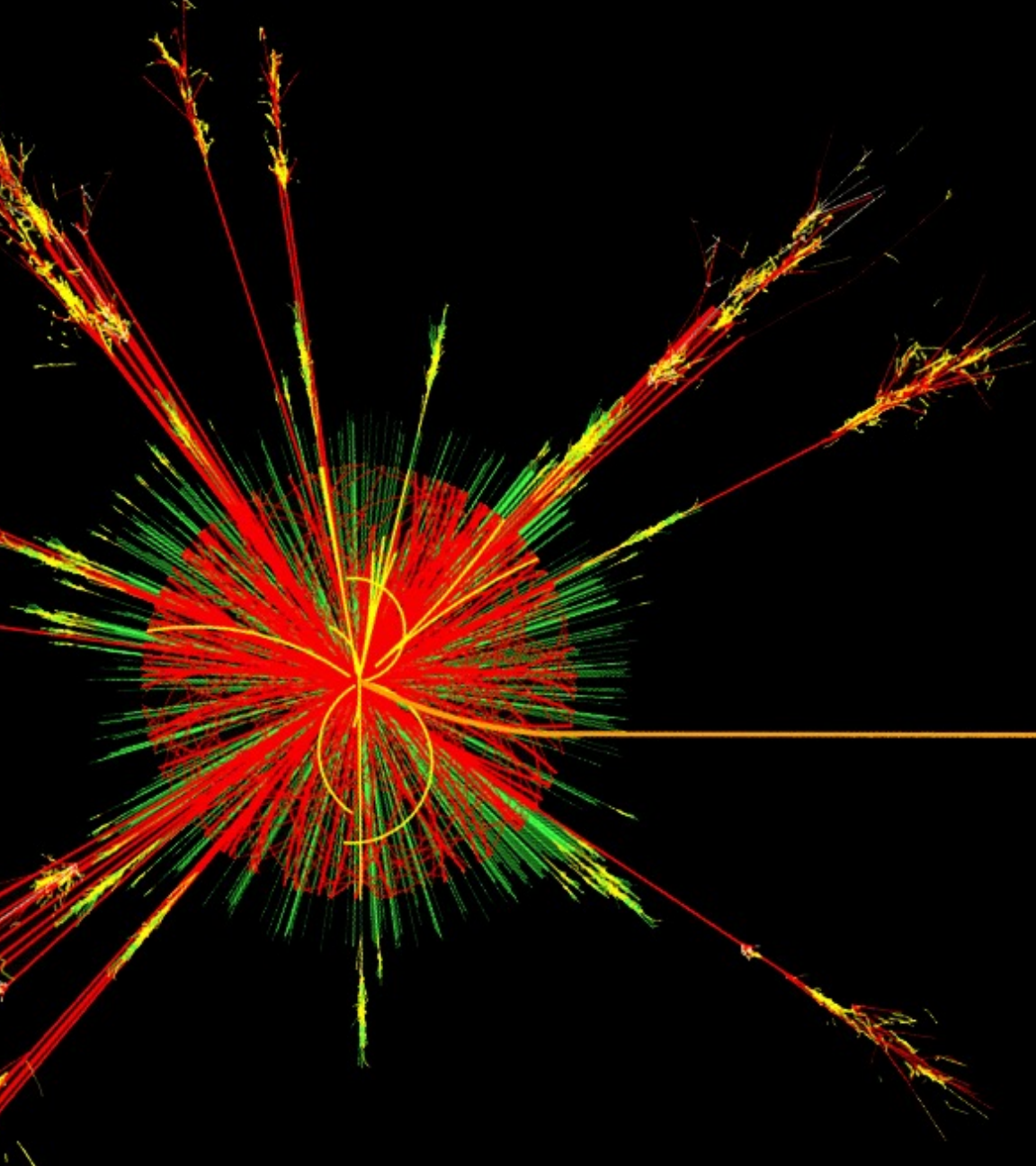
Lifetime 290 fs

Mass 1777 MeV

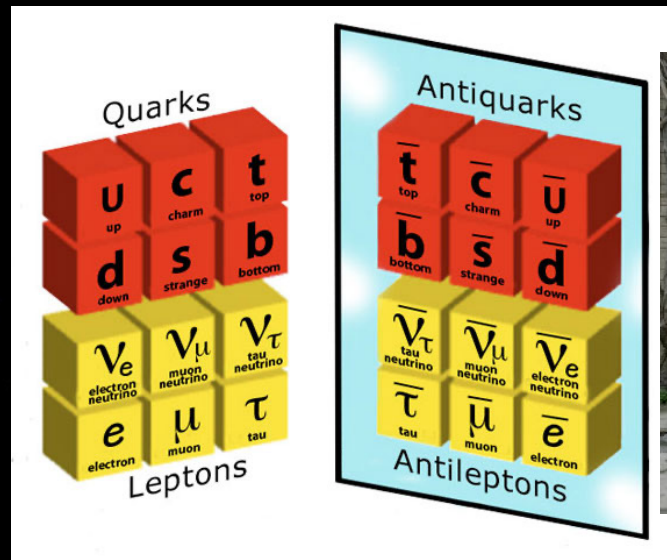
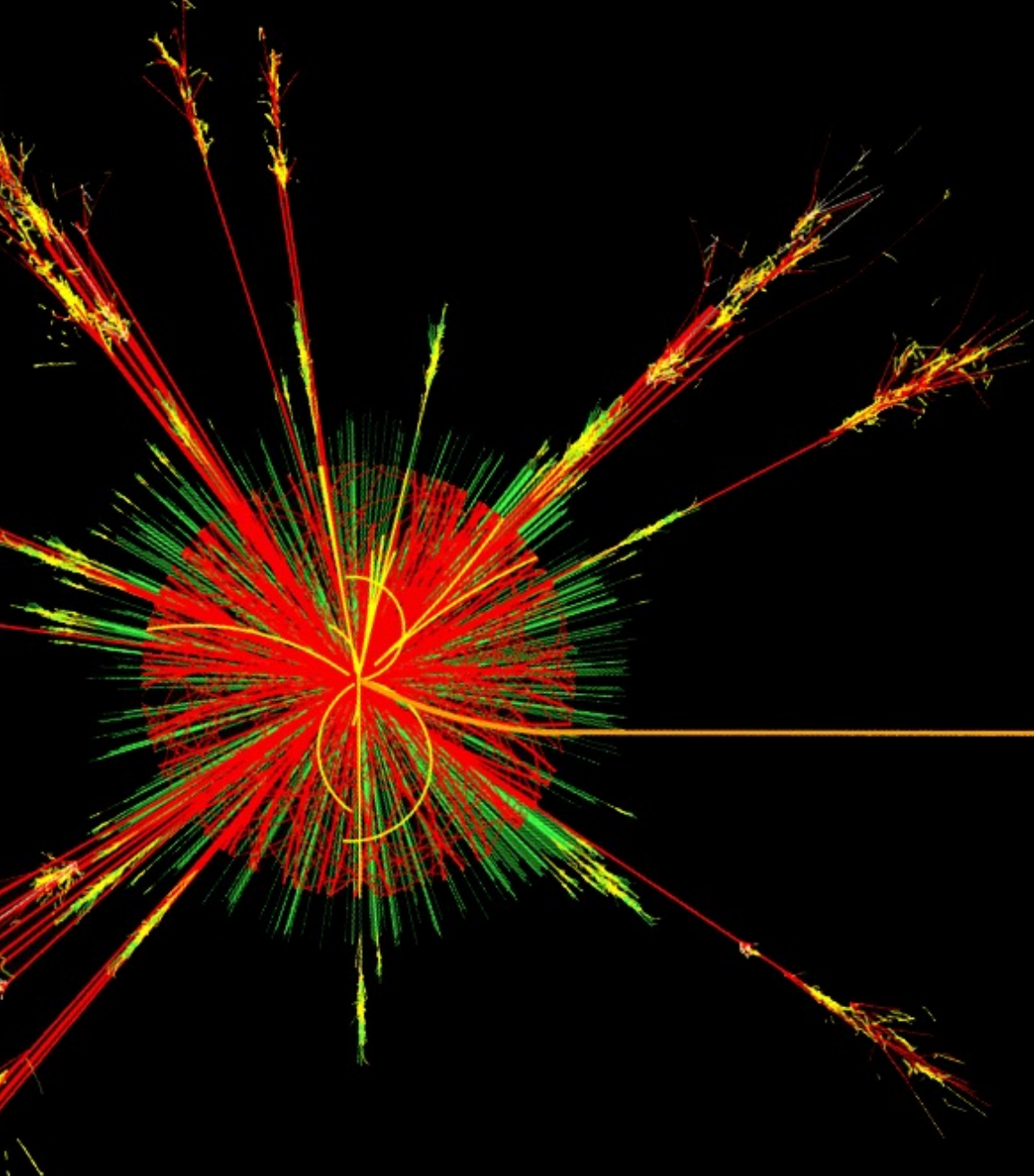


Hence...



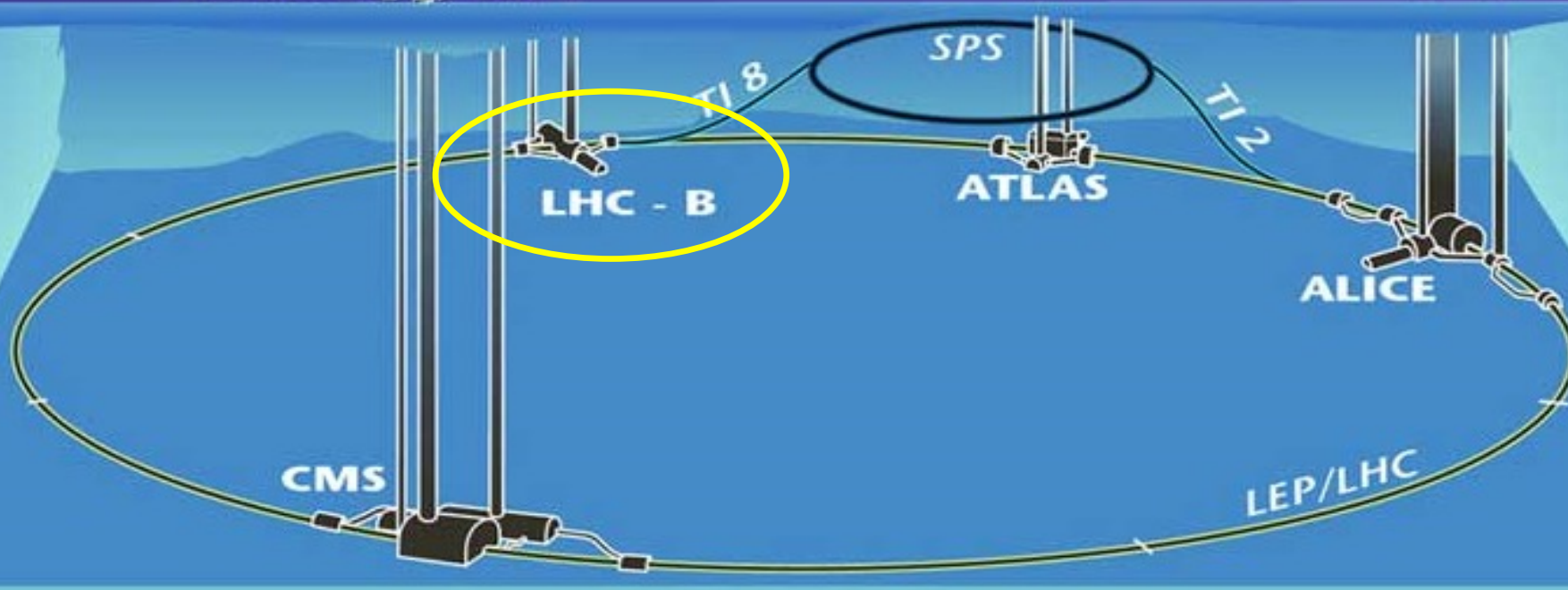
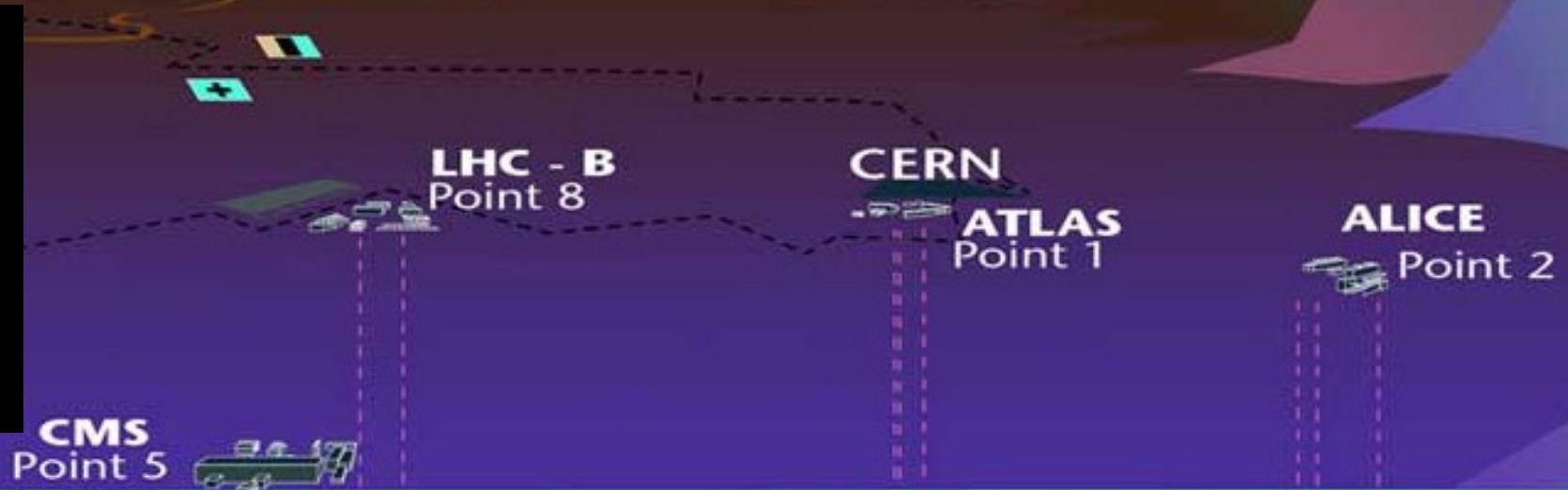
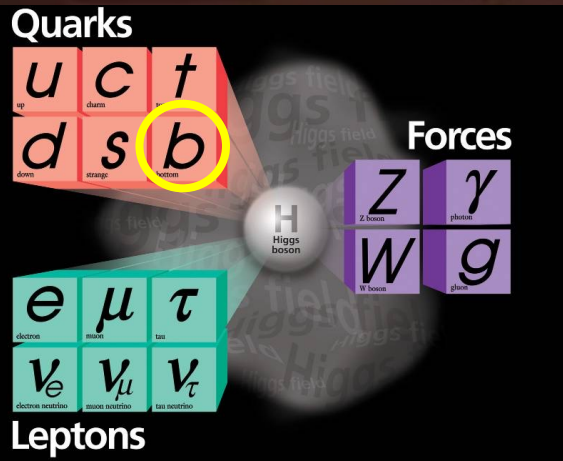


2: Symmetry between matter and antimatter?

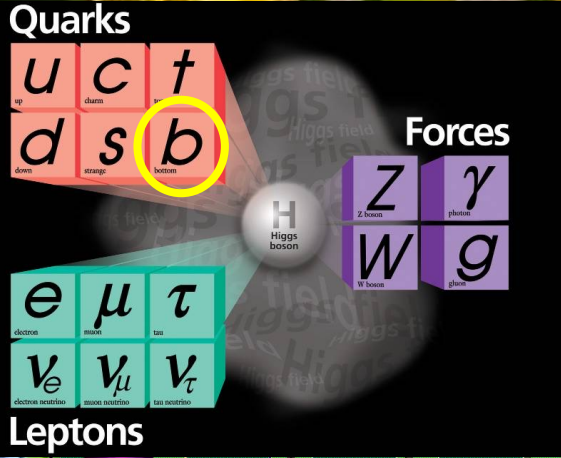


2: Symmetry between matter and antimatter?

LHCb Experiment: *decays of b-particles*



LHCb Detector: B-particles



Zoom in on collision point

Reconstruct millions of B-particle decays and select interesting cases. Do we observe differences between matter and antimatter?

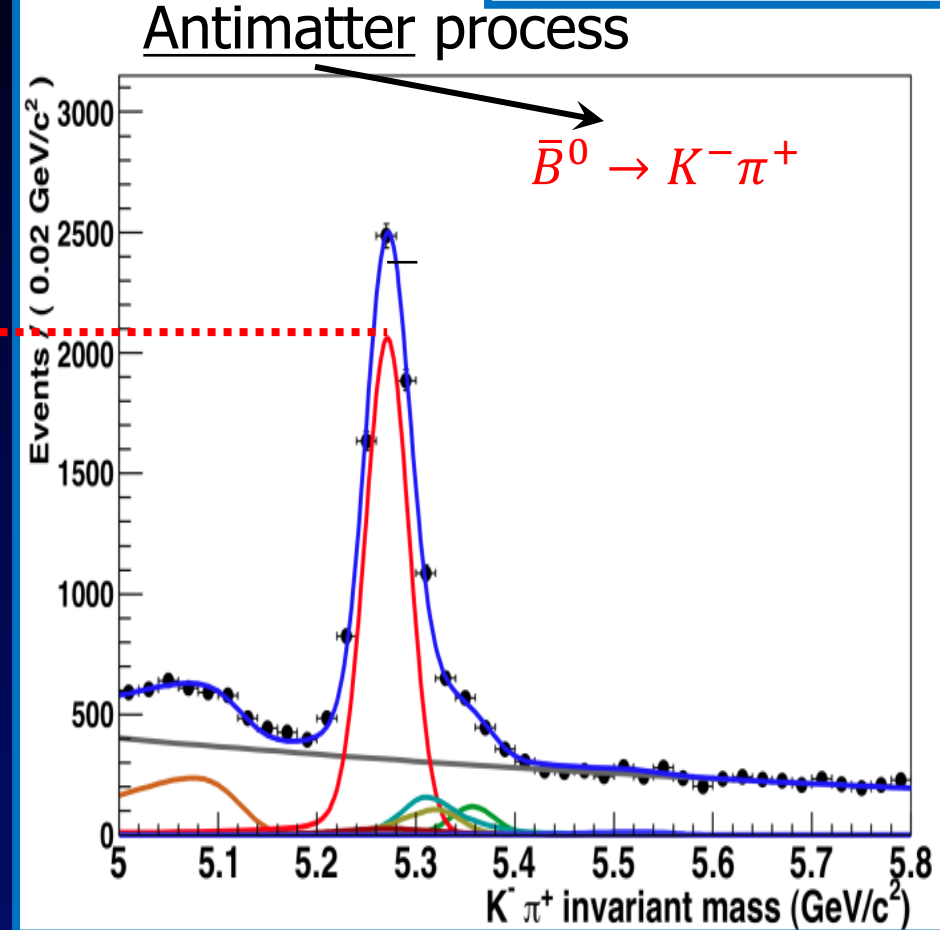
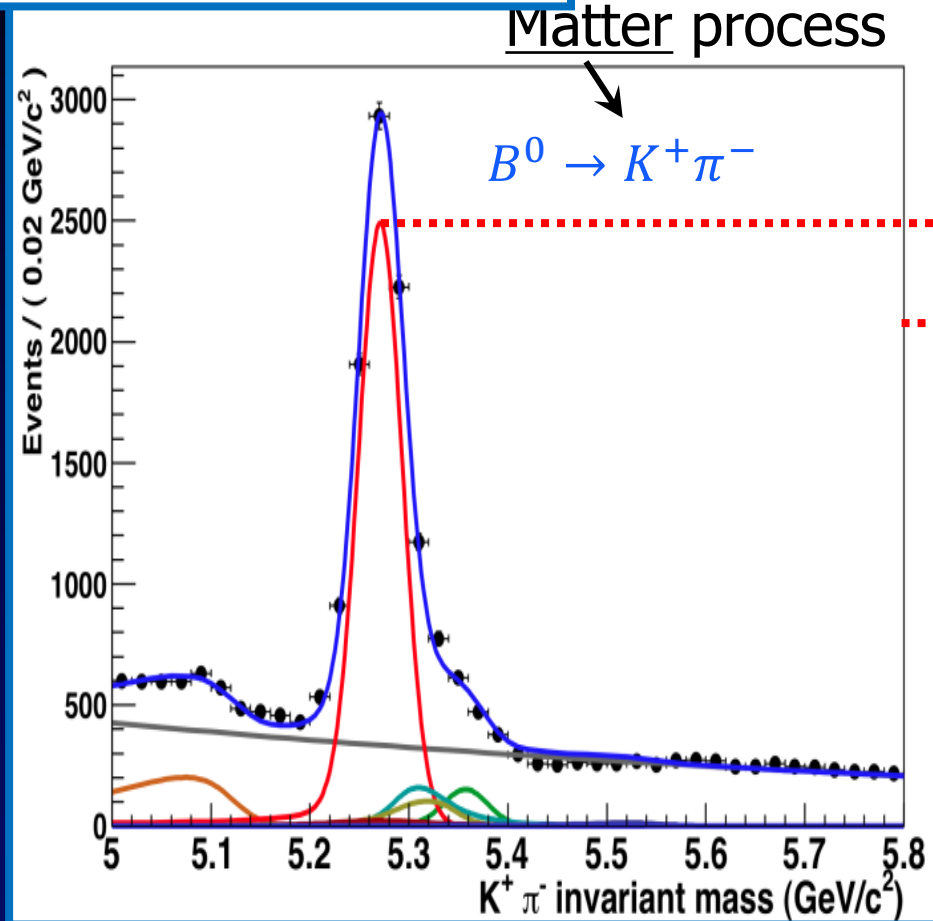


23 sep 2010 19:49:24
Run 79646 Event 143858637

B-decay process: matter vs antimatter

B particle decay into
a K^+ and a π^- particle

anti-B particle decay into
a K^- and a π^+ particle



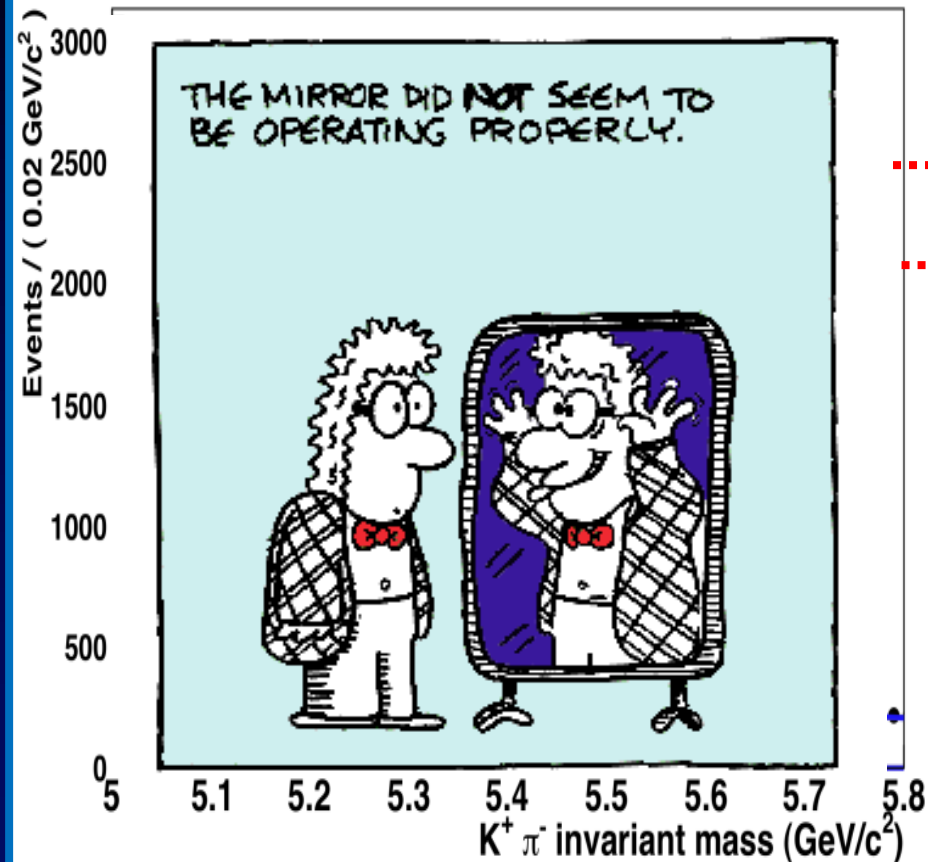
Asymmetrie: matter and antimatter decay processes proceed differently!
Quantum forces between particles and anti-particles ***not always identical!***

B-decay process: matter vs antimatter

***B* particle** decay into
a K^+ and a π^- particle

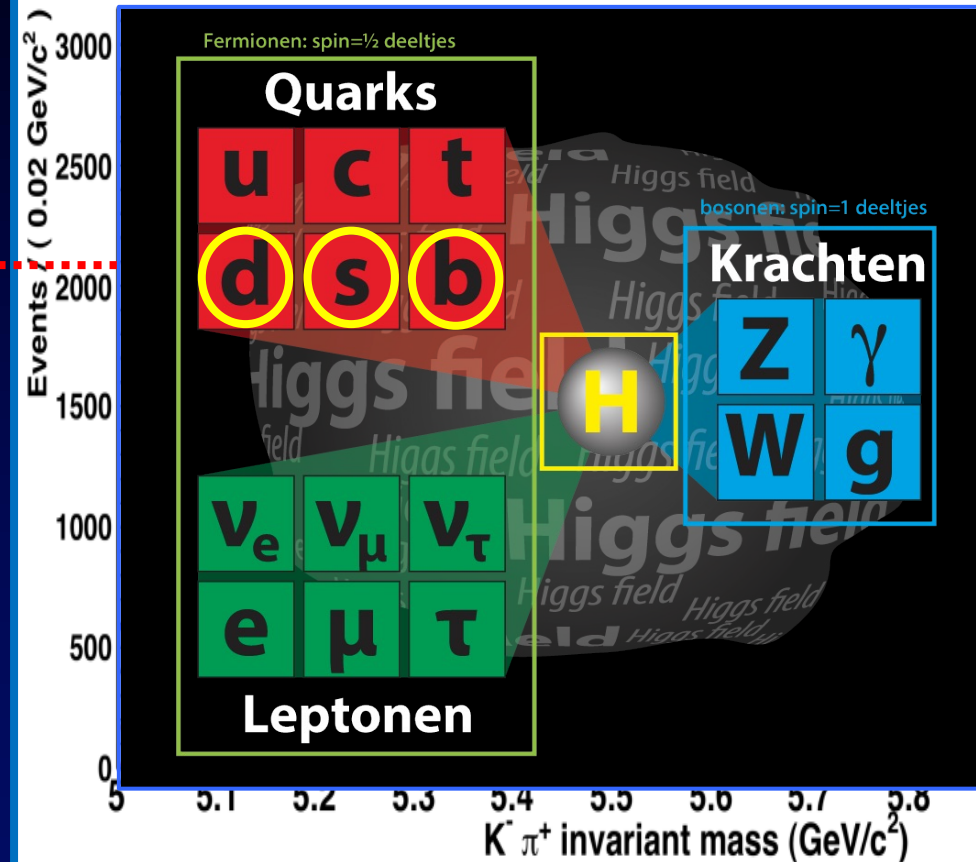
***anti-B* particle** decay into
a K^- and a π^+ particle

Matter process



The matter – antimatter
symmetry is broken

Antimatter process



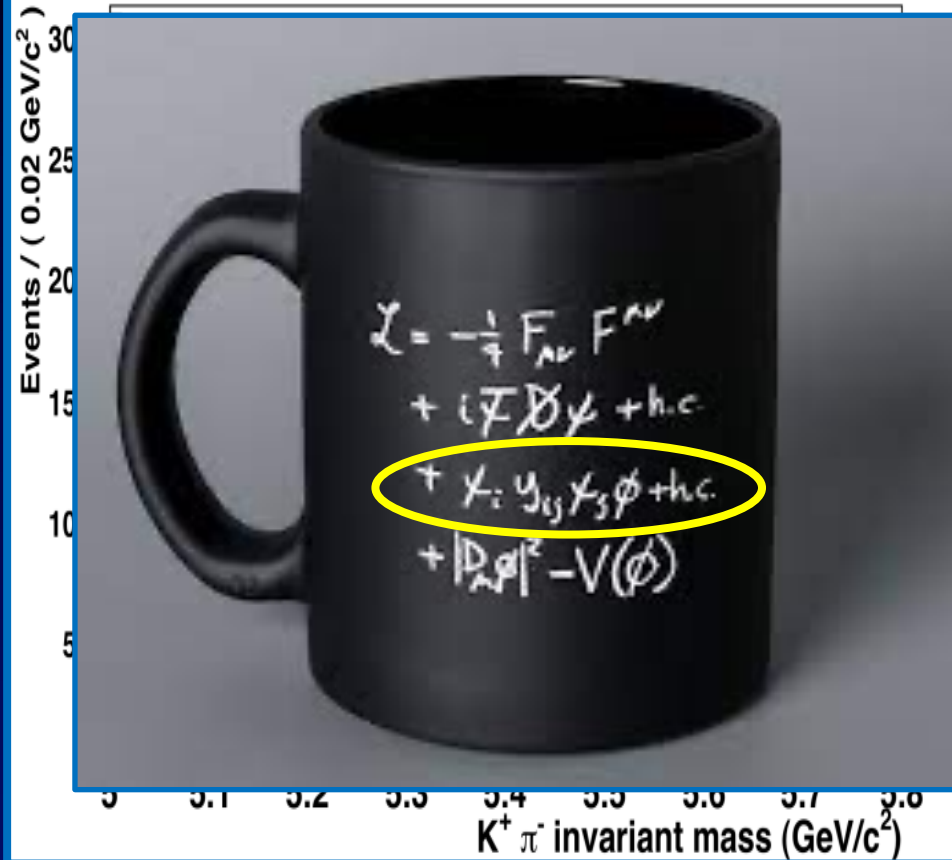
This ***only happens*** if there are at least
three generations of particles !!!

B-decay process: matter vs antimatter

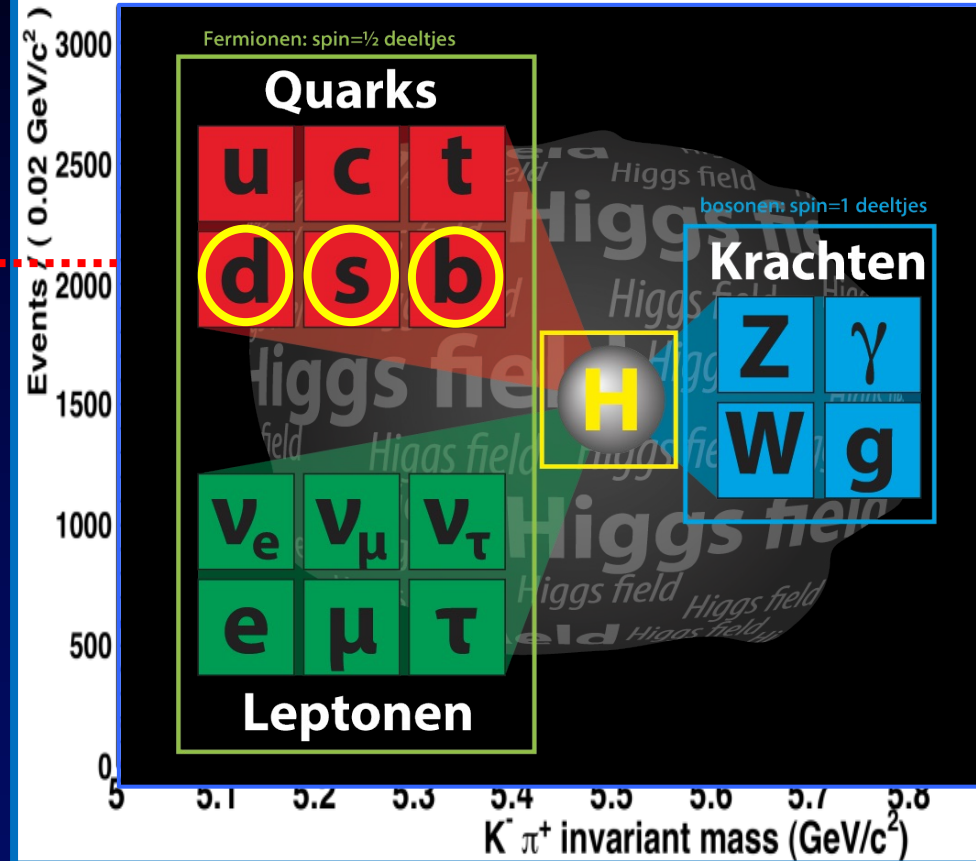
B particle decay into
a K^+ and a π^- particle

anti-B particle decay into
a K^- and a π^+ deeltje

Matter process



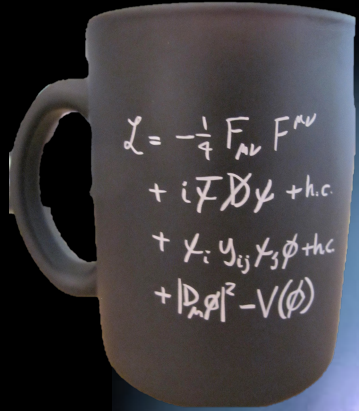
Antimatter process



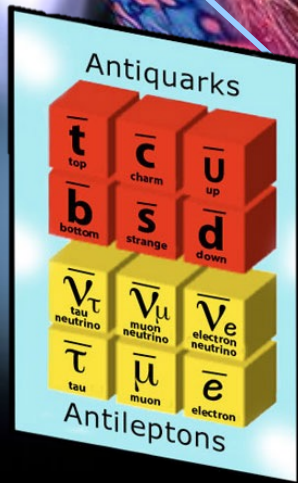
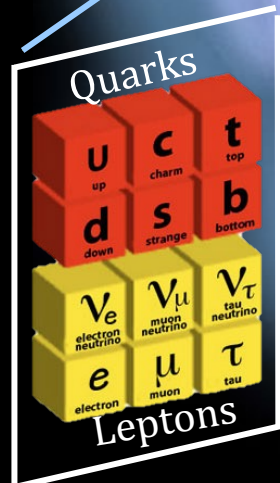
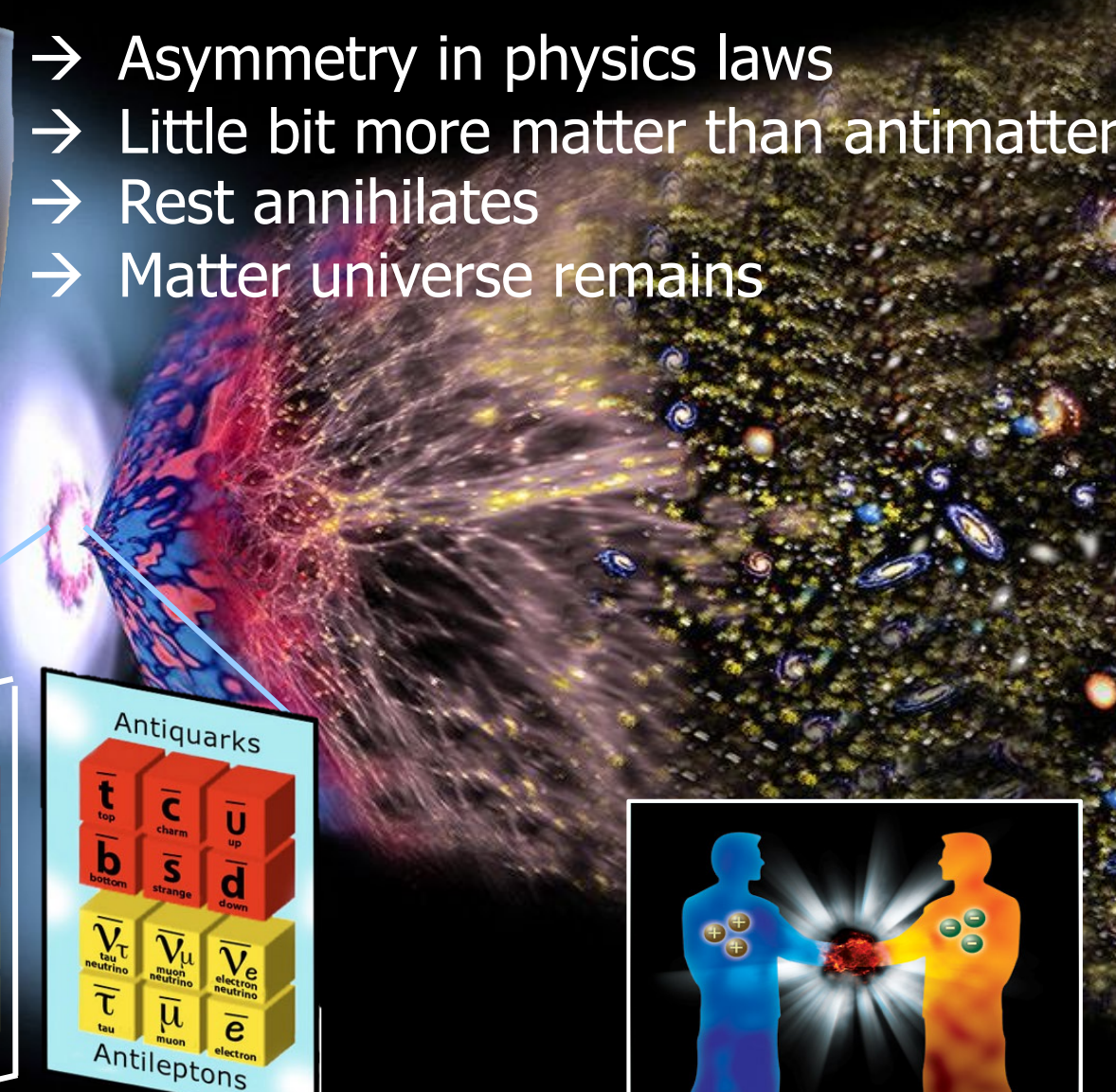
The matter – antimatter
symmetry is broken

This **only happens** if there are at least
three generations of particles !!!

Early Universe: What happened to antimatter?



- Asymmetry in physics laws
- Little bit more matter than antimatter
- Rest annihilates
- Matter universe remains

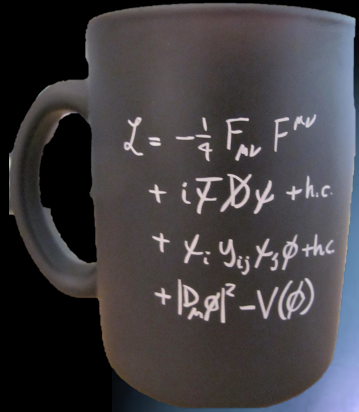


50.000001%

49.999999%

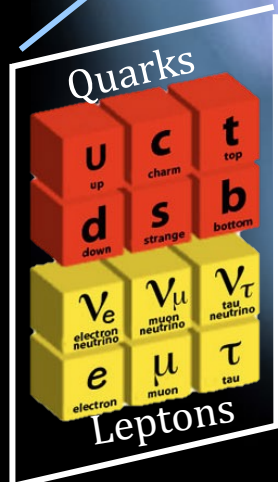


Early Universe: What happened to antimatter?

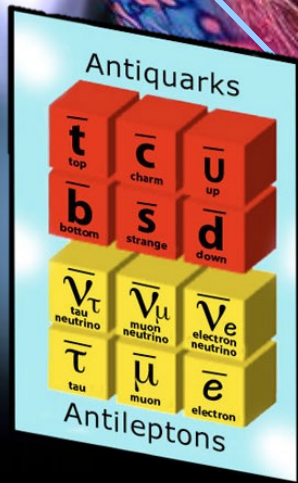


Why are there three identical copies of all particles?
→ *Is it the simplest universe that can exist?!*

However: it does not work!
Asymmetry is not large enough.
Explanation requires a new force!

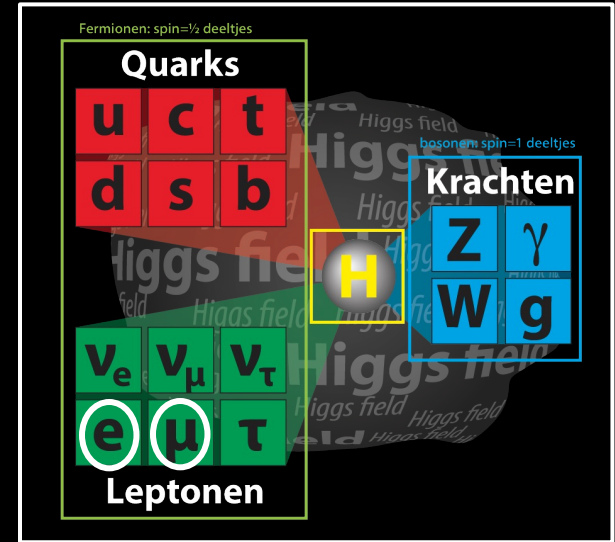
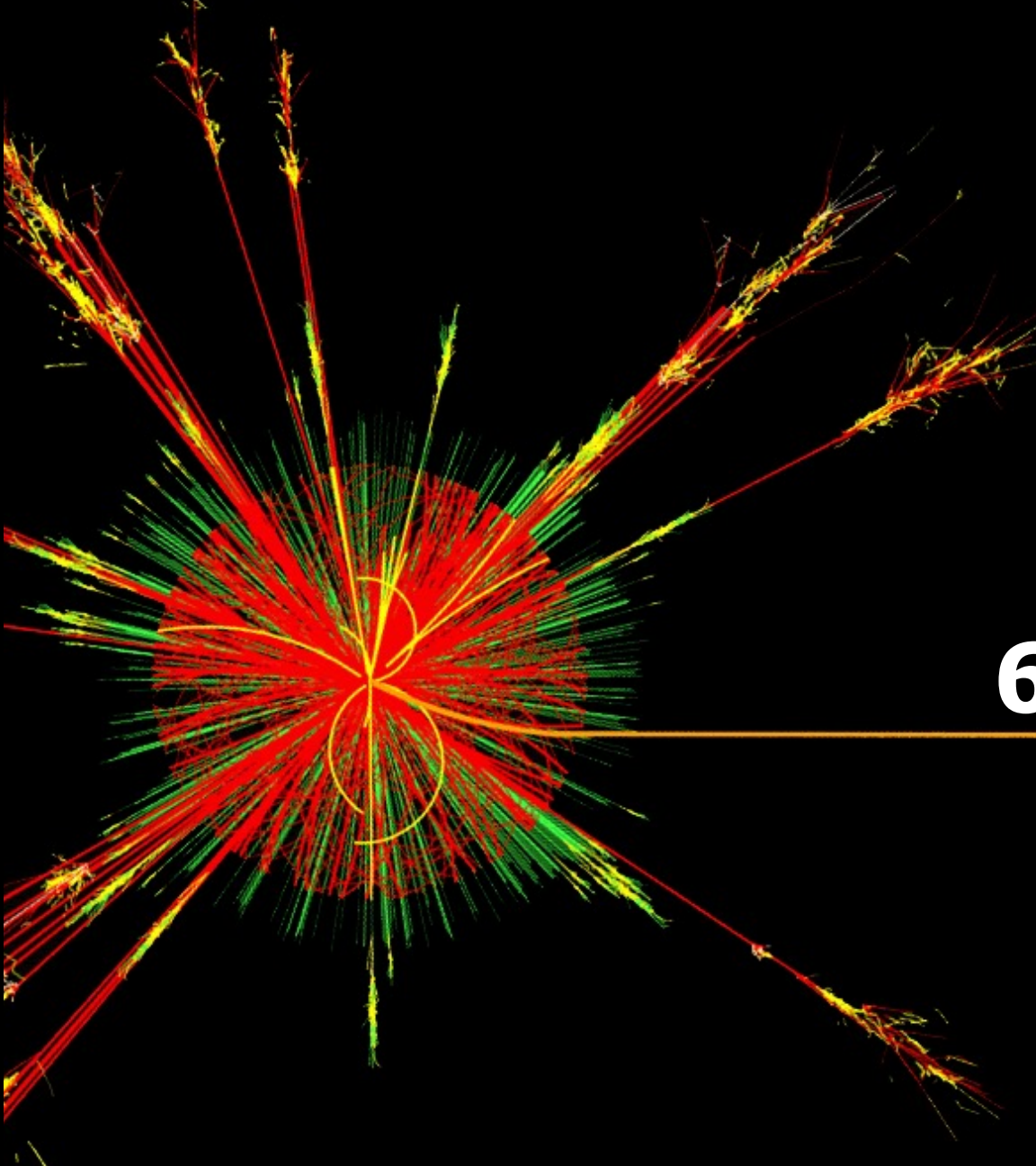


50.000001%

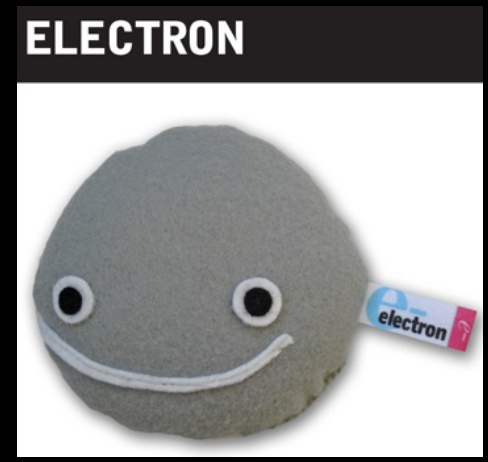


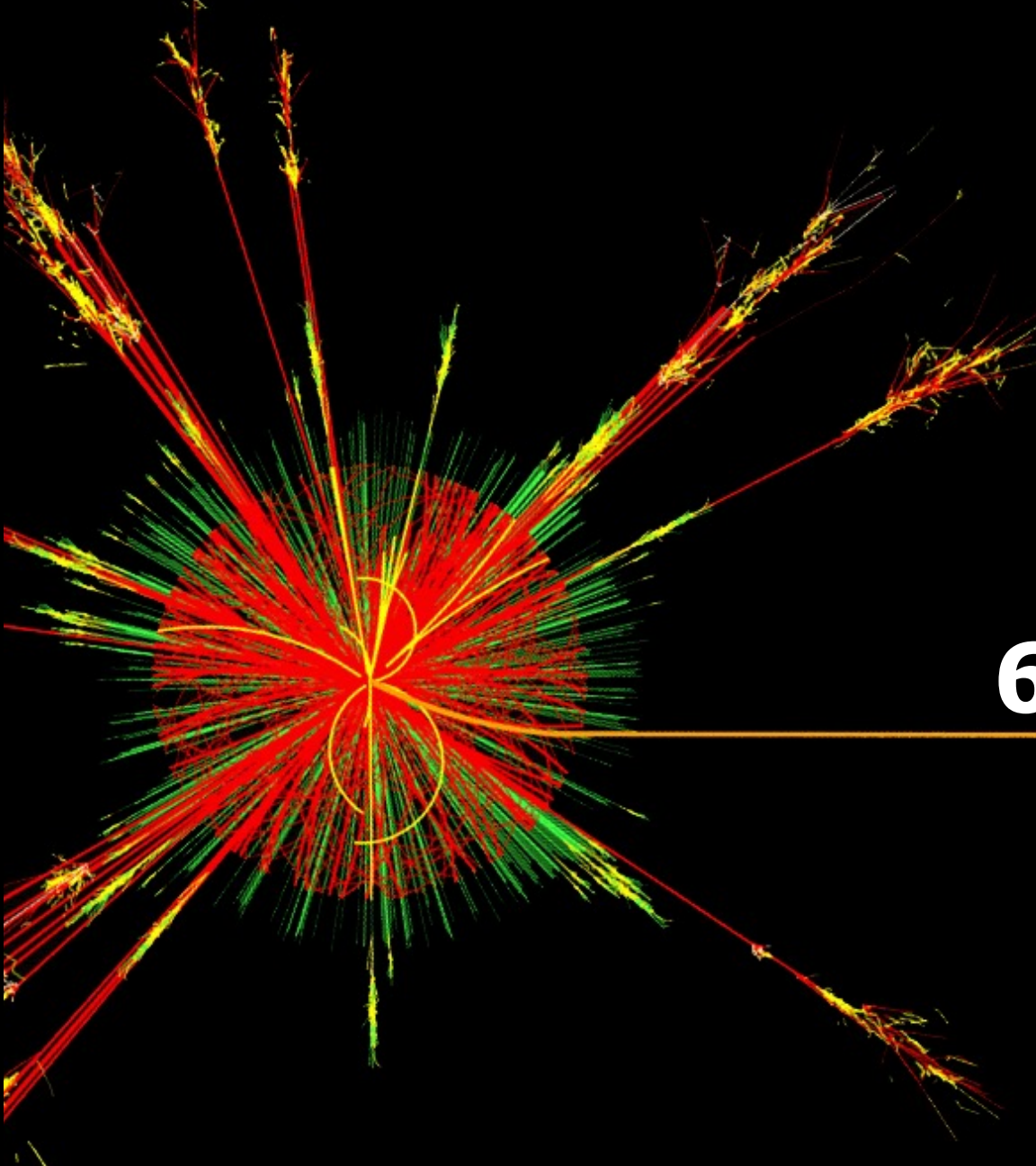
49.999999%



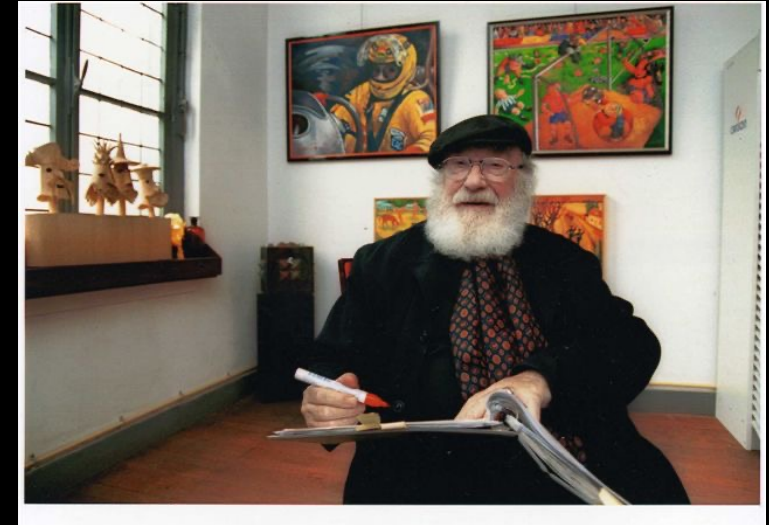


6: A new force of Nature?



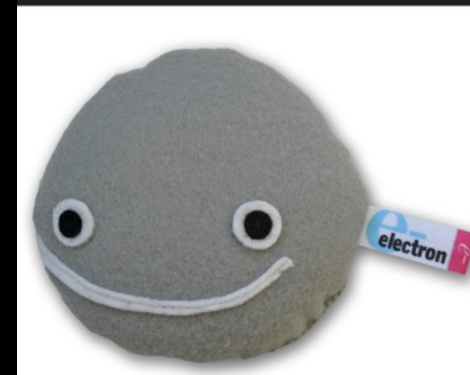


Pieke Dassen: art



6: A new force of Nature?

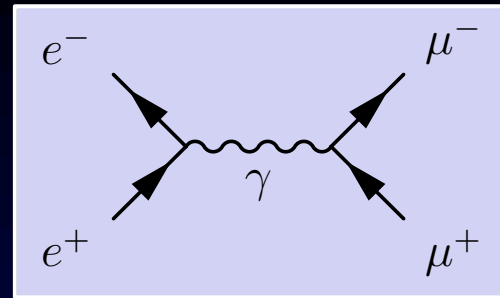
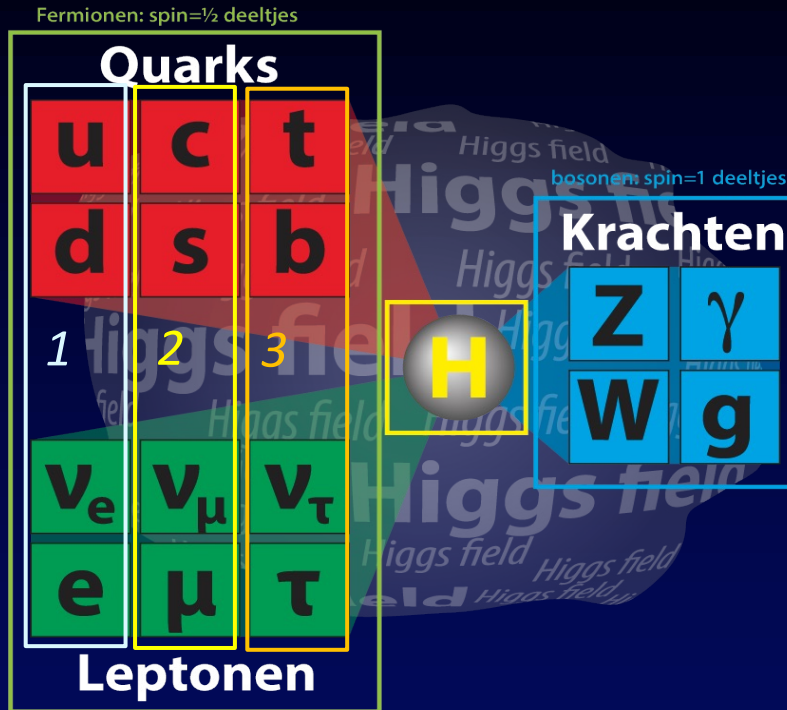
ELECTRON



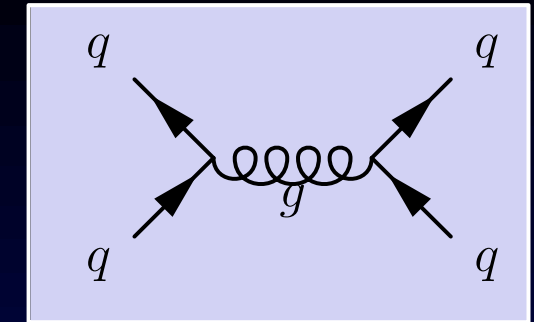
MUON



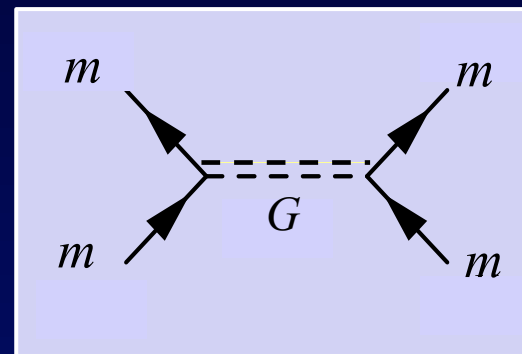
Standard Model: Universality of the Forces



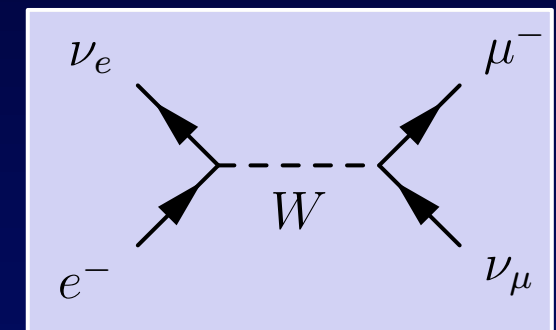
Elektromagnetism



Strong Nuclear Force



Gravity



Weak Nuclear Force

Forces are identical for particles of 1st, 2nd en 3rd generation.

➔ "Universality"

Fermionen: spin=1/2 deeltjes

Quarks

u	c	t
d	s	b

Higgs field

Krachten

Z	γ
W	g

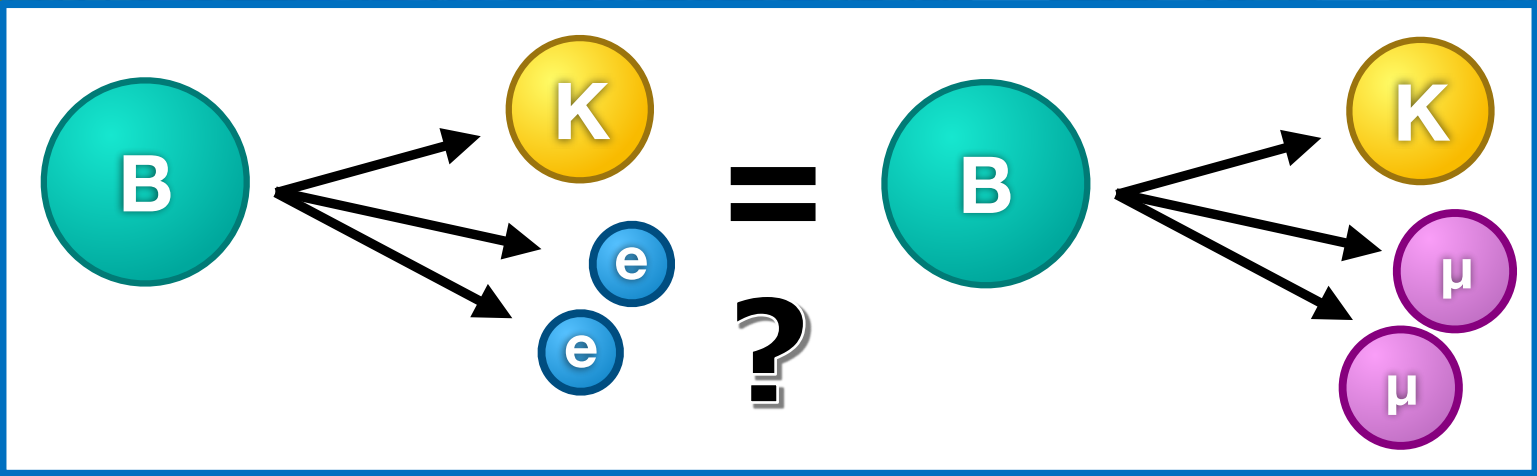
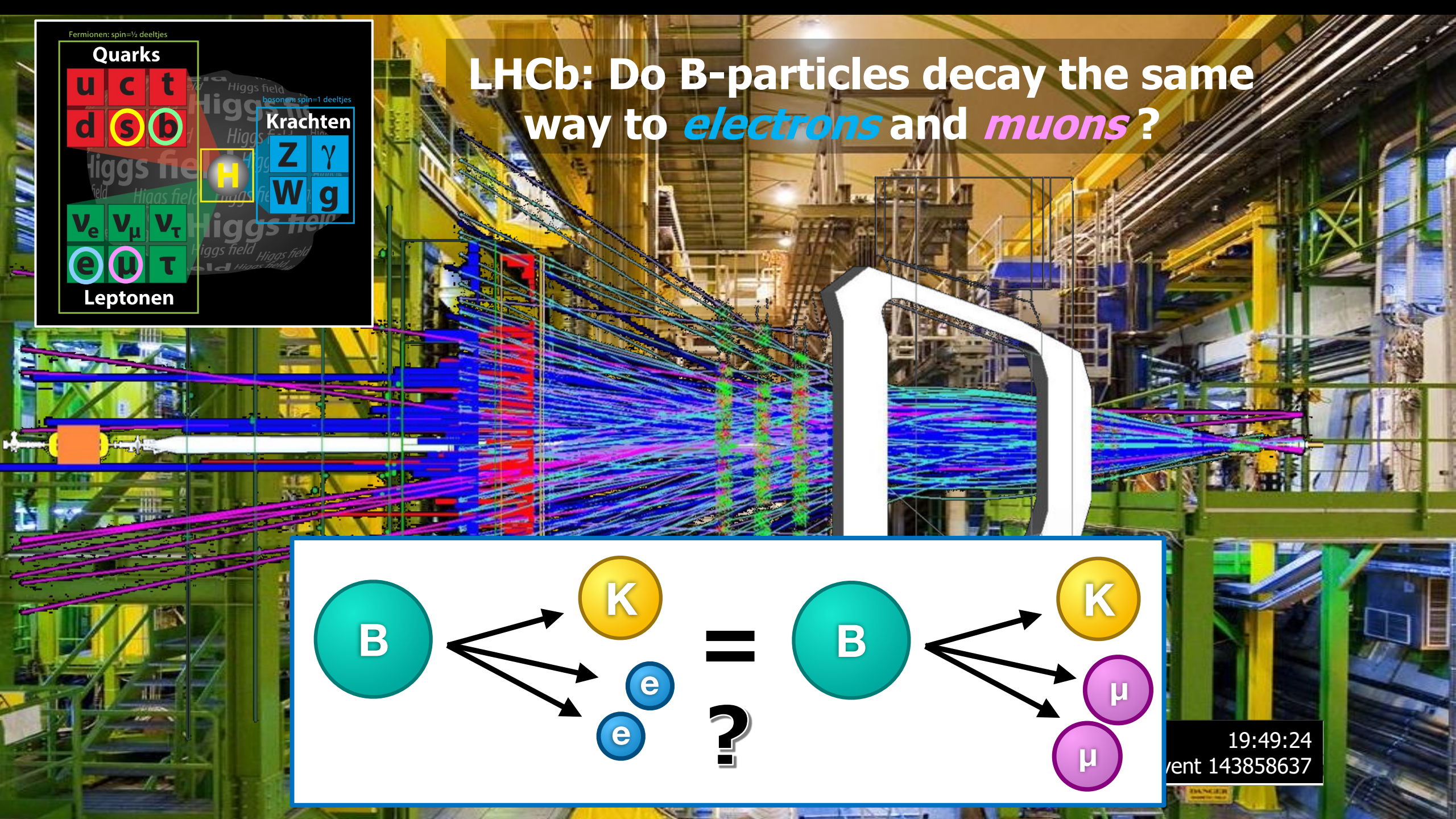
Higgs field

Leptonen

ν_e	ν_μ	ν_τ
e	μ	τ

Higgs field

LHCb: Do B-particles decay the same way to *electrons* and *muons*?



LHCb: Do B-particles decay the same way to *electrons* and *muons*?

Fermionen: spin=1/2 deeltjes

Quarks

u	c	t
d	s	b

Higgs field
bosonen: spin=1 deeltjes

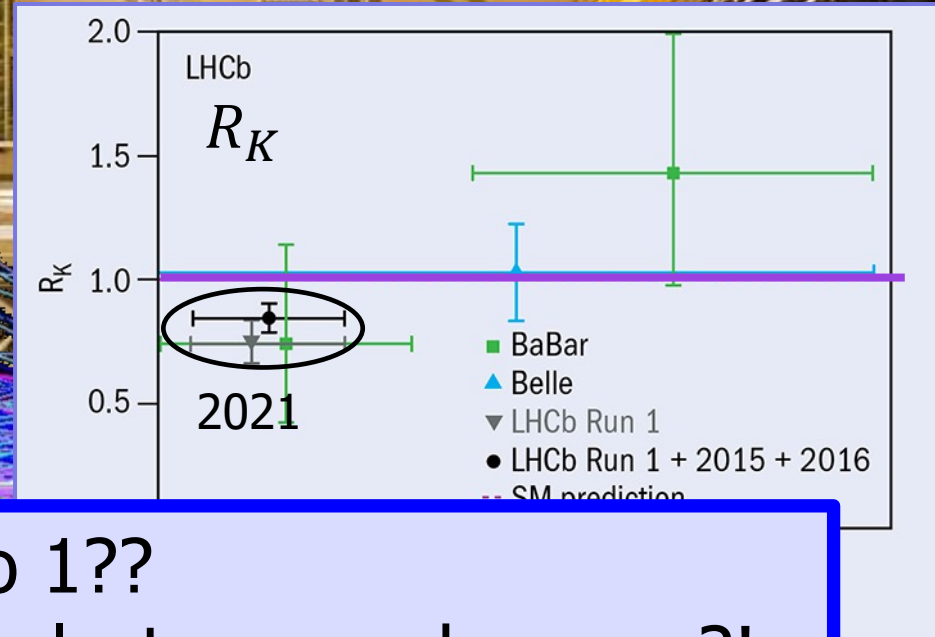
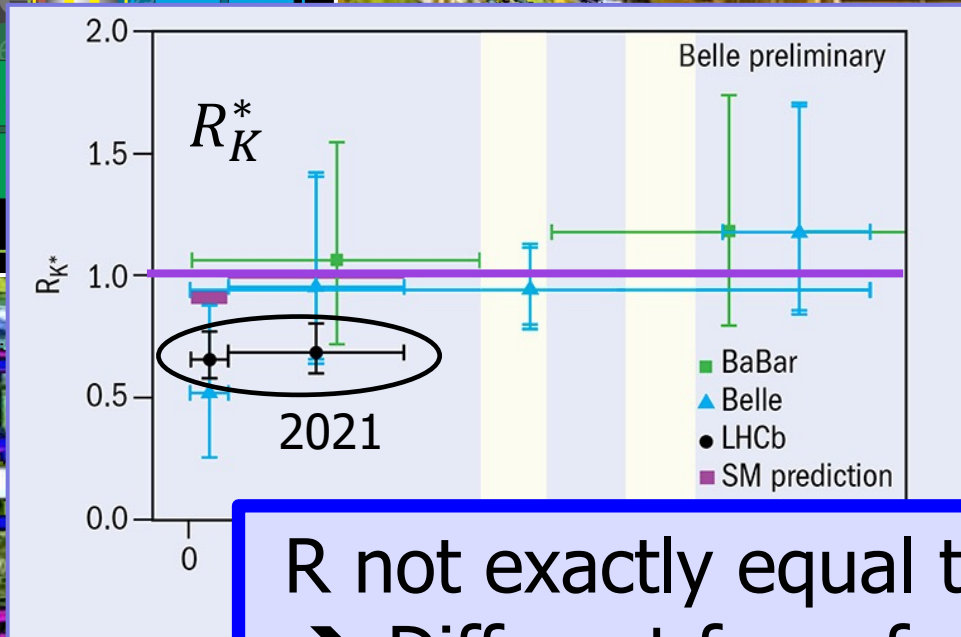
Krachten

Z	γ
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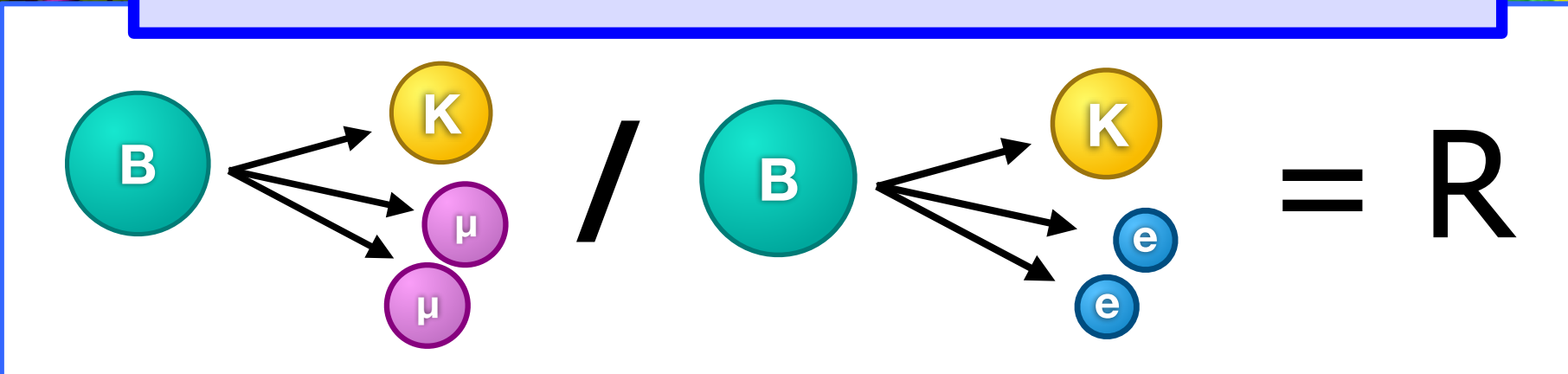
Higgs field

ν_e	ν_μ	ν_τ
e	μ	τ

Leptonen



R not exactly equal to 1??
 → Different force for electrons and muons?!



23 March 2021: Headlines... "cautious excitement"

Menu **nrc**

Voorzichtige opwinding onder fysici: deeltje gedraagt zich vreemd

Deeltjesfysica Het muon, het zware broertje van het elektron, gedraagt zich niet altijd als verwacht. Dat kan duiden op een barstje in het standaardmodel.

Margriet van der Heijden 23 maart 2021 Leestijd 3 minuten



Cern experiment hints at new force of nature - Guardian

Experts reveal 'cautious excitement' over unstable particles that fail to decay as standard model suggests



Are we discovering a new force for muon particles?!

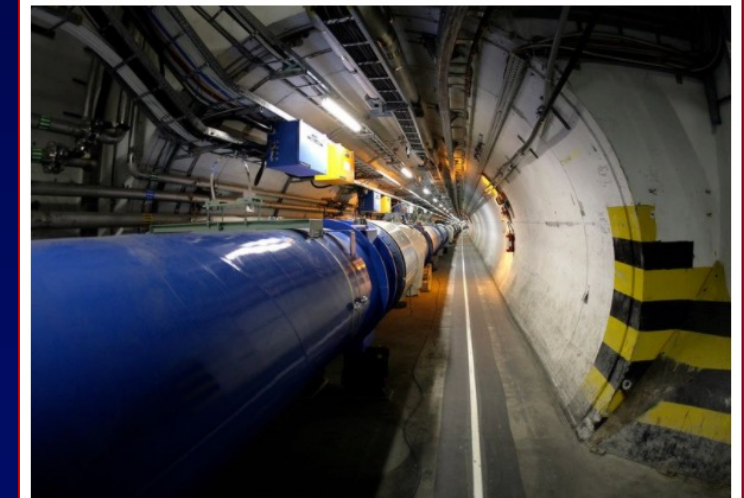
de Volkskrant

NIEUWS

Natuurkundigen van Cern vinden aanwijzing die ons begrip van de werkelijkheid op zijn kop kan zetten

Een gloednieuw deeltje, een nog onbekende natuurkracht... fysici bij onderzoeksinstituut Cern zien ons begrip van de werkelijkheid op z'n kop kunnen zetten. 'Dit is een belangrijke ontdekking voor het onderzoek doe.'

George van Hal 23 maart 2021, 9:00



De tunnel van deeltjesversneller LHC bij Cern, Genève. In de blauwe buis zwiepen deeltjes met bijna de lichtsnelheid rond tot ze op elkaar knallen. Tussen de brokstukken van die botsing zoeken fysici naar aanwijzingen voor hoe de wereld op het kleinste niveau werkt. Beeld AP



TELEGRAAF.NL

Experts zijn nieuwe natuurkracht op het spoor: 'We trilden helemaal'

Na de vondst van het Higgs-deeltje, negen jaar geleden, klinken er nu opnieuw opgetogen ...

NEWS / LIFE

CERN data on 'beauty quarks' behaviour may rewrite physics as we know it

24 MAR 2021

Beauty quarks or B mesons particles are not decaying as they should and while the findings may warrant "cautious excitement", more research needs to be done, scientists say.



FILE PHOTO: A view of the Large Hadron Collider at CERN, near Geneva, Switzerland. (CERN)

Twee weken later in Fermilab ... muon magnetic moment?!

Menu **nrc**

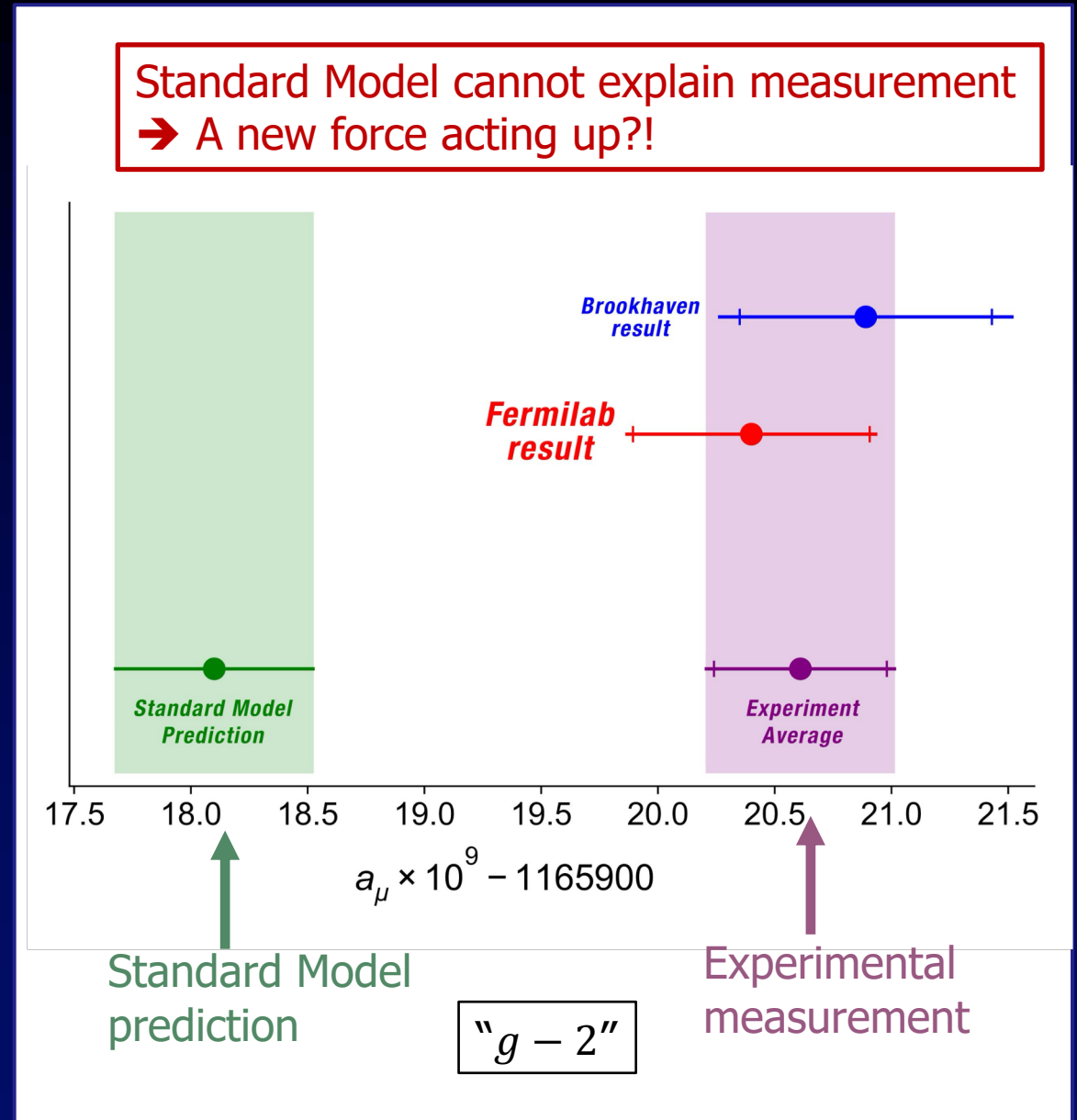
Opnieuw barstje in standaardmodel van deeltjesfysica

Natuurkunde Gaat het standaardmodel van de deeltjesfysica breken? Resultaten uit een Amerikaans experiment leiden tot opwinding.

Dorine Schenk 7 april 2021 Leestijd 3 minuten



De Muon g-2-ring in het Fermilab in de buurt van Chicago. Het experiment wordt uitgevoerd bij een temperatuur van -268 graden Celsius.
Foto Reidar Hahn/Fermilab



Fermionen: spin=1/2 deeltjes

Quarks

u	c	t
d	s	b

Krachten

Z	γ
W	g

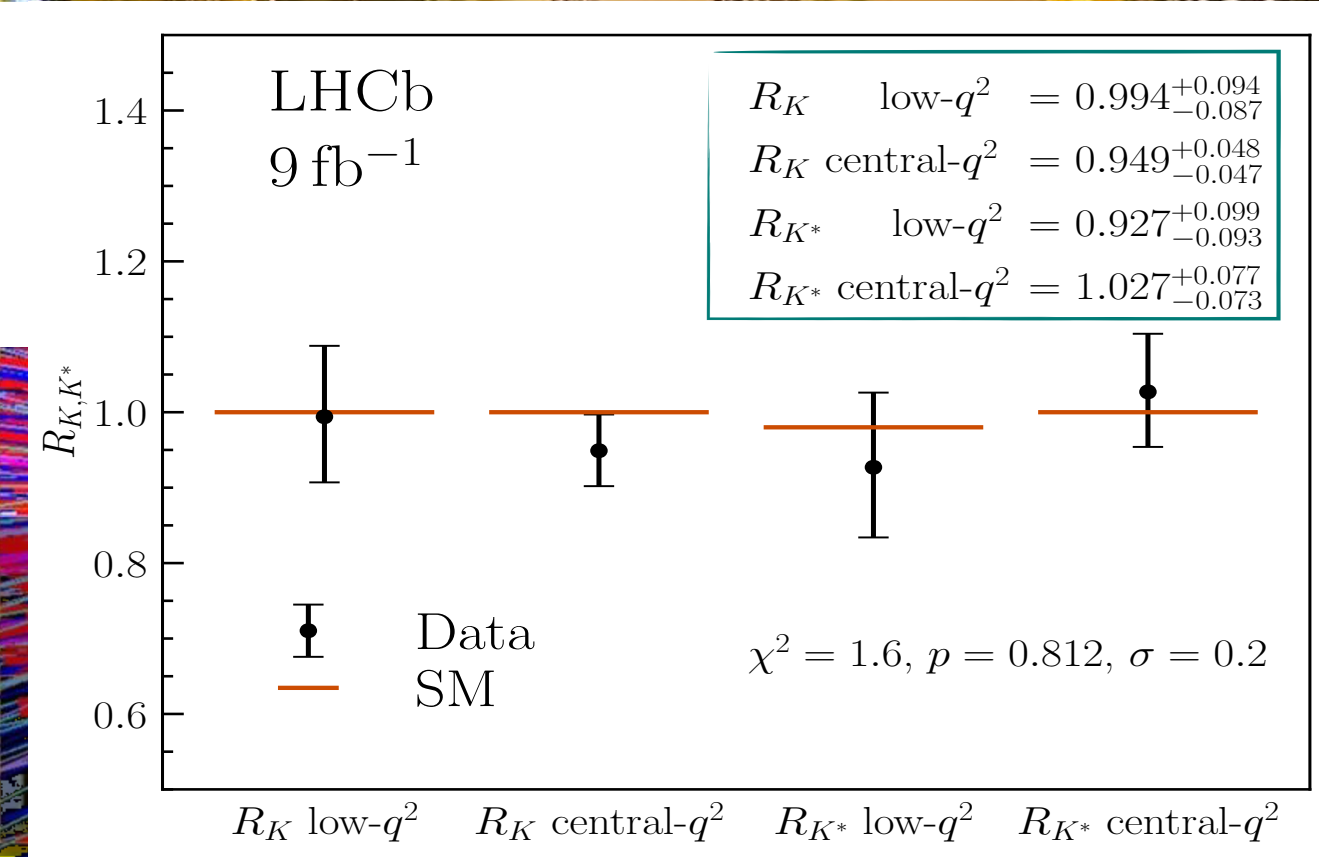
Leptonen

ν_e	ν_μ	ν_τ
e	μ	τ

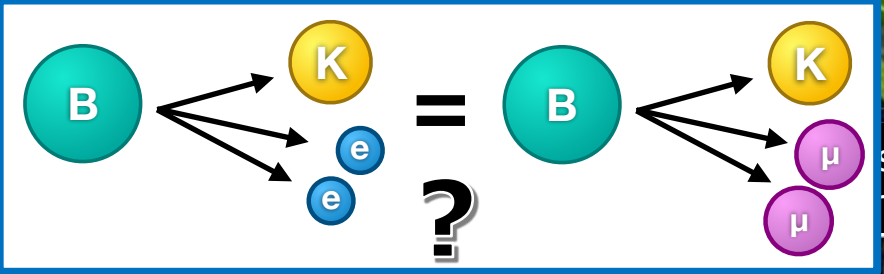
Higgs field

H

LHCb: Do B-particles decay the same way to *electrons* and *muons*?



December 2022:
new measurement
for *electrons*...



Fermionen: spin=1/2 deeltjes

Quarks

u	c	t
d	s	b

Higgs field

Krachten

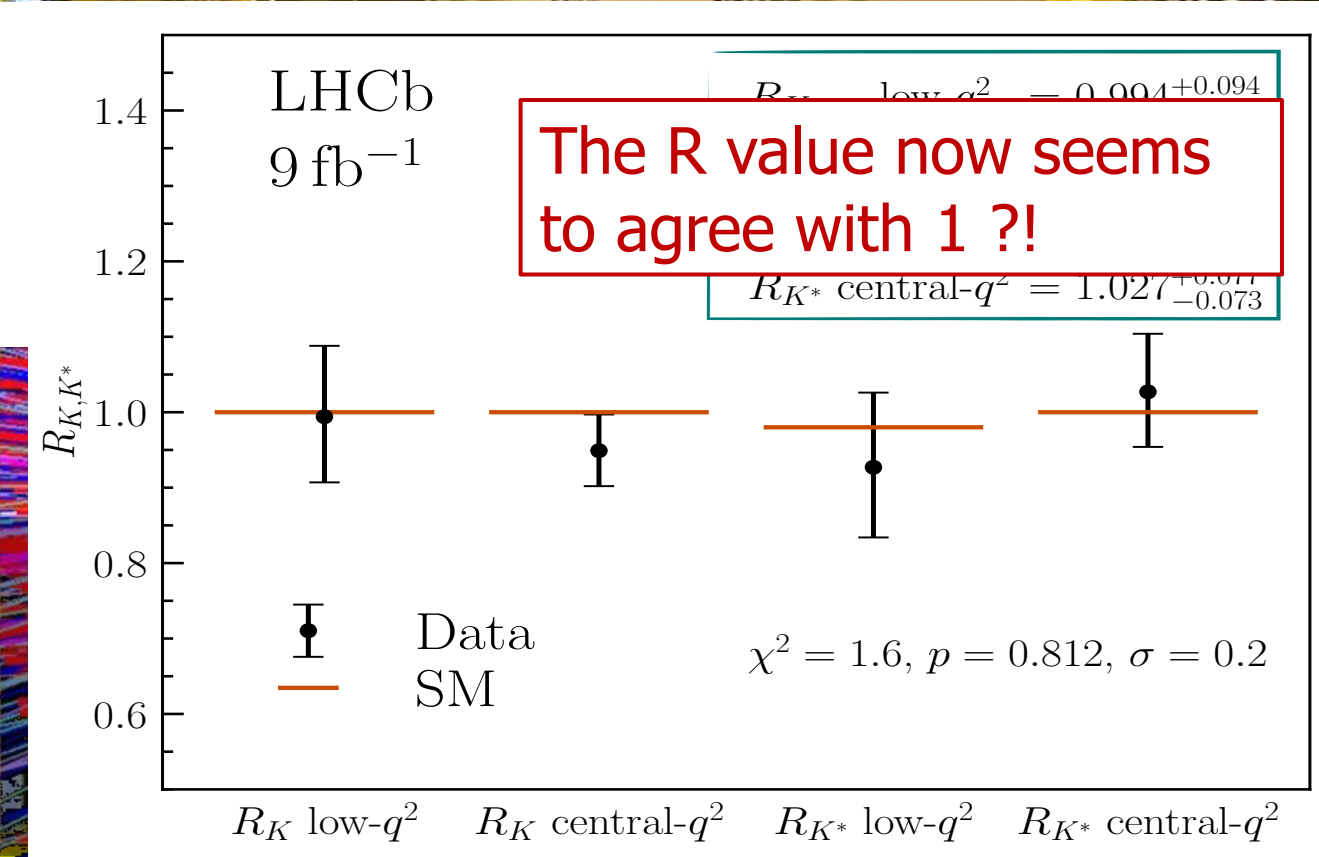
Z	γ
W	g

Higgs field

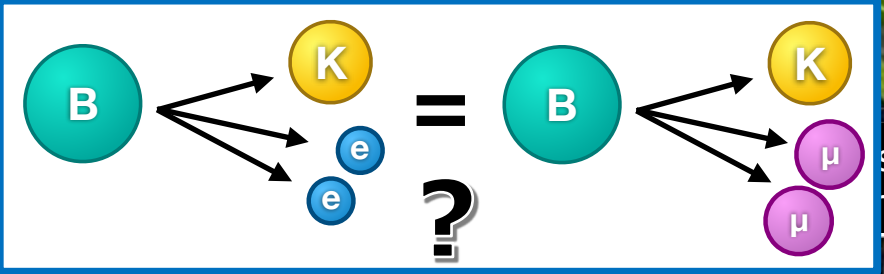
Leptonen

ν_e	ν_μ	ν_τ
e	μ	τ

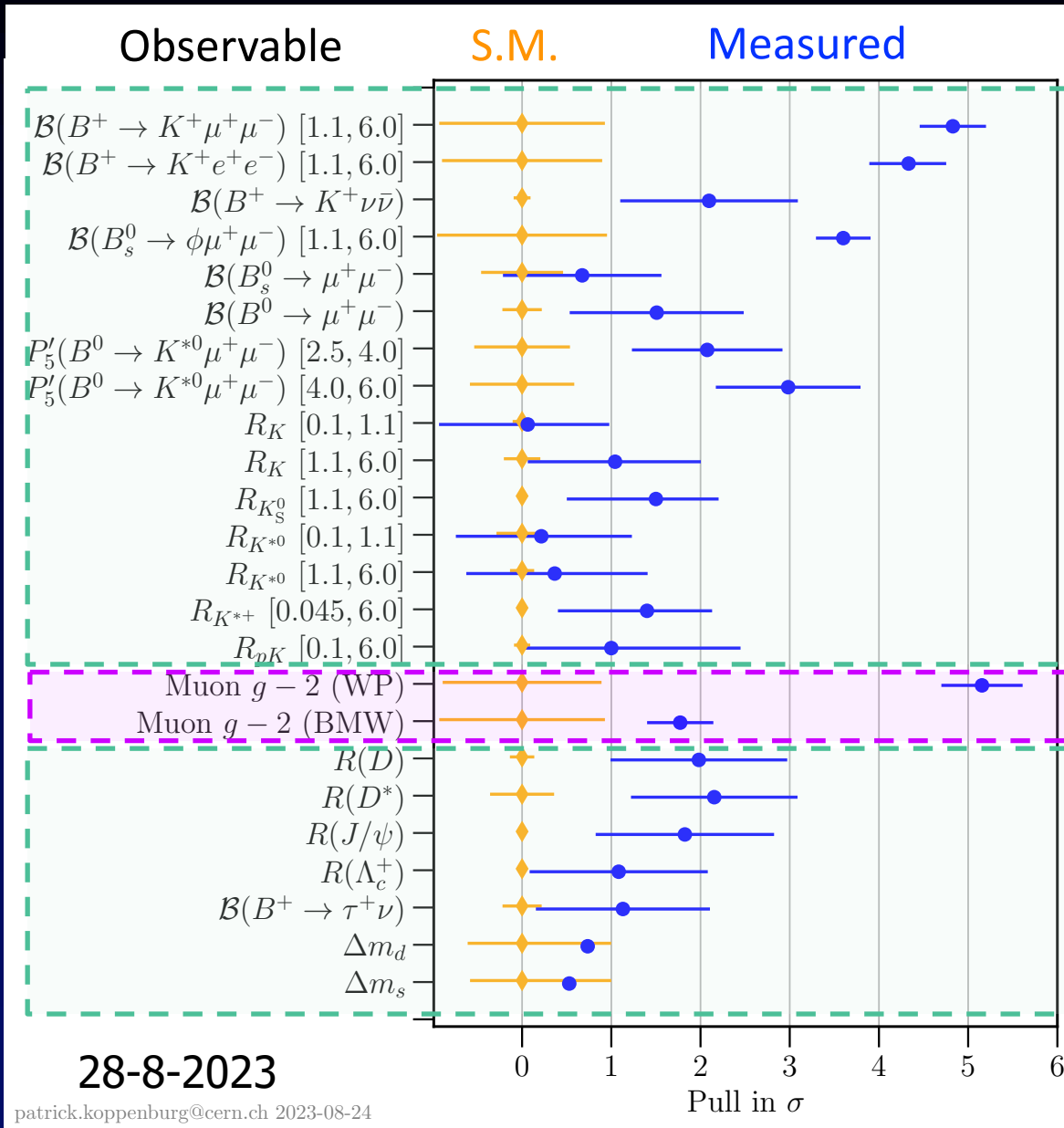
LHCb: Do B-particles decay the same way to *electrons* and *muons*?



December 2022:
new measurement
for *electrons*...



But for muons more and more measurements disagree!



LHCb results

Fermilab g-2 result

The puzzle deepens further!

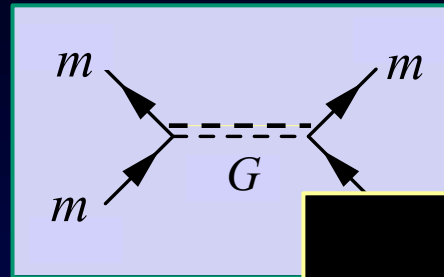
28-8-2023

Four(?) fundamental forces of nature

Gravity:

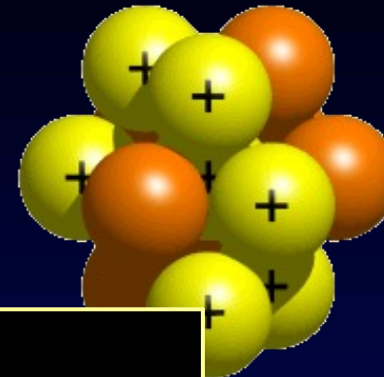


Quantum
Graviton exchange?

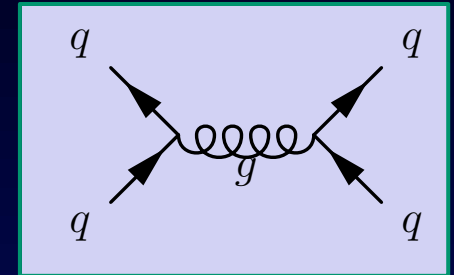


Acts on particles with mass

Strong nuclear force:



Quantum
gluon exchange:



quarks

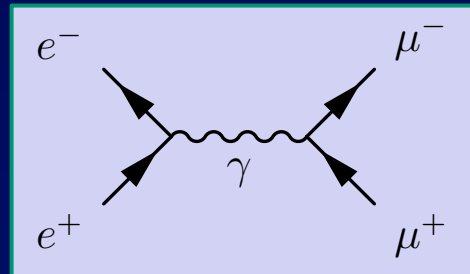
+ ????

Fifth force?

Electromagnetism:

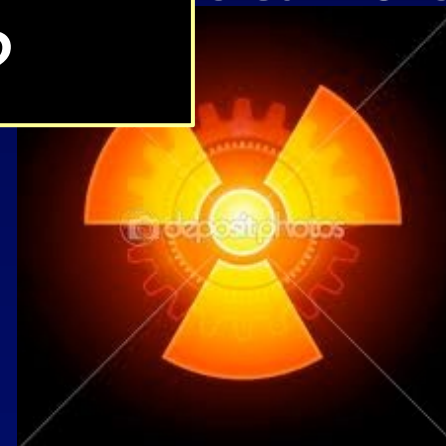


Quantum
photon exchange

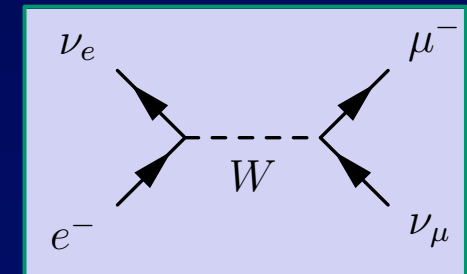


Acts on all charged particles

Weak nuclear force:



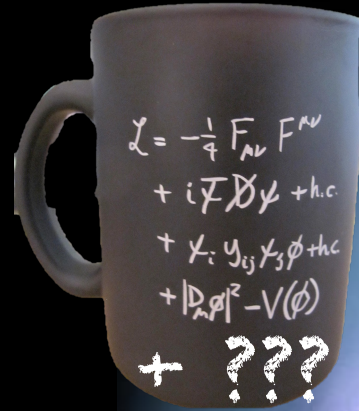
Quantum
W, Z exchange:



Acts on all particles

How did antimatter disappear in the early universe?

Why is there something rather than nothing?



Through a fifth force during the Big Bang...?

Quarks

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

Leptons

ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino
e electron	μ muon	τ tau

50.000001%

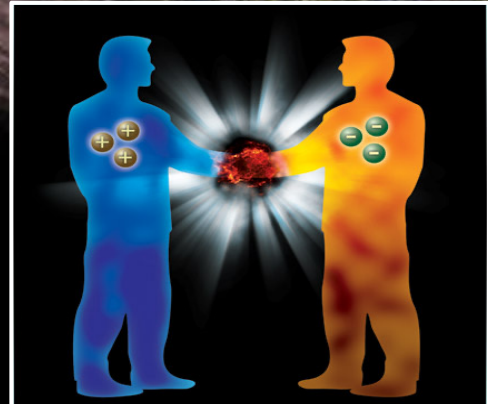
Antiquarks

\bar{t} top	\bar{c} charm	\bar{u} up
\bar{b} bottom	\bar{s} strange	\bar{d} down

Antileptons

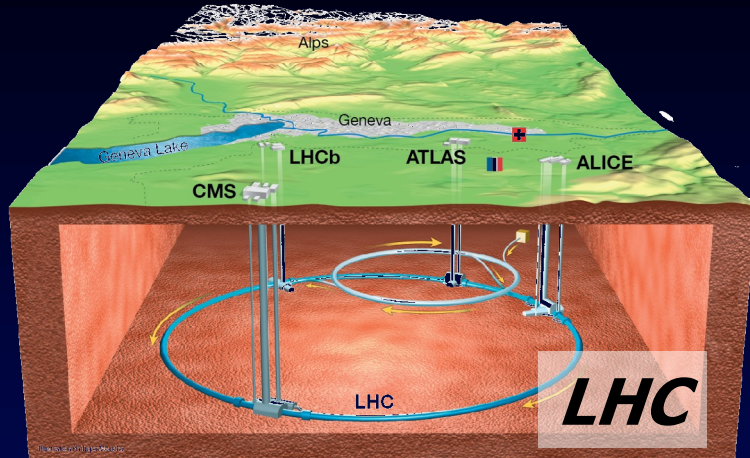
$\bar{\nu}_\tau$ tau neutrino	$\bar{\nu}_\mu$ muon neutrino	$\bar{\nu}_e$ electron neutrino
$\bar{\tau}$ tau	$\bar{\mu}$ muon	\bar{e} electron

49.999999%

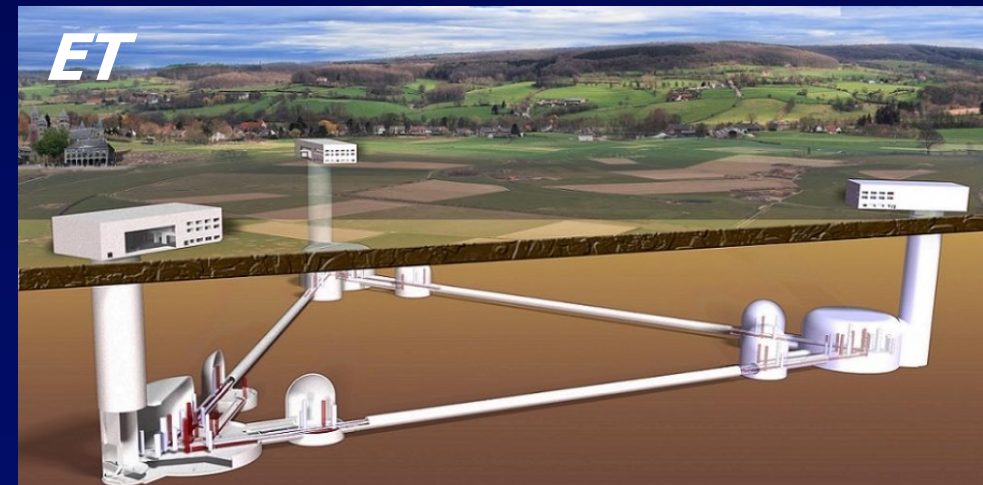
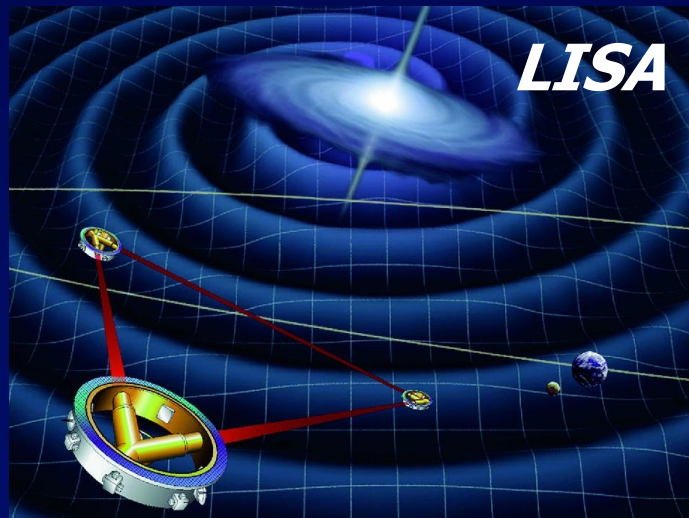


Future: "Circles and Triangles"

Particle Colliders: simulate physics of the Big Bang ...

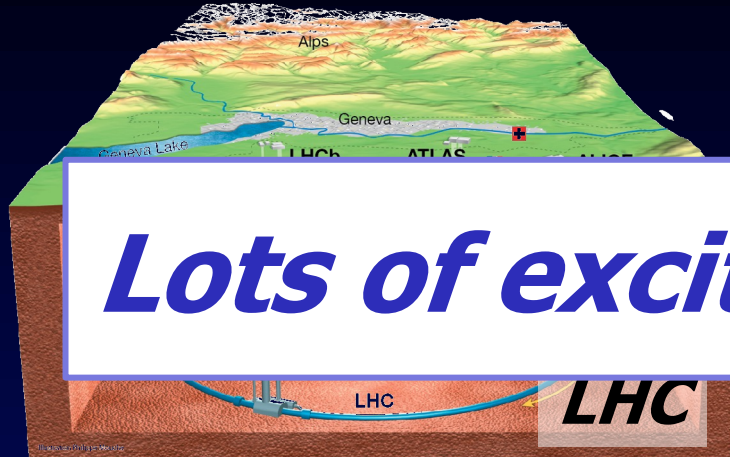


Gravitation-detectors: listening to the Big Bang...



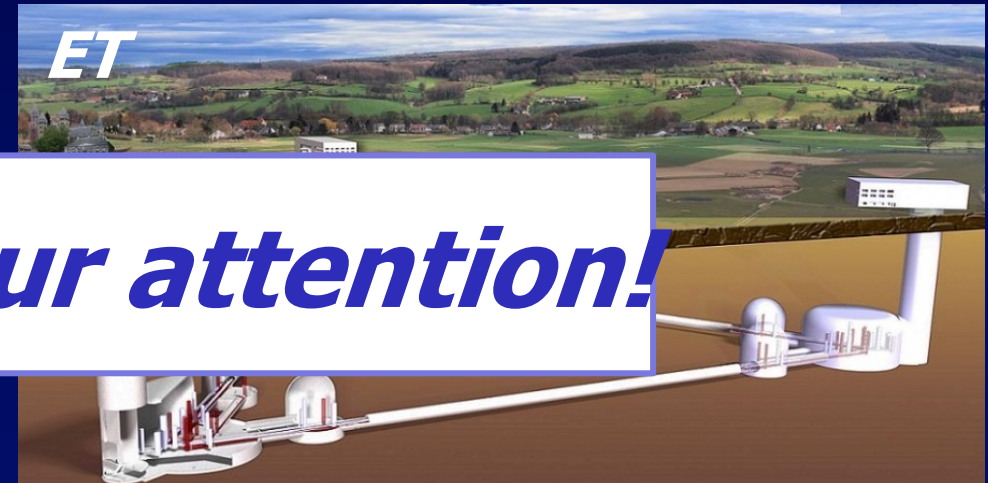
Future: "Circles and Triangles"

Particle Colliders: simulating physics of the Big Bang ...



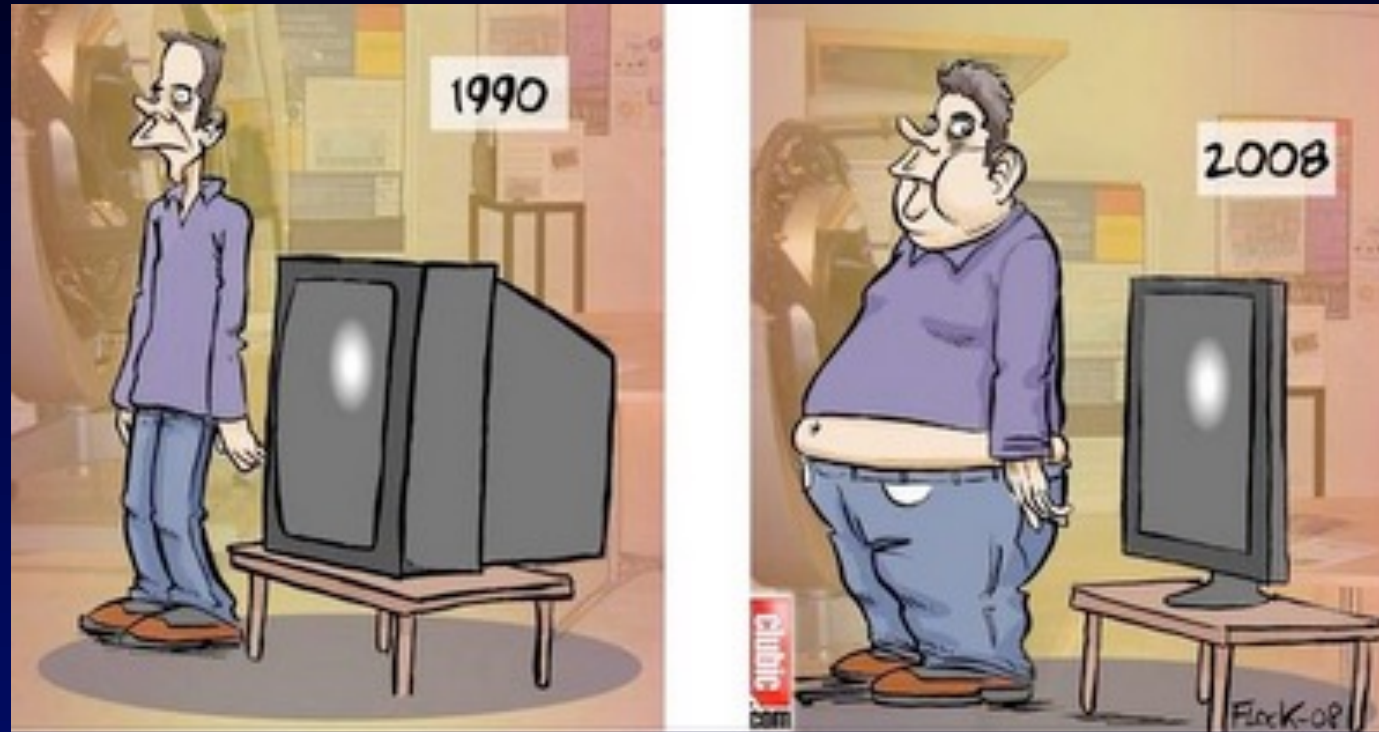
Lots of exciting research ongoing

Gravitation-detectors: listening to the Big Bang...



Thanks for your attention!

Applications of Science





* NOU..... IK GA. *

Quantum Velden Theorie

Deeltjes en Krachten zijn "**velden**"

denk aan quantum golffuncties: $\psi(x,t)$

De fundamentele grootheid is de **Lagrangiaan**
(Klassieke mechanica: Bewegingsvergelijkingen volgen)

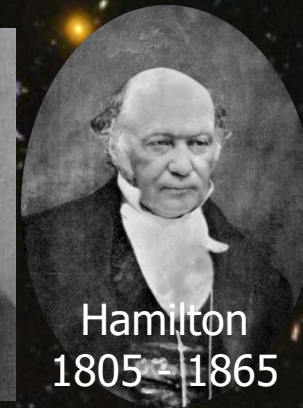
$$\mathcal{L} = T - V$$

T = Kinetische energie

V = Potentiele energie



Lagrange
1736 - 1813



Hamilton
1805 - 1865

Standaardmodel van Quantum Velden Theorie (Recept voor experts):

- Schrijf de Lagrangiaan voor alle bestaande deeltjes en krachten (Elektromagnetisme + Zwakke kracht + Sterke kracht, vergeet Zwaartekracht)
- Eis dat de Lagrangiaan een aantal wiskundige symmetrieën heeft.
- De rest volgt vanzelf: het gedrag van alle deeltjes en hun interacties!

Het Standaard Model van elementaire deeltjes

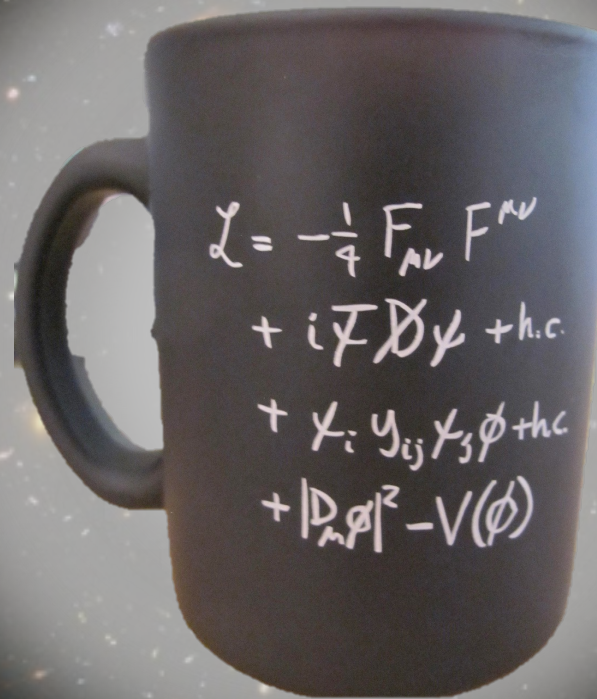
Werkt bij zeer kleine
afstanden
(Kwantummechanica)

(en tegelijkertijd)

Werkt bij zeer hoge
energie (Speciale
Relativiteitstheorie)

Beschrijft alle
natuurkrachten
**behalve
zwaartekracht**

Onduidelijk theorie
ook voor Big Bang
natuurkunde geldig is



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

Beschrijft alle
bekende materie
**(behalve
donkere)**

17 onvoorspelde parameters
(dus niet heel erg predictive?)

Beschrijft maar verklaart niet tal
van opvallende structuren in de natuurwetten

Donkere Materie



Zichtbare "baryonische" materie



waterstof (H)

helium (He)

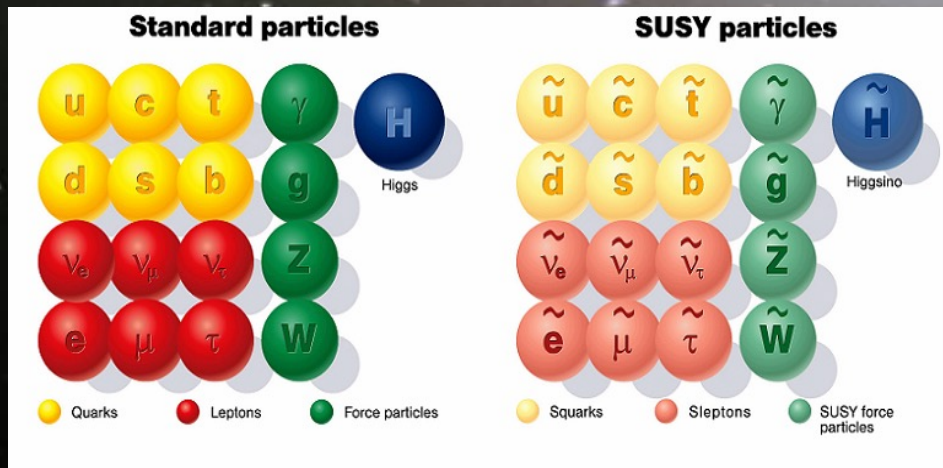
Spiraalarm rotatie en gravitationele lenzen



Donkere Materie

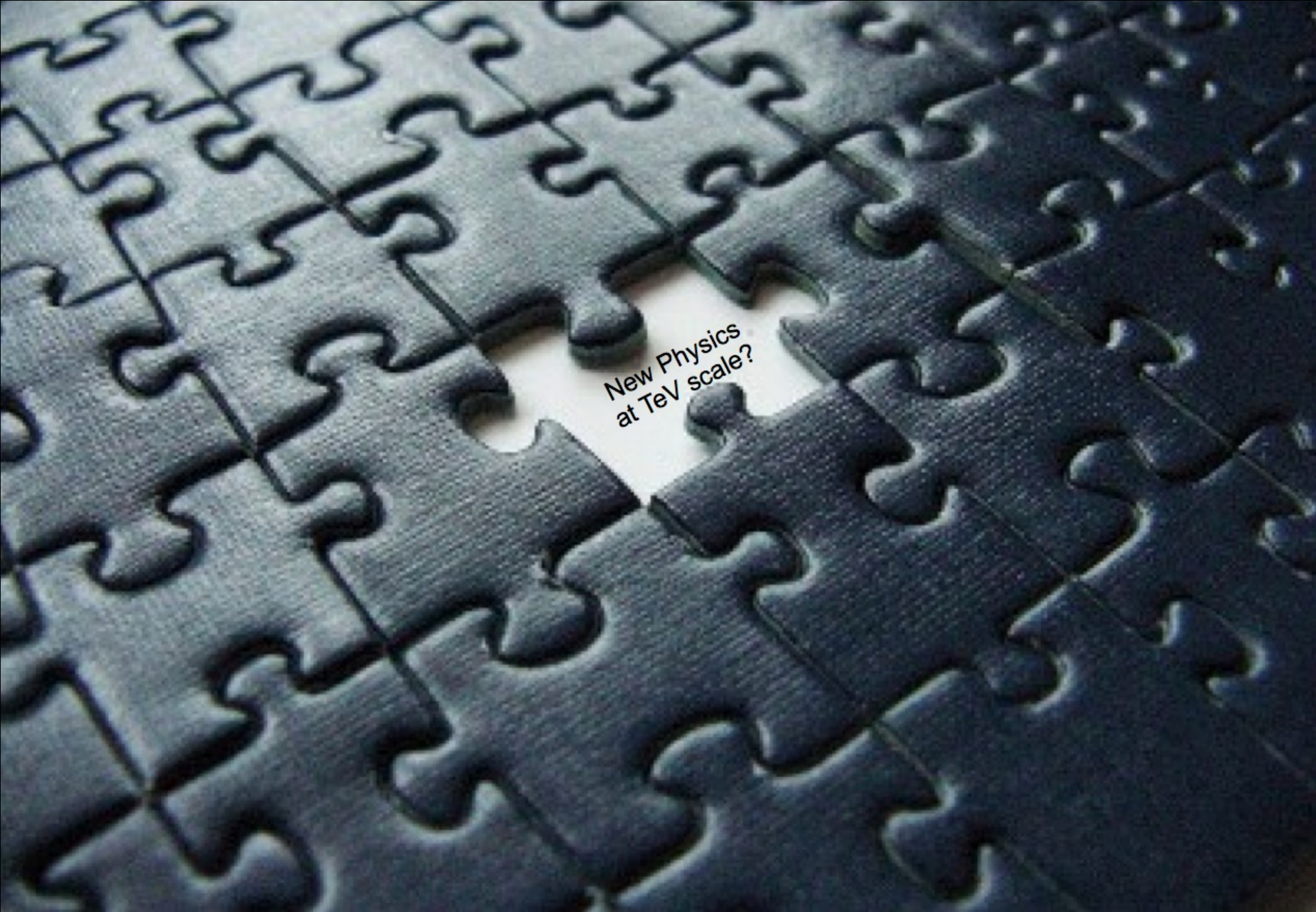
He H

donkere energie & donkere materie





“The Dark Side rules the Universe”



New Physics
at TeV scale?

