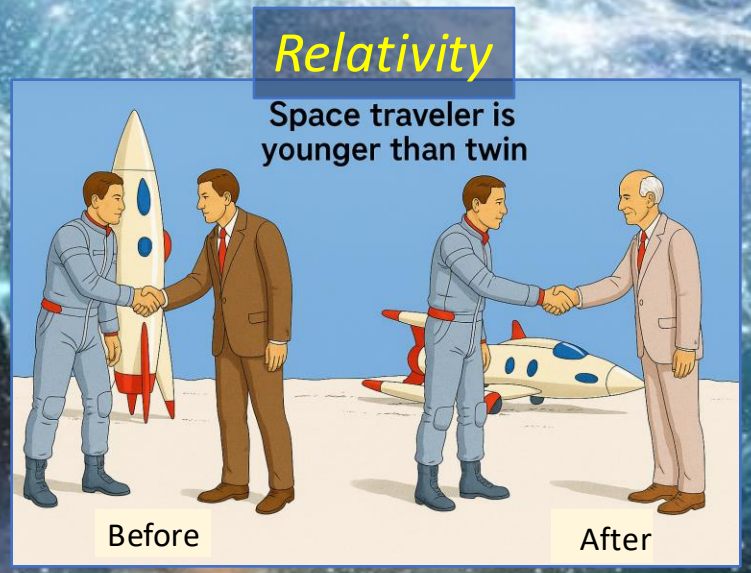
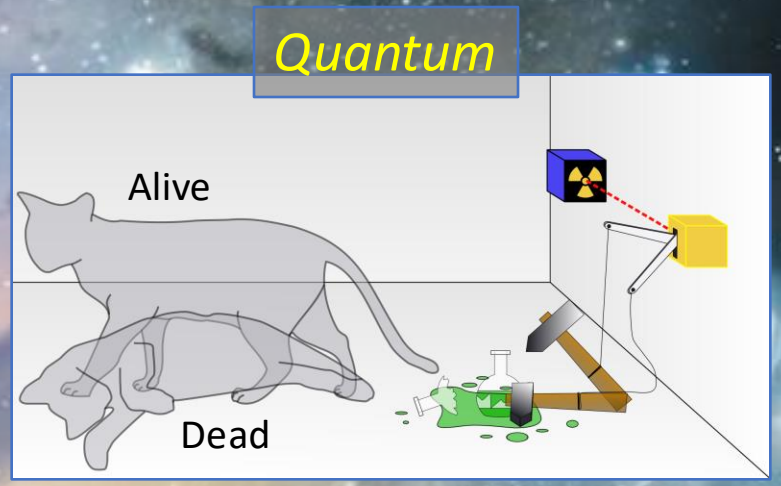
The Relativistic Quantum World

A lecture series on
Relativity Theory and Quantum Mechanics





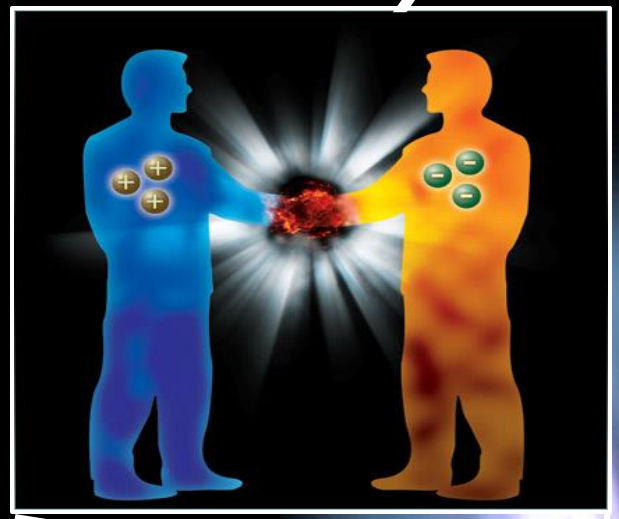
Marcel Merk
Studium Generale Maastricht
Sep 10 – Oct 8, 2025

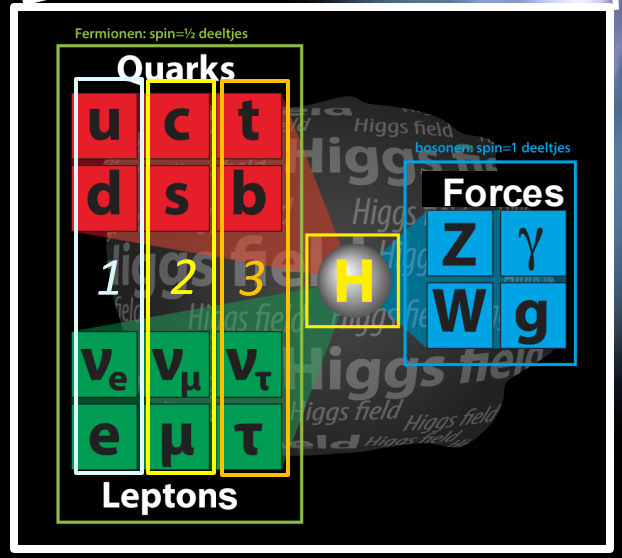
The Relativistic Quantum World

Relativity	Sep. 10:	Lecture 1: The Principle of Relativity and the Speed of Light Lecture 2: Time Dilation and Lorentz Contraction
	Sep. 17:	Lecture 3: The Lorentz Transformation and Paradoxes Lecture 4: General Relativity and Gravitational Waves
Quantum Mechanics	Sep. 24:	Lecture 5: The Early Quantum Theory Lecture 6: Feynman's Double Slit Experiment
	Oct. 1 :	Lecture 7: Wheeler's Delayed Choice and Schrodinger's Cat Lecture 8: Quantum Reality and the EPR Paradox
Standard Model	Oct. 8:	Lecture 9: The Standard Model and Antimatter Lecture 10: Why is there something rather than nothing?

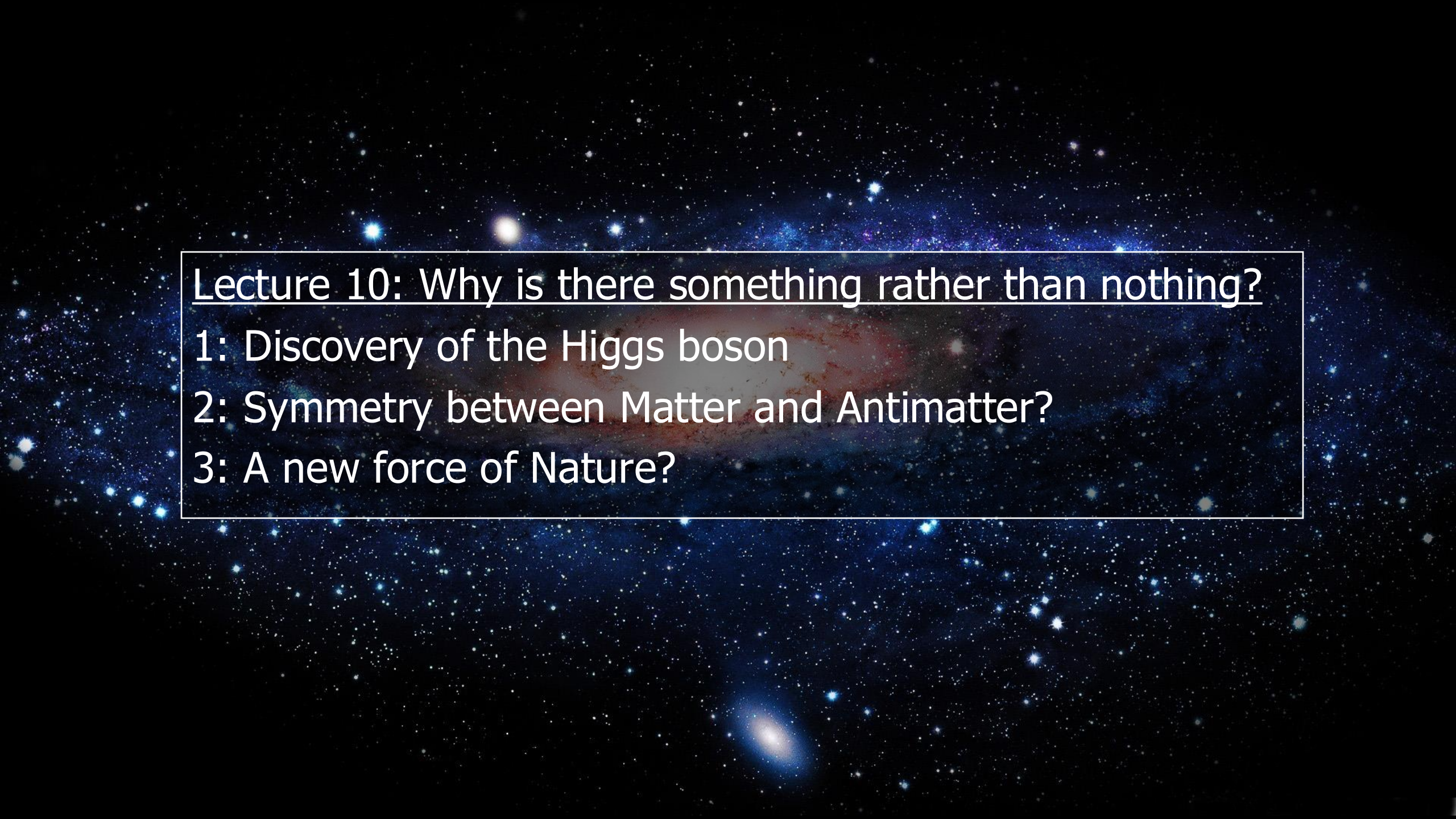
Lecture notes, written for this course, are available: www.nikhef.nl/~i93/Teaching/
Prerequisite for the course: High school level physics & mathematics.

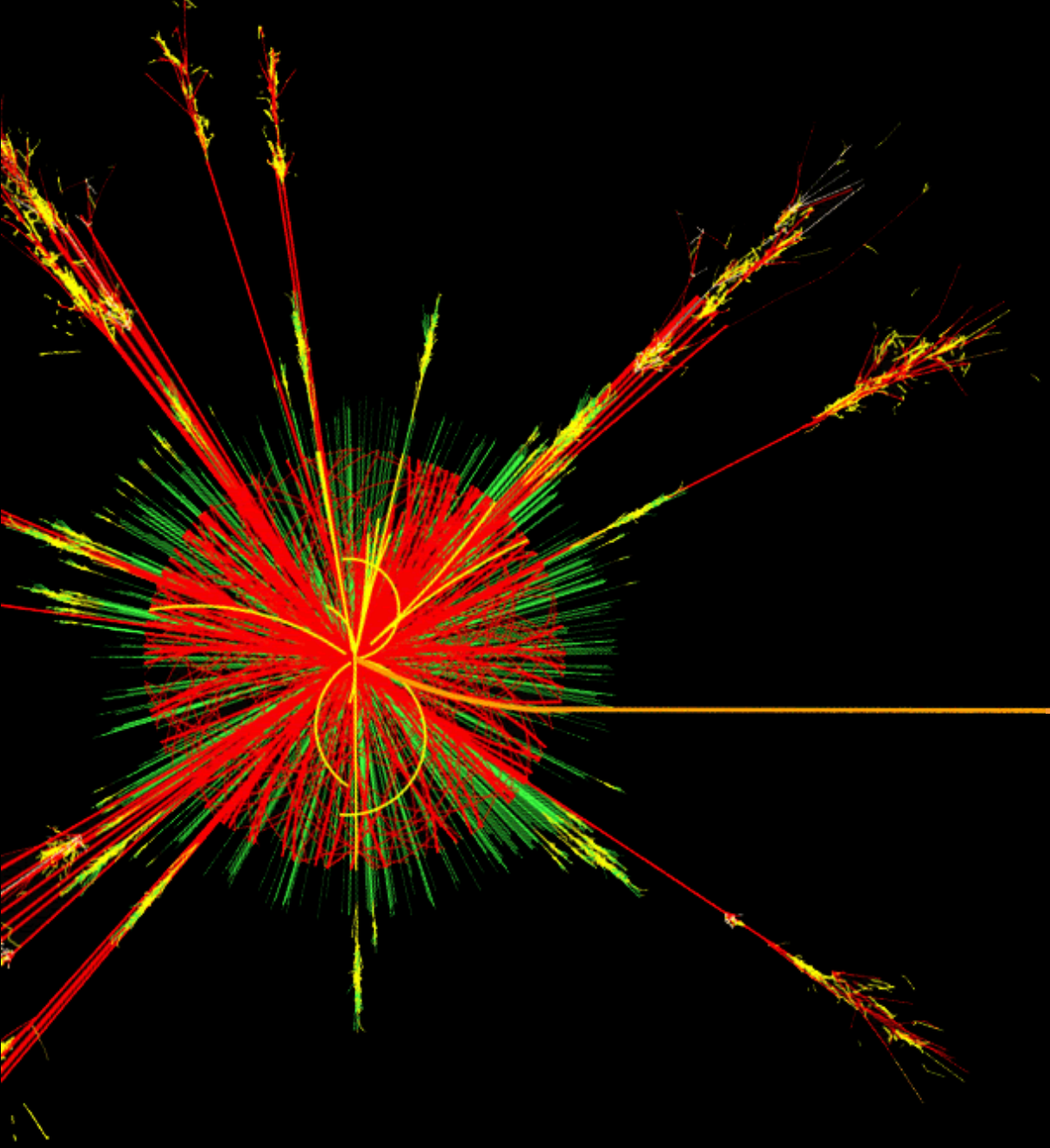
Why is there something rather than nothing?



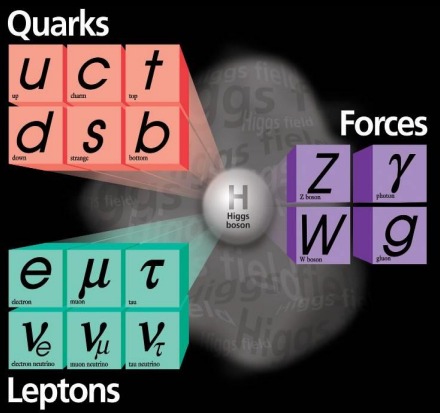


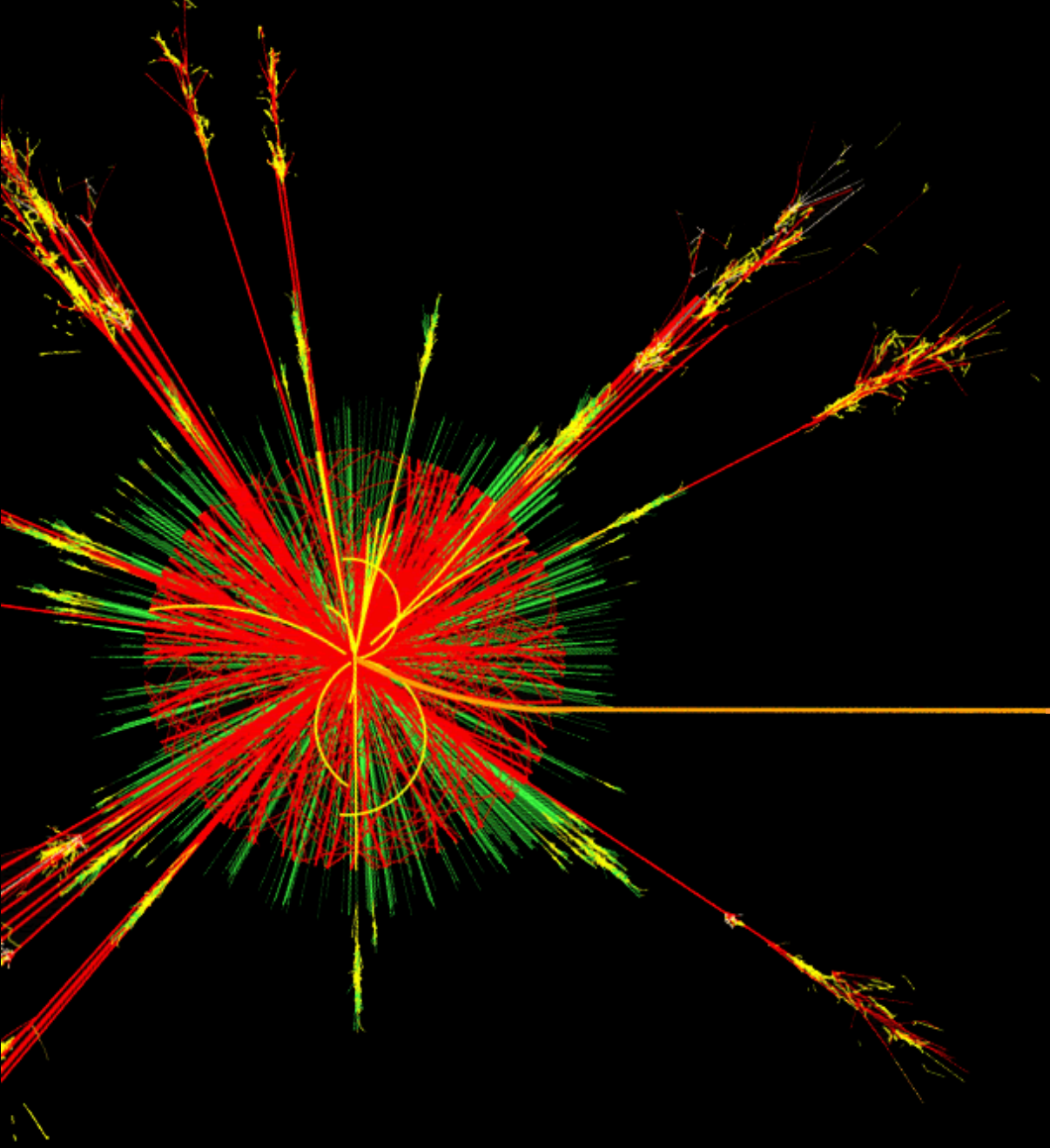
"Flavor" puzzle: why are there three generations of fundamental particles?

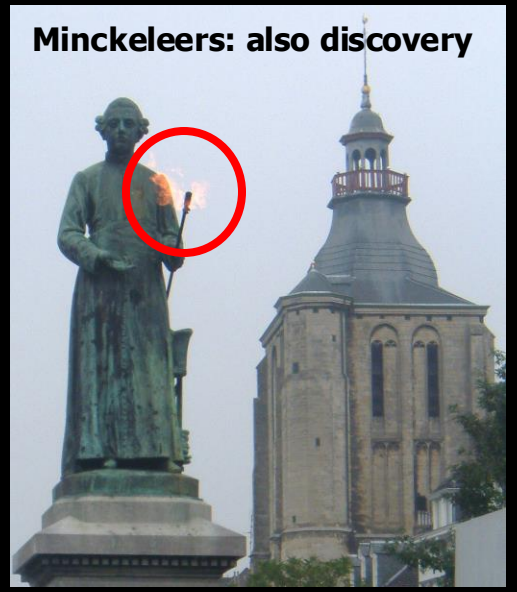

Lecture 10: Why is there something rather than nothing?
1: Discovery of the Higgs boson
2: Symmetry between Matter and Antimatter?
3: A new force of Nature?



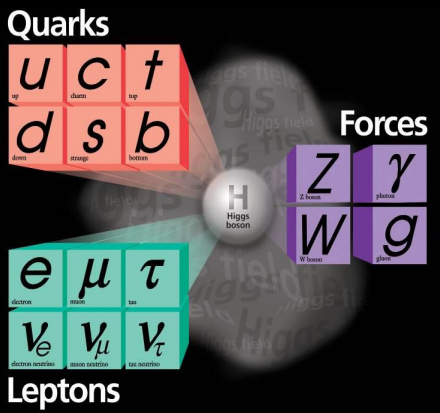
1: Discovery of the Higgs boson



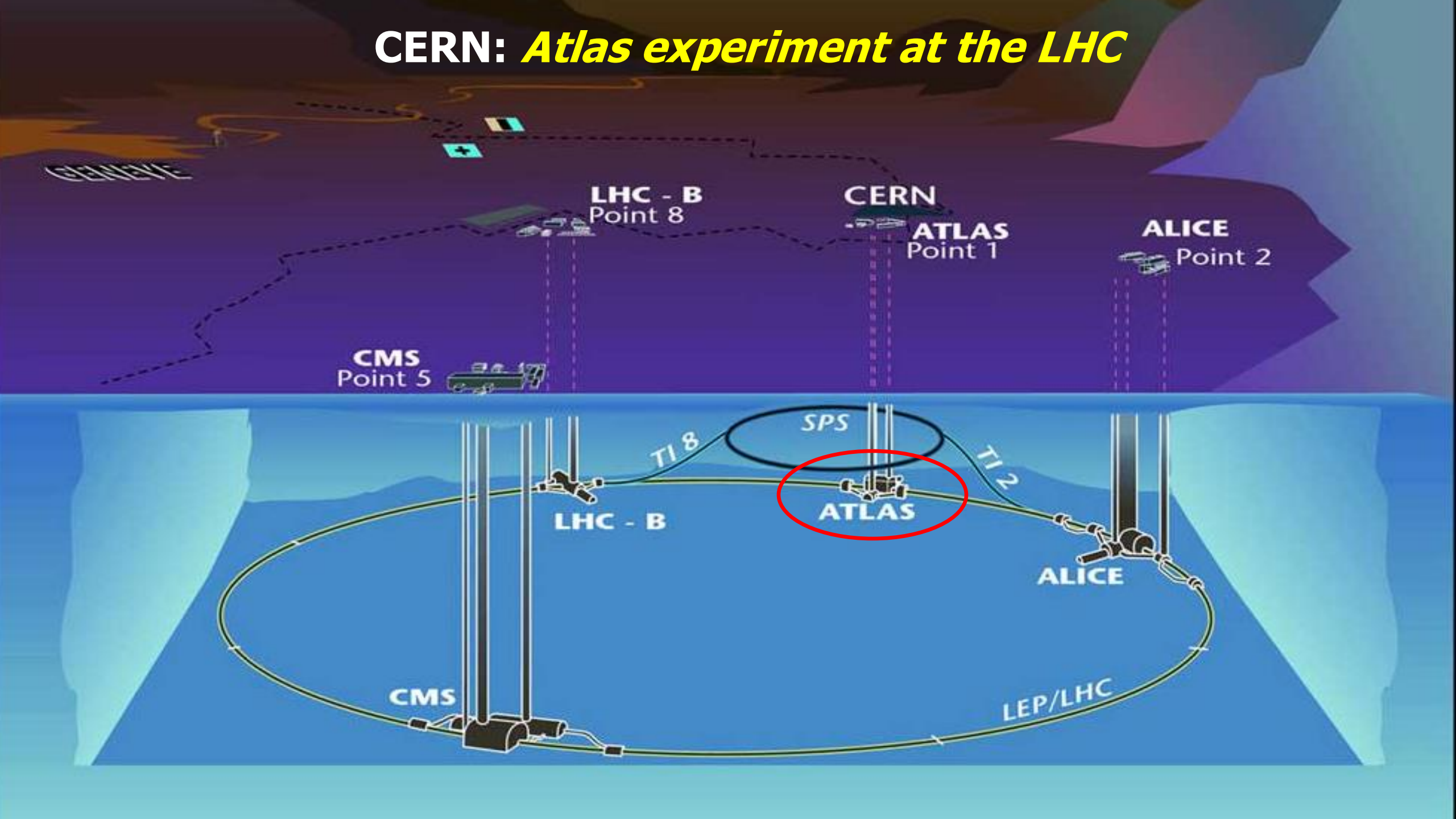




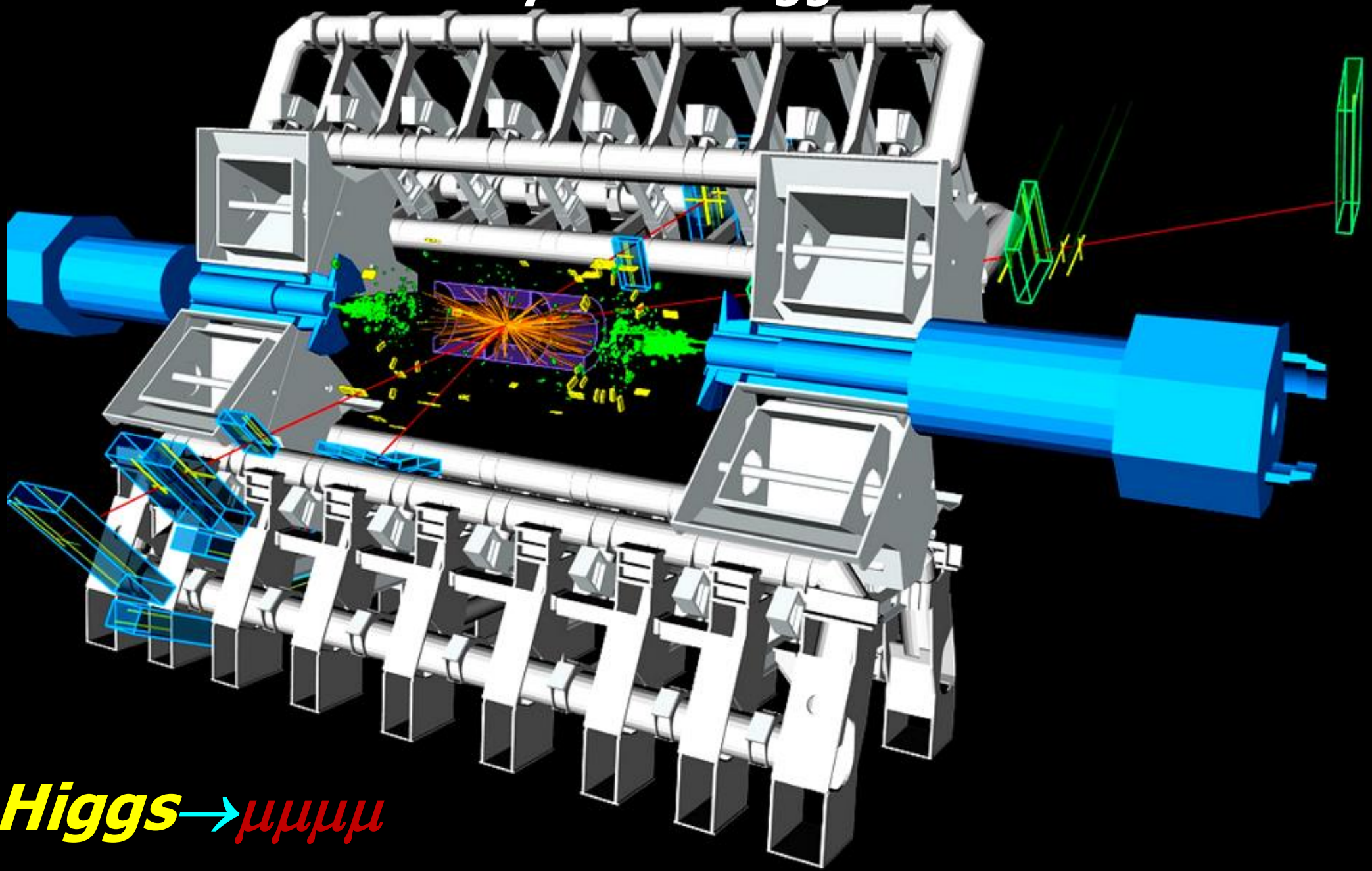
1: Discovery of the Higgs boson



CERN: *Atlas experiment at the LHC*

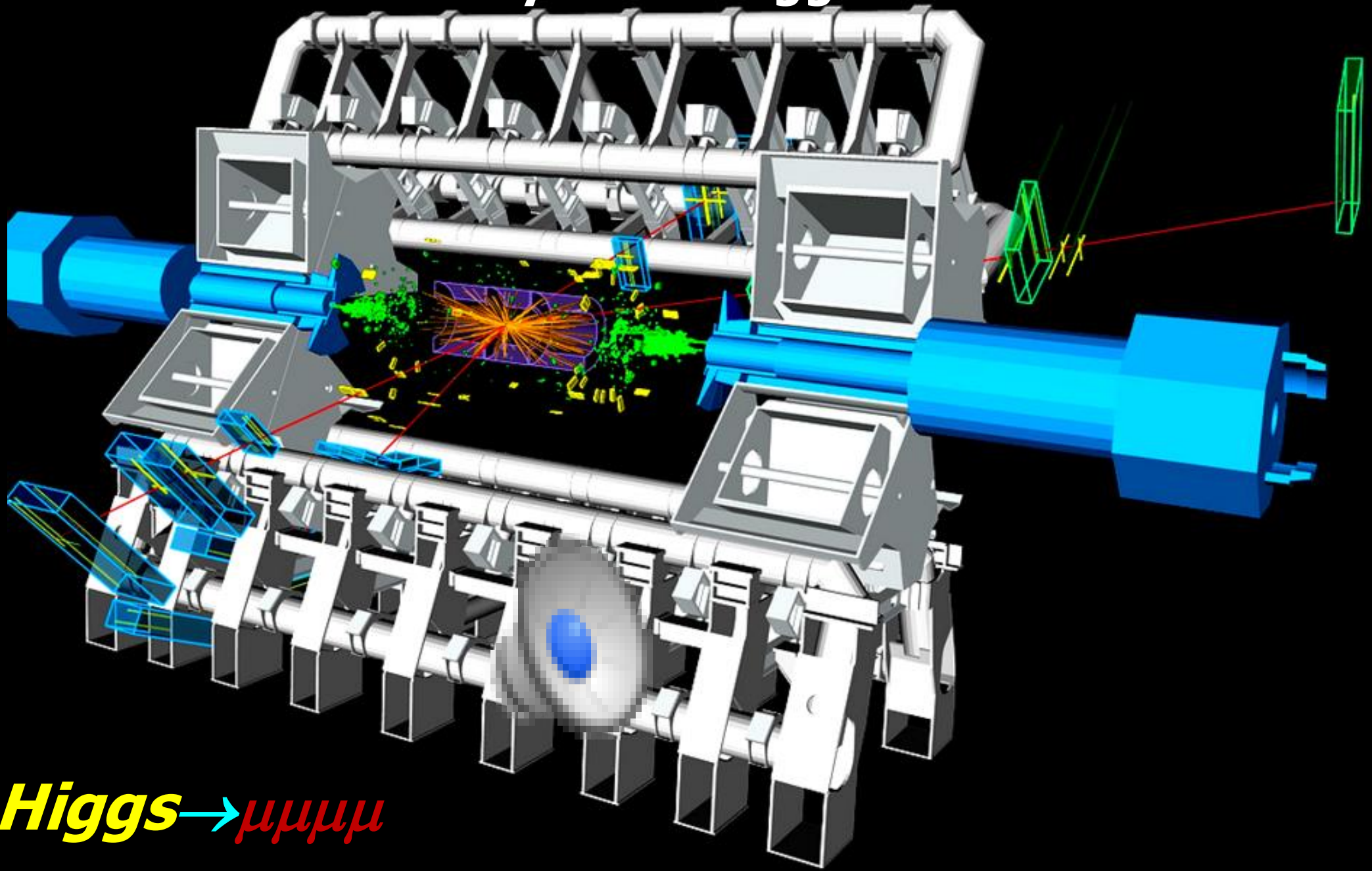


Discovery of the Higgs boson



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

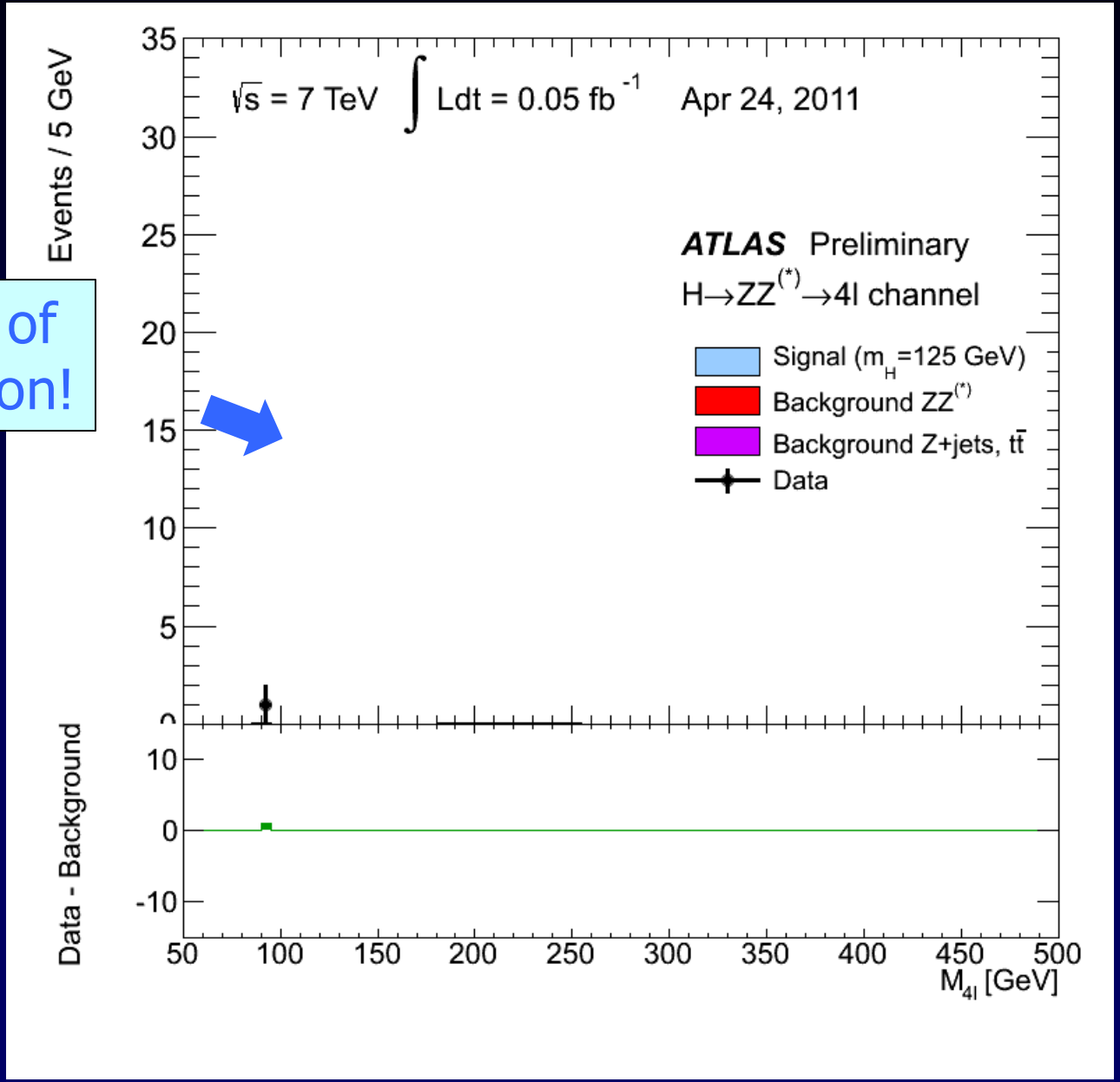
Discovery of the Higgs boson



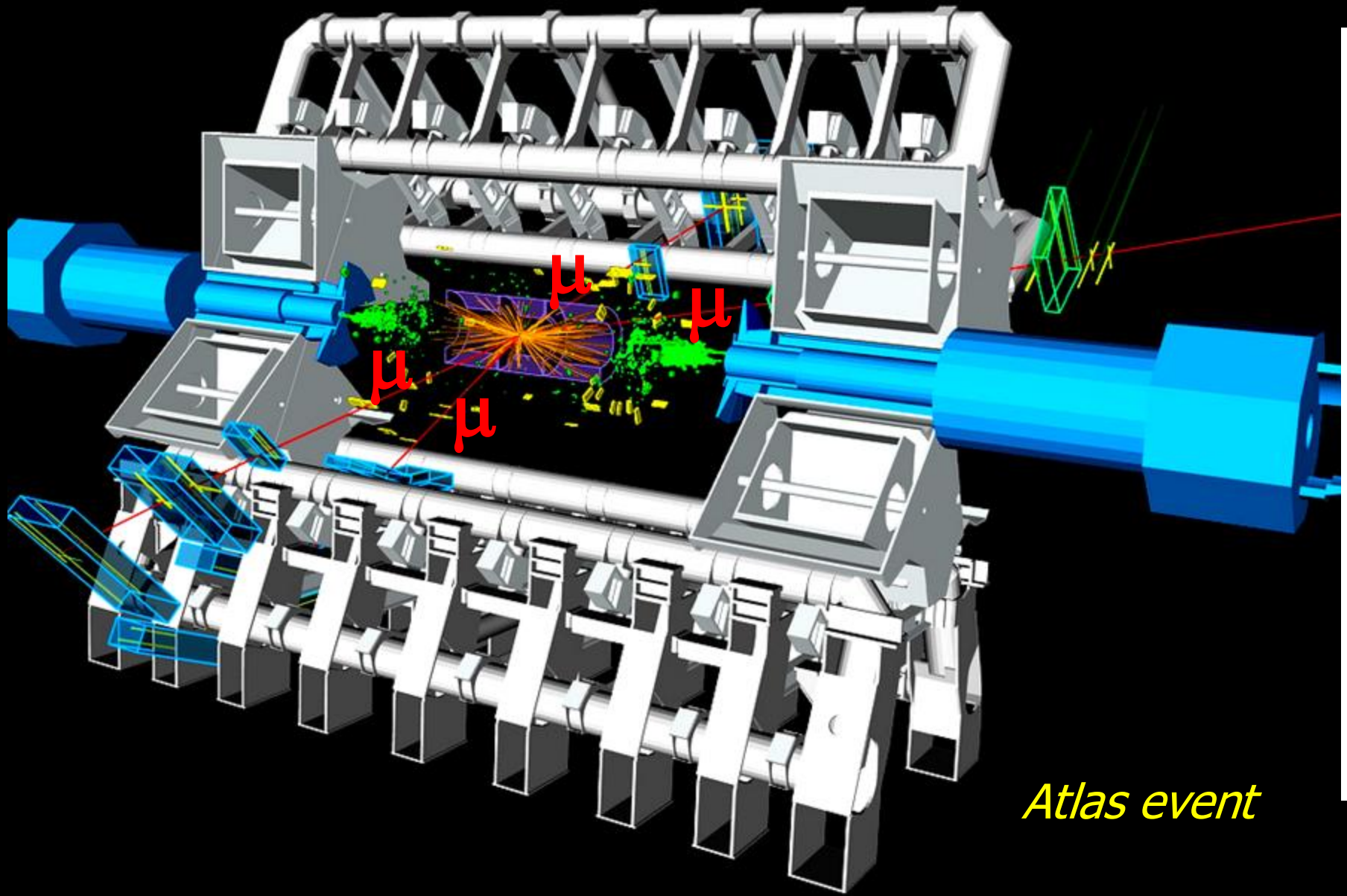
pp→Higgs→μμμμ

Higgs: collecting data and testing theory

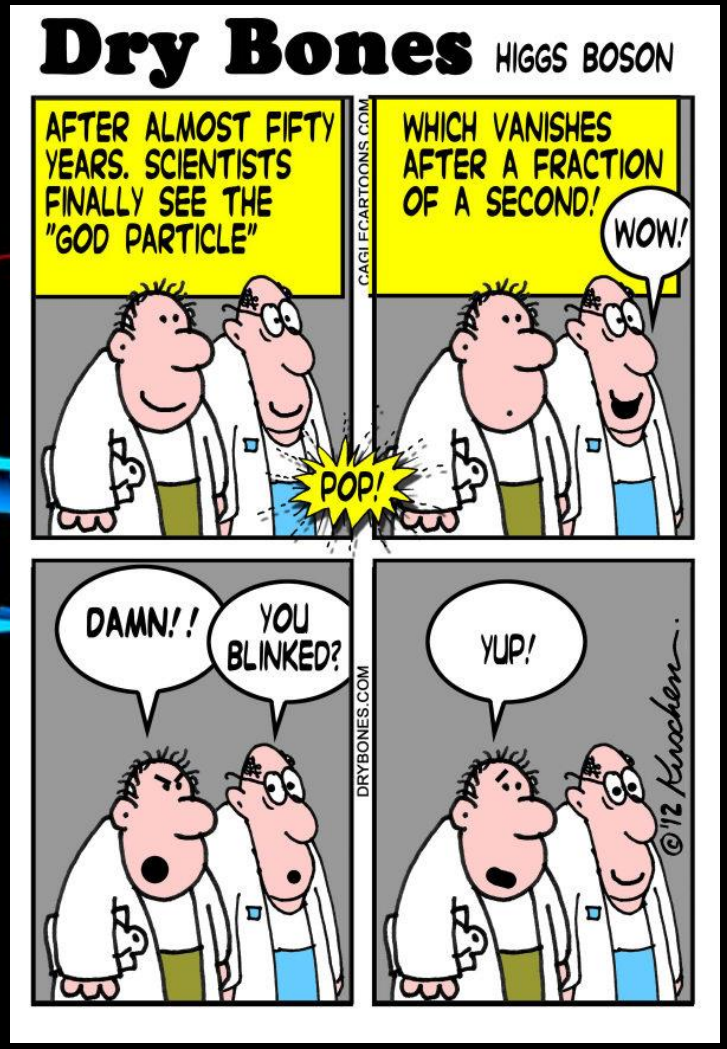
Discovery of Higgs boson!



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



Atlas event



4 July 2012

Announcement Higgs discovery

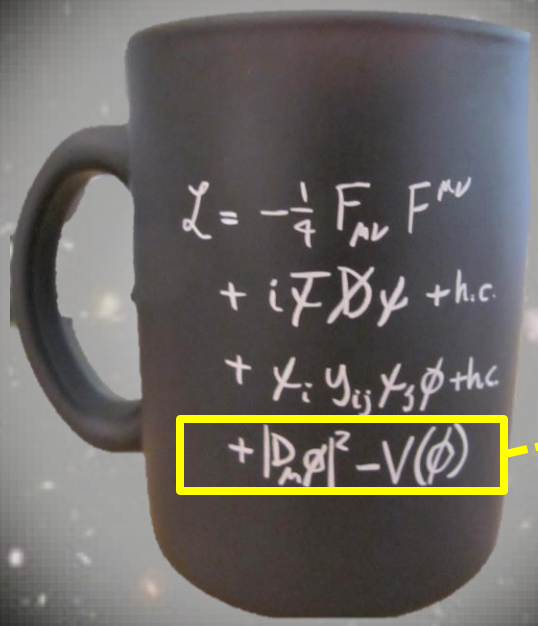
2013 Nobel prize in Physics

Robert Brout

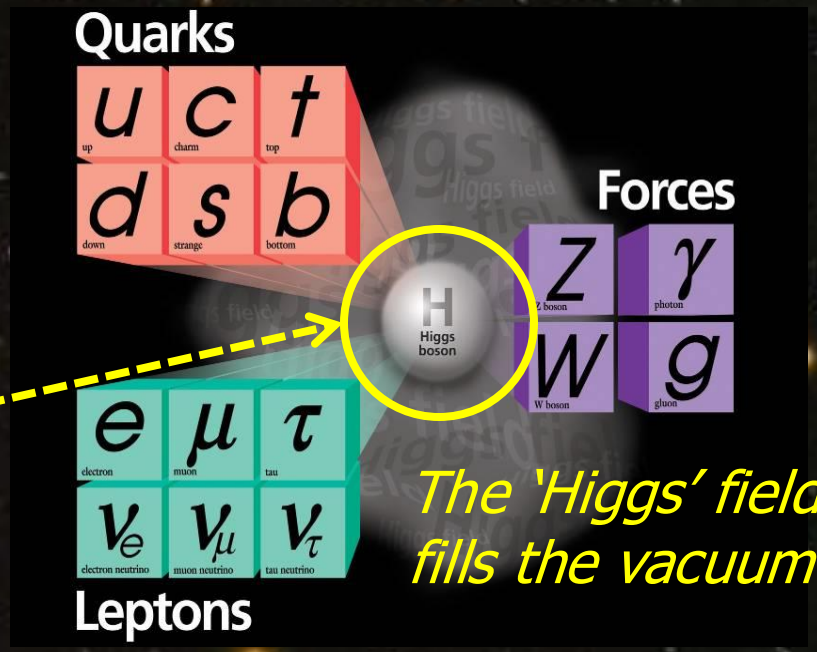
Francois Englert Peter Higgs

What did we discover?

"The formula"



"The building blocks"



The 'Higgs' field fills the vacuum

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

$$\phi \rightarrow H$$

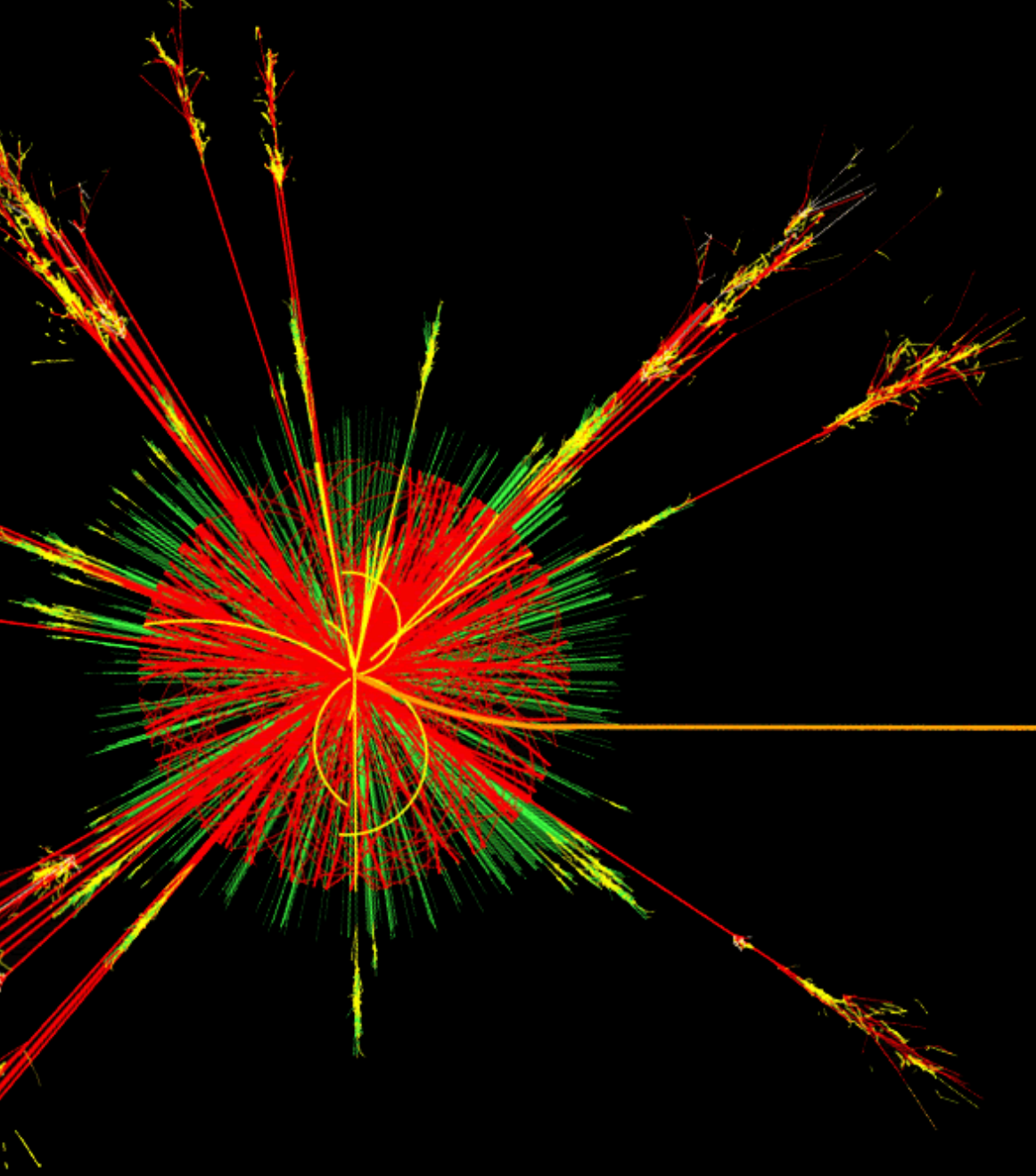
Higgs field

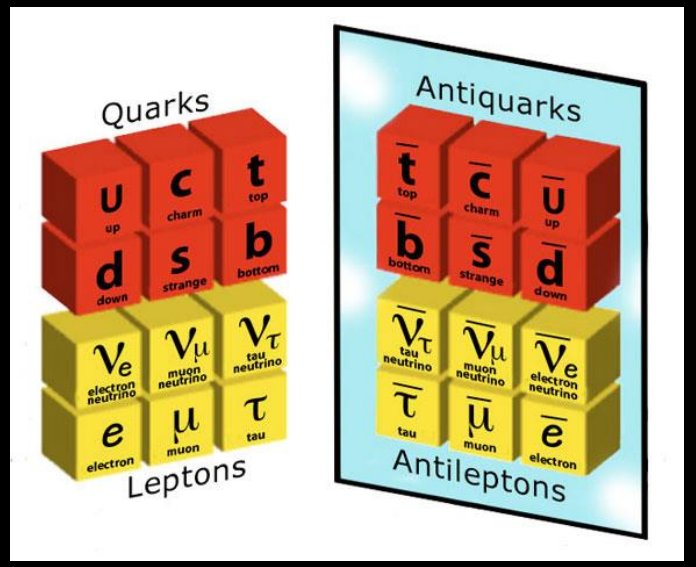
Higgs particle
a "field-quantum"

July 4, 2012: The Vacuum

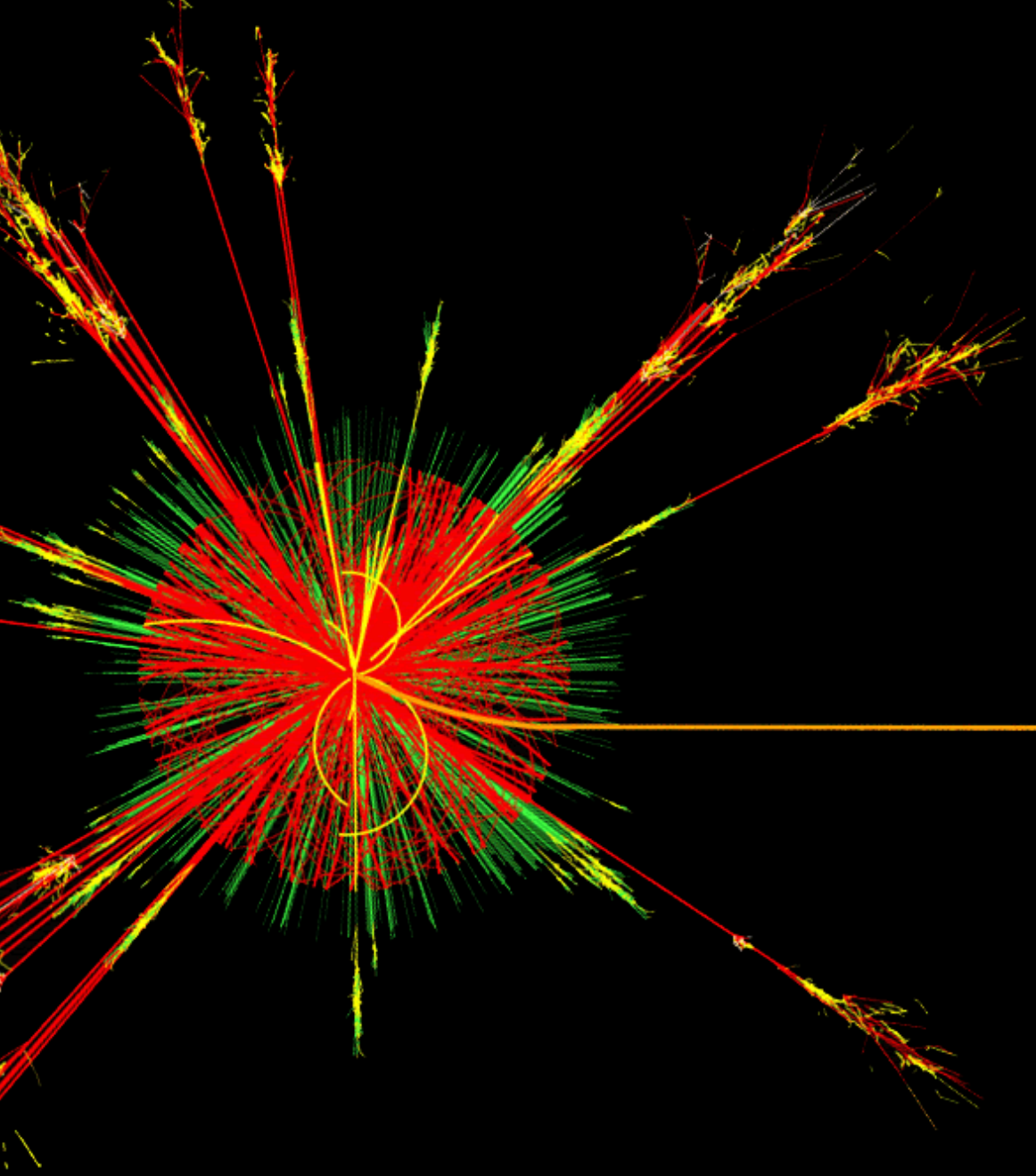
Hence…

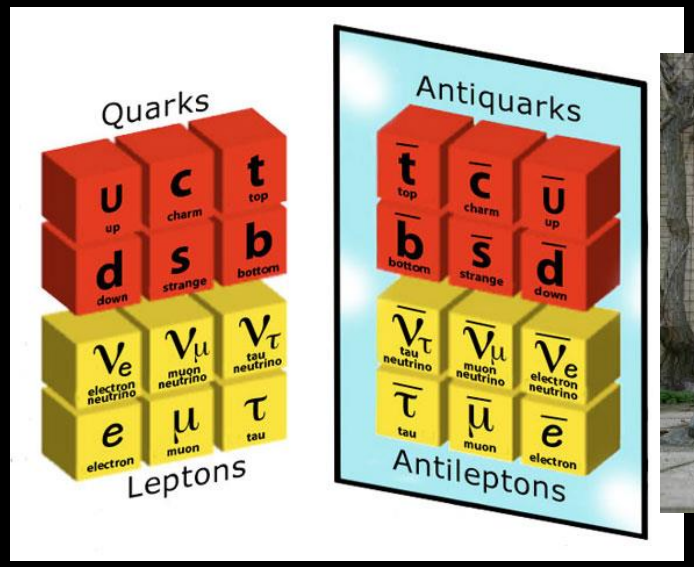

SEE, DEAR? WE'RE JUST BIG-BOSONED!
SCIENTISTS FIND HIGGS BOSON PARTICLE THAT GIVES ALL THINGS MASS
SUPER GULP
THE COLUMBUS DISPATCH





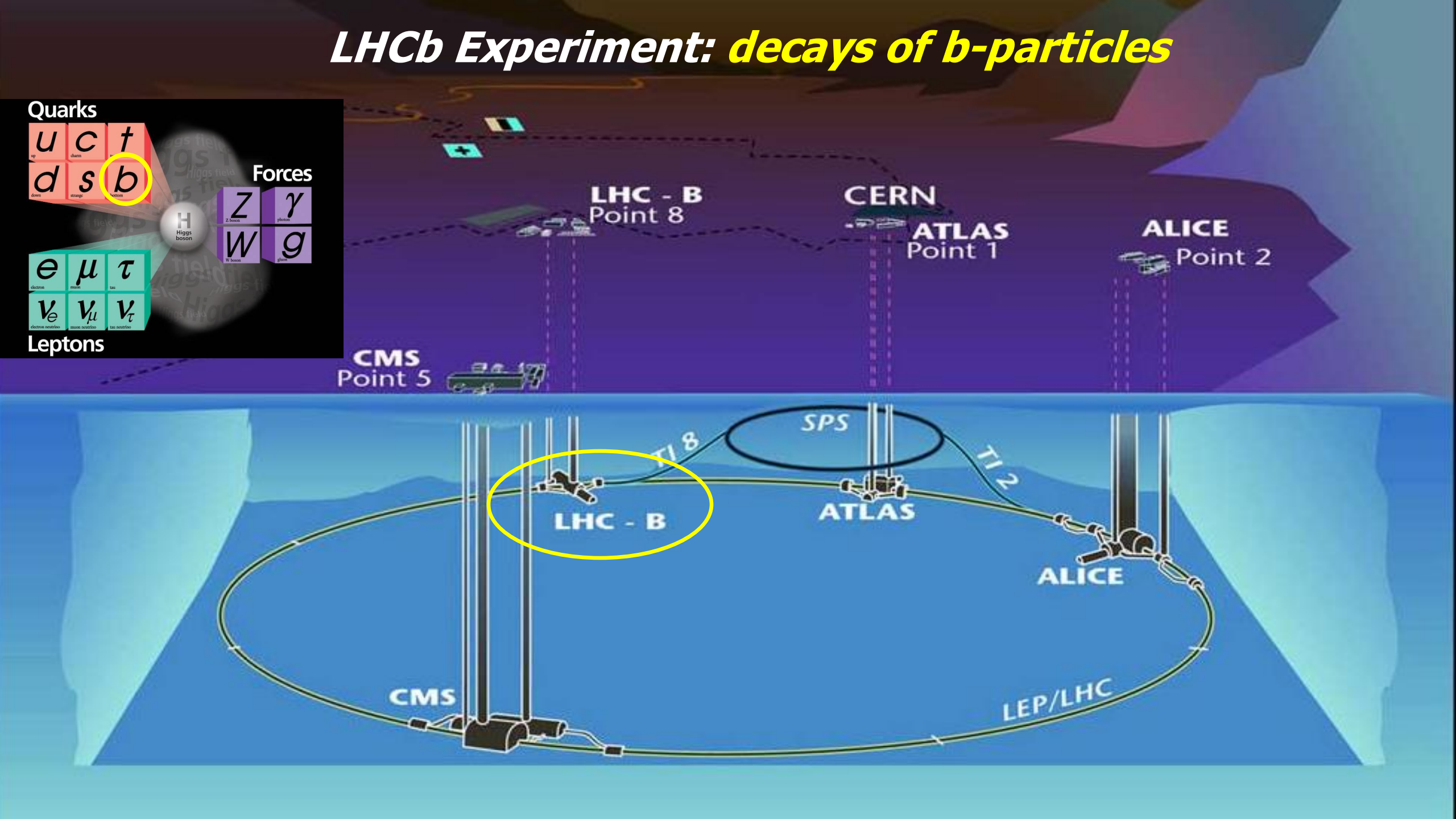
2: Symmetry between matter and antimatter?



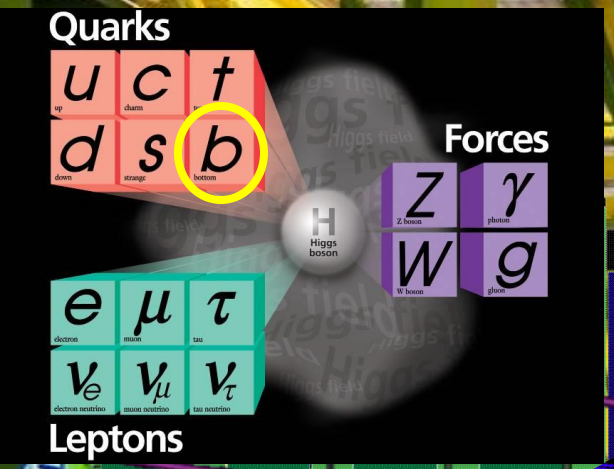


2: Symmetry between matter and antimatter?

LHCb Experiment: decays of b-particles



LHCb Detector: B-particles



Zoom in on collision point

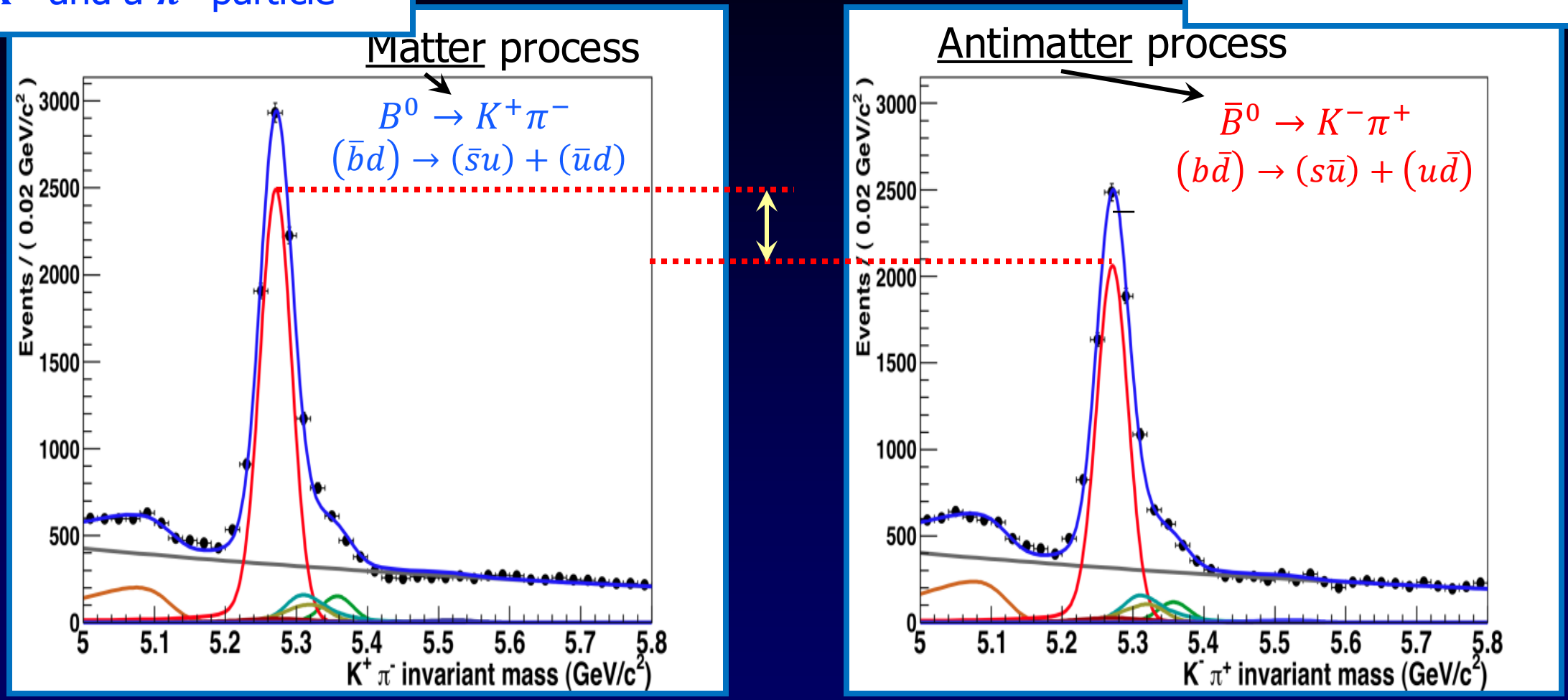
Reconstruct millions of B-particle decays and select interesting cases.
Do we observe differences between matter and antimatter?

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

2012: B-meson 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



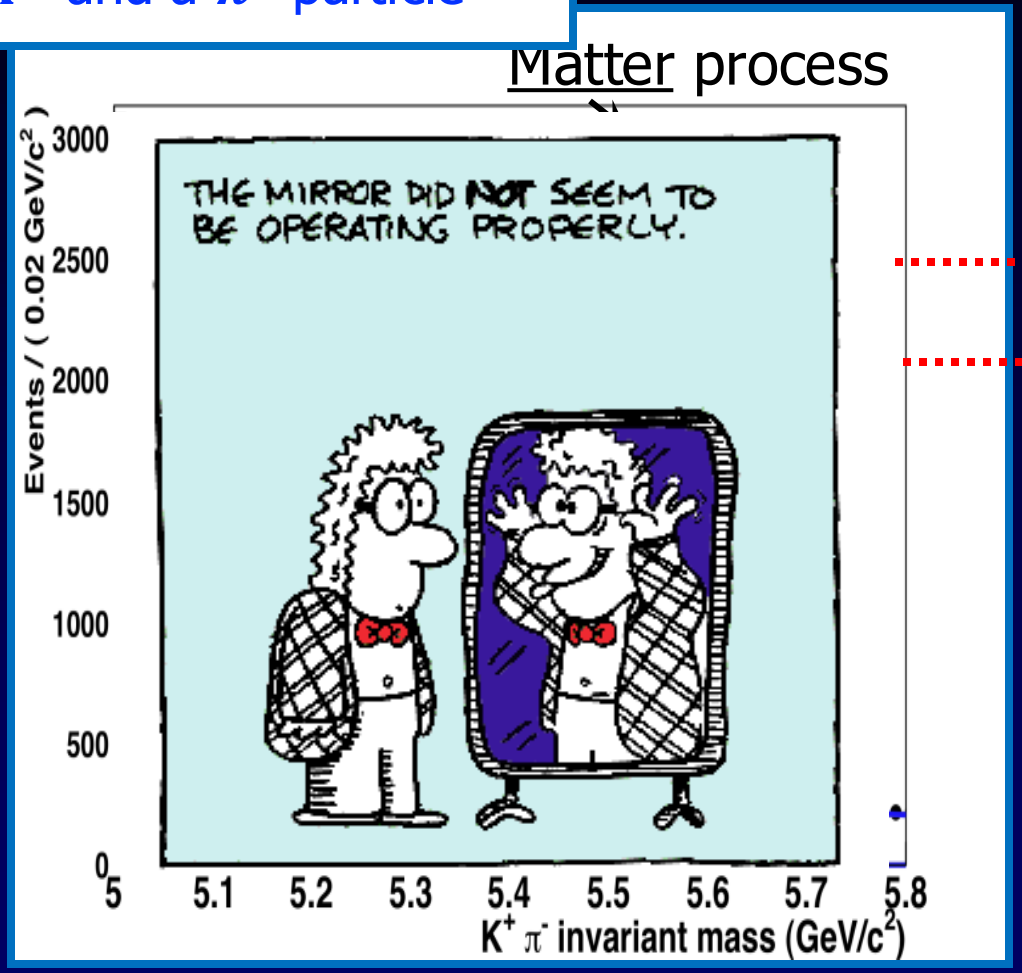
Asymmetry: matter and antimatter decay processes proceed differently!
Quantum forces between particles and anti-particles ***not always identical!***

2012: B-meson decay process: matter vs antimatter

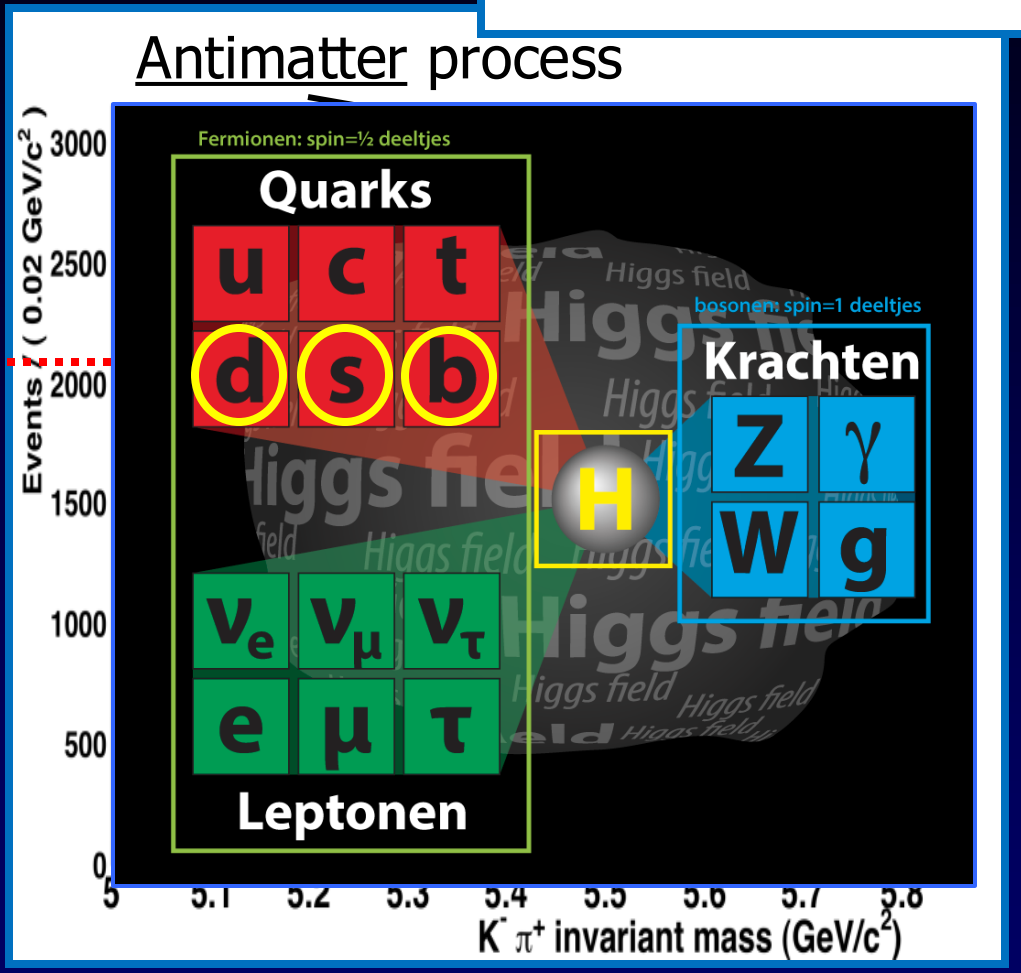
B particle decay into a K^+ and a π^- particle

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

Matter process

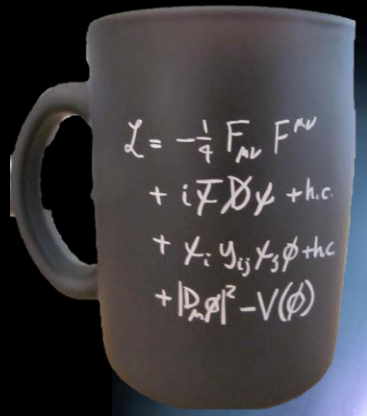


Antimatter process

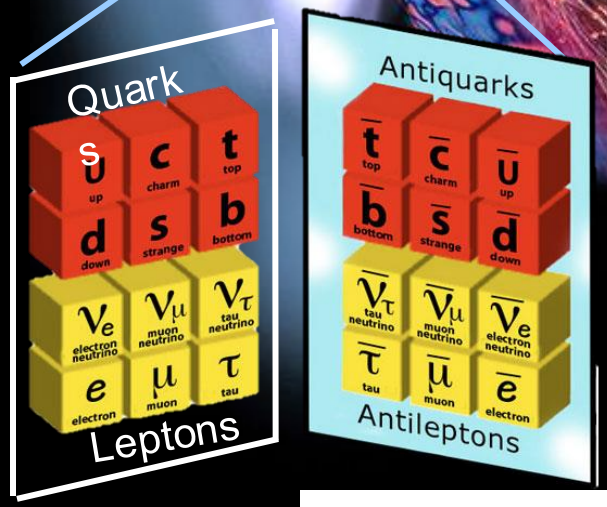


Asymmetry: matter and antimatter decay processes proceed differently!
Quantum forces between particles and anti-particles ***not always identical!***

Early Universe: How did the antimatter disappear?



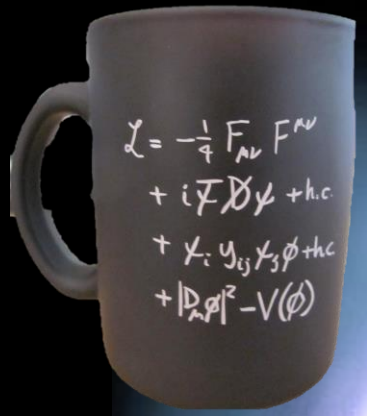
- → Asymmetry in physics laws
- → Little bit more matter than antimatter
- → Rest annihilates
- → Matter universe remains



50.000001% | 49.999999%

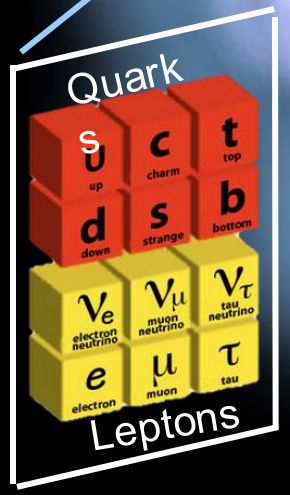
"Perfect, don't touch it further!"

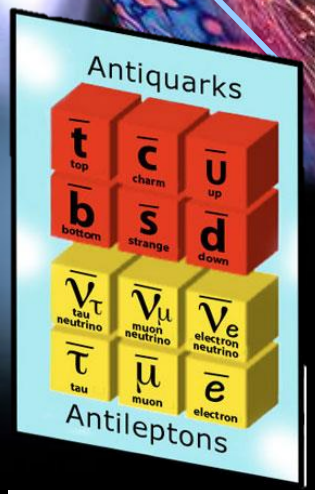
Early Universe: How did the antimatter disappear?



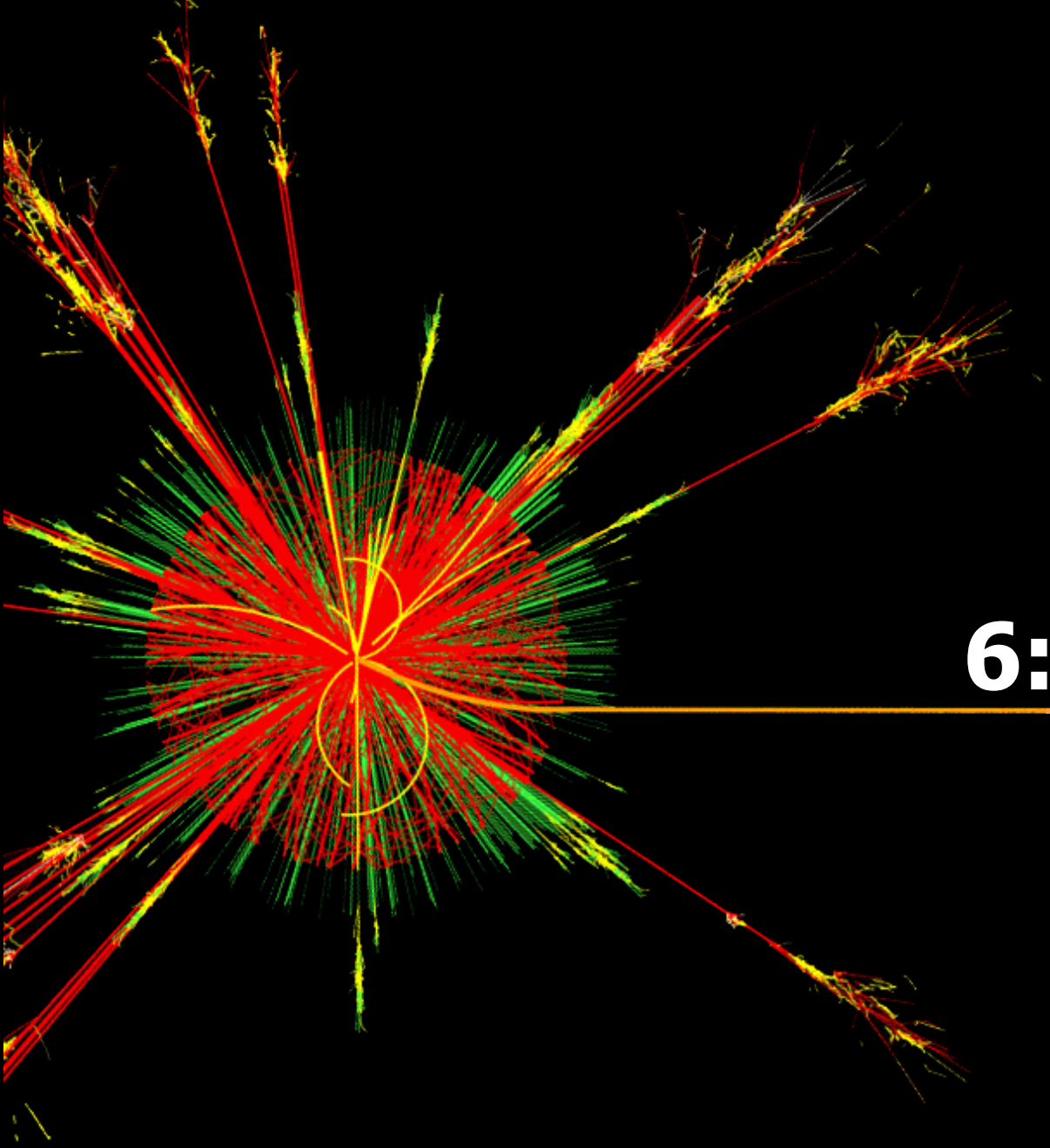
Why are there three identical copies of all particles?
➔ *Is it the simplest universe that can exist?!*

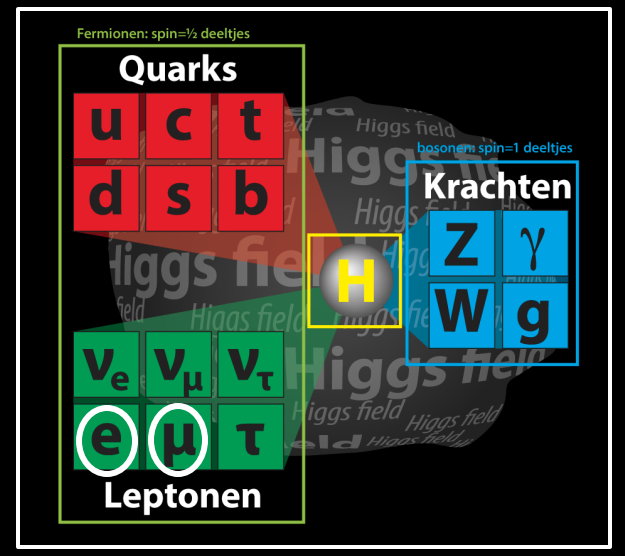
However: it does not work!
Asymmetry is not large enough.
Explanation requires a new force!



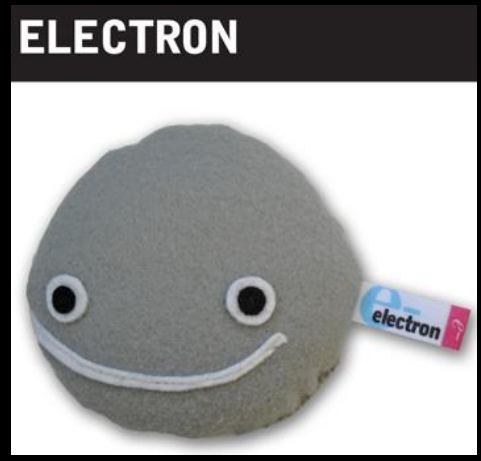


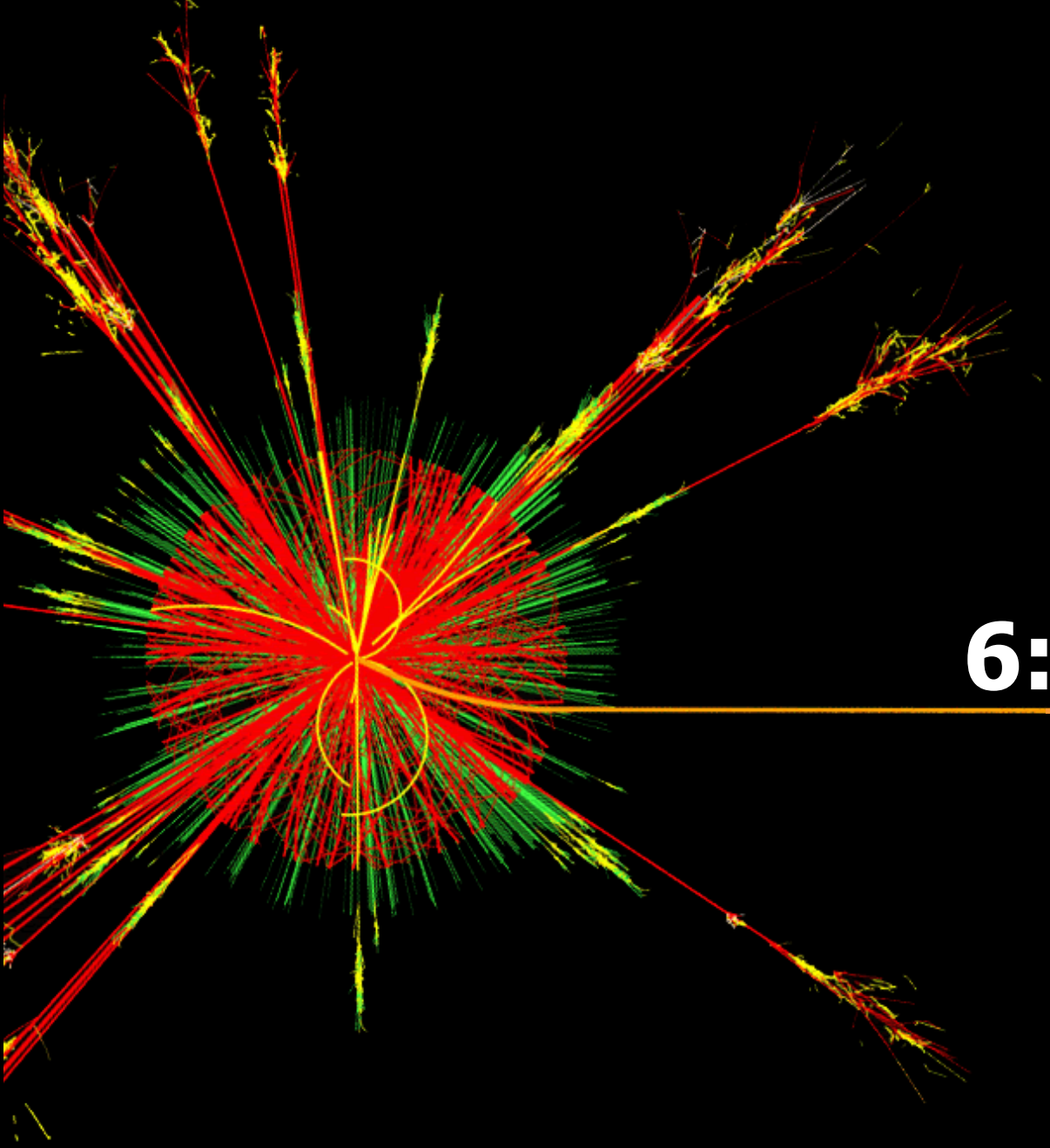
50.000001% 49.999999%



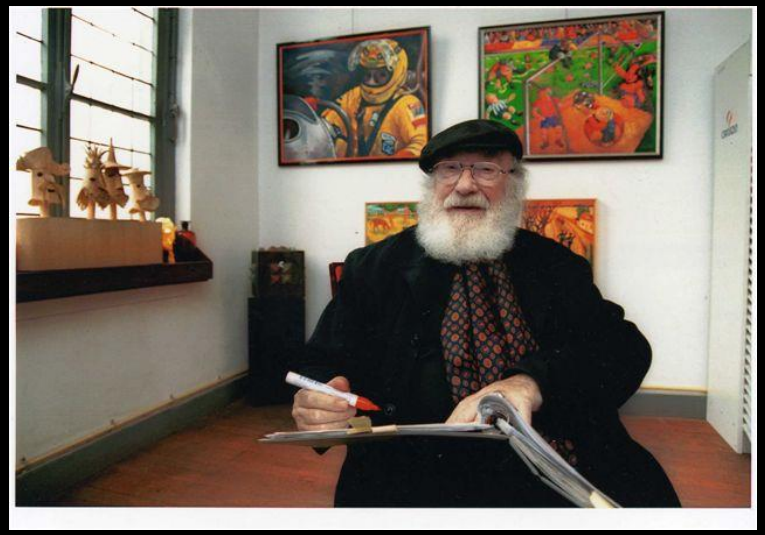


6: A new force of Nature?

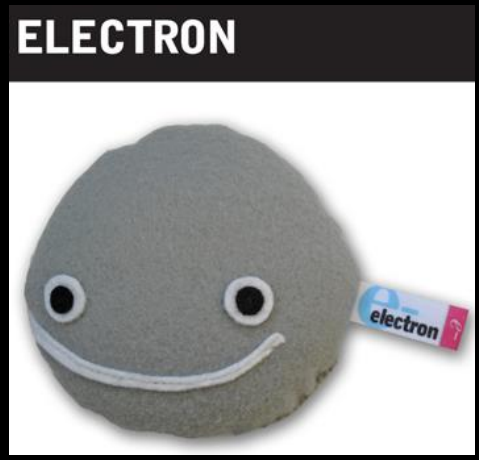




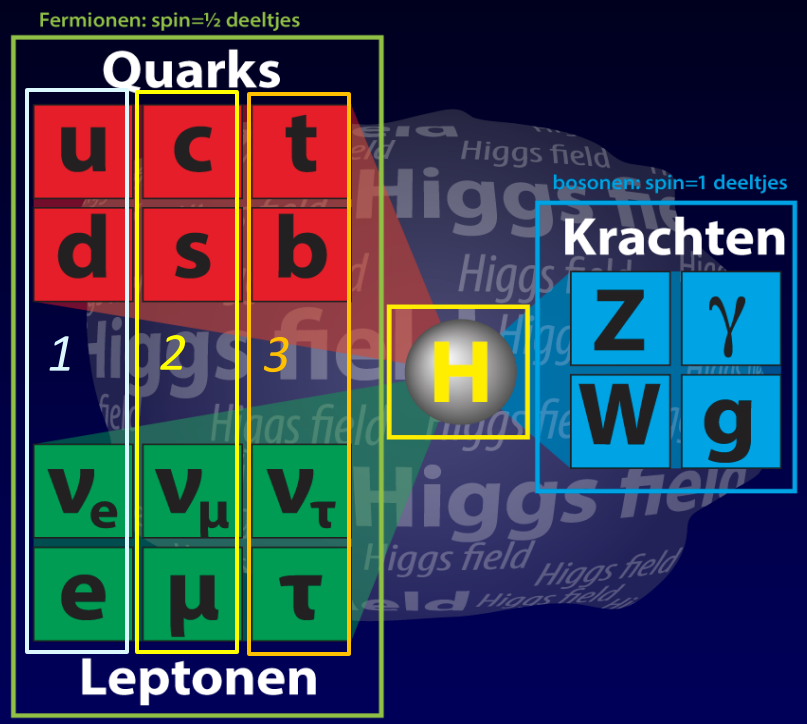
Pieke Dassen: art

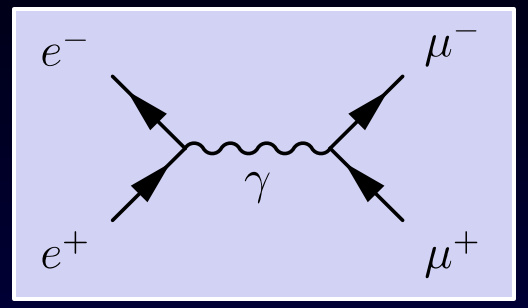


6: A new force of Nature?

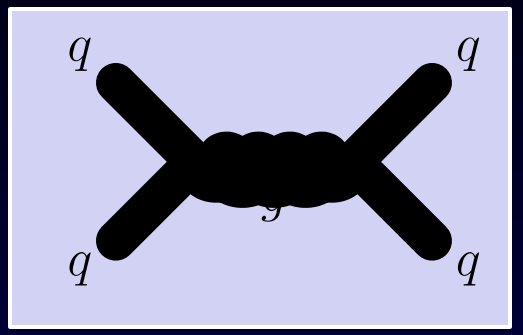


Standard Model: Universality of the Forces

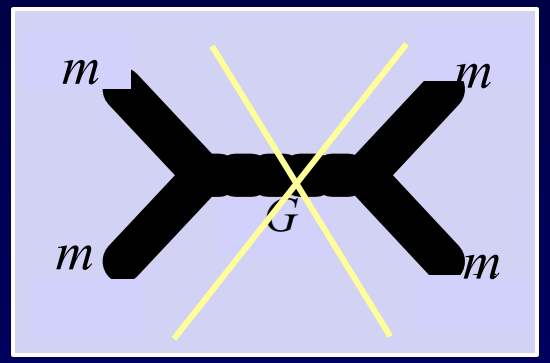




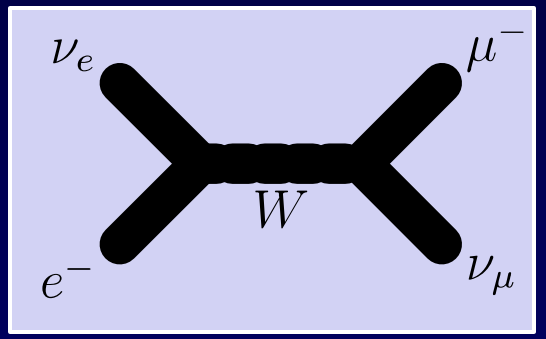
Elektromagnetism



Strong Nuclear Force



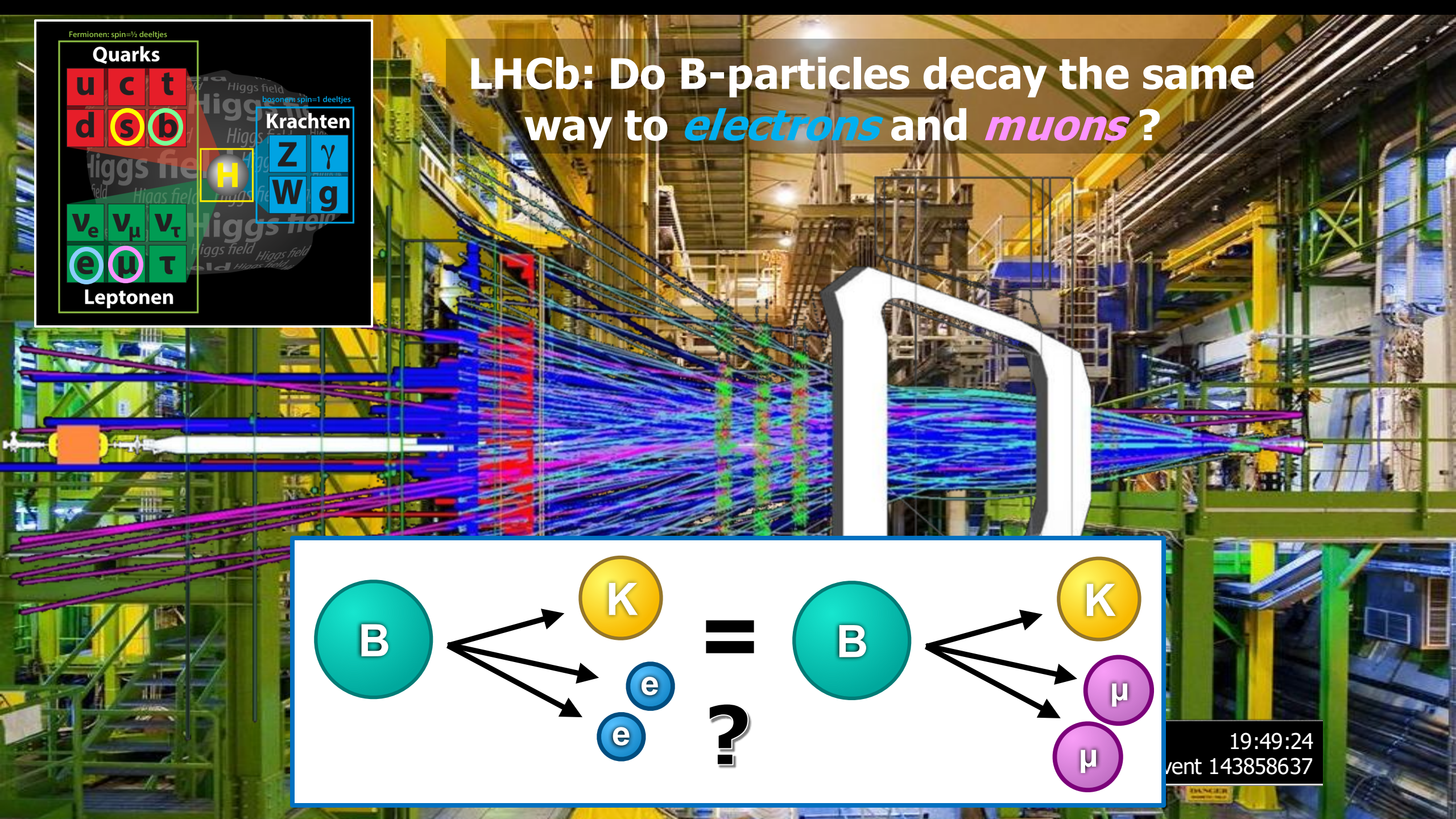
Gravity

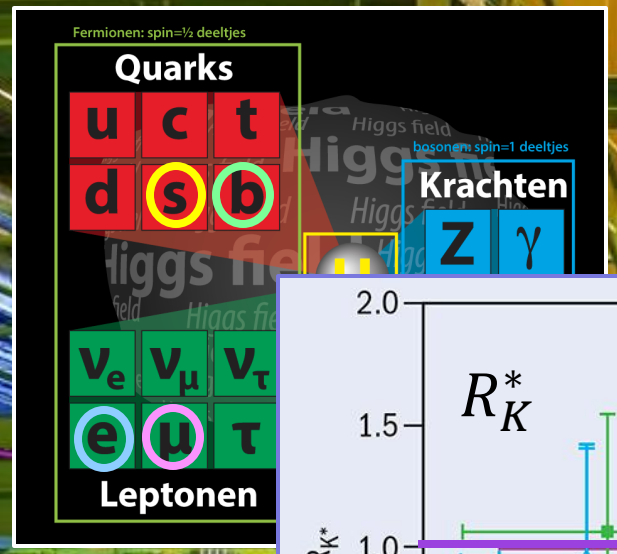


Weak Nuclear Force

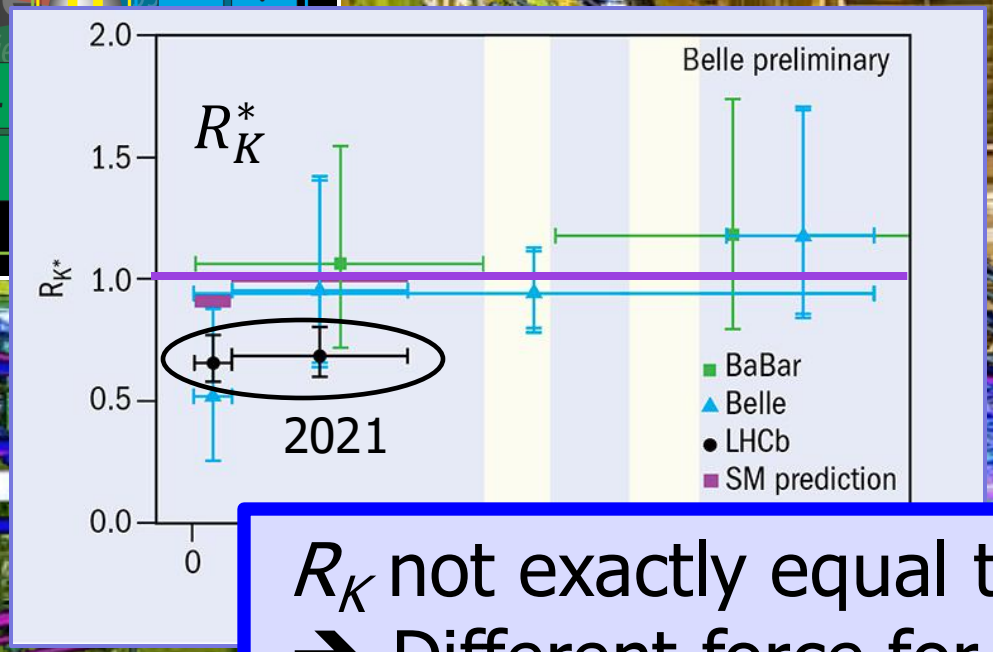
Forces are identical for particles of 1st, 2nd en 3rd generation.

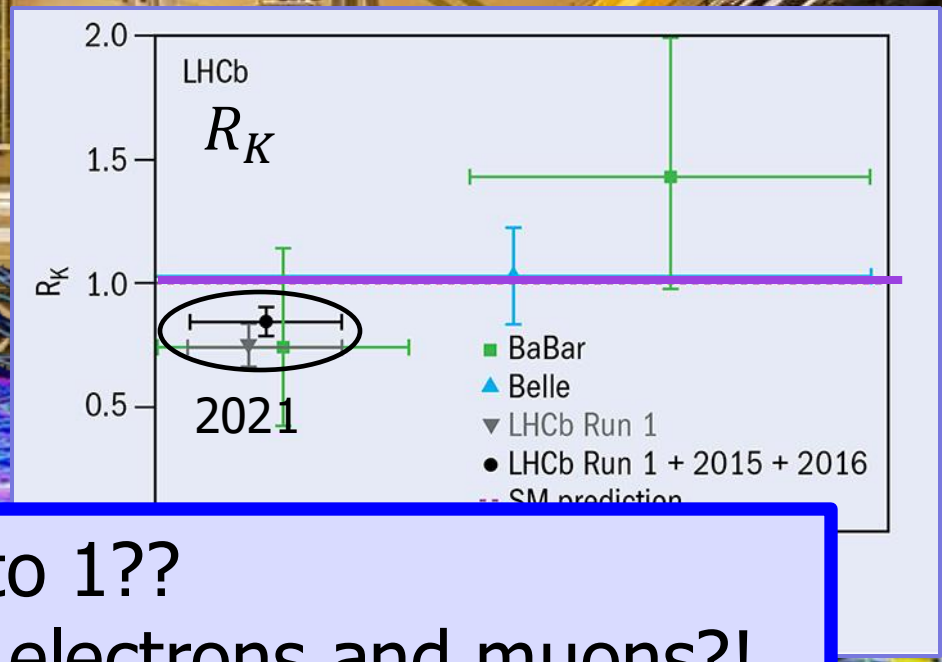
➔ "Universality"


Fermionen: spin=½ deeltjes
Quarks
u c t
d s b
Leptonen
ν_e ν_μ ν_τ
e μ τ
bosonen: spin=1 deeltjes
Krachten
Z γ
W g
H
Higgs field
LHCb: Do B-particles decay the same way to electrons and muons ?
B
K
e
e
=
?
B
K
μ
μ
19:49:24
vent 143858637



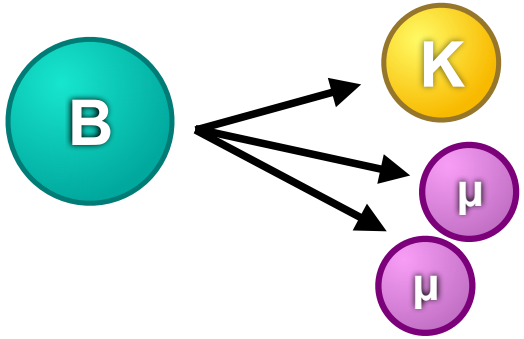
LHCb: Do B-particles decay the same way to *electrons* and *muons* ?



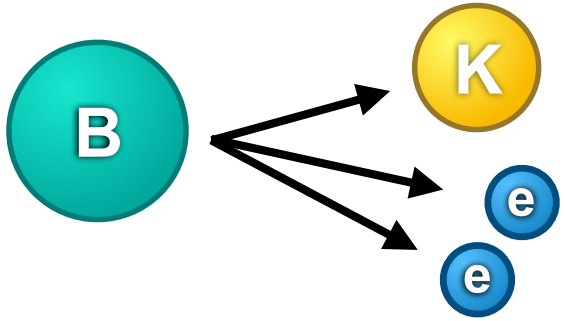


R_K not exactly equal to 1??

➔ Different force for electrons and muons?!



$/$



$= R_K$

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 kán 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?!

TELEGRAAF.NL

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

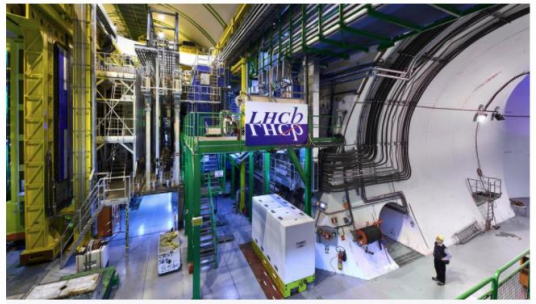
Na de vondst van het Higgs-deeltje, negen jaar geleden, klinken er nu opnieuw opgetogen …

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)

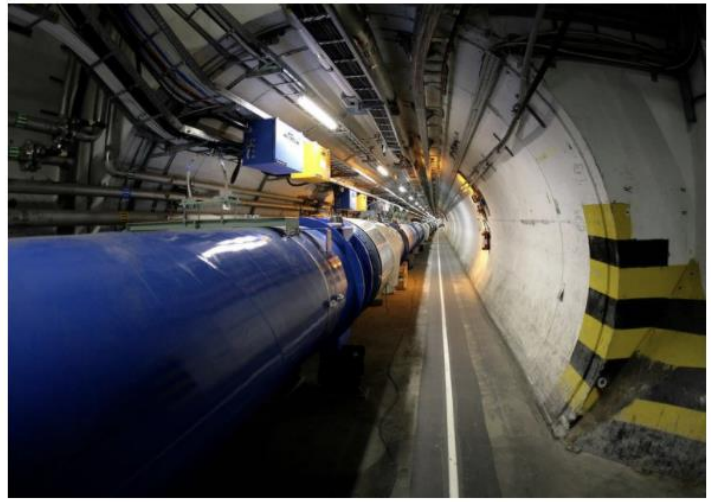
deVolkskrant

NIEUWS

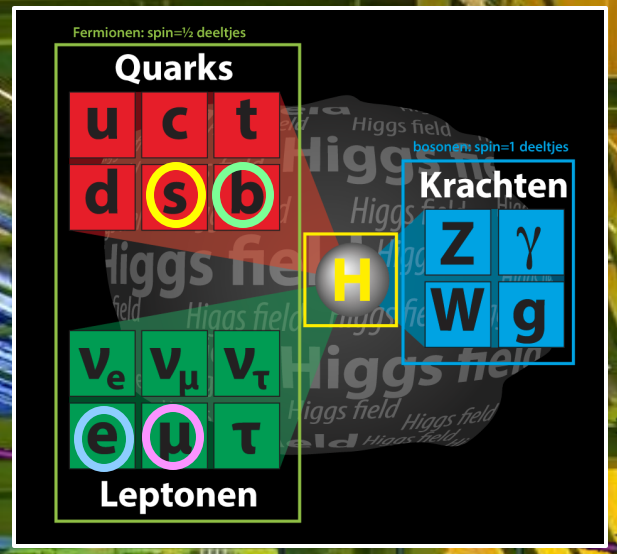
Natuurkundigen van Cern vinden aanwijzing die ons begrip van de werkelijkheid op zijn kop kan zetten

Een gloednieuw deeltje, een nog onbekende natuurkracht… fysici bij onderzoeksinstituut Cern zien …s begrip van de werkelijkheid op z'n …maken ze dinsdag bekend. 'Dit is … onderzoek doe.'

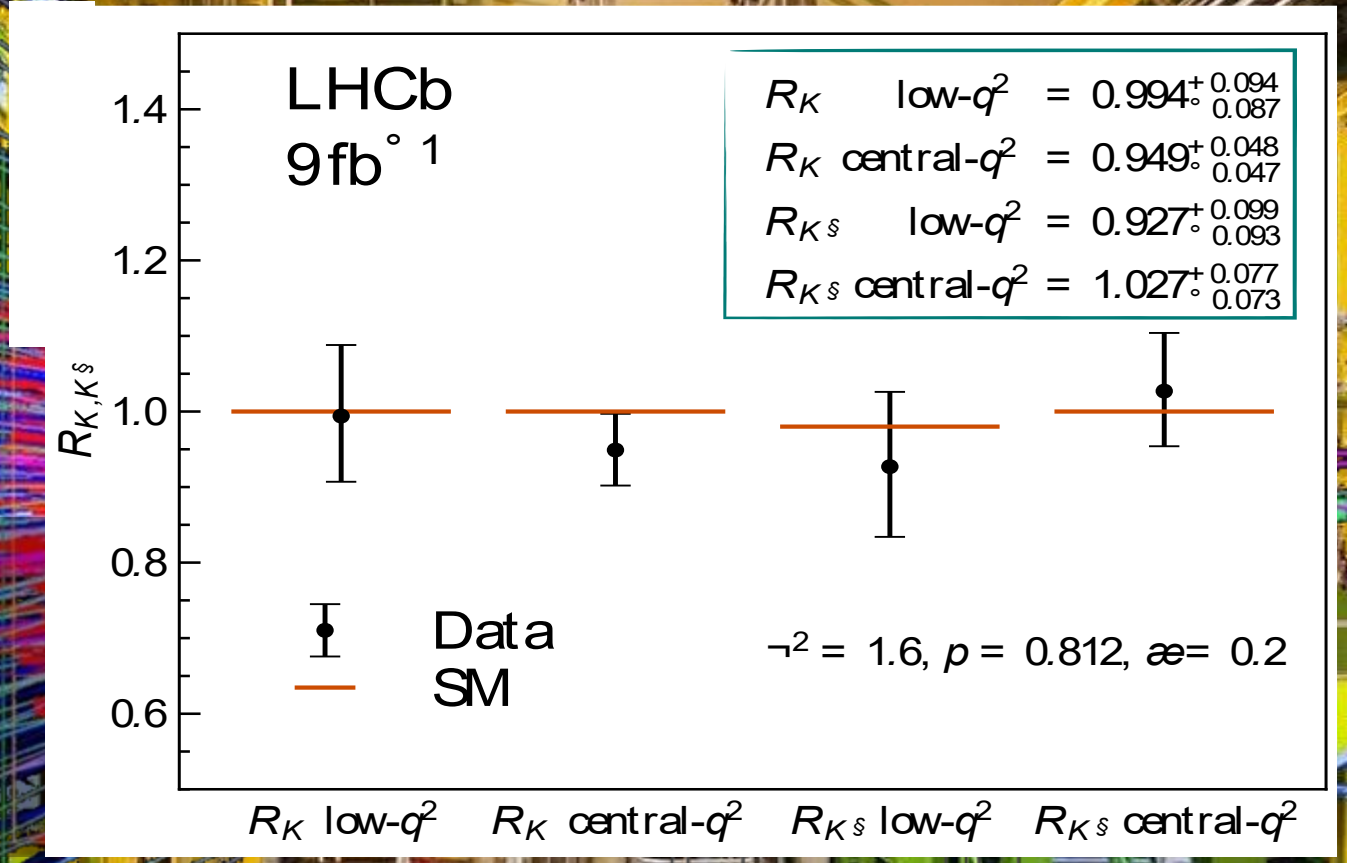
George van Hal 23 maart 2021, 9:00



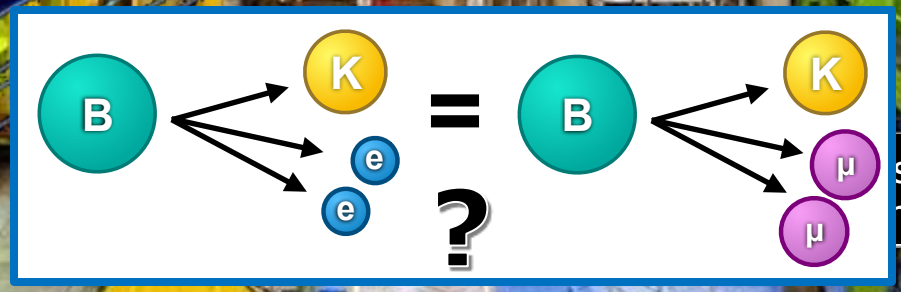
De tunnel van deeltjesversneller LHC bij Cern, Genève. In de blauwe buis zwiepen deeltjes met bijna de lichtsnelheid rond tot ze op elkaar knallen. Tussen de brokstukken van die botsing zoeken fysici naar aanwijzingen voor hoe de wereld op het kleinste niveau werkt. Beeld AP



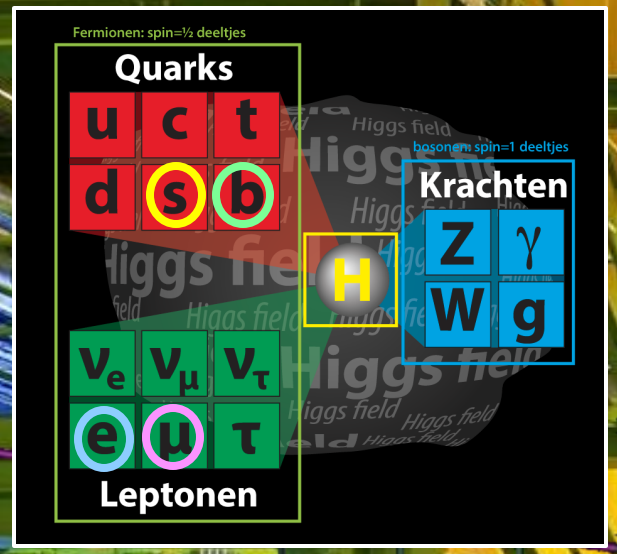
LHCb: Do B-particles decay the same way to *electrons* and *muons*?



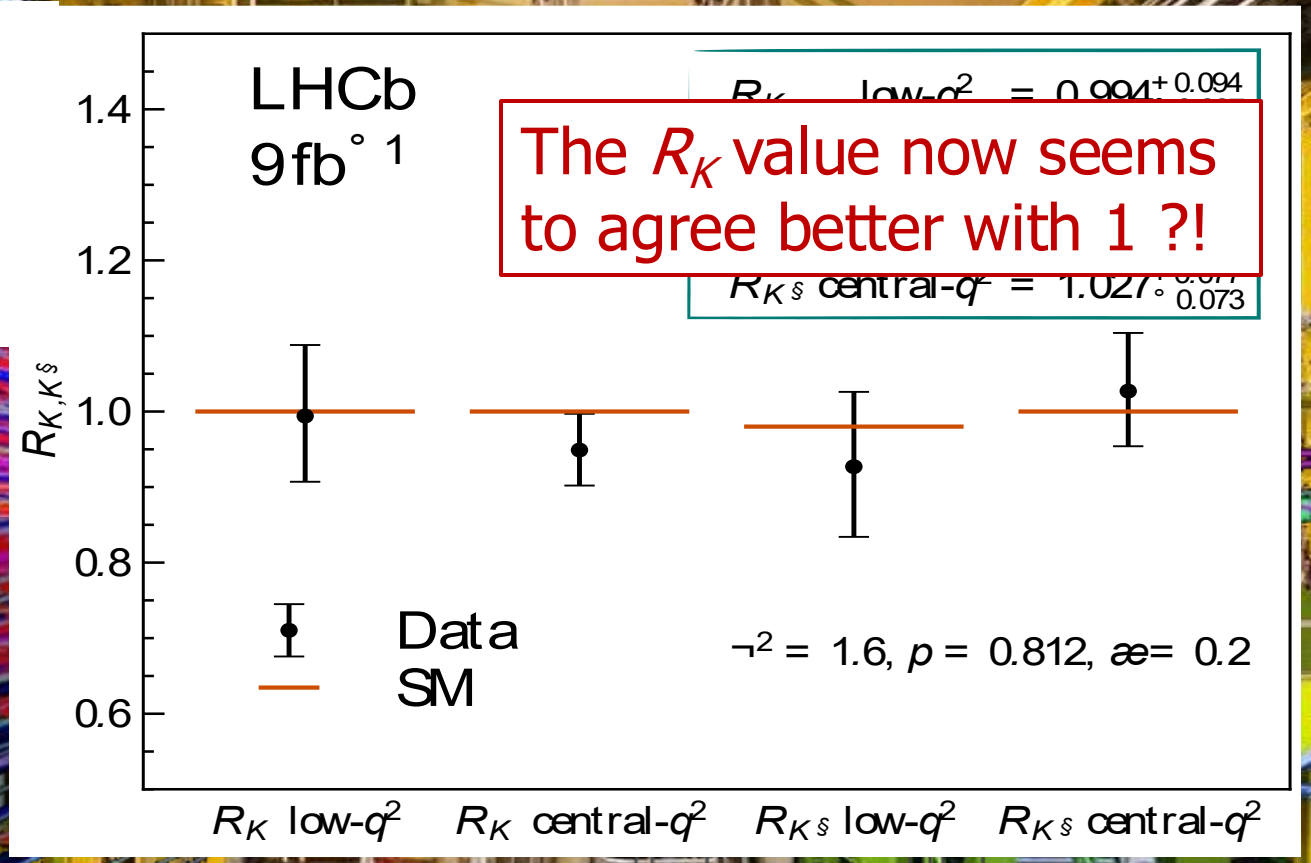
December 2022: new measurement for electrons...



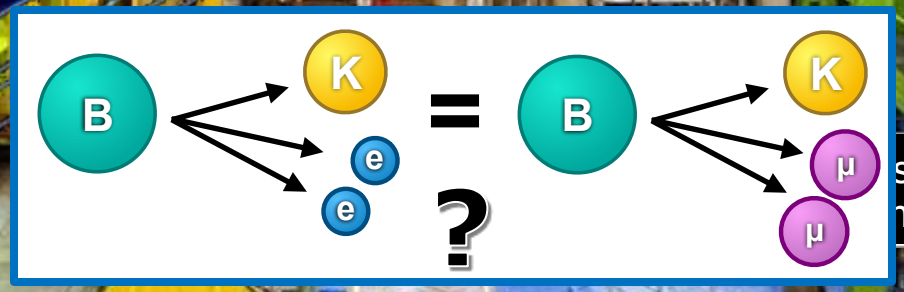
sep 2010 19:49:24
n 79646 Event 143858637



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

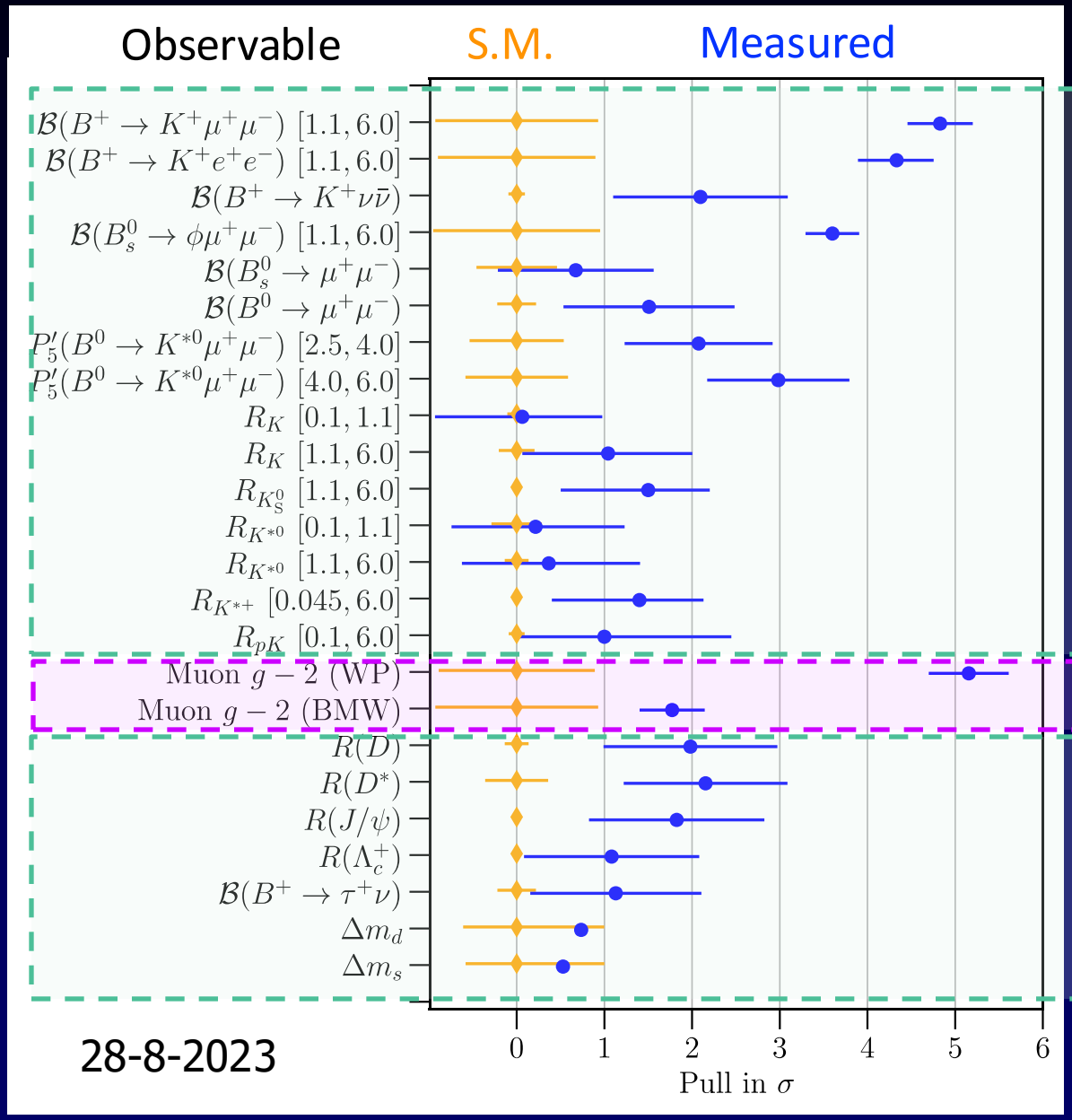


December 2022: new measurement for electrons...



sep 2010 19:49:24
n 79646 Event 143858637

But for ***muons*** more and more measurements disagree with SM!



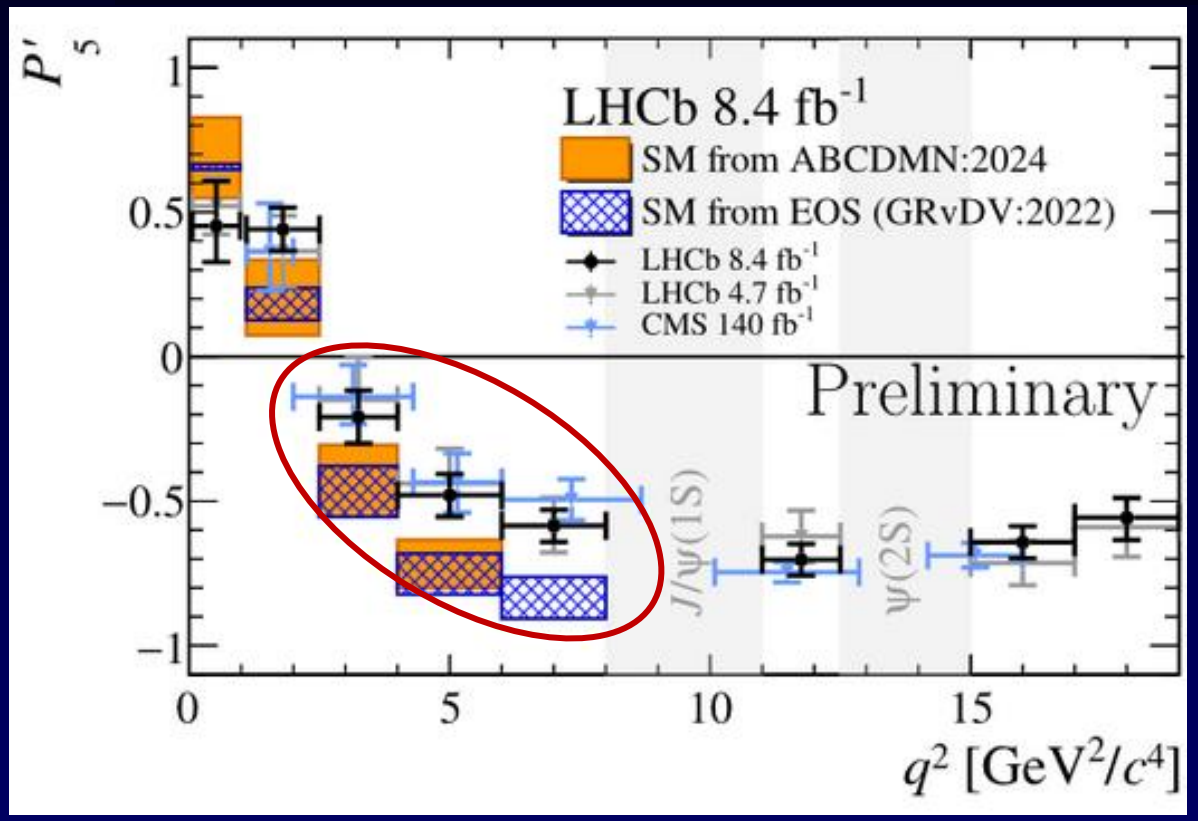
LHCb results

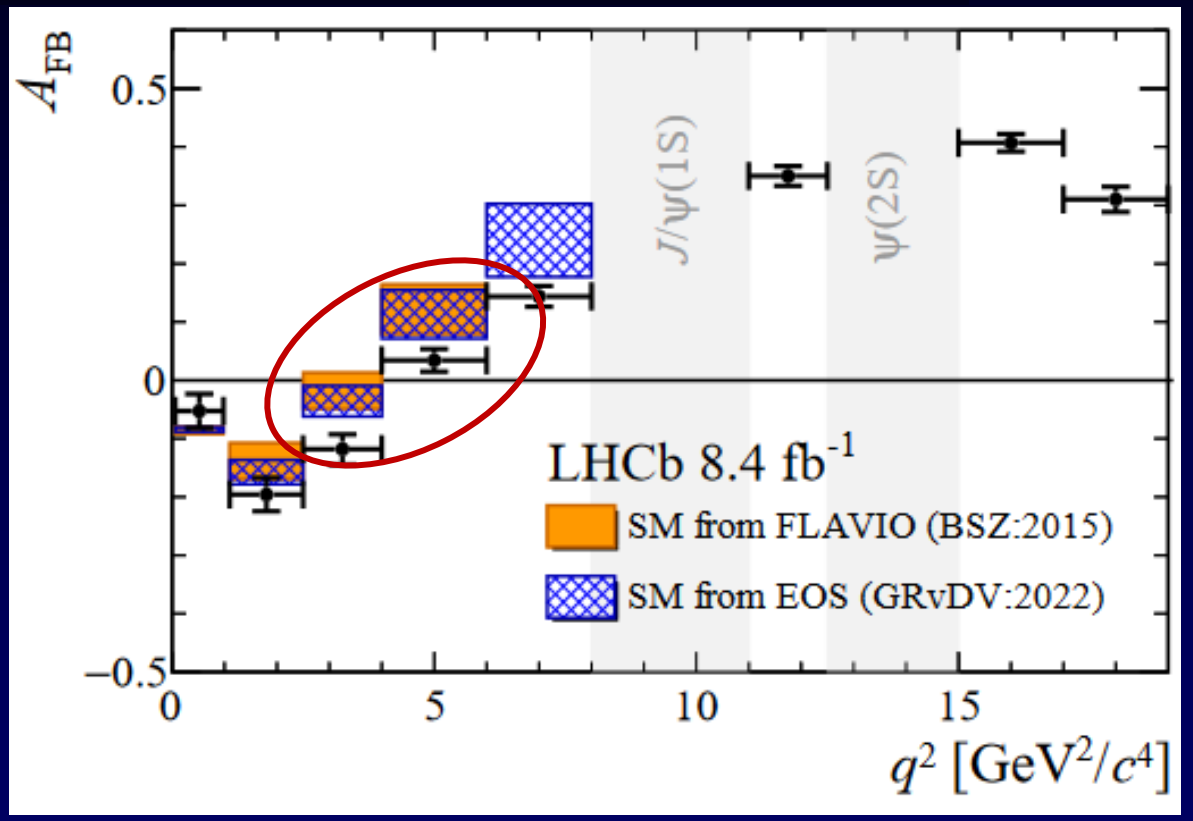
Fermilab g-2 result

The puzzle deepens further!

Observing deviations from the Standard Model predictions

1 Sept 2025: new LHCb results for $B \to K\mu\mu$



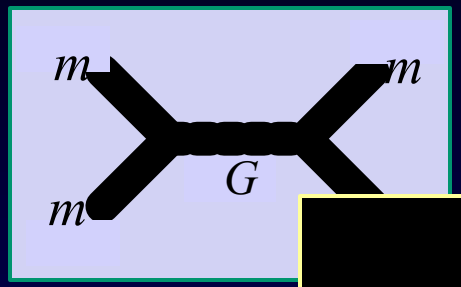


The effects are not yet statistically convincing but seem to have consistent pattern pointing towars a potential new force… ?

Four(?) fundamental forces of nature

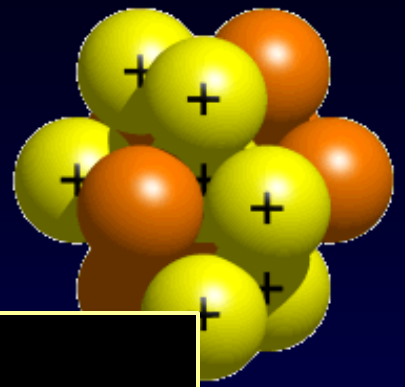
Graivity:

Quantum
Graviton exchange?

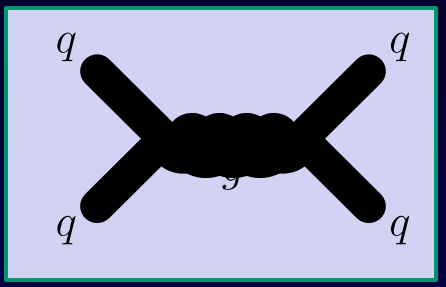


Acts on particles with mass

Strong nuclear force:



Quantum
gluon exchange:

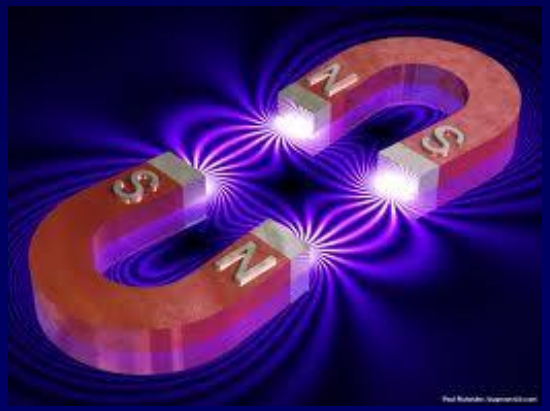


n quarks

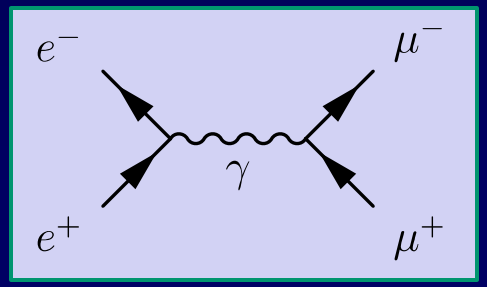
+ ???

Fifth force?

Electromagnetism:



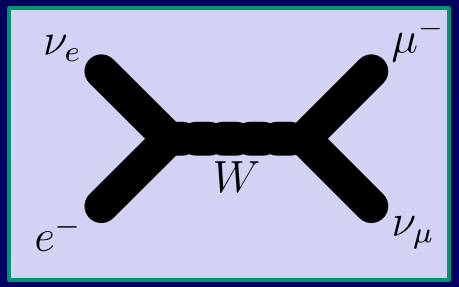
Quant
photon ex



Acts on all charged particles

clear force:

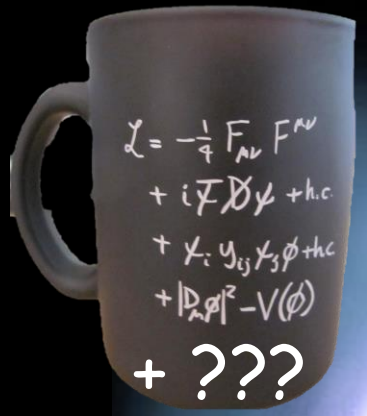
Quantum
W, Z exchange:



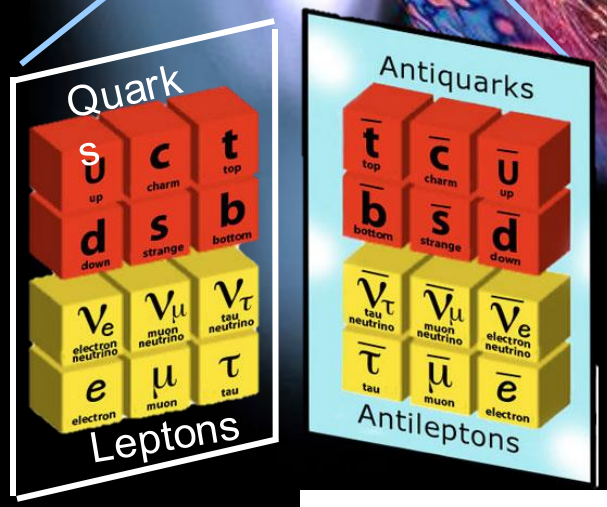
Acts on all particles

How did antimatter disappear in the early universe?

Why is there something rather than nothing?

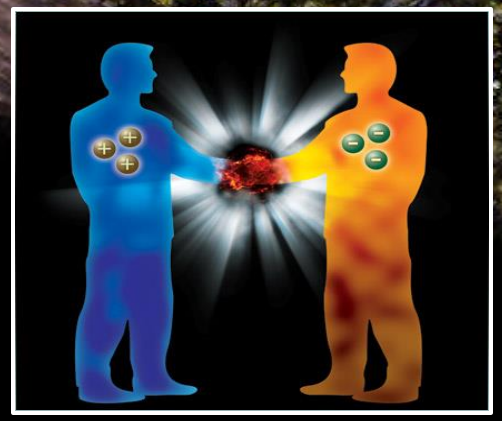


Through a fifth force during the Big Bang…?



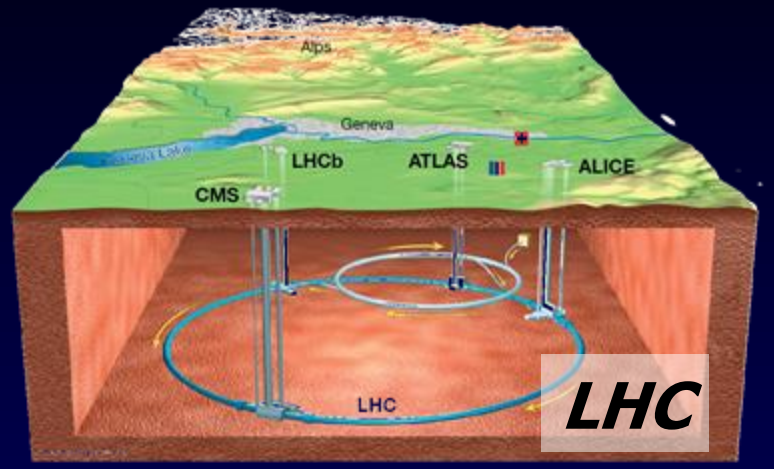
50.000001%

49.999999%



Future: "Circles and Triangles"

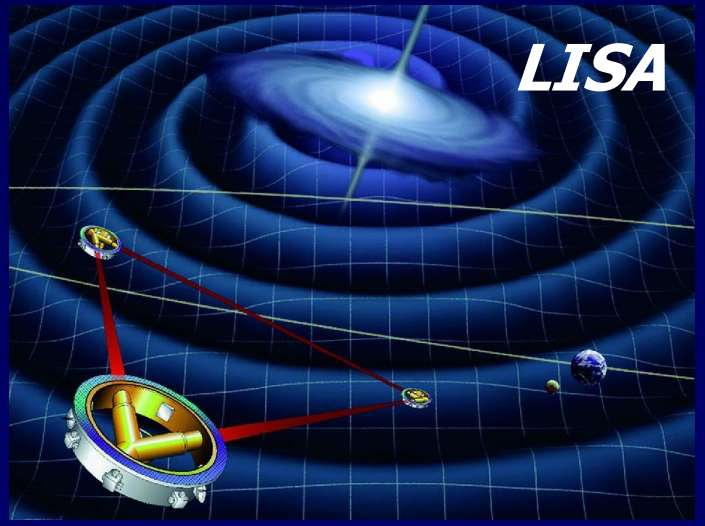
Particle Colliders: simulating physics of the Big Bang …

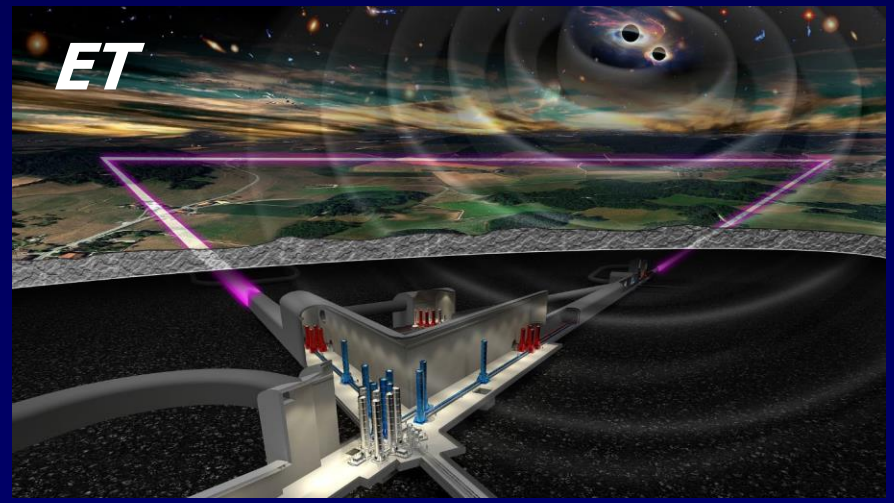


LHC


FCC

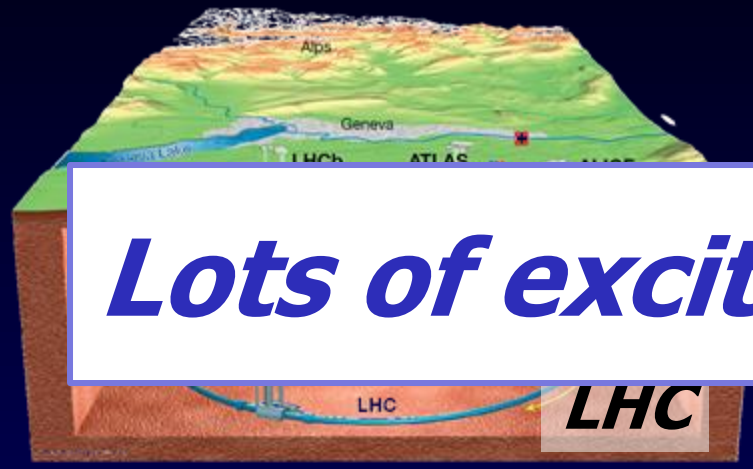
Gravitation-detectors: listening to the Big Bang…


LISA


ET

Future: "Circles and Triangles"

Particle Colliders: simulating physics of the Big Bang …



LHC


FCC

Lots of exciting research ongoing

Gravitation-detectors: listening to the Big Bang…


LISA


ET

Thanks for your attention!


HORSEY
©2012 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!"
WE'RE OUT OF BEER.
PERSPECTIVE IS EVERYTHING.

1897

Electron, e

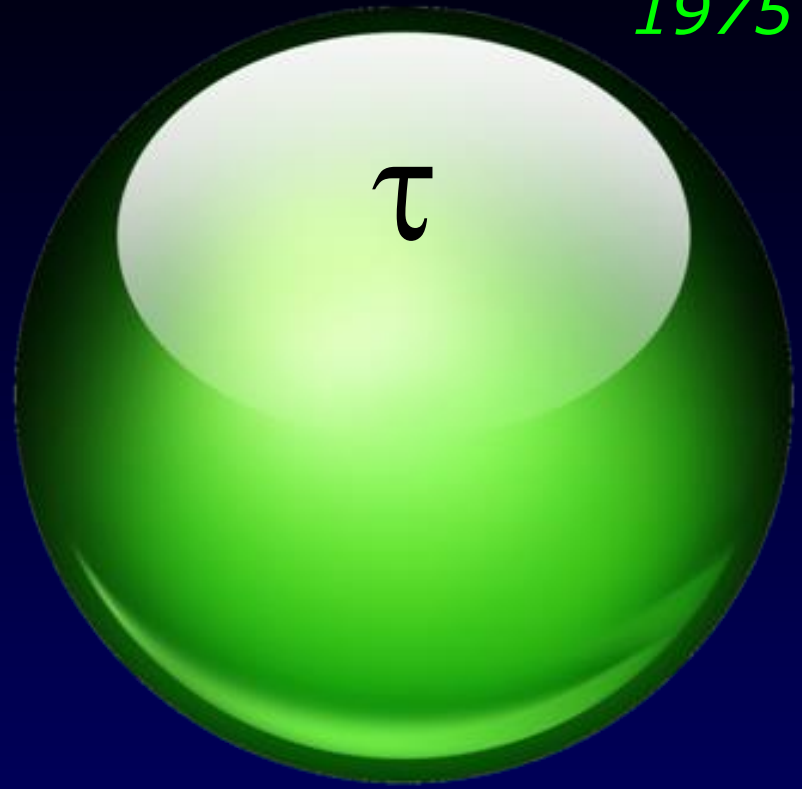
Spin ½
Charge −1
Lifetime ∞
Mass .511 MeV

1937

Muon, μ

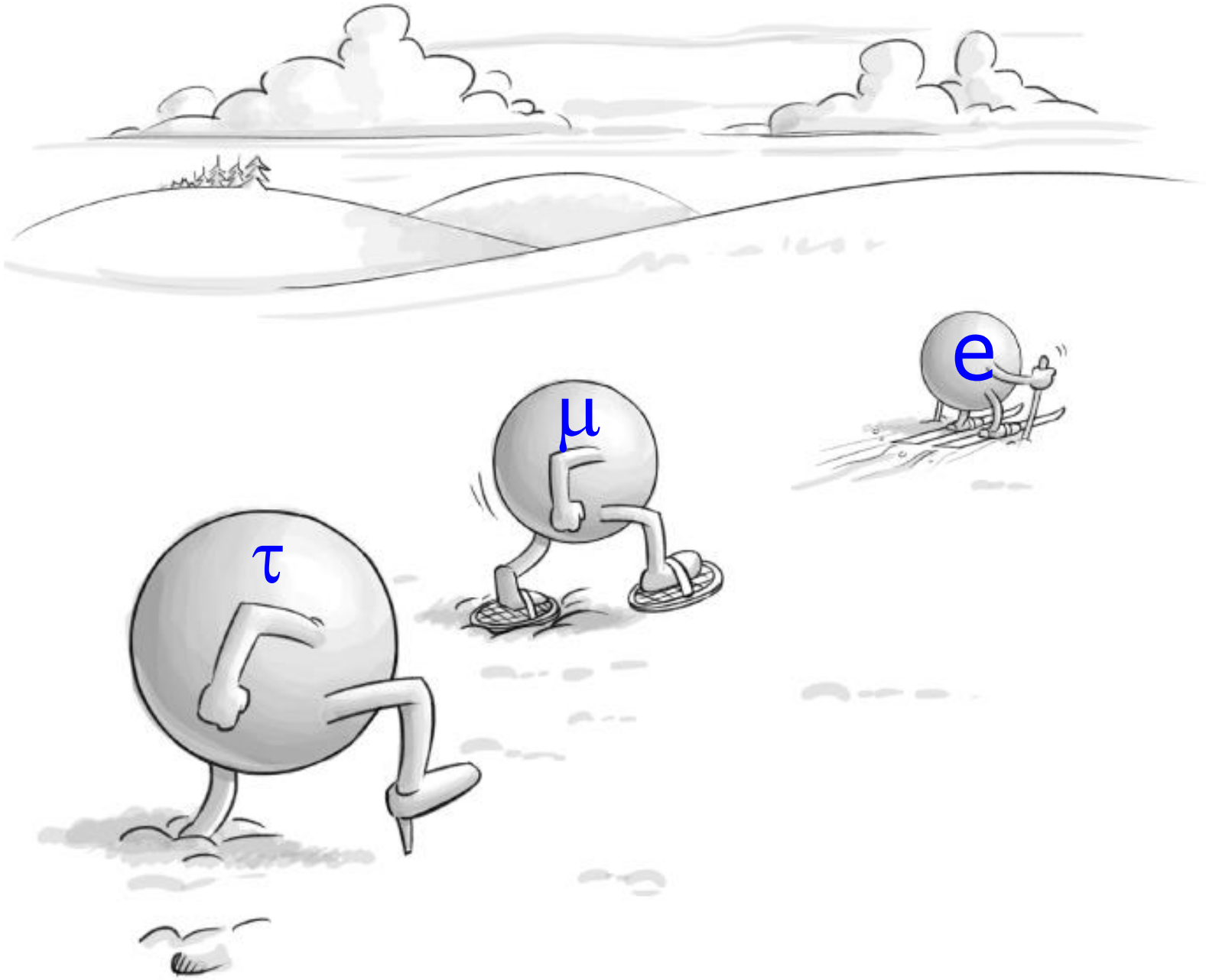
Spin ½
Charge −1
Lifetime 2.2 μs
Mass 106 MeV

1975



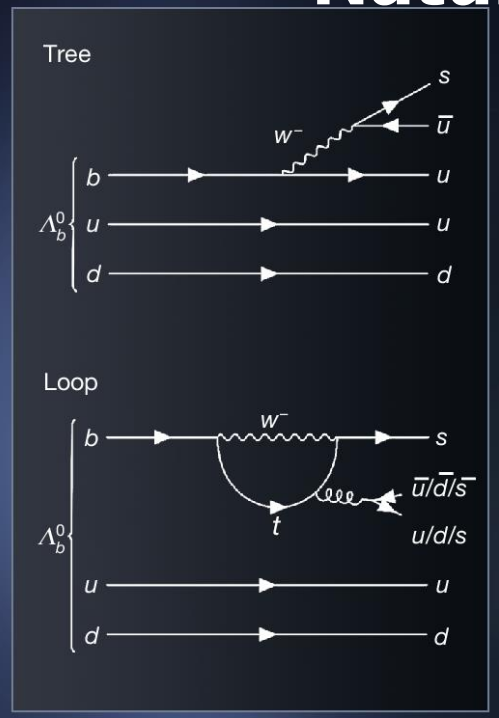
Tau, τ

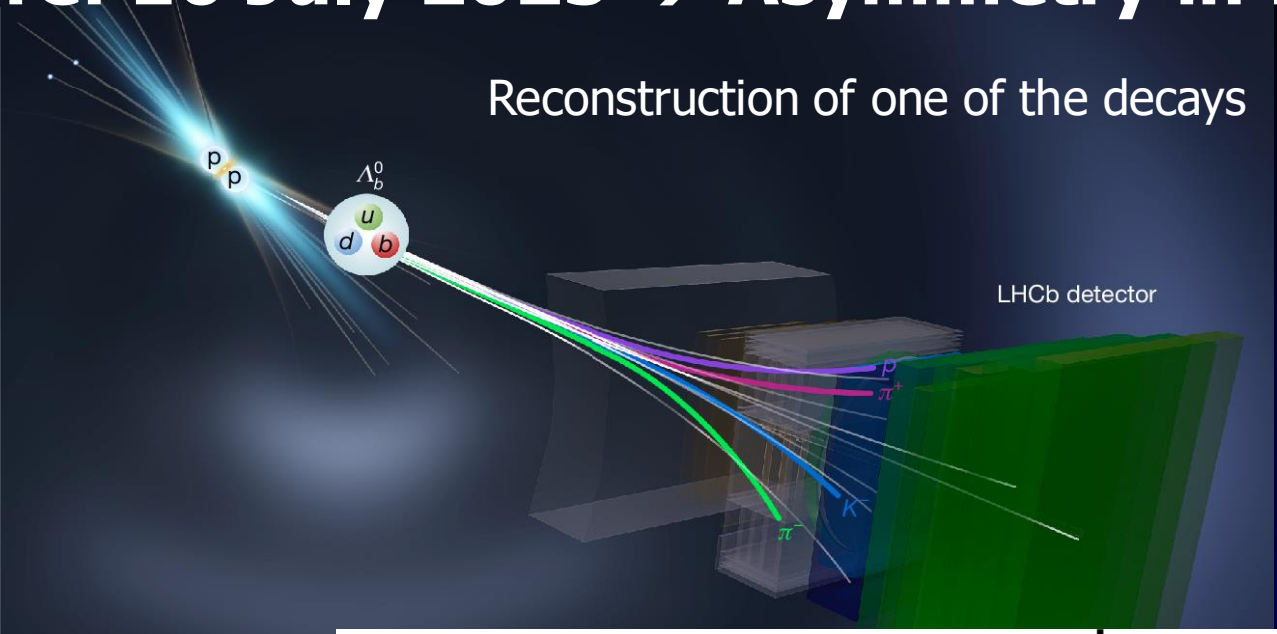
Spin ½
Charge −1
Lifetime 290 fs
Mass 1777 MeV



© Jean-Paul Keulen

Nature: 16 July 2025 → Asymmetry in Baryons!!



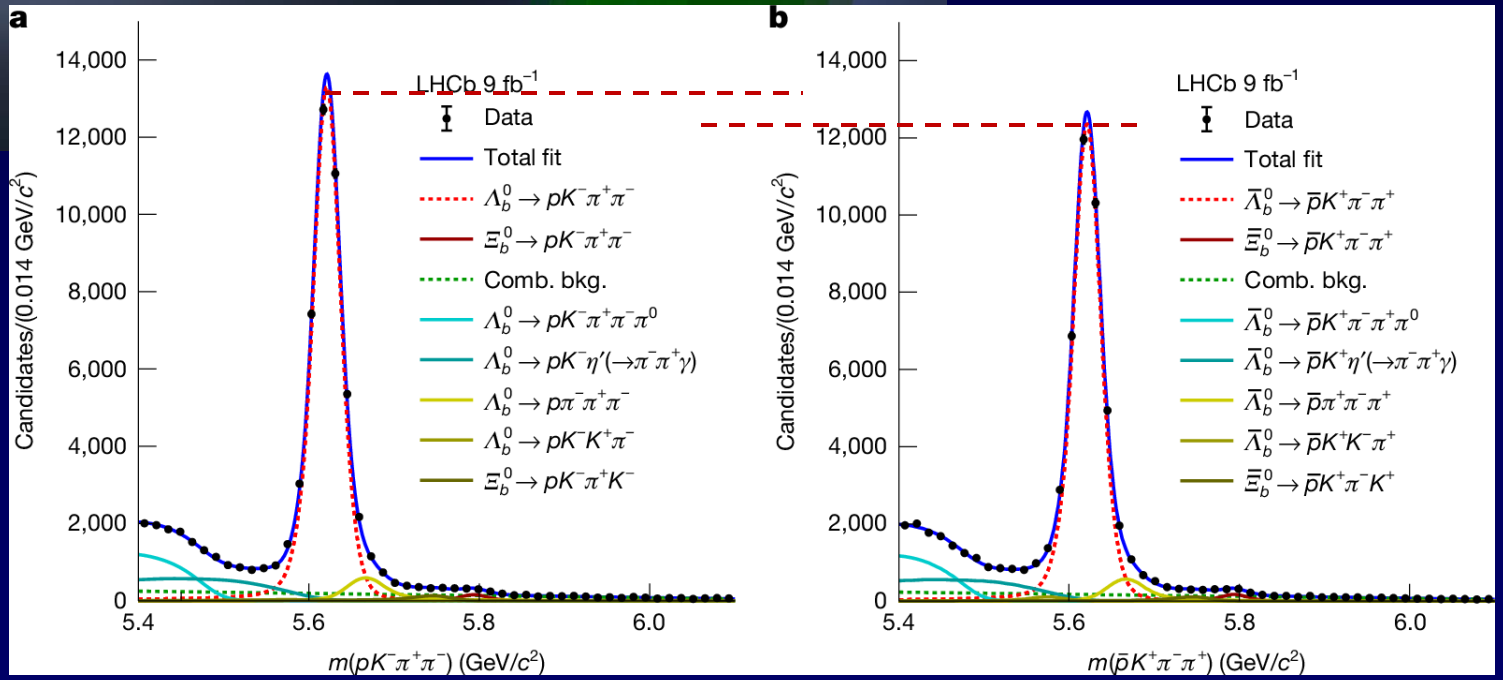


Baryons are particle like proton and neutron. Constituetns of our atoms

Matter vs antimatter asymmetry:

$A_{CP} = (2.45 \pm 0.46 \pm 0.1)\%$

➔ 2.5 %



Twee weeks later in Fermilab … muon magnetic moment?!

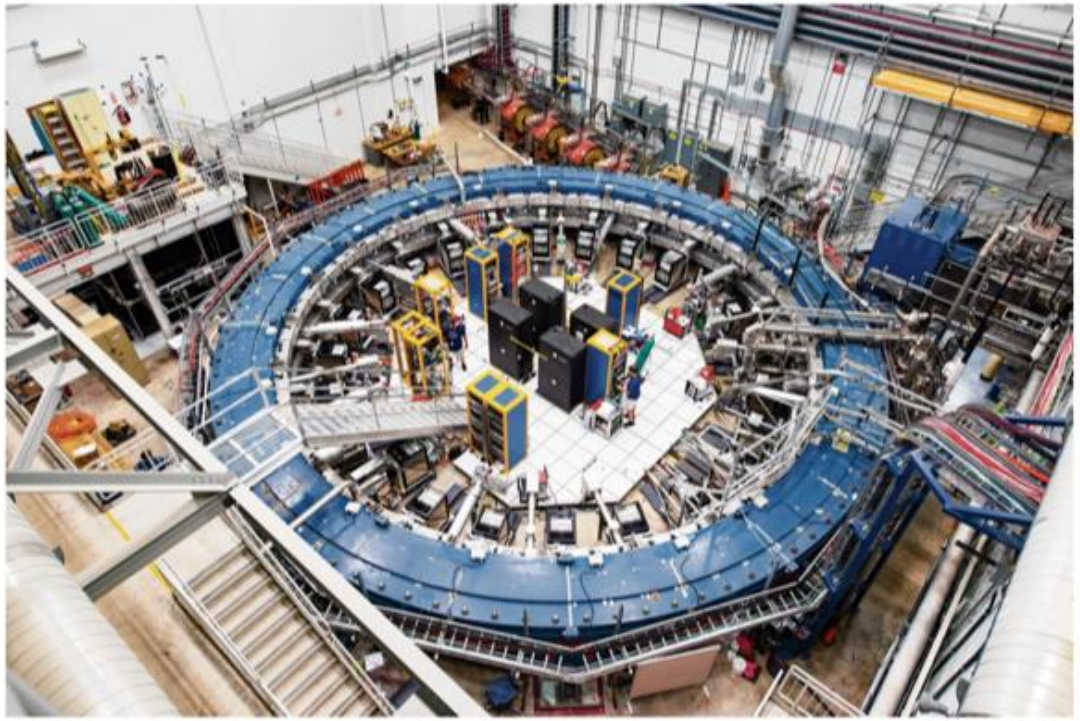
"Again trouble in Standard model"

Menu nrc

Opnieuw barstje in standaardmodel van deeltjesfysica

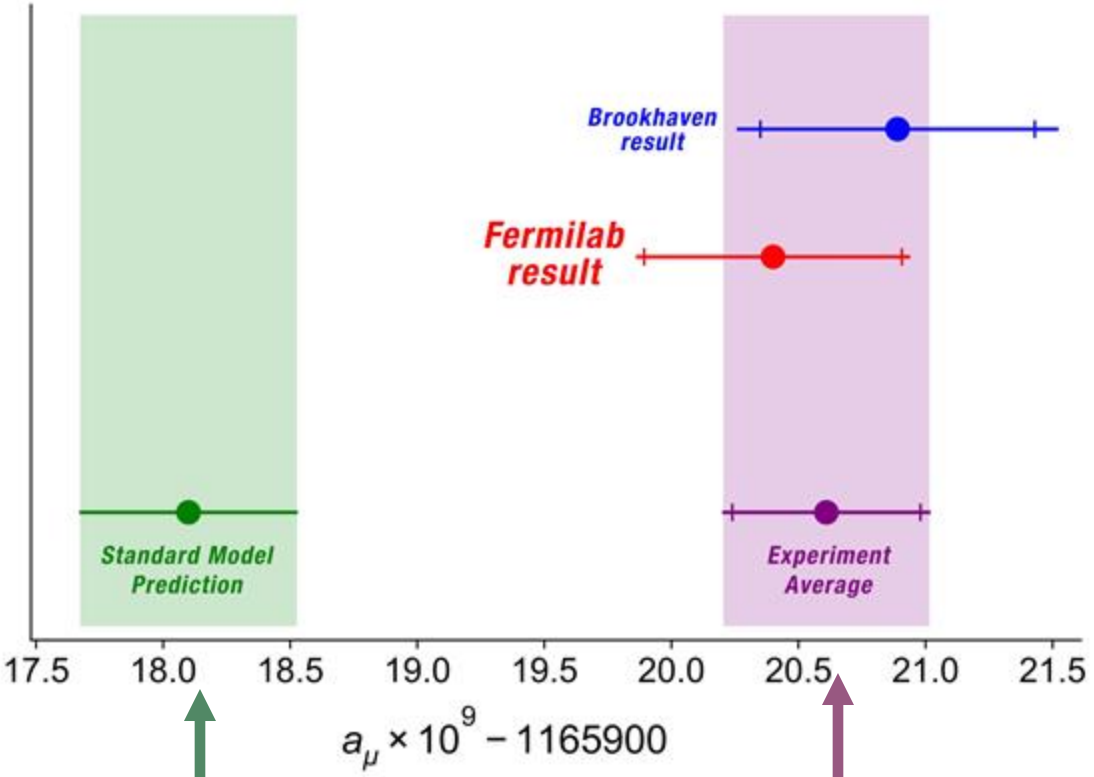
Natuurkunde Gaat het standaardmodel van de deeltjesfysica breken? Resultaten uit een Amerikaans experiment leiden tot opwinding.

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

Standard Model cannot explain measurement
➔ A new force acting up?!

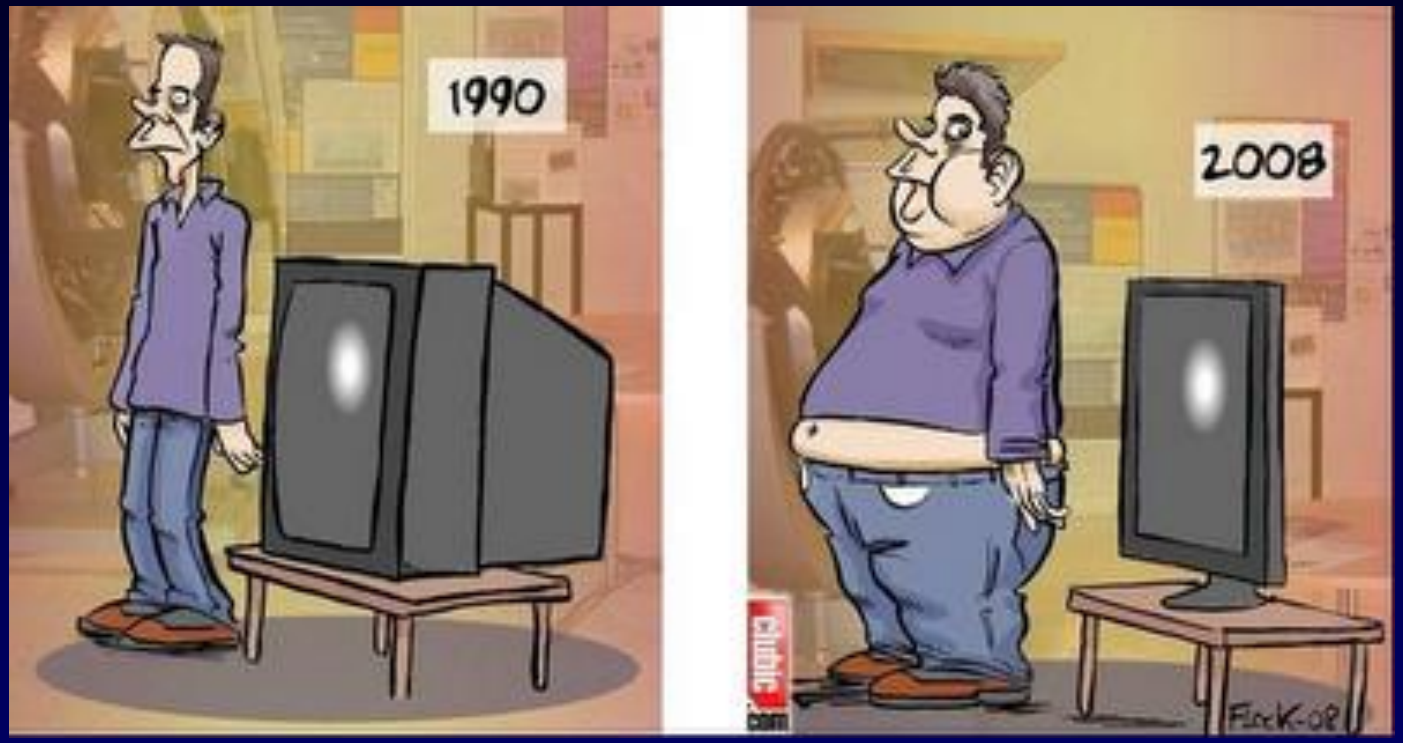


Standard Model prediction

"$g-2$"

Experimental measurement

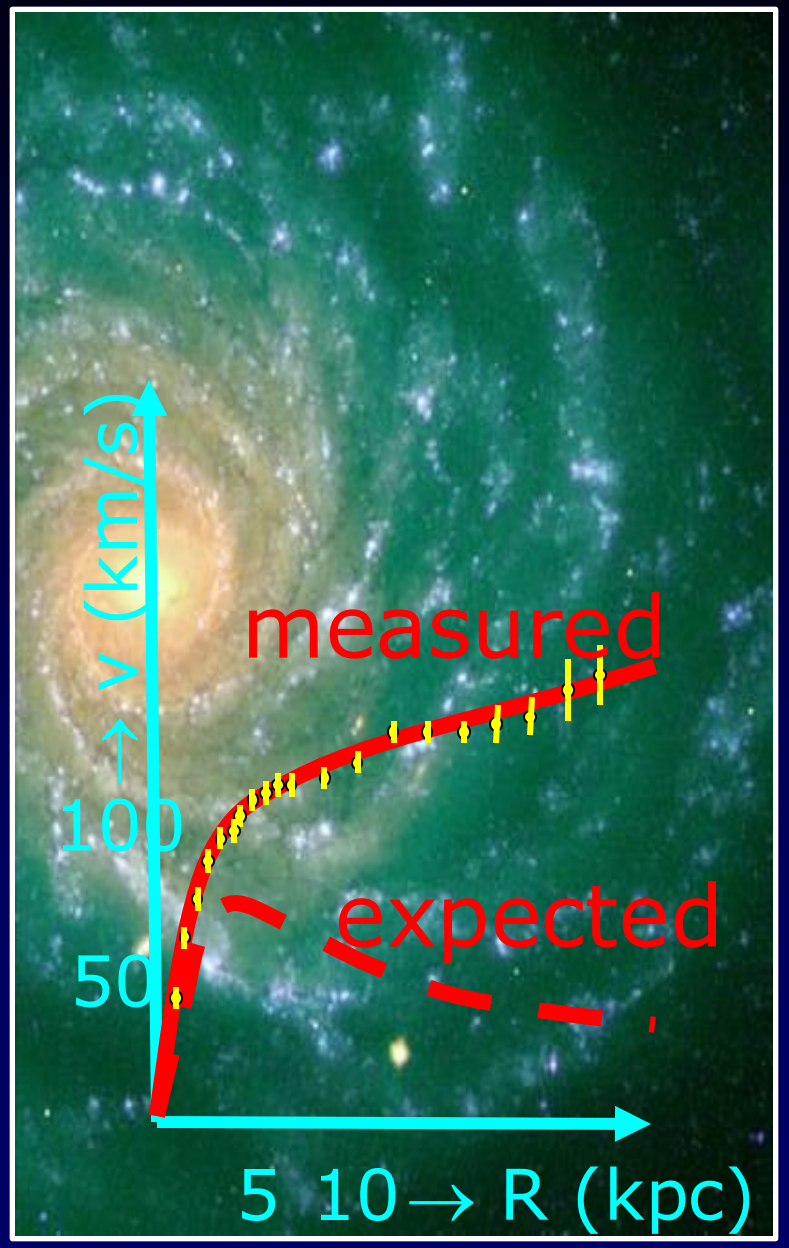
Applications of Science



Dark Matter

Visible “baryonic” matter

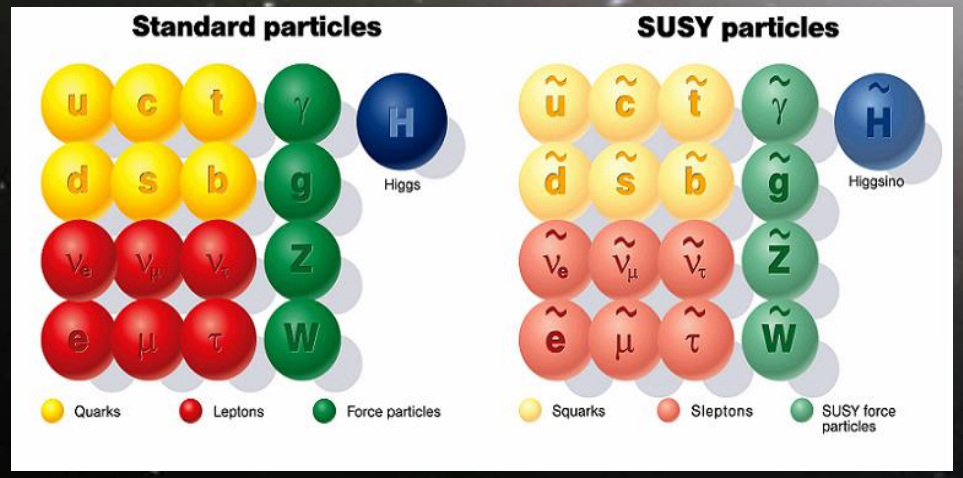
Spiralarm rotation and gravitational lensing



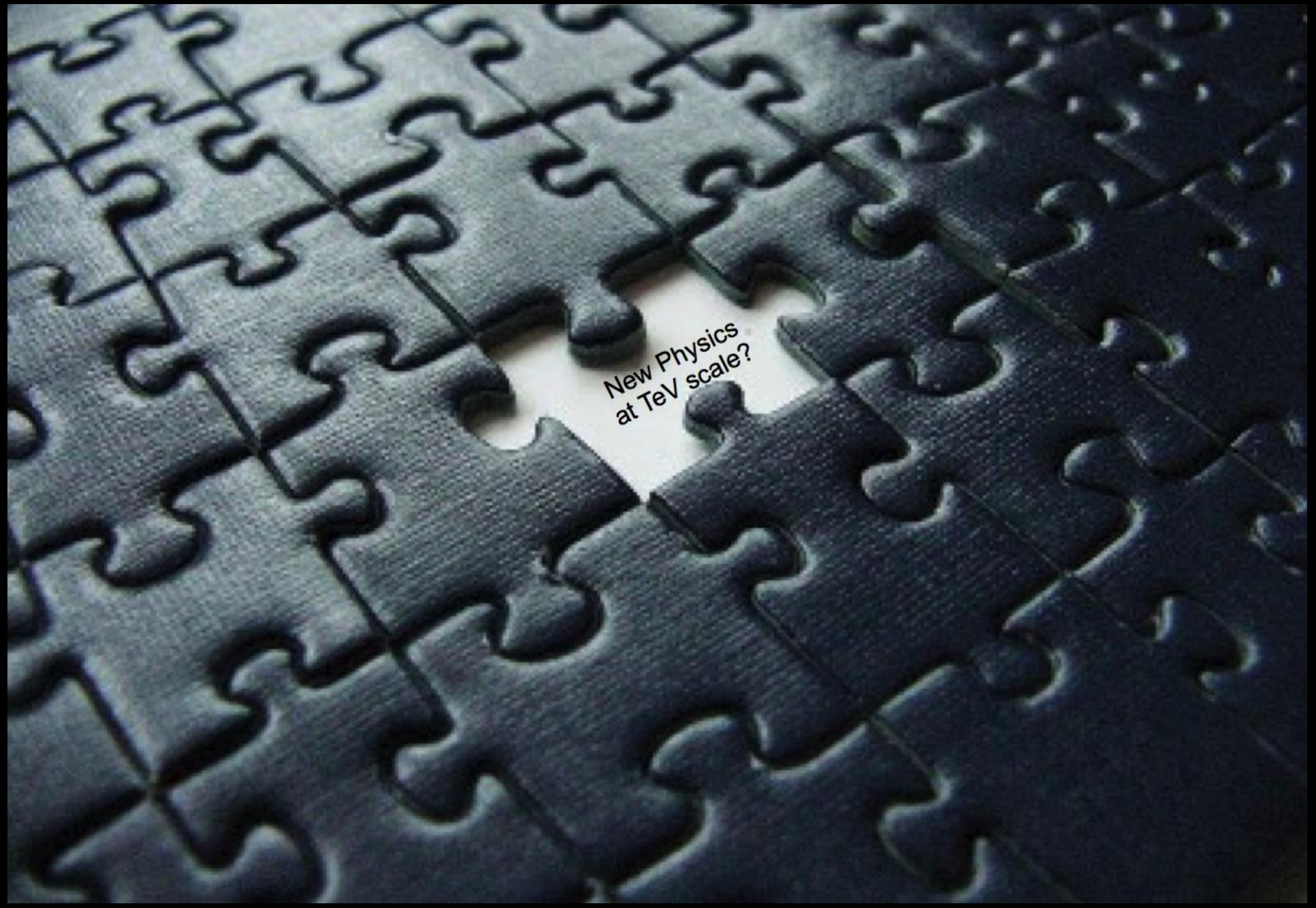
Dark Matter

He H

dark energy & dark matter



“The Dark Side rules the Universe”


New Physics
at TeV scale?