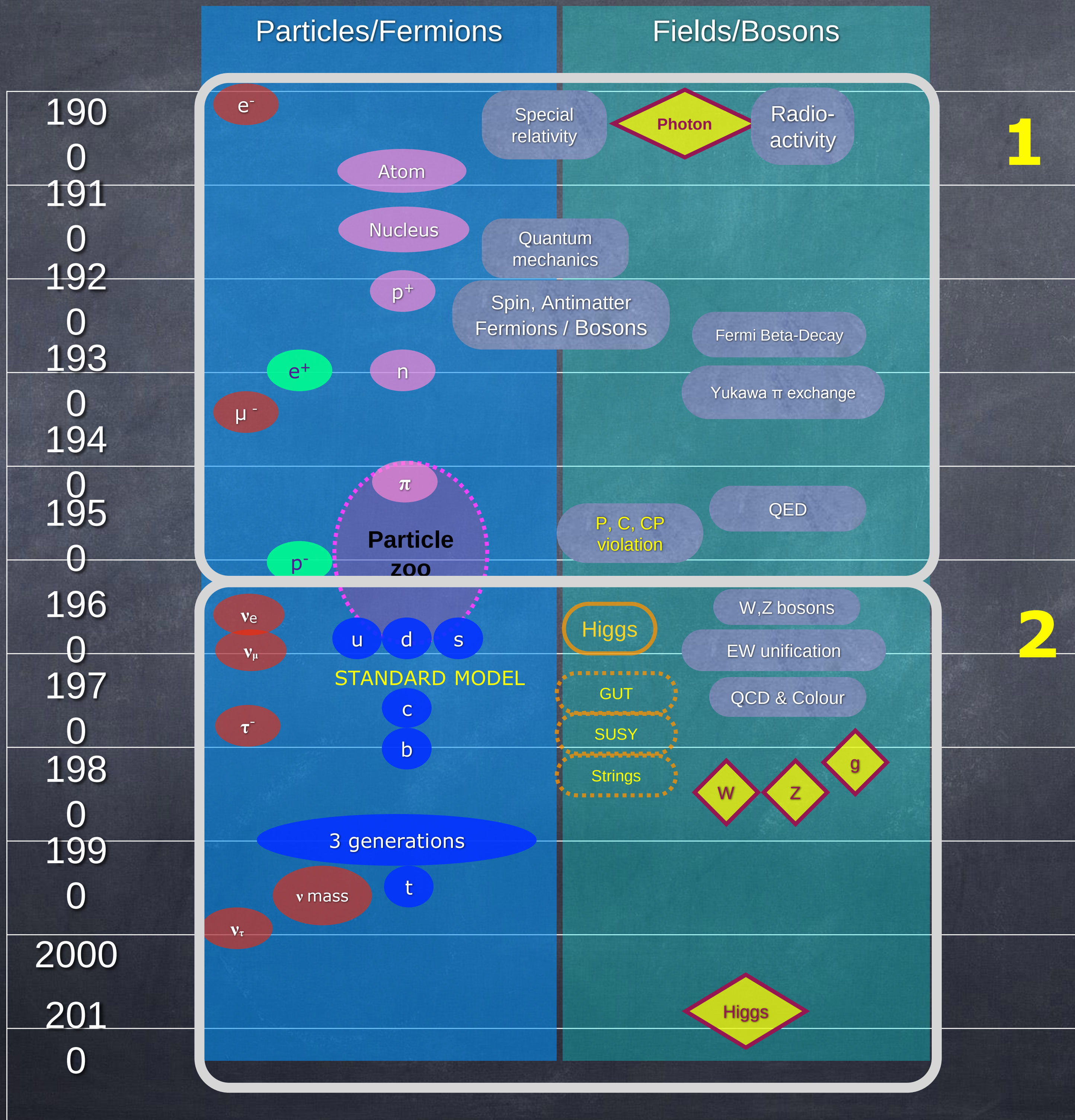
STRUCTURE OF MATTER

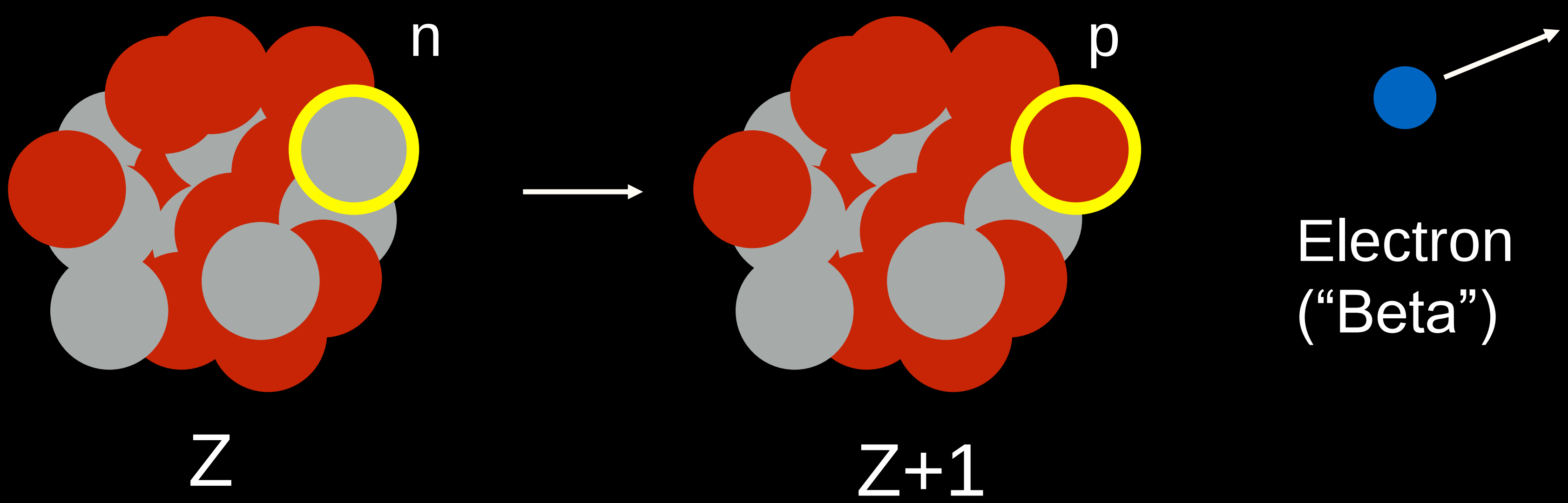
Discoveries and Mysteries

Part 2

Rolf Landua
CERN

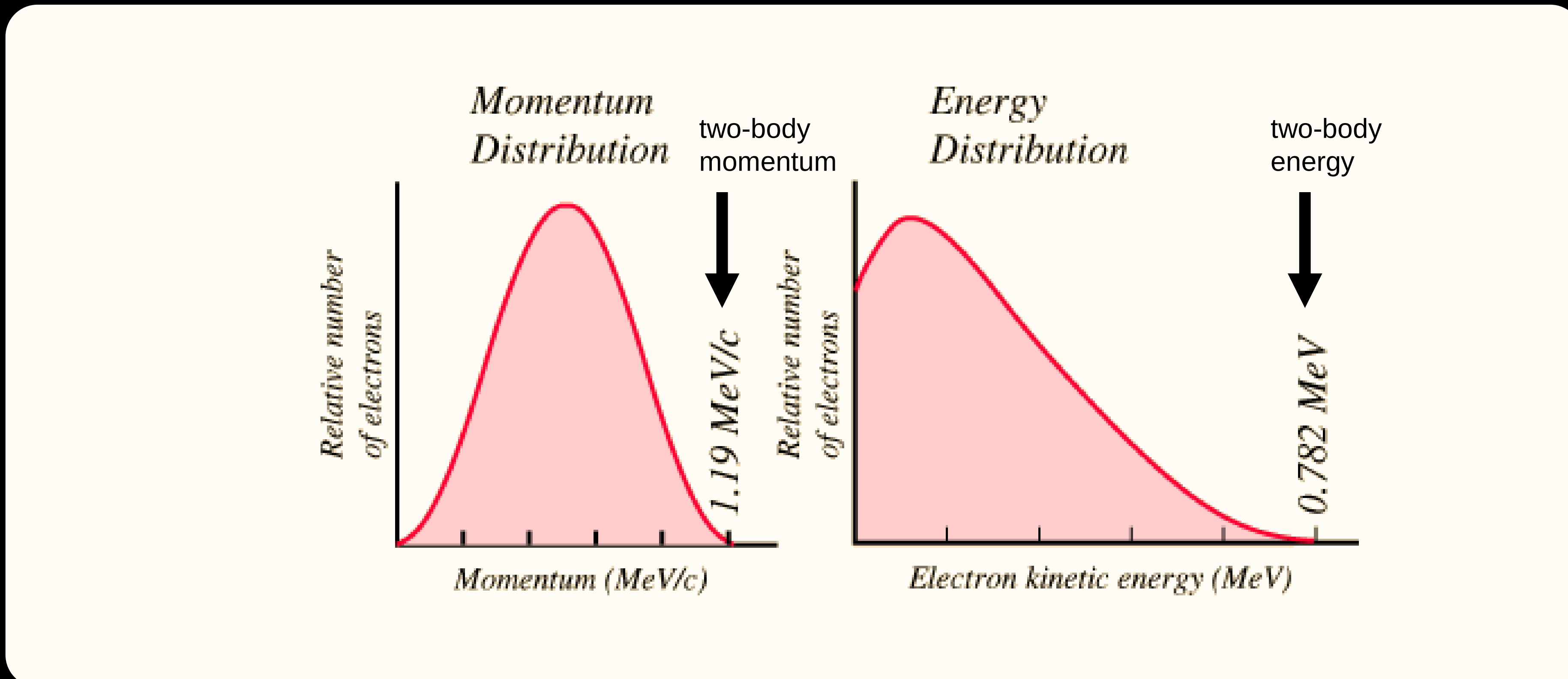

Particles/Fermions
Fields/Bosons
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
1
2
e^-
Atom
Nucleus
p^+
e^+
n
μ^-
π
Particle zoo
p^-
ν_e
ν_μ
u
d
s
STANDARD MODEL
c
b
τ^-
3 generations
ν mass
t
ν_τ
Special relativity
Photon
Radio-activity
Quantum mechanics
Spin, Antimatter Fermions / Bosons
Fermi Beta-Decay
Yukawa π exchange
QED
P, C, CP violation
Higgs
W,Z bosons
EW unification
QCD & Colour
GUT
SUSY
Strings
g
W
Z
Higgs

WEAK INTERACTION



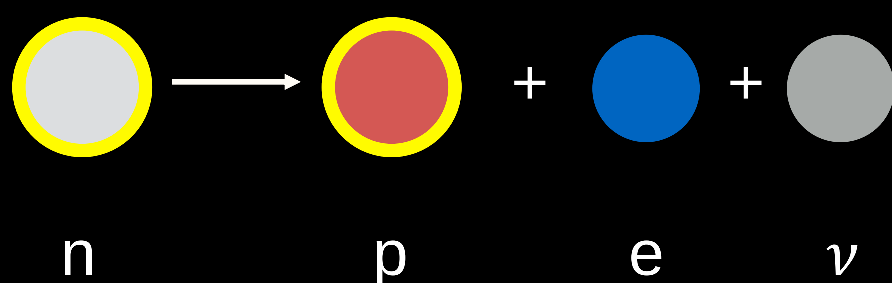
Henri Becquerel (1900): Beta-radiation = electrons

Two-body reaction? But electron energy/momentum is continuous:

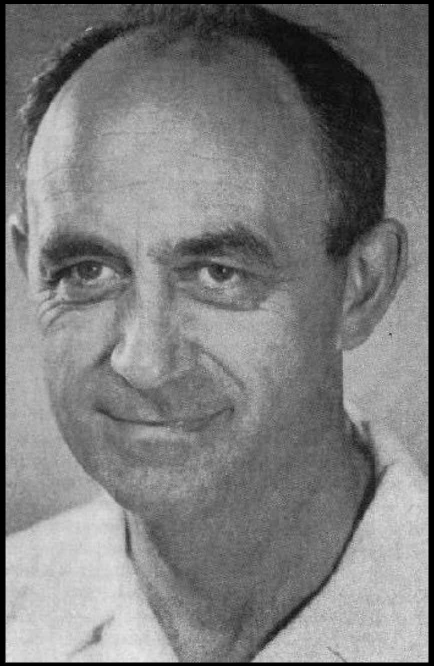


W. Pauli (1930) postulate:

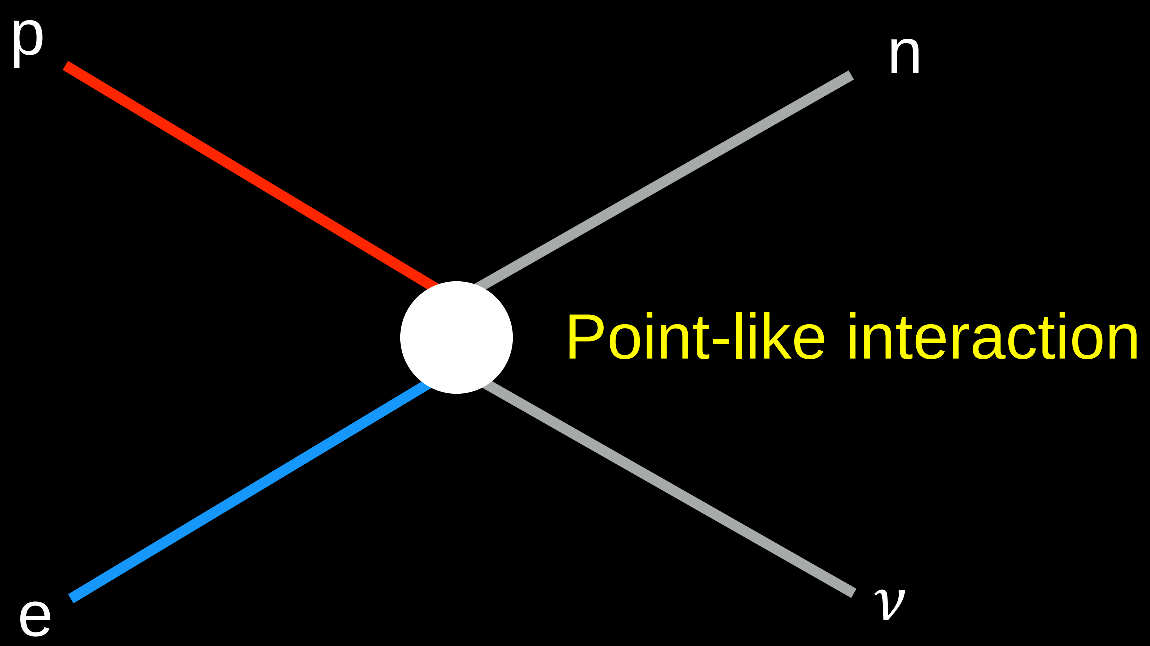
- there is a third particle involved
- neutral
- very small or zero mass
- “Neutrino” (Fermi)



FERMI THEORY (1934)



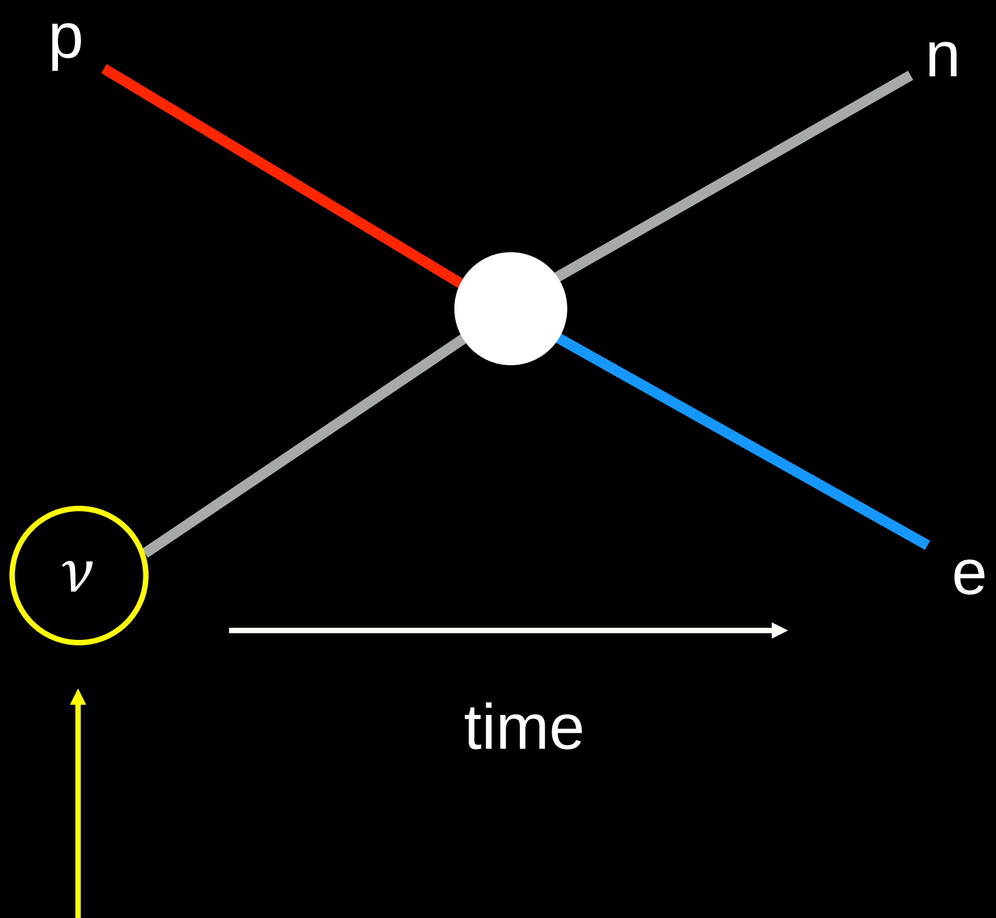
Enrico Fermi



W = Overlap of the four wave functions x Universal constant G

$G \sim 10^{-5} / M^2_p$ = “Fermi constant”

FERMI: PREDICTION ABOUT NEUTRINO INTERACTIONS



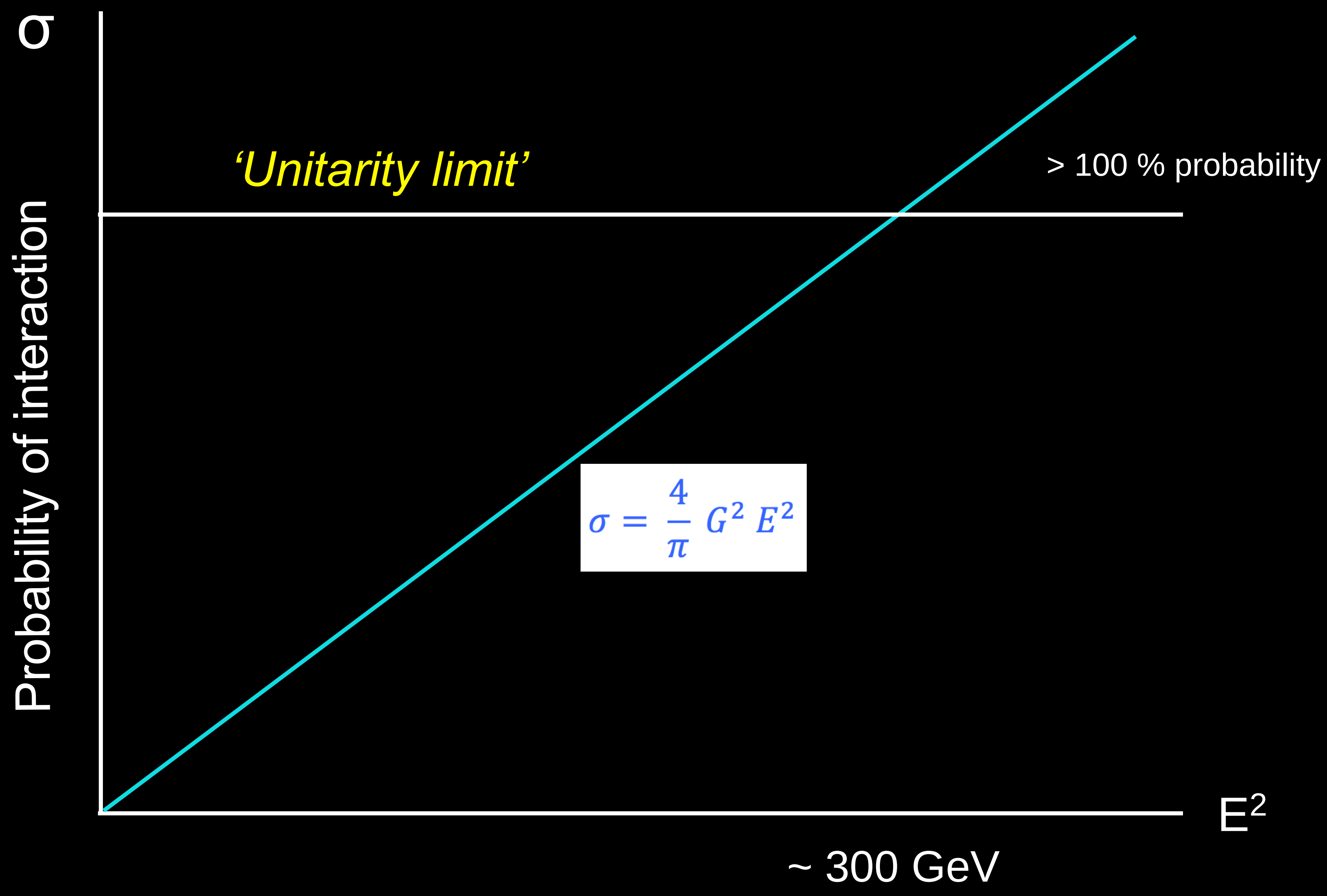
$$\sigma = \frac{4}{\pi} G^2 E^2$$

E = 1 MeV: $\sigma = 10^{-43}$ cm^2

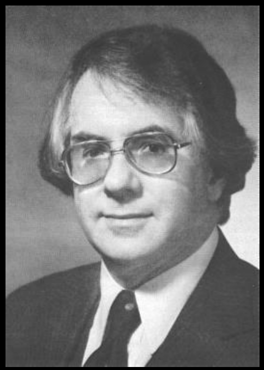
(Range: 10^{20} cm ~ 100 l.yr)

Reines, Cowan (1956):
Neutrino 'beam' from reactor
Reactions prove existence of neutrinos

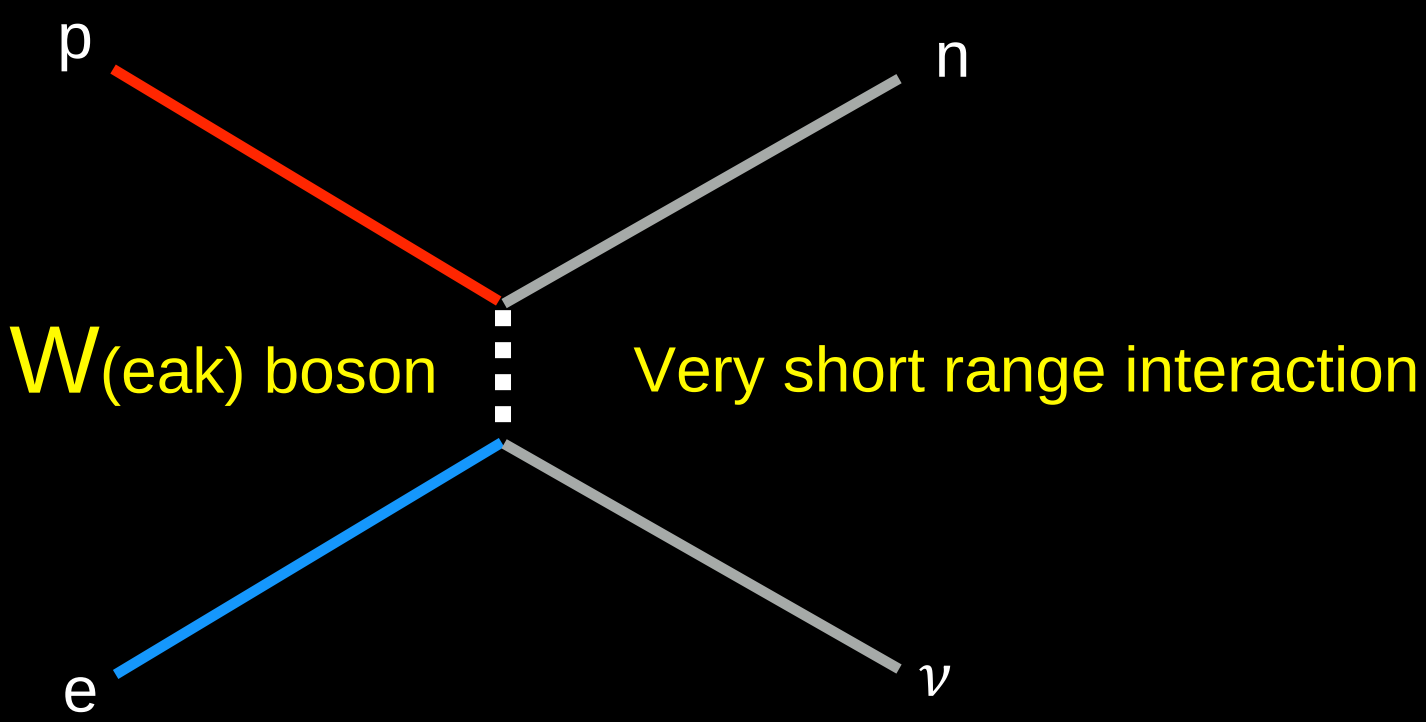
and then ….. THE PREDICTION FAILED !!



GLASGOW REFORMULATES FERMI THEORY (1958)

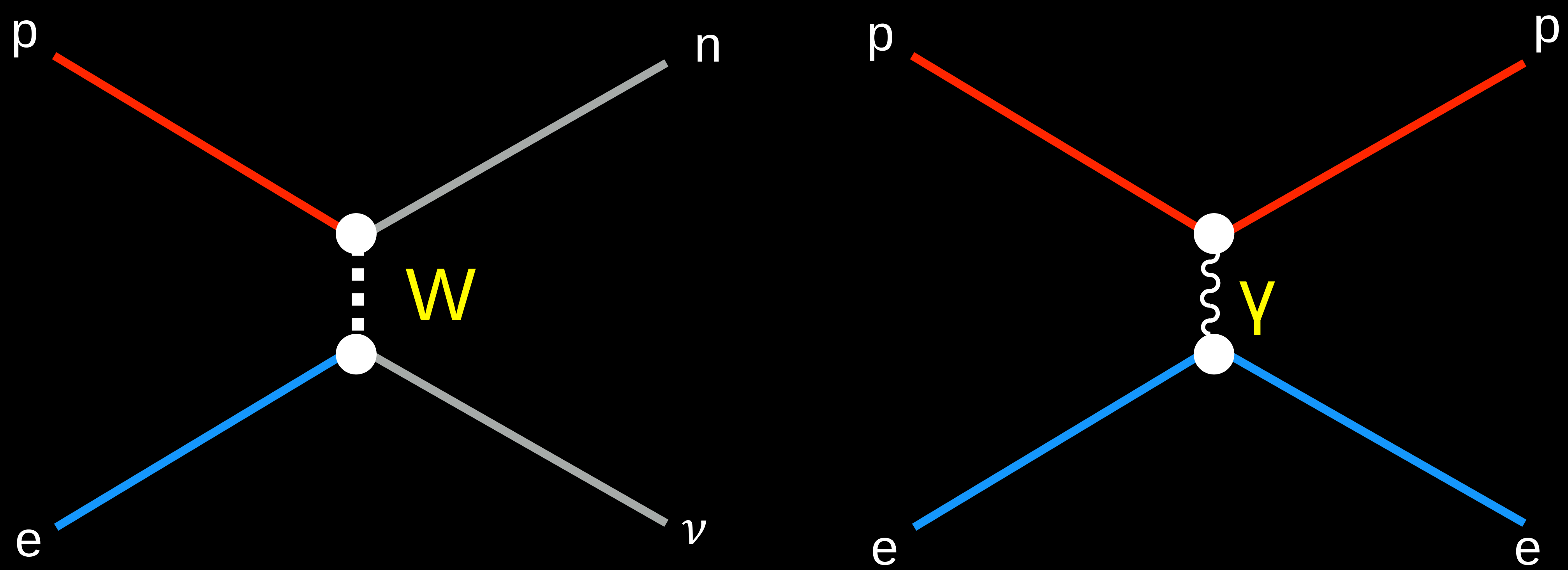


S. Glashow



If mass of W boson ~ 100 GeV : theory o.k.

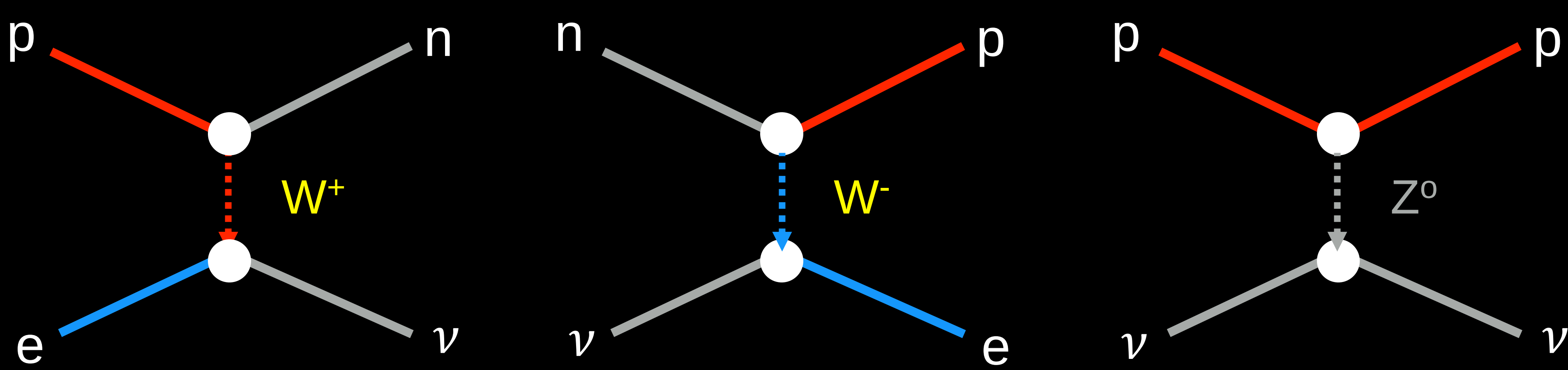
Interesting: at high energies, coupling of weak and e.m. interaction similar !



Leads to idea of ELECTRO-WEAK UNIFICATION
(Glashow, Salam, Weinberg)

ELECTRO-WEAK UNIFICATION

“Charged currents” ($W^{\pm}$) and “Neutral Current” (Z^o)

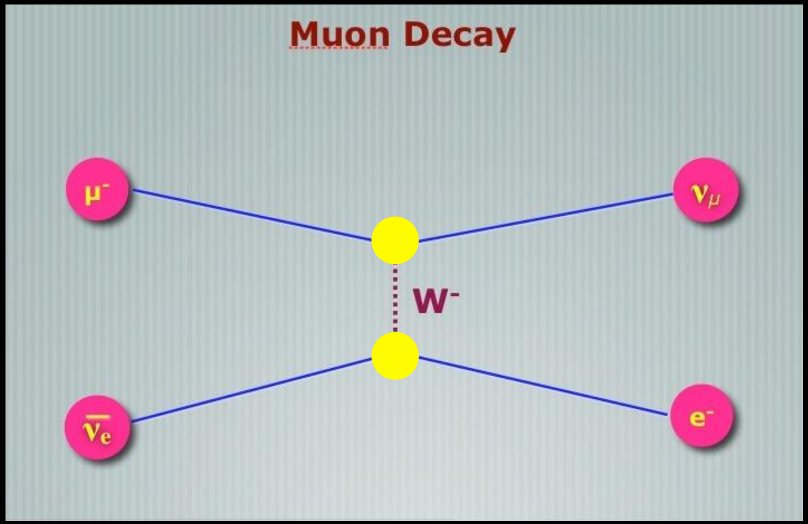


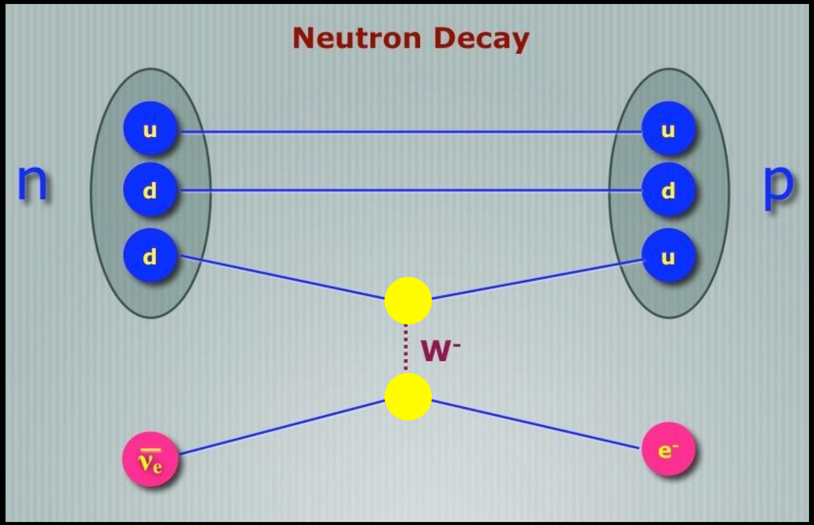
$p + e \longrightarrow n + \nu$ $\quad$ $n + \nu \longrightarrow p + e$ $\quad$ $p + \nu \longrightarrow p + \nu$

Z^o is the ‘massive’ brother of the photon

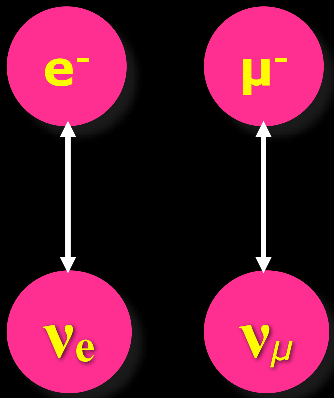
Idea of “weak symmetry breaking” through ‘Higgs mechanism’

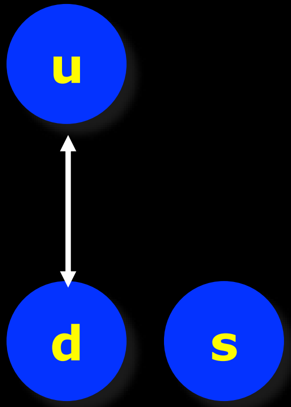
Interesting: electroweak interaction is (approx.) the same for leptons and quarks !



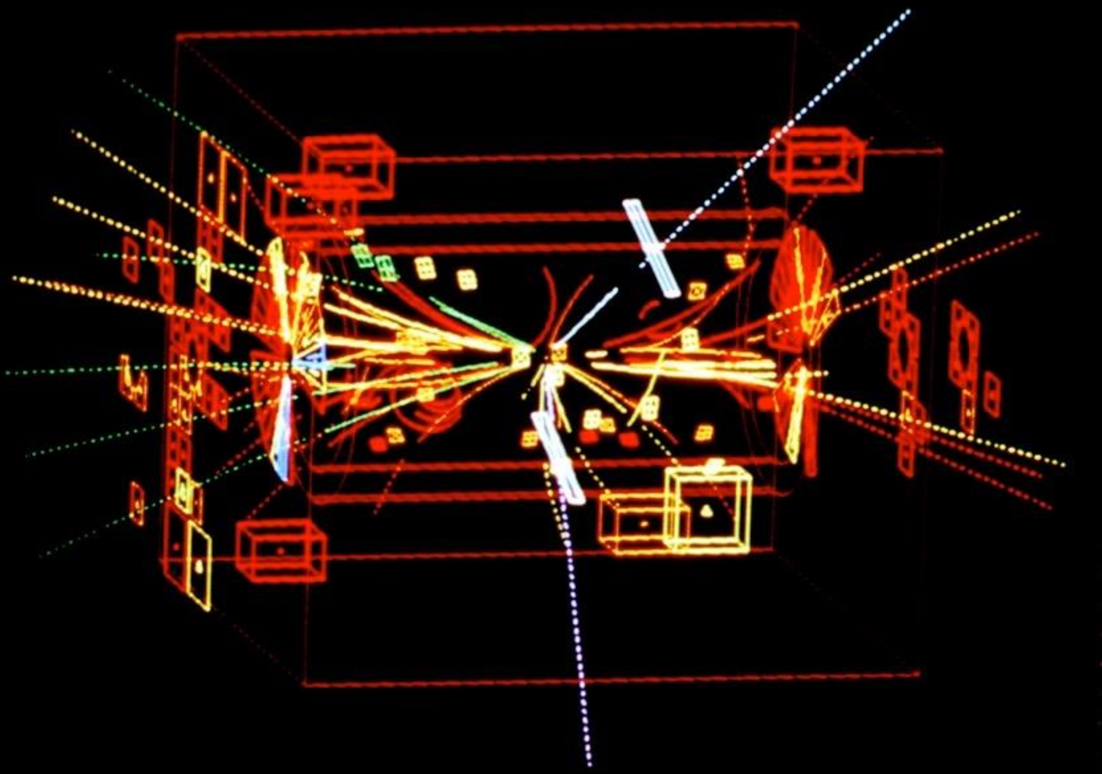


"Universality*" - transmitted by W, Z bosons, same strength!





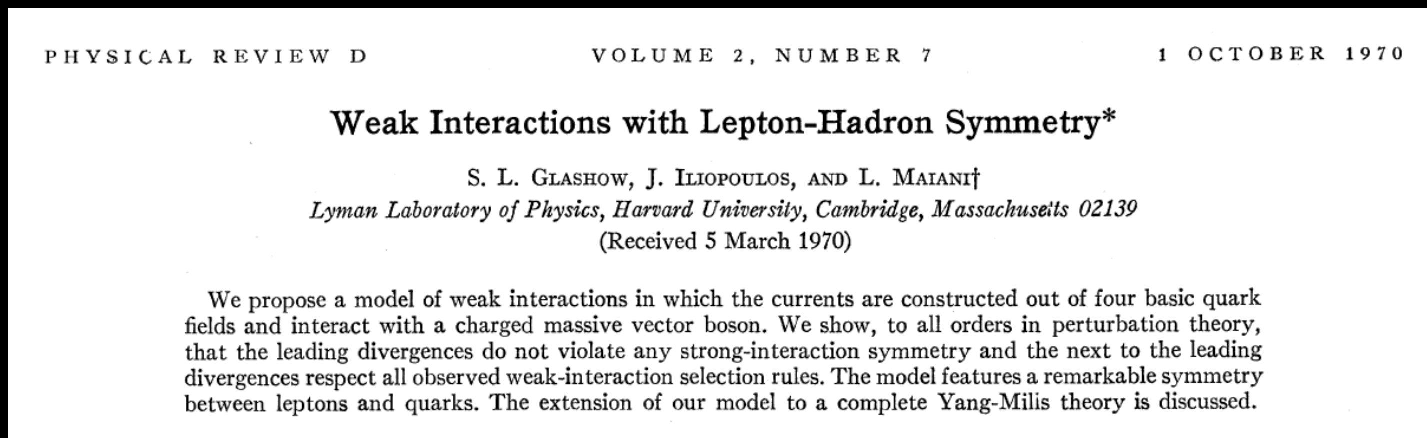
DISCOVERY OF THE WEAK BOSONS AT CERN (1983)



(C. Rubbia, S. van der Meer)

THE CHARM QUARK

A legendary paper, predicting the ‘charm’ quark (Glashow, Iliopoulos, Maiani)



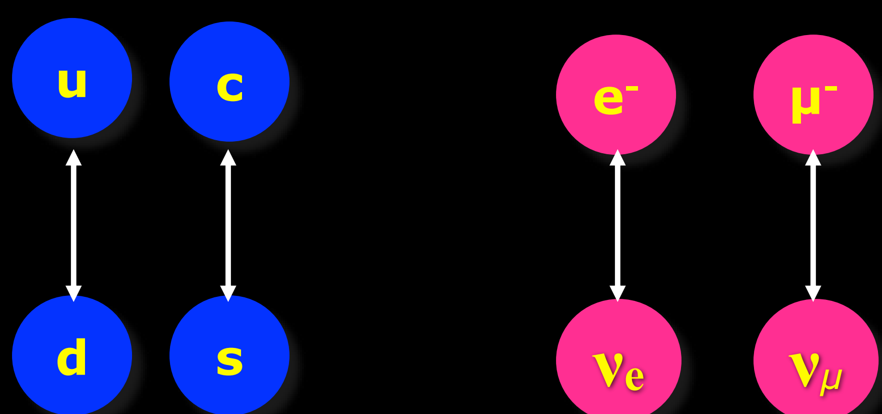
PHYSICAL REVIEW D VOLUME 2, NUMBER 7 1 OCTOBER 1970

Weak Interactions with Lepton-Hadron Symmetry*

S. L. GLASHOW, J. ILIOPOULOS, AND L. MAIANI†
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02139
(Received 5 March 1970)

We propose a model of weak interactions in which the currents are constructed out of four basic quark fields and interact with a charged massive vector boson. We show, to all orders in perturbation theory, that the leading divergences do not violate any strong-interaction symmetry and the next to the leading divergences respect all observed weak-interaction selection rules. The model features a remarkable symmetry between leptons and quarks. The extension of our model to a complete Yang-Milis theory is discussed.

Quarks Leptons



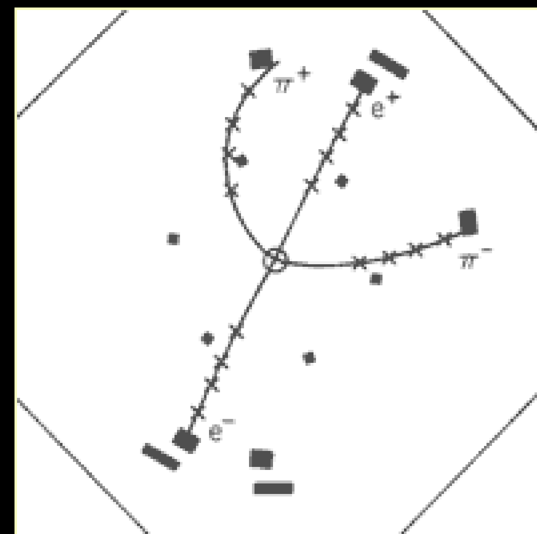
The charm quark was discovered (J/ψ meson = charm-anticharm bound state) in November 1974

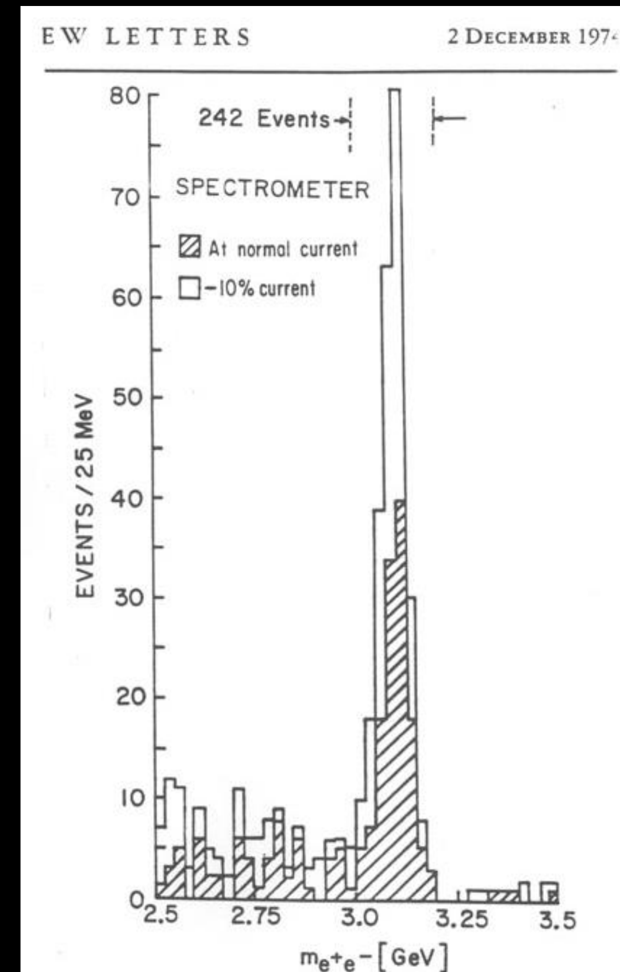
Discovery of the ‘charm’ quark 1974

1974

“NOVEMBER REVOLUTION”
(11 November 1974)

'Psi' am SLAC (Burt Richter)
'J' at Brookhaven (Sam Ting)
Compromise: J/Psi





ᶠIG. 2. Mass spectrum showing the existence of *J*. sults from two spectrometer settings are plotted owing that the peak is independent of spectrometer rrents. The run at reduced current was taken two nths later than the normal run.

“Extremely” long lifetime (~10^{-20} sec)
Decay only possible through electroweak interaction

Surprise, surprise: THIRD FAMILY

1975

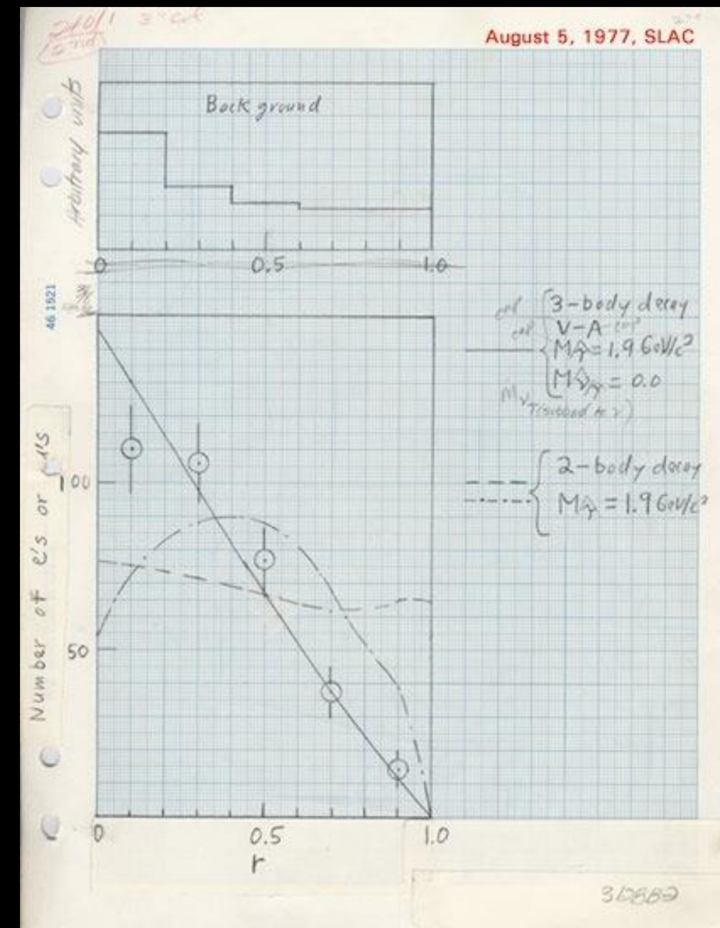
Martin Perl

A new 'heavy electron' with 3500 x m_e

... and who ordered that?

THERE MUST BE A WHOLE NEW FAMILY

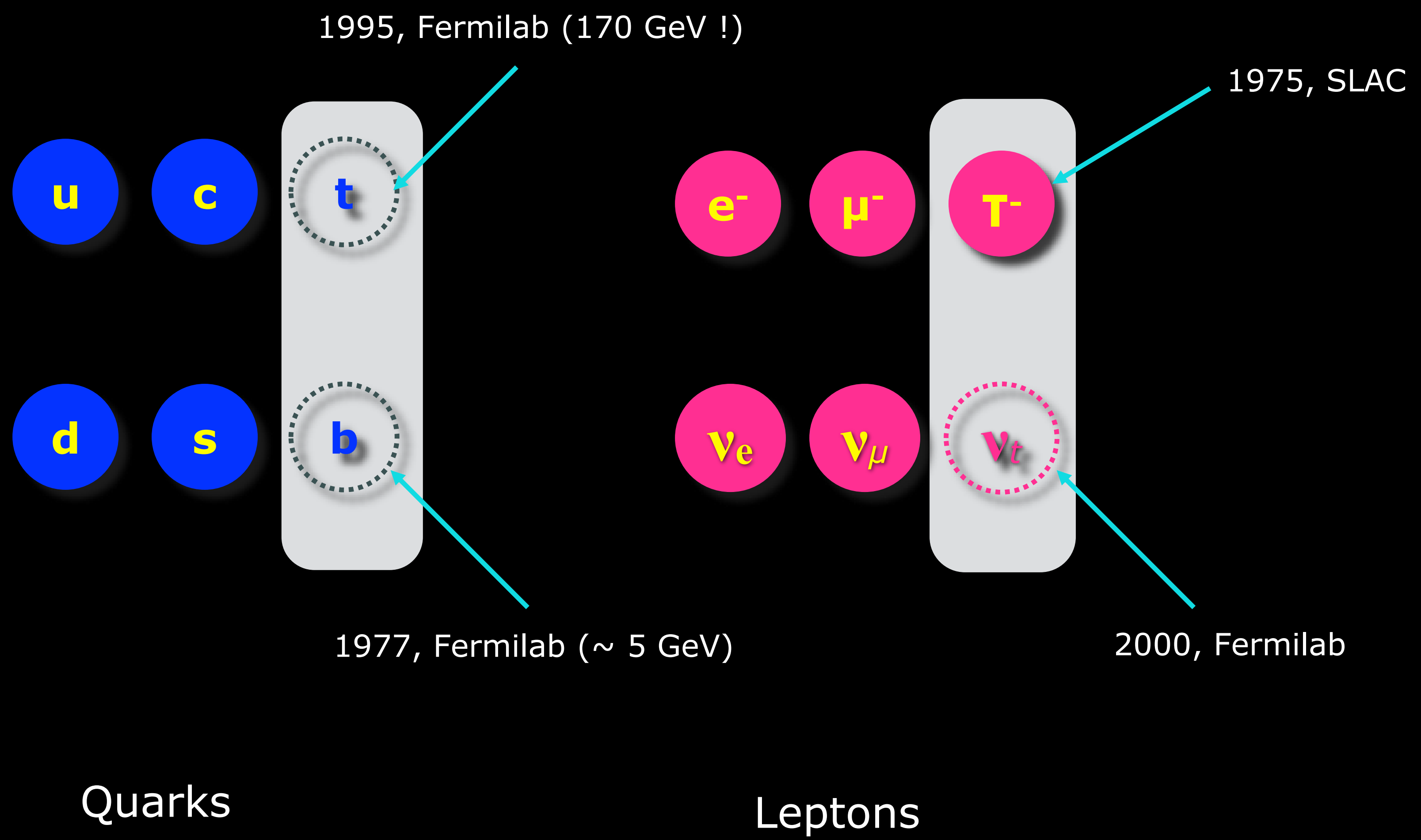
another neutrino (the 'tau neutrino'), and two more quarks ('top' and 'bottom')



Marty Perl's logbook page

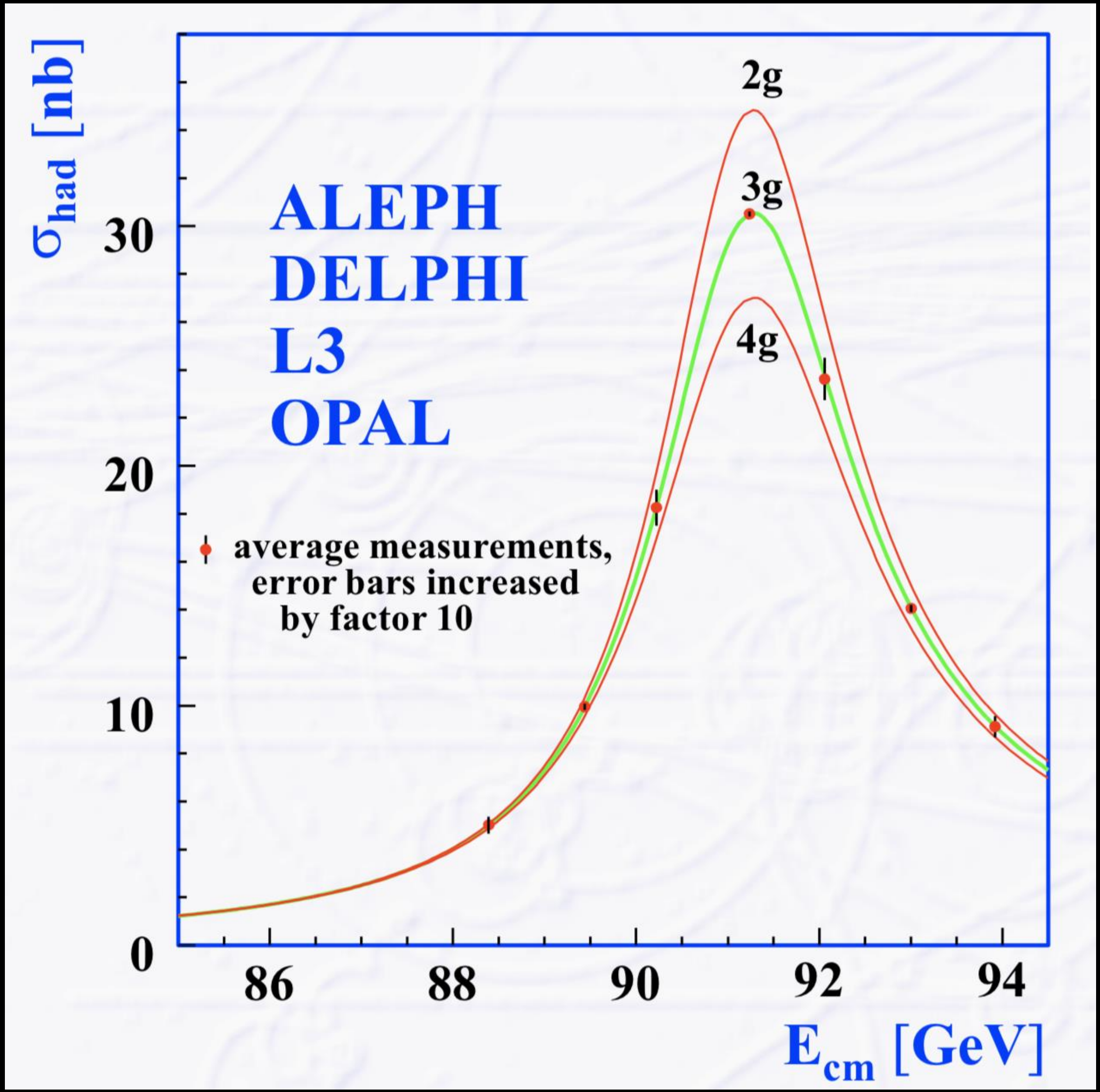
Surprise, surprise: THIRD FAMILY

A new lepton (called “tau”) is discovered (heavy brother of e and μ)



Exactly 3 families of quarks and leptons. 1991

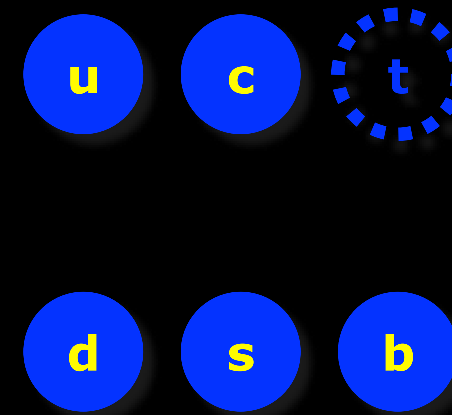
$e^+e^- \longrightarrow Z^o \longrightarrow e^+e^-$

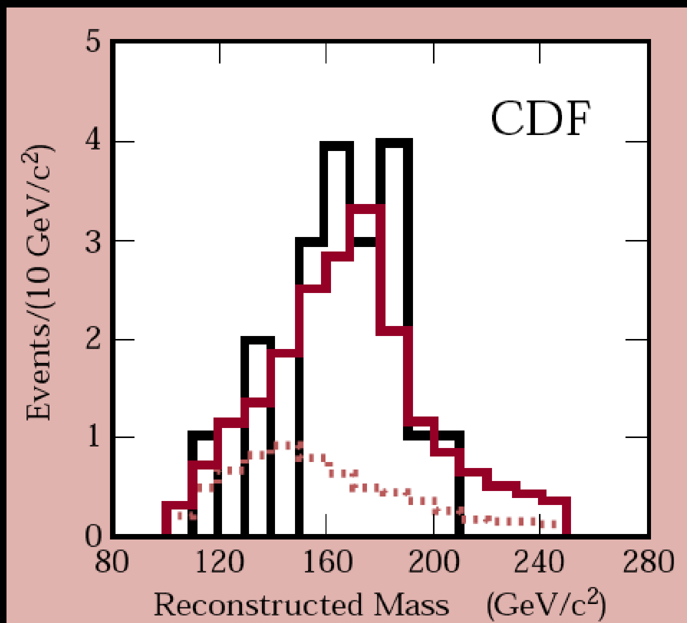


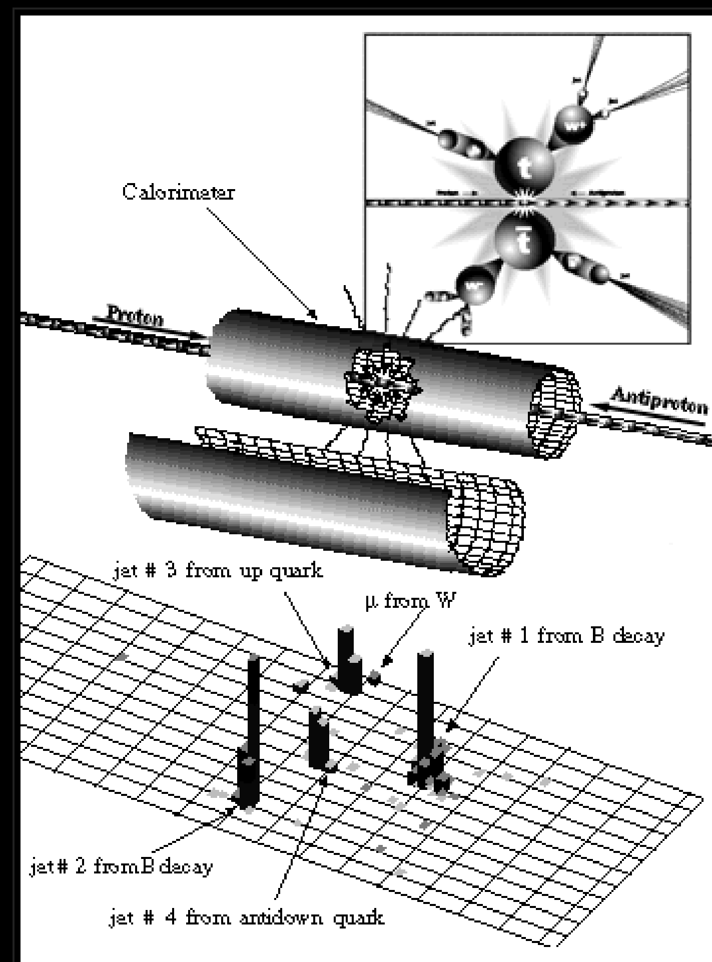
LEP measures the decay width of the Z^o particle

Discovery of the ‘Top’ Quark (Fermilab). 1995

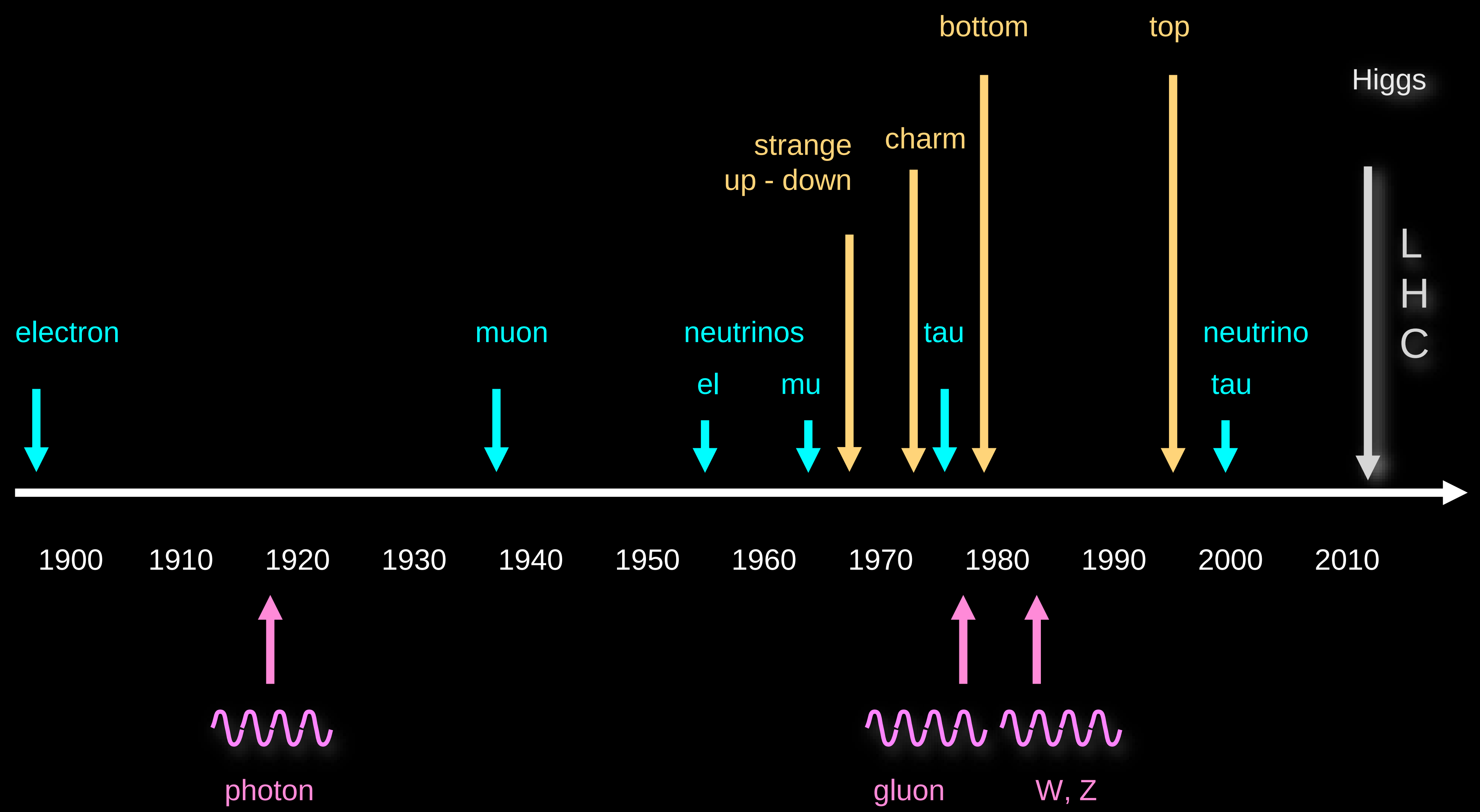
1995





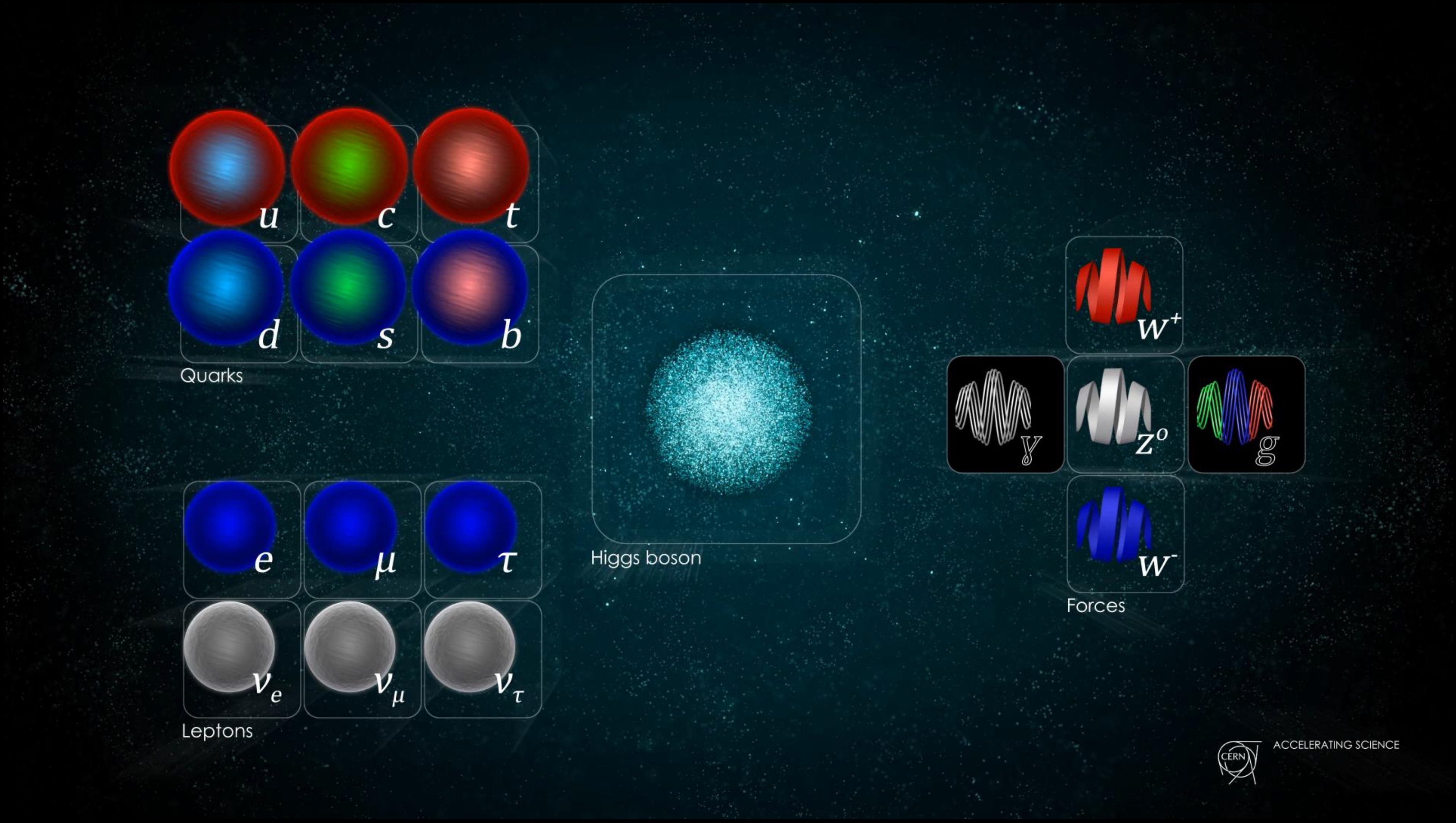


Experiments at accelerators have discovered the whole set of fundamental particles

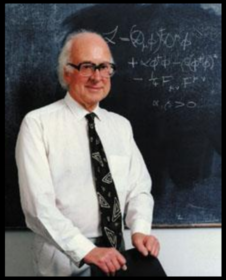


The Higgs boson discovery

Standard model: ‘Periodic system’ of particles



The Brout-Englert-Higgs (BEH) field idea



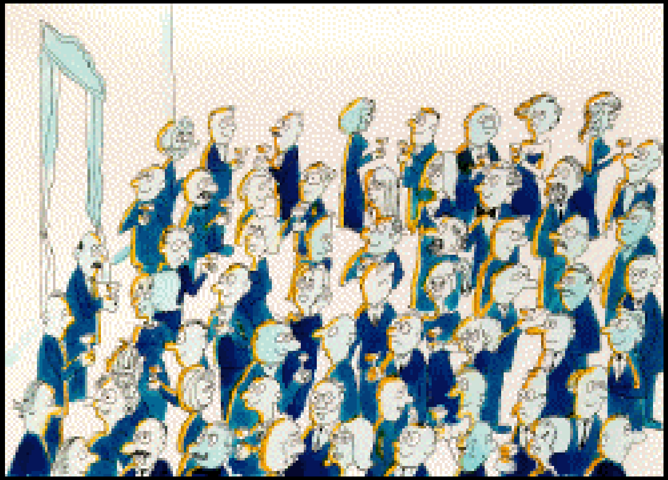
Sir Peter Higgs

the entire Universe is filled with a homogeneous field

particles interacting with this field obtain inertia (=rest mass)

the BEH field interaction is proportional to the mass of the particle

The 'cocktail party' explanation of the Higgs mechanism



A cocktail party ...

The BEH field ....

.. a famous person wants to traverse the room...

... a massless particle enters...

.. but the guests cluster around and slow down its movement...

... the interaction with the BEH field produces the inertia of the particle ...

The ‘Higgs boson’

A rumour is spreading among the guests ...

.. they cluster together to exchange the information among themselves...

The BEH field ...

... is excited by an energy concentration and forms an excitation by self-interaction ...

Animation: Higgs mechanism

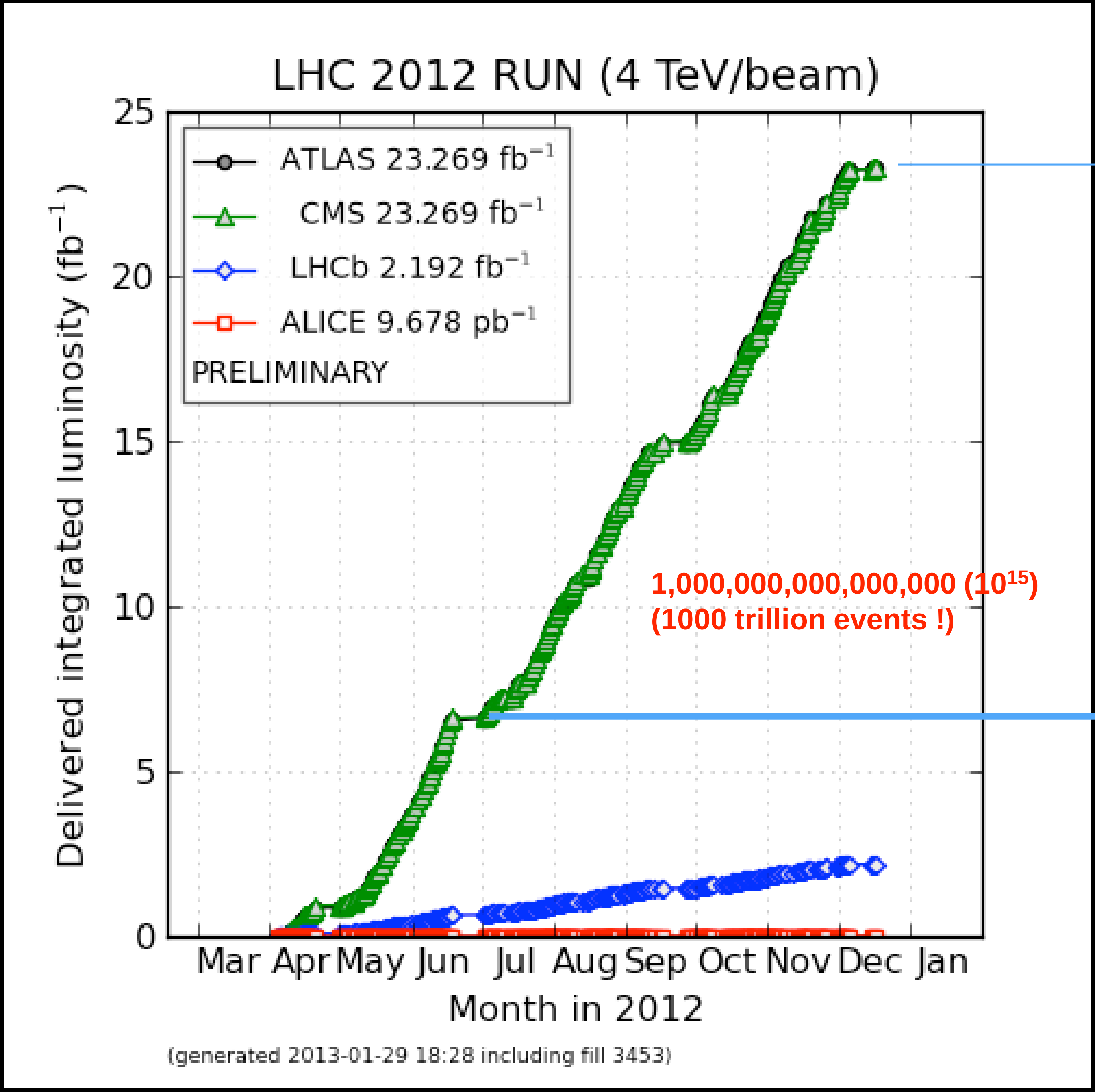
Exciting the Brout-Englert-Higgs field: the "Higgs boson"

... but this happens on average once per 10,000,000,000 (10^{10}) collisions !

The Higgs boson can decay in two photons ...

but only with a probability of 0.2 %

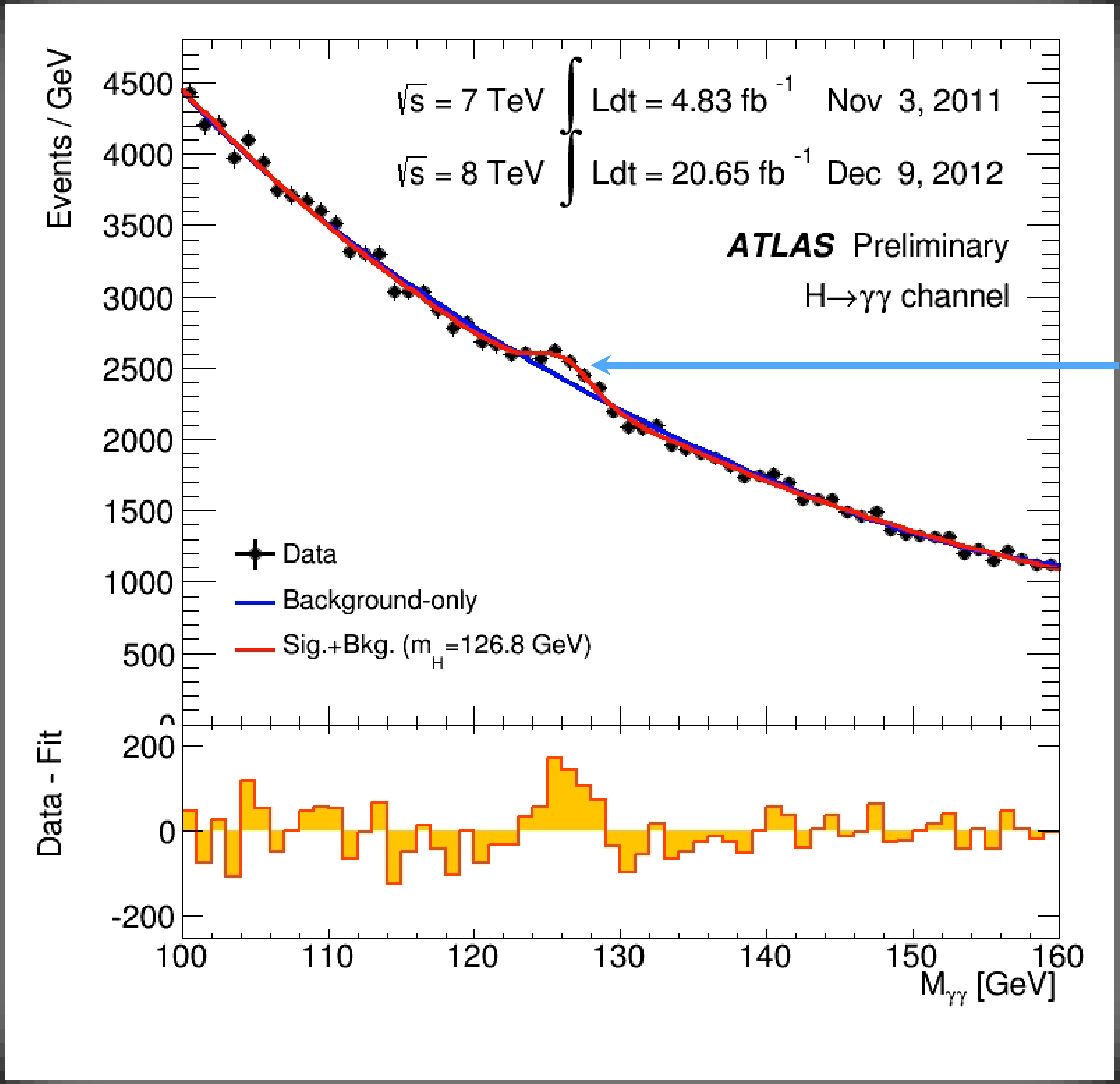
The CERN hunt for the Higgs boson



15.12.2012

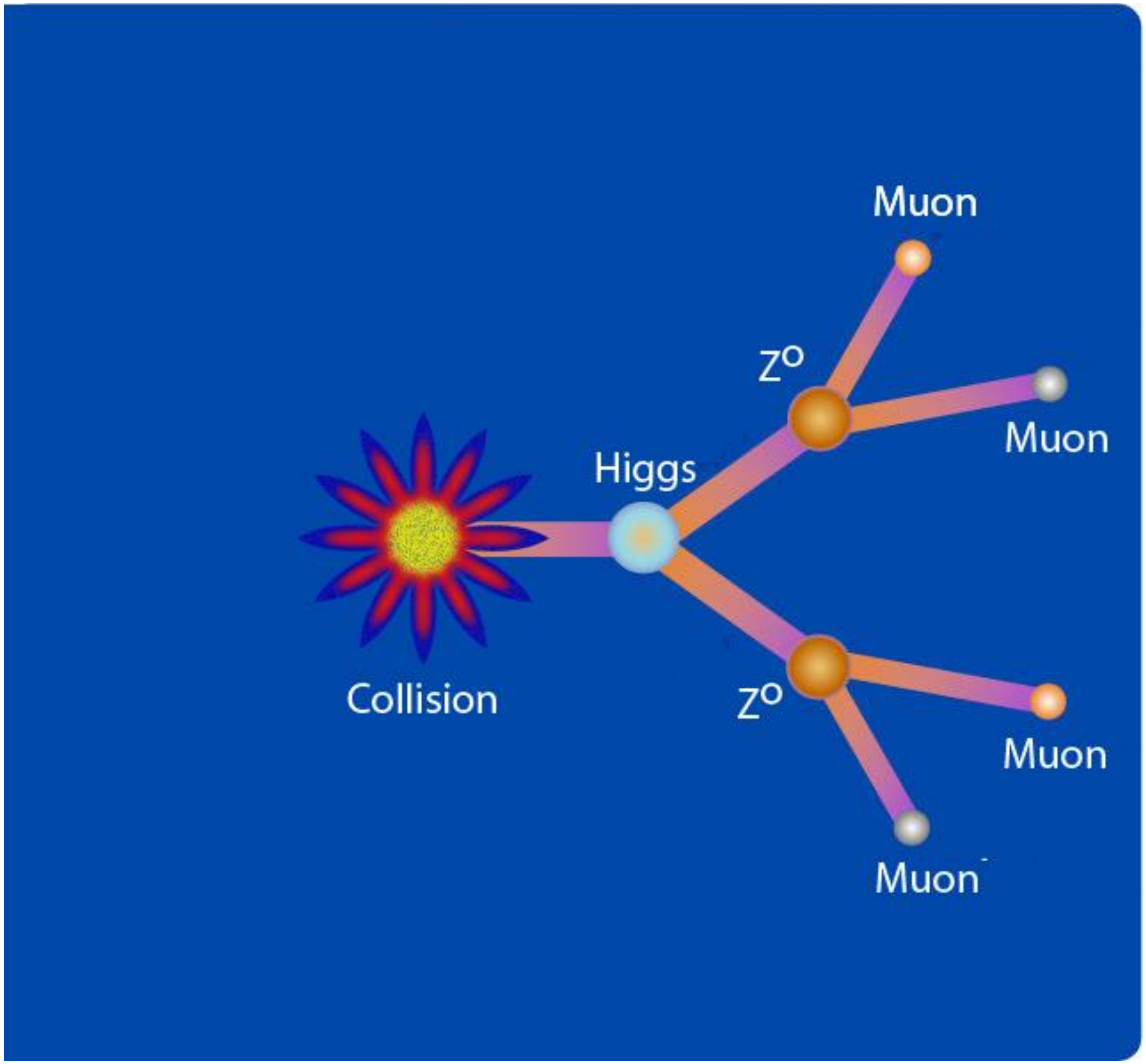
4.7.2012

The evolution of the histogram with two-photon events

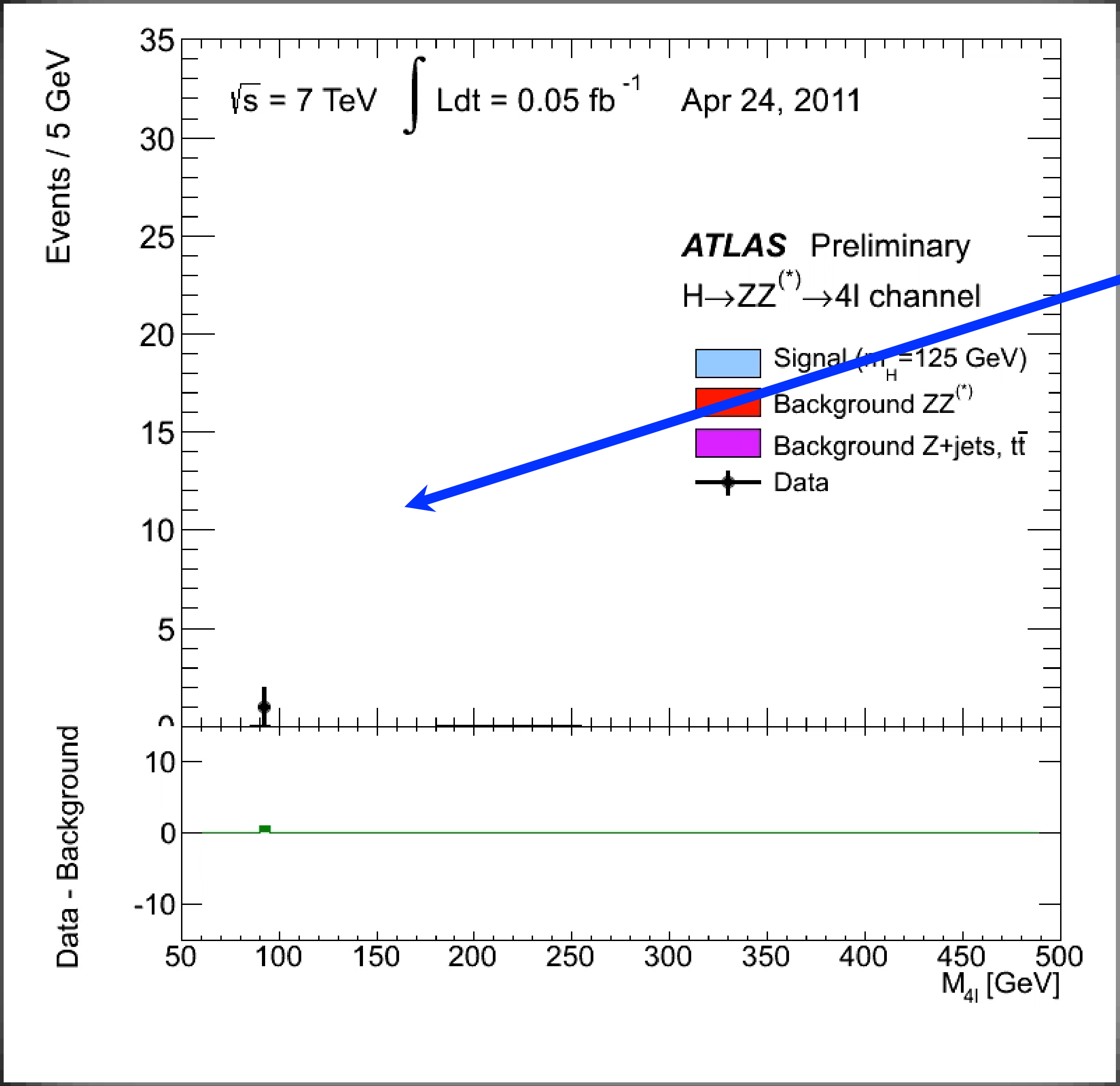


Higgs boson

Higgs decay into four muons



The evolution of the histogram with four leptons



Higgs boson

What does this mean?

- the Higgs boson exists, therefore ...
- the Brout-Englert-Higgs field exists
- we know how particles obtain their mass
- the "Standard model" is complete

Even more:

- empty space is not 'empty'
- perhaps a connection to 'dark energy' ?

Higgs boson ID: Mass, Width, Production, Decay

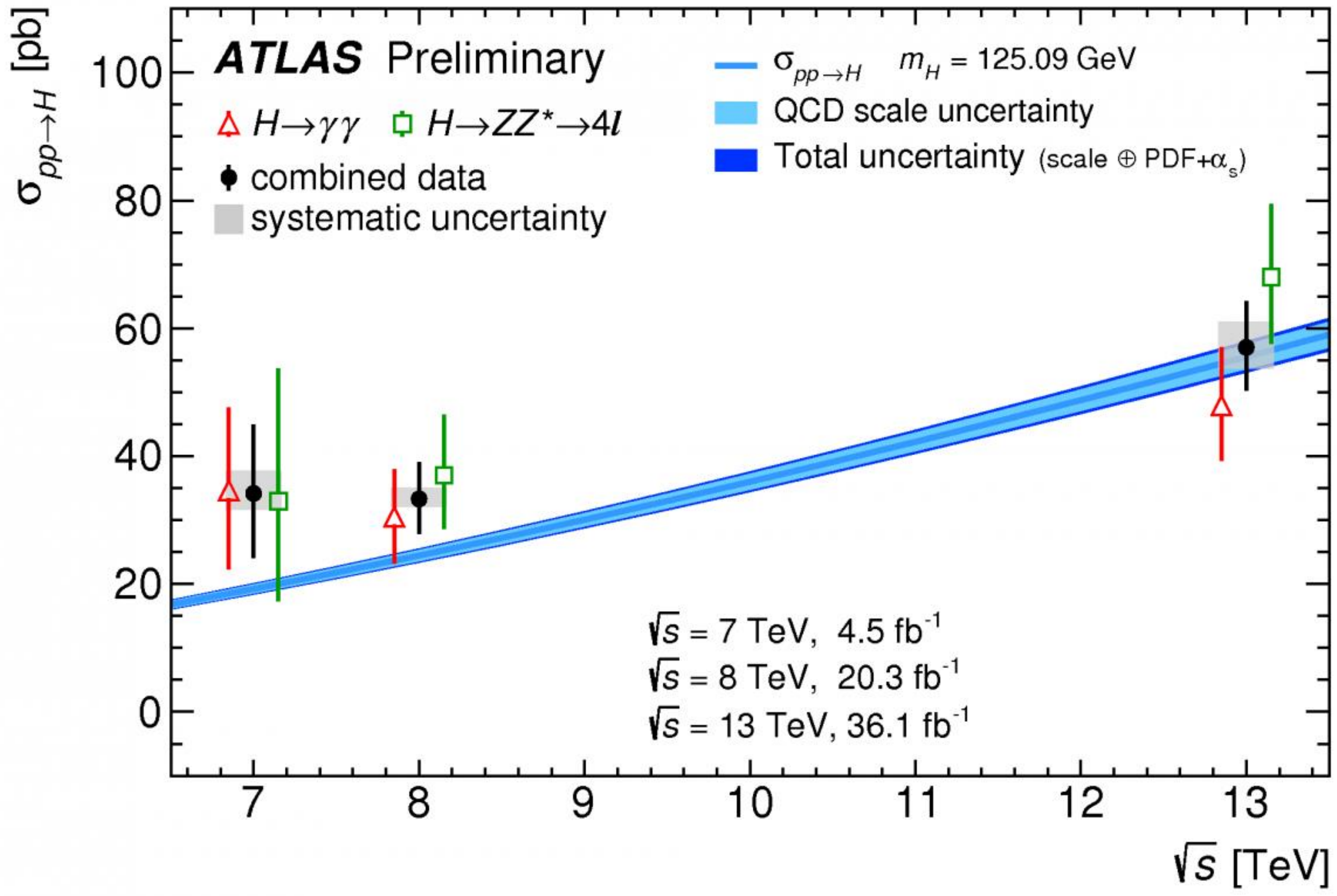
Mass: free parameter of BEH theory (~ self-coupling of BEH field)

$$\mathbf{M_H = 125.09 \pm 0.21\ GeV}$$

But: once the Higgs boson mass is known, the other parameters are predicted:

1) **Lifetime** ($1.5 \cdot 10^{-22}$ s, width ~ 4 MeV; too small to be measured)
2) **Production cross-section in p-p collisions at different energies**
3) **Decay probability**

Higgs production cross-section: as predicted by S.M.

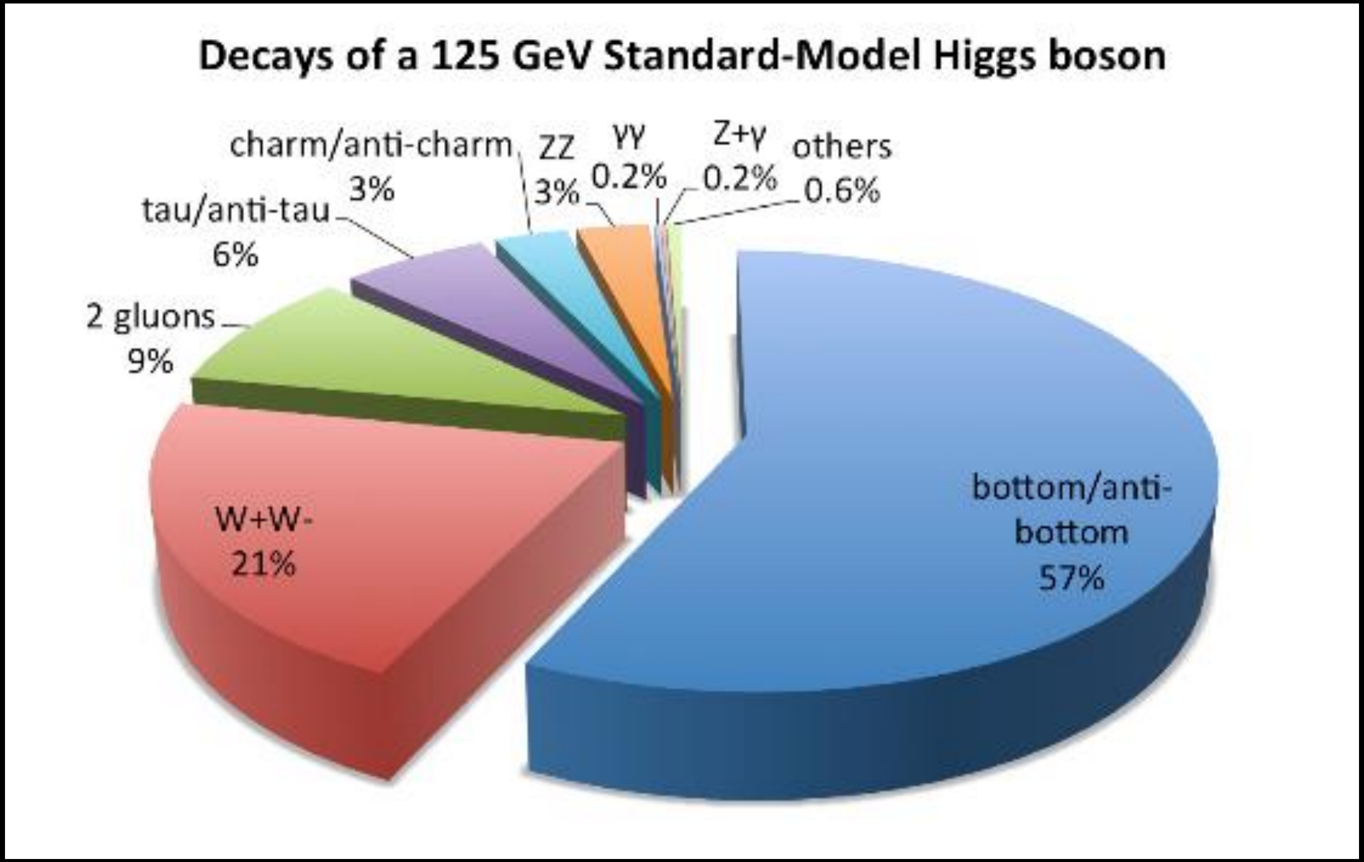


Perfect agreement - as predicted by S.M.

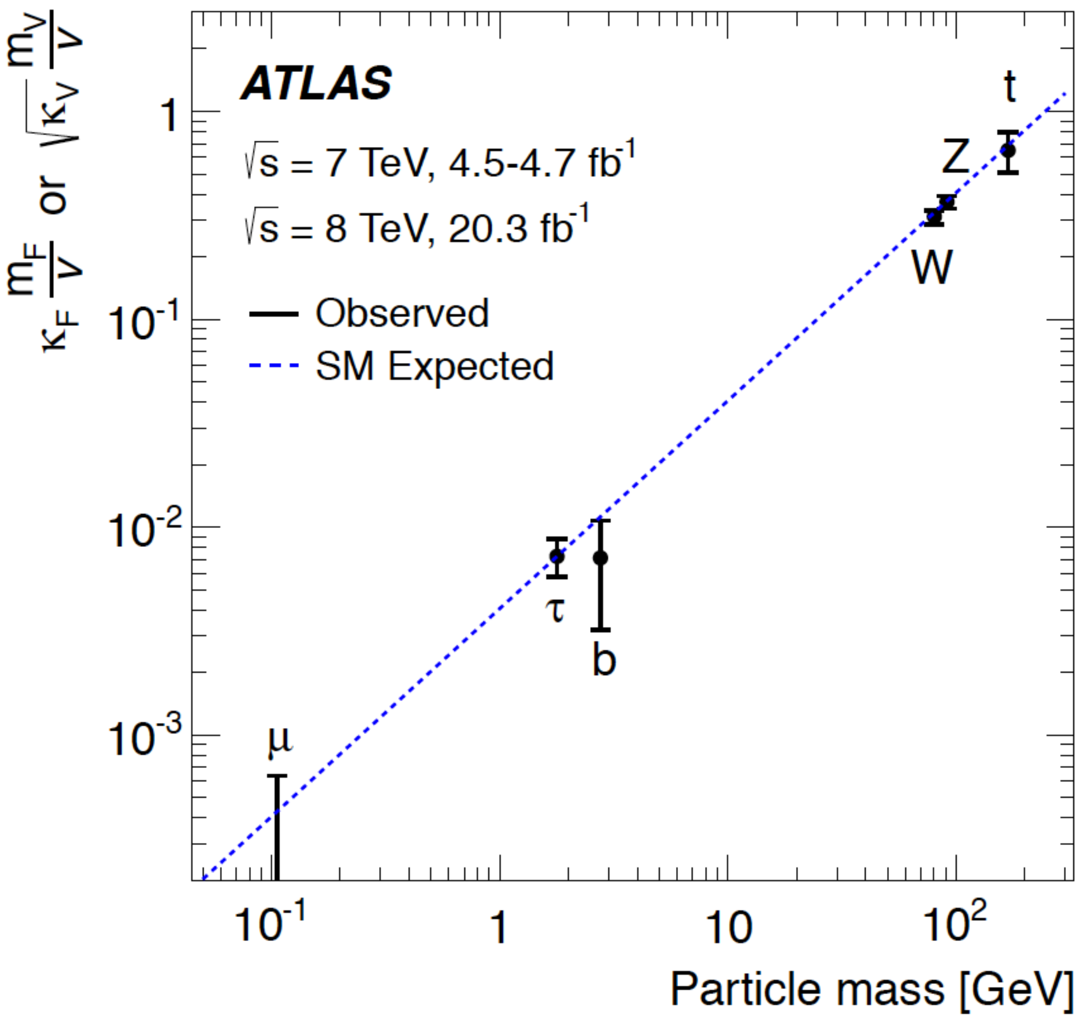
Higgs decay?

Key prediction

Decay probability is proportional to the mass of the daughter particles



Higgs decay rate proportional to particle mass ?



Perfect linear dependence - as predicted by S.M.

What about new particles?

Finding new particles …. X(750) saga

December 2015:

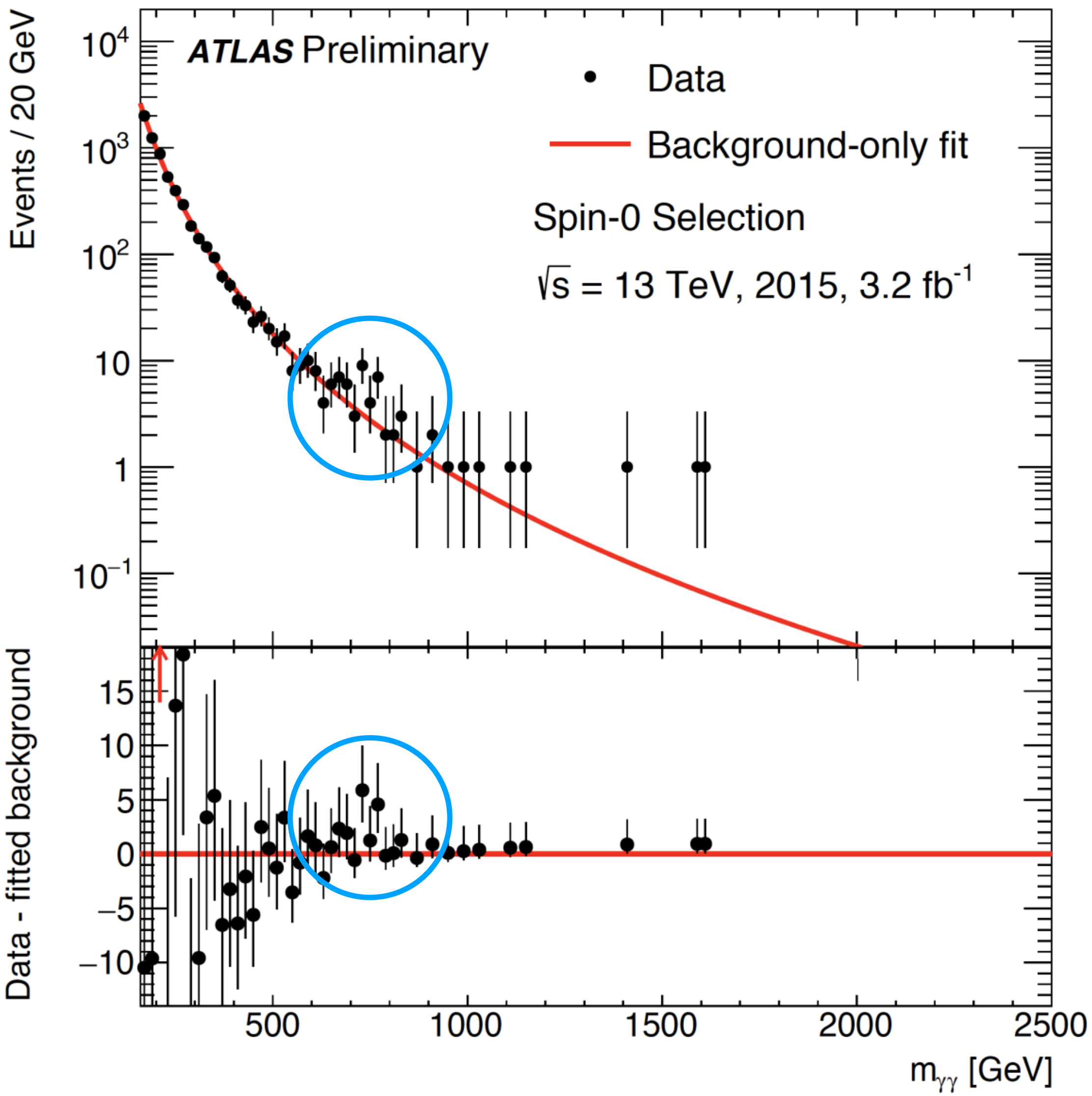
ATLAS presents ~3-sigma bump

M ~ 750 GeV

Decay into 2 photons

(CMS also sees 'something' at this mass)

(3.2 fb^{-1} at 13 TeV)



… or not: the end of the X(750) saga

2016:

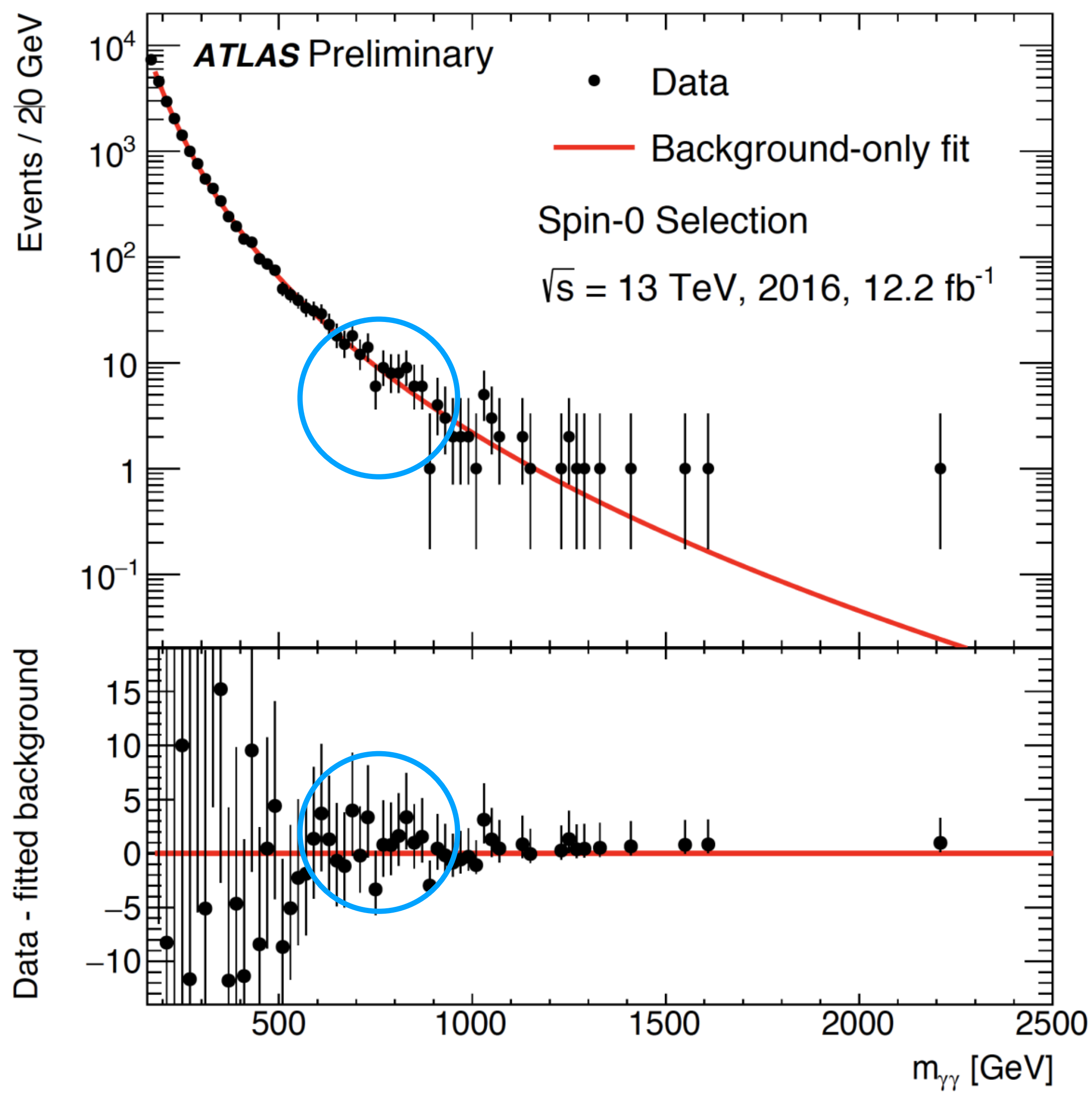
ATLAS publishes plot with 4x data

NO BUMP !

(12.2 fb^{-1} at 13 TeV)

as statistics increases, significance decreases …

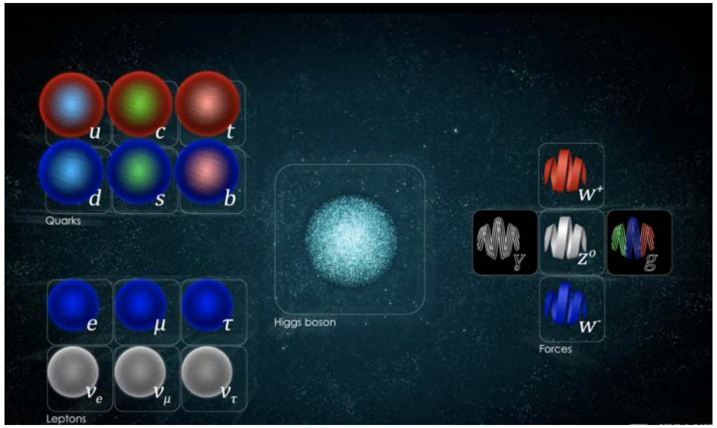
It was 'just' a statistical fluctuation.



What next ?

The known Unknowns: the Standard Model

How did Nature choose this ‘Standard Model’ ?

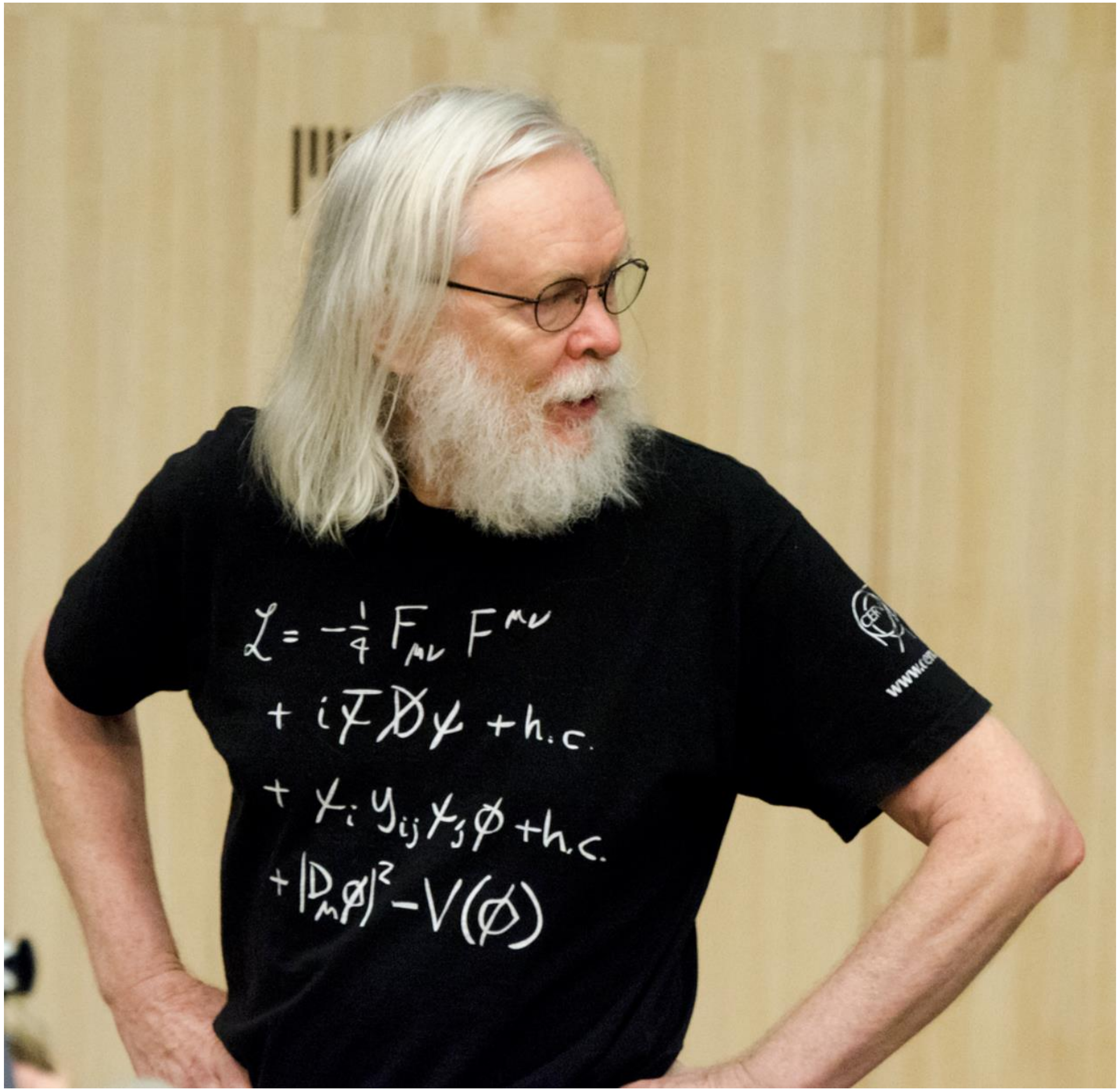


Cook book recipe
for a ‘Goldilocks’ universe

Describes a ‘tasty’ universe
including friendly stars, life

Drives theorists nuts …

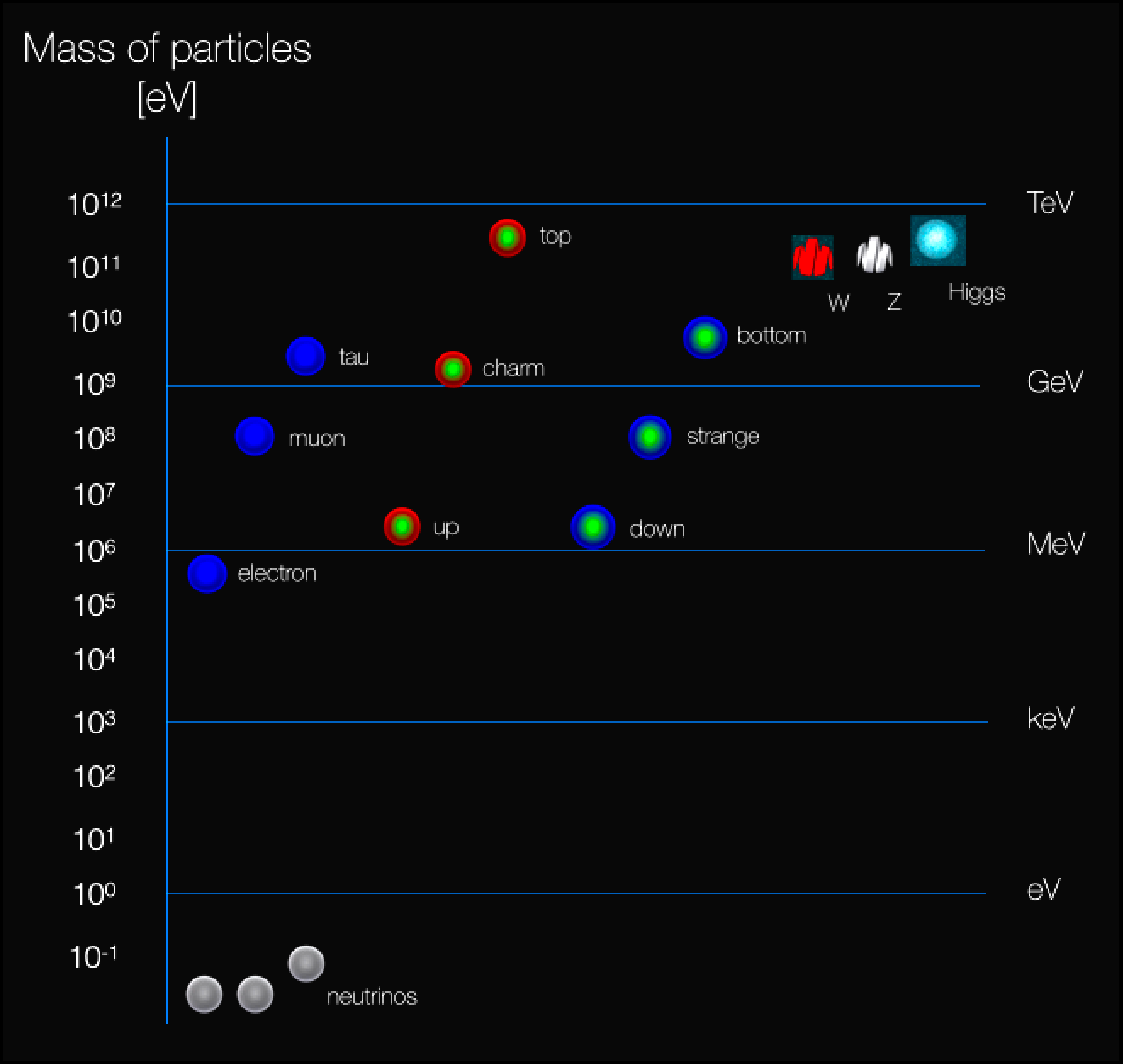
The ‘Standard Model’ ?



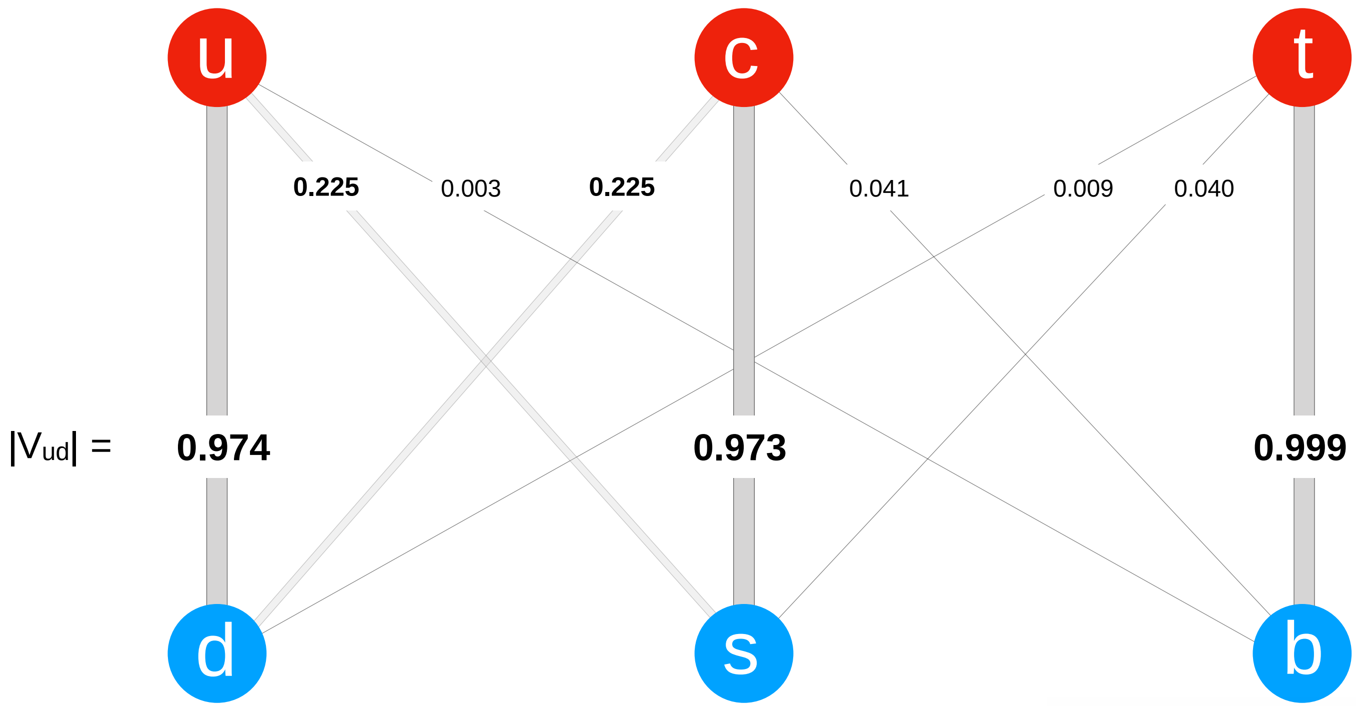
The Standard Model is not exactly ‘elegant’

$$
\mathcal{L}_{SM} =
\begin{aligned}
&-\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4} g^2_s f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \tfrac{1}{2} i g^2_s (\bar{q}^\sigma_i \gamma^\mu q^\sigma_j) g^a_\mu + \\
&\bar{G}^a \partial^2 G^a + g_s f^{abc} \partial_\mu \bar{G}^a G^b g^c_\mu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c^2_w} M^2 Z^0_\mu Z^0_\mu - \\
&\tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \tfrac{1}{2}\partial_\mu H \partial_\mu H - \tfrac{1}{2} m^2_h H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2 \phi^+ \phi^- - \tfrac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \\
&\tfrac{1}{2c^2_w} M \phi^0 \phi^0 - \beta_h [\tfrac{2M^2}{g^2} + \tfrac{2M}{g} H + \tfrac{1}{2}(H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-)] + \tfrac{2M^4}{g^2} \alpha_h - i g c_w [\partial_\nu Z^0_\mu (W^+_\mu W^-_\nu - \\
&W^+_\nu W^-_\mu) - Z^0_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu (W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)] - 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^-_\mu \partial_\nu W^+_\mu) + A_\mu (W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)] - \tfrac{1}{2} g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \\
&\tfrac{1}{2} g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c^2_w (Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s^2_w (A_\mu W^+_\mu A_\nu W^-_\nu - \\
&A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w [A_\mu Z^0_\nu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - 2 A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha [H^3 + \\
&H \phi^0 \phi^0 + 2H \phi^+ \phi^-] - \tfrac{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 - \tfrac{1}{2} g \tfrac{M}{c^2_w} Z^0_\mu Z^0_\mu H - \tfrac{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)] + \tfrac{1}{2} g [W^+_\mu (H \partial_\mu \phi^- - \phi^- \partial_\mu H) - W^-_\mu (H \partial_\mu \phi^+ - \phi^+ \partial_\mu H)] + \tfrac{1}{2} g \tfrac{1}{c_w} (Z^0_\mu (H \partial_\mu \phi^0 - \\
&\phi^0 \partial_\mu H) - i g \tfrac{s^2_w}{c_w} M Z^0_\mu (W^+_\mu \phi^- - W^-_\mu \phi^+) + i g s_w M A_\mu (W^+_\mu \phi^- - W^-_\mu \phi^+) - i g \tfrac{1-2c^2_w}{2c_w} Z^0_\mu (\phi^+ \partial_\mu \phi^- - \\
&\phi^- \partial_\mu \phi^+) + i g s_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \tfrac{1}{4} g^2 W^+_\mu W^-_\mu [H^2 + (\phi^0)^2 + 2\phi^+ \phi^-] - \\
&\tfrac{1}{4} g^2 \tfrac{1}{c^2_w} Z^0_\mu Z^0_\mu [H^2 + (\phi^0)^2 + 2(2s^2_w - 1)^2 \phi^+ \phi^-] - \tfrac{1}{2} g^2 \tfrac{s^2_w}{c_w} Z^0_\mu \phi^0 (W^+_\mu \phi^- + W^-_\mu \phi^+) - \\
&\tfrac{1}{2} i g^2 \tfrac{s^2_w}{c_w} Z^0_\mu H (W^+_\mu \phi^- - W^-_\mu \phi^+) + \tfrac{1}{2} g^2 s_w A_\mu \phi^0 (W^+_\mu \phi^- + W^-_\mu \phi^+) + \tfrac{1}{2} i g^2 s_w A_\mu H (W^+_\mu \phi^- - \\
&W^-_\mu \phi^+) - g^2 \tfrac{s_w}{c_w} (2c^2_w - 1) Z^0_\mu A_\mu \phi^+ \phi^- - g^1 s^2_w A_\mu A_\mu \phi^+ \phi^- - \bar{e}^\lambda (\gamma\partial + m^\lambda_e) e^\lambda - \\
&\bar{\nu}^\lambda \gamma\partial \nu^\lambda - \bar{u}^\lambda_j (\gamma\partial + m^\lambda_u) u^\lambda_j - \bar{d}^\lambda_j (\gamma\partial + m^\lambda_d) d^\lambda_j + i g s_w A_\mu [-(\bar{e}^\lambda \gamma^\mu e^\lambda) + \tfrac{2}{3}(\bar{u}^\lambda_j \gamma^\mu u^\lambda_j) - \\
&\tfrac{1}{3}(\bar{d}^\lambda_j \gamma^\mu d^\lambda_j)] + \tfrac{ig}{4c_w} Z^0_\mu [(\bar{\nu}^\lambda \gamma^\mu (1+\gamma^5) \nu^\lambda) + (\bar{e}^\lambda \gamma^\mu (4s^2_w - 1 - \gamma^5) e^\lambda) + (\bar{u}^\lambda_j \gamma^\mu (\tfrac{4}{3} s^2_w - \\
&1 - \gamma^5) u^\lambda_j) + (\bar{d}^\lambda_j \gamma^\mu (1 - \tfrac{8}{3} s^2_w - \gamma^5) d^\lambda_j)] + \tfrac{ig}{2\sqrt{2}} W^+_\mu [(\bar{\nu}^\lambda \gamma^\mu (1+\gamma^5) e^\lambda) + (\bar{u}^\lambda_j \gamma^\mu (1 + \\
&\gamma^5) C_{\lambda\kappa} d^\kappa_j)] + \tfrac{ig}{2\sqrt{2}} W^-_\mu [(\bar{e}^\lambda \gamma^\mu (1+\gamma^5) \nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\lambda\kappa} \gamma^\mu (1+\gamma^5) u^\lambda_j)] + \tfrac{ig}{2\sqrt{2}} \tfrac{m^\lambda_e}{M} [-\phi^+ (\bar{\nu}^\lambda (1 - \\
&\gamma^5) e^\lambda) + \phi^- (\bar{e}^\lambda (1+\gamma^5) \nu^\lambda)] - \tfrac{g}{2} \tfrac{m^\lambda_e}{M} [H (\bar{e}^\lambda e^\lambda) + i \phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda)] + \tfrac{ig}{2M\sqrt{2}} \phi^+ [-m^\kappa_d (\bar{u}^\lambda_j C_{\lambda\kappa} (1 - \\
&\gamma^5) d^\kappa_j) + m^\lambda_u (\bar{u}^\lambda_j C_{\lambda\kappa} (1+\gamma^5) d^\kappa_j] + \tfrac{ig}{2M\sqrt{2}} \phi^- [m^\lambda_d (\bar{d}^\lambda_j C^\dagger_{\lambda\kappa} (1+\gamma^5) u^\kappa_j) - m^\kappa_u (\bar{d}^\lambda_j C^\dagger_{\lambda\kappa} (1 - \\
&\gamma^5) u^\kappa_j] - \tfrac{g}{2} \tfrac{m^\lambda_u}{M} H (\bar{u}^\lambda_j u^\lambda_j) - \tfrac{g}{2} \tfrac{m^\lambda_d}{M} H (\bar{d}^\lambda_j d^\lambda_j) + \tfrac{ig}{2} \tfrac{m^\lambda_u}{M} \phi^0 (\bar{u}^\lambda_j \gamma^5 u^\lambda_j) - \tfrac{ig}{2} \tfrac{m^\lambda_d}{M} \phi^0 (\bar{d}^\lambda_j \gamma^5 d^\lambda_j) + \\
&\bar{X}^+ (\partial^2 - M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \tfrac{M^2}{c^2_w}) 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^0_\mu (\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^-) - \tfrac{1}{2} g M [\bar{X}^+ X^+ H + \bar{X}^- X^- H + \tfrac{1}{c^2_w} \bar{X}^0 X^0 H] + \tfrac{1-2c^2_w}{2c_w} i g M [\bar{X}^+ X^0 \phi^+ - \\
&\bar{X}^- X^0 \phi^-] + \tfrac{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^-] + \\
&\tfrac{1}{2} i g M [\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0]
\end{aligned}
$$

Why **these** masses of elementary particles?



Quark mixing in weak interactions ?



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

weak eigenstates — CKM matrix — mass eigenstates

4 free parameters

(3 mixing angles, 1 phase)

Origin of CP violation in S.M.

What lies behind the Standard Model?

Strength of the three interactions

- $\alpha_{em}, \theta_W, \alpha_s$

Higgs field v.e.v. and Higgs boson mass

- v, m_H

CKM matrix parameters (weak mixing of quarks)

- $\theta_{12}, \theta_{23}, \theta_{13}, \delta_{13}$

Quark and lepton masses

- $m_u, m_d, m_c, m_s, m_t, m_b, m_e, m_\mu, m_\tau$

Neutrino masses and mixing angles

- $m_{\nu_1}, m_{\nu_2}, m_{\nu_3}, \theta_{12}, \theta_{23}, \theta_{13}, \delta_{13}$

QCD vacuum angle

- θ_{QCD}

Why is Nature so stable?

26 free parameters

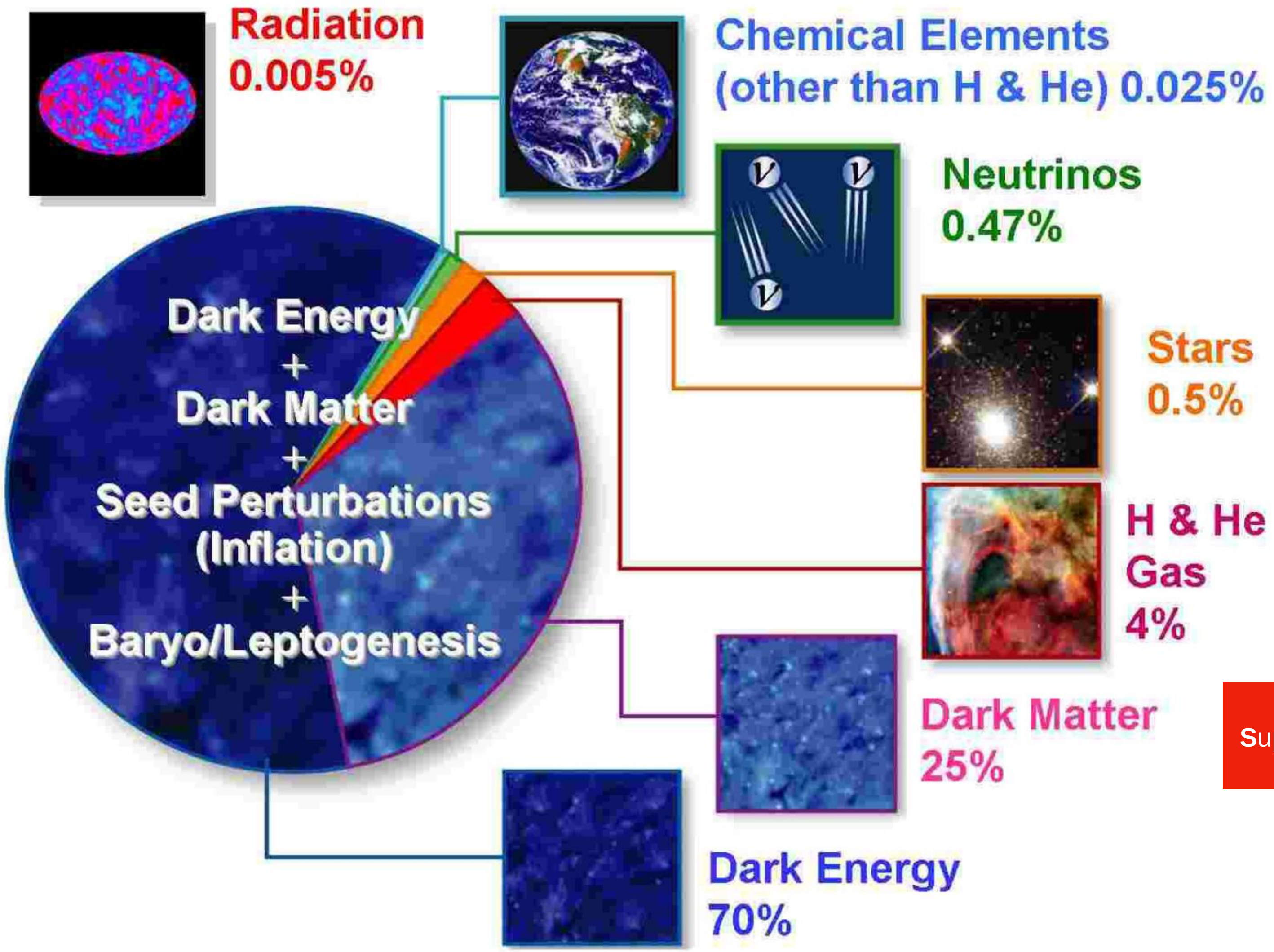
why these values?

Known problems of the Standard Model

- Origin of 3 families of particles (‘periodic table’)
- Origin of forces (three forces, different strengths)
- Origin of different particle masses, mixing angles
- Neutrino masses, mixing angles
- Antimatter disappearance after Big Bang
- Higgs mass relatively light (metastable universe)

Known problems with the Universe

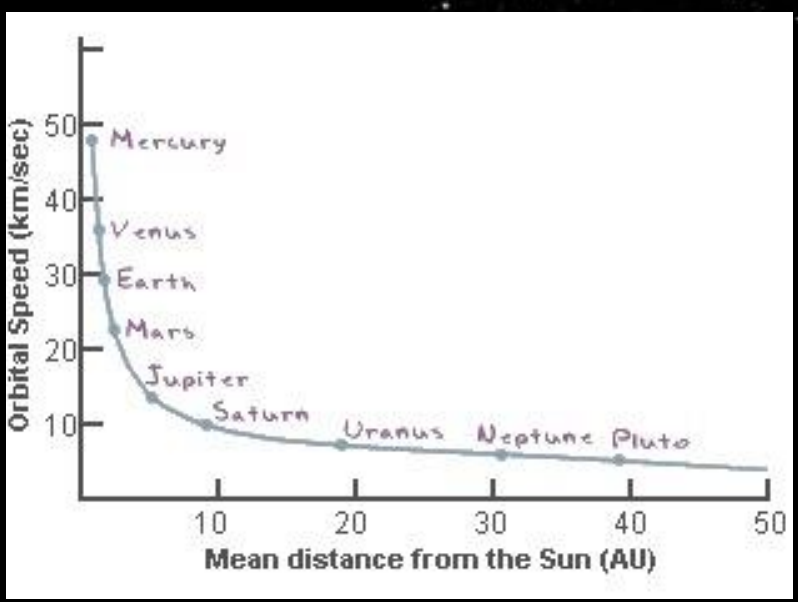
The strange toppings on the cosmic pizza



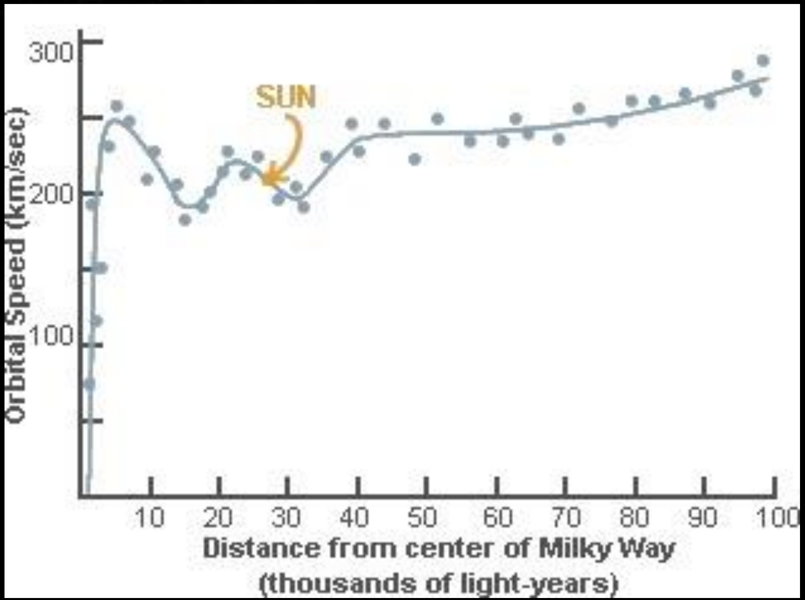
Lightest **S**upersymmetric **P**article ?

EVIDENCE FOR “DARK MATTER”

Orbital speed vs Distance from center
(Kepler - expect $r^{-1/2}$ dependence)

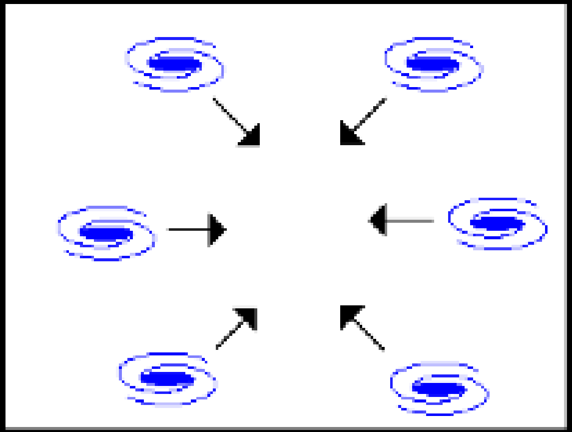


One central mass (Sun)



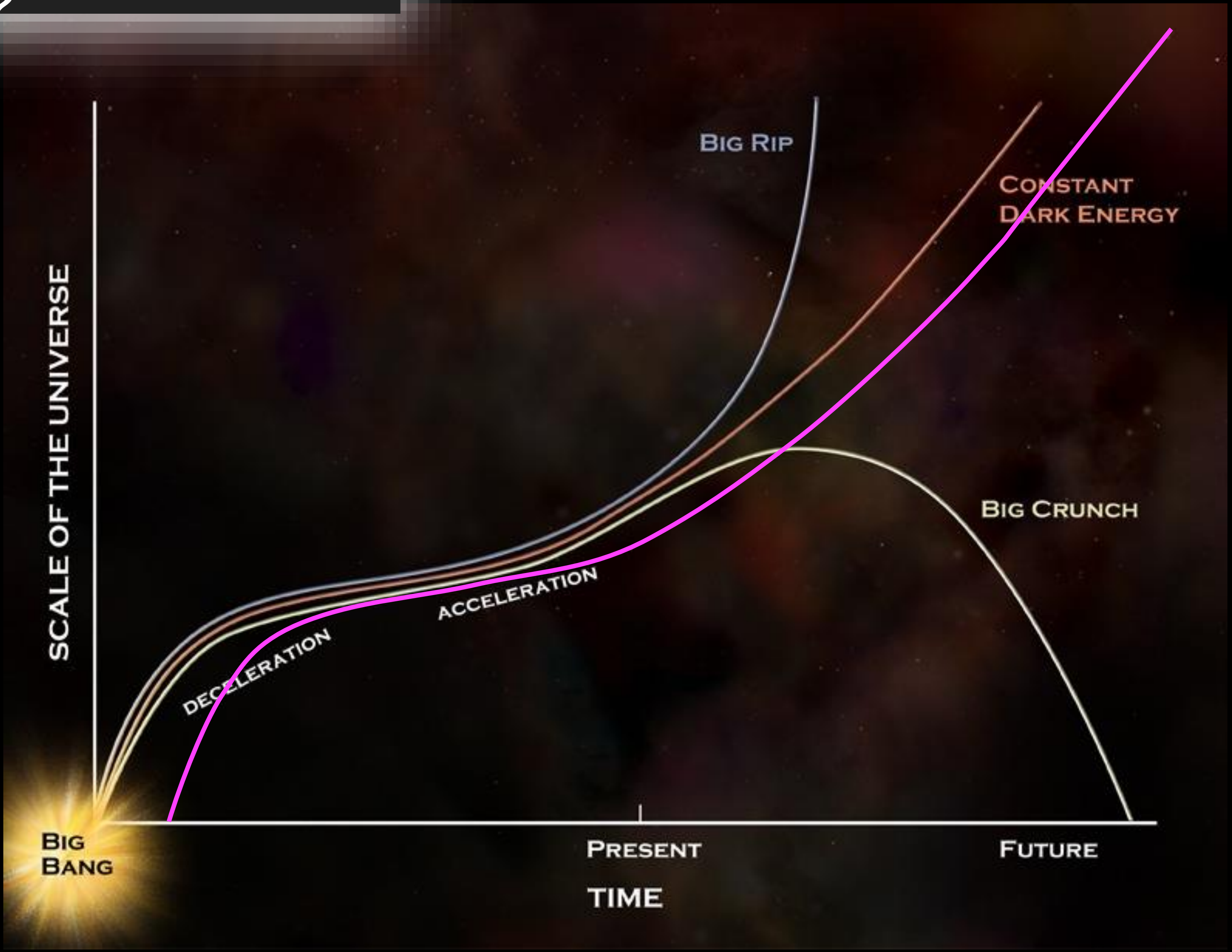
Milky Way

MORE EVIDENCE FOR "DARK MATTER"



GRAVITATIONAL LENSING

Dark energy ...?



The expansion of the Universe accelerates ...

What next ?

a) Extra dimensions ? Strong gravity at small distances ?

b) Supersymmetric particles ?

c) New fundamental interactions ?

d) New generations of quarks/leptons ?

e) Leptoquarks ?

f) Something completely new ?

Interlude: the Planck scale

Boundary for quantum theory, gravity, and space-time

System of units based on three fundamental constants (G, c, h)
Dimensionally independent - length, time, and mass (energy)

$$\ell_P = \sqrt{\frac{\hbar G}{c^3}} = 1.6 \times 10^{-35} \ \text{m}$$

$$T_P = \sqrt{\frac{\hbar G}{c^5}} = 0.54 \times 10^{-43} \ \text{s}$$

$$M_P = \sqrt{\frac{\hbar c}{G}} = 2.2 \times 10^{-8} \ \text{kg}$$

$$E_P = M_P c^2 = 1.2 \times 10^{19} \ \text{GeV}$$

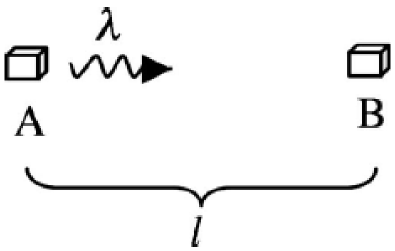


Fig. 3. A light pulse is sent from A and reflected back from B. Its energy causes a distortion of the spacetime between A and B and hence affects the length ℓ.

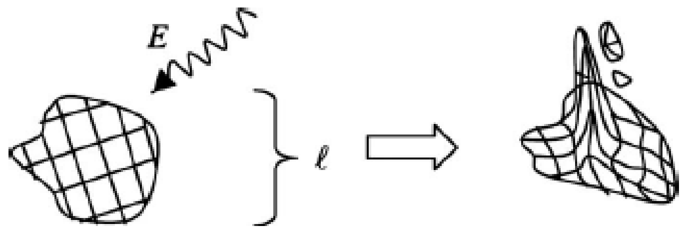
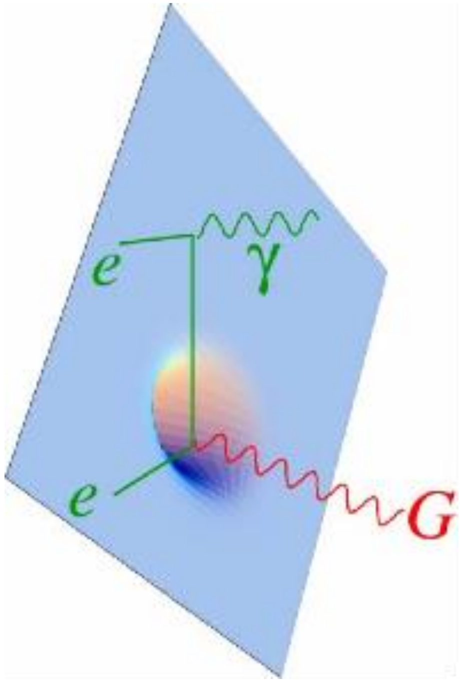


Fig. 5. A region of space of size ℓ to be measured in time ℓ/c. As the size approaches the Planck length, there can occur wild variations in the geometry, including such things as black holes and wormholes.

http://www.stat.physik.uni-potsdam.de/~pikovsky/teaching/stud_seminar/Planck_scale.pdf



Randall-Sundrum type models

More than 3 macroscopic dimensions of space ?

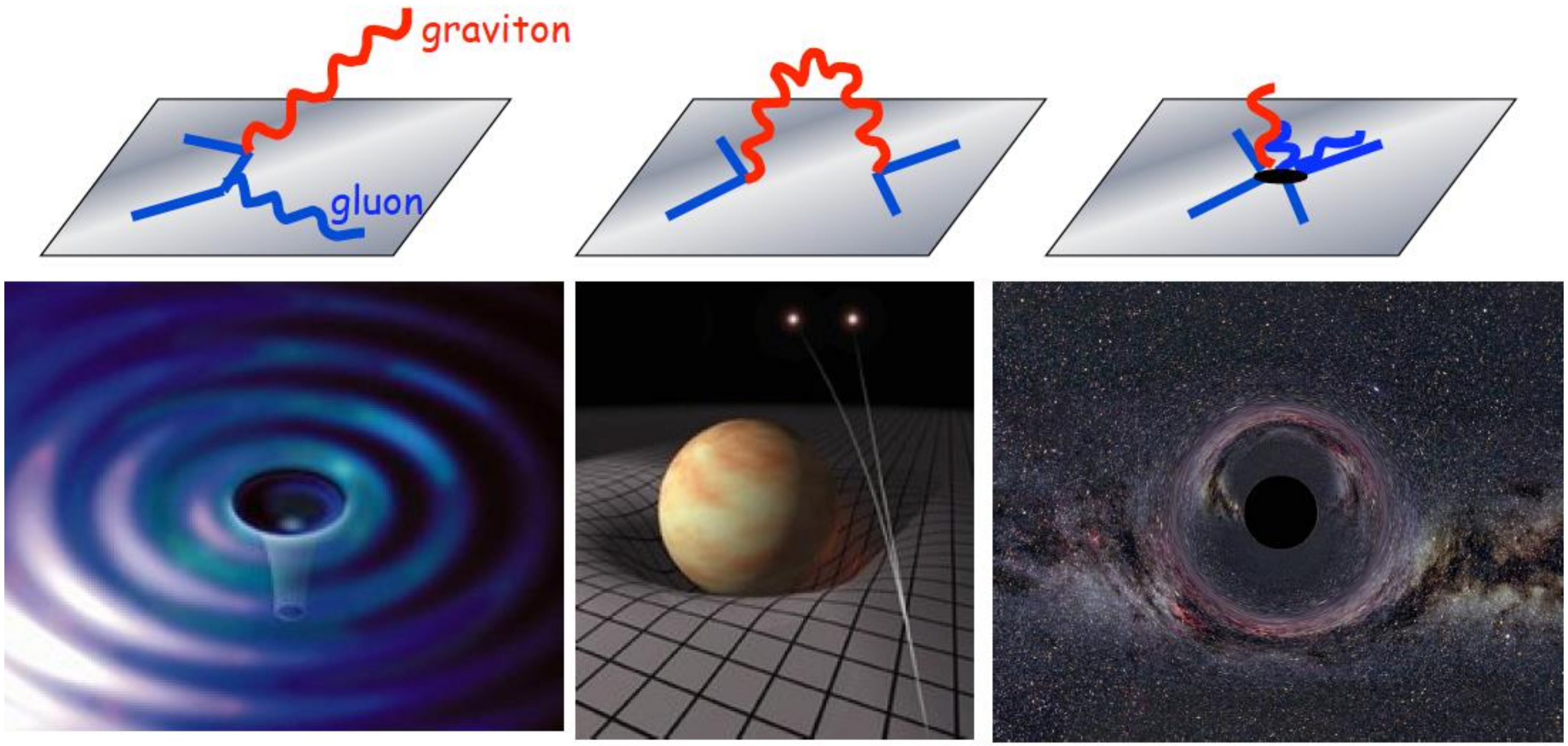
Is the graviton propagating in 4- or more dimensions of space?

Does gravity become very strong at small dimensions ?

Micro-black holes ?

Gravity and extra dimensions ?

Probing gravity at the LHC?



Gravitational wave
jet + $\not{E}_T$

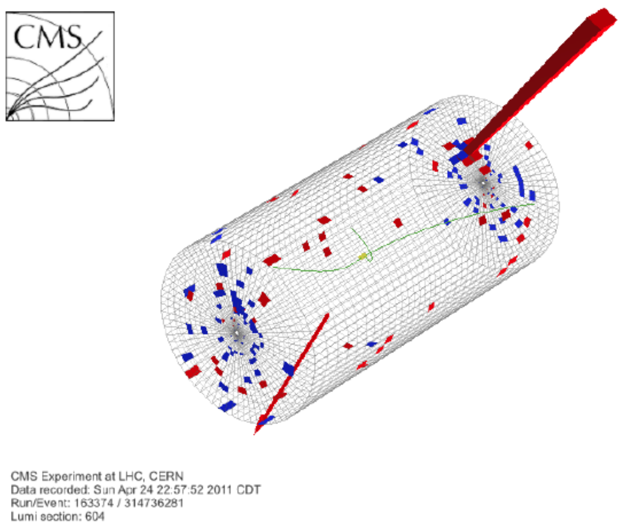
Gravitational deflection
dijet

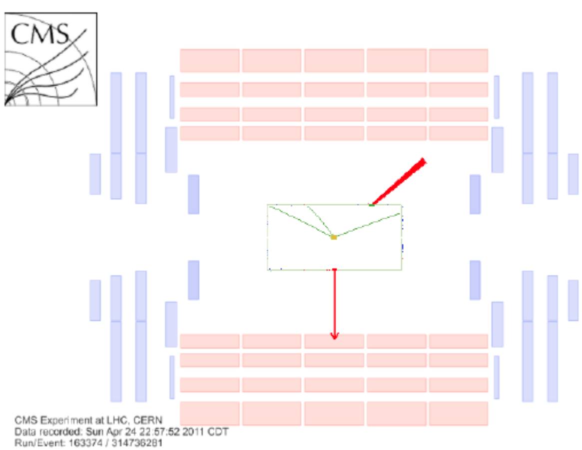
Black hole
multiparticle event

Gravitational phenomena into collider arena

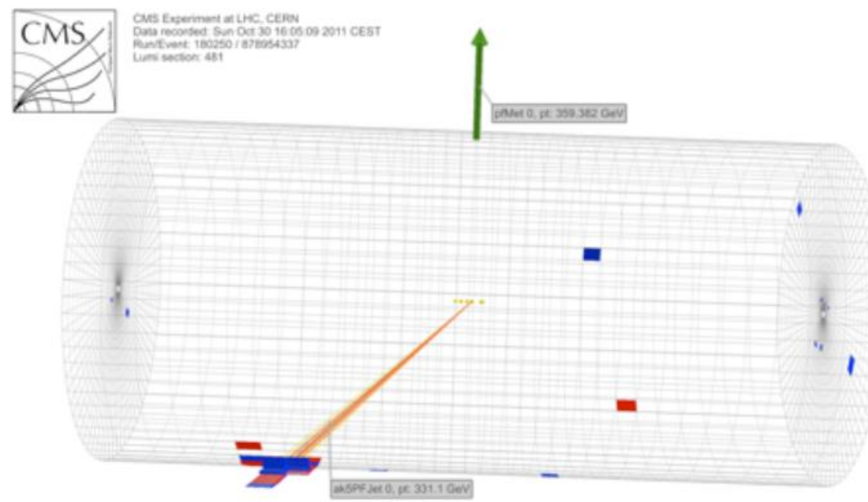
Characteristic signatures of ‘missing energy/momentum’

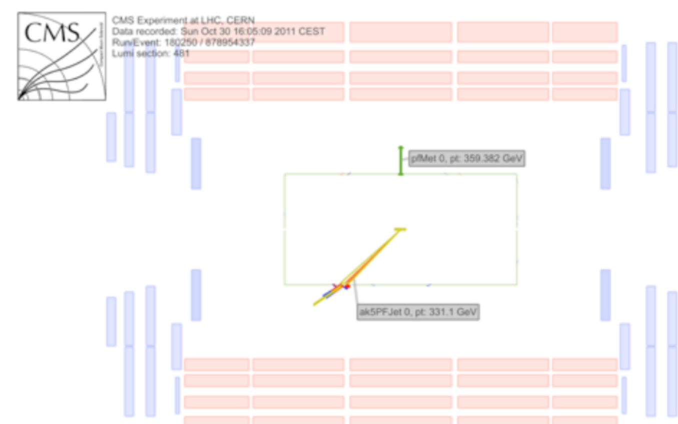
Monophoton event





Monojet event





Supersymmetry vs dark matter ?

Hierarchy problem:

Higgs mass (10^2 GeV) << Planck Scale (10^{19} GeV)

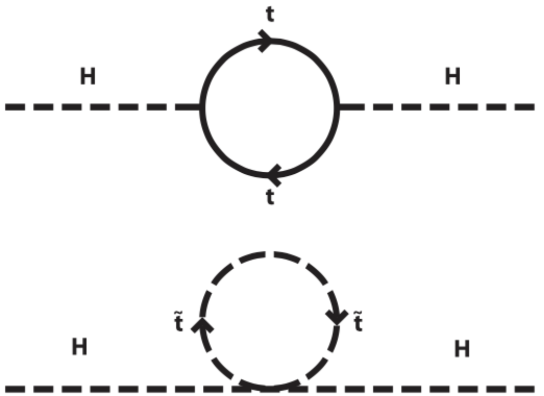
Possible solution:

Supersymmetry

Fermions	Bosons
Spin 1/2	**Spin 0, Spin 1**
electron	selectron (S=0)
quark	squark (S=0)
photino	**photon (S=1)**
gluino	**gluon (S=1)**
gaugino (Wino, Zino)	**W, Z (S=1)**

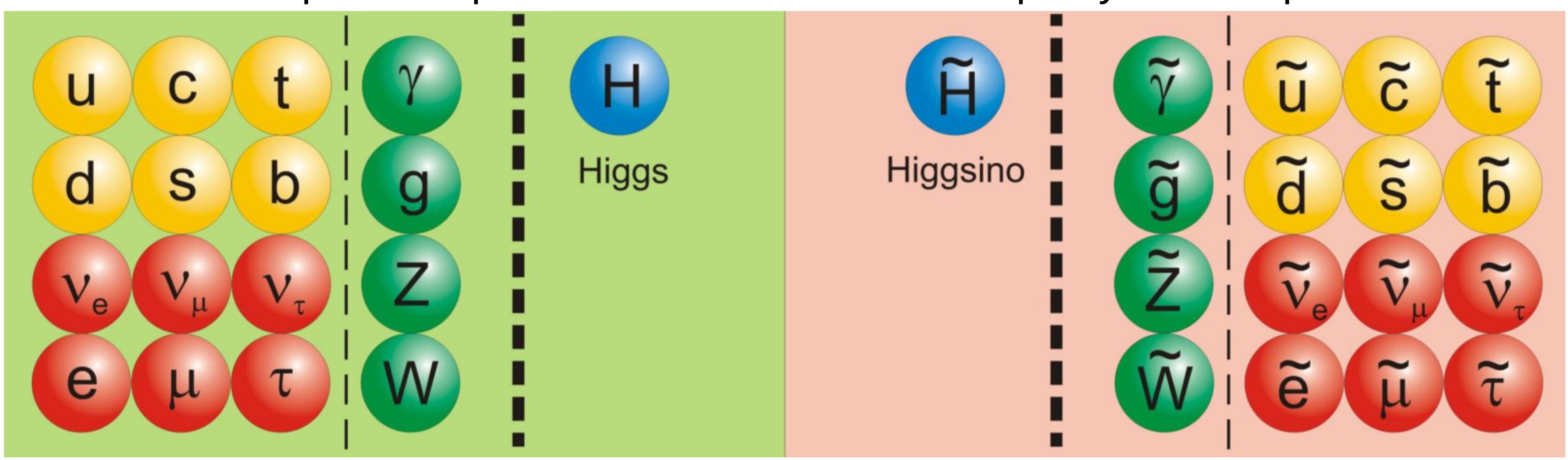
divergent

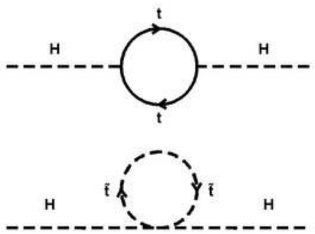
cancels divergence



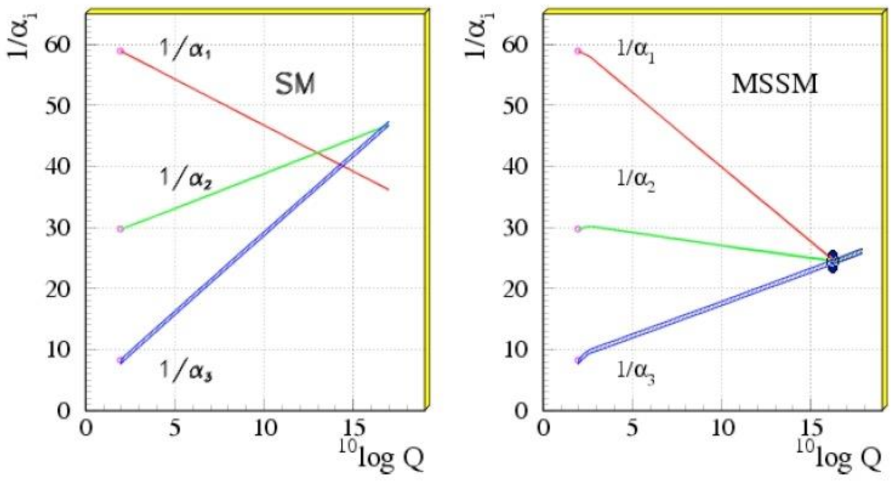
Known particle spectrum

supersymmetric partners



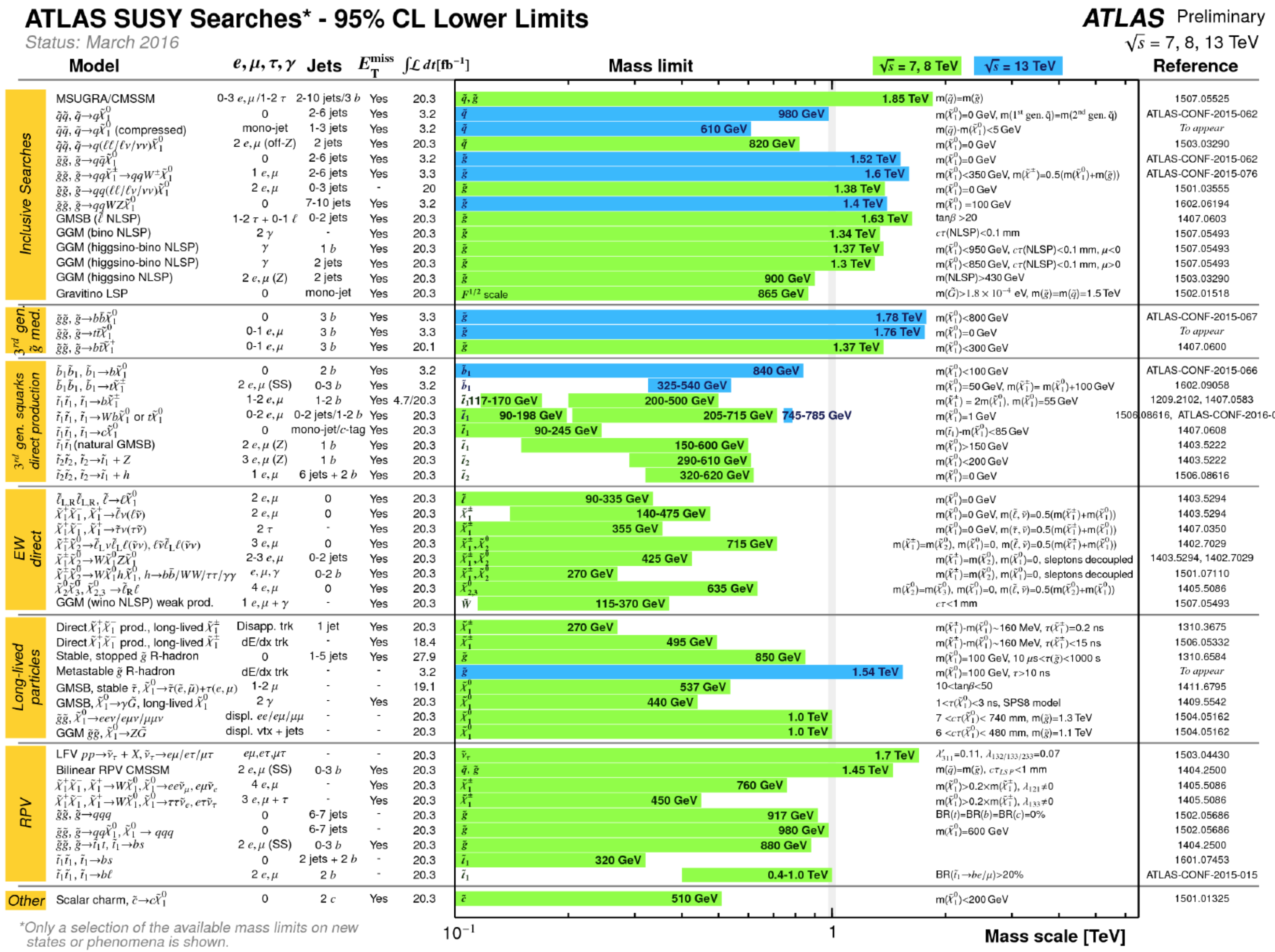


t
H
H
t
t̃
t̃
H
H

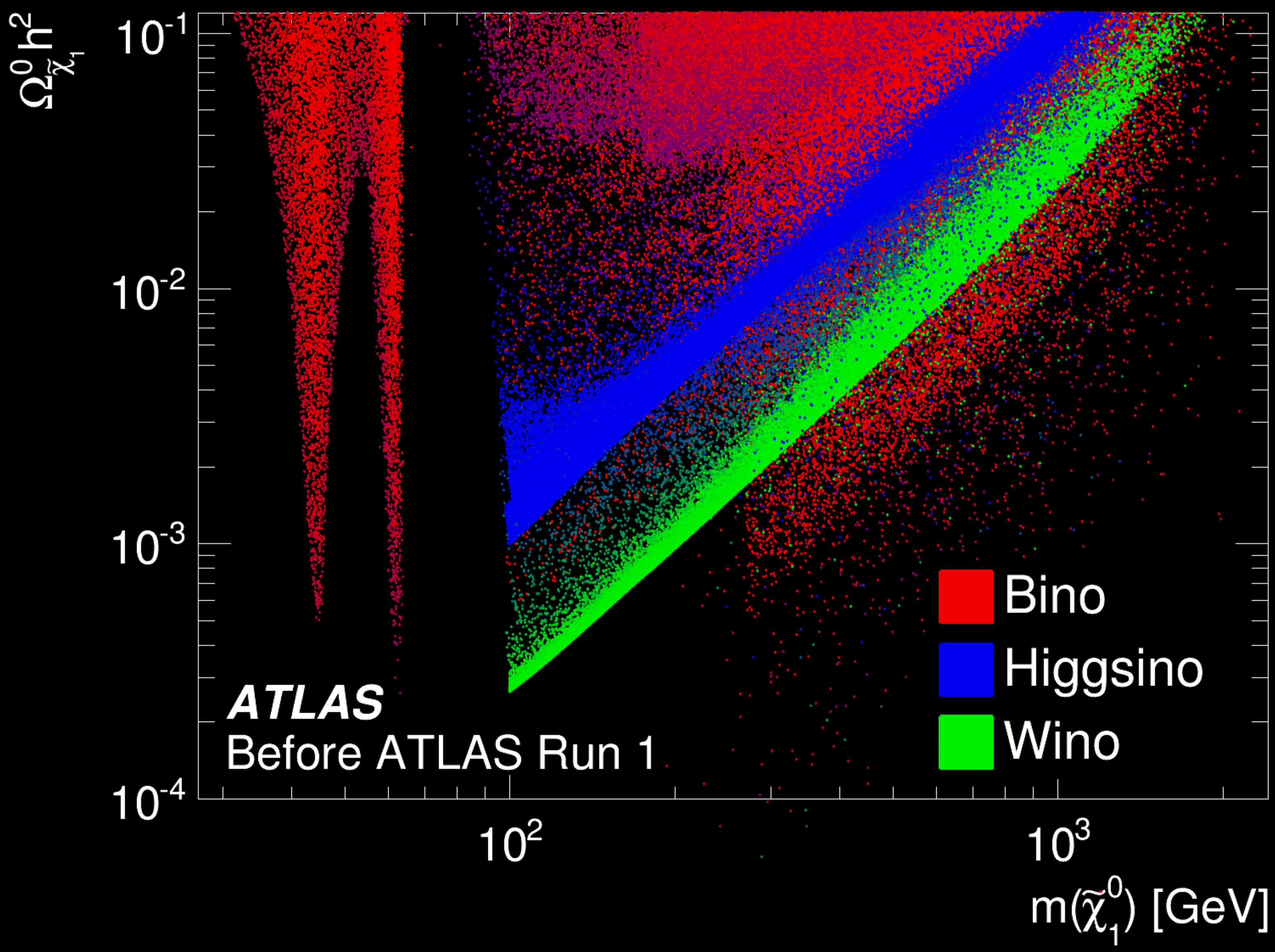


$1/\alpha_i$
$1/\alpha_1$
SM
$1/\alpha_2$
$1/\alpha_3$
$^{10}\log Q$
$1/\alpha_1$
MSSM
$1/\alpha_2$
$1/\alpha_3$
$^{10}\log Q$

No sign of SUSY … yet



Excluding SUSY models

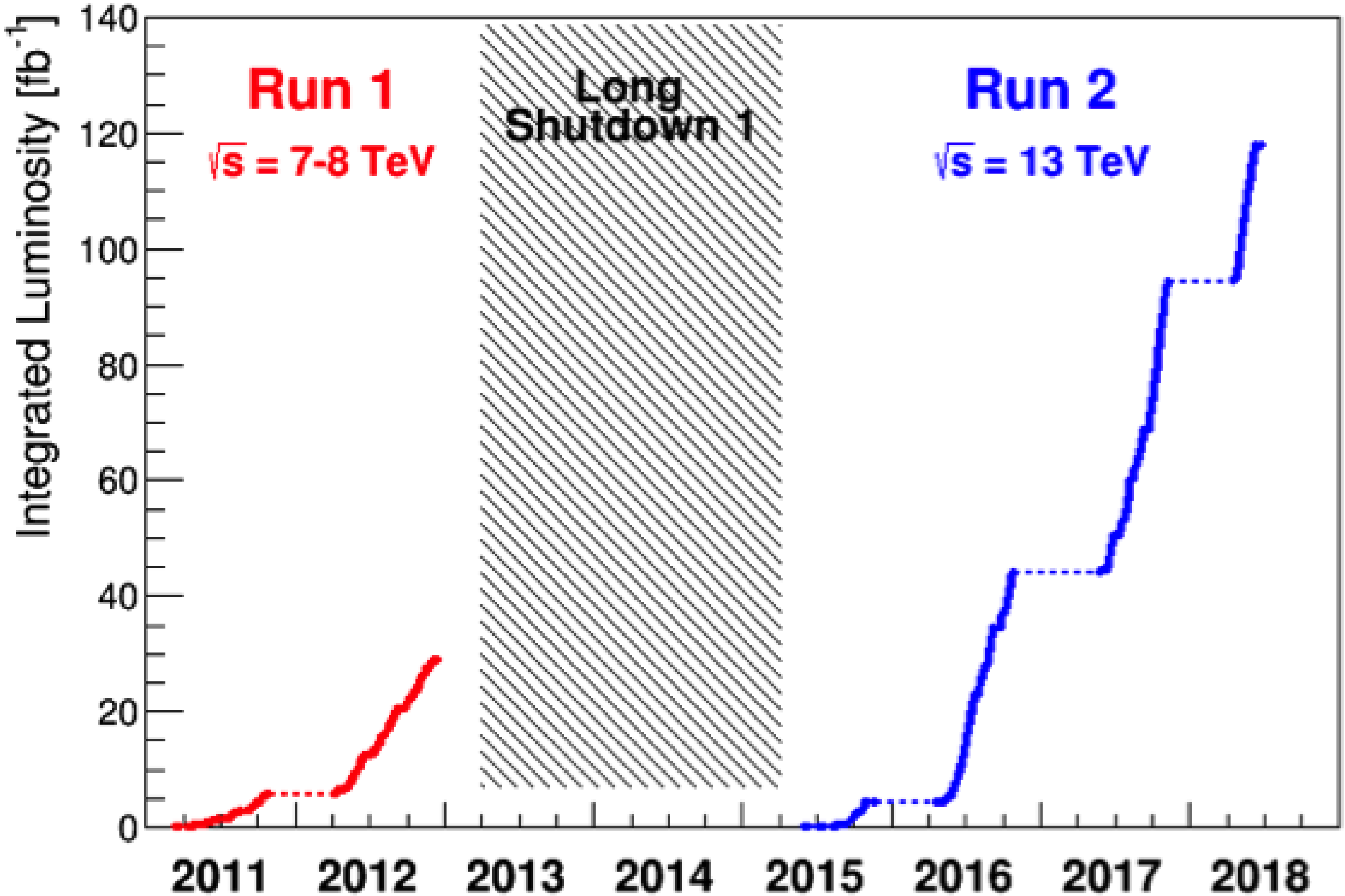


Prospects of particle physics

- Higher luminosity (until 2035)
- Higher energy (afterwards)

Goal: maximize number of collision events ("integrated luminosity")

ATLAS and CMS each ~ 120 fb^{-1} = 12 · 10^{15} p-p collisions



1 fb^{-1} ~ 10^{14} p-p collisions

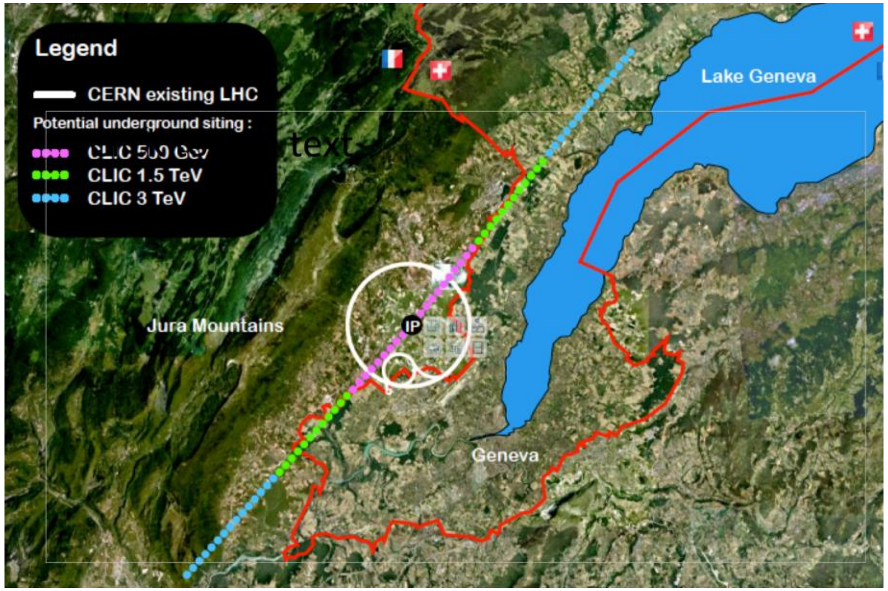
CERN Schedule 2015 - 2035 with Hi-Lumi phase

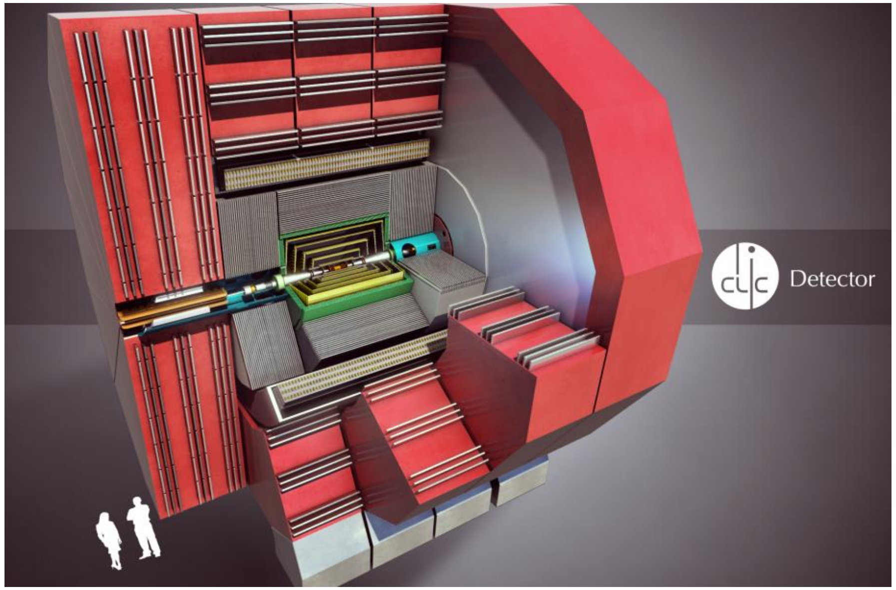
Final goal LHC: 3000 fb^{-1}

Phase 2 = High-Luminosity operation

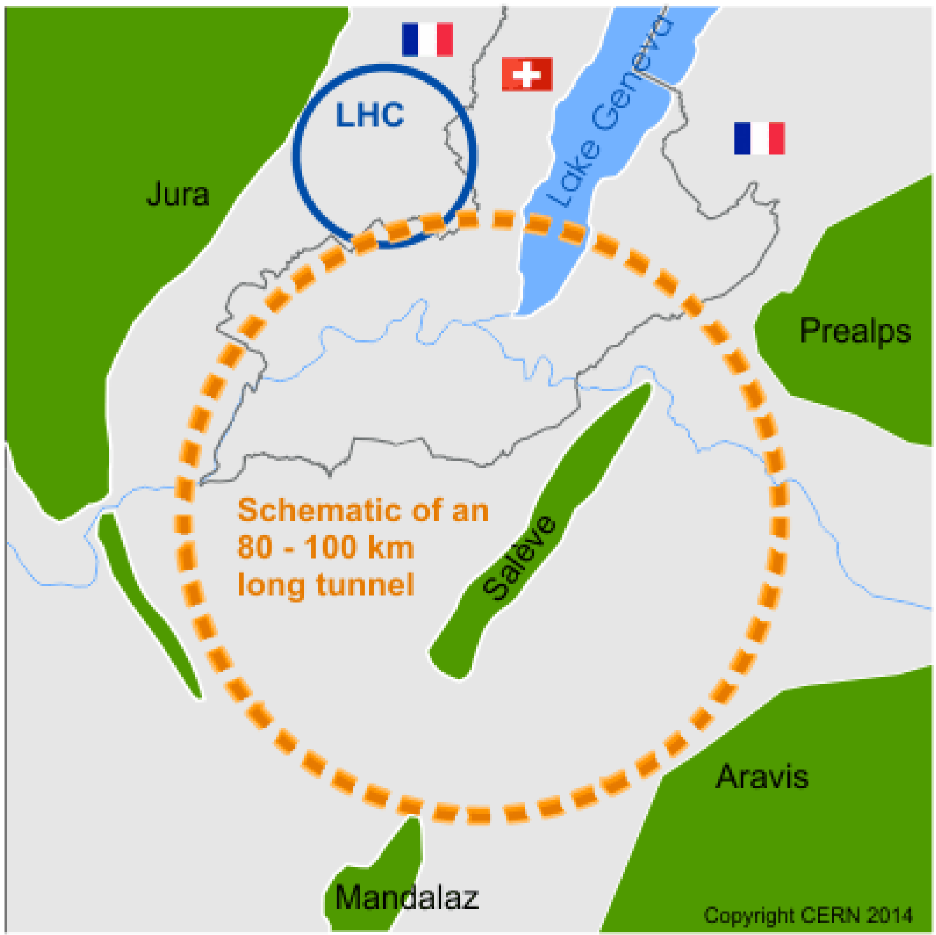
Linear Collider

CLIC: 3 TeV $e^+ e^-$ Collider ?





Future circular collider - project study (FCC)



Conceptual design report ~ late 2018

Circular collider in new tunnel

80- 100 km circumference

Circular proton-proton collider
100 TeV collision energy (p+p)

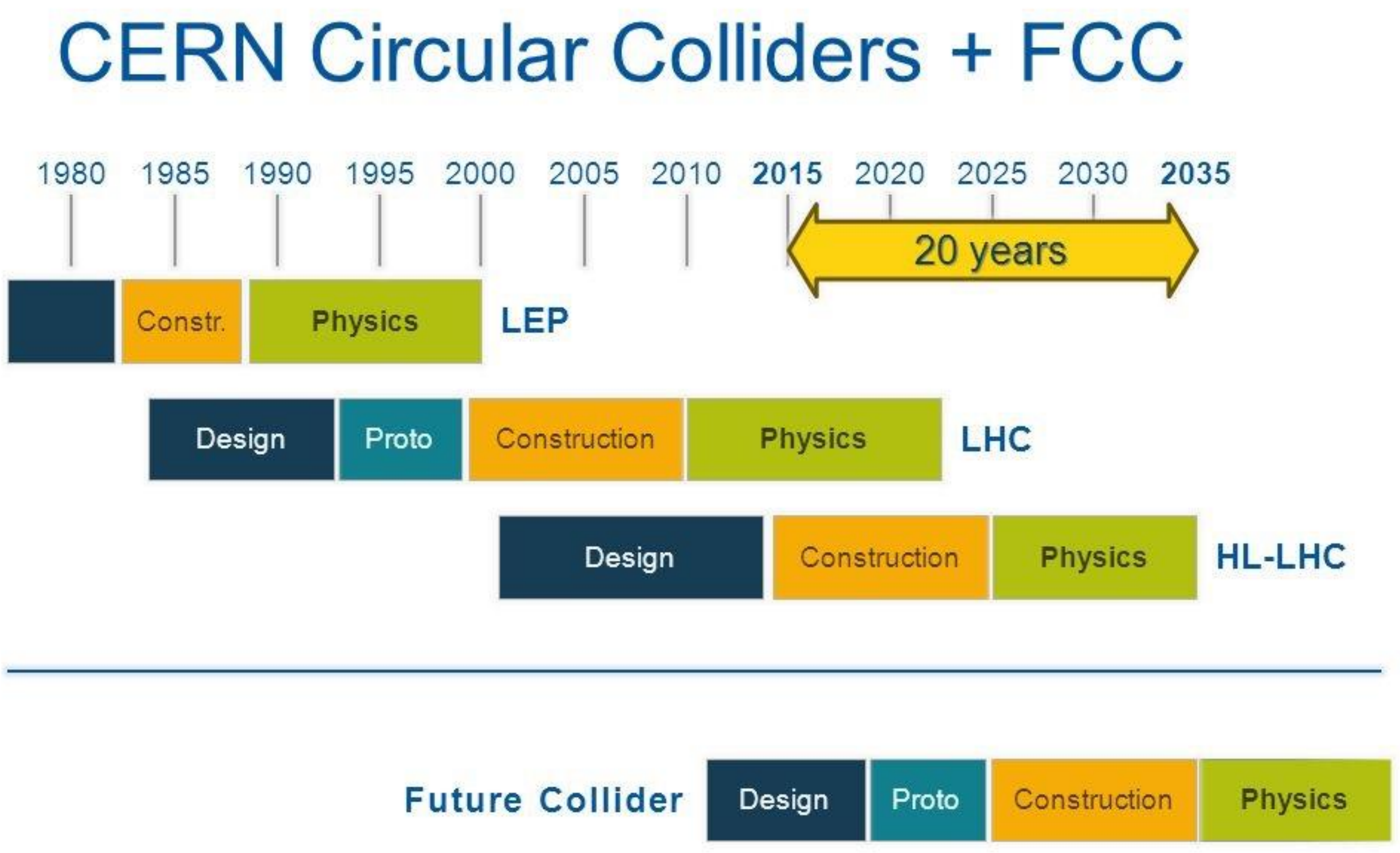
Circular electron-positron collider (VLEP)
(***350 GeV c.m.*** energy, t-tbar threshold)

Lepton-Hadron collider (like HERA)
(***50 TeV p + 100 GeV e***)

Alternatively:

30 TeV p-p collider in LHC tunnel ?
(***16 T magnets***)

How to get there ?



Mysteries of the 21st century

1900 - 2000: Phantastic progress in understanding matter and the Universe

We know what matter is made of.
We know the principle steps in the evolution of the Universe.

Some of the big physics questions of the 21st century

What is dark matter?
How did the antimatter disappear?
What is the structure of empty space: the BEH field? dark energy?
What is the origin of (three?) particle families? What is a ‘particle’?
Where is the connection between quarks and leptons ?
What is the origin of the constants of Nature?