Part II

Part I

Discoveries for physics revolutions

Part II

Introduction to the Standard Model of Particle Physics

Part III

Beyond the SM: SUSY and ToE

A romantic dream for an unified description of the universe?

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Credit to: Rolf Landua, CERN

Introduction to the "Standard Model" of Particle physics

1. SM was developed throughout the latter half of the 20th century, as a collaborative effort of scientists around the world;

1. SM is a theory concerning the electromagnetic, weak, and strong nuclear interactions;

1. It mediates the dynamics of the known subatomic particles;

2. Following the QED example, the SM is a paradigm of a Quantum Field Theory (QFT). Interacting particles exchange a force carrier called gauge boson;

3. the force carriers are bundles of energy (quanta) of gauge fields;

4. The gauge fields are included in the Lagrangian to ensure invariance (in addition to rotation, translation and reference frame invariance of special relativity) under certain transformations. Once quantized the quanta of the gauge fields are the force carriers called gauge bosons.

5. This mechanism leads to the unification of forces embodied in the SM.

Force carrier Particles

- The quantum excitations of the gauge field can be interpreted as particles. The Standard Model contains the following particles, each of which is an excitation of a particular field:

- Gluons, excitations of the strong gauge field.

- Photons, $W^{\pm}$ bosons, and Z bosons, excitations of the electroweak gauge fields.

- BEH (Higgs) bosons, excitations of one component of the Higgs field, which gives mass to fundamental particles.

Strong nuclear interaction

- 1930 Many particles were discovery in the cosmic rays and collider experiments: particle zoology rapidly growing;
- 1973 Looking for basic constituents, Bardeen, Fritzsch, Gell-Mann proposed a model based on 3 quarks, with fractional electric charge, with three type of strong charges, namely: red, green and blue (color charges);
- Soon the discovery of new particles announced the existence of other quarks: six at the end;

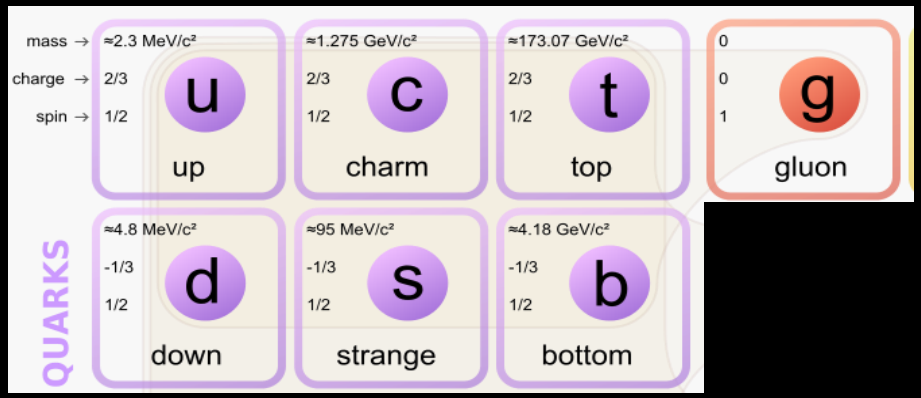
Quantum Chromo Dynamics

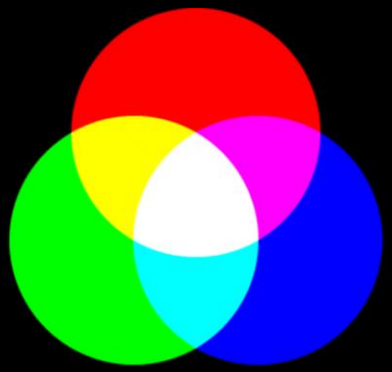
this has nothing to do with our visible colours!! Just an analogy

Theory constructed in analogy to QED

QCD: 3 different charges ("colour charge") [red, green, blue]*

'Strong force' between quarks is transmitted by (8) gluons (massless), the bosons





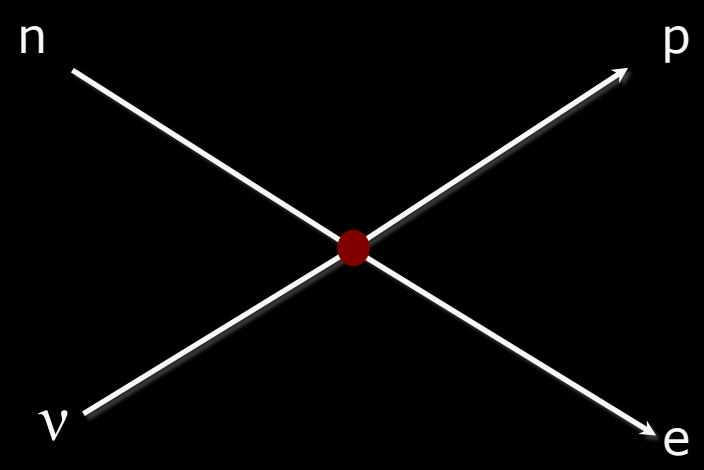
Dogma of QCD: Only colour-neutral bound states are allowed, explains:

MESONS = Quark-Antiquark

BARYONS = 3-Quark states

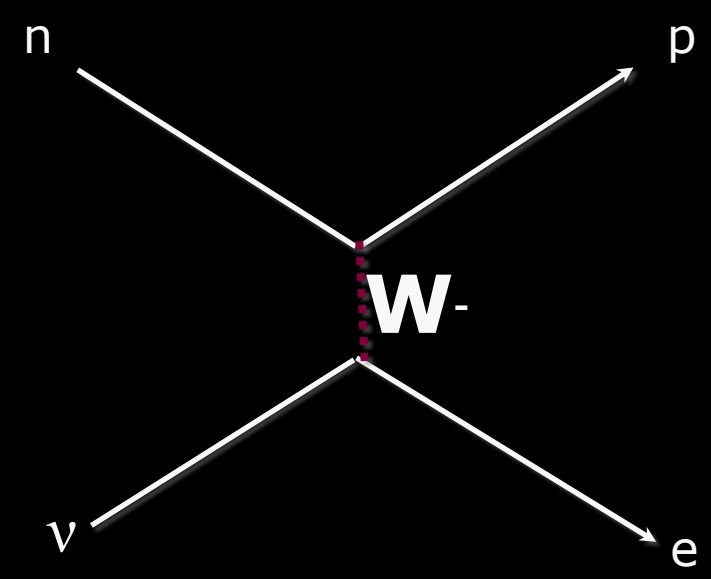
Weak interaction

Fermi model turn out
to be inconsisten at E>300GeV
Probability of this reaction > 100% (E > 300 GeV)

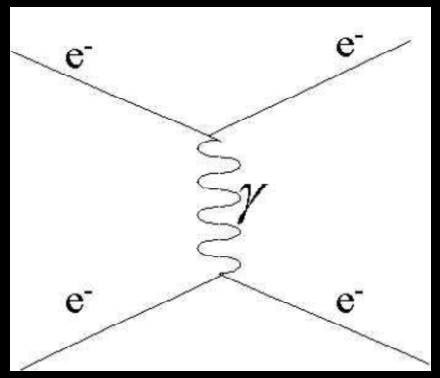


Fermi model

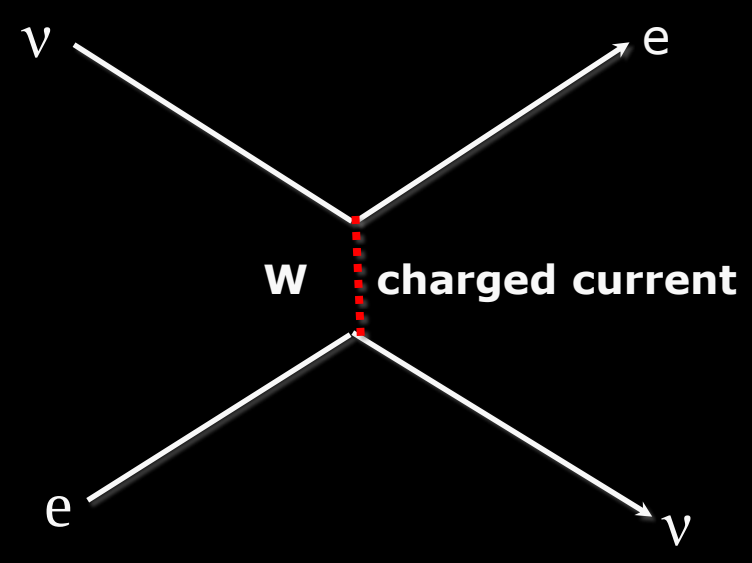
New Idea (1958)
S. Glashow

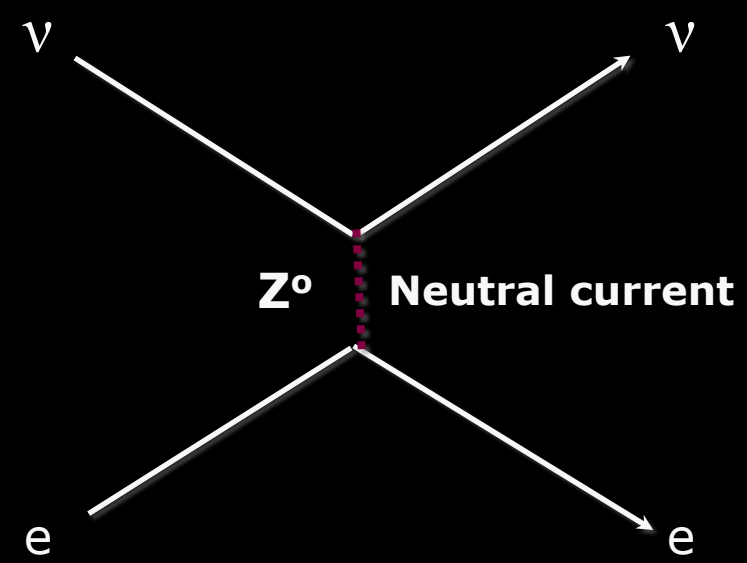


Weak interaction transmitted by massive vector bosons
(in analogy to photon exch
Large mass (80 GeV) explains
short range ($2 \cdot 10^{-18}$ m) and small cross-sections



Unification of electromagnetic and weak interaction



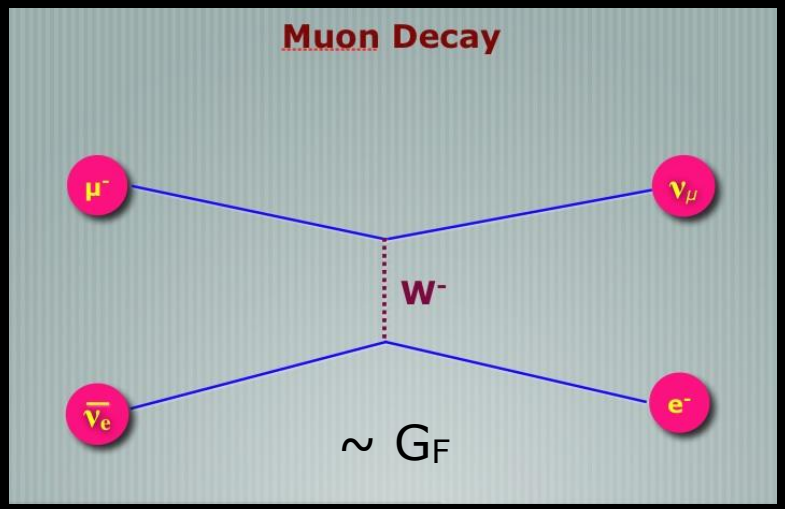


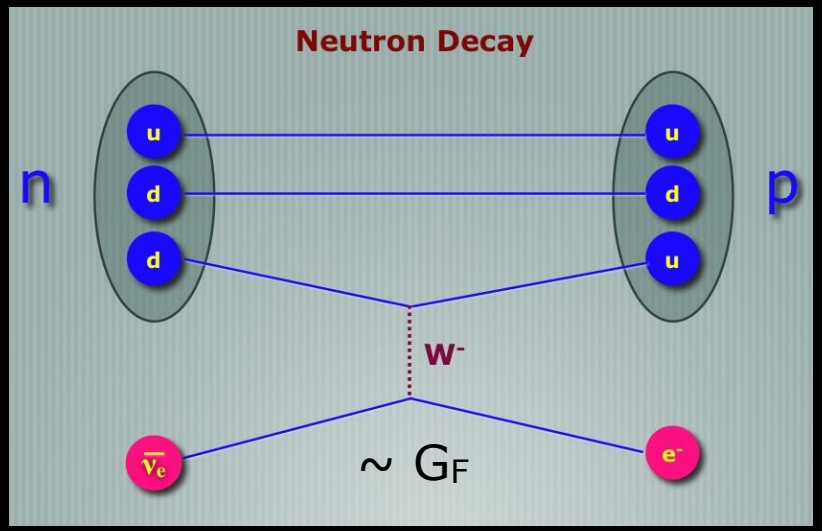
Glashow, Salam, Weinberg (1968) - Electroweak Force

- The electromagnetic and weak interaction are different aspects of the same 'electroweak' force
- All quarks and leptons have a 'weak' charge
- There should be a 'heavy photon' (Z^o) and two charged vector boson ($W^{\pm}$) of mass ~ 50-100 GeV
- **The W,Z bosons acquire their mass by interacting with the "Higgs field" (1964)**

Fields

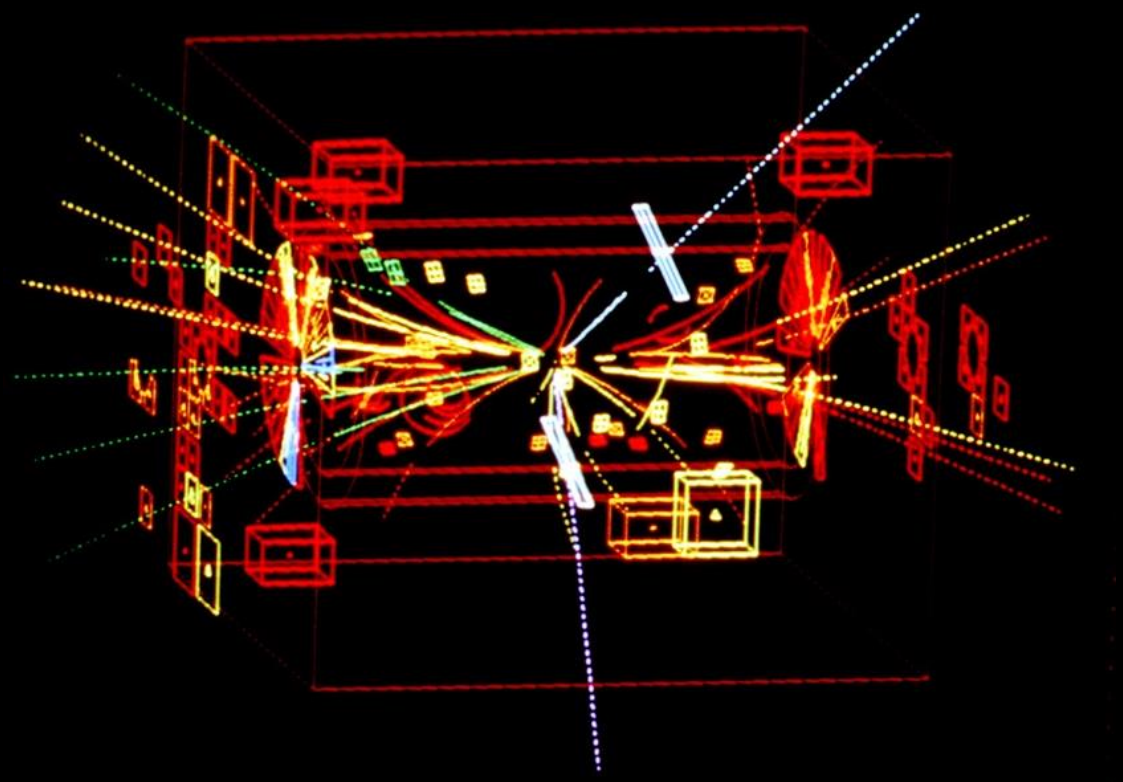
Electroweak interaction is the SAME for leptons and quarks





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

Discovery of the W, Z bosons at CERN-LEP (1983)



(C. Rubbia, S. van der Meer)

New experimental confirmation of the standard model via the detection of the weak gauge bosons

How do particles obtain their respective masses?

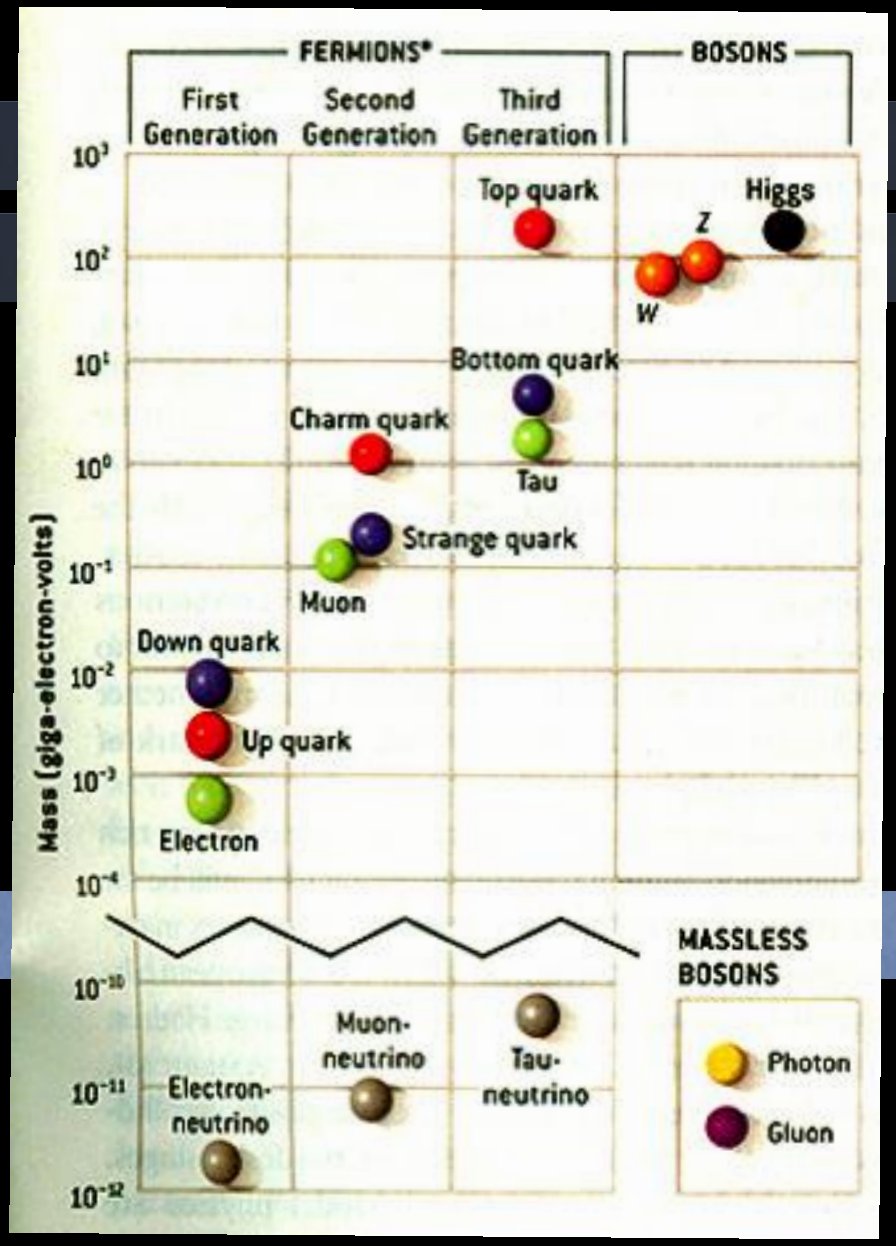
1 TeV →

100 GeV →

1 GeV →

1 MeV →

0.01 eV →



The Brout-Englert-Higgs field idea

The Brout-Englert-Higgs field idea:

the entire Universe is filled with a homogeneous field

massless 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...

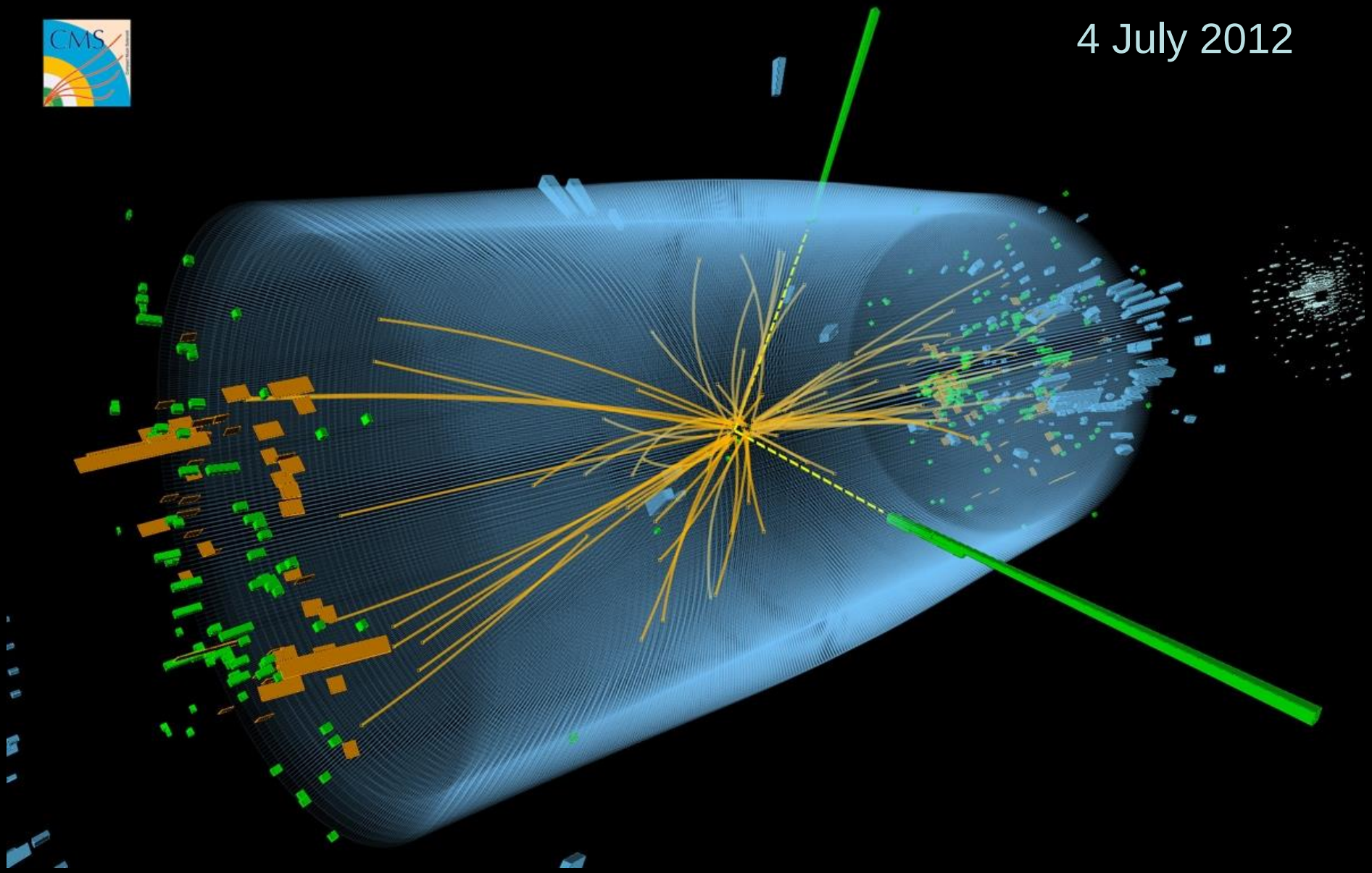
The BEH field ...

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

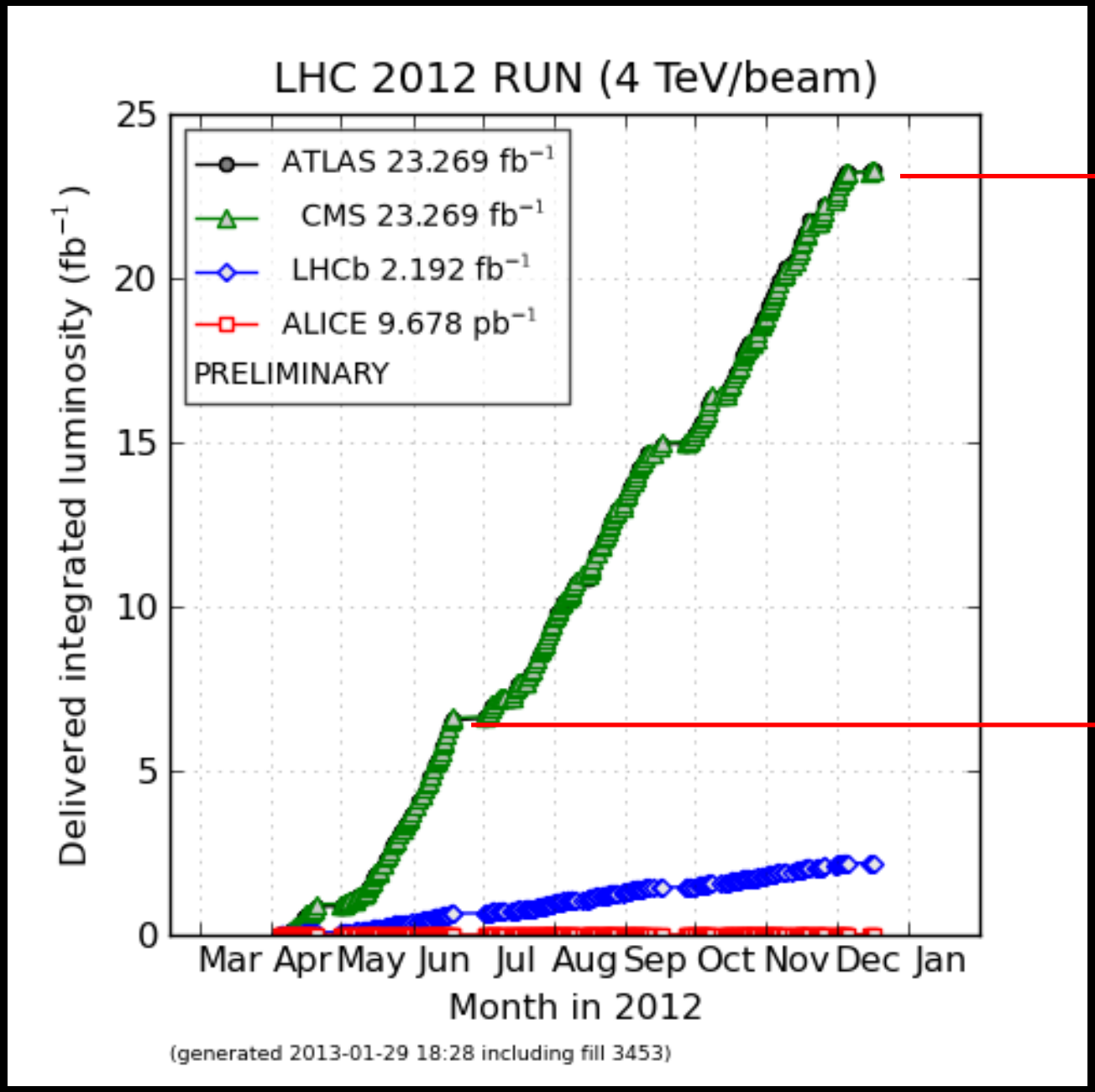
Stimulating the BEH field by pp colisions at the LHC , the corresponding waves can apper as particle thanks to the duality wave-particle in the QM

How do we know that it is the Higgs boson ?

4 July 2012



2011 - 2012 : Data taking with LHC

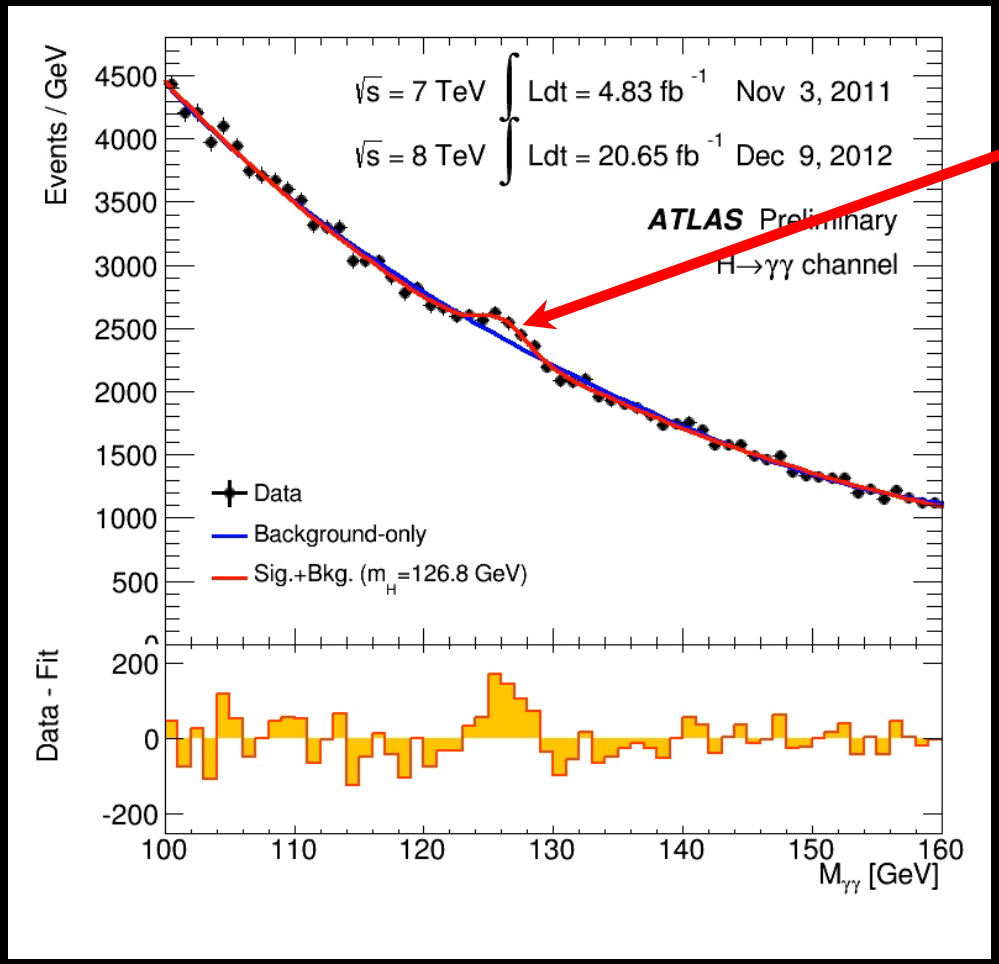


15.12.2012

3,000,000,000,000,000 ($3 \cdot 10^{15}$)
(3000 trillion events !)

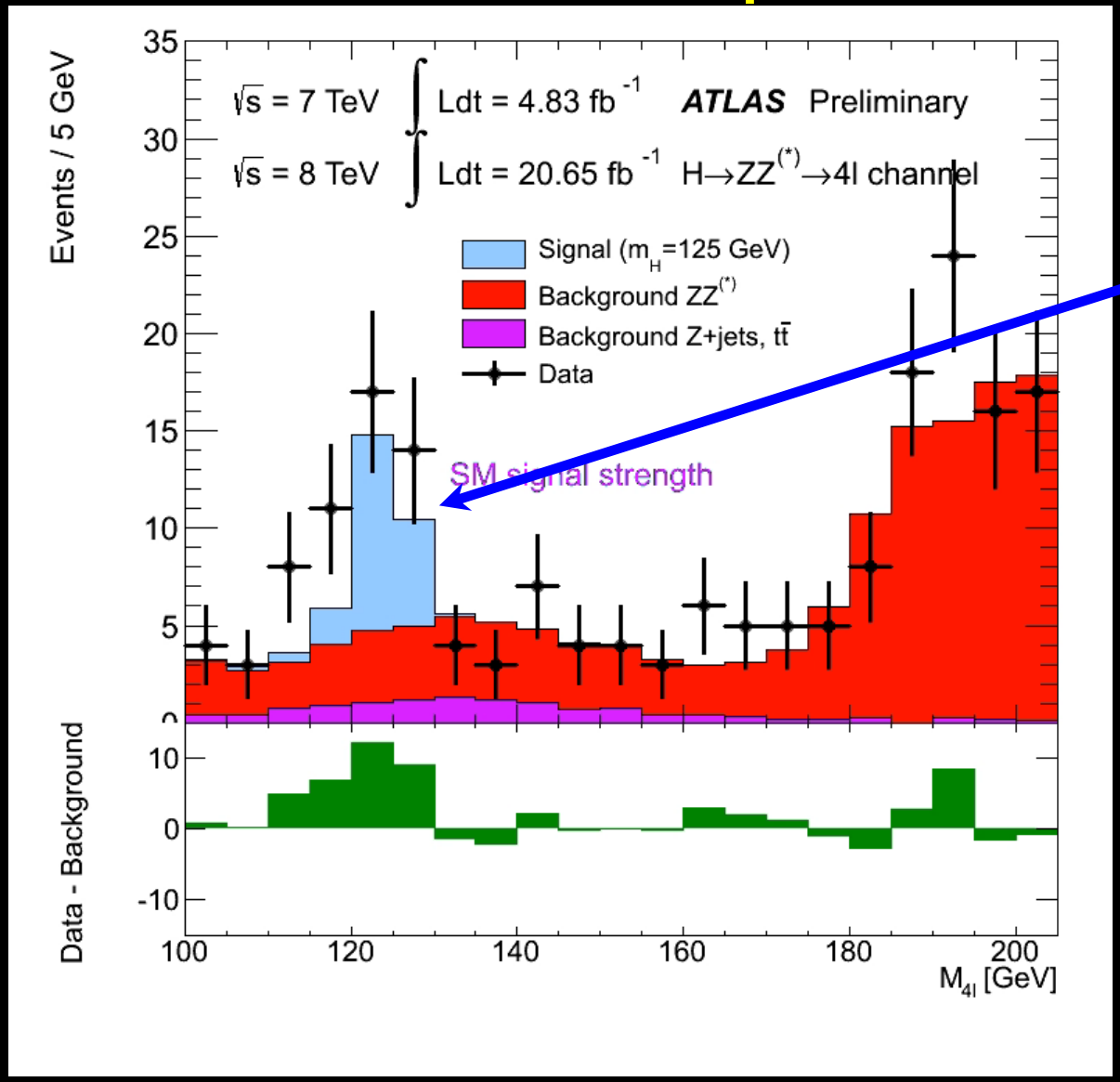
4.7.2012

The evolution of the histogram with two-photon events



Higgs boson

The evolution of the histogram with four leptons

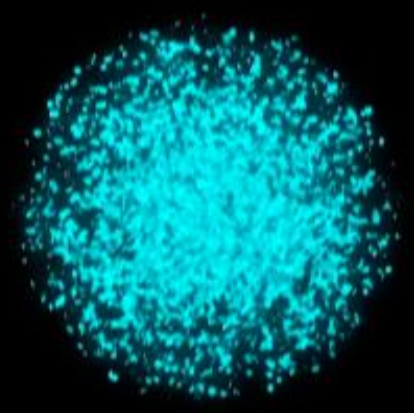


Higgs boson

Is it the Higgs boson?

Update 14.3.2013: CERN Press Release
More data confirm: new particle = Higgs boson

Higgs boson decay



$\gamma\gamma$

Z^0 - Z^0

Tau- Antitau

Bottom - Antibottom

Theoretical expectations compatible with observations

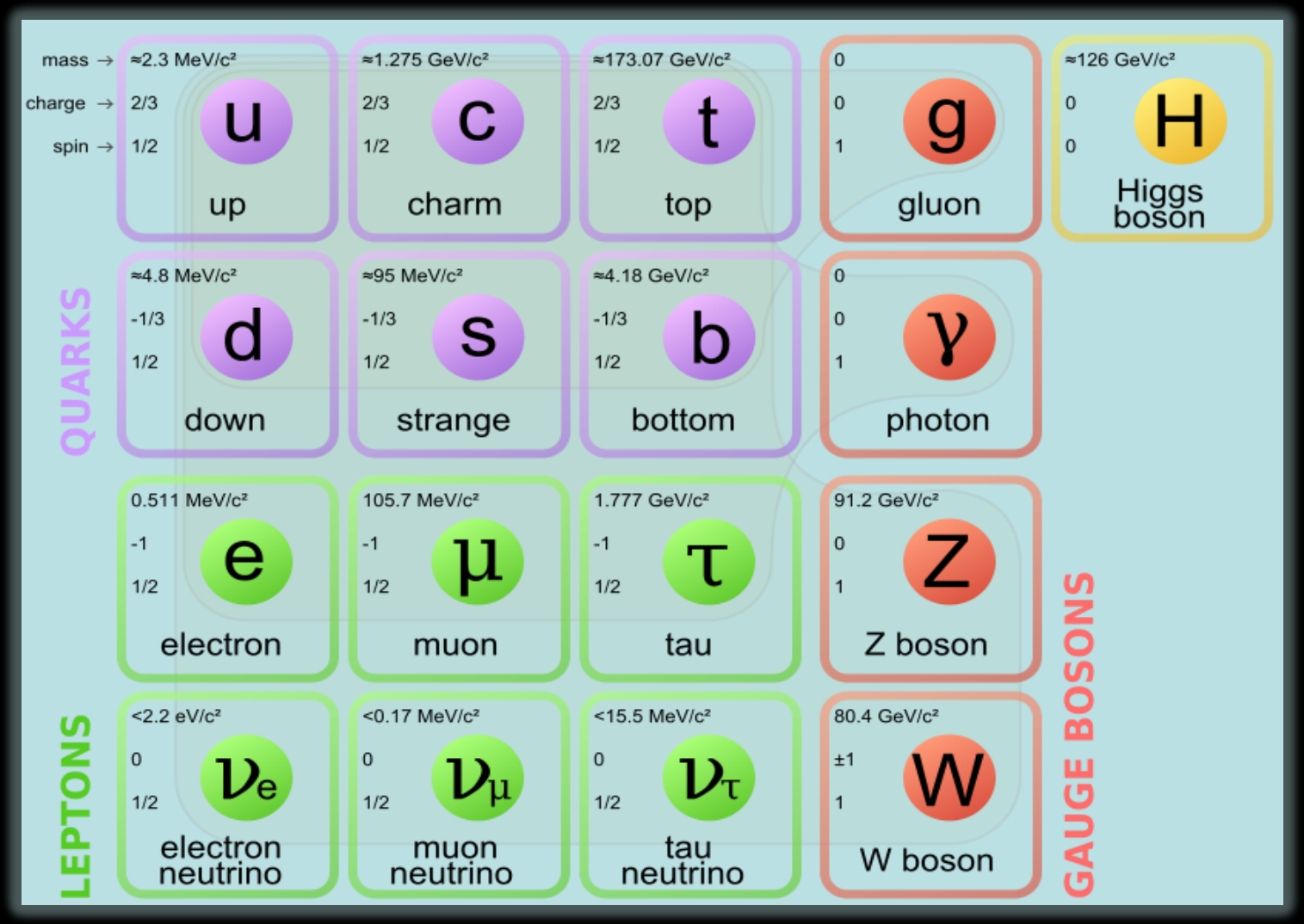
What does this mean?

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

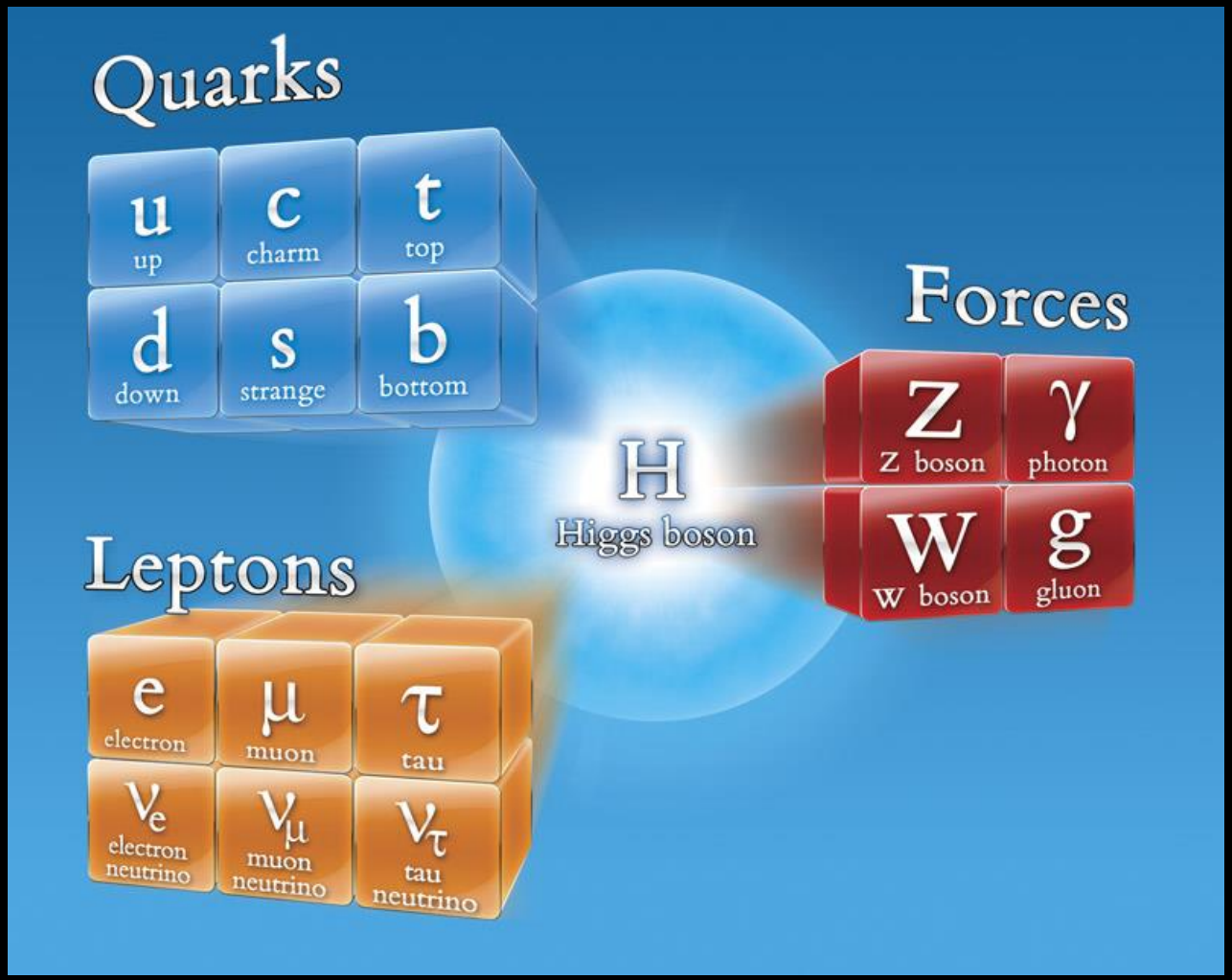
Even more:

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

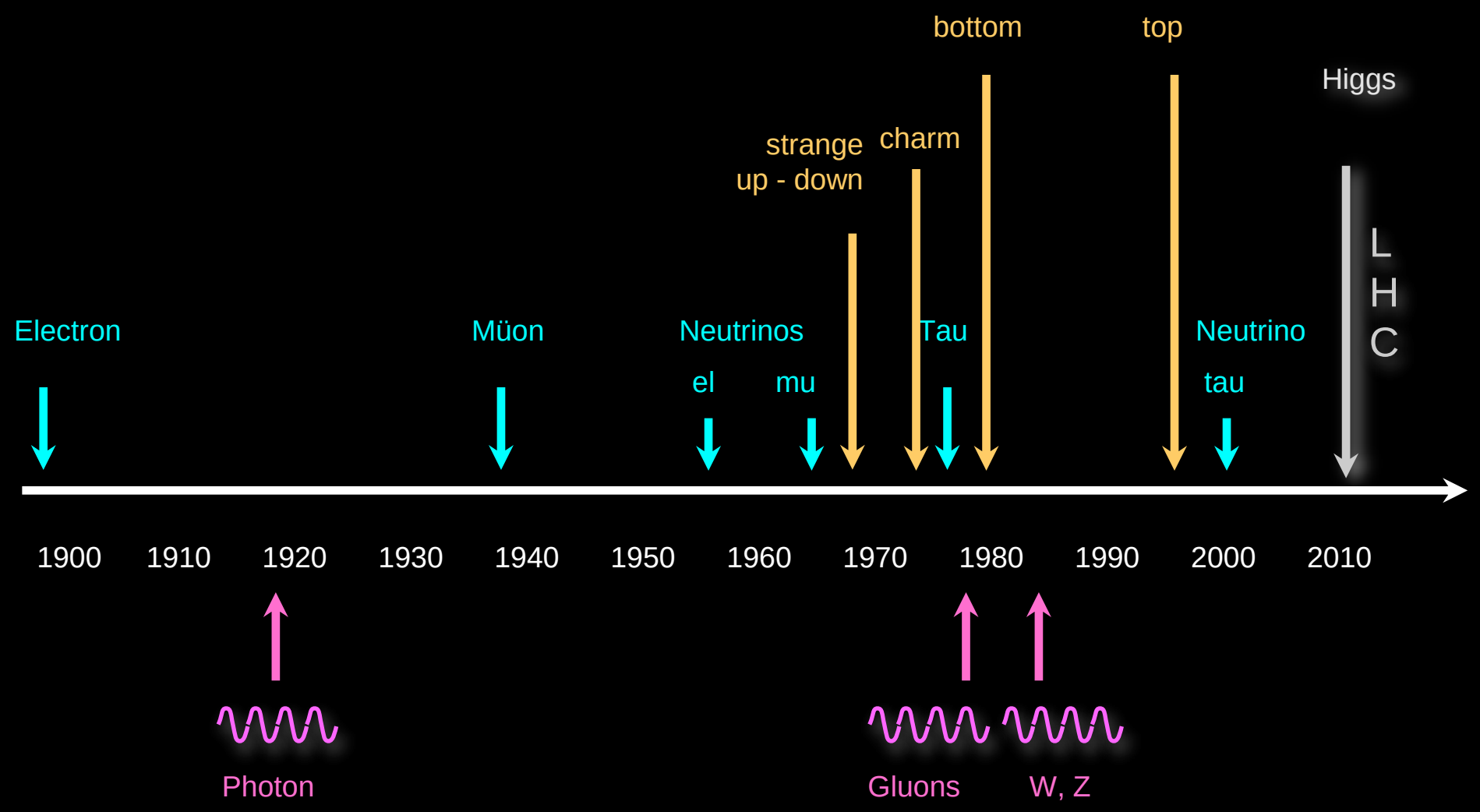
The SM ‘element table’



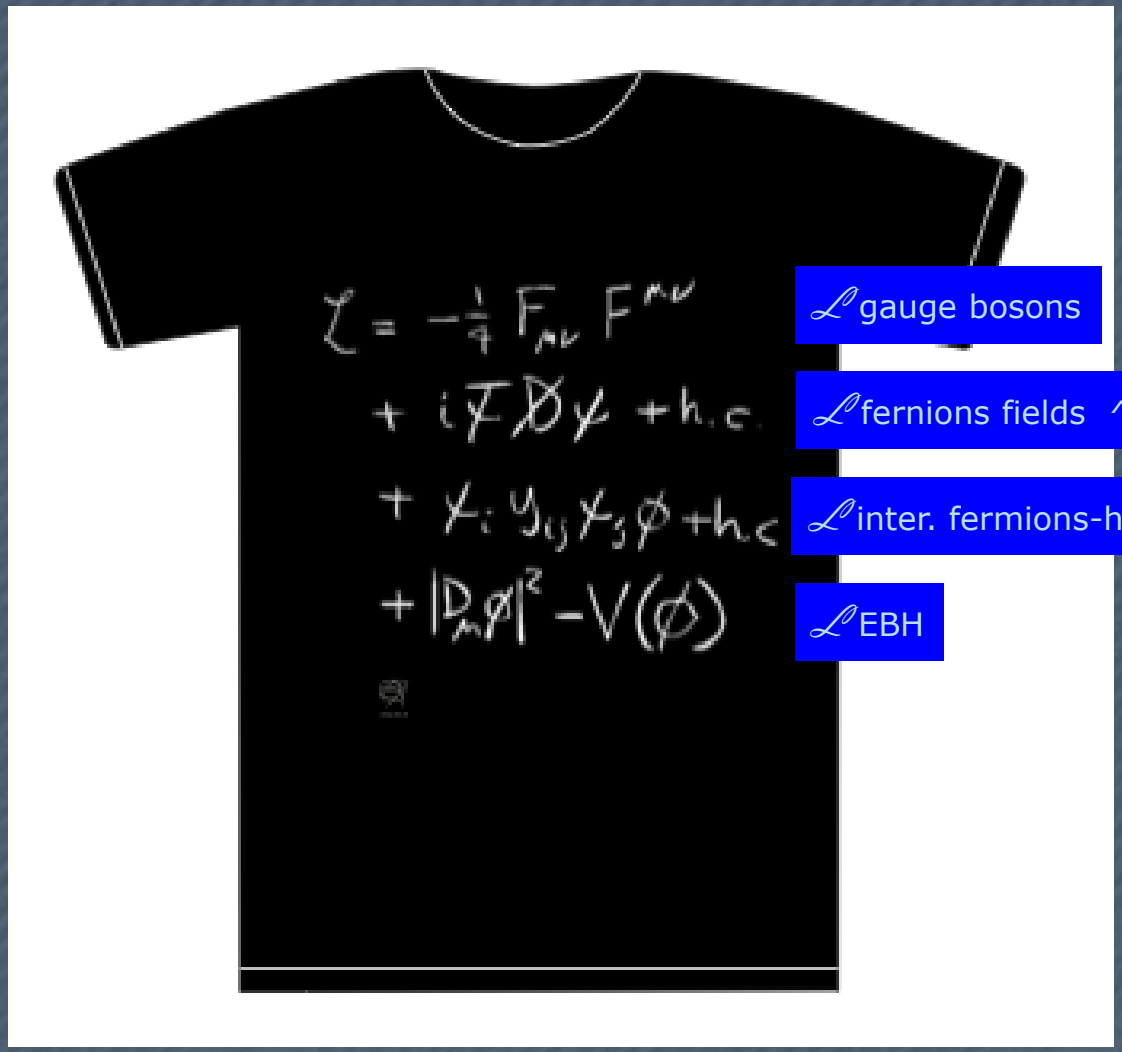
BEH boson


Quarks
u
up
c
charm
t
top
d
down
s
strange
b
bottom
Leptons
e
electron
μ
muon
τ
tau
νe
electron neutrino
νμ
muon neutrino
ντ
tau neutrino
H
Higgs boson
Forces
Z
Z boson
γ
photon
W
W boson
g
gluon

Experiments at accelerators have discovered all particles of the SM



Contributions to the SM Lagrangian



$\mathcal{L}$ gauge bosons

$\mathcal{L}$ fernions fields ^ gauge interactios

$\mathcal{L}$ inter. fermions-higgs

$\mathcal{L}$ EBH

Summary part II

- STANDARD MODEL: In analogy with QED, weak and strong interactions are described as gauge theory. SM is a paradigm of a Quantum Field Theory (QFT);
- paceful existence of Electromagetic, weak, QCD and Higgs Mechanism.;
- BEH mechanism providing mass to elementary particles experimentally proved by ATLAS-CMS at LHC.