From the Plum Pudding to the string theory

Revolutionary ideas and discoveries in the 20th century for a modern particle physics

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Outlines

- Disclaimer!
- Introduction to particle physics 1
  - From the Plum-Pudding atomic model to the Bohr model;
  - Special relativity -> general relativity (GR);
  - Quantum Mechanics (QM)
  - Quantum Field Theory (QFT)
- Introduction to particle physics 2
  - The standard model (SM) of forces and particles;
  - The BEH boson (Higgs boson)
- Introduction to particle physics 3
  - Beyond the SM: Supersymmetry (SUSY) for the electro-strong unification (GUT),
  - Beyond GUT: GR + QM : String theories?, M-theory? Loop quantum Gravity?.....

past present future

Introduction to the "Standard Model"

- In the first half of 20th century the zoology of the particle became very populated (cosmic rays and colliders);
- SM was developed throughout the latter half of the 20th century, as a collaborative effort of scientists around the world;
- SM is a theory concerning the electromagnetic, weak, and strong nuclear interactions in the framework of the space-time of SR;
- It mediates the dynamics of the known subatomic particles;

Introduction to the "Standard Model"

- Following the QED example, the SM is a paradigm of a Quantum Field Theory (QFT). Interacting particles exchange a force mediator called gauge boson;
- the force mediator are bundles of energy (quanta) of gauge fields;
- The gauge fields are included to ensure invariance (in addition to rotation, translation and reference frame invariance of special relativity) of the interaction (Lagrangian) under certain transformations.
- Once the gauge field is quantized, the quanta of the gauge fields are the force mediators called gauge bosons.
- This mechanism leads to the unification of forces embodied in the SM.

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;

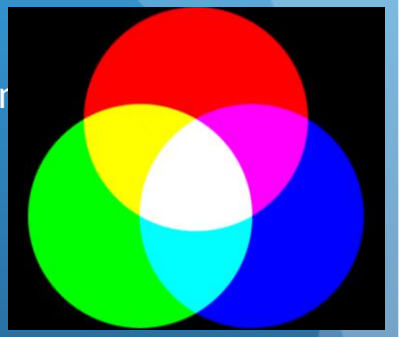
Quantum Chromo Dynamics

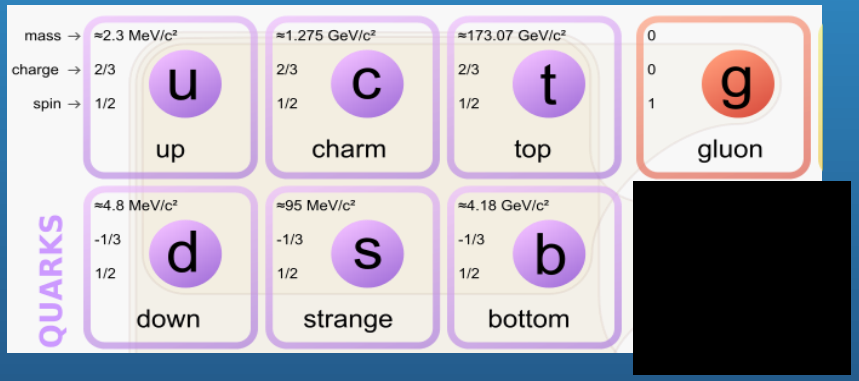
this has nothing to do with our visible colours!! Just an analogy

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 gauge boson





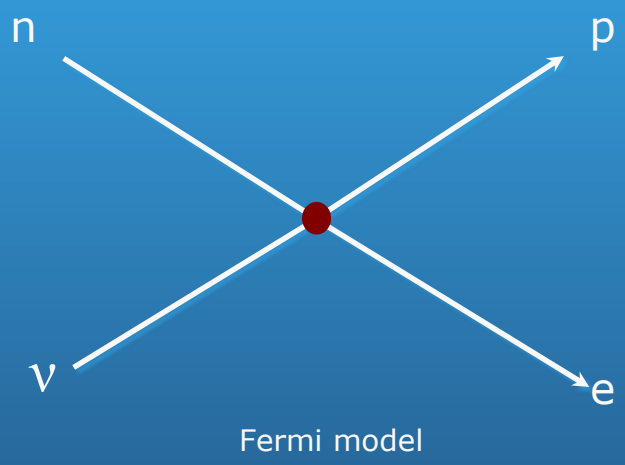
Dogma of QCD: Only colour-neutral bound states are allowed, explains:

MESONS = Quark-Antiquark

BARYONS = 3-Quark states

Weak interaction

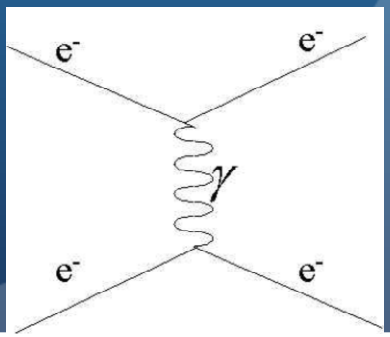
Fermi model turn out
to be inconsisten at E>300GeV
Probability of this reaction > 100% (E > 300 GeV)



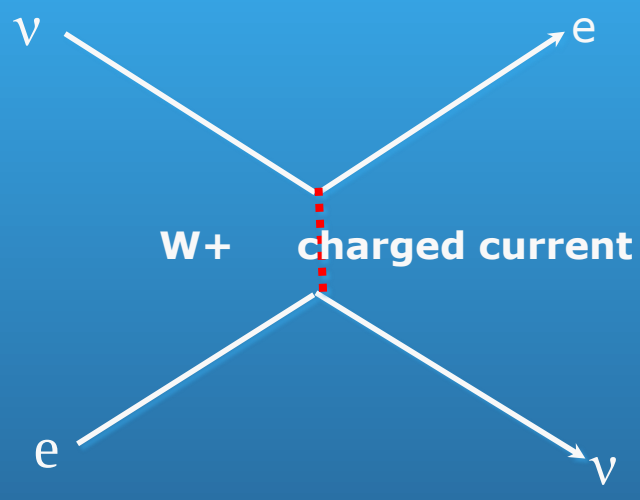
Fermi model

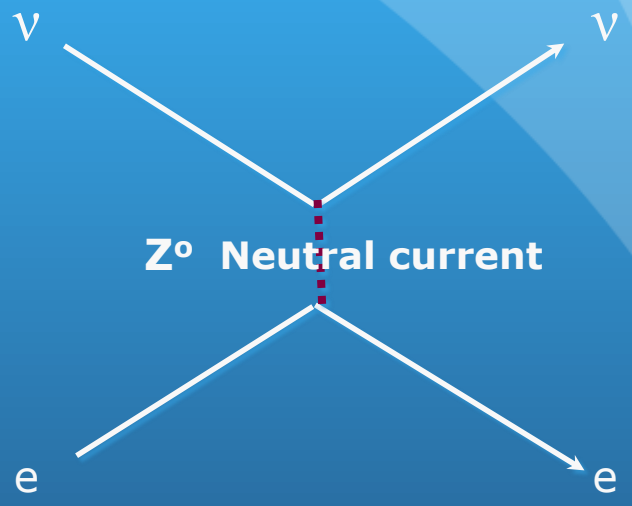
New Idea (1958)
S. Glashow

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



Weak Interaction



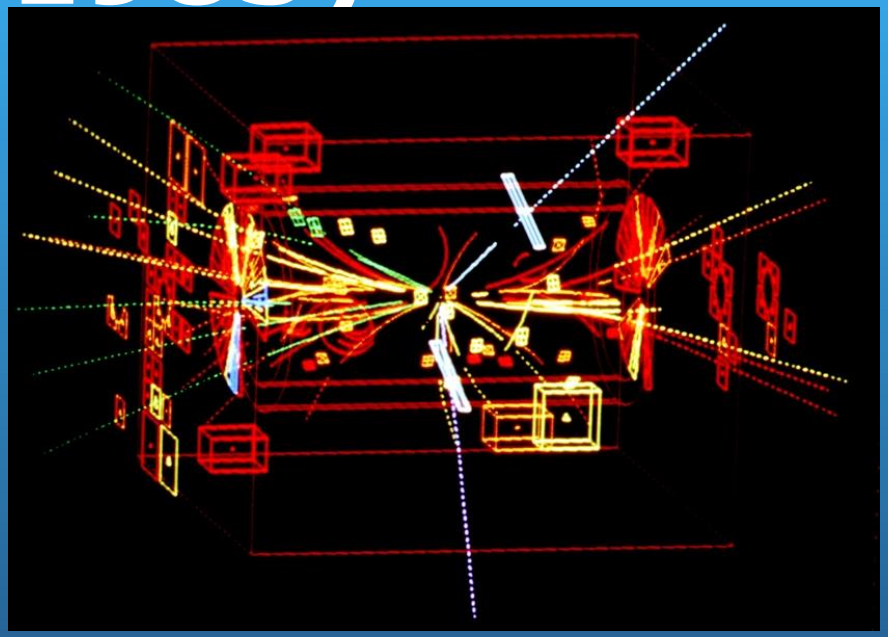


Glashow, Salam, Weinberg (1968) - Electroweak Force

- The electromagnetic and weak interaction are different aspects of the same 'electroweak' force
- All quarks and leptons have a 'weak' charge and feel the w.i. in the same way*
- w.i. range ->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)**

*Assuming a little bit of 'quark' mixing

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



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

(C. Rubbia, S. van der Meer)

The BEH Boson

How do particles obtain their respective masses

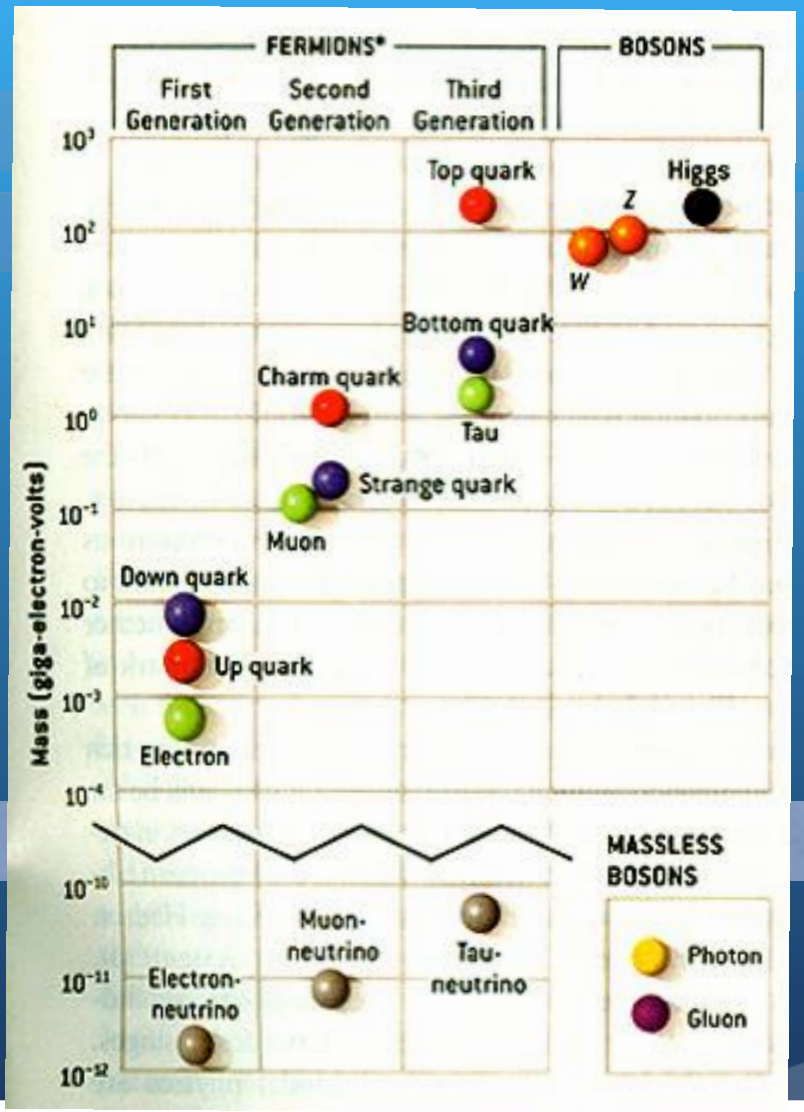
1 TeV →

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

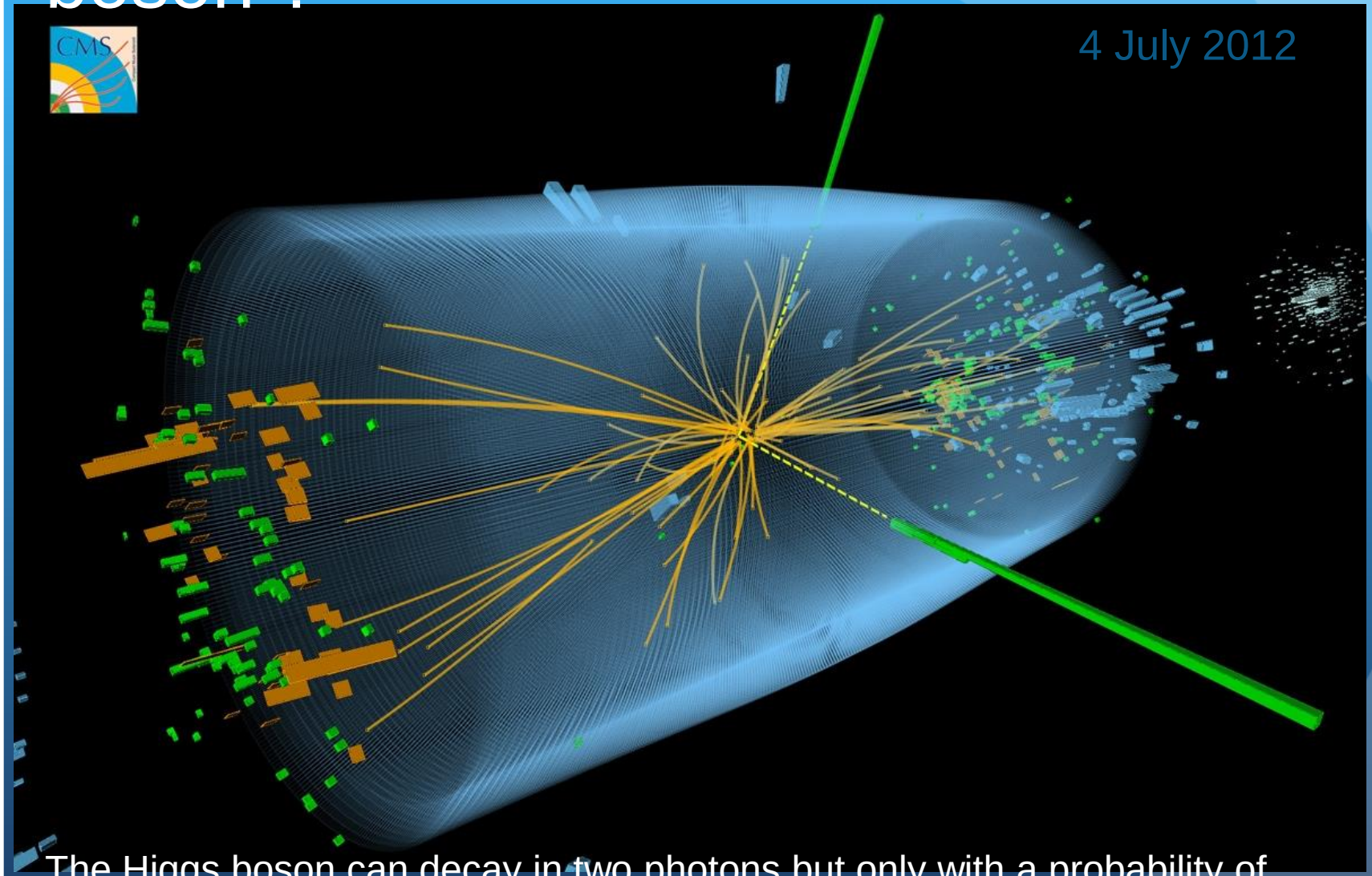
A rumour is spreading among the guests ...

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

The BEH field ...

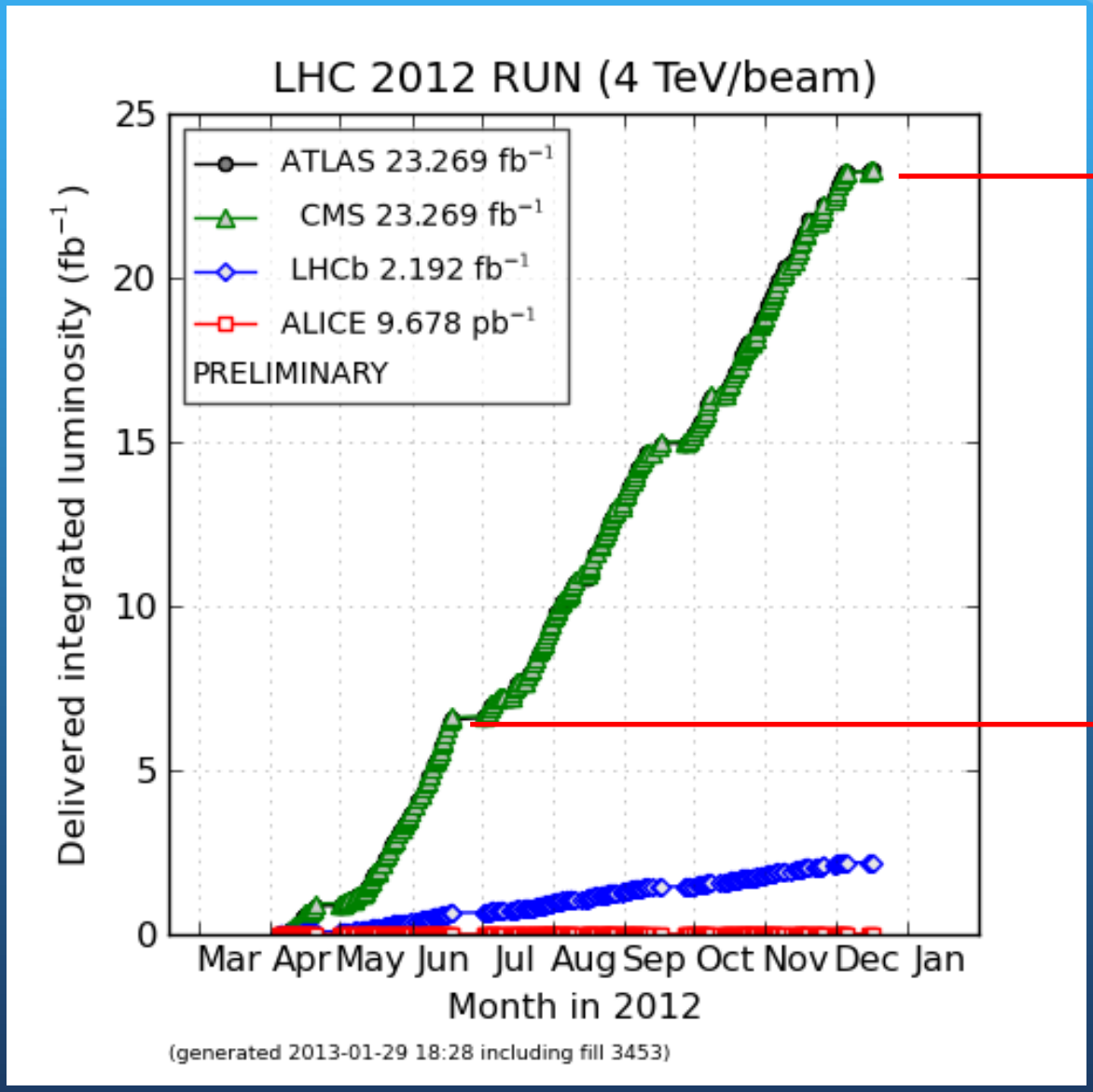
... is excited by an energy concentration and forms an excitation by self-interaction ...

How do we know that it is the Higgs boson ?



The Higgs boson can decay in two photons but only with a probability of 0.2 %

2011 - 2012 : Data taking with LHC

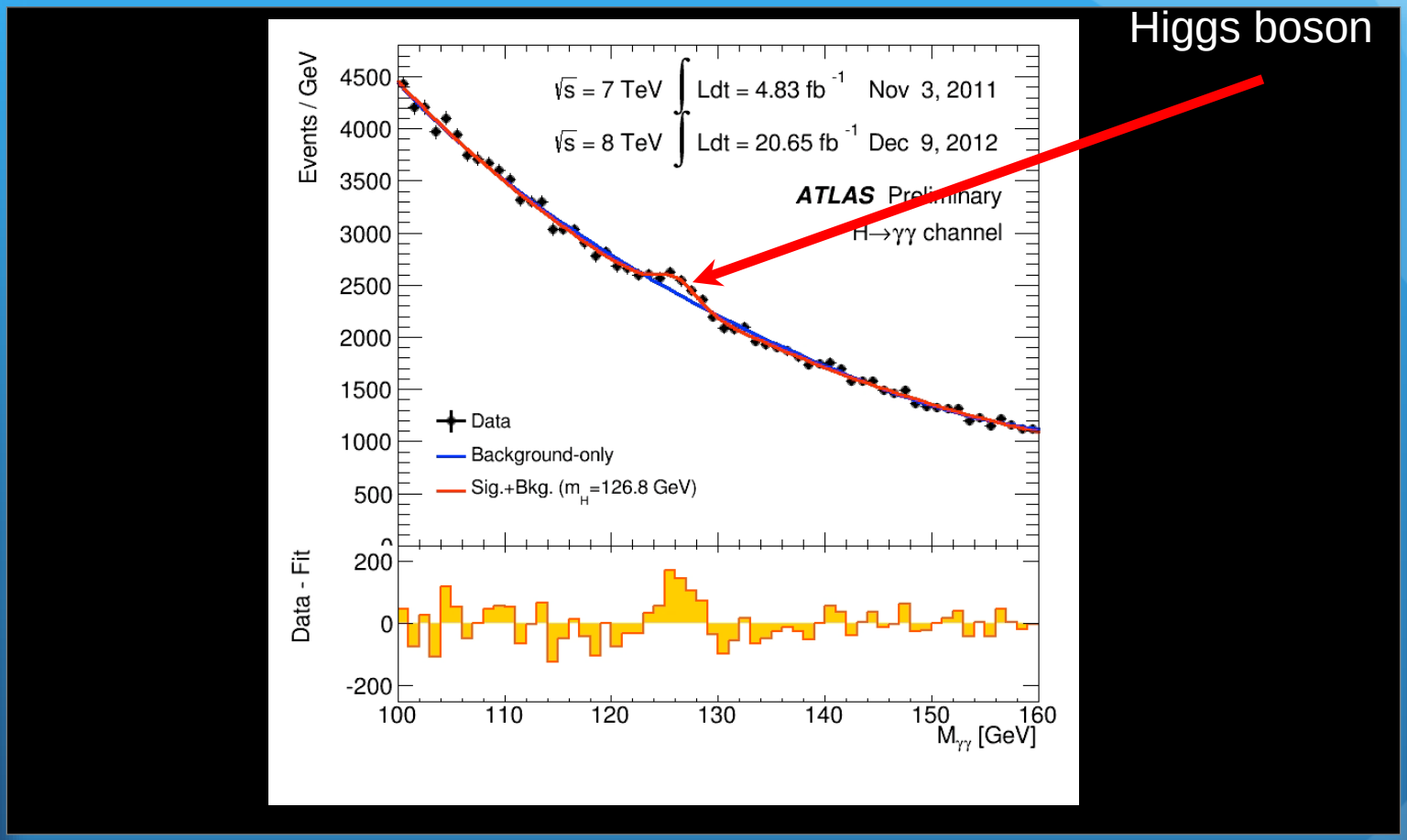


15.12.2012

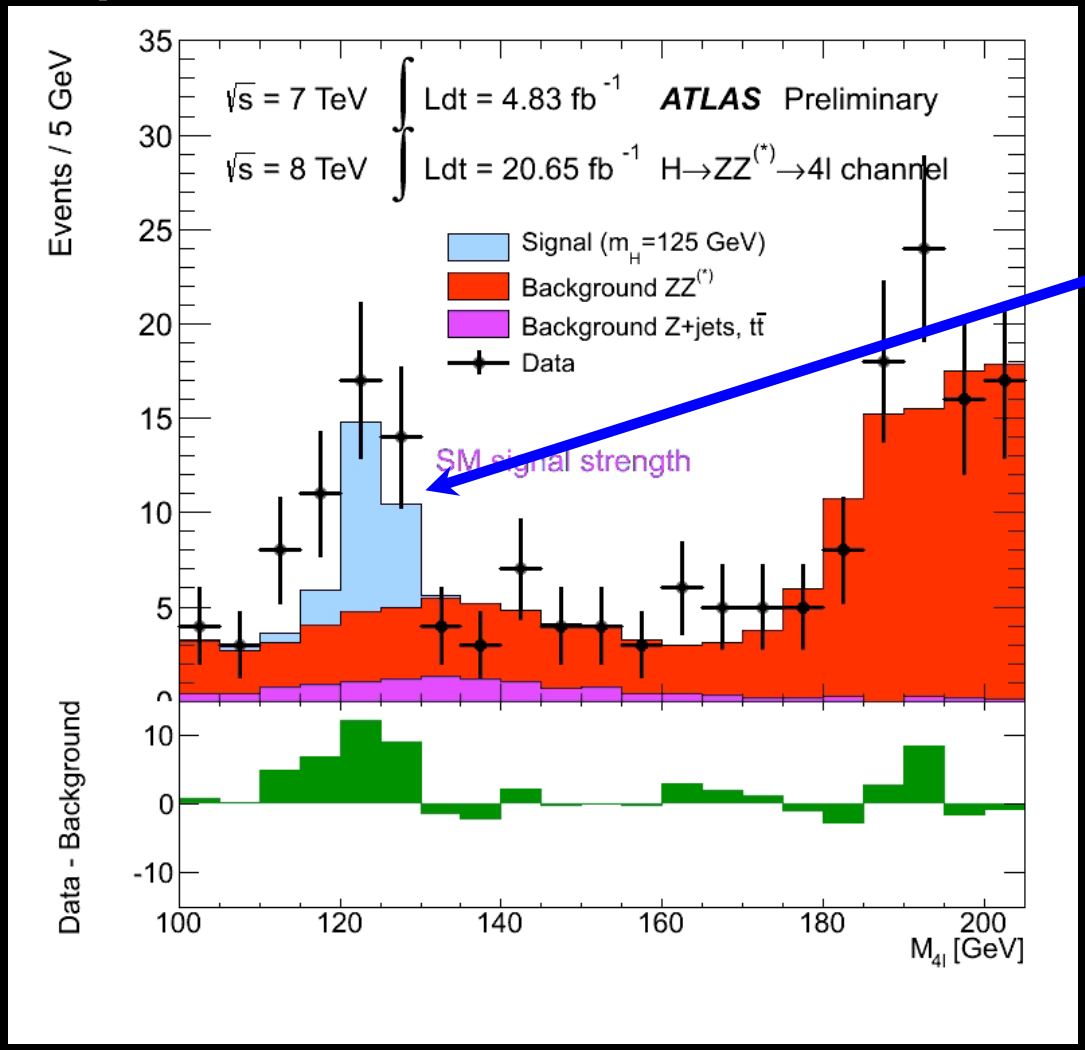
3,000,000,000,000,000 ($3 \cdot 10^{15}$)
(3000 trillion events !)

4.7.2012

The evolution of the histogram with two-photon events



The evolution of the histogram with four leptons

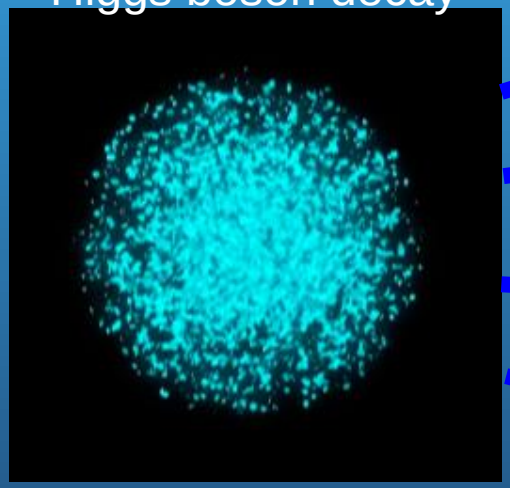


Higgs boson

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

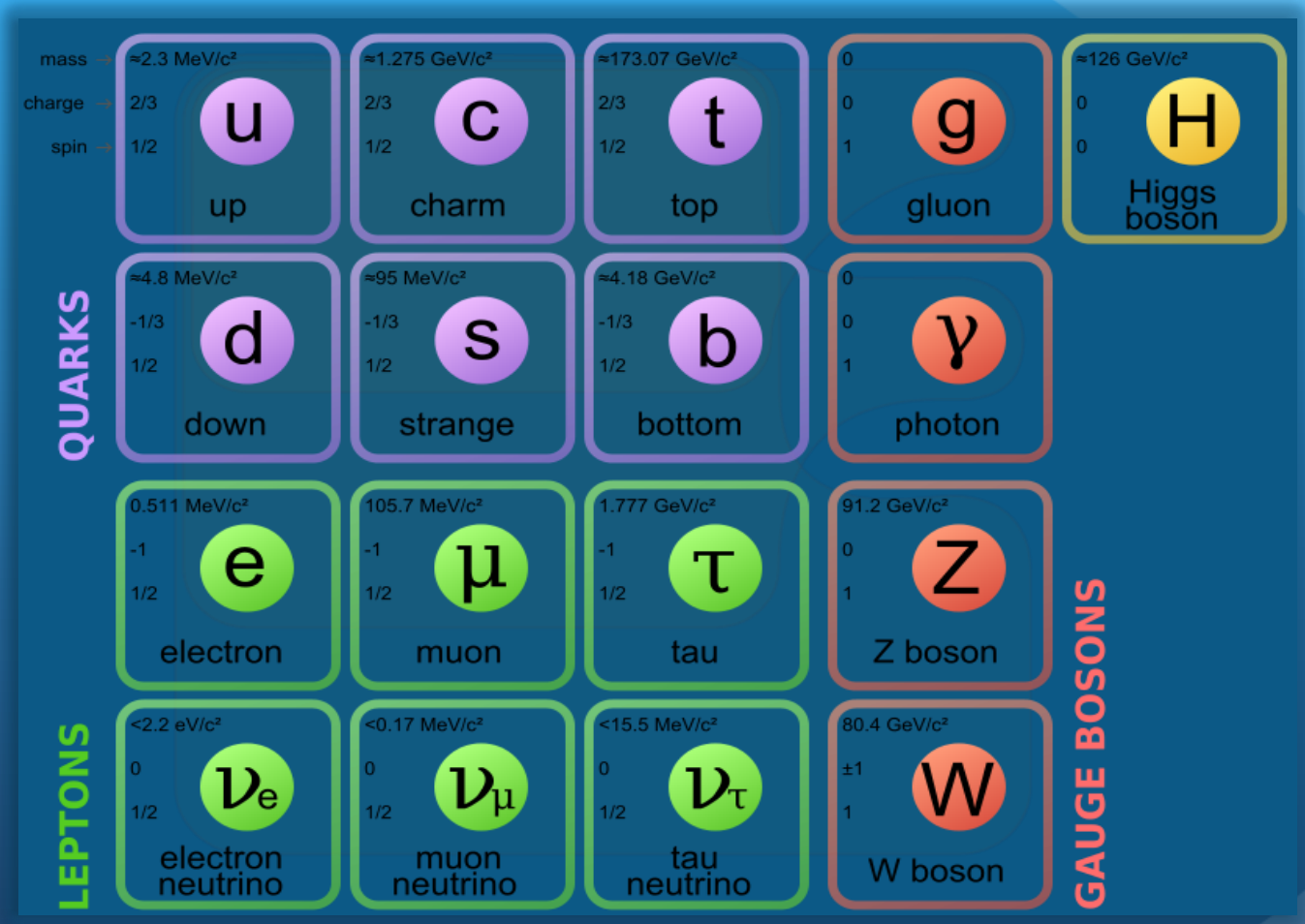
What does this mean?

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

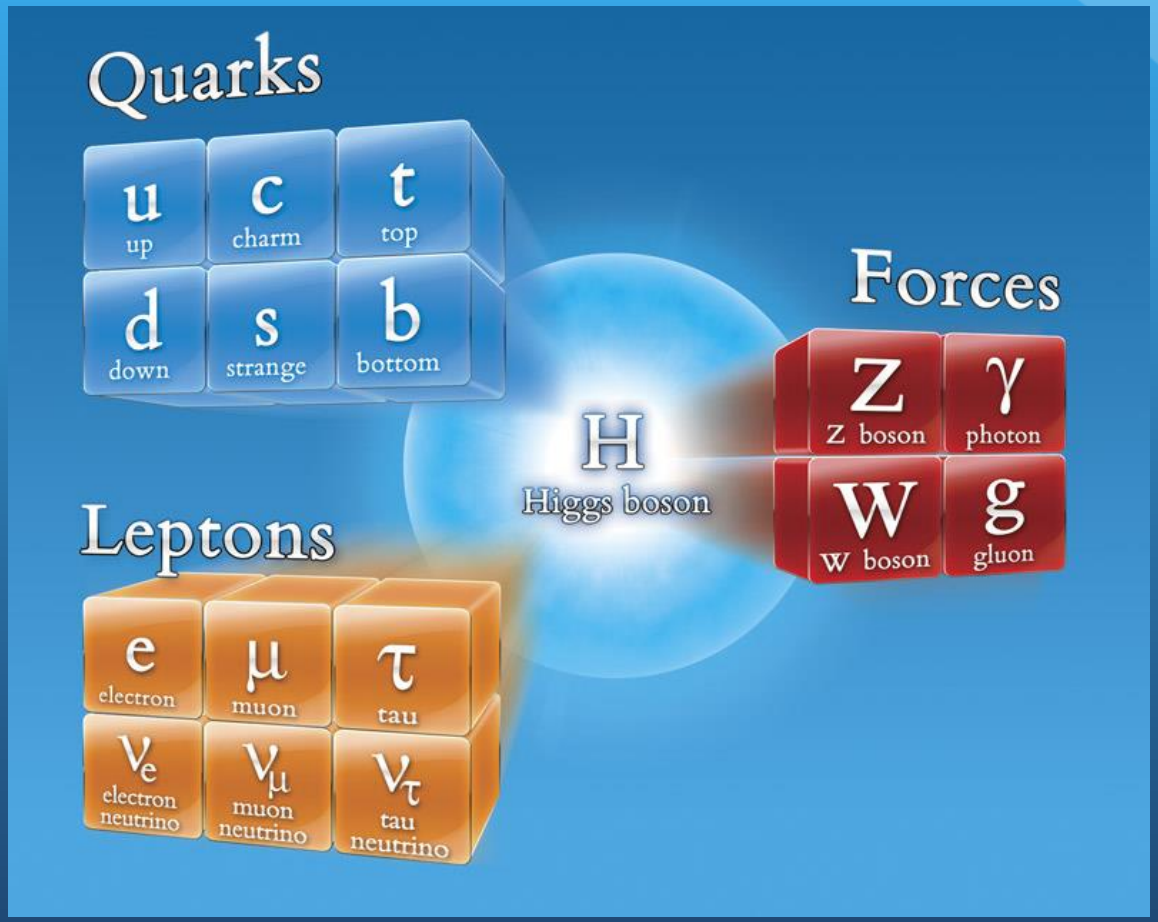
Even more:

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

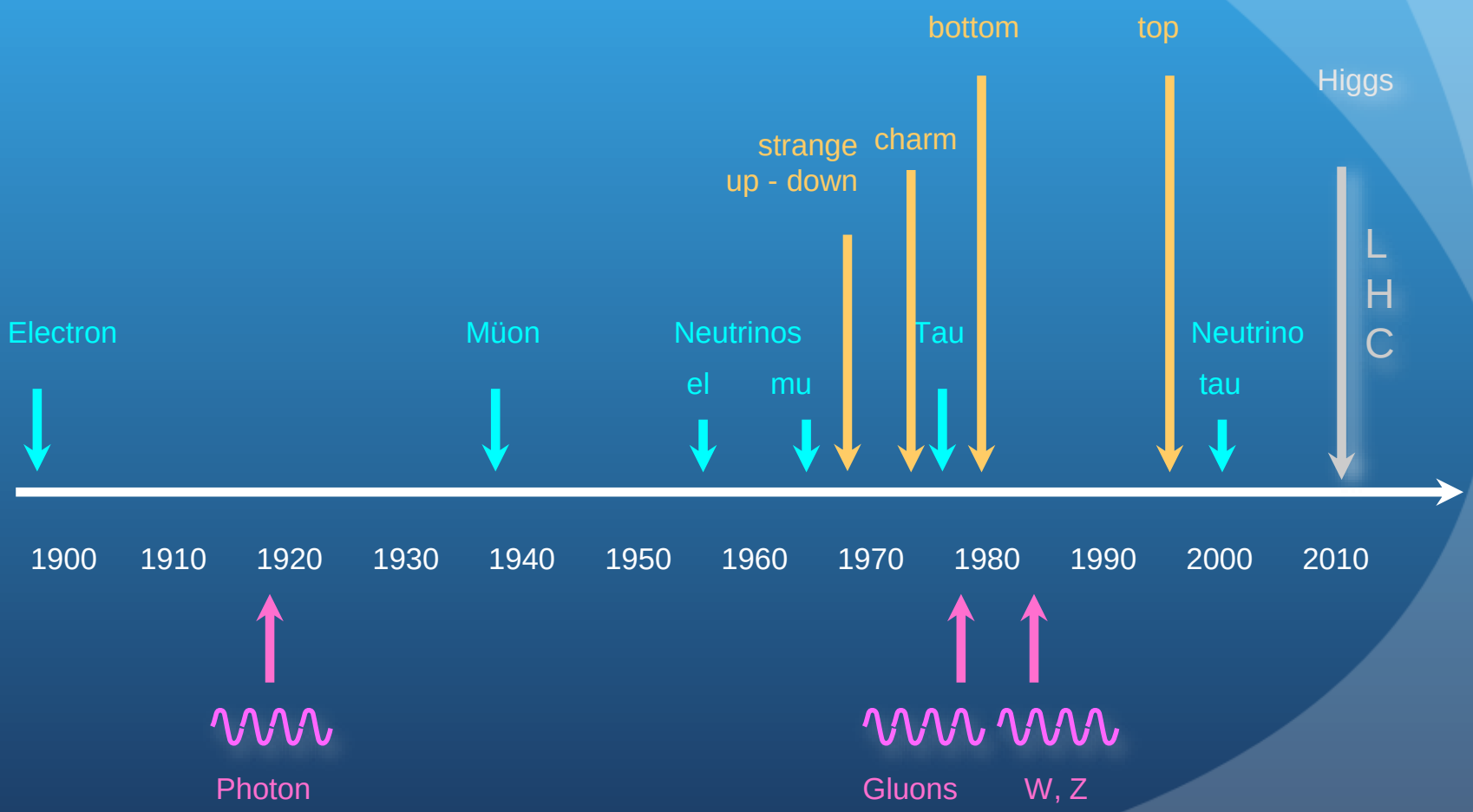
The SM 'element table'



BEH boson

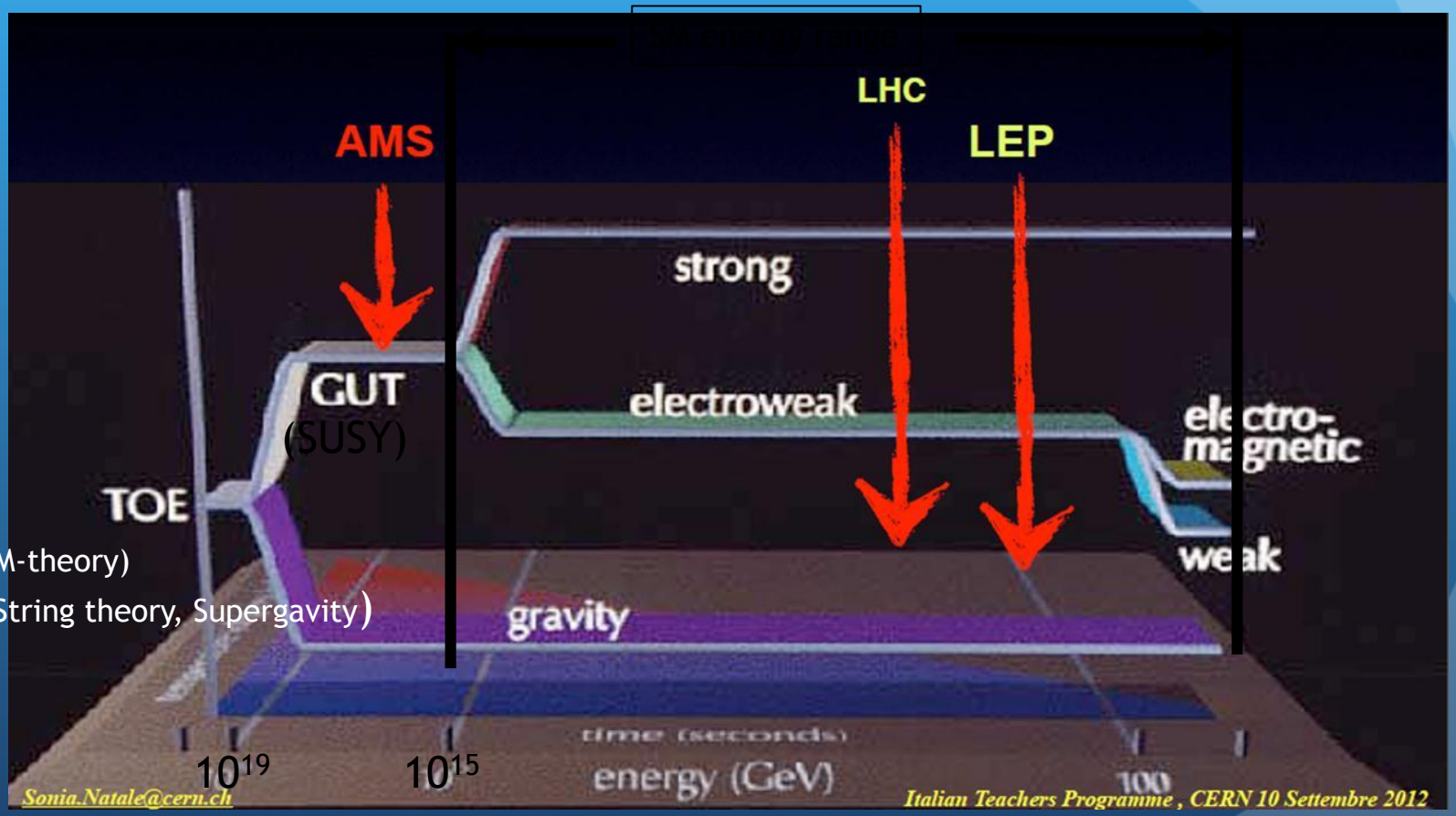

Quarks
u
up
c
charm
t
top
d
down
s
strange
b
bottom
Forces
Z
Z boson
γ
photon
W
W boson
g
gluon
H
Higgs boson
Leptons
e
electron
μ
muon
τ
tau
νe
electron neutrino
νμ
muon neutrino
ντ
tau neutrino

Experiments at accelerators have discovered all particles of the SM

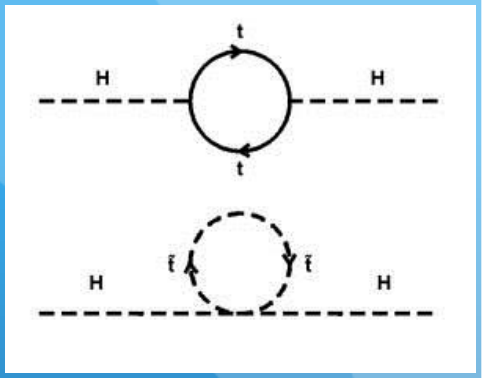


Supersymmetry (SUSY) & String theory

Beyond the SM towards a Theory of Everithing

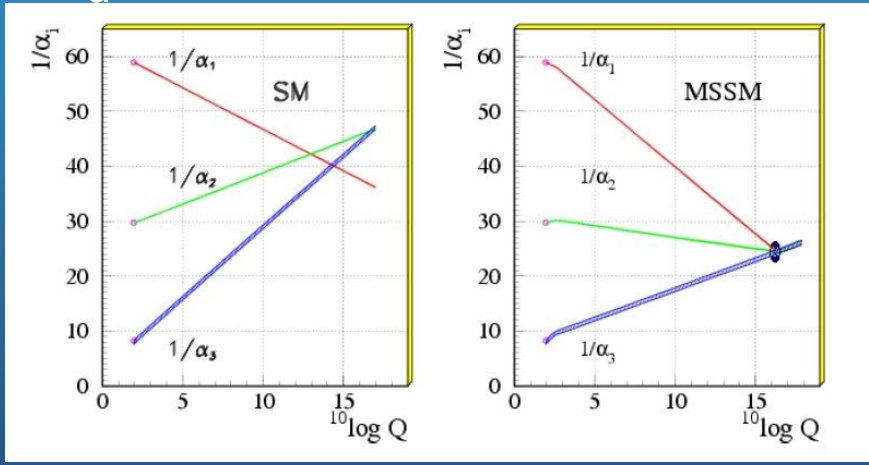


Why SUSY



1) “Protection of the Higgs boson mass (M ~ 10^2 GeV)
from vacuum fluctuations up to Planck mass (~10^{19} GeV)

2) Predicts unification of electroweak and strong interaction at ~10^{17} GeV
ù



3) May explain the cosmological matter-antimatter asymmetry

4) **Lightest supersymmetric particle = dark matter ??**

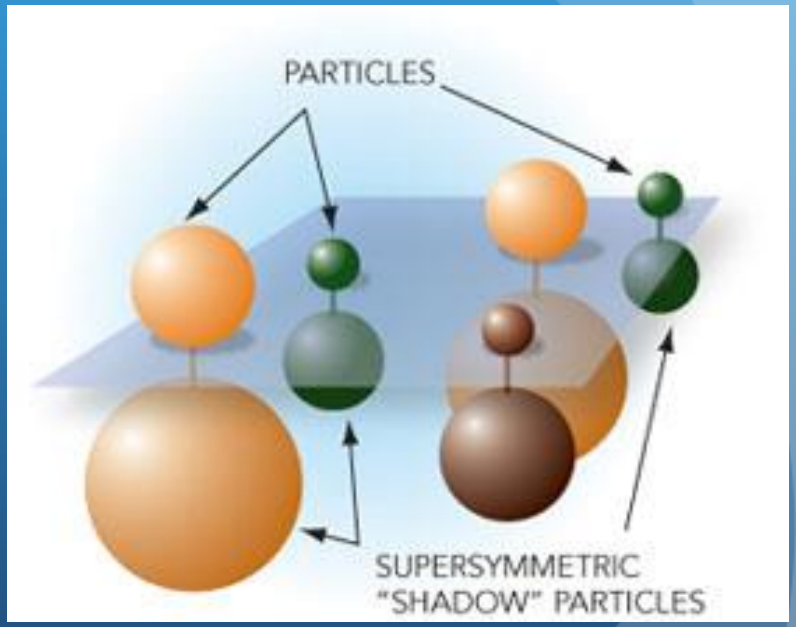
SUPERSYMMETRY

A connection between particles (spin 1/2) and fields (spin 1) ? LCH

FERMIONS (quarks, electrons, neutrinos) interact through the exchange of BOSONS (gluons, photon, W/Z bosons)

"SUPERSYMMETRY" predicts a complete symmetry between FERMIONS AND BOSONS: each fermion has a boson partner, and vice versa:

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)



But: no such SUSY partner has ever been seen. So ...
if they exist, they must have a large mass (> 1 TeV)

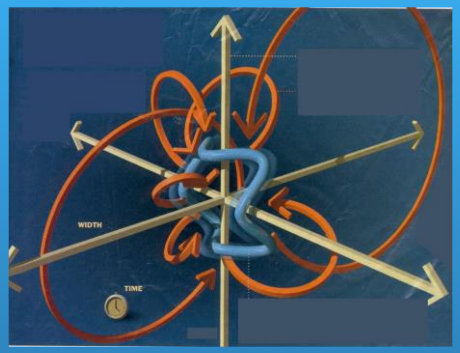
The Large Hadron Collider (2015 - ...)

New discoveries are waiting !

String Theory

String theory

What is a particle?

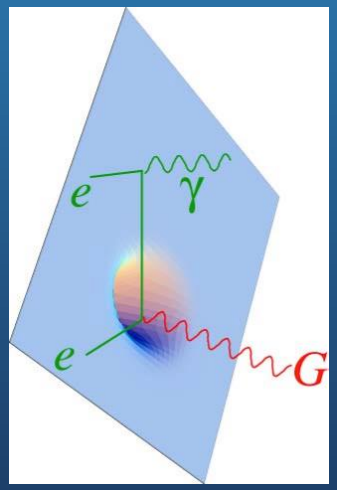


Superstrings in 9+1 dimensions?

Little strings of string energy vibrating in a 9+1 dimensional space ?
L ~10^{-35} m (Planck length)
Standard model particles: different vibration modes, open/closed strings
GRAVITON-like particle contained (unification of SM and gravity?)

BUT: why did 6 dimensions disappear? how did they disappear?
is there a unique way to go from 10 to 4 dimensions?

Quantum Gravitation



More than 3 macroscopic dimensions of space?

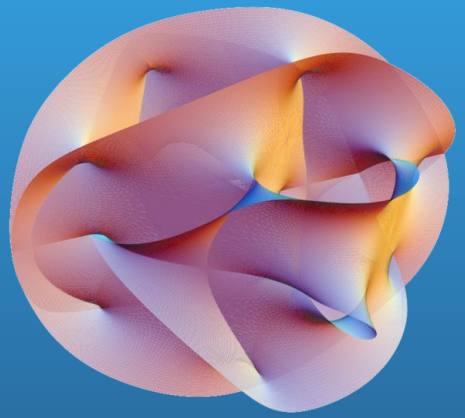
Is the graviton propagating in 4- or more dimensions of space?

Micro-black holes ?

MORE MYSTERIES

There exist five type of string theory, the M-theory integrate all of them as special case

M-theory*): p-brane in 11 dimension for the unification of SM+Gravity in a Theory of Everithing (ToE)



This image of the en:Calabi-Yau manifold appeared on the cover of the November 2007 issue of en:Scientific American.

*) http://en.wikipedia.org/wiki/M-theory

A p-brane is a physical object that generalizes the notion of a point particle to higher dimensions. For example, a point particle can be viewed as a brane of dimension zero, while a string can be viewed as a brane of dimension one.

Branes are dynamical objects which can propagate through spacetime according to the rules of quantum mechanics. They have mass and can have other attributes such as charge. A *p*-brane sweeps out a (*p*+1)-dimensional volume in spacetime called its *worldvolume*. Physicists often study fields analogous to the electromagnetic field which live on the worldvolume of a brane.

Loop quantum gravity (LQG)

- Contender of string theory, the loop quantum gravity unify the QM with the Einstein GR;
- The space is discrete and quanta of gravitational field (10^{-35} m, Plank scale) are connected one to the other by ever changing ‘links’
- The LQG space is quantized and forms a kind of foam where there is no need of string or supersymmetry to unify quantum mechanics with GR.

Summary part 2-3

- 1900 – 2015: Fantastic progress in understanding matter and the Universe;
- SM: a complete framework to describe the subnuclear world but…;
- There are evidence that new physics is required (expected) after the discovery of BEH boson: is supersymmetry the good candidate?
- It would provide naturally the electro-strong unification;
- And for a TOE? String in 10 dimensions for the unification of gravitational and electro-strong forces; there exist 5 string theory;
- Loop quantum gravity as alternative candidates to String;
- M-theory in 11 dimension to unify the five string theories (special cases)!
- A lot of work to be done but now let LHC to provide experimental data to discriminate such abundance of theory!