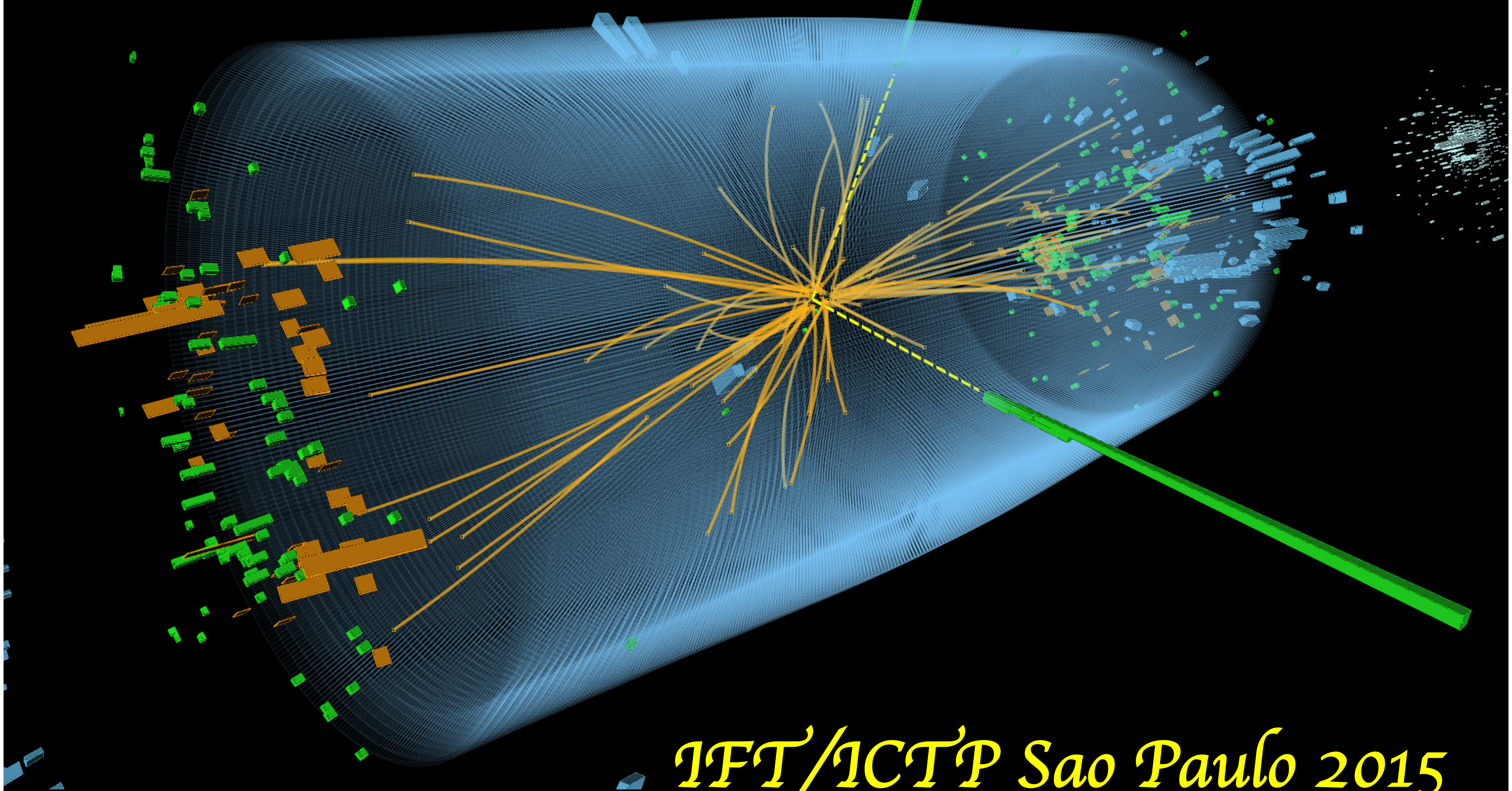
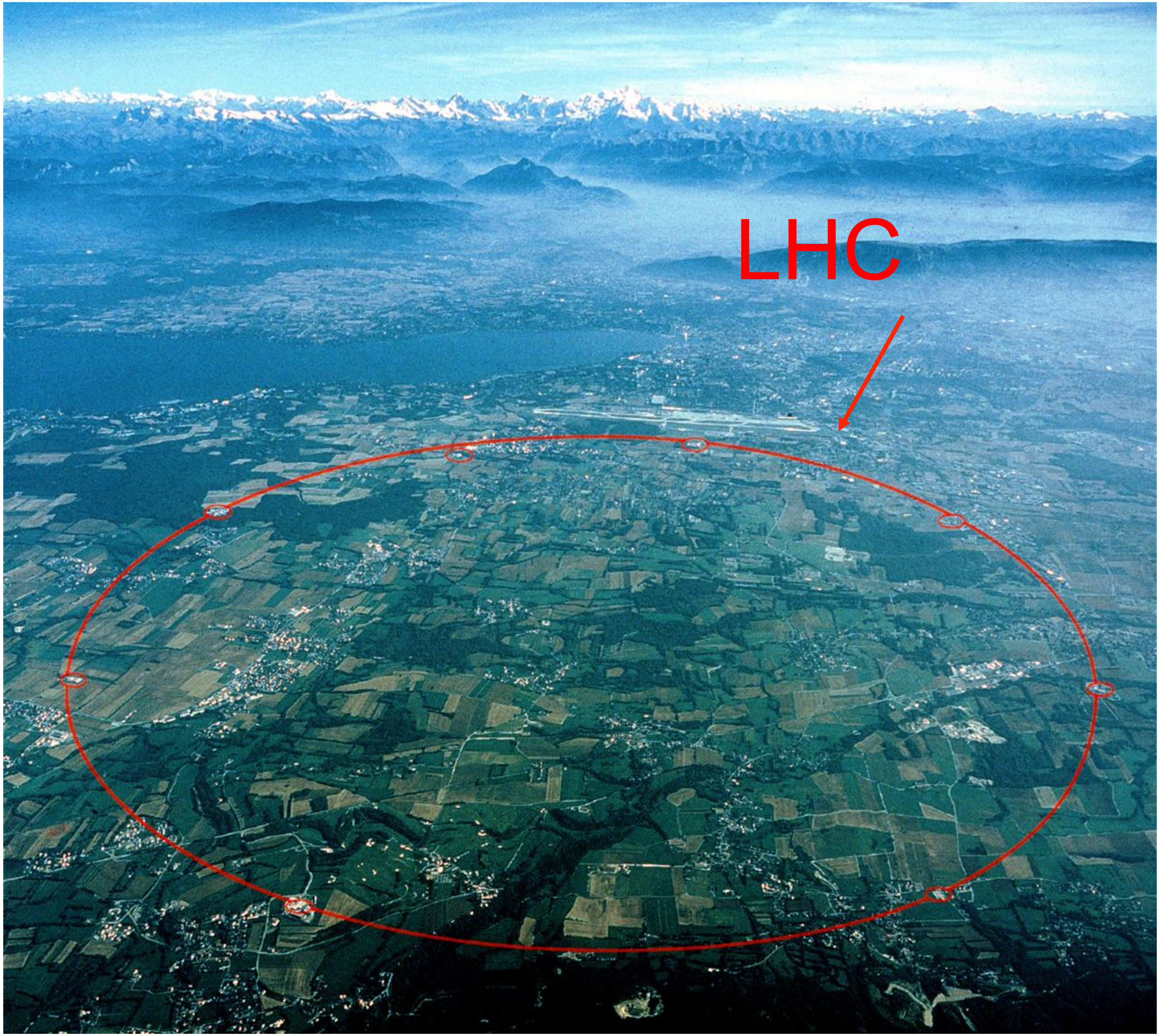
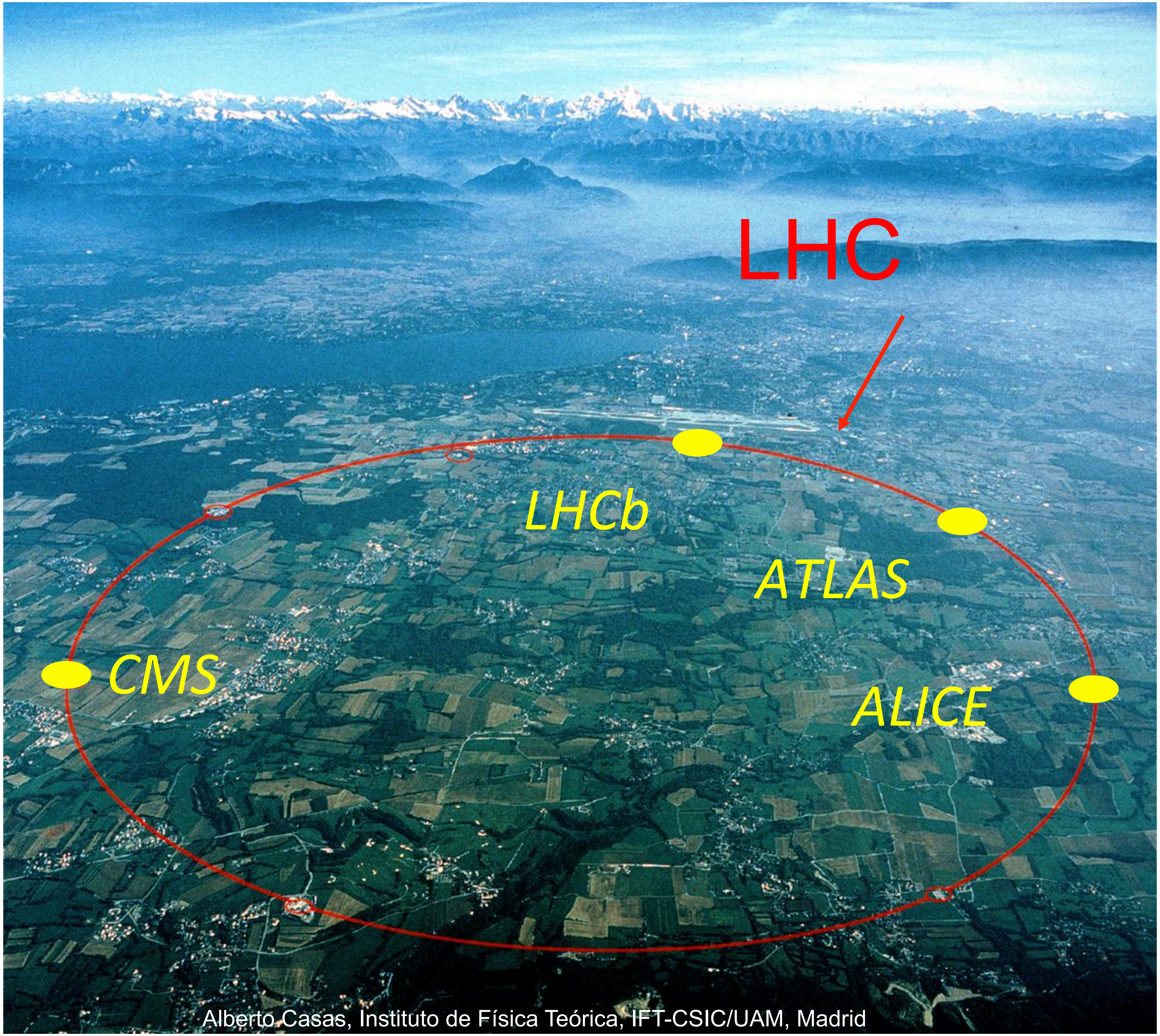
The LHC and the frontier of particle physics

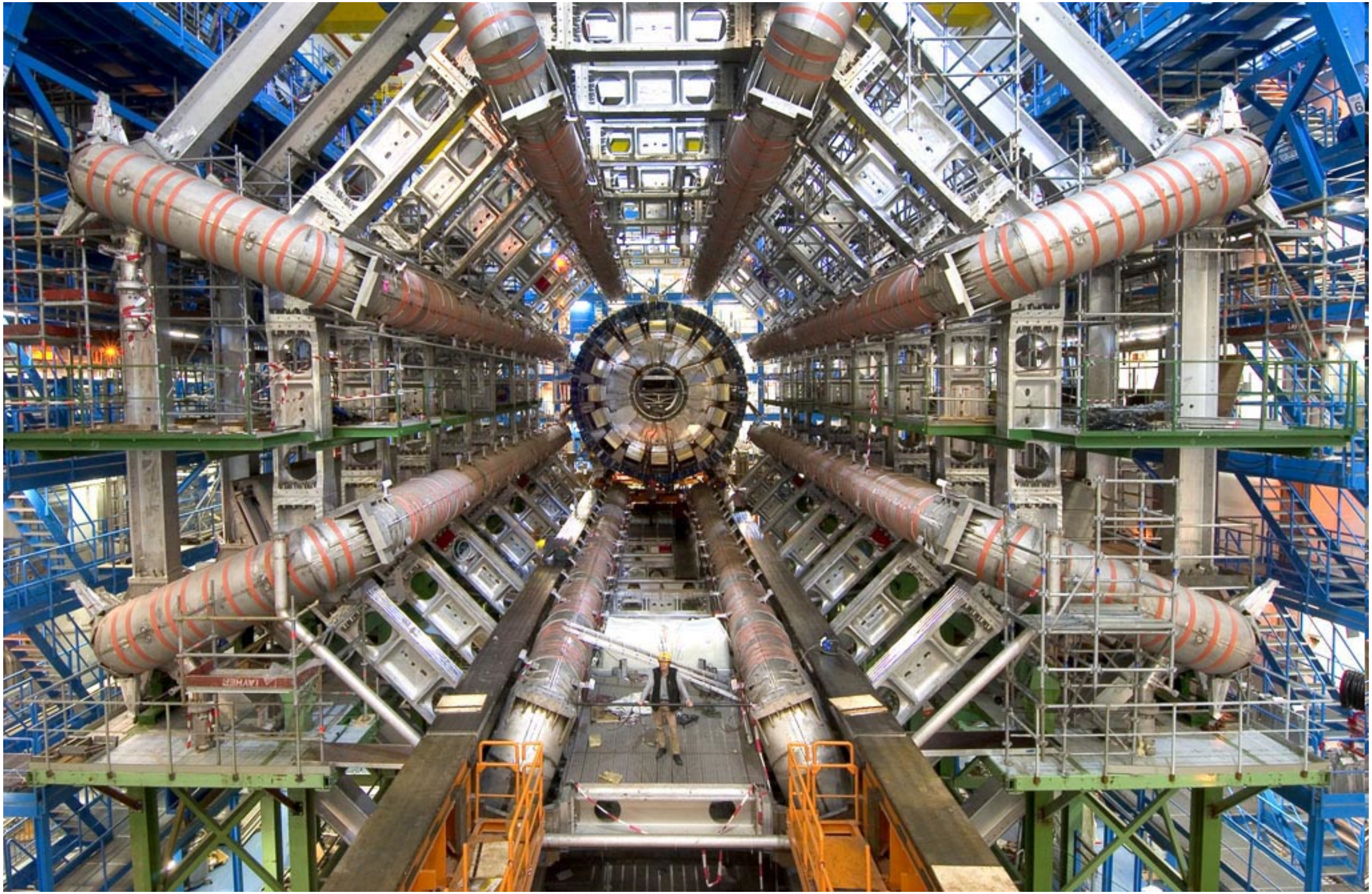
Alberto Casas



IFT/ICTP Sao Paulo 2015


LHC


LHC
LHCb
ATLAS
CMS
ALICE
Alberto Casas, Instituto de Física Teórica, IFT-CSIC/UAM, Madrid



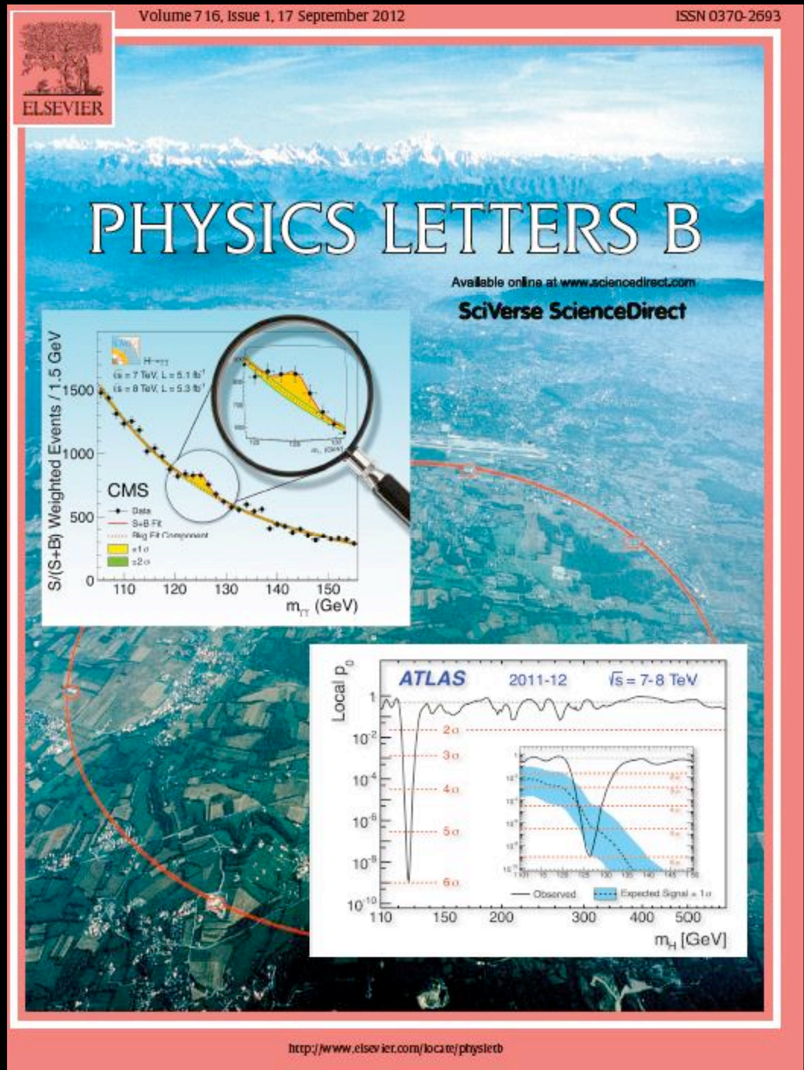
In each collision, tens of particles are produced

Analyzing them, one expects to learn fundamental aspects of how nature works

The LHC has already obtained a “historic” success

July-4th 2012

CERN (Geneva)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Available online at www.sciencedirect.com
SciVerse ScienceDirect
CMS
S/(S+B) Weighted Events / 1.5 GeV
$m_{\gamma\gamma}$ (GeV)
ATLAS
2011-12
$\sqrt{s}$ = 7-8 TeV
Local p_0
m_H [GeV]
http://www.elsevier.com/locate/physletb


Science
21 December 2012 | $10
BREAKTHROUGH
of the YEAR
The HIGGS
BOSON
AAAS

Dic 10, 2013


NAT MDCCC XXXIII OB MDCCC XCVI
ALFR NOBEL


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¿Is this enthusiasm justified?

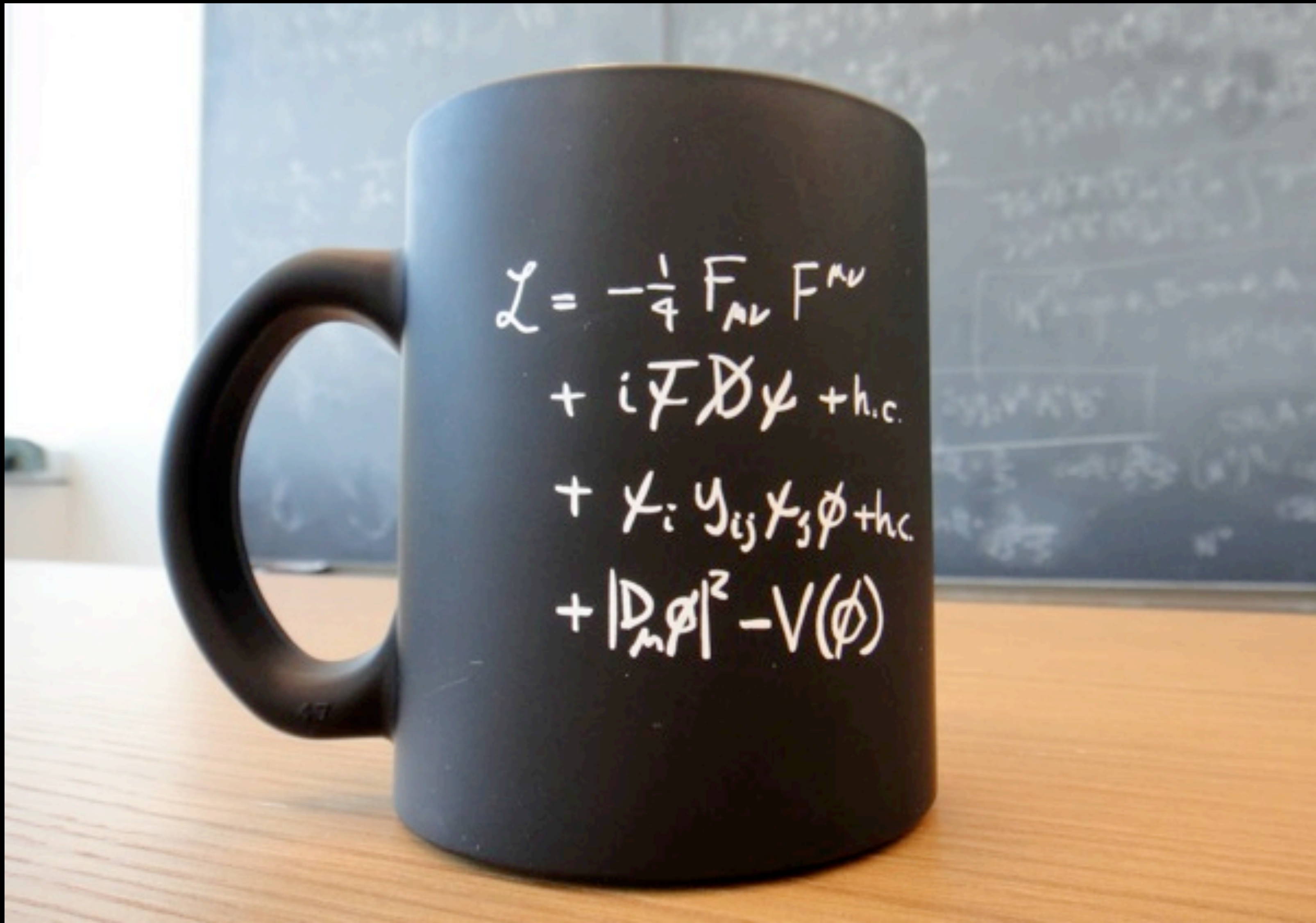
The discovery of the Higgs boson sheds light on basic concepts:

- ★ Vacuum
- ★ Electromagnetic forces
- ★ Weak forces
- ★ Mass

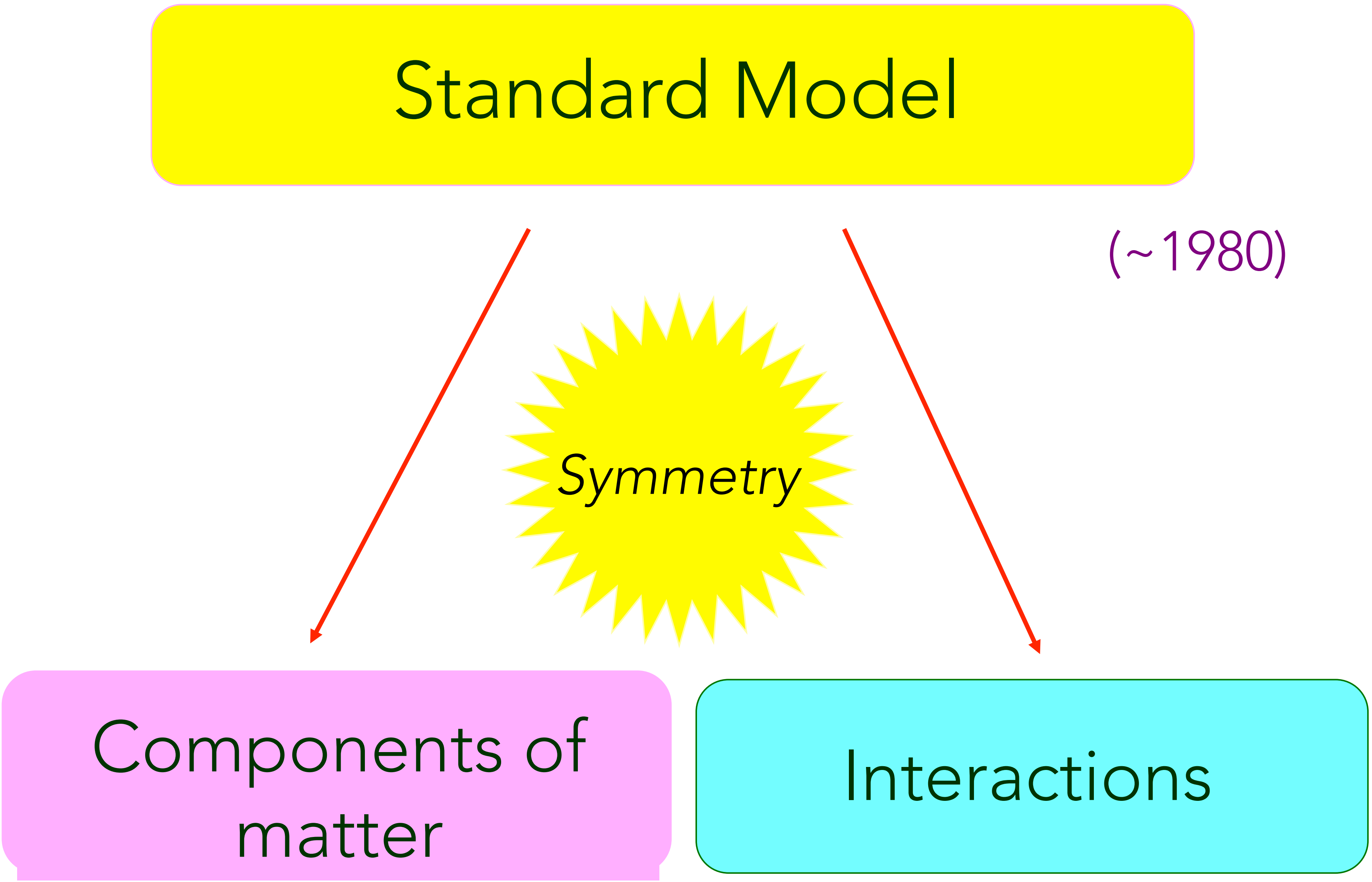
To understand the crucial importance of the Higgs boson, we have to recall the Standard Model of particle physics and the role it plays in it.

Standard Model

$\equiv$ frontier of particle physics



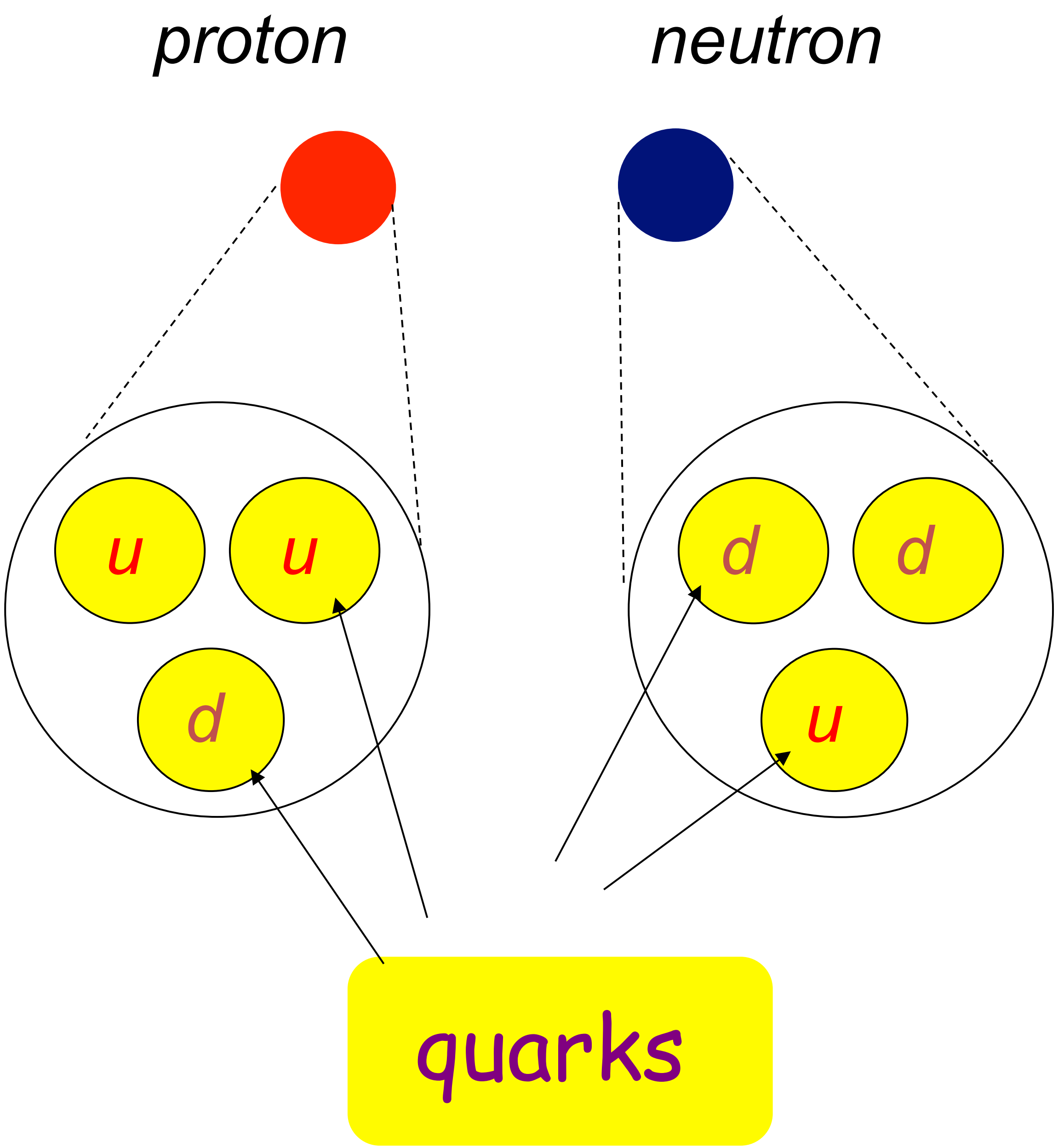
$$\phi \equiv Higgs$$


Standard Model
(~1980)
Symmetry
Components of matter
Interactions

Matter

1932	p, n, e ν
1937	μ
1940s	π, K mesons
1950s	Λ, Δ, Σ, ...

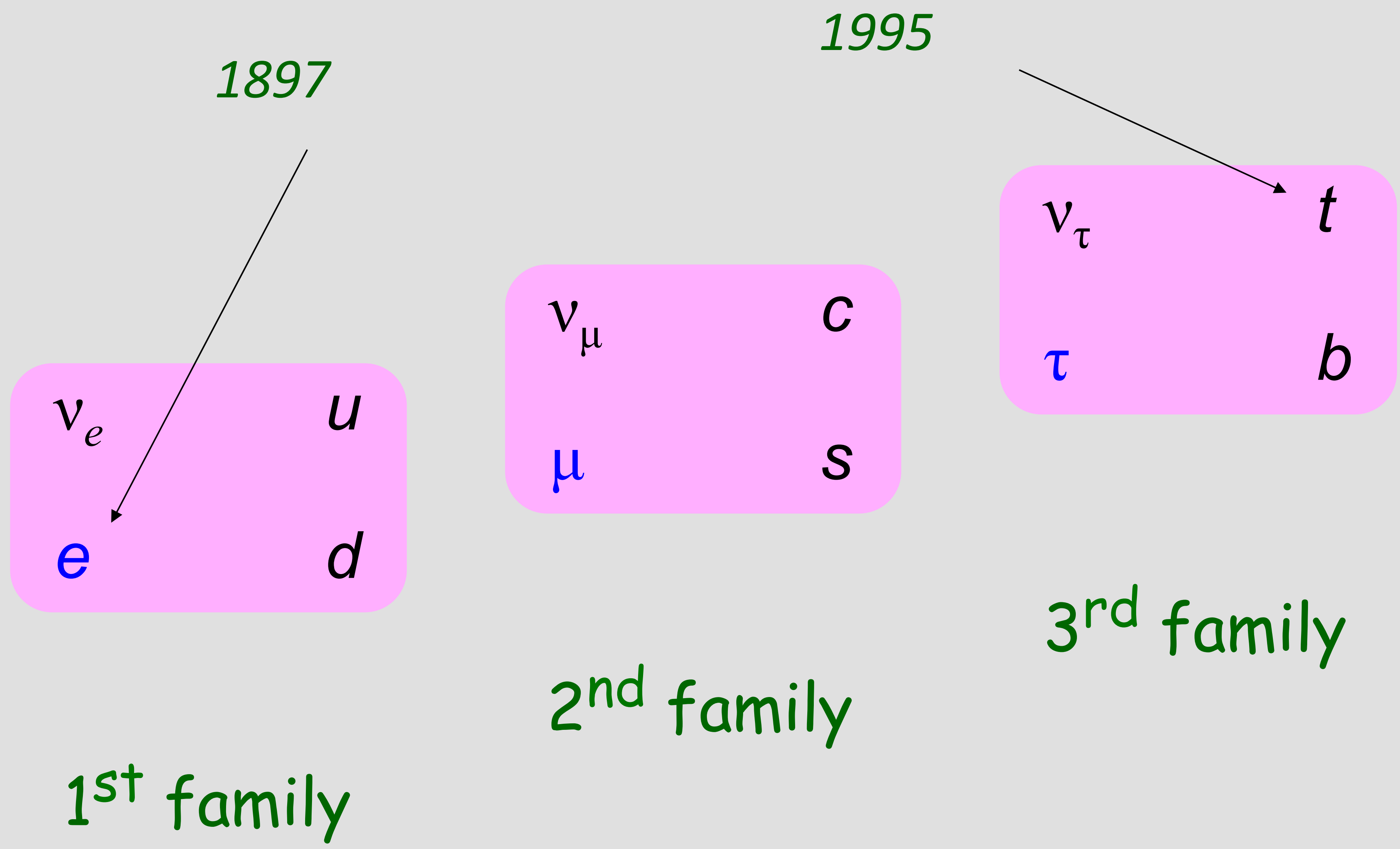
At present there are clasified about 300 particles


proton
neutron
u
u
d
d
d
u
quarks

ν_e	u
e	d

1st family of elementary particles

Almost everything is made of them


1897
1995
ν_e u
e d
ν_μ c
μ s
ν_τ t
τ b
1st family
2nd family
3rd family

ν_e	u
e	d

1st family

ν_μ	c
μ	s

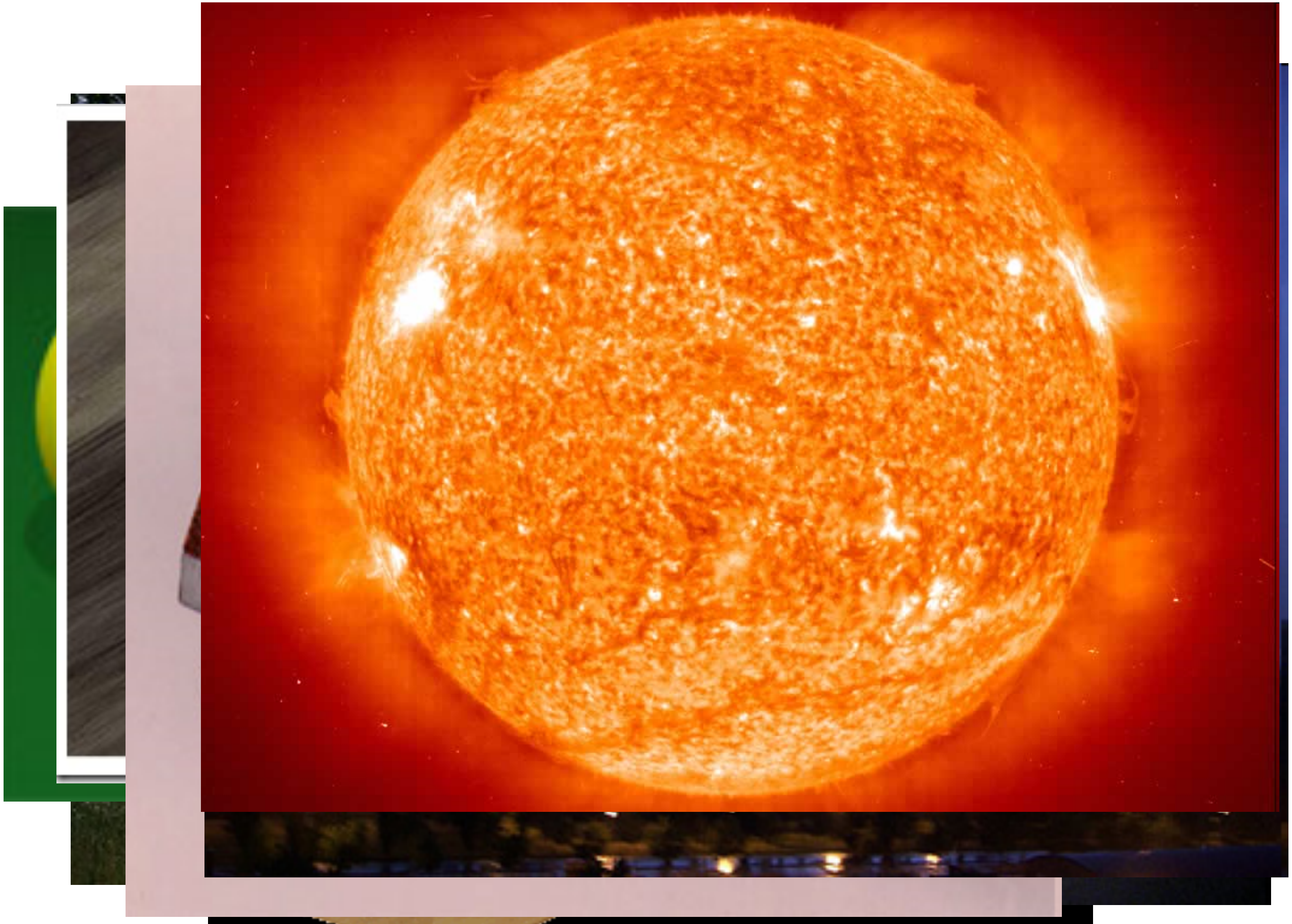
2nd family

ν_τ	t
τ	b

3rd family

¿Why?

Interactions



All those interactions are manifestations of just

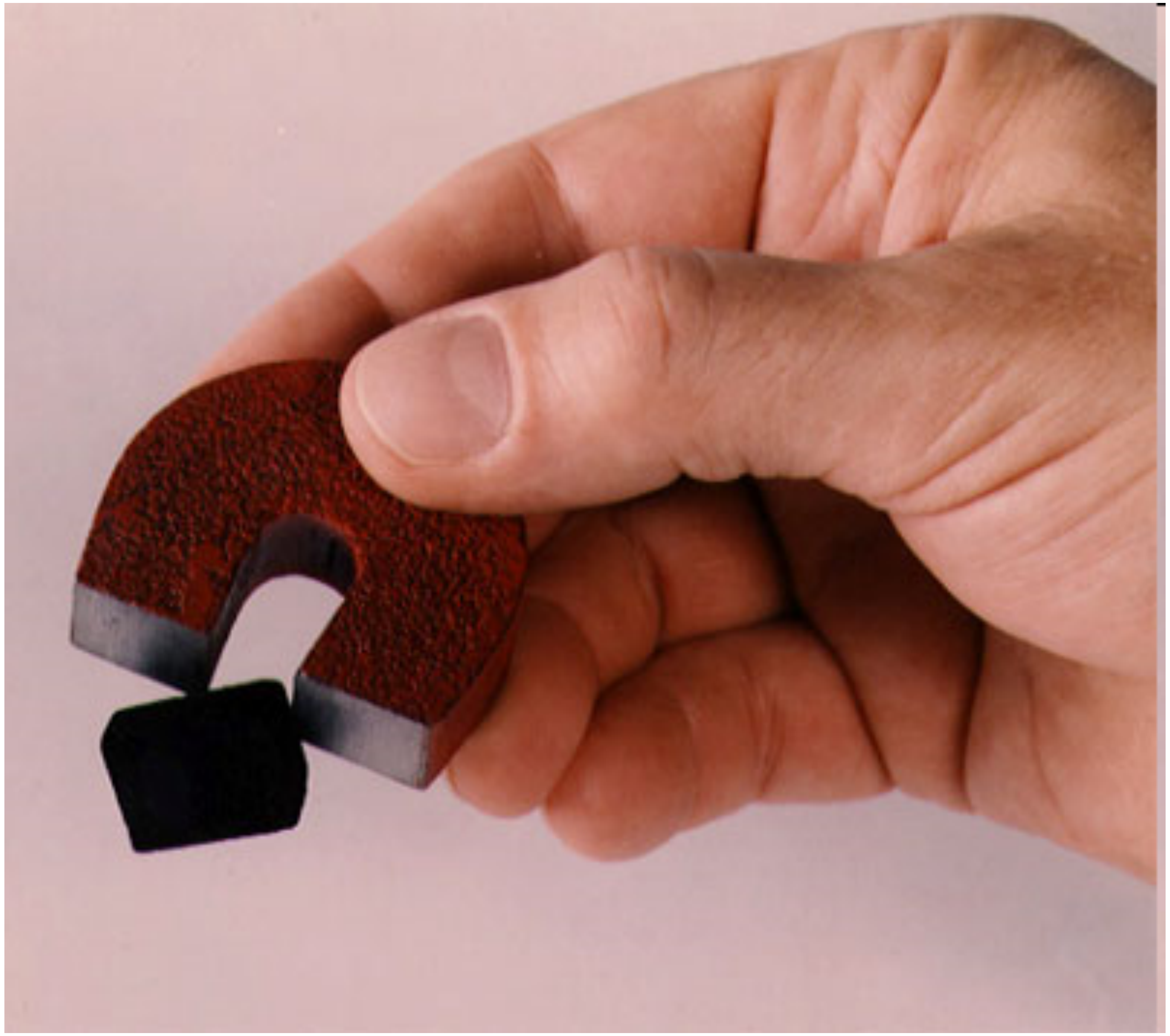
4 basic interactions

gravitational

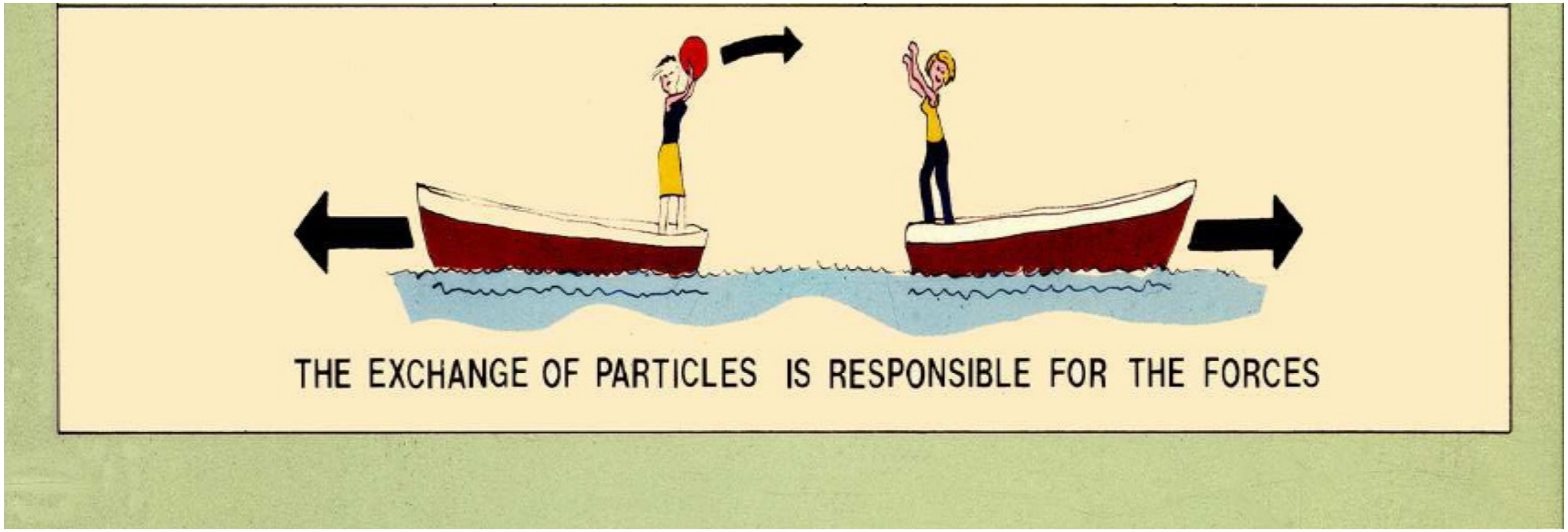
strong

electromagnetic

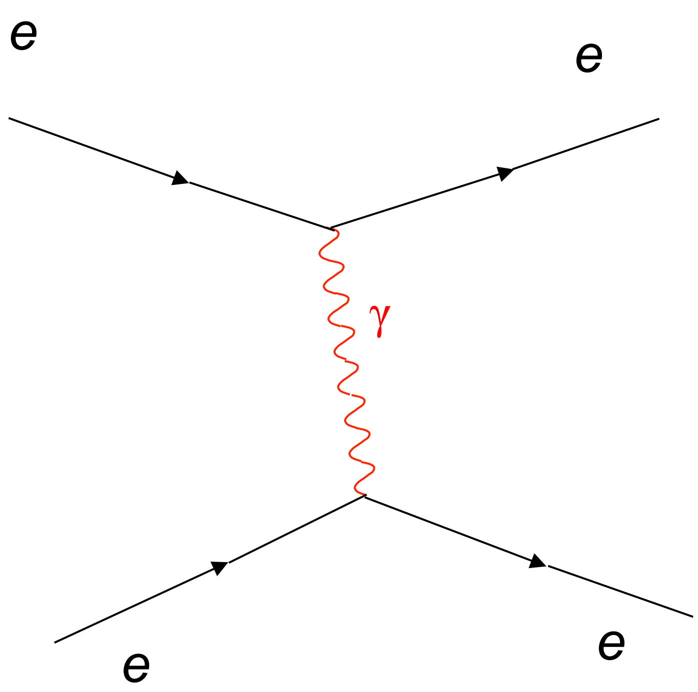
weak



All these interactions are mediated by other particles: messengers of the interaction



All these interactions are mediated by other particles: messengers of the interaction



Electromagnetic Interaction

≡ Interchange of photons

- spin 1 (2)
- massless

Interaction	Messenger
Electromagnetic	**γ (photon)**
Strong	**g (gluon)**
Weak	**W, Z** bosons
Gravitational	**G (graviton)**

they have
a mass!

Symmetry

Symmetry ≡ Invariance under transformations of the basic equations

...maybe the most important concept of modern particle physics

The basic laws of nature possess an enormous symmetry

...and that symmetry explains many things

For instance:

The laws of physics have time-invariance:

they do not change with time

Energy Conservation

- Time translations — Energy conservation
- Space translations — Momentum conservation
- Rotations — Angular mom. conservation
-
-
-

Internal symmetries

$$\psi \equiv \text{electron}$$

$$\psi \longrightarrow e^{i\alpha}\psi \qquad \alpha \equiv const. \qquad \text{U(1)}_{EM}$$

$$\mathcal{L} = \bar{\psi}(i\gamma^{\mu}\partial_{\mu} - m)\psi$$

$$\mathcal{L} \longrightarrow \mathcal{L}$$

Electric charge conservation

Local (gauge) internal symmetries

$$\psi \longrightarrow e^{i\alpha(x)}\psi$$

$$\mathcal{L} = \bar{\psi}(i\gamma^\mu \partial_\mu - m)\psi$$

$$\mathcal{L} \longrightarrow \mathcal{L} - \bar{\psi}(\partial_\mu \alpha)\psi$$

Local (gauge) internal symmetries

$$\psi \longrightarrow e^{i\alpha(x)}\psi$$

$$\mathcal{L} = \bar{\psi}(i\gamma^\mu\partial_\mu - m)\psi$$

$$\mathcal{L} \longrightarrow \mathcal{L} - \bar{\psi}(\partial_\mu\alpha)\psi$$

Local (gauge) internal symmetries

$$\psi \longrightarrow e^{i\alpha(x)}\psi \qquad A_\mu \longrightarrow A_\mu + \partial_\mu \alpha(x)$$

$$\mathcal{L} = \bar{\psi}(i\gamma^\mu \partial_\mu + \gamma^\mu A_\mu - m)\psi$$

$$\mathcal{L} \longrightarrow \mathcal{L}$$

Electromagnetic interaction

$A_\mu \equiv$ gauge boson (photon)

Local symmetries

Interactions

Yang & Mills (1954)

The messengers of those interactions must be massless bosons

(a mass term, $\frac{1}{2}M_A^2 A_\mu A^\mu$, violates the local symmetry)

The electromagnetic interaction and the photons...

... are a consequence of a local symmetry of nature, $U(1)_{EM}$

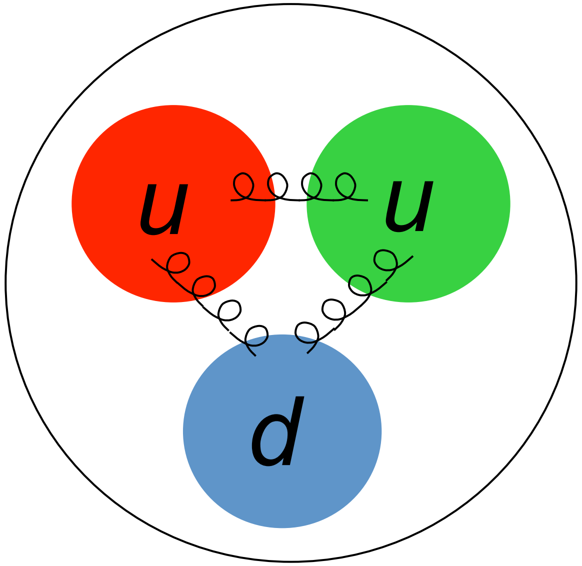
The strong interactions...

... are the consequence of another local symmetry:

COLOR $SU(3)_C$

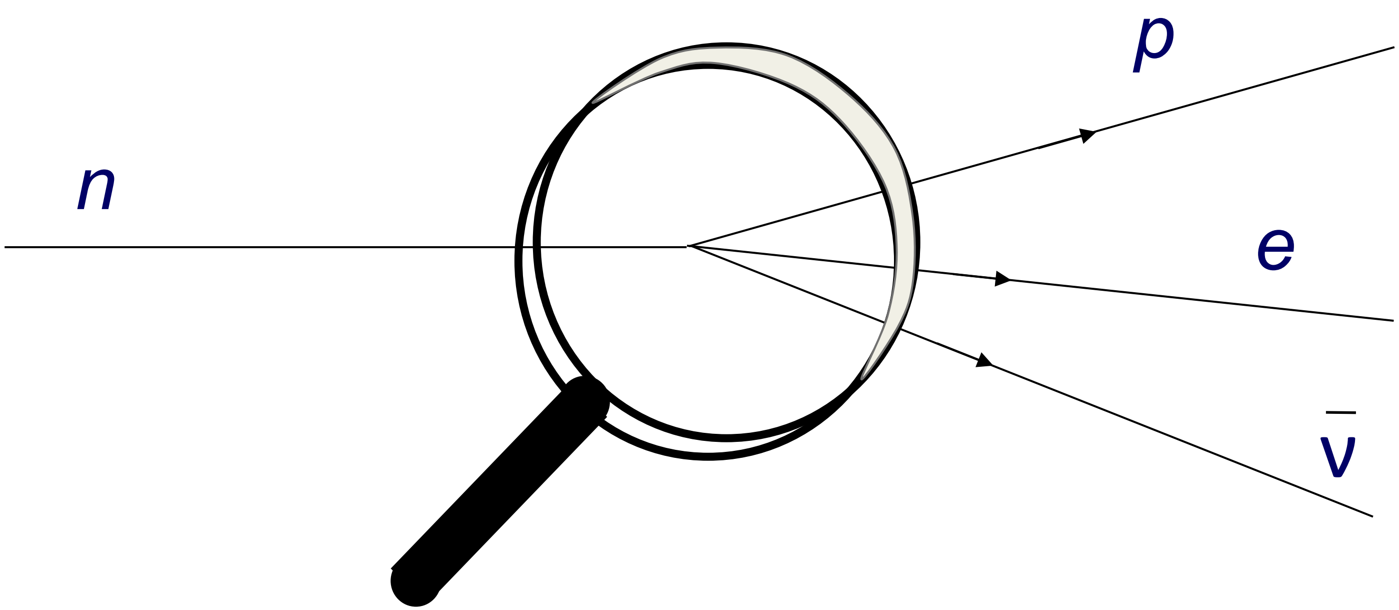
(~1970s)

8 (massless) gluons



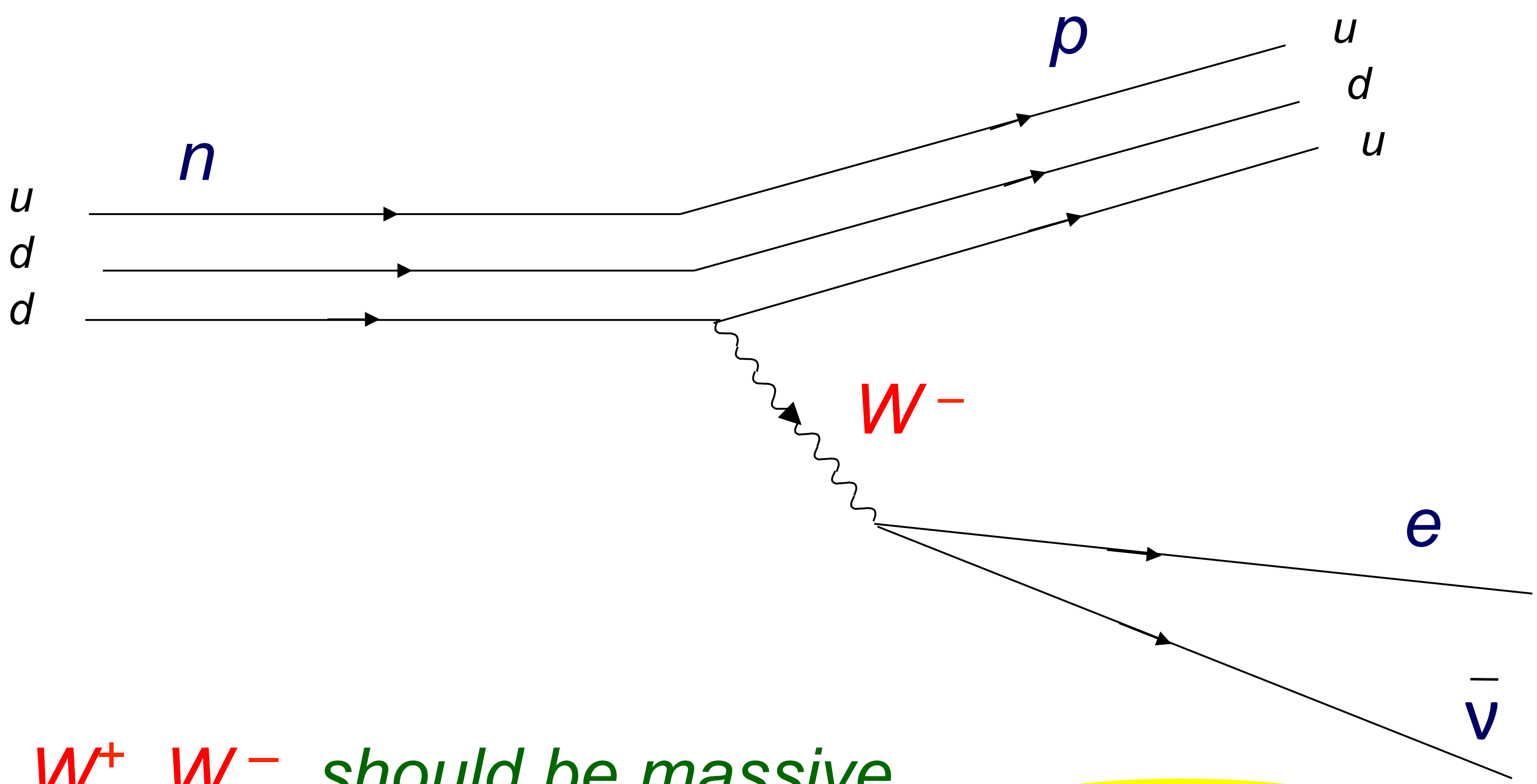
protón

Weak interactions:



Fermi (1933)

Weak interactions:



W^+, W^- *should be massive*

problem

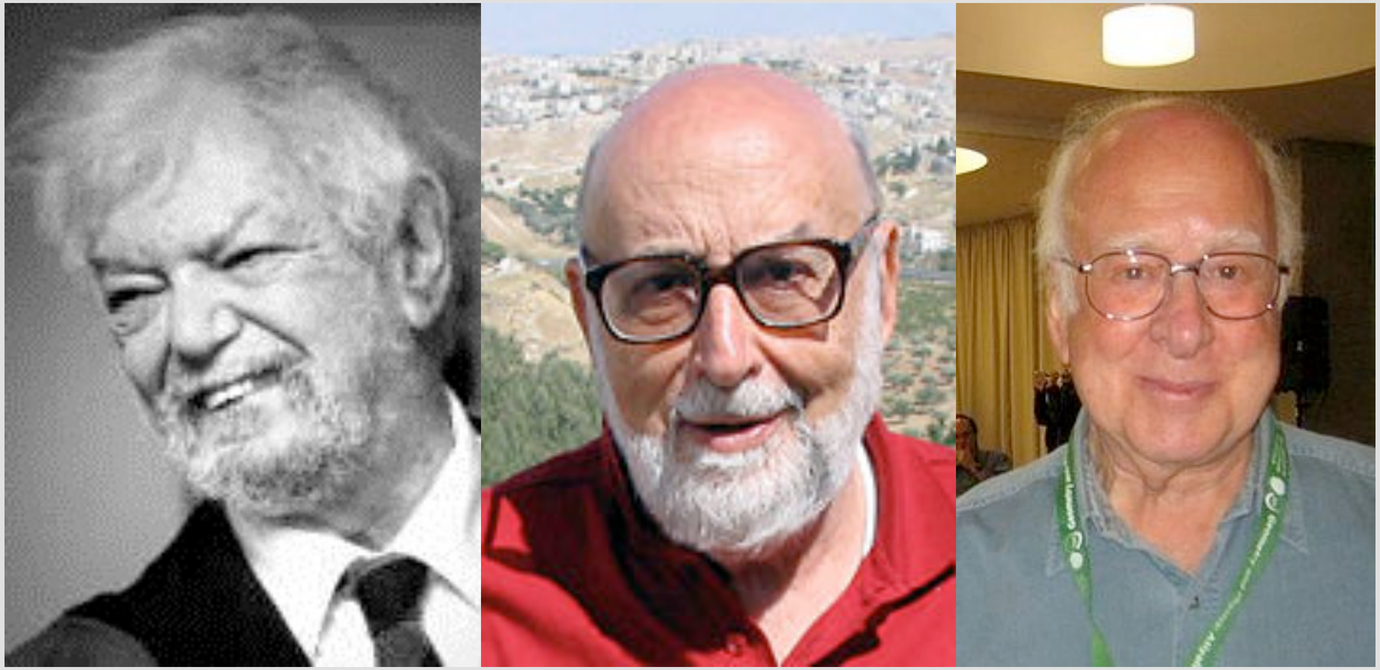
Alternative:

★ Add a mass term for the W bosons, giving up to a local symmetry from which the weak interaction would arise.

...but this does not work

Without the local symmetry the theory becomes inconsistent!

We need a mechanism that gives mass to the particles without spoiling the symmetry



R. Brout F. Englert P. Higgs

Higgs Mechanism

1964

★ Add a new (spin zero) field: H

$$\mathcal{L}_H = (D_\mu H)^\dagger D_\mu H - V(H)$$

with $D_\mu H = (\partial_\mu - igA_\mu)H$

$\mathcal{L}_H$ is invariant under the local transformation

★ Assume that $V(H)$ is such that $\langle H \rangle = v \neq 0$

$\mathcal{L}_H$ contains $g^2 v^2 A_\mu A^\mu$,

which plays the job of a mass term for A_μ

More precisely:

$$H(x) = \frac{1}{\sqrt{2}}(v + h(x))\ e^{i\xi(x)/v}$$

$$(D_\mu H)^\dagger D_\mu H = \frac{1}{2}(\partial_\mu h)^2 + \frac{1}{2}(\partial_\mu \xi)^2$$
$$+\frac{1}{2}g^2 v^2 A_\mu A^\mu - gvA_\mu \partial_\mu \xi + \cdots$$

Recall

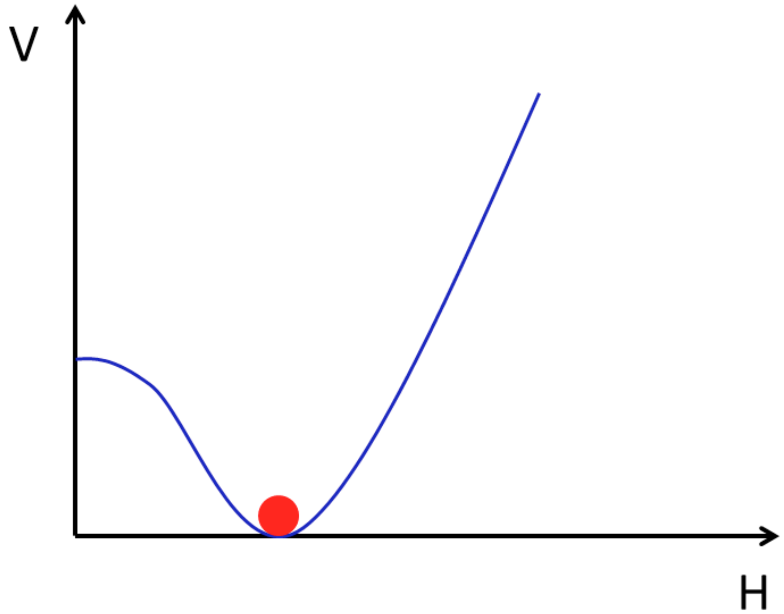
$$D_\mu H = (\partial_\mu - igA_\mu)H$$

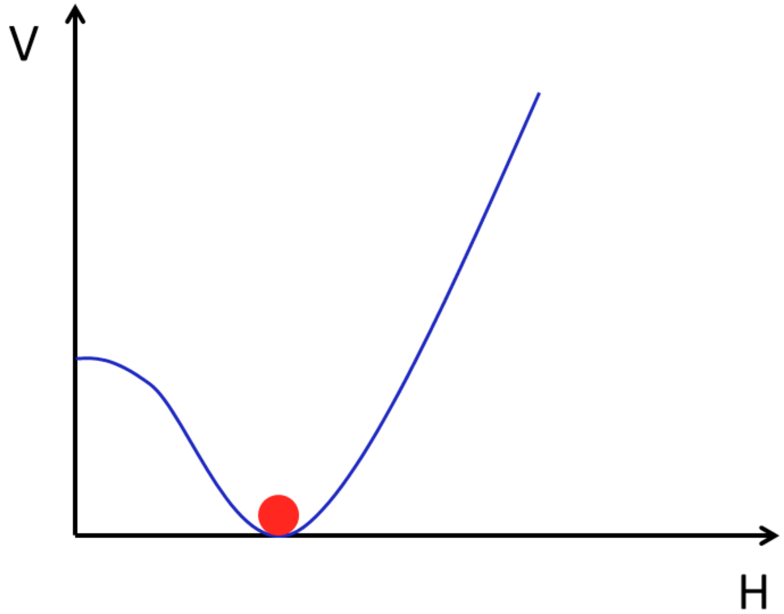
$$= \frac{1}{2}(\partial_\mu h)^2 + \frac{1}{2}g^2 v^2 B_\mu B^\mu + \cdots$$

$$B_\mu = A_\mu - \frac{1}{gv}\partial_\mu \xi$$

Why $\langle H \rangle \neq 0$??

$V(H)$ must have a non-trivial minimum



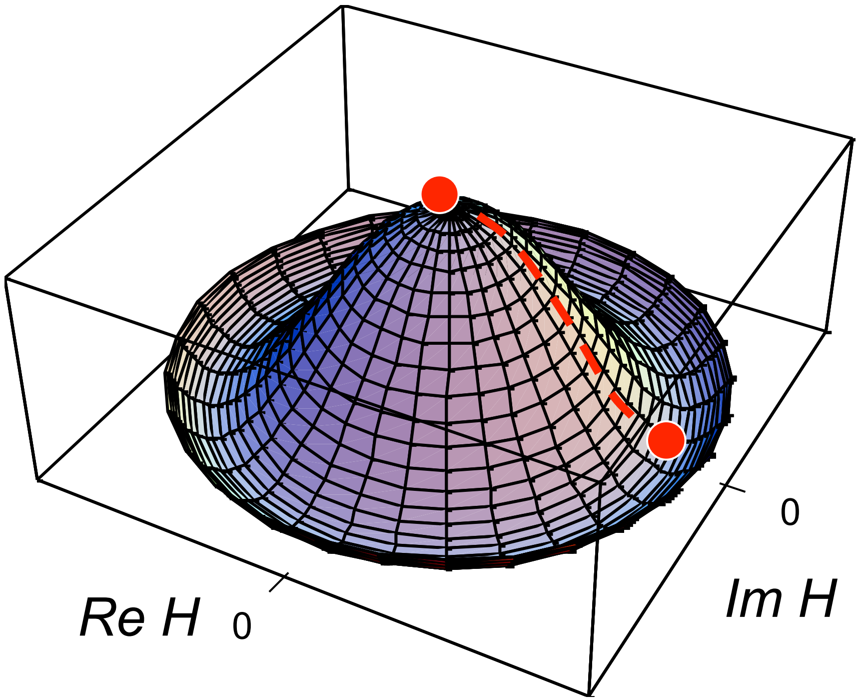


$$V(H) = m^2|H|^2 + \lambda|H|^4, \quad m^2 < 0$$

$$\longrightarrow \langle H \rangle = m/\sqrt{\lambda}$$

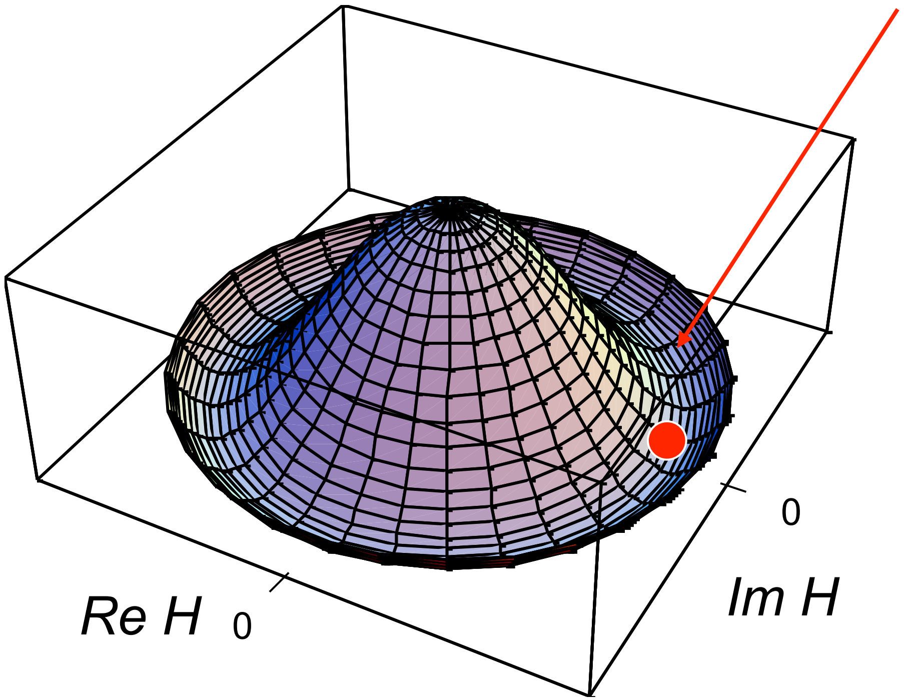
spontaneous symmetry breaking

Spontaneous symmetry breaking



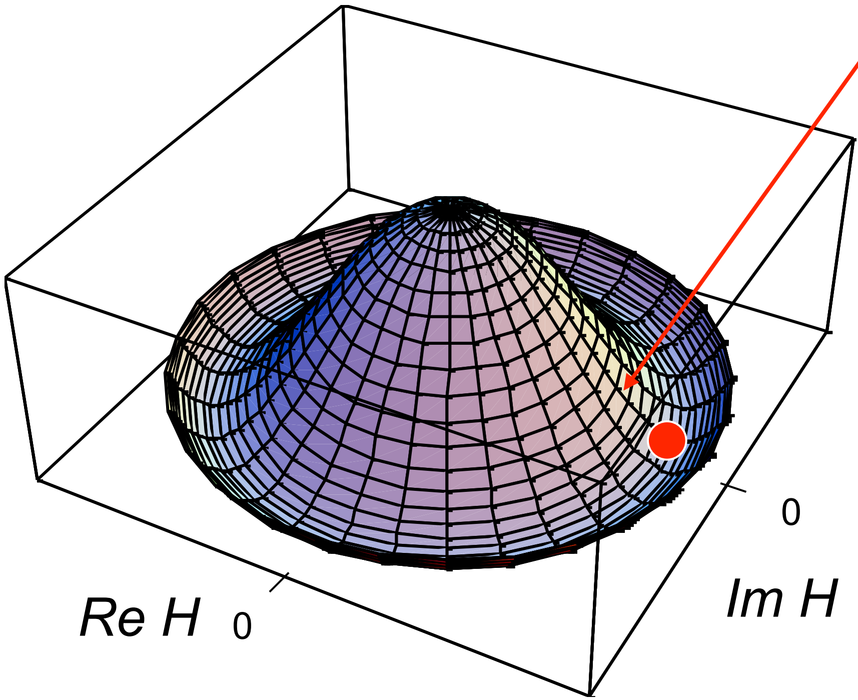
Higgs mehanism

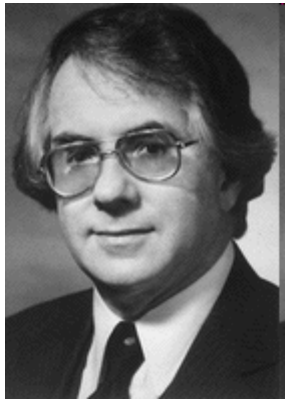
gives mass to
the gauge boson



Higgs mechanism

Particle with mass
(Higgs boson)





Glashow

Weinberg

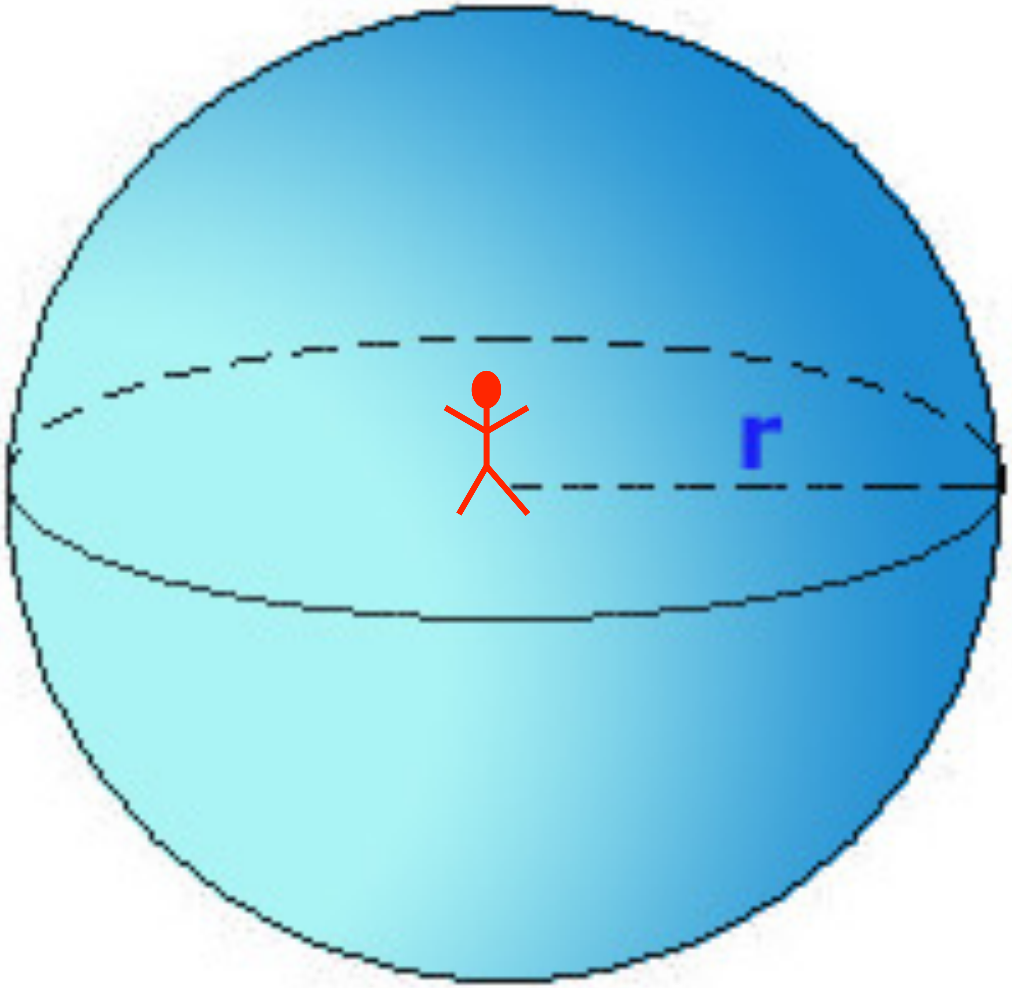
Salam

1960s

Electroweak symmetry: EW $SU(2)\times U(1)$

EW $\xrightarrow{\text{Spont. Breaking}}$ EM

$$\langle H \rangle$$


r

EW $\xrightarrow{Rupt.\ Esp.}$ EM

★ En el proceso 3 partículas mediadoras:

$W^+,\ W^-,\ Z$

(Descubiertas en el CERN en 1983)

adquieren masa

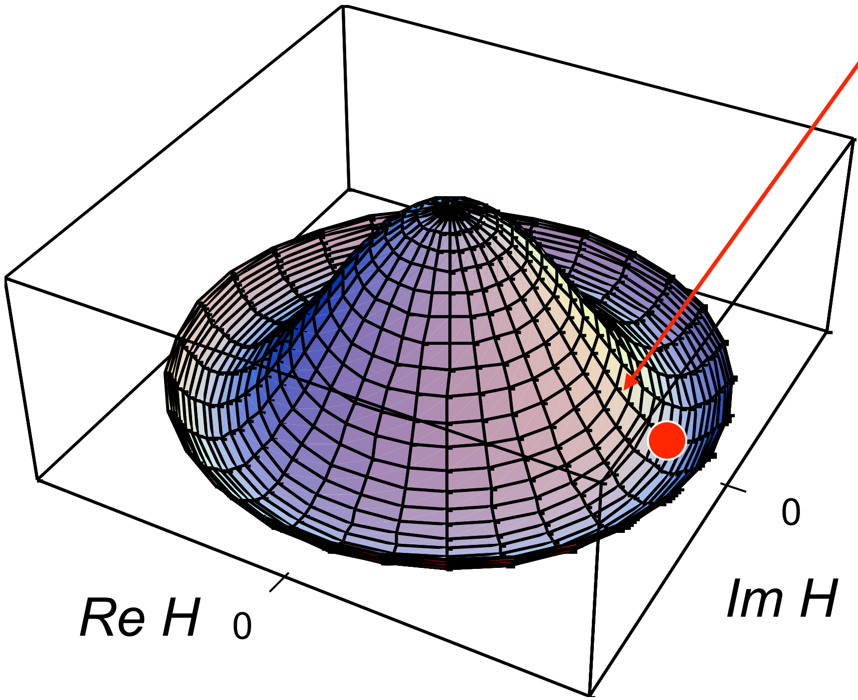
★ Y una partícula mediadora:

γ (fotón)

queda sin masa

Higgs mechanism

Particle with mass
(Higgs boson)



Not only the W, Z bosons require the Higgs to get a mass

All the SM particles get masses thanks to the Higgs field

E.g. consider the electron mass term

$$m_e \bar{\psi}\psi = m_e \bar{\psi}_L \psi_R + h.c.$$

Under a certain E.W. transformation (called hypercharge), $\psi_L, \ \psi_R$ transform as

$$\psi_L \longrightarrow e^{-i\alpha/2}\psi_L$$

$$\psi_R \longrightarrow e^{-i\alpha}\psi_R$$

$$m_e \bar{\psi}_L \psi_R \longrightarrow e^{-i\alpha/2} \ m_e \bar{\psi}_L \psi_R$$

Solution

Since H transforms as $H \longrightarrow e^{i\alpha/2}H$, instead of

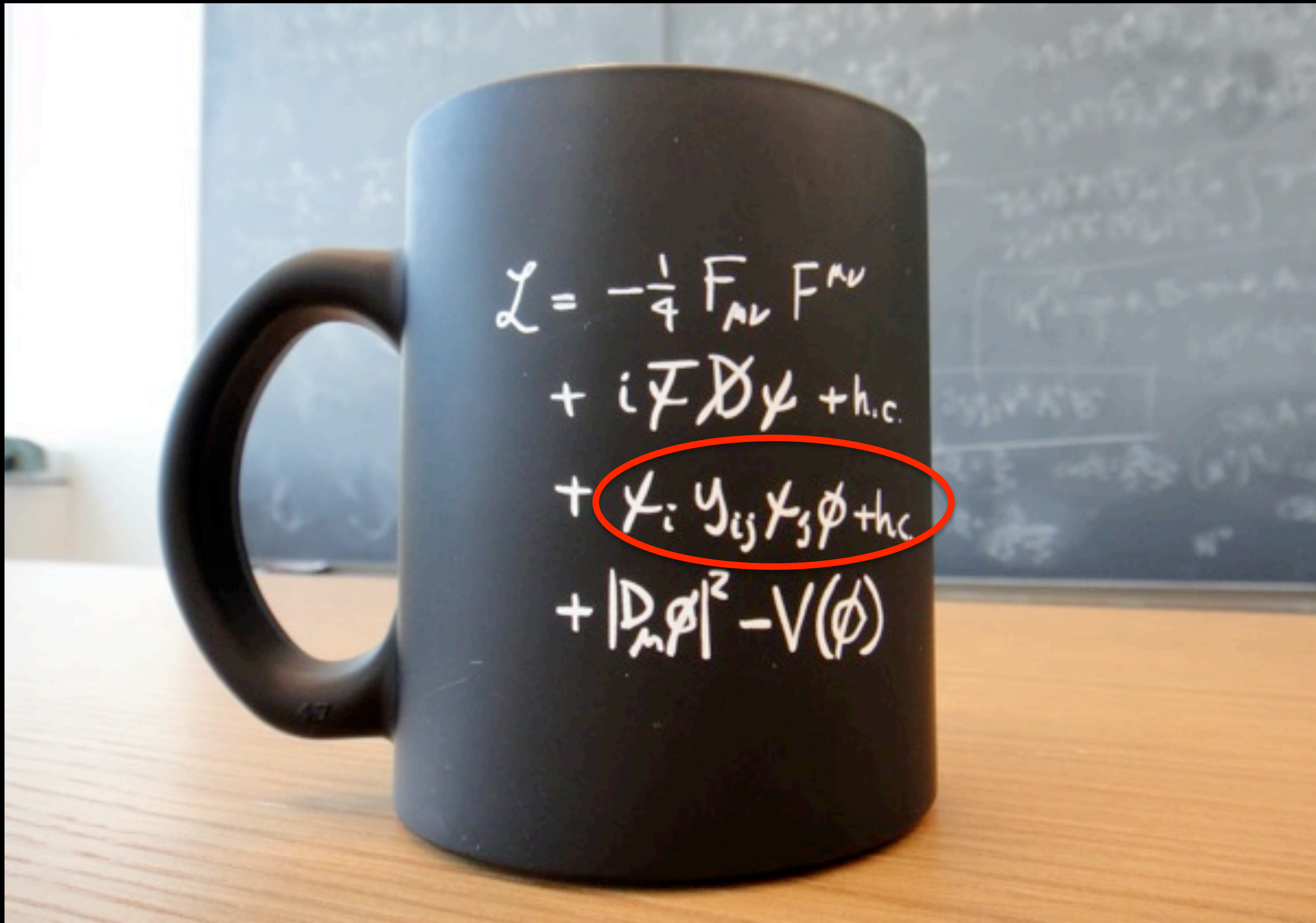
$m_e\bar{\psi}_L\psi_R$ consider

$$y_e H\bar{\psi}_L\psi_R$$

which is invariant (though not a mass term)

$$H = v + h$$

$$y_e H\bar{\psi}_L\psi_R = \underbrace{y_e v}_{\equiv m_e}\,\bar{\psi}_L\psi_R + \underbrace{y_e h}_{\text{interaction}}\,\bar{\psi}_L\psi_R$$

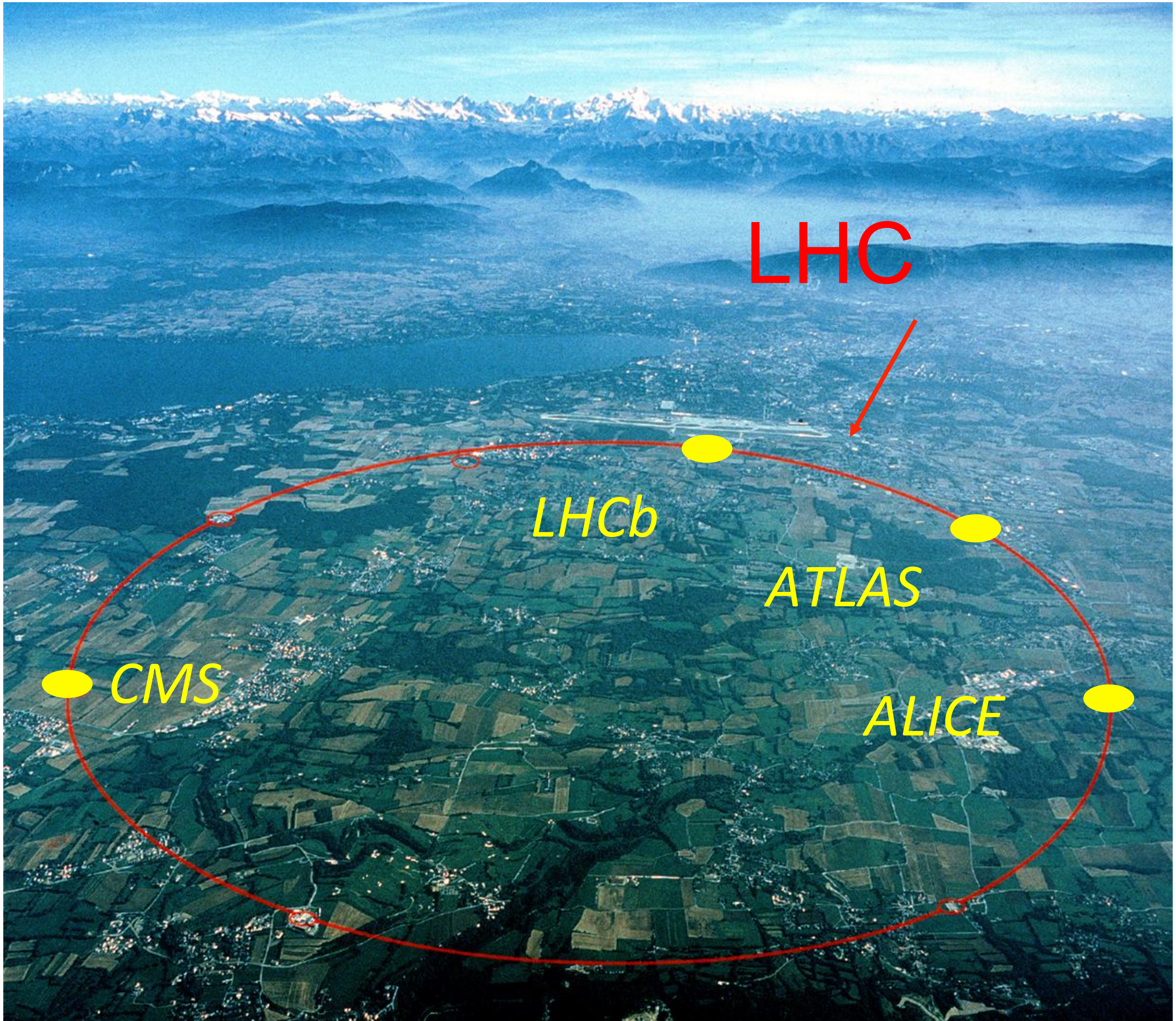


$$\phi \;\equiv\; Higgs$$

To “shake the vacuum” we need a machine able to accelerate particles up to enormous energies...

and make them crash !

LHC


LHC
LHCb
ATLAS
CMS
ALICE

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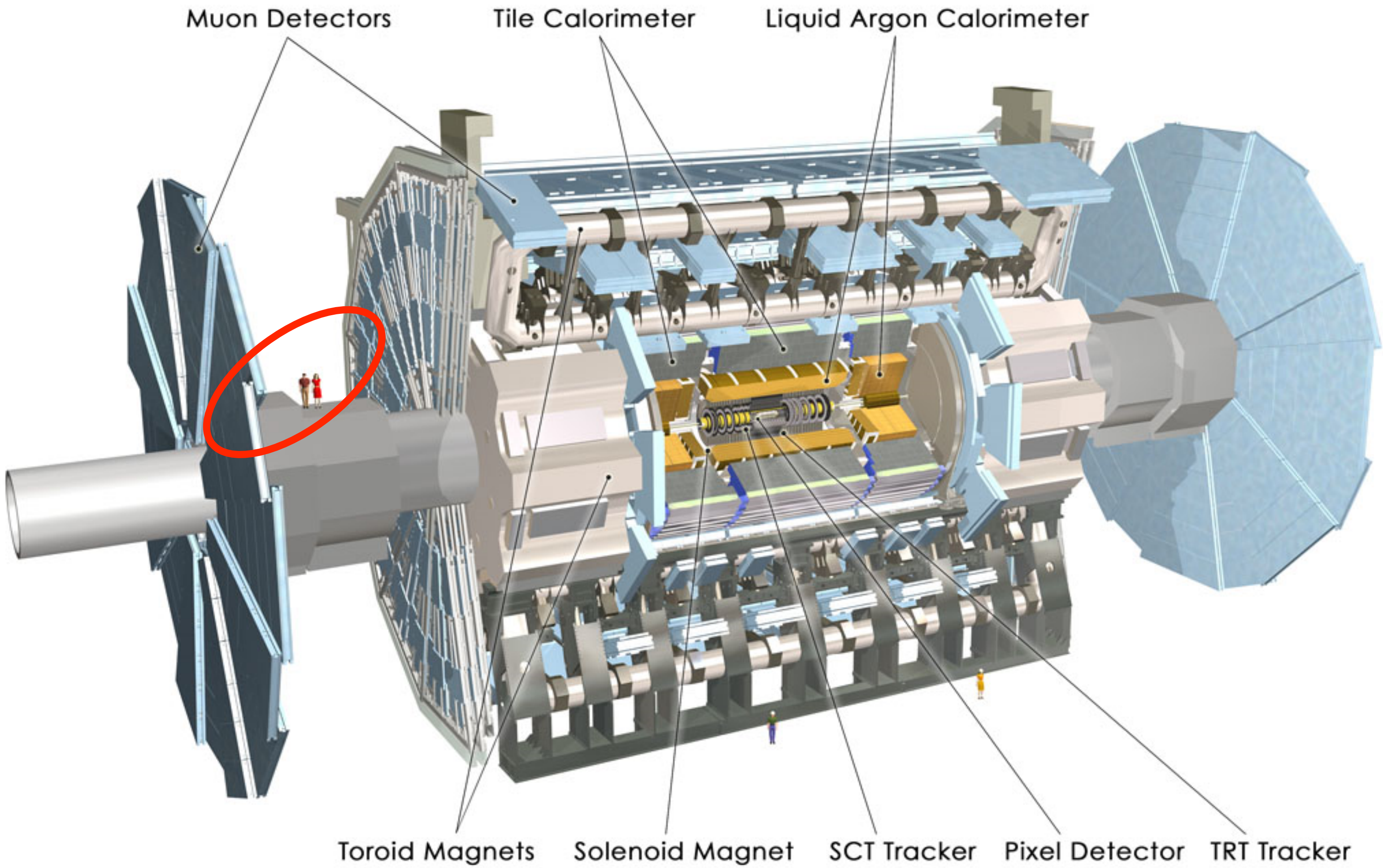
Detector ATLAS

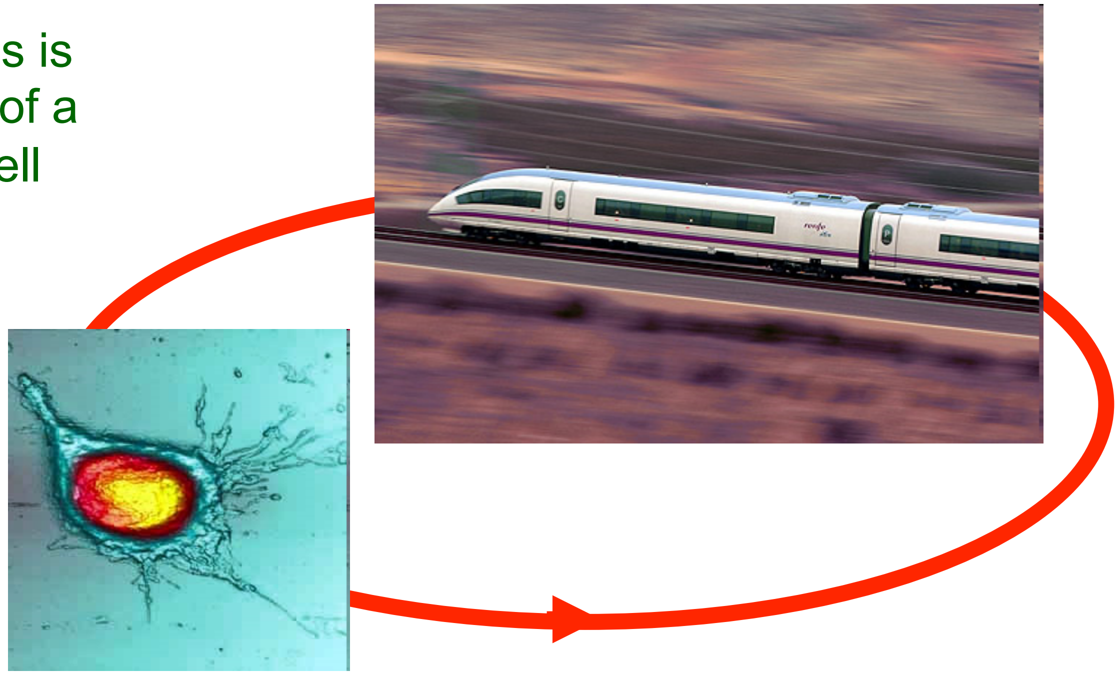


The LHC accelerates the protons up to energies of 6.5 TeV (~7000 times its mass)

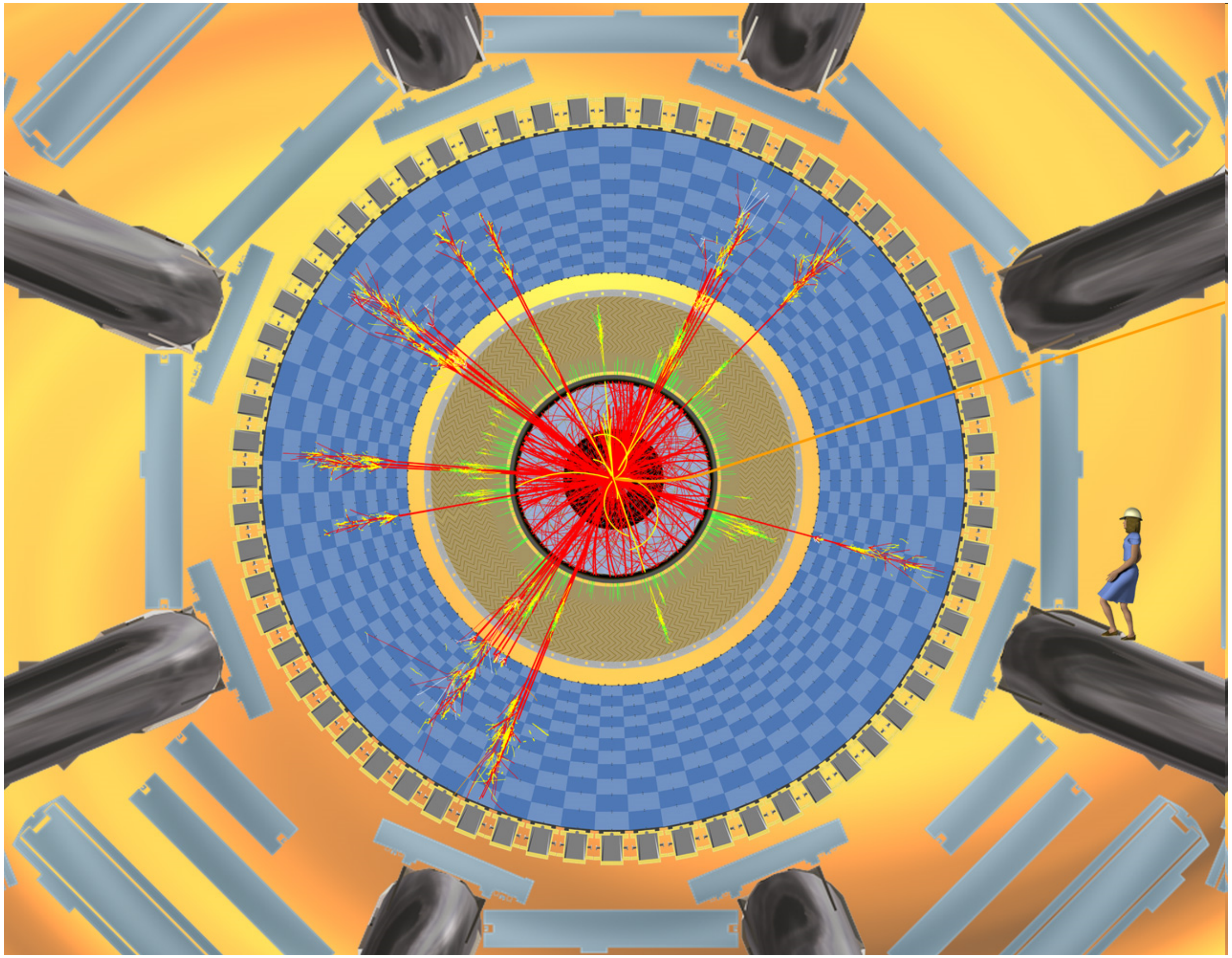
At a given time, in the ring there are 300 trillions of protons circulating in each way.

...their kinetic energy is like the one of a train of 400 Ton. at 150 Km/h

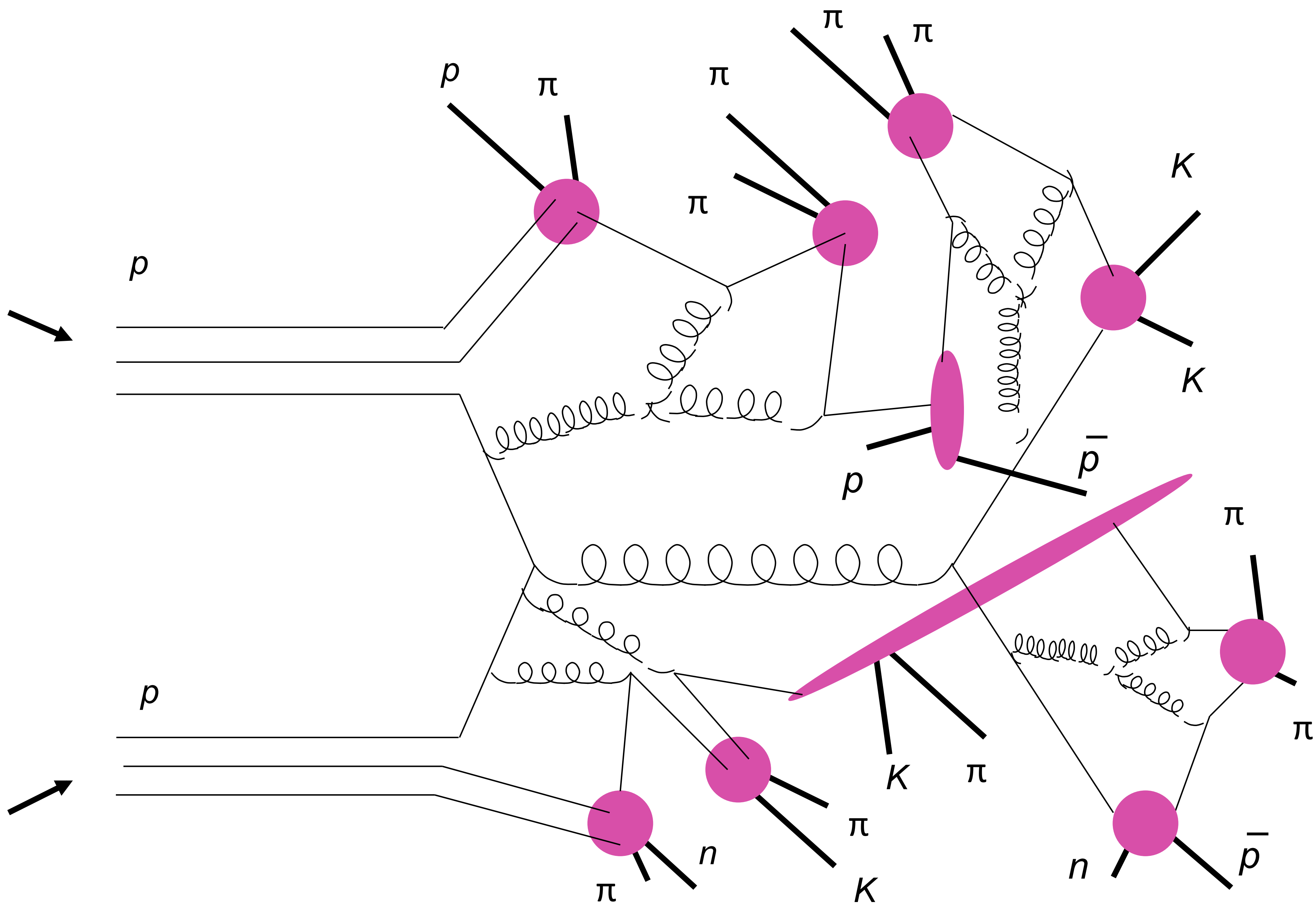
...their total mass is similar to a that of a typical human cell



The collisions are produced at the pace of ~ one billion times per second.




Collision



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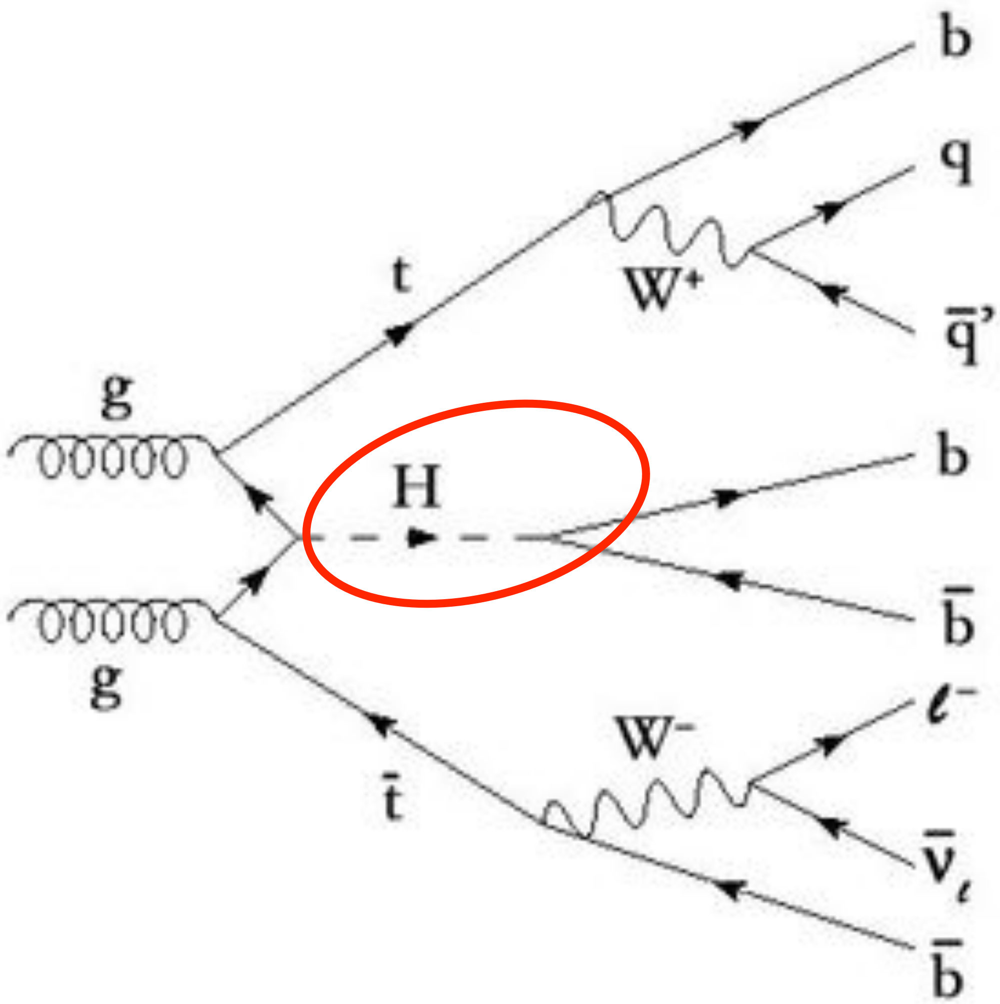
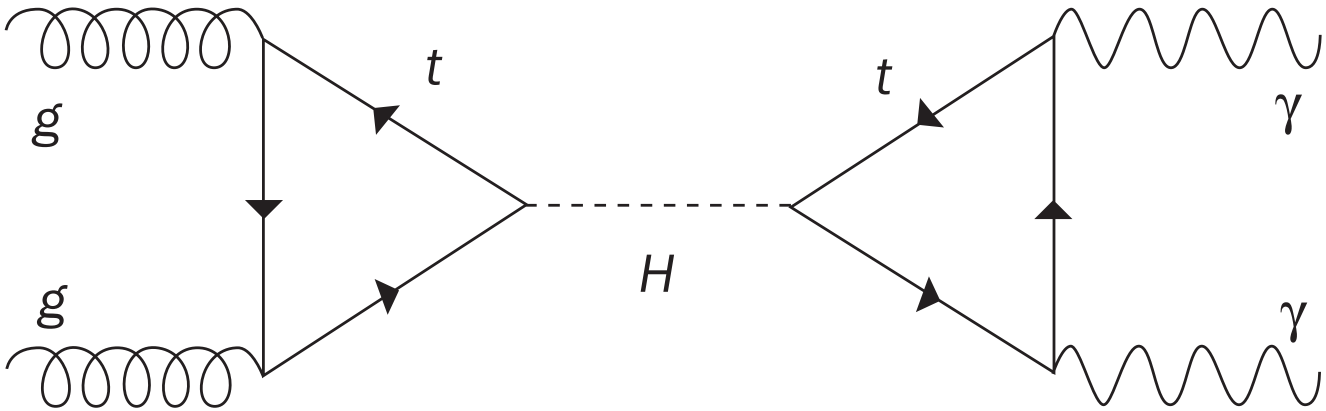
In each collision, tens of particles are produced

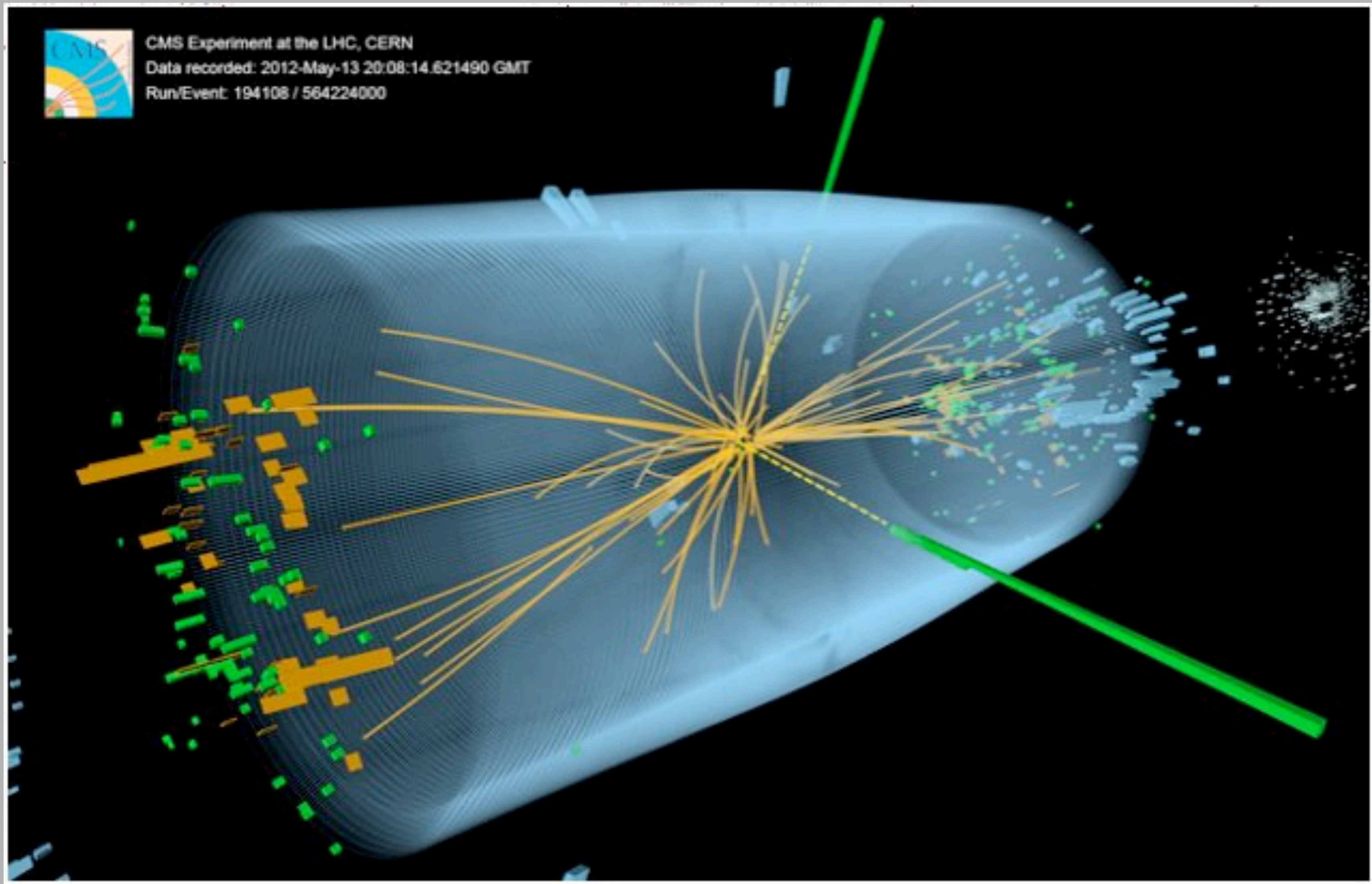
From the study of those particles the existence and properties of the Higgs boson must be inferred


b
q
t
W+
q̄'
g
H
b
b̄
g
ℓ−
W−
t̄
ν̄ℓ
b̄

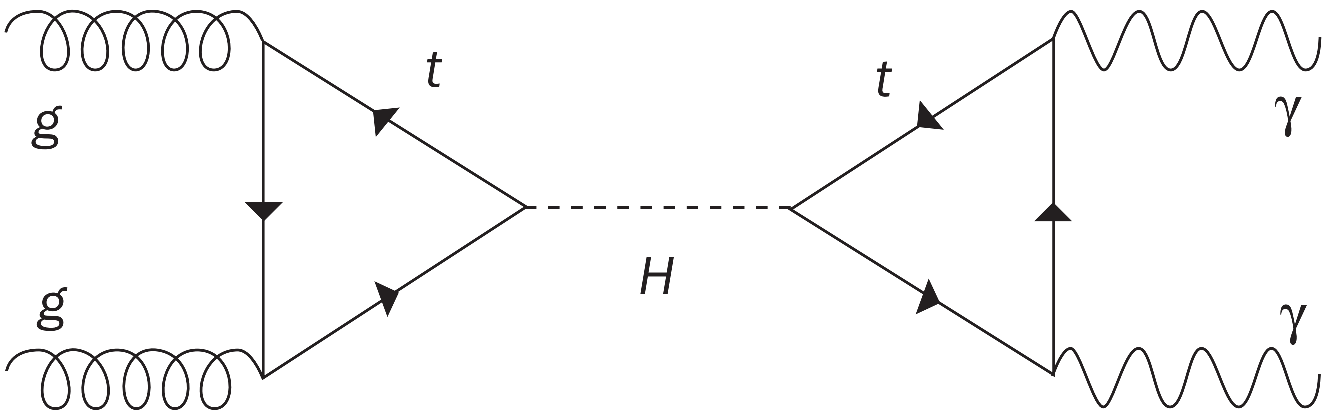
One of the ways in which a Higgs boson can decay, leaving a quite clear signal in the detectors is the

decay into two photons

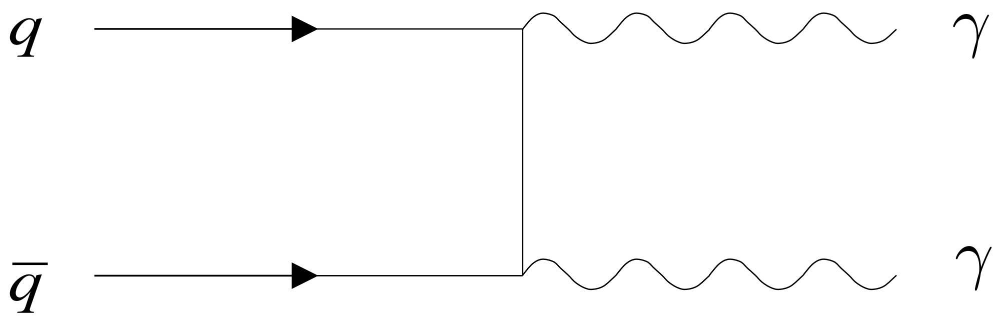


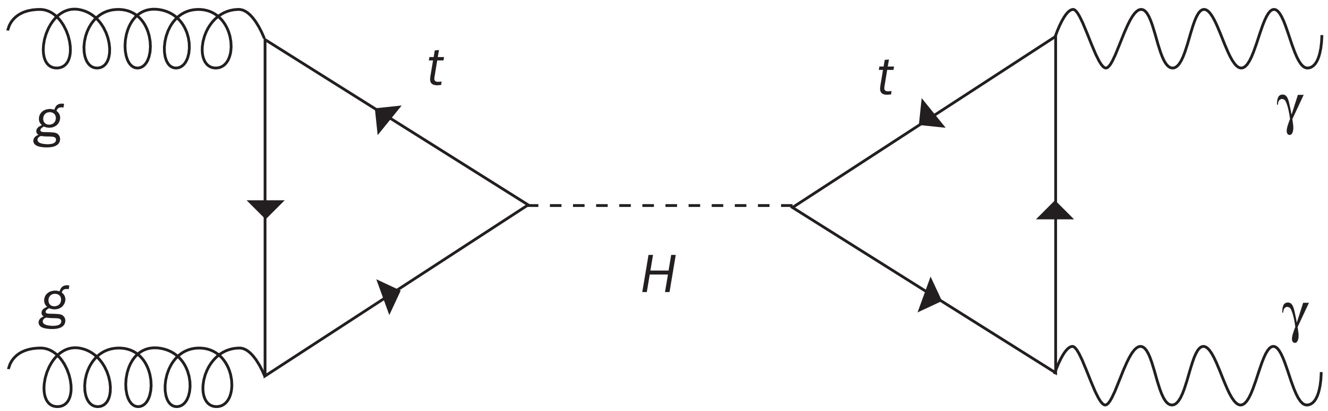

CMS Experiment at the LHC, CERN
Data recorded: 2012-May-13 20:08:14.621490 GMT
Run/Event: 194108 / 564224000

decay into two photons

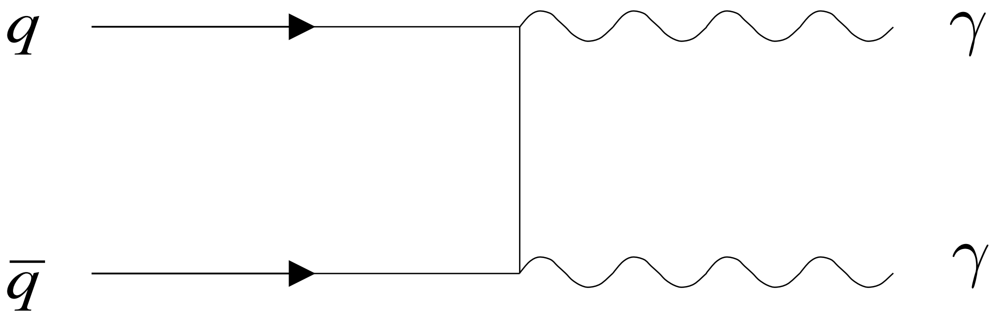


However there are background events where a Higgs boson has not been produced

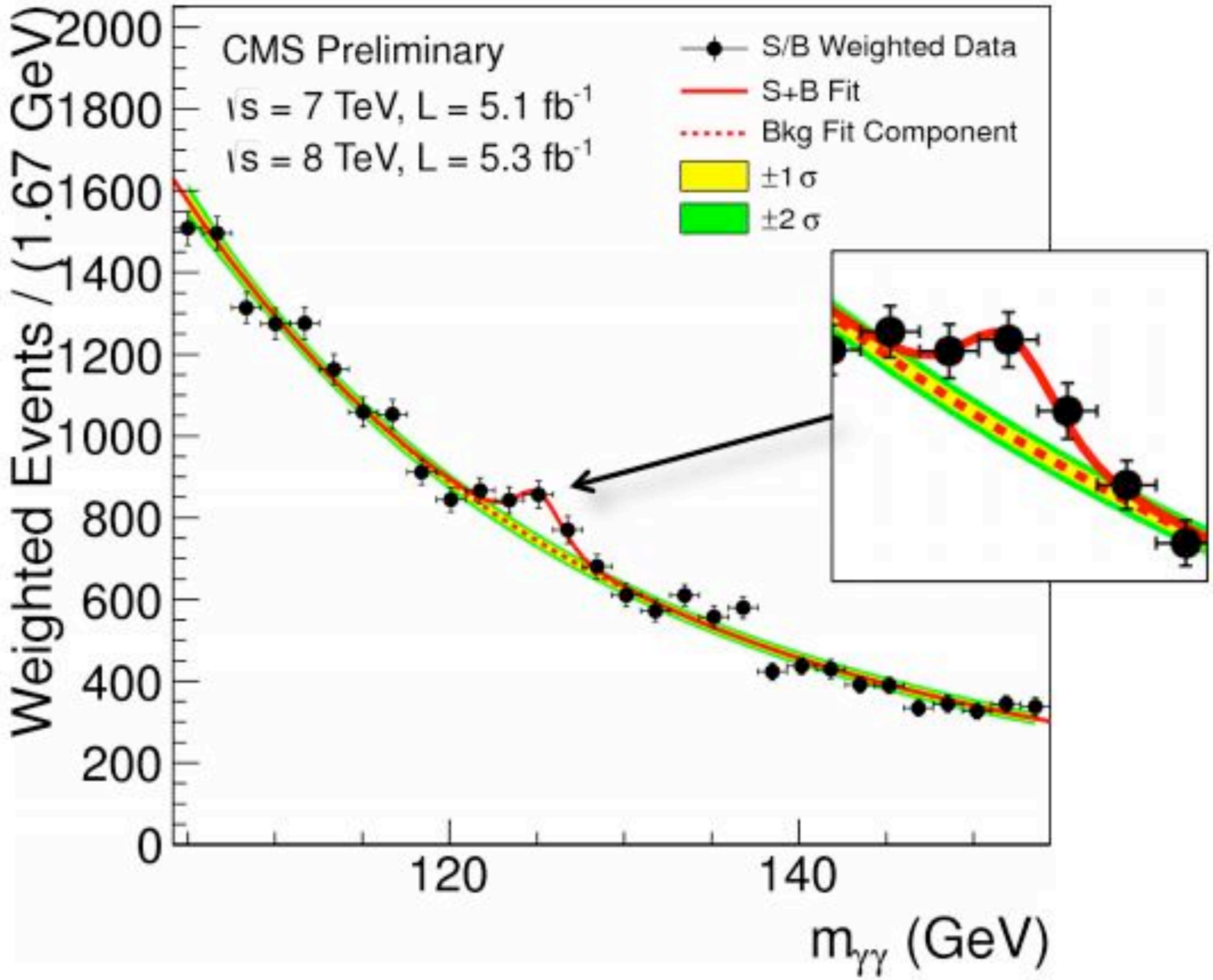




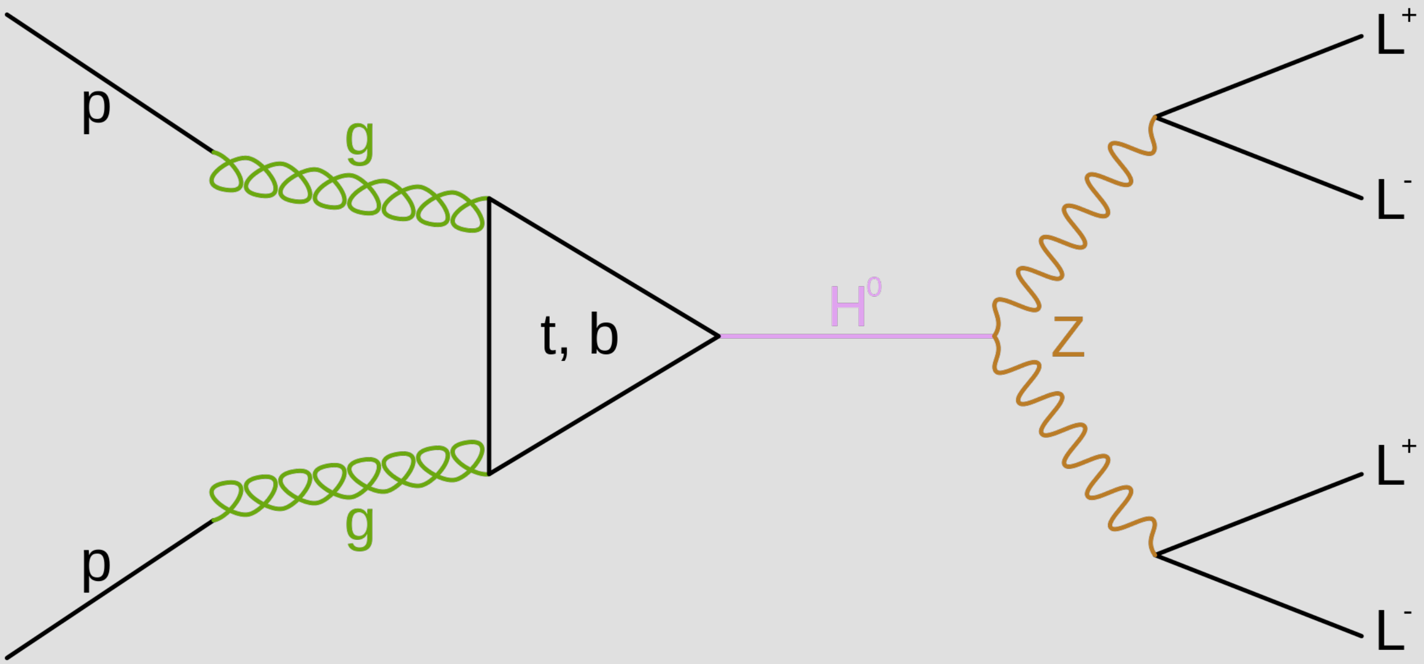
$$m_{\gamma\gamma} = m_H$$



$$m_{\gamma\gamma} \neq m_H$$



$$M_{\rm Higgs} \simeq 125 \text{ GeV}$$



p
g
t, b
H0
Z
L+
L-
L+
L-
g
p

Are we sure that the discovered particle is the SM Higgs boson?

Note that

The Higgs boson is an excitation of the vacuum.

Hence, it must have the same quantum numbers as vacuum

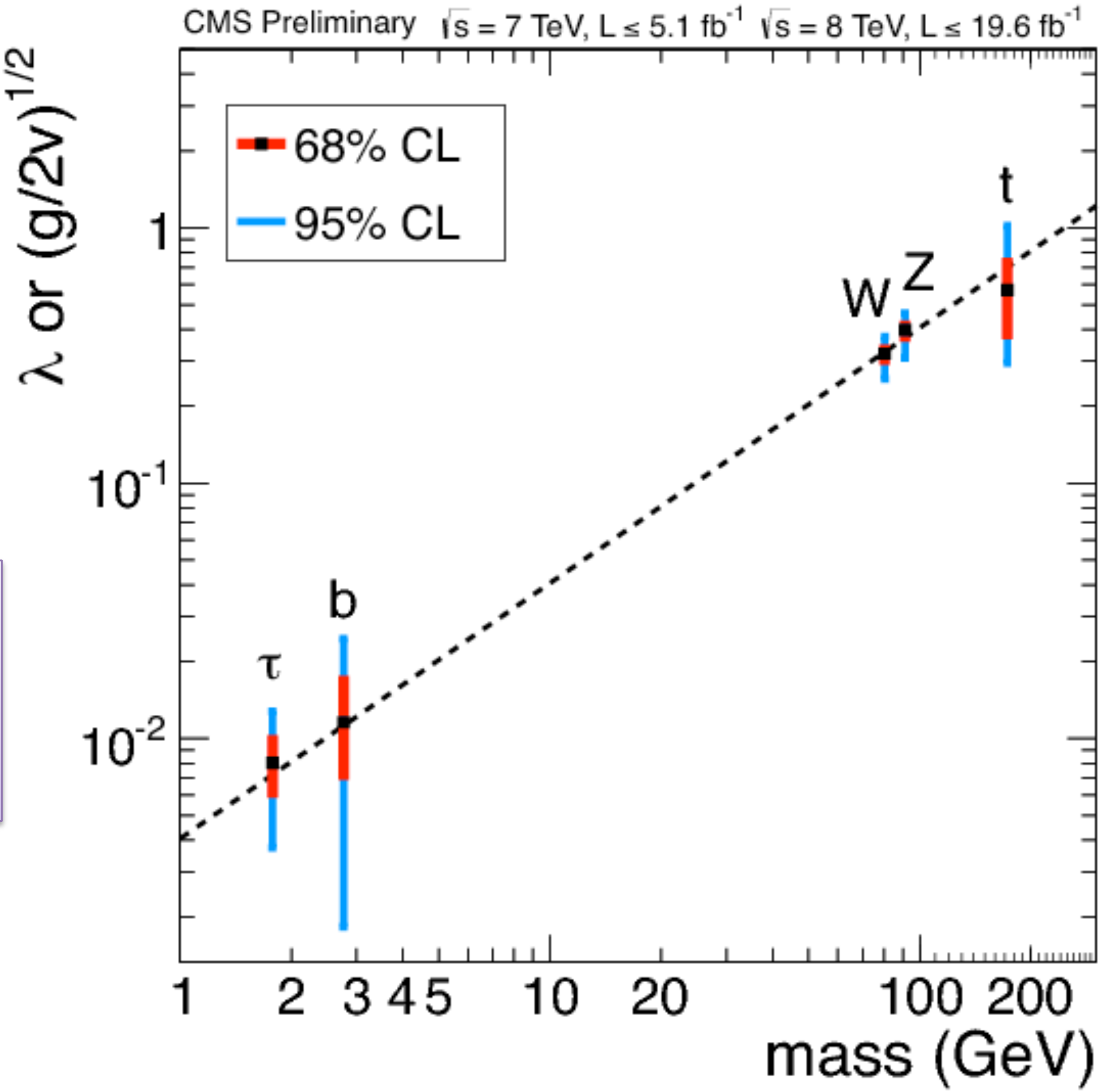
$$Q_{el} = 0, \quad J = 0, \quad P = +$$

... and it does!

Moreover, recall

$$y_e H \bar{\psi}_L \psi_R = \underbrace{y_e v}_{\equiv m_e} \bar{\psi}_L \psi_R + \underbrace{y_e h}_{\text{interaction}} \bar{\psi}_L \psi_R$$

So we expect interactions of the Higgs boson with the SM particles with a strength proportional to their mass



Meaured Higgs couplings vs the SM predictions

The discovery of the Higgs boson closes a succesful chapter in the history of physics, the one of the Standard Model;

But it opens new ones...

★ Is it really the SM Higgs boson?

★ Why does the Higgs couple to each elementary particle with a different strength?

ν_e	u
e	d

1[st] family

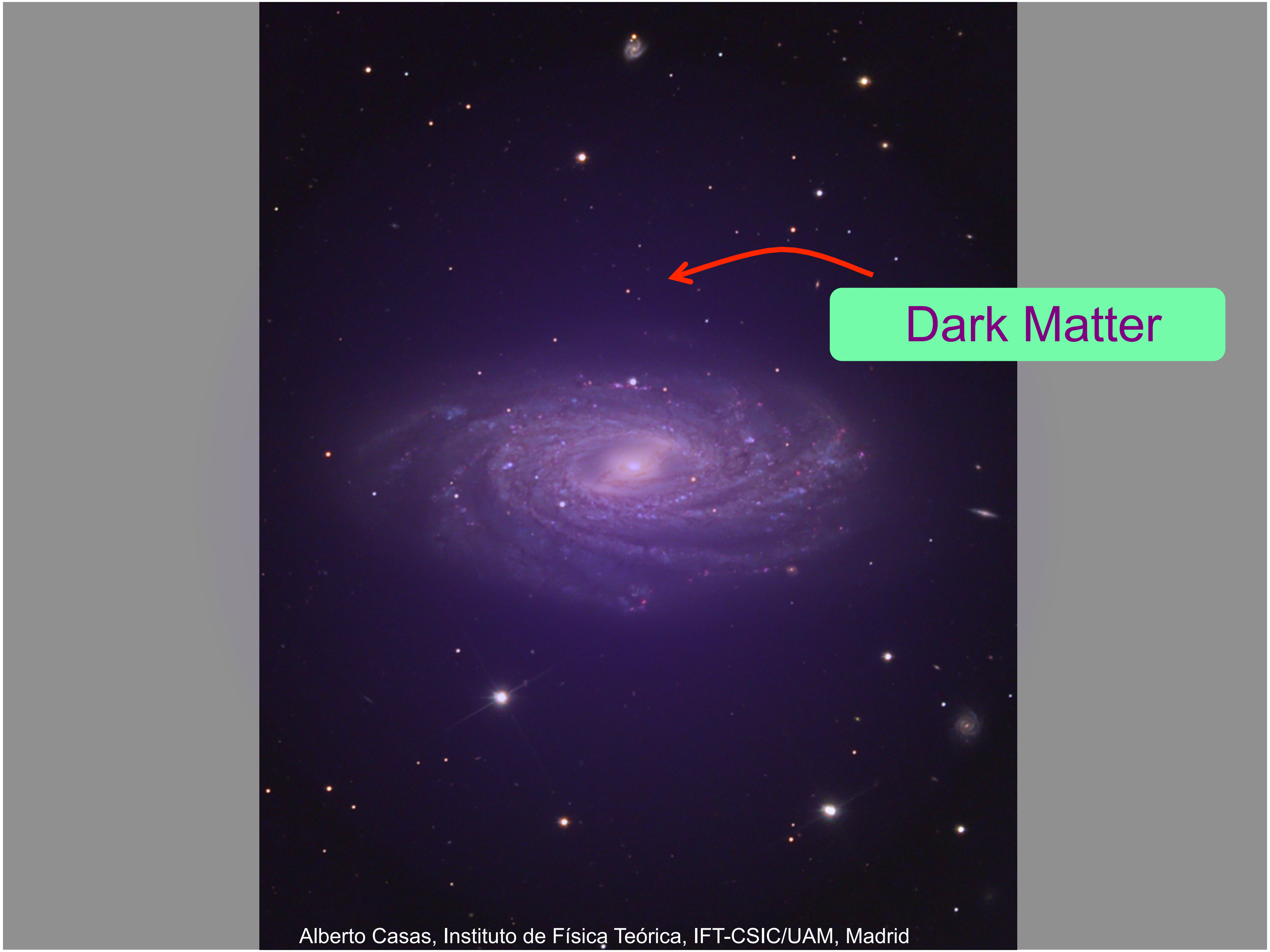
ν_μ	c
μ	s

2[nd] family

ν_τ	t
τ	b

3[rd] family

There are other reasons to believe in the existence of new fundamental physics, beyond the Standard Model


Dark Matter
Alberto Casas, Instituto de Física Teórica, IFT-CSIC/UAM, Madrid


Dark Energy
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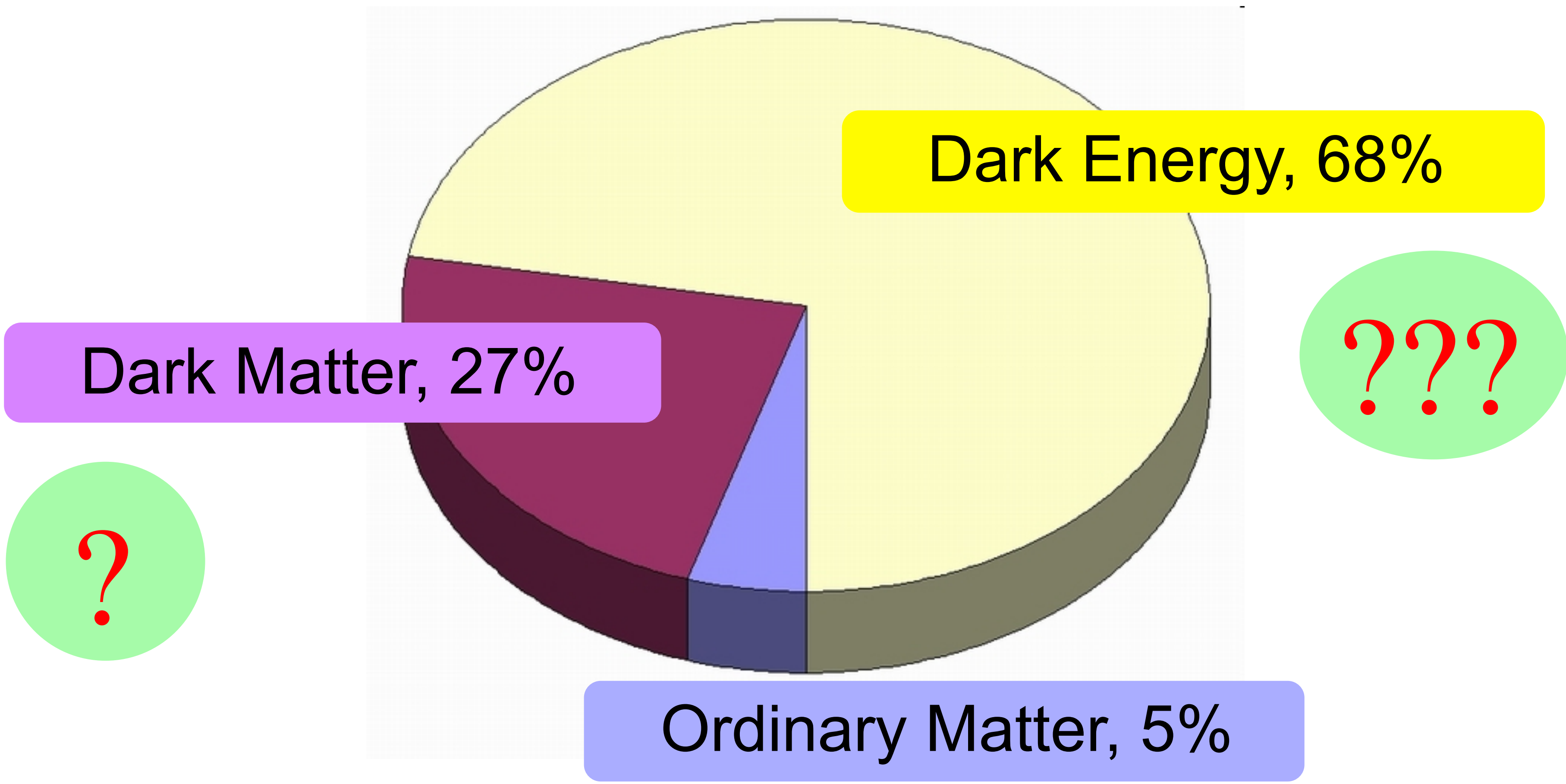
Composition of the Universe



Theoretical Problems

★ Consistency with Gravitation (General Relativity)

→ String Theory

So, there are strong reasons to believe in the existence of physics beyond the Standard Model

To find it out is the second (and even more ambitious) goal of the LHC

Nevertheless the previous hints do not give any indication about what is the energy-scale at which that new physics could be found.

Hence, the possibility that it will be discovered at the LHC, which has a limited energy, is somehow a matter of good luck.

However there is a hint that points out in the direction of new physics at the reach of the LHC, thus it has a great theoretical and experimental relevance.

Naturalness Problem

Why are the masses of the elementary particles what they are...

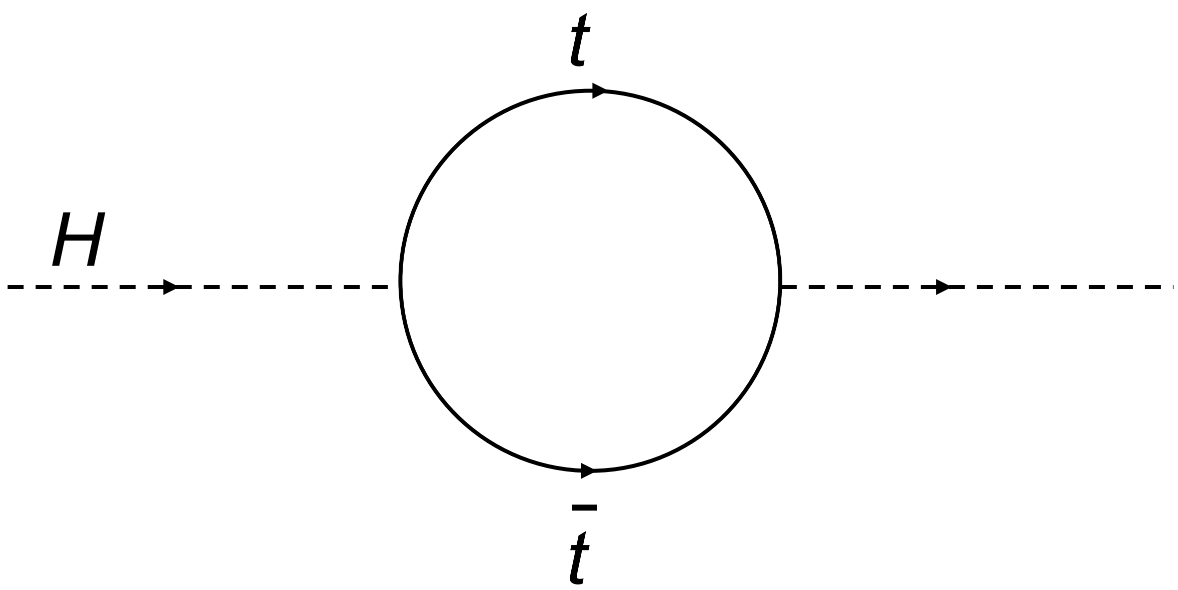
and are not, for instance, a million times larger?

Recall

$$V(H) = m^2|H|^2 + \lambda|H|^4, \quad m^2 < 0$$

$$\longrightarrow \langle H \rangle = m/\sqrt{\lambda}$$

Naturalness Problem



Gigantic quantum contributions to the Higgs mass, and thus to $\langle H \rangle$, unless there exists new physics at

$$\lesssim \mathcal{O}(\mathrm{TeV})$$

Standard
Model
Quantum
Gravity
Energy
200 GeV
M_P

Which new physics?

Supersymetry

Composite H

Extra Dimensions

...

Supersymmetry

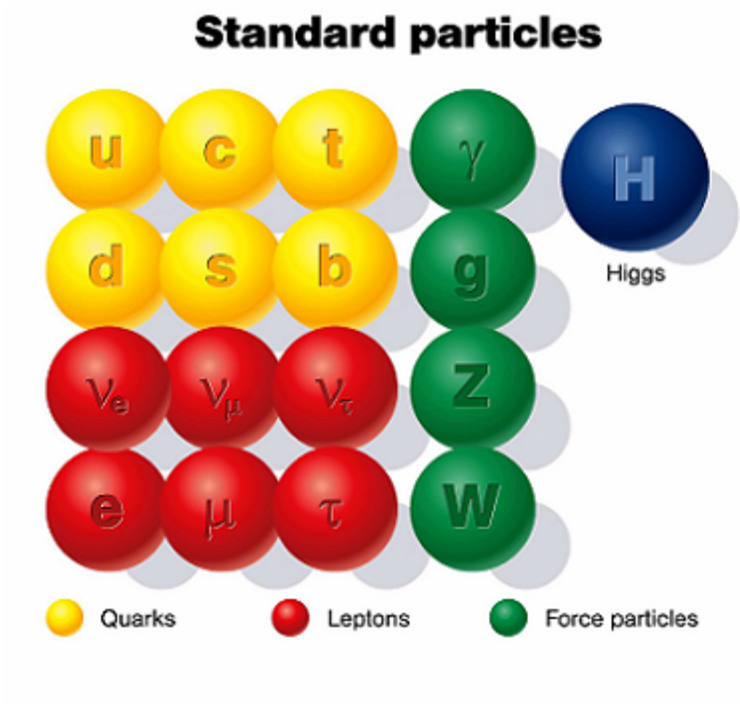
Symmetry that relates particles with different spin

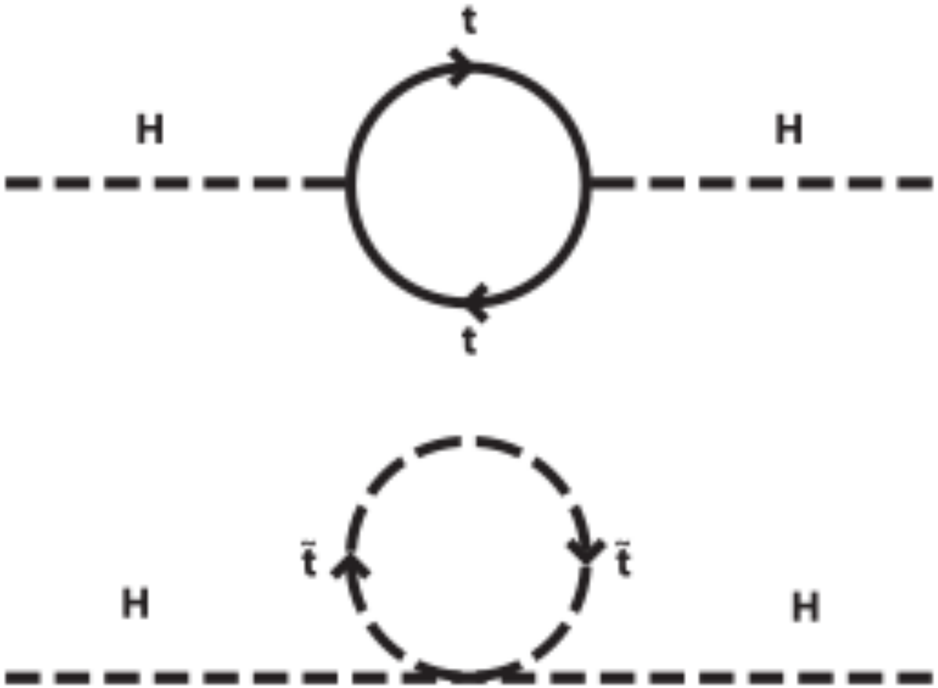
$$e \longrightarrow \tilde{e}$$

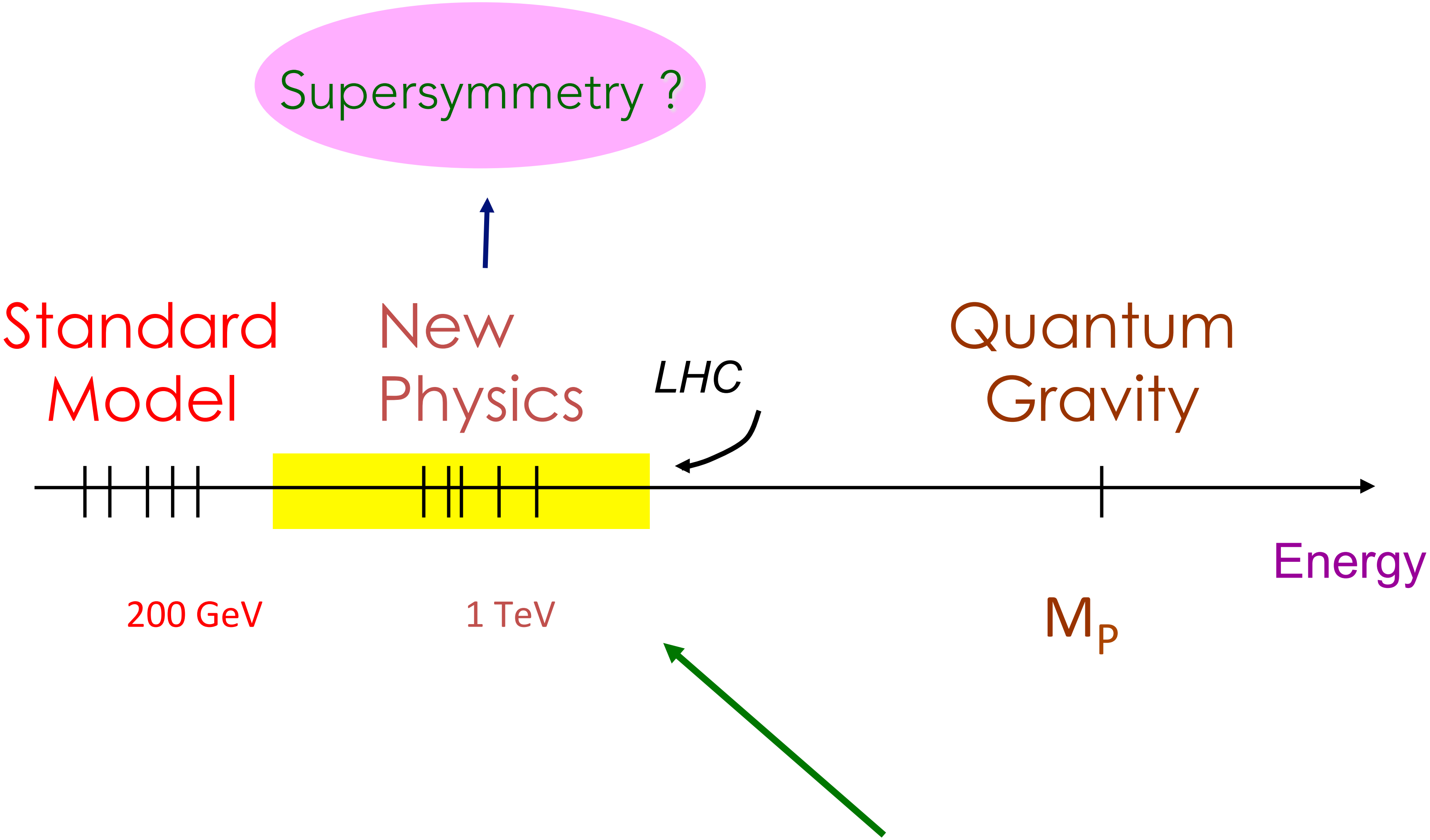
The situation reminds the prediction of antiparticles by Dirac in 1928

$$e^{-} \longrightarrow e^{+}$$

Supersymmetry

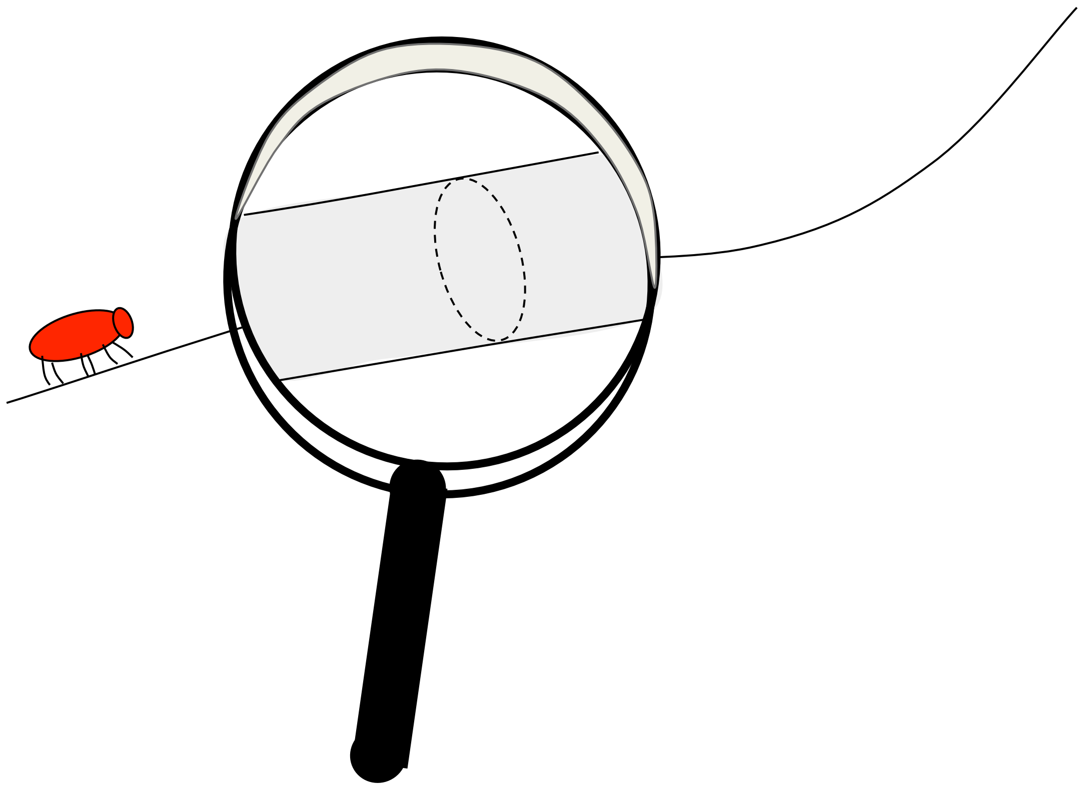



t
H
H
t
t̄
t̄
H
H



One of these extra particles could be the responsible for the Dark Matter.

Compact Extra Dimensions



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The absence of hints of new physics from the run I of LHC has created in part of the community the sense that there is a tension between the LHC results and the arguments behind the (usual interpretation of the) naturalness problem.

There are speculations that the naturalness problem is not really a problem. This might be the case if we have misconceptions about the computation of the quantum corrections.

But it is still a bit too early to think that the naturalness argumentss are wrong.

The LHC has just started its second run with up-graded energy, and there is a big expectation that new physics related to the naturalness problem is going to be found.

A pessimistic scenario is that the naturalness problem is sound but the new physics is just a bit too heavy to be discover at the LHC. Than would be really unfortunate, and cannot be discarded.

But there is the exciting possibility that new fundamental physics will be discovered at the LHC. And this would amount to a discovery even more important than the Higgs boson

The next years are going to be fascinating