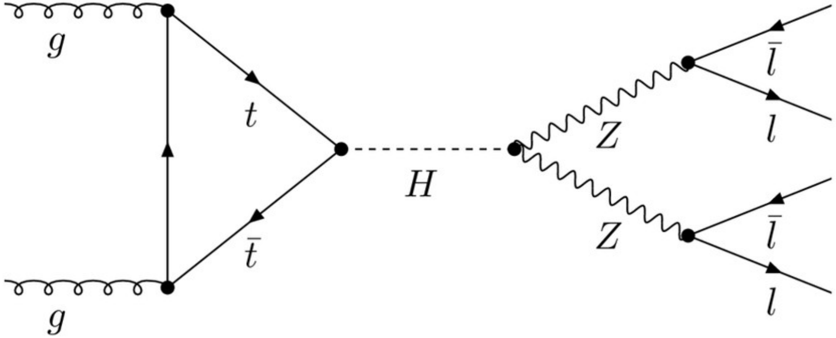
Discussion

Introduction to the BEH mechanism



Université de Strasbourg

Hello everyone

This is not a course, this is a discussion ! So feel free to interrupt, ask questions or share your own interpretations on the subject

What I will do :

- provide interpretations
- consider $\hbar = c = 1$

What I will not do :

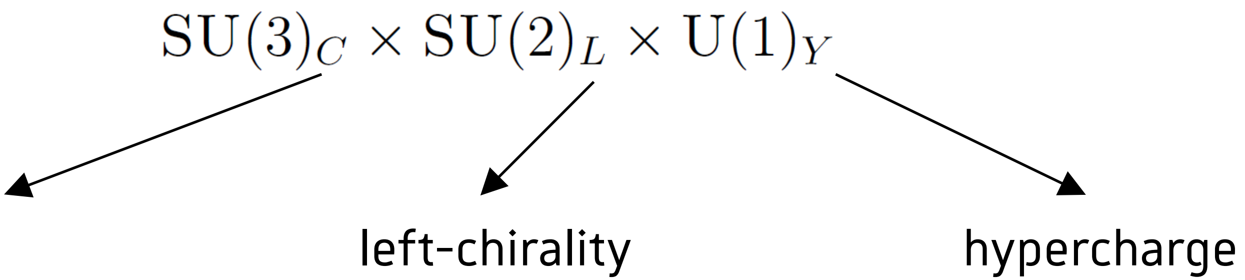
- run the computations

- Standard model
- Quantum field theory
- Supersymmetry

Introduction

The Standard Model of particle physics :

- describes three of the four known fundamental interactions
- classifies all known elementary particles



$$\mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$$

color

left-chirality

hypercharge

The particles in the model are massless :

- bosons : Higgs mechanism
- fermions : Yukawa interactions with Higgs

Introduction

1960

- physicists had a powerful theory of unified electromagnetic and weak interactions, but the gauge bosons predicted were massive

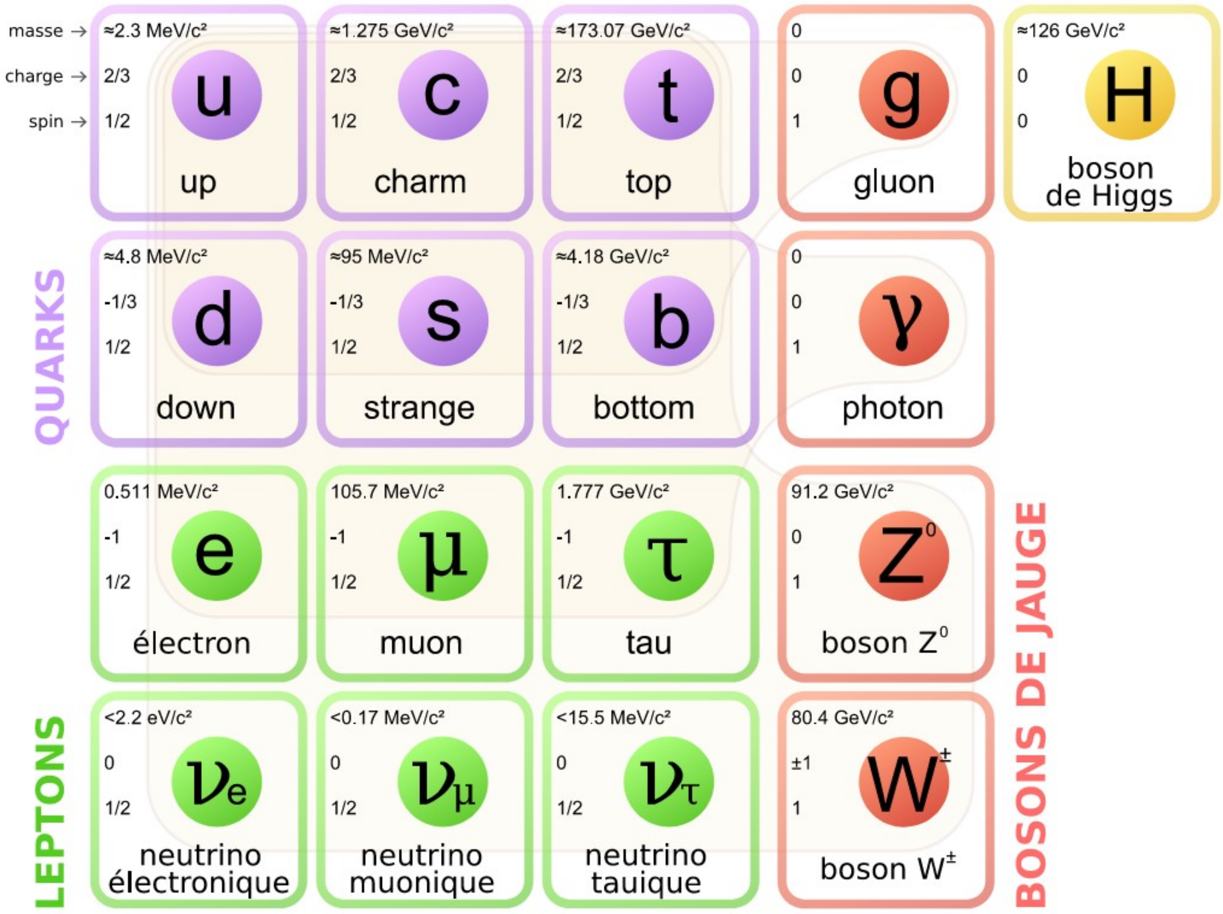
1964

- R. Brout, F. Englert and P. Higgs introduced the BEH mechanism that gives mass to elementary particles while retaining the structure of their original interactions

1983

- discovery at CERN (SPS) of the W and Z bosons

Standard Model



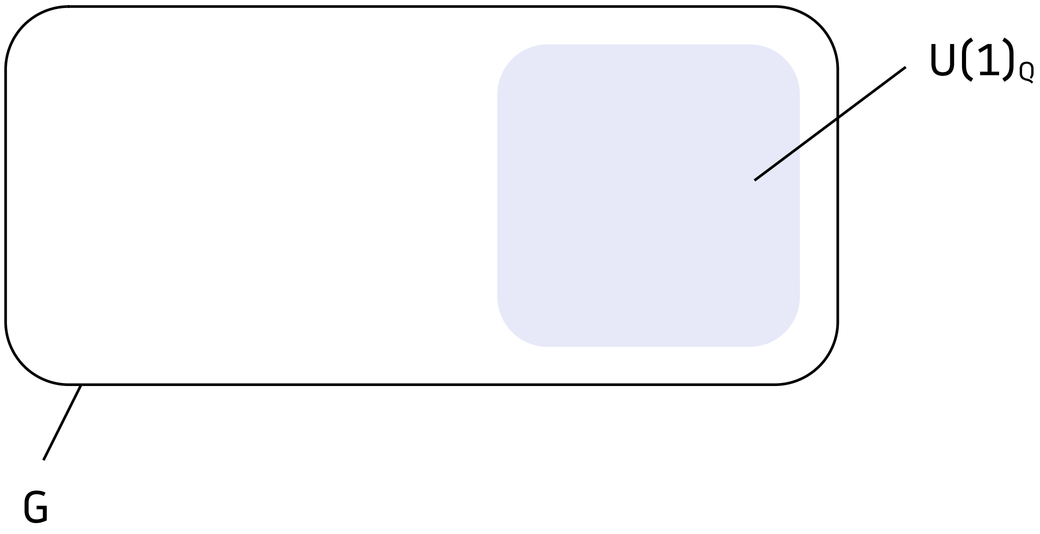
masse → charge → spin →	≈2.3 MeV/c^2 2/3 1/2 u up	≈1.275 GeV/c^2 2/3 1/2 c charm	≈173.07 GeV/c^2 2/3 1/2 t top	0 0 1 g gluon	≈126 GeV/c^2 0 0 H boson de Higgs
QUARKS	≈4.8 MeV/c^2 -1/3 1/2 d down	≈95 MeV/c^2 -1/3 1/2 s strange	≈4.18 GeV/c^2 -1/3 1/2 b bottom	0 0 1 γ photon	
	0.511 MeV/c^2 -1 1/2 e électron	105.7 MeV/c^2 -1 1/2 μ muon	1.777 GeV/c^2 -1 1/2 τ tau	91.2 GeV/c^2 0 1 Z^0 boson Z^0	BOSONS DE JAUGE
LEPTONS	<2.2 eV/c^2 0 1/2 ν_e neutrino électronique	<0.17 MeV/c^2 0 1/2 ν_μ neutrino muonique	<15.5 MeV/c^2 0 1/2 ν_τ neutrino tauique	80.4 GeV/c^2 ±1 1 $W^\pm$ boson $W^\pm$	

This is a wrong way of seeing things ...but at least it is visual

- 6 quarks
- 6 leptons
  - 3 charged
  - 3 neutrinos
- 4 gauge bosons
- 1 Higgs boson

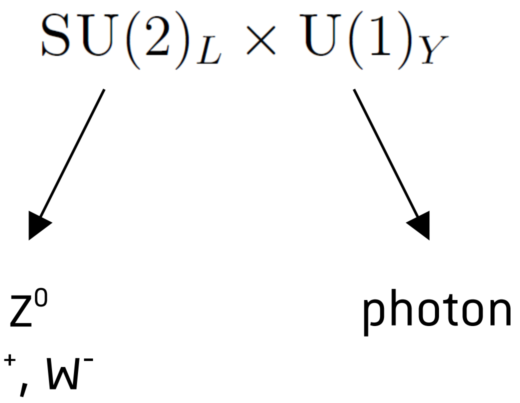
Electroweak

The starting point for the construction an electroweak gauge theory, that generalizes QED to include the weak interactions, is to identify the appropriate gauge group *G* and also the corresponding representations under which the fields transform



$\mathrm{U}(1)_Q$

G



$\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$

Z^0

W^+, W^-

photon

Huge problem : mass terms are forbidden in the Lagrangian

Toy model

Consider a single complex scalar field coupled to a U(1) gauge field :

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + |D_\mu\phi|^2 - V(\phi)$$

$$\partial_\mu - ieA_\mu$$

$$\mu^2|\phi|^2 + \lambda|\phi|^4$$

most general form so that the theory is renormalizable and invariant

Key ingredients :

- symmetries → constraints on Lagrangians
- vacuum → spontaneous breaking
- Goldstone theorem → particle content

Toy model (Goldstone theorem)

Hello I am a system and I have a continuous symmetry, but my symmetry is spontaneously broken !

$$\Big\downarrow \textit{Noether's theorem}$$

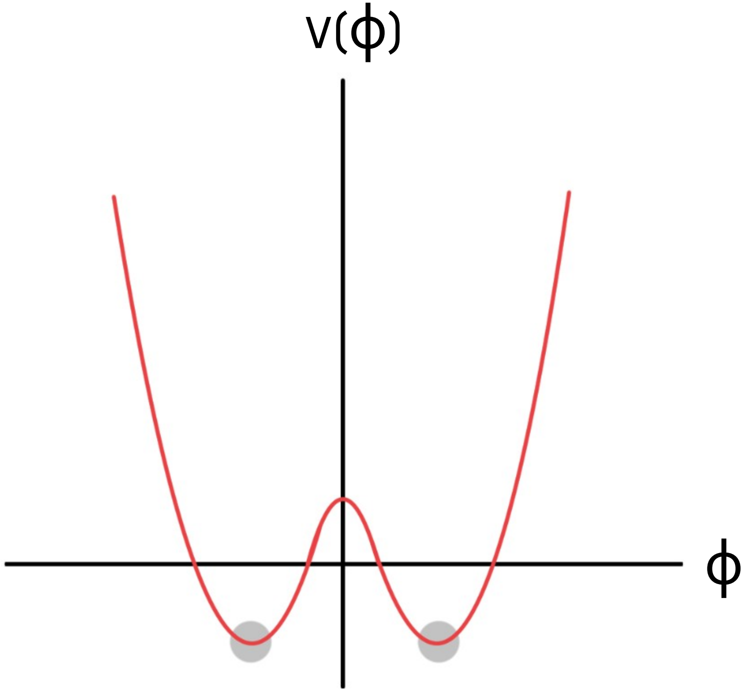
conserved charge

When a continuous symmetry of a system is broken, massless scalar particles called Nambu-Goldstone bosons appear, one per symmetry generator that is broken

(in the case of supersymmetric theories, massless Goldstone fermions appear when the symmetry is of fermionic nature)

Toy model

- if $\mu^2 < 0$:



V(ϕ) has a minimum at : $\langle \phi \rangle = \pm\sqrt{-\frac{\mu^2}{2\lambda}}$

The vacuum breaks the U(1) symmetry and we can decompose :

$$\phi = \frac{1}{\sqrt{2}} e^{i\frac{\chi}{v}} (v + h)$$

vacuum expectation value

dynamical field

Toy model

Inserting the expression of the vacuum expectation value into the Lagrangian :

mass of the gauge field

$$
\begin{aligned}
\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}e^2v^2A^\mu A_\mu + \frac{1}{2}\left(\partial_\mu h\partial^\mu h + \partial_\mu\chi\partial^\mu\chi\right) \\
+ \mu^2h^2 - evA_\mu\partial^\mu\chi + (h, \chi \text{ interactions})
\end{aligned}
$$

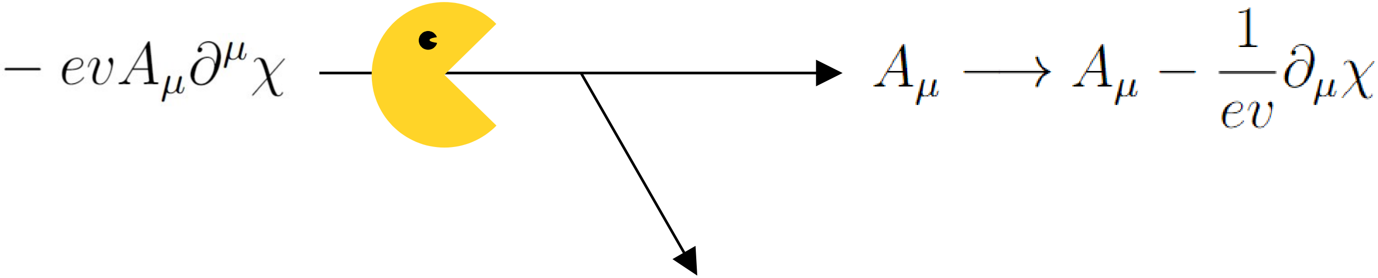
mass of the Higgs-like boson

hum ?..

- how to interpret the additional field ?
- did we use gauge invariance ?..

Toy model

Mass is a new degree of freedom given to gauge bosons, that arises from symmetry breaking and gauge transformation :



$$-evA_\mu\partial^\mu\chi$$

$$A_\mu \longrightarrow A_\mu - \frac{1}{ev}\partial_\mu\chi$$

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}e^2v^2A^\mu A_\mu + \frac{1}{2}\partial_\mu h\partial^\mu h - V(h)$$

The Goldstone scalar field is eaten by the gauge boson and transformed into its longitudinal component

SU(2)xU(1)

Let’s define the generators of the groups, the gauge fields and the gauge transformations :

• generators :	$i\boldsymbol{T}, \qquad \boldsymbol{T} = (T_1, T_2, T_3)$ $[T_a, T_b] = i\epsilon_{abc}T_c$	iY
• gauge fields :	$\mathbf{A}_\mu$	B_μ

What is the link between the generators ? $Q = T_3 + Y$

SU(2)xU(1)

The transformation law for the **SU(2)** gauge field is :

$$\mathbf{A}_\mu(x).\mathbf{T} \rightarrow e^{i\alpha(x).\mathbf{T}}\mathbf{A}_\mu(x).\mathbf{T}e^{-i\alpha(x).\mathbf{T}} + \frac{i}{g}(\partial_\mu e^{i\alpha(x).\mathbf{T}})e^{-i\alpha(x).\mathbf{T}}$$

The transformation law for the **U(1)** gauge field is :

$$B_\mu(x) \rightarrow B_\mu(x) - \frac{1}{g'}\partial_\mu\beta(x)$$

Because of the direct product structure of the gauge group it is necessary to introduce two coupling constants g and g′, one for each factor in the gauge group. The existence of two coupling parameters is crucial to the structure of electroweak theory, although means that the theory is not really fully unified

SU(2)xU(1)

The computations are not interesting so focus on the interpretation

$\mathbf{A}_\mu$

mass exactly zero

B_μ

mass exactly zero

gauge eigenstates

"rotation" →

$$W_\mu = \frac{1}{\sqrt{2}}\left(A_{1\mu} - iA_{2\mu}\right)$$

$$m_W^2 = \frac{1}{4}\, g^2 v^2$$

$$Z_\mu = \cos\theta_W A_{3\mu} - \sin\theta_W B_\mu$$

$$m_Z^2 = \frac{1}{4}\,(g^2 + g'^2)v^2$$

$$A_\mu = \sin\theta_W A_{3\mu} + \cos\theta_W B_\mu$$

mass exactly zero

mass eigenstates

SU(2)xU(1)

The mass of the bosons are generated by symmetry breaking, what about the fermions ?

Take the example of the electron and its neutrino, generalization is straightforward :

$$L(x) = \begin{pmatrix} \nu_e(x) \\ e_L(x) \end{pmatrix}$$

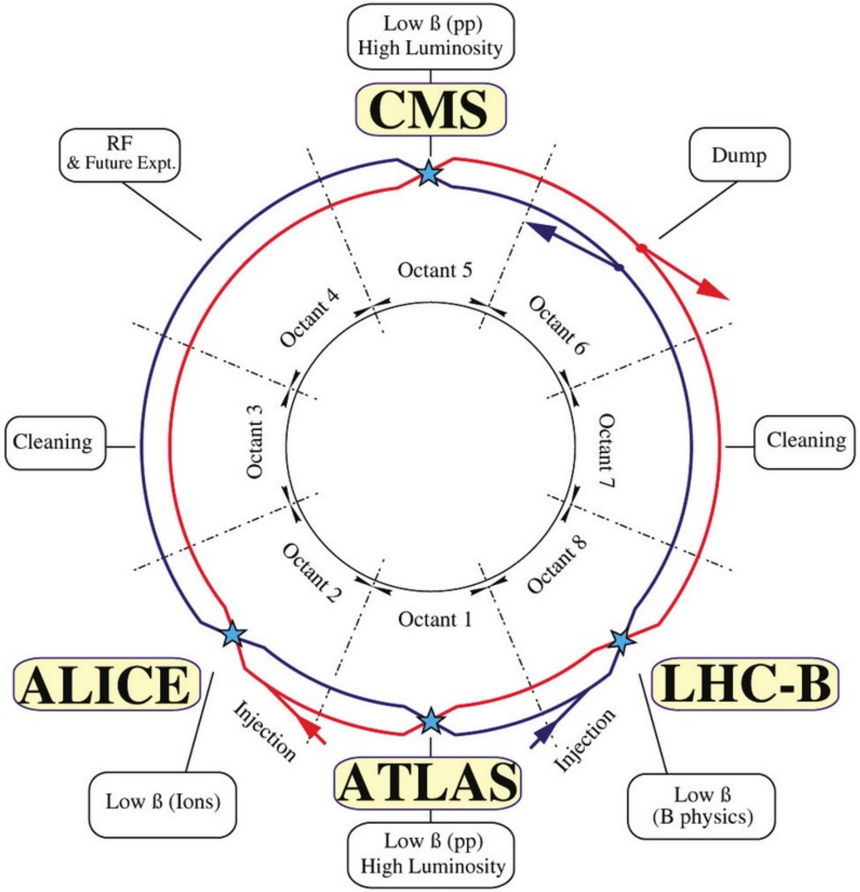
- the neutrino and the left-handed electron are put into an SU(2) doublet which forms a two dimensional representation of SU(2) weak isospin

$$R(x) = e_R(x)$$

- the right chiral component of the electron is taken as a weak iso-singlet, in the trivial singlet representation of SU(2)

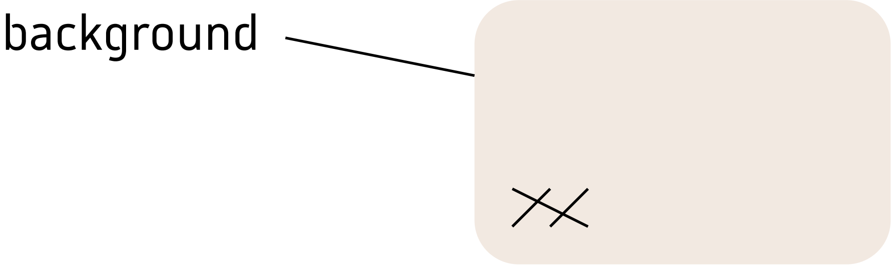
It does not feel the weak interaction

LHC

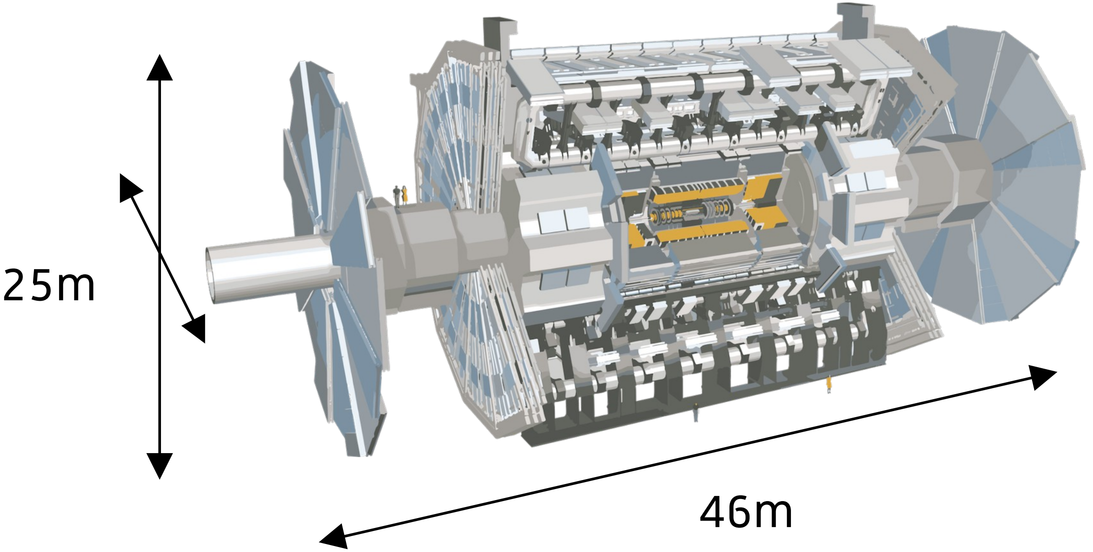


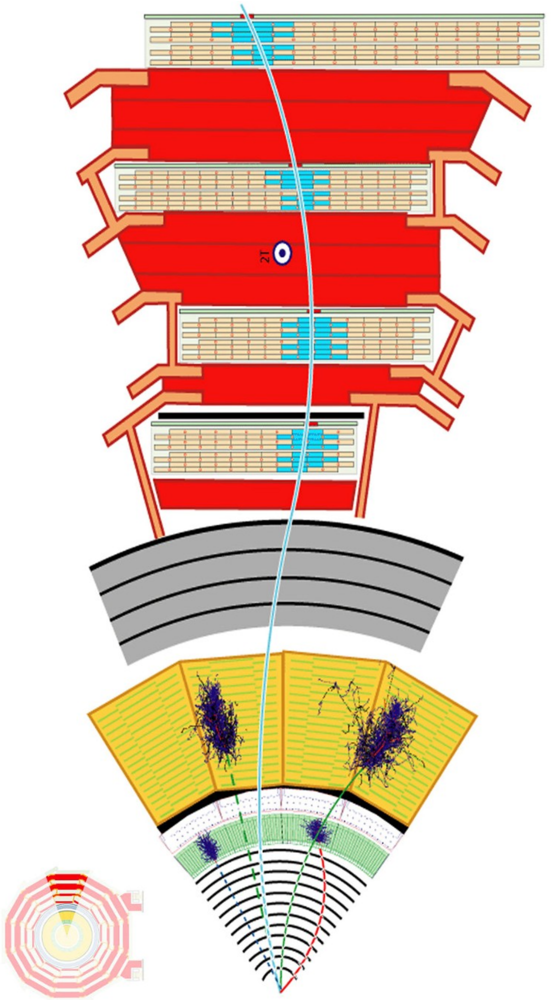
- 27 km
- 1650 magnets
- energy in the COM : 14 TeV

In particle physics, we only have information about the incoming particles and the products after the events, so we need to reconstruct everything



LHC



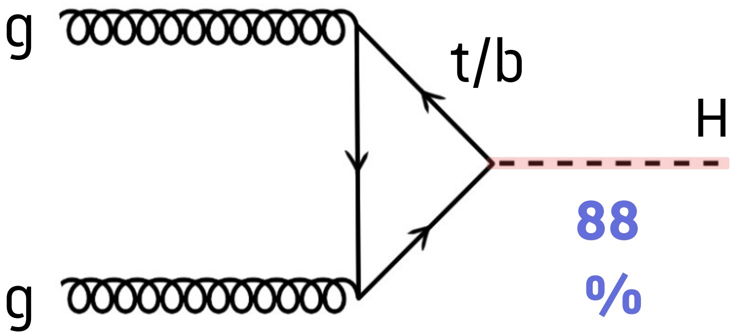


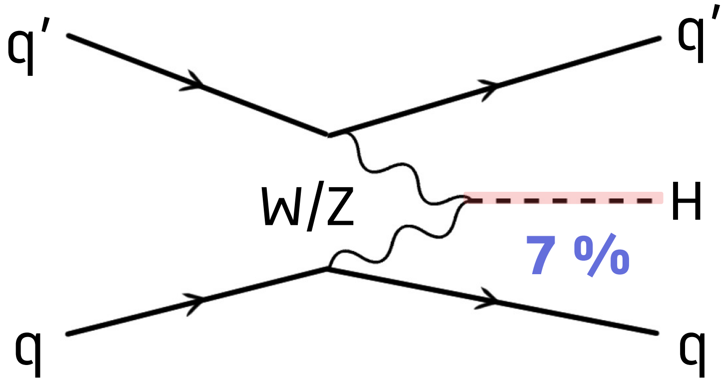
Important features for a particles detector :

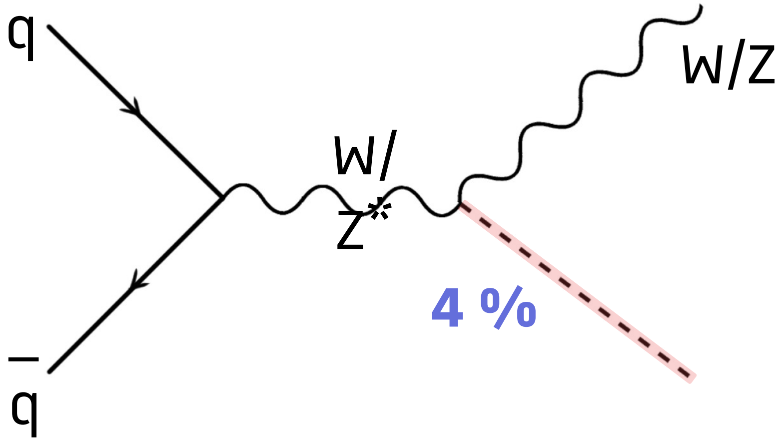
- calorimeters
- trackers

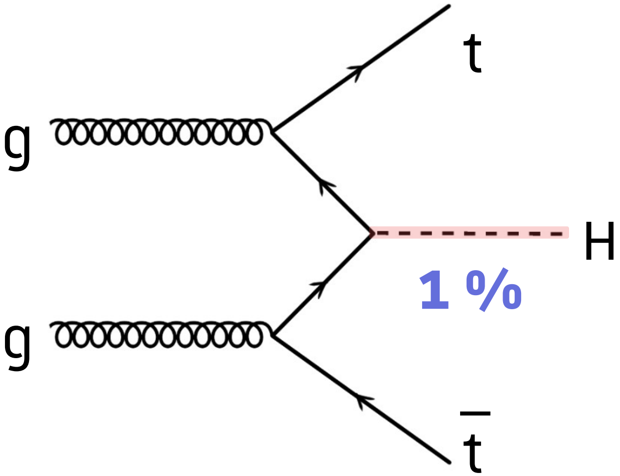
→ optimized for each type of particle

Production modes

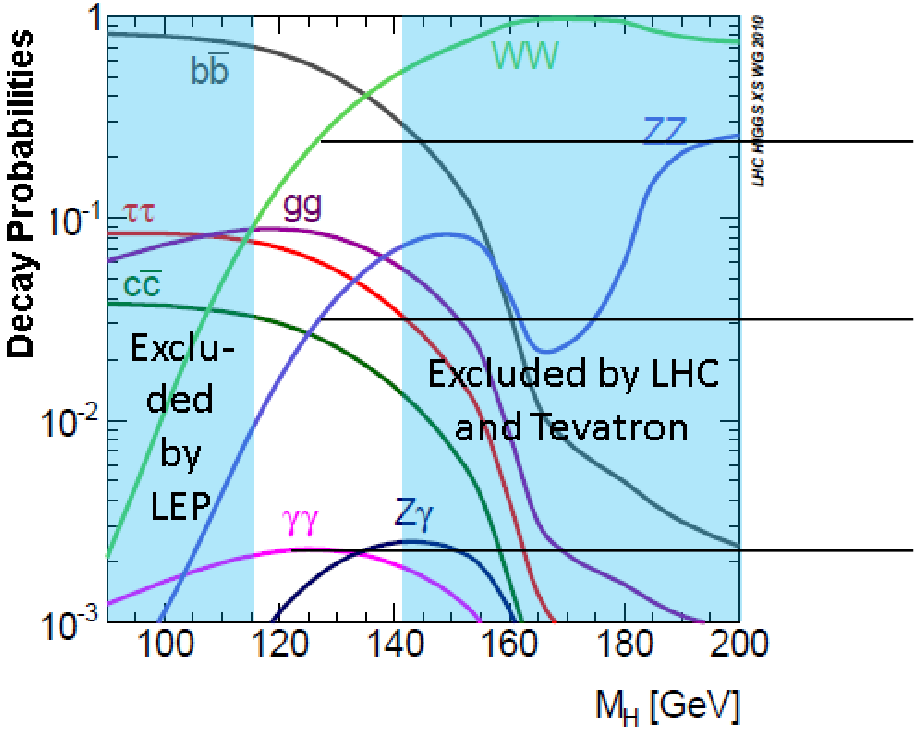








Decay modes

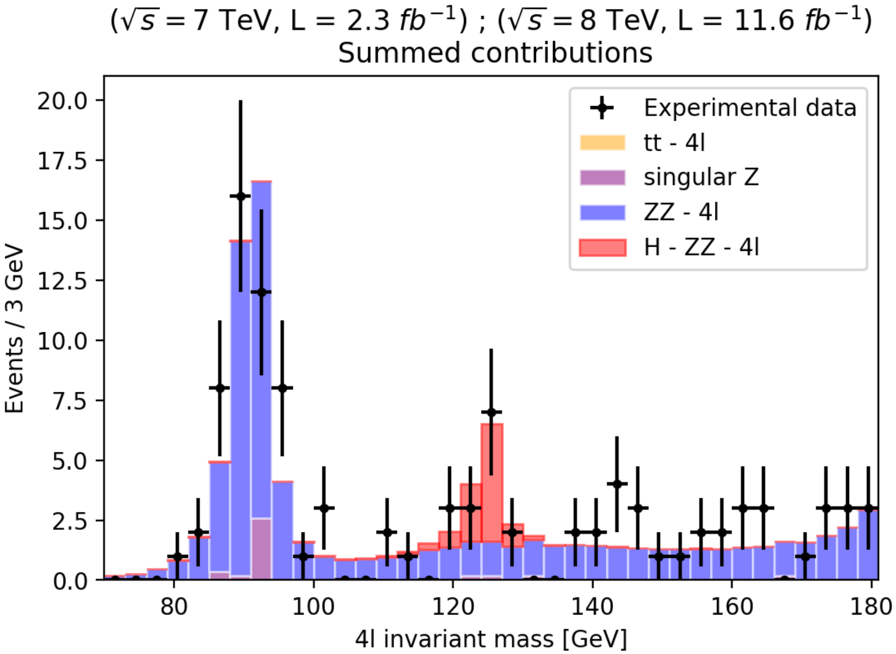


- $H \rightarrow WW^* \rightarrow e\,\nu\,\mu\,\nu$
- $H \rightarrow ZZ^* \rightarrow$ 4 leptons
- $H \rightarrow \gamma\gamma$

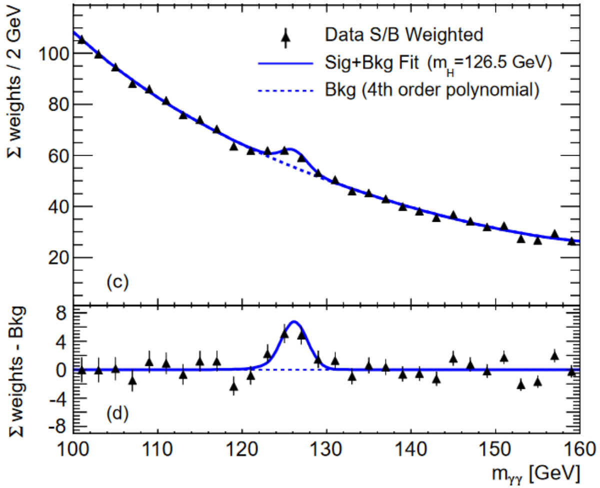
these are the only channels explored

The decay channel depends on the mass of the Higgs boson

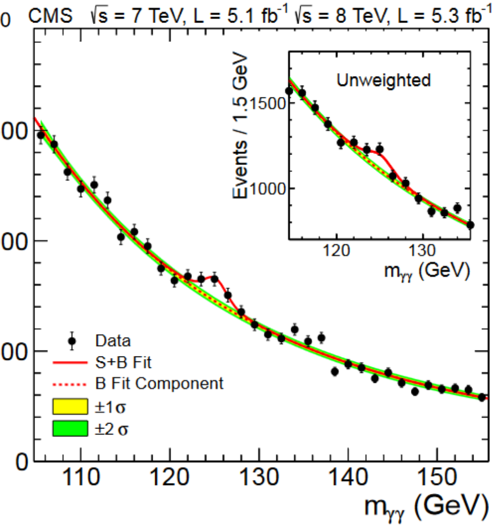
Decay modes



Number of events as a function of the invariant mass of the 4 leptons (ATLAS collaboration)



Number of events as a function of the invariant mass of the photons



Problems

The Higgs mechanism is a powerfull answer to the problem of mass generation in a gauge theory, and at a small cost (a single complex scalar field), but it brings some problems :

- neutrinos : the Standard Model says they are massless, **they cannot be** else they wouldn't oscillate, and it is **IMPOSSIBLE** to generate their mass this way
- hierarchy : the contributions to the squared mass of the Higgs boson are huge, why is it so light (125GeV) ?
- naturalness : where does it come from ? Why does it have a non-vanishing vev ?

NO ANSWER FOR NOW