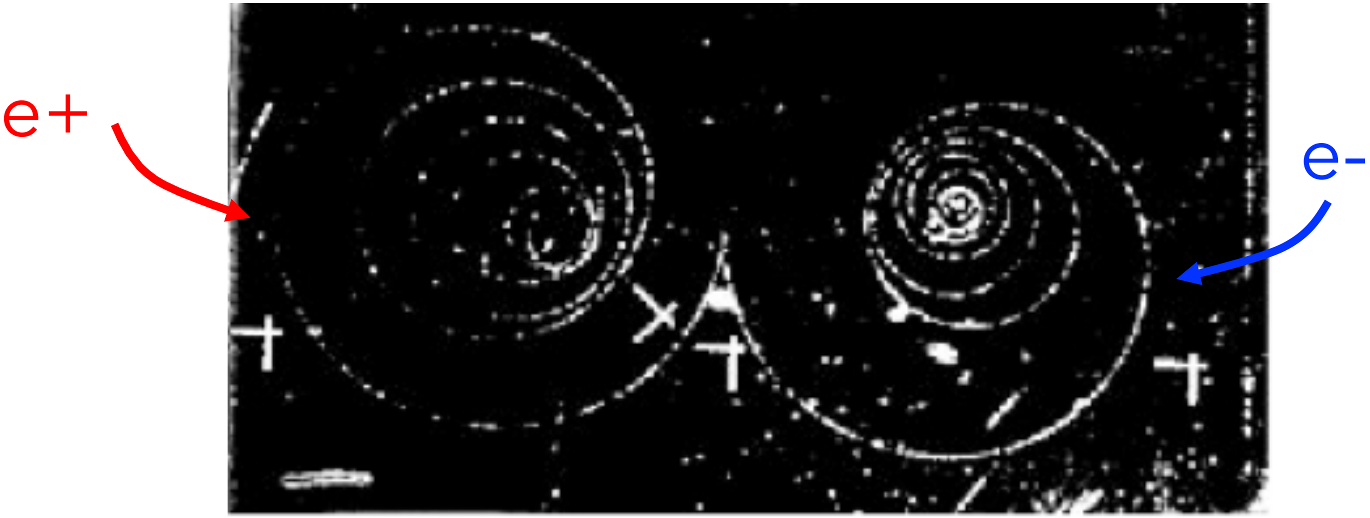
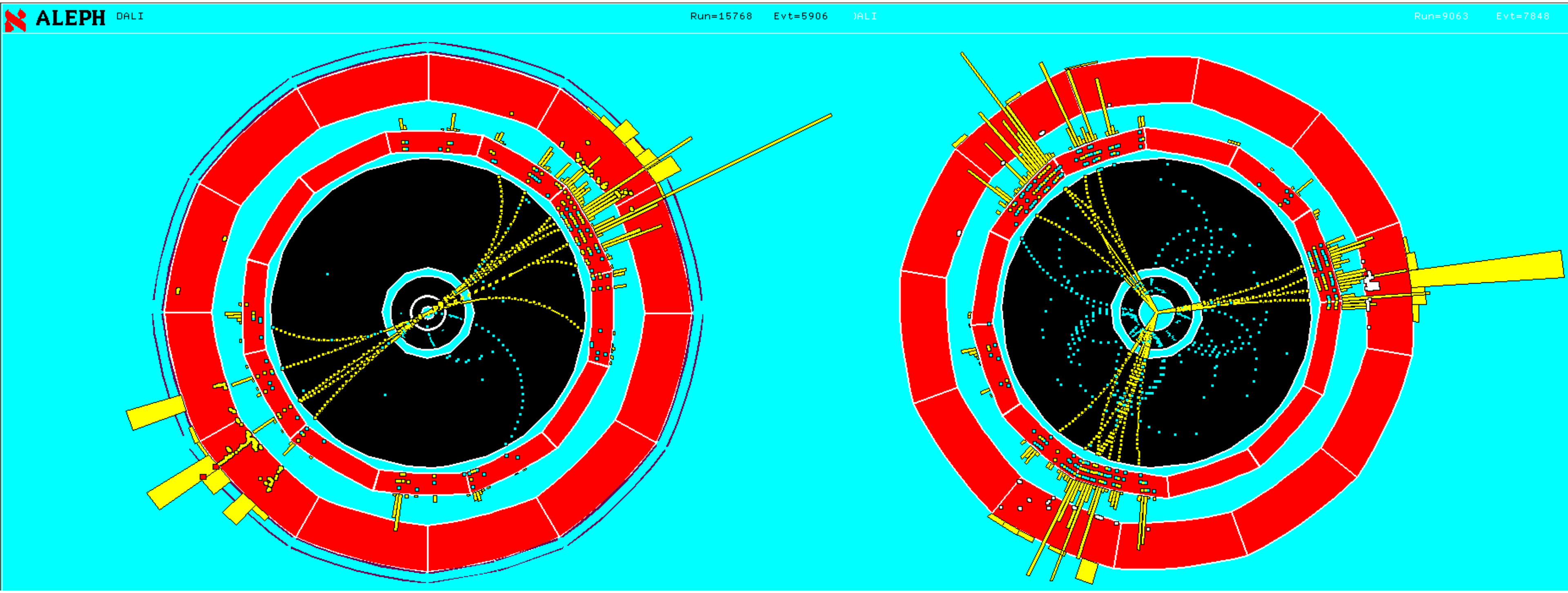
Standard Model

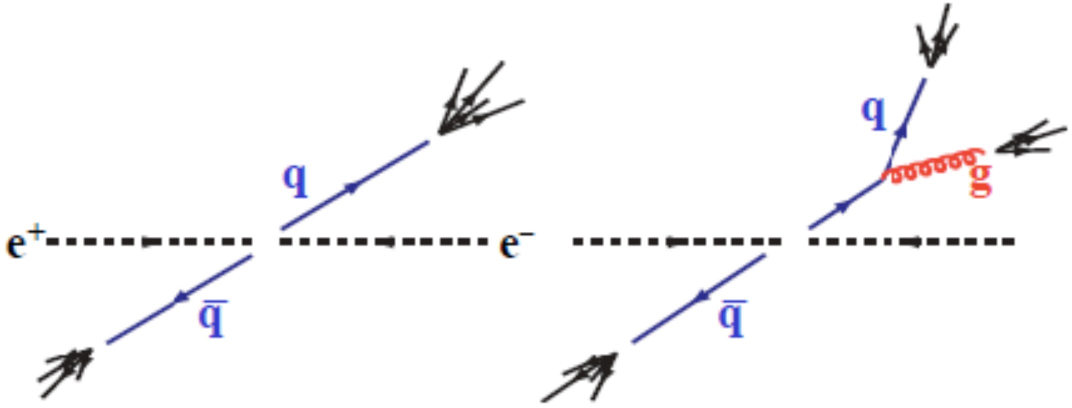
Can we see the particles vectors of the interactions ?

The photon ?



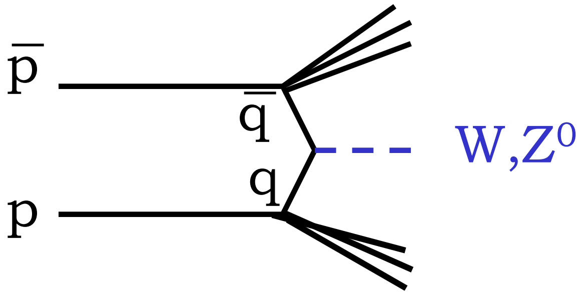
Can we see gluons ?





$$R_{3/2} = \frac{\sigma_{3\ \mathrm{jets}}}{\sigma_{2\ \mathrm{jets}}} \sim \alpha_s$$

Can we see W and Z^0 ?



$u\bar{d} \to W^+$

$u\bar{u}, d\bar{d} \to Z^0$

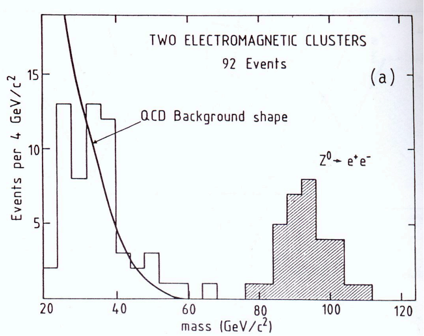
$W^+ \to \mu^+ \nu_\mu$

Missing in the detecctor

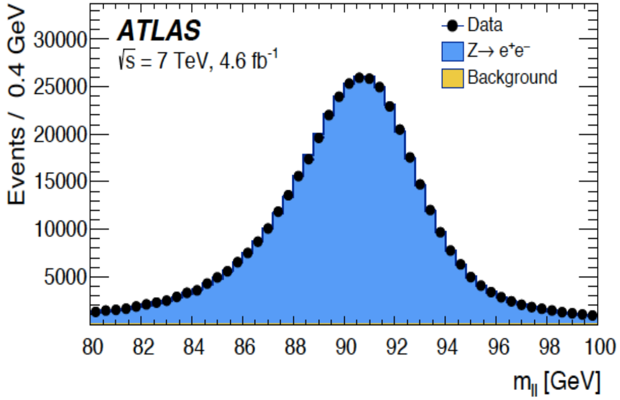
$$m_T = \sqrt{2 p_T^{\ell} p_T^{\text{miss}} (1 - \cos\Delta\phi)},$$

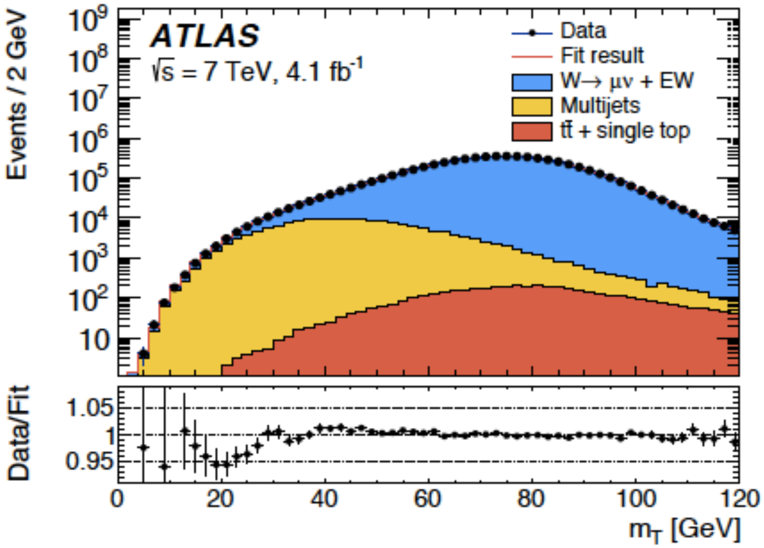
angle between the lepton and the missing E direction

UA1 (1983) : $Z^0 \to e^+e^-$

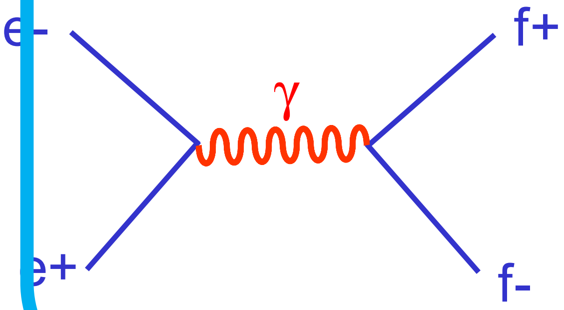


ATLAS (2017) : $Z^0 \to e^+e^-$

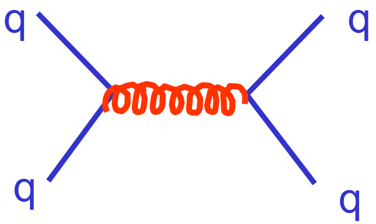




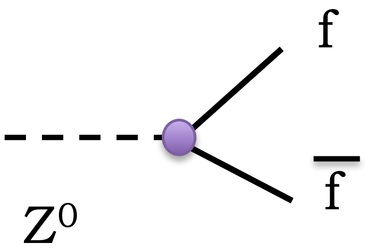
QED

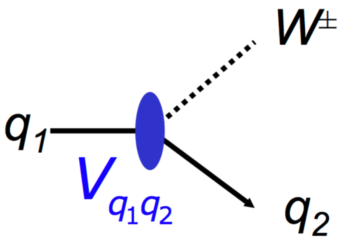


QCD
Strong interaction



Weak interaction





continuous symmetries

Continuous symmetry : additive quantum number (conserved)

- space-time symmetry (translation, rotation)

For a unitary transformation T_α one can write $T_\alpha = \exp(-i\alpha Q)$
Q is called the transformation's generator

# of generators = # of parameters in the transformation (eg : 3 generators for the rotation)
The momentum operators are the generators of the translation

- internal symmetry (gauge symmetry : EM) : if global : quantum number conservation (eg baryonic one) ; if local : « appearance » of a vector field (the photon) see later…

Electric charge

- Additive quantum number

Additive quantum number : is a quantity which takes discrete values and the value for a system is equal to the sum of the values of the components of the system

- Analogy with translation

$$S(\alpha) = e^{-i\alpha/\hbar\, Q}$$

Symmetry operator associates to electric charge

Observable : electric charge

- If $S(\alpha)$ commute with H : conservation of electric charge
- In a reaction $\{q_i; i=1\ldots n\} \rightarrow \{q_f; f=1\ldots m\}$ on aura $\sum_{i=1}^{n} q_i = \sum_{f=1}^{m} q_f$
- Since all the physical states have a determined charge, the effect of these operators will be to multiply all the wave function by a phase factor

$e^{-i\alpha q/\hbar}$ q Is the Electric charge of the system

Transformation of phase or global gauge transformation

Same other additive quantum numbers are (baryonics, leptonic…). Those are also called internal symmetries

.. Local gauge transformation

- $e^{-i\alpha q/\hbar}$: global gauge transformation →do not modify the Schrödinger eq

- $e^{-iq/\hbar\alpha(\vec{x},t)}$ local gauge transformation if $\psi(\vec{x},t)$ satisfy Schrödinger eq

$$\boxed{\psi'(\vec{x},t) = e^{-iq/\hbar\alpha(\vec{x},t)}\psi(\vec{x},t) \qquad \text{does not satisfy it !}}$$

- For the charge particles the solution is the following : in presence of an electromagnetic field the Schrödinger eq. is modified such that

$$\frac{1}{2m}\left(-i\nabla + q\vec{A}\right)^2 \psi = \left(i\frac{\partial}{\partial t} + eV\right)\psi \qquad (*)$$

If we define

$$\begin{aligned}
\psi(\vec{x},t) &\rightarrow \psi'(\vec{x},t) = e^{-iq/\hbar\alpha(\vec{x},t)}\psi(\vec{x},t) \\
A &\rightarrow A' \quad = A + \nabla\alpha \\
V &\rightarrow V' \quad = V - \frac{\partial\alpha}{\partial t}
\end{aligned}$$

The eq (*) does not change if

$$\left(\psi, \vec{A}, V\right) \rightarrow \left(\psi', \vec{A}', V'\right)$$

Symmetry group→ interaction (ex : local gauge invariance → γ)

$$\boxed{e^{-iq/\hbar\alpha(\vec{x},t)}} \Rightarrow (\vec{A}, V)$$ of the « classical » electromagnetism

We could state… that if we impose a local gauge invariance we have to make appearing a field. $(\vec{A}, V)$

If we quantize this field, it is seen as a particle γ

Quantum
Field
Theory

The charge is the quantum number conserved by this symmetry transformation
(the value of q has to be determined : free parameter of theory)

U(1)

1 boson / 1 quantum number : the charge

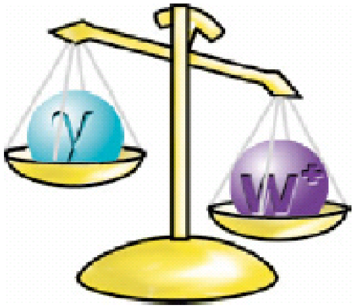
The existence of a a local invariance $e^{-iq/\hbar\alpha(\vec{x},t)}$ implies the existence of an electromagnetic interaction (field V, A) proportional to the charge q (the value of q should be determined since is a free parameter of theory !)

electroweak unification

Symmetry	**Vector bosons**	**Charges**
U(1) electromagnetism	γ	e
SU(2)	3 bosons	g, g'
$U(1)_Y \otimes SU(2)_L$	γ, W^+, W^-, Z^0	e, g $g \sin\theta_W = e$

Maximal parity violation in Weak interaction

Problem with the mass scales



→ m_γ=0

→ but also m_W=0 and m_Z=0

→ All the particles are massless … !

Experimentally : m_γ=0 (to a very good extend … 10^{-17} …)

m_W = 80 GeV

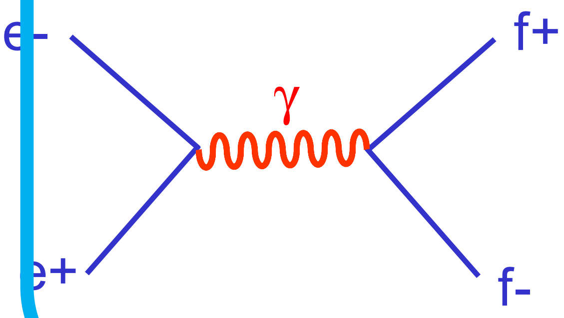
m_Z = 91 GeV

Experimentally : m_e~0.5 MeV

…

m_{top} ~ 170 GeV

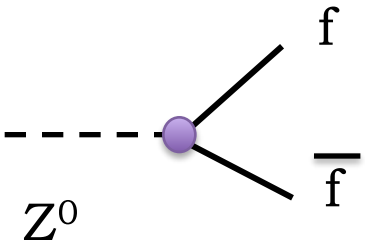
QED

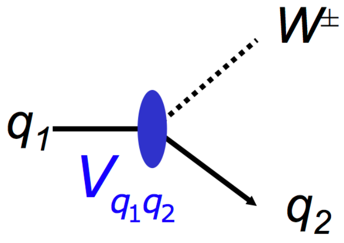


QCD
Strong interaction

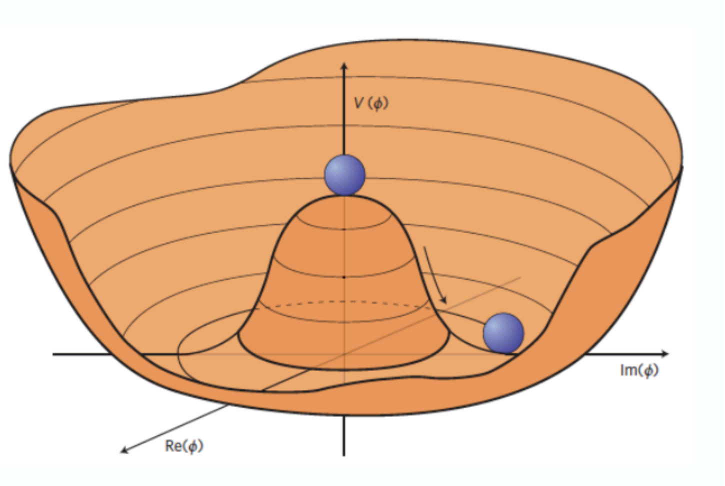
+ Higgs mechanism !

interaction





The Higgs mechanism and the Higgs boson



- Complex doublet scalar field : the Higgs field : 3 components absorbed : masses to the W and Z.

- One remaining component : the Higgs boson

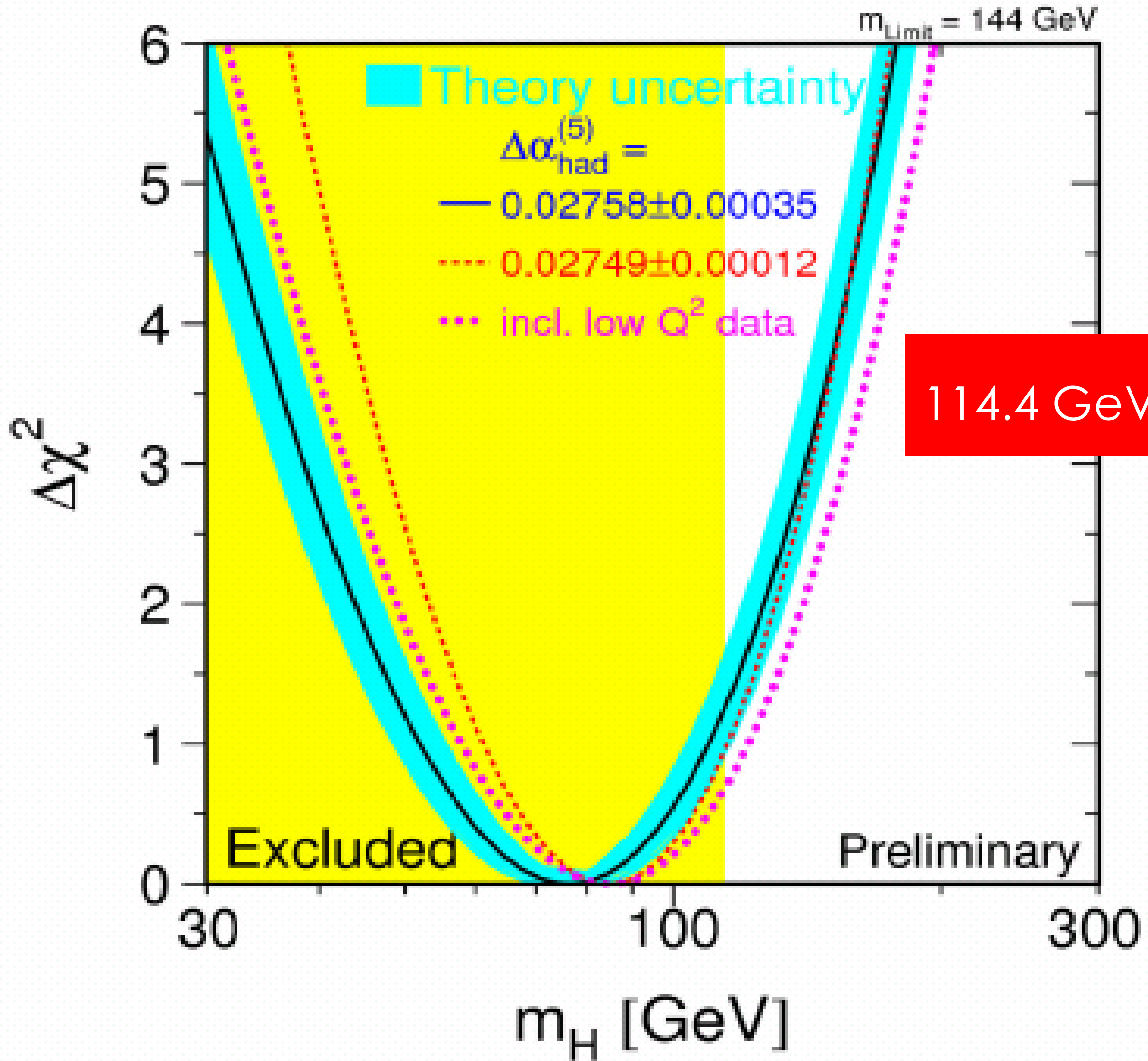
- Higgs field : it is the interaction of the elementary particles with the Higgs field which gives them masses

Its properties are predicted (spin, couplings proportionnal to masses)

But not its mass itself !

Search for it during many years

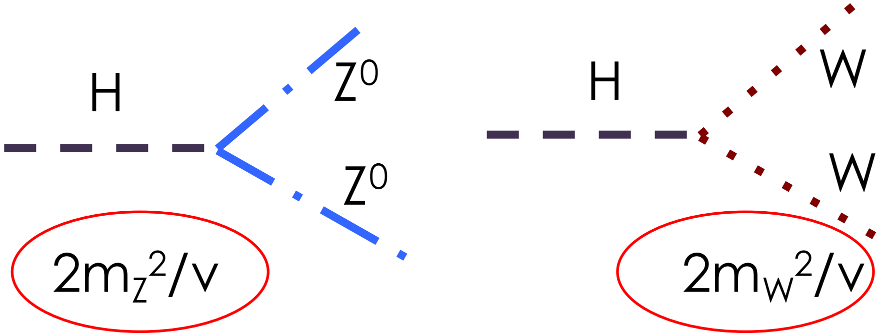
At many colliders … a lot at LEP from √s = 90 GeV …. to 200 GeV



114.4 GeV < M_{Higgs}< 182 GeV at 95%CL

… and TeVatron collider
√s = 1.8 TeV ($p\bar{p}$)

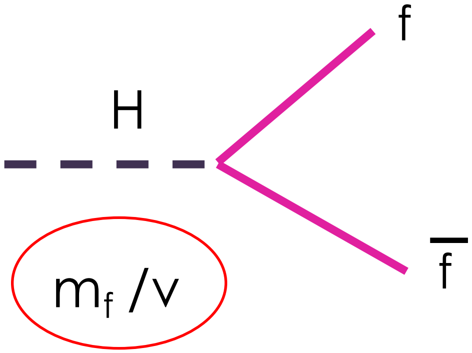
Higgs coupling to the gauge bosons



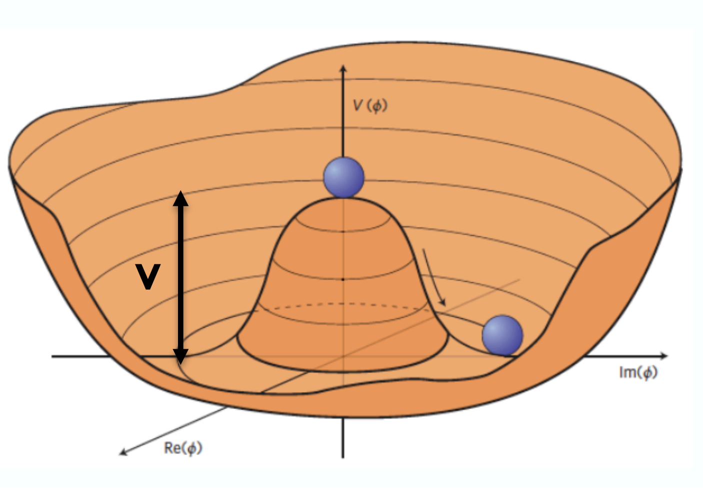
$2m_Z^2/v$

$2m_W^2/v$

Higgs coupling to fermions:



m_f/v



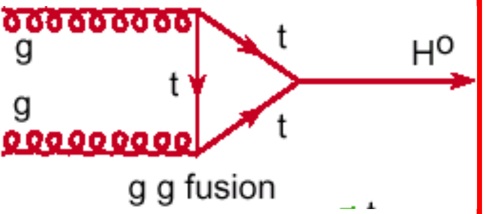
These couplings determine the production and decay probabilities (for a given Higgs mass)

⇒ experimental tests

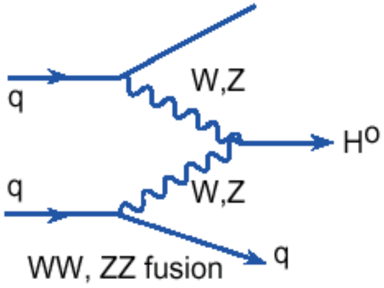
Production (at the LHC)

In the proton : light quarks and gluons → small/no direct coupling to H
→ First produce heavy particles !

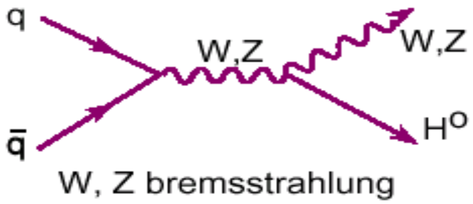
Gluon fusion

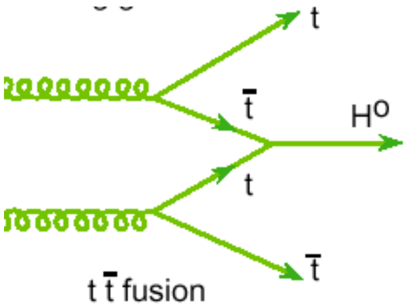


Vector boson fusion



Associated production (W/Z, tt)





86 %

7 %

5 %

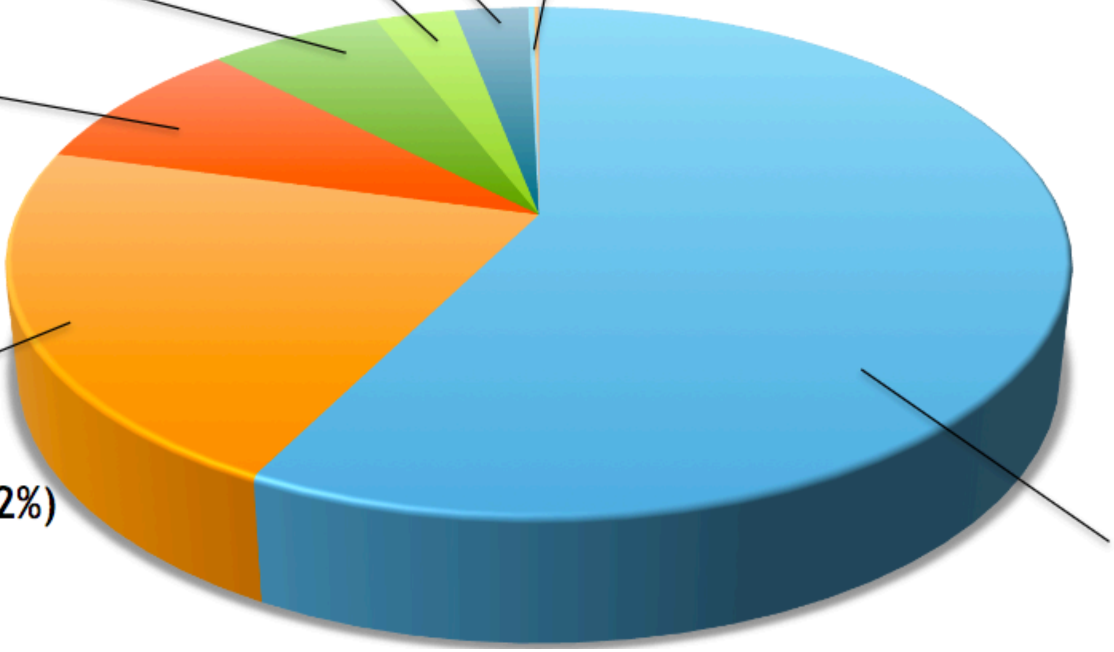
0.6 %

For a 125 GeV H boson

Decay (~~at the LHC~~)

Observed decay modes:
γγ, ZZ, WW, ττ

Missing bb,cc, μμ, Zγ



H→ZZ*→4l
Rare (3%)
S/B>>1
ΔM/M ~ 1-2%

H→ττ
Abundant (6%)
S/B<1
ΔM/M ~ 10-20%

H→cc (2.9%)

H→γγ
Very rare (0.2%)
S/B<1
ΔM/M ~ 1-2%

H→gg (8.5%)

H→WW*→2l2ν
Very Abundant (22%)
S/B<1
ΔM/M ~ 30%

H→bb
Abundant (58%)
S/B<<1
ΔM/M ~ 10-20%

CERN/LHCC 92-3
LHCC/I 1
1 October 1992

LABORATOIRE EUROPÉEN POUR LA PHYSIQUE DES PARTICULES
CERN EUROPEAN LABORATORY FOR PARTICLE PHYSICS

CMS

The Compact Muon Solenoid

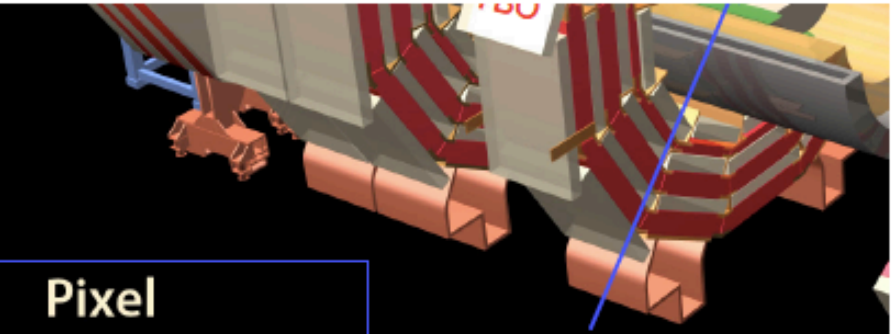
CMS

ating
stals

tilator/brass
leaved

Muon End-Caps

Cathode Strip Ch. (**CSC**)
Resistive Plate Ch. (**RPC**)

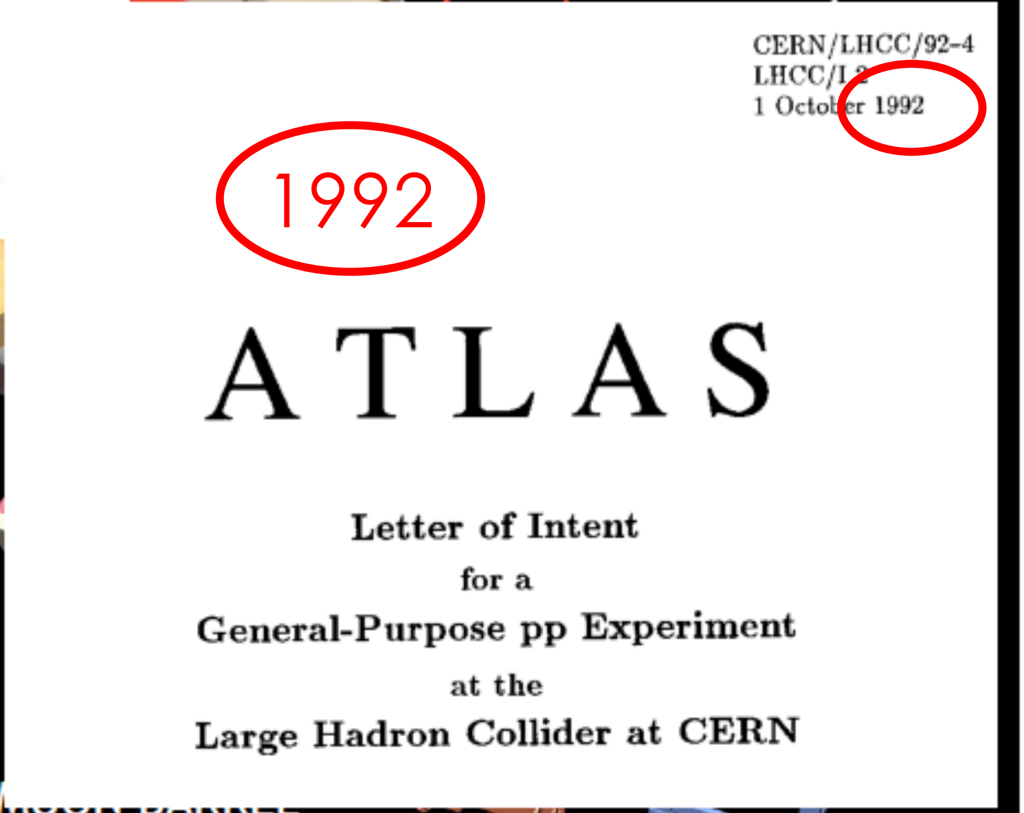


- Pixel
- Tracker
- ECAL
- HCAL
- Muons
- Solenoid coil

Pixels & Tracker

- Pixels (100x150 μm²) ~ 1 m² 66M channels
- Silicon Microstrips ~ 210 m² 9.6M channels

MUON BARREL
Drift Tubes (DT) and
Resistive Plate Chambers (RPC)



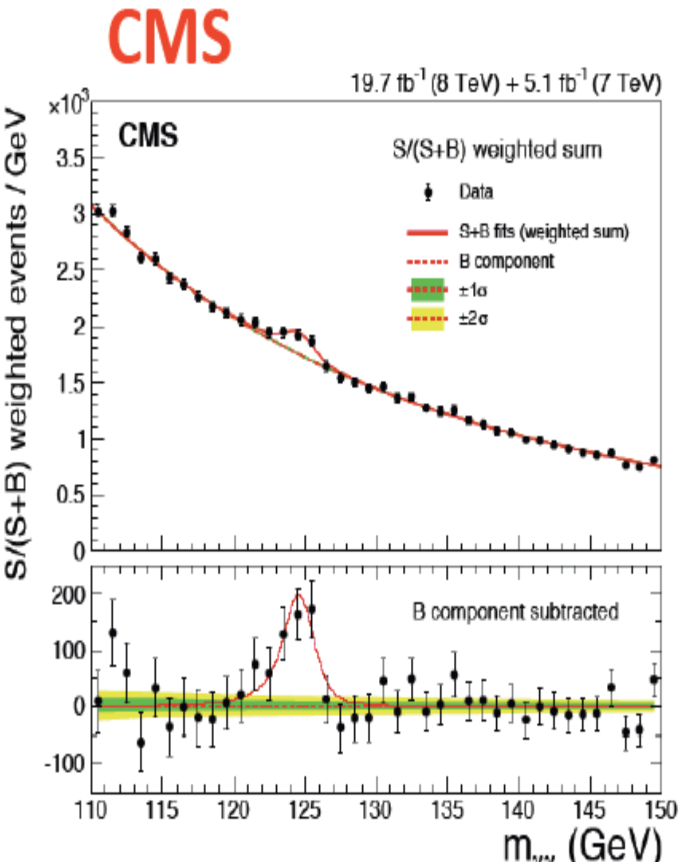
CERN/LHCC/92-4
LHCC/I 2
1 October 1992

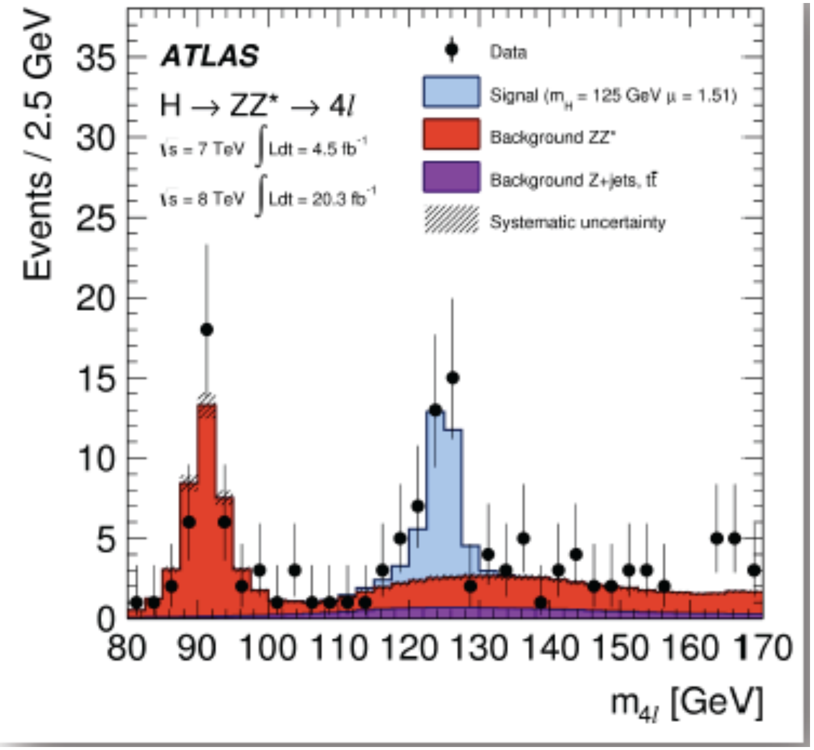
1992

ATLAS

Letter of Intent
for a
General-Purpose pp Experiment
at the
Large Hadron Collider at CERN

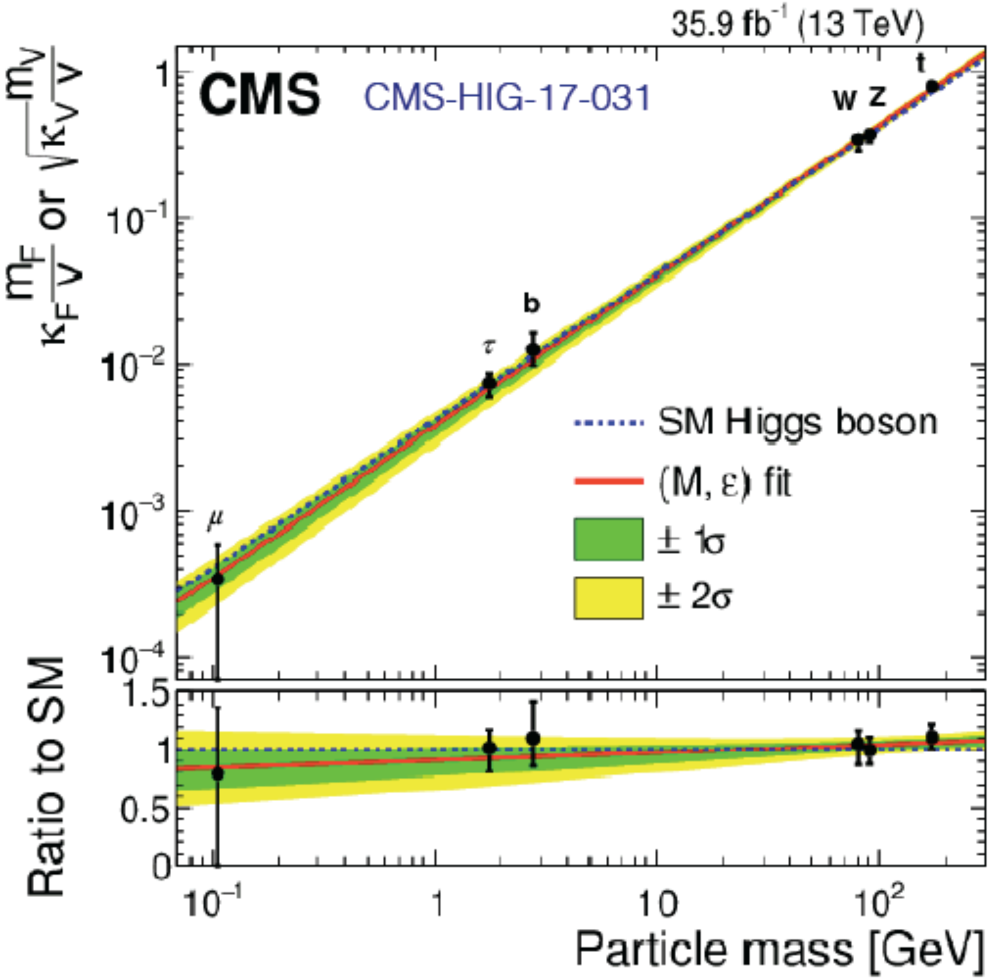
2012 : discovery of the Higgs boson by ATLAS and CMS

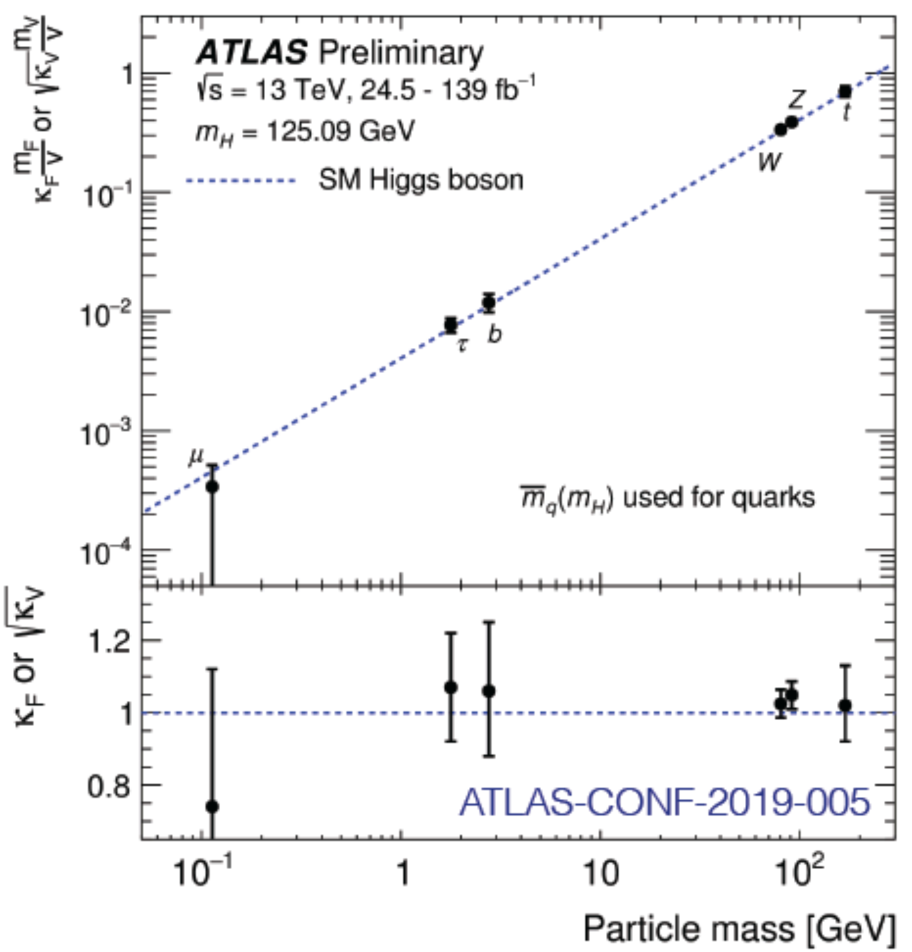




2019 M = 125.10 ± 0.14 GeV PDG, precision 0.1 % !

SM : couplings proportionnal to the masses of the particles



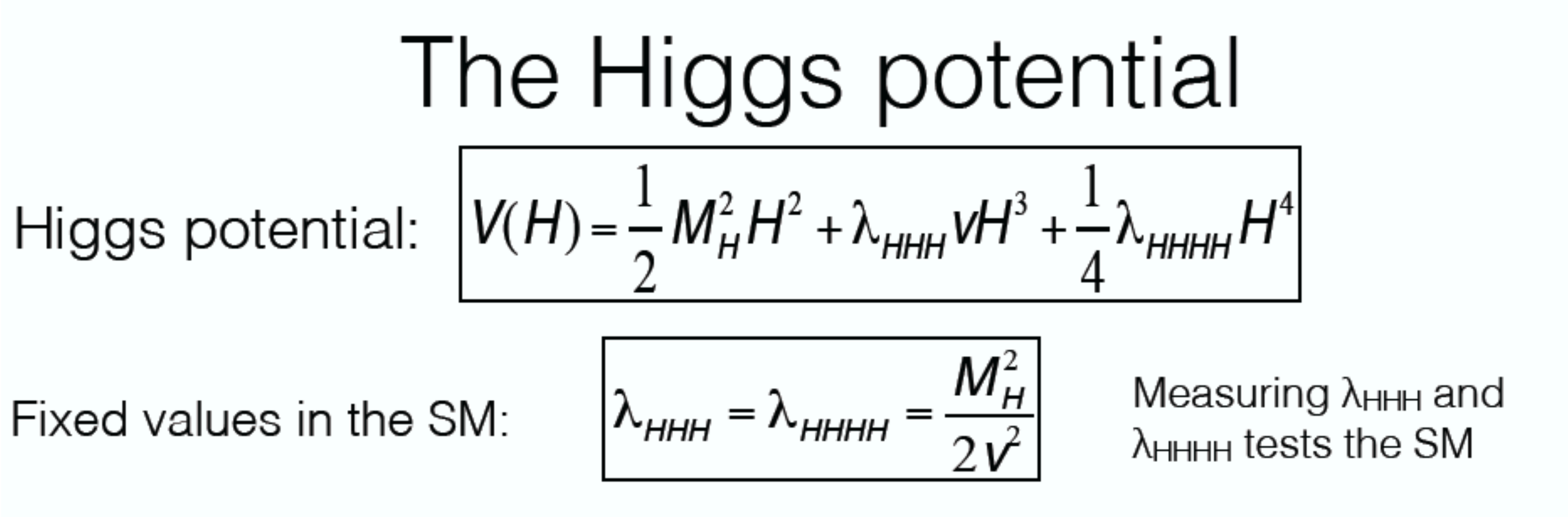


No big surprise (yet)

LeptonPhoton 2019 (E. Vryonidou)

Next important step :

Higgs self coupling



The Higgs potential

Higgs potential: $$\boxed{V(H)=\frac{1}{2}M_H^2H^2+\lambda_{HHH}vH^3+\frac{1}{4}\lambda_{HHHH}H^4}$$

Fixed values in the SM: $$\boxed{\lambda_{HHH}=\lambda_{HHHH}=\frac{M_H^2}{2v^2}}$$

Measuring λ_{HHH} and λ_{HHHH} tests the SM

Standard Model in summary

- Stron interaction
- Unification of the weak and electromagnetic interactions
- Discovery of the Higgs particle validates the Higgs mechanism hypothesis
- Still quite a number of free parameters (19), mainly in the fermionic sector
- Amazing agreement between theory and experiments in thousands of observables !

Overall summary

- Main discoveries:
  - 12 elementary fermion matter particles (+ antimatter)
  - Boson vectors of the three interactions
  - Higgs particle
  - Fundamental role played by symmetries (P, gauge symmetries)
  - The Standard Model works amazingly well !

- Open questions :
  - Why three families ?
  - Why so different masses for the fermions ?
  - No particle in the SM to explain the Dark Matter observation
  - The amount of CP violation in the SM does not explain the observed matter/antimatter asymmetry of the Universe

This is not the end of the story →

Q1 : unification ? more symmetries ?

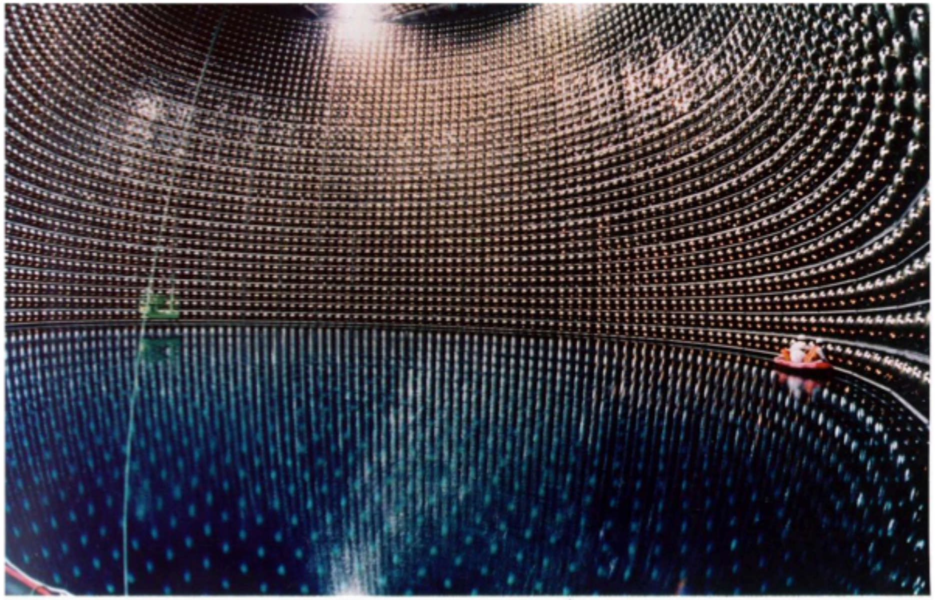
An example : relate the charge of the quarks to the electron charge and the number of colors

Q(d)=1/3 Q(e)

$$\begin{pmatrix}\begin{pmatrix}\nu_e\\ e^-\end{pmatrix}\\ \overline{d_r}\\ \overline{d_g}\\ \overline{d_b}\end{pmatrix}_L$$

But:

- several additional particles (unobserved)
- instability of the proton : strong exp. constraints



Detecteur SuperKamiokande
50000 tons of water
3 .10^{34} nuclei(protons and neutrons)

$$p \rightarrow e^+ \pi^0$$
$$n \rightarrow e^+ \pi^-$$

lifetime> 10^{33} ans

Unification > 10^{15} GeV

(larger than the life of the Universe ($1.4\ 10^{10}$ ans)

Supersymetry : symmetry between fermions and bosons

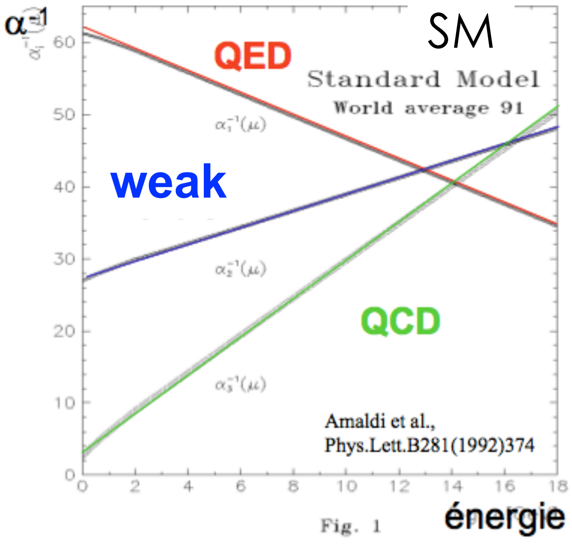
Fermions **bosons**

$$\begin{pmatrix} u \\ d \end{pmatrix}_L \begin{pmatrix} \nu_e \\ e \end{pmatrix}_L \overset{\text{SUSY}}{\longleftrightarrow} \begin{pmatrix} \tilde{u} \\ \tilde{d} \end{pmatrix}_L \begin{pmatrix} \tilde{\nu}_e \\ \tilde{e} \end{pmatrix}_L$$

squarks,
sleptons

Neutralinos,
charginos,
gluinos

$$\tilde{W}_\mu \longleftrightarrow W_\mu$$



Amaldi et al.,
Phys.Lett.B281(1992)374

Fig. 1

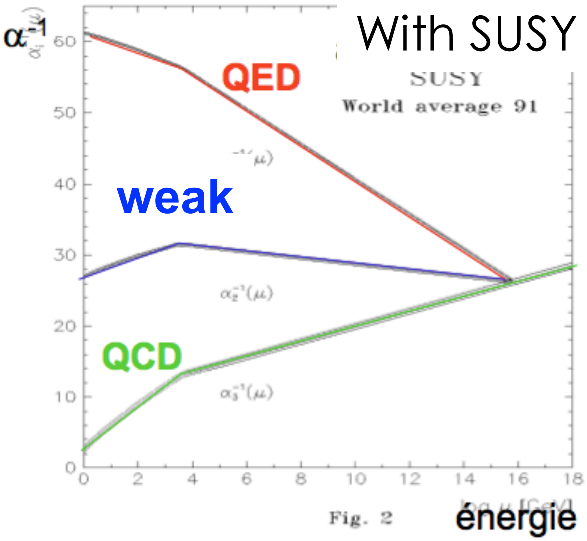
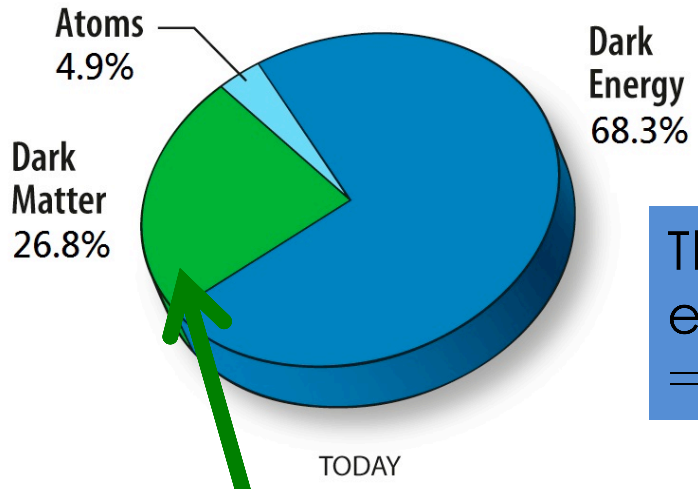


Fig. 2

But : no particles observed (yet)

Q2 : do we understand what the Universe is made of ?

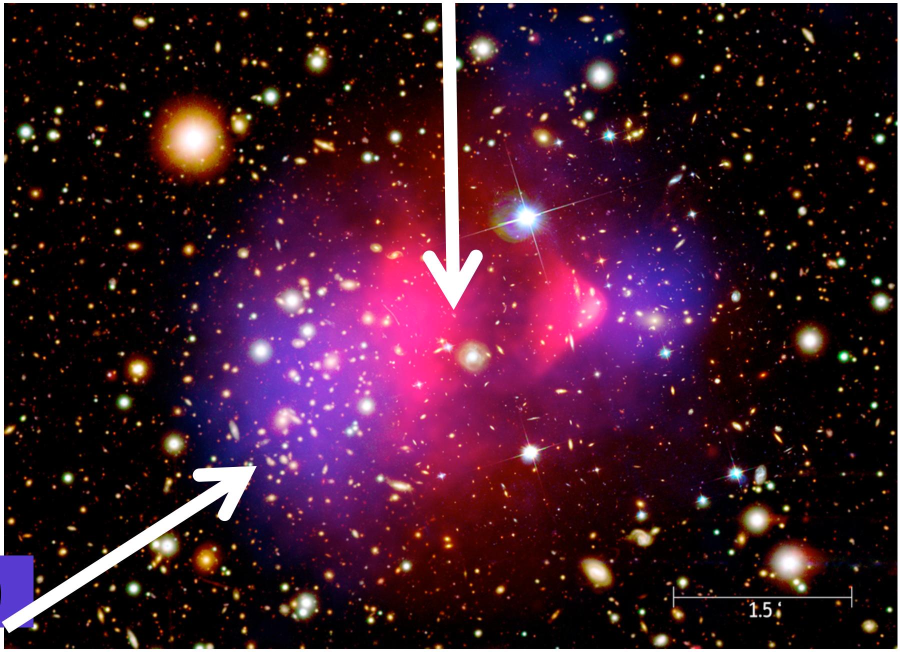


The expansion of the Universe is faster than expected (Big Bang + general relativiy) ⇒somthing else in the game : “Dark Energy”

Not ordinary matter

Slowed down in the collision

Baryonic matter (X-rays)



Only sensitive to gravitation

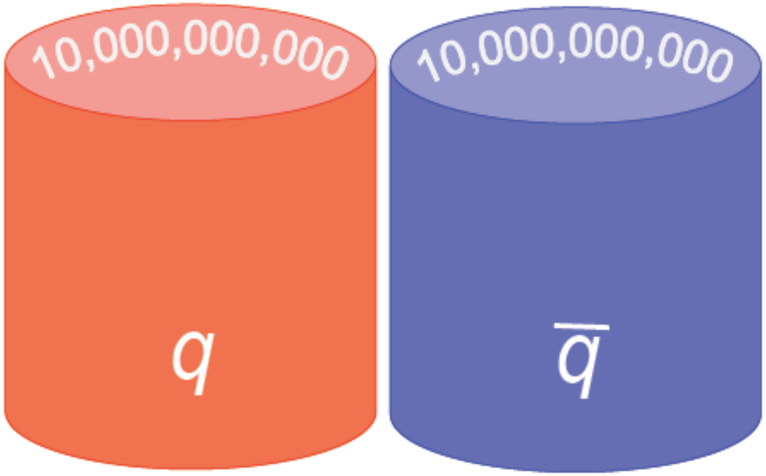
Dark Matter (weak lensing)

Bullet cluster

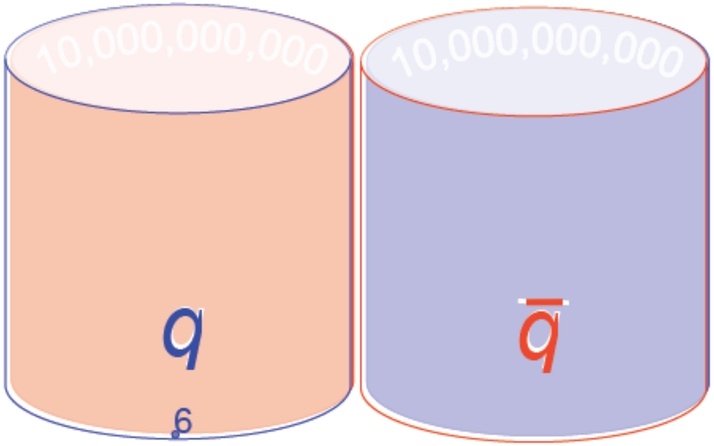
Q3 : where is the anti-matter?

No evidence for the original, “primordial” cosmic antimatter:

- Absence of anti-nuclei amongst cosmic rays in our galaxy
- Absence of intense γ−ray emission due to annihilation of distant galaxies in collision with antimatter



Early universe



Current universe

Along the way matter was prefered

Equal amounts of matter and anti-matter

A bit of matter
a lot of photons

$$N_{\text{Baryons}}/N_{\text{Photons}} \sim 6\ 10^{-10}$$

Sakharov conditions :

- Baryon number B violation.
- C-symmetry and CP-symmetry violation.
- Interactions out of thermal equilibrium.

THANK YOU FOR YOUR ATTENTION !