Introduction to Particle Physics

Swedish Teacher program 2022

Lecture II

Lecture II
Introduction to the SM

- The Standard Model
- The Higgs mechanism in the SM (hints)
- The detection of the Higgs boson

The most part of figures and formulas are from A. Bettini, Introduction to elementary particle physics. II edition Cambridge U.P. 2016

SM mathematical features

- SM is based on:
  - Gauge Quantum Field Theory (QFT) that incorporates:
    - The Special Relativity (already introduced);
    - The Quantum Mechanics (already introduced);
    - Gauge invariance of the interactions (to be introduced!)
- Rather complex mathematical framework following the Quantum Electro Dynamics (QED) that successfully describe the electromagnetic interaction as gauge QFT !

Gauge invariance in the EM field

1. There are forces (Coulomb) between stationary charges and additional forces (magnetic) between moving charges;

2. Electromagnetic radiation is emitted by accelerating charges and can be absorbed or scattered by bodies with electrical structure

3. Classical EM defines the fields **E** and **B** which obey Maxwell's equations (1830, Unification of electrostatic and magnetism)

$$
\begin{aligned}
Div\mathbf{E} &= \frac{\rho}{\varepsilon_0} \\
Div\mathbf{B} &= 0 \\
Curl\mathbf{E} &= -\frac{\partial \mathbf{B}}{\partial t} \\
Curl\mathbf{B} &= \mu_0(\mathbf{j} + \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t})
\end{aligned}
\qquad (2.1)
$$

- But this formulation is not invariant under Lorentz transform (L.I.) of space-time coordinates.

Gauge invariance in the EM field

1st step:

1st and 4th Maxwell equations (**E**,**B**) implies the conservation of the charge:

$$\nabla \cdot \boldsymbol{J} - \frac{\partial \rho}{\partial t} = 0 \qquad (2.2)$$

To express the Maxwell equations in a LI form, it is convenient to define the vector potential ***A*** and the scalar potential φ, such:

$$\mathbf{B} = Curl\ \boldsymbol{A}$$

$$\mathbf{E} = -\ \mathrm{grad}\varphi - \frac{\partial \boldsymbol{A}}{\partial t} \qquad (2.3)$$

The properties of ***A*** are such that the four-vector (***A***, φ/c) transforms exactly as (**r**,ct) or the (**p**,E/c).

So, the reformulation of the Maxwell equations using ***A*** and φ become L.I.!

Gauge invariance in the EM. field

2nd step a)

In addition, the EM field shows a very important property, that of the gauge invariance. If **A** and φ are simultaneously changed in the following way:

$$\boldsymbol{A} \rightarrow \boldsymbol{A}' = \boldsymbol{A} + grad\chi; \ \ \varphi \rightarrow \varphi' = \varphi - \frac{\partial \chi}{\partial t} \qquad (2.4)$$

where χ is a scalar function of space and time $\chi = \chi(x, y, z, t)$ (called gauge function), the observable fields E and B are unchanged!

Gauge invariance in the EM. field

2nd step b)

In fact replacing (2.4) in (2.3) , there is no change in E and B.

$$\mathbf{B}' = curl\boldsymbol{A}' = curl(\boldsymbol{A} + grad\chi) = curl\boldsymbol{A} = \mathbf{B}$$

$$\mathbf{E}' = -\,grad\varphi' - \frac{\partial \boldsymbol{A}'}{\partial t} = -grad\left(\varphi - \frac{\partial \chi}{\partial t}\right) - \frac{\partial(\boldsymbol{A} + \boldsymbol{grad}\,\chi)}{\partial t} = -\,grad\varphi - \frac{\partial \boldsymbol{A}}{\partial t} = \mathbf{E}$$

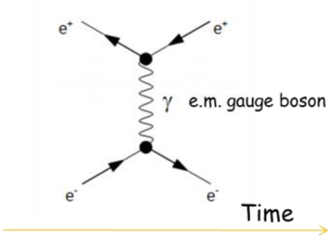
The (2.4) is called gauge transformation. The EM theory is said gauge invariant or the EM has the gauge symmetry property.

The theoretical motivations for charge conservation in the Relativistic Electrodynamics are extremely strong , since they are consequence of the gauge invariance of the theory;

Gauge invariance in QED

- The scattering amplitude in QED is given by the matrix element of the interaction Hamiltonian:

$$M_{fi} = \langle \psi_f | H_{QED} | \psi_i \rangle \text{ where } H_{QED} = H_{QED}(\boldsymbol{A}_{QM\ field}, \varphi_{QM\ field})$$



Electromagnetic interaction

Gauge invariance in QED

- The gauge invariance of the QED Lagrangian (replacing the Hamiltonian) is ensured if the wave function of the charged particles is transformed at the same time as the quantum potential field $\boldsymbol{A}_{QM\ field}, \varphi_{QM\ field}$(V. Fock 1929) .

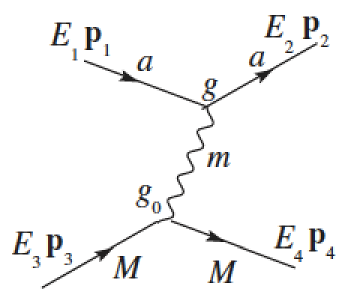
- For an electron: $\psi \Longrightarrow \psi' = e^{i\chi(\mathbf{r},t)}\,\psi$

- ψ is itself an operator of the field electrons that create and destroy the electron. The local gauge invariance of the Lagrangian implies the electric charge conservation,

- Warning: the invariance held if the gauge boson, the photon in this case, is massless, as it is !

Feynman diagrams for the QED

Quantum electrodynamics



Basic diagram for the elastic scattering of two particles.

The relevant quantity is now the four-momentum transfer. Its norm is

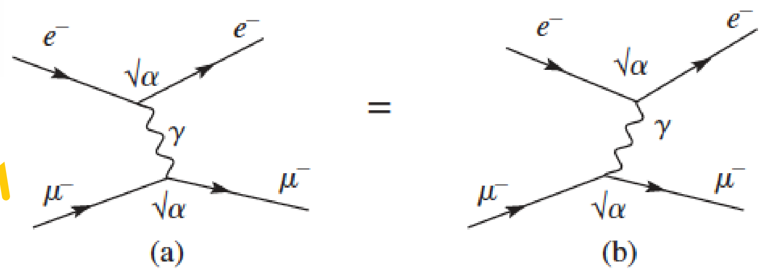
$$t \equiv (E_2 - E_1)^2 - (\mathbf{p}_2 - \mathbf{p}_1)^2 = (E_4 - E_3)^2 - (\mathbf{p}_4 - \mathbf{p}_3)^2$$

Scattering amplitude:

$$f(t) = \frac{g_0 g}{m^2 - t}$$

← Probability amplitude for the mediator

The probability of this process, cross section, is proportional to the $|1/m^2-t|^2$, the coupling constants, and to the phase space.

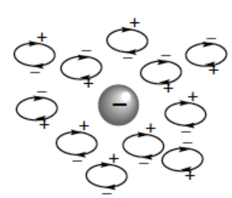


Feynman diagram for the electron–muon scattering.

$$\alpha = \frac{1}{4\pi\varepsilon_0}\frac{q_e^2}{\hbar c} \approx \frac{1}{137},$$

fine structure constant is the EM coupling constant

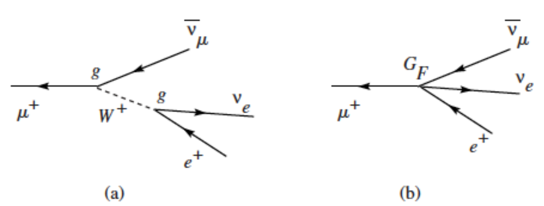
α is NOT constant! depends on the E because of the electric charge depends on E! Running constant



A charge in a vacuum.

Weak Interaction

- WI are responsible of the decays in the radioactivity;
- E. Fermi 1933 first theoretical description of B decay;
- Matter and anti-mater behave differently w.r.t WI!! Reason of matter/anti-matter asymmetry in the Universe ??



Muon beta decay.

$$\frac{G_F}{(\hbar c)^3} = \frac{\sqrt{2}}{8}\frac{g^2}{(M_W c^2)^2} \qquad \text{(SI)}$$

- WI would be a gauge QFT if the vector bosons mediating the interaction are assumed massless! WARNING: $W^\pm$, Z^0 are massive!!
- We need a mechanism providing mass to the $W^\pm$, Z^0 without destroying the gauge invariance! Higgs mechanism!

Some Feynman diagrams of the WI

7.1 Classification of weak interactions

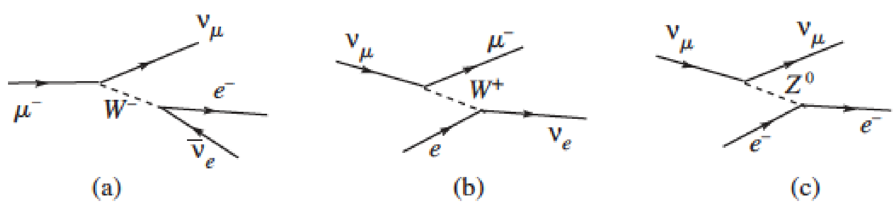


Fig. 7.1. Three leptonic processes.

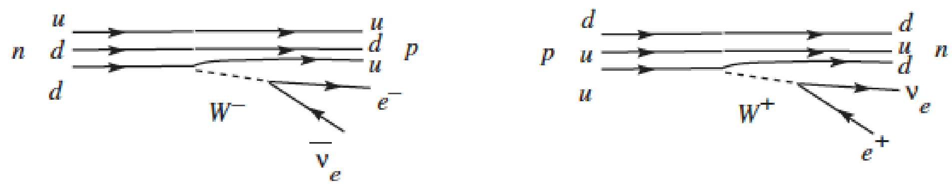


Fig. 7.2. Beta decay of the nucleons.

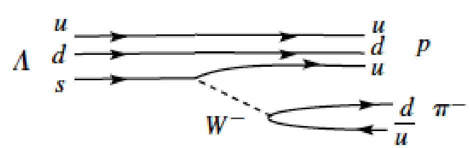
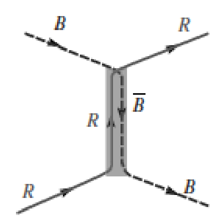


Fig. 7.3. A non-leptonic decay.

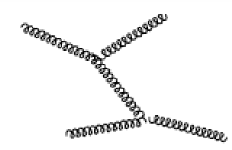
Similarity with EM scattering!
Z^0 couples matter and antimatter fermion partners

Quantum Chromo Dynamics (QCD)

- Deep inelastic scattering with e on p and n demonstrate the existence of partons : finally recognized as quarks!
- Quarks interact strongly. Their strong charges are named colors,
- Their values are: Red, Green Blue (RGB). Anti-colors exists.
- 8 Gluons are the interaction mediators. They are massless. Differently from the photon, they are charged as well!
- QCD is a "gauge QFT". The strong charge is conserved!

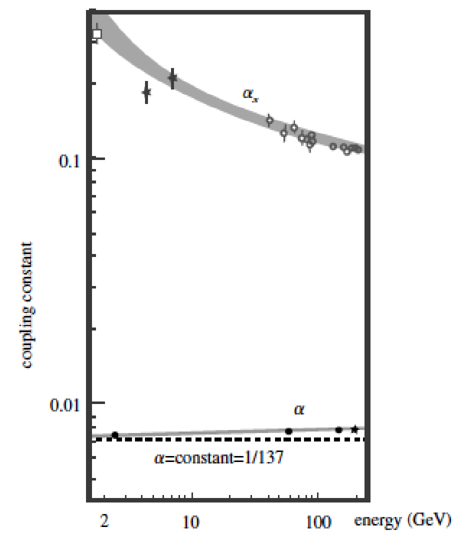


Quark scattering with gluon exchange



(b)

Gluon scattering with gluon exchange



The evolution of α and α_s. (Courtesy of Mele 2005, CERN)

Origin of hadron masses and Quantum Vacuum

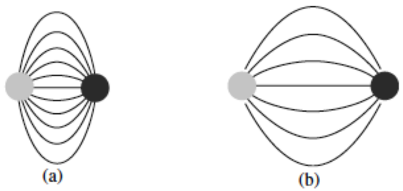


Fig. 6.26. The electrostatic field-lines between two equal and opposite charges. The lines going to infinity are not drawn for simplicity.

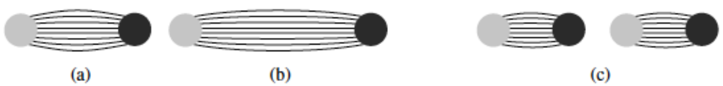


Fig. 6.27. Sketch of the colour field-lines between a quark and an antiquark.

Fig. 6.29. Diagrams of the vacuum polarisation by (a) a positron–electron pair, (b) a quark–antiquark pair.

$$\Delta t \leq \frac{1}{2m}.$$

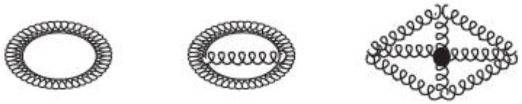


Fig. 6.31. Diagrams of the vacuum polarisation by gluons.

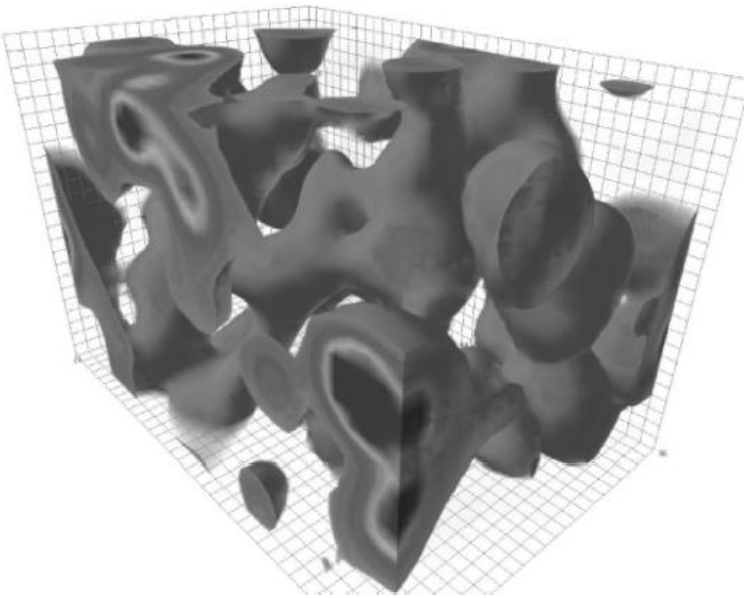
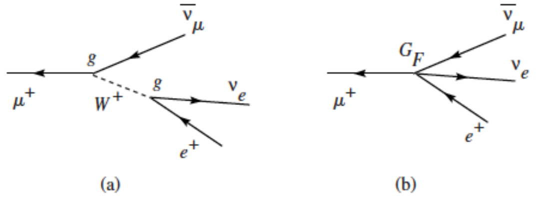


Fig. 6.32. The quantum vacuum. (D. Leinweber, CSSM, University of Adelaide http://www.physics.adelaide.edu.au/theory/staff/leinweber/VisualQCD/)

Unification in the Standard Model

- Space-time and local gauge symmetry are of fundamental importance in building the basic laws of the nature, the Standard Model;

- EW unification started in 1960. From Fermi to gauge QFT:



Muon beta decay.

At that time, with a raw approximation, neglecting the quadri-momentum transfer, the M_W could already be estimated:

$$\frac{G_F}{(\hbar c)^2} \approx \frac{g^2}{M_W^2 c^4} \quad so\ that \quad \frac{M_W^2 c^4\, G_F}{4\pi(\hbar c)^3} \approx \frac{g^2}{(4\pi\hbar c)}$$

If $\frac{g^2}{(4\pi\hbar c)}$ *is to have the same value* $\frac{e^2}{4\pi\varepsilon_0\hbar c} = \alpha = \frac{1}{137}$ then $M_W c^2 \approx 88\ GeV$!
(83 GeV the measured value!)

Unification in the Standard Model

- More formally:
- The EW predict three gauge bosons and the relationship of their masses with two parameters: G_F and $sen\theta_W$ with θ_W called "weak mixing angle.
- The latter parameter imposes the photon does not couple with neutral particles, while the Z^0 does.

$$M_W = \left(\frac{g^2\sqrt{2}}{8G_F}\right)^{1/2} = \sqrt{\frac{\pi\alpha}{\sqrt{2}G_F}}\frac{1}{\sin\theta_W} = \frac{37.3}{\sin\theta_W}\ \text{GeV}. \qquad M_W/M_Z = \cos\theta_W.$$

- $sen\theta_W$ can be measured only indirectly and it was done by UA1 and UA2 measuring the M_W and M_{Z^0} (1983).

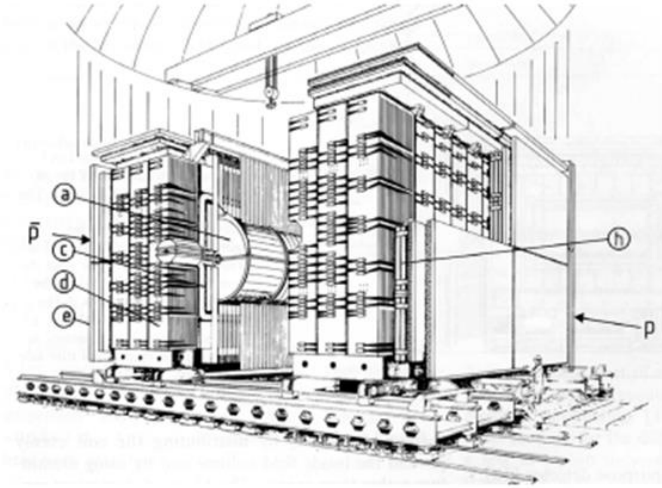


Fig. 9.12. Artist's view of the UA1 experiment, shown in its open configuration. The labels indicate the components: (a) tracking central detector, (c) magnetic field coil, (d) hadronic calorimeters, (e) drift chambers for μ detection, (h) Fe absorber. (Albajar *et al.* 1989)

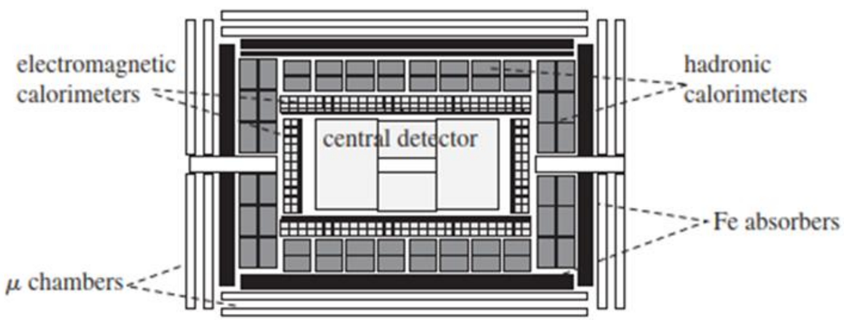


Fig. 9.13. Simplified horizontal cross section of UA1.

Figure 9.12 shows an artist's view of the UA1 experiment, when open. Figure 9.13 shows the UA1 logic structure. The two beams travelling in the vacuum pipe enter the detector from the left and the right respectively, colliding at the centre of the detector. A particle produced in the collision meets in series the following elements:

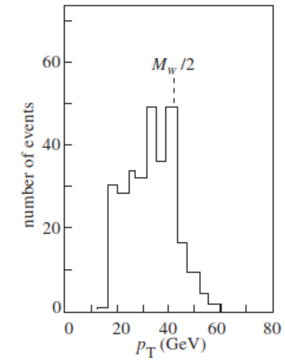


Fig. 9.17. Electron p_T distribution for W events. (Adapted from Albajar *et al.* 1989)

$UA1:\ M_{M_W} = 83\ \pm 3\ GeV$

9.7 *The discovery of W and Z* 335

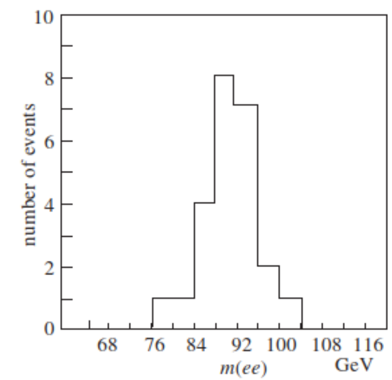


Fig. 9.21. Distribution of $m\,(e^+e^-)$ for the first 24 UA1 events. (Adapted from Albajar *et al.* 1989)

$Z^0 \rightarrow e^- + e^-\quad UA1:\ M_{Z^0} = 93\ \pm 3\ GeV$

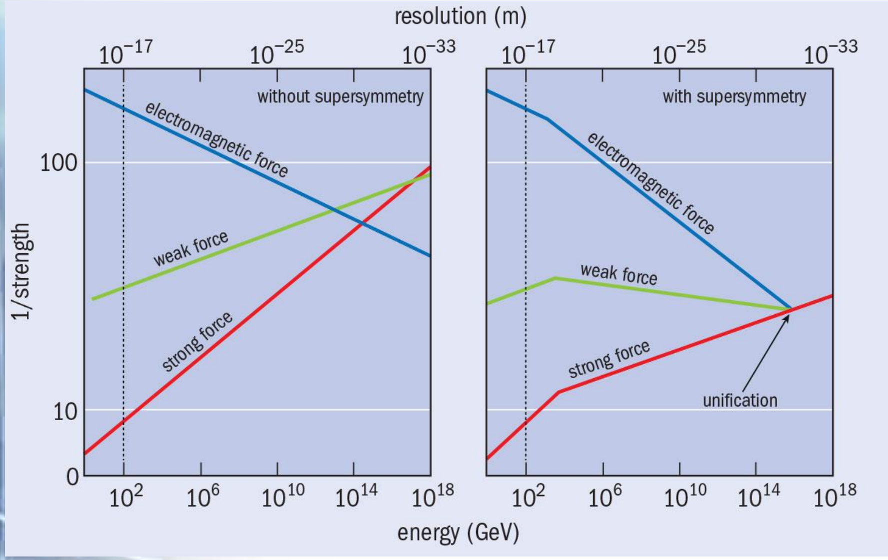
$$\mathrm{UA1}:\ \sin^2\theta_W = 0.211 \pm 0.025$$

$$\mathrm{UA2}:\ \sin^2\theta_W = 0.232 \pm 0.027.$$

And the interaction coupling constant constants?

- The EM and Weak coupling constant are not independent but correlated by the EW theory. On the contrary , EW and DCD , both being gauge theories, are unified by the theoretical framework while their coupling constant are independent.

- EW and QCD together form the SM of fundamental interactions . What about the evolution of their coupling constant?



Comments in Beyond the SM! (lecture III)

The Higgs mechanism

- The Higgs mechanism was proposed (1960) to provide mass to the weak gauge bosons $W^{\pm}$ and Z°, the interaction carriers, without destroying the gauge invariance of the EW Lagrangian !

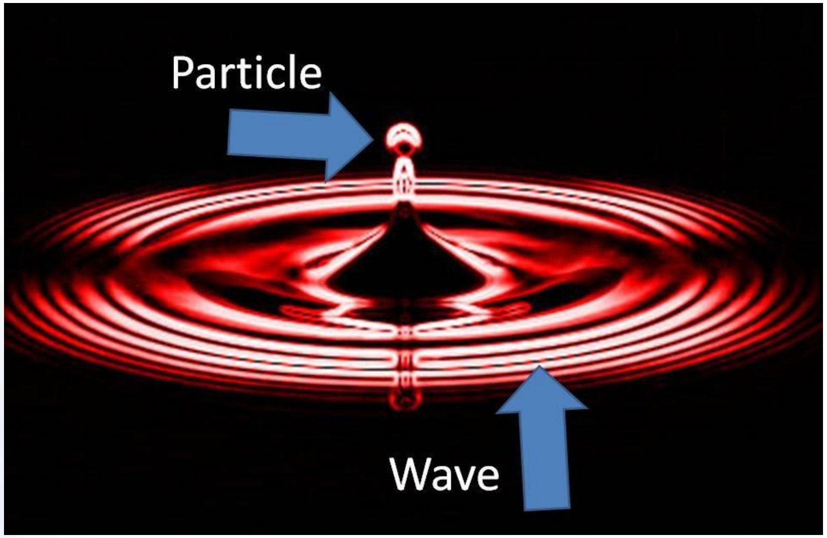
- this was to unify the Weak and EM interactions in a gauge QFT (Electroweak interaction);

- After about 50 years, The Higgs boson was observed at the LHC and presented on the 4th July 2012 at CERN;

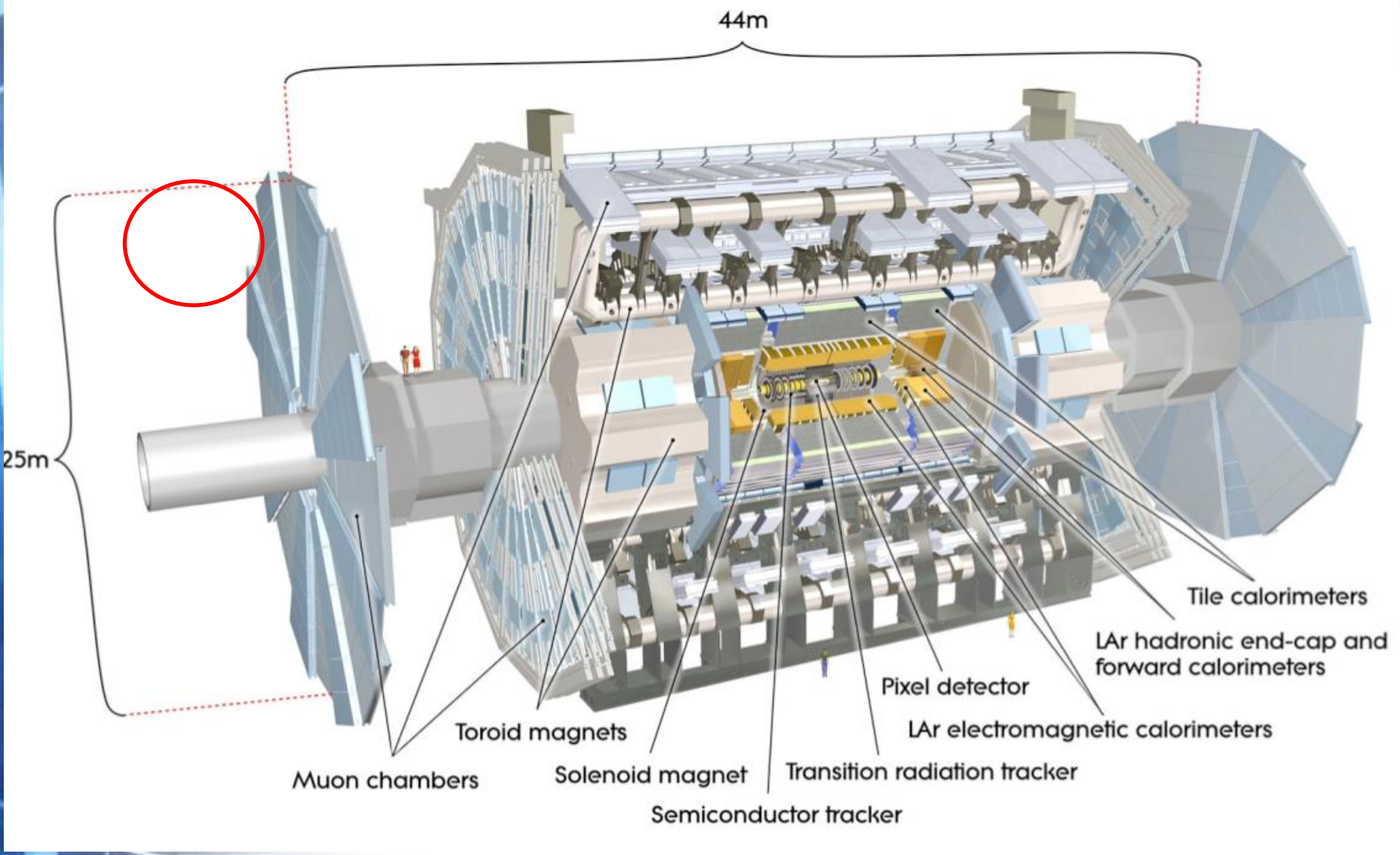
- The Higgs field fills the Universe with a non zero value and provides mass to the fundamental particles;

Observation of the Higgs boson

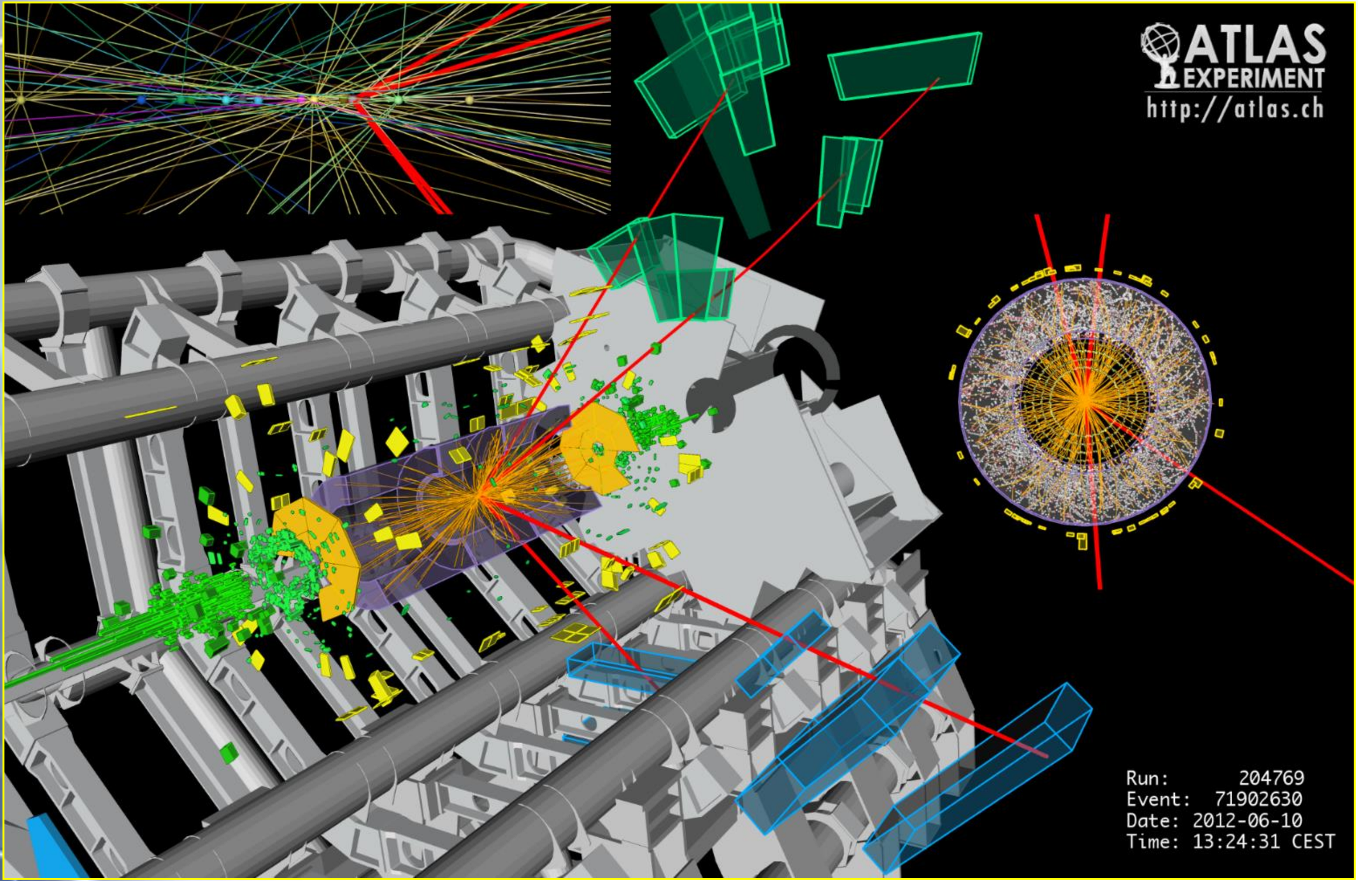
Two protons interacting in the LHC excite the Higgs field that manifests itself with the emission of the boson with a mass of 126 GeV.



The "giant" of LHC: ATLAS



H→Z^0Z^0→4 leptons



What an Invariant mass plot is

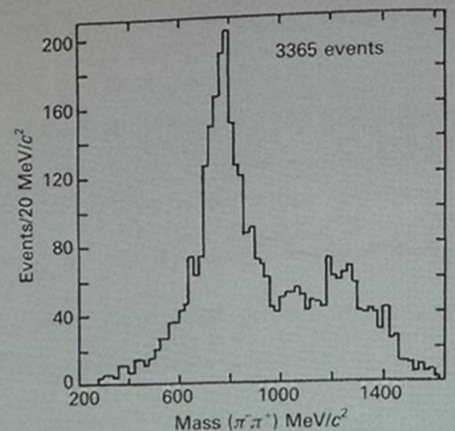


Fig. 2.7 A histogram of the number of events against the mass of $\pi^+\pi^-$ system in the final state of the reaction

$$\pi^- + p \rightarrow \pi^+ + \pi^- + n,$$

at incident π^- momenta of 2.75 and 3.00 GeV/c. The peak at a mass of 770 MeV/c^2 is due to the reaction

$$\pi^- + p \rightarrow \rho^0 + n,$$

followed by

$$\rho^0 \rightarrow \pi^+ + \pi^-.$$

A smaller peak at a mass of 1270 MeV/c^2 is due to the production of a spin 2 particle, the f_2, which decays in the same way as the ρ^0. The peak due to the ρ^0 has a width of about 150 MeV, corresponding to a mean life of approximately 4×10^{-24} s. Both peaks are superimposed on smooth background of events in which the two pions do not come from the decay of a heavier bosons like the ρ^0 and the f_2. (Data from Hagopian *et al.*, 1966.)

(How is the mass of the $\pi^+\pi^-$ system calculated? If a particle of mass M is to be observed, then its total energy E and momentum P satisfy

$$Mc^2 = \sqrt{(E^2 - (\mathbf{P}.\mathbf{P})c^2)}.$$

If it decays before direct observation into particle 1 and particle 2, then

$$E = E_1 + E_2,$$

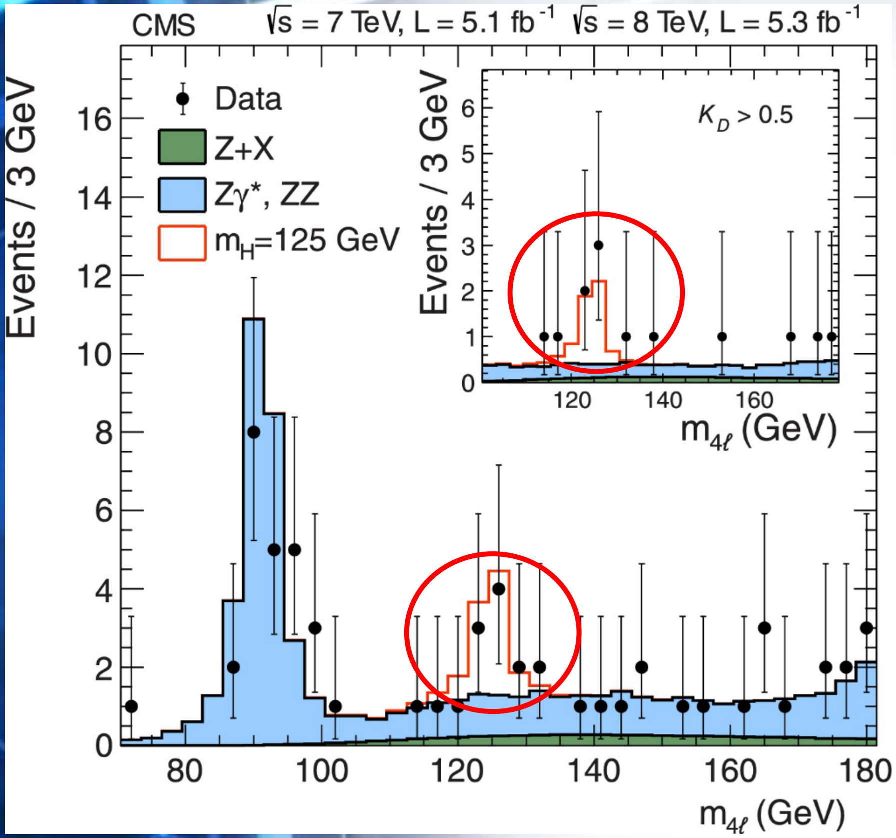
$$\mathbf{P} = \mathbf{P}_1 + \mathbf{P}_2.$$

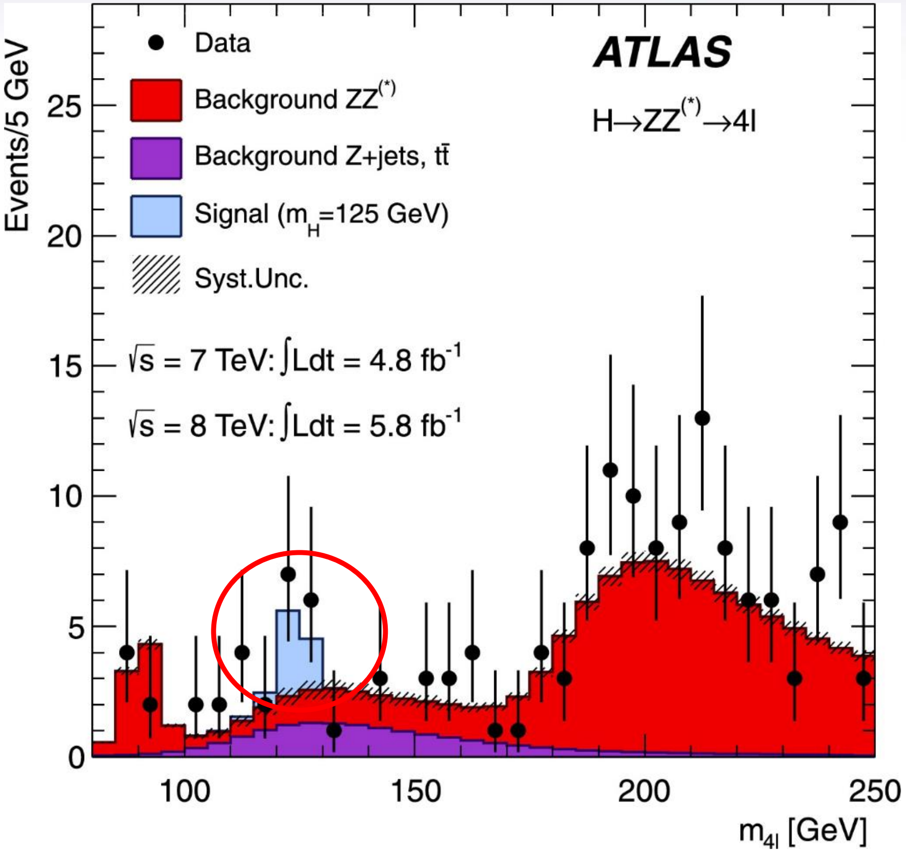
Therefore

$$Mc^2 = \sqrt{((E_1 + E_2)^2 - (\mathbf{P}_1 + \mathbf{P}_2).(\mathbf{P}_1 + \mathbf{P}_2)c^2)}.$$

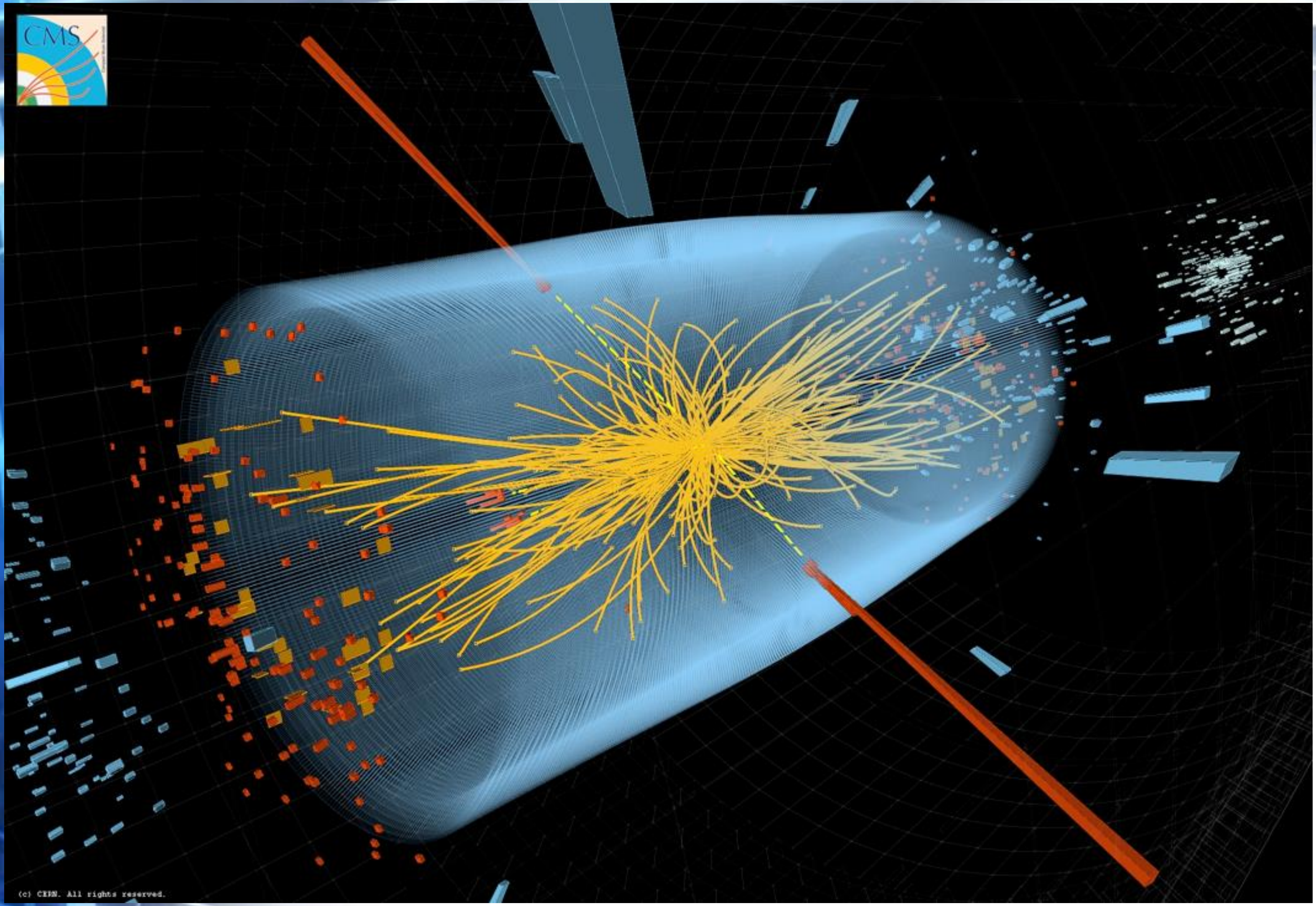
Thus if the hypothesis is that two particles are the product of the decay of another, calculation of the right-hand side, using measurements of their energies and momenta, will give the mass of this parent. It is this mass which determines the abscissa for each event entered into the histogram. The prominent peak is consistent with the production of a particle of mass 770 MeV/c^2 and width 153 MeV decaying into $\pi^+\pi^-$.)

Invariant mass plot H→ZZ→4 leptons

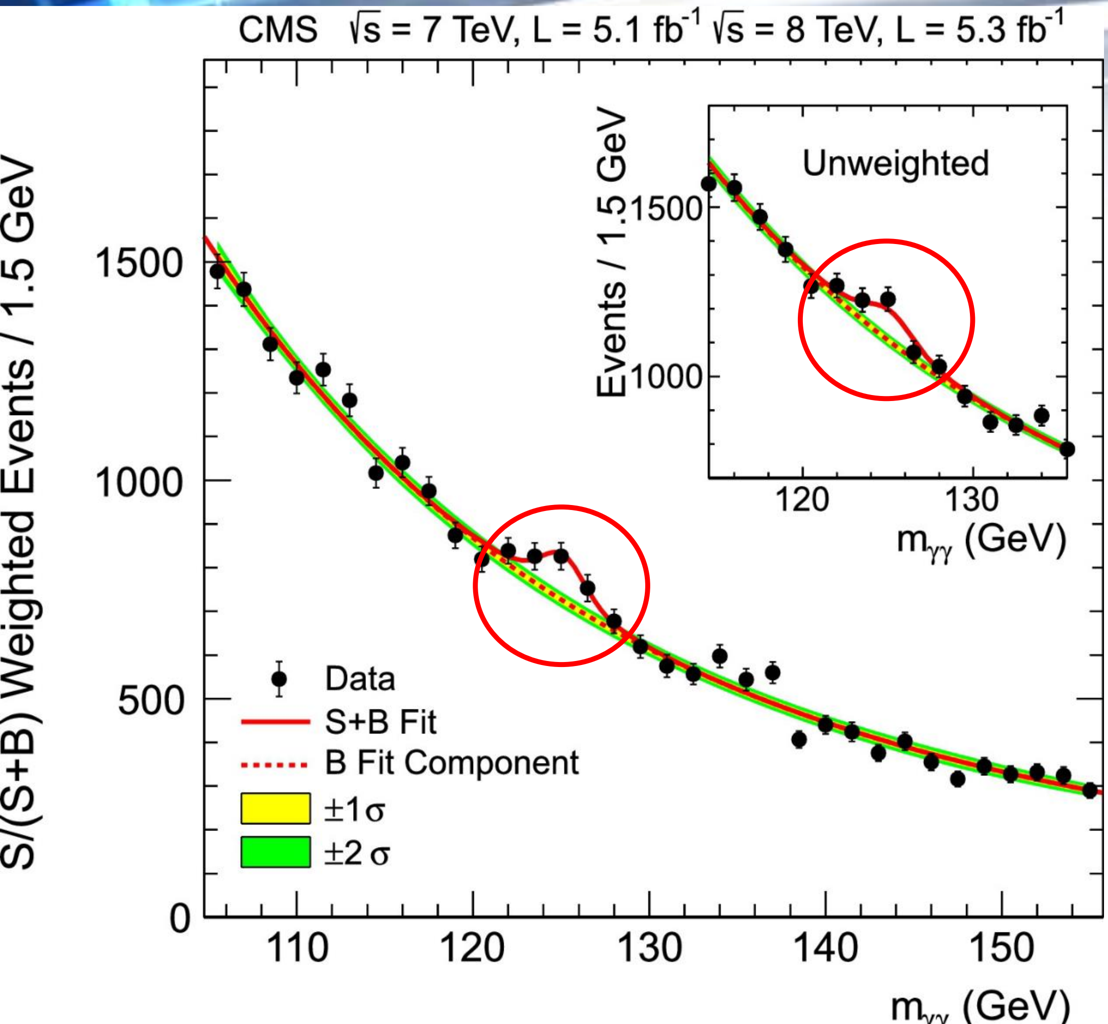


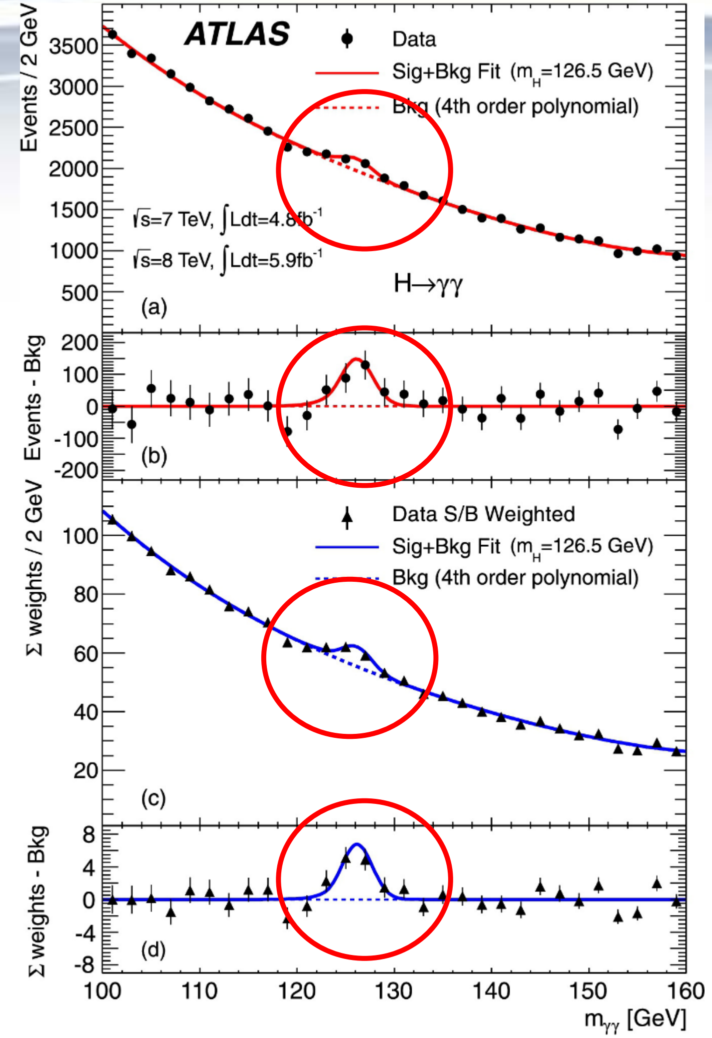


H→γγ

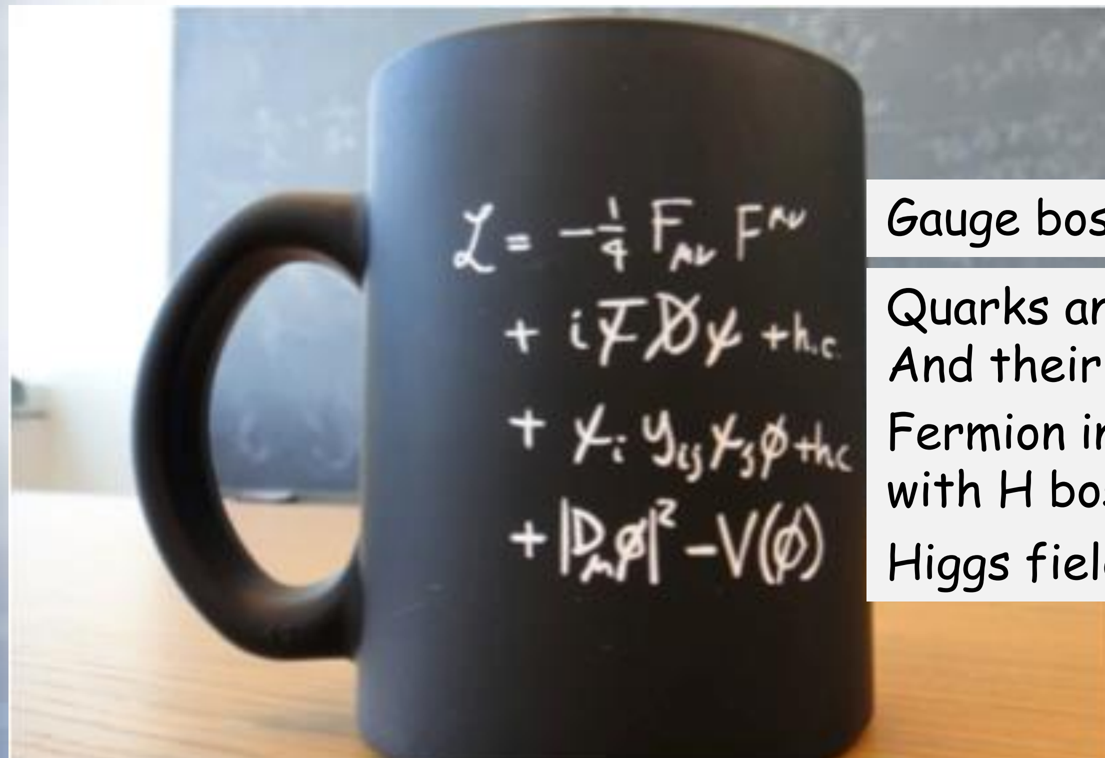


$H \to \gamma\gamma$





the SM Lagrangian



Gauge bosons: W,Z, photon

Quarks and leptons
And their gauge interaction

Fermion interactions
with H boson

Higgs field

Summary lecture II

- The SM is a paradigm of the gauge QFT. The SM incorporates the Quantum Mechanics and the Special Relativity;

- The requirement of the gauge invariance for the EW and Strong interactions provides the "charges conservation" and imposes
  - the existence of 4 electo-weak gauge bosons $W^{\pm}$, Z^{o}, γ,
  - and 8 strong gauge bosons, the gluons;

- The Higgs mechanism provides mass to three electroweak bosons $W^{\pm}$ Z^{o} without breaking the local gauge invariance;

- The detection of the H boson confirmed the effectiveness of SM but still some holes remain (dark matter, dark energy, many ad hoc parameters, no gravity…)