# Introduction to Particle Physics

Swedish Teacher program 2016

Lecture II

The Standard Model

# Lecture II

- Few lines on Special Relativity;
- Few lines on Quantum mechanics
- Less than few lines on Quantum Field Theory
- The Lagrangian of the SM
- The detection of the Higgs boson

# Special relativity

Postulates:

- The formulations of the mechanics and Maxwell equation (EM) have to be equivalent in all the inertial reference systems;
- The velocity of the light c is the limit and it is invariant (the same value) in all the inertial reference systems;

# Lorentz transformation and Energy-mass relation

For the covariance of the mechanics and EM, the space-time coordinates must transform according to the Lorentz transformation:

**Lorentz Transformation,**

From O to O', i.e.,
x, y, z, t → x', y', z', t'

$$x' = \frac{x - ut}{\sqrt{1 - u^2/c^2}}$$

$$y' = y$$

$$z' = z$$

$$t' = \frac{t - (u/c^2)x}{\sqrt{1 - u^2/c^2}}$$

New relation Energy-mass

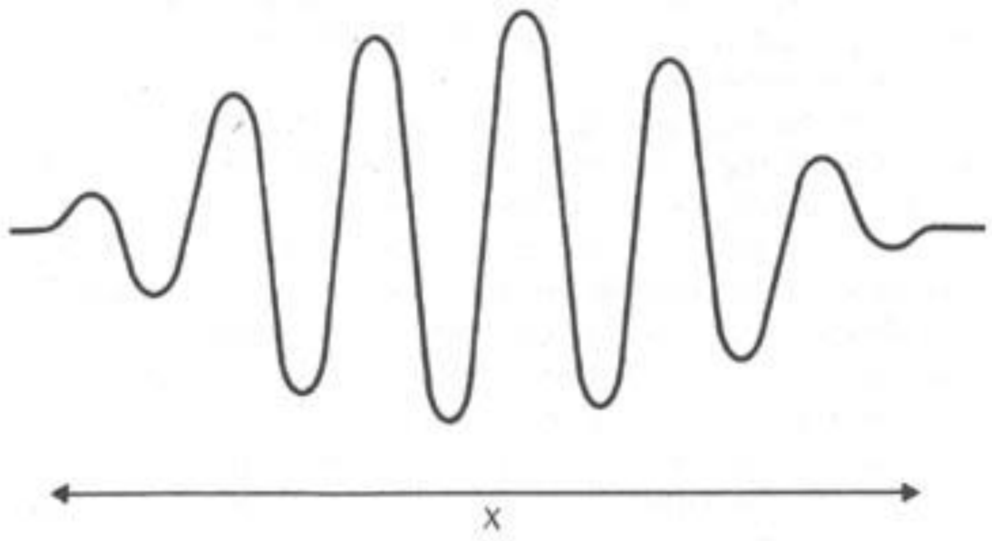
$$E^2 = p^2c^2 + m^2c^4$$

# Quantum Mechanics

- In classical mechanics exist particles (bodies ) or waves.
- The knowledge of the observables (E, v,..) means the knowledge of the state (objective reality) ;
- 1905 (Einstein) New observation: Photoelectric effect shown that in EM waves of frequency $\nu$, the energy was concentrated in quanta with $E=h\nu$ (photon), h is the Plank constant;
- $h=6\ 10^{-34}$ j*s is the minimum quanta of Action S exchanged in quantum interactions.
- 1923 (De Broglie) Surprising observation, Electrons diffusions trough  crystals produced interference pattern. Electrons behaved as wave! $\lambda = h/p$ !

wave-particle Duality!

# Quantum Mechanics



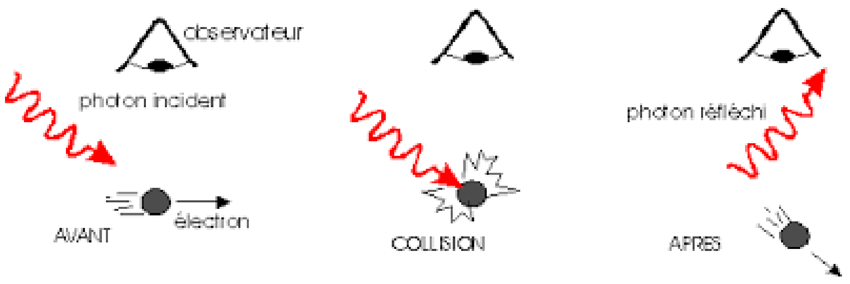

a wave packet corresponding to a particle located somewhere in the region X

# Uncertainty principle

- The wave-particle duality brought to the Heisenberg uncertainty principle:

$$\Delta p \, \Delta x \geq \frac{1}{2} \hbar$$

$$\Delta E \, \Delta t \geq \frac{1}{2} \hbar$$




In the QM, Separation of state and observables imposed.

# Propagation of a wave-particle

## Antimatter and Dirac equation

**Schrödinger's equation (1926) is non-relativistic**

(cannot account for creation/annihilation of particles)

**Schrödinger Equation (1926):**

$$\left(i\hbar\frac{\partial}{\partial t} + \frac{\hbar^2}{2m}\Delta - V\right)\Phi = 0$$

$$E = \frac{p^2}{2m} + V$$

classical ↔ quantum correspondance

$$E \to i\hbar\frac{\partial}{\partial t} \quad \& \quad p \to i\hbar\frac{\partial}{\partial x}$$

**Klein-Gordon Equation (1927):**

$$\left(\frac{1}{c^2}\frac{\partial^2}{\partial t^2} - \Delta + \frac{m^2c^2}{\hbar^2}\right)\Phi = 0$$

$$\frac{E^2}{c^2} = p^2 + m^2c^2$$

**Dirac Equation (1928):**

$$\left(i\gamma^\mu\partial_\mu - \frac{mc}{\hbar}\right)\Psi = 0$$

$$E = \begin{cases} +\sqrt{p^2c^2 + m^2c^4} & \text{matter} \\ -\sqrt{p^2c^2 + m^2c^4} & \text{antimatter} \end{cases}$$

$$E = \vec{\alpha}\vec{p}\,c + \beta mc^2$$

$$\gamma^0 = \beta,\ \gamma^i = \beta\alpha^i,\ \{\gamma^\mu, \gamma^\nu\} = 2\eta^{\mu\nu}$$

**positron ($e^+$) discovered by C. Anderson in 1932**

Christophe Grojean BSM II CERN, July 2015

# Quantum Field Theory

- Field: it has a value in each point of the space:
  - Temperature (scalar field)
  - Electric and magnetic fields (vector fields) ;
- In particle physics fields are fundamental entities;

# Quantum Field Theory

Quick remind on the AM

## What is $S$?

$$S = \int_{t_1}^{t_2} L(x, \dot{x})dt, \qquad \dot{x} \equiv \frac{dx}{dt} = v$$

- The solution of the requirement that $S$ is minimal is given by the E-L equation

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{x}}\right) = \frac{\partial L}{\partial x}$$

- Once we know $L$ we can find $x(t)$ up to initial conditions
- To find a minimum of function we solve an algebraic eq. For the action we have a differential eq.
- Mechanics is reduced to the question "what is L?"

Y. Grossman HEP theory (1) CERN, July 1, 2015 p. 6

## An example: Newtonian mechanics

We assume particle with one DOF and

$$L = \frac{mv^2}{2} - V(x)$$

- We use the E-L equation

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{x}}\right) = \frac{\partial L}{\partial x} \qquad L = \frac{mv^2}{2} - V(x)$$

- The solution is $-V'(x) = m\dot{v}$, aka $F = ma$
- Here $F = ma$ is the output, not the starting point!
- So how do we find what is L?

Y. Grossman HEP theory (1) CERN, July 1, 2015 p. 7

# QFT inspired by AM

## Solving field theory

We also have an E-L equation for field theories

$$\partial_\mu \left( \frac{\partial \mathcal{L}}{\partial (\partial_\mu \phi)} \right) = \frac{\partial \mathcal{L}}{\partial \phi}$$

- We have a way to solve field theory
- Just like in Newtonian mechanics, we want to get $\mathcal{L}$ from symmetries!

Y. Grossman HEP theory (2) CERN, July 2, 2015 p. 4

- In Field theory we want to solve wrt the field value ⟩(x, t) in a point. In field theory x and t are parameters!

# Quantum Field Theory

- Inspired by the analytical mechanics, the Standard Model Lagrangian is determined by symmetries :
  - L invariance w.r.t Lorentz transform (external symmetry)
  - L invariance w.r.t. local transformation (internal symmetries) by introducing vector gauge fields describing the fundamental interactions;

- Excitations of the vector gauge fields are the force carrier particles (boson) of the interactions!! (particle –wave duality)

(details: https://indico.cern.ch/event/387970/attachments/775407/1063369/mkraemer_CERN_2015_SM1.pdf)

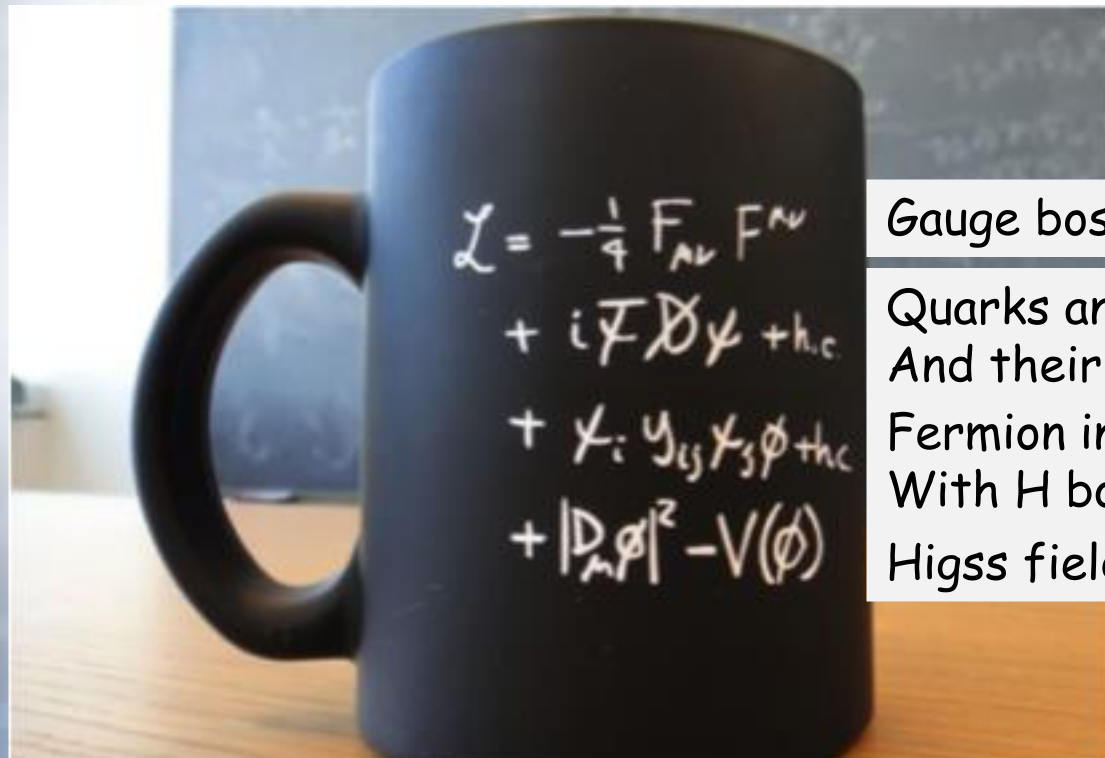
# The Higgs mechanism

- The Higgs mechanism was proposed (1960) to provide mass to the weak force carries $W^{\pm}$ and $Z^{\circ}$ that rewe required unify the Weak and EM interactions in a QFT (Electroweak interaction);

- The Higgs boson has been observed at the LHC and presented on the 4 July 2012 at CERN;

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

# Finally the SM Lagrangian




Gauge bosons

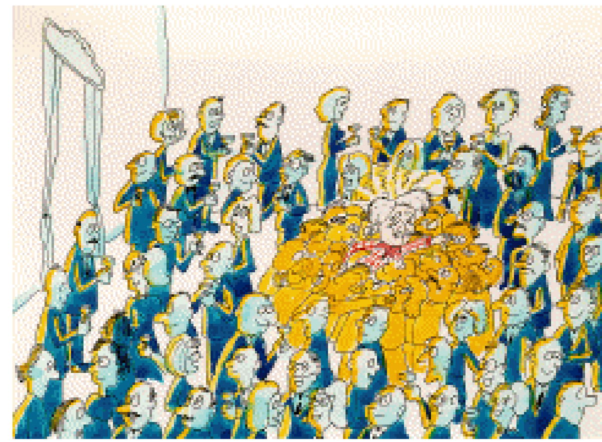
Quarks and leptons
And their gauge interactions

Fermion interactions
With H boson

Higss field

# The Higgs field idea

The ‘cocktail party’ explanation of the Higgs mechanism

A cocktail party ...

.. a famous person wants to traverse the room...

.. but the guests cluster around and slow down its movement...

The BEH field ....

... a massless particle enters...

... the interaction with the BEH field produces the inertia of the particle ...

# The Higgs boson

A rumour is spreading among the guests ...

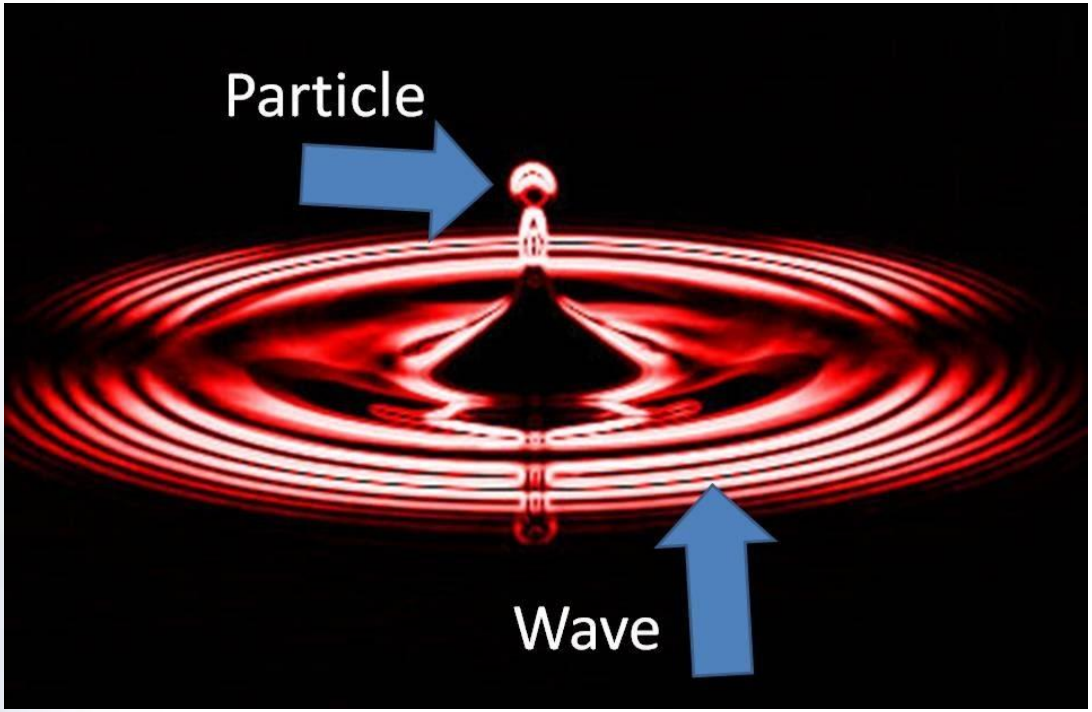
.. they cluster together to exchange the information among themselves...

The BEH field ...

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

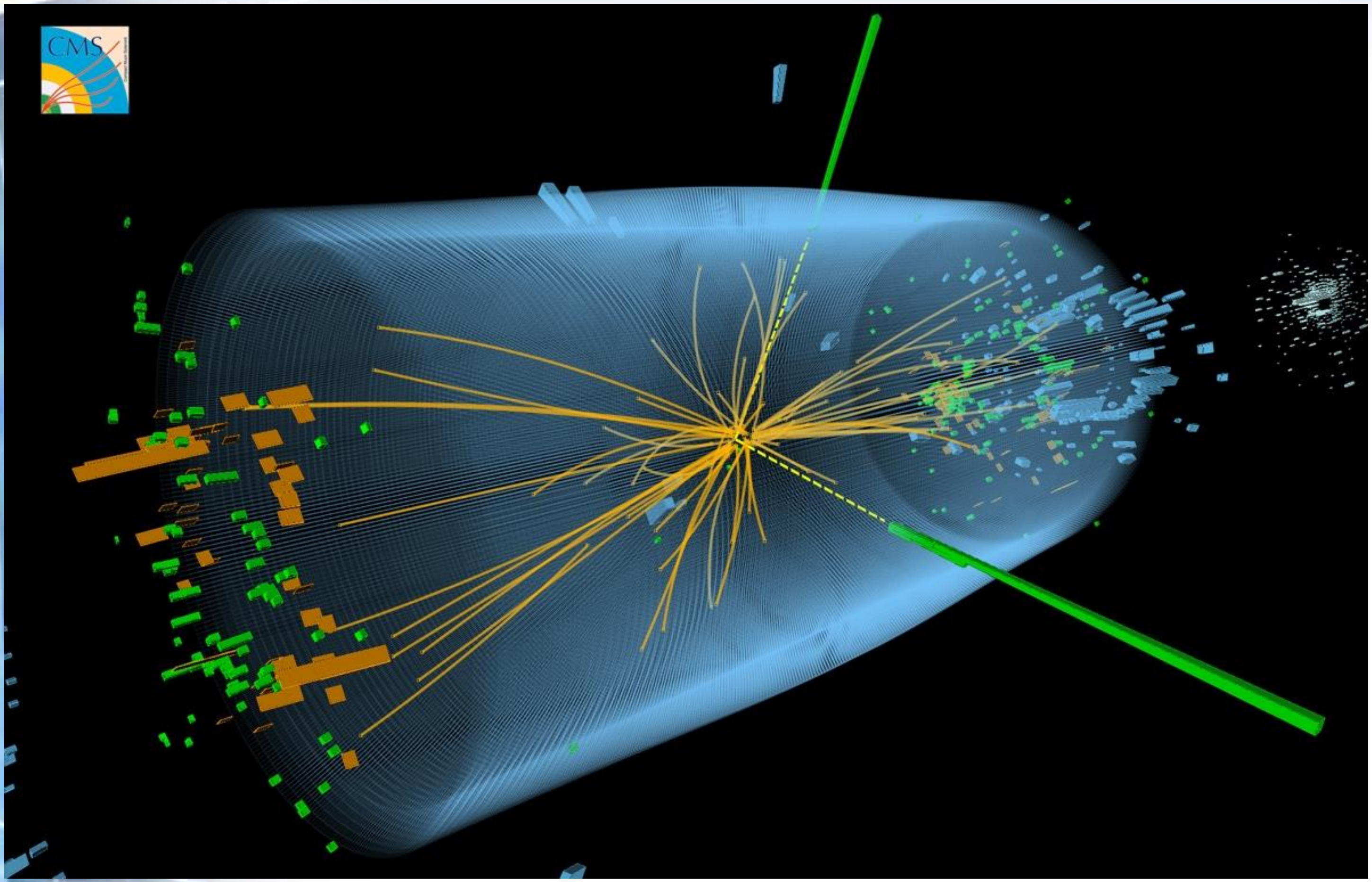
# Observation of the Higgs boson

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.

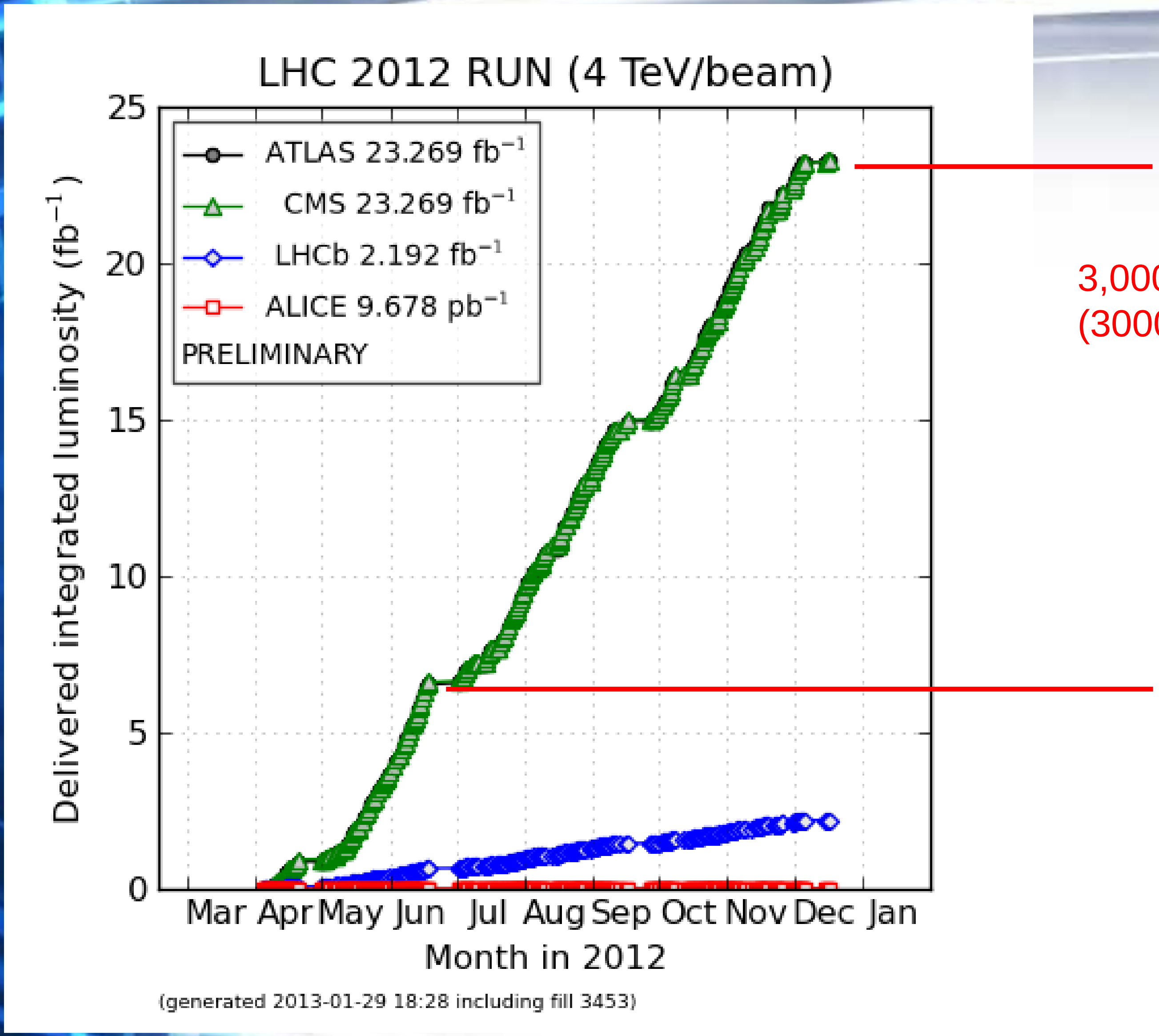


# Higgs boson discovery

4 July 2012

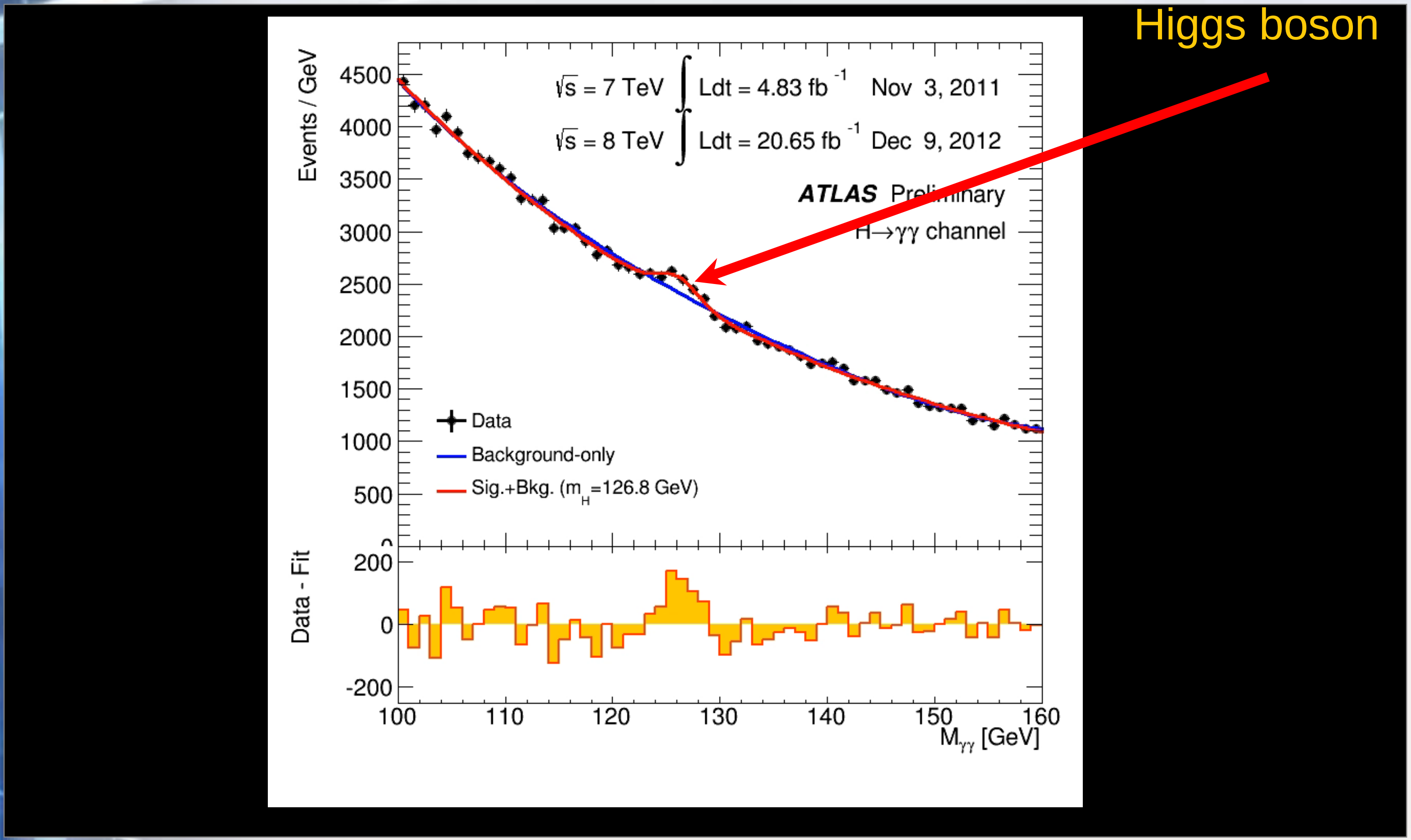


# 2011 - 2012 : Data taking with LHC

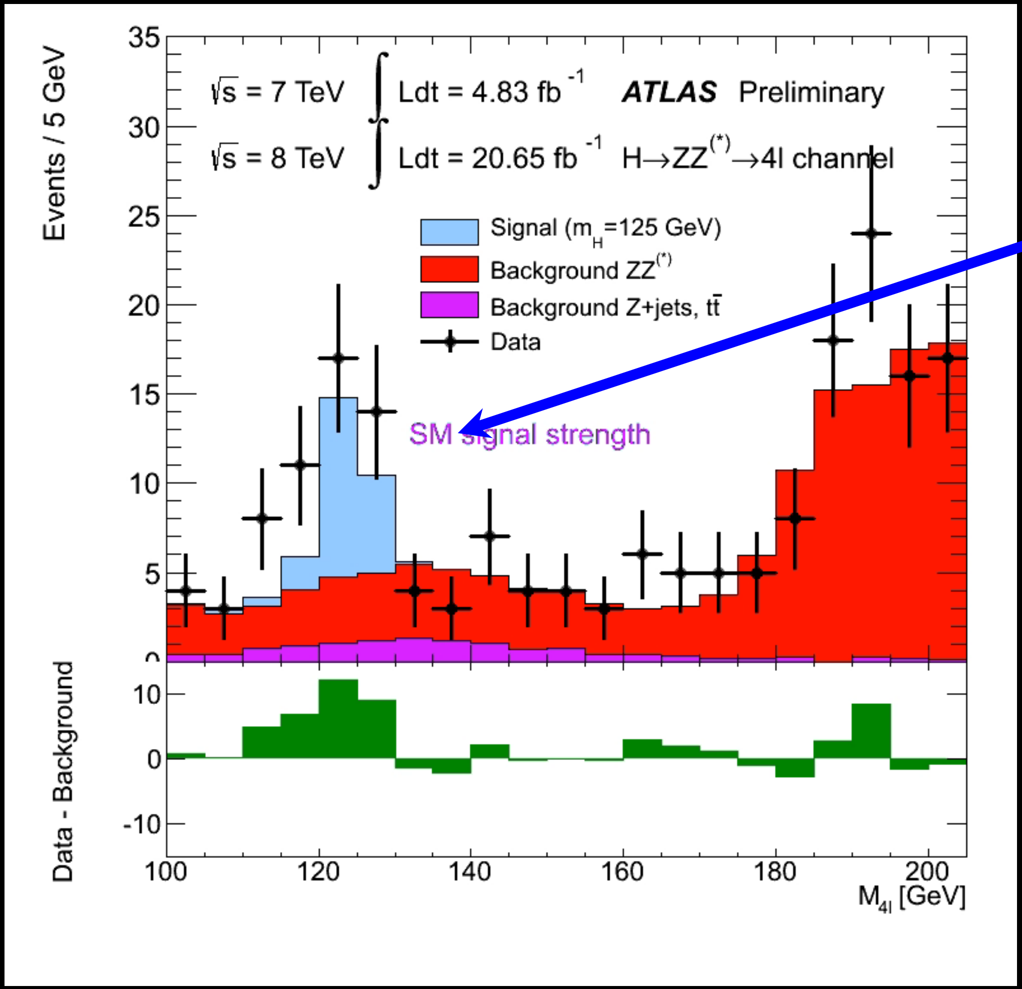



3,000,000,000,000,000 ($3 \cdot 10^{15}$)
(3000 trillion events !)

# The evolution of the histogram with two-photon events



# The evolution of the histogram H--->4lepton events




Higgs boson

# SM successes and holes

| Successes | Holes |
| --- | --- |
| Consistent with experiments | Incomplete (eg. no gravity) |
| No deviations seen | Few explanations |
| Predictions (eg Higgs) proven | Many ad-hoc additions to fit experimental data |

Need to find a breakdown to move forward.
**Need experiments.**

# Summary lecture II

- The SM is a paradigm of the QFT;
- The SM Lagrangian is built by symmetries
  - L invariance w.r.t Lorentz transform (external symmetry)
  - L invariance wrt local transformation (internal symmetries) by introducing vector gauge fields describing the fundamental interactions;
- Excitations of the vector gauge fields are the force carrier particles (bosons) of the interactions!!
- The detection of the H boson once more confirmed the effectiveness of SM;
- Still some holes (dark matter, dark energy, many ad hoc parameters, no gravity…