Discovery of the Higgs Boson

Before, during and after

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Outline

1. What is the Standard Model ?
2. Why did we need a Higgs boson ?
3. How the Higgs was found
4. After the Higgs discovery: what now?

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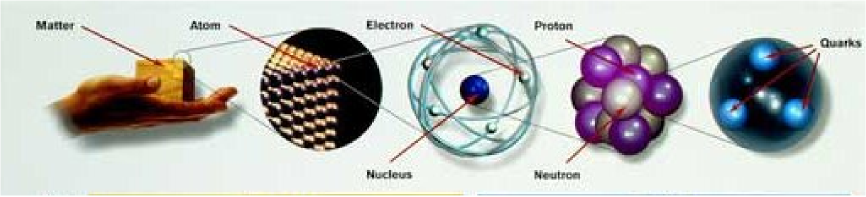
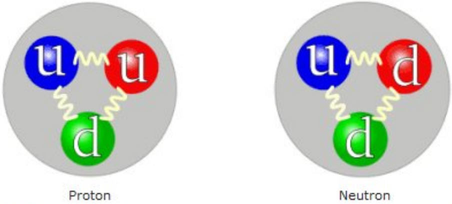
Zooming on the elementary particles



- Atom $\rightarrow$ nucleus $\rightarrow$ proton/neutron $\rightarrow$ quarks



Quark composition of a proton and a neutron (diagrams from *Wikipedia*)

- Atom $\rightarrow$ electrons

Describing forces between particles

- Why do electrons go around the nucleus ?
  Electromagnetic force
- What keeps quarks bound inside the nucleus ?
  Strong nuclear force
- What causes radioactive beta decay of the nucleus ?
  Weak nuclear force

Elementary particles and Fundamental forces

That is the Standard Model of Particle Physics !

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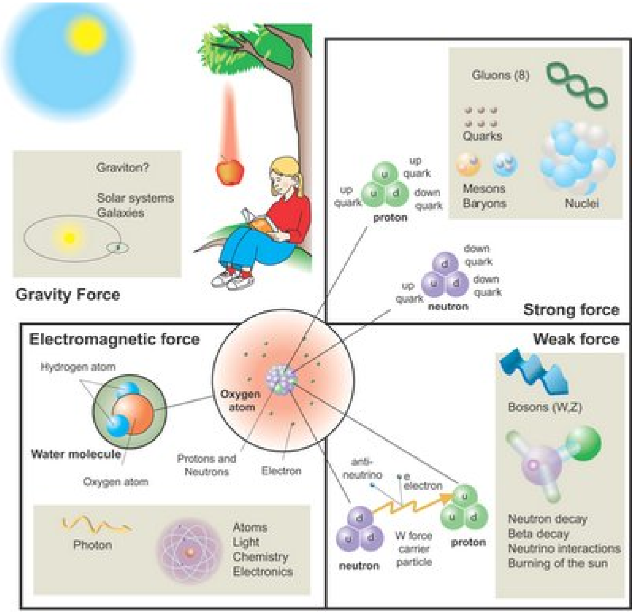
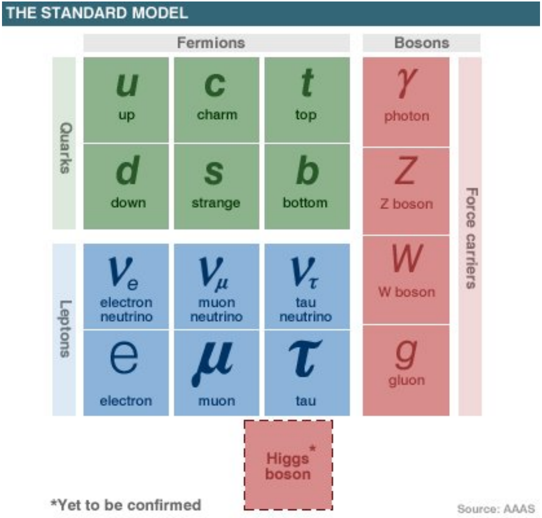
Explaining nature using particles and forces



The Standard Model of Particle Physics: June 2012



- γ: EM
- $g(8)$: strong
- $W^{\pm}, Z$: weak

- We observe all these particles !

Fermions and bosons

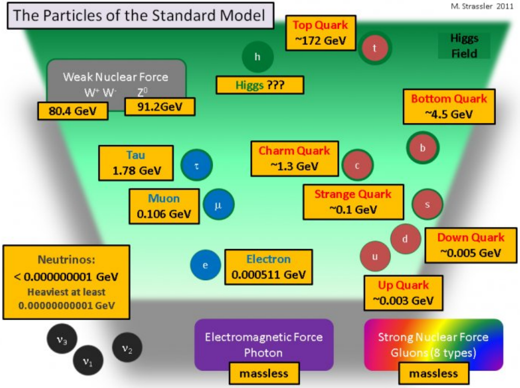
Enrico Fermi

Fermions:
Spin 1/2, 3/2, ...
Similar particles cannot stay together
Quarks, leptons
(e.g. electrons)

Satyendra Nath Bose

Bosons:
Spin 0, 1, 2, ...
Similar particles like to stay together
Force carriers, Higgs
(e.g. photons)

Masses of the particles



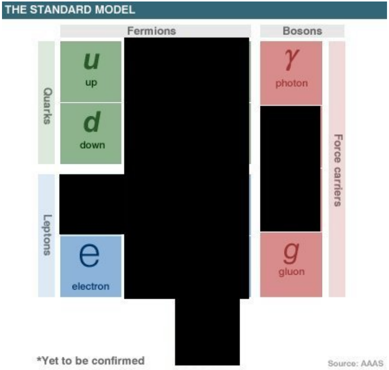
1 GeV $\approx$ proton mass

- All fermions have masses
- Photon and gluons massless
- $W^{\pm}$ and Z have large masses ($\sim 100\times$ proton mass)

Outline

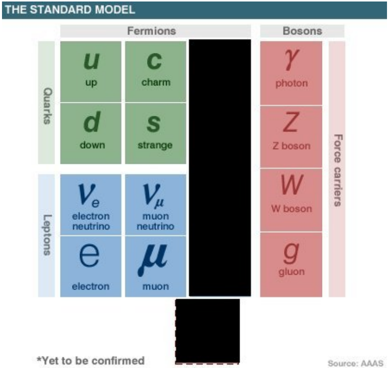
Why do we expect a new particle: understanding atom

- To understand cathode rays
  (electrons)
- To explain the substructure of a particle
  (u and d quarks for proton and neutron properties)



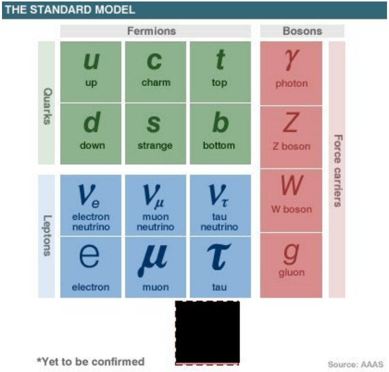
Why do we expect a new particle: 1935-1970

- For explaining radioactive beta decay (electron neutrino)
- Some particles come completely unexpected (muon, muon neutrino, strange quark)
- To explain the absence of some reactions (charmed quark)



Why do we expect a new particle: 1975-2000

- To allow for matter-antimatter asymmetry
  (quarks from the third family)
- For completing the family pattern
  (leptons from the third family)



Why did we expect a Higgs ?

The most common answer

To give masses to elementary particles

The most natural question

But why cannot the particles just have masses to begin with ?
Why can "mass" not be an intrinsic property of a particle ?

This is not a philosophical question, but a scientific one.

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Symmetry: foundation of the Standard Model

- Symmetries allow us to describe things in a compact form
- Gauge symmetry: changes in the descriptions of particles that do not change the final observations
- Very powerful principle: when you identify the Gauge symmetry, you can predict all interactions
- We have tested and confirmed the Standard Model through thousands of experiments !

Gauge symmetry is extremely important: like the conservation of energy and momentum. Cannot throw it away !

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So what's the problem ?

Implications of Gauge symmetry

- Fundamental particles (fermions) need to be massless
- Force carriers (Gauge bosons) need to be massless
- Weak interactions need to be long range

Observations

- Fundamental particles (quarks, leptons) have masses
- Photon and gluon massless, but $W^{\pm}, Z$ have large masses
- Weak interactions are short-range, confined to the nucleus

A consistency problem !

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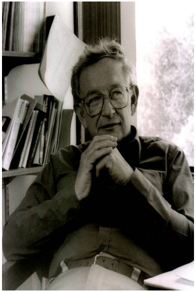
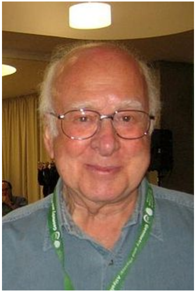
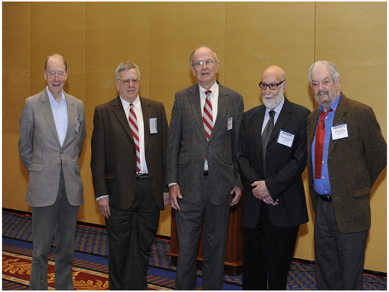
The proposed solution

Anderson - Higgs - Kibble, Guralnik, Hagen, Englert, Brout

- "Spontaneous symmetry breaking" mechanism can give masses to Gauge bosons: Anderson 1962
- For weak interactions, this mechanism gives rise to an elementary particle: Higgs+, 1964
- "Higgs boson" name given by Benjamin Lee, 1966

Higgs field, particle mass and Higgs boson

The Goddamn particle

- Proposed in 1964, not found till 1992
  (and took 30 more years)

- Leon Lederman wrote the book “The Goddamn Particle”

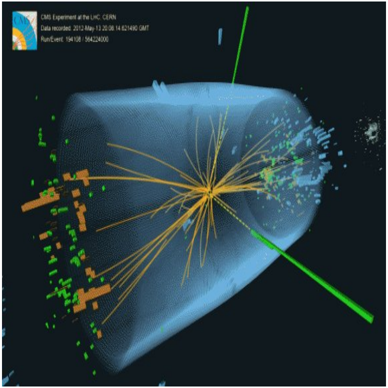
  “.. the publisher wouldn’t let us call it the Goddamn Particle, though that might be a more appropriate title, given its villainous nature and the expense it is causing.”

- The publisher changed the title to “The God particle”

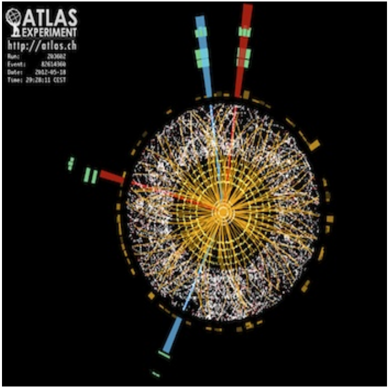
- The book sold a lot of copies

And the Higgs boson was found in 2012 !

$H \to \gamma\gamma$



$H \to ZZ^* \to \ell\ell\ell\ell$



Outline

LHC accelerator and detectors

Some numbers

- Accelerator: 27 km circumference
- Proton-proton collision Energy: 8000 GeV
- Collisions per second: 20 Millions
- Total Number of Collisions: 10^{15} (a thousand trillion)

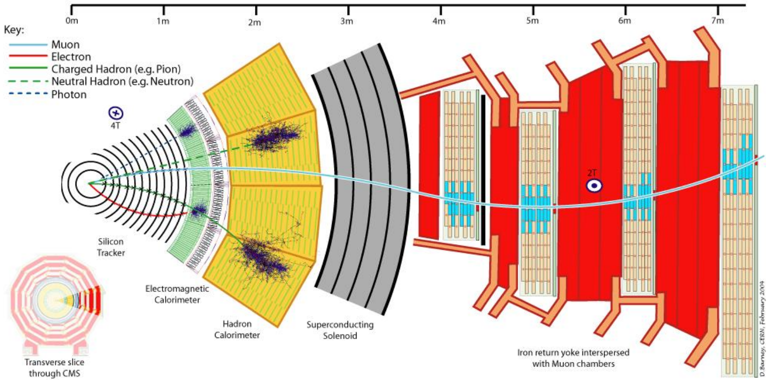
The CERN tunnel

The CMS collaboration (where India participates)

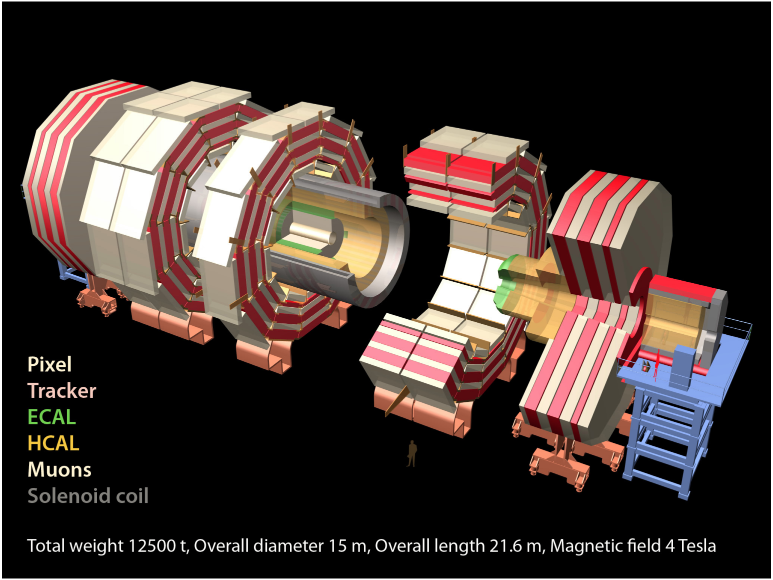
Some numbers

- 3600 physicists, engineers, students
- 183 institutes, 38 countries
- Detector weight: 12500 tons
- Diameter: 15 m, length: 22 m

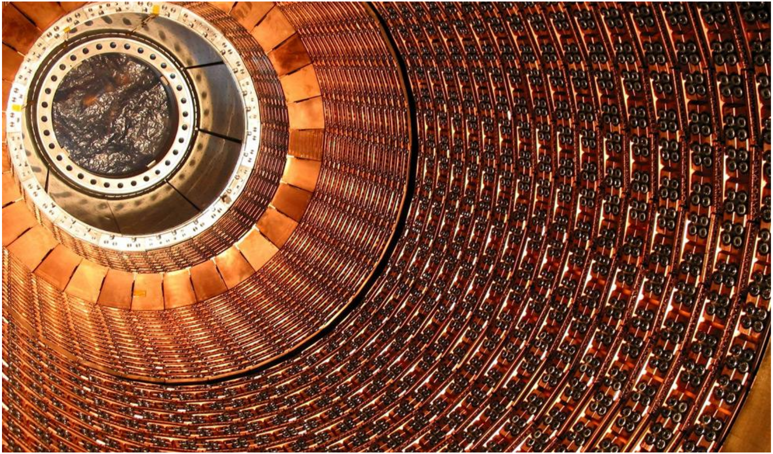
Detection of particles: CMS



Assembly of the detector: CMS



Inside the detector: ATLAS



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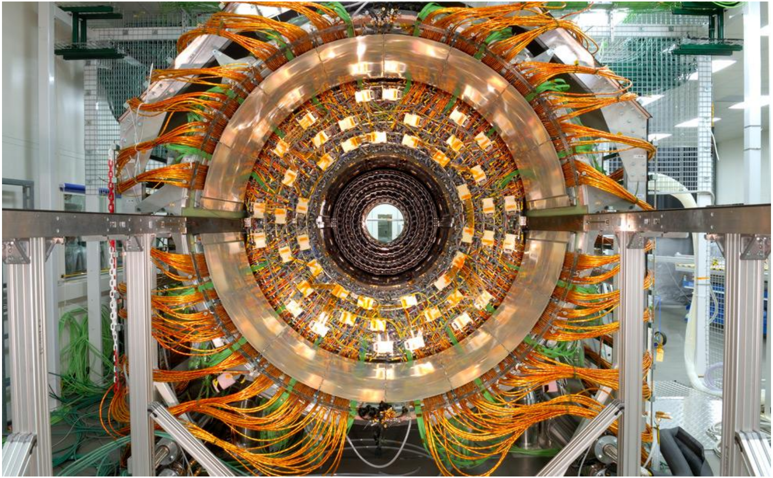

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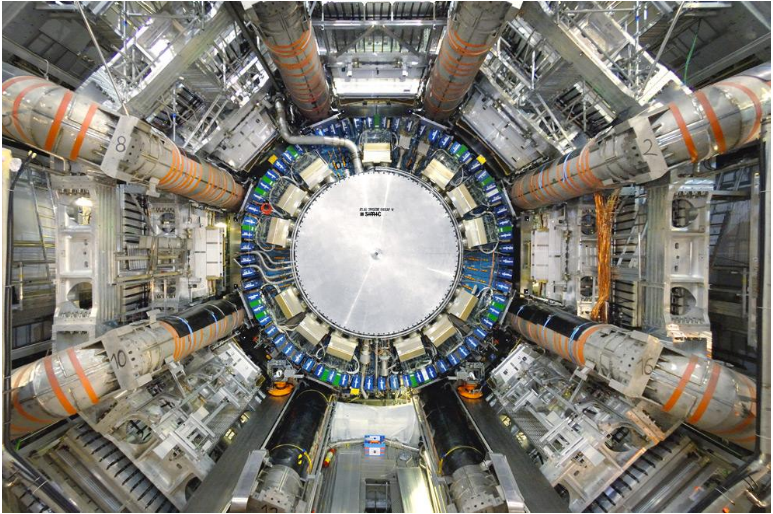
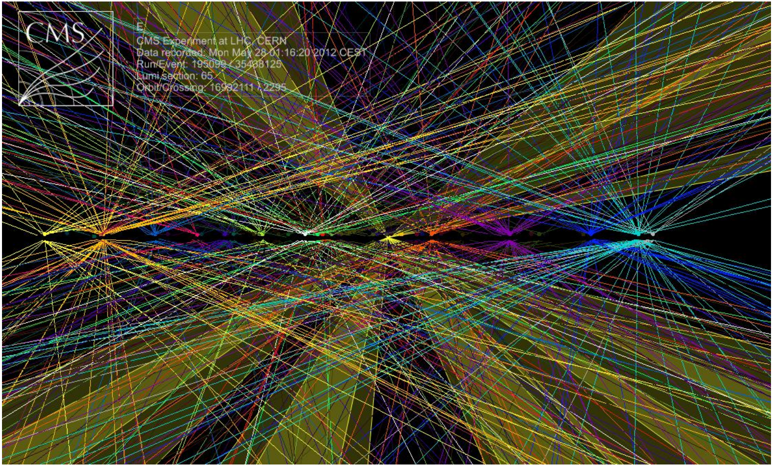
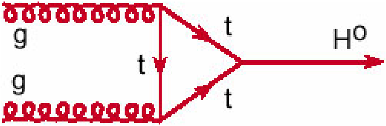


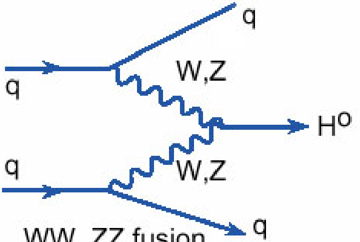
A typical proton-proton collision event



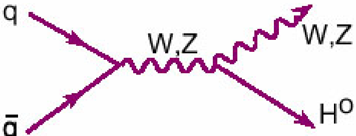
How is Higgs produced ?



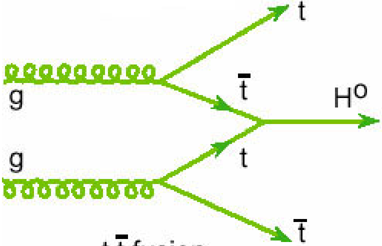
g g fusion



WW, ZZ fusion



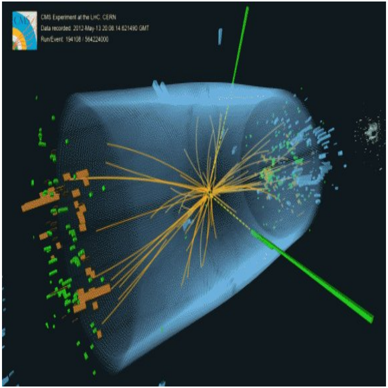
W, Z bremsstrahlung



t $\bar{t}$ fusion

Detecting Higgs through its decays

$H \to \gamma\gamma$



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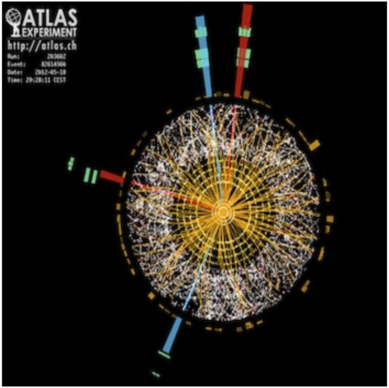
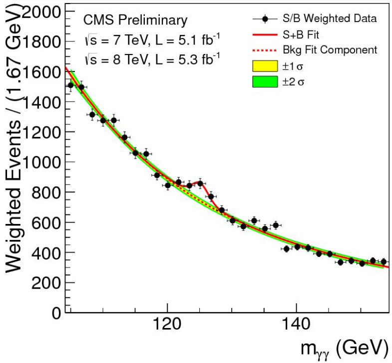


Other modes: $H \to WW$, $H \to b\bar{b}$, $H \to t\bar{t}$

Main problem: signal vs background

- Number of Higgs events: a few lakh
- Number of background events: 1000 trillions

Even after removing background using particle identification techniques, a lot of background still stays

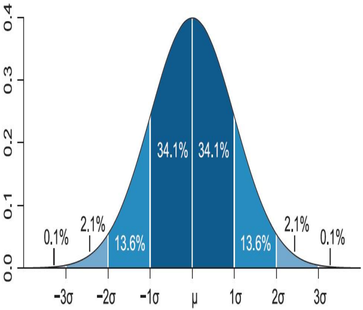


- Are we sure this peak is not a statistical fluctuation ?

Statistical significance of signals

Statistical significance shows the confidence in a statement

- The sun will rise tomorrow: 100%
- The coin will land heads up: 50%
- It will rain in the next hour: ?



Statical significance	Confidence level
1 sigma	68.3 %
2 sigma	95.45%
3 sigma	99.73%
4 sigma	99.994 %
5 sigma	99.999942%

5 sigma is taken to be discovery

Outline

Is this the Higgs of the Standard Model ?

- Looks and waltks, but does it quack ?
- Is it, perhaps, a part of a new theory beyond the Standard Model, like Supersymmetry or Extra dimensions ?
- Only more experiments will give the answer
- LHC may discover new particles from these new theories, or we may need new specialized experiments

Other open problems in particle physics

- Masses of neutrinos
- Matter-antimatter asymmetry
- Dark matter and dark energy: make 96% of the universe
- Grand Unification of all forces (including gravity)

Another perspective on this result

- A triumph of theory and experiment !
- Thousands of people from more than 45 countries, many of whom would never meet each other in their lives, worked for more than 20 years towards a common goal and succeeded.
- This is a great achievement of mankind and global collaborative nature of science, and we all should be proud of it