The discovery of the Higgs boson

Fabiola Gianotti, CERN Physics Department
(Honorary Professor, University of Edinburgh)

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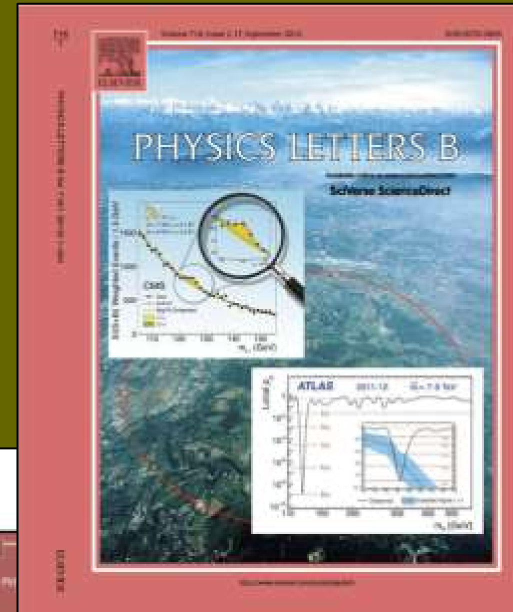

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ELSEVIER

Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC ☆

ATLAS Collaboration *

This paper is dedicated to the memory of our ATLAS colleagues who did not live to see the full impact and significance of their contributions to the experiment.

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ABSTRACT

A search for the Standard Model Higgs boson in proton–proton collisions with the ATLAS detector at ... ely 4.8 fb^{-1} ... he channels ... previously ... esults from ... vidence for ... s presented. This observation, which has a significance of 5.9 standard deviations, corresponding to a background fluctuation probability of 1.7×10^{-9}, is compatible with the production and decay of the Standard Model Higgs boson.

The culmination of a long path ...
An arrival and a starting point ...

The long path to bring the Standard Model to theoretical and experimental "completion" (an oversimplified view …)

'30s
Fermi theory of weak interactions

'50s
Yang and Mills theories
Parity violation

'60s
p, n structure
DIS experiments

Quark model.
Spontaneous symmetry breaking
(Nambu, Goldstone, Brout, Englert, Higgs …)

'70s
Standard Model of EW interactions
(Glashow, Weinberg, Salam with strong contributions also from Cabibbo and Maiani)
QCD: asymptotic freedom
Renormalization of QFT

Discovery of weak neutral currents
Discovery of charm (J/ψ) and bottom (Υ) quarks, and of τ-lepton

'80s
W, Z discovery at CERN

'90s
Discovery of top quark at Tevatron
Precise Z, W measurements at LEP, SLC, Tevatron

2012
Higgs discovery at LHC

Theory | Experiments

Note: until now, fermions (c, b, t, τ) discovered in US, bosons (W, Z, H) in Europe ..!

The long path of the LHC (few milestones…)

1984 : First studies for a high-energy pp collider in the LEP tunnel
1989 : Start of SLC and LEP e^+e^- colliders
1994 : LHC approved by the CERN Council
1996 : Construction of LHC machine and experiments start
2000 : End of LEP2
2003 : Start of LHC machine and experiments installation
2009 : 23 November: first LHC collisions ($\sqrt{s}$ = 900 GeV)

> 20 years from conception to start of operation

2010 : 30 March: first collisions at $\sqrt{s}$ = 7 TeV
2012 : 1st May: collision energy to $\sqrt{s}$ = 8 TeV
2012 : 4th July: discovery of a Higgs-like boson

+ 20 years of physics exploitation ?

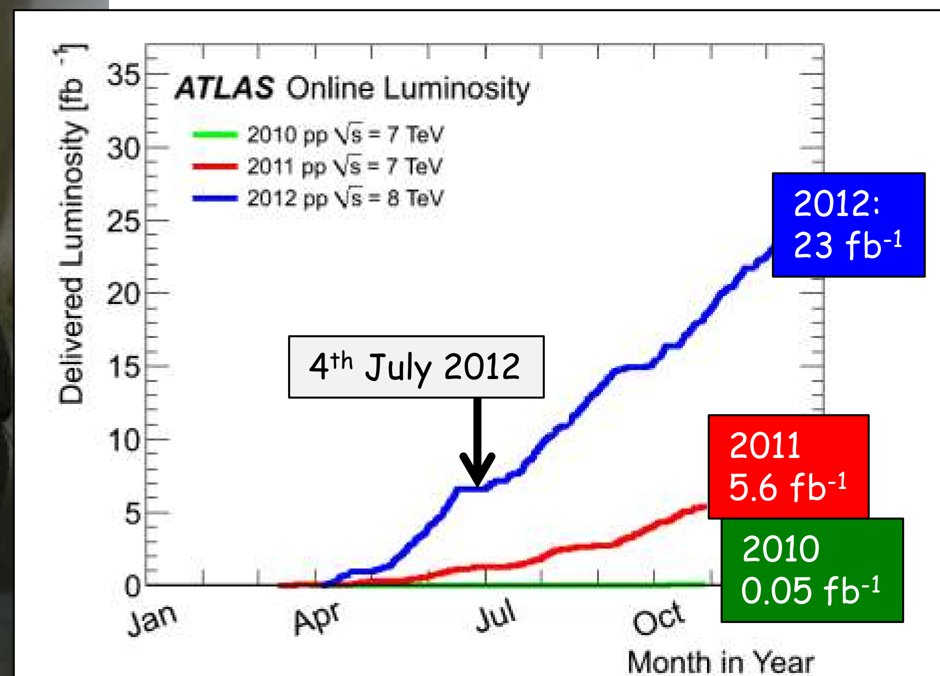
The LHC has required:

- innovative technologies (superconducting magnets, cryogenics, electronics, computing, ..)
- new concepts, lot of ingenuity to address challenges and solve problems
- huge efforts of the worldwide community (ideas, technology, people, money)
- patience, perseverance, determination, optimism …

An unprecedented accelerator:

- 1232 high-tech superconducting dipole magnets, 8.3 T field → 12 kA (30% built by Ansaldo)
- 7600 km NbTi superconducting cable in 100 tons of superfluid Helium at 1.9K

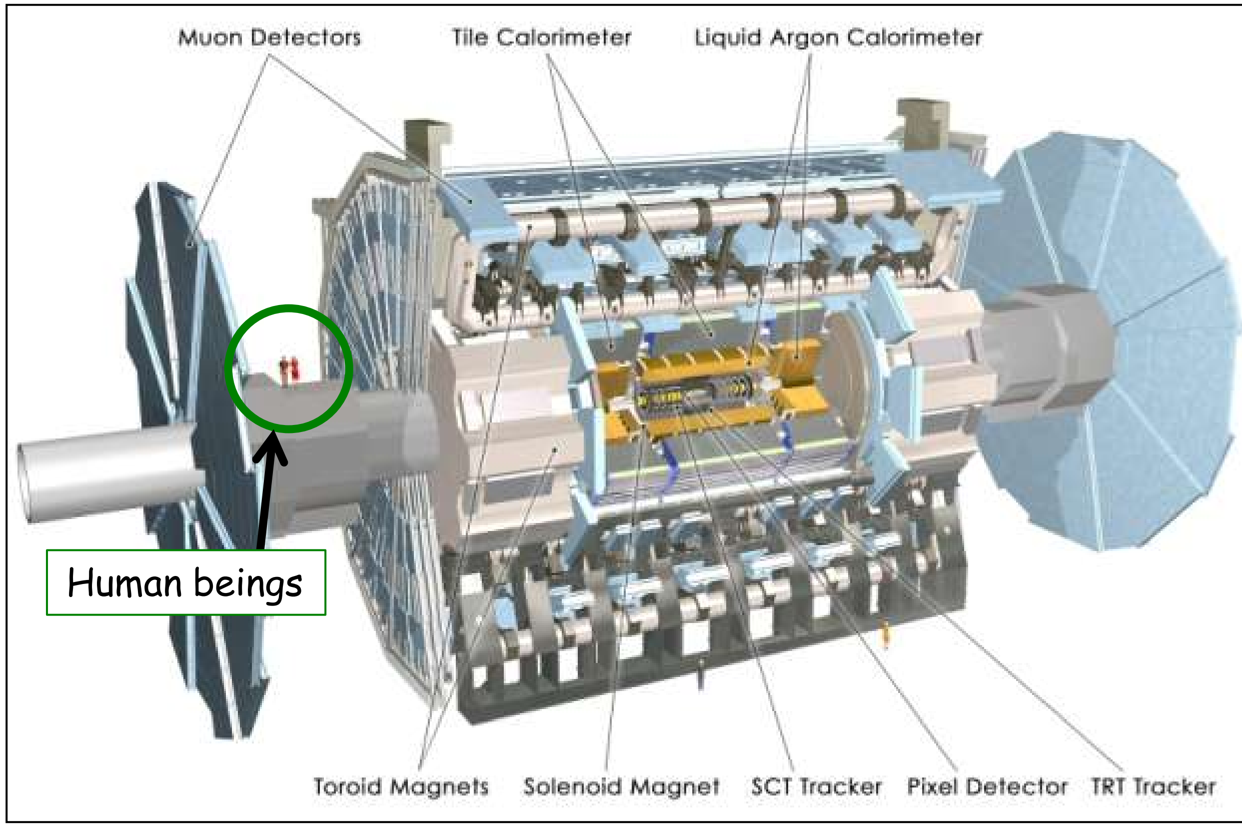
ATLAS: 5 billion events recorded

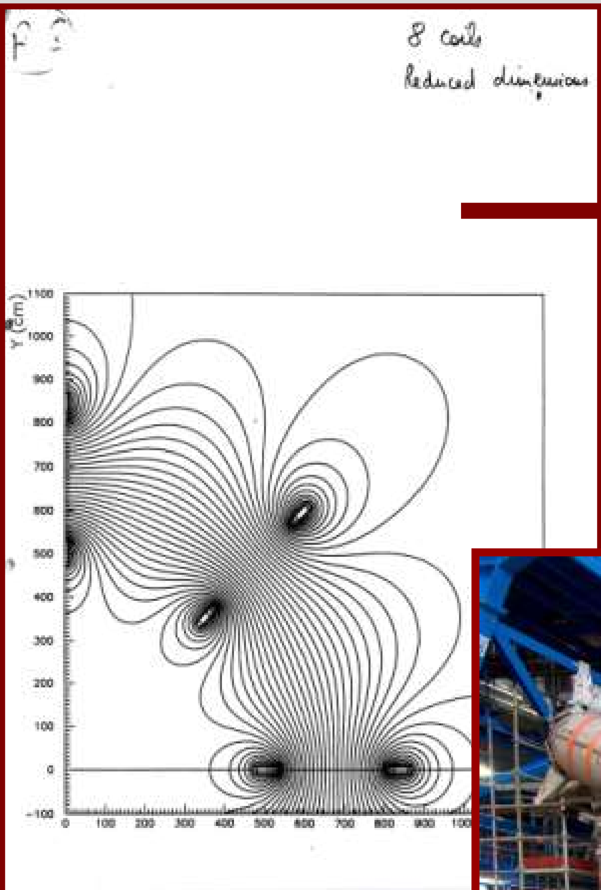


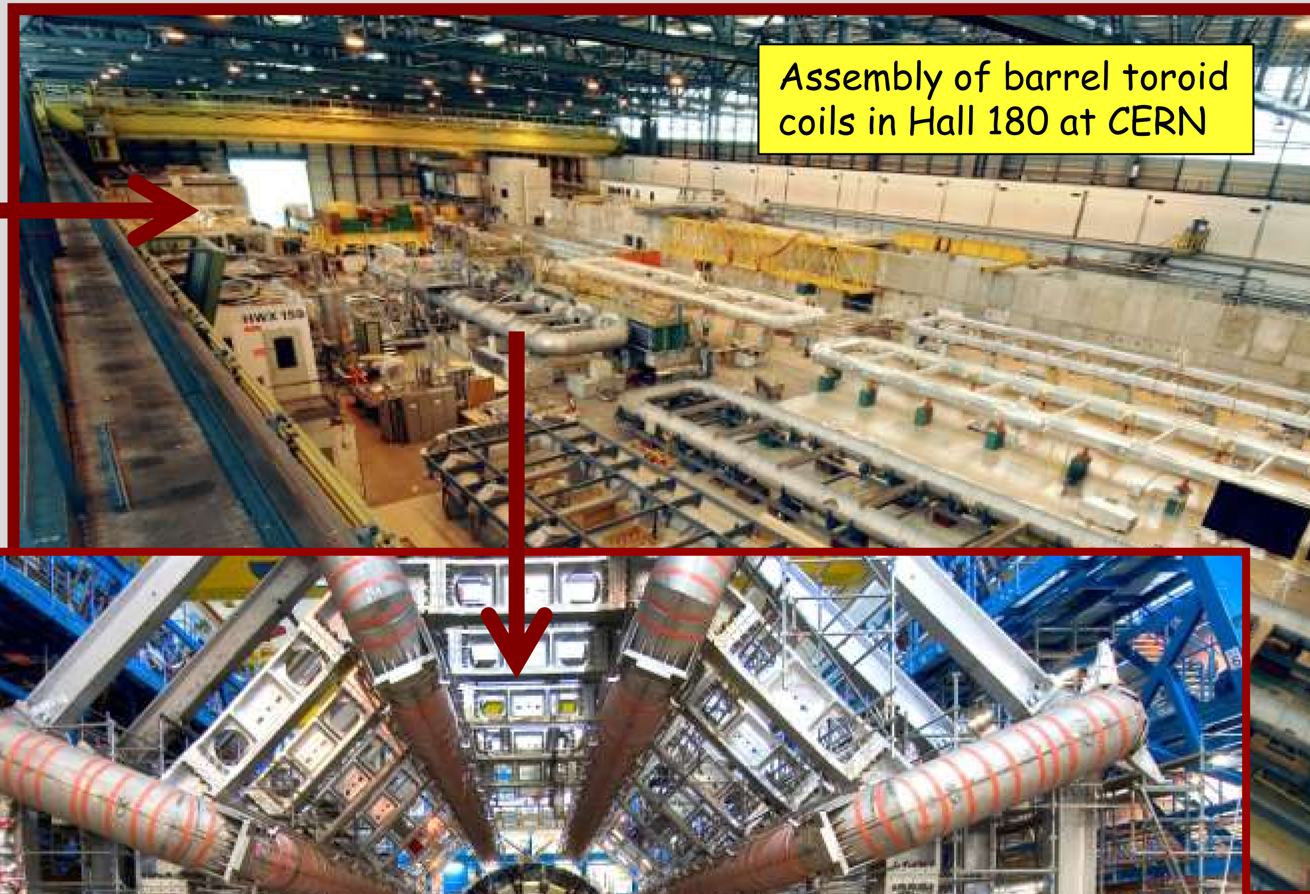
Unprecedented experiments
(complexity, technology, performance)

ATLAS

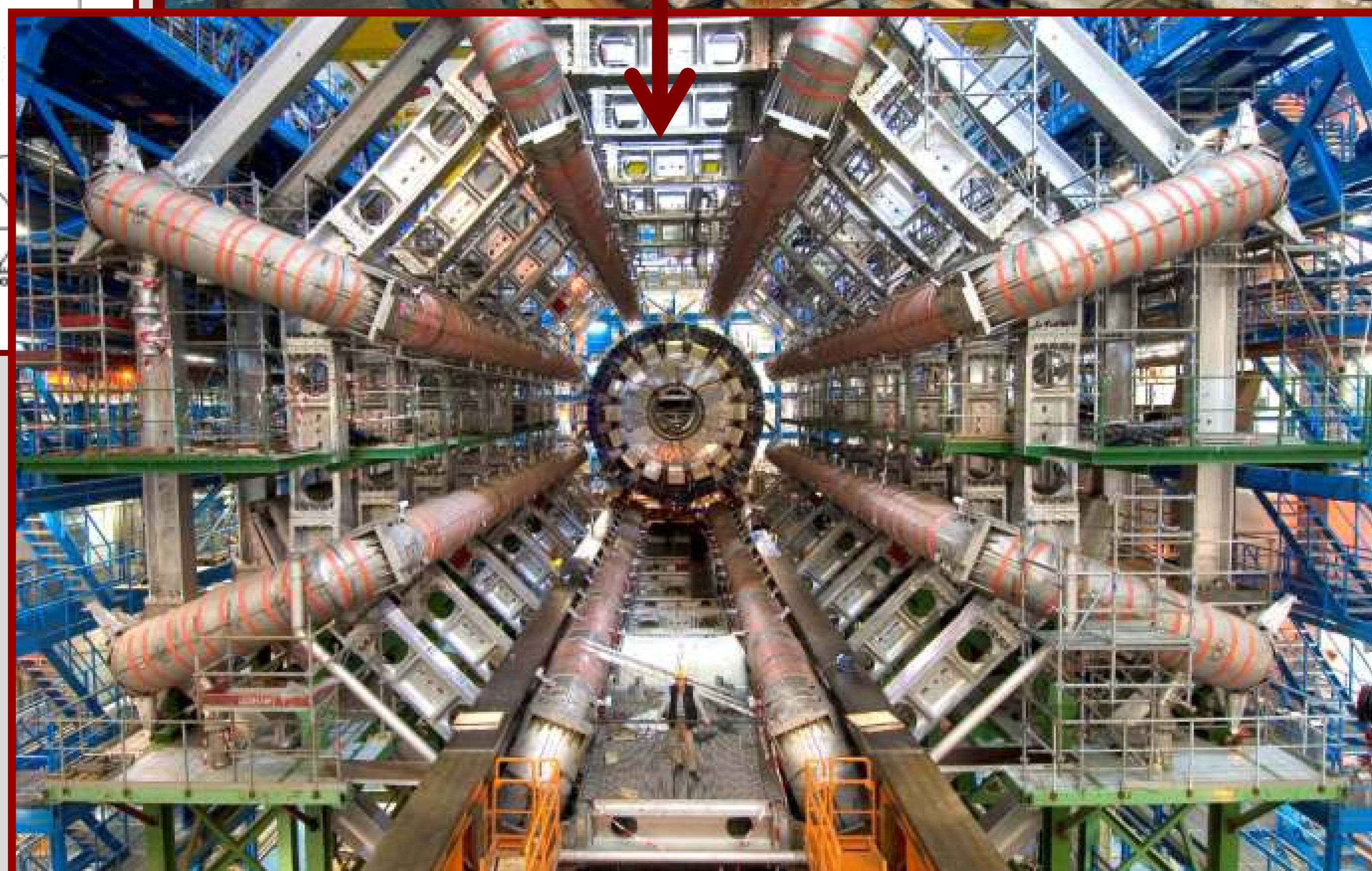
Length : ~ 46 m
Radius : ~ 12 m
Size: 0.5 x Notre Dame
Weight : ~ 7000 tons
~10^8 electronic channels
3000 km of cables



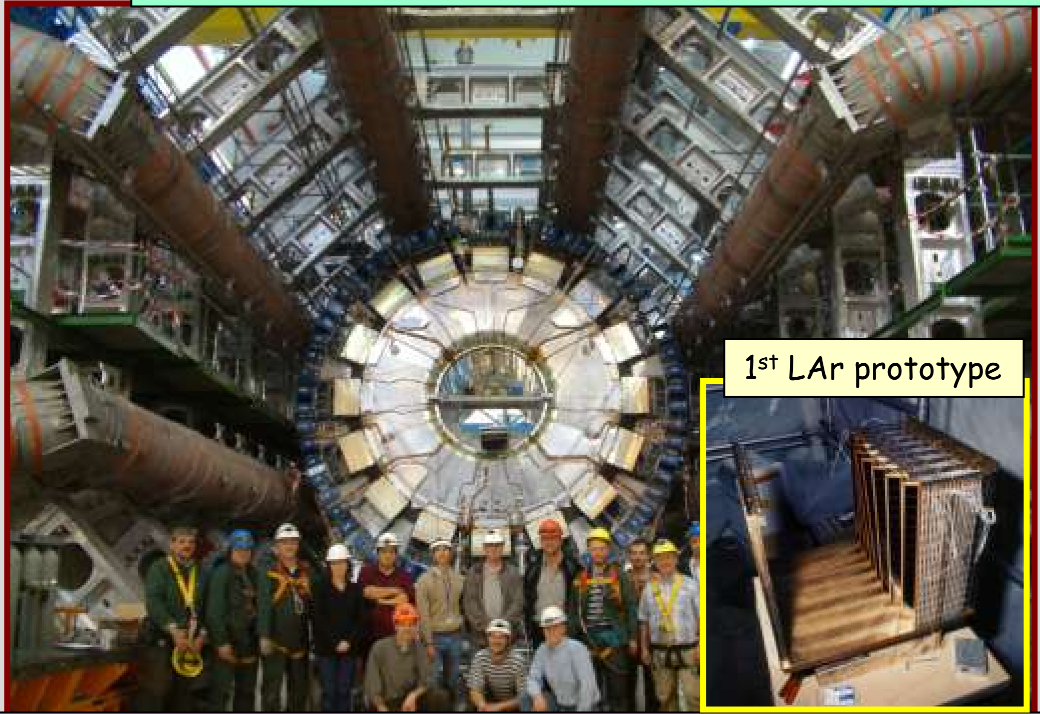




Assembly of barrel toroid coils in Hall 180 at CERN



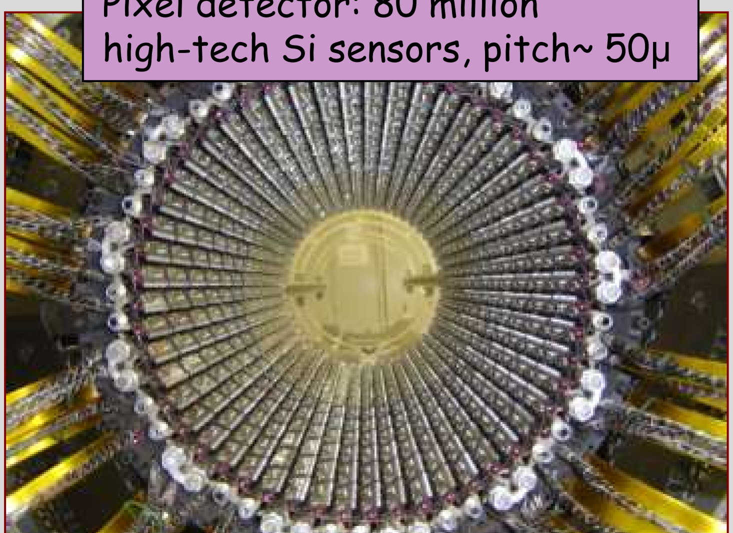
3 examples of the very strong Italian contribution to ATLAS

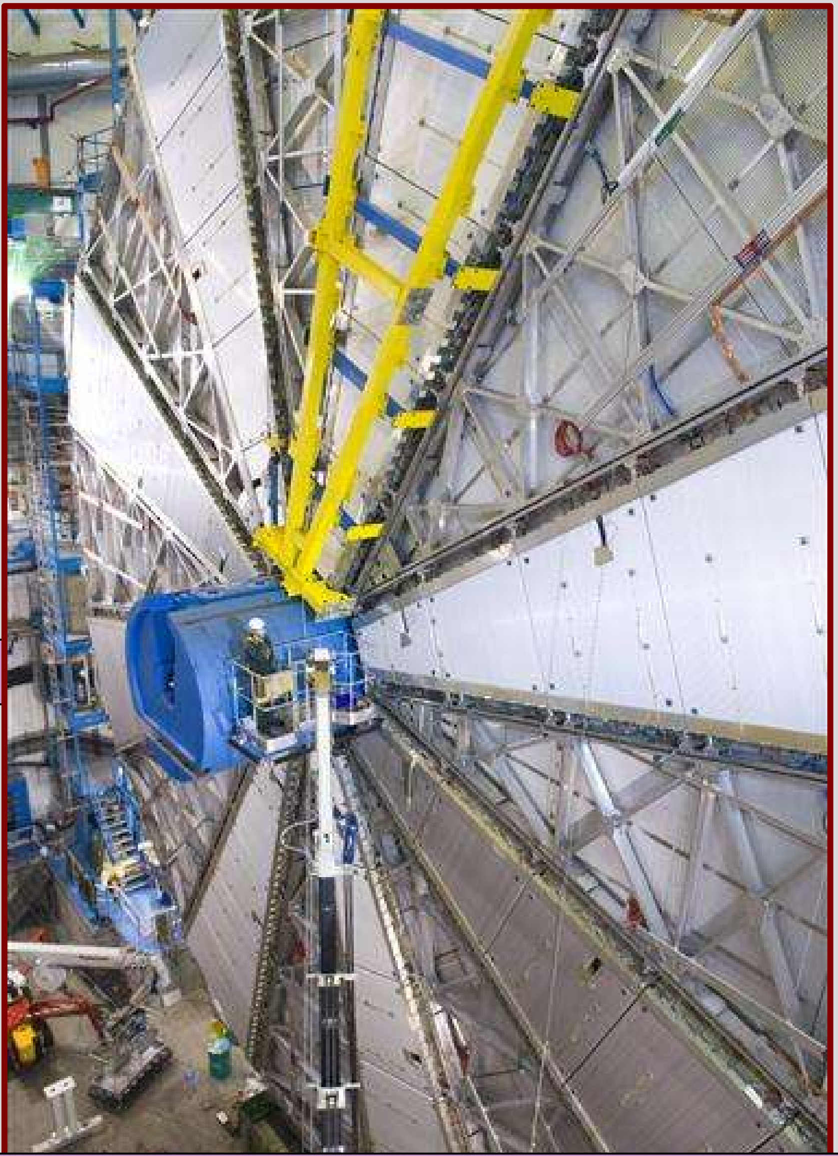


1st LAr prototype

Liquid-argon electromagnetic and Tile hadronic calorimeters

Pixel detector: 80 million
high-tech Si sensors, pitch~ 50μ

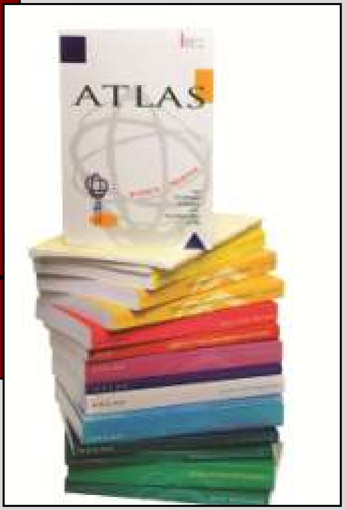




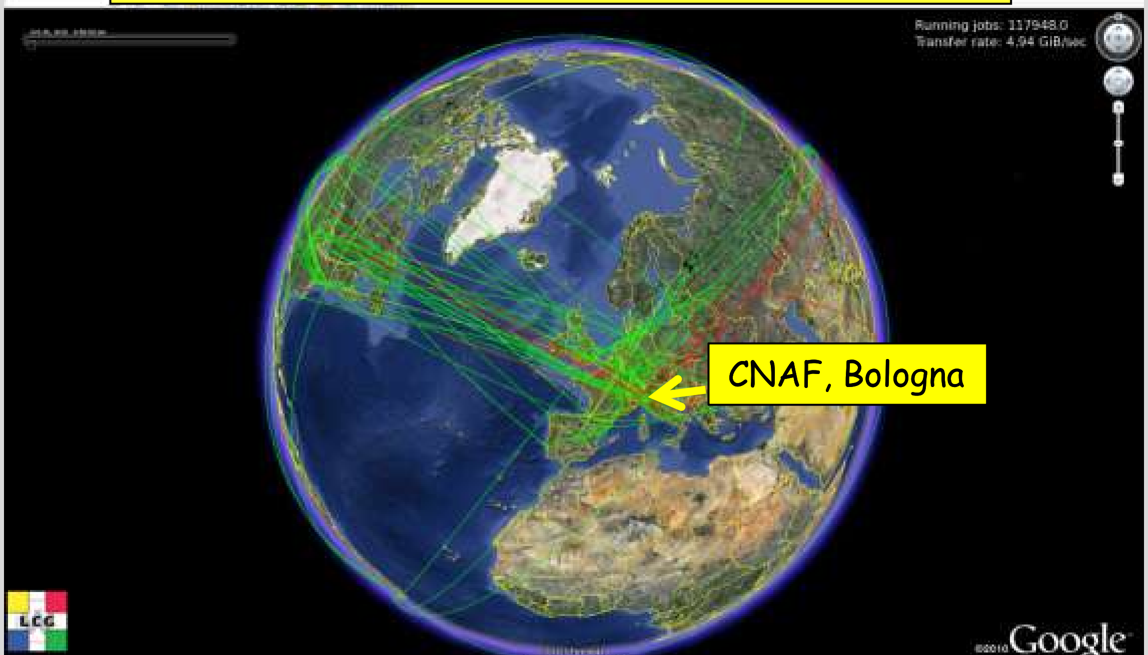
Muon Spectrometer: ~ 5500 gas-based devices
(mainly drift chambers) covering > 1 football field

AND ....

Thousands of quality controls of individual components
15 years of tests with beams,
20 years of detector and physics simulations,
17 Technical Design Reports,
8 years of world-wide computing data challenges

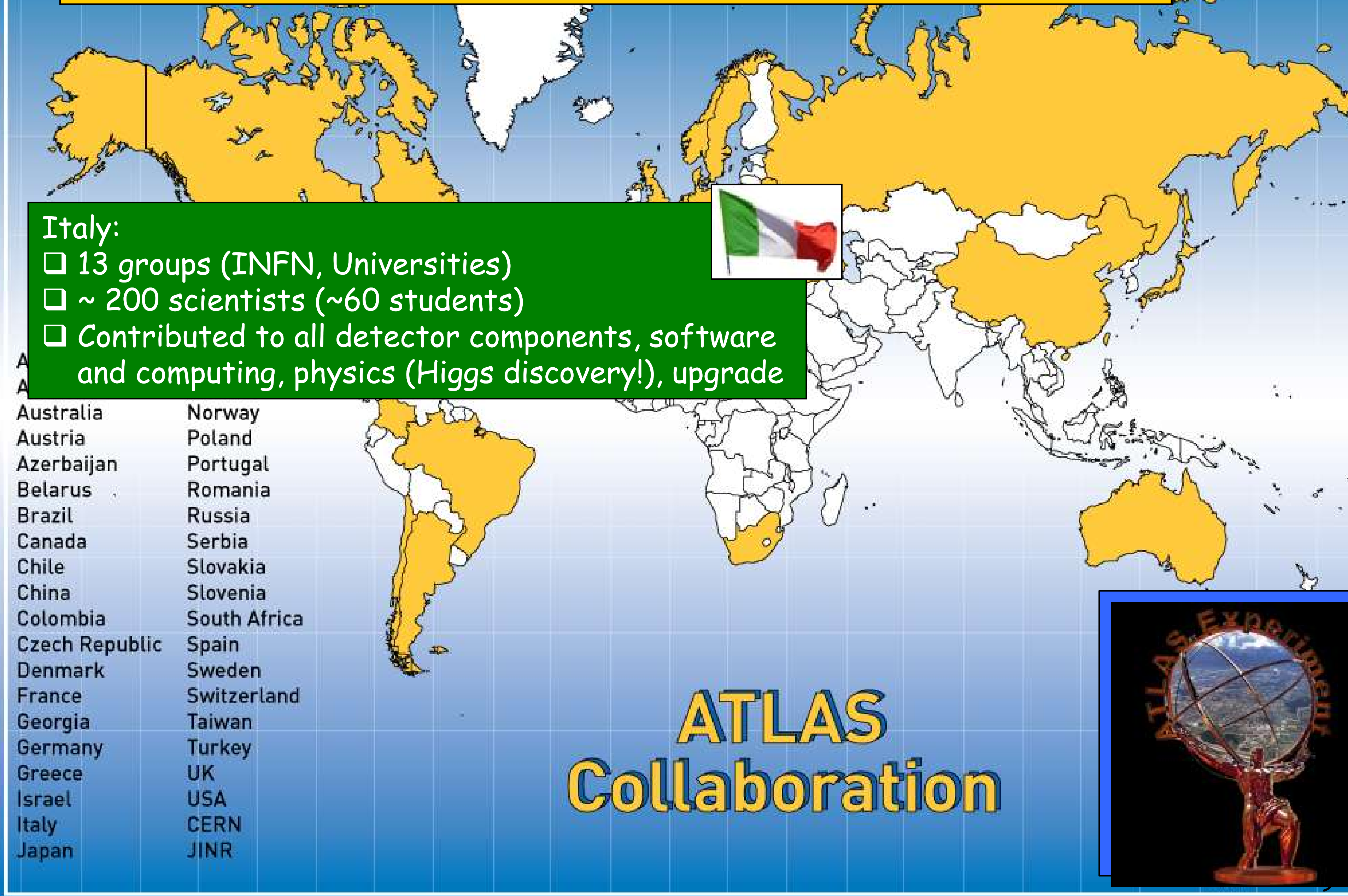


Worldwide LHC Computing Grid (WLCG):
~ 150 computing centres, ~ 35 countries

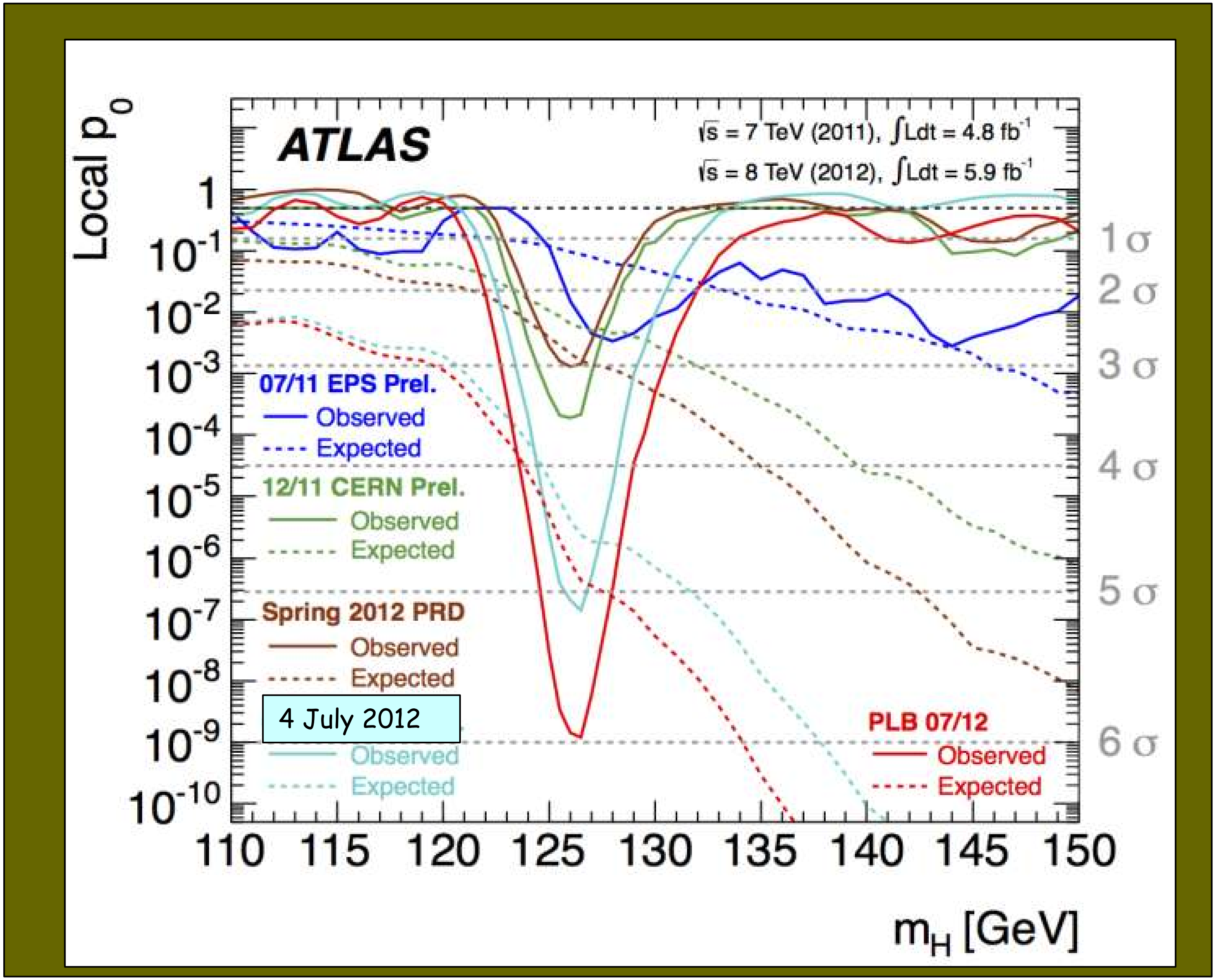


~ 3000 scientists (1000 PhD students) from 177 Institutions and 38 Countries

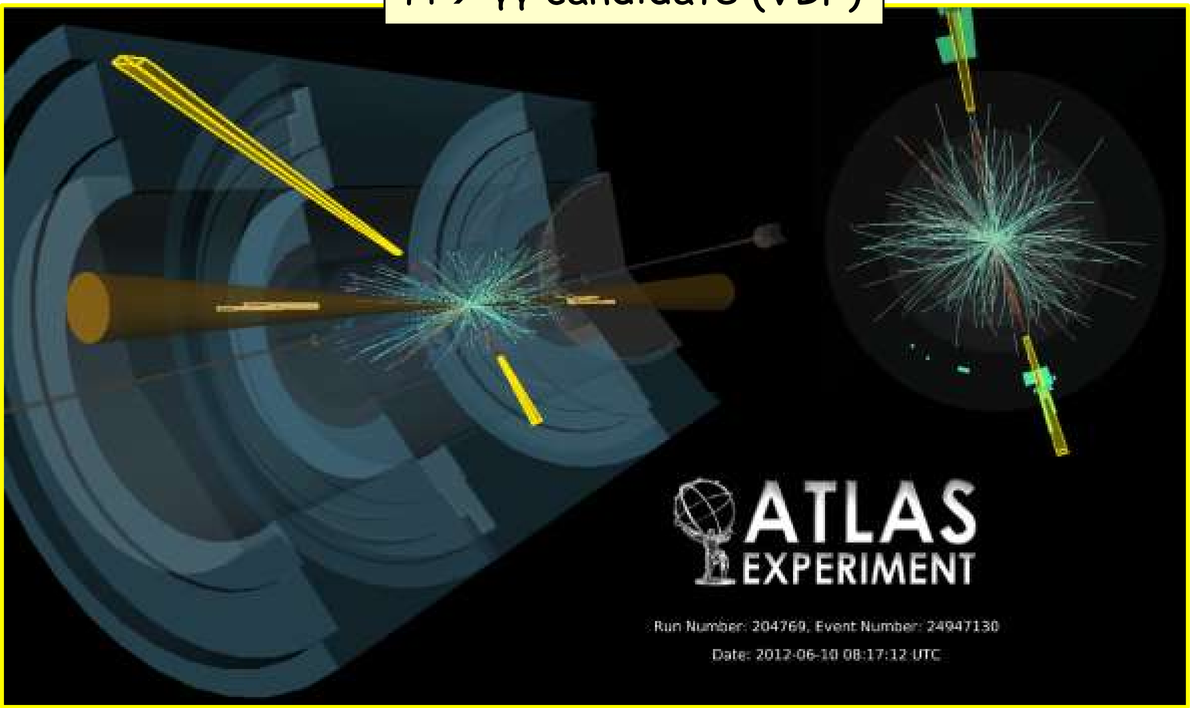
Italy:
- 13 groups (INFN, Universities)
- ~ 200 scientists (~60 students)
- Contributed to all detector components, software and computing, physics (Higgs discovery!), upgrade

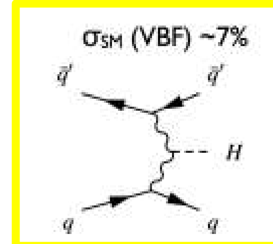


History: evolution of the excess with time



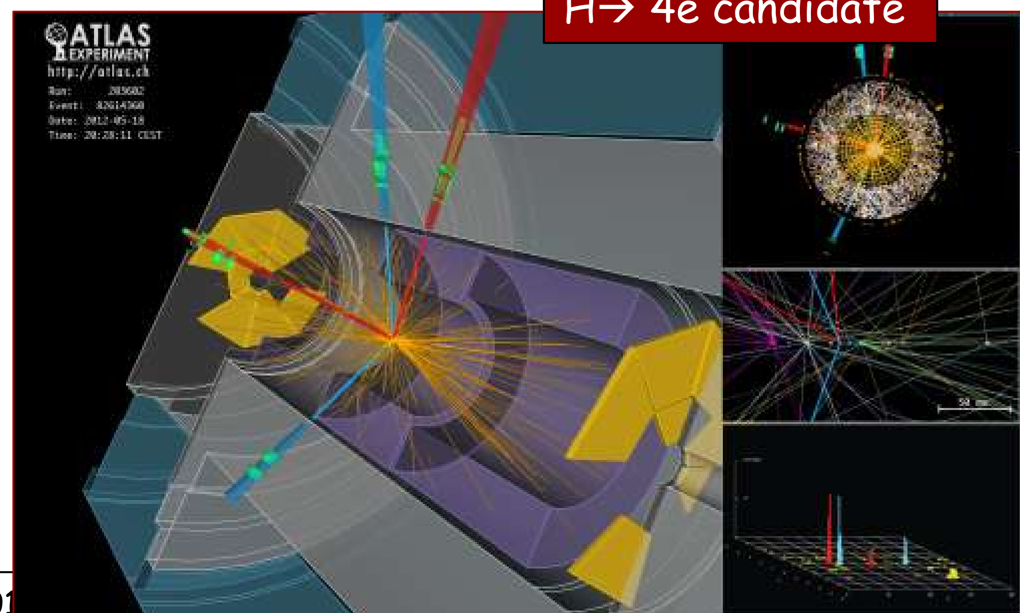
H→ γγ candidate (VBF)





M_{jj} ~ 2 TeV !

H→ 4e candidate

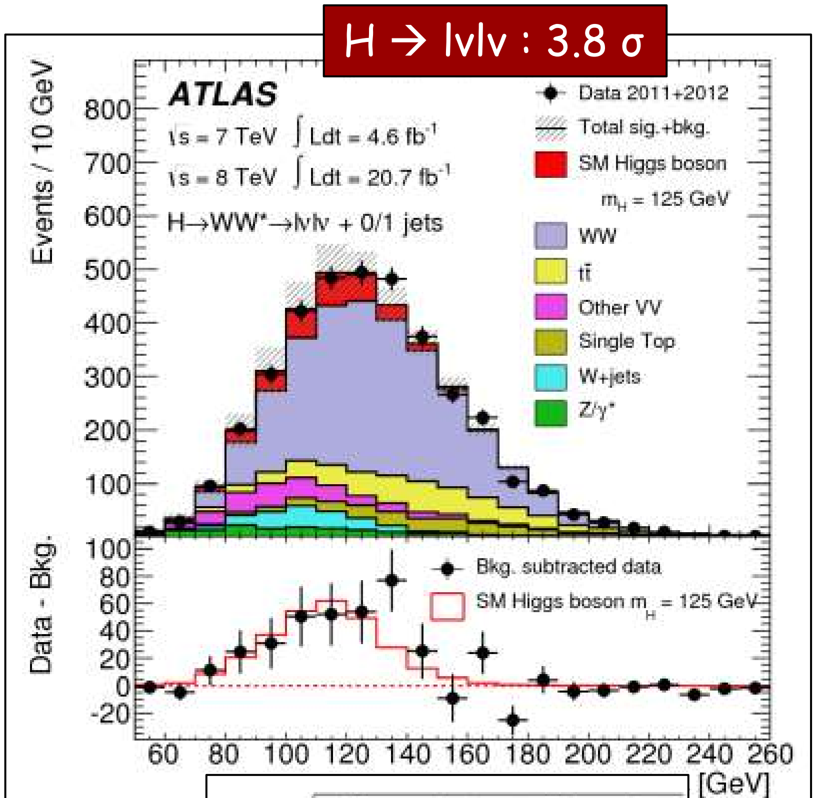


Finding the Higgs boson was not easy: one H→ 4e produced every 10^{13} pp collisions
→ required ingenuity, lots of ideas in data analysis and a huge amount of meticulous experimental work
(<u>in large part made by young people</u> !)

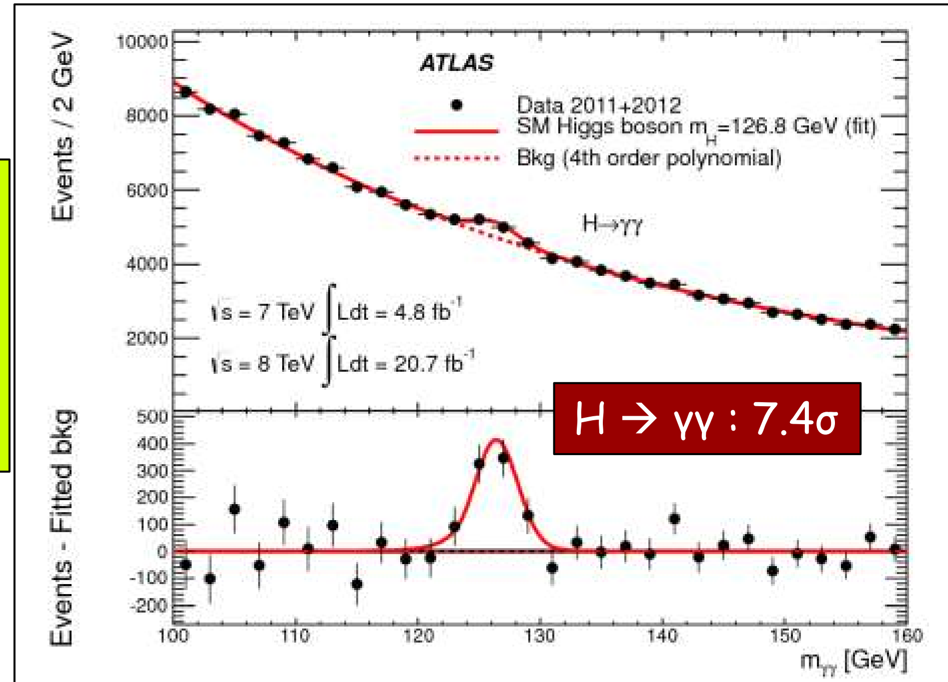
Where do we stand today ?

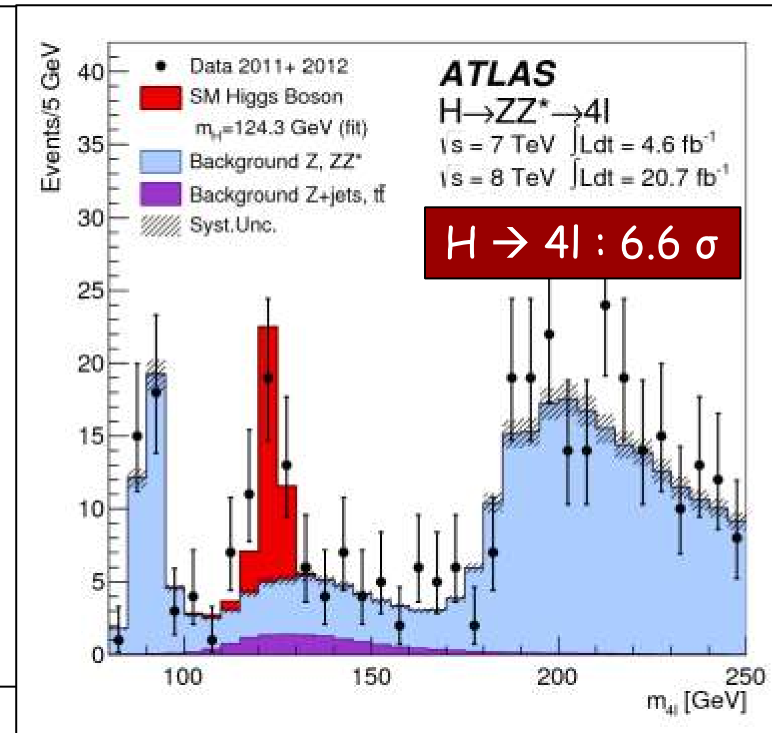
Full ATLAS Run-1 dataset: ~ 25 fb^{-1}
~ 700 Higgs events after all selection

Combining all channels (γγ, ZZ, WW, ττ, bb):
~ 10σ significance or 10^{-24} probability
excess due background fluctuation



$$m_T = \sqrt{(E_T^{\ell\ell} + E_T^{miss})^2 - (\mathbf{P}_T^{\ell\ell} + \mathbf{P}_T^{miss})^2}$$

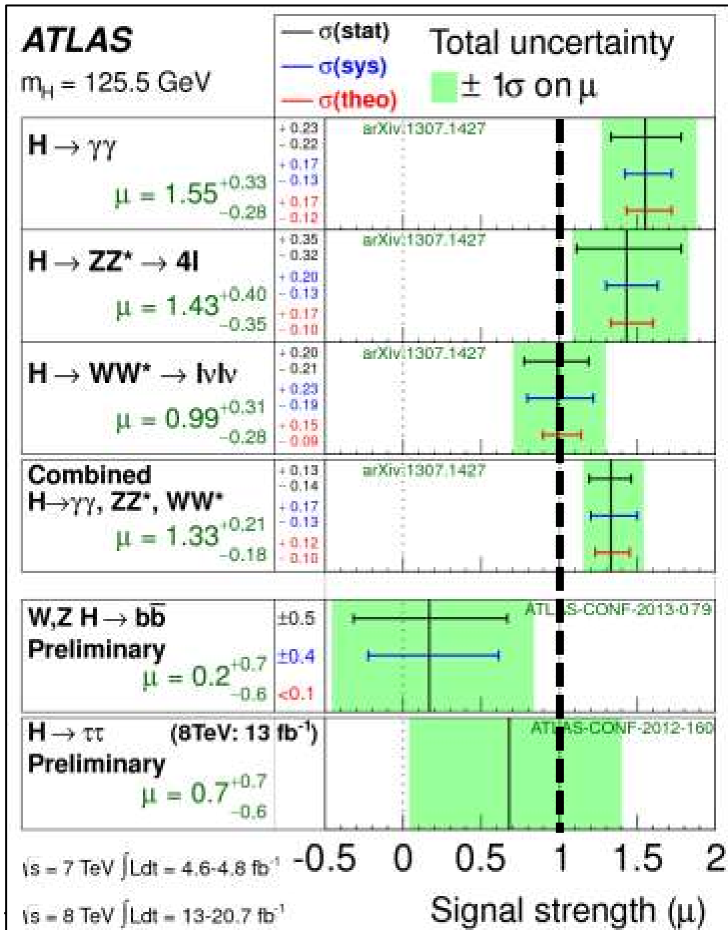


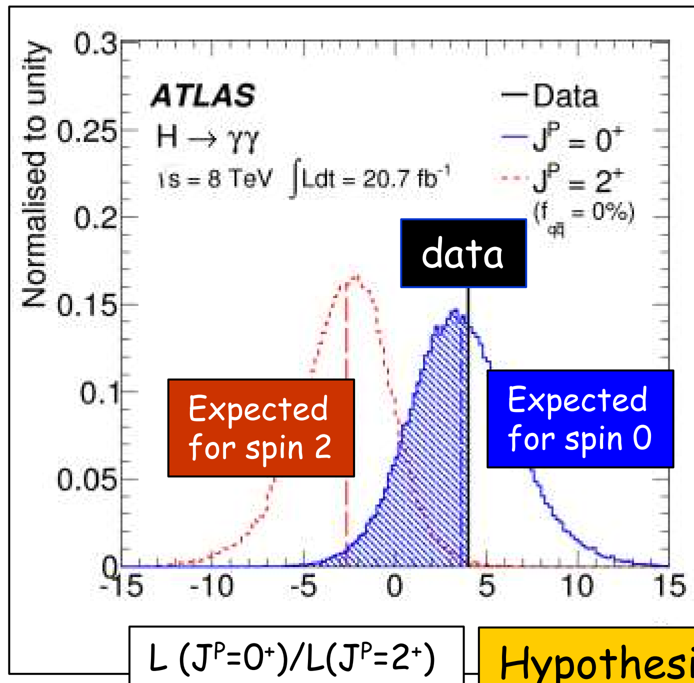


A new phase started: precise measurements of the properties of the new particle (only a few examples here …)

The first 2 questions:
- ❑ is it A Higgs boson ?
- ❑ is it THE SM Higgs boson ?

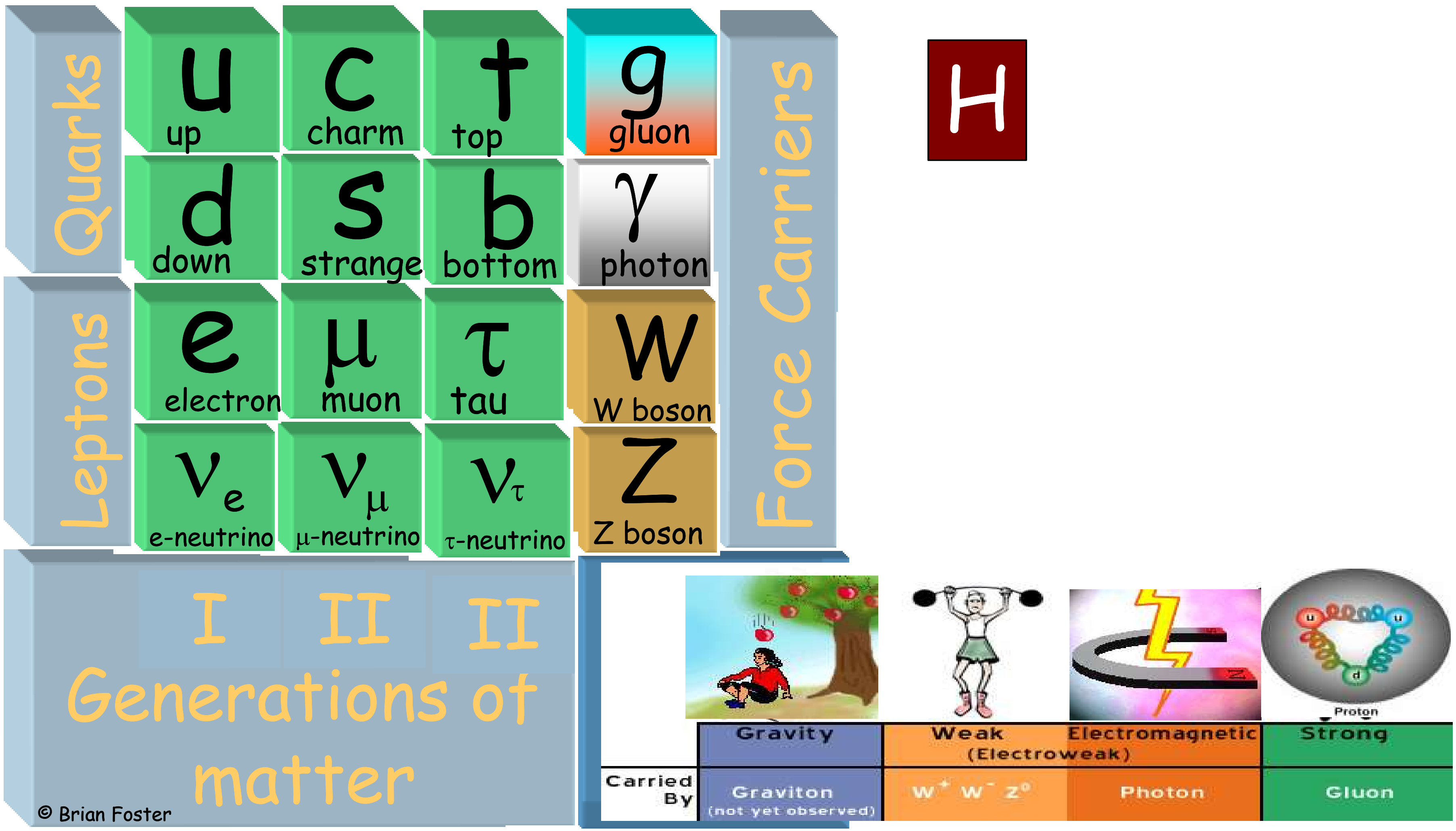
Two "fingerprints":
- ❑ To accomplish its job (EWSB, providing mass) it interacts with other particles (in particular W, Z) with strength proportional to their masses
- ❑ zero spin (scalar)

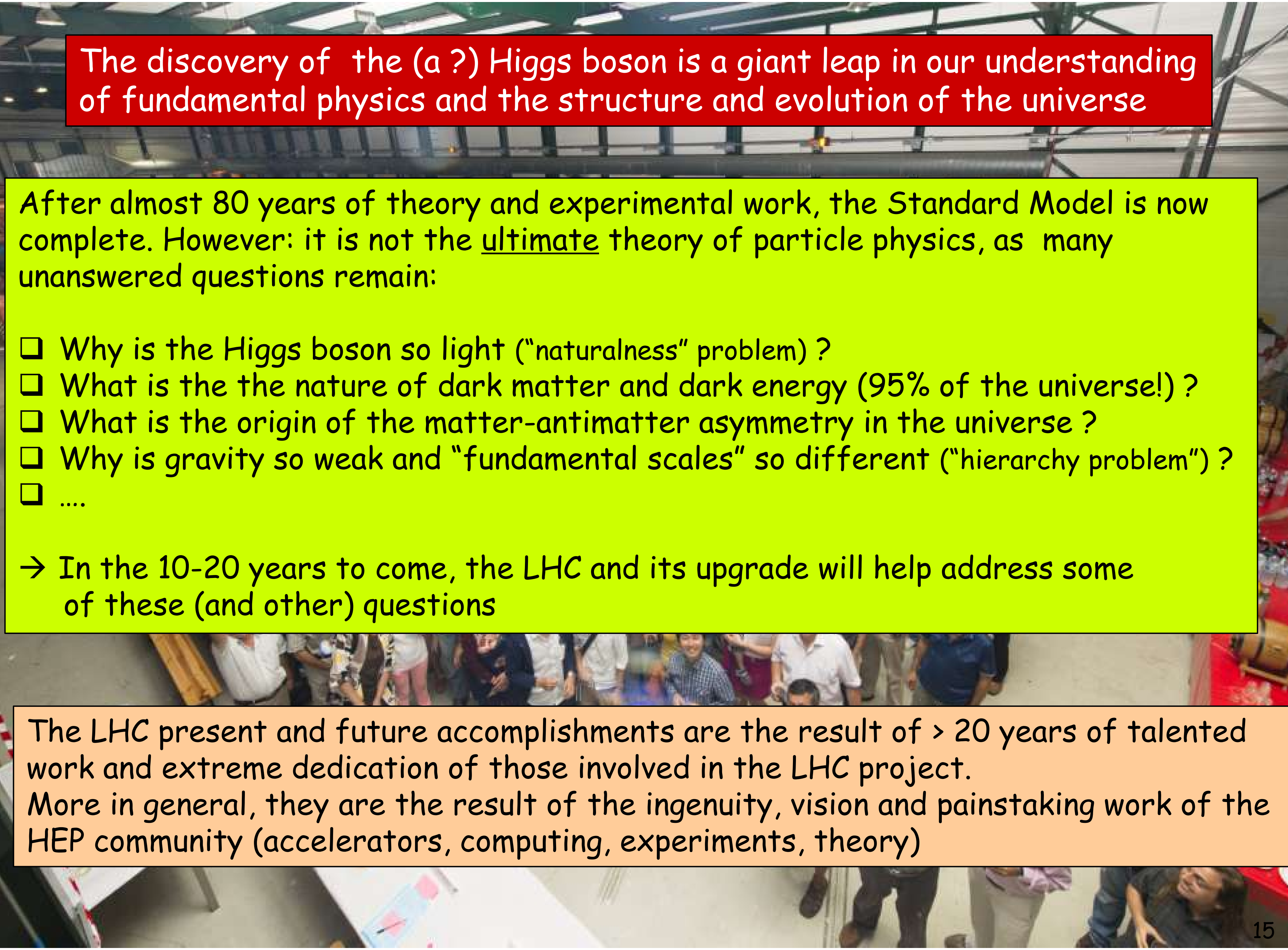




Hypothesis	Rejection (C.L.)
0^-	97.8%
1^+	99.97%
1^-	99.7%
2^+	99.9%

The world of elementary particles after 4 July 2012





The discovery of the (a ?) Higgs boson is a giant leap in our understanding of fundamental physics and the structure and evolution of the universe

After almost 80 years of theory and experimental work, the Standard Model is now complete. However: it is not the ultimate theory of particle physics, as many unanswered questions remain:

- Why is the Higgs boson so light ("naturalness" problem) ?
- What is the the nature of dark matter and dark energy (95% of the universe!) ?
- What is the origin of the matter-antimatter asymmetry in the universe ?
- Why is gravity so weak and "fundamental scales" so different ("hierarchy problem") ?
- ….

→ In the 10-20 years to come, the LHC and its upgrade will help address some of these (and other) questions

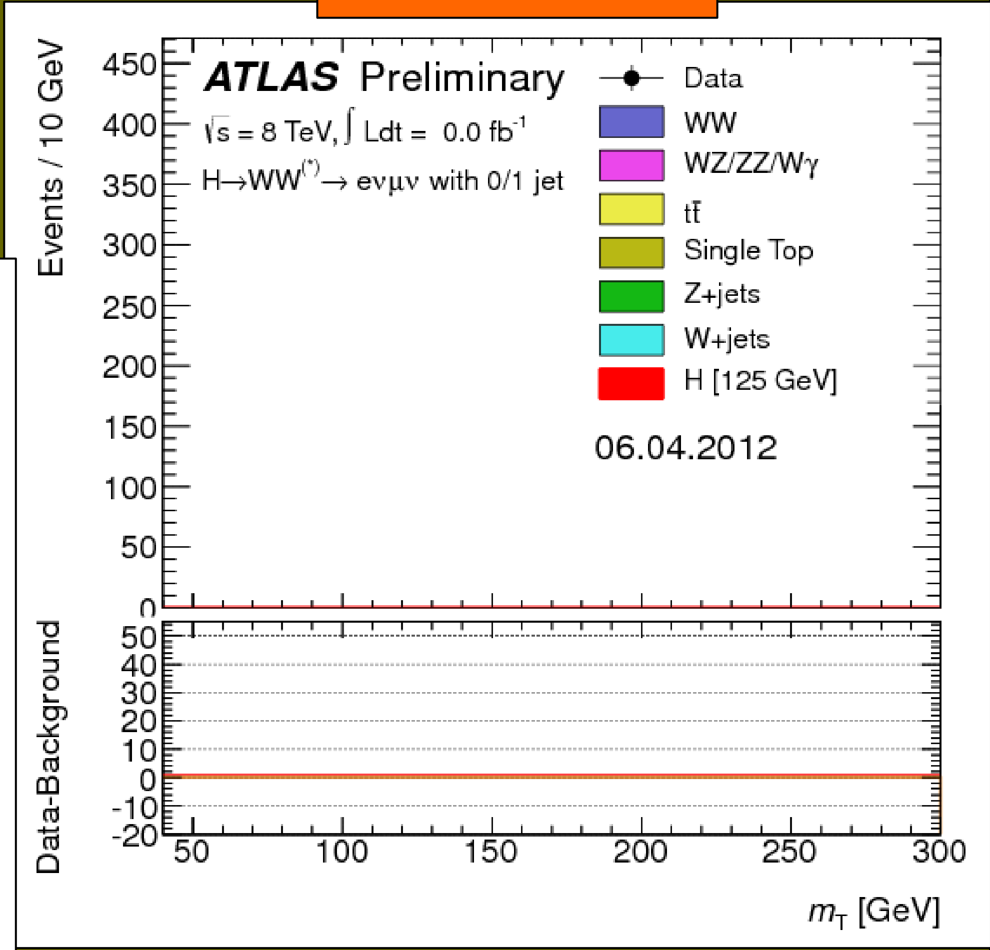
The LHC present and future accomplishments are the result of > 20 years of talented work and extreme dedication of those involved in the LHC project.
More in general, they are the result of the ingenuity, vision and painstaking work of the HEP community (accelerators, computing, experiments, theory)

I am deeply grateful to SIF for the Enrico Fermi Prize and extremely honoured.
I share it with all my ATLAS colleagues, in particular the > 200 Italian physicists, engineers and technicians, and the many young people of our wonderful Collaboration

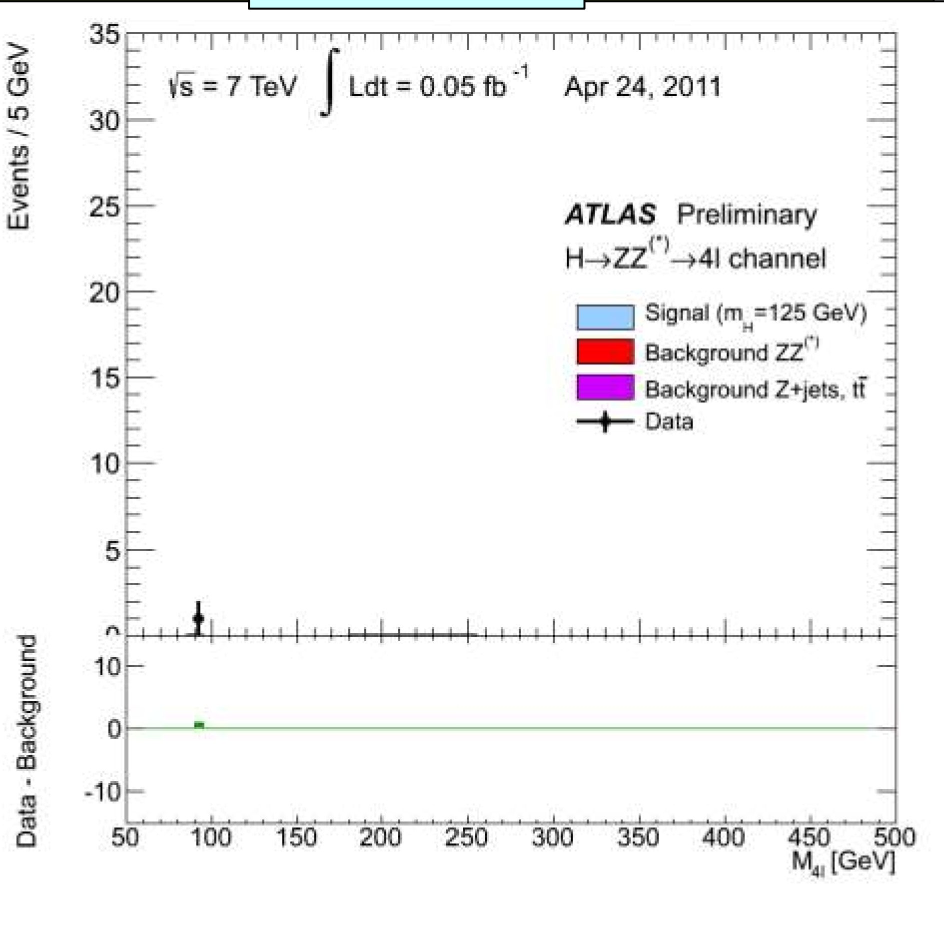
GRAZIE !

Birth and evolution of a signal

H→ WW*→ lνlν



H→ ZZ*→ 4l



SPARES

Age distribution of the ATLAS population