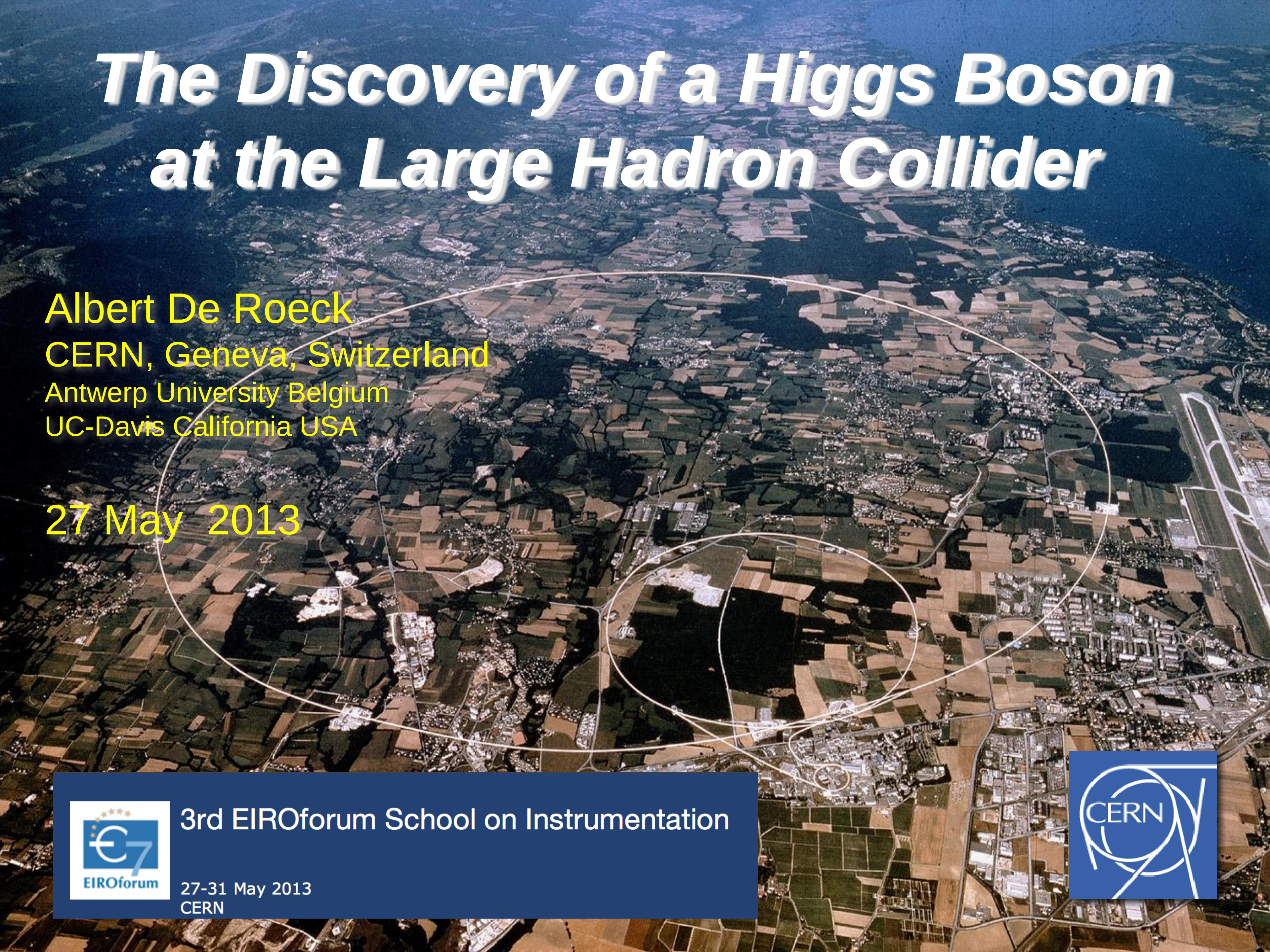


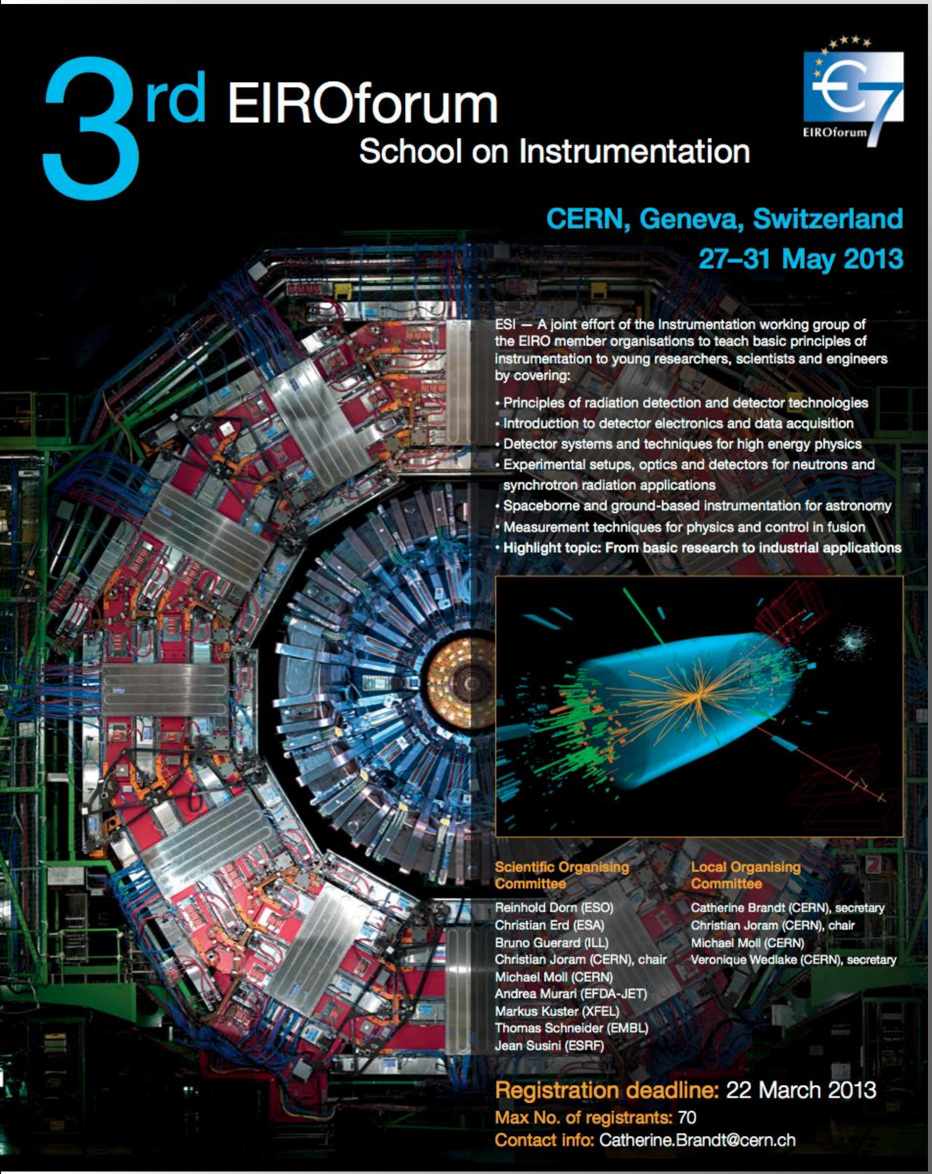
The Discovery of a Higgs Boson at the Large Hadron Collider

Albert De Roeck
CERN, Geneva, Switzerland
Antwerp University Belgium
UC-Davis California USA

27 May 2013

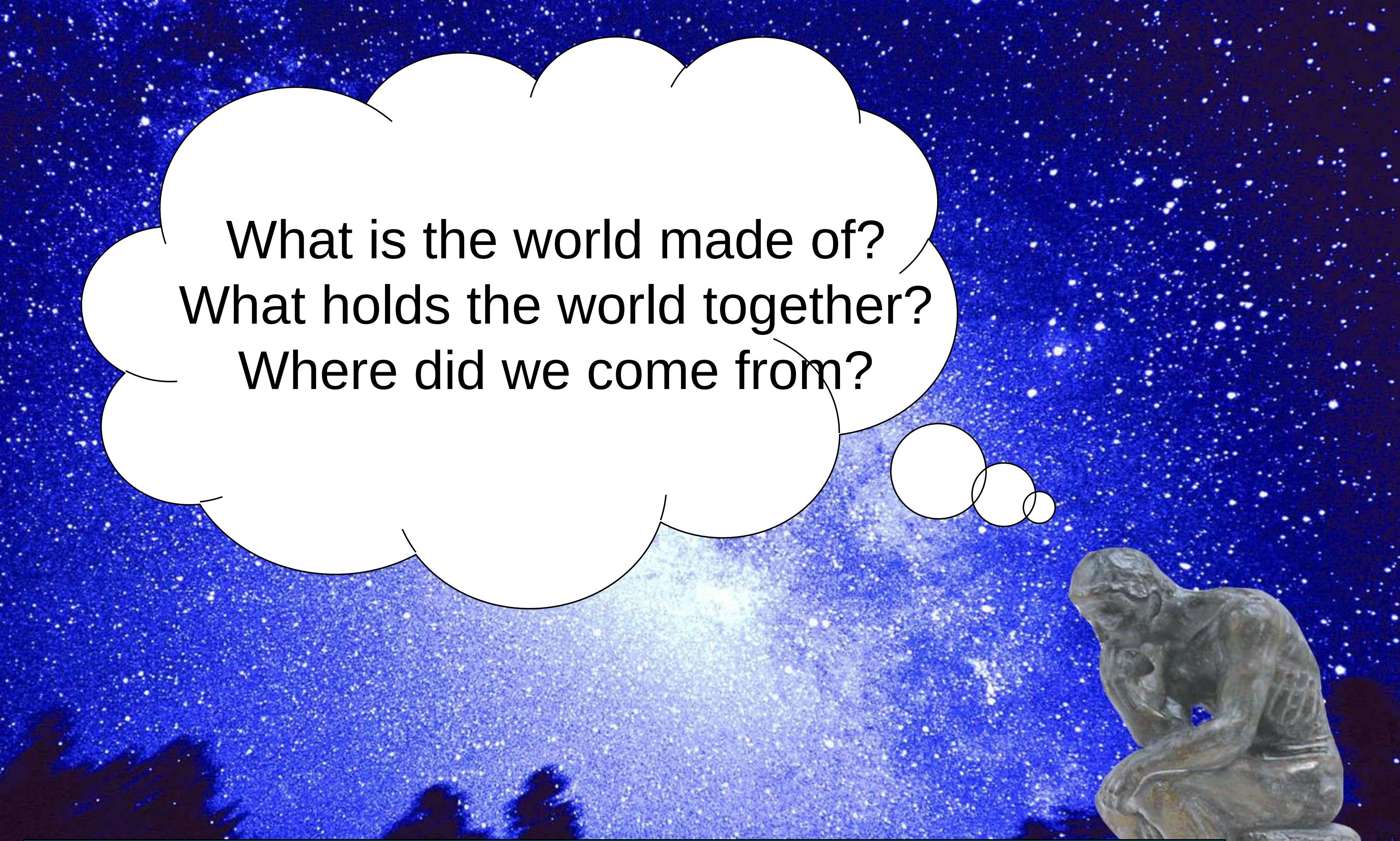
EIROforum
3rd EIROforum School on Instrumentation
27-31 May 2013
CERN

CERN



Outline

- Introduction
- Higgs particle searches
- The birth of a new particle
- Studies of Higgs properties
- What is next?
- Summary



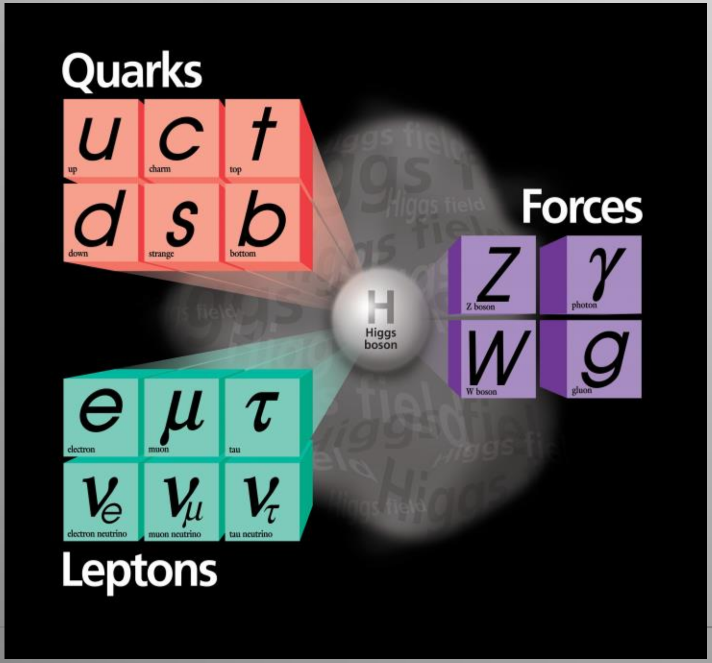
Particle physics is a modern name for centuries old effort to understand the laws of Nature

E. Witten (String Theorist)

The "Standard Model"

Over the last 100 years: combination of
Quantum Mechanics and Special Theory of relativity
along with all new particles discovered has led to the
Standard Model of Particle Physics.
The new (final?) "Periodic Table" of fundamental elements:

Matter particles



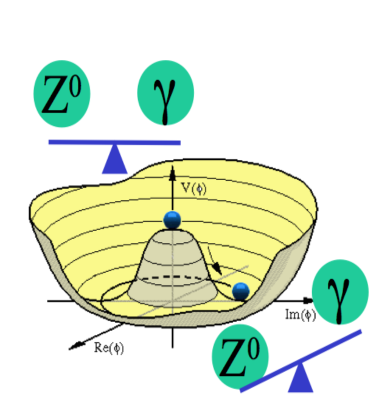
Force particles

The most basic mechanism of the SM, that of granting mass to particles remained a mystery for a long time
A major step forward was made in July 2012 with the discovery of what could be the long-sought Higgs boson!!

- Forces: weak, strong and electromagnetic
- Gravity plays no role so far in experimental HEP

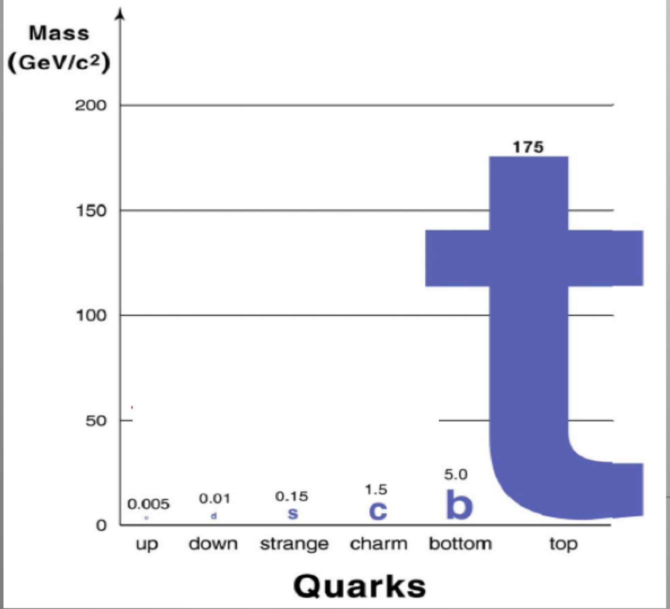
The Origin of Particle Masses

- At ‘low’ energy the Weak force is much weaker than the Electromagnetic force: Electroweak Symmetry Breaking
- The W an Z bosons are very massive (~ 100 proton masses) while the photon is massless.
- The proposed mechanism(*) in 1964 gives mass to W and Z bosons and predicts the existence of a new elementary ‘Higgs’ particle,. Extend the mechanism to give mass to the Fermions via Yukawa couplings.

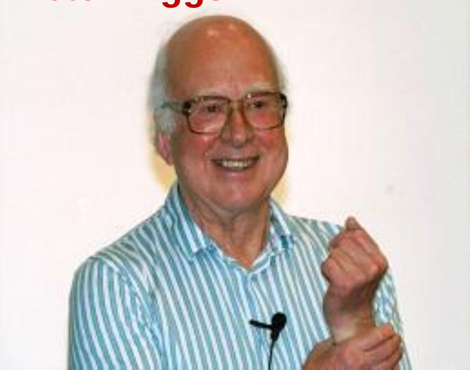


(*) Higgs, Brout Englert, Kibble, Hagen and Guralnik, and…

The Higgs (H) particle is the quantum of the new postulated field and has been searched for since decades at eg LEP and the Tevatron, and now at the large hadron collider @ CERN



Peter Higgs



Francois Englert

The Hunt for the Higgs

Where do the masses of elementary particles come from?

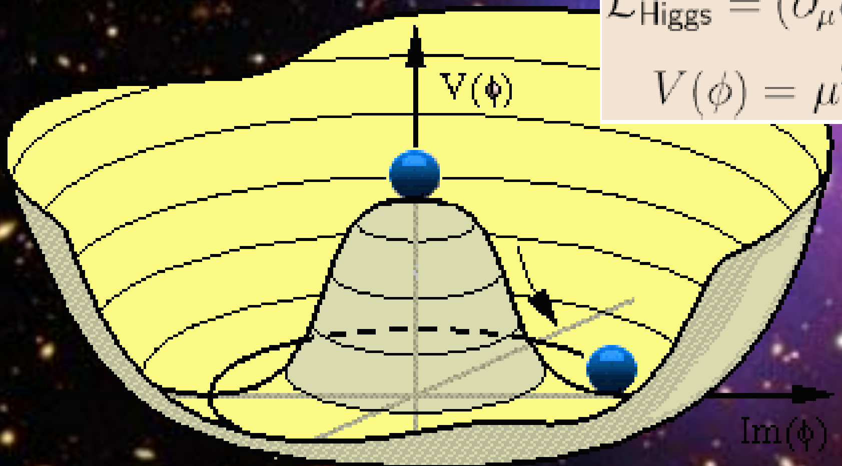
The key question (pre-2012): Does the Higgs particle exist? If so, where is the Higgs?

Massless particles move at the speed of light -> no atom formation!!

We do not know the mass of the Higgs Boson

$$\mathcal{L}_{\text{Higgs}} = (\partial_\mu \phi)^\dagger (\partial^\mu \phi) - V(\phi)$$

$$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2$$



Scalar field with at least one scalar particle

It could be anywhere from 114 to ~700 GeV

This Search Requires…….

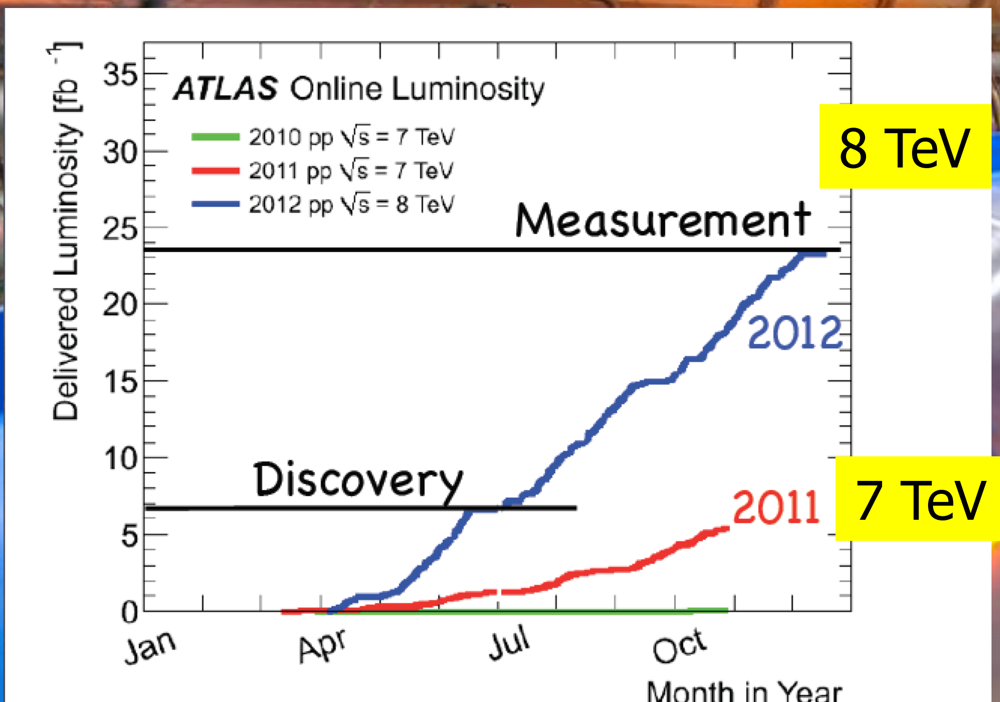
1. Accelerators : powerful machines that accelerate particles to extremely high energies and bring them into collision with other particles

2. Detectors : gigantic instruments that record the resulting particles as they "stream" out from the point of collision.

3. Computing : to collect, store, distribute and analyse the vast amount of data produced by these detectors

4. Collaborative Science on Worldwide scale : thousands of scientists, engineers, technicians and support staff to design, build and operate these complex "machines".

- Several thousand billion protons
- Each with the energy of a fly
- 99.9999991% of light speed
- They orbit a 27km ring 11 000 times/second
- A billion collisions a second in the experiments



Luminosity = # events/cross section/time

LHC operation is now stopped for 2 years, and the machine is being prepared for running at 13-14 TeV from 2015 onwards

100 meter underground

Experiments at the LHC

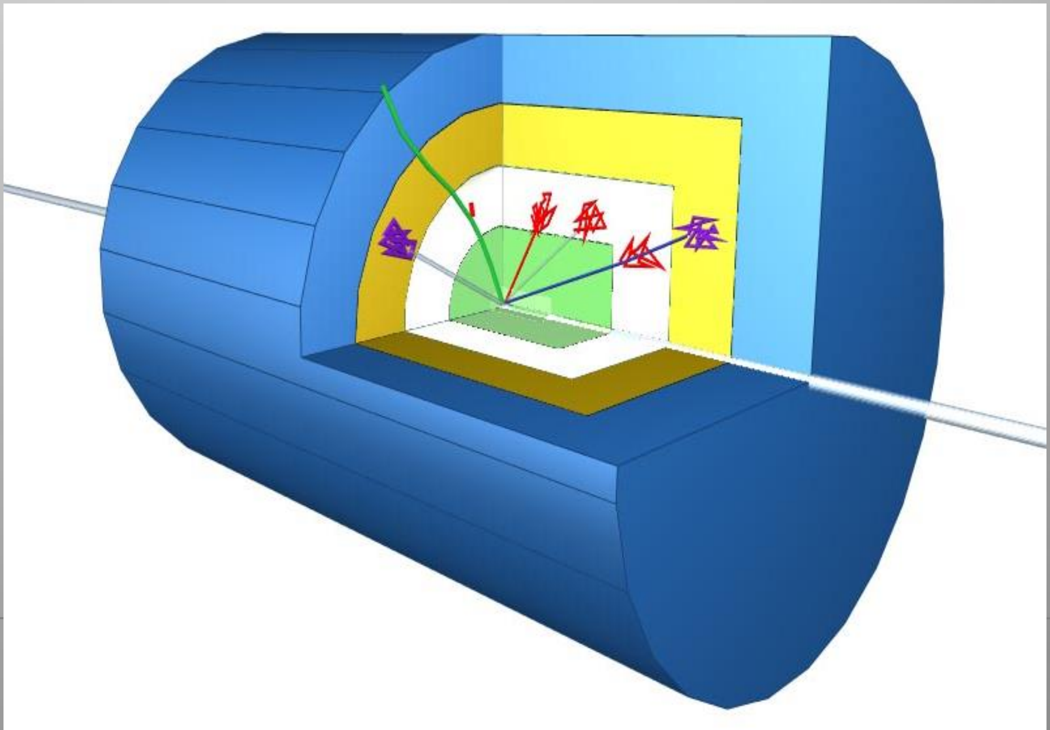
Schematic of a LHC Detector

Physics requirements drive the design!

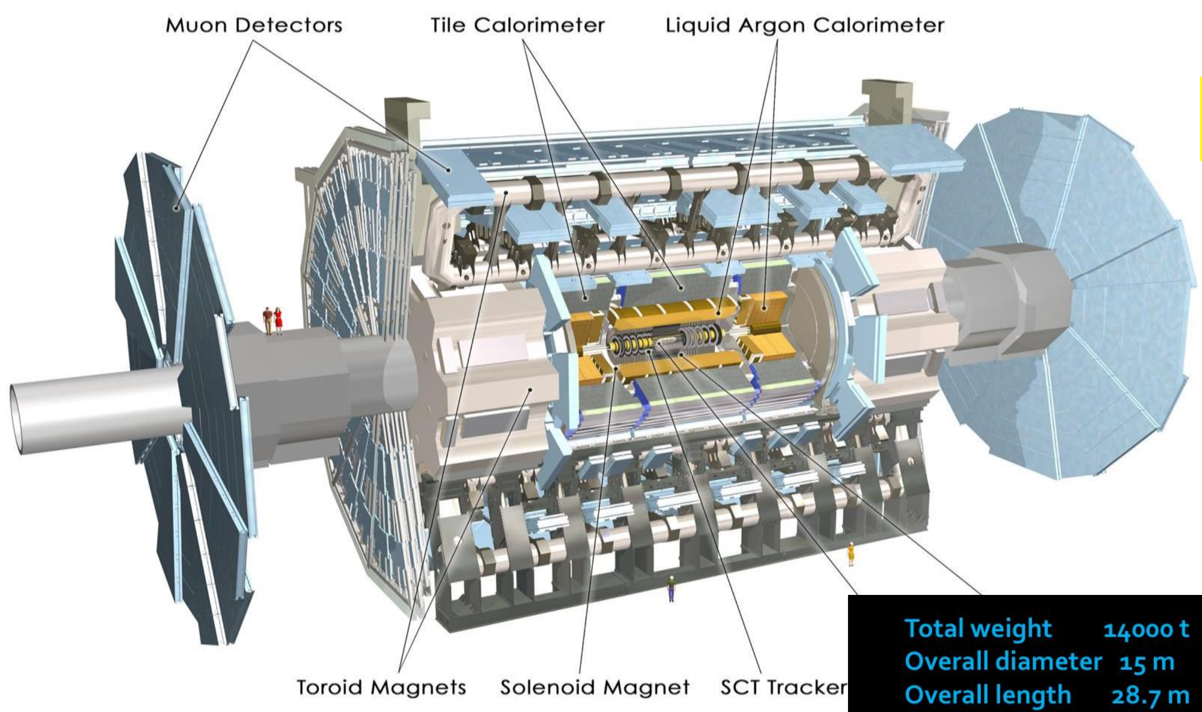
Analogy with a cylindrical onion:

Technologically advanced detectors comprising many layers, each designed to perform a specific task.
Together these layers allow us to identify and precisely measure the energies and directions of all the particles produced in collisions.

Such an experiment has ~ 100 Million read-out channels!!



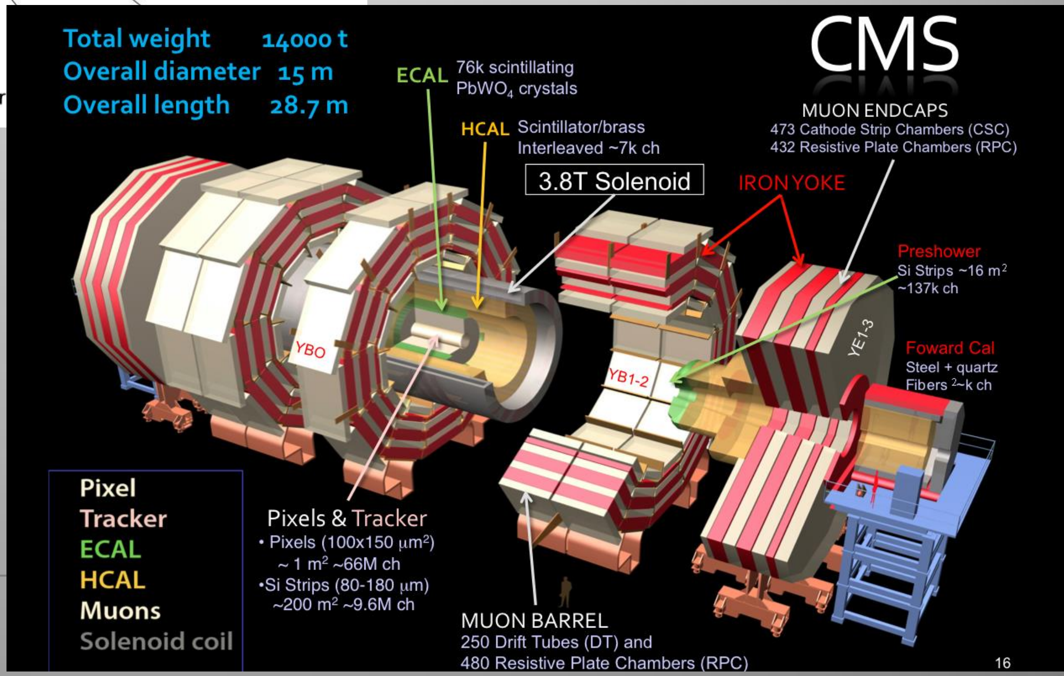
The Higgs Hunters @ the LHC



The ATLAS experiment

CMS	ATLAS
14 ktons	7 ktons
B=3.8 T	B=2 T
15x29 m	22x45 m

The CMS experiment



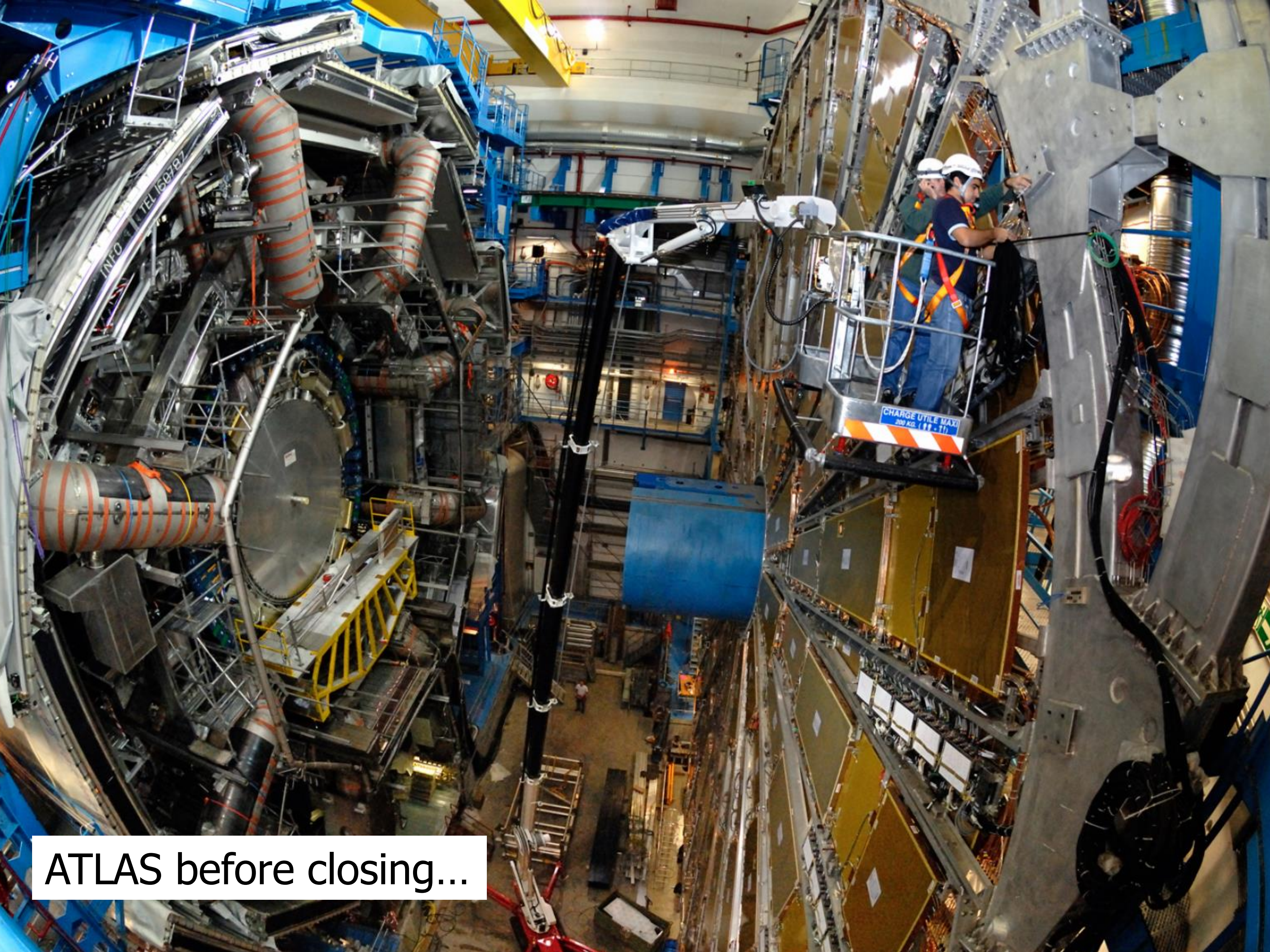
These experiments use different technologies for their detector components

ATLAS & CMS Detector Challenges

- Precise tracking of charged particles in a strong magnetic field
- Energy measurements in calorimeters with excellent resolution and granularity
- Lepton/photon identification and precise jet and lepton/photon measurements
- b-quark jet identification: vertex detectors
- Hermeticity, full coverage: measure 'missing momentum in an event'
- Trigger selection: reduce input data by a factor 10^5
- Huge backgrounds: radiation hardness
- Bunch cross every 25 nanoseconds: timing and synchronization
- High granularity of the sub-detectors
- Pile-up!!! Many collisions per bunch crossing

CMS Collaboration June 27, 2012

The CMS Collaboration: >3300 scientists and engineers, >800 PhD students from ~179 Institutions in 41 countries .



ATLAS before closing…

The Physics Program at LHC

Data taking started in 2010

Now we have more than 200 reviewed scientific papers per experiment!

Mostly measurements/test of the strong and electroweak force at 7 and 8 TeV

-Are quarks the elementary particles?	So far yes
-Do we see supersymmetric particles?	Not yet
-Do we see extra space dimensions?	Not Yet
-Do we see micro-black holes?	No

->The Discovery of a Higgs-like particle!!

Higgs Hunters

Higgs Hunting Basics

Needle-in-the-hay-stack problem

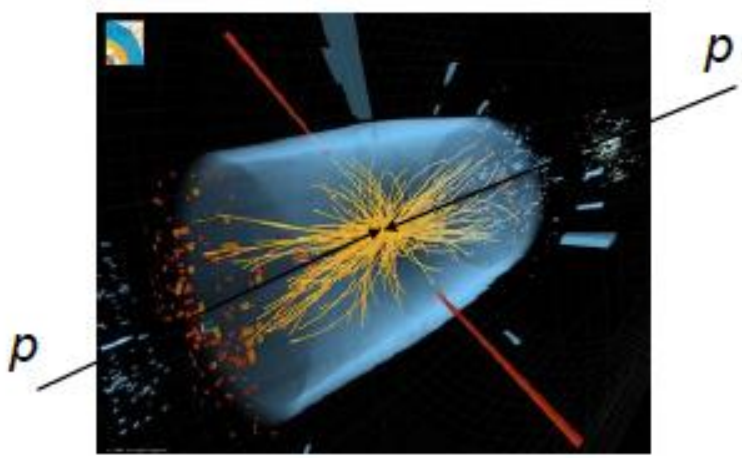
- need high energy:

  $E = mc^2$

- need lots of data

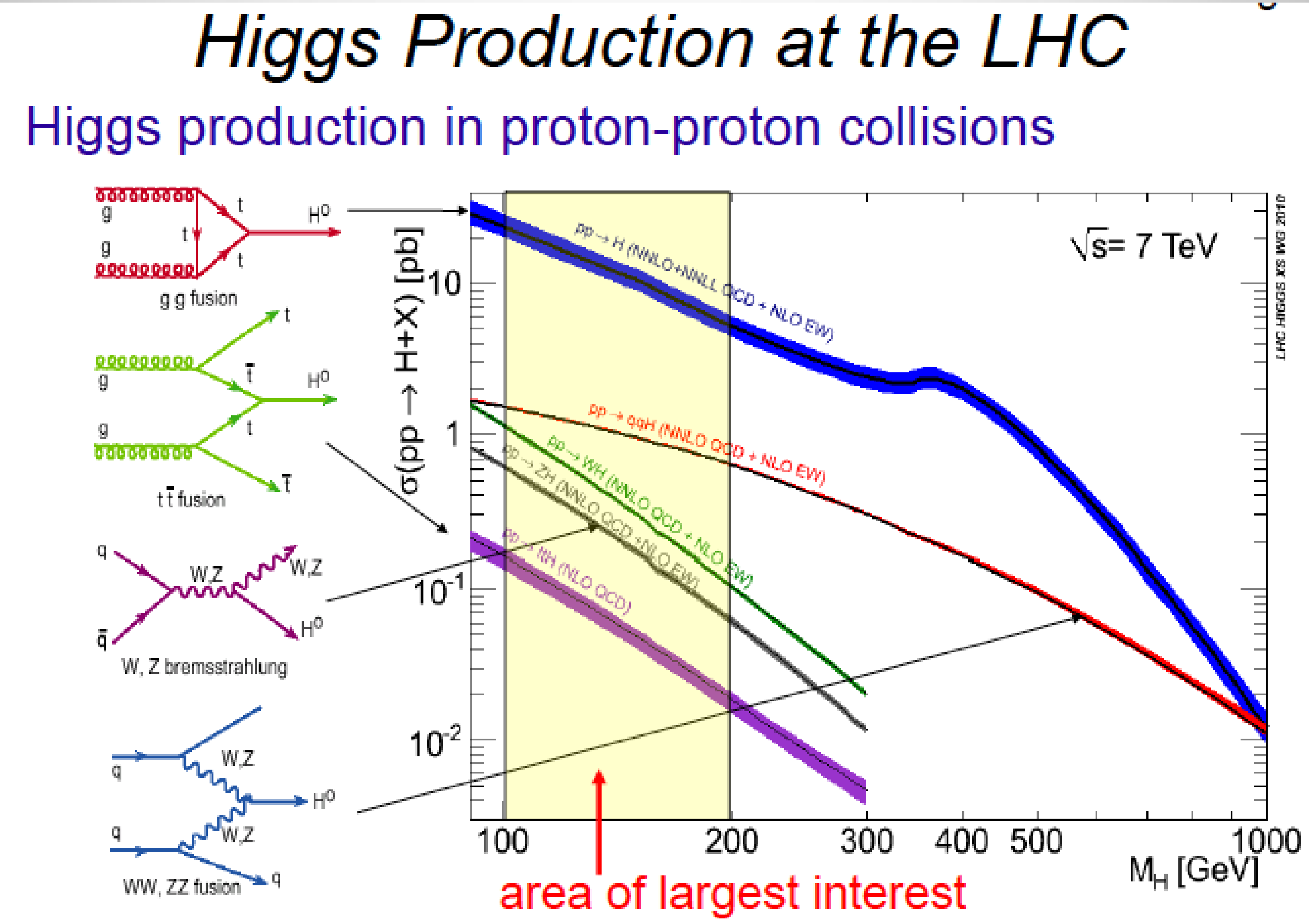
non-deterministic and very rare

order 1 in 10^{11}



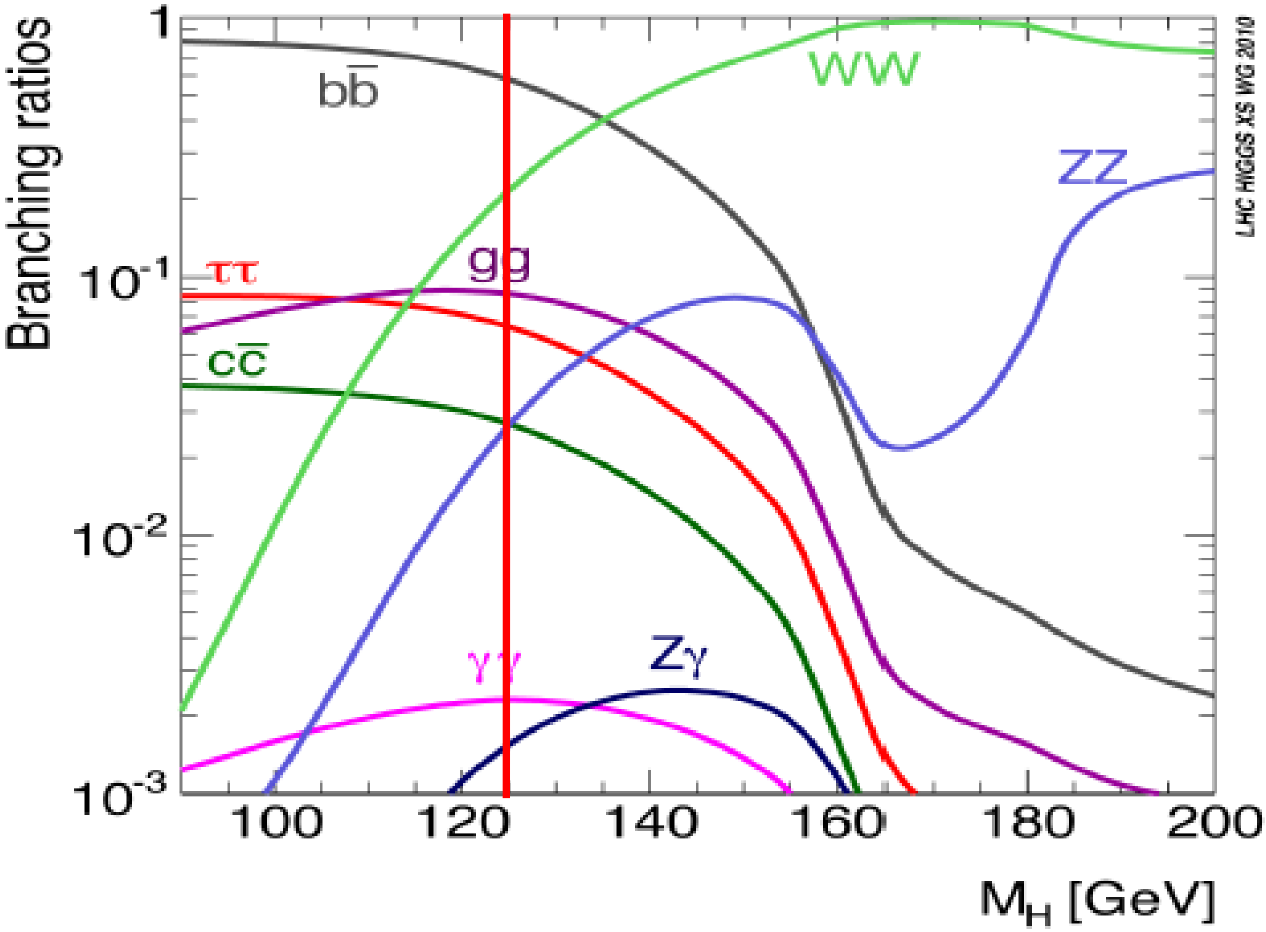
* for us finding the Higgs it was 48 years = 1,513,728,000 sec

Higgs Production Channels vs Mass



We now start to have data on all production channels

Higgs Decay Channel vs. Mass



Higgs boson couples to mass

$$\Gamma_{Hff} \sim m_f^2$$

Messy: many channels, many subsequent decays *etc. etc.*

- common: leptons/photons essential for any search
- 5 channels are most promising

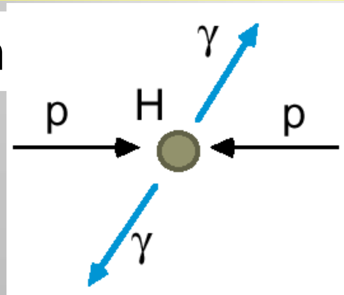
Higgs Boson Searches (simulation)

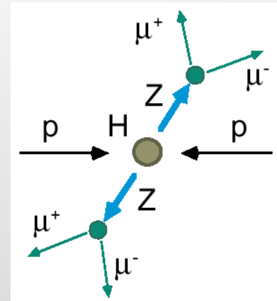
Low M_H < 140 GeV/c²

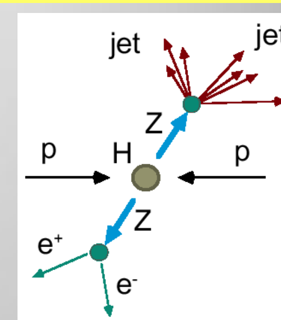
Medium 130<M_H<500 GeV/c²

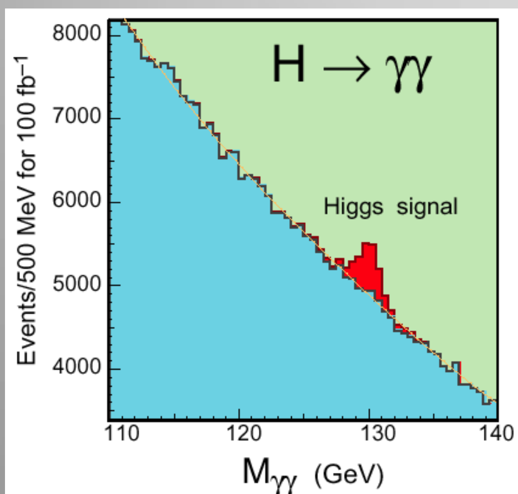
High M_H > ~500 GeV/c²

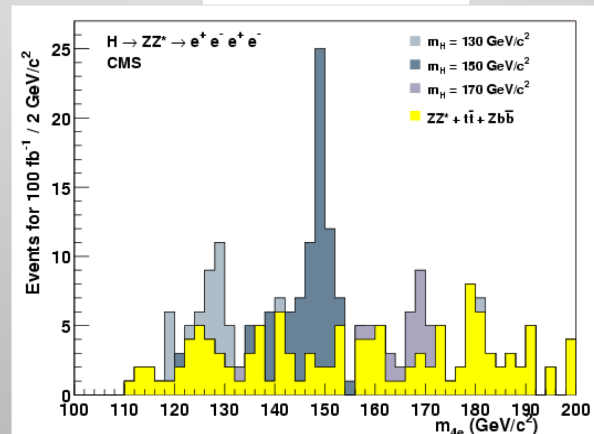
simulation

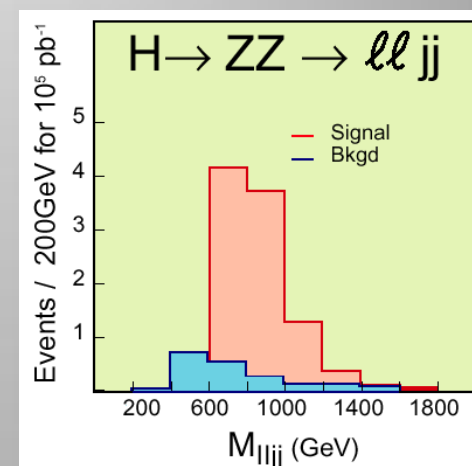


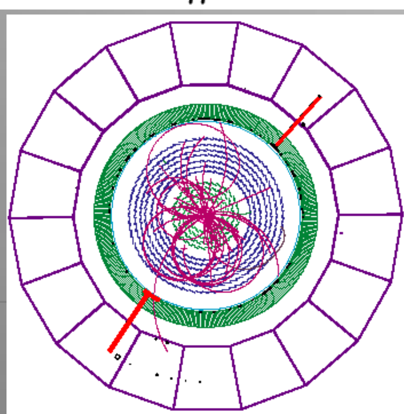


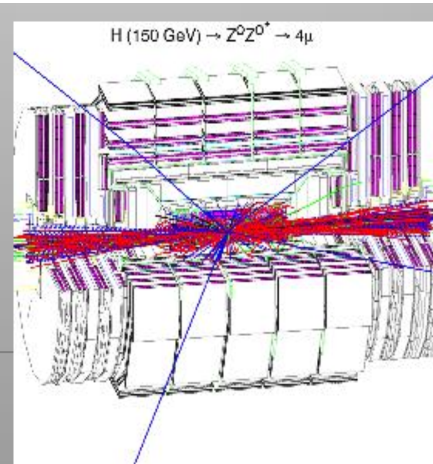


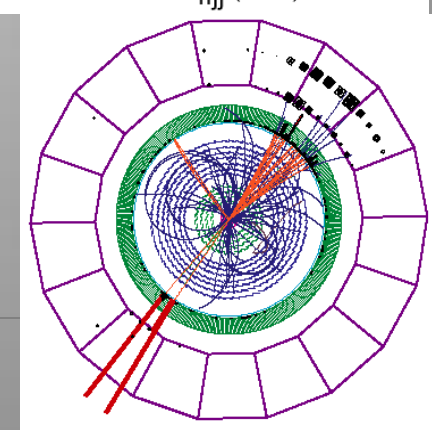












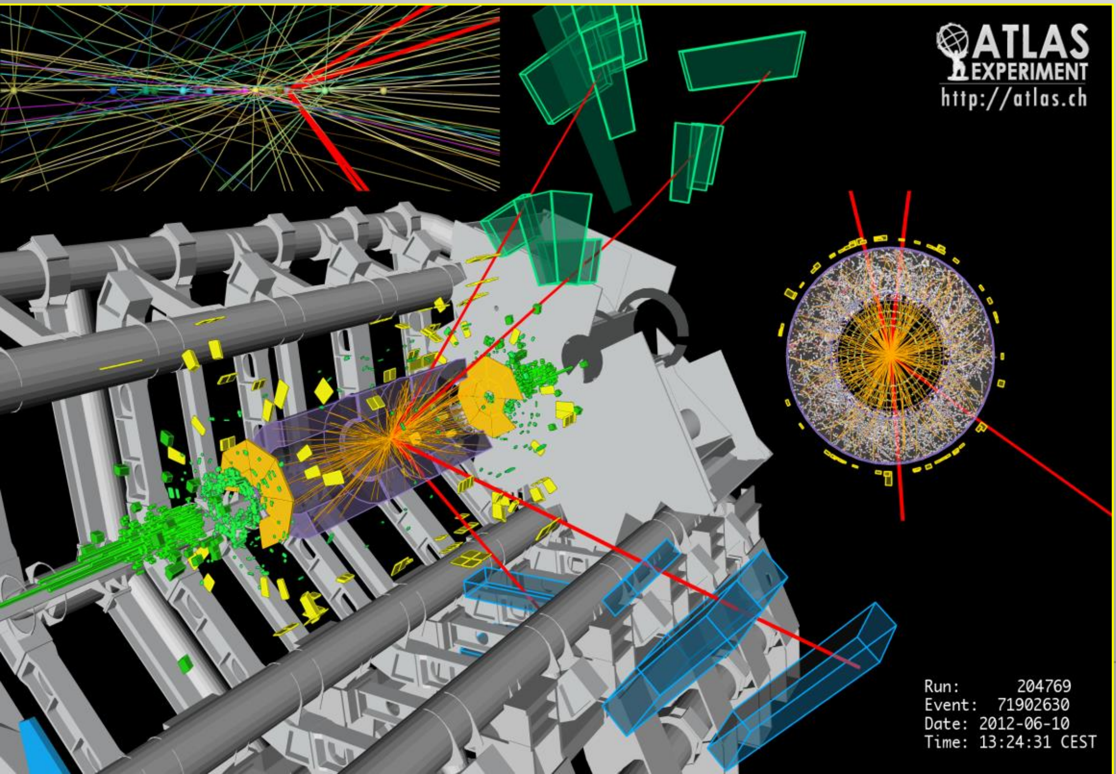
Searches for the Higgs Particle

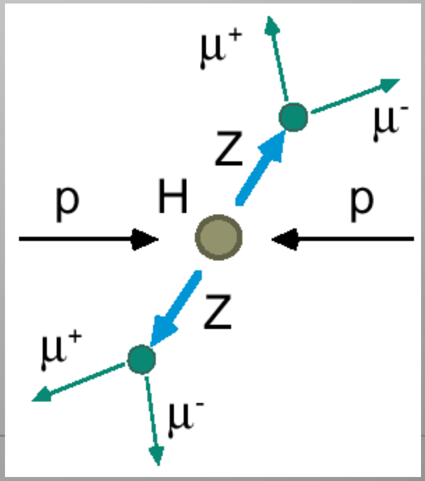
A Higgs particle will decay immediately, eg in two heavy quarks or two heavy (W,Z) bosons

Example: Higgs(?) decays into ZZ and each Z boson decays into μμ

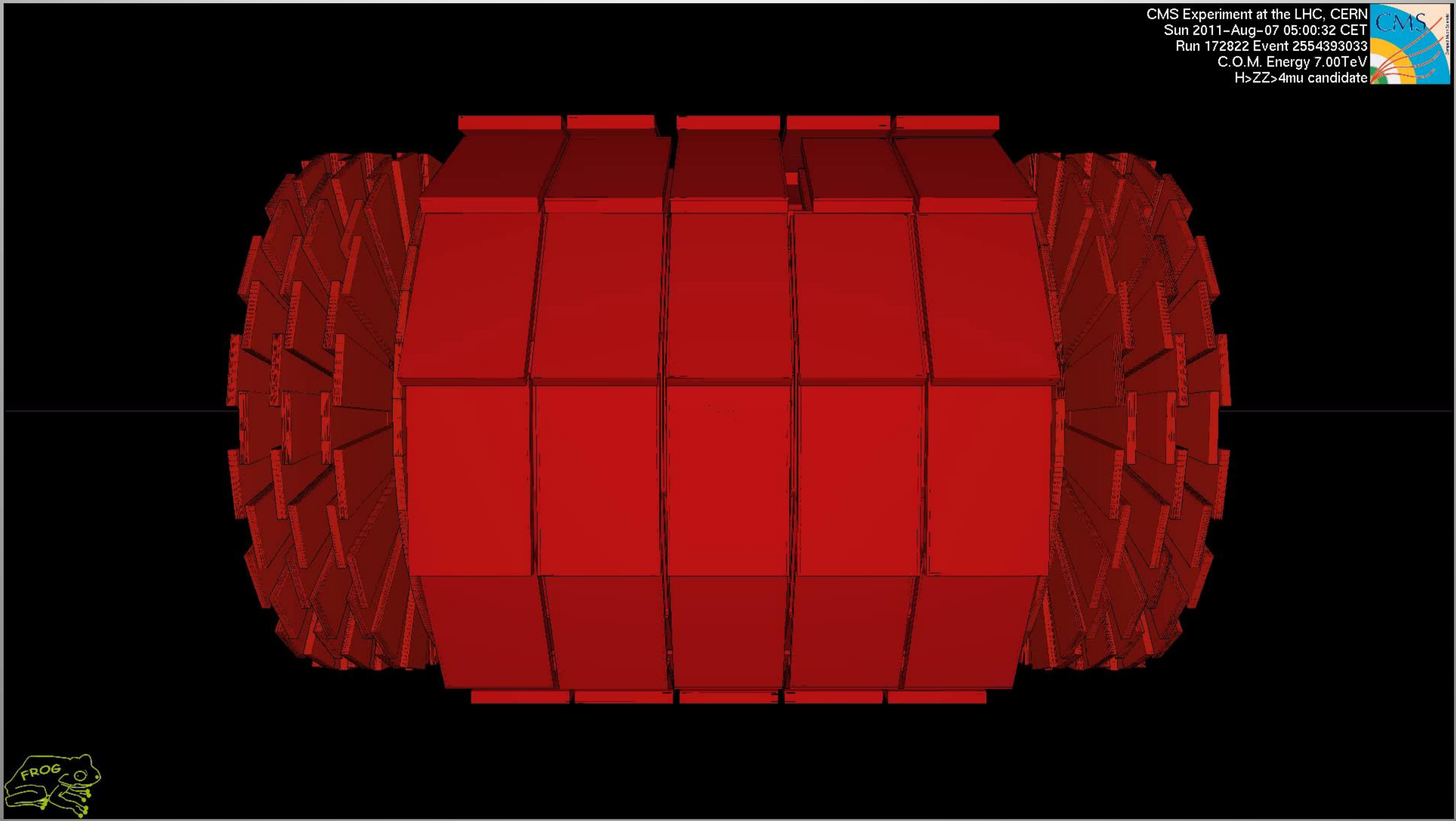
So we look for 4 muons in the detector

But two Z bosons can also be produced in LHC collisions, without involving a Higgs!
We cannot say for on event by event (we can reconstruct the total mass with the 4 muons)

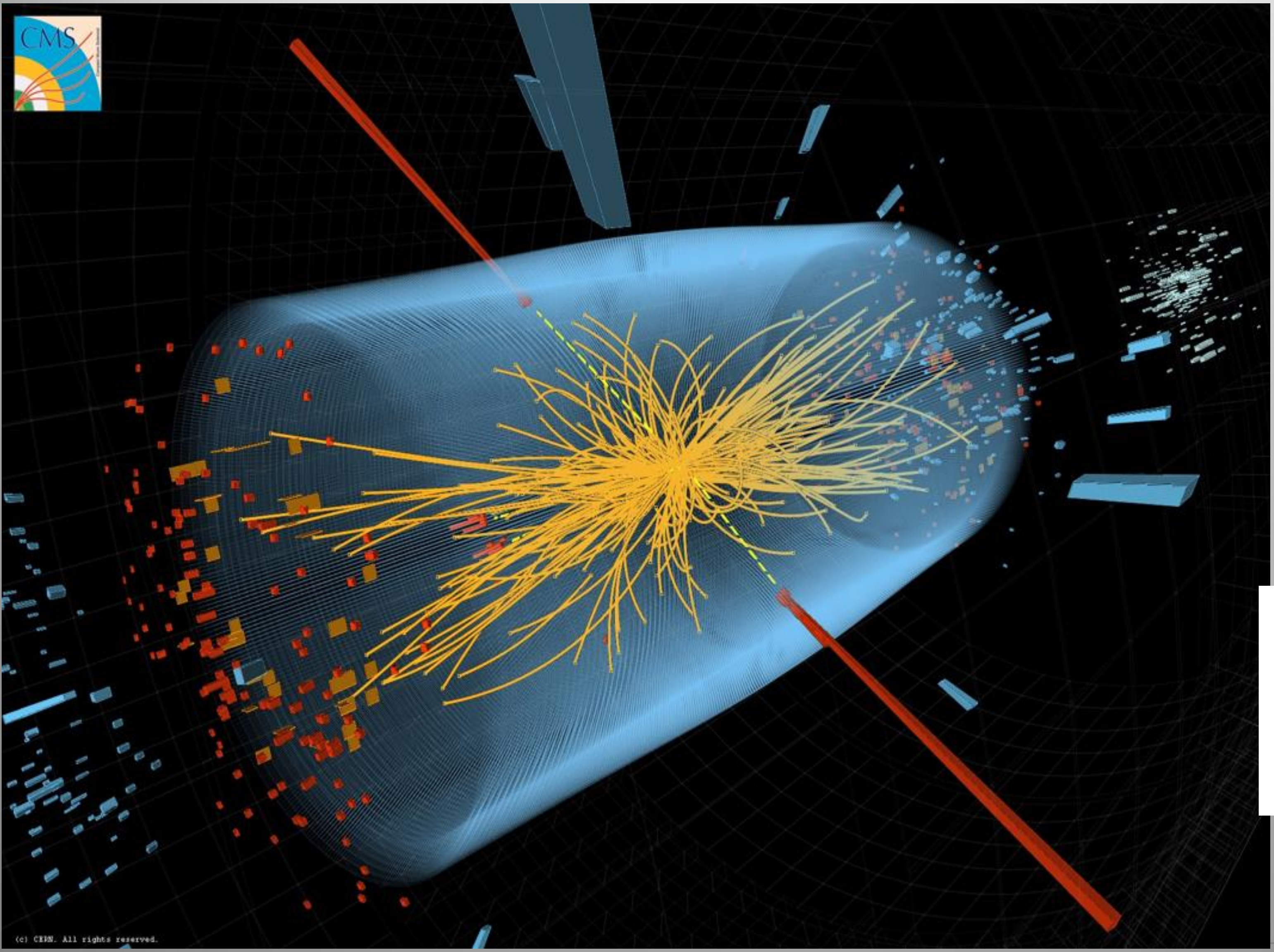


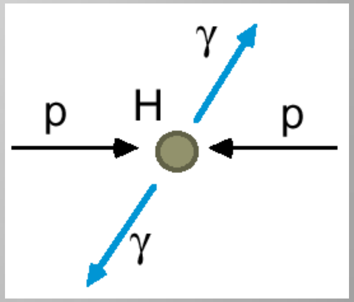


A real collisions: ZZ-> 4 muons



Searches for the Higgs Particle





A Higgs or
a ‘background’
process without
a Higgs?

July 4th 2012

- Official announcement of the discovery of a Higgs-like particle with mass of 125-126 GeV by CMS and ATLAS.
- Historic seminar at CERN with simultaneous transmission and live link at the large particle physics conference of 2012 in Melbourne, Australia

CERN

Melbourne

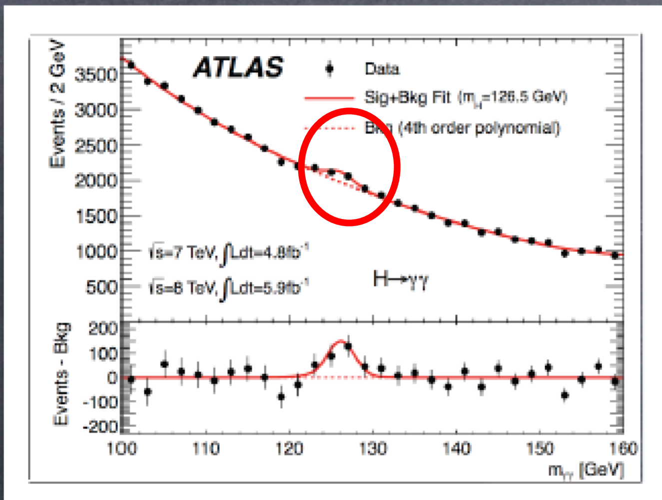
Followed live around the world…

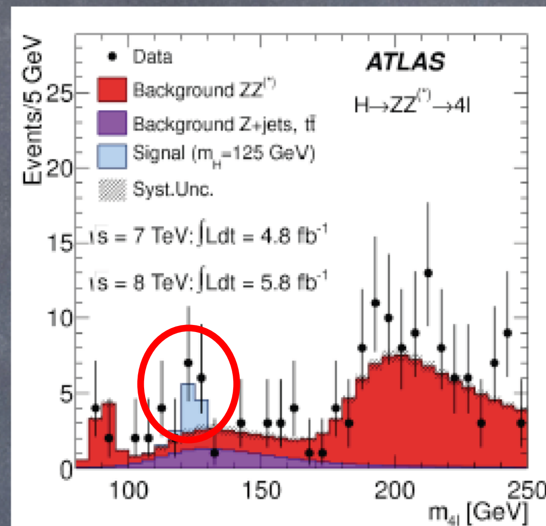
Summer 2012: Results

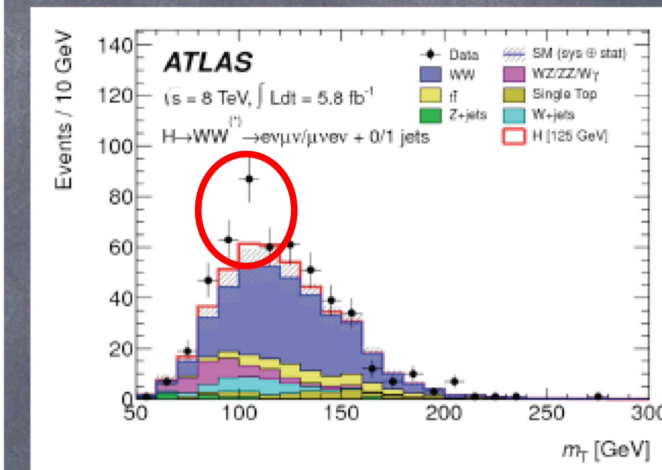
Higgs → 2 photons!!

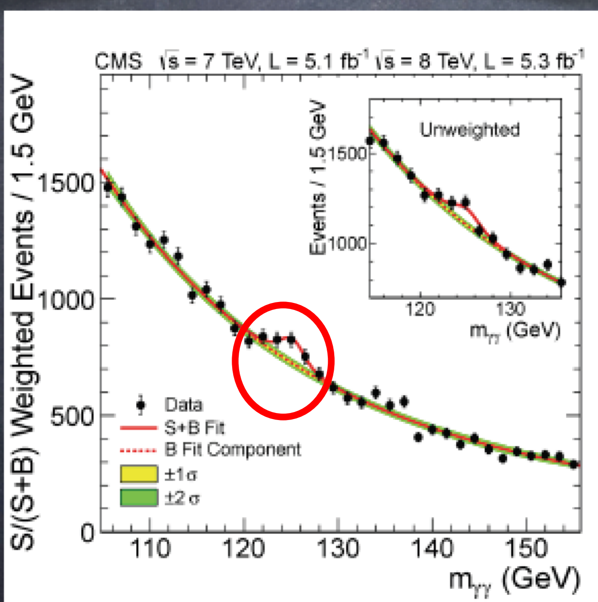
Higgs → 2Z →4 leptons!!

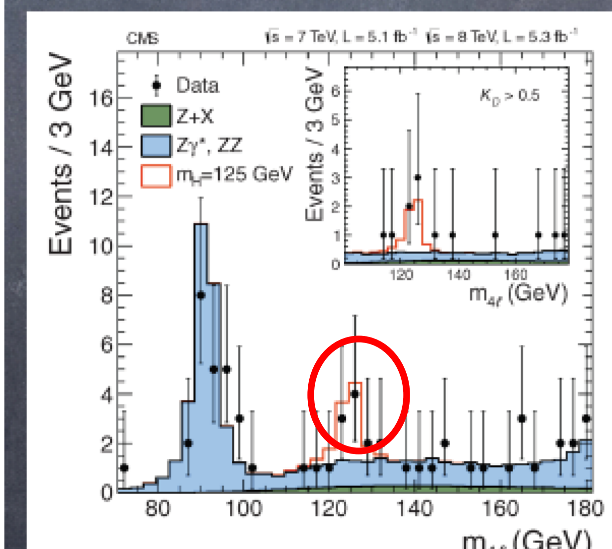
Higgs → 2W →2l2v!!

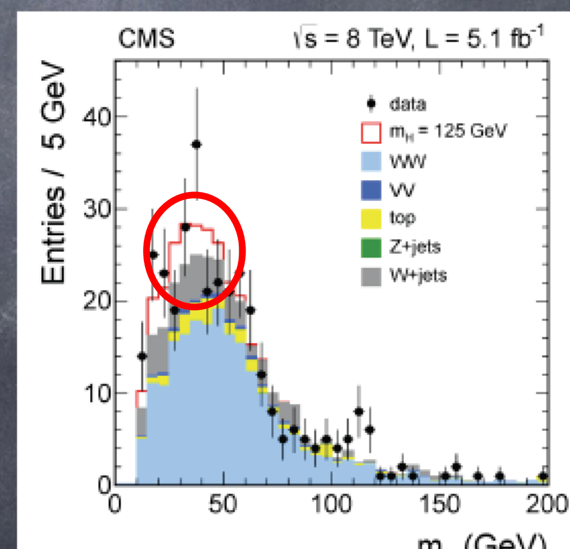












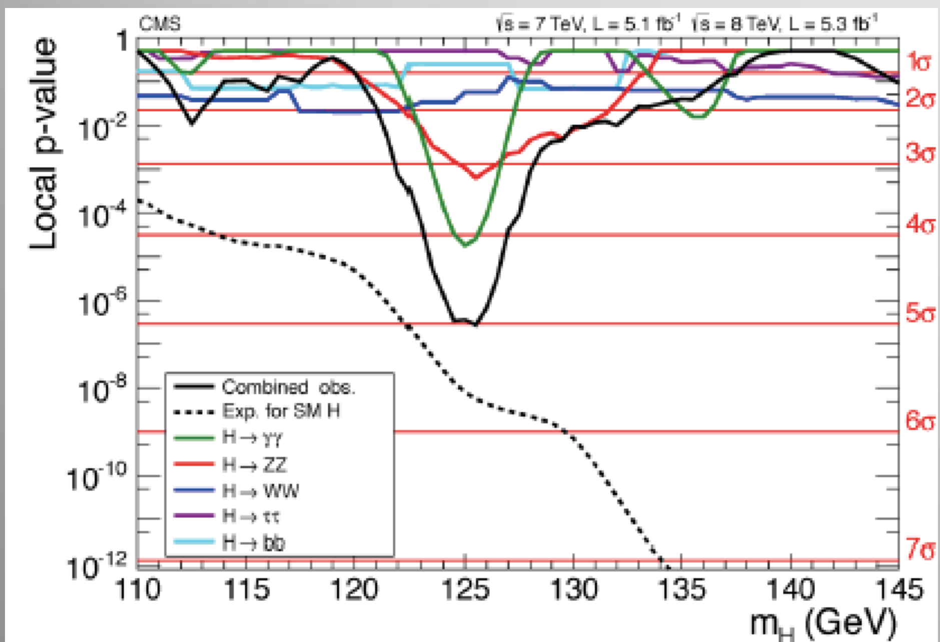
Summer 2012: Results

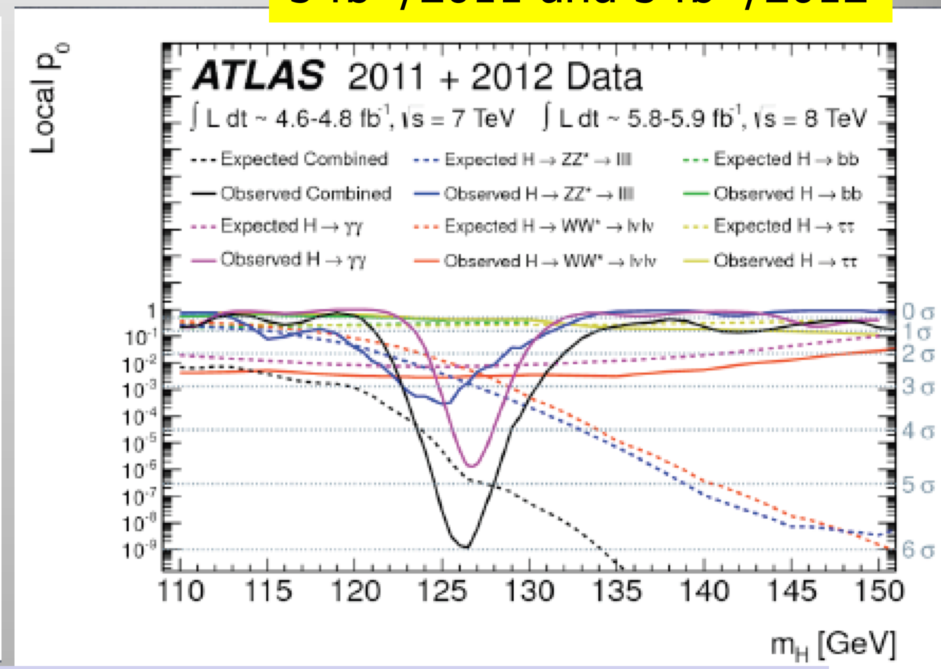
Both experiments see an excess ~125 GeV in the γγ, ZZ and WW channel

→Adding up al the channels gives the following combination

Shown is the compatibility with a 'background only hypothesis"

5 fb^{-1}/2011 and 5 fb^{-1}/2012



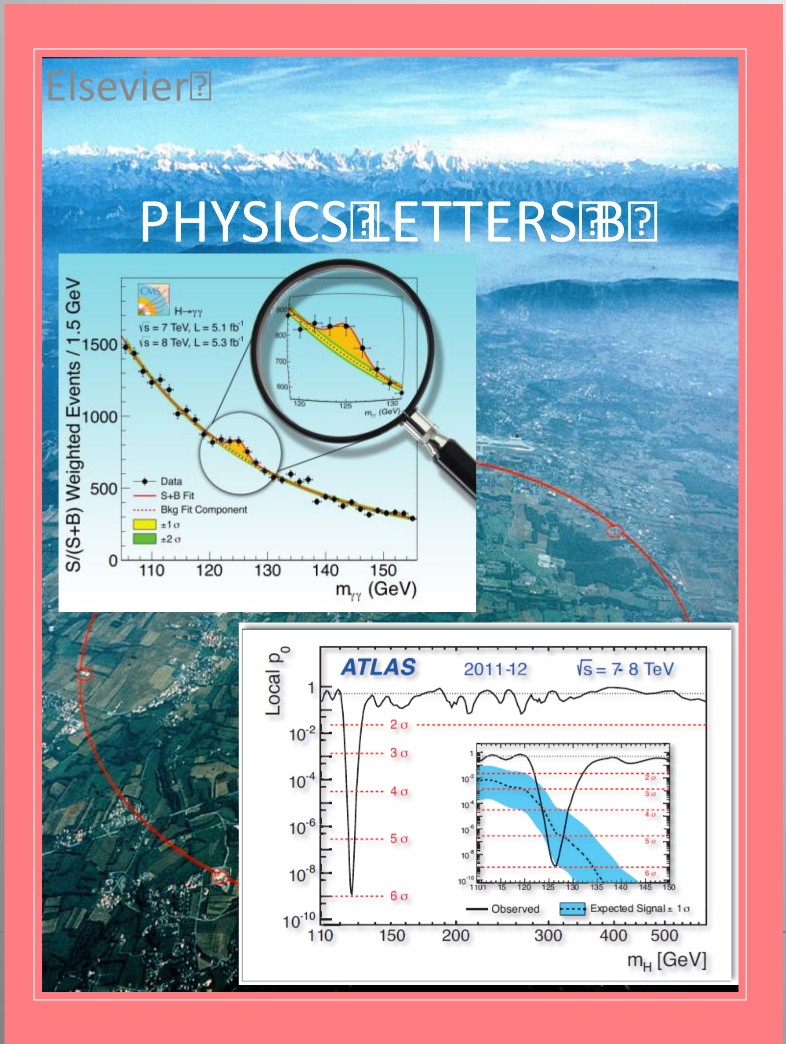


CMS and ATLAS observe a new boson with a significance of about 5 sigma (1 chance in 3 million to be wrong!!!)

The particle is consistent with a Higgs-like boson

Higgs Publications…

Special booklet PLB edition with the ATLAS and CMS papers



Also…

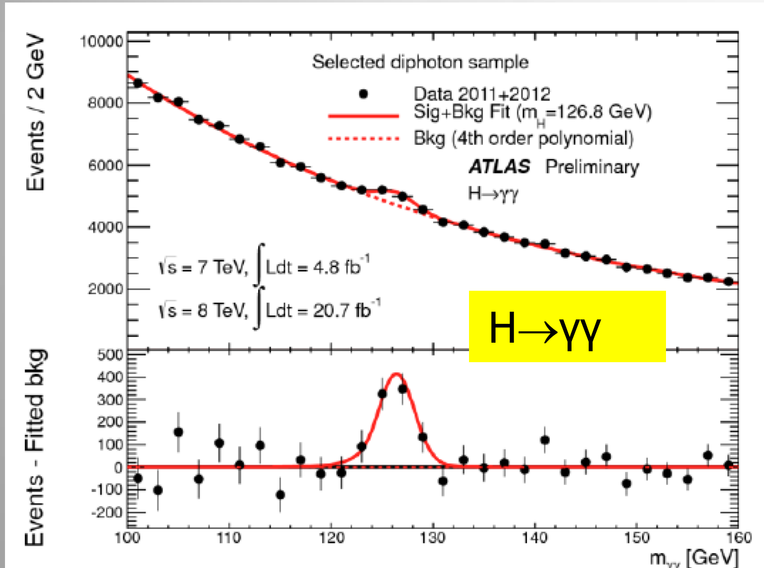
Is it really the Higgs Boson?

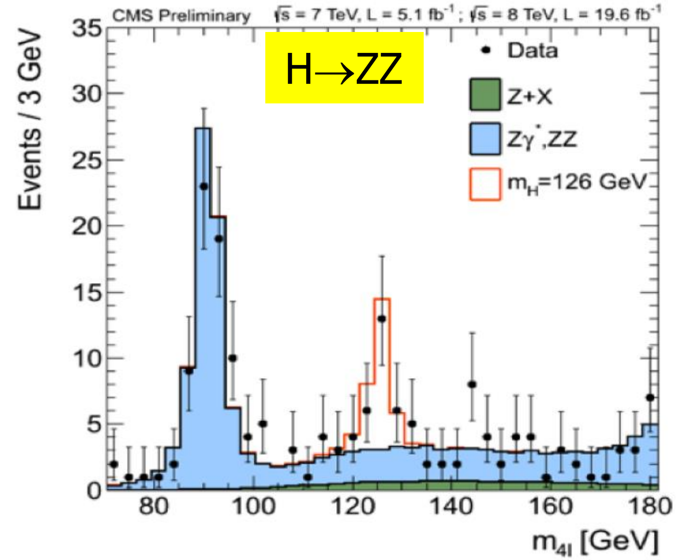
We, experimentalists, called it a “Higgs-like” particle

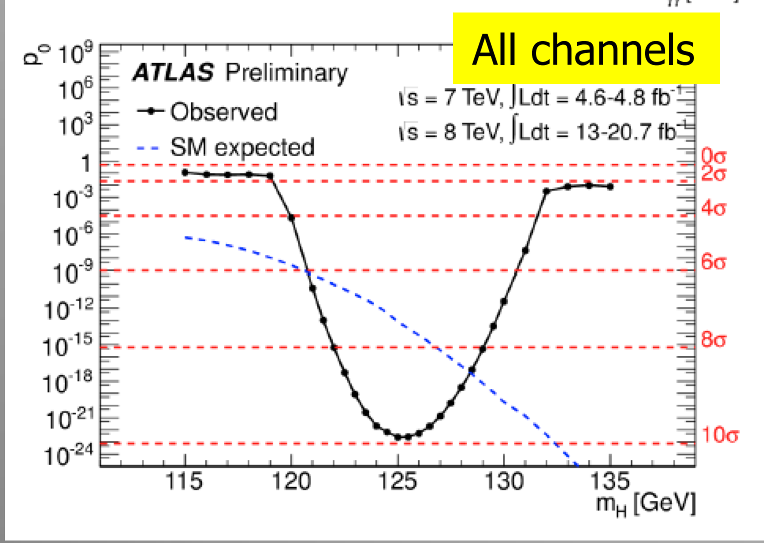
- Does this new particle have all the properties that we expect a Higgs Boson to have?
  - So far it seems to couple as expected to photons, heavy Z and W bosons, but at the time of the discovery it was not seen that they also couple to quarks or leptons
- What are the quantum numbers of this new particle?
  - EG Spin and Parity: for the SM Higgs we expect it to have spin = 0 and parity = +.
- Is there more than one Higgs-like particle? Some theories beyond the Standard Model predict these…
- Does it have ‘exotic’ properties?

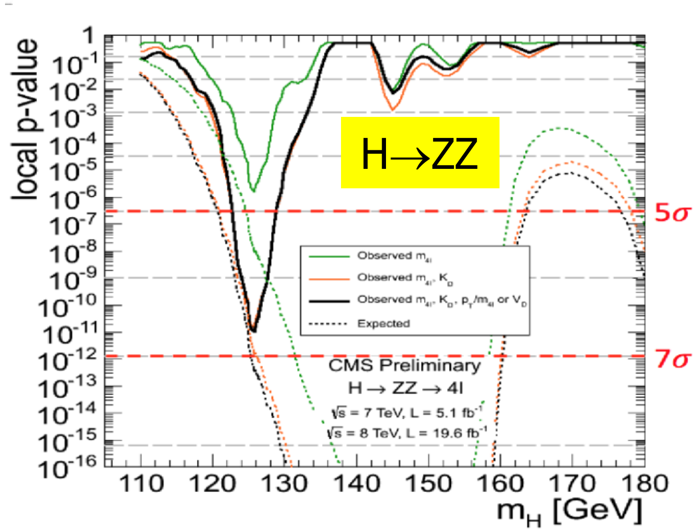
Still a lot of questions to be answered in summer 2012!!
Let’s look at the new updates with full 2012 data (~ 25 fb^{-1})

Update with the Full 2012 Data Sample







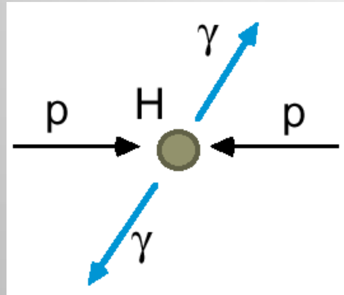


Increased data sample with
a factor of ~3

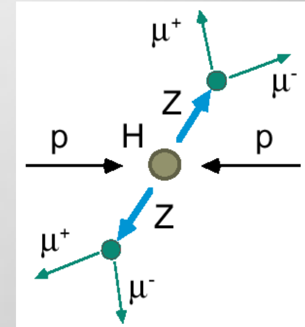
The particle is clearly still with us, now with a significance of >10σ !!

We now enter the phase of measuring the properties of the new particle

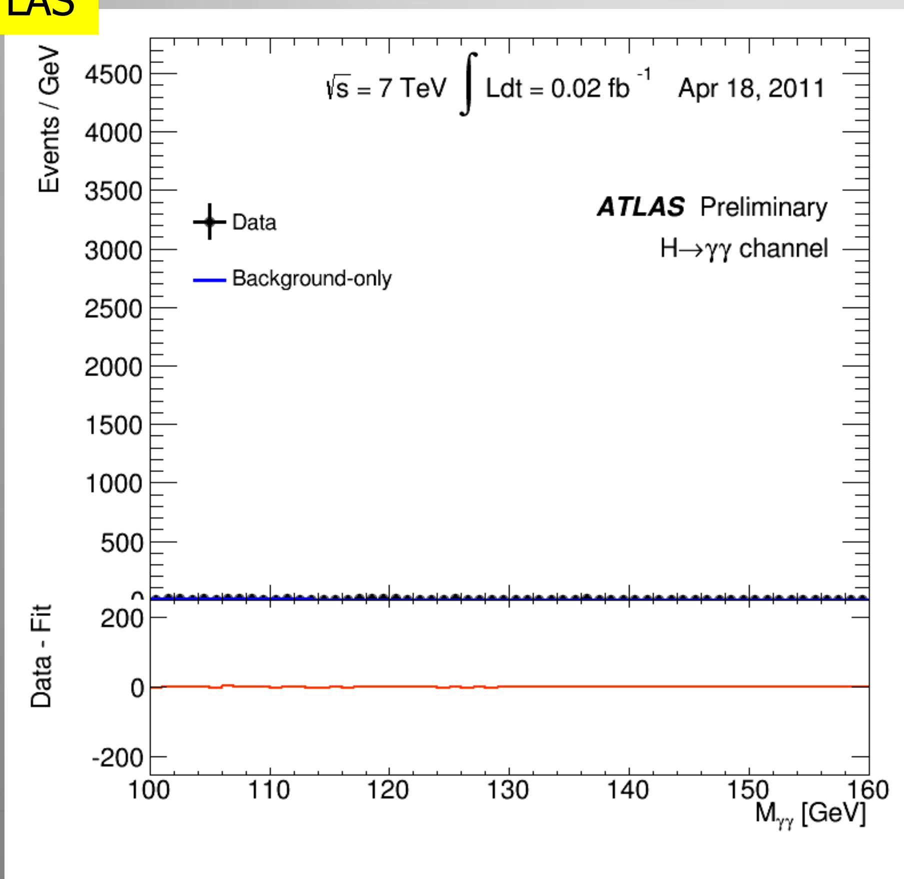
The Birth of a Particle



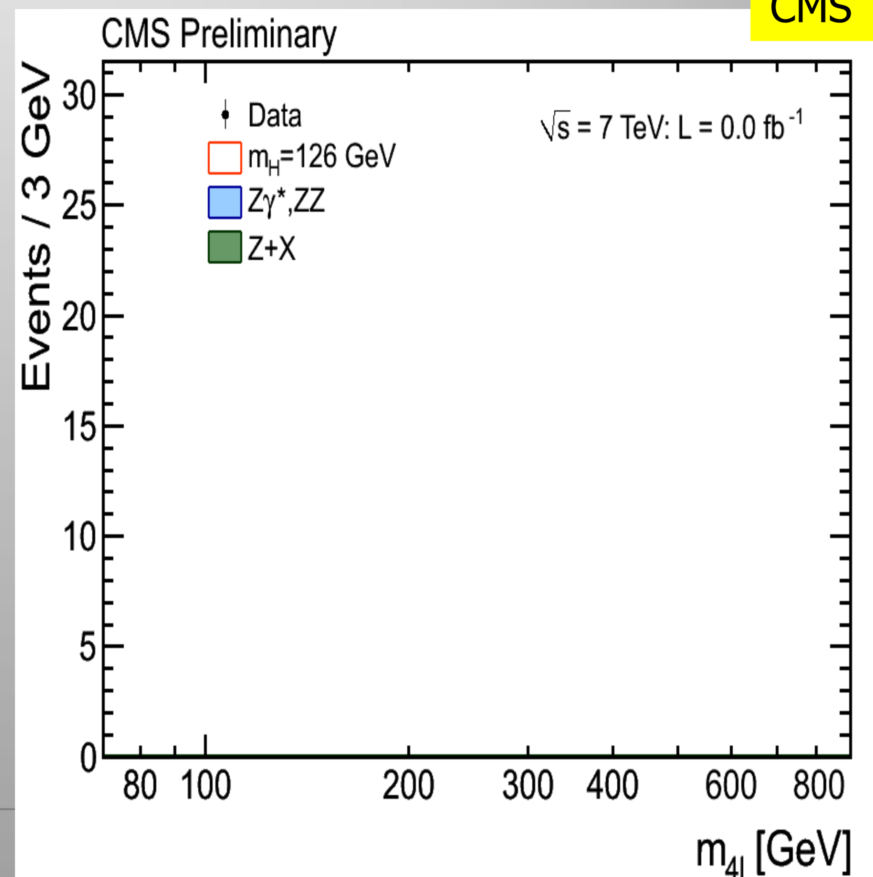
“History” of the data accumulation during the last two years



ATLAS



CMS

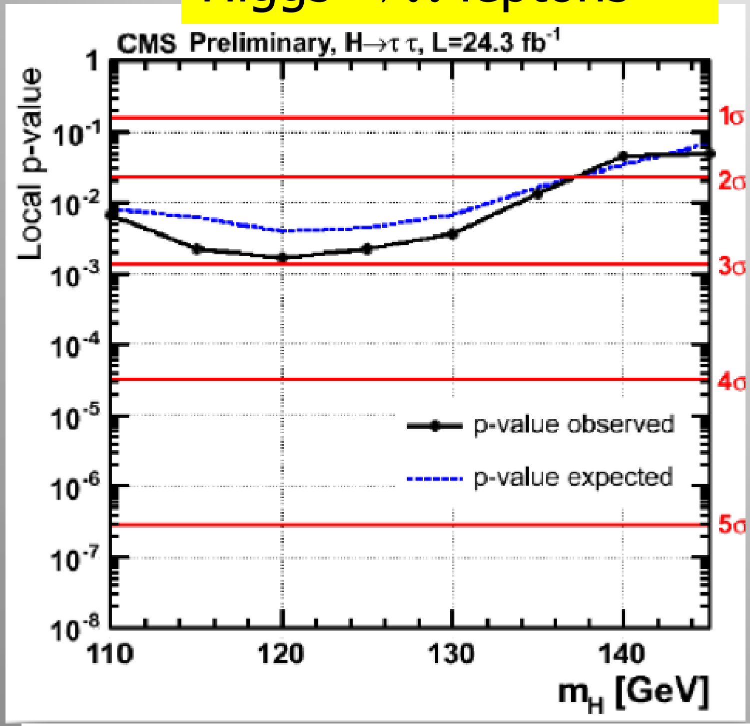


Does this Particle Decay into Fermions?

- The BEH-mechanism was proposed in 1964 to give mass to W and Z bosons
- Does it also give mass to the fermions? Does the particle couple to fermions?

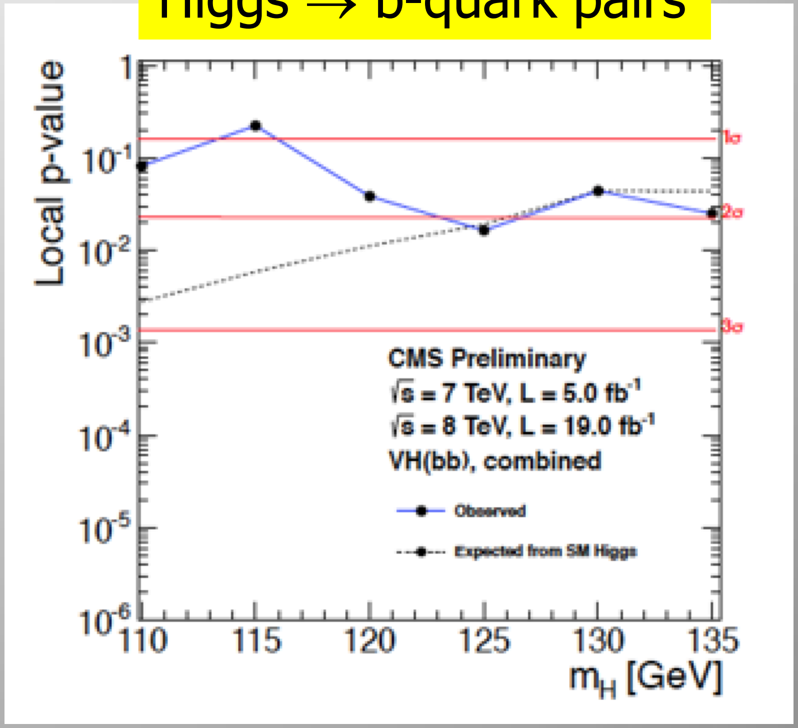
  $\Rightarrow$ Direct test: check for the decays $H \to$ tau tau and $H \to$ b quark pairs

Higgs $\to \tau\tau$ leptons



Significance 2.85σ at 125 GeV

Higgs $\to$ b-quark pairs



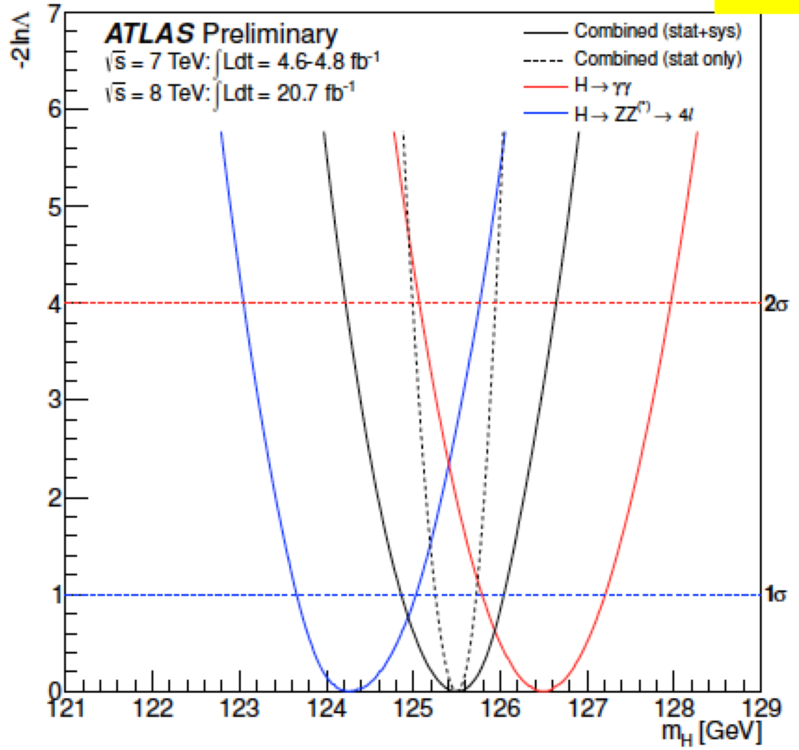
Significance 2.1σ at 125 GeV

Yes: A mild excess is building up also for these channels!!

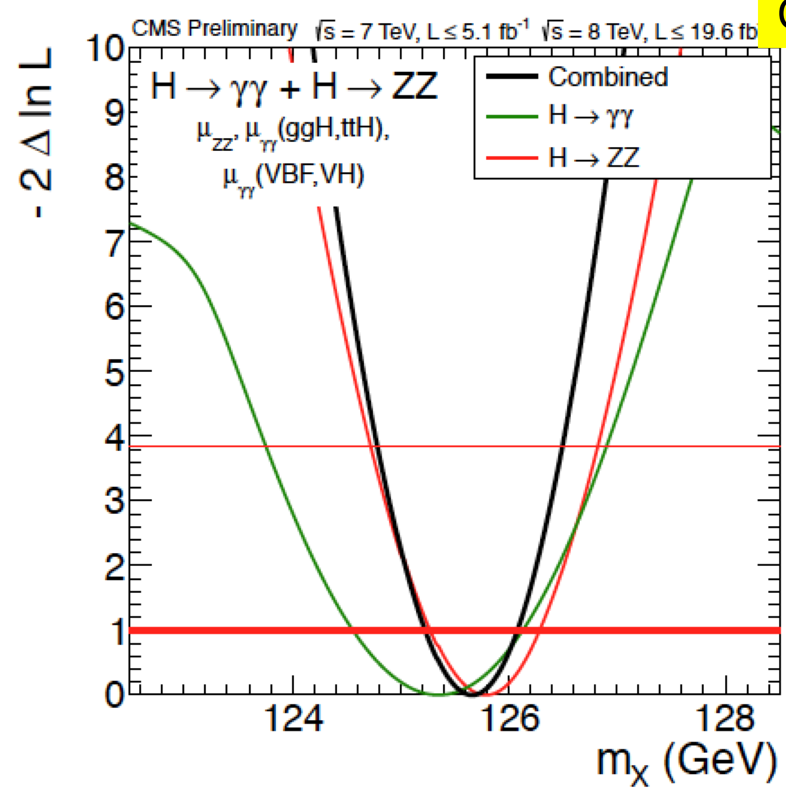
The Mass of the Particle

Determine the mass from ZZ and 2-photon channels which show a peak!

ATLAS



CMS



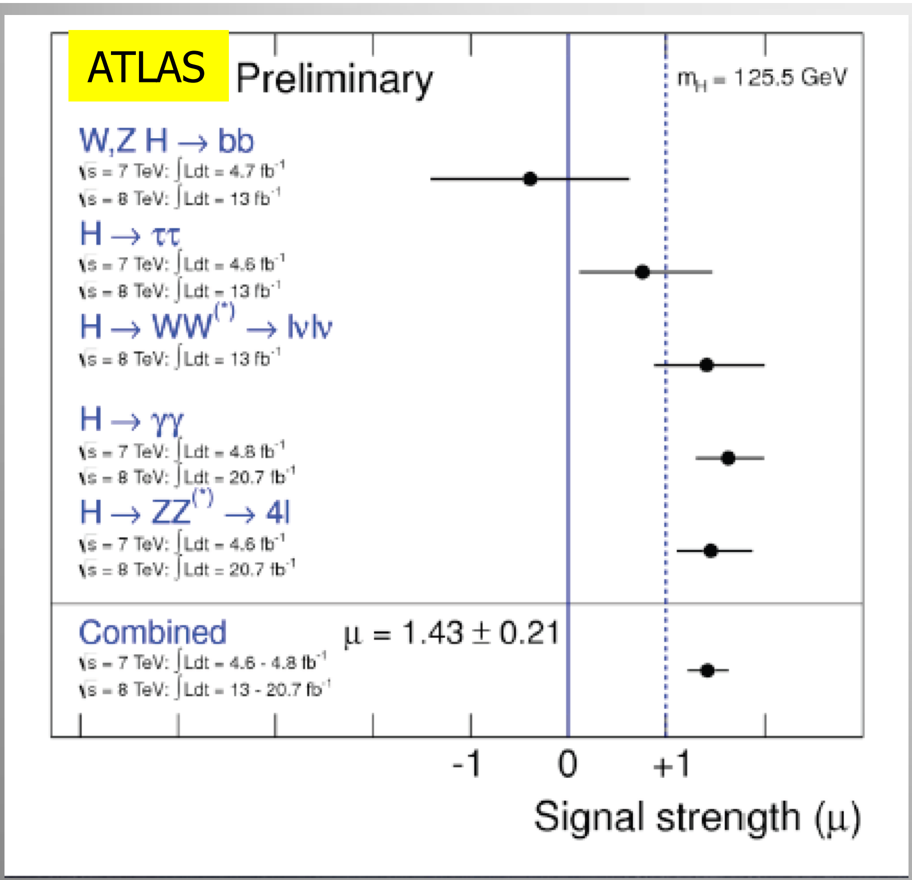
$$\hat{m}_H = 125.5 \pm 0.2(stat)^{+0.5}_{-0.6}(syst)\ \mathrm{GeV}$$

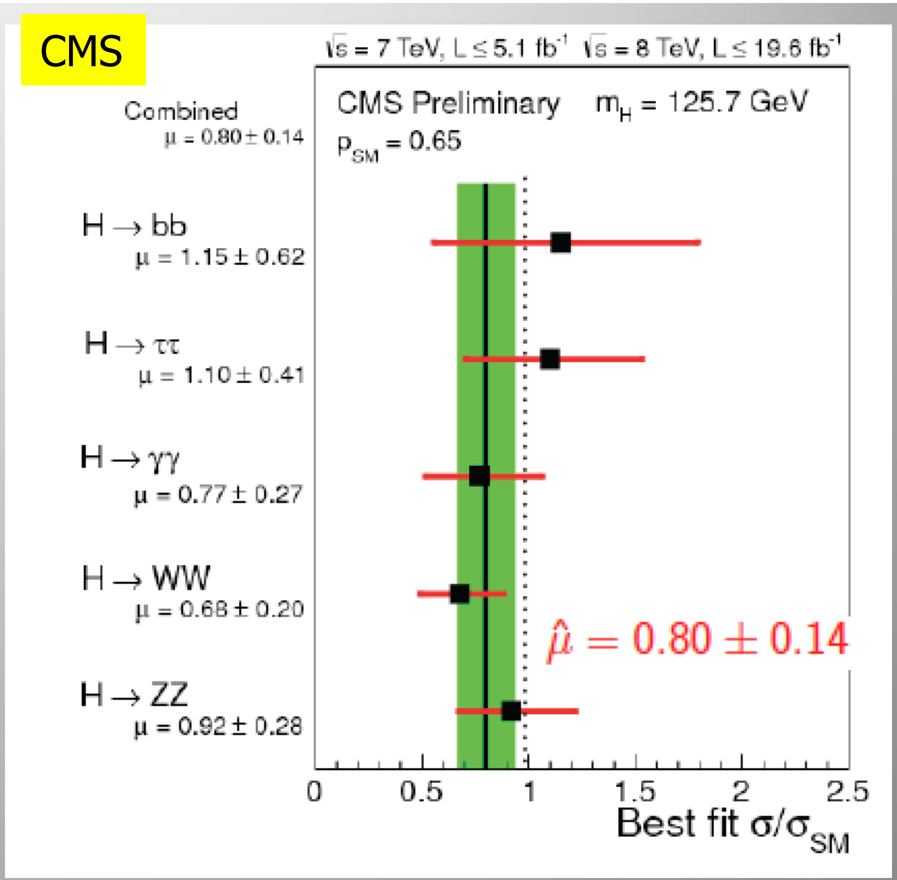
$$\hat{m}_H = 125.7 \pm 0.3(stat) \pm 0.3(syst)\ \mathrm{GeV}$$

ATLAS and CMS observe the same particle!! ☺

Signal Strength

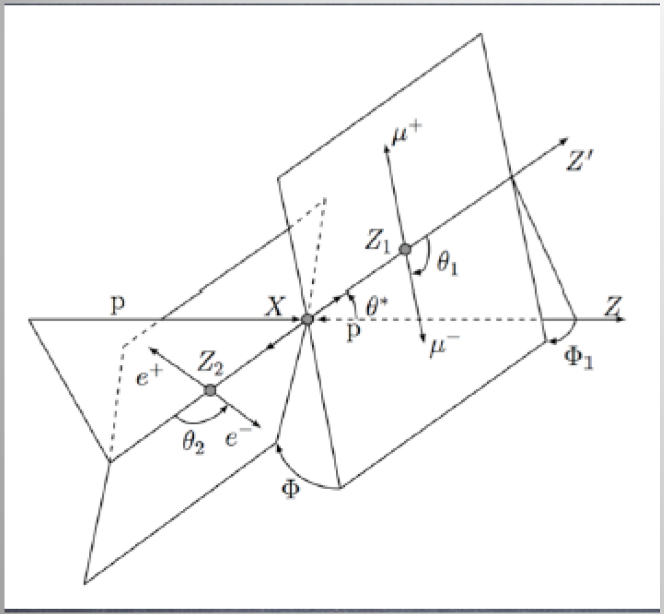
- Signal strength μ is the observed over Standard Model expected cross section
- For μ=1 the production rate is compatible with Standard Model expectation





ATLAS a bit above and CMS a bit below μ=1…

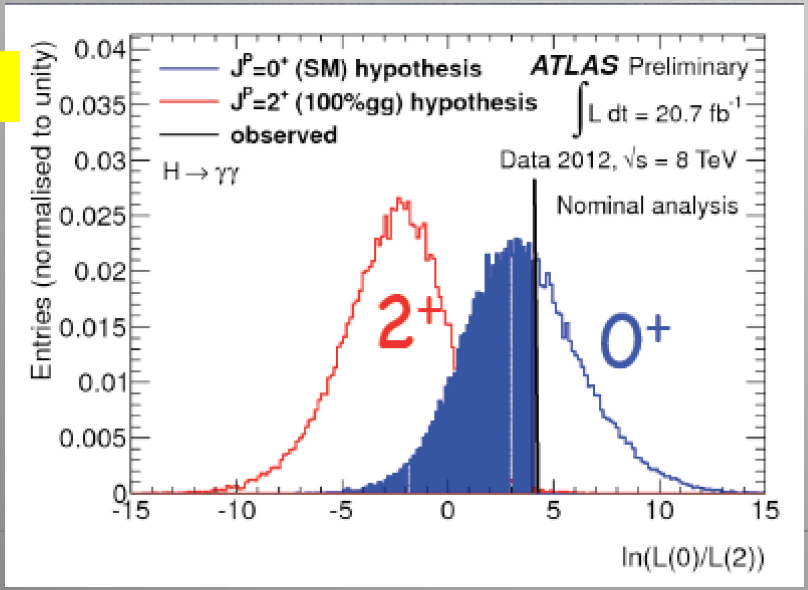
The Spin of the New Particle



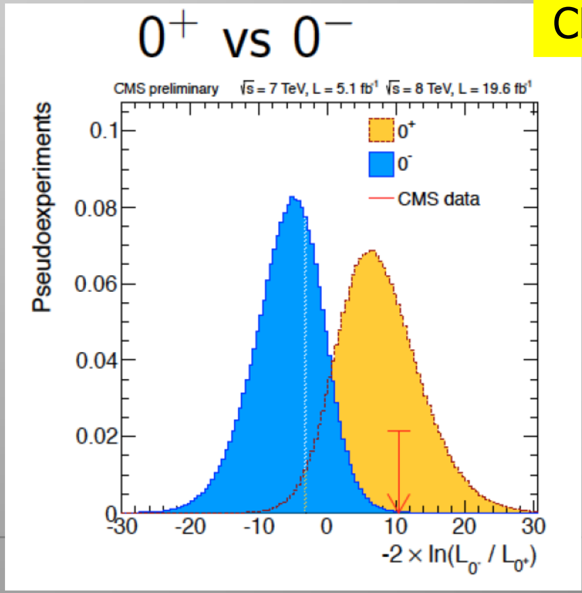
- Study angular correlations in the decays of the particle; build likelihoods and test spin- and parity hypotheses
- Use the ZZ, 2-photon and WW final states

=> Particle consistent with a 0^+ state!!

ATLAS

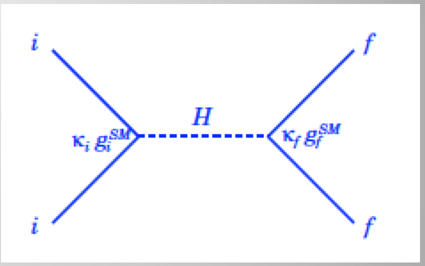


CMS

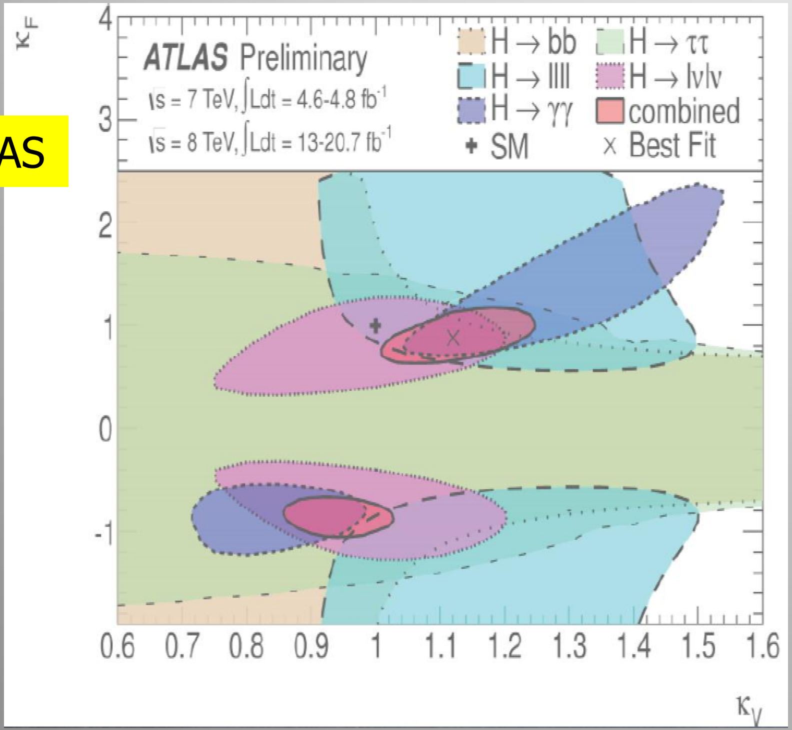


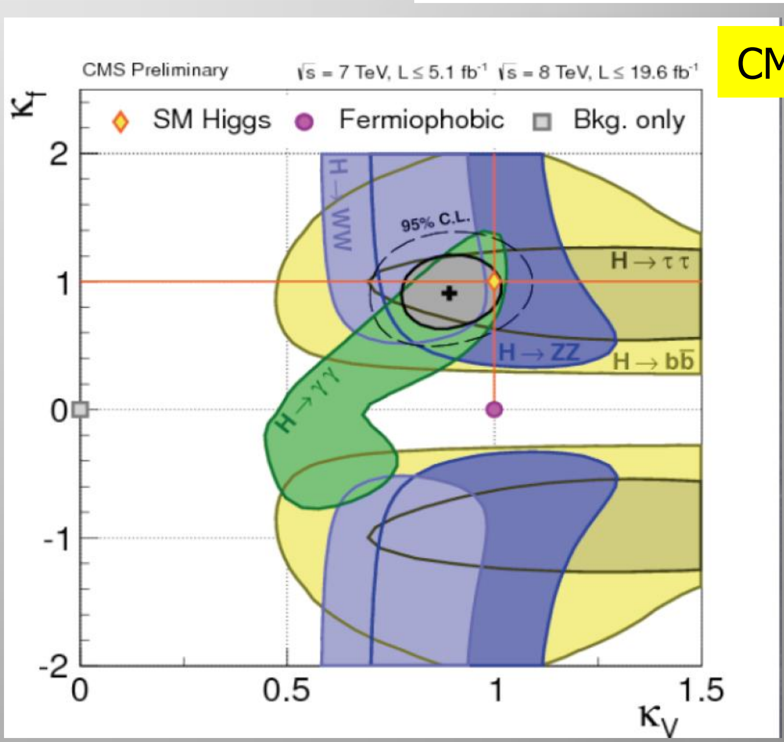
Couplings to the New Particle

- Use information of all production and decay channels
- κ_f and κ_V are scale factors w.r.t. the Standard Model values for fermions and vector bosons



ATLAS





CMS

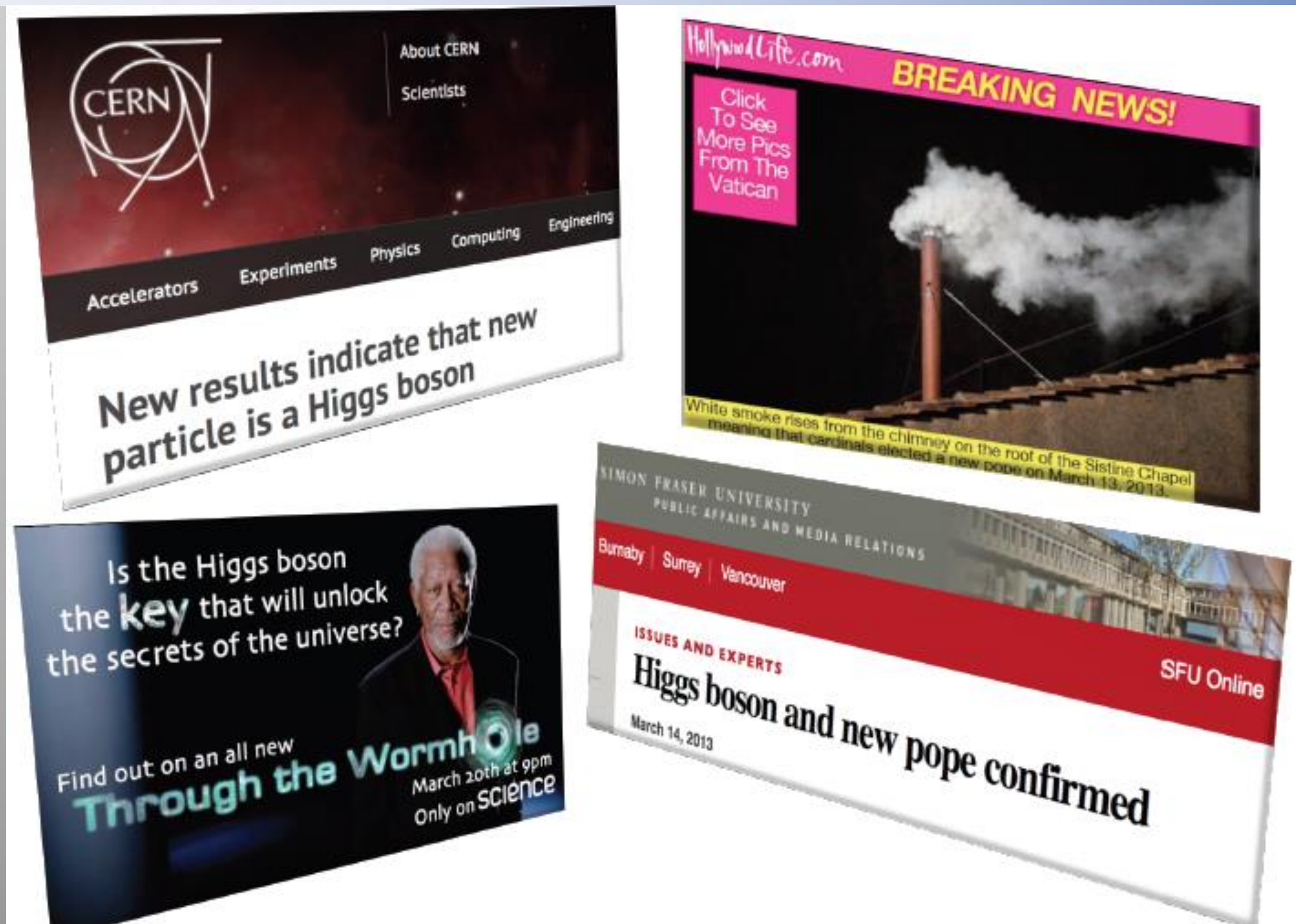
⇒ Couplings compatible Standard Model values, but large uncertainties

…Future data will decide…

The News Since July 2012

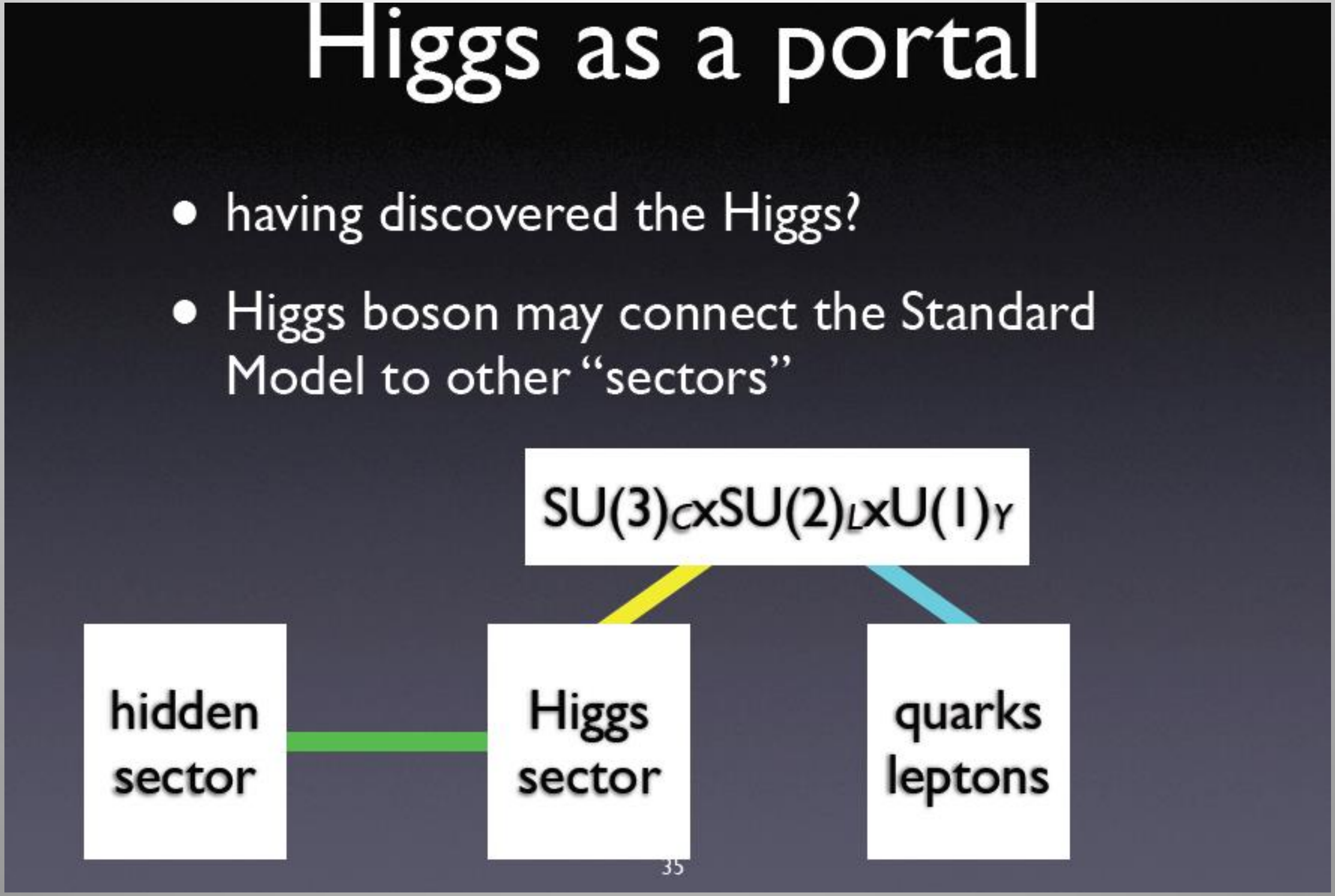
- Results based on the full data set of 2011-2012 have been released this spring.
- The discovery of the new particle has been confirmed with more added collisions
- Signals in the fermion-channels start building up
- We tested the spin: it is compatible with a 0+ state and not with (simple) 0- or spin 2 (1) states
- The mass is getting measured better with time, in the range125-126 GeV. A naïve average gives 125.6 GeV
- The couplings to Bosons and Fermions are consistent with the SM predictions (but these are not very precise yet; Surprises possible…)

March 2013 News



Following the data released by ATLAS and by CMS last March, we now call it a Higgs boson (instead of a Higgs-like boson)

What is Next?

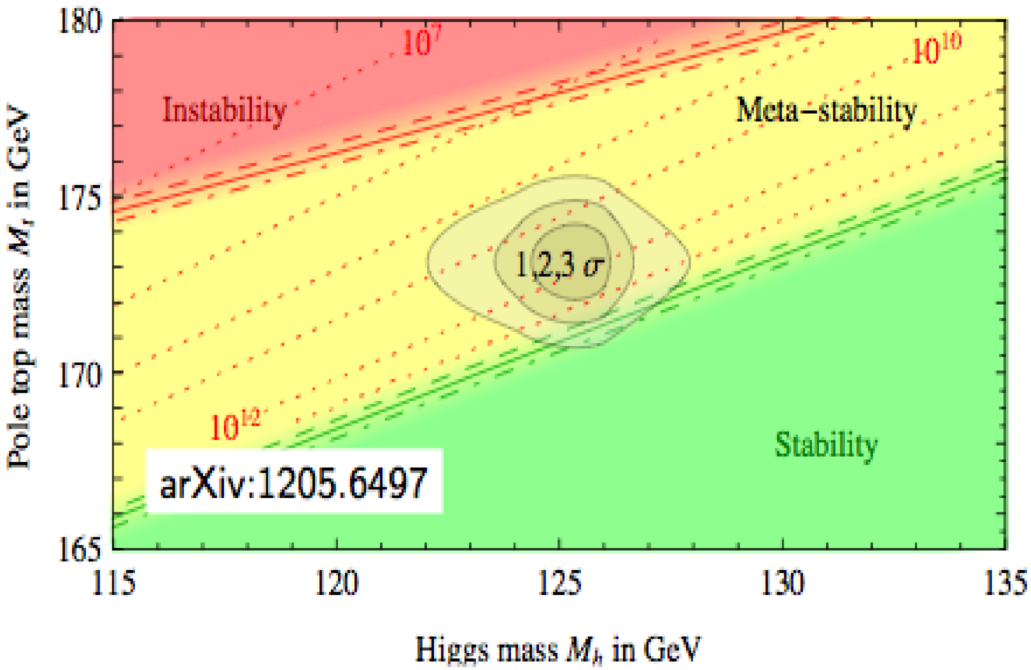


Need for precision measurements with ~100x the present statistics

LHC upgrade ! Experiment upgrades!! (Other machines?)

Consequences for our Universe?

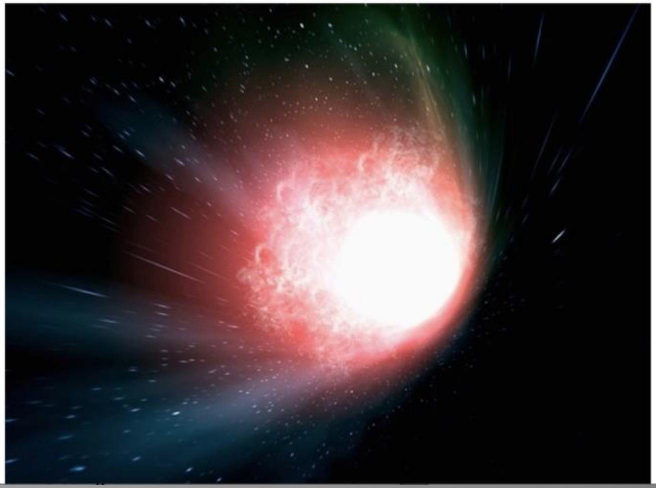
Important SM parameter → stability of EW vacuum



Precise measurements of the top quark mass and first measurements of the Higgs mass:

Our Universe meta-stable ? Will the Universe disappear in a Big Slurp? (NBCNEWS.com)

Will our universe end in a 'big slurp'? Higgs-like particle suggests it might



Summer 2012 the CMS and ATLAS experiment found a new particle, with a mass of 125-126 GeV, which looked like the long sought Higgs boson, postulated in 1964.

March 2013: The full statistics of 2011+2012 (about a factor 3 more data) confirms the existence of the new particle.

The spin and couplings to W and Z bosons are consistent with the expectation for a Higgs boson. Hence we call it from now onwards “a Higgs particle”. This is a brand new particle, as we never seen before.

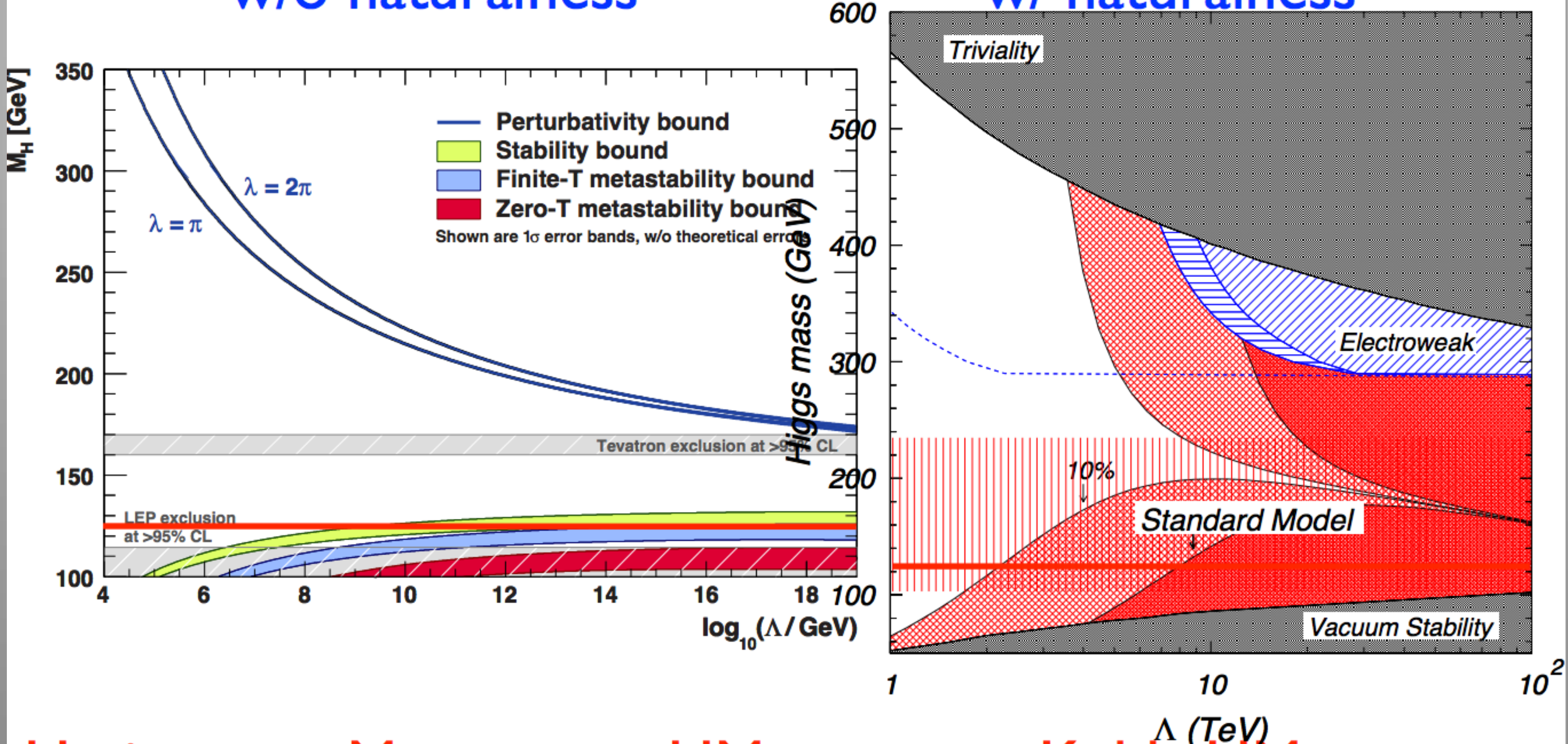
This Higgs boson is likely to carry the ‘genetic code’ for the physics Beyond the Standard Model. Present studies do not yet reveal any BSM signatures but have only a ~20% precision.

This could only be done with the excellent & sophisticated detectors we have (and accelerator)!! You have a big challenge for the future where we need high quality upgrades, new detectors…

This is only the beginning!!!

Higgs and New Physics

w/o naturalness | w/ naturalness

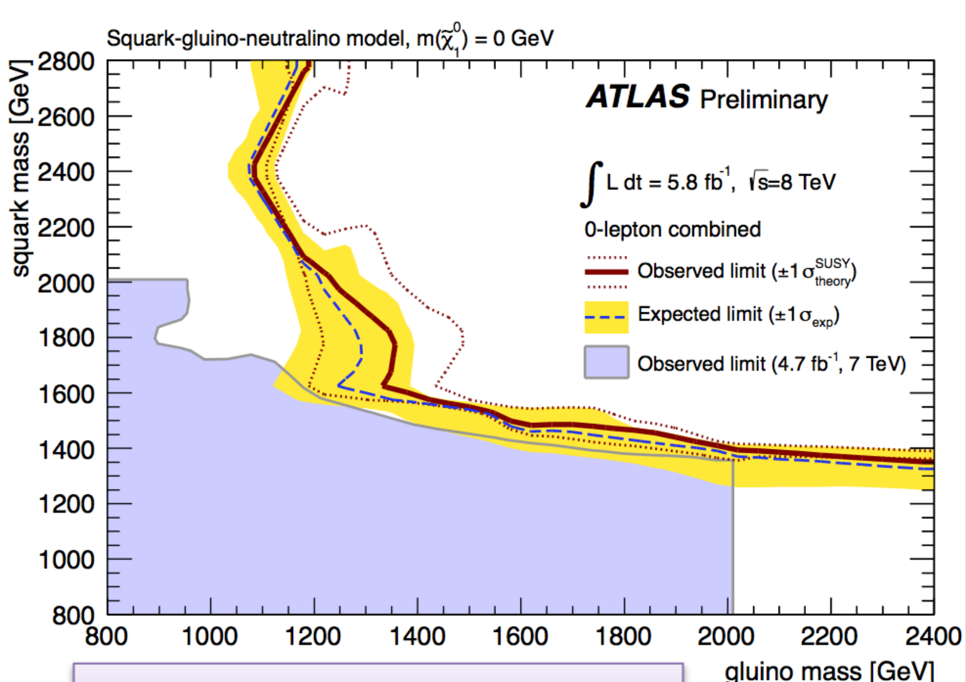


Harigayama, Matsumoto, HM | Kolda HM

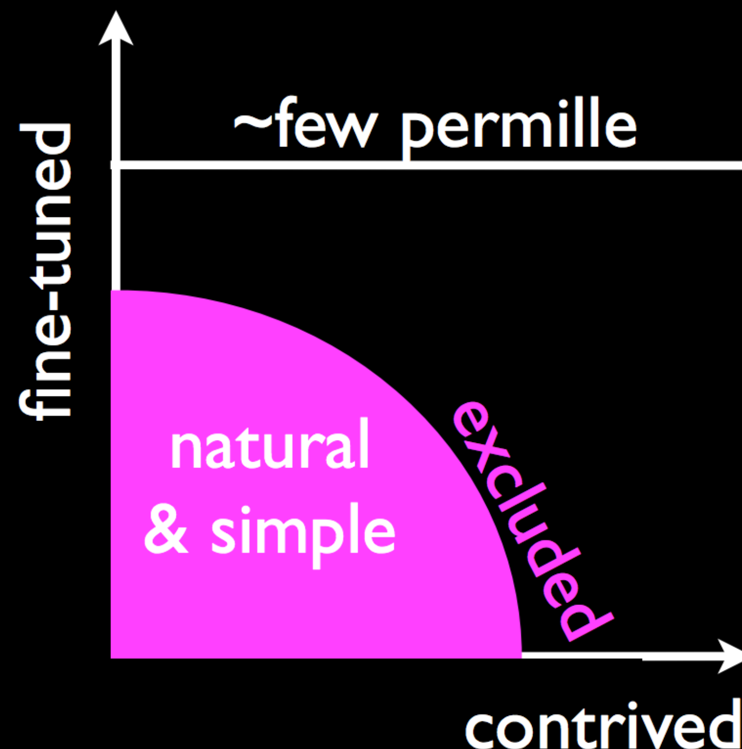
Standard Model not a stable theory at High Energies. Beyond-SM needed

Supersymmetry?

no sign of new physics



ATLAS-CONF-2012-109



Higgs and Supersymmetry

Effects on the Higgs couplings can be very subtle

- Predictions of current best fits in simple SUSY models
- Current uncertainties in SM calculations [LHC Higgs WG]
- Comparisons with
  - LHC
  - HL-LHC
  - ILC
  - TLEP
- **Don't decide before HE-LHC**