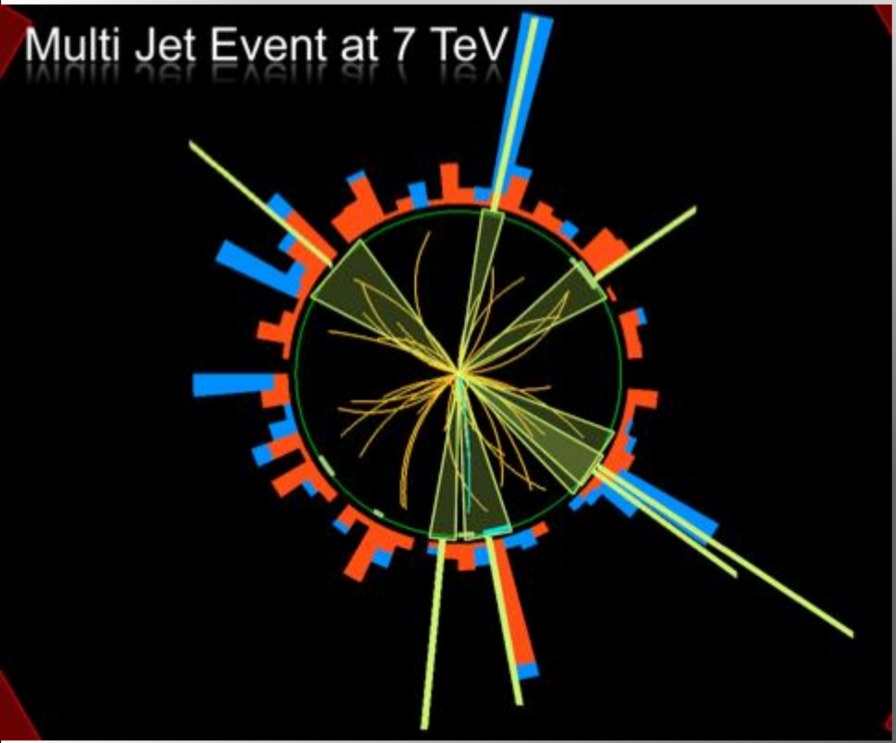
The Discovery of the Higgs Boson with the CMS Experiment

Albert De Roeck
CERN, Geneva, Switzerland
Antwerp University Belgium
UC-Davis California USA
IPPP, Durham UK
BU, Cairo, Egypt

6 May 2013



Outline

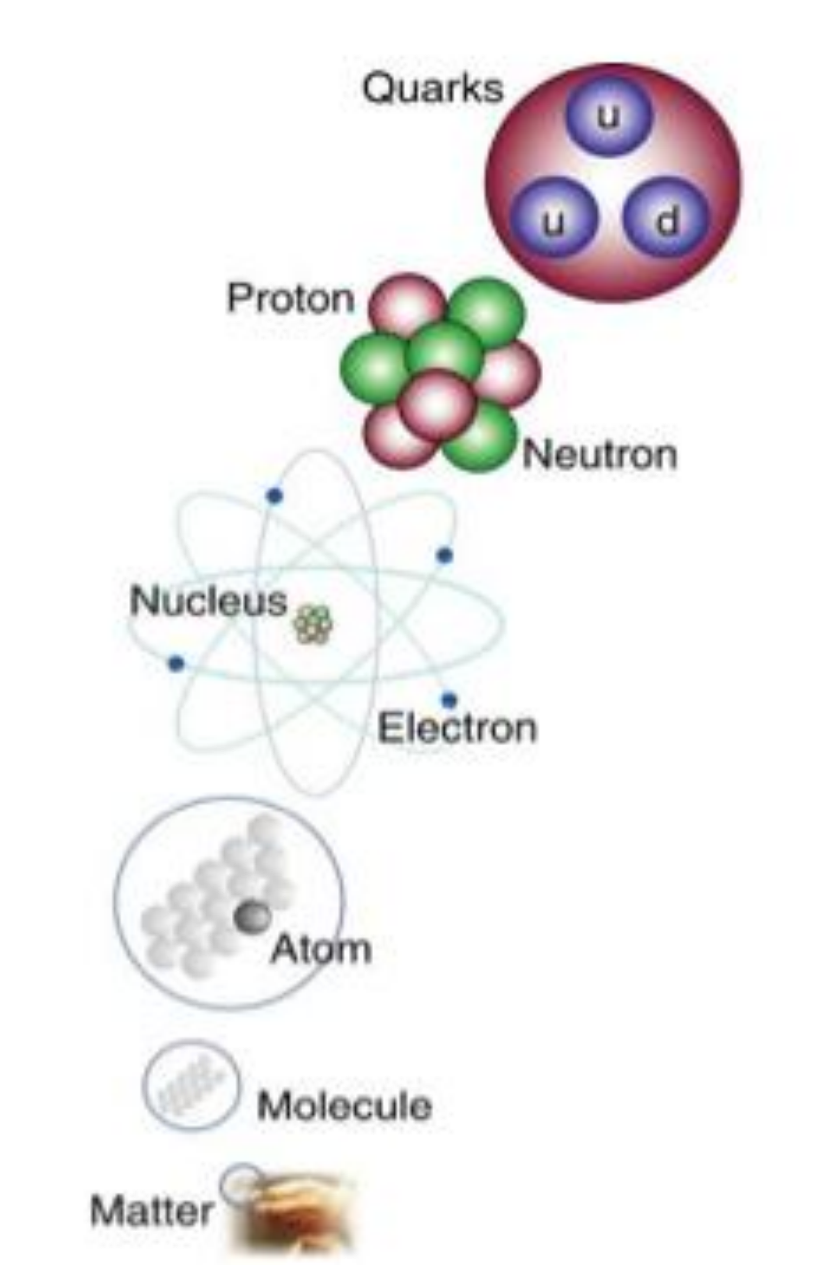
- Introduction
- Higgs searches
- The birth of a new particle
- Studies of Higgs properties
- What is next?
- Summary

What is the world made of?
What holds the world together?
Where did we come from?

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

E. Witten (String Theorist)

The Structure of Matter



Quarks and electrons are the smallest building blocks of matter that we know of today

Are there still smaller particles?

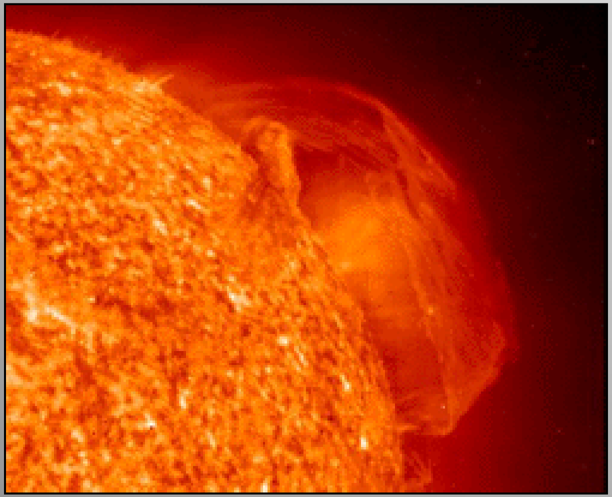
The Large Hadron Collider will address this question!

The Fundamental Forces of Nature

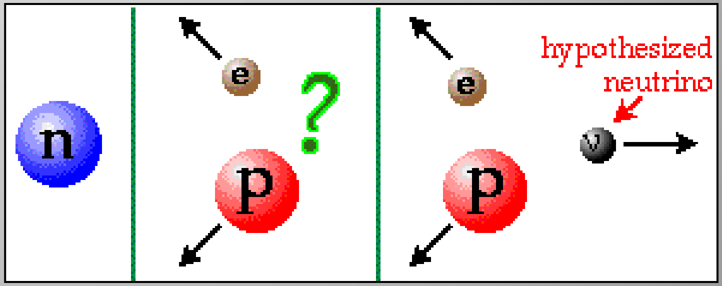
Electromagnetism:
gives light, radio, holds atoms together

Strong Nuclear Force:
holds nuclei together

Weak Nuclear Force:
gives radioactivity



together they make the Sun shine

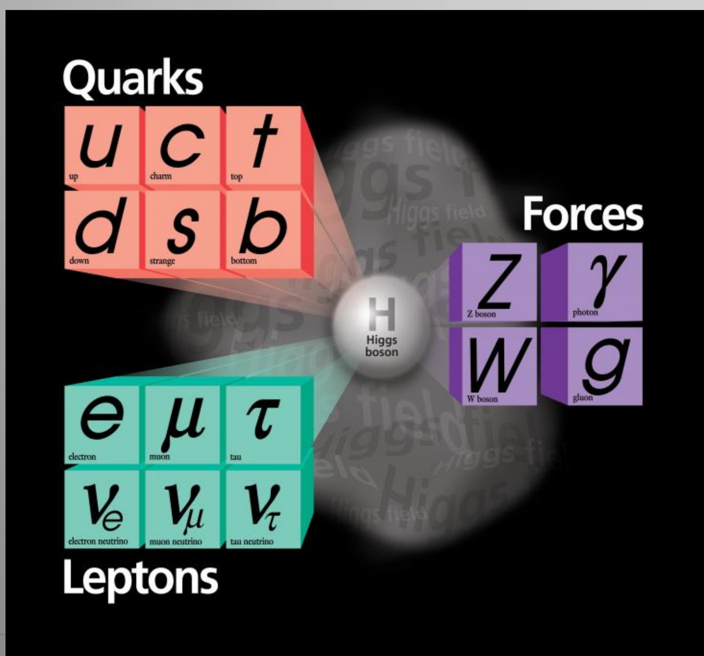


Gravity: holds planets and stars together

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

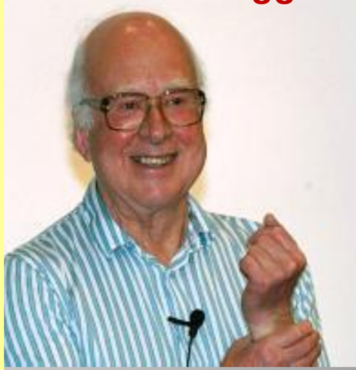


Force particles

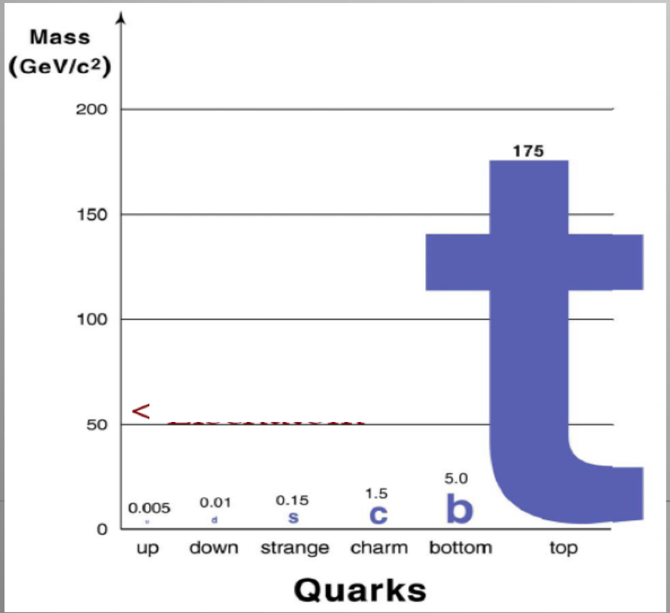
The most basic mechanism of the SM, that of granting mass to particles remained a mystery for a long time
A major step forward was made in July 2012 with the discovery of what could be the long-sought Higgs boson!!

The Origin of Particle Masses

Peter Higgs



- 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 by P. Higgs, R. Brout and F. Englert, and Kibble, Hagen and Guralnik gives mass to W and Z bosons and predicts the existence of a new elementary particle, the‘Higgs’ particle. This mechanism is further extended to give mass to the Fermions via Yukawa couplings.



The Higgs (H) particle has been searched for since decades at accelerators, LEP (CERN), Tevatron (Fermilab, Chicago) and the large hadron collider @ CERN

Francois Englert

The Hunt for the Higgs

Where do the masses of elementary particles come from?

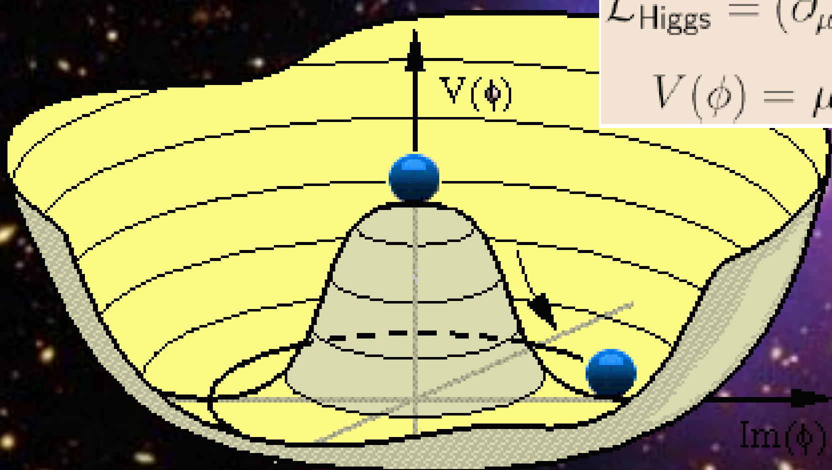
The key question (pre-2012):
Does the Higgs exist?
If so, where is the Higgs?

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

We do not know the mass of the Higgs Boson

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

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

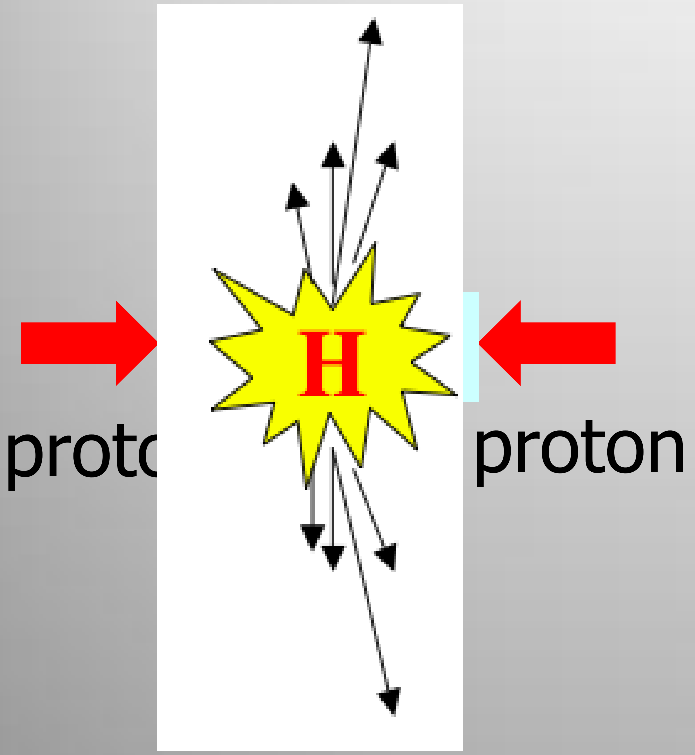


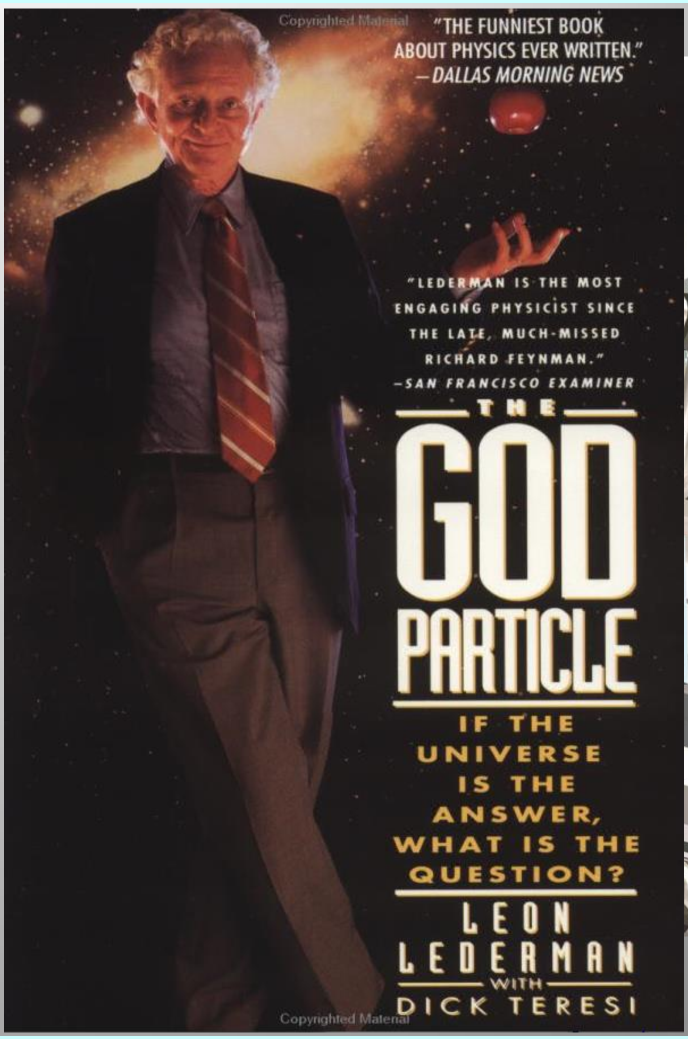
Scalar field with at least one scalar particle

It could be anywhere from 114 to ~700 GeV

The Higgs Particle

Technique: Produce and detect Higgs Particles at Particle Colliders





The Higgs particle is the last missing particle in the Standard Model

This Search Requires…….

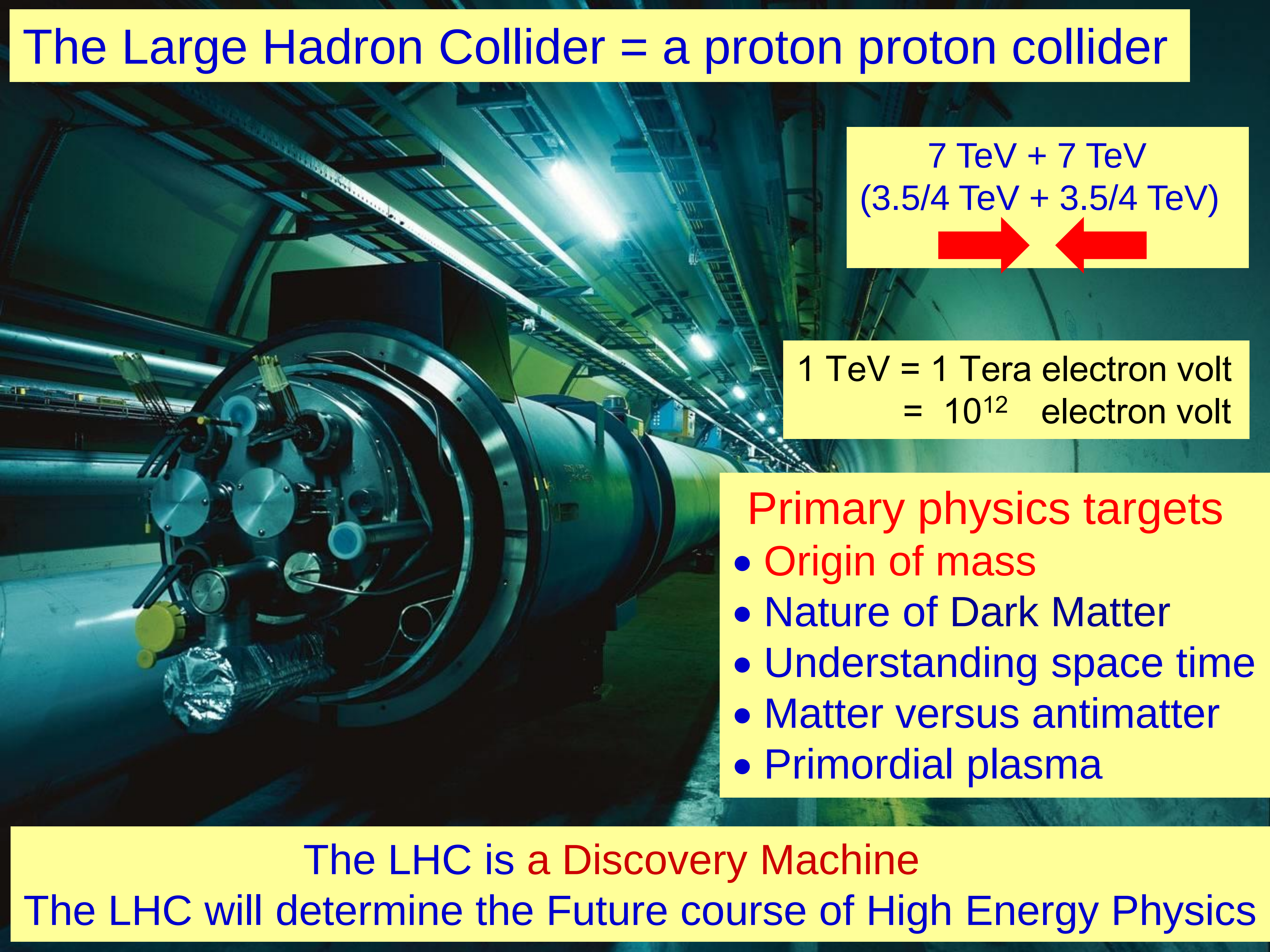
1. Accelerators : powerful machines that accelerate particles to extremely high energies and bring them into collision with other particles

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".

The Large Hadron Collider = a proton proton collider



7 TeV + 7 TeV
(3.5/4 TeV + 3.5/4 TeV)

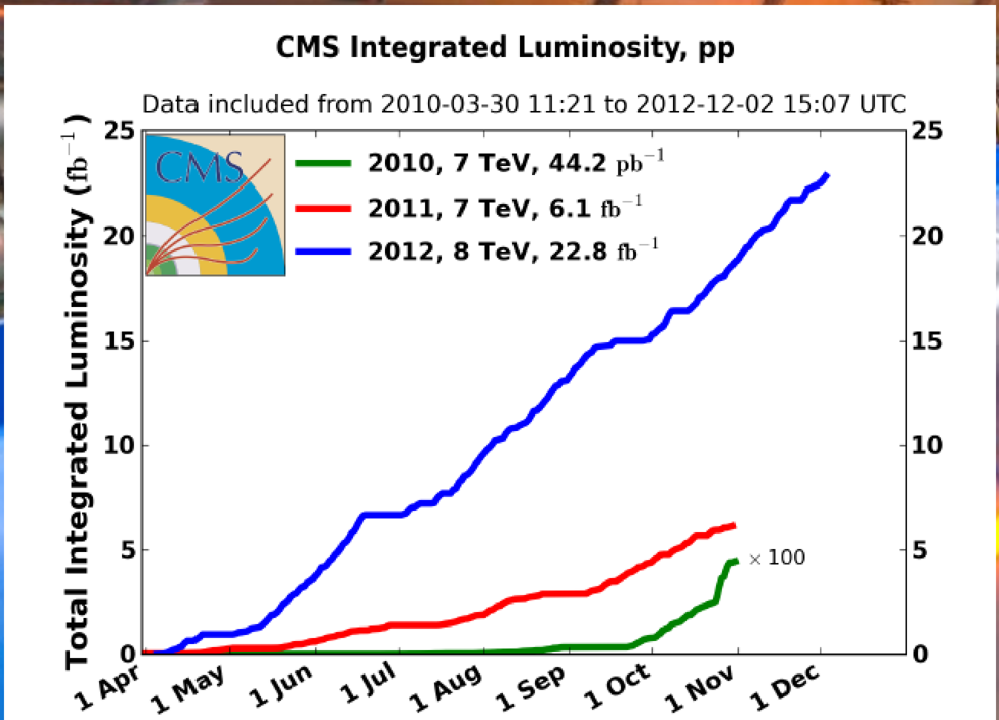
1 TeV = 1 Tera electron volt
= 10^{12} electron volt

Primary physics targets

- Origin of mass
- Nature of Dark Matter
- Understanding space time
- Matter versus antimatter
- Primordial plasma

The LHC is a Discovery Machine
The LHC will determine the Future course of High Energy Physics

- 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

The LHC is an Extraordinary Machine

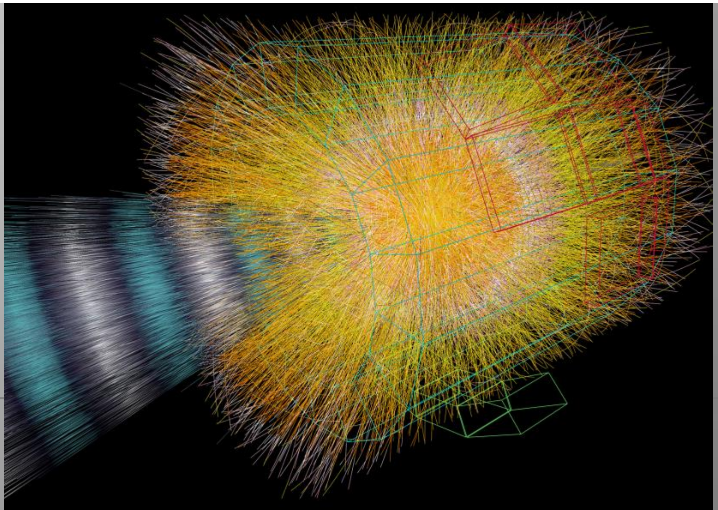
LHC facts

The LHC is …

Colder than the empty Space in the Universe: 1.9K ie above absolute zero

The emptiest place in our solar system. The vacuum is better than on the moon

Hotter than in the sun: temperature in the collisions is a billion times the one in the centre of the sun



Experiments at the LHC

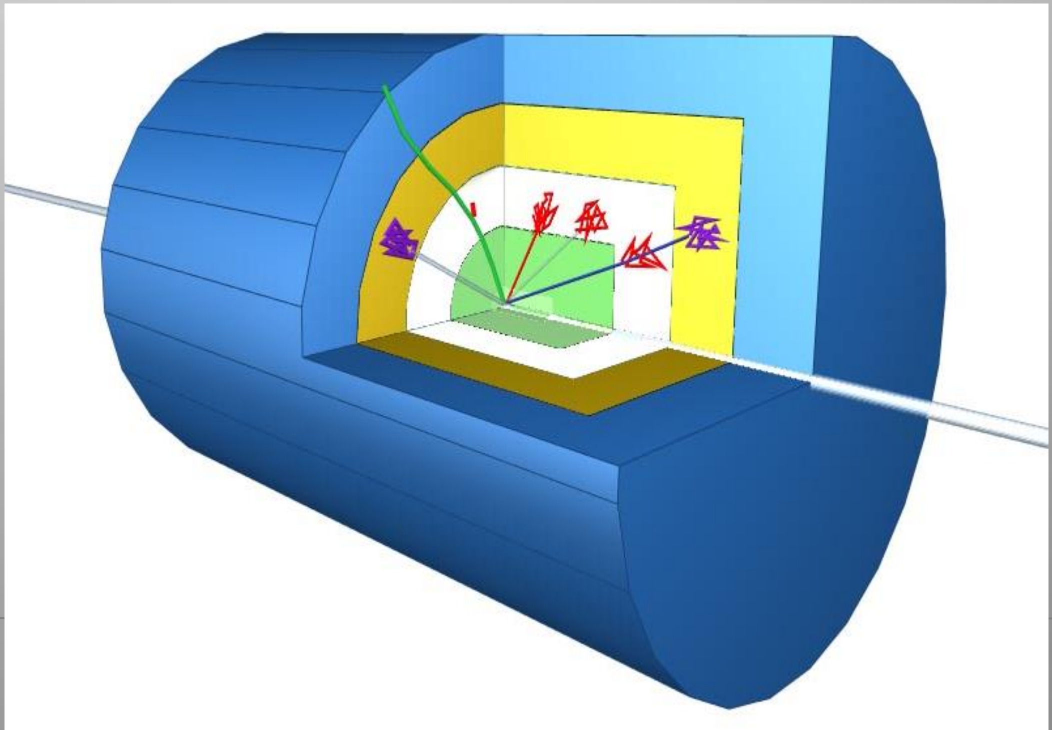
Schematic of a LHC Detector

Physics requirements drive the design!

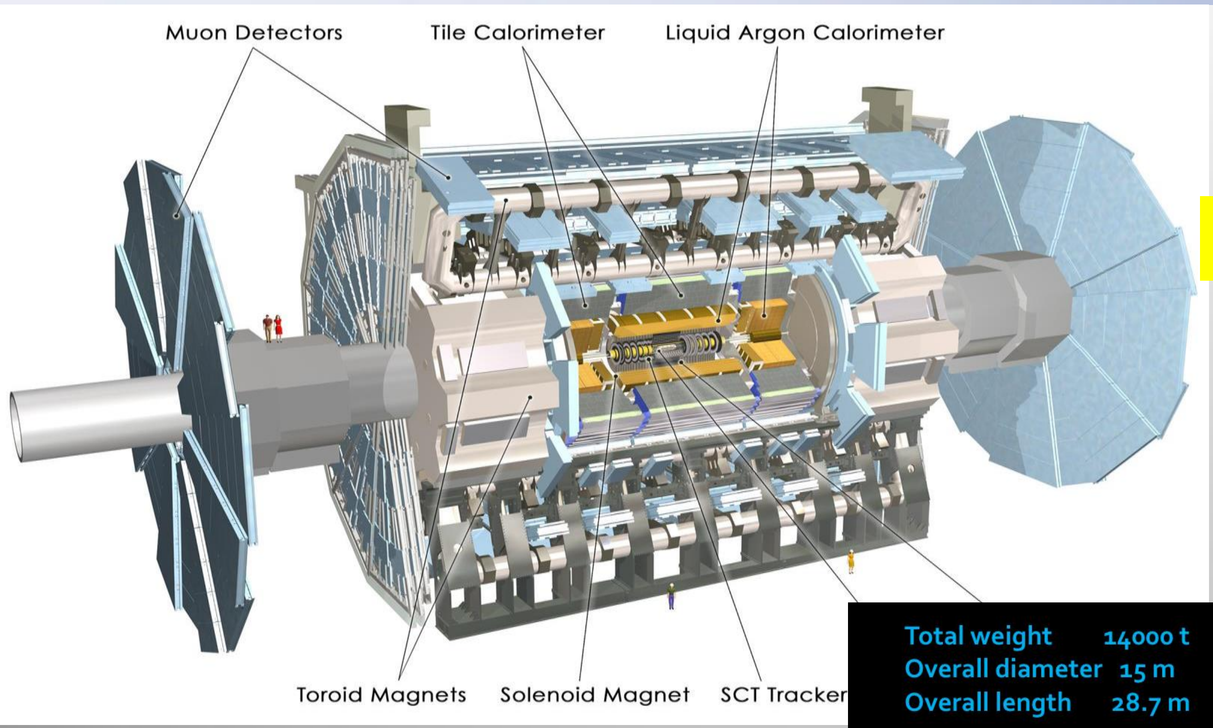
Analogy with a cylindrical onion:

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!!

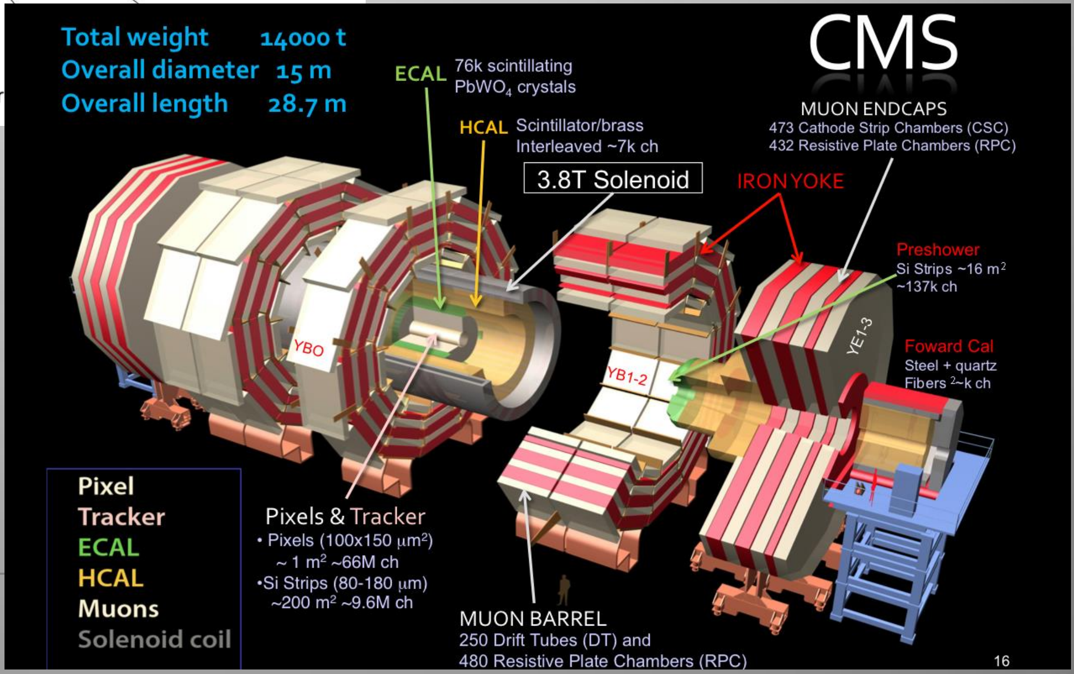


The Higgs Hunters @ the LHC



The ATLAS experiment

The CMS experiment



These experiments use different technologies for their detector components

CMS Collaboration June 27, 2012

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

About 1/8th of the collaboration

Belgium is a member of CMS

CMS before closure

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

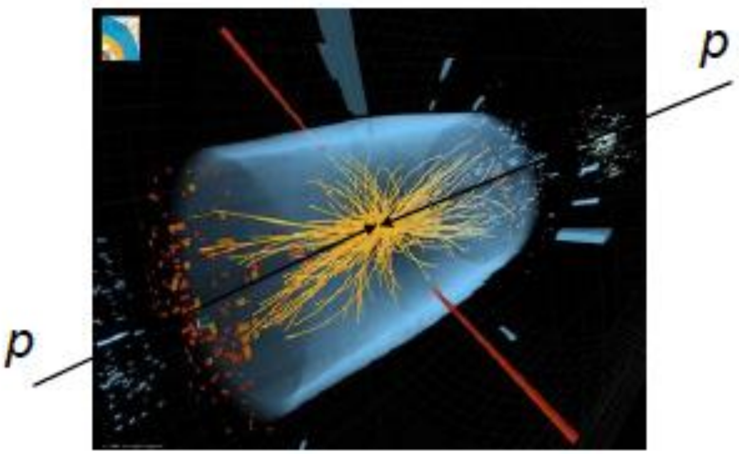
- need high energy:

  $E = mc^2$

- need lots of data

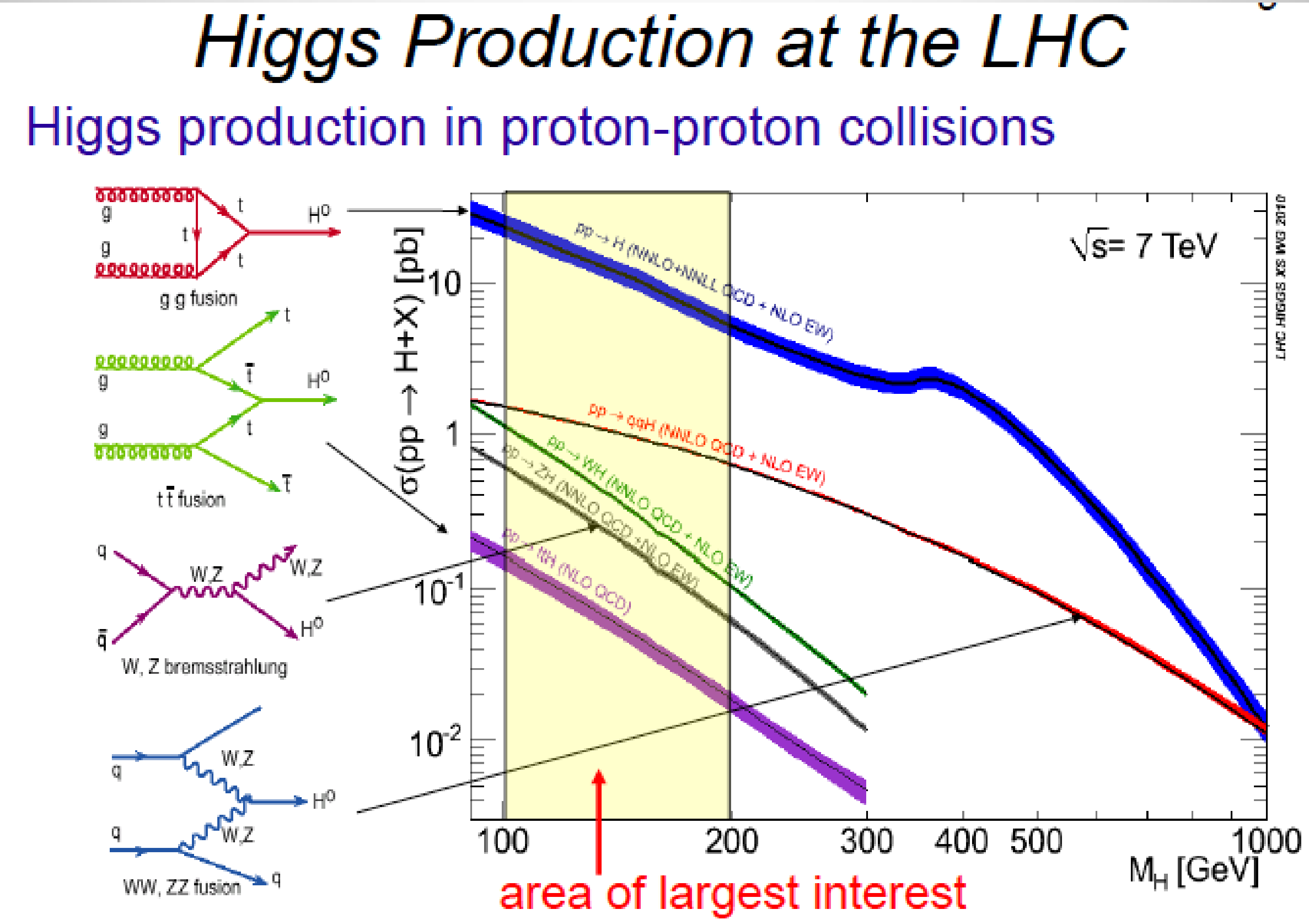
non-deterministic and very rare

order 1 in 10^{11}



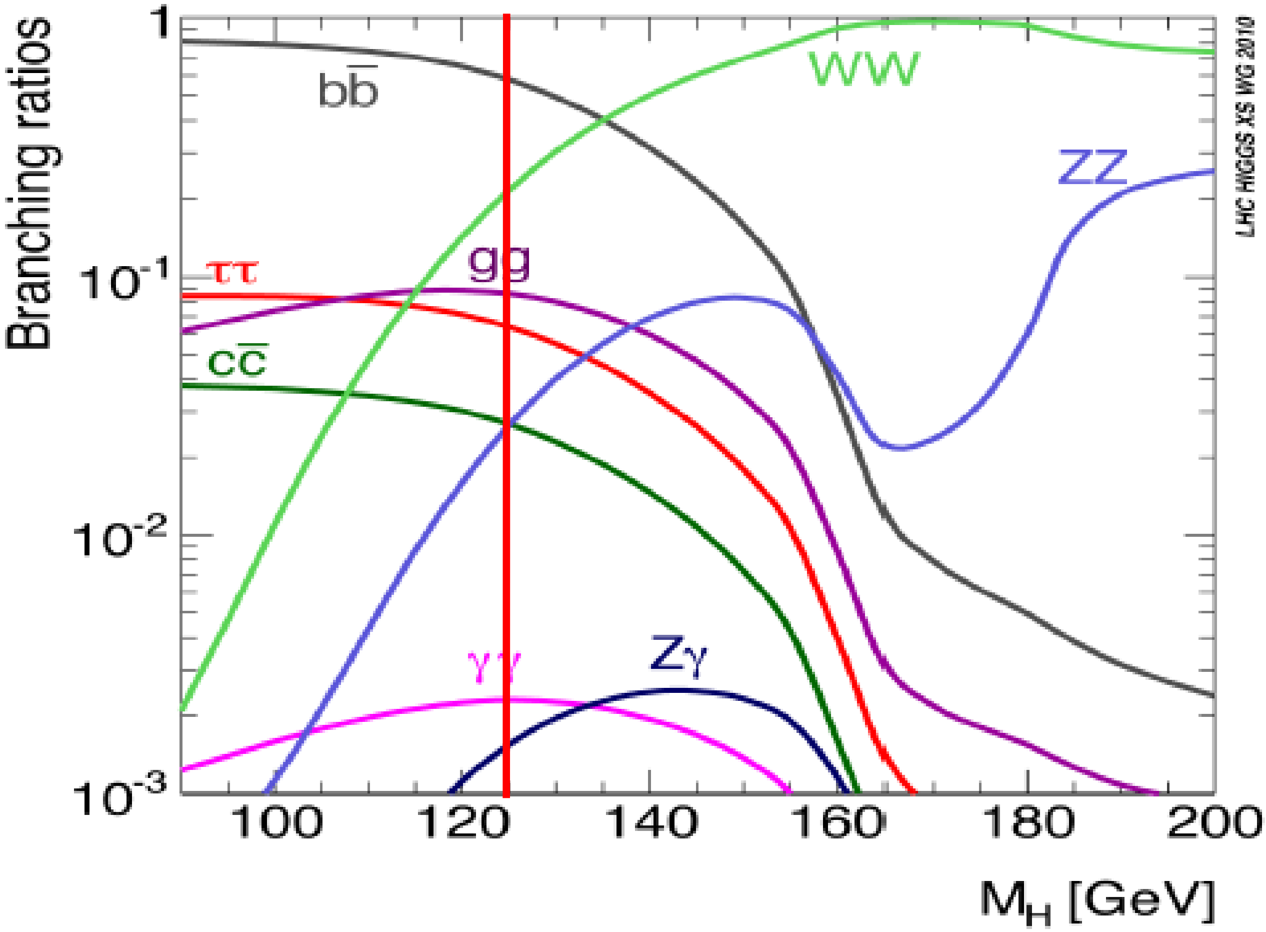
* for us finding the Higgs it was 48 years = 1,513,728,000 sec

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 Hunting at the LHC

Higgs Hunting – The big five

The big five are the five most sensitive search channels at the LHC

Higgs Hunting at the LHC

Overview – The big five

Channel	m_H range [GeV/c^2]	data set [fb^{-1}]	Data used CMS [fb^{-1}]	m_H resolution
1) $H \rightarrow \gamma\gamma$	110-150	5+5/fb	2011+12	1-2%
2) $H \rightarrow$ tau tau	110-145	5+12/fb	2011+12	15%
3) $H \rightarrow bb$	110-135	5+12/fb	2011+12	10%
4) $H \rightarrow WW \rightarrow l\nu l\nu$	110-600	5+12/fb	2011+12	20%
5) $H \rightarrow ZZ \rightarrow 4l$	110-1000	5+12/fb	2011+12	1-2%

Many more channels studied eg also "invisible Higgs decays" (Bristol)

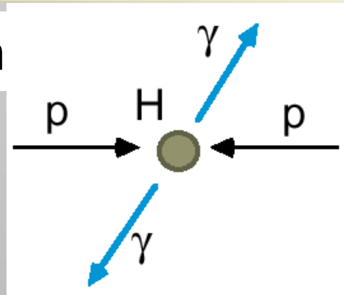
Higgs Boson Searches (simulation)

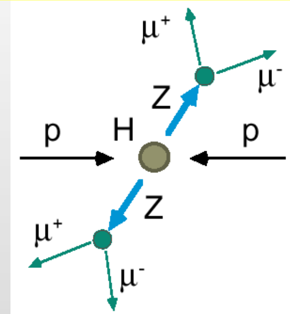
Low M_H < 140 GeV/c²

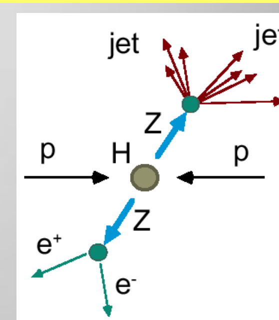
Medium 130<M_H<500 GeV/c²

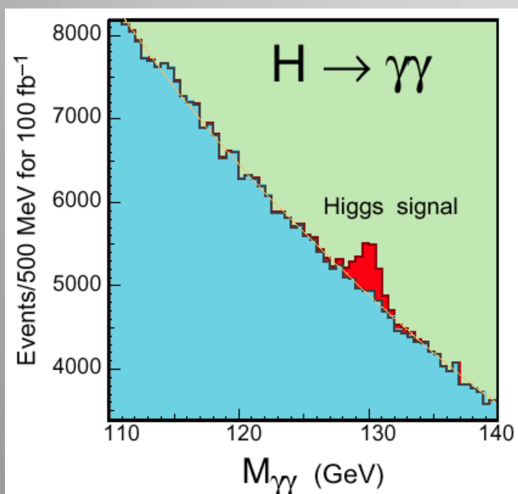
High M_H > ~500 GeV/c²

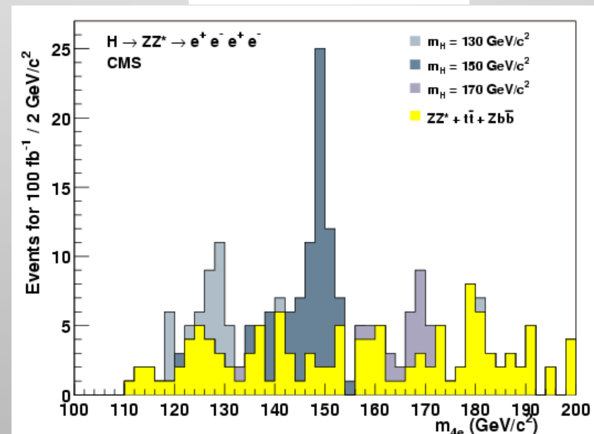
simulation

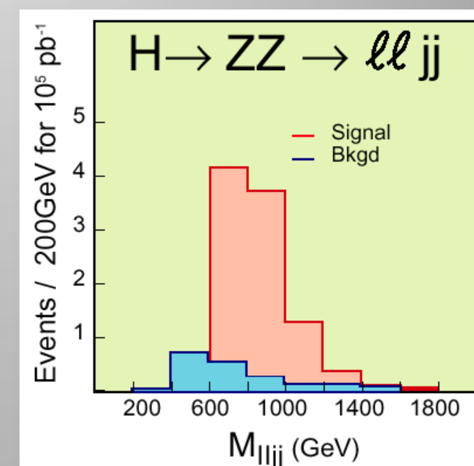


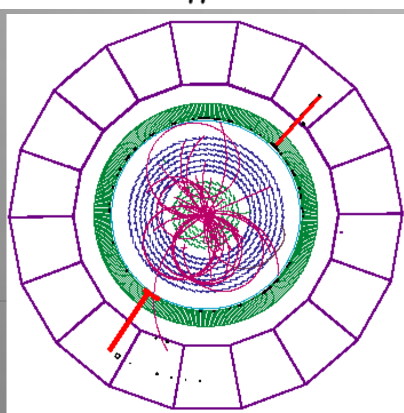


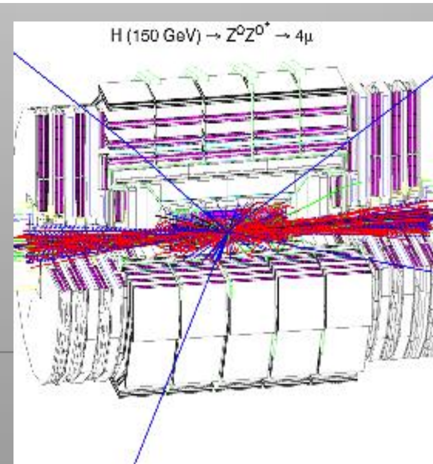


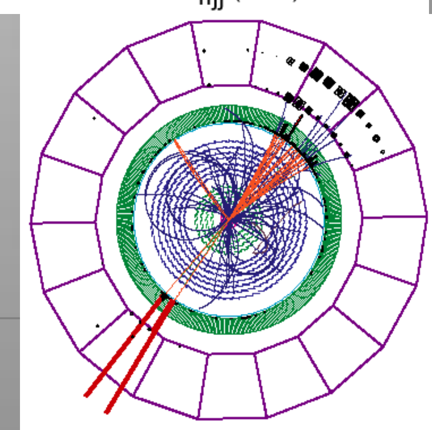












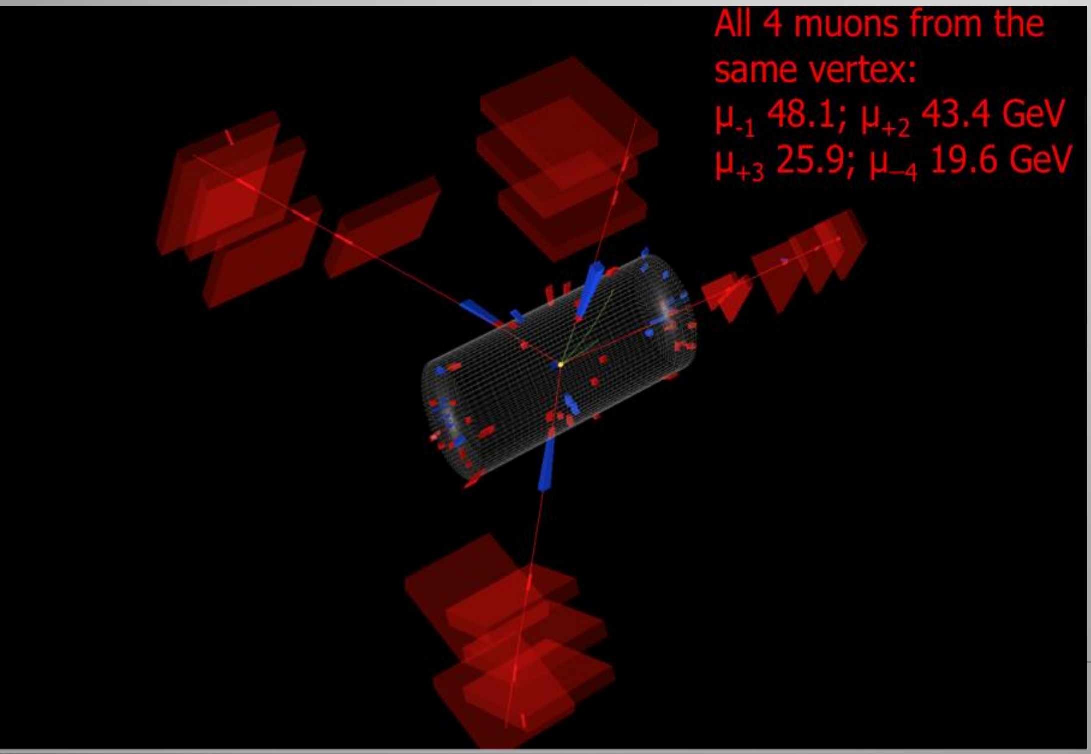
Searches for the Higgs Particle

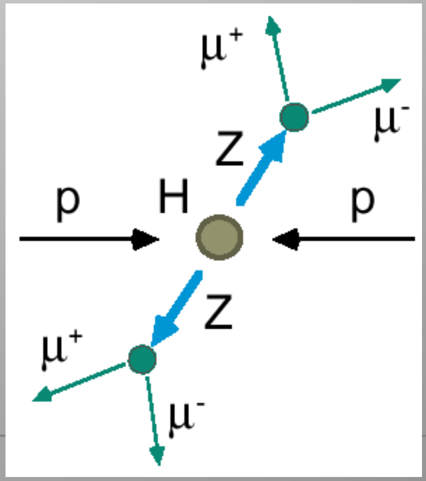
A Higgs particle will decay immediately, eg in two heavy quarks or two heavy (W,Z) bosons

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

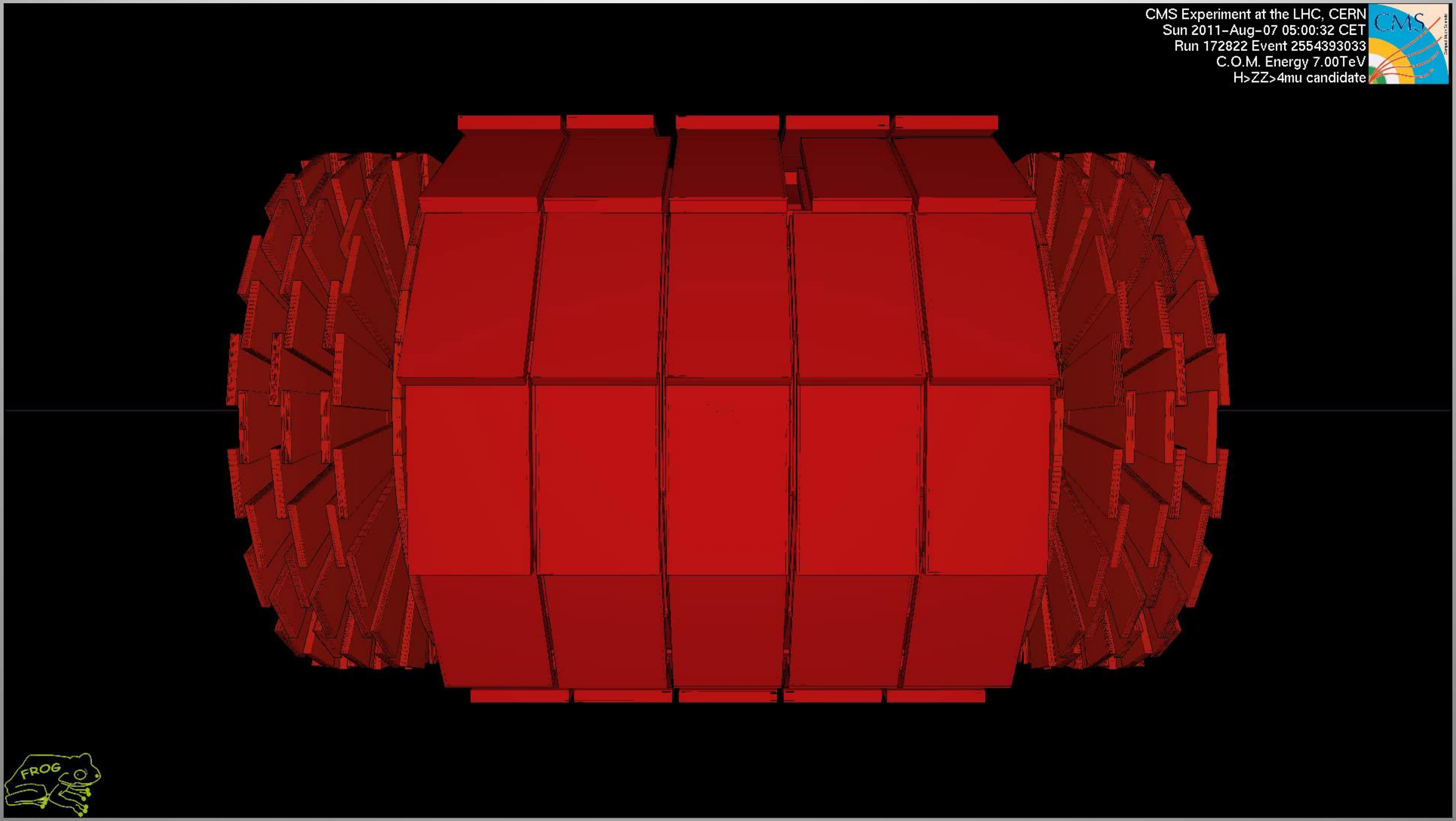
So we look for 4 muons in the detector

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)

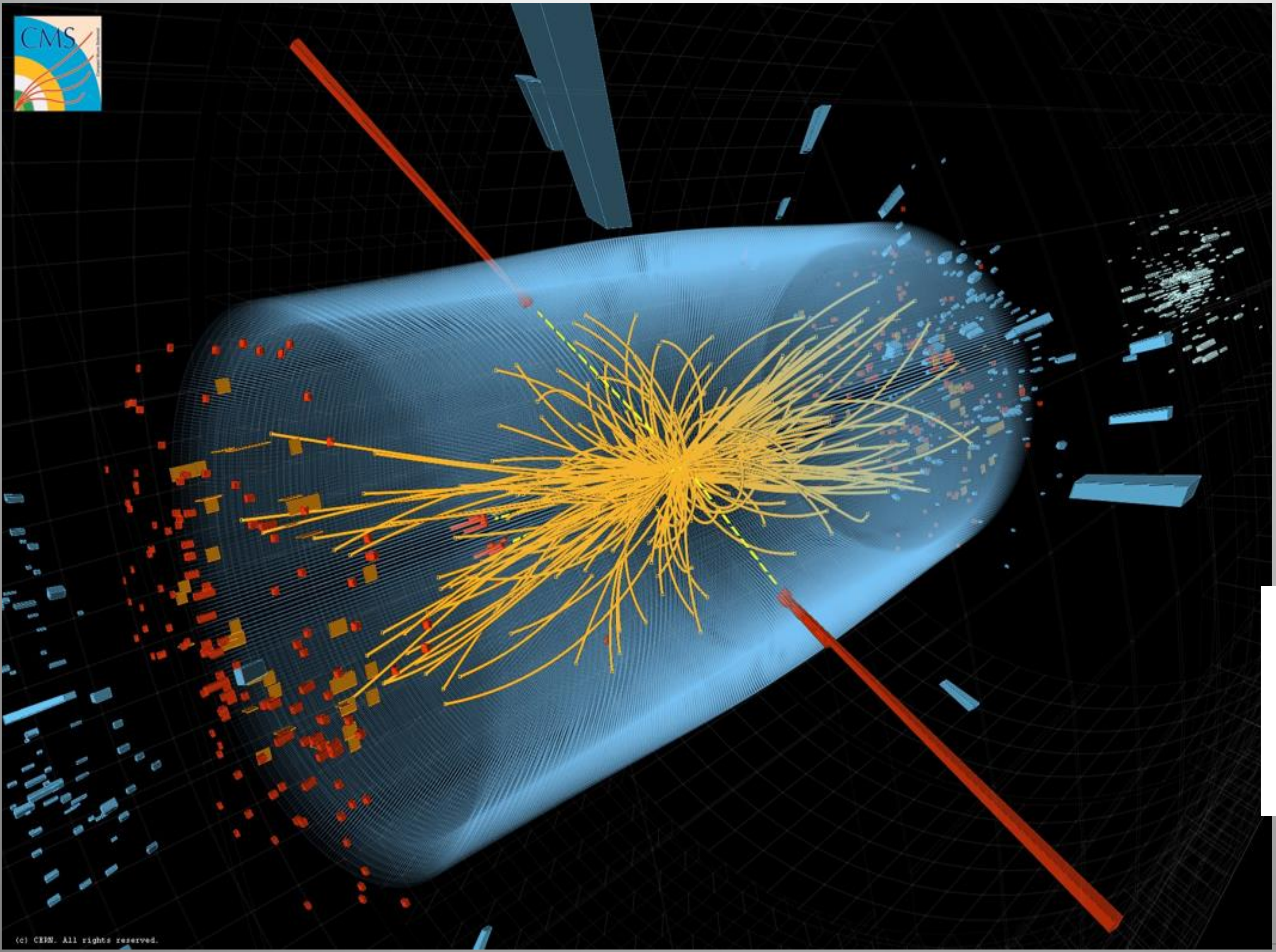


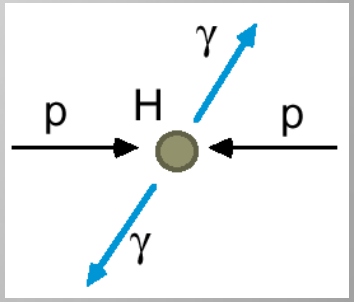


A real collisions: ZZ-> 4 muons



Searches for the Higgs Particle





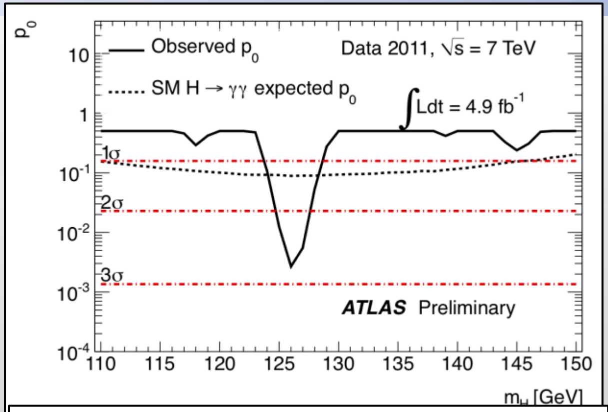
A Higgs or
a ‘background’
process without
a Higgs?

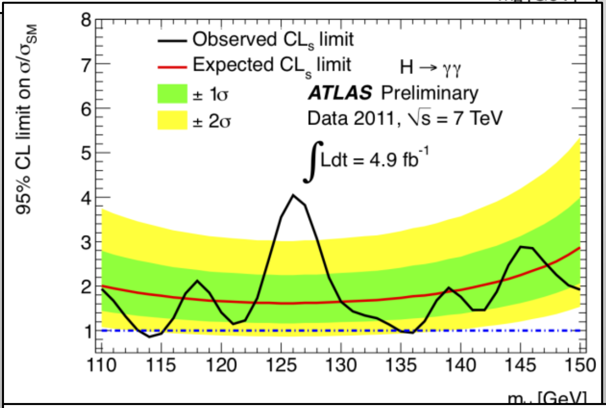
Aside :Profile likelihood Ratio, p_0 and CL_s

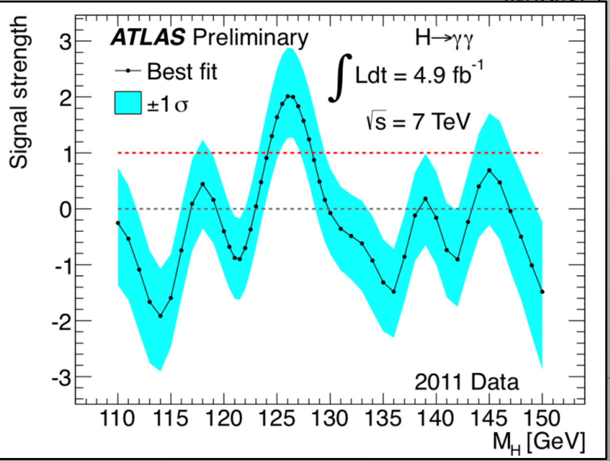
- Local significance p_0 to test background hypothesis

- $CL_s = CL_{s+b}/CL_b$ (log-likelihood ratio) to test signal hypothesis

- estimate signal strength (relative to expectation)







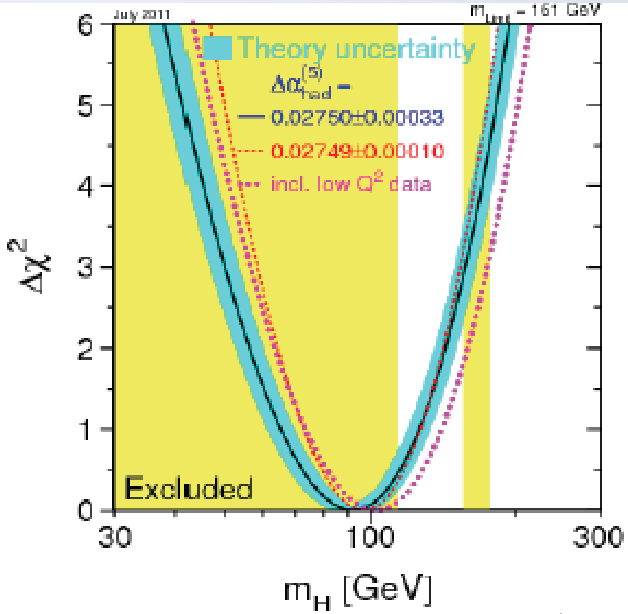
3 sigma= "Evidence"

1 chance in 1000 to be wrong!

5 sigma="Discovery"

1 chance in 3 million to be wrong!!!

Pre-LHC Information on the Higgs



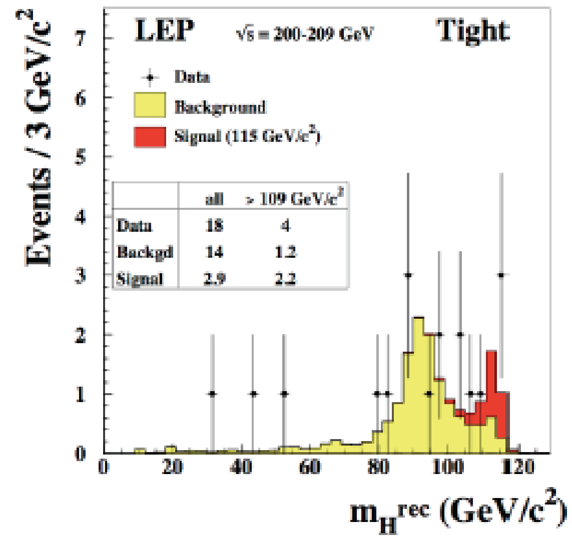
$\Delta\chi^2$ from fit to electroweak measurements from LEP, SLD and Tevatron **assuming the SM**

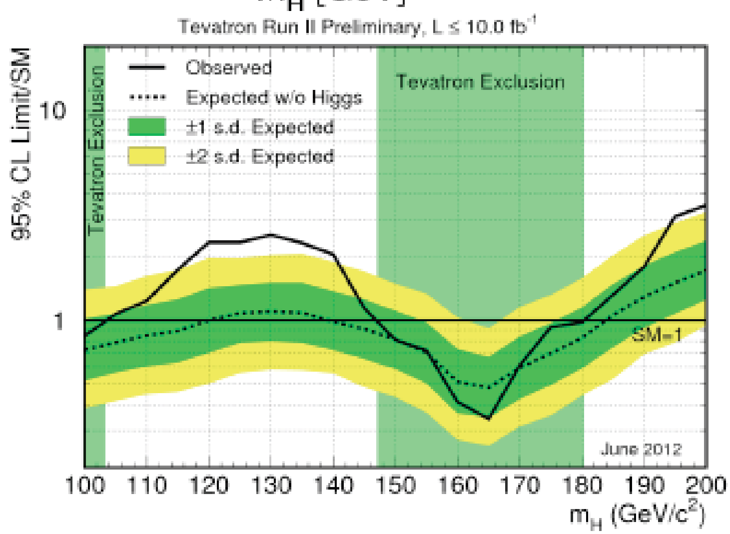
Preferred value for the mass: 92^{+34}_{-26} GeV

Upper bound: $M_H < 161\,\text{GeV}$

LEP direct search:

$M_H > 114.4\,\text{GeV}$





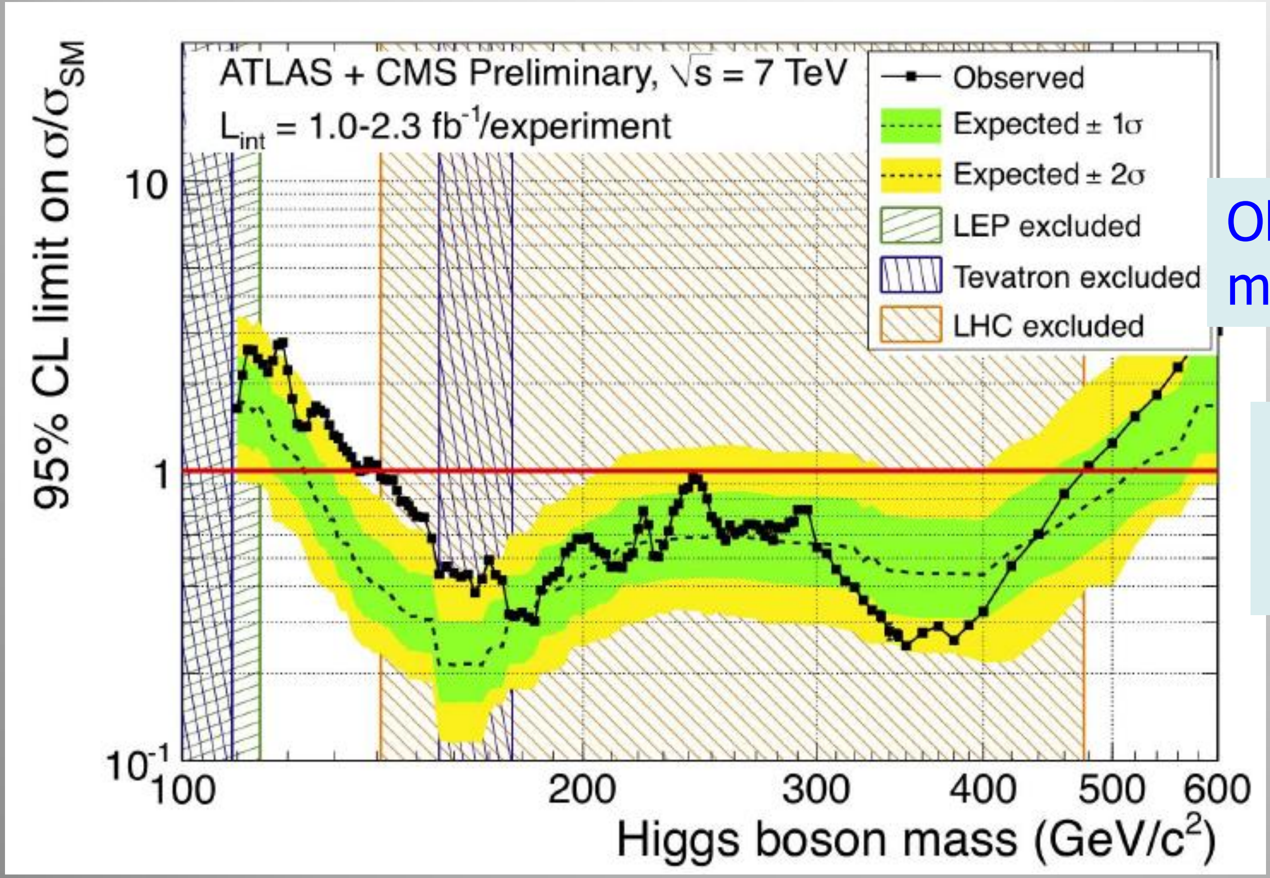
Tevatron exclusion @95% CL (June 2012):

$100-103\,\text{GeV}$ $\quad$ $147-180\,\text{GeV}$

....Enter the LHC !

Fall 2011:Where is the Higgs Boson?

November 2011 -- HCP Paris Meeting: no sign of a Higgs boson yet



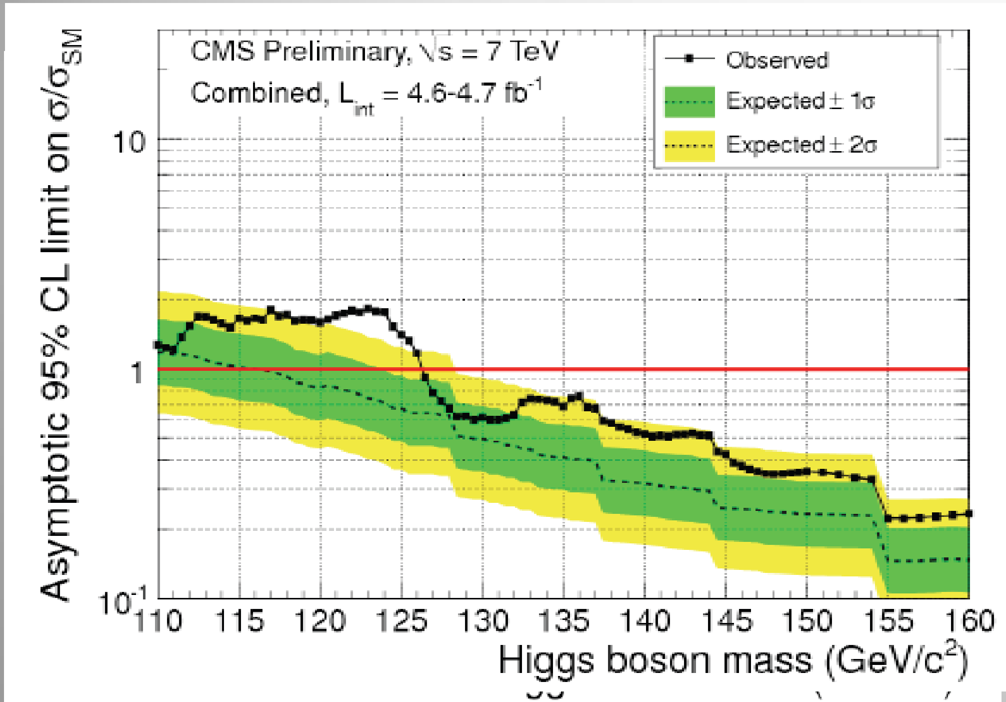
Observed 95% CL exclusion mass range: 141-476 GeV

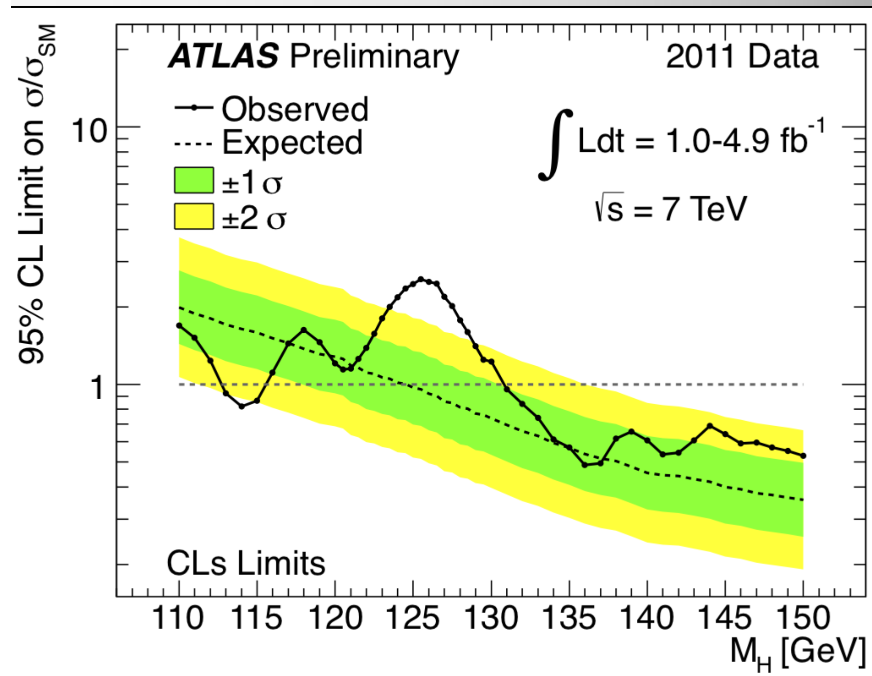
Higgs can live only in the range 114.4 -141 GeV or above 476 GeV

If we would exclude the Higgs in the full range, this would be a major discovery!!!

New Phenomena are expected to be observed ~1 TeV @ LHC

The Higgs Search by December 2011





All the data from 2011 was now analysed and the combination of the big five showed the following:

-We see – for the first time-- an excess of events building up in a region over expectation from pure background. Cool!

Is this the first sign of the 'growing Higgs signal? We can't say for sure….

→These questions will be answered with the 2012 data (4 x 2011 data)

The Higgs Boson

The Washington Post
NATIONAL

Spring 2012

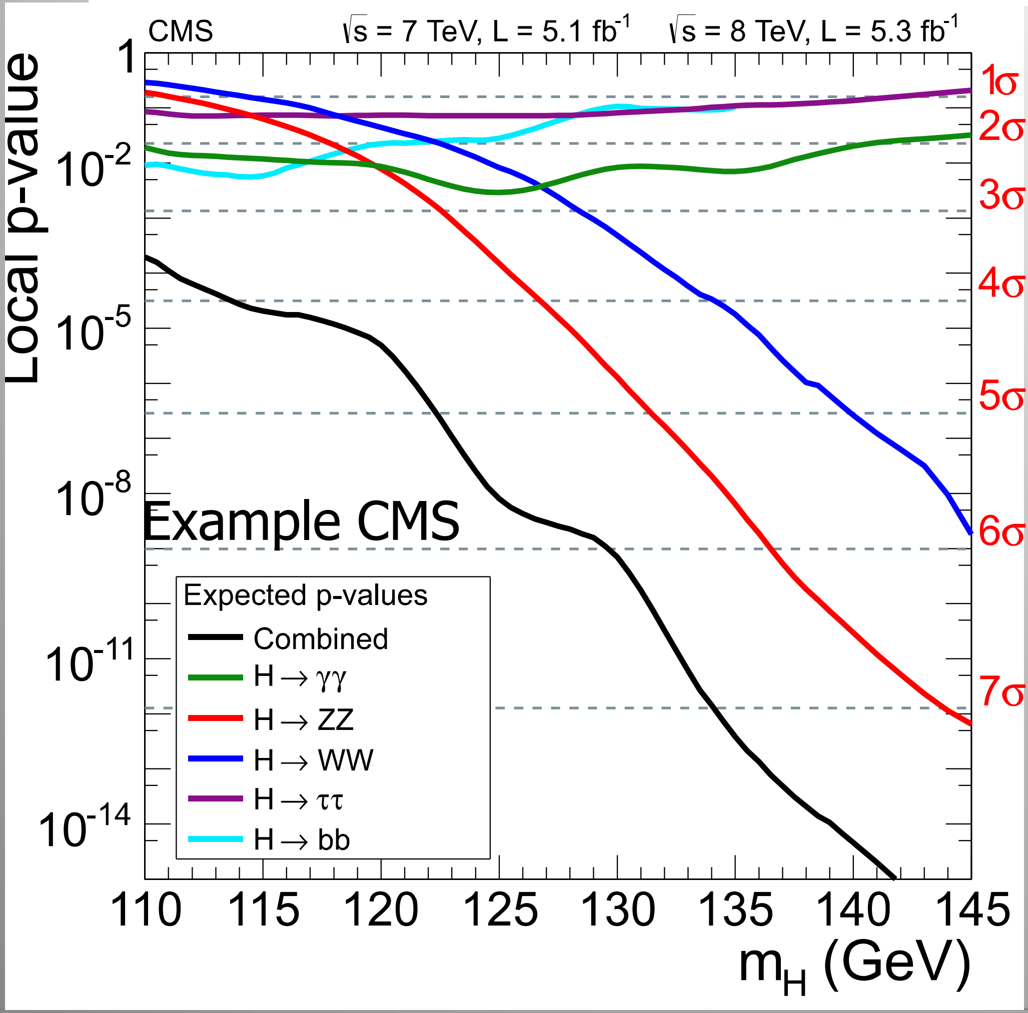
Physicists hope to find the Higgs boson, key to unified field theory, this year

Fabrice Coffrini/Agence France-Presse via Getty Images - A superconducting solenoid magnet, the largest of its kind, is part of the Large Hadron Collider, which is searching for the Higgs boson.

The suspense was building up…

Expected Sensitivity by Summer 2012

By summer we got another 5 fb^{-1} of data at 8 TeV
We also improved the analyses in CMS



Most of the heavy lifting is done by γγ and ZZ final states, since those modes exploit the excellent mass resolution (~1-2%) of CMS

We could have a discovery summer 2012

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

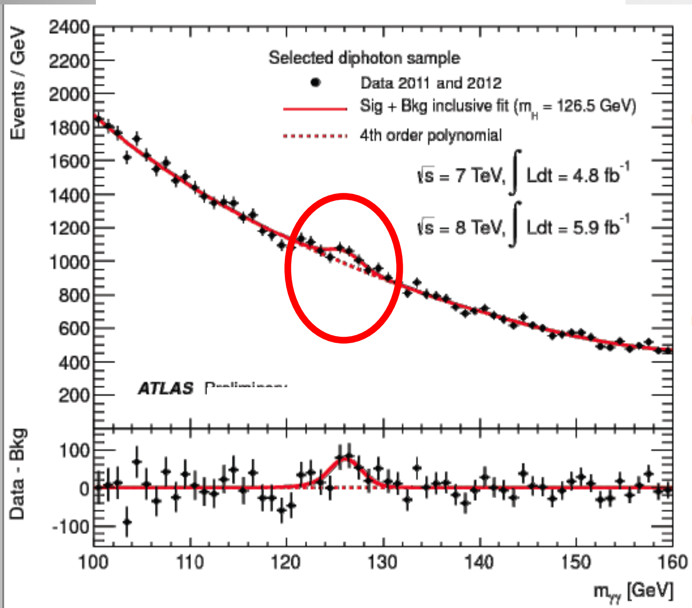
CERN

Melbourne

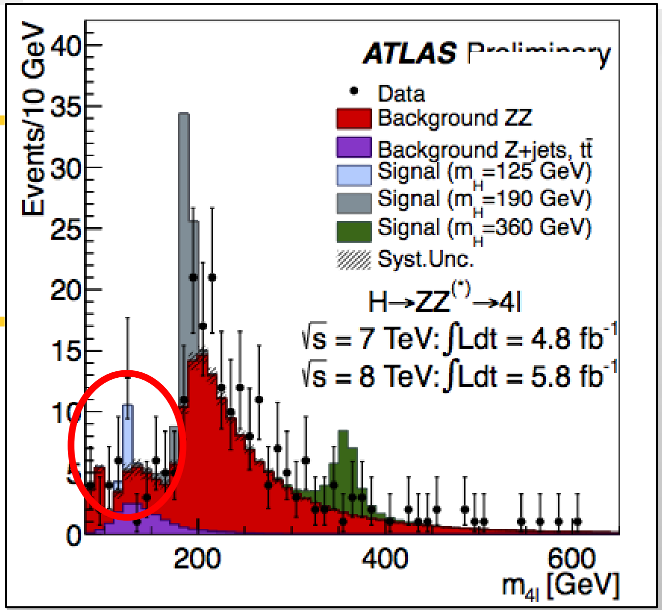
Followed live around the world…

Summer 2012: Results

Higgs → 2 photons!!

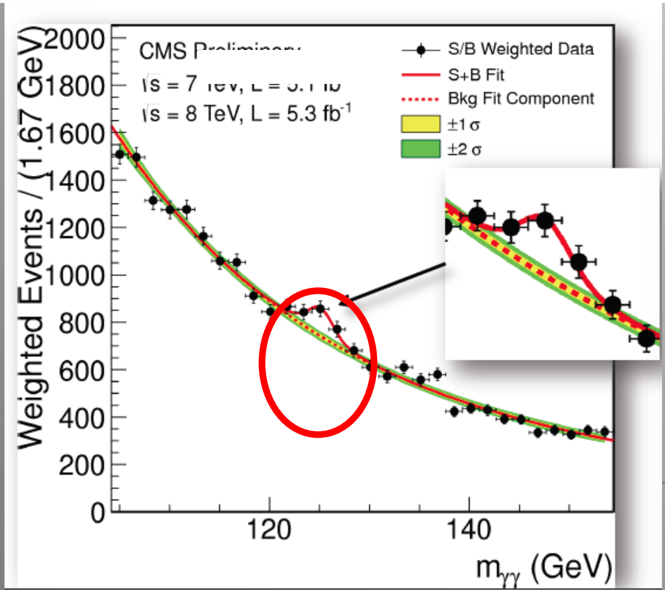


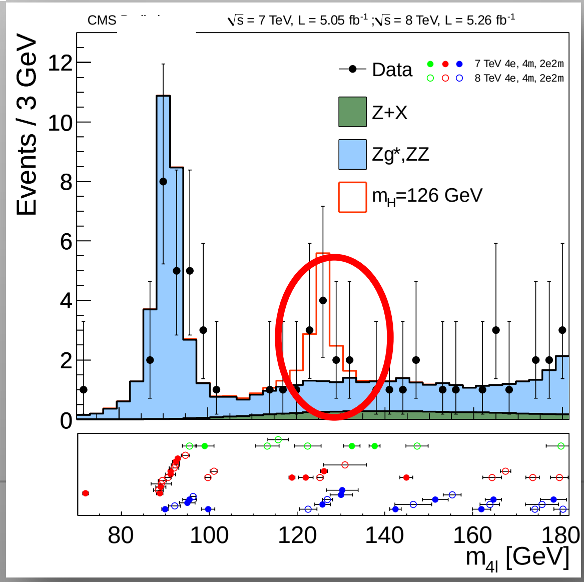
Higgs → 2 Z →4 leptons!!



A clear "excess" of events seen in both experiments around 125-126 GeV

It became very significant in 2012



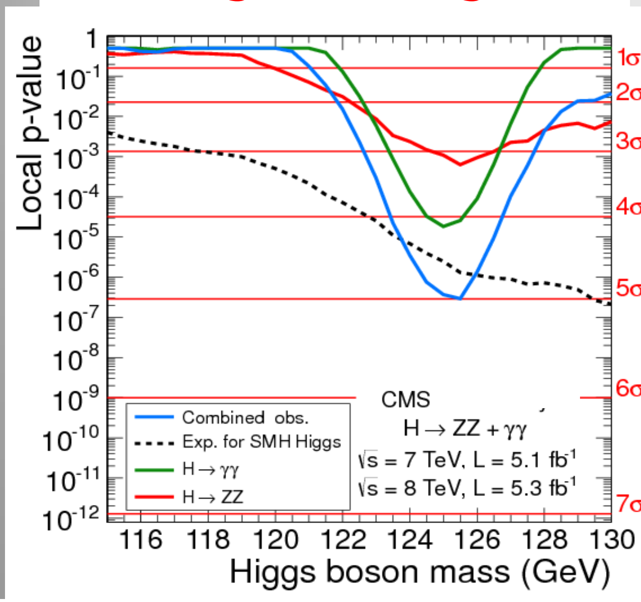


Sophisticated Statistical Methods have used to fully analyse this.

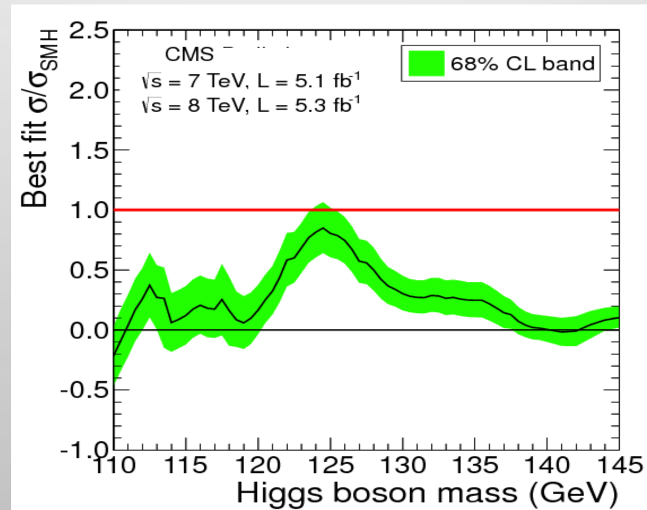
And the result is…→

Results from the Experiments

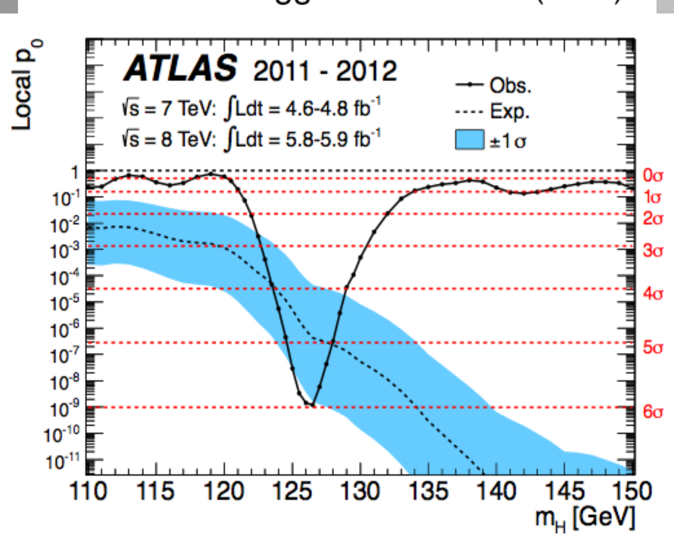
Statistical combination:
Total signal strength

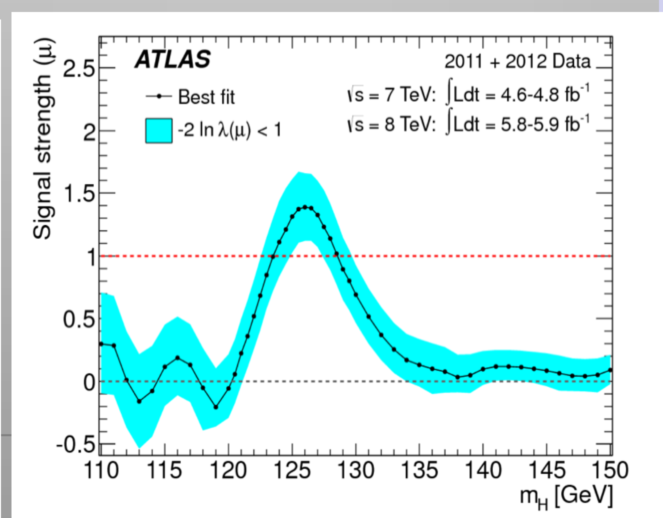


Compatibility with
a Standard Model Higgs



CMS and ATLAS observe a new boson with a significance of about 5 sigma



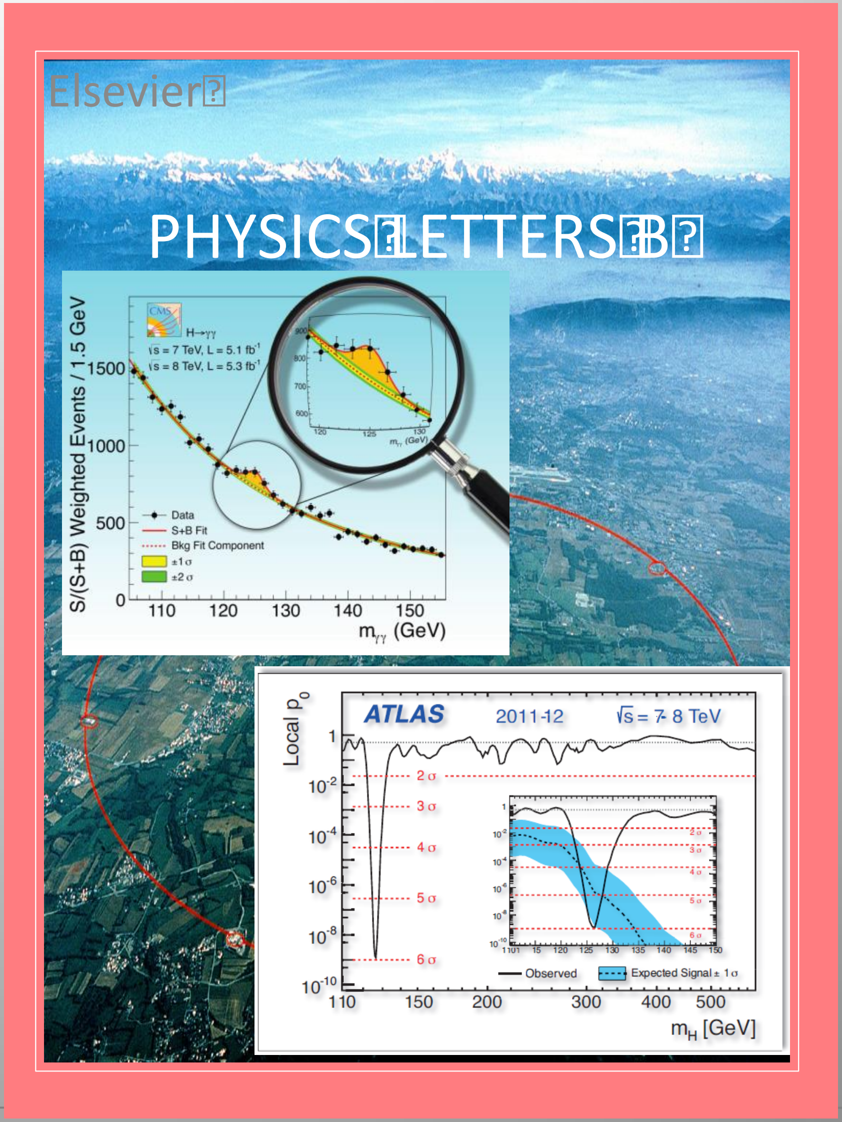


The particle is consistent with a Higgs-like boson

Higgs Publication

Two papers are published side by side in the same issue of PLB

Special booklet edition with the two papers and an art cover



The Press… (5th July 2012)

The discovery of the Higgs made the headlines worldwide

Hawking lost $100 bet over Higgs boson

What Comes After Higgs Boson?

the Atlantic wire what matters now

'God Particle' 'Discovered': European Researchers Claim Discovery of Higgs Boson-Like Particle

HOW THE HIGGS COULD BECOME ANNOYING

Yes, the discovery of the Higgs boson is thrilling and game-changing. But it could also introduce some aggravating situations.

Хиггс увидит бозон

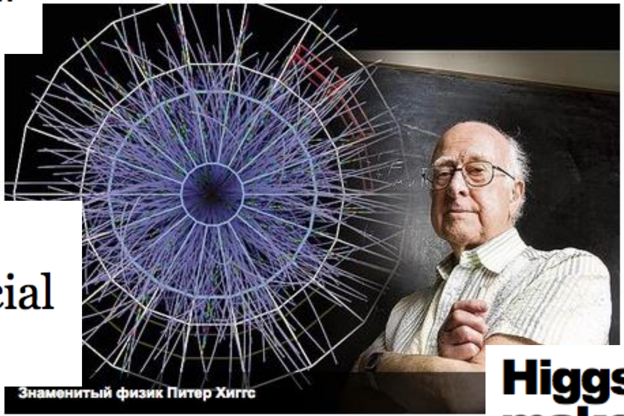
В CERN открыли бозон Хиггса

Текст

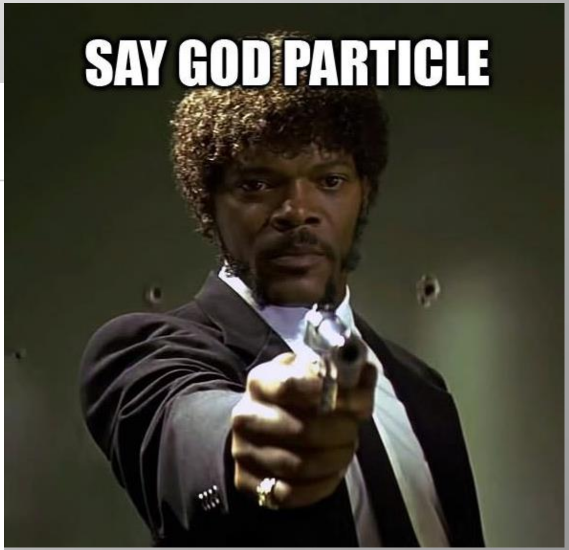
— 3.07.12 15:13 —

ТЕКСТ: АЛЕКСАНДРА БОРИСОВА

D: SCIENCEUNSEEN.COM



Знаменитый физик Питер Хиггс



Discovery of Higgs Boson Bittersweet News in Texas

Scientists Set The Higgs Boson To Music

3 Ways the Higgs Boson Discovery Will Impact Financial Services

Higgs boson researchers consider move to Cloud computing

"Within another decade the Cloud will be where grid computing is now"

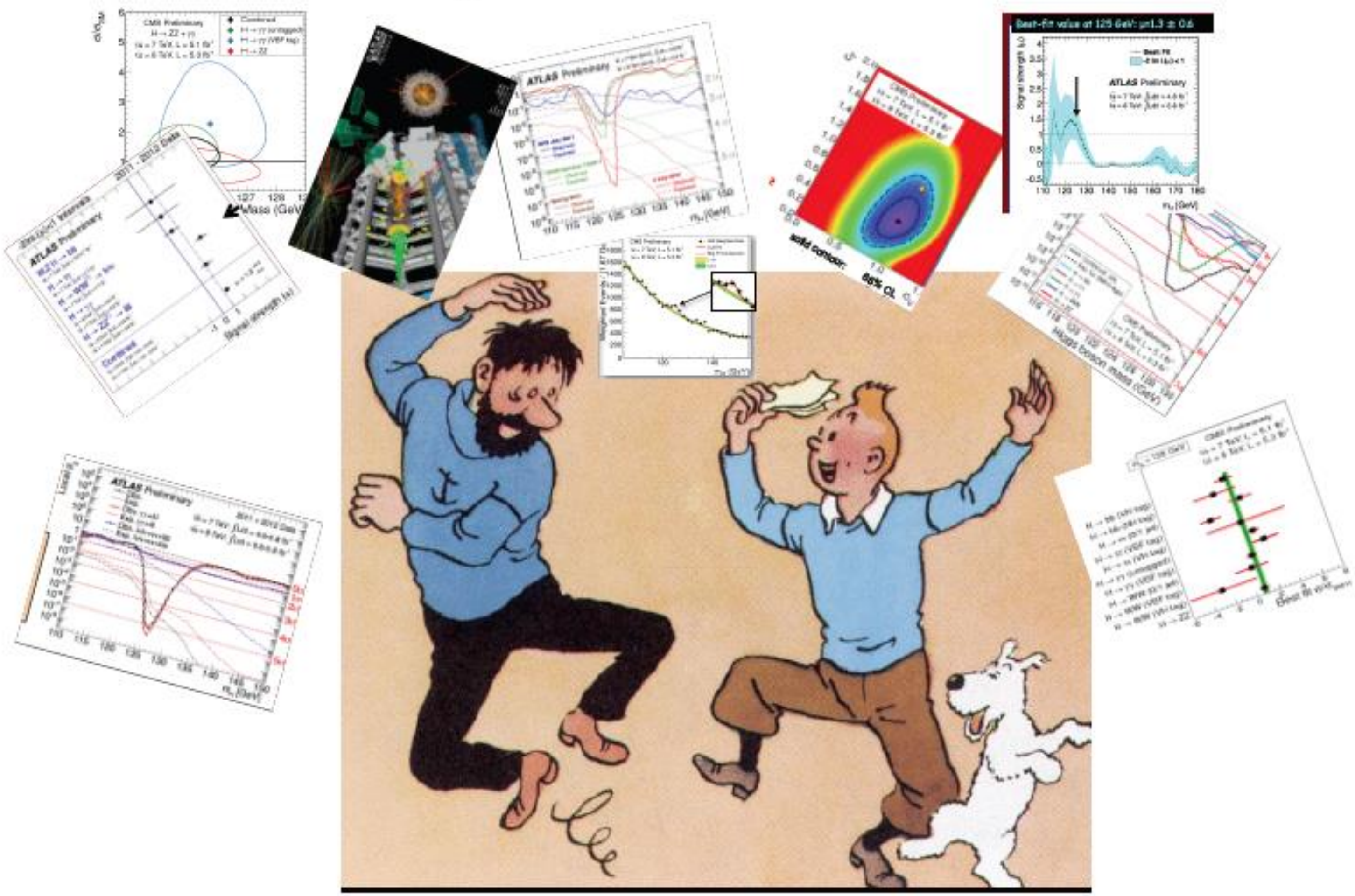
Higgs boson discovery could make science fiction a reality

Discovery of the 'God particle' could make science fiction a reality, and answer one of the most basic questions of our universe: How did light become matter — and us?

The Theorists…

A. Pomarol ICHEP2012

… and finally plenty of new relevant data has begun to fall over us!



The Community (The day after…)

Confronting the MSSM and the NMSSM with the Discovery of a Signal in the two Photon Channel at the LHC
R. Benbrik, M. Gomez Bock, S. Heinemeyer, O. Stal, G. Weiglein, L. Zeune

Have We Observed the Higgs (Imposter)?
Ian Low, Joseph Lykken, Gabe Shaughnessy

2:1 for Naturalness at the LHC?
Nima Arkani-Hamed, Kfir Blum, Raffaele Tito D'Agnolo, JiJi Fan

The apparent excess in the Higgs to di-photon rate at the LHC: New Physics or QCD uncertainties?
I. Baglio, A. Djouadi, R. M. Godbole

Testing No-Scale F-SU(5): A 125 GeV Higgs Boson and SUSY at the 8 TeV LHC
Tianjun Li, James A. Maxin, Dimitri V. Nanopoulos, Joel W. Walker

Higgs boson of mass 125 GeV in GMSB models with messenger-matter mixing
A. Albaid, K.S. Babu

125 GeV Higgs Boson, Enhanced Di-photon Rate, and Gauged U(1)_PQ-Extended MSSM
Haipeng An, Tao Liu, Lian-Tao Wang

Higgs discovery: the beginning or the end of natural EWSB?
Marc Montull, Francesco Riva

The Social Higgs
Daniele Bertolini, Matthew McCullough

Could two NMSSM Higgs bosons be present near 125 GeV?
John F. Gunion, Yun Jiang, Sabine Kraml

First Glimpses at Higgs' face
J. R. Espinosa, C. Grojean, M. Muhlleitner, M. Trott

Precision Unification in λSUSY with a 125 GeV Higgs
Edward Hardy, John March-Russell, James Unwin

Implications of the Higgs Boson Discovery for mSUGRA
Sujeet Akula, Pran Nath, Gregory Peim

Global Analysis of the Higgs Candidate with Mass ~ 125 GeV
John Ellis, Tevong You

The Higgs sector of the phenomenological MSSM in the light of the Higgs boson discovery
Alexandre Arbey, Marco Battaglia, Abdelhak Djouadi, Farvah Mahmoudi

Is the resonance at 125 GeV the Higgs boson?
Pier Paolo Giardino, Kristjan Kannike, Martti Raidal, Alessandro Strumia

Constraining anomalous Higgs interactions
Tyler Corbett, O. J. P. Eboli, J. Gonzalez-Fraile, M. C. Gonzalez-Garcia

Higgs After the Discovery: A Status Report
Dean Carmi, Adam Falkowski, Eric Kuflik, Tomer Volansky, Jure Zupan

Are There Hints of Light Stops in Recent Higgs Sear
Matthew R. Buckley, Dan Hooper

The Theories

But not so excellent for all theorists:

Specially for fans of **Higgsless models:**

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!!
Let's look at the new updates with full 2012 data (~ 20 fb^{-1})

The Science Press

ARTICLE

A New Boson with a Mass of 125 GeV Observed with the CMS Experiment at the Large Hadron Collider

The CMS Collaboration*†

The Higgs boson was postulated nearly five decades ago within the framework of the standard model of particle physics and has been the subject of numerous searches at accelerators around the world. Its discovery would verify the existence of a complex scalar field thought to give mass to three of the carriers of the electroweak force—the W^+, W^-, and Z^0 bosons—as well as to the fundamental quarks and leptons. The CMS Collaboration has observed, with a statistical significance of five standard deviations, a new particle produced in proton-proton collisions at the Large Hadron Collider at CERN. The evidence is strongest in the diphoton and four-lepton (electrons and/or muons) final states, which provide the best mass resolution in the CMS detector. The probability of the observed signal being due to a random fluctuation of the background is about 1 in 3×10^6. The new particle is a boson with spin not equal to 1 and has a mass of about 1.25 giga–electron volts. Although its measured properties are, within the uncertainties of the present data, consistent with those expected of the Higgs boson, more data are needed to elucidate the precise nature of the new particle.

+ similar article by ATLAS

The News since July 4th

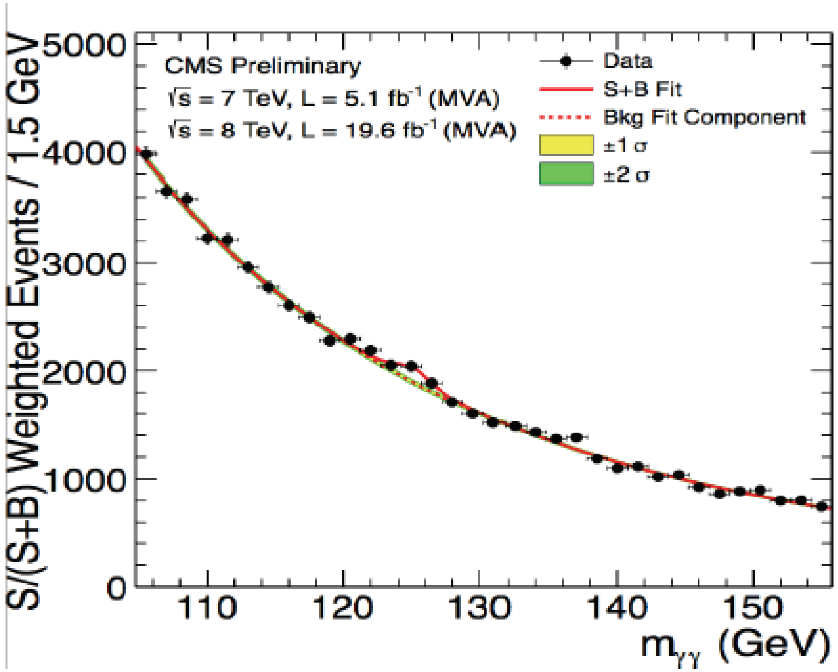
- The full data set of 2011-2012 used, giving an increase of about a factor 3 w.r.t 4^{th} of July
- The discovery of the new particle has been confirmed with more added collisions
- We got a first glimpse of the spin: it is a more likely a parity state 0+ as compared to a 0- (as should be if it is really a Higgs)
- Also seems to favour more spin 0 compare to spin 2
- The mass is getting measured better with time, and in the range125-126 GeV
- The couplings to Bosons and Fermions are consistent with the SM predictions (but these are not very precise yet; Surprises possible)

Results: Higgs into 2 Photons

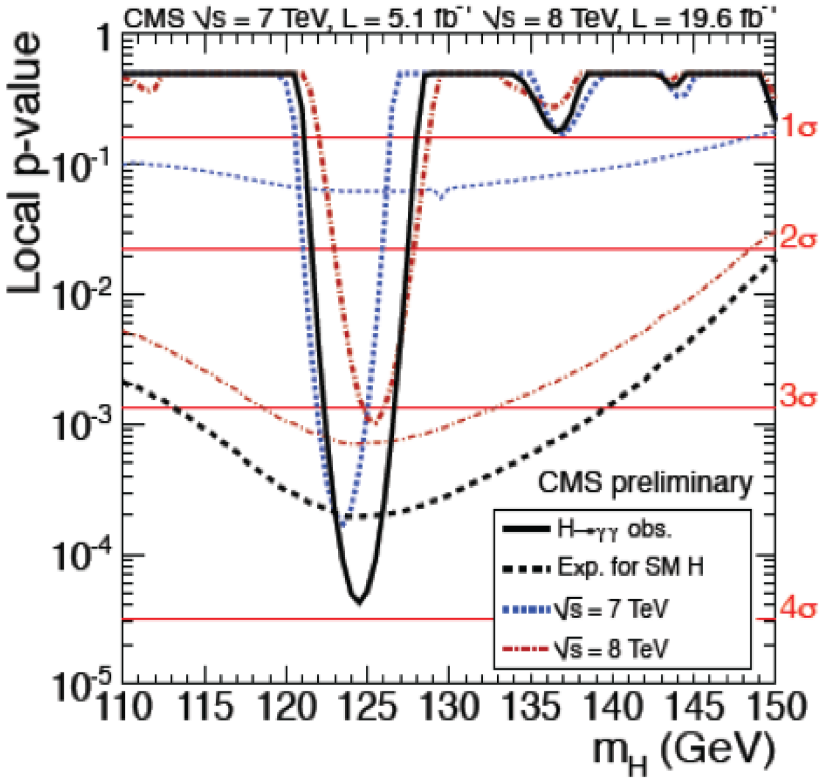
Di-Photon Mass

Different categories/classes inter-consistency

MVA mass-factorized



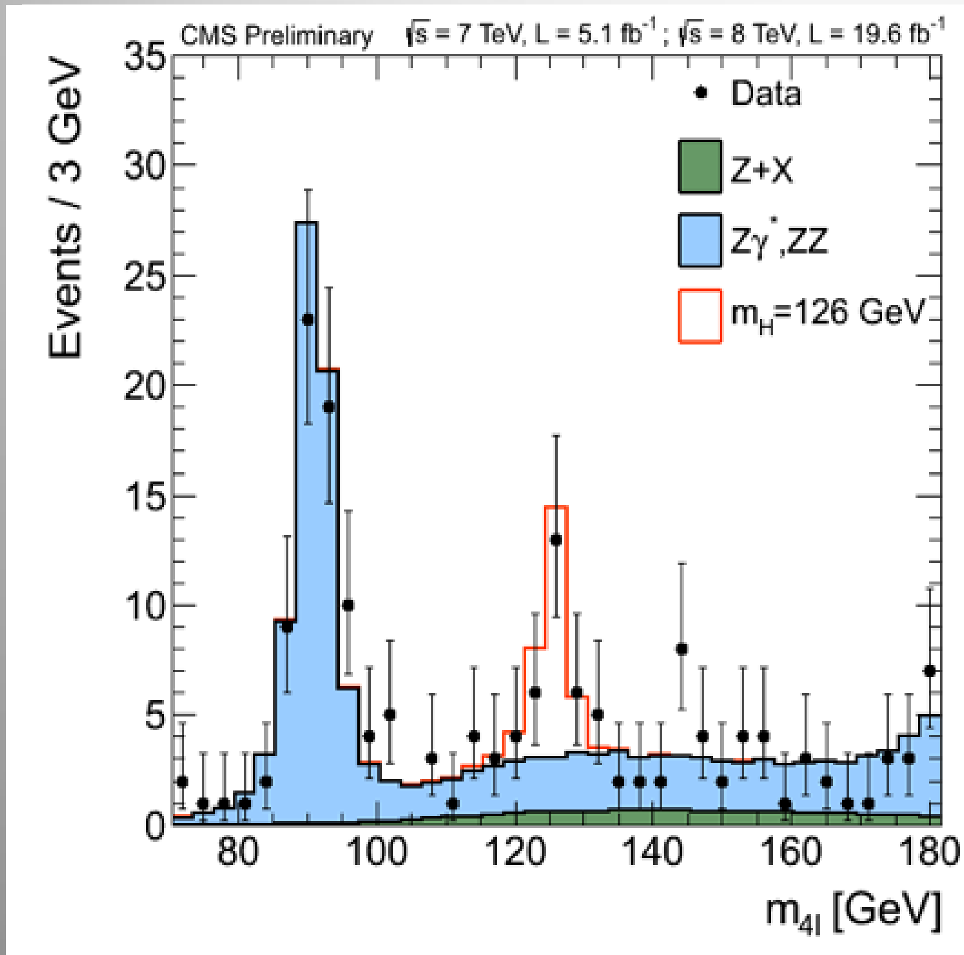
Each event category is **weighted by its S/(S+B)**
only for visualization purposes

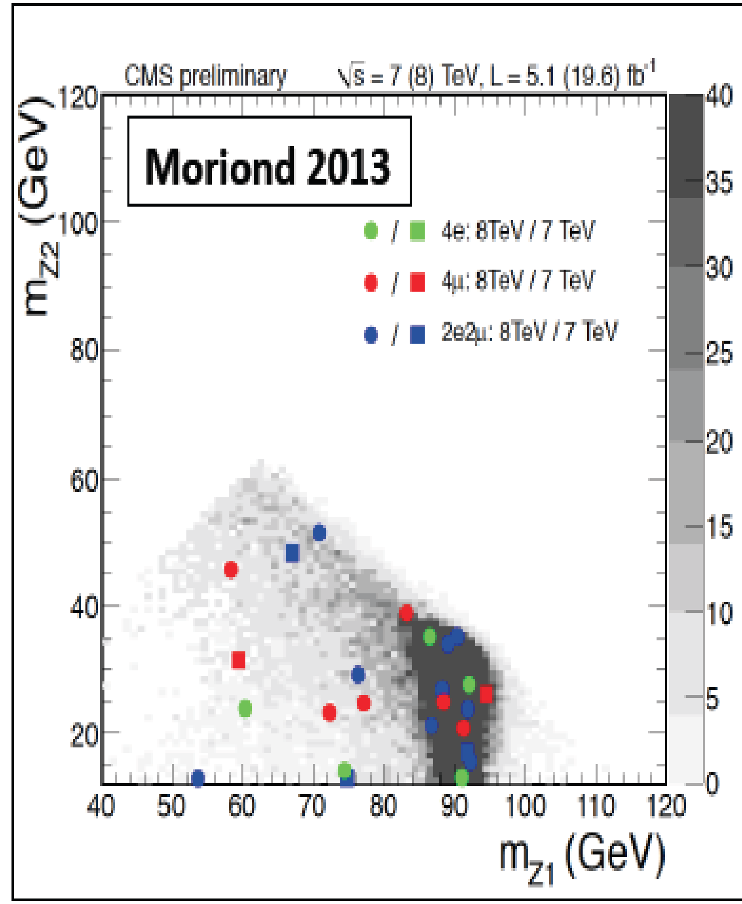


7+8 TeV: σ/σ_{SM} @ 125.0 GeV = 0.78 $^{+0.28}_{-0.26}$

From top to bottom: W,Z associated, Vector Boson fusion, and gg fusion classes

Higgs into two Z bosons to 4 leptons

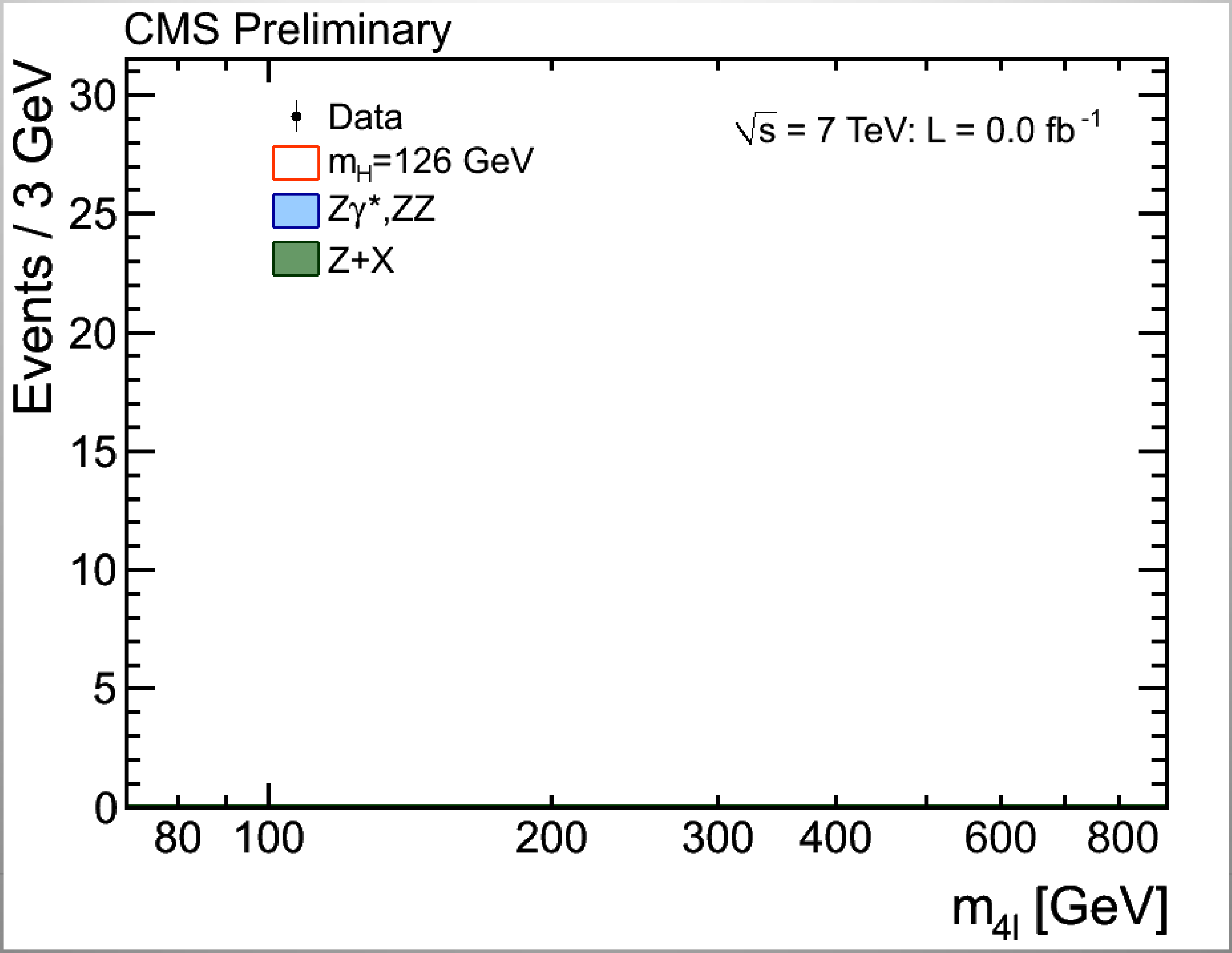




Peak around 125 GeV got more significant

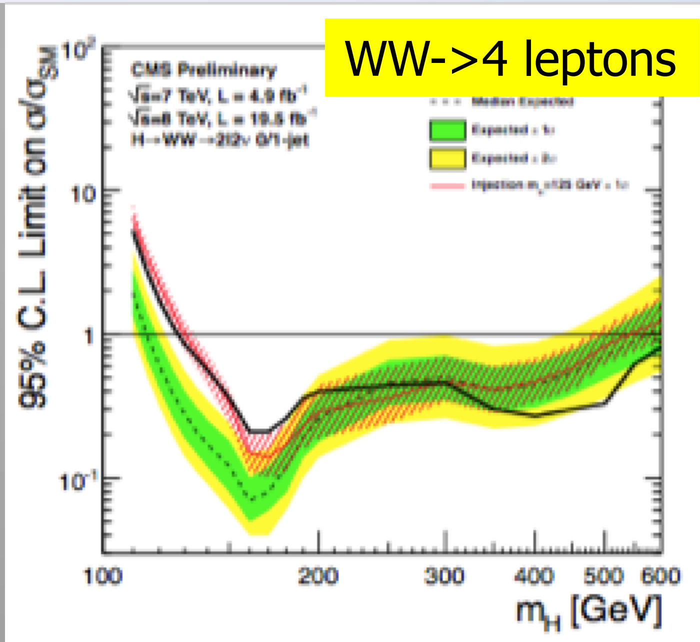
- *m(Z₁)* versus *m(Z₂)* distribution looks as expected

The Birth of a Particle

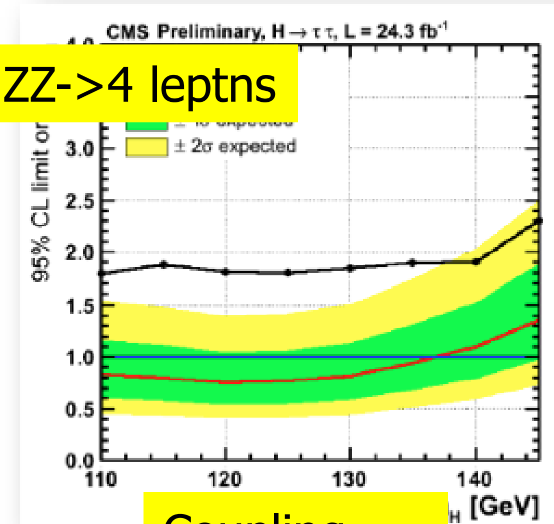


More New Results (CMS)

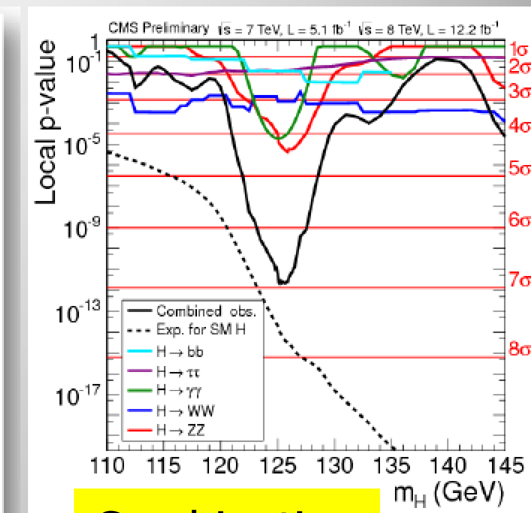
WW->4 leptons



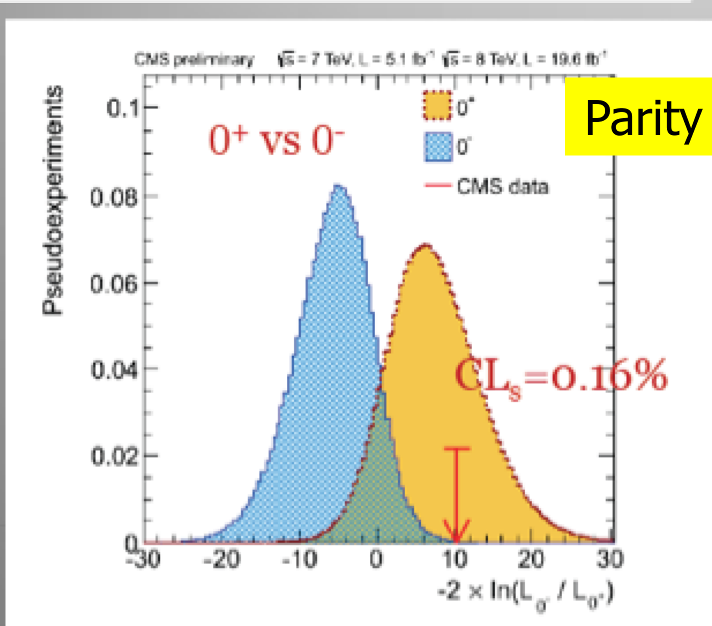
ZZ->4 leptns



Coupling
to fermions?
H->tautau

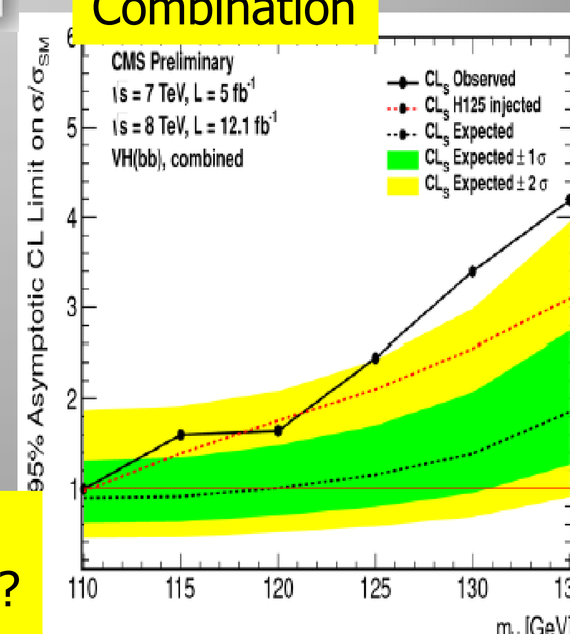


Combination



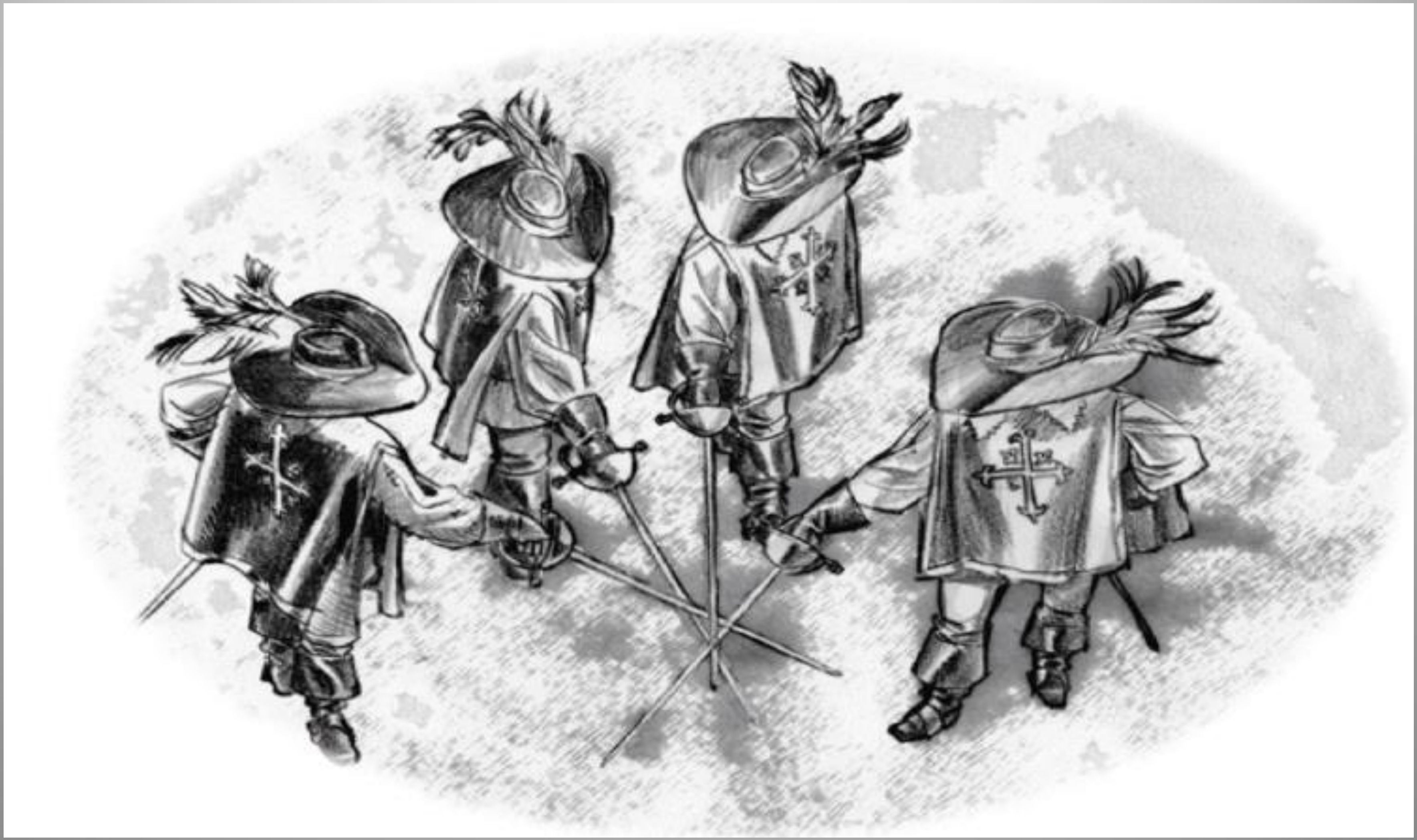
Parity test

Mild excess for
couplings to fermions



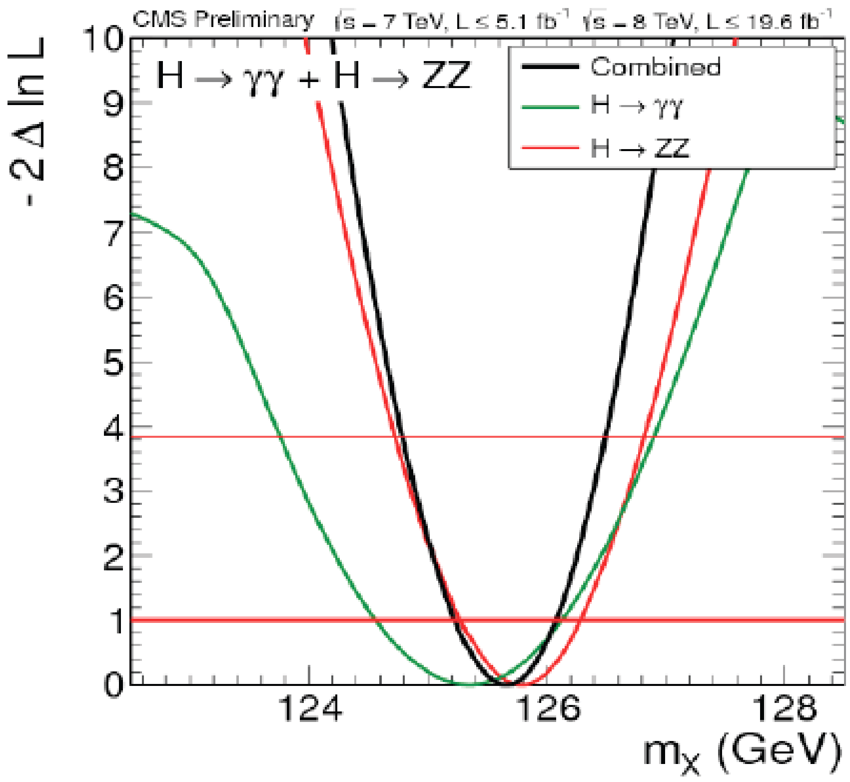
Coupling
to fermions?
H->bb

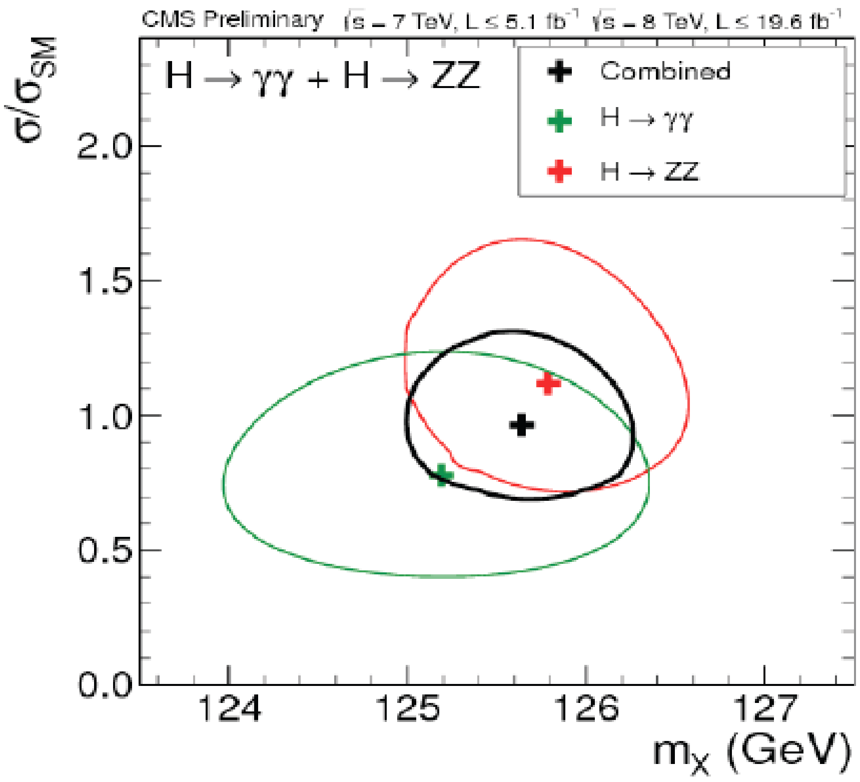
Channel Combination & Higgs Properties



The Mass of the New Particle

Use the ZZ and 2-photon channel, that have a ~1-2% resolution





$$m_X = 125.6 \pm 0.3^{(stat)} \pm 0.3^{(syst)}\ \text{GeV} =$$
$$= 125.6 \pm 0.4\ \text{GeV}$$

Is it a Standard Model Higgs Boson?

Summary of the big five channels

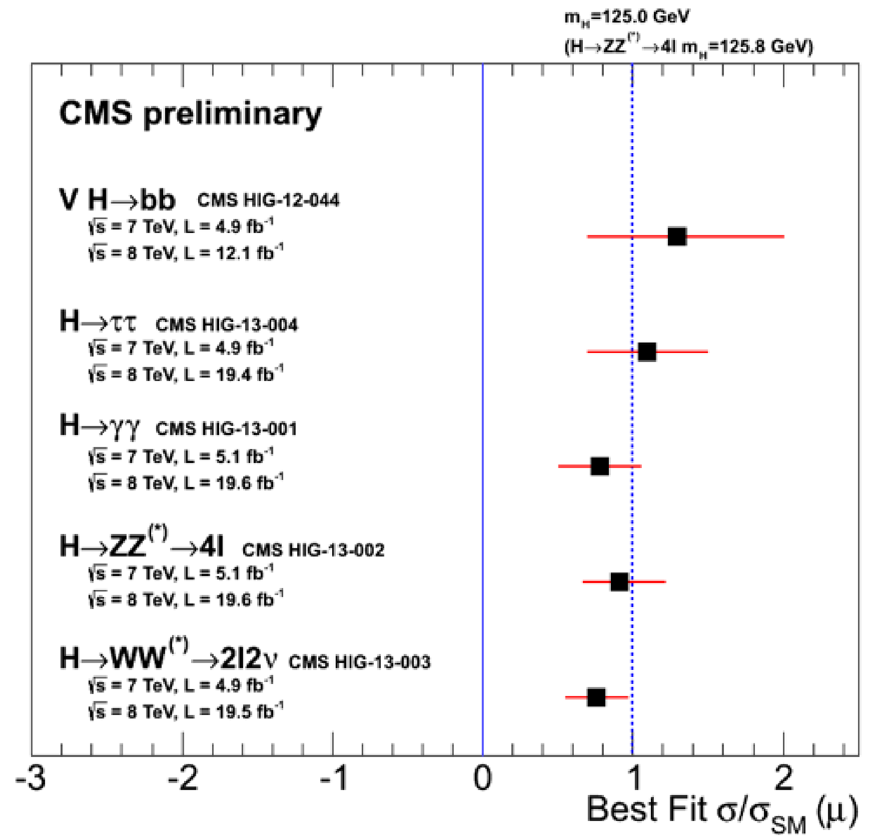
@m_H = 125.7 GeV

Decay	Expected	Observed
ZZ	7.1 σ	6.7 σ
γγ	3.9 σ	3.2 σ
WW	5.3 σ	3.9 σ
bb	2.2 σ	2.0 σ
ττ	2.6 σ	2.8 σ

ggF, VBF, VH

3.4 σ combined

Soon will be updated with full statistics

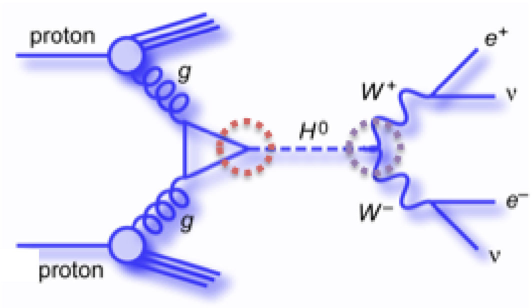


The measurement of the channels are compatible with those of a Standard Model Higgs !!

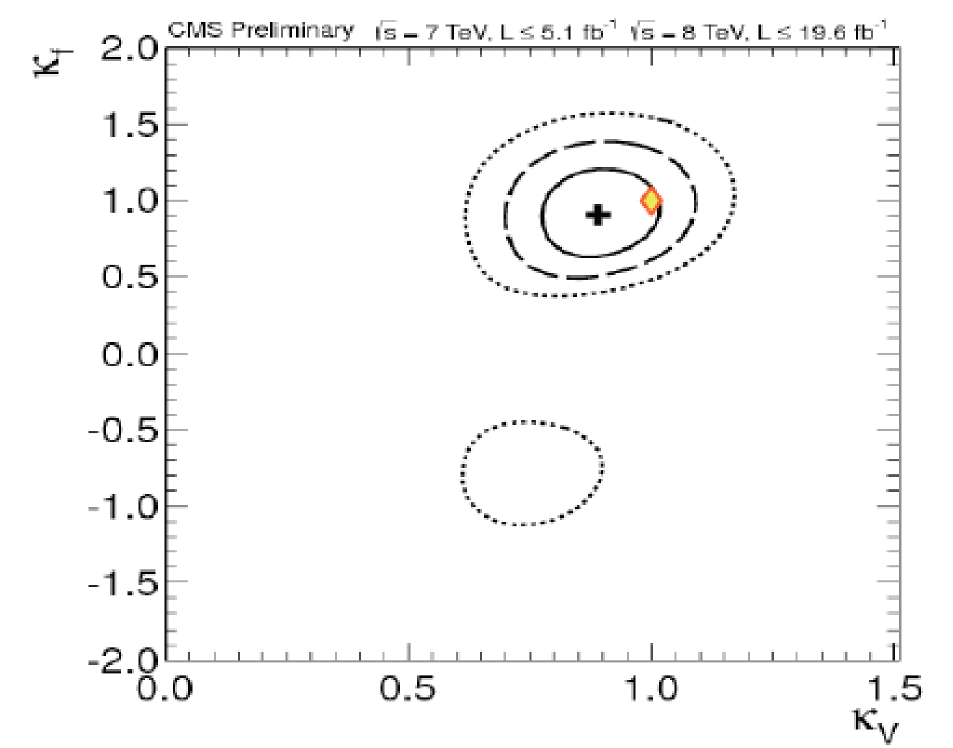
Couplings to Fermions and Bosons

Couplings scaled by κ_X:

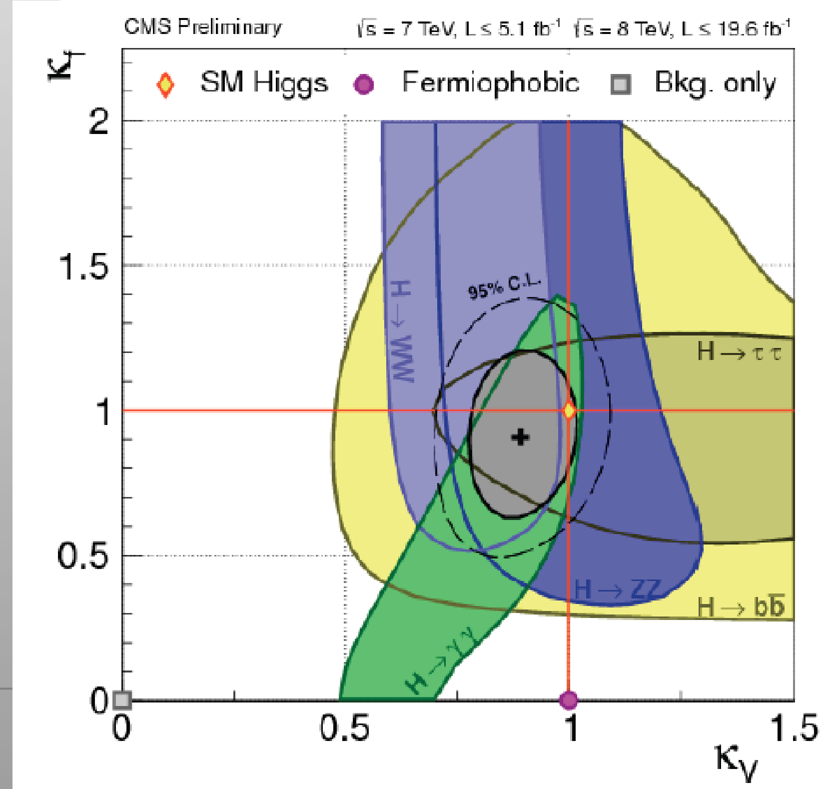
Hff:	κ_f	*HVV:*	κ_V
HWW:	κ_W		$\lambda_{WZ} = \kappa_W / \kappa_Z$
HZZ:	κ_Z		*In SM,* $\kappa_X = 1$



Overall result

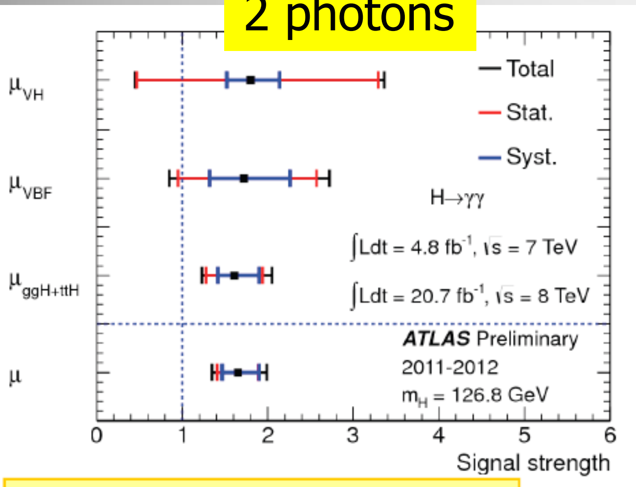


Contributions from all channels



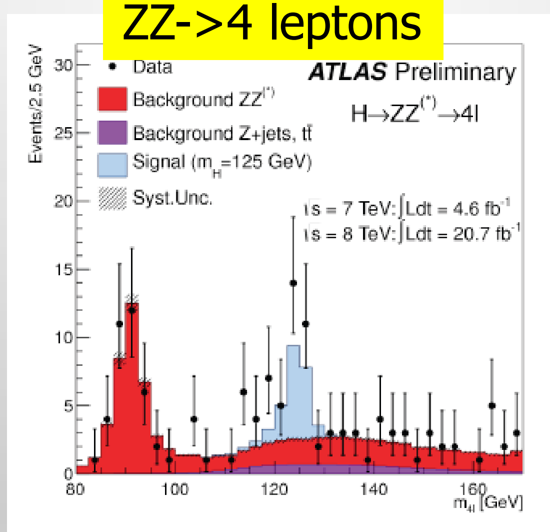
ATLAS Result Update

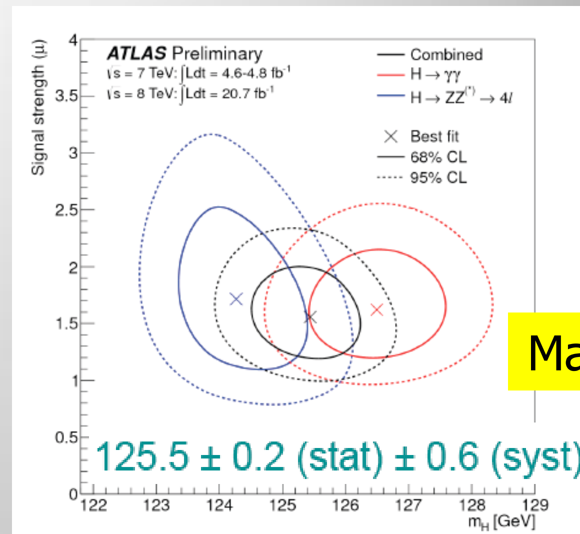
2 photons



$\mu=1.65^{+0.34}_{-0.30} = 1.65 \pm 0.24\ (stat)\ ^{+0.25}_{-0.18}\ (syst)$

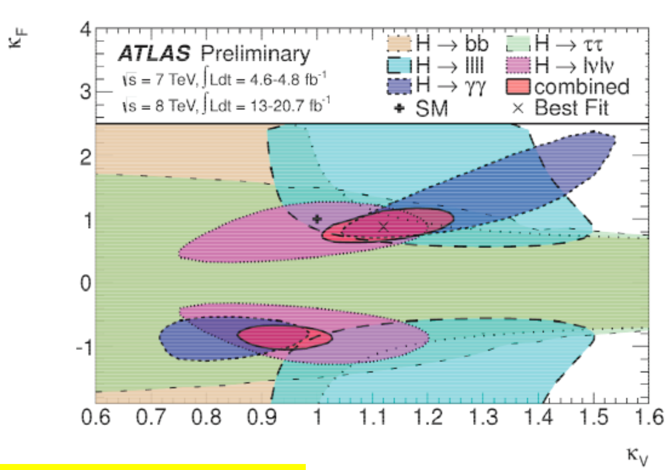
ZZ->4 leptons



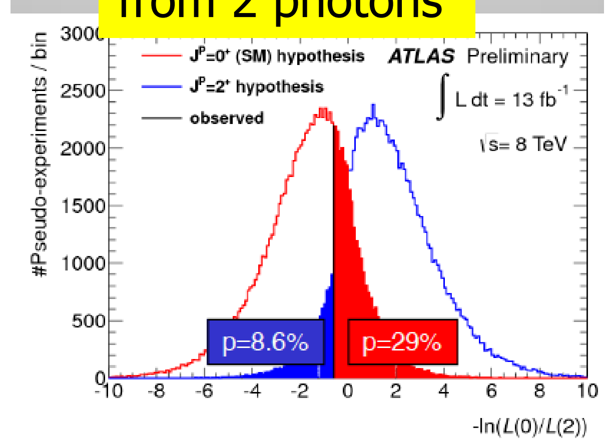


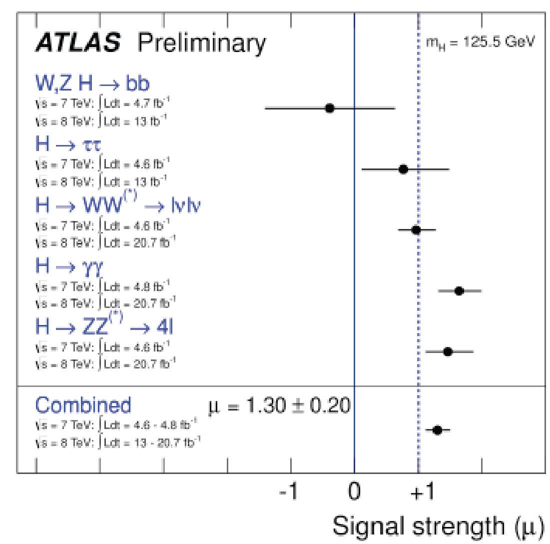
Mass

125.5 ± 0.2 (stat) ± 0.6 (syst) GeV



Spin separation from 2 photons

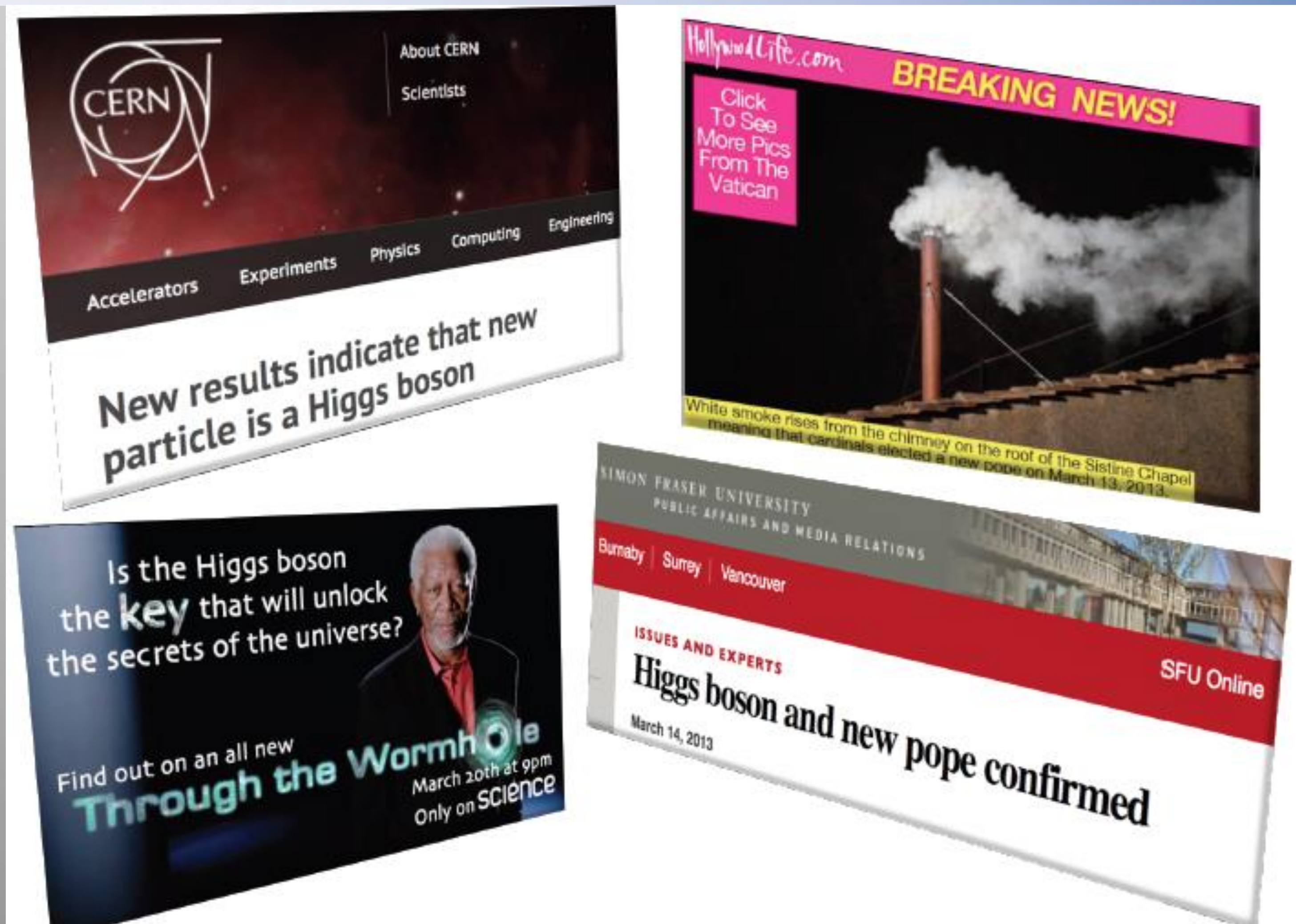




Combination

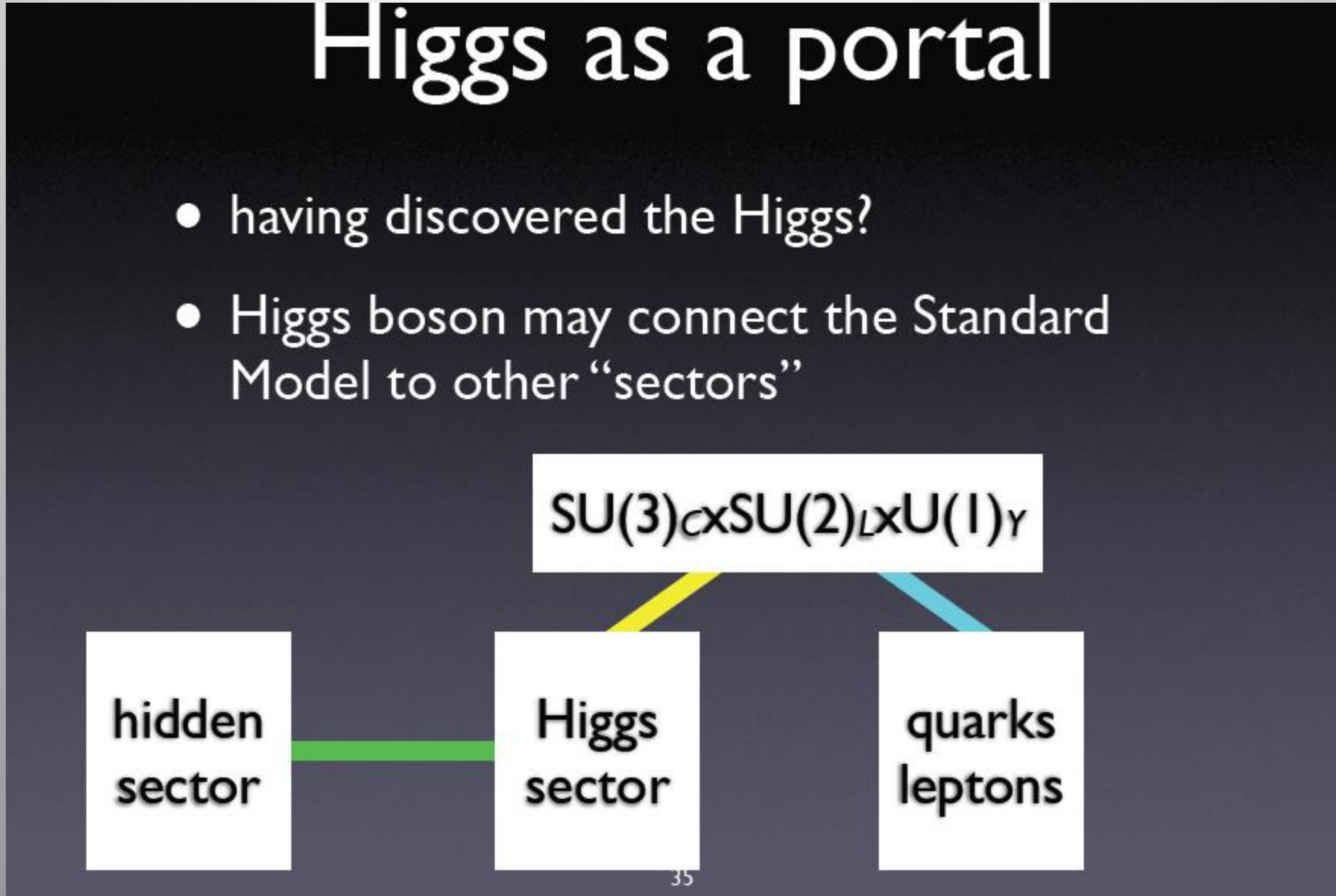
Generally the same conclusion on eg spin, mass,
Some possible differences in strength (but compatible with CMS results)

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?

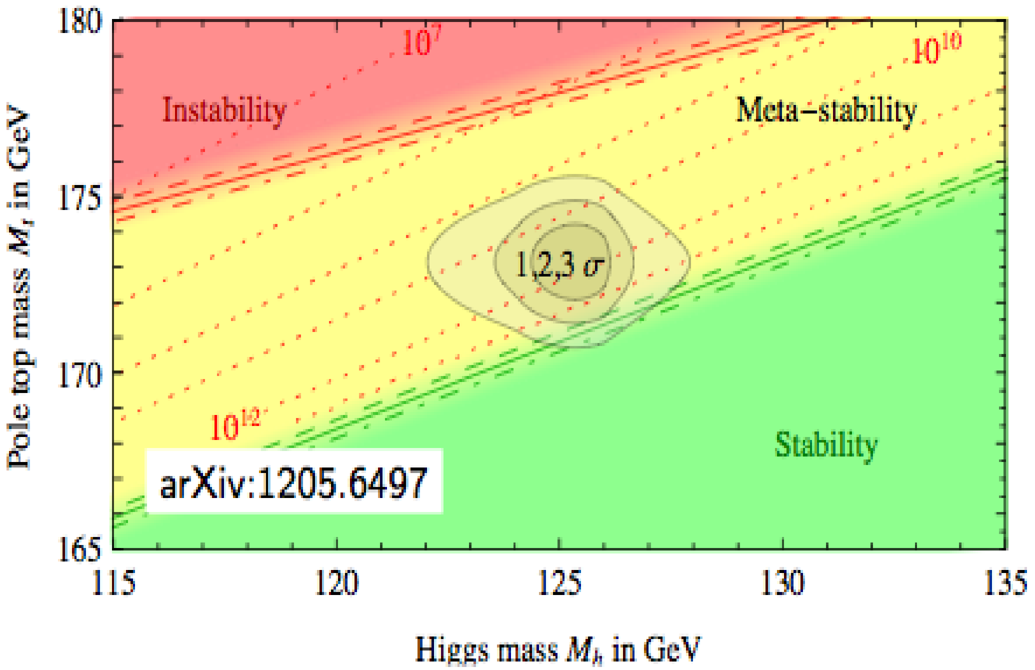


Need for precision measurements with ~100x the present statistics

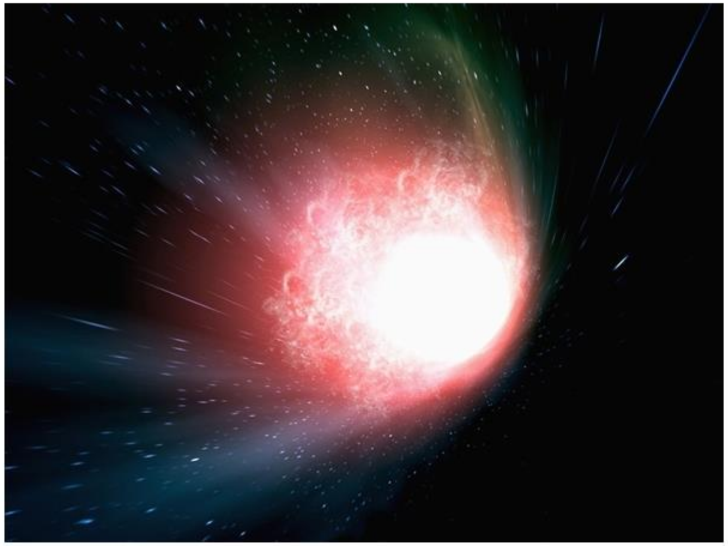
LHC upgrade ! Experiment upgrades!! (Other machines?)

Consequences for our Universe?

Important SM parameter → stability of EW vacuum



Precise measurements
of the top quark and
first measurements of the
Higgs mass:
Our Universe meta-stable ?
Will the Universe disappear
in a Big Slurp? (NBCNEWS.com)



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. ATLAS and CMS are in fair agreement on the measurements of this particle.

The new data allows for a first rough study of the properties of this 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. We will have to aim at the ~few % level of precision at the LHC..

This is only the beginning!!!