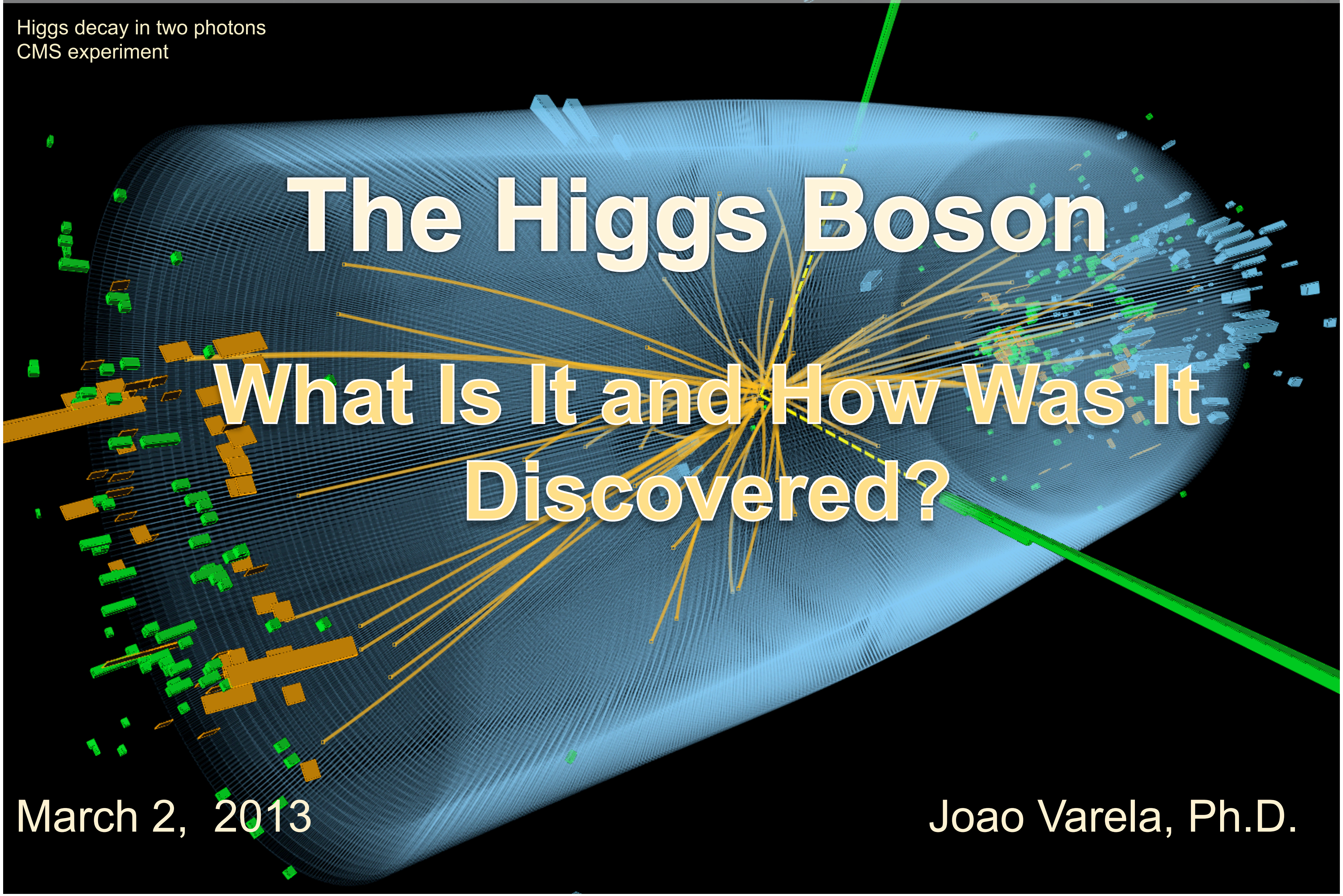
SCIENTIFIC AMERICAN Travel BRIGHT HORIZONS 16


Higgs decay in two photons
CMS experiment

The Higgs Boson

What Is It and How Was It Discovered?

March 2, 2013

Joao Varela, Ph.D.

Outline of the lecture

- What is the Higgs boson
- How to search for the Higgs boson
- Discovery of the Higgs boson in 2011-12 data

What in the world is a Higgs boson?

What is a Higgs boson?

Google

what is the higgs boson

Search

About 9,420,000 results (0.19 seconds)

9.42 million answers

Wikipedia:

The **Higgs boson** or **Higgs particle** is an elementary particle in the Standard Model of particle physics.

The **Higgs field** is a **quantum field** with a non-zero strength that fills all of space, and explains why fundamental particles such as **quarks** and **electrons** have **mass**.

What is a Higgs Boson?

Standard Model answer:

It’s the quantum of Higgs field.

Higgs field:

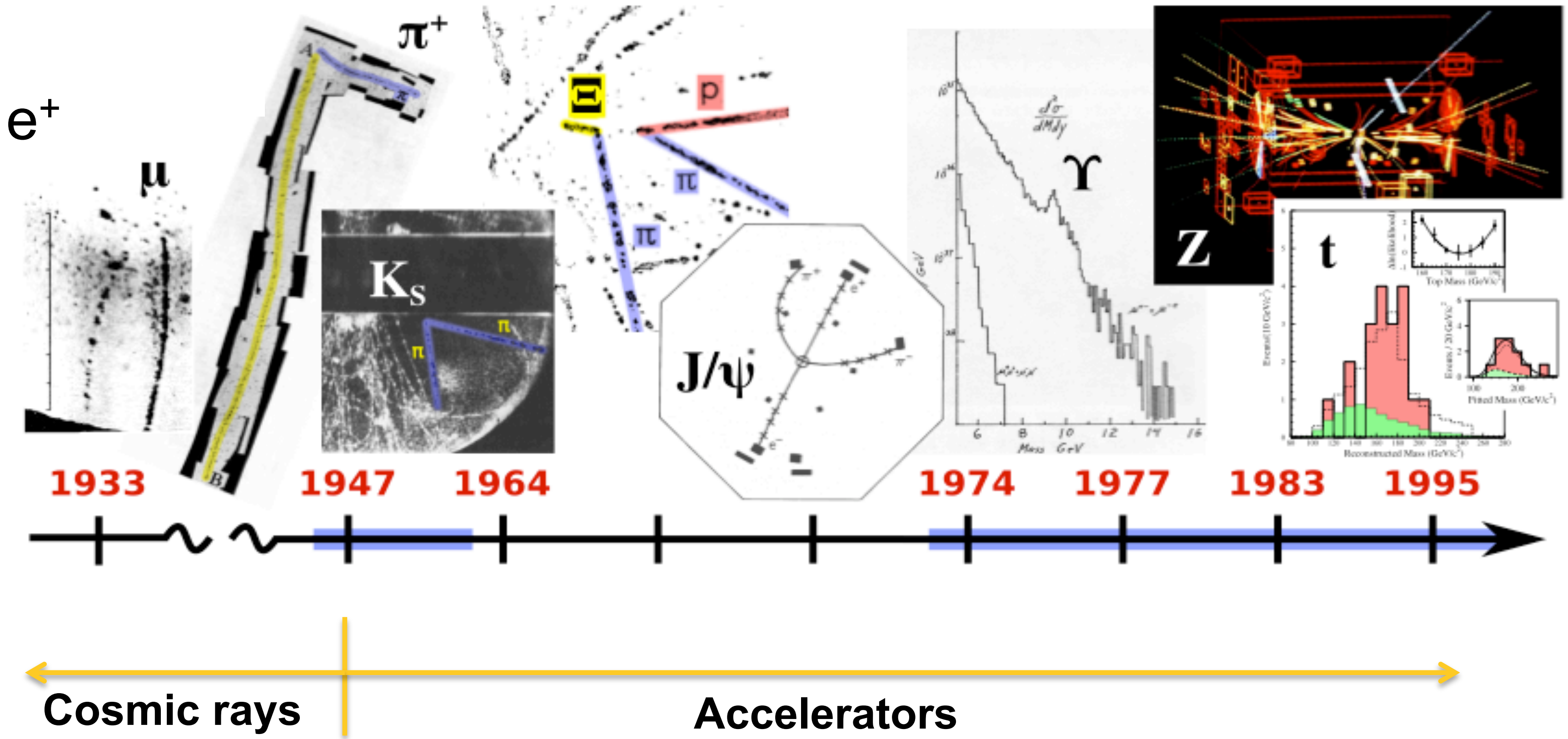
1) Allows the W and Z bosons to have mass, and thus

2) Makes possible the unified theory of the electromagnetic and weak forces.

3) Gives mass to the quarks and leptons

20th century: SM of Elementary Particles

From X-rays and radioactivity to the Higgs boson



Quantum Field Theory

The Quark Model

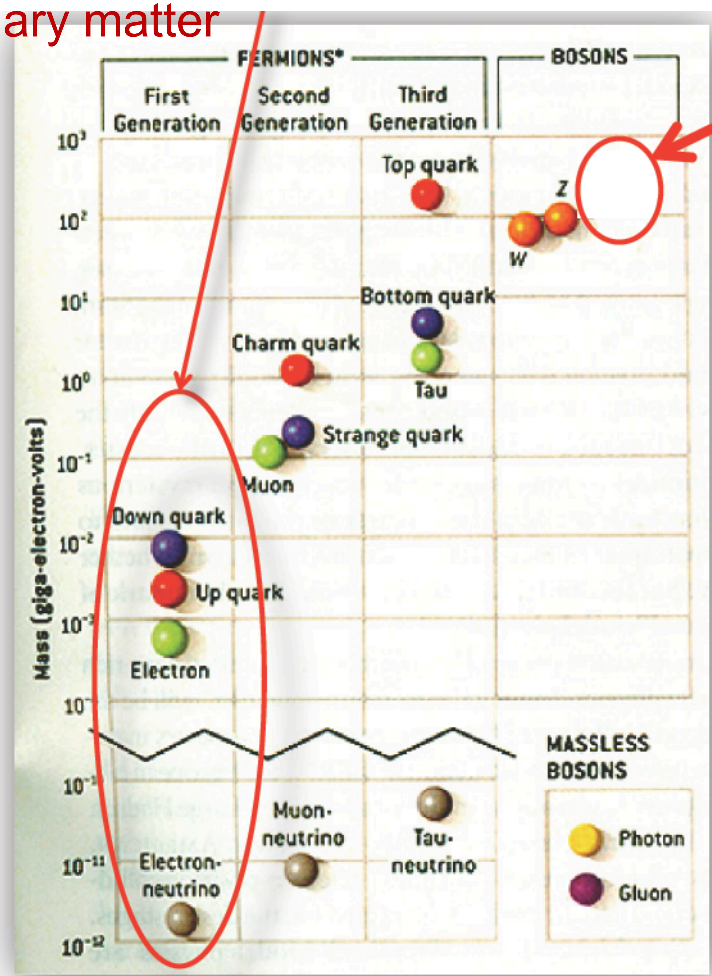
Electroweak Theory

The Standard Model

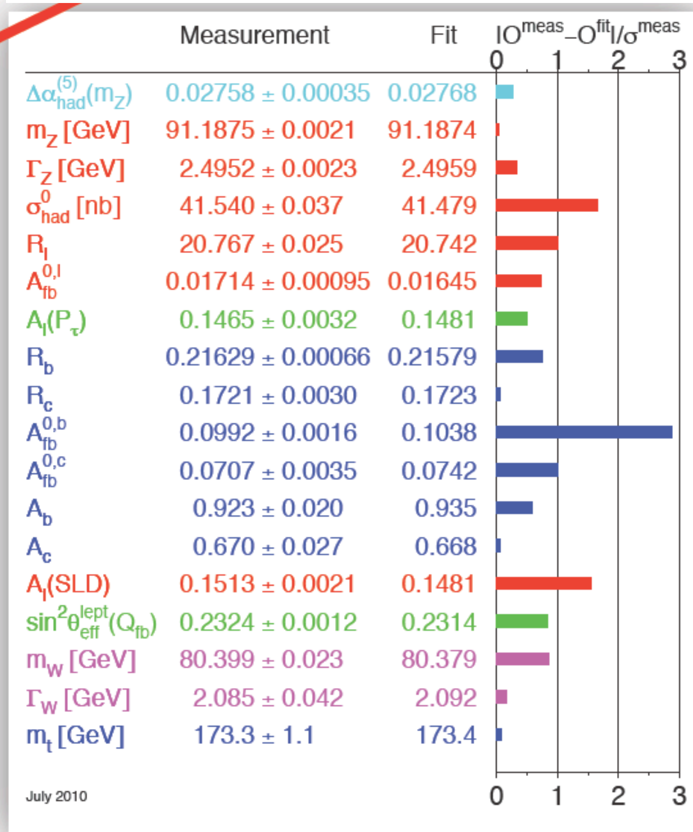
Theory describing the elementary particles and their interaction

Amazing agreement with ALL experimental data

Ordinary matter



1 Missing Element: Higgs



Confirmed at sub 1% level!

What is mass?

Mass is a basic property of particles:

Since Newton, mass is a measure of inertia:

$$F=m.a$$

Mass is also source of gravitation force.

Without mass there would be no atoms, stars, galaxies, Universe.

1 GeV = $1.78\ 10^{-27}$ Kg

Mass is energy:

Particle at rest:

$E=mc^2$ mass energy (c = speed of light)

Moving particle:

$E^2 = (mc^2)^2 + (pc)^2$ mass energy + kinetic energy

Particles with zero mass (m=0) move at speed of light

Higgs: particle or field?

Basic principle of Quantum Mechanics:

Every particle has an associated field

Einstein Nobel Prize:

Light waves are composed quanta of energy called photons

More generally, the electromagnetic field (radio waves, microwaves, light, X-rays, gamma rays) is made of photons

The Higgs field is composed of Higgs particles

Fermions and bosons

Fermions:

- spin is semi-integer
- only one fermion can occupy a particular quantum state at any given time
- particles of matter
- Examples: electron, muons, quark, neutrino **(spin ½)**

Bosons:

- spin integer
- more than one boson can occupy the same quantum state
- mediators of forces
- Examples: photon, W boson, Z boson , gluon **(spin 1)**

Higgs boson has spin 0

It is the first elementary scalar observed in Nature!

Spin variables

Particles of spin 1, like the electroweak bosons, have three spin variables which are related to the oscillations of the field:

- 1 oscillation mode along the direction of motion
- 2 oscillation modes transverse to the motion

Massless particles, such as the photon, cannot oscillate along the direction of motion

Massive particles can.

Yang-Mills theories

Fundamental interactions are derived from a principle of symmetry (local gauge invariance)

Yang–Mills theories describe the behavior of elementary particles:

- Unification of the Electromagnetic and Weak forces: U(1) x SU(2)
- Quantum Chromodynamics (Strong force): SU(3)

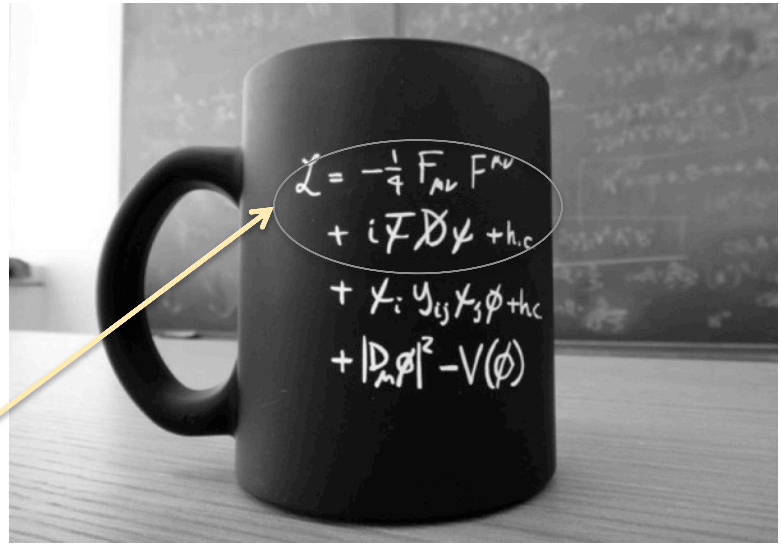
It forms the basis of our current understanding of particle physics, the Standard Model.

Electroweak unification

Weak forces: radioactivity, neutrinos, Sun

Electromagnetic and **weak forces** have the same origin

The **electroweak theory** is based in a **underlying symmetry** between the two interactions



The equations of this theory imply that **all particles have zero mass**

BUT:

Electromagnetic interaction:

Photon **m=0**

Weak interaction:

Bosões W e Z **m~80-90 GeV**

Different masses of γ, W and Z **breaks the symmetry**

How the electroweak model is built?

Start with *two* abstract forces:

W force: 3 massless quanta

SU(2)

B force: 1 massless quantum

U(1)

Let the observed physical quanta with no electrical charge be mixtures!

photon

77% B^0, 23% W^0

Z^0

77% W^0, 23% B^0

Electroweak bosons

There are then four force quanta for the combined “electroweak force”:

These are the modern quanta, except THEY WOULD BE ALL MASSLESS.
And the *FORCES’ STRENGTHS WOULD BE ABOUT EQUAL*.

Reality: $W^{\pm}$ are massive and associated force appears to be weak!

The Z^0 boson is the intermediate of the “neutral current” neutrino events discovered at CERN (Gargamelle)

Who got the idea?

Breakthrough ideas to allow non-zero masses, known as the “Higgs mechanism”, came from many directions in the 1960’s:

Englert-Brout, Higgs
Guralnik-Hagen-Kibble

We use “Higgs” as a composite person (partly Peter Higgs).

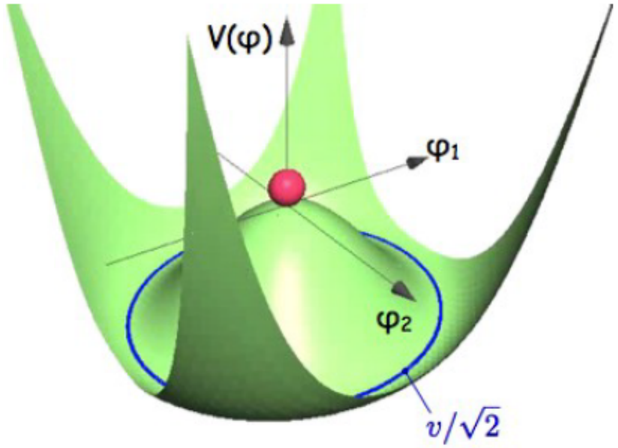
It all started from nothing: the vacuum!
In classical physics, a vacuum exists in a volume where you remove all matter.

The Higgs exists in the vacuum

Key postulate of the “Higgs mechanism”:

A new force field, the Higgs field, has an *average value in the vacuum* that became non-zero as the early universe cooled.

Spontaneous symmetry breaking



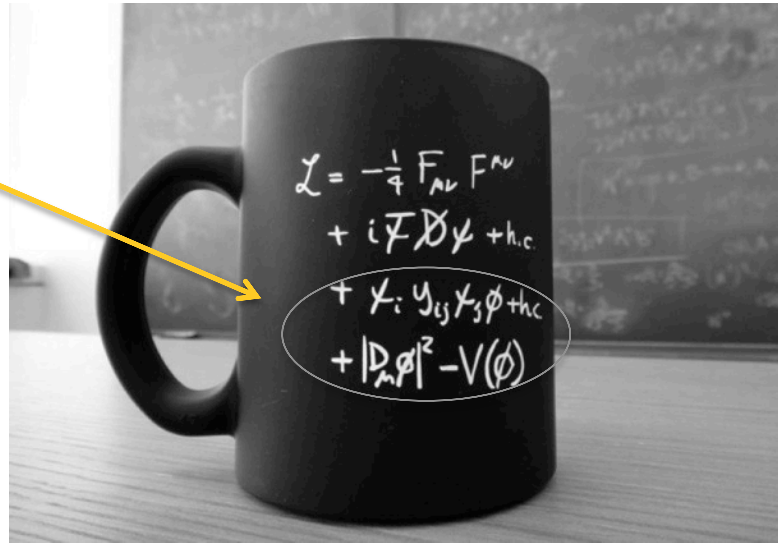
Higgs field in the equations:

- The Higgs field fills the space of the whole Universe
- The field has a non-zero value in the energy minimum
- Symmetry is broken when the field is at a minimum
- W and Z particles get mass through the interaction with the Higgs field

Glashow-Weinberg-Salam model

1967-68: Steven Weinberg and Abdus Salam took Glashow's theory and added:

A Higgs field with *four components*, related in a particular way



Then they introduced the non-zero average value of the Higgs field and looked at the consequences

Goldstone bosons?

The four components became:

one massive Higgs boson 

and three new massless bosons called "Goldstone" bosons.

Now we have in total:

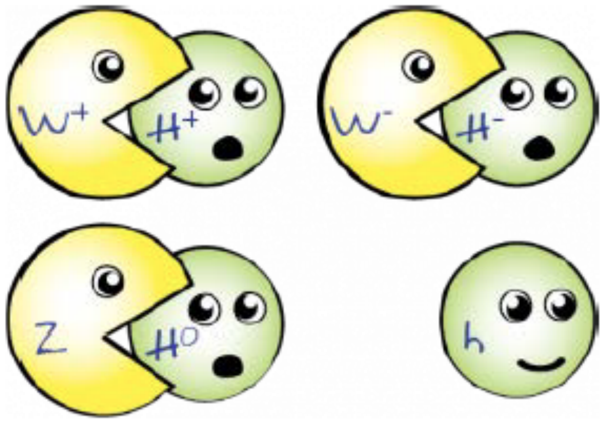
four massless force quanta and three massless Goldstone bosons

A math miracle happens

The three variables describing Goldstone bosons become the description of the oscillations of the W^+, W^-, and Z^0 in their directions of motion!

There was not a fourth Goldstone boson to the same to the photon, so it stayed massless.

The colloquial way to say it:
"The W^+, W^-, and Z^0 eat the Goldstone bosons and acquire a mass"



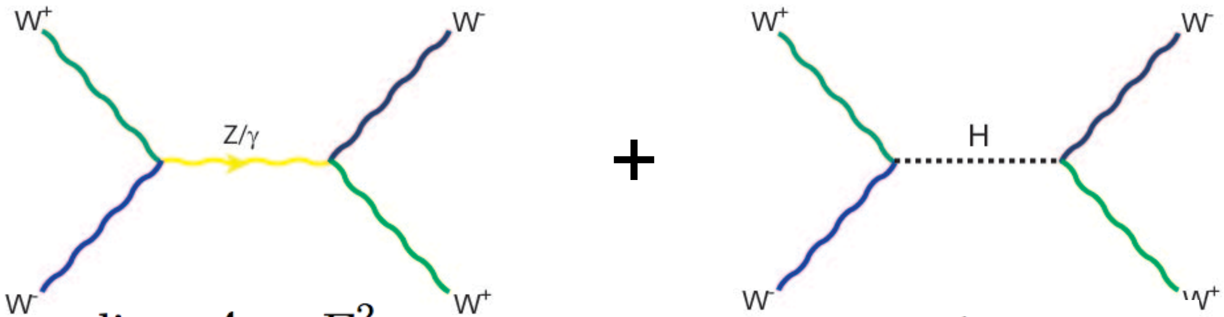
Added bonus

Non-zero average value of the Higgs field can also give masses to the quarks, electrons and muons – to all point-like particles.

Old theoretical problem affecting the quantum theory of the weak force :

the probability of two W's interacting becomes larger than 1 at high energies (> 1 TeV).

This is solved by the Higgs field!



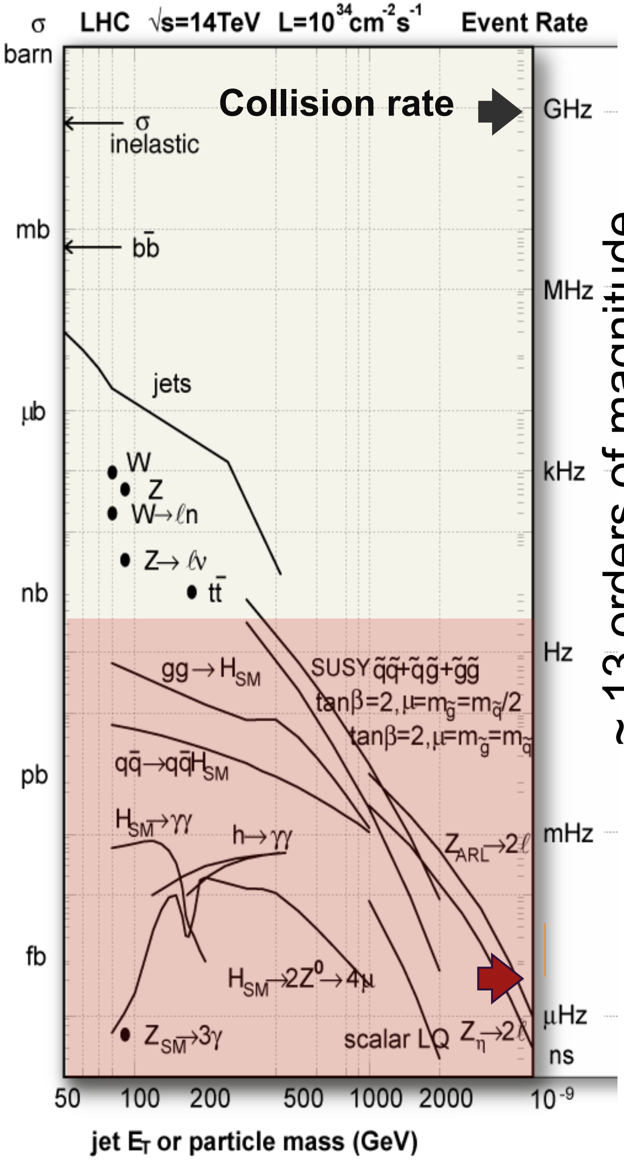
$$\lim_{E\to\infty} \mathcal{A} \propto E^2 \qquad \lim_{E\to\infty} \mathcal{A} \propto \text{const.}$$

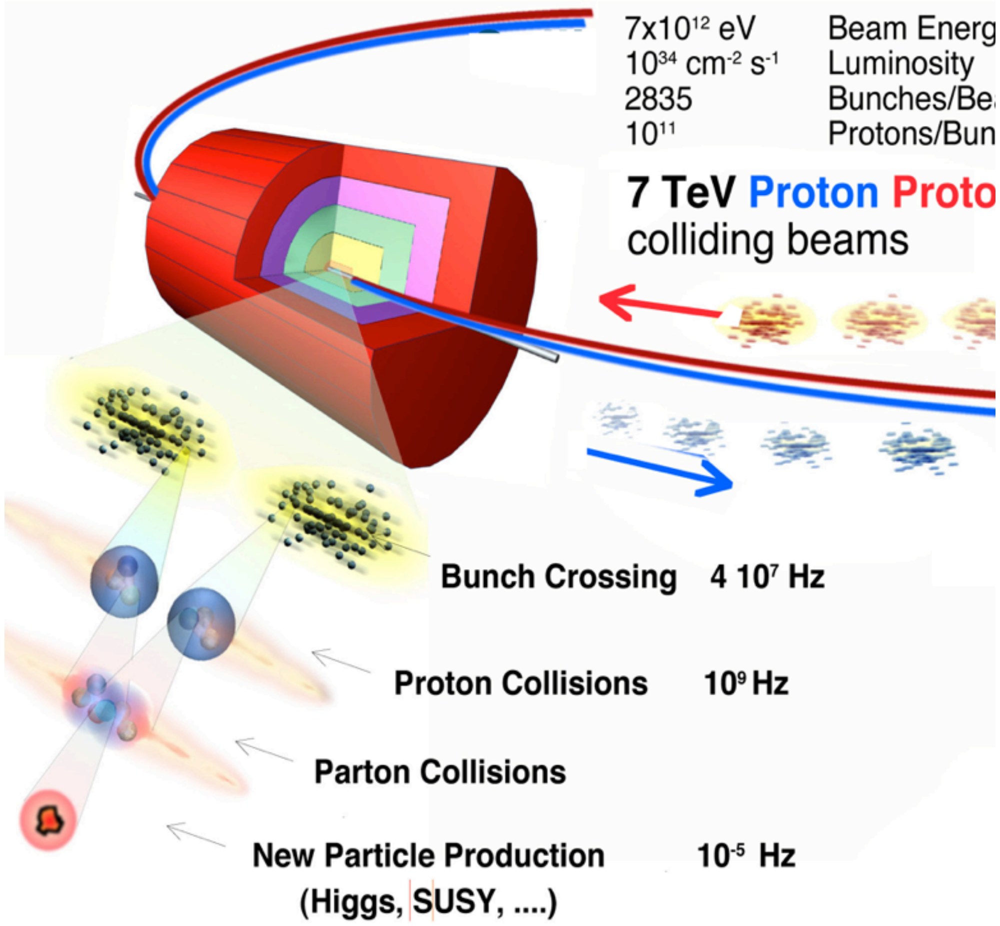
There was just *one little loose end…*

In spite of decades of attempts, there was no direct experimental confirmation or falsification of the Higgs field or the Higgs Boson!

How to search for the Higgs boson?

Proton collisions at LHC





LHC 2010-12:

Collision Energy	**7 – 8 TeV**
Luminosity	**10^{32-34} $cm^{-2}s^{-1}$**

The LHC energy scale

Standard Model does not work at high energy without the Higgs particle or alternative "new physics"

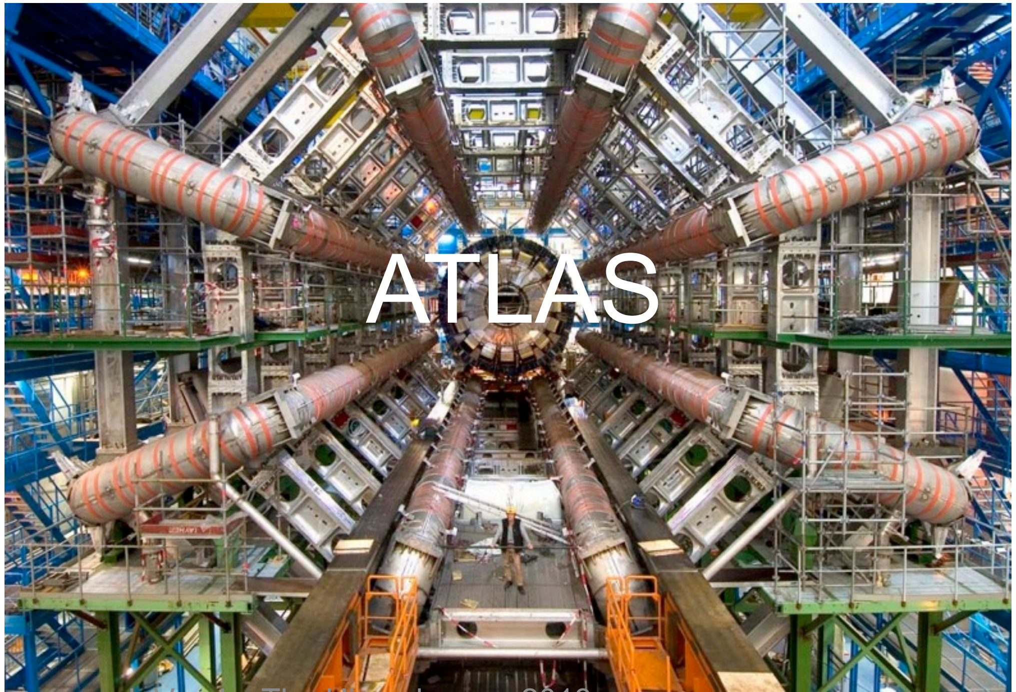
Based on the understanding of the theory and on the experimental observations, we expected the Higgs or "new physics" to appear at an energy around:

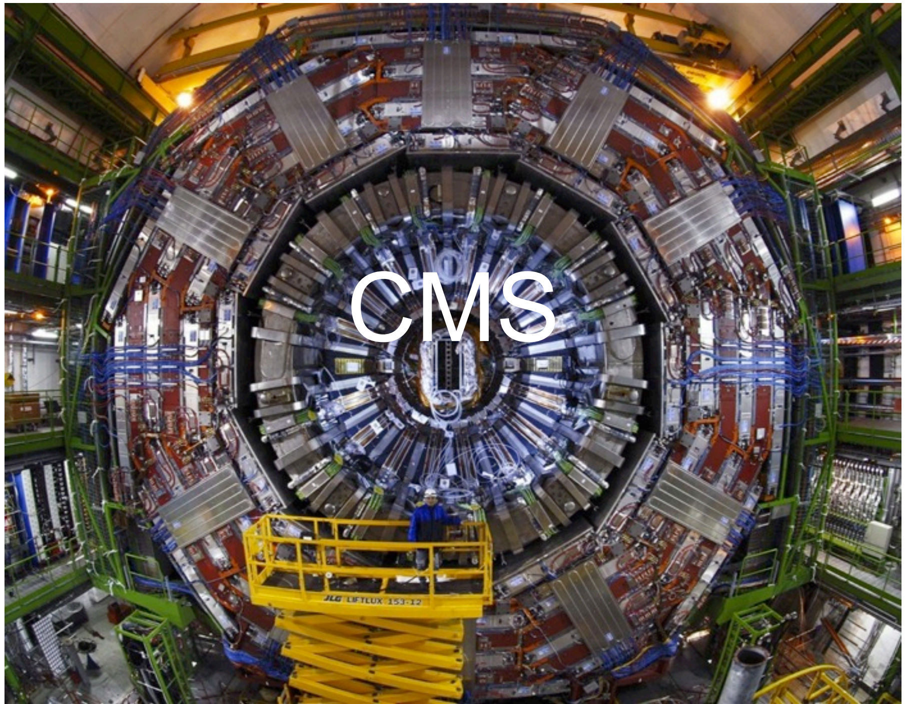
1 Tera electronVolt (TeV) = 10^{12} electronVolt

accessible for the first time.

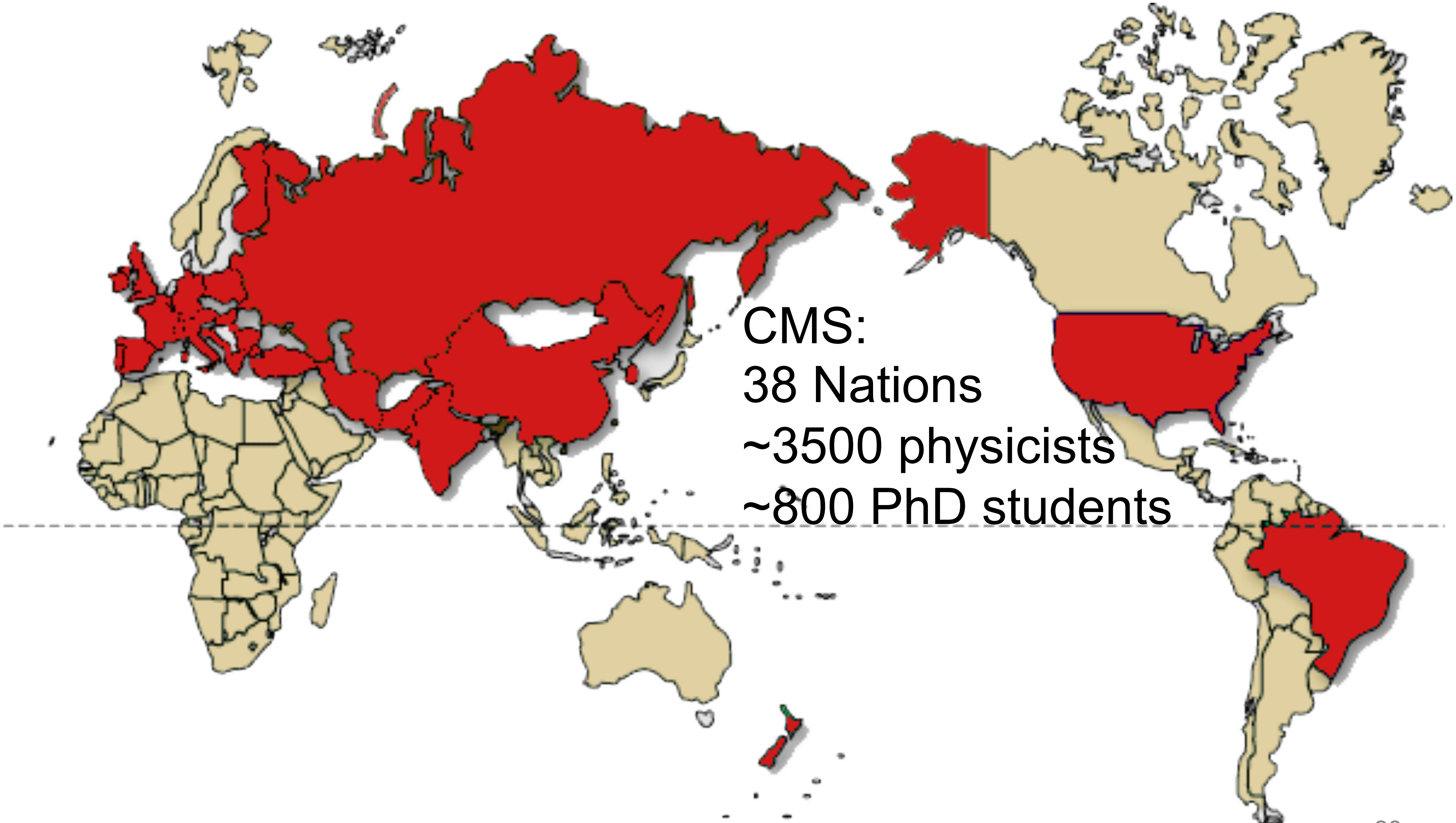
LHC accelerator

LHC Detectors



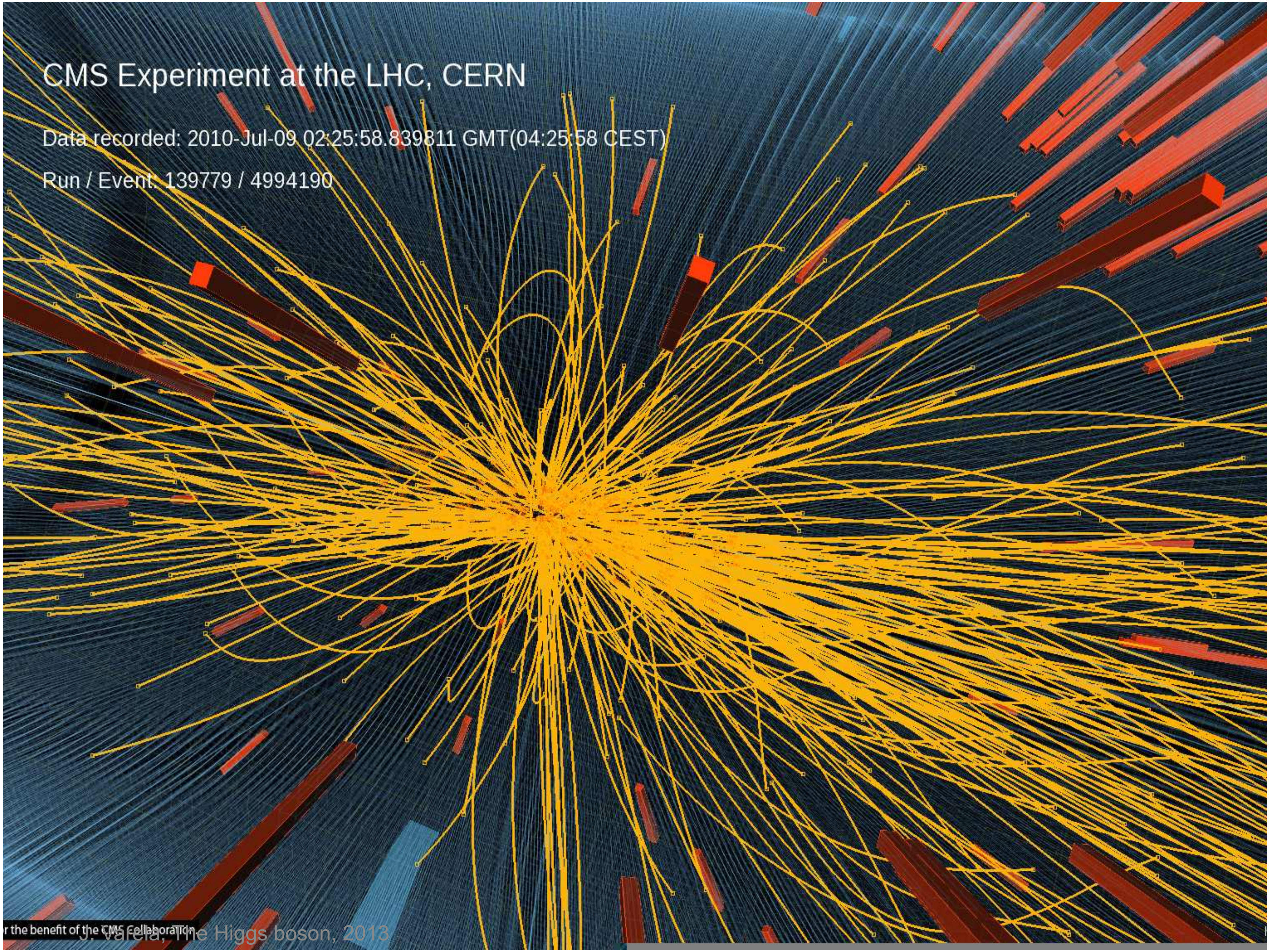


World-wide collaborations



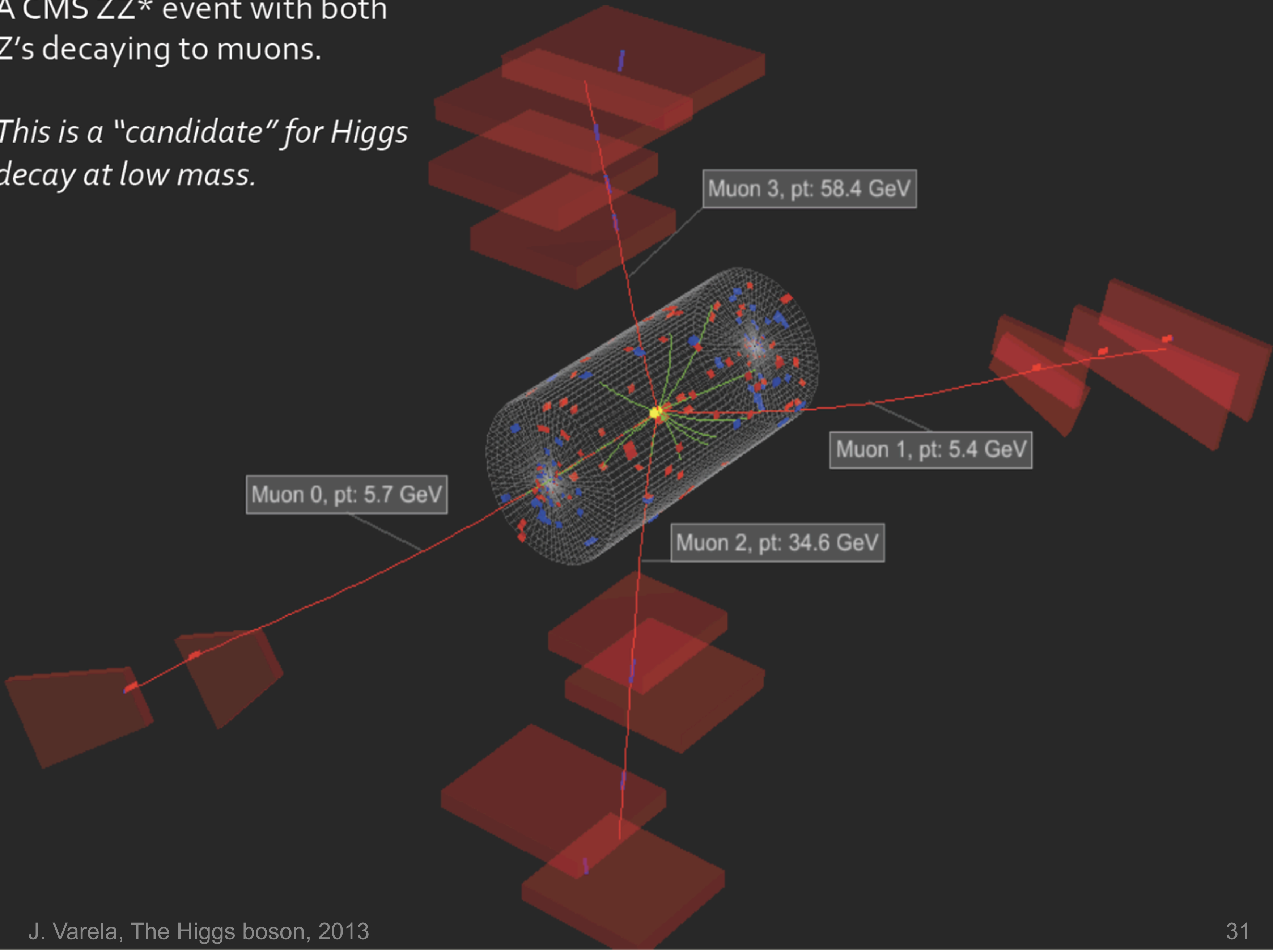
CMS:
38 Nations
~3500 physicists
~800 PhD students


15% of the
CMS people

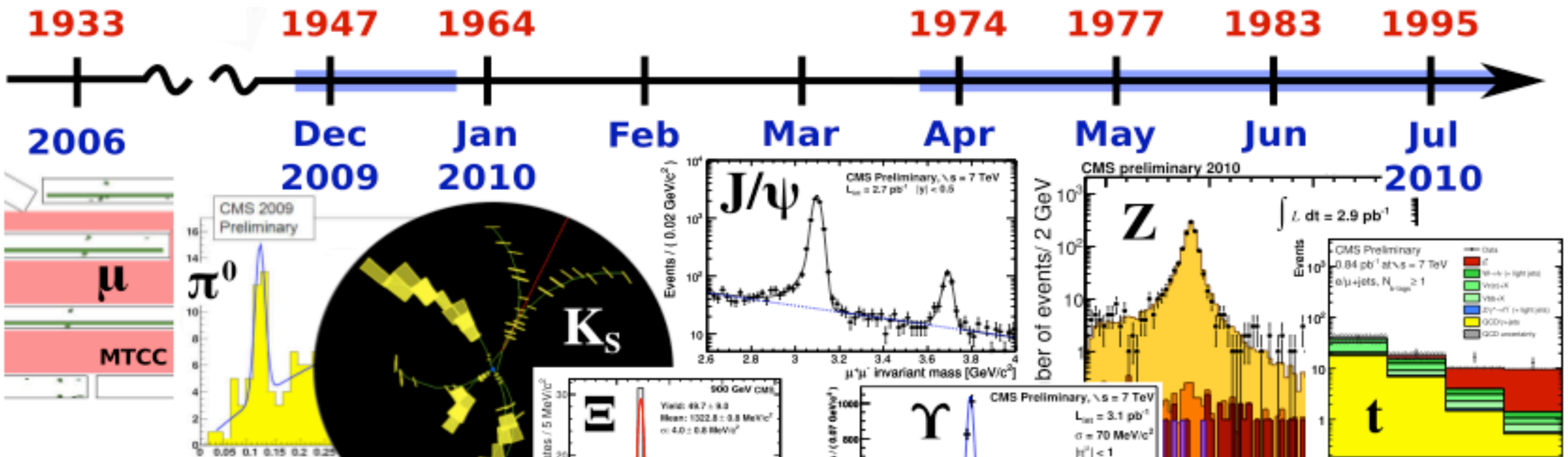

CMS Experiment at the LHC, CERN
Data recorded: 2010-Jul-09 02:25:58.839811 GMT(04:25:58 CEST)
Run / Event: 139779 / 4994190

A CMS ZZ* event with both Z's decaying to muons.

This is a "candidate" for Higgs decay at low mass.

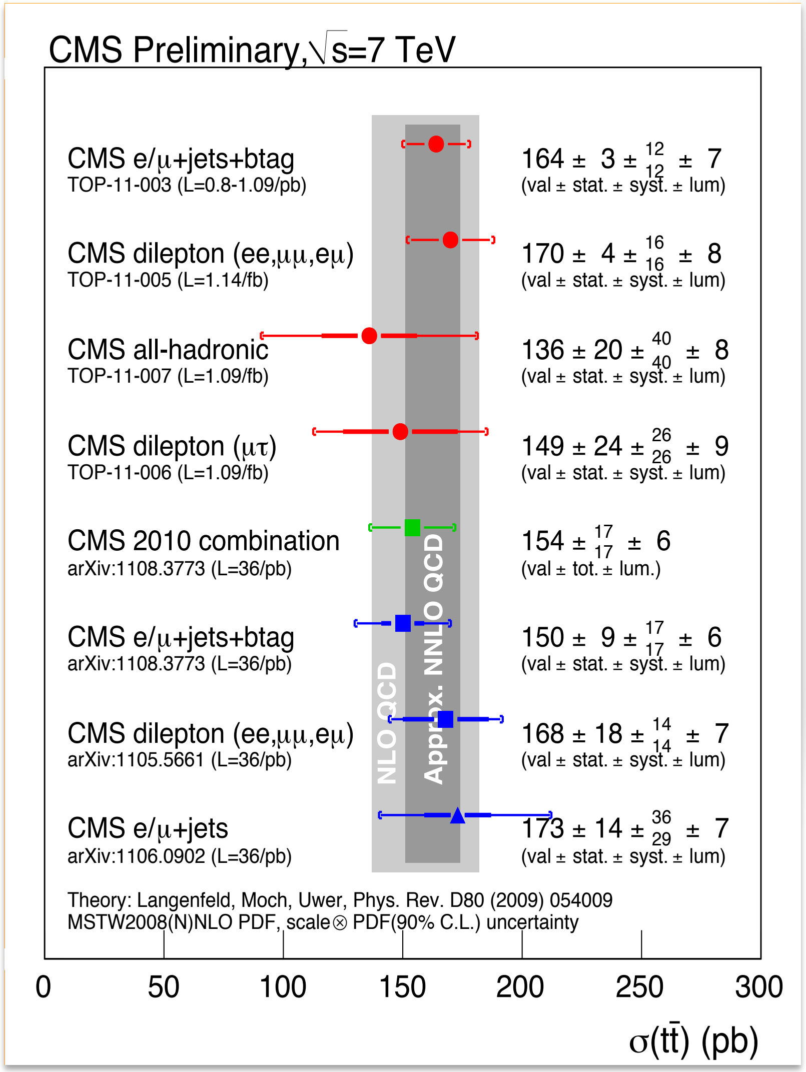


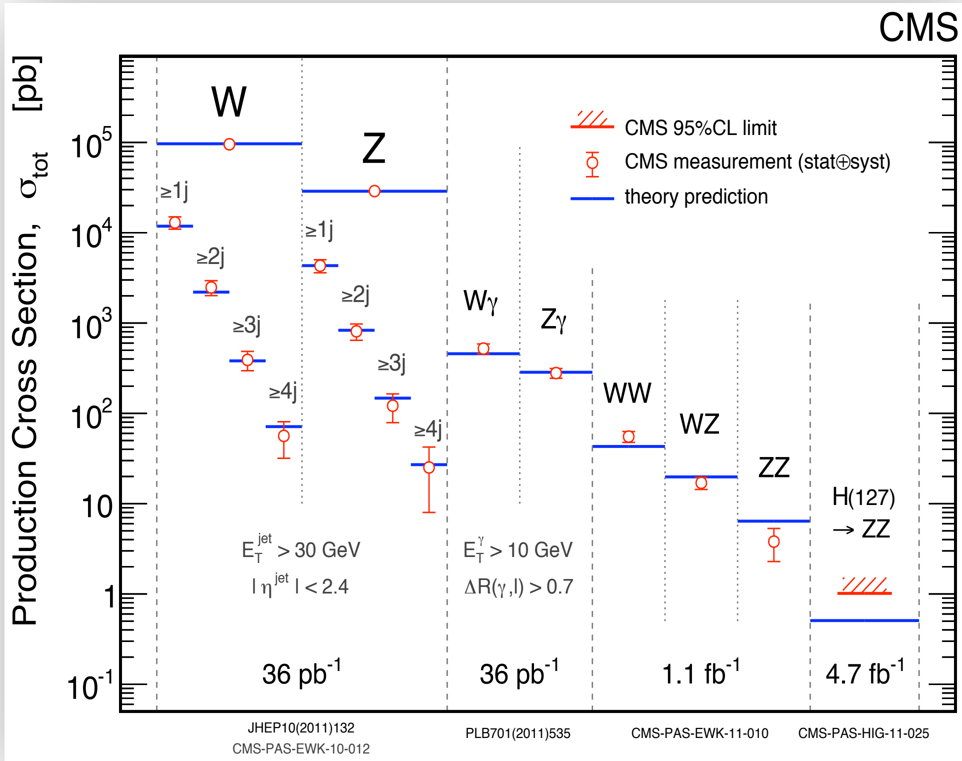
Rediscovery of the Standard Model at LHC



"Rediscovery" in CMS (dates approximate)

Standard Model at 7 TeV (2010-2011)

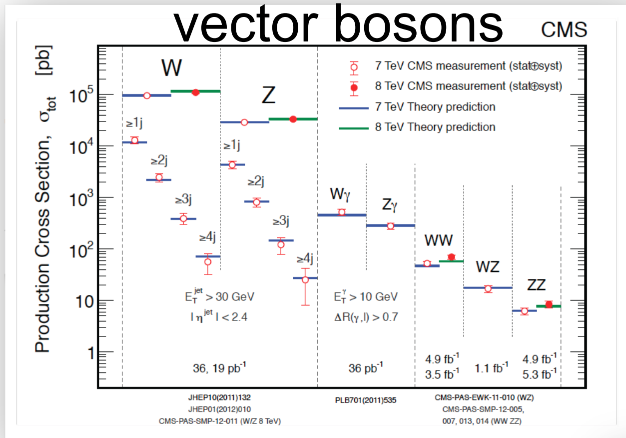


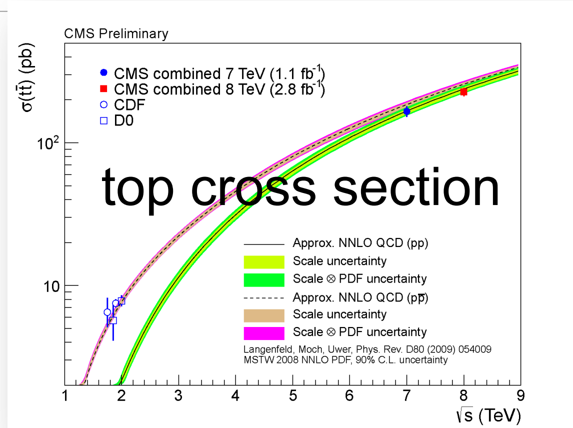


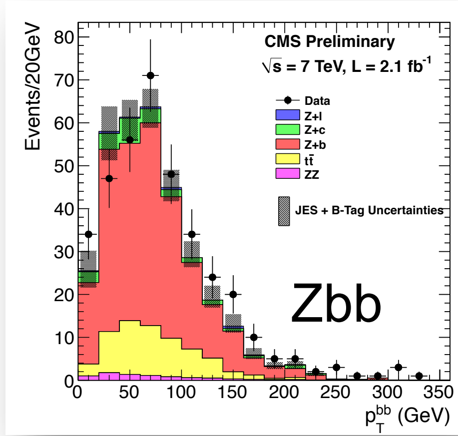
- **Fabulous agreement**
- **Lots of data**

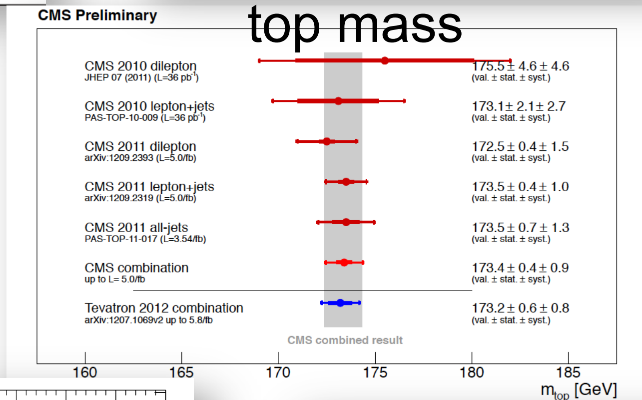
… on to the Higgs…

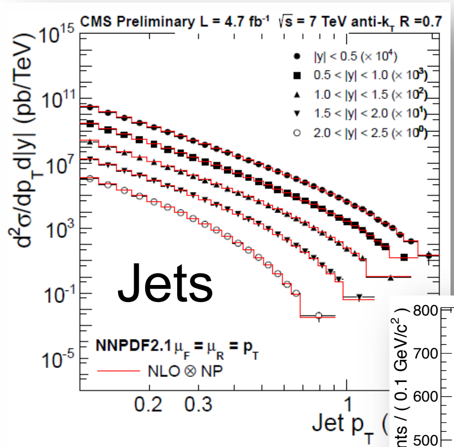
…and many more physics results

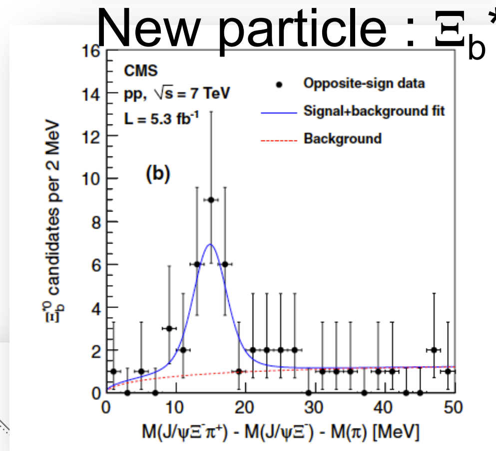


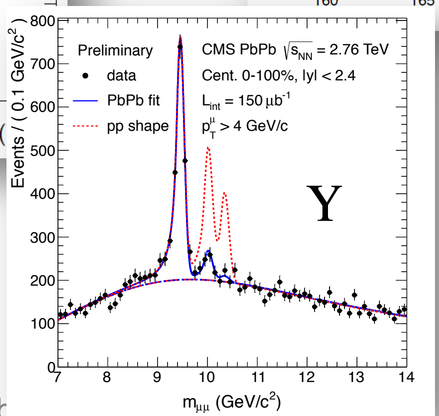


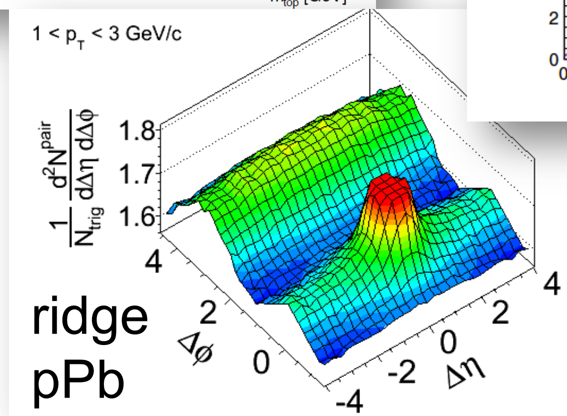












More than 500 papers from LHC

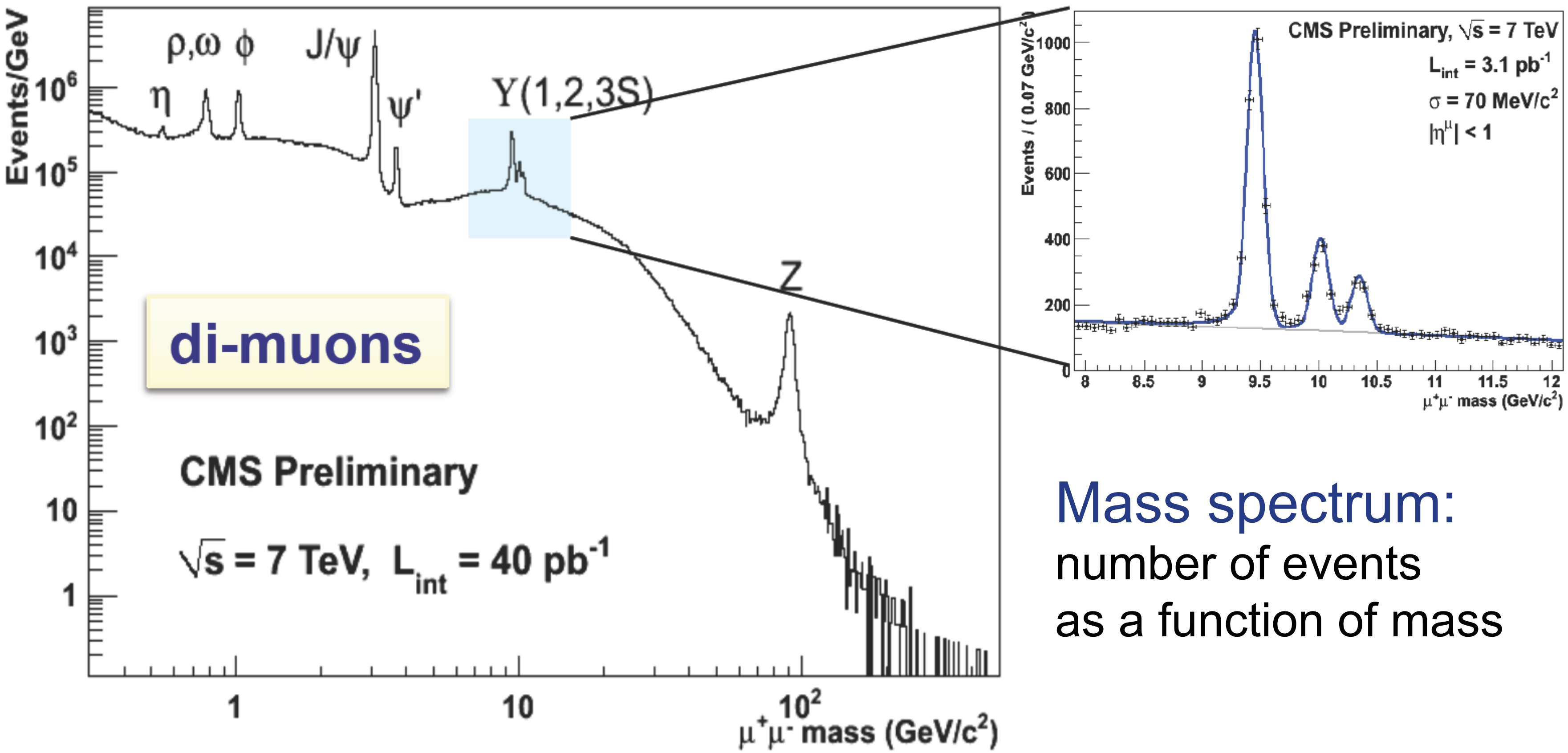
How do we analyze the data?

Mass spectrum of muon pairs

Events with two muons:

Search for particles X decaying in two muons

Compute m(X) from the energy-momentum of the two muons

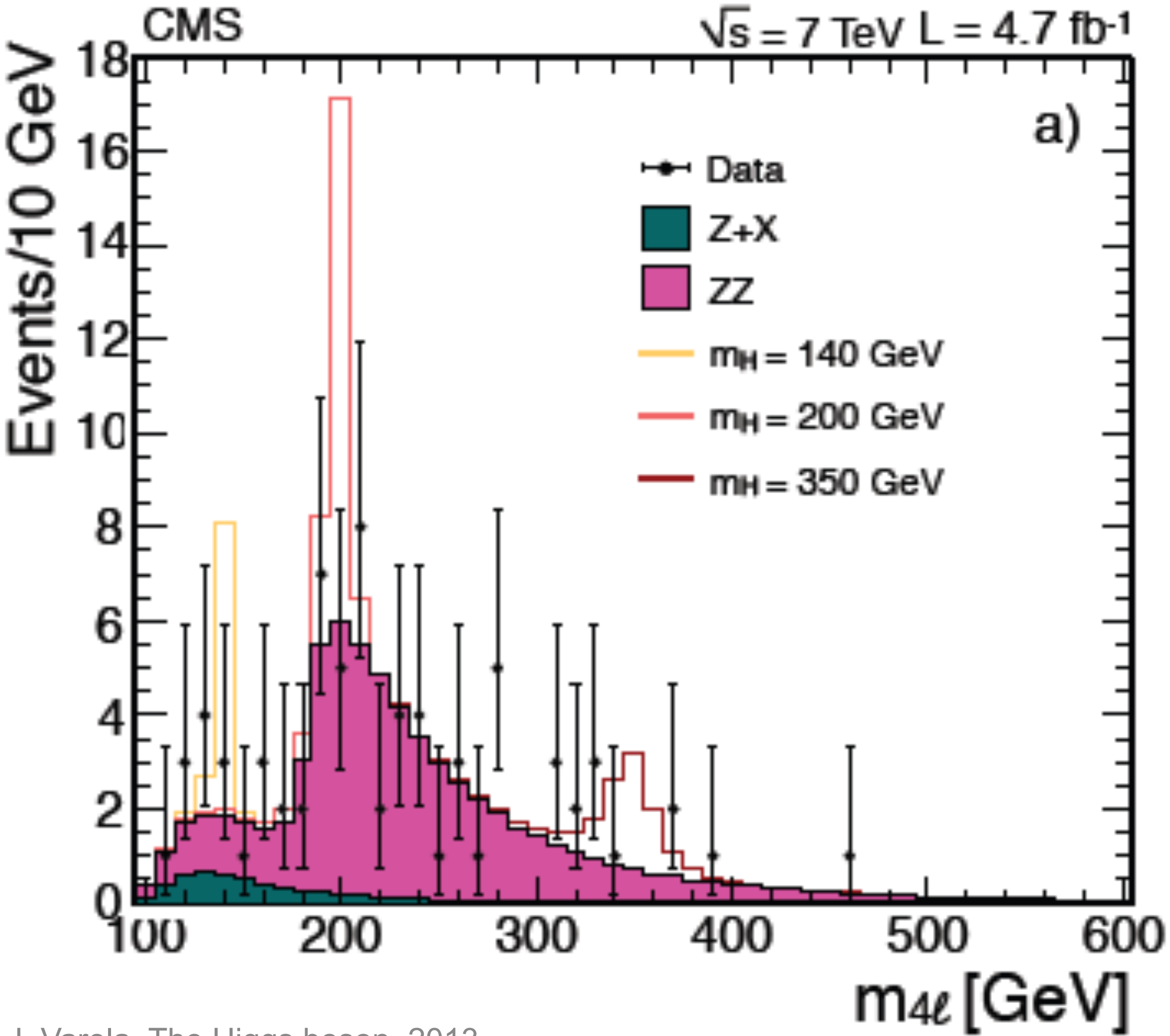


Mass spectrum:

number of events
as a function of mass

H → ZZ → 4 leptons

Mass spectrum of 4 leptons

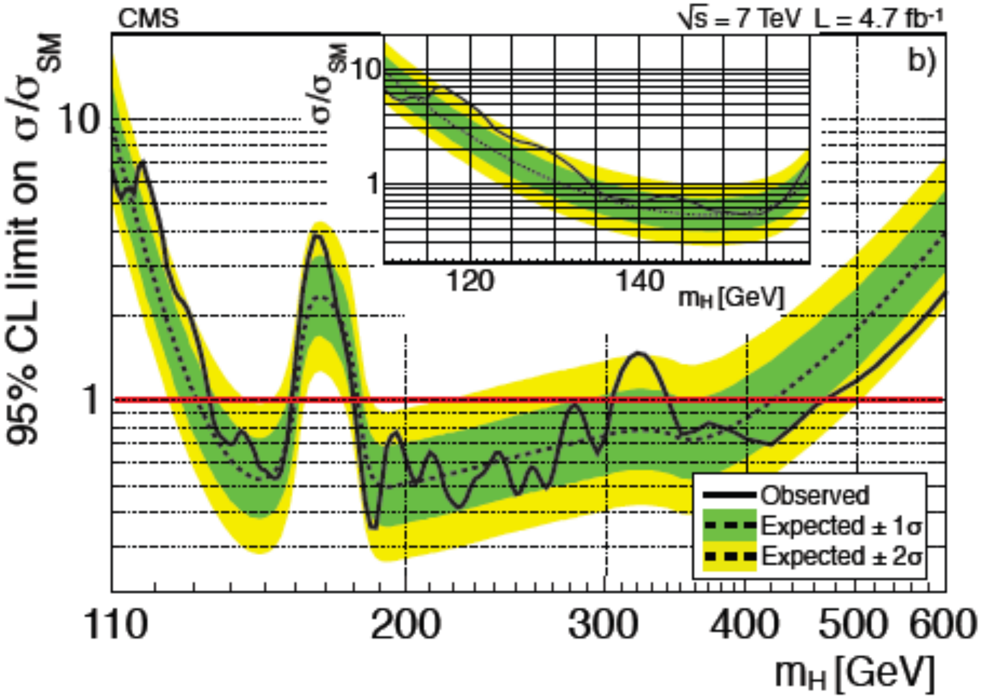


Rare process with low statistics

Requires sophisticated methods to isolate signal from background

Experimental limits

Limits on the cross section (probability) of Higgs production and decay in the channel H → ZZ → 4 leptons



Cross section relative to the SM predicted cross section

= 1 means that with 95% probability the cross section is equal or smaller than the SM prediction

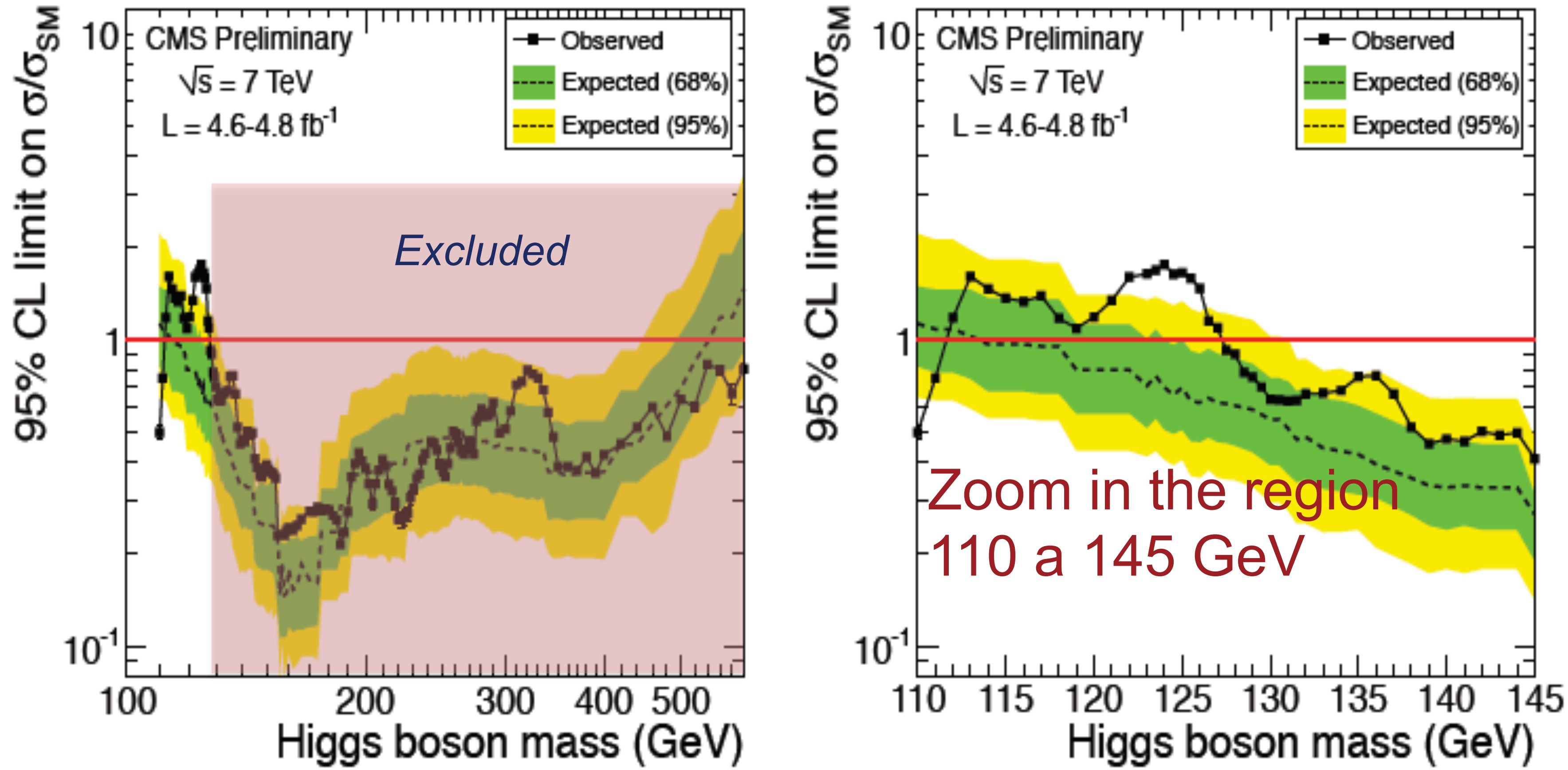
observed limit, measured experimentally

expected limit, computed from simulation data

uncertainty bands on the expected limit (1 e 2 standard deviations)

Higgs limits in 2011

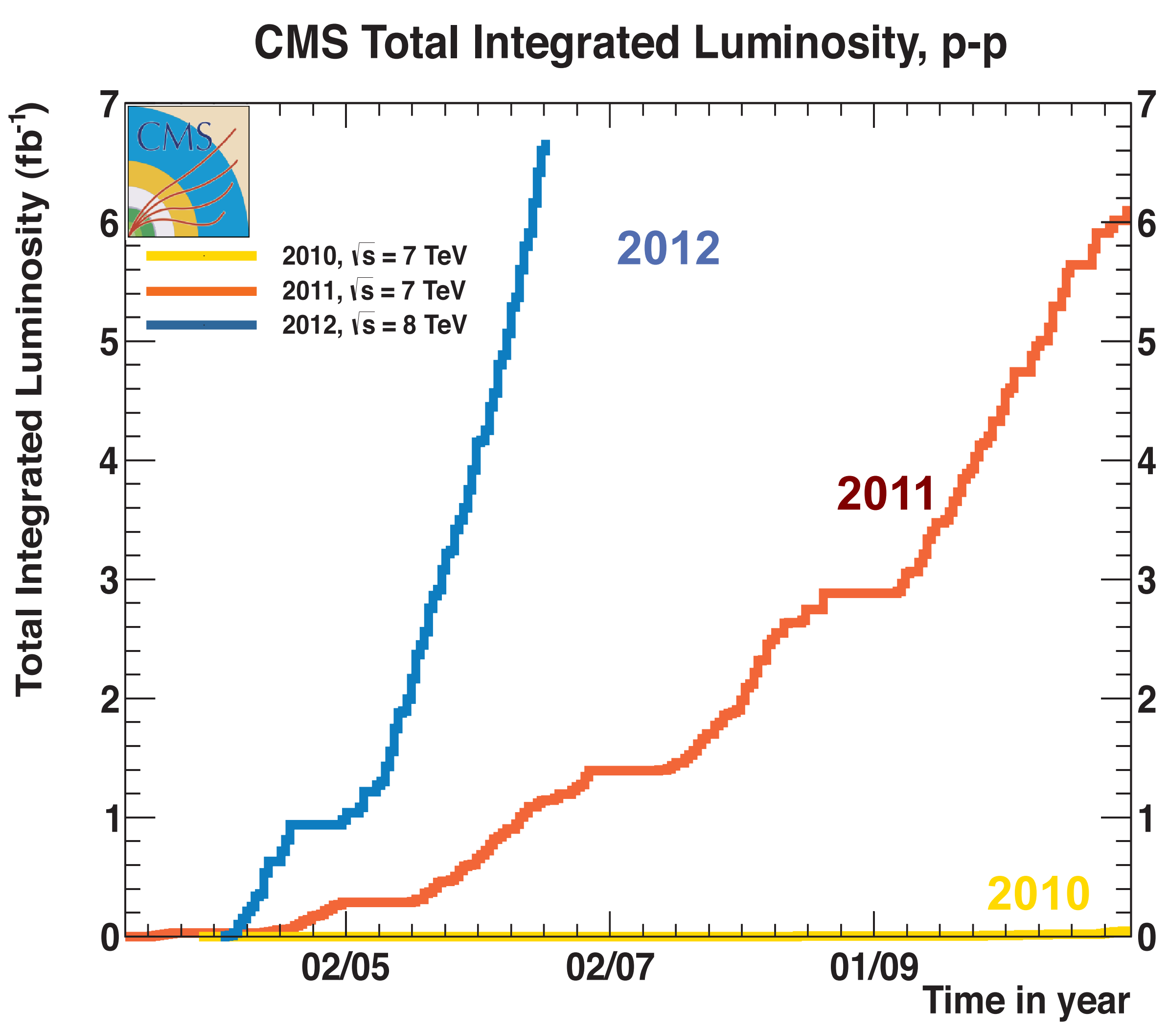
All channels combined



Higgs boson excluded in 127.5 - 600 GeV

Discovery of the Higgs boson in 2011-12 data

LHC performance: 2010-2011-2012



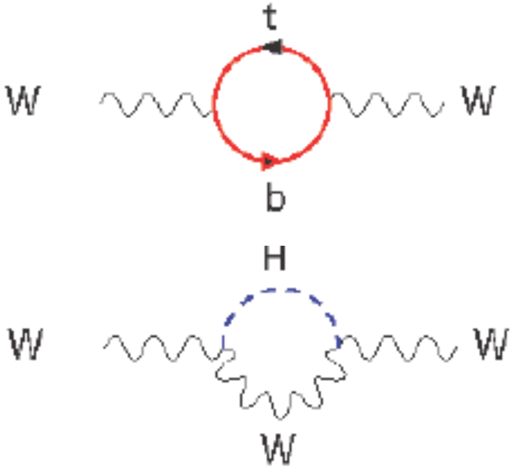
Stellar performance of the LHC enables all experiments to produce significant physics results

Many thanks to the LHC teams and the many others who made this possible!

Higgs, top quark and W masses

In the Standard Model, the Higgs, top and W masses are interdependent

Precise measurements of top and W mass allow to predict Higgs mass



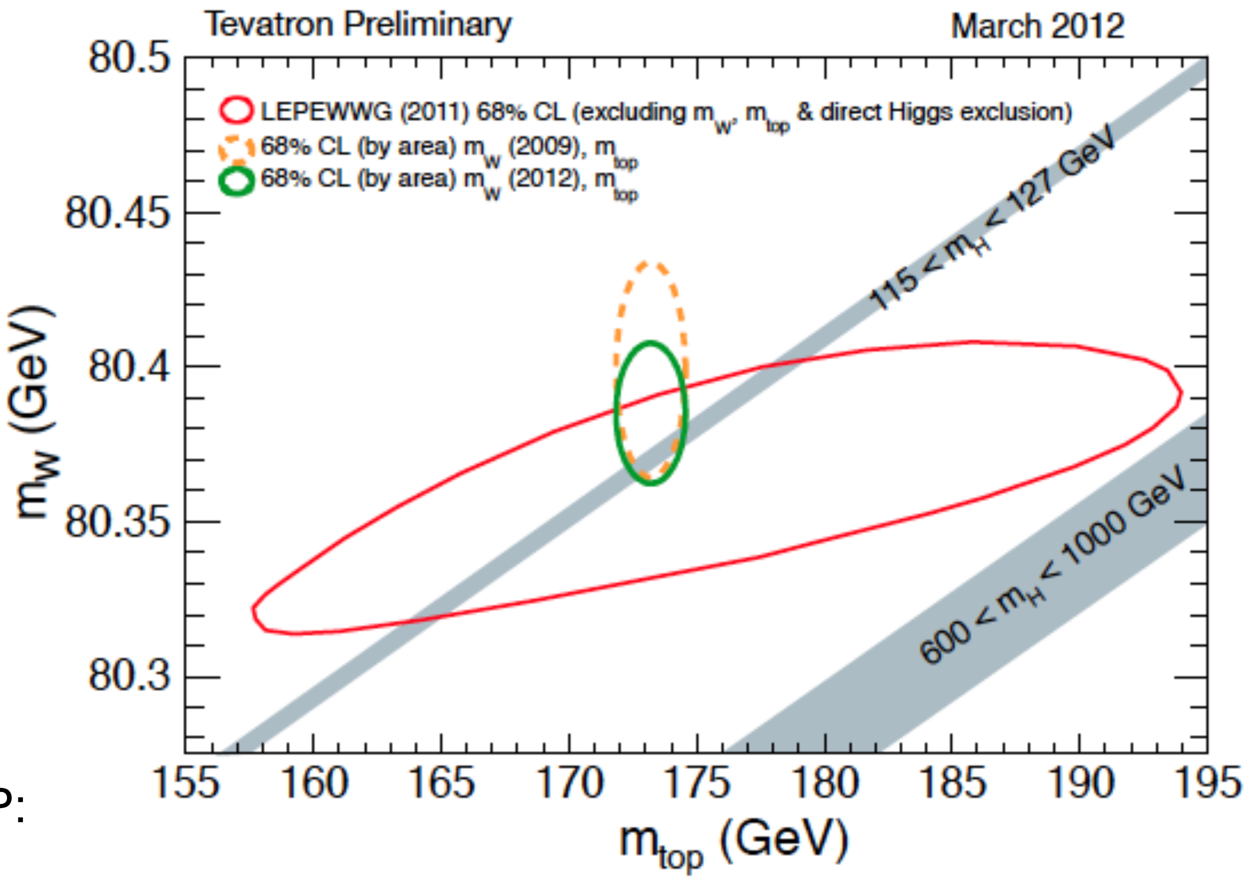
As of March 2012

- M_t=173.18 ± 0.94 GeV
- M_W=80.385 ± 0.015 GeV

➔ M_H<158 GeV at 95% CL

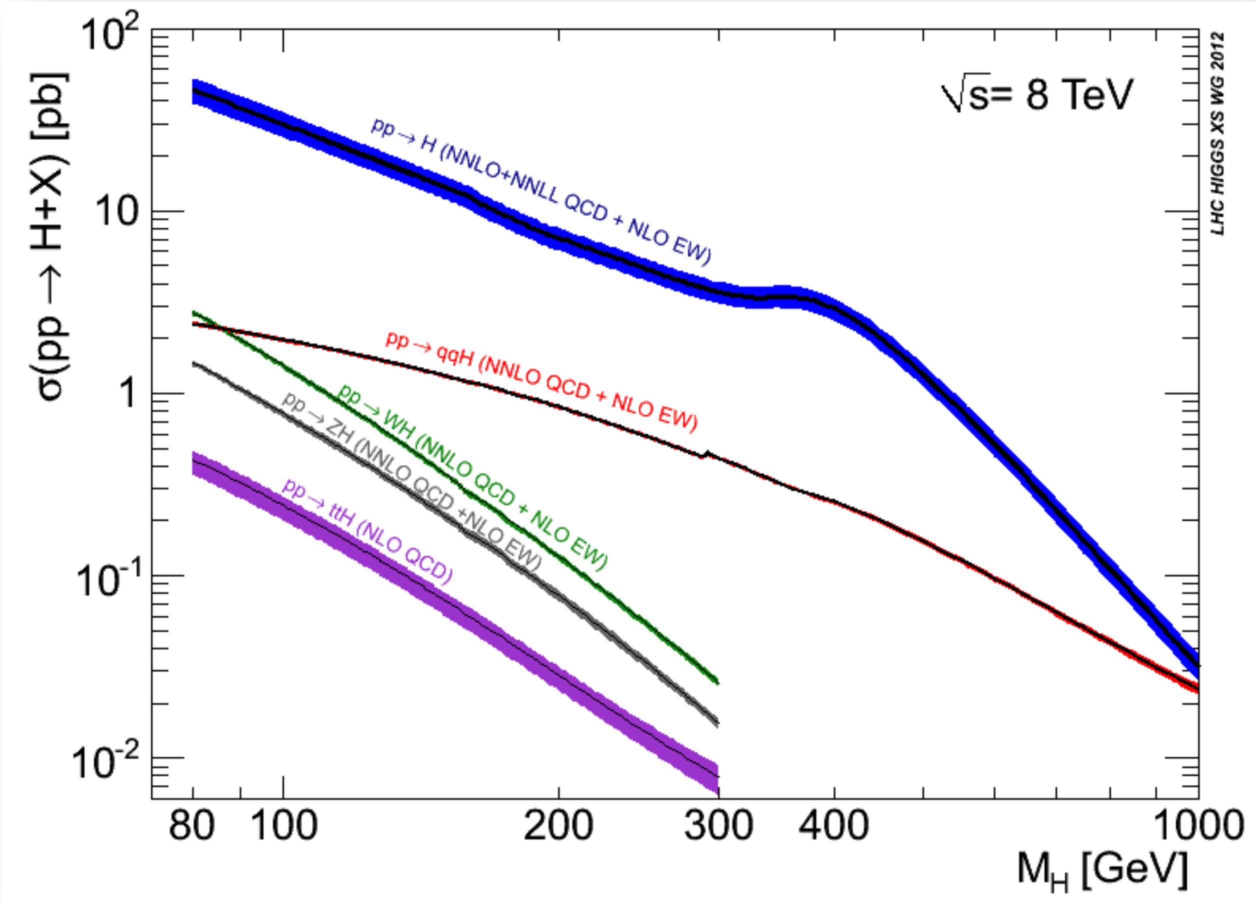
From direct searches at LEP:

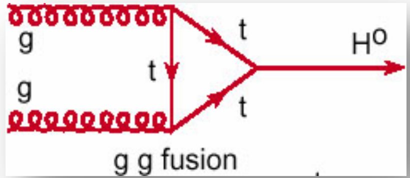
- M_H>114 GeV

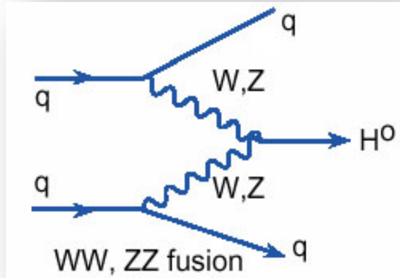


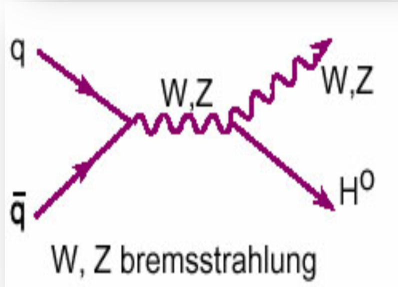
Higgs boson production

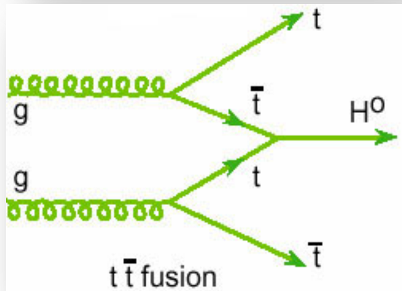
Higgs production rates are predicted by the Standard Model as a function of the Higgs mass









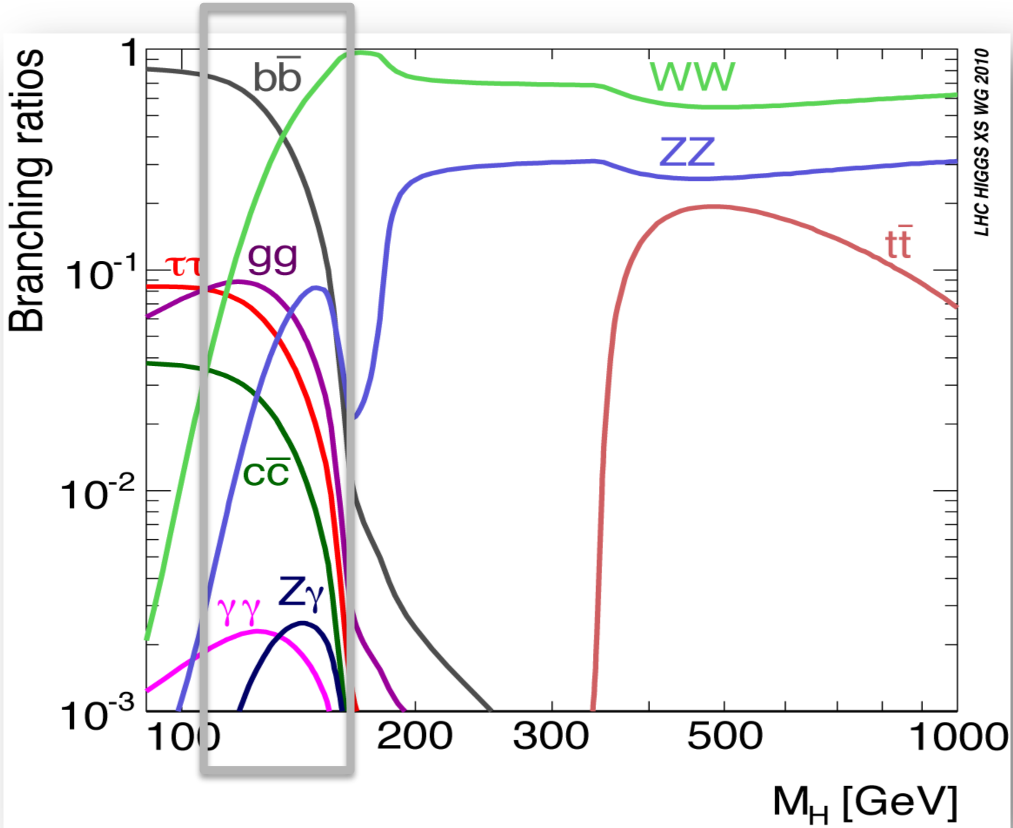


Higgs boson decays

Five Higgs decay modes were exploited

Low mass region is very rich but also very challenging:

- High sensitivity, high resolution: ZZ, γγ
- High sensitivity, low resolution: WW
- Low sensitivity, low resolution: bb, ττ



Datasets

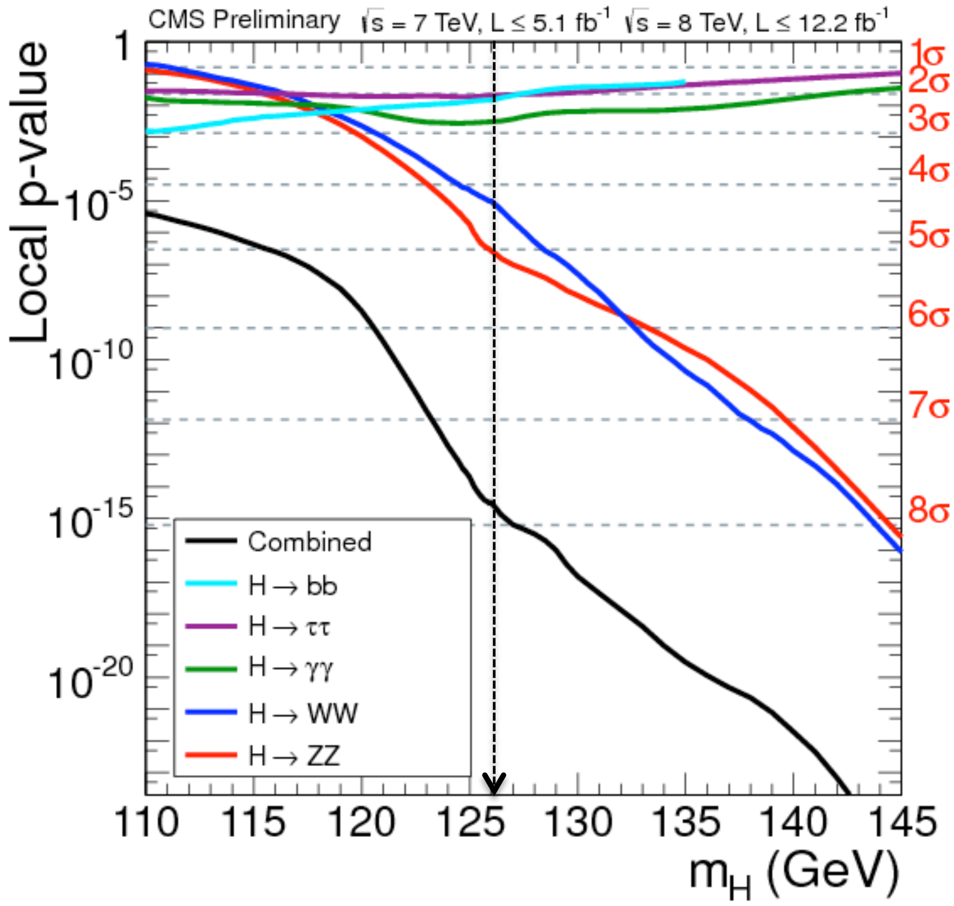
Channel	m_H range [GeV/c^2]	data set [fb^{-1}]	Data used CMS [fb^{-1}]	m_H resolution
1) $H \rightarrow \gamma\gamma$	110-150	5+5/fb	2011+12	1-2%
2) $H \rightarrow$ tau tau	110-145	5+12/fb	2011+12	15%
3) $H \rightarrow bb$	110-135	5+12/fb	2011+12	10%
4) $H \rightarrow WW \rightarrow l\nu l\nu$	110-600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

Data collected in 2011 and until September 2012

Higgs expected sensitivity

p-values

Probability that background fluctuates to give an excess as large as the signal size expected for a SM Higgs.

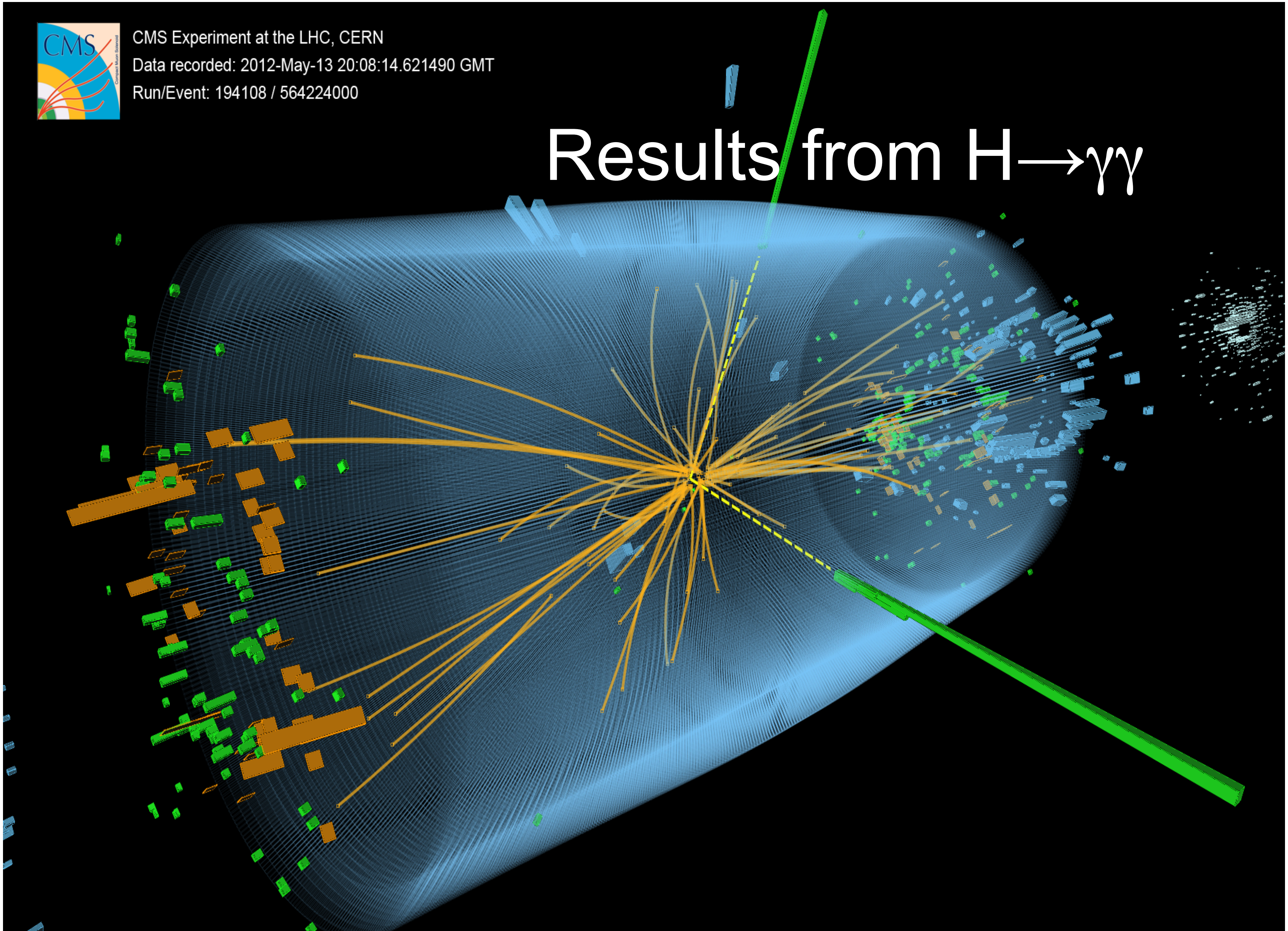


Discovery:

5σ (sigma) = probability of one in 3 million

Expected sensitivity at 126 GeV: 7.8 sigma

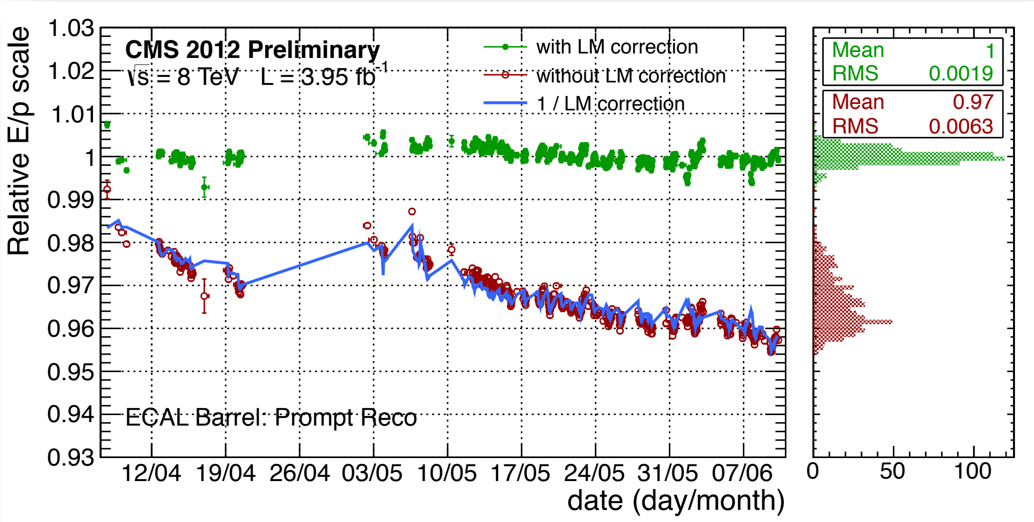
Results from H→γγ

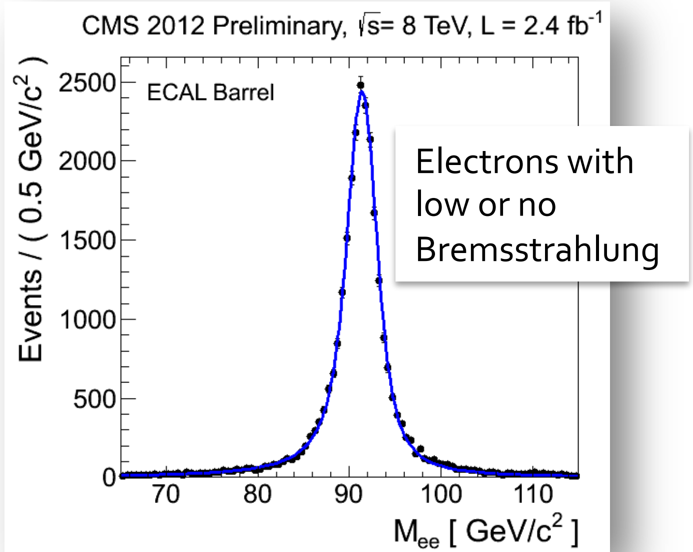


Photon energy calibration

Single electron energy scale (E/p) stability in barrel measured with W →eν events

Z→ee invariant mass distribution for electrons measured in the barrel



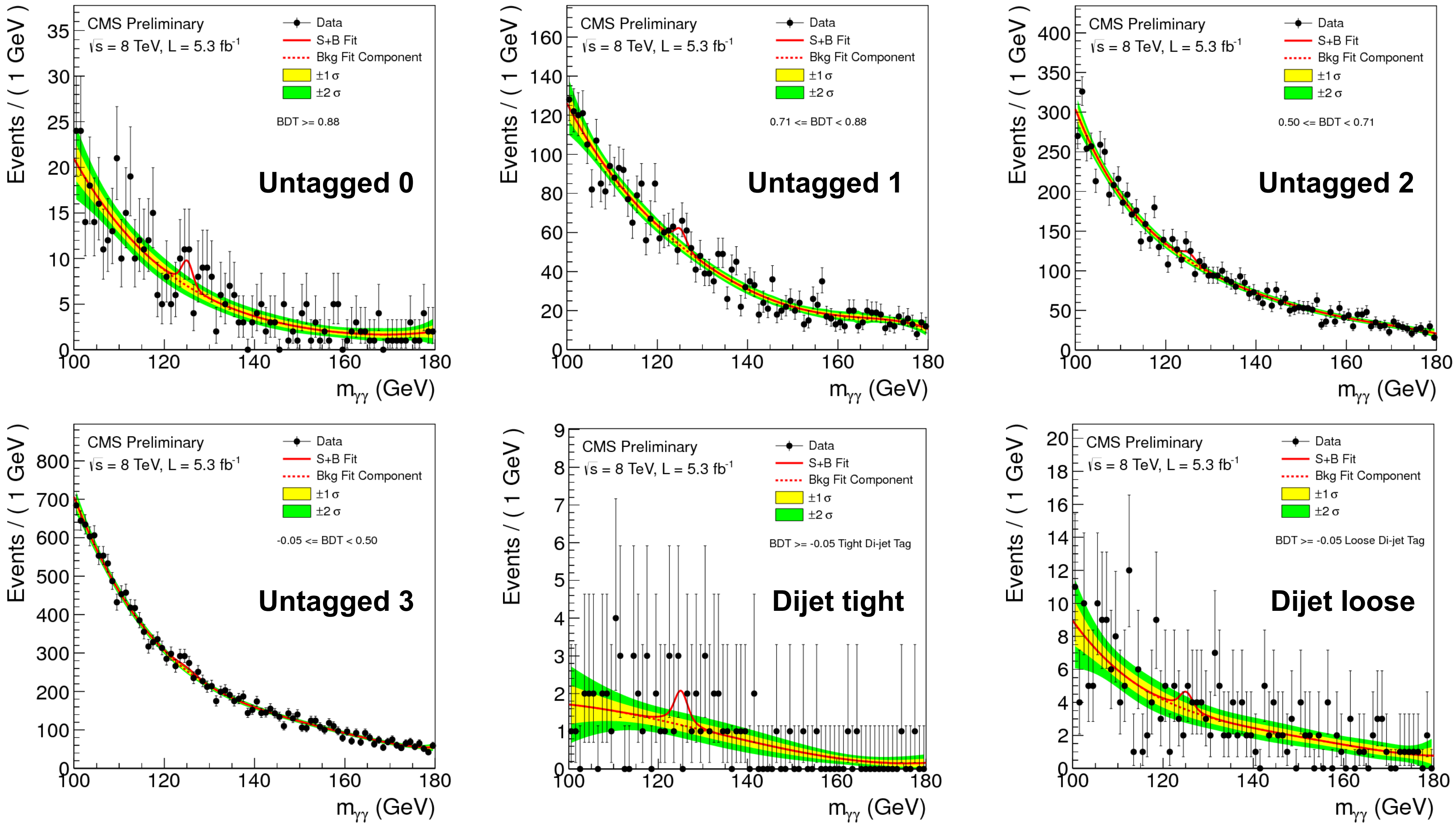


- **W→eν E/p:** Stable E scale during 2012 run after light monitoring corrections:
  - ECAL Barrel (EB): RMS stability after corrections 0.19%
- **Z→ee:** Good resolution with preliminary energy calibration for 2012:
  - Instrumental resolution: 1.0 GeV in ECAL Barrel (~1%)

Di-photon mass spectra

Combined fit of signal and background to all 11 categories

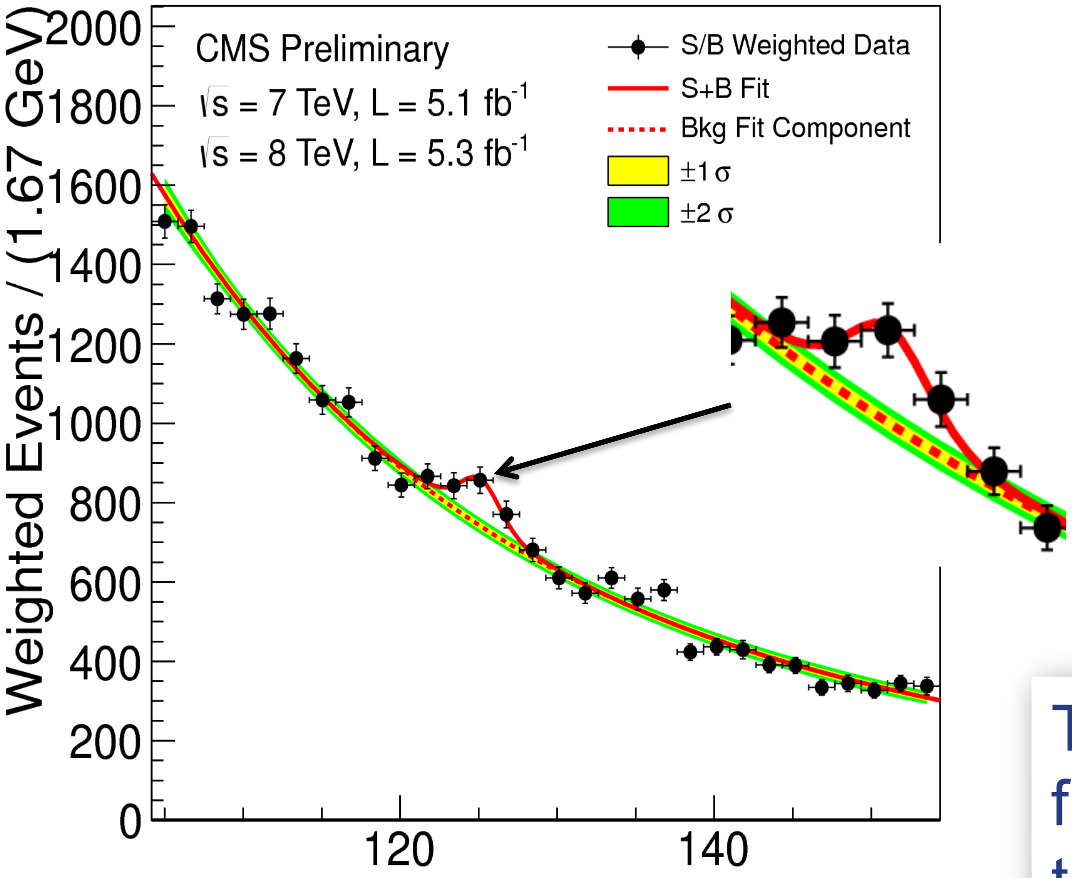
8 TeV data



Results from H→γγ

Di-photon mass distribution

Sum of mass distributions for each event class, weighted by S/B



In the γγ mass distribution there is an excess of events above background, at a mass near 125 GeV.

The observation of the two-photon final state implies that the **new particle is a boson**, not a fermion, and that **it cannot be a "spin 1" particle.**

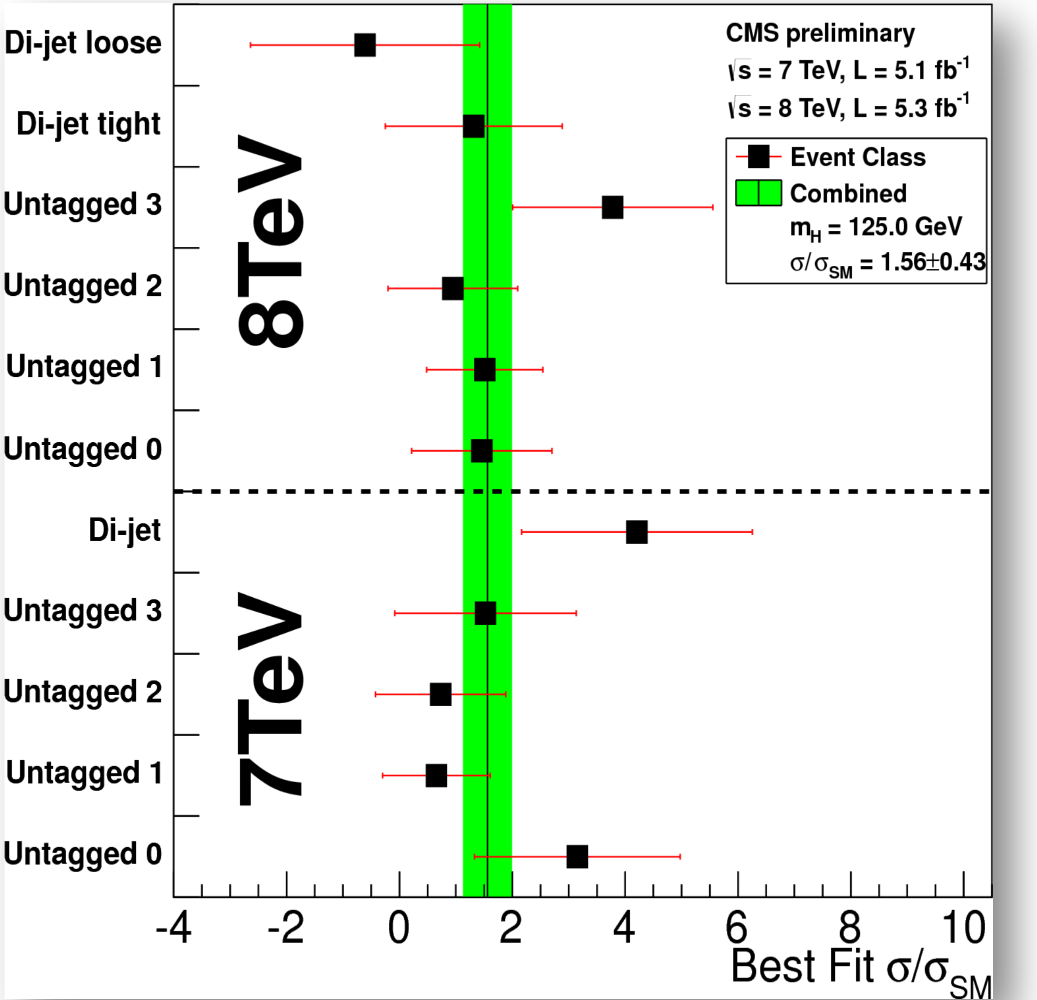
There is no other fundamental particle with these properties

J. Varela, The Higgs boson, 2013

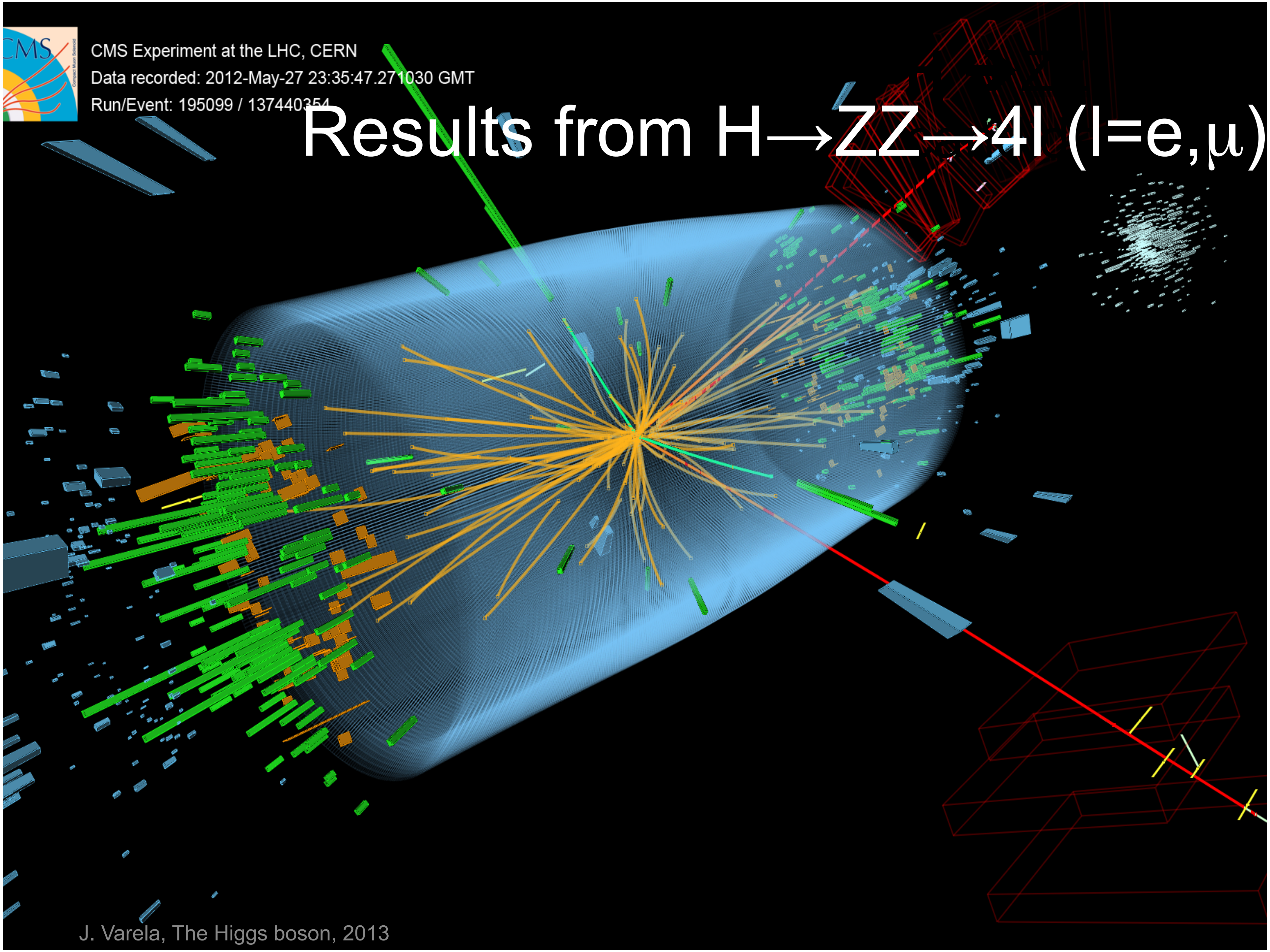
$H \rightarrow \gamma\gamma$ signal strength

Best fit signal strength consistent between different classes

Combined best fit signal strength (m_H=125 GeV):
σ/σ_{SM} = 1.56±0.43 x SM

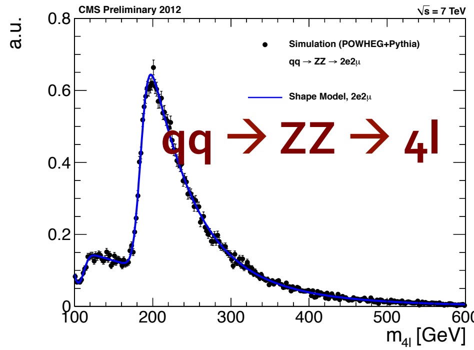


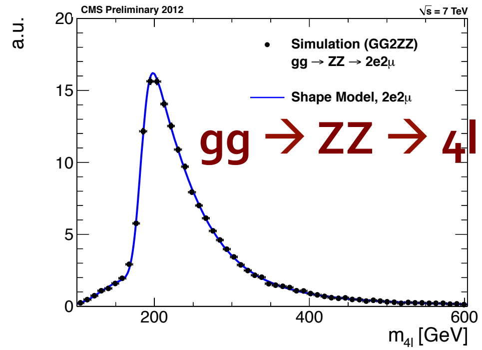
Results from H→ZZ→4l (l=e,μ)



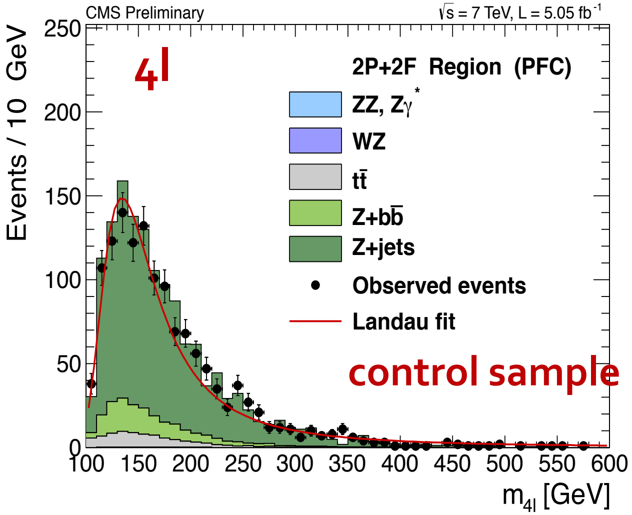
ZZ background models

- **Irreducible background ZZ → 4l**
  - Estimated **using simulation**
  - Phenomenological shape models
  - Corrected for data/simulation scale

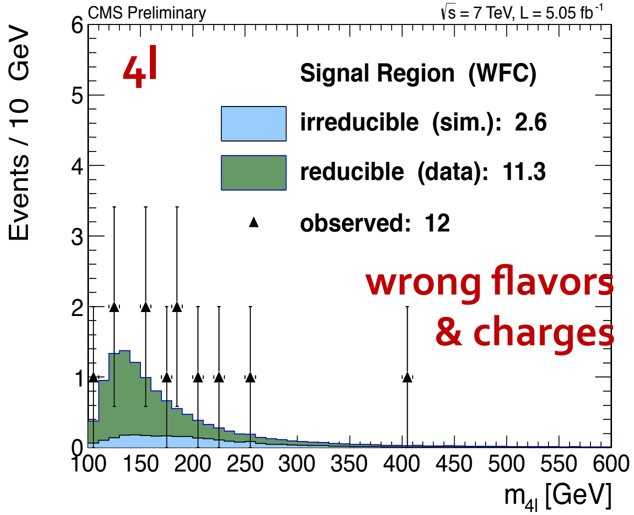




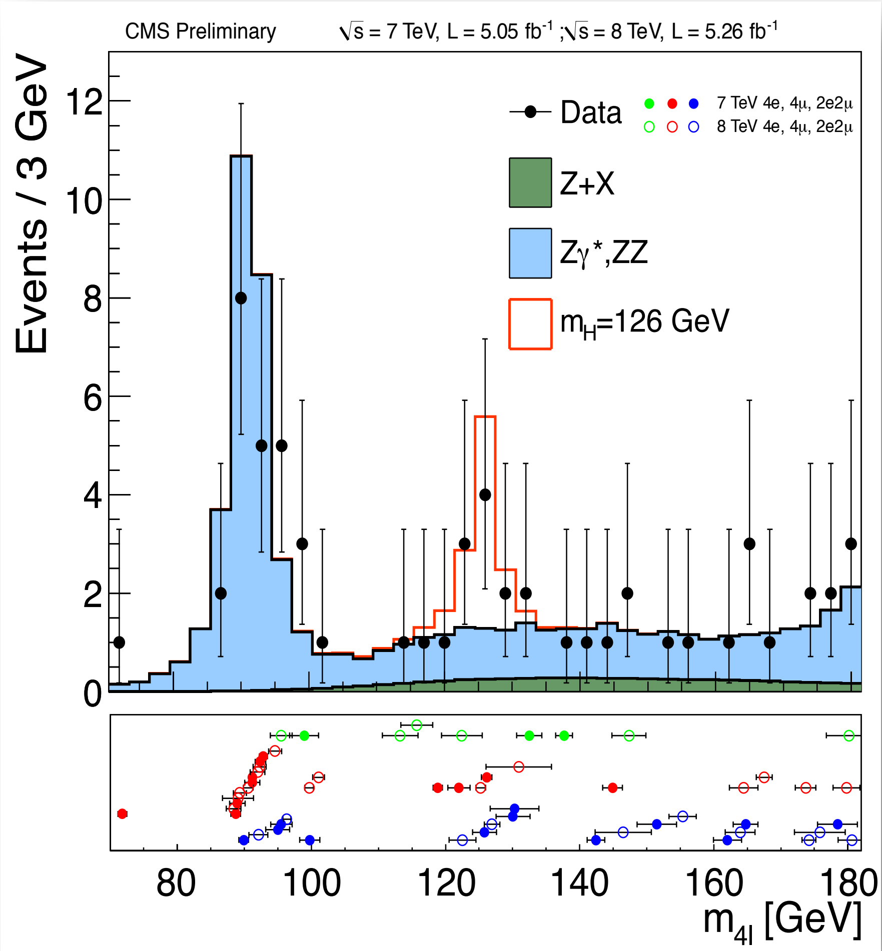
- **Reducible backgrounds estimated from data**
  - Extrapolation from control samples enriched with misidentified leptons
  - Total uncertainty ~50%



Validation in **data**



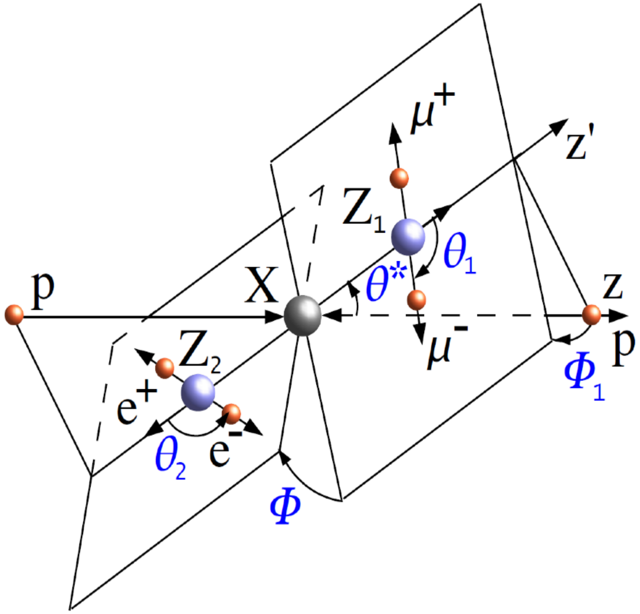
Four lepton mass spectrum



Mass distribution for the four leptons (two pairs of electrons, or two pairs of muons, or the pair of electrons and the pair of muons).

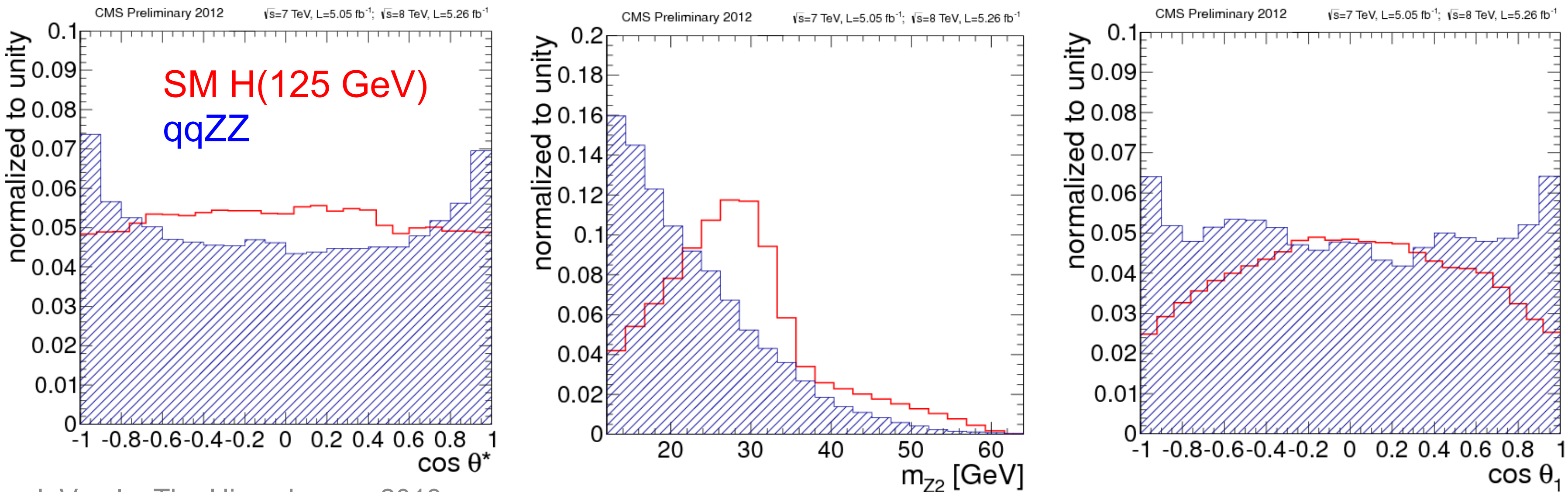
Accounting also for the decay angle characteristics, it yields an **excess of 3.1 sigma above background at a mass of 125.6 GeV.**

ZZ→4l angular distributions



Matrix Element Likelihood Analysis:
uses kinematic inputs for
signal to background discrimination
$\{m_1, m_2, \theta_1, \theta_2, \theta^*, \Phi, \Phi_1\}$

$$K_D = \left[1 + \frac{\mathcal{P}_{\rm bkg}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}{\mathcal{P}_{\rm sig}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}\right]^{-1}$$

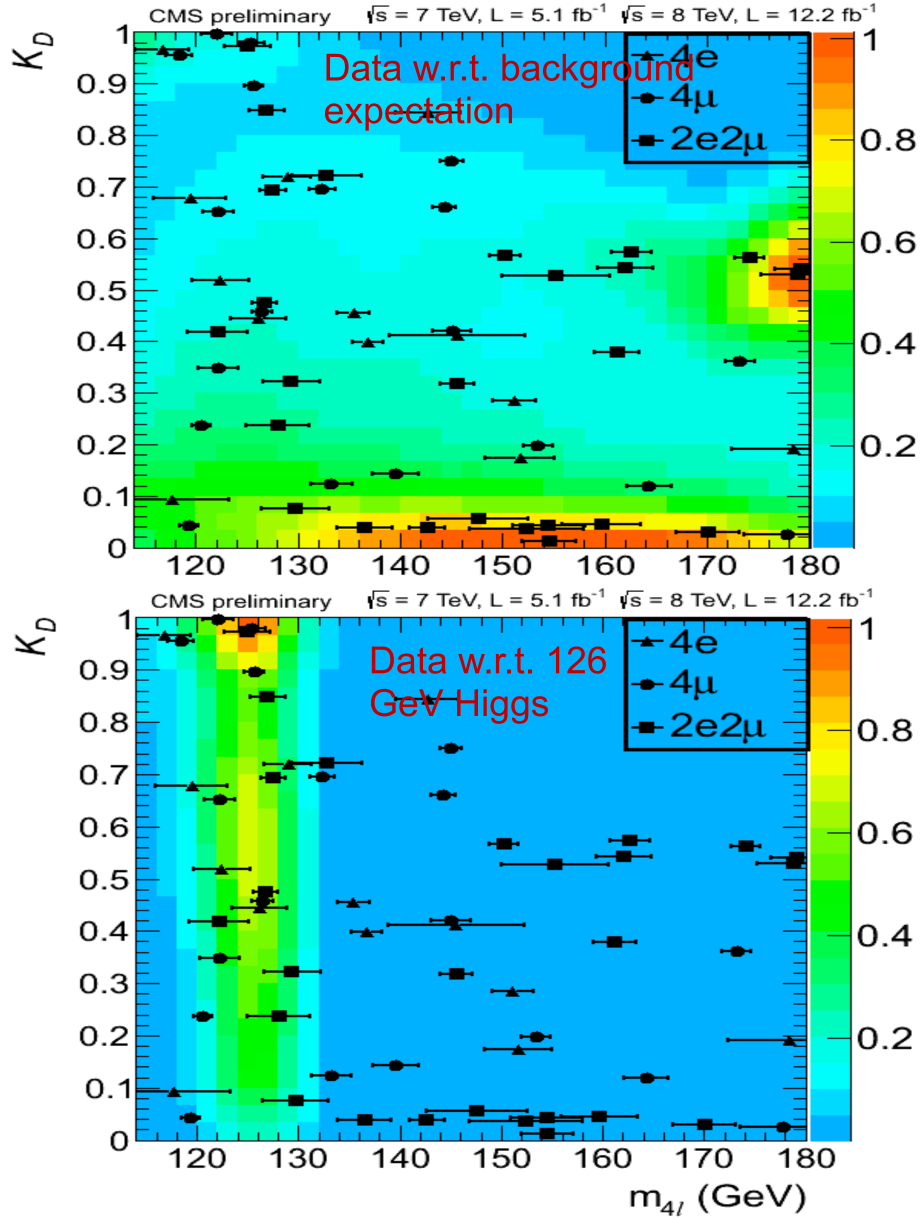


K_D versus m_{4l} distributions

K_D discriminant versus m_{4l}

– Data points shown with per-event mass uncertainties

- Top: Data w.r.t. background expectation
- Bottom: Data w.r.t 126 GeV Higgs expectation



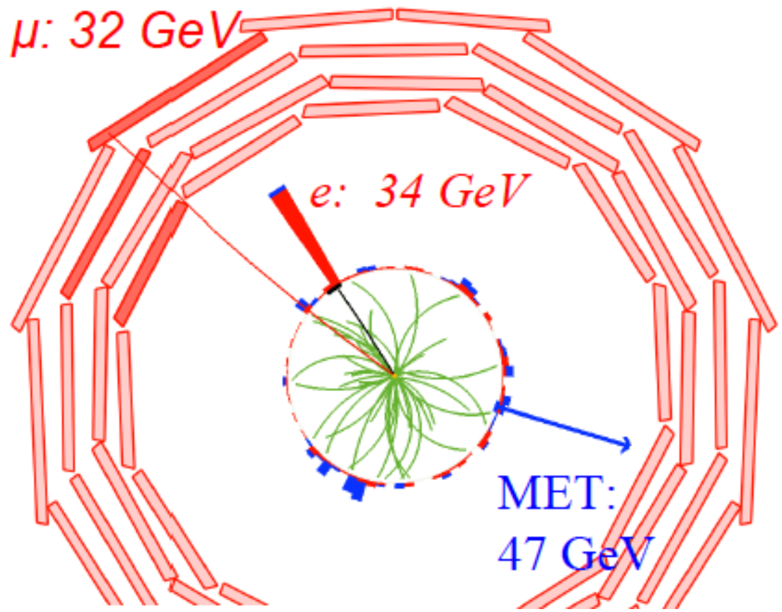
H → WW → 2l 2ν

Signature

- 2 opposite charged leptons
- 2 neutrinos = missing transverse energy (MET)

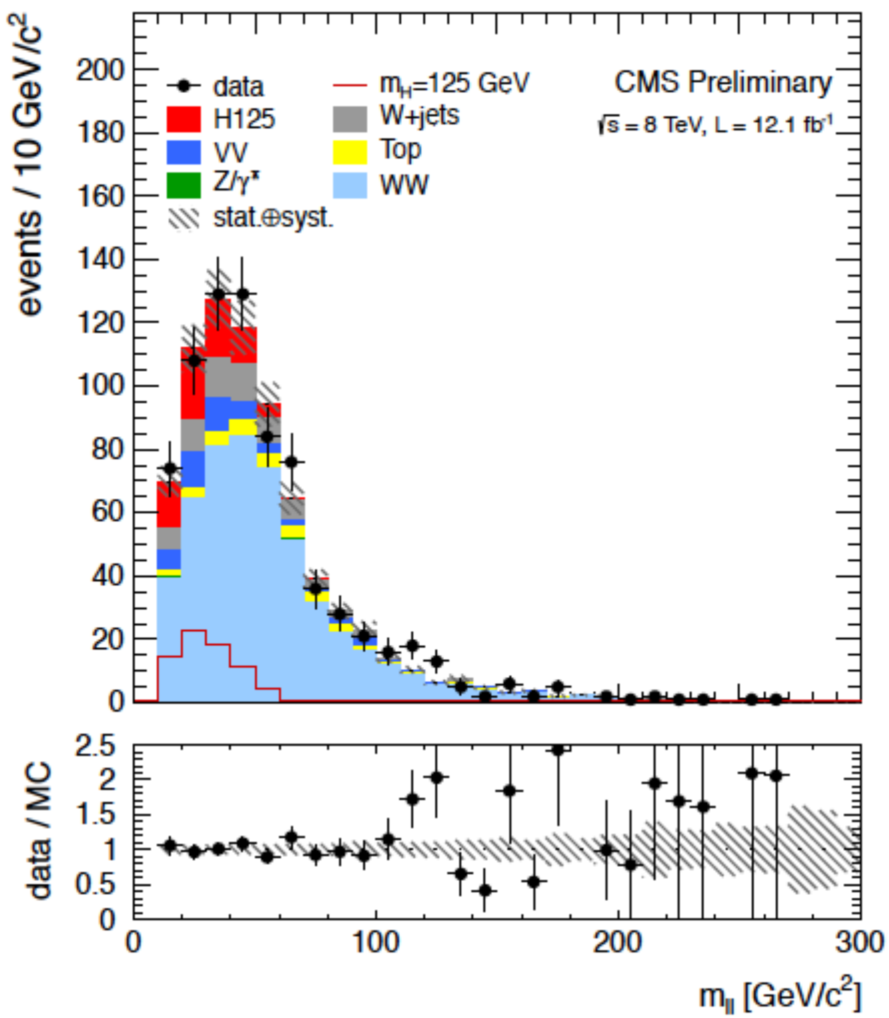
Analysis challenges

- understand backgrounds:
  WW, W+jets, top, DY

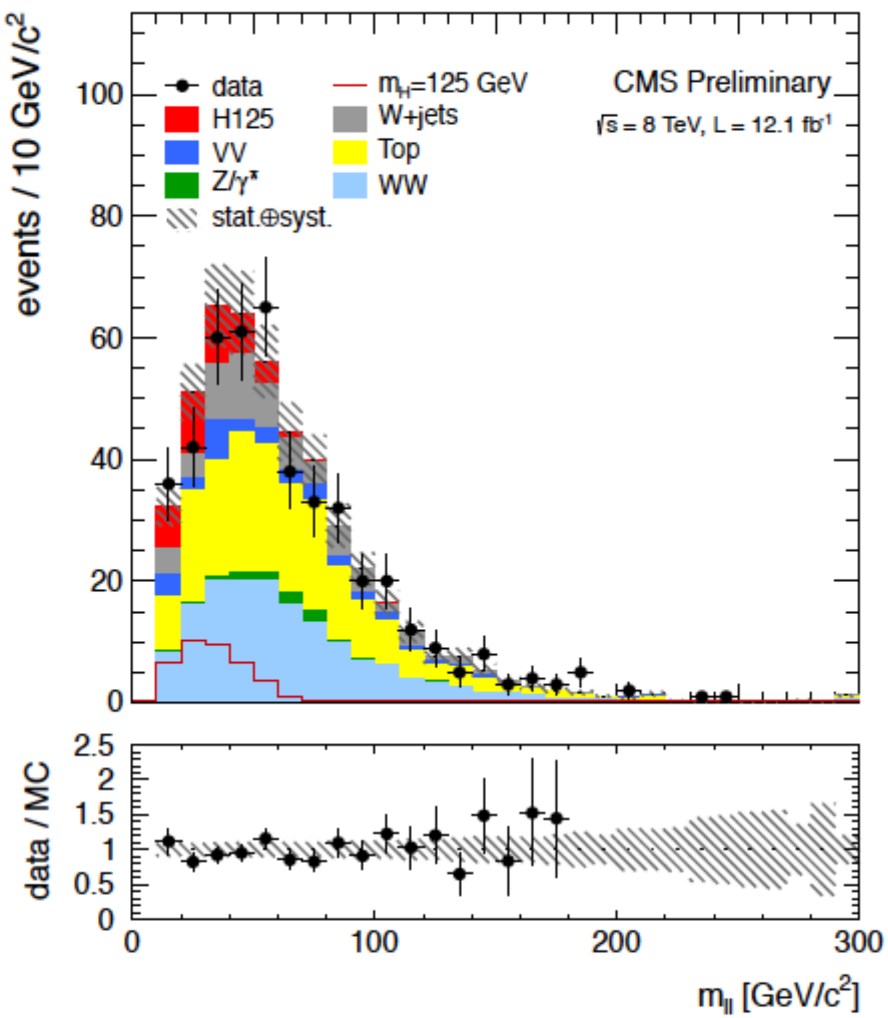


H→WW analysis

e-μ mass in the 0-jet category



e-μ mass in the 1-jet category

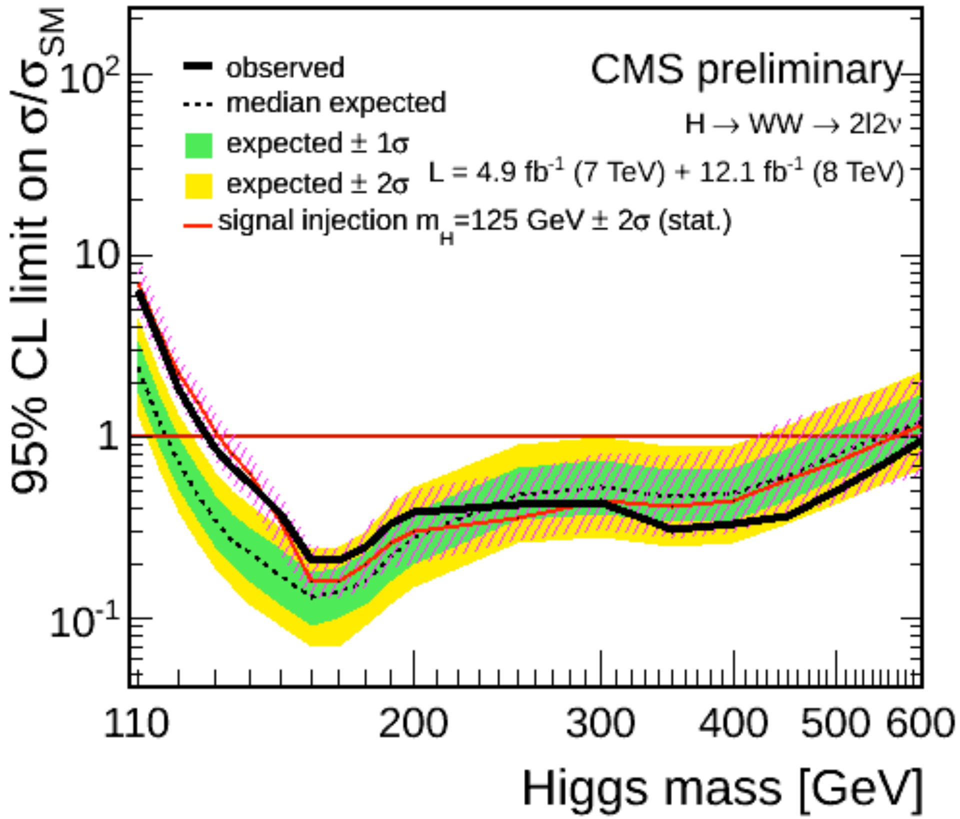


Results from H→WW analysis

For a mass of 125 GeV:

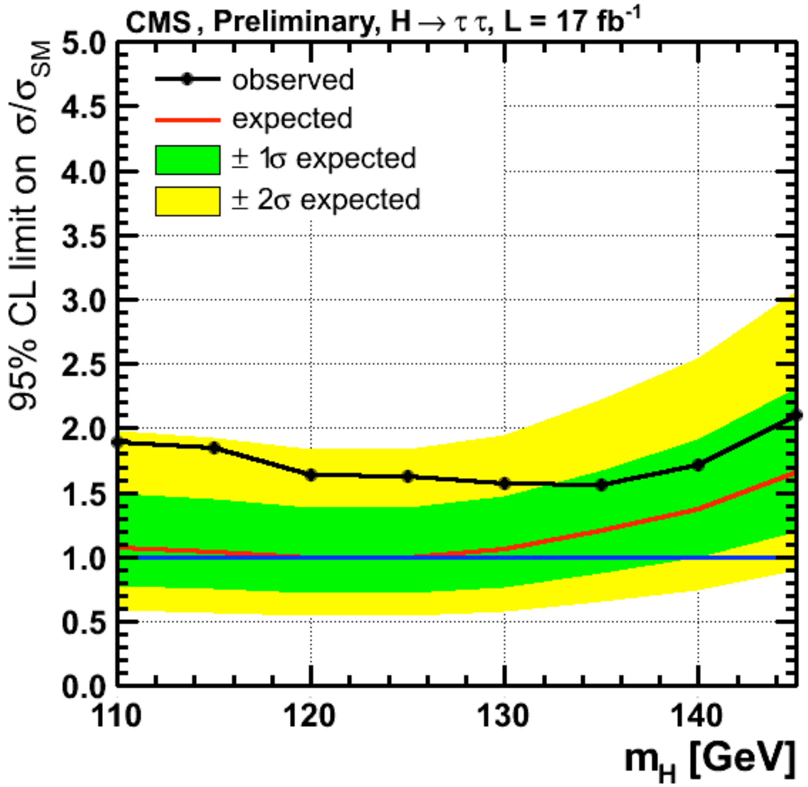
- Observed signal significance: 3.1 sigma

- Signal strength σ/σ_{SM} : 0.74±0.25



Results from H → ττ analysis

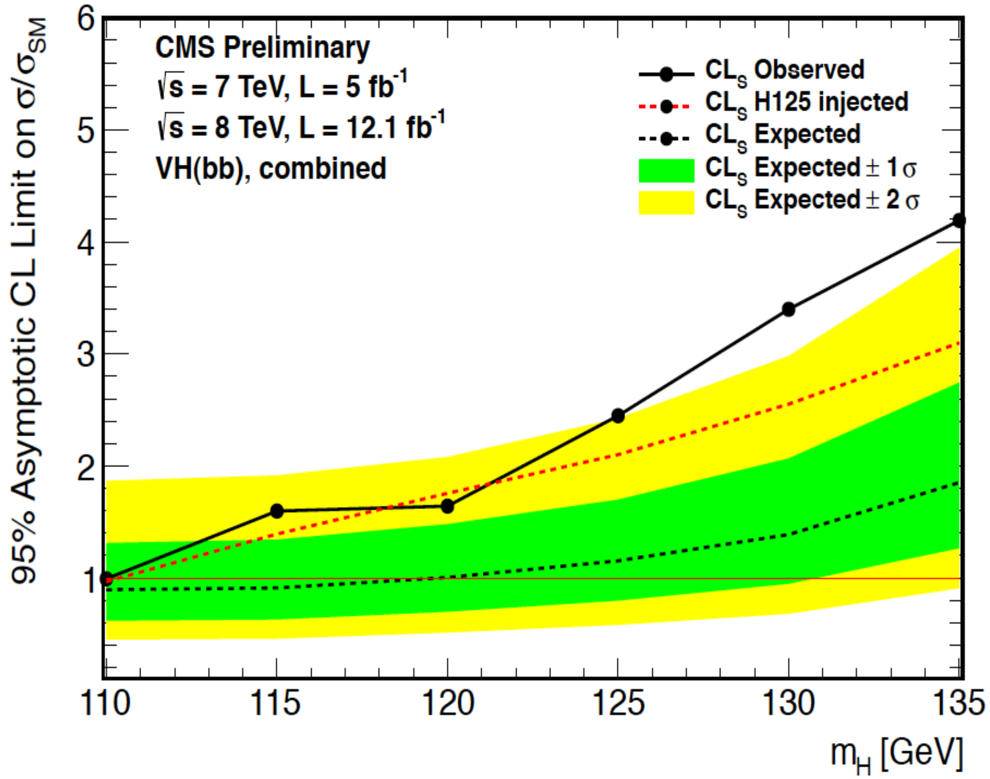
7 and 8 TeV data; all categories combined



Mild excess at low mass ~ 1.5 sigma

Combined σ/σ_{SM} at m_H = 125 GeV: 0.7±0.5

Results from VH → Vbb analysis

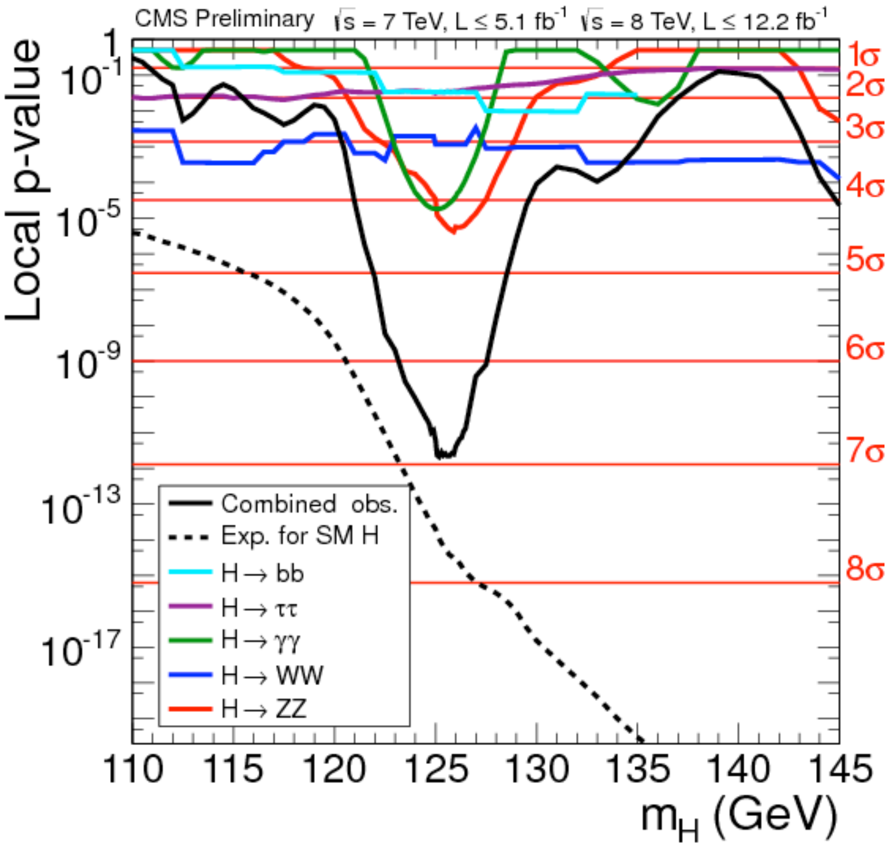


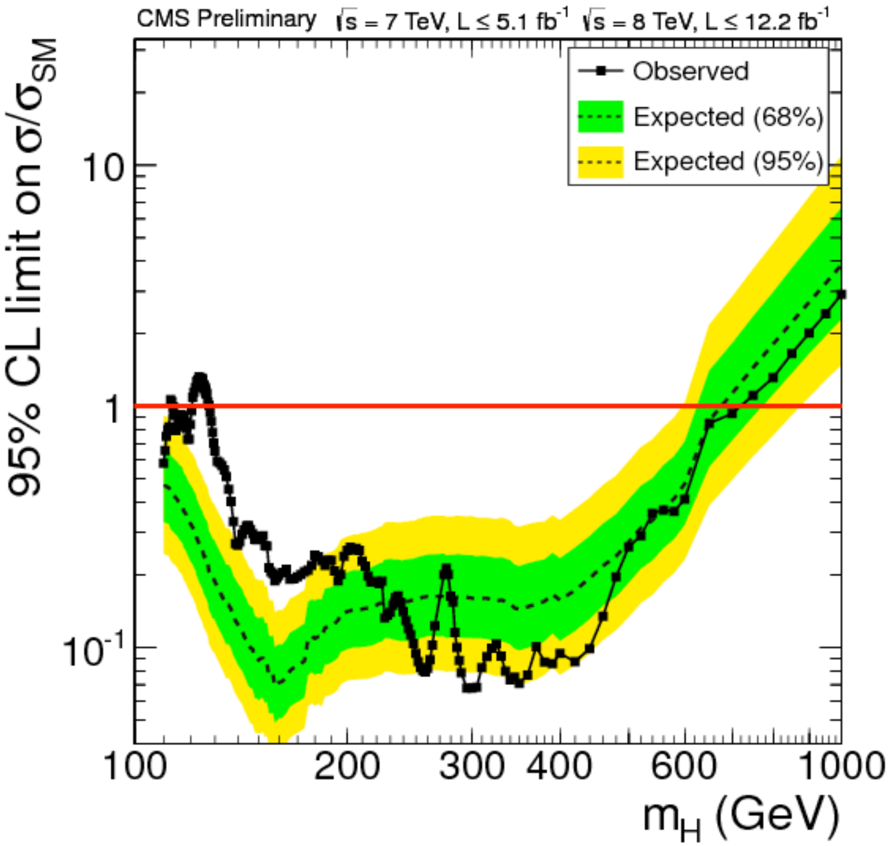
At 125 GeV:

- The significance of the excess is 2.2 σ
- Combined signal strength: $1.3^{+0.7}_{-0.6}$

Higgs combined results

Combination of 5 channels: bb, ττ, WW, ZZ, γγ

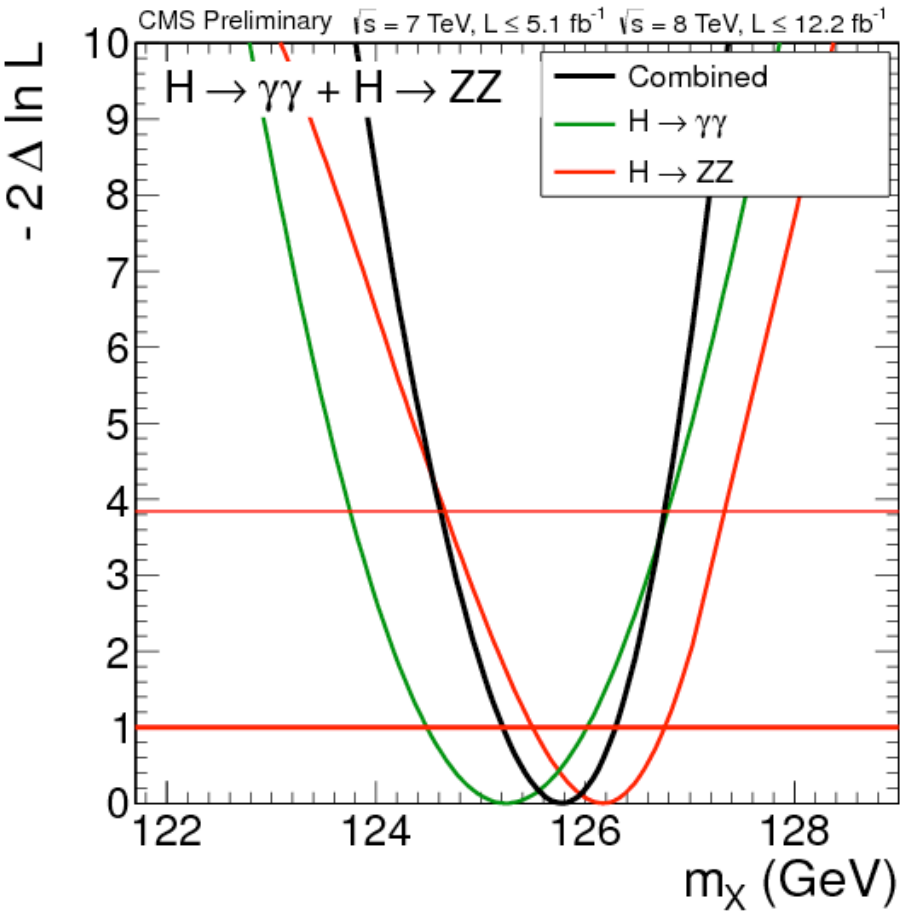




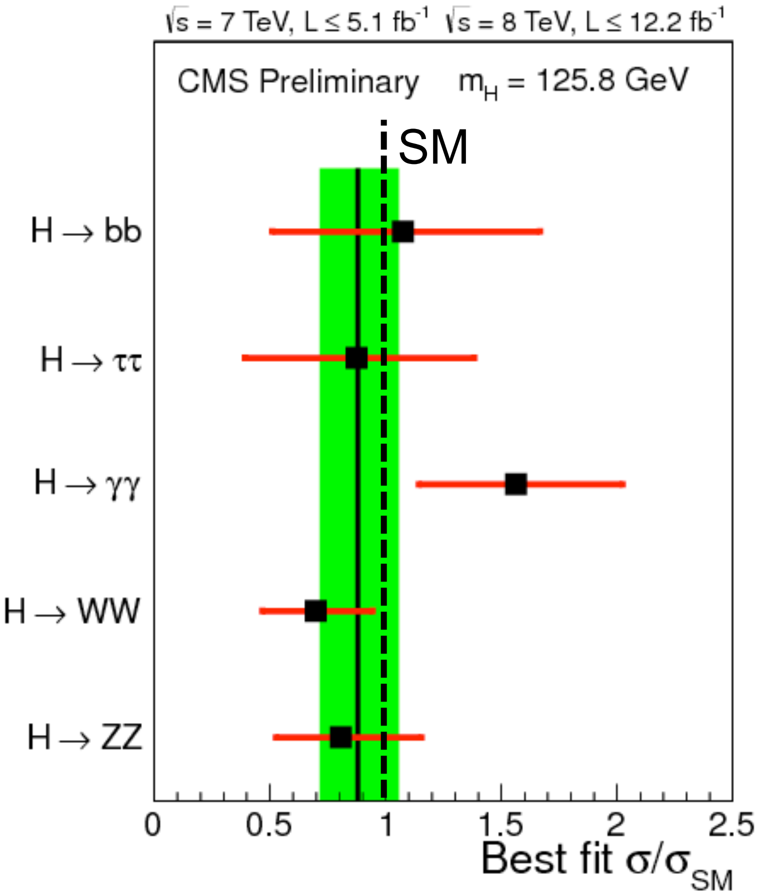
Observed significance 6.9σ versus 7.8σ expected

Mass of the new resonance

Mass measurement from the two high-resolution channels: **$m_X = 125.8 \pm 0.6$ GeV**



Signal strength at m_H=125.8 GeV



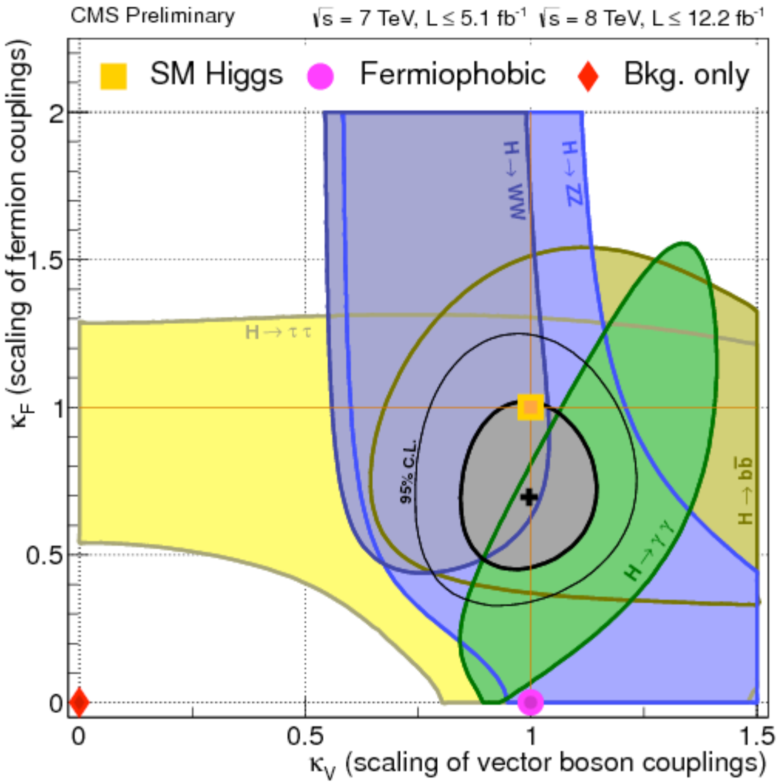
Overall best-fit signal strength in the combination:

$$\sigma/\sigma_{SM} = 0.88 \pm 0.21$$

Signal strengths consistent with each other and with SM

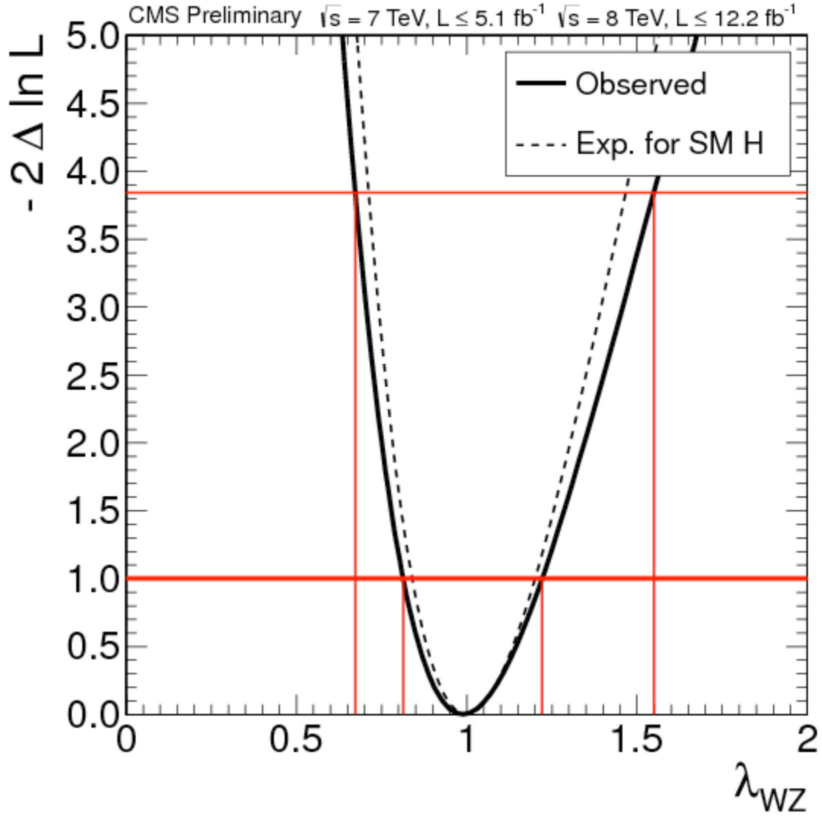
Couplings to fermions and bosons

Fermion and Vector Boson Couplings



Custodial Symmetry

$\lambda_{WZ} = \kappa_W/\kappa_Z$

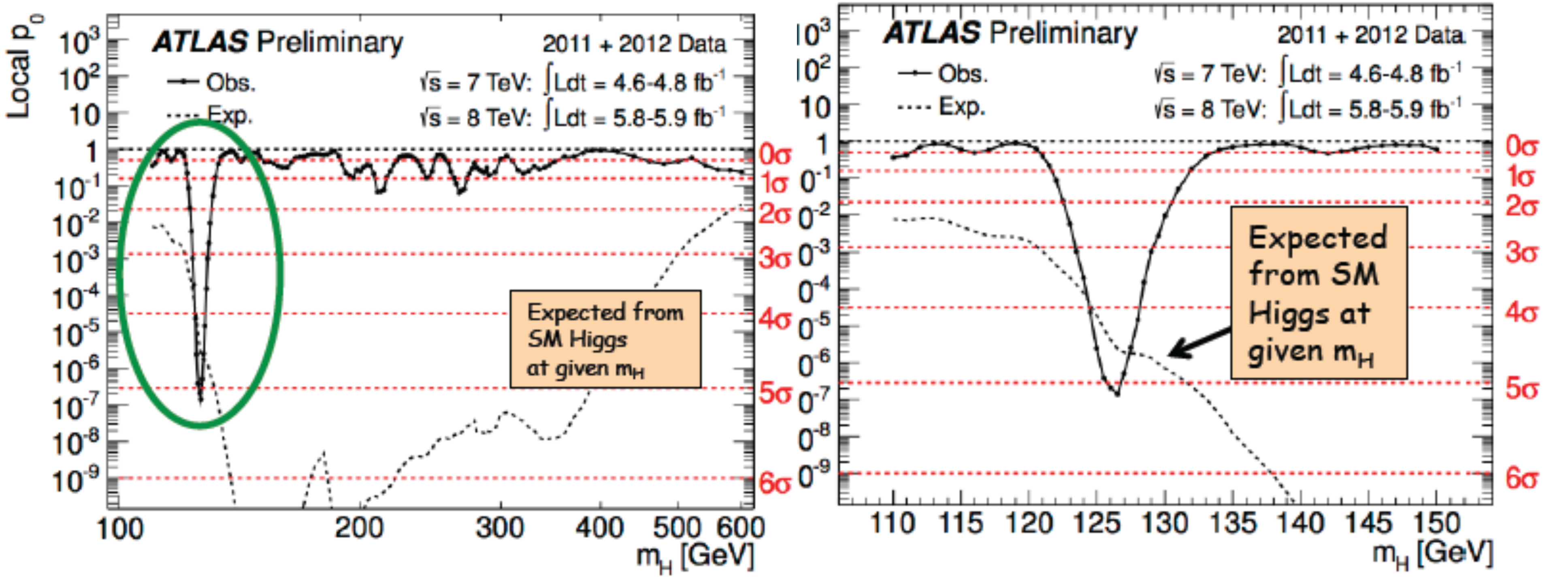


Couplings look consistent with SM Higgs

Results from ATLAS

Combination of γγ and ZZ channels in 2012 + all channels in 2011

July 2012



Significance 5 sigma at m= 126.5 GeV

Both LHC experiments have observed a new boson with a mass near **125 GeV** at significance above **5 σ** !

The New York Times

Wednesday, July 4, 2012 Last Update: 6:54 AM ET

Discovery of New Particle Could Redefine Physical World

By DENNIS OVERBYE
21 minutes ago

The discovery by physicists at CERN's Large Hadron Collider, if confirmed to be the Higgs boson particle, could lead to a new understanding of how the universe began.

- The Lede Blog: What in the World Is a Higgs Boson?
  4:16 AM ET

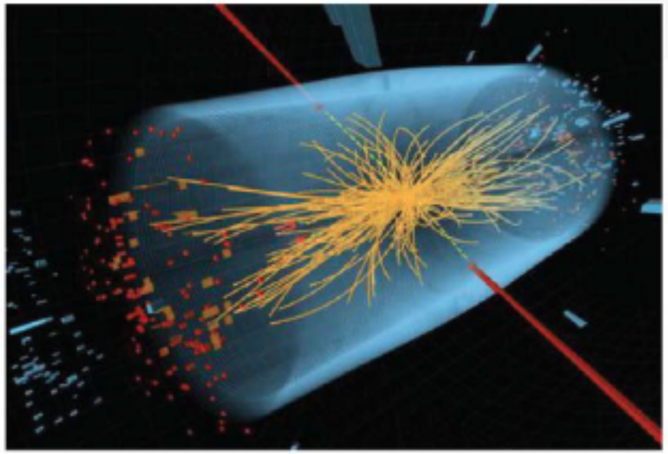
Fabrice Coffrini/Agence France-Presse — Getty Images

CERN officials held a press conference near Geneva on Wednesday.

LA NEWS DEL GIORNO | CANALE: Politica 10:21 - Roma, 4 lug 2012

Il Bosone di Higgs esiste, oggi l'annuncio del Cern a Ginevra

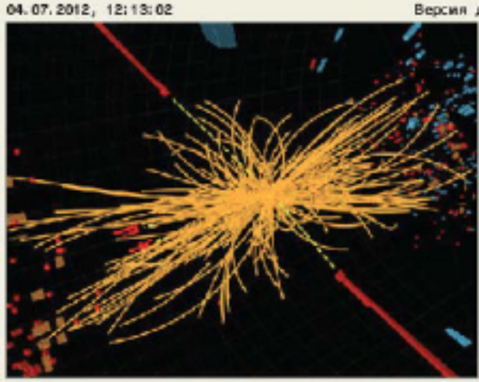
Tanti indizi per il "Santo Graal" della fisica quantistica teorizzato nel 1964. E' l'ultima particella ancora da scoprire



Roma, 4 lug. (TMNews) - L'enigma relativo all'esistenza del "bosone di Higgs", il "Santo Graal" della fisica delle particelle elementari, potrebbe essere oramai vicino alla soluzione: la conferenza stampa in programma oggi al Cern potrebbe dissipare gli ultimi dubbi.

LENTA·RU вторник, Прогресс
издание Rambler Media Group

04.07.2012, 12:13:02 Версия для печати | PDA

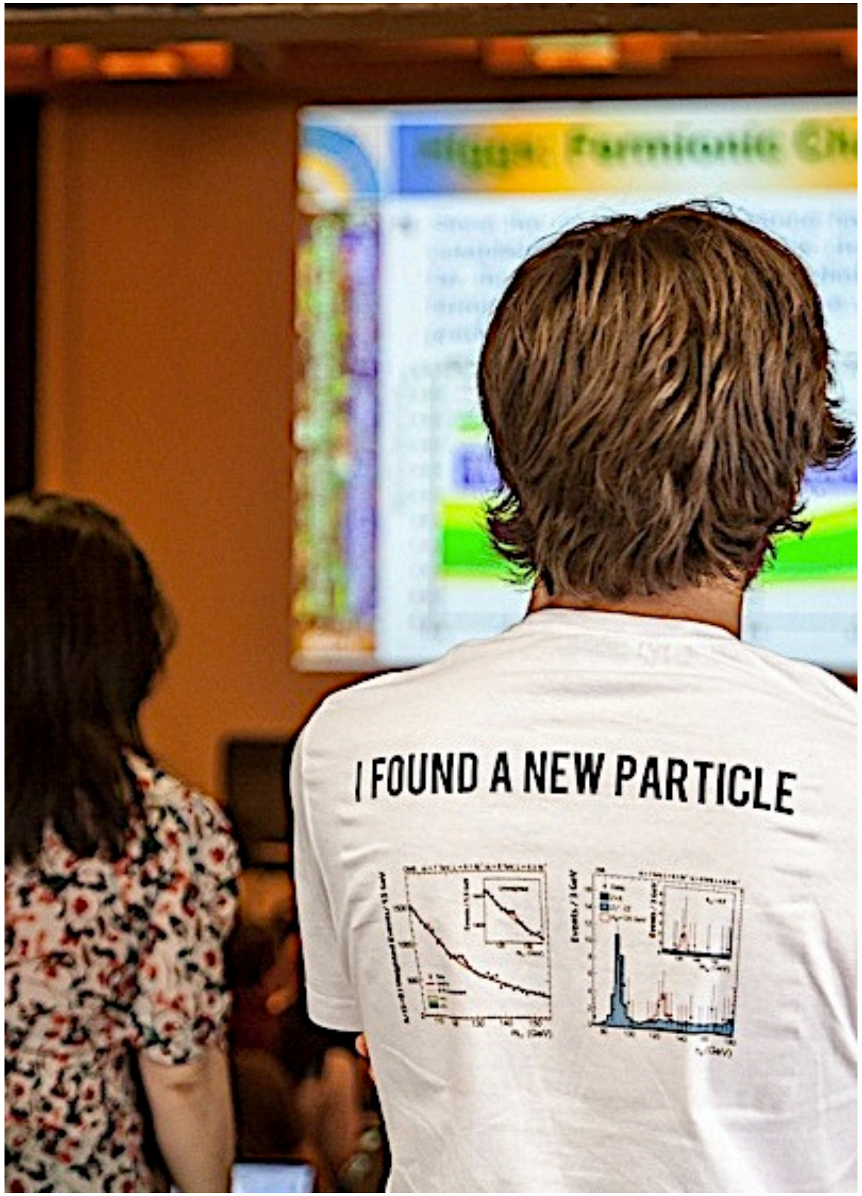


Изображение с сайта CERN

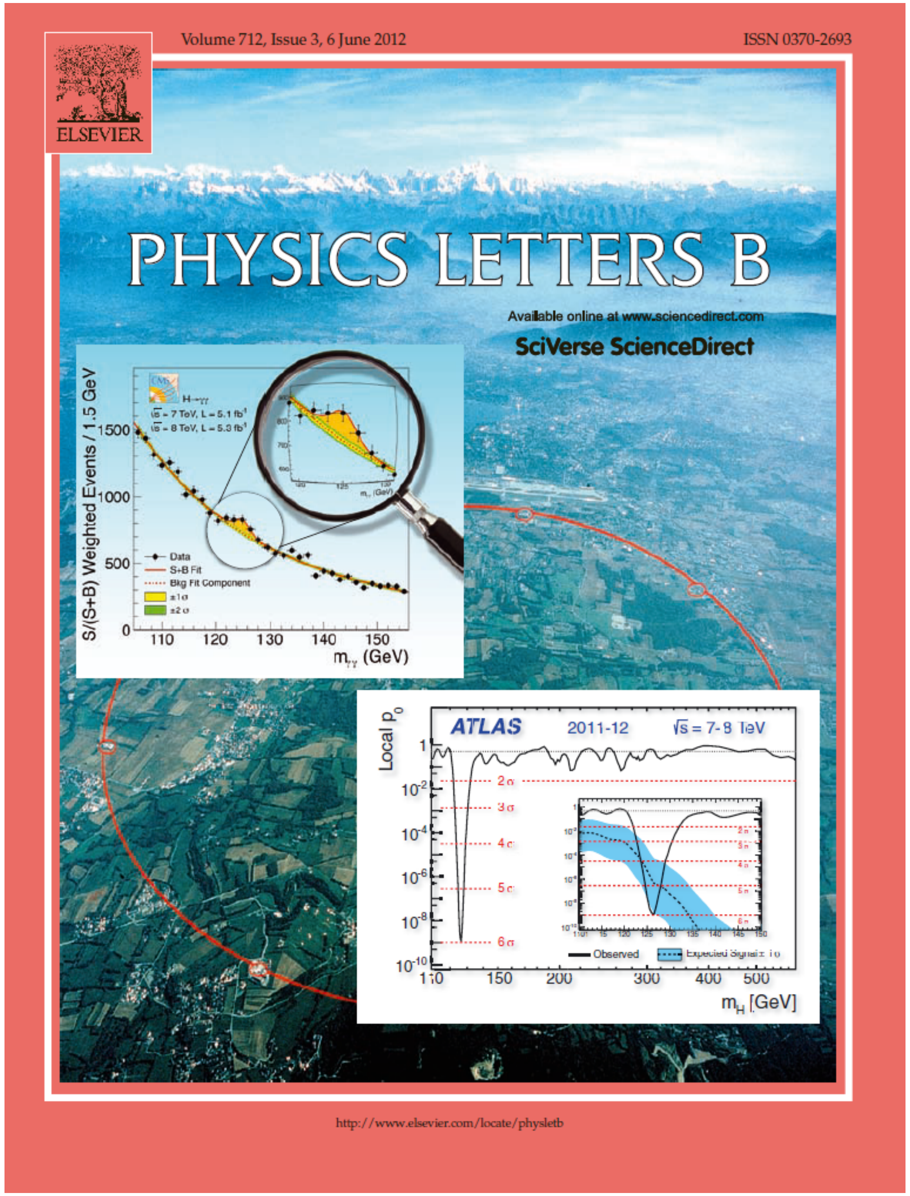
Физики обнаружили претендента на роль бозона Хиггса

Physicists discover a candidate for the boson Higgs

A new boson was discovered



A new boson was discovered



ATLAS and CMS papers:

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

"…compatible with the production and decay of the Standard Model Higgs boson."

Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC

"…consistent, within uncertainties, with expectations for the standard model Higgs boson."

What is this boson?

We still don't know exactly what it *is*!

Is there 1 Higgs boson, or more?
Is it point-like, or composite?
Is it spin 0, or not?
Are all probabilities as predicted, or not?

Red answer = "New Physics"!

Beyond the Higgs:

New physics beyond the Standard Model is likely…

A major discovery in physics

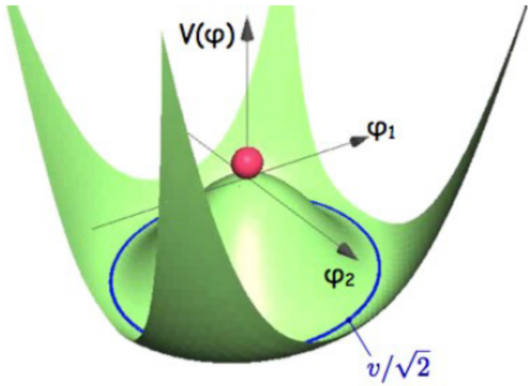
The **new boson** is either the SM Higgs or a Higgs-like particle

Electroweak symmetry breaking is very likely due to some kind of Higgs field

The hypothesis that the **space is filled with a Higgs field** since the origin of the Universe is a plausible assumption.

A new framework to understand the Universe. Cosmological models become more plausible:

- The Universe inflation after the big-bang
- Energy of a Higgs-like field as the source of all matter in the Universe



End of Lecture 4