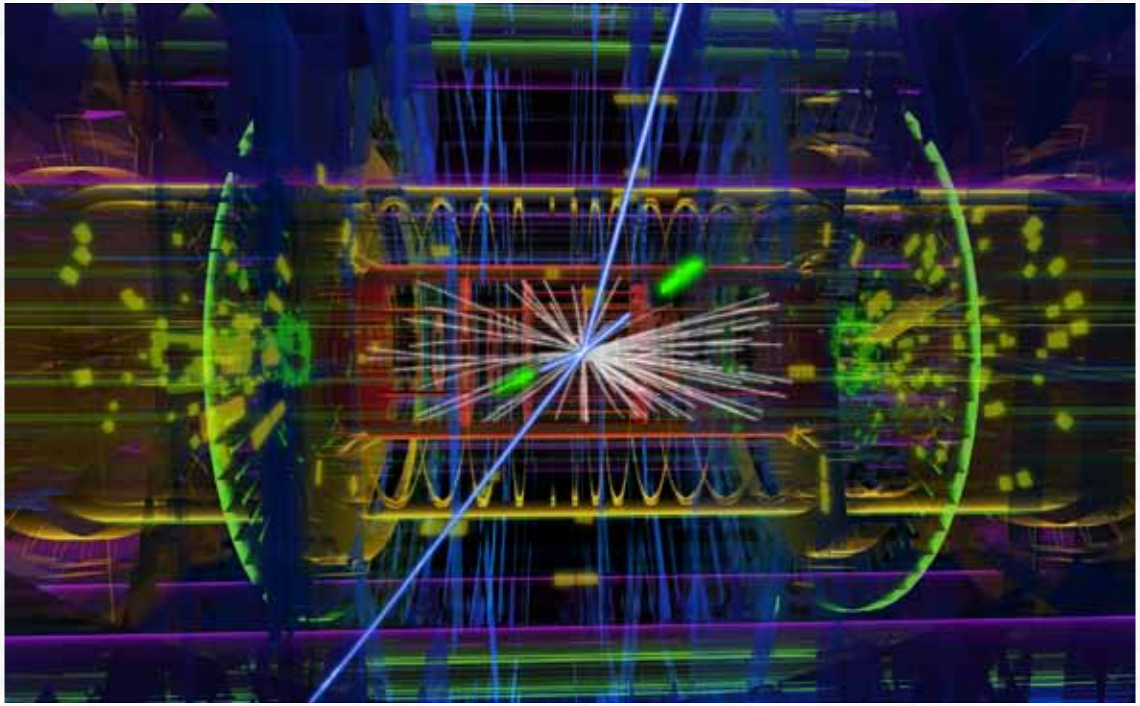
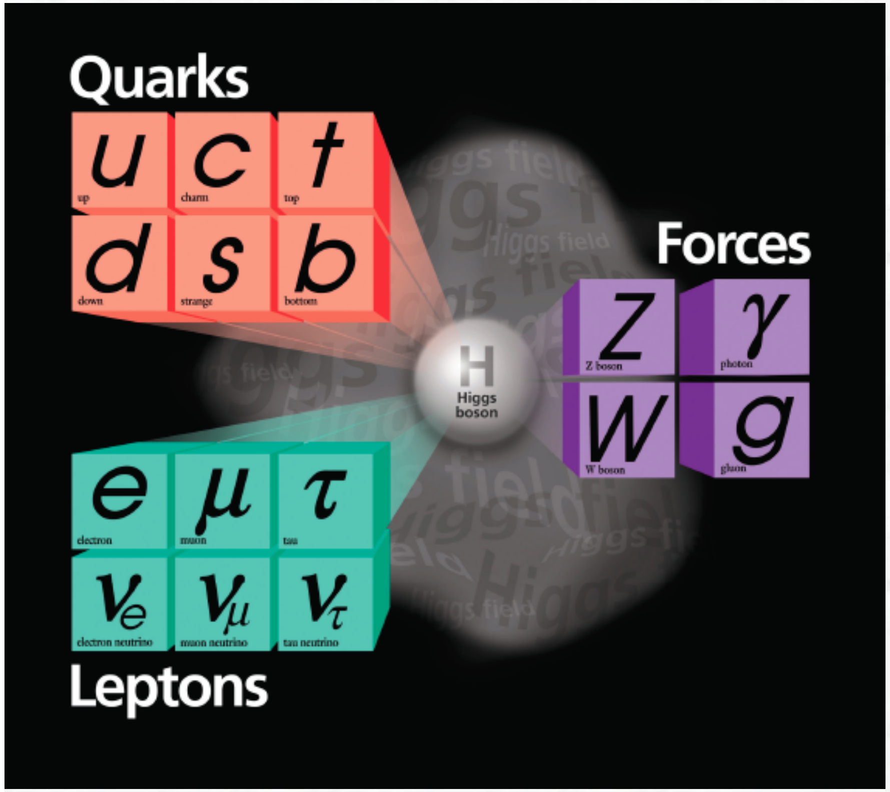
12. Search for the Higgs Boson at the LHC

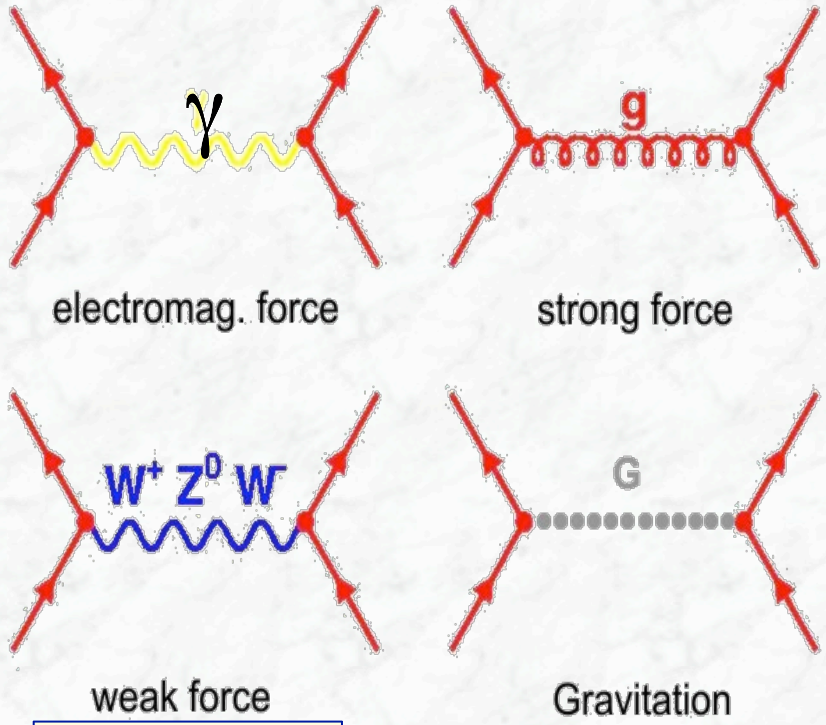
or:

Discovery of the Higgs Boson at the LHC



The Standard Model of Particle Physics





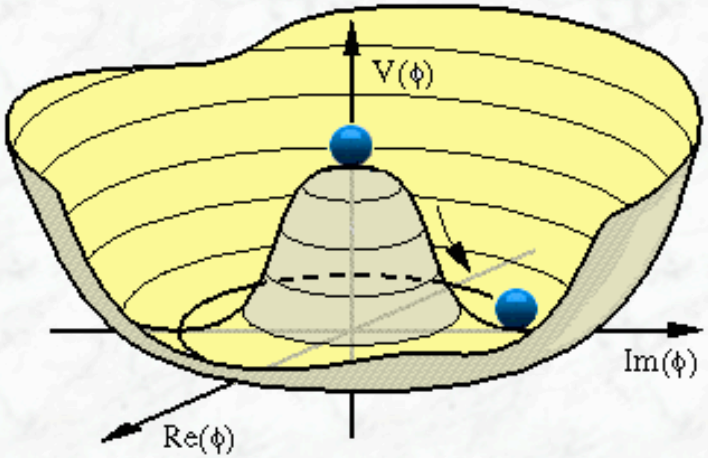
$m_W \approx 80.4$ GeV
$m_Z \approx 91.2$ GeV

(i) Constituents of matter: quarks and leptons

(ii) Four fundamental forces
(described by quantum field theories, (except gravitation), → massless particles)

(iii) The Higgs field (problem of mass)

The Higgs Mechanism



Complex scalar (spin 0) field ϕ with potential:

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

For $\lambda > 0$, $\mu^2 < 0$:
"Spontaneous Symmetry Breaking"

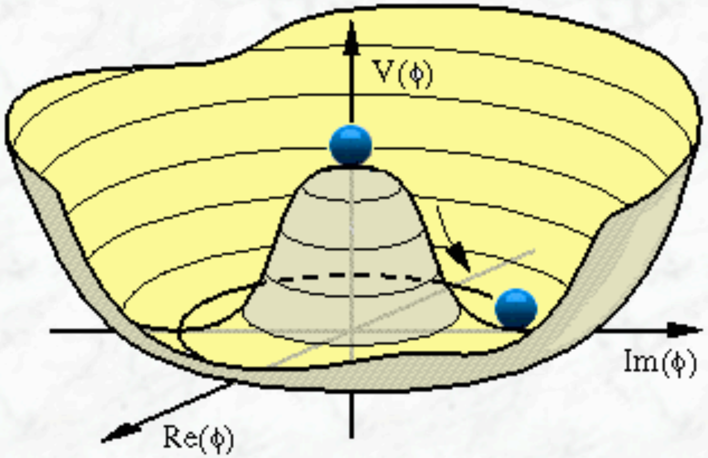
→ Omnipresent Higgs field: vacuum expectation value $v \approx 246$ GeV

→ Higgs Boson (mass not predicted, except $m_H <\sim 1000$ GeV)

→ Particles acquire mass through coupling to the Higgs field
(additional free parameters for the fermions)

F. Englert and R. Brout. Phys Rev. Lett. 13: 321-323 (1964)
P.W. Higgs, Phys. Rev. Lett. 13: 508-509 (1964)
G.S. Guralnik, C.R. Hagen, and T.W.B. Kibble. Phys. Rev. Lett. 13: 585-587 (1964)

The Higgs Mechanism

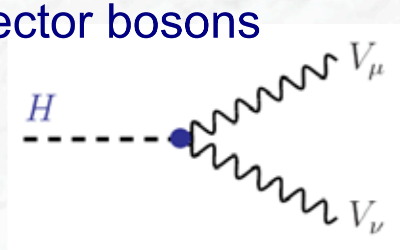


Complex scalar (spin 0) field ϕ with potential:

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

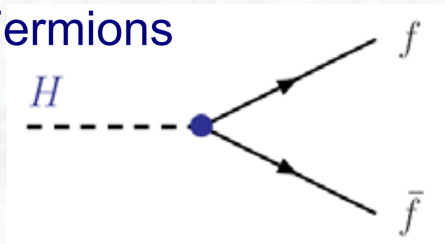
For $\lambda > 0$, $\mu^2 < 0$:
"Spontaneous Symmetry Breaking"

Vector bosons



$$g_{HVV} = 2M_V^2/v = 2(\sqrt{2}G_\mu)^{1/2} M_V^2$$

Fermions



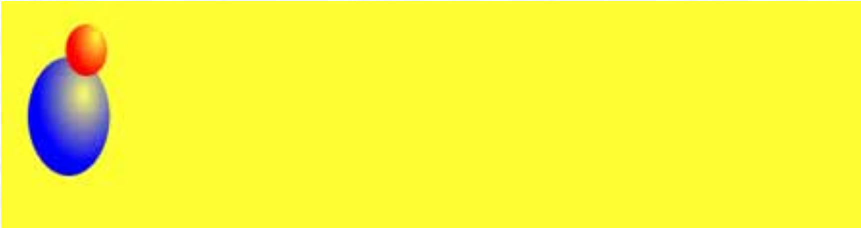
$$g_{Hff} = m_f/v = (\sqrt{2}G_\mu)^{1/2} m_f$$

- Coupling proportional to mass
- Higgs bosons decay preferentially into the heaviest available particles

Principle of mass generation

Empty vacuum:

All particles are massless,
move with the speed of light

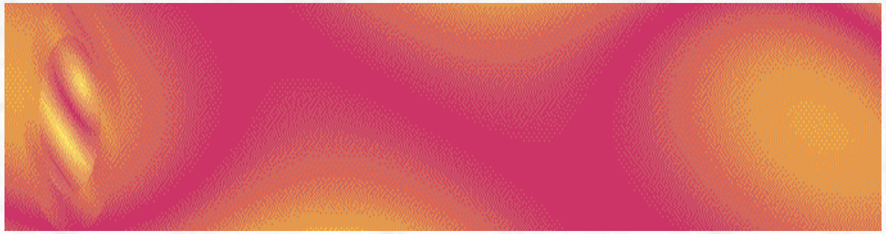


Higgs “background” field:

Particles interact with the Higgs field, v<c,
interpreted as mass,
mass depends on the interaction strength

Higgs particle:

Excitation of the field



Why do we need the Higgs field?

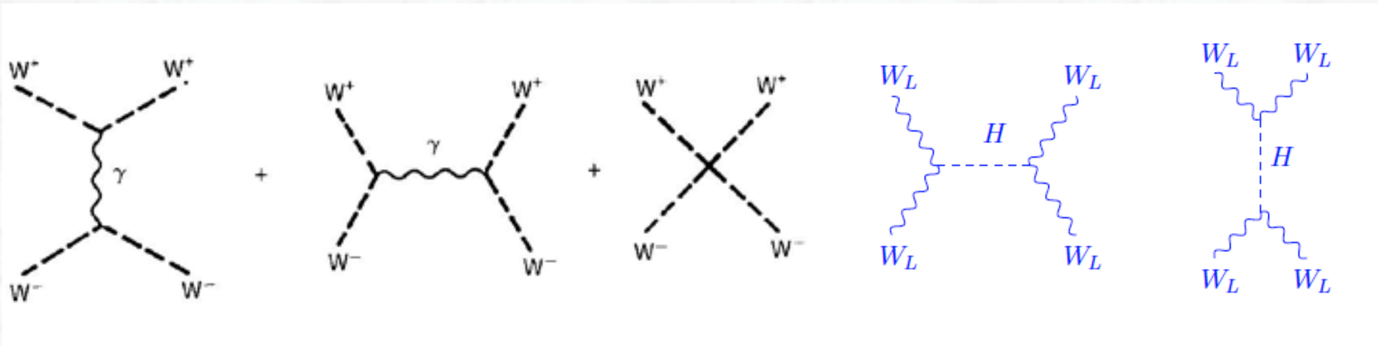
The Higgs field enters the Standard Model to solve two fundamental problems:

- Masses of the vector bosons W and Z and fermions

Experimental results: $M_W = 80.385 \pm 0.015$ GeV / c^2
$M_Z = 91.1875 \pm 0.0021$ GeV / c^2

Standard Model gauge theories require massless gauge fields

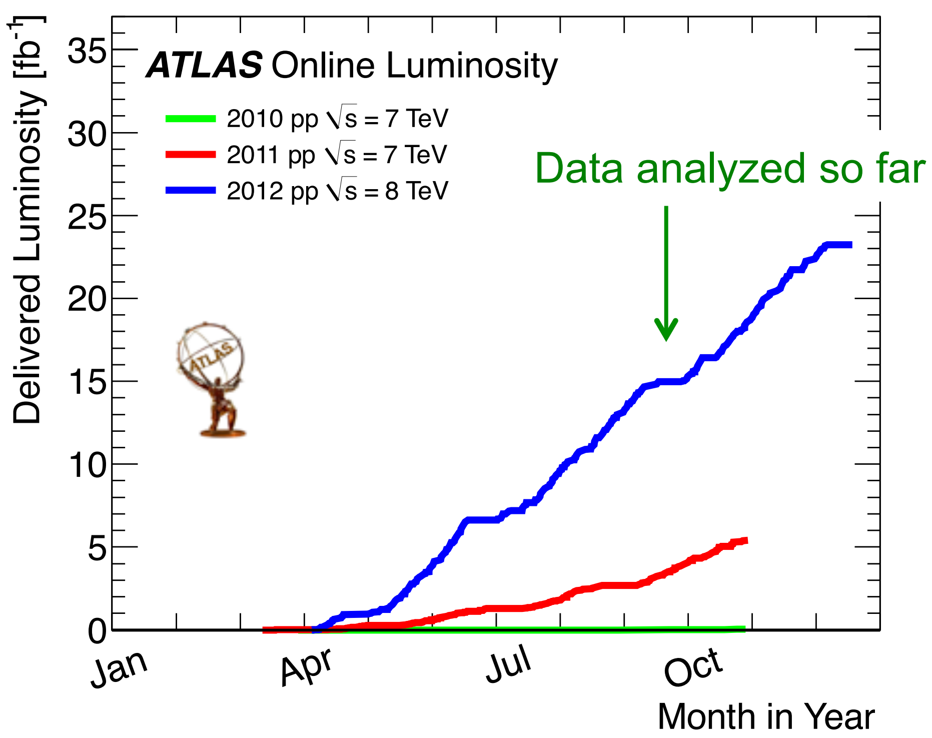
- Divergences in the theory (scattering of W bosons)



$$-iM(W^+W^- \rightarrow W^+W^-) \sim \frac{s}{M_W^2} \quad \text{for} \quad s \rightarrow \infty$$ (no Higgs boson)

$$-iM(W^+W^- \rightarrow W^+W^-) \sim m_H^2 \quad \text{for} \quad s \rightarrow \infty$$ (with Higgs boson)

Data taking in 2011/ 2012



Until end 2012:

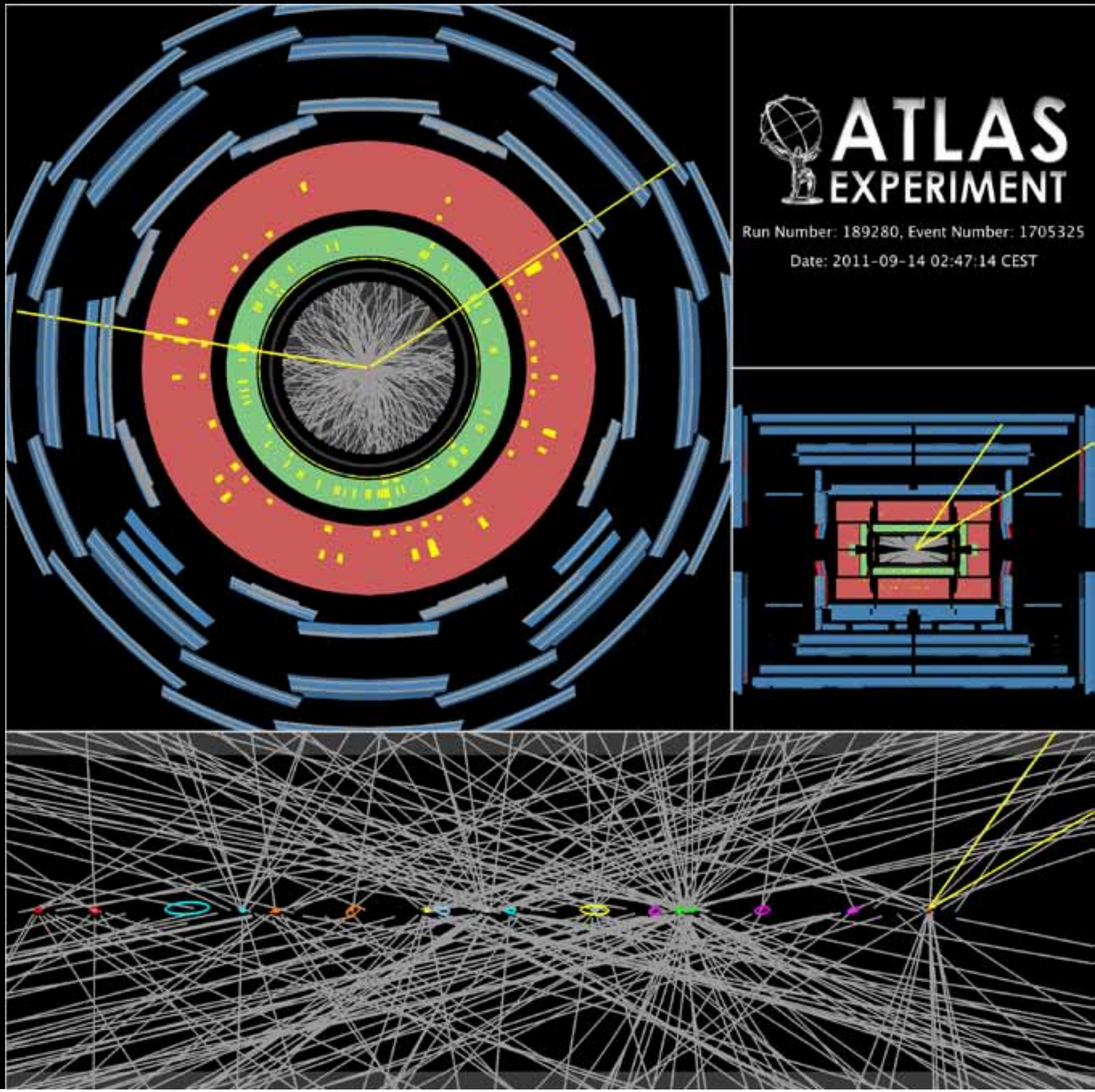
> 10^{15} pp collisions

~10^{10} pp collisions recorded

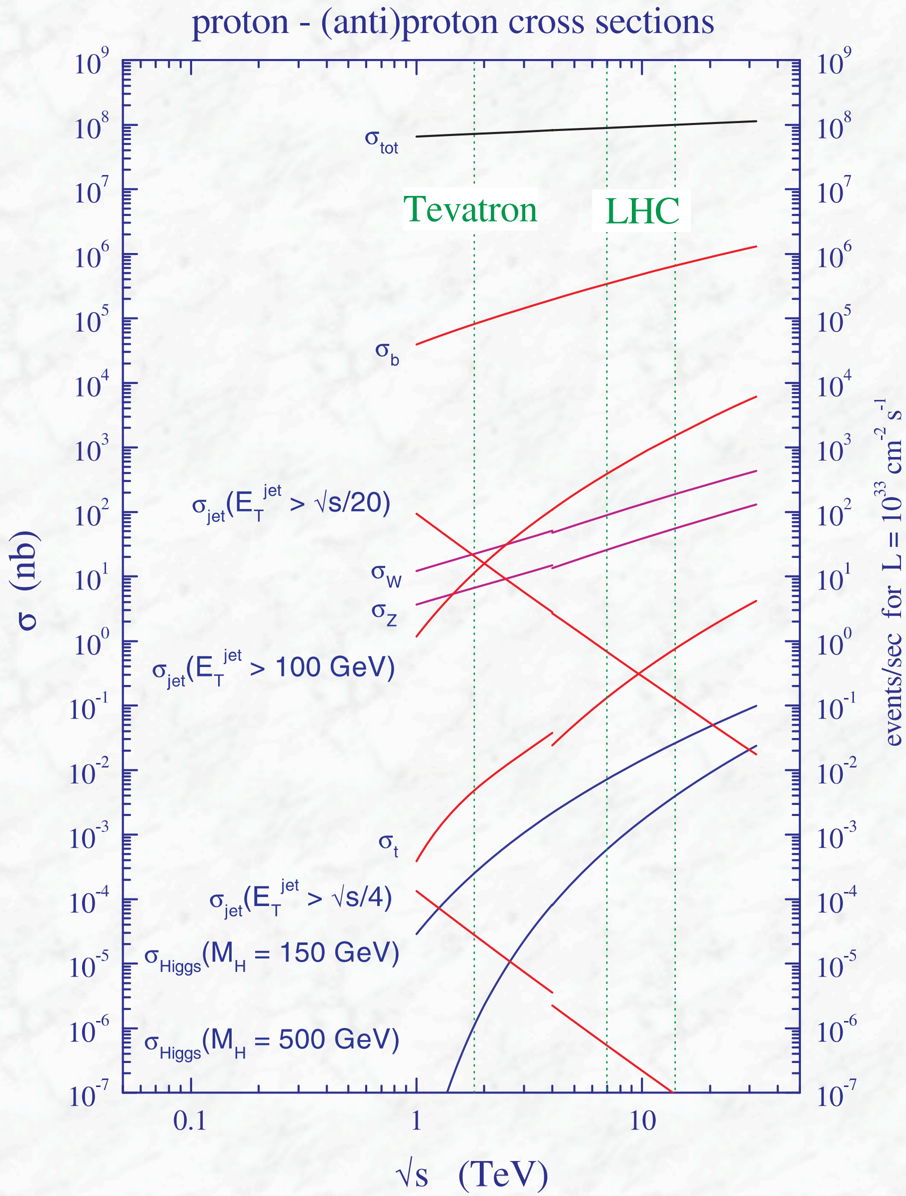
25 ·10^{6} Z → μμ decays produced

- Excellent LHC performance in 2011and 2012 (far beyond expectations)
- Peak luminosity seen by ATLAS: 7.7 10^{33} cm^{-2} s^{-1} (world record, 2012)
- Excellent performance of the experiments in recording the data (efficiency ~93.5%, working detector channels >99%, speed of data analysis,…)

$Z \rightarrow \mu^+ \mu^-$ with 20 superimposed events



Production Rates and Cross Sections at the LHC



$$N = \sigma \cdot L$$

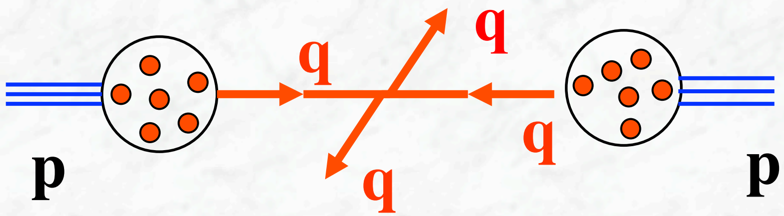
$$\left[\frac{1}{s}\right] = \left[cm^2 \cdot \frac{1}{cm^2 \cdot s}\right]$$

Rates for the design luminosity:
$\sqrt{s}$ = 7 TeV, L = 10^{33} cm^{-2} s^{-1}:

- Inelastic proton-proton collisions: 10^8 / s
- bb pairs 5 10^5 / s
- tt pairs 1 / s
- W → e ν 15 / s
- Z → e e 1.5 / s
- **Higgs (150 GeV) 0.02 / s**
- **Gluino, Squarks (1 TeV) 0.003 / s**

Proton–proton collisions

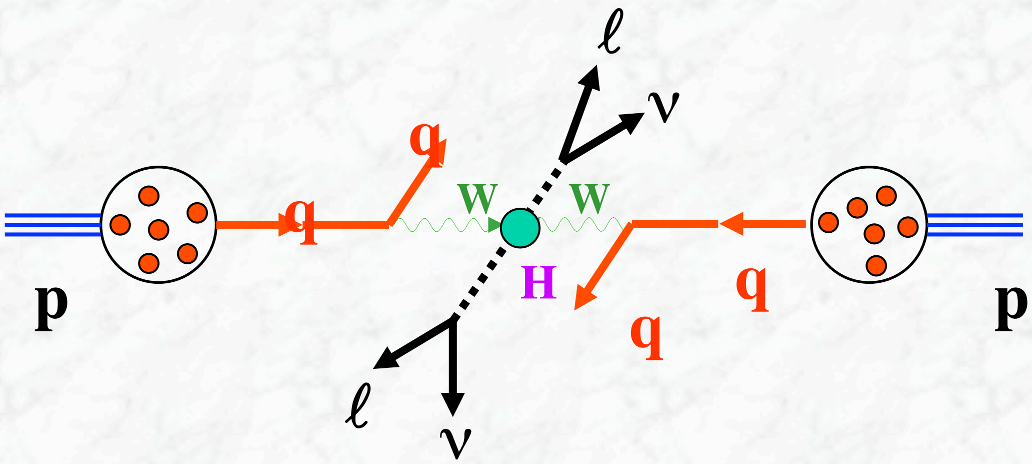
Scattering of the constituents of the proton, i.e. quarks and gluons:



No leptons in the initial and final state

Leptons with large transverse momentum: ⇒ interesting physics !

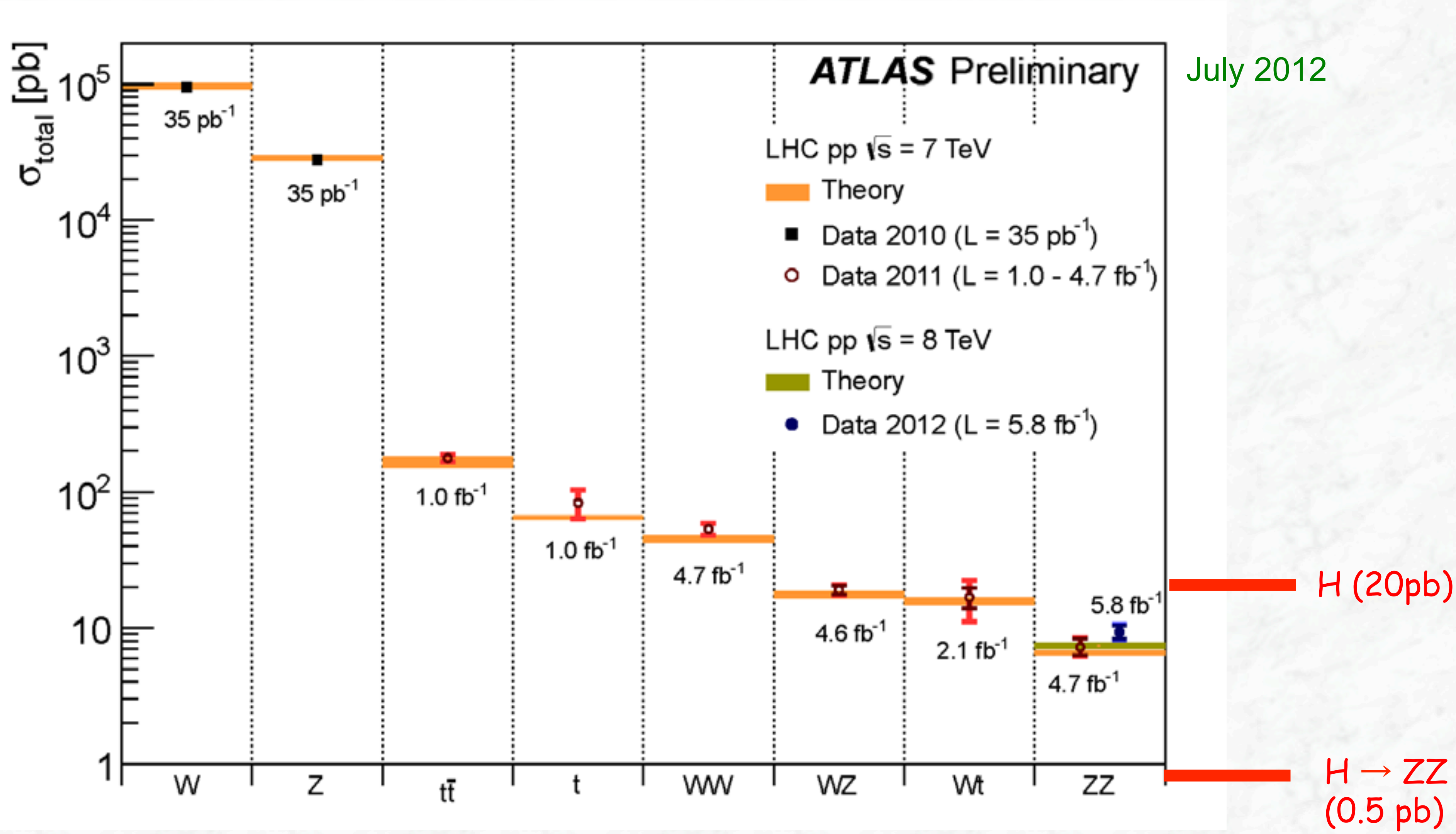
Example: Higgs boson production and decay



Important signatures:

- Leptons and photons
- Missing transverse energy

The Standard Model at the LHC



4th July 2012

Higgs boson-like particle discovery claimed at LHC

COMMENTS (1665)

By Paul Rincon
Science editor, BBC News website, Geneva

The moment when Cern director Rolf Heuer confirmed the Higgs results

Cern scientists reporting from the Large Hadron Collider (LHC) have claimed the discovery of a new particle consistent with the Higgs boson.

Frankfurter Allgemeine
Wissen

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Aktuell > Wissen > Physik & Chemie

Erfolg bei Suche nach Higgs-Teilchen

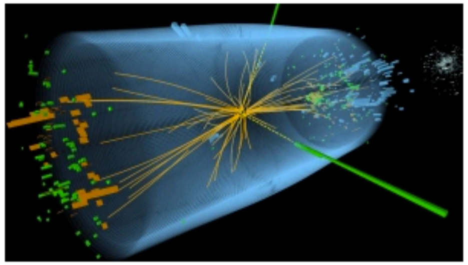
„Eine wissenschaftliche Sensation"

04.07.2012 · Wissenschaftler im Teilchenforschungszentrum Cern in Genf glauben, das jahrzehntelang gesuchte Higgs-Teilchen gefunden zu haben. Monatelang war im weltgrößten Teilchenbeschleuniger danach gefahndet worden – jetzt liegen die bahnbrechenden Ergebnisse vor.

Von MANFRED LINDINGER

Artikel Bilder (3) Lesermeinungen (190)

Selten waren die Erwartungen am europäischen Forschungszentrums Cern bei Genf, dem Mekka der Teilchenphysik, so groß wie an diesem Mittwoch morgen. Alle drängten in den großen Hörsaal und wollten dem Seminar beiwohnen, zu dem der Generaldirektor des Cern, Rolf-Dieter Heuer, eingeladen hatte. Im Hörsaal saßen viele Veteranen des Cern,



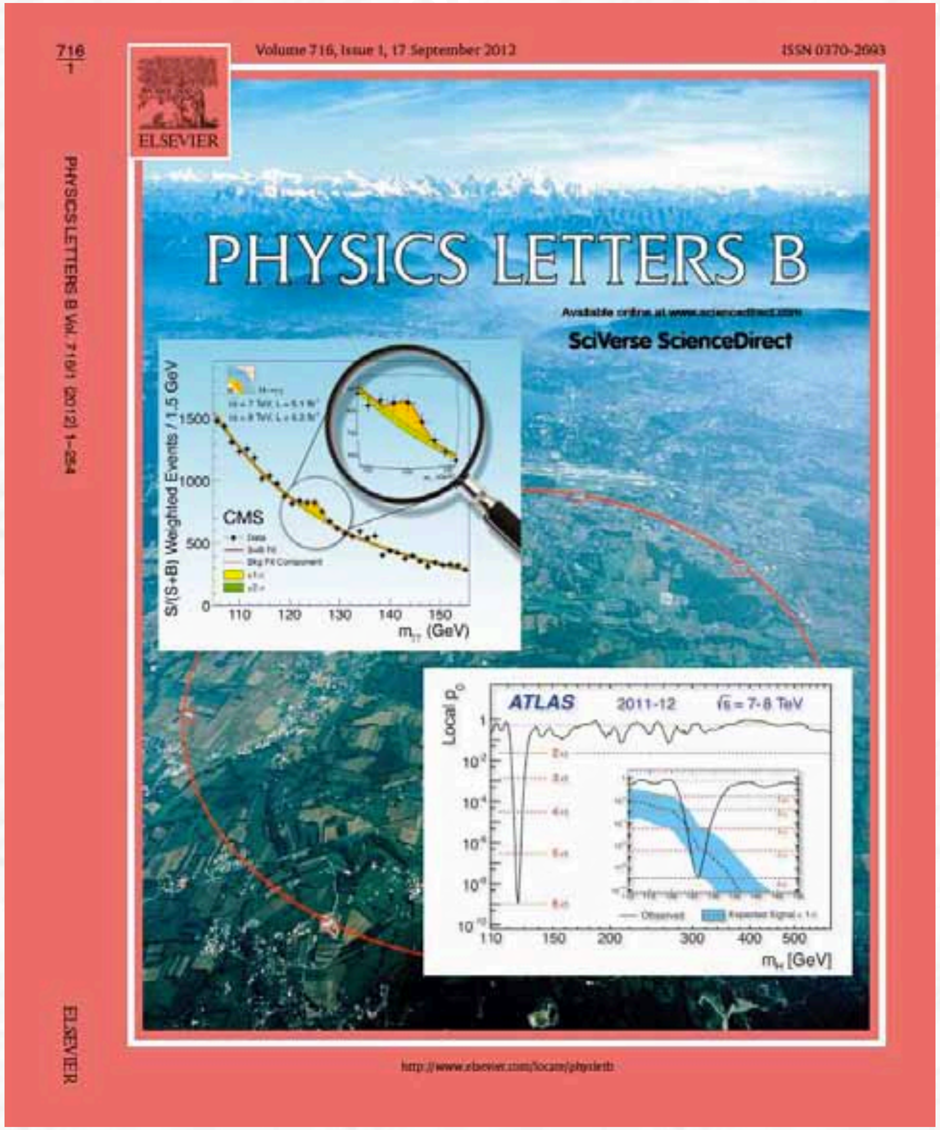
© DAPD

Die Grafik einer Proton-Proton-Kollision im Experiment stellt die zu erwarteten Charakteristiken zweier hochenergetischer Photonen beim Zerfall des

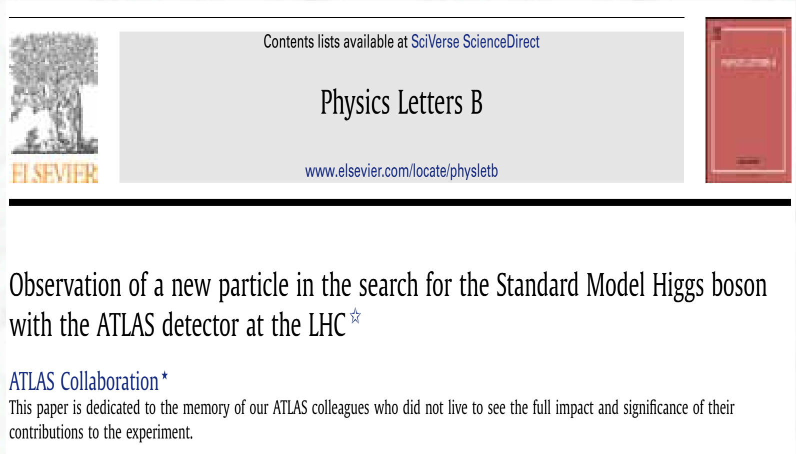
CERN auditorium
4th July 2012

…. and the evening before

Observation of a New Particle



Submission to PLB on 31. July 2012



Contents lists available at SciVerse ScienceDirect

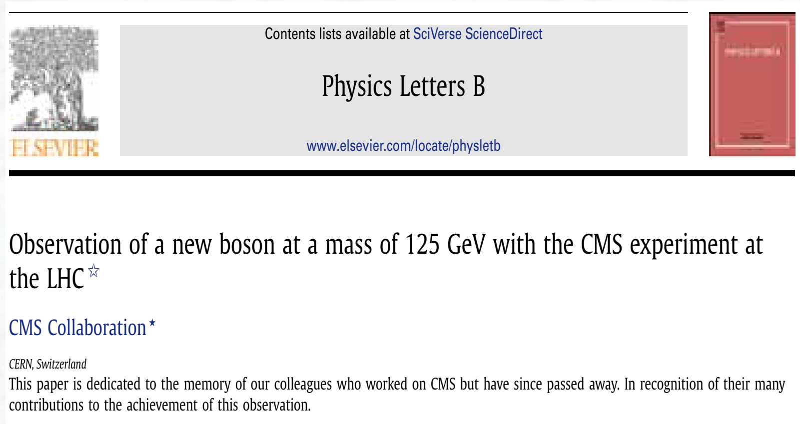
Physics Letters B

www.elsevier.com/locate/physletb

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

ATLAS Collaboration *

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



Contents lists available at SciVerse ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

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

CMS Collaboration *

CERN, Switzerland

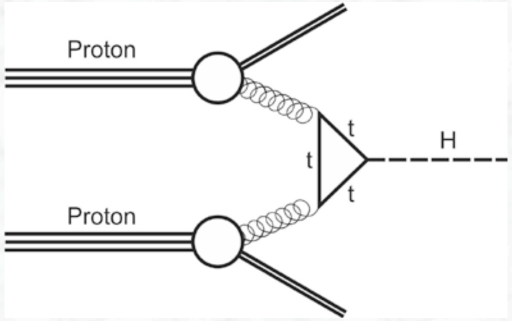
This paper is dedicated to the memory of our colleagues who worked on CMS but have since passed away. In recognition of their many contributions to the achievement of this observation.

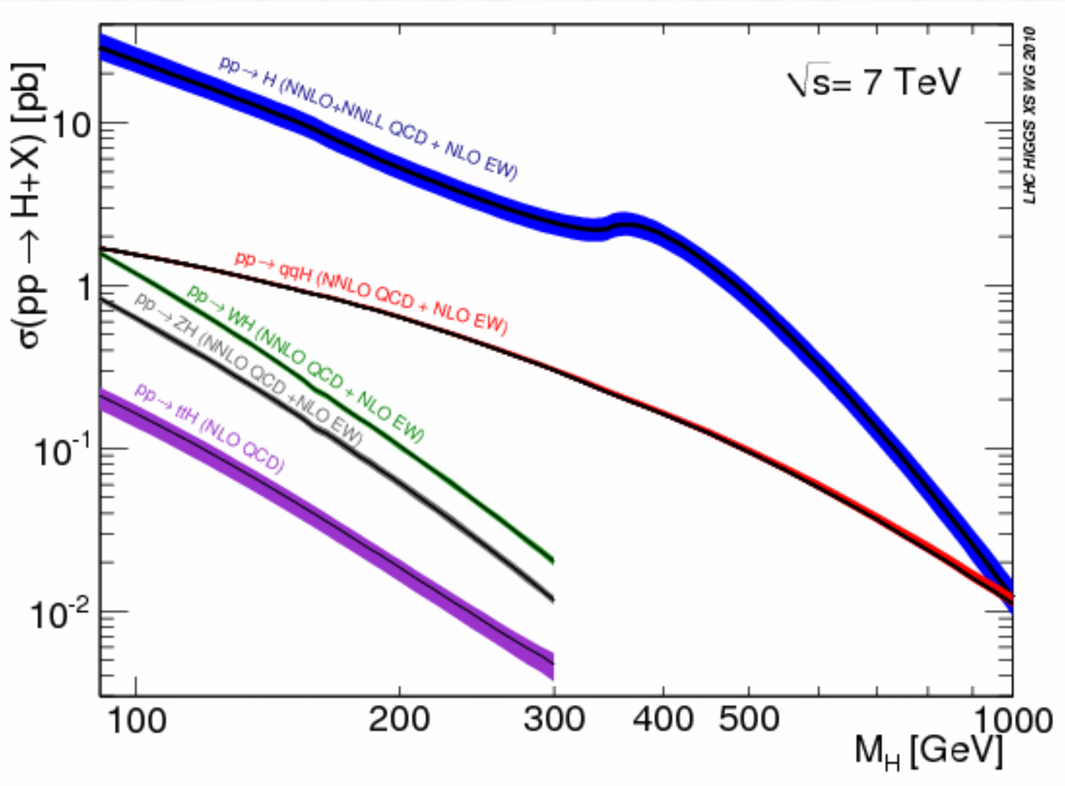
Decay observed into particles with same spin and electric charge sum = 0

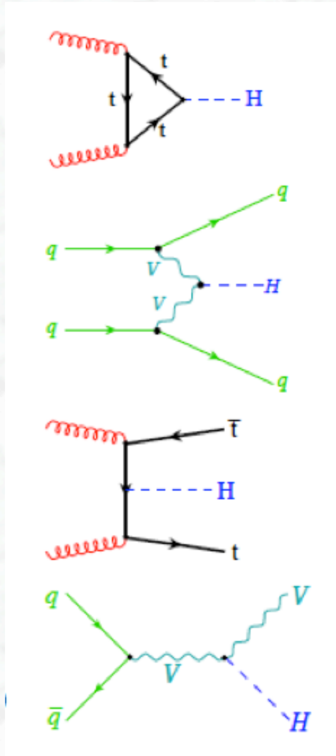
→ a new neutral boson has been discovered


Science
21 December 2012 | $10
BREAKTHROUGH
of the YEAR
The HIGGS
BOSON
AAAS

Higgs Boson Production







Gluon Fusion

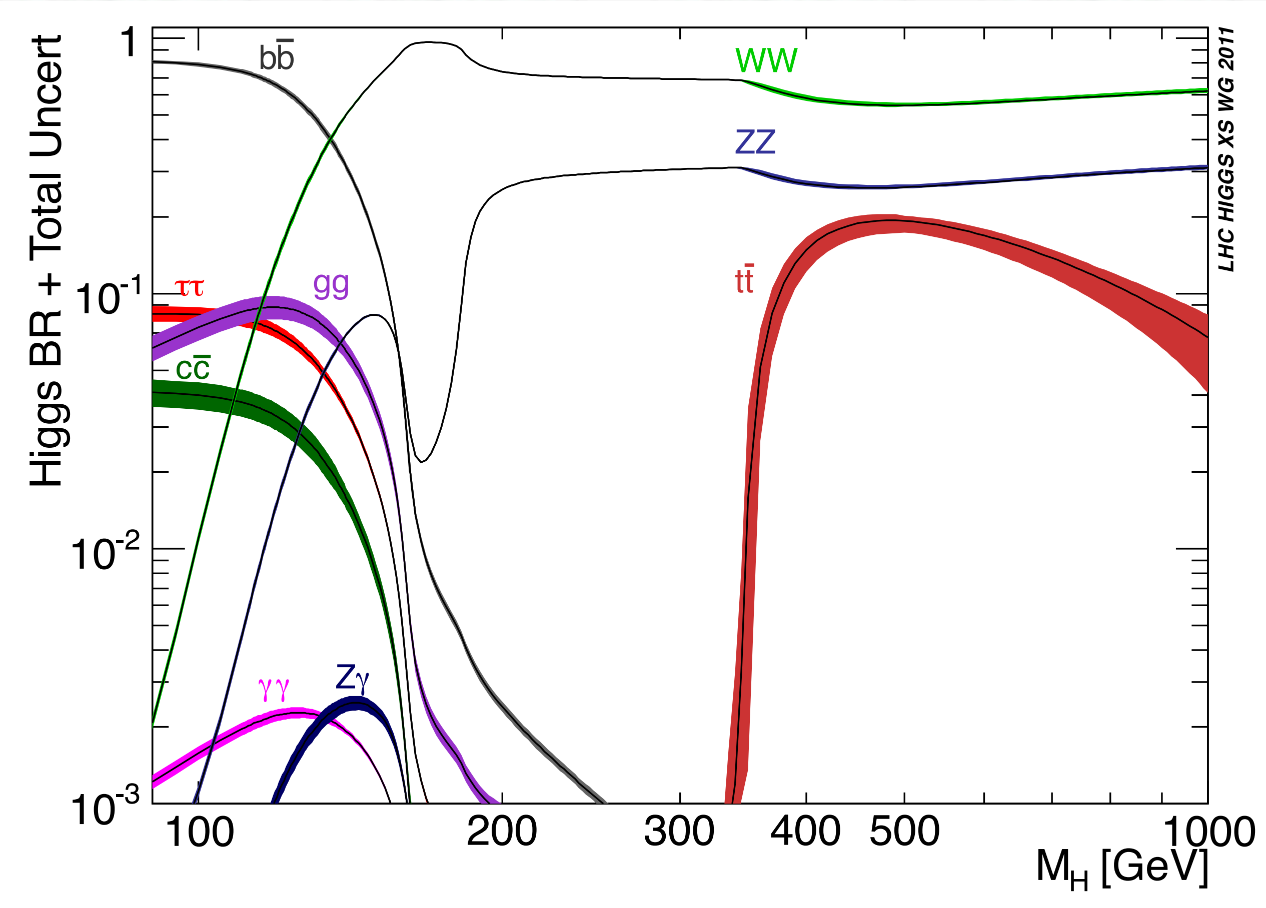
Vector boson fusion

tt associated production

WH/ZH associated production

*) LHC Higgs cross-section working group

Useful Higgs Boson Decays at a Hadron Collider

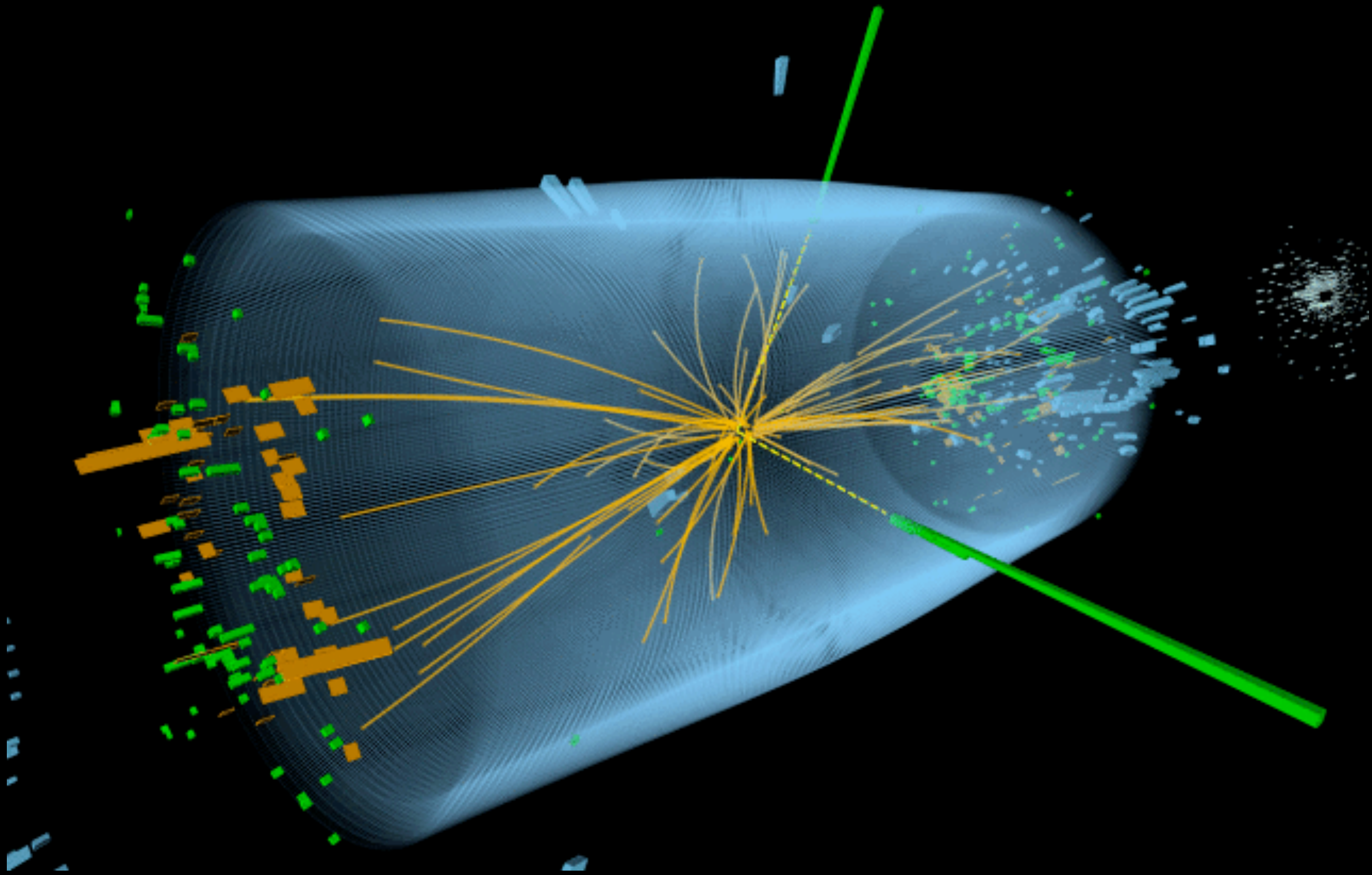


Important channels: $H \rightarrow WW \rightarrow \ell\nu\ \ell\nu$

$H \rightarrow \gamma\gamma$

$H \rightarrow ZZ \rightarrow \ell^+\ell^-\ \ell^+\ell^-$

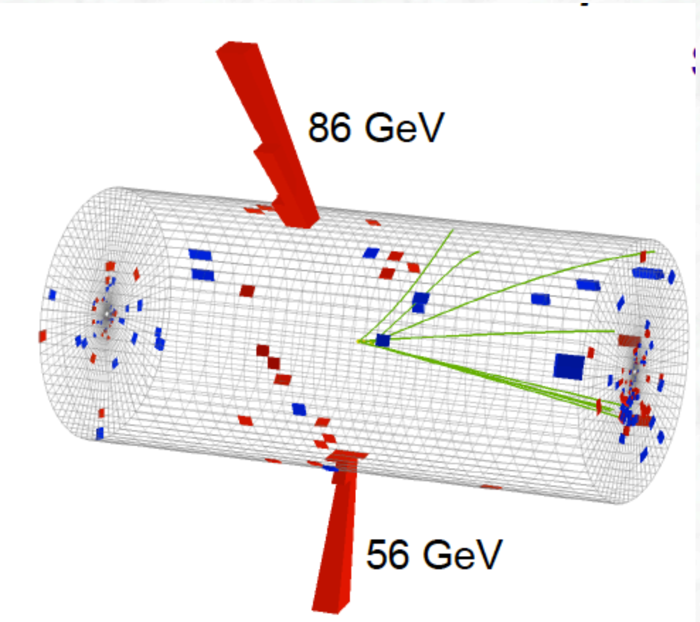
Evidence for the Higgs particle



Expected number of decays in data:
m_H = 125 GeV

~ 950 H → $\gamma\gamma$
~ 60 H → ZZ → 4 ℓ
~ 9000 H → WW → $\ell\nu$ $\ell\nu$

Search for the H → γγ decay

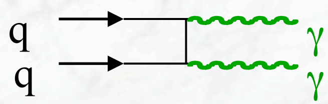


- 2 photons (isolated) with large transverse momenta

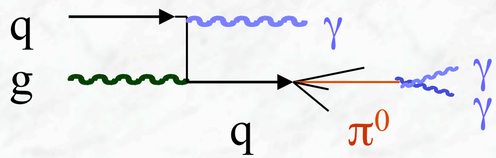
- Mass of the Higgs boson can be reconstructed $m_{\gamma\gamma}$

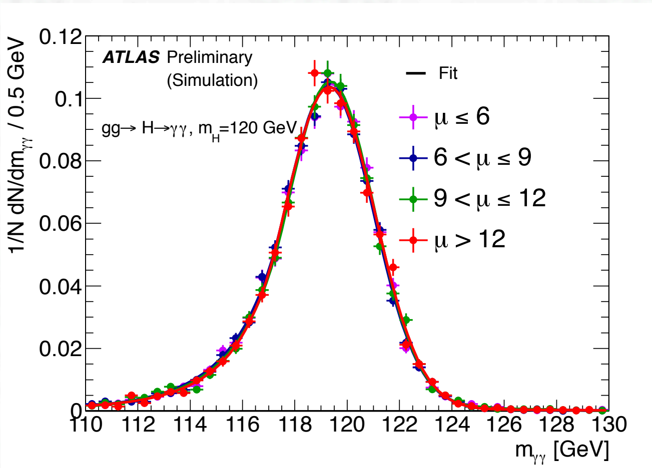
  Both experiments have a good mass resolution
  ATLAS: ~1.7 GeV/c² for m_H ~120 GeV/c²

- Challenges:
  - signal-to-background ratio
    (small, but smooth irreducible γγ background)

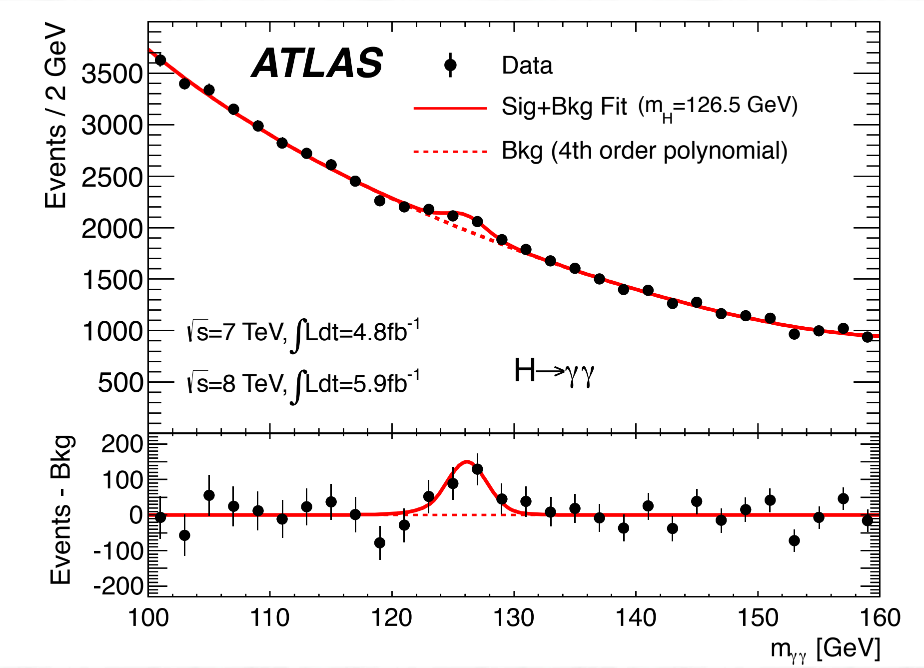


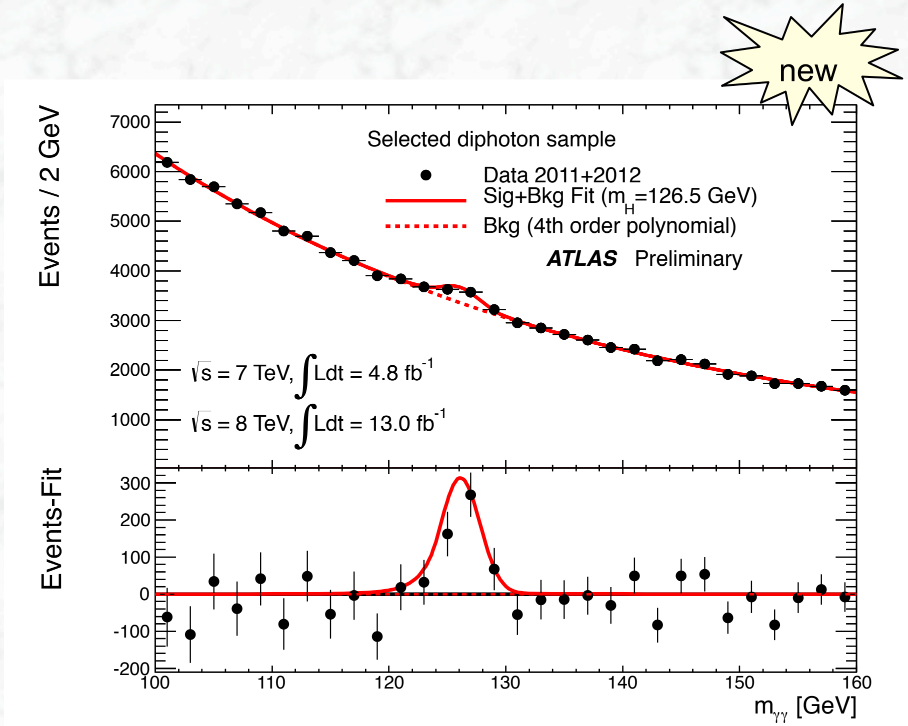
  - reducible backgrounds from γj and jj
    (several orders of magnitude larger than irreducible one)





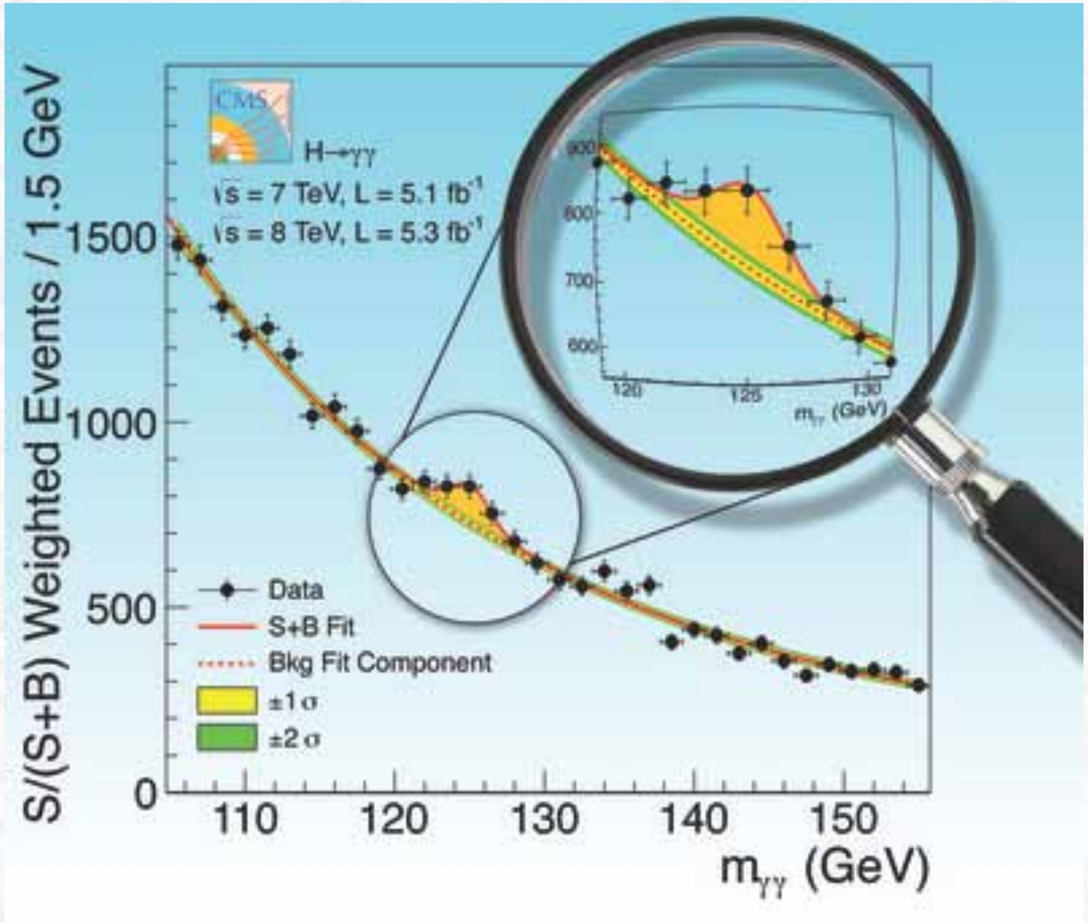
Result of the ATLAS search for H → γγ



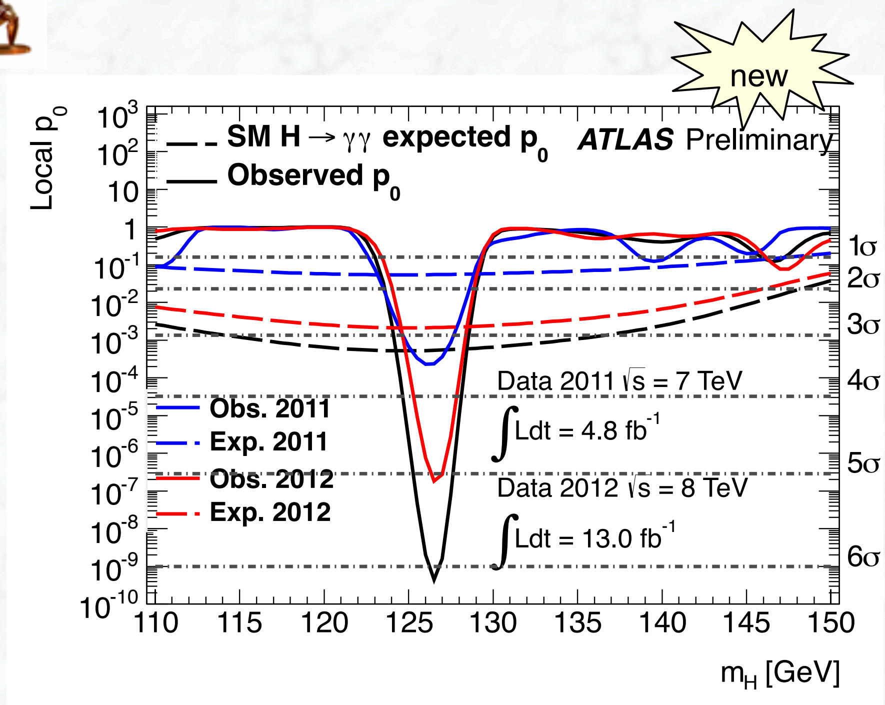


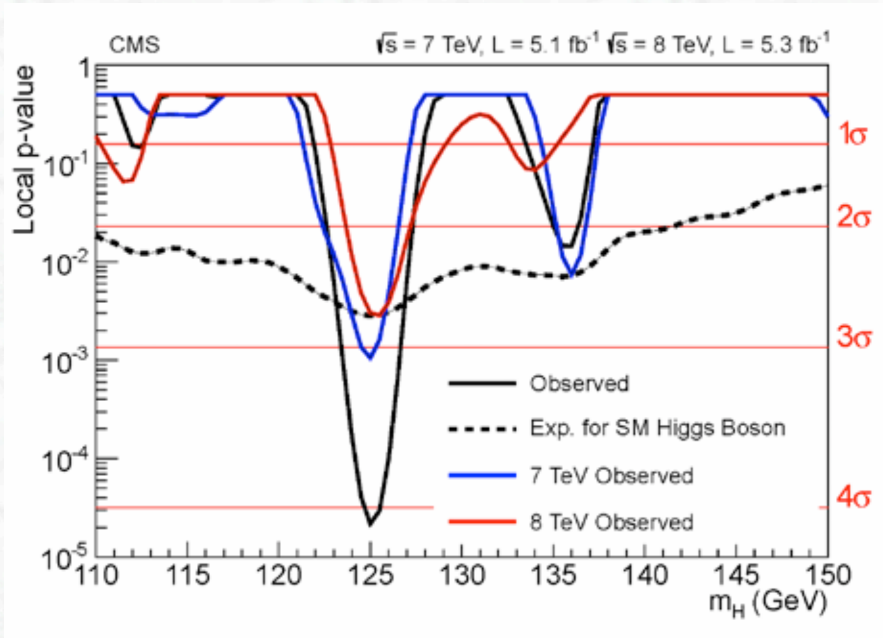
- Background model: exponential / polynomial function, determined directly from data (different models have been used → systematics)

What does the competition see ?



Search for H → γγ: compatibility with background hypothesis





- Maximum deviation from background-only expectation observed for:

	ATLAS			CMS	
	m_H~126 GeV/c²			m_H ~125 GeV/c²	
- local p_0-value:	2 •10⁻⁶	4.5σ	(July 2012)	2.5 •10⁻⁵	4.1σ
	4.4 •10⁻¹⁰	6.1σ	(Dec. 2012)		

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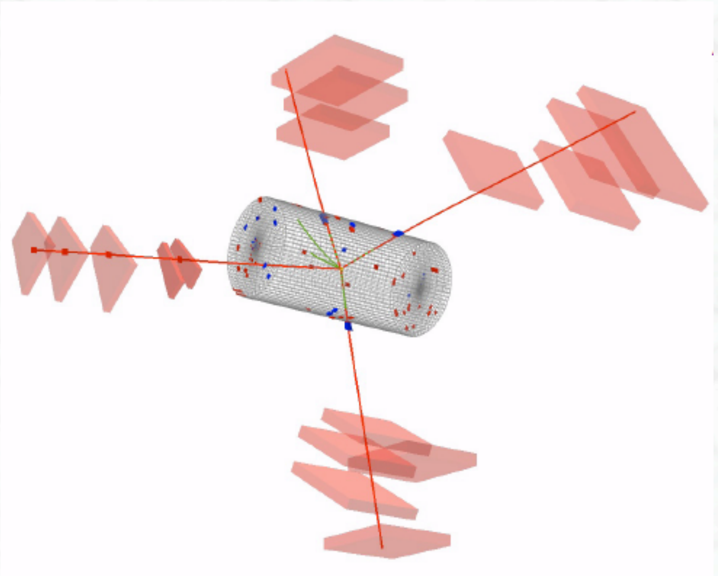
* p_0: consistency of the data with the background-only hypothesis

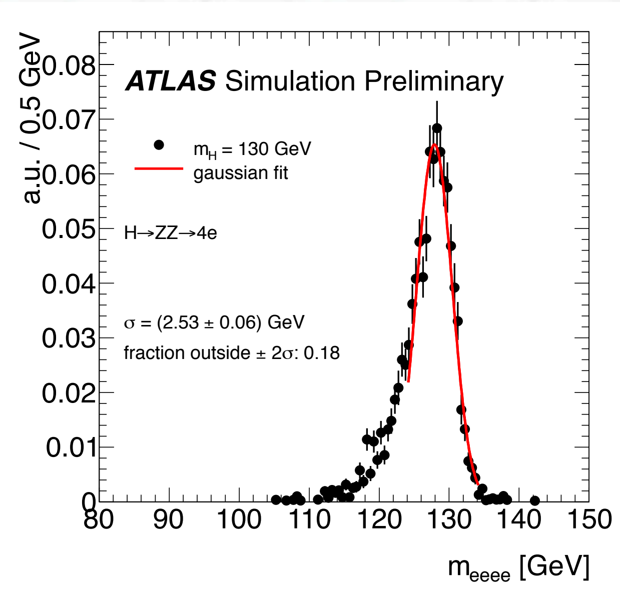
Search for the H → ZZ$^{(*)}$ → ℓ⁺ℓ⁻ ℓ⁺ℓ⁻ decay



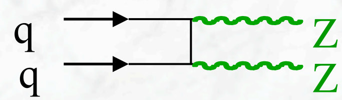
- The "golden mode"
  4 leptons (isolated) with large transverse momenta

- Mass of the Higgs boson can be reconstructed $m_{4\ell}$

  Both experiments have a good mass resolution
  ATLAS: ~2.5 GeV/c^2 (4e) for m_H ~130 GeV/c^2
  ~2.0 GeV/c^2 (4μ) for m_H ~130 GeV/c^2



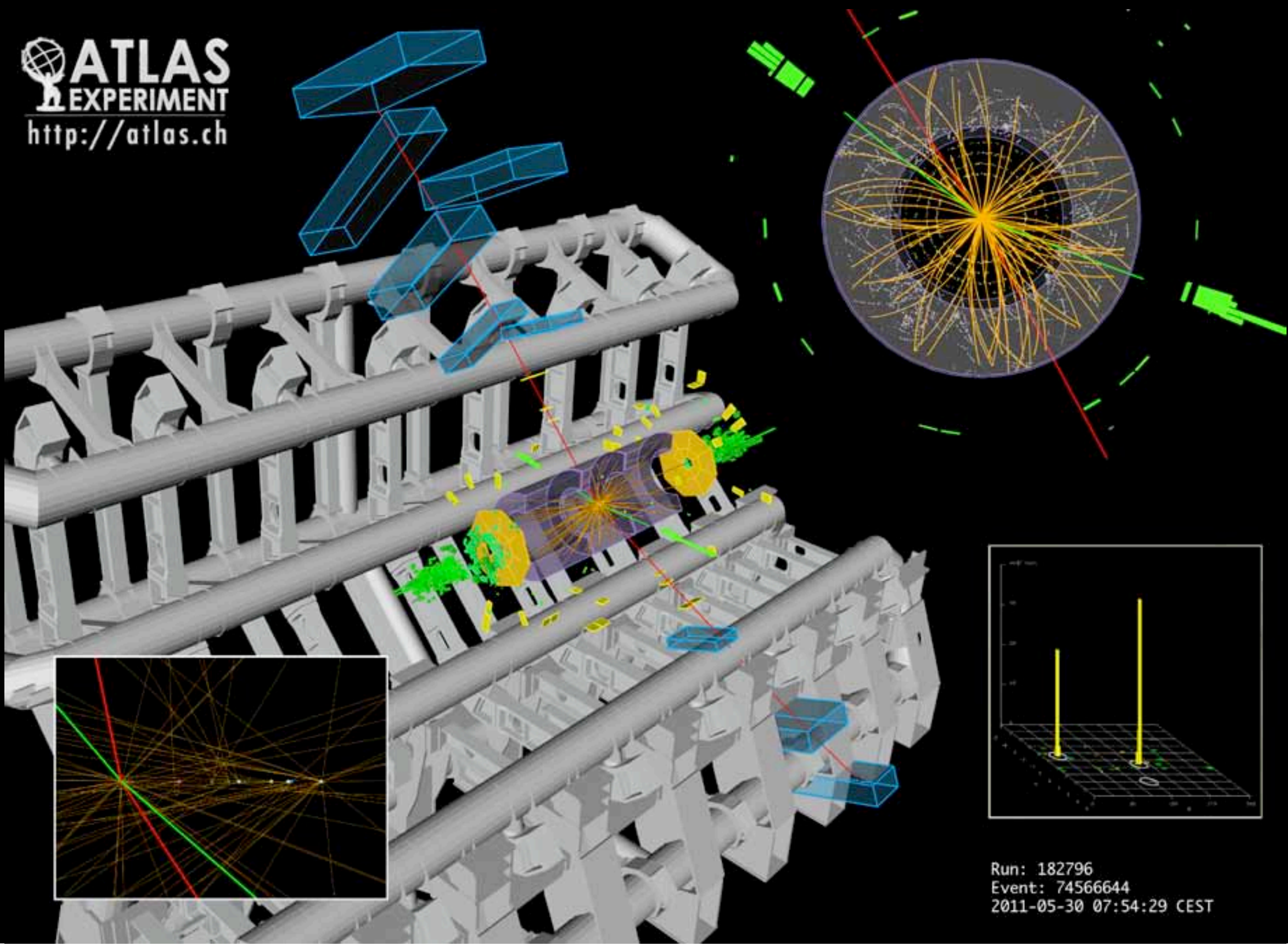
- Low signal rate, but also low background:
  - Mainly from ZZ continuum



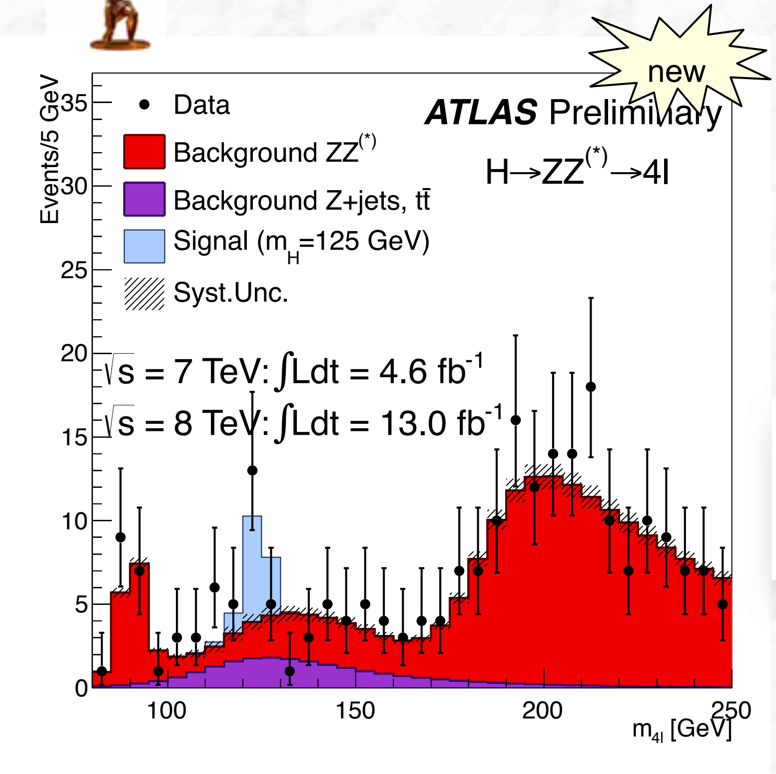
- In addition from tt and Zbb events:
  tt → Wb Wb → ℓν cℓν ℓν cℓν
  Z bb → ℓℓ cℓν cℓν
  however: leptons are non-isolated and do not originate from the primary vertex

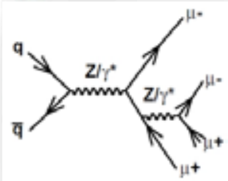
  rejection possible in excellent LHC tracking detectors

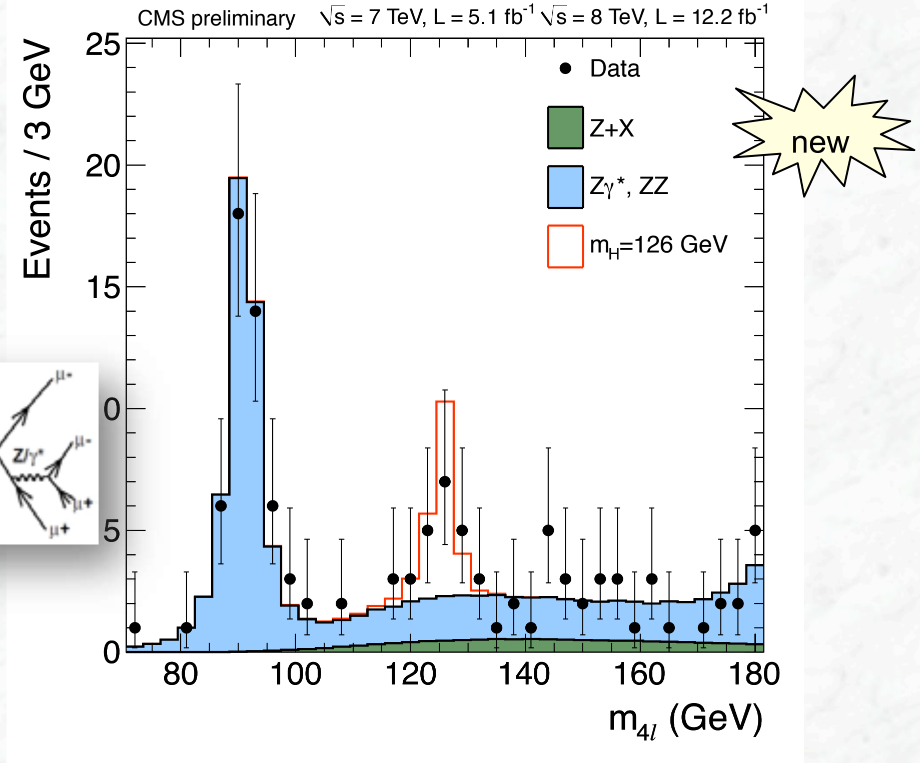
Candidate event for a $H \rightarrow ZZ \rightarrow e^+e^- \mu^+ \mu^-$ decay



4ℓ invariant mass spectra



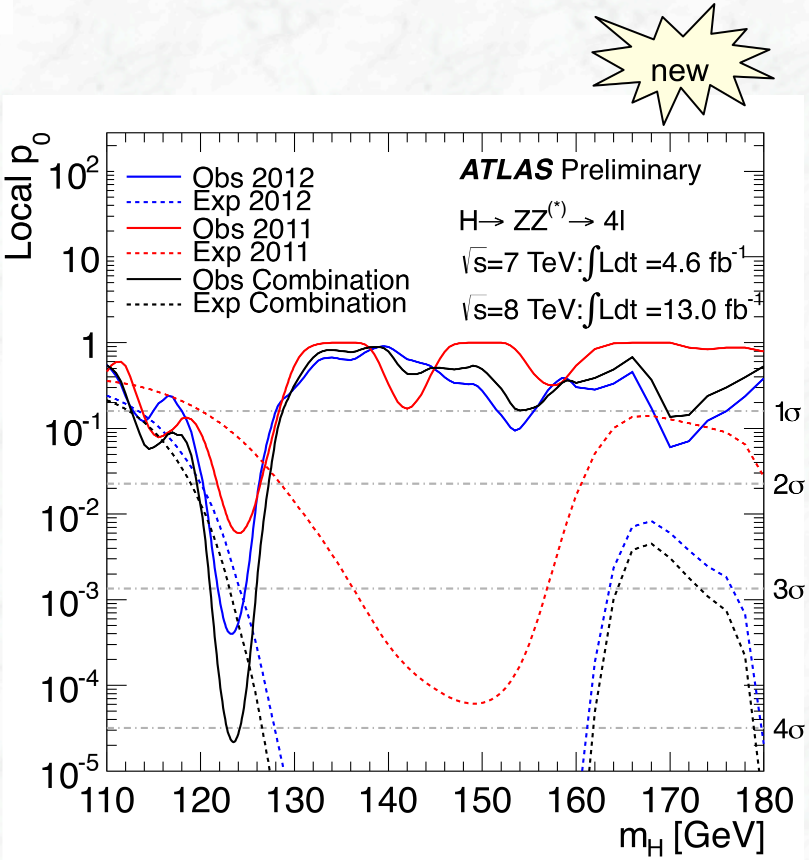


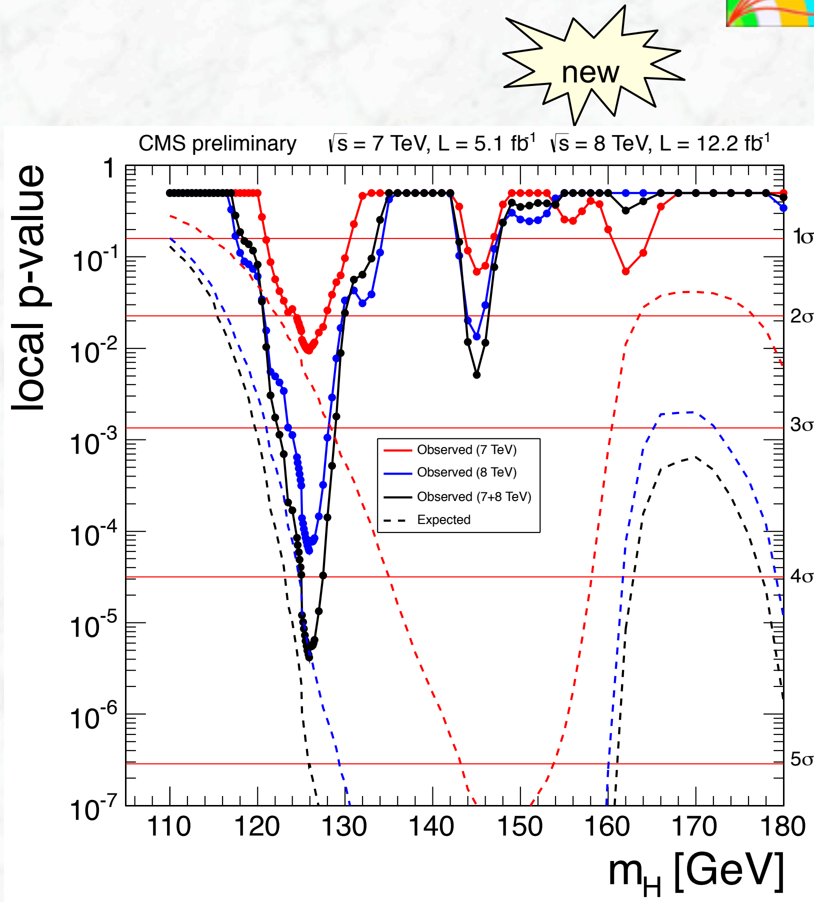


- Reducible backgrounds from Z+jets, tt giving two genuine + two fake leptons measured using background-enriched, signal-depleted control regions in data

- Irreducible background from non-resonant continuum ZZ production, normalized in high-mass region.

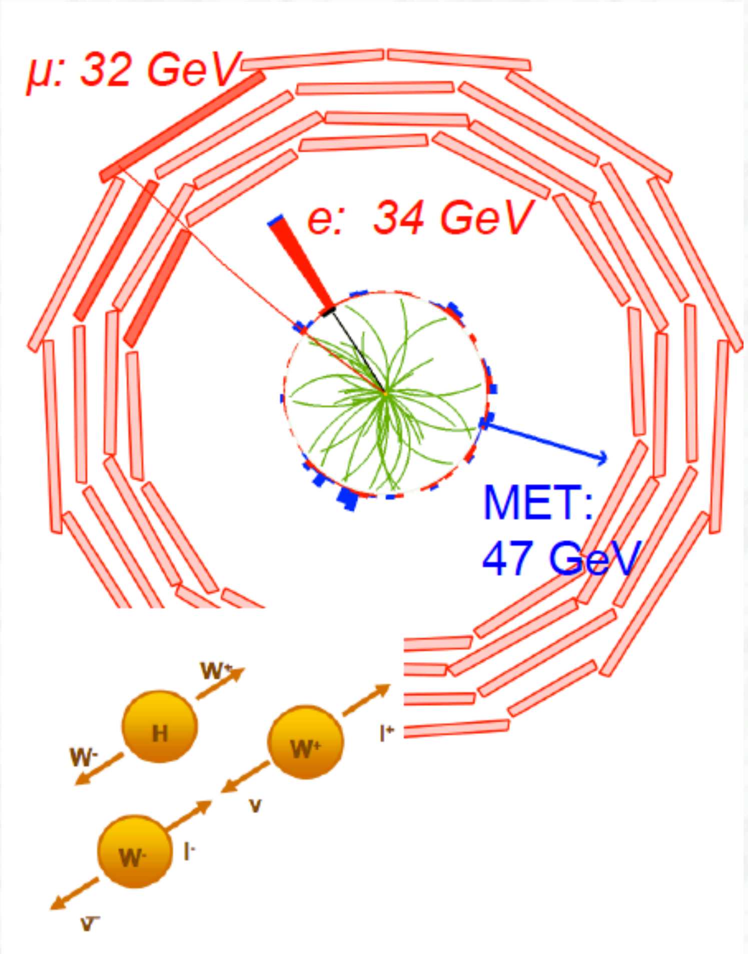
H → ZZ → 4ℓ: compatibility with background hypothesis





Significance for H → 4ℓ channel alone now above 4σ in both experiments

Search for H → WW → ℓν ℓν decay



- 2 leptons (e or μ) with large transverse momenta

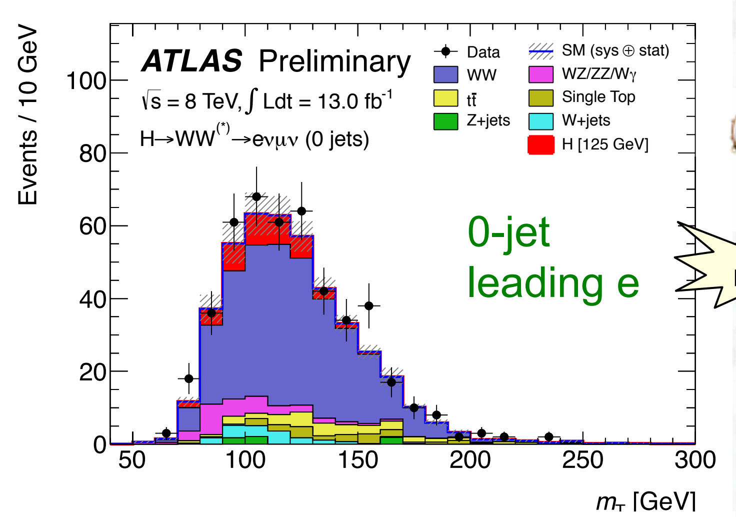
  Leptons from Higgs boson decay (spin-0 particle) are expected to have a small angular separation

- 2 neutrinos

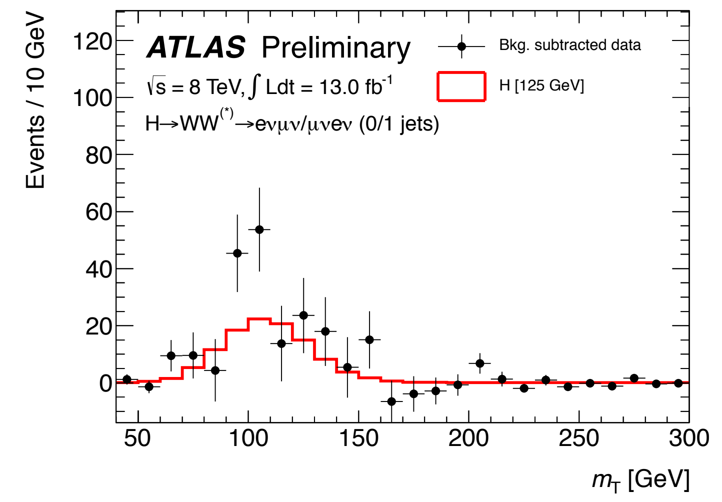
  → large missing transverse energy

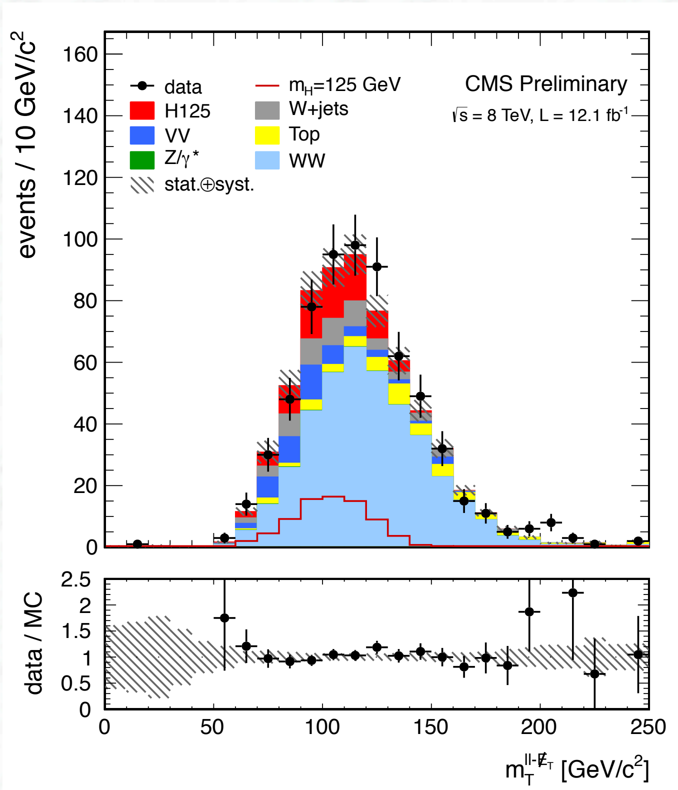
  → Higgs boson mass cannot be reconstructed, use transverse mass

Transverse mass distributions after final cuts for the H → WW → ℓν ℓν search



new



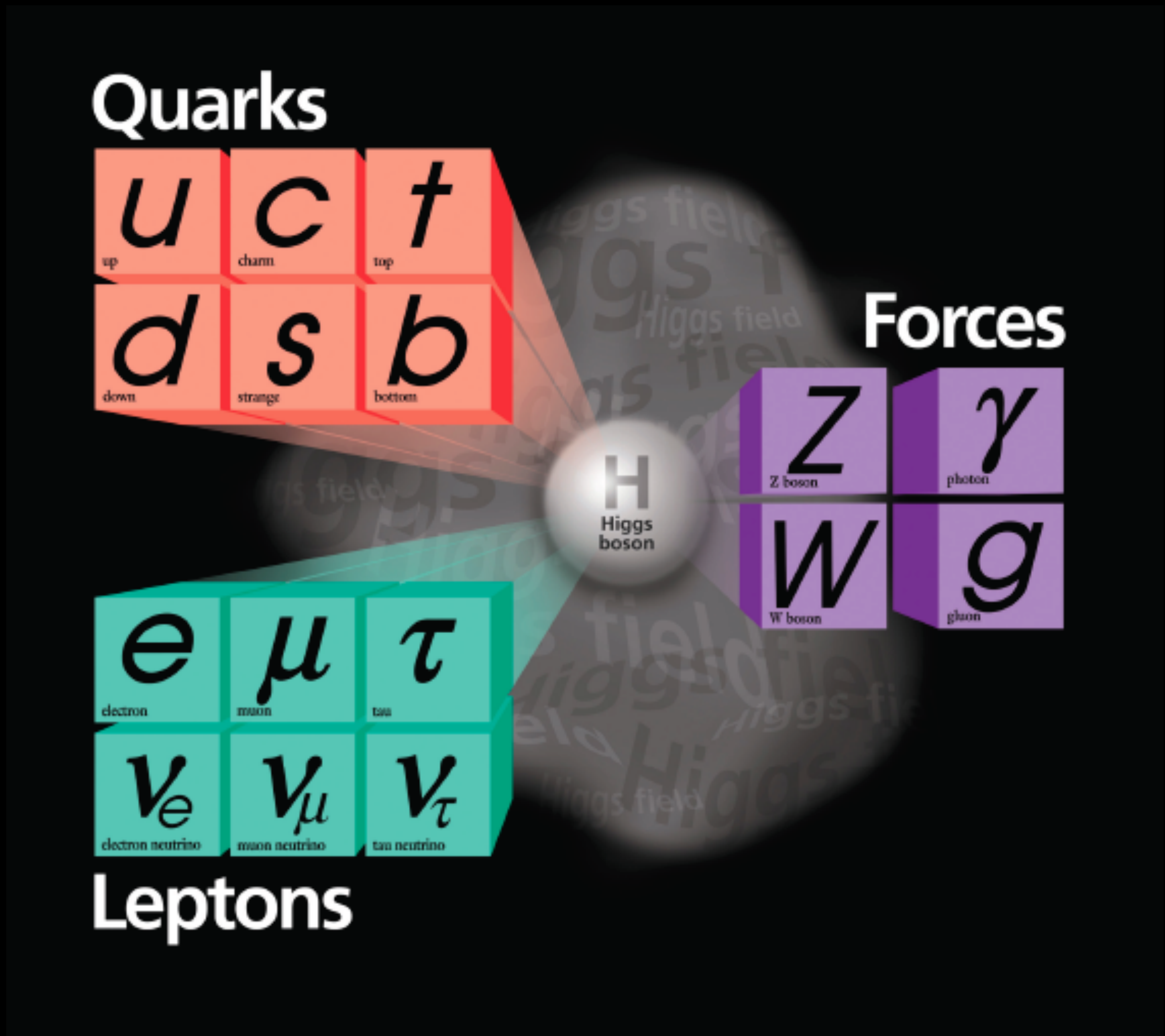


new

Clear excess visible in both experiments

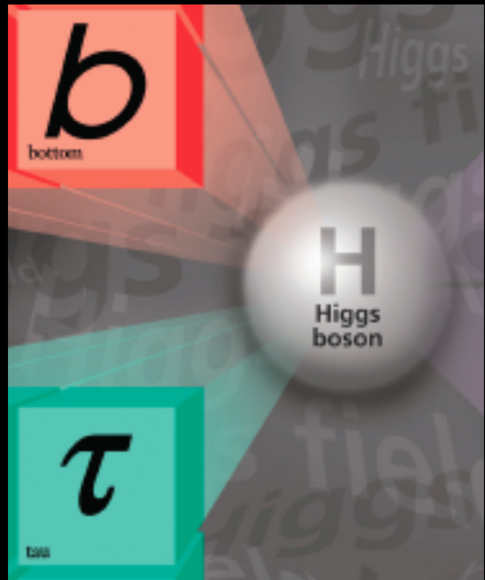
Data – background (all channels combined)

Signal strength a bit high



Couplings to quarks and leptons ?

Where are the τ and b decays ?

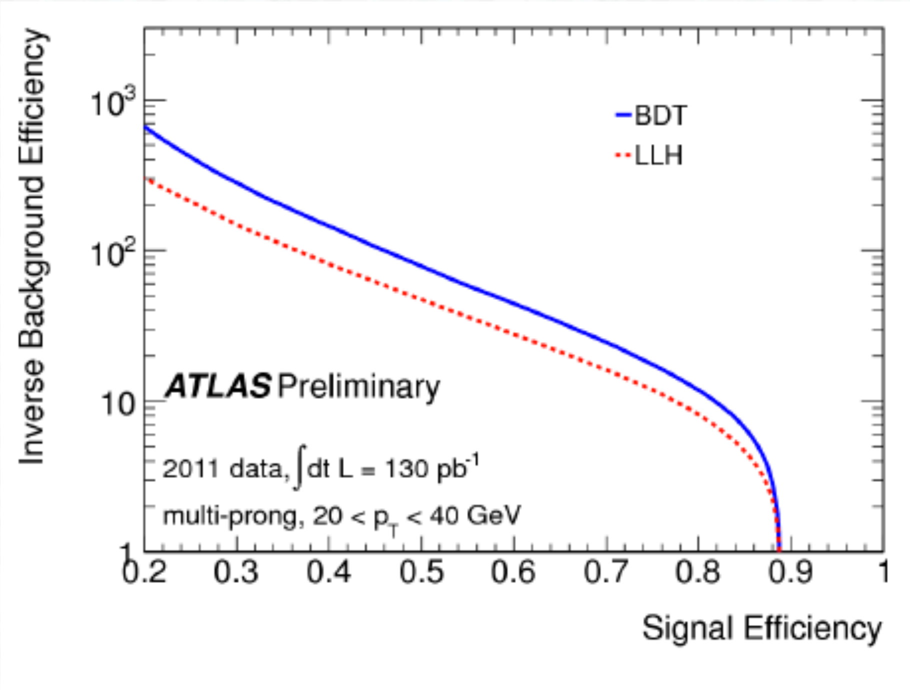


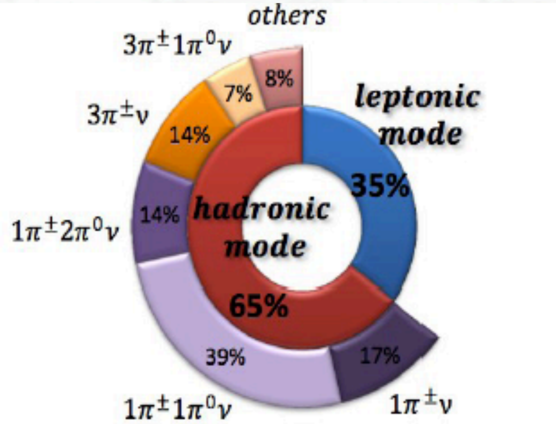
Why is the search in these decay modes so challenging?

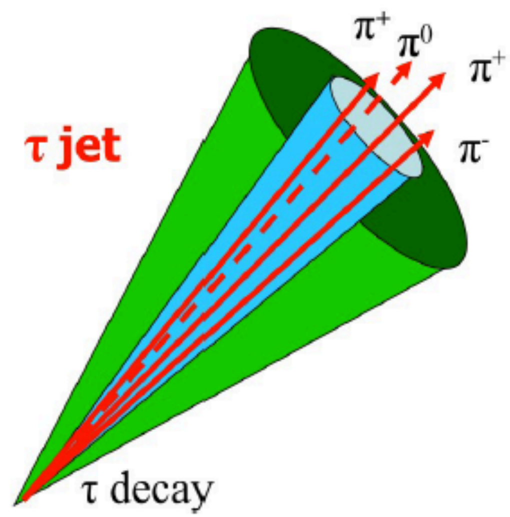
- The τ lepton is the heaviest lepton

  m_τ = 1.78 GeV /c^2, lifetime 2.9 10^{-13} s

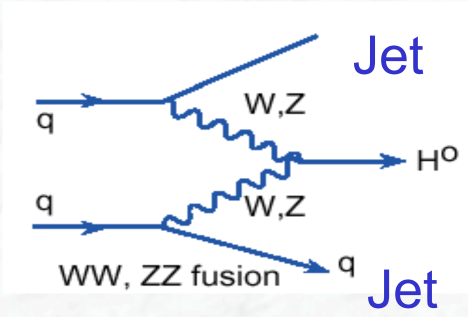
- Challenge: distinguish hadronic τ decays from hadronic jet activity



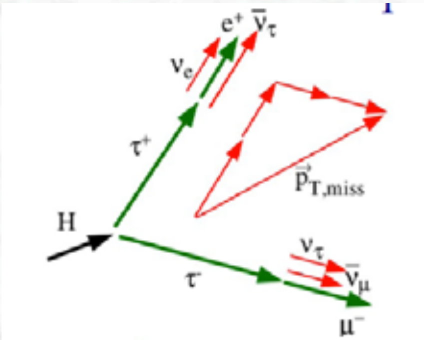


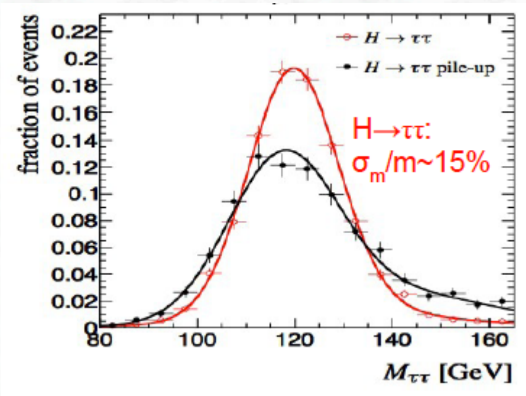


- Small signal rate, compared to large background from jet production via QCD processes
  → smaller vector boson fusion need to be used

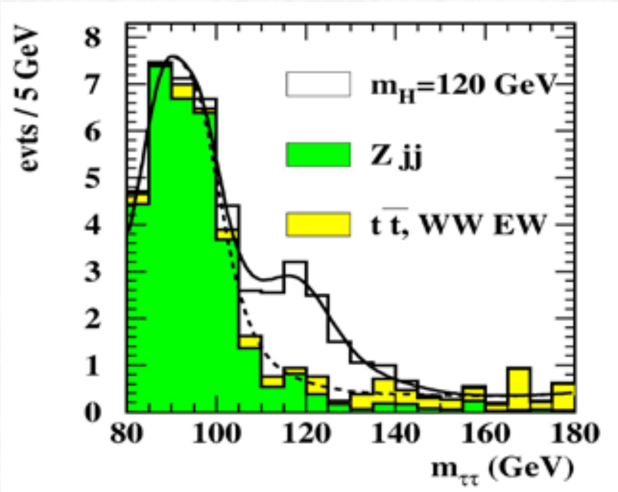


- Neutrinos in the final state
  → poor mass resolution





- Small signal in presence of a large $Z \to \tau\tau$ background



Expected signal

Monte Carlo Simulation !
~30 fb^{-1}

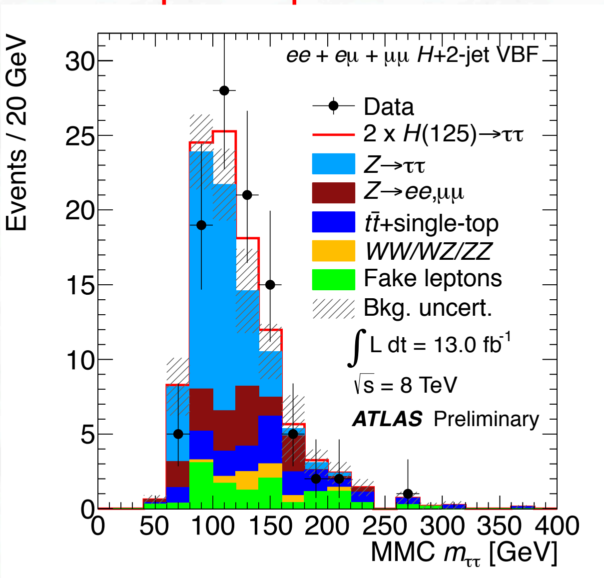
Results based on 13 fb^{-1} data at $\sqrt{s}$ = 8 TeV:

- Analysis is split into three sub-channels:

  - H → ττ → ℓ νν ℓ νν (lepton-lepton decay mode)
  - H → ττ → ℓ νν had ν (lepton-hadron decay mode)
  - H → ττ → had ν had ν (hadron–hadron decay mode)

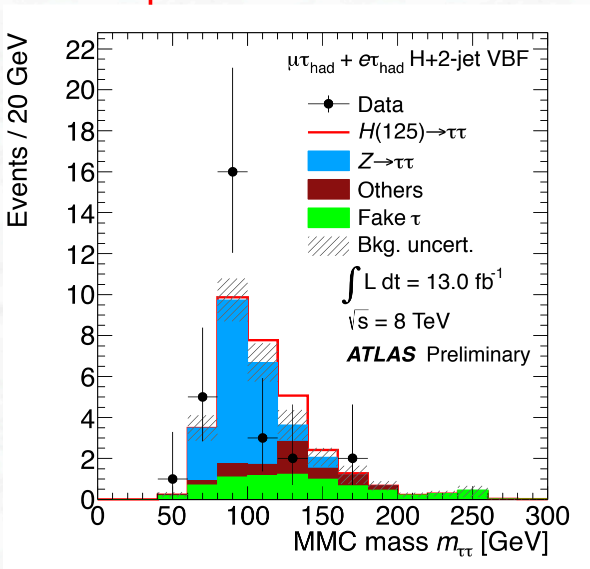
new

lepton-lepton



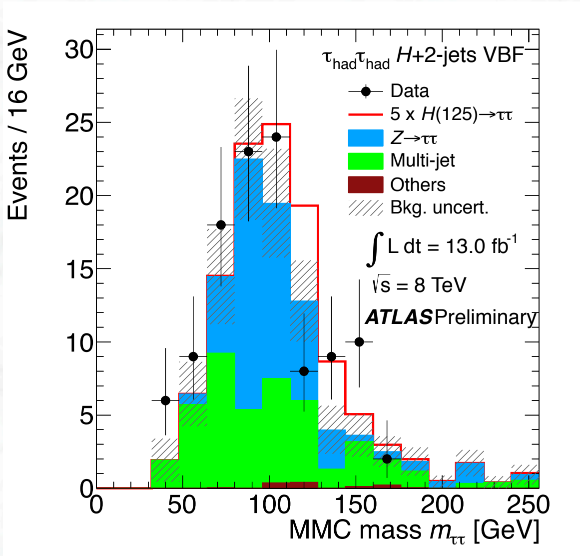
2 x SM Higgs signal

lepton-hadron



1 x SM Higgs signal

hadron-hadron

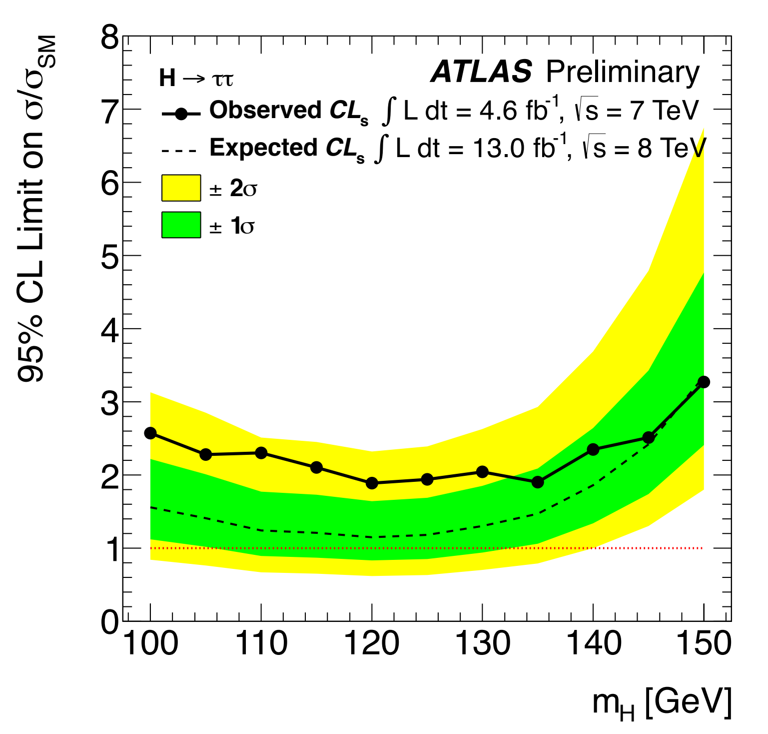


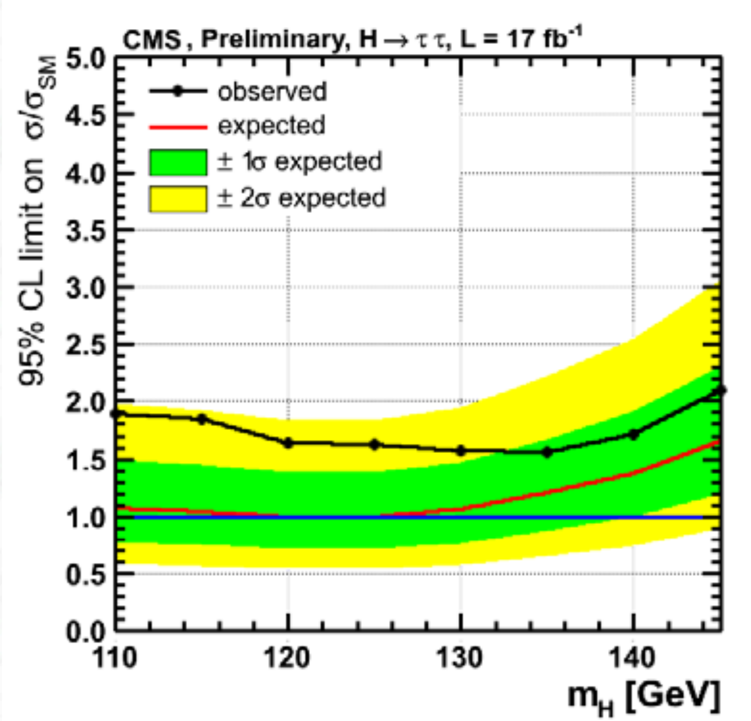
5 x SM Higgs signal

Results of H → ττ searches

new

- Discovery sensitivity for a signal not yet reached !
- Can decays in τ leptons be excluded ?
  → 95% C.L. limits on cross section
  (normalized to Higgs boson expectations)

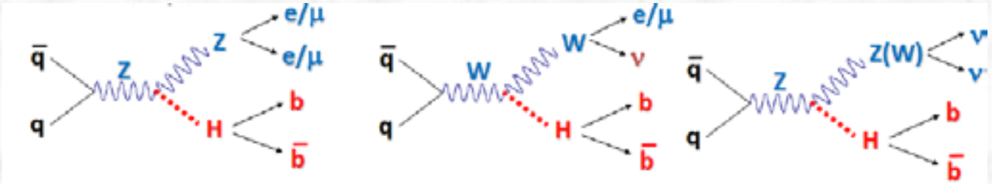


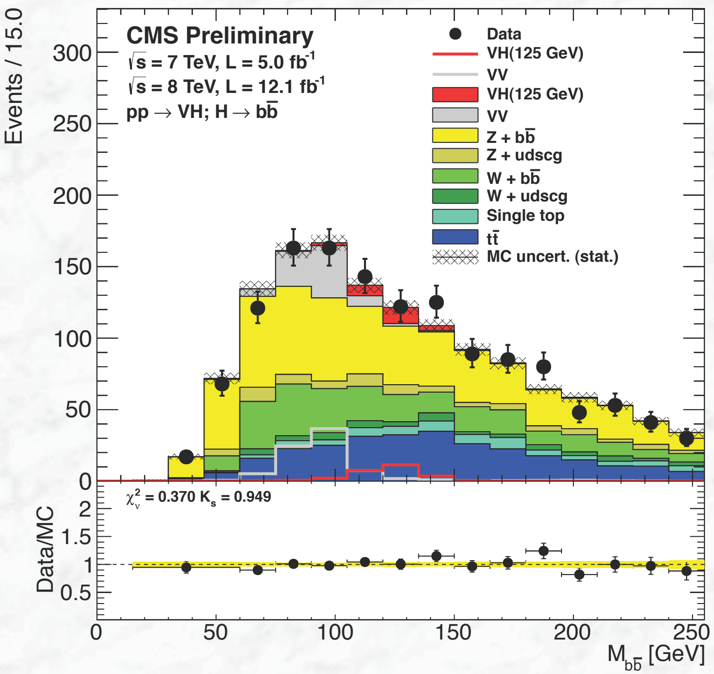


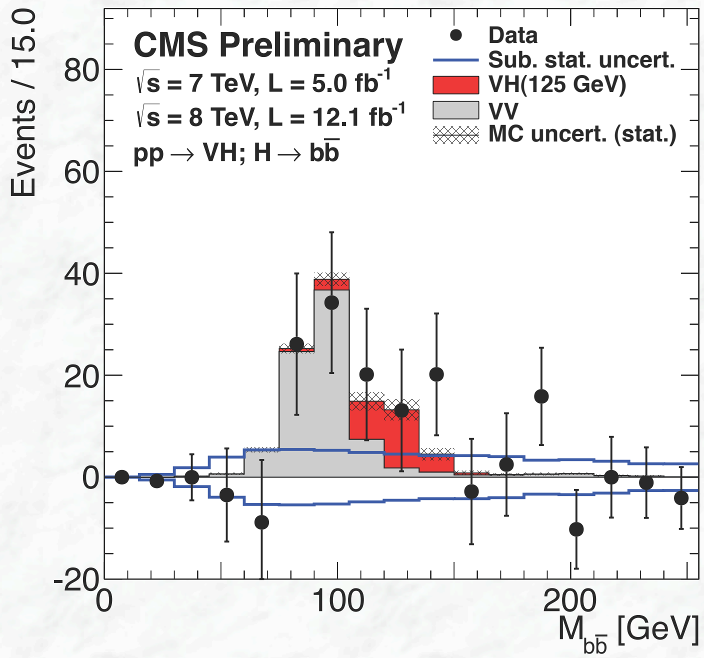
Data favour a signal contribution, but are compatible with the background-only hypothesis at the 2σ level

Results on H → bb searches

new



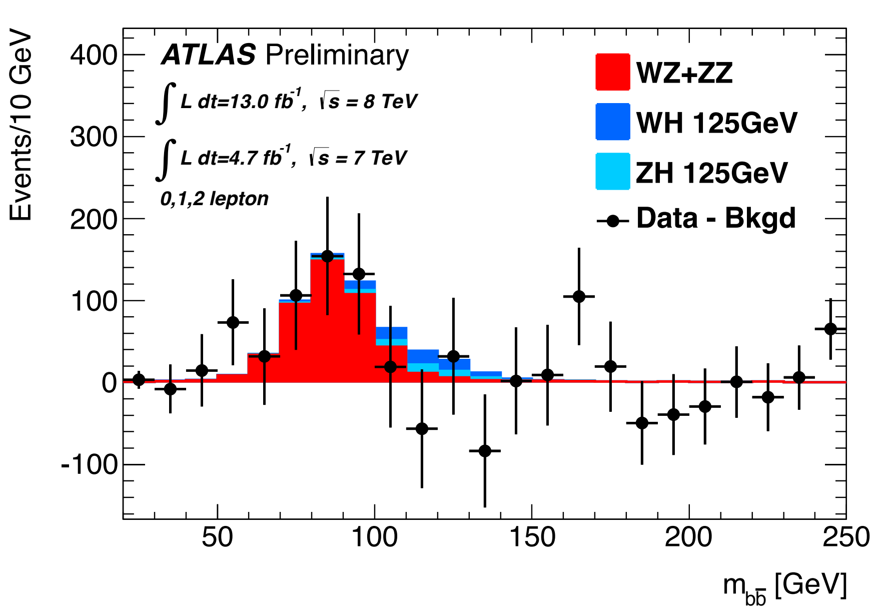


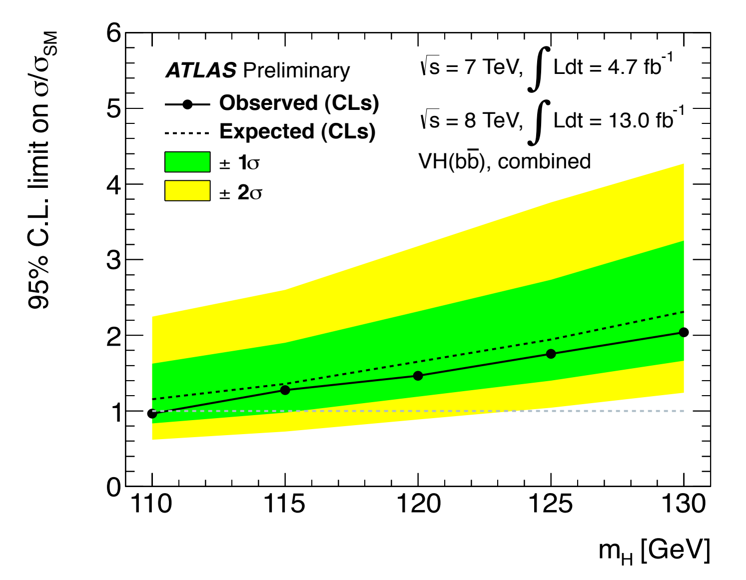


- Small excess is showing up around 125 GeV
- However, the significance is still small !

Results on H → bb from ATLAS

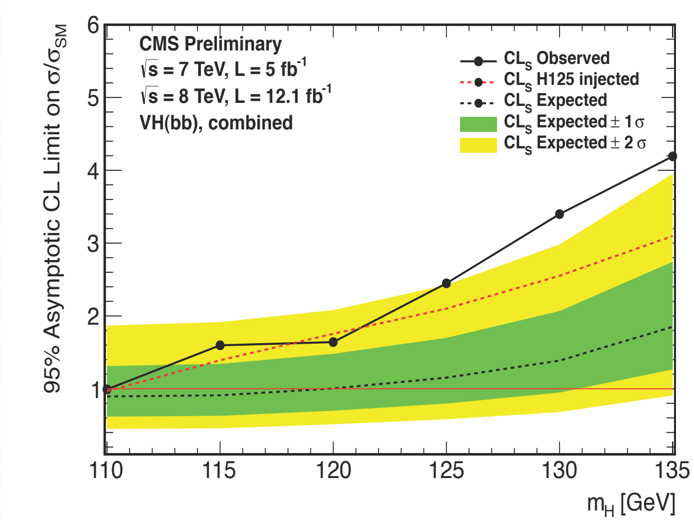
new



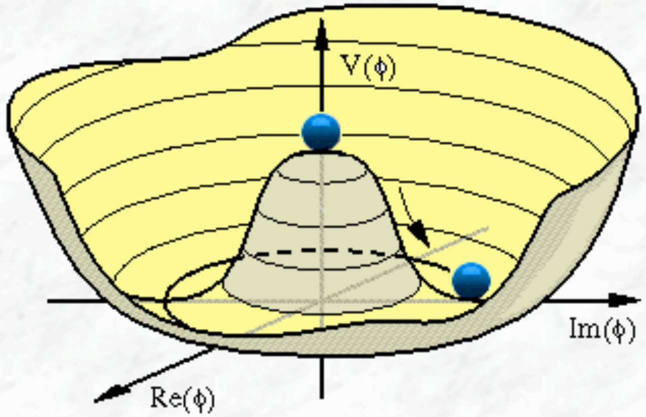


- No excess visible around 125 GeV for ATLAS

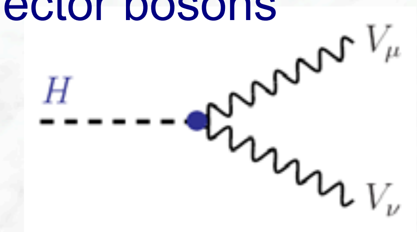
- ~2σ excess for CMS



Is it the Higgs Boson ?

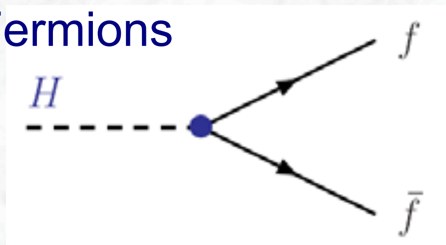


Vector bosons



$$g_{HVV} = 2M_V^2/v = 2(\sqrt{2}G_\mu)^{1/2}\, M_V^2$$

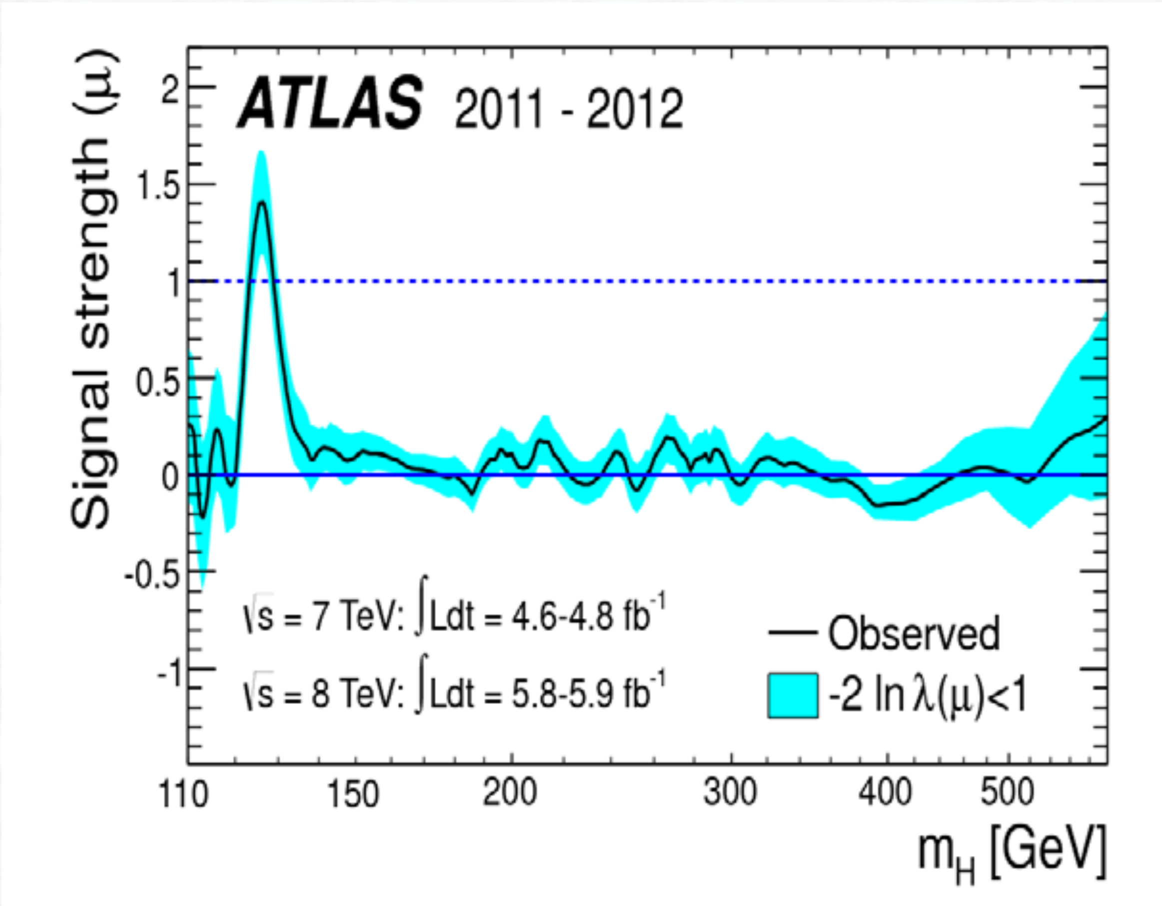
Fermions



$$g_{Hff} = m_f/v = (\sqrt{2}G_\mu)^{1/2}\, m_f$$

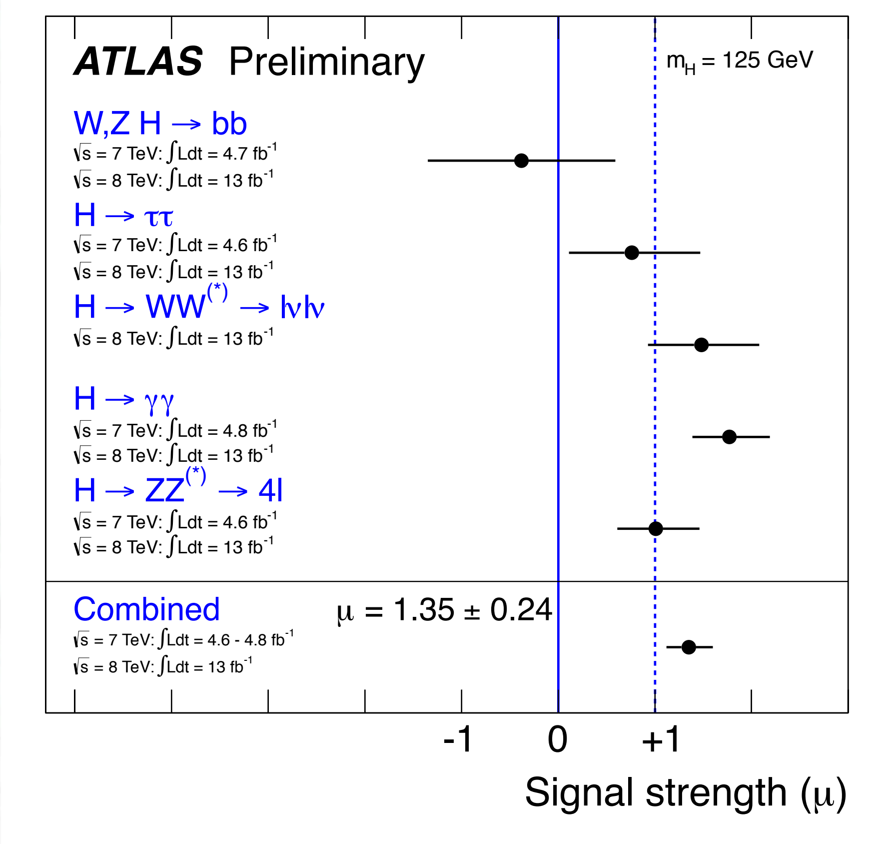
Signal strength of the new particle

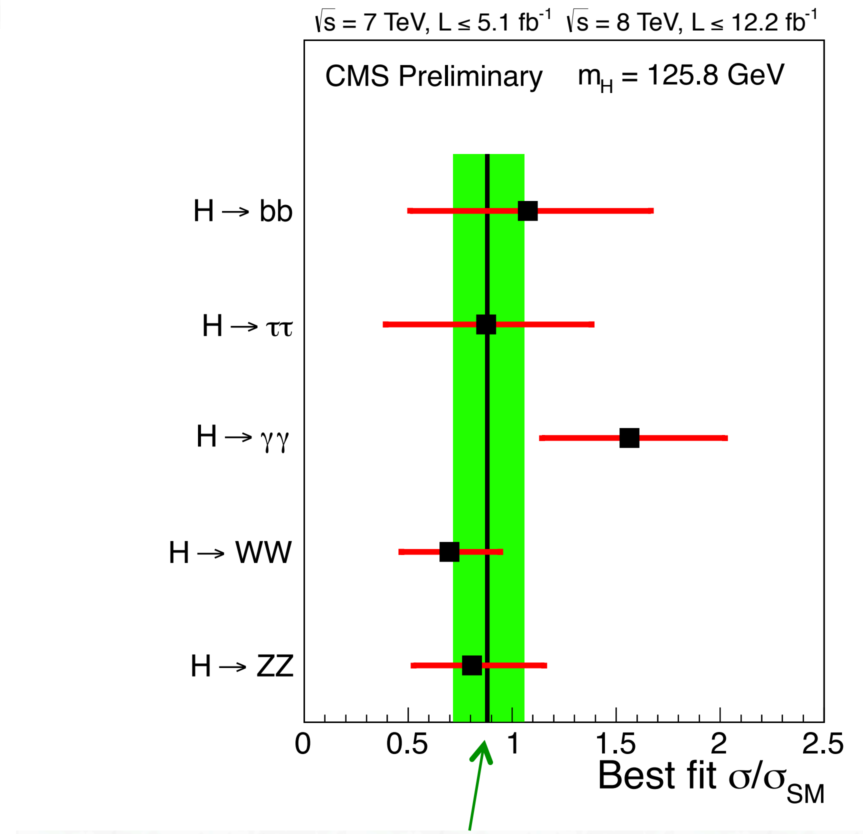
Determination of „best“ signal strength $\mu = \sigma_{observed}/\sigma_{SM}$



Signal strength in individual decay modes

-including new data-



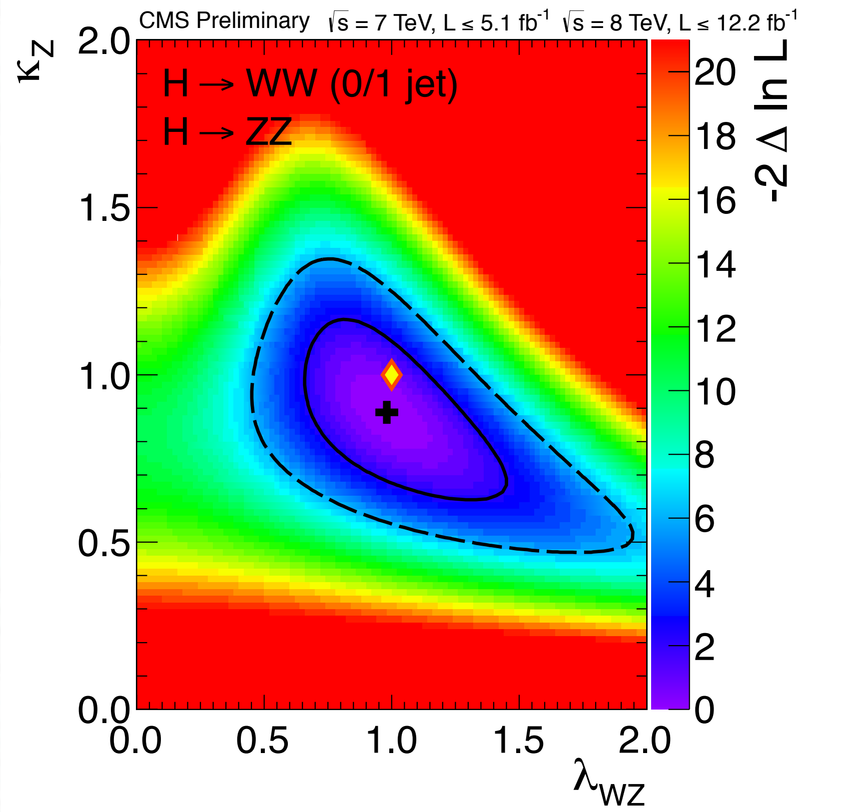


$\mu = 0.88 \pm 0.21$

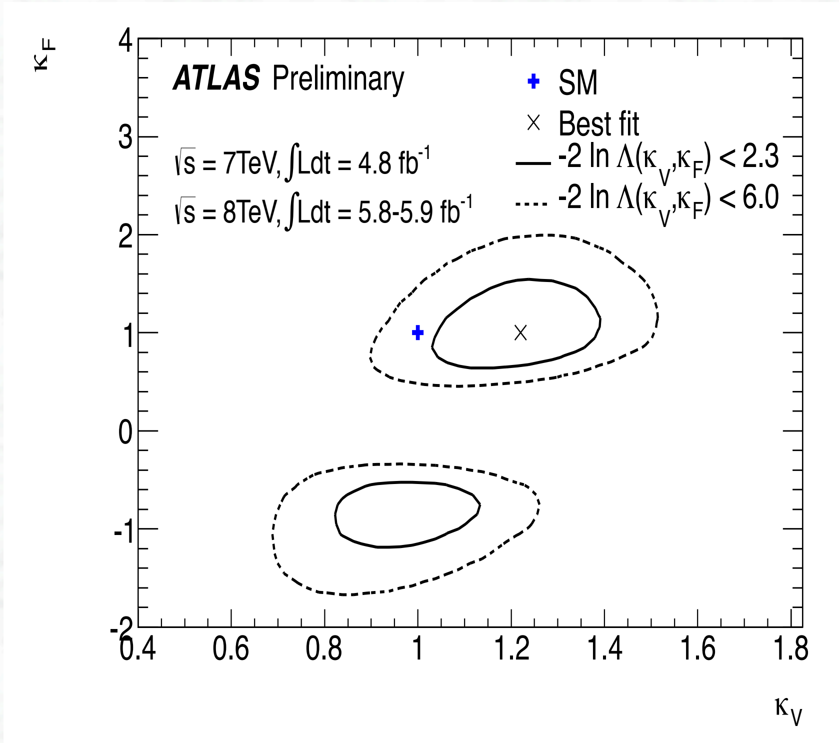
- Data are consistent with the hypothesis of a Standard Model Higgs boson !
- Experimental uncertainties are still too large to get excited about “high” γγ and “low” fermionic (ττ and bb) signal strengths !

Test of coupling strengths

Couplings to W and Z bosons



W,Z versus fermion couplings



λ_{WZ} = ratio of W/Z coupling strength (normalized to ratio in the SM)

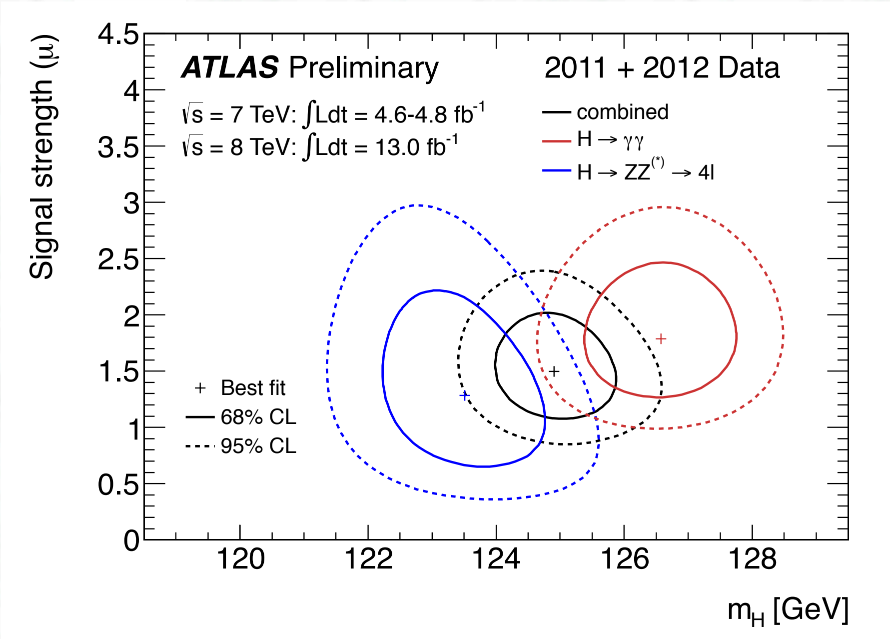
κ_Z = scale factor for Z coupling strength

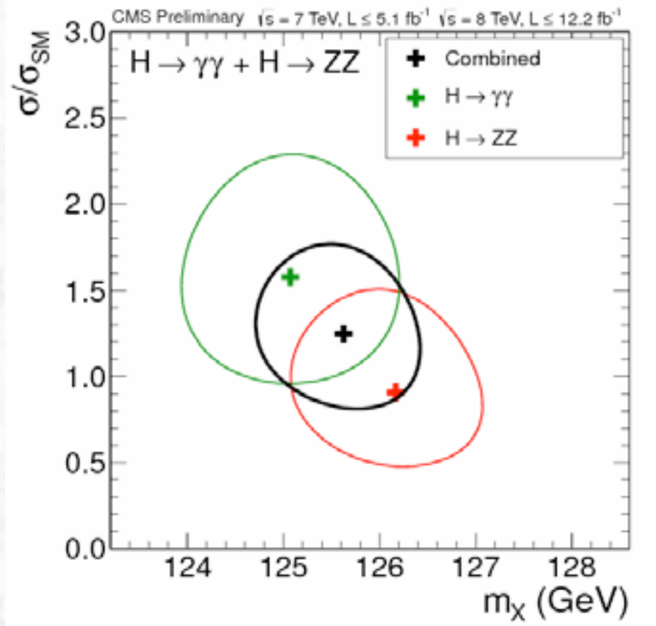
κ_V = common scale factor for all fermion couplings (t, b, τ, …..)

κ_V = common scale factor for W,Z couplings

Determination of mass and signal strength

signal strength $\mu = \sigma_{observed}/\sigma_{SM}$





$m_H = 125.2 \pm 0.3\ (\text{stat}) \pm 0.6\ (\text{syst})$ GeV

$m_H = 125.8 \pm 0.4\ (\text{stat}) \pm 0.4\ (\text{syst})$ GeV

Observed mass difference between the two channels:
$\Delta m = 3.0 \pm 0.8\ (\text{stat}) \pm 0.6\ (\text{syst})$ GeV (2.7σ)

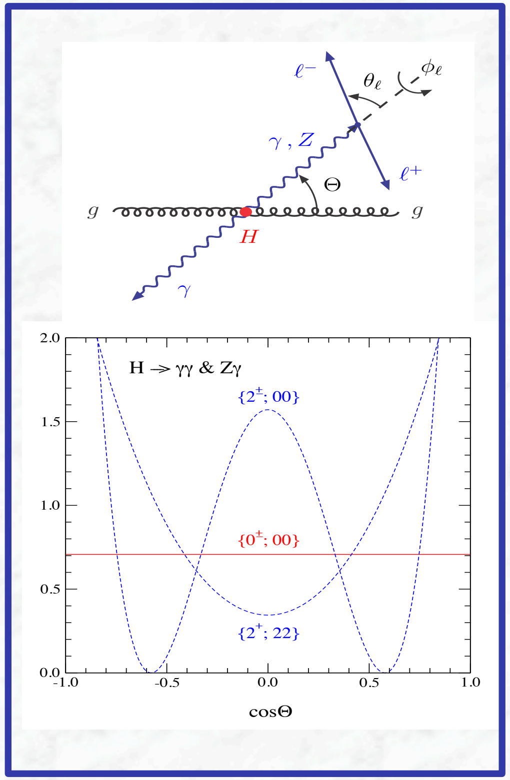
Relative signal strength for the two decay modes are constrained to their SM expectations for a Higgs boson

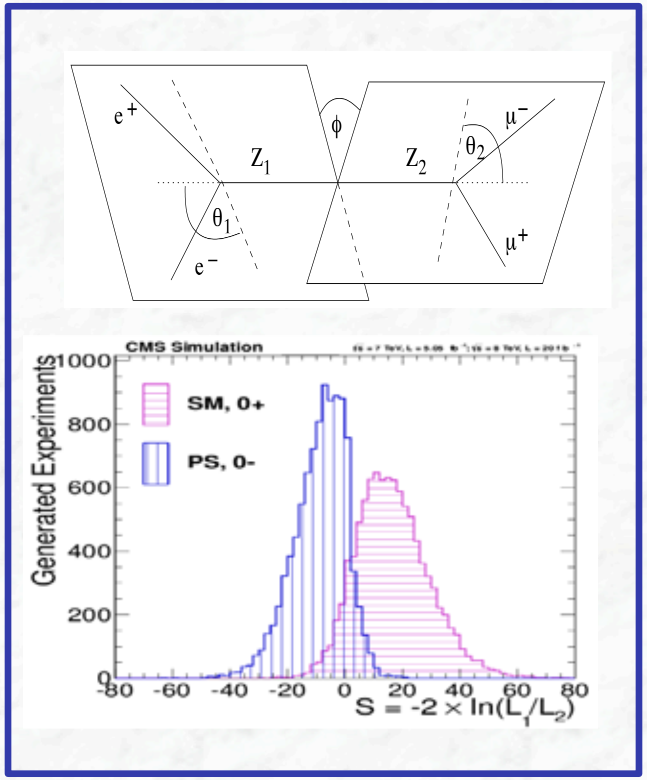
Spin and CP ?

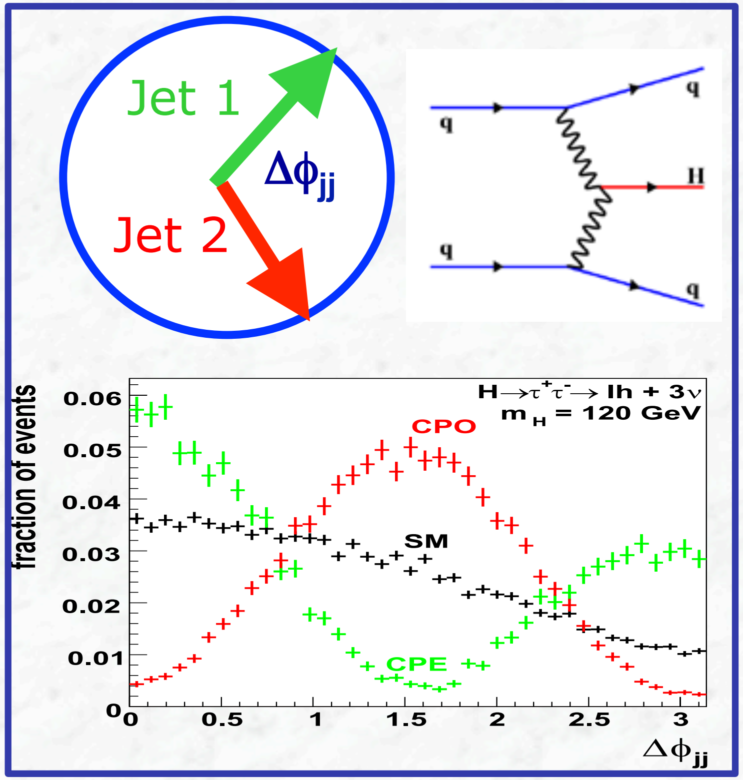
Determination of spin: - should be 0

- spin=1 excluded by observing $H \rightarrow \gamma\gamma$ (Landau-Yang theorem)

→ falsify spin = 2, 1, ... with data from this year by analysis of angular correlations



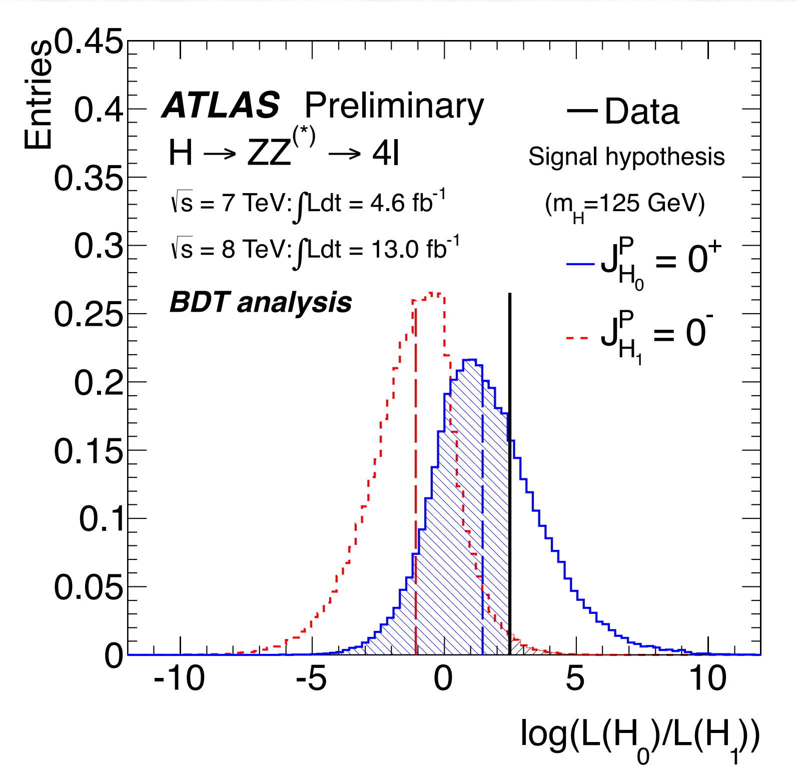


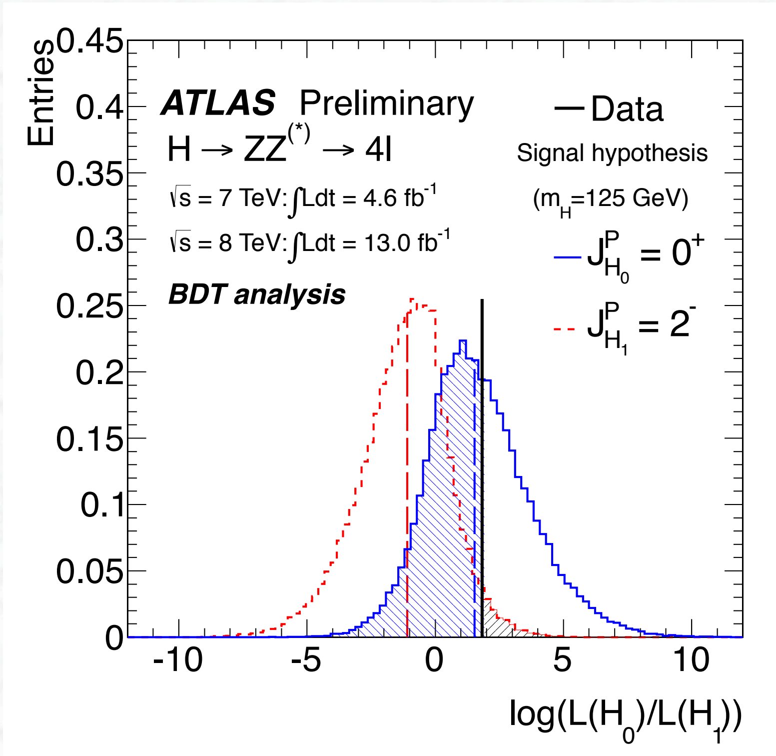


CP-Properties: even, odd or mixture also from angular correlations

More generally: investigate Lorentz structure of couplings of new boson to all particles

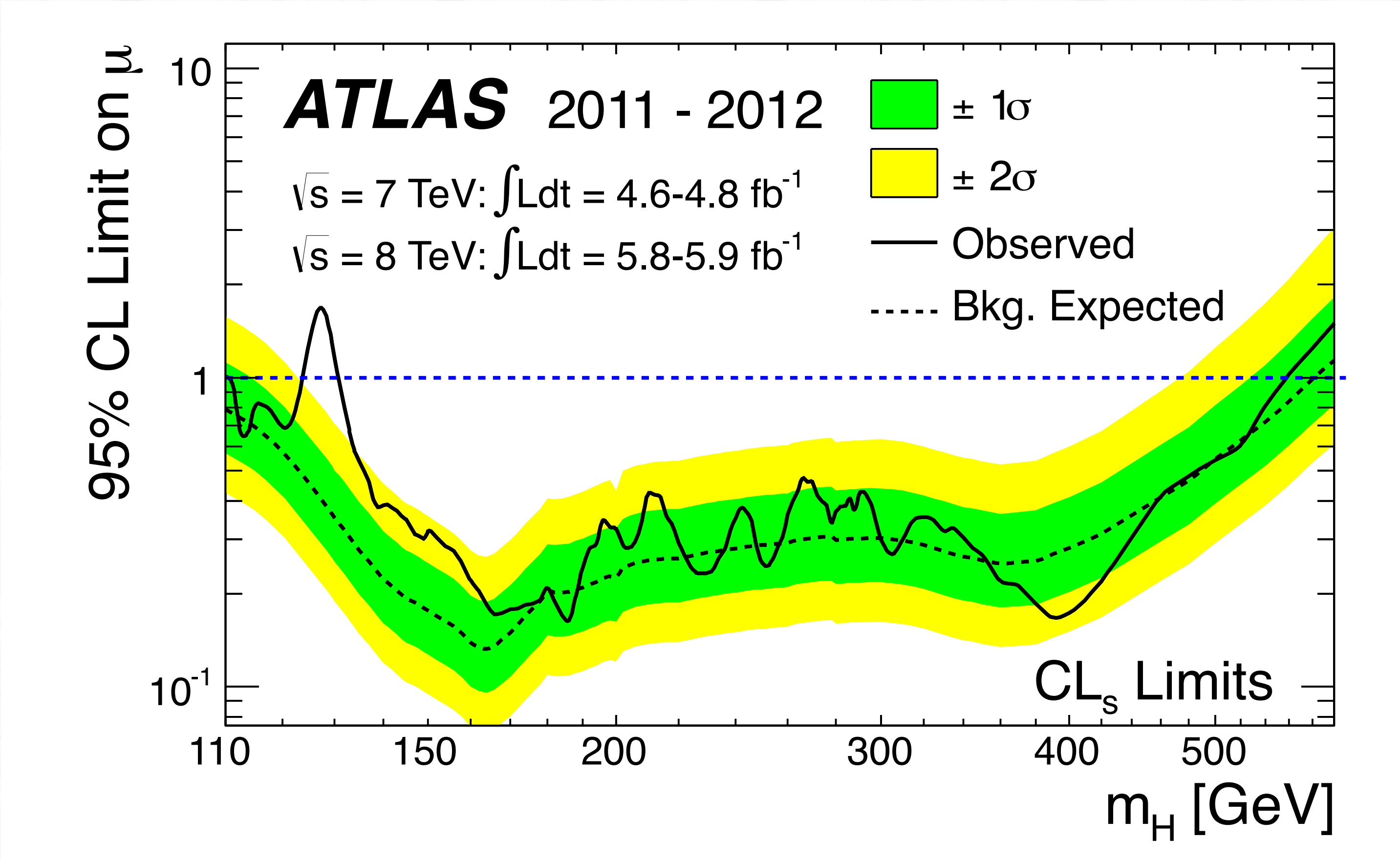
Spin and CP ?





Compatible with $J^P = 0^+$ (favoured hypothesis)

Are there more Higgs bosons at high mass?



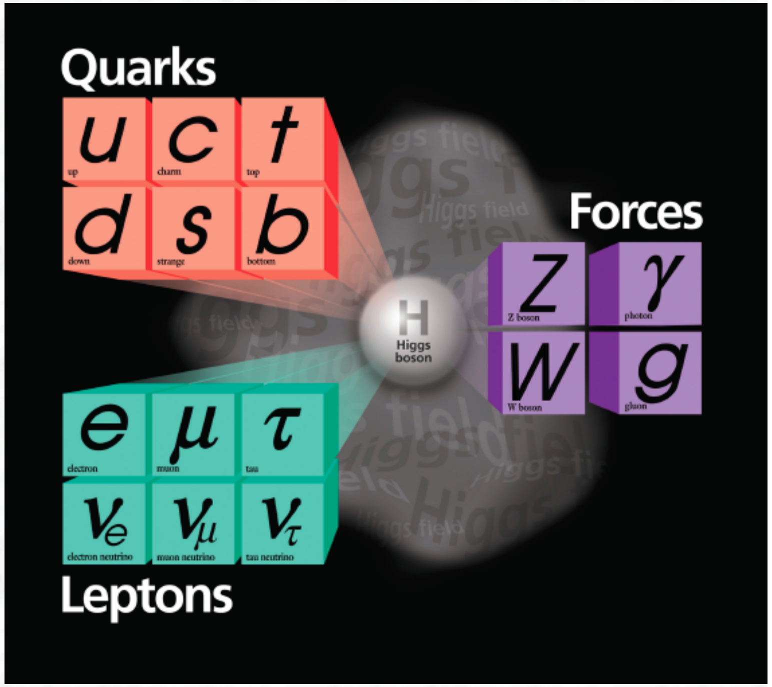
Importance for Physics

-if it is the Standard Model Higgs boson-

- Milestone discovery

- First “elementary” particle with spin 0

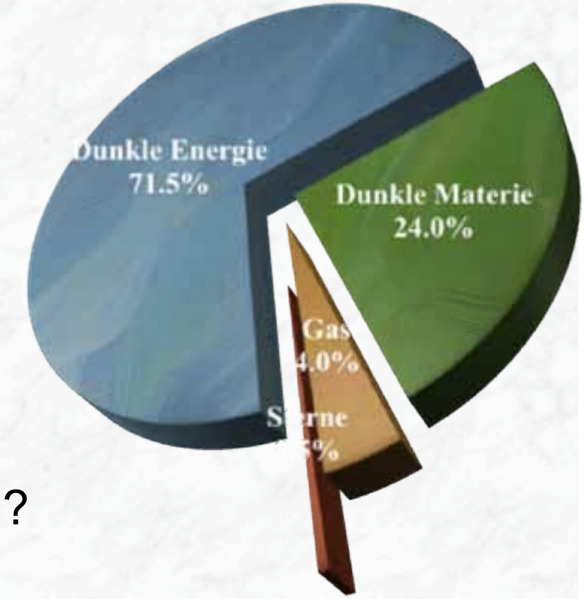
  Manifestation of the Higgs field,
  related to mass of elementary particles

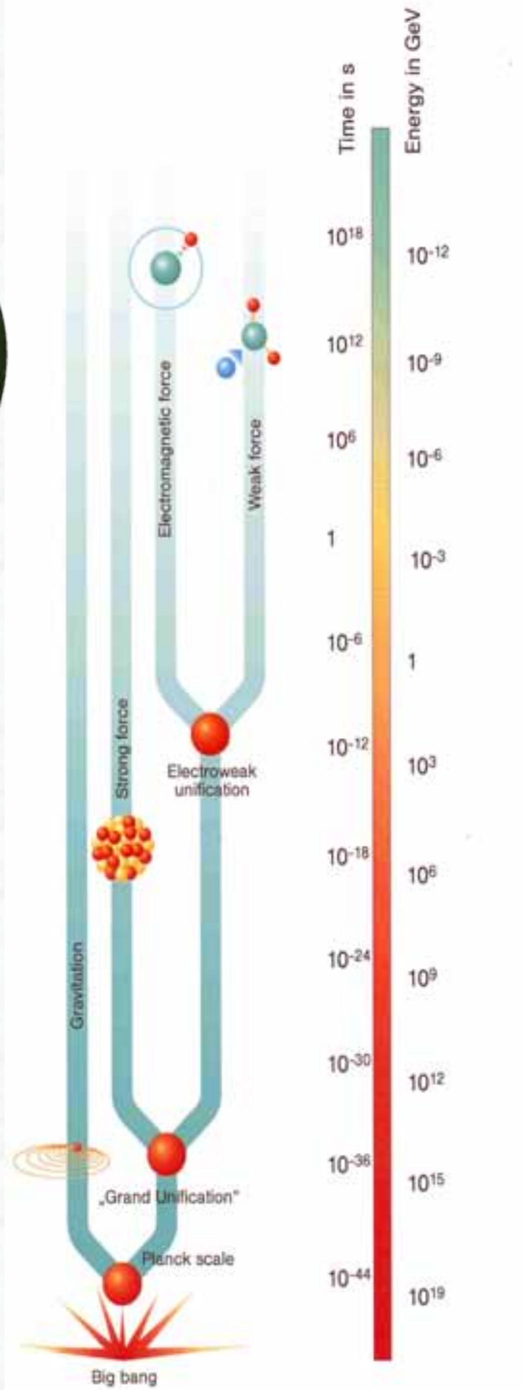


- So far:
  All measurements are consistent with the hypothesis of the Standard Model Higgs boson

  However: more precise measurements are needed to establish the true nature of this new particle
  (Spin, CP, couplings to fermions and bosons, self-coupling (?))

Key questions of particle physics





1. Mass

What is the origin of mass?

Does the Higgs particle exist?

2. Unification

- Can the interactions be unified?
- Are there new types of matter, e.g. supersymmetric particles ?

  Are they responsible for the Dark Matter in the universe?

3. Flavour

- Why are there three generations of particles?
- What is the origin of the matter-antimatter asymmetry (Origin of CP violation)

Conclusions

- With the operation of the LHC at high energies, particle physics has entered a new era
- Performance of the LHC and the experiments is superb
- A milestone discovery made in July 2012

  - Data are consistent with a Standard Model Higgs boson with a mass ~125 GeV, but also with other (extended) models
  - Evidence for decays in heavy fermions ($\tau\tau$ and bb) is building up

- More data and a combination of the results of the two experiments are needed to determine the true nature of the new particle (Spin, CP, couplings to fermions and bosons)
- More precise and more conclusive results are expected in Spring / Summer 2013
- … and hopefully the discovery of the Higgs-like particle it a portal to other exciting discoveries at the LHC