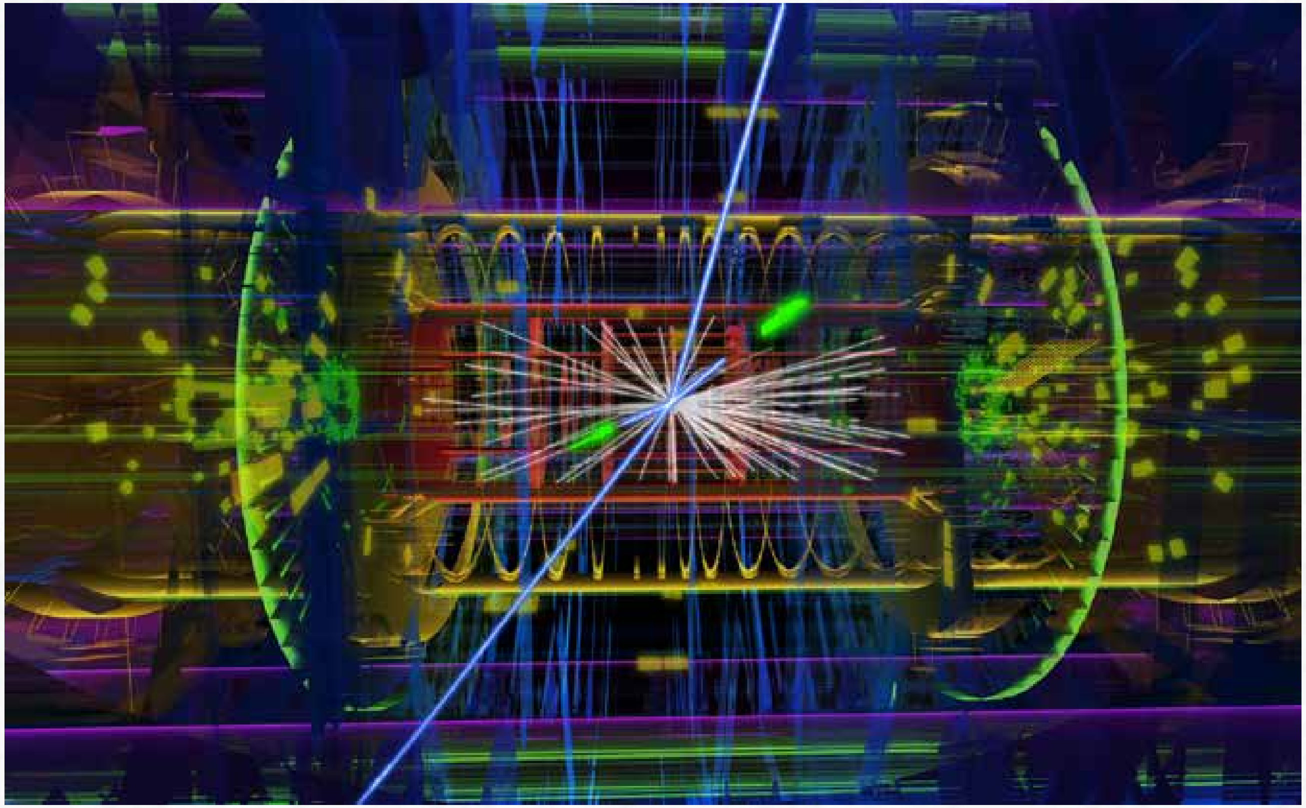
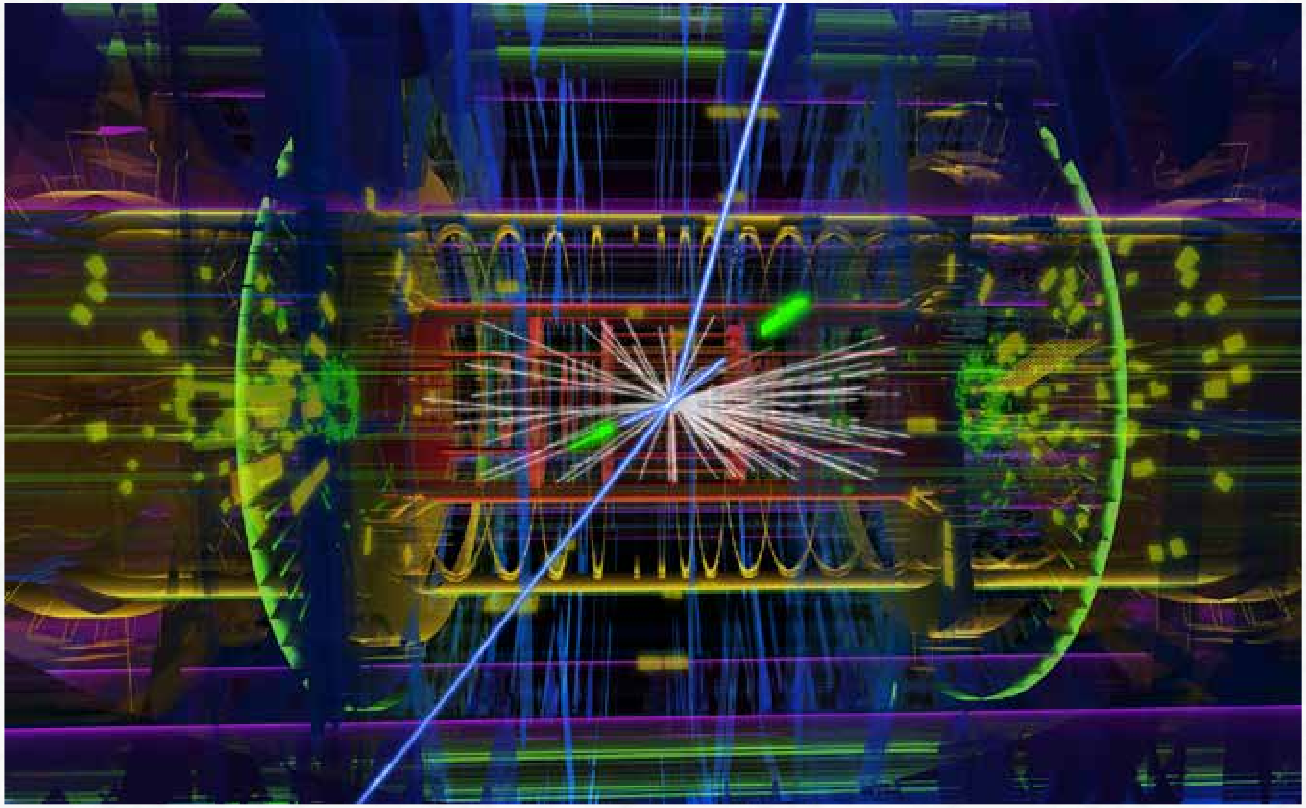
Entdeckung eines Higgs-artigen Teilchens am LHC



Karl Jakobs
Physikalisches Institut
Universität Freiburg

Entdeckung eines Higgs-artigen Teilchens am LHC



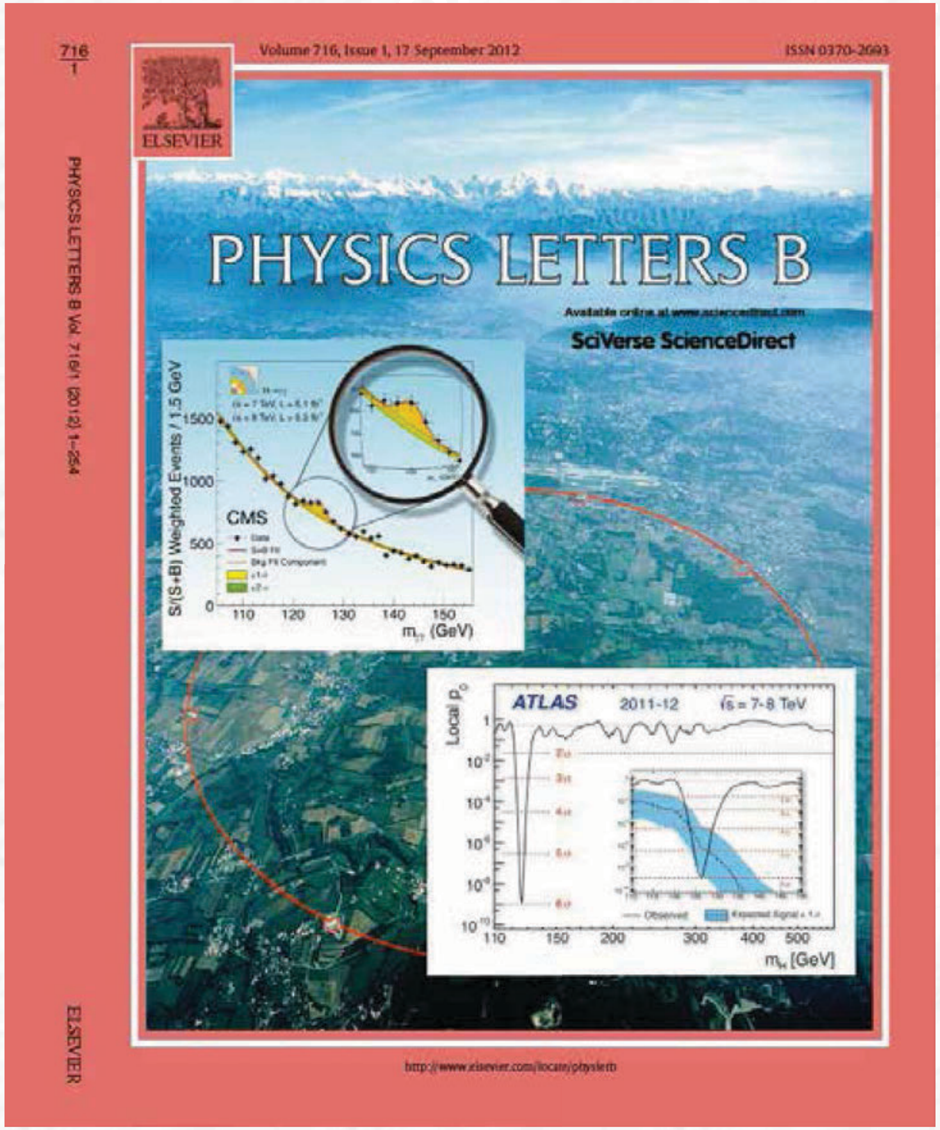
The ATLAS and CMS Collaborations

4^{th} July 2012

From the editorial:

The top Breakthrough of the Year – the discovery of the Higgs boson – was an unusually easy choice, representing both a triumph of the human intellect and the culmination of decades of work by many thousands of physicists and engineers

Observation of a New Particle



Submission to PLB on 31st 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 ☆

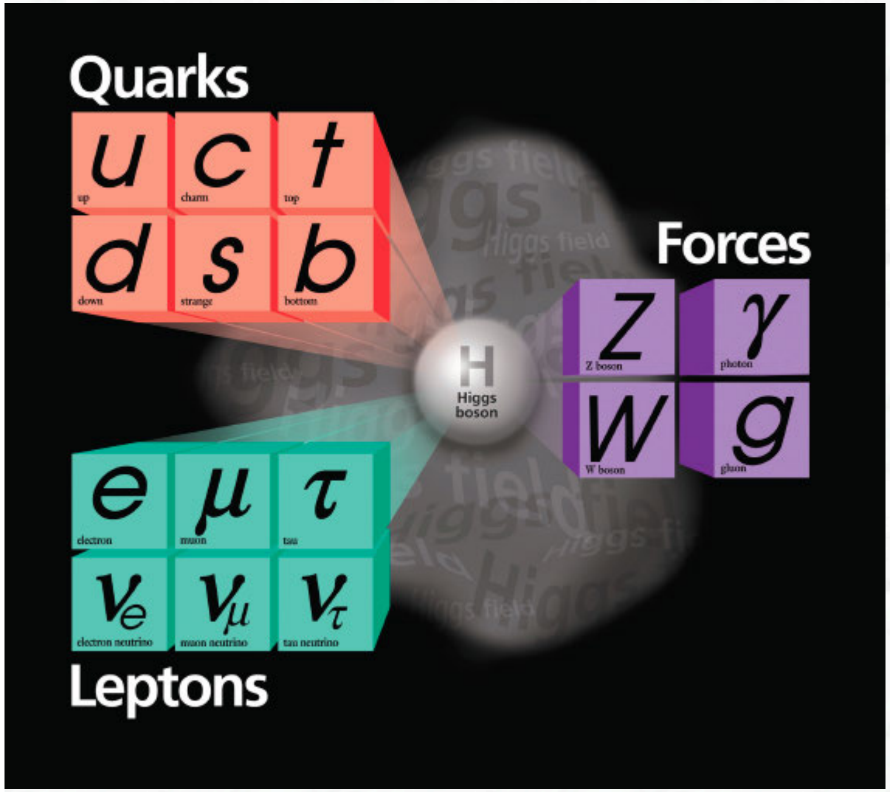
CMS Collaboration *

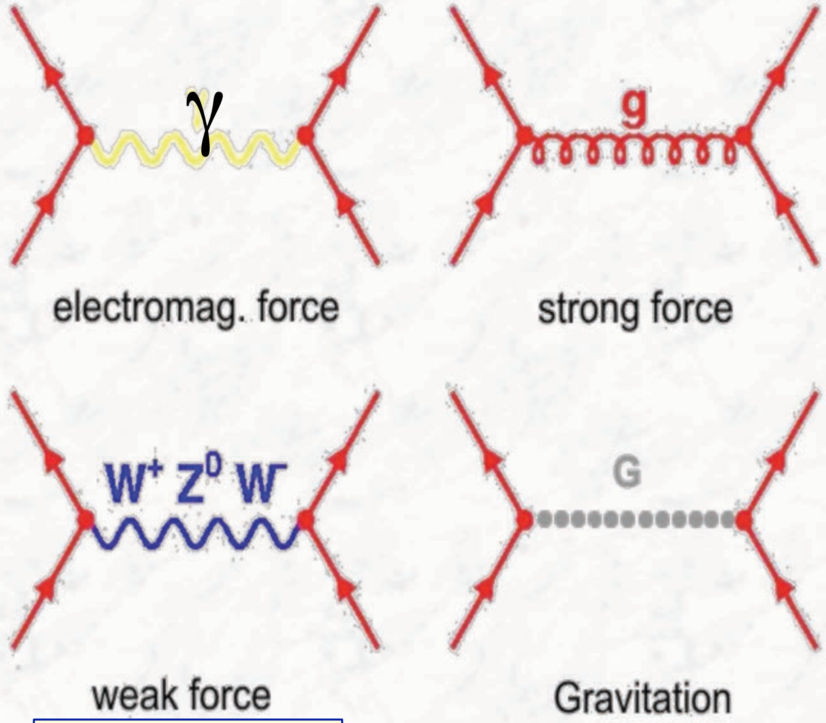
CERN, Switzerland

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

The Standard Model of Particle Physics





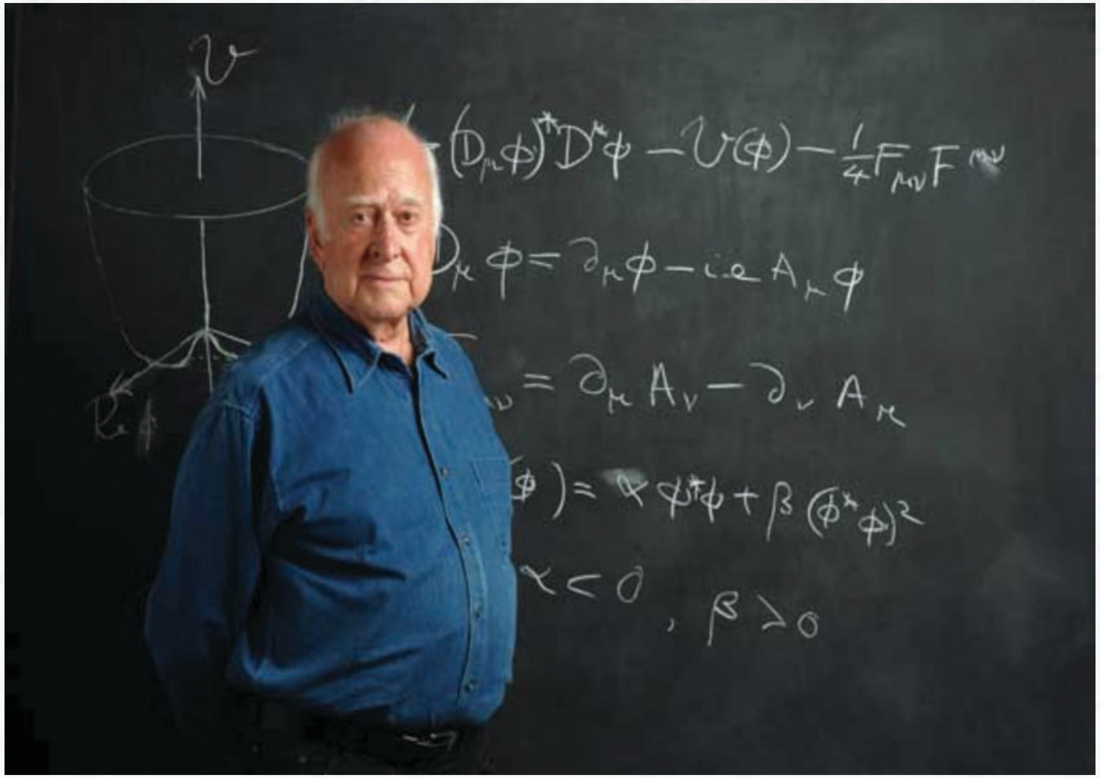
$m_W \approx 80.4$ GeV
$m_Z \approx 91.2$ GeV

(i) Constituents of matter: quarks and leptons (spin-½ fermions)

(ii) Four fundamental forces: described by quantum field theories (except gravitation)
→ massless spin-1 gauge bosons

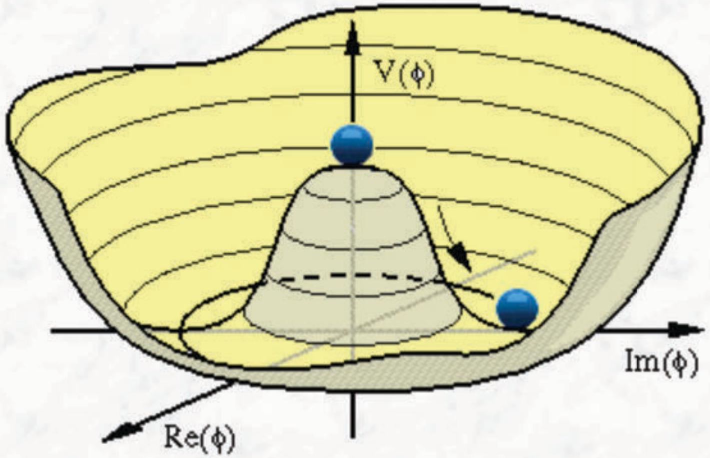
(iii) The Higgs field: → scalar field, spin-0 Higgs boson

The Brout-Englert-Higgs Mechanism



F. Englert and R. Brout. Phys. Rev. Lett. 13 (1964) 321;
P.W. Higgs, Phys. Lett. 12 (1964) 132, Phys. Rev. Lett. 13 (1964) 508;
G.S. Guralnik, C.R. Hagen, and T.W.B. Kibble. Phys. Rev. Lett. 13 (1964) 585.

The Brout-Englert-Higgs Mechanism



Complex scalar (spin 0) field ϕ with potential:

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

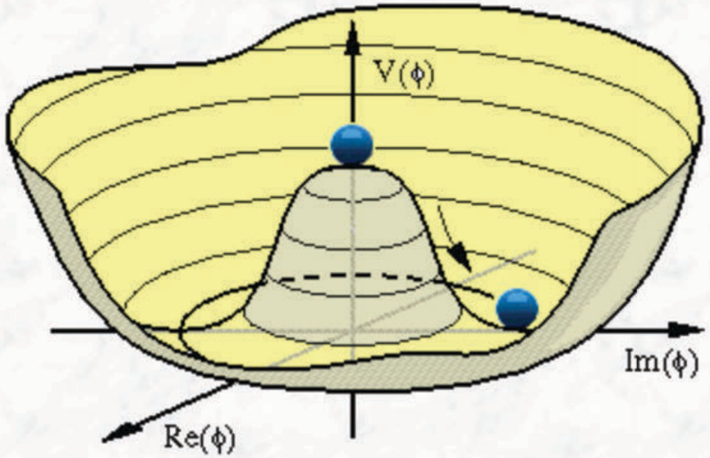
For $\lambda > 0$, $\mu^2 < 0$:
"Spontaneous Symmetry Breaking"

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

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

→ Particles acquire mass through couplings to the Higgs field

The Brout-Englert-Higgs Mechanism



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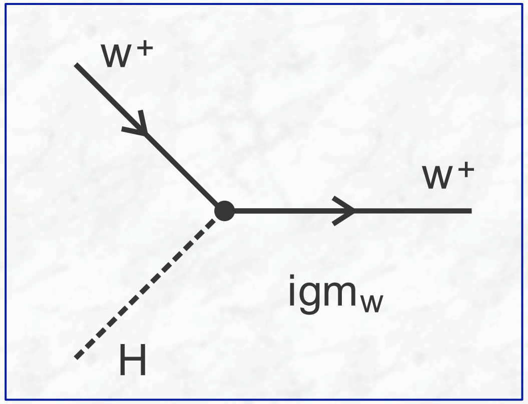
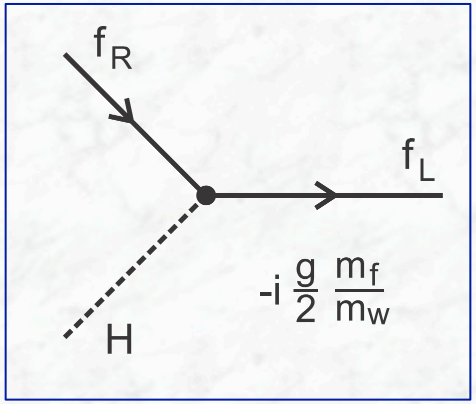


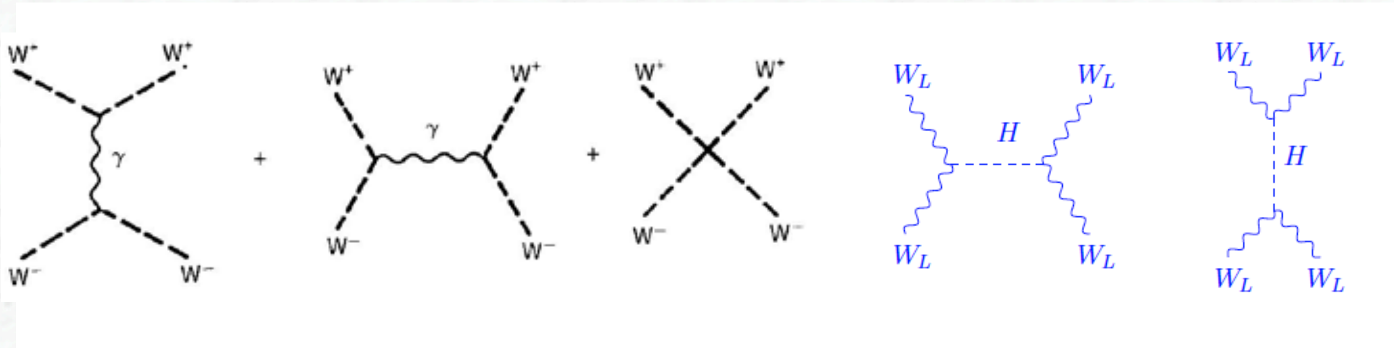


- Couplings proportional to mass
- Higgs boson decays preferentially into the heaviest accessible particles

The Higgs field solves two fundamental problems:

(i) Masses of the vector bosons W and Z and fermions

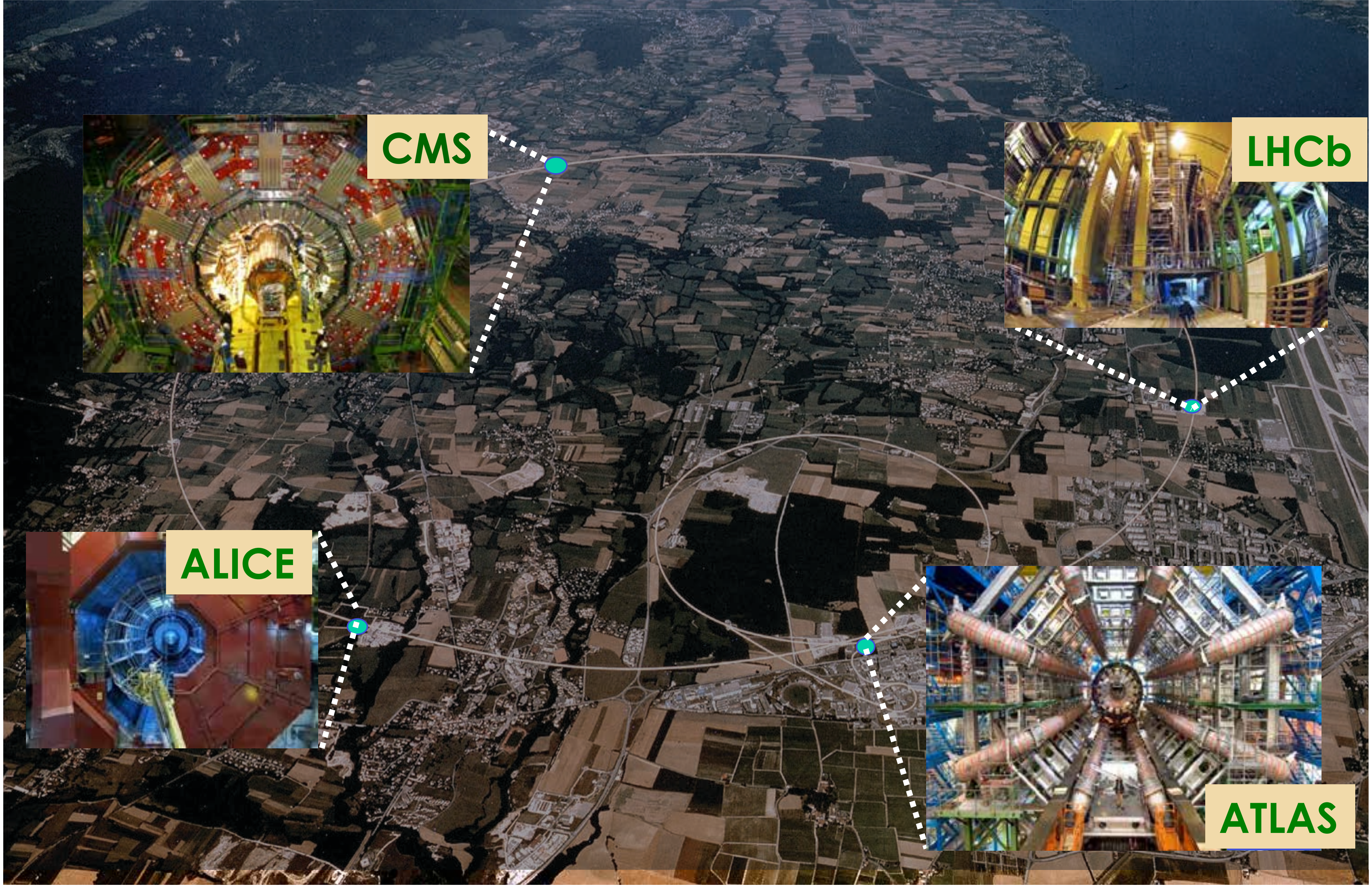
(ii) Divergences in the theory (scattering of W bosons)
("Ultraviolet regulator")



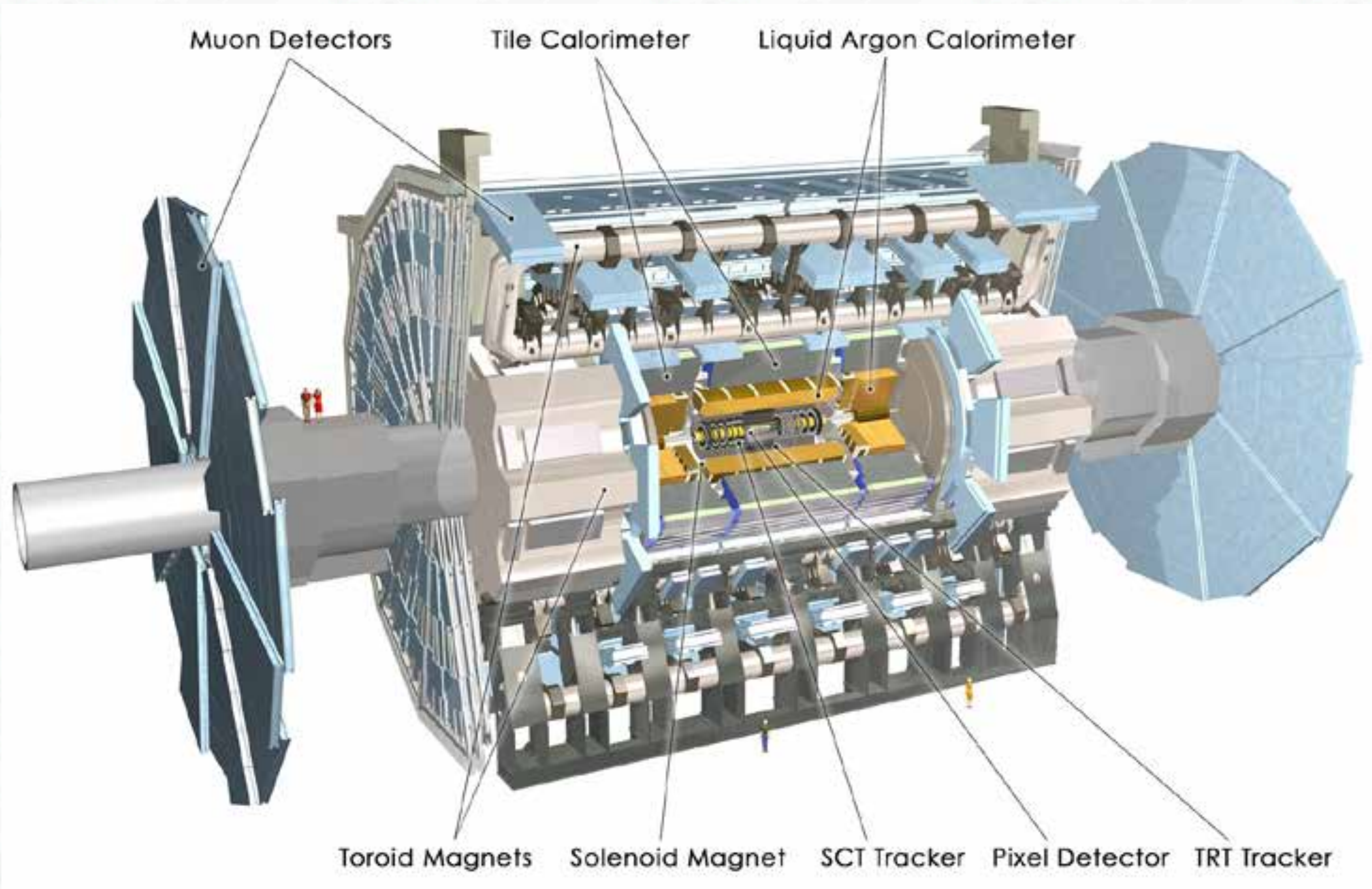
$$-iM(W^+W^- \rightarrow W^+W^-) \sim \frac{s}{M_W^2} \quad \text{for} \quad s \rightarrow \infty$$ (no Higgs boson)

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

The Large Hadron Collider



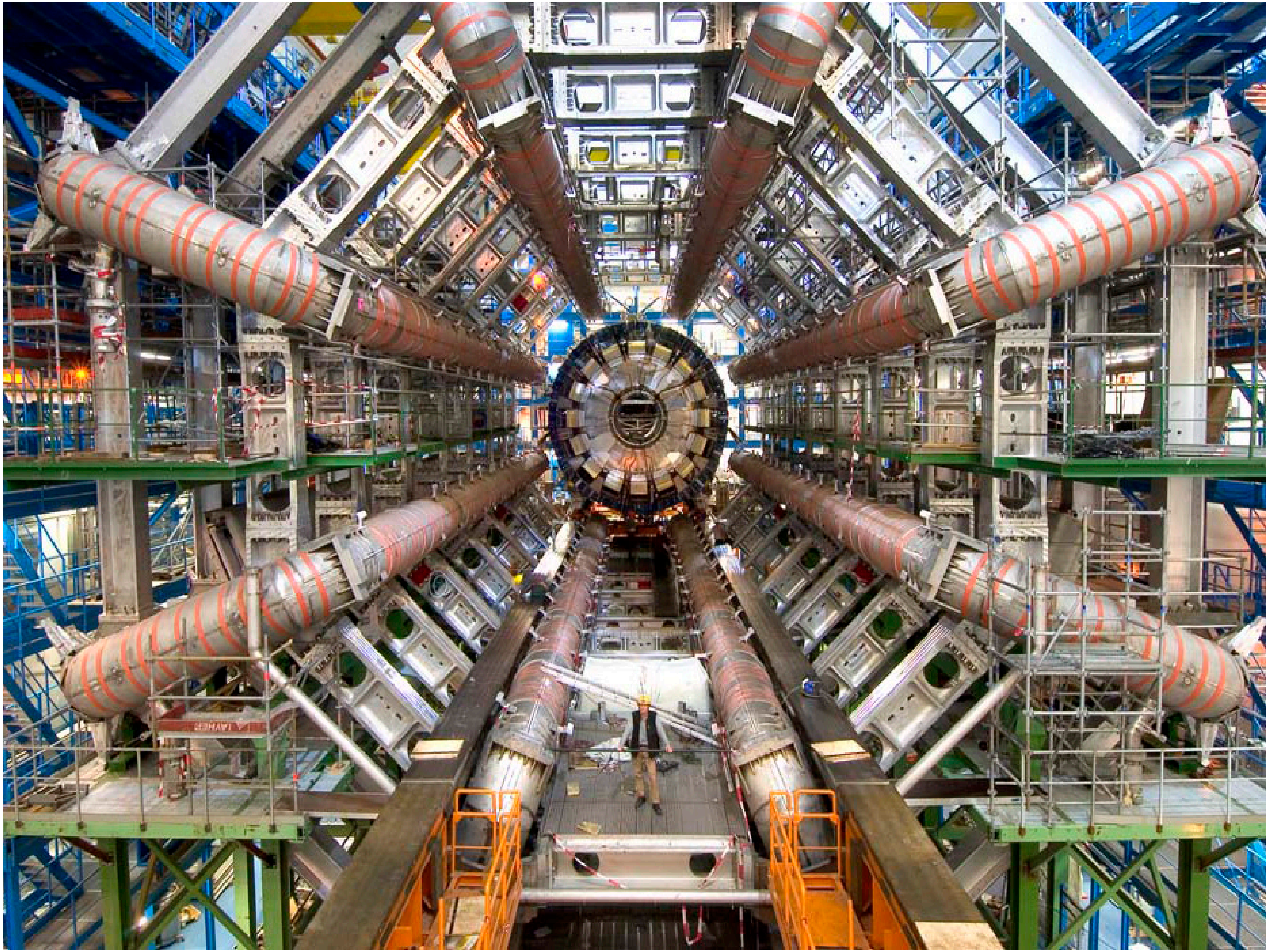
The ATLAS experiment



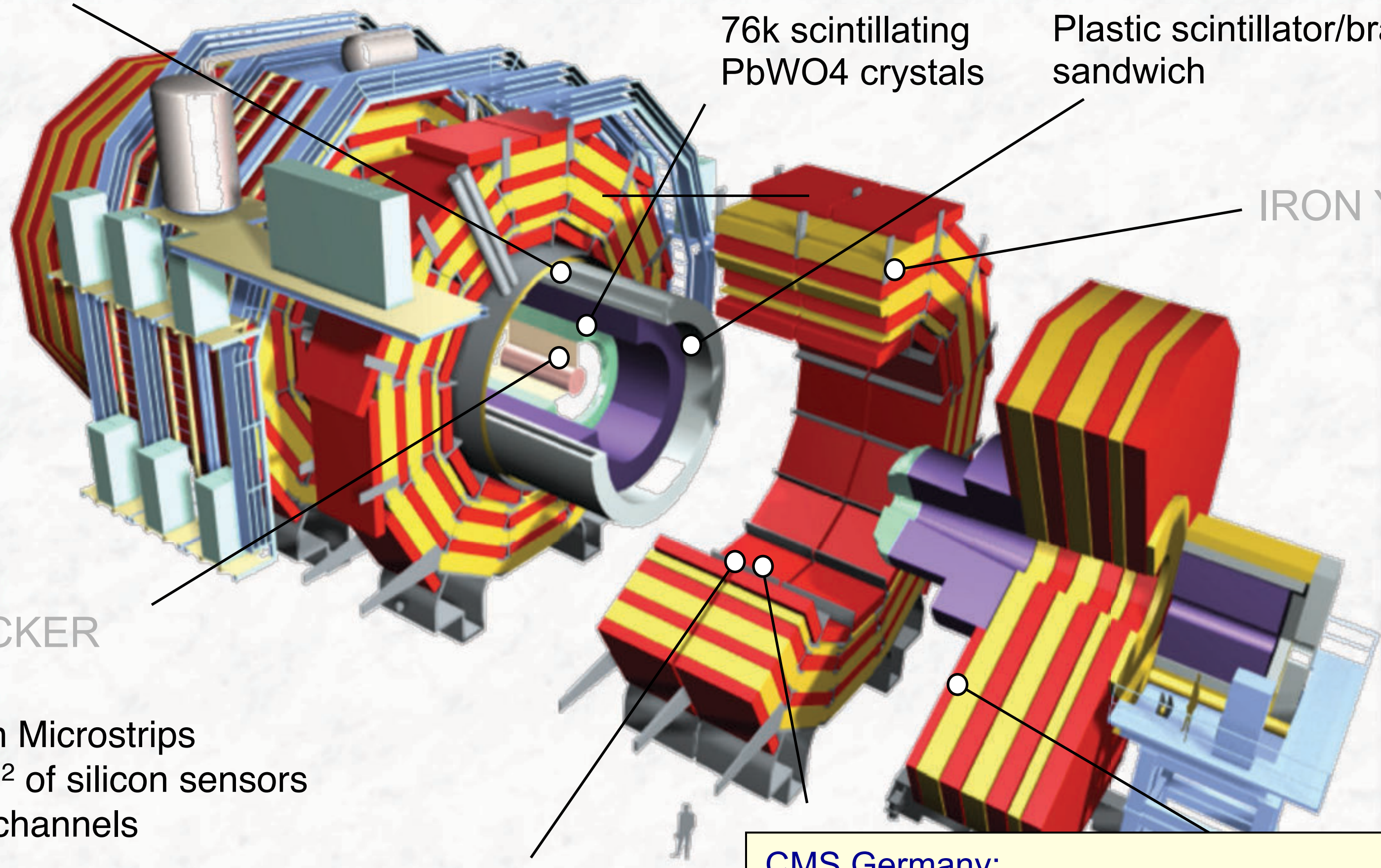
Diameter	25 m
Barrel toroid length	26 m
End-cap end-wall chamber span	46 m
Overall weight	7000 Tons

ATLAS Germany:
BMBF-Forschungsschwerpunkt ATLAS

- HU Berlin, Bonn, DESY, Dortmund, Dresden Freiburg, Giessen, Göttingen, Heidelberg, Mainz, LMU München, MPI München, Siegen, Würzburg, Wuppertal
- ~ 420 scientists (~200 students)



The CMS experiment



Superconducting Coil, 4 Tesla

CALORIMETERS

ECAL
76k scintillating PbWO4 crystals

HCAL
Plastic scintillator/brass sandwich

IRON YOKE

TRACKER

Pixels
Silicon Microstrips
210 m^2 of silicon sensors
9.6M channels

MUON BARREL

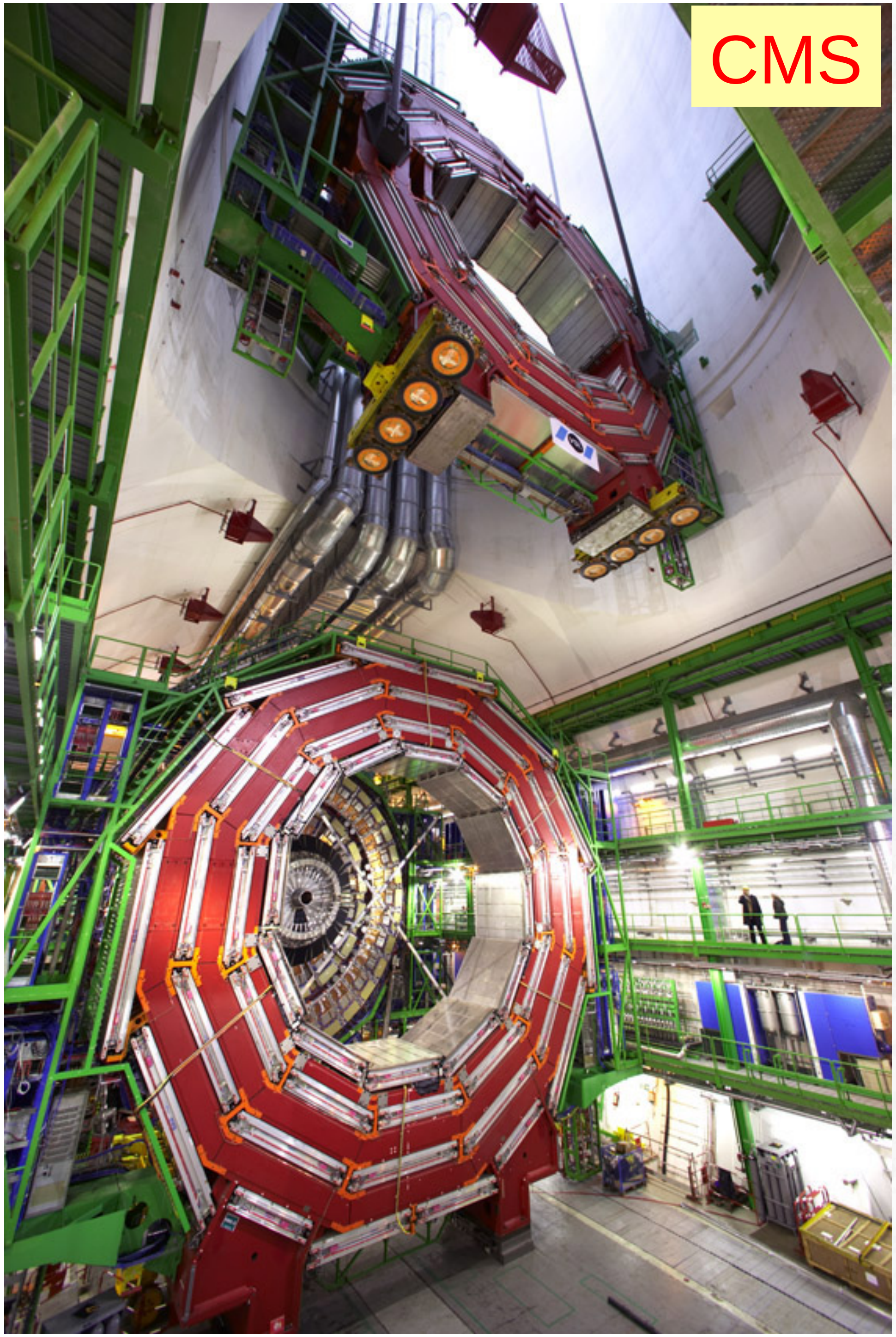
Drift Tube Chambers (**DT**)

Resistive P
Chambers (

Total weight	12500 t
Overall diameter	15 m
Overall length	21.6 m

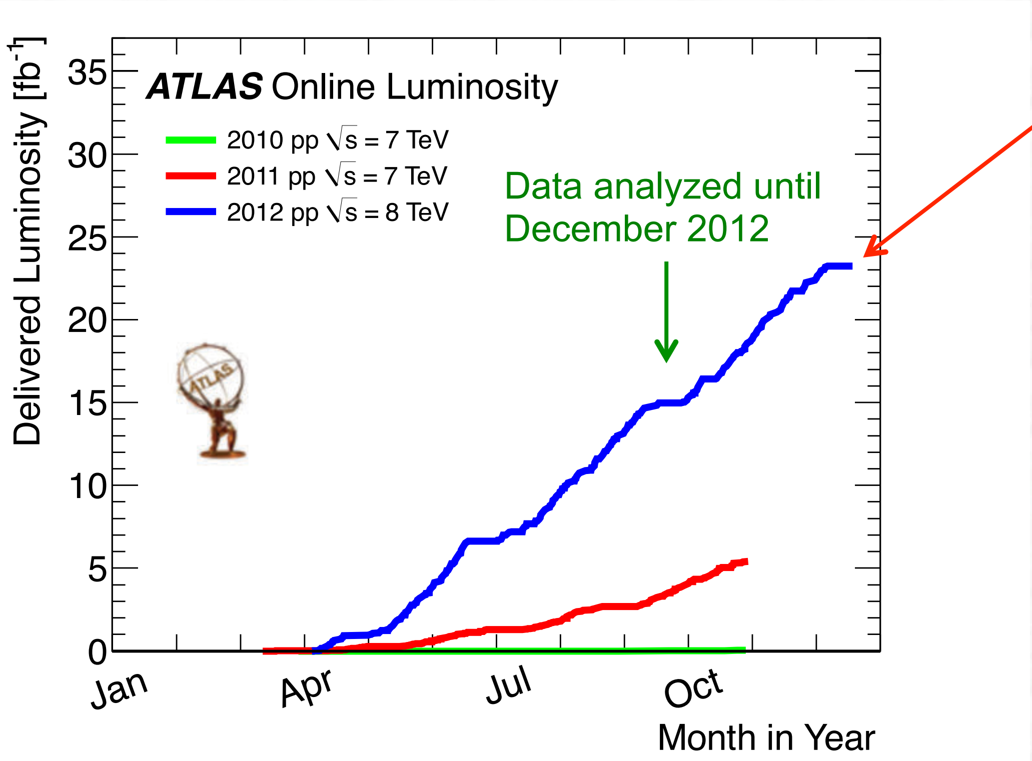
CMS Germany:
BMBF-Forschungsschwerpunkt CMS

- Aachen (Ib, IIIa, IIIb), DESY, Hamburg, Karlsruhe
- ~ 200 scientists (~90 students)


CMS

Data taking in 2011/ 2012

new



Some results with the full dataset

Until end 2012:

> 10^{15} pp collisions

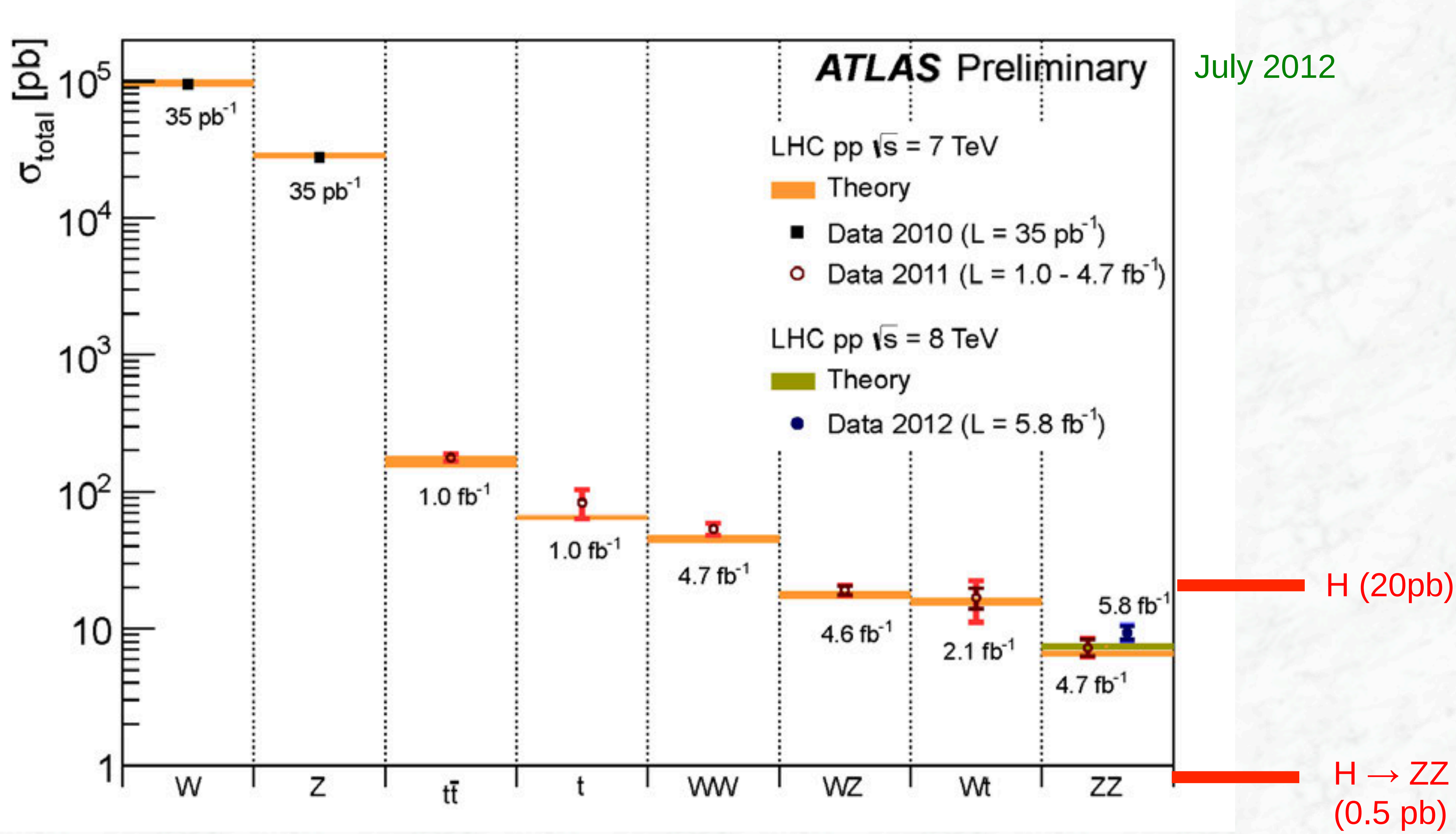
~10^{10} pp collisions recorded

$25 \cdot 10^6$ Z → μμ decays produced

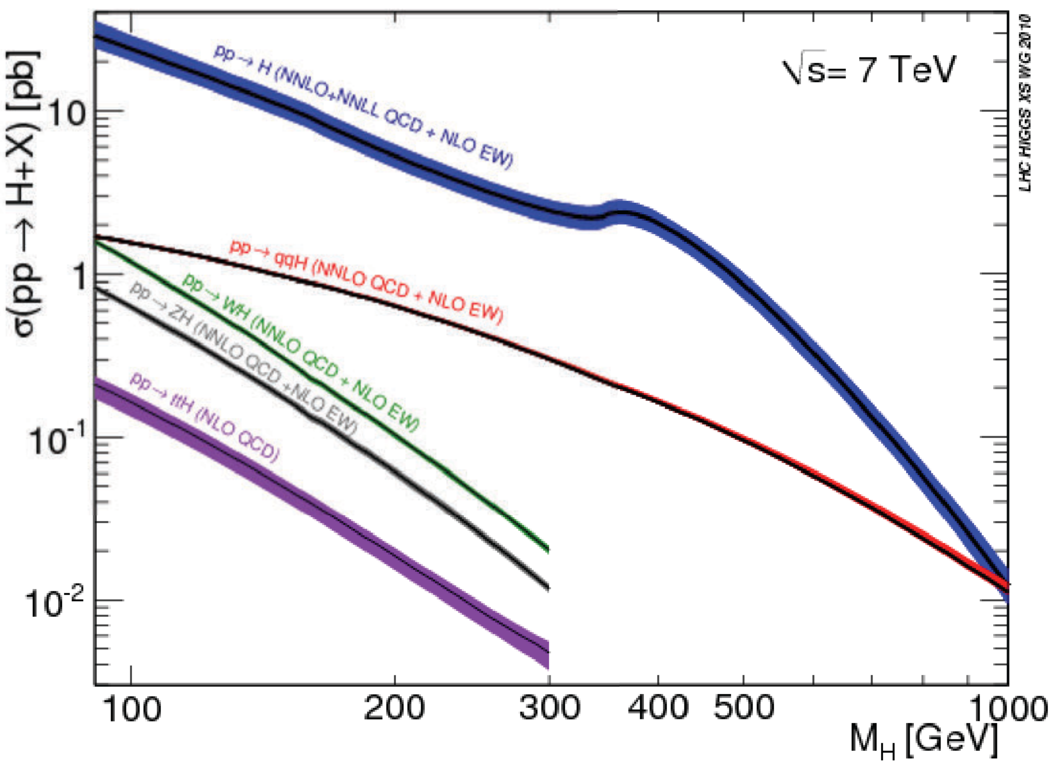
- Excellent LHC performance
  Peak luminosities > 7 10^{33} cm^{-2} s^{-1} (world record, 2012)

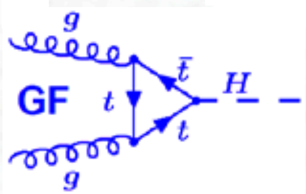
- Excellent performance of the experiments:
  - Data recording efficiency ~93.5%
  - Working detector channels >99%
  - Speed of data analysis

The Standard Model at the LHC

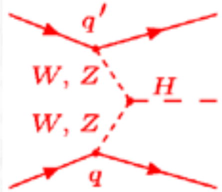


Higgs Boson Production

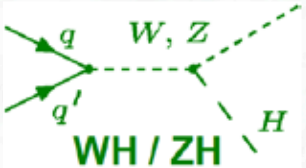




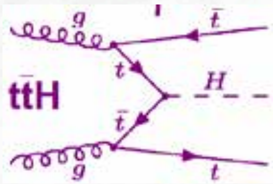
Gluon fusion



Vector boson fusion



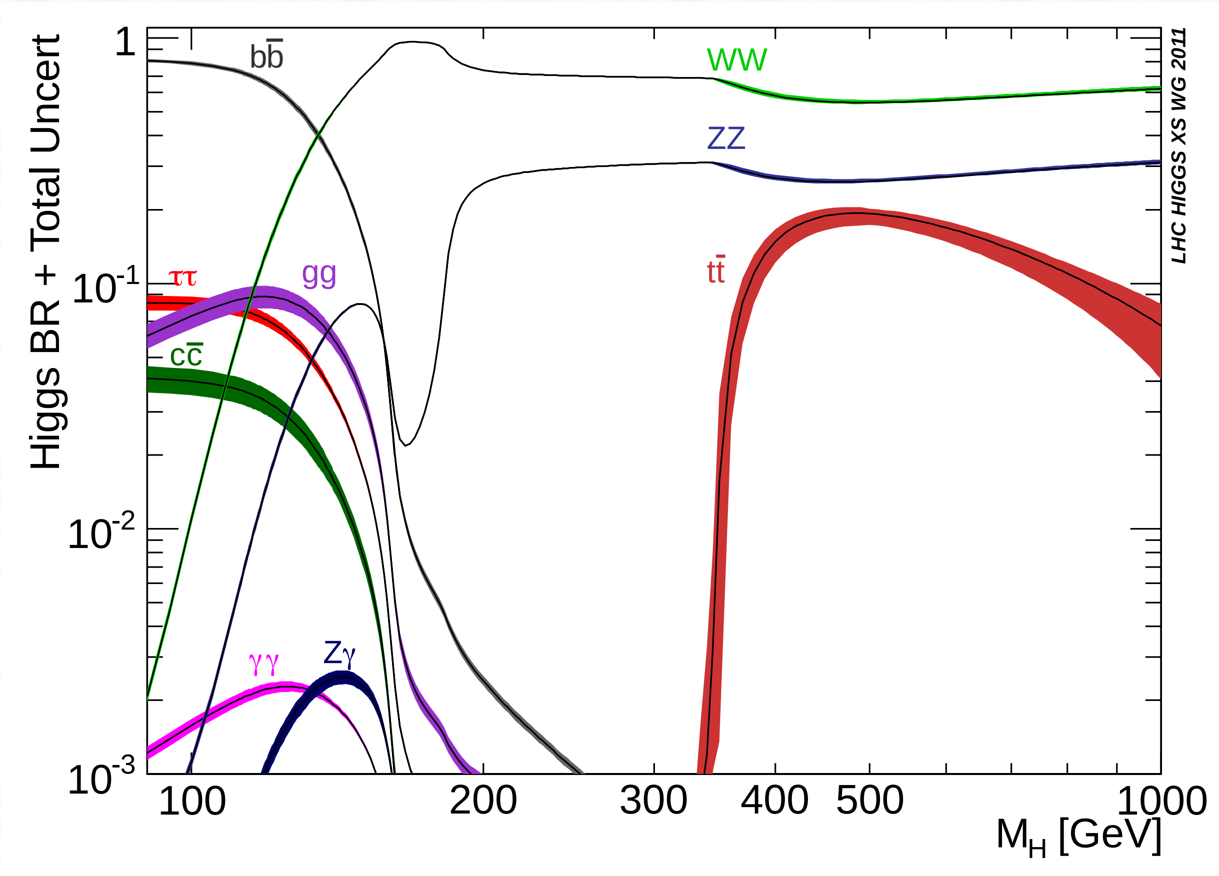
WH/ZH associated production



tt associated production

*) LHC Higgs cross-section working group
Large theory effort

Higgs Boson Decays

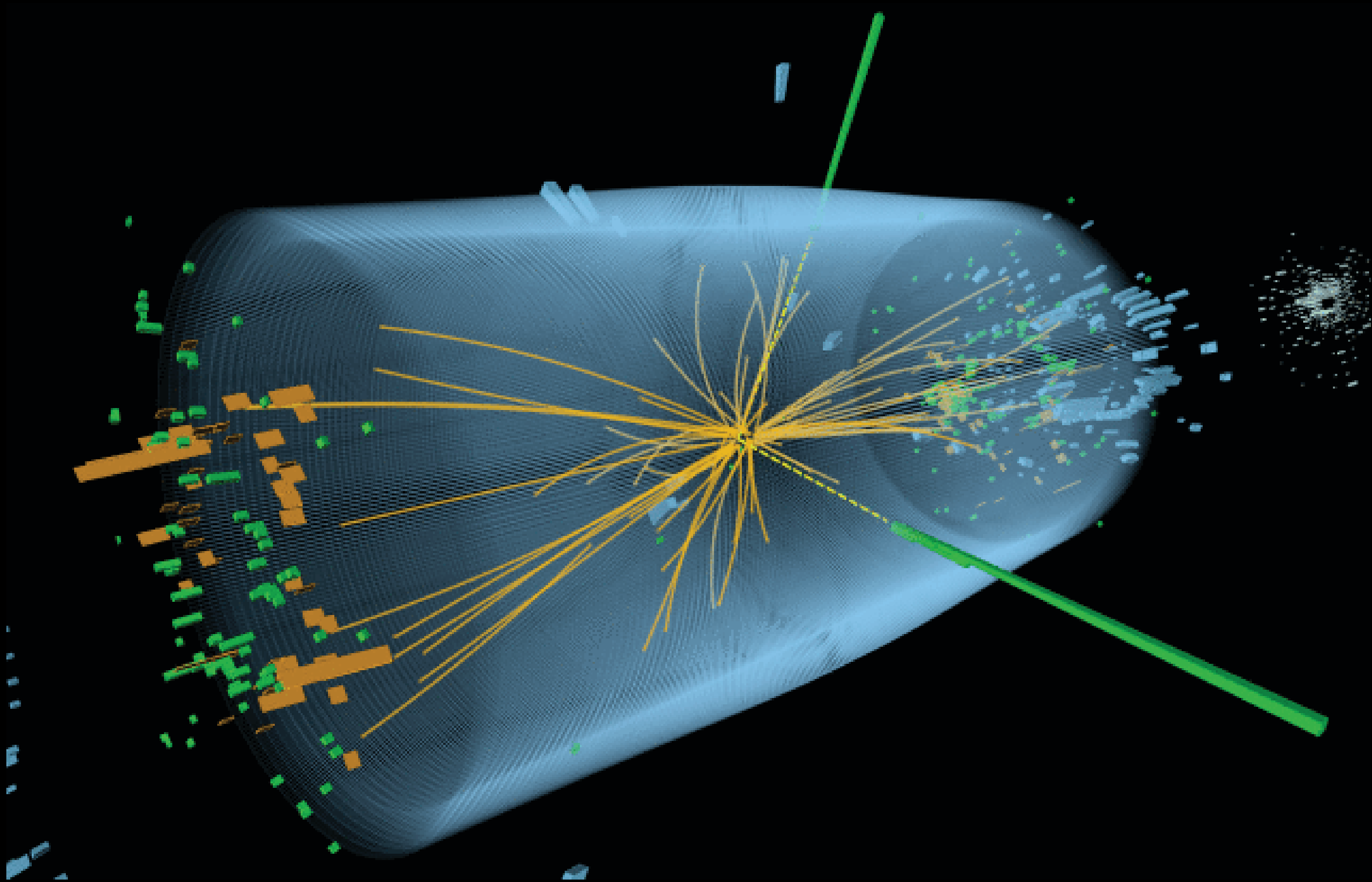


Important channels at hadron colliders: $H \rightarrow WW \rightarrow \ell\nu\ \ell\nu$

$H \rightarrow \gamma\gamma$

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

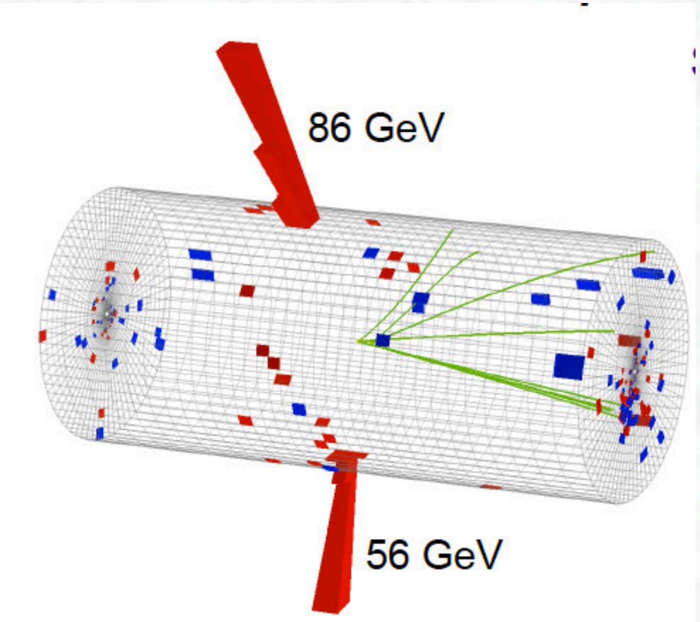
Discovery of a Higgs-like particle

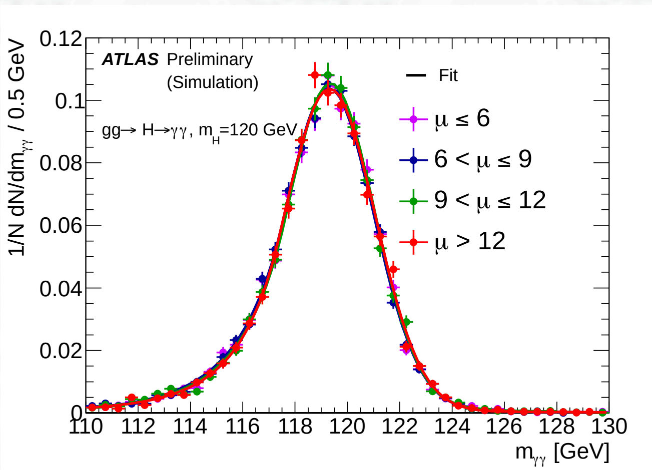


Expected number of decays in data:
m_H = 125 GeV

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

Search for the H → $\gamma\gamma$ decay



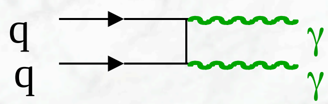


- 2 photons (isolated) with large transverse momenta

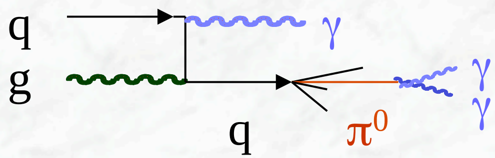
- Mass of the Higgs boson can be reconstructed $m_{\gamma\gamma}$

  Both experiments have a good mass resolution
  ATLAS: ~1.7 GeV/c^2 for m_H ~120 GeV/c^2

- Challenges:
  - signal-to-background ratio
    (small, but smooth irreducible $\gamma\gamma$ background)



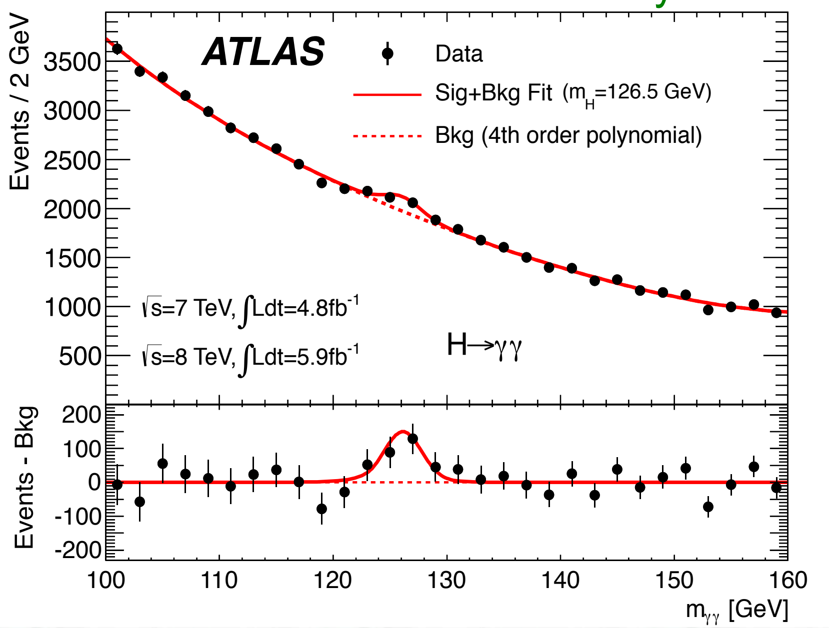
  - reducible backgrounds from γj and jj
    (several orders of magnitude larger than irreducible one)



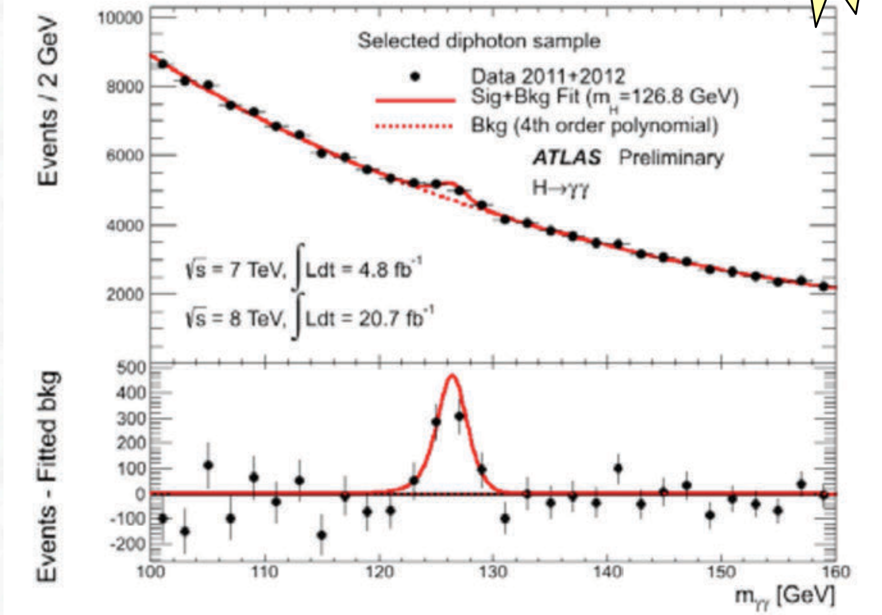
Result of the ATLAS search for H → $\gamma\gamma$

new

July 2012



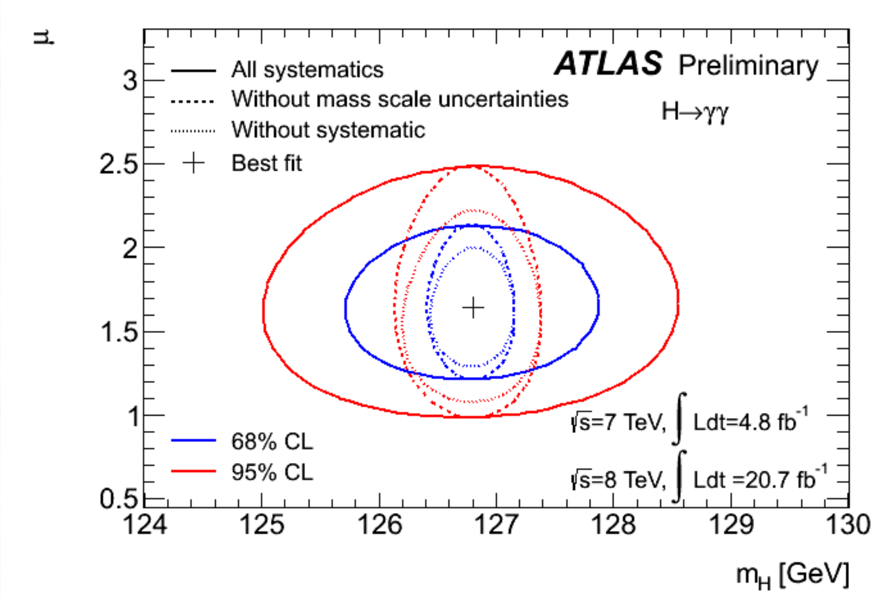
Full dataset



- p_0 value for consistency of data with background-only: ~ 10^{-13} (7.4σ)

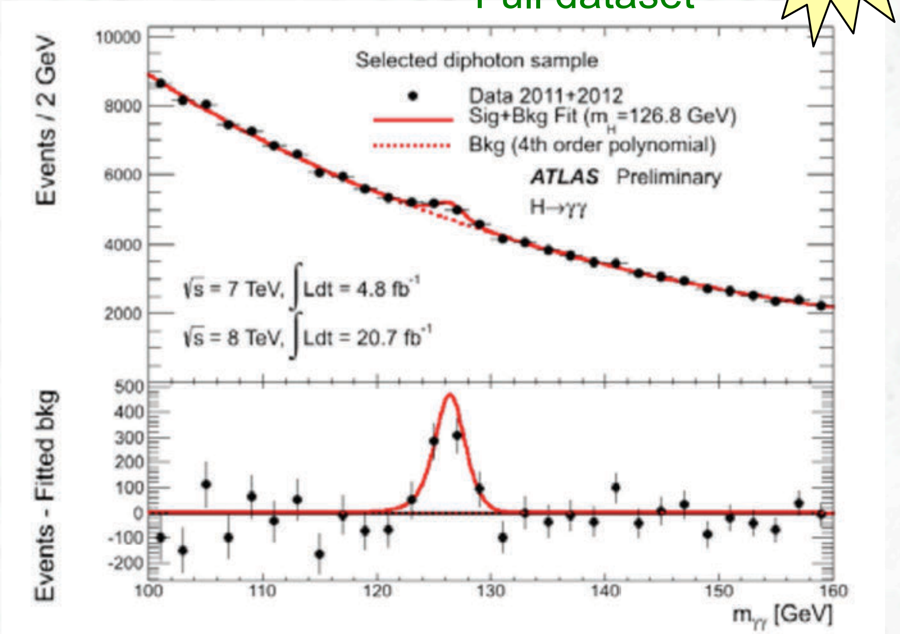
More details: “Eingeladener Vortrag” by Kerstin Tackmann (Thursday)
(Hertha-Sponer Preisträgerin)

Result of the ATLAS search for H → γγ



new

Full dataset



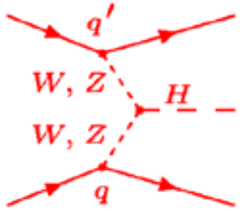
Mass: $m_H = 126.8 \pm 0.2\,(\text{stat}) \pm 0.7\,(\text{syst})$ GeV

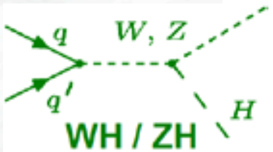
Signal strength: $\mu := \sigma / \sigma_{SM} = 1.65 \pm 0.24\,(\text{stat})\,^{+0.17}_{-0.13}\,(\text{syst})\,^{+0.18}_{-0.13}\,(\text{theo})$

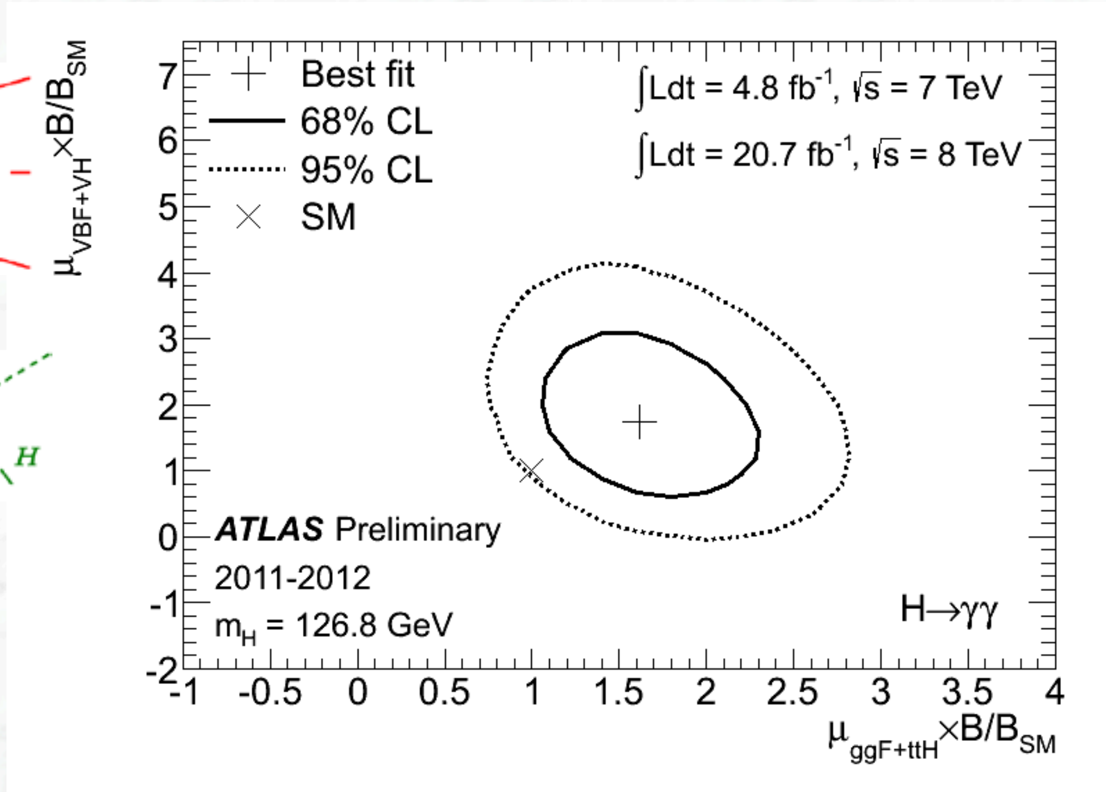
Separation of different production processes for H → γγ

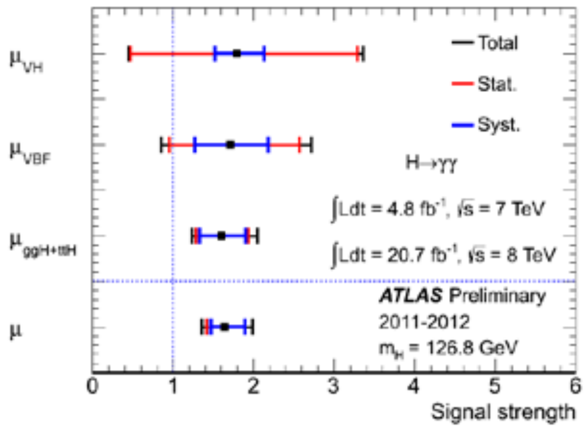
Full dataset

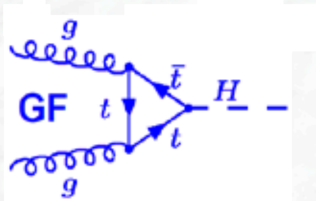
new

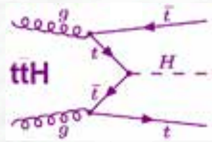






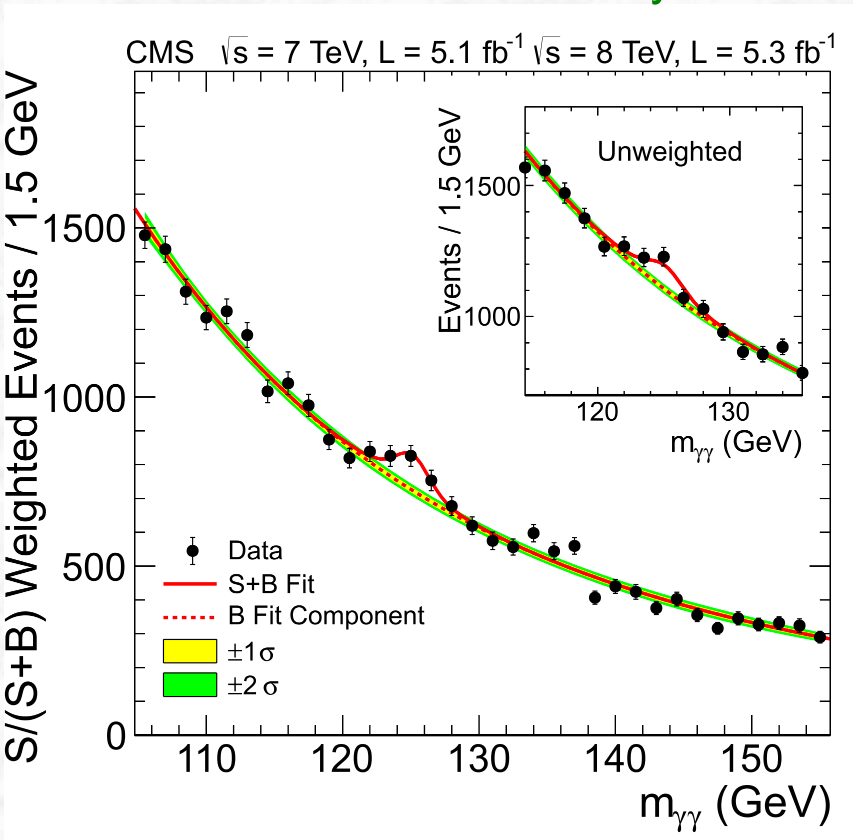


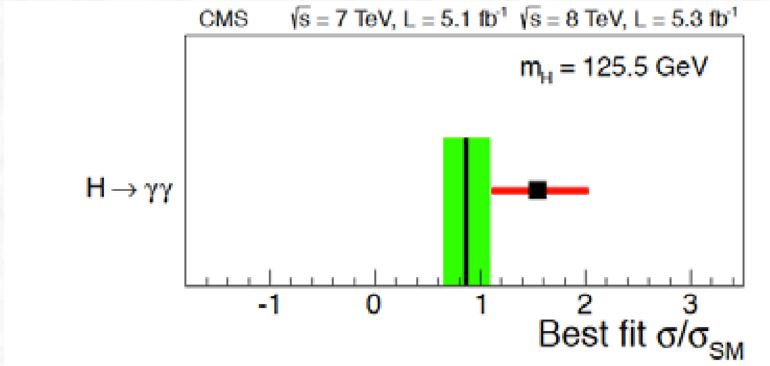


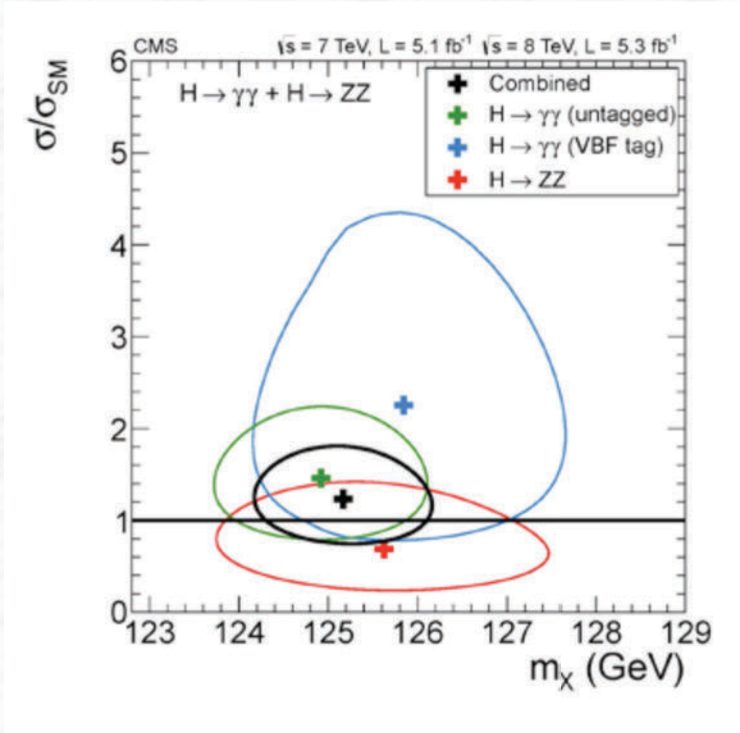


Result of the CMS search for H → γγ

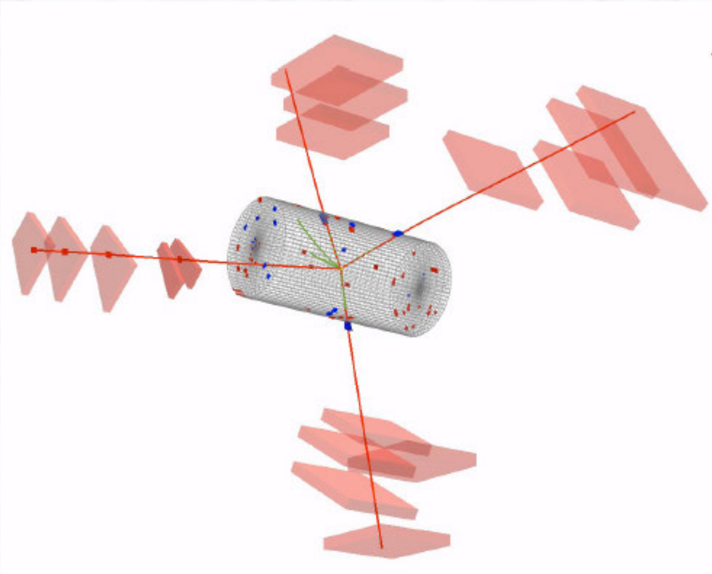
July 2012







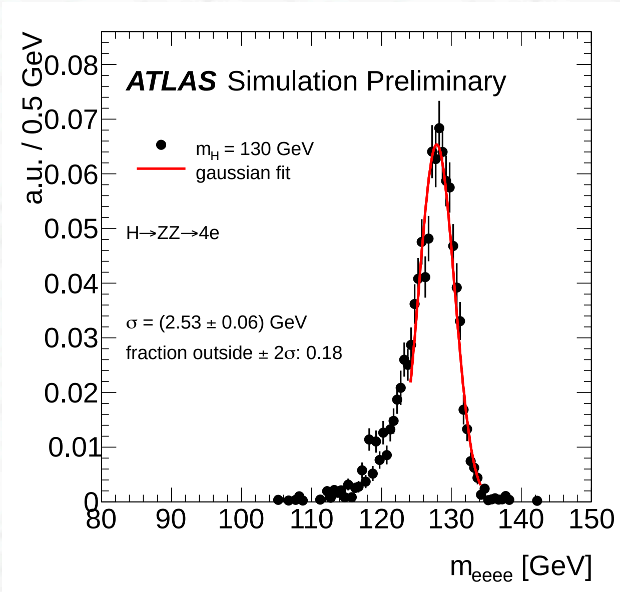
Search for the H → ZZ$^{(*)}$ → $\ell^+\ell^- \ell^+\ell^-$ decay



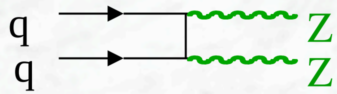
- The “golden mode”
  4 leptons (isolated) with large transverse momenta

- 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

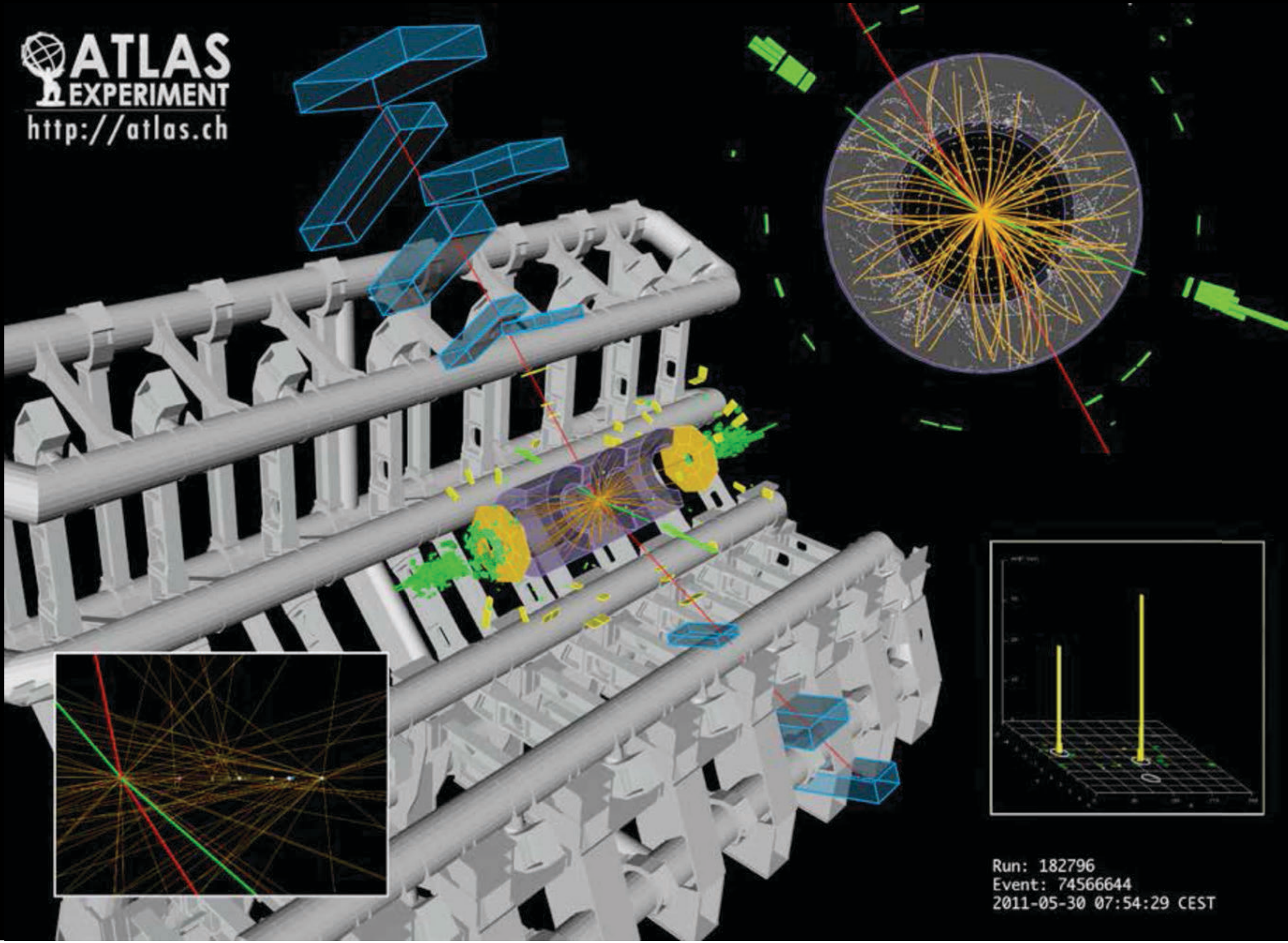


- Low signal rate, but also low background
  - Mainly from ZZ continuum



- In addition from tt and Zbb events:
  tt → Wb Wb → $\ell\nu$ c$\ell\nu$ $\ell\nu$ c$\ell\nu$
  Z bb → $\ell\ell$ c$\ell\nu$ c$\ell\nu$

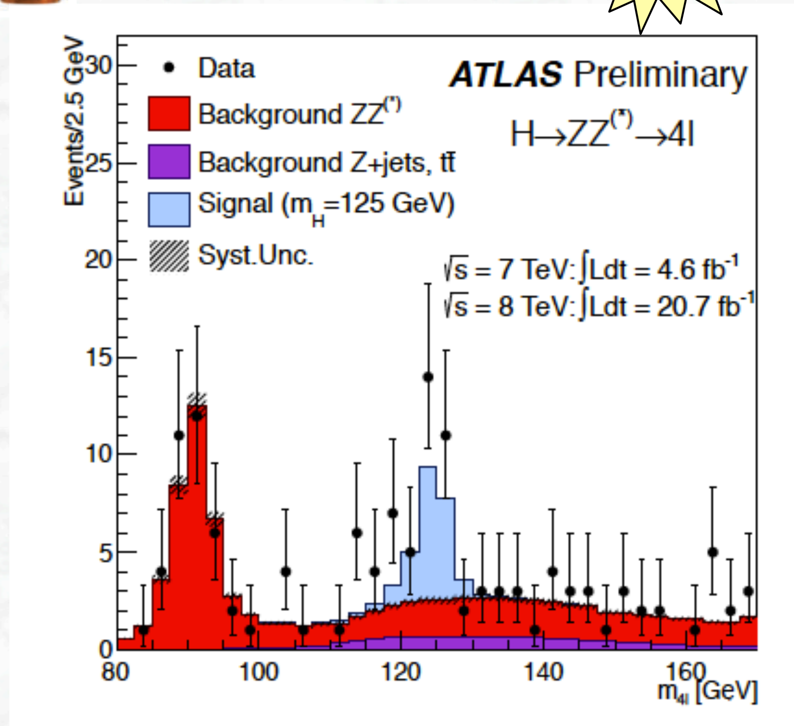
Candidate event for a H → ZZ → $e^+e^- \mu^+ \mu^-$ decay



4ℓ invariant mass spectra

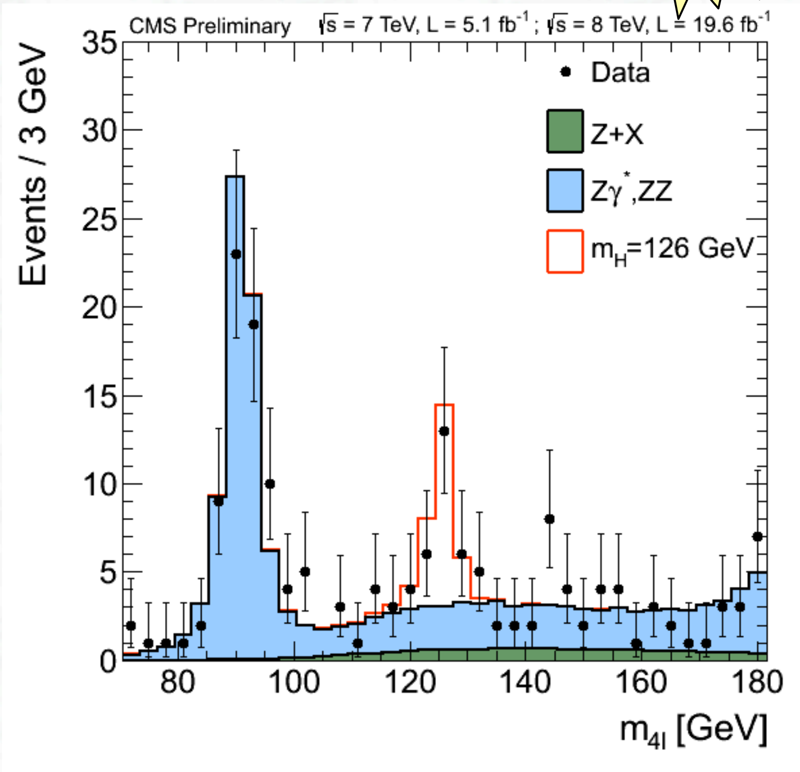
Full dataset

new



Full dataset

new



- p_0-values in both experiments

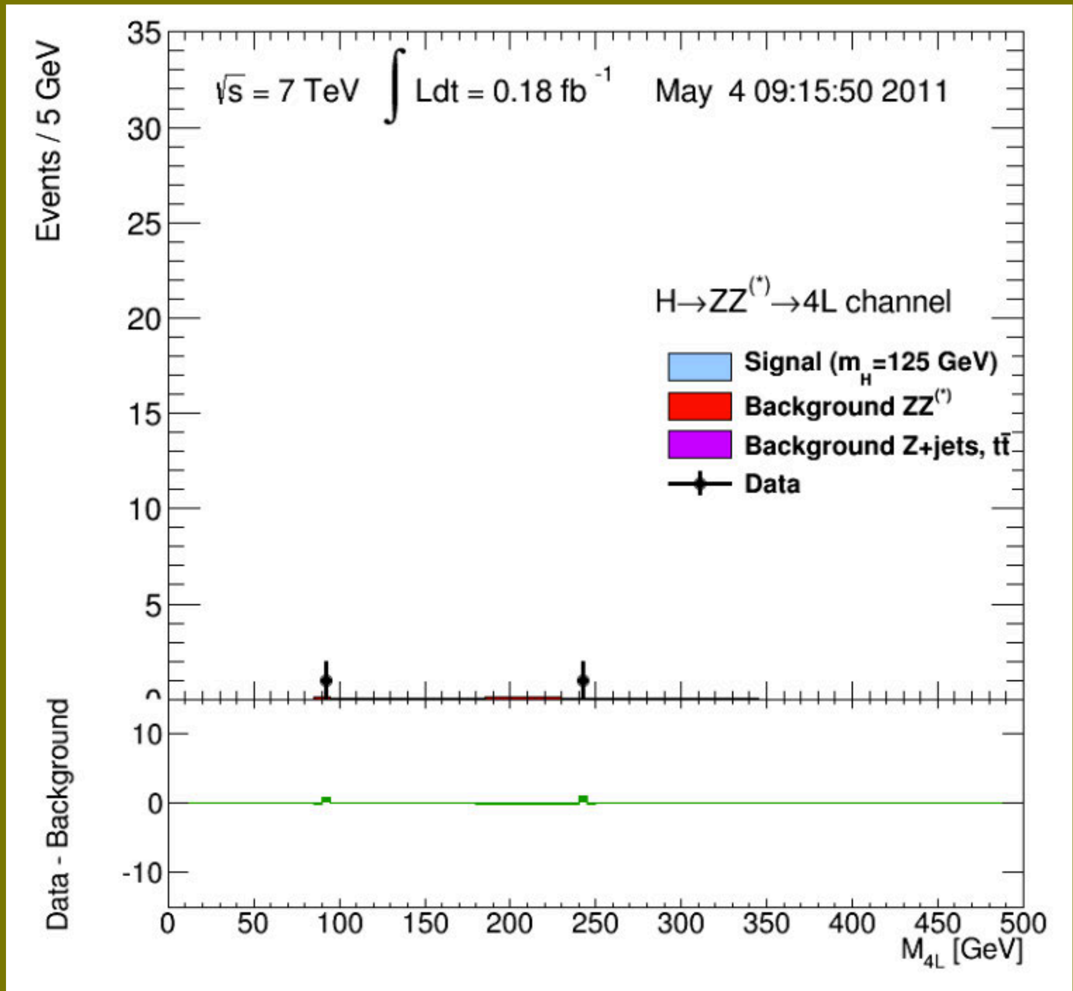
  ~10^{-11} (> 6σ)

Signal strengths:

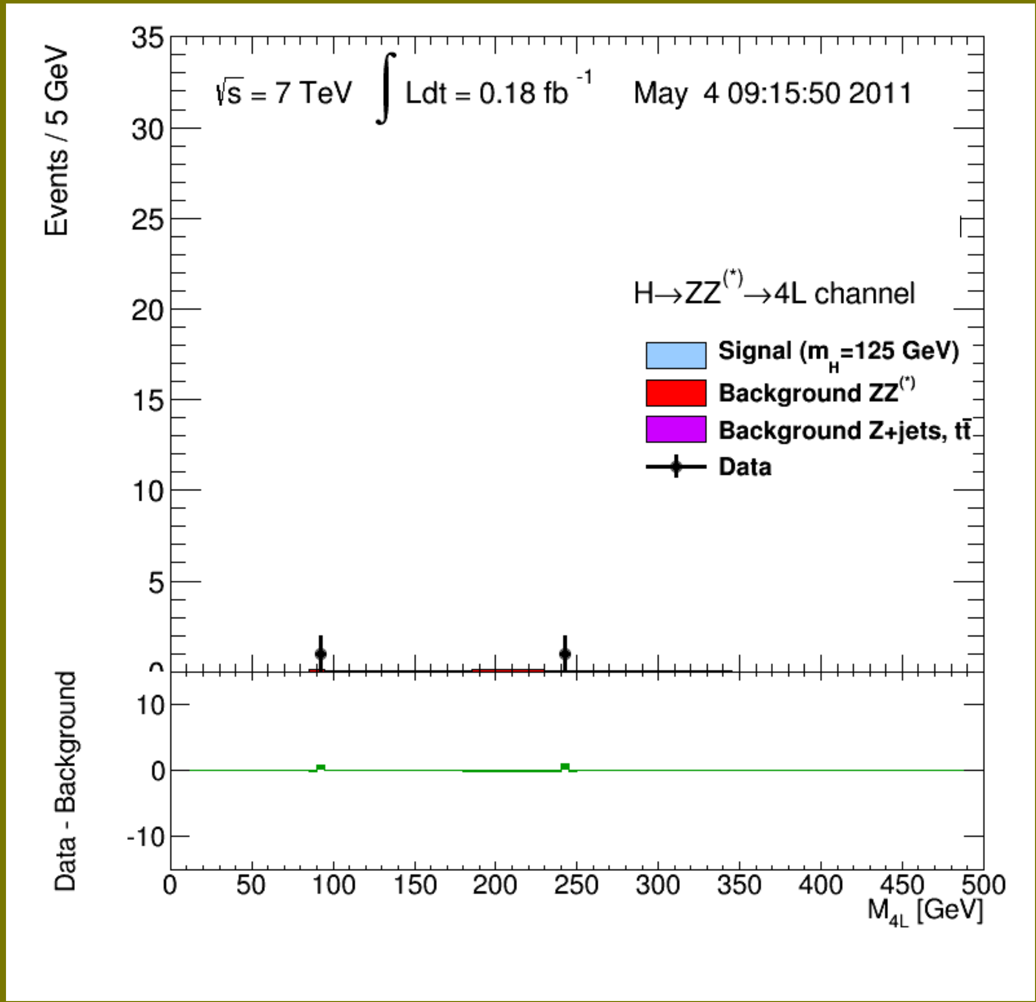
ATLAS: $\mu = 1.7 \pm 0.5$

CMS: $\mu = 0.91^{+0.30}_{-0.24}$

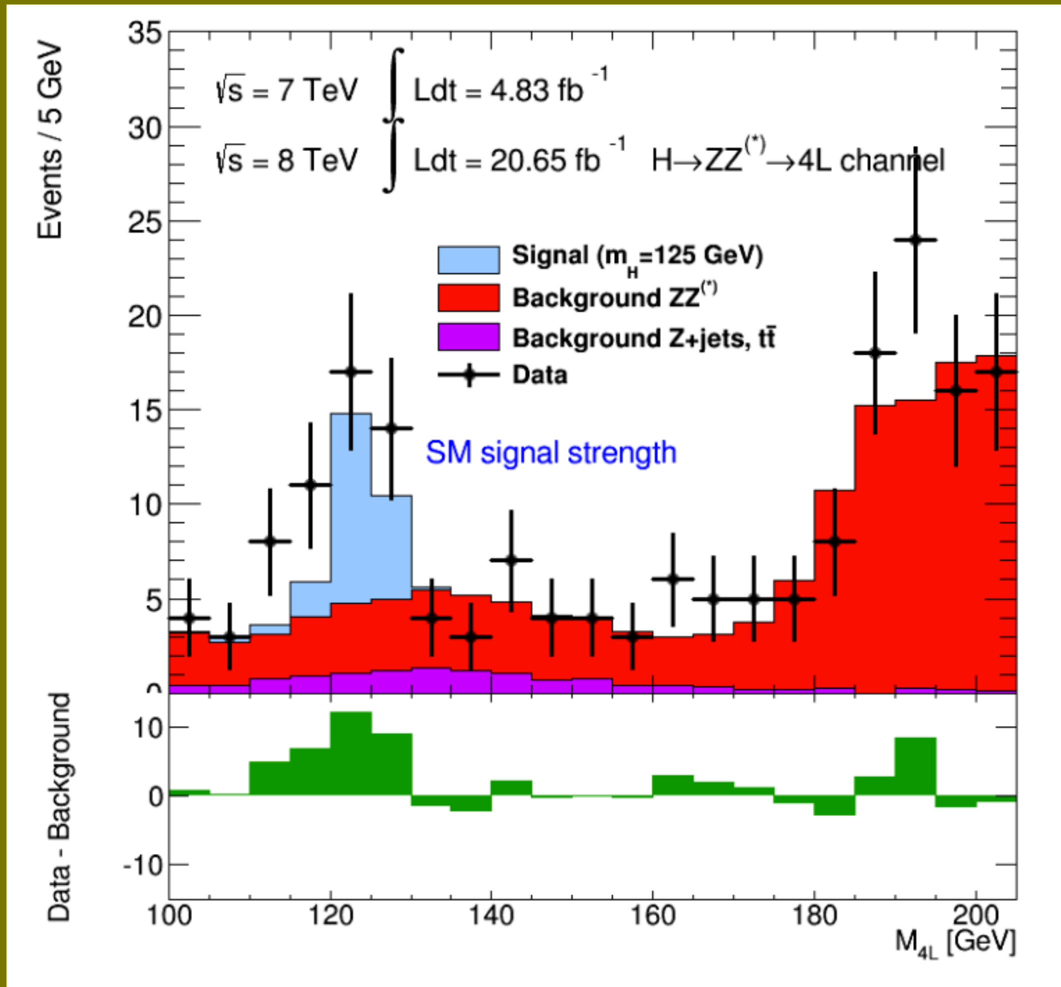
Time evolution of the $H \rightarrow ZZ \rightarrow 4\ell$ signal



Time evolution of the H → ZZ → 4ℓ signal



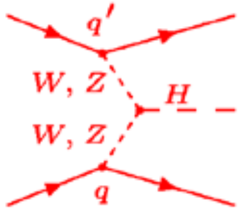
Time evolution of the H → ZZ → 4ℓ signal

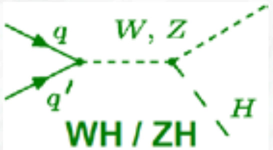


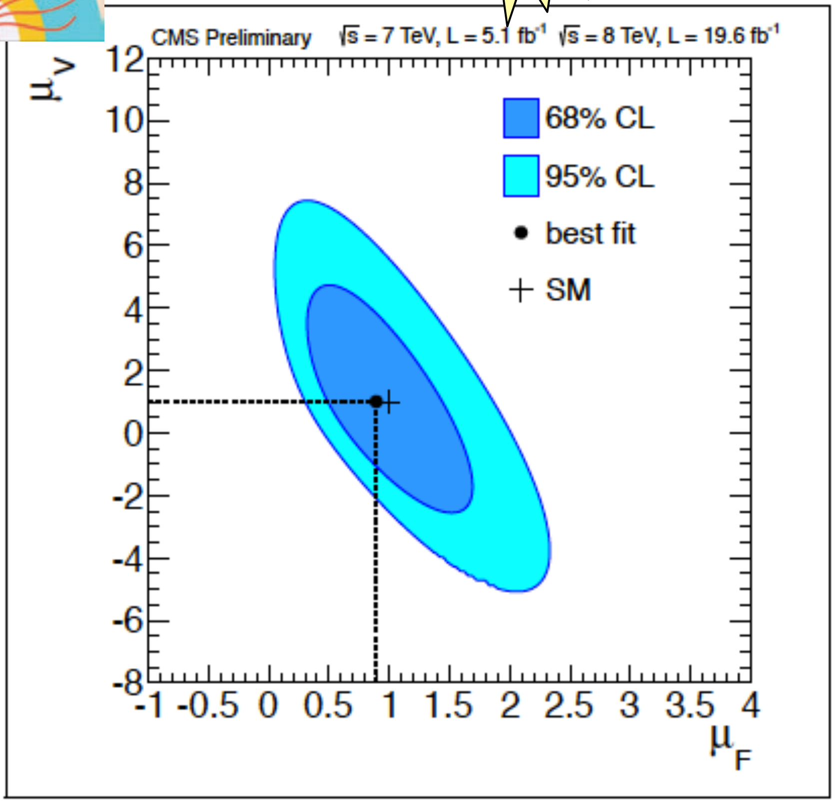
Separation of different production processes for H → ZZ → 4ℓ

new

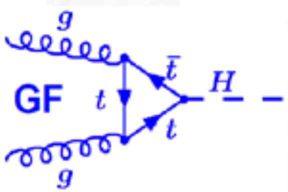
Full dataset

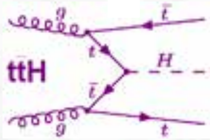






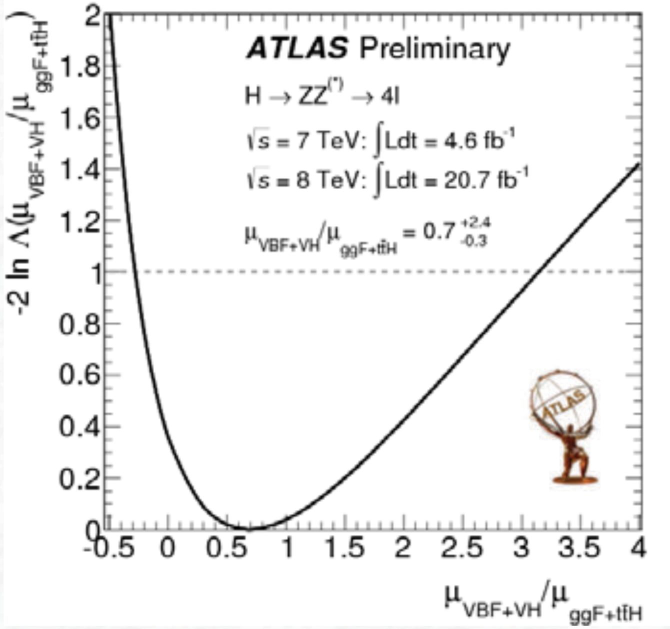
- μ_V (qqH, ZH, WH) $= 1.0^{+2.4}_{-2.3}$
- μ_F ($gg \to$ H, $t\bar{t}$H) $= 0.9^{+0.5}_{-0.4}$





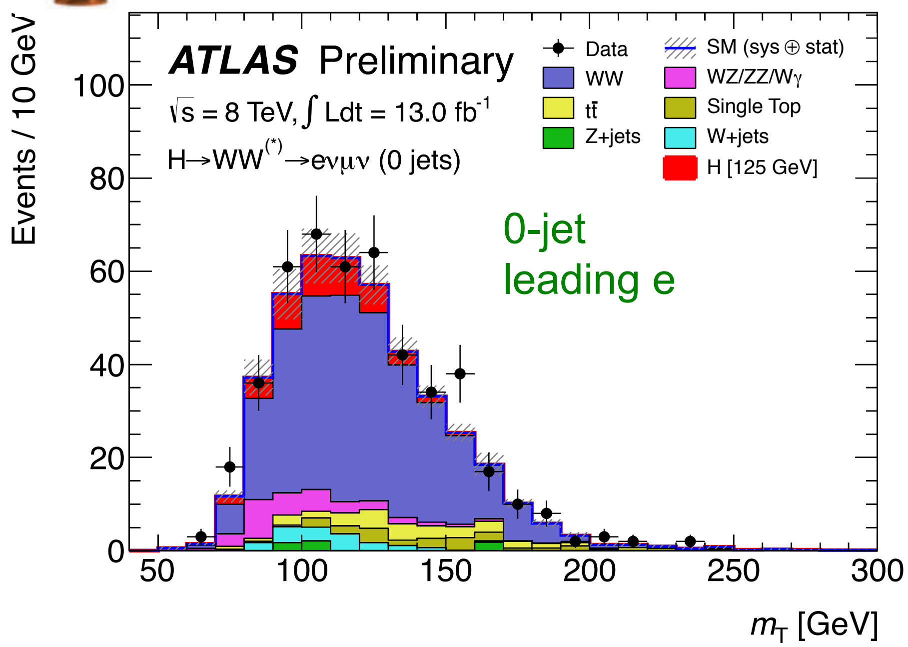
new

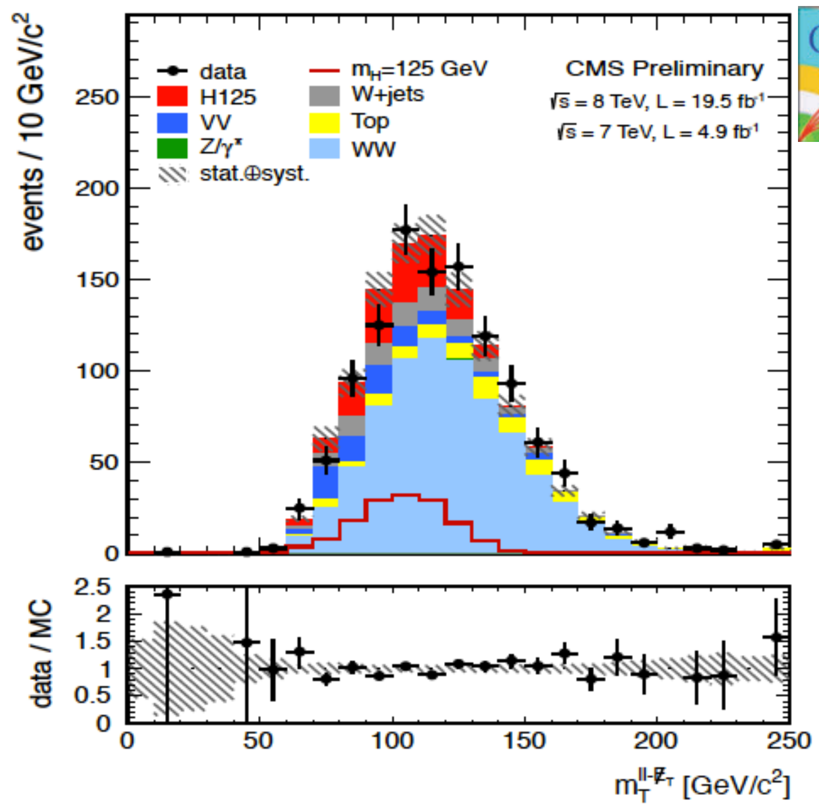
Full dataset



Results on the search for H → WW → ℓν ℓν decays

Full dataset new





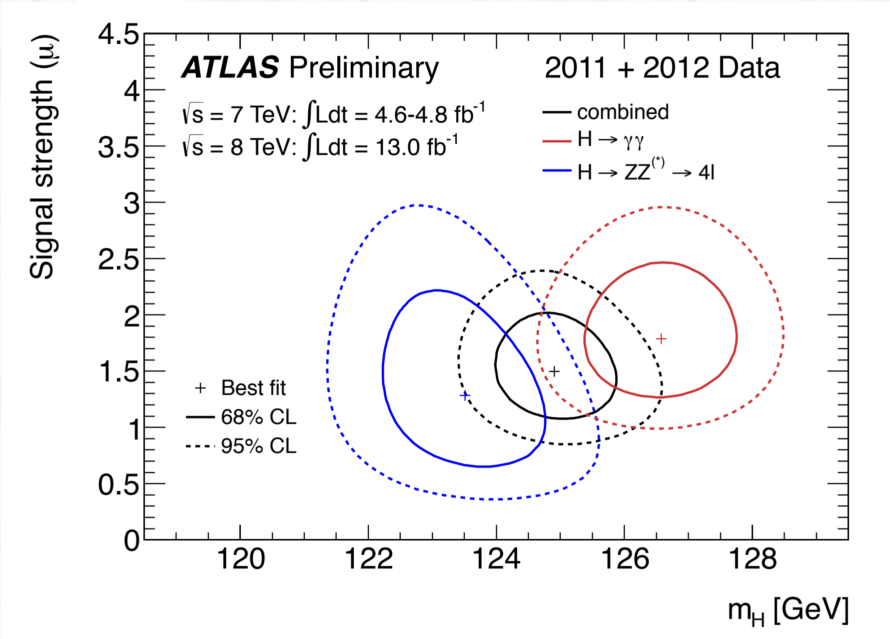
Signal strength:

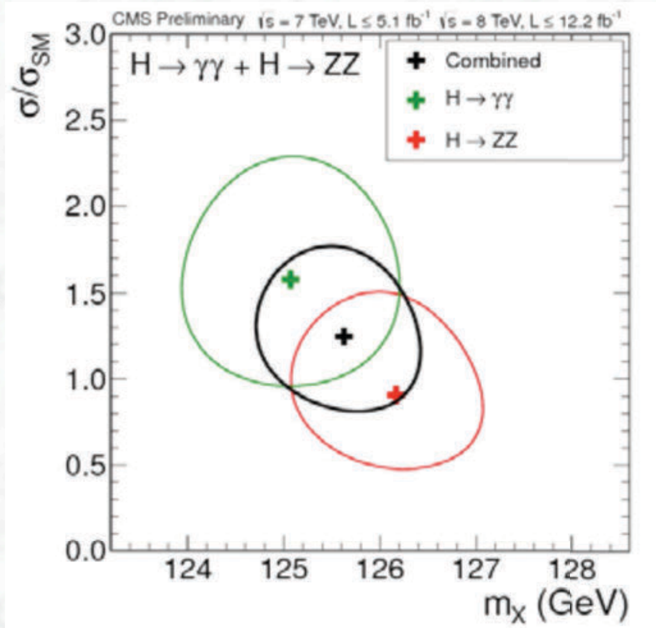
ATLAS: $\mu = 1.4 \pm 0.3$

CMS: $\mu = 0.76 \pm 0.21$

Clear excess in both experiments

Determination of mass, compatibility of channels





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

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

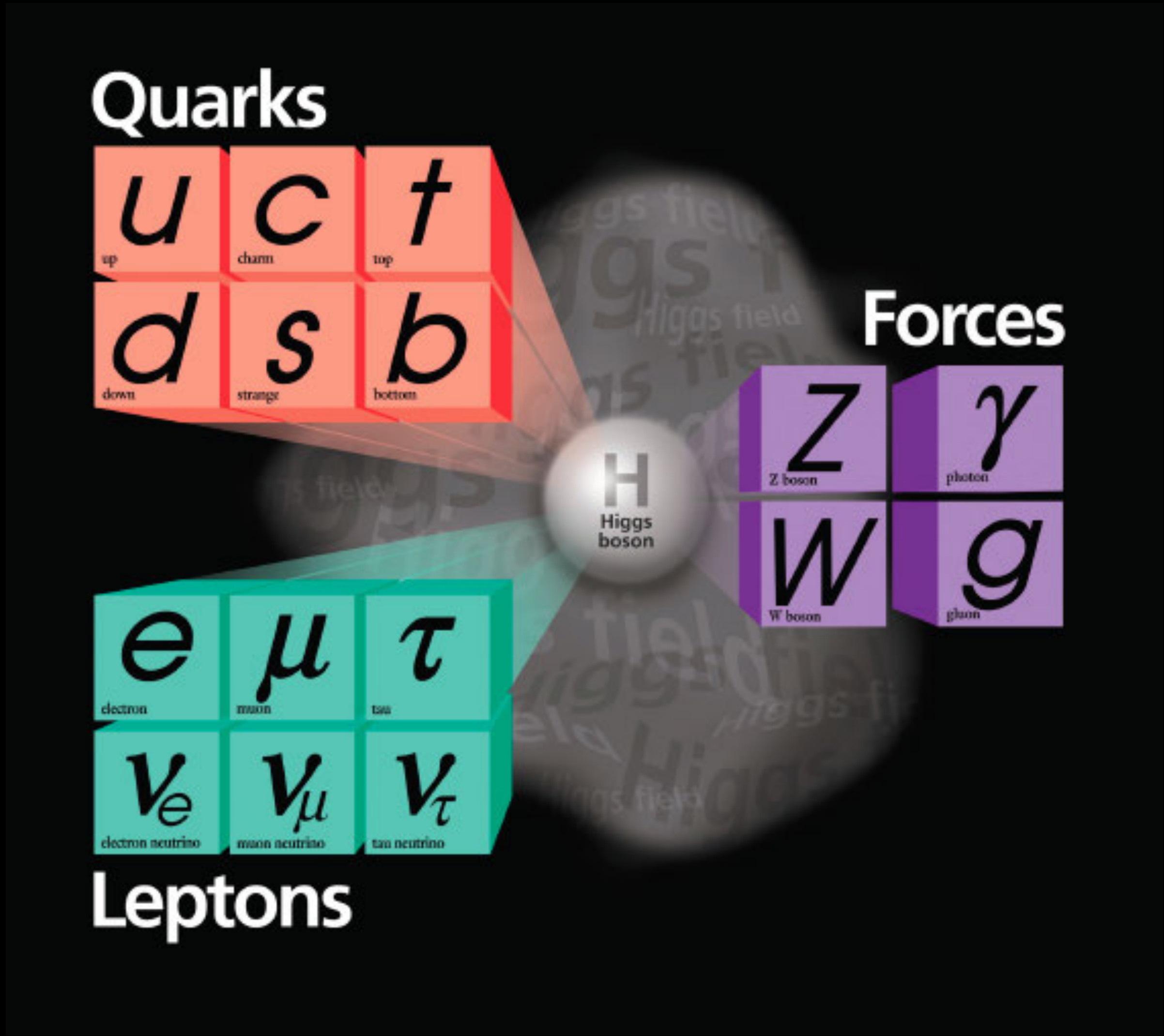
Updated mass values (full dataset, preliminary):

$m_H\ (\gamma\gamma) = 126.8 \pm 0.2\ (\text{stat}) \pm 0.7\ (\text{syst})$ GeV

$m_H(4\ell) = 124.3^{+0.6}_{-0.5}\ (\text{stat})\ ^{+0.5}_{-0.4}\ (\text{syst})$ GeV

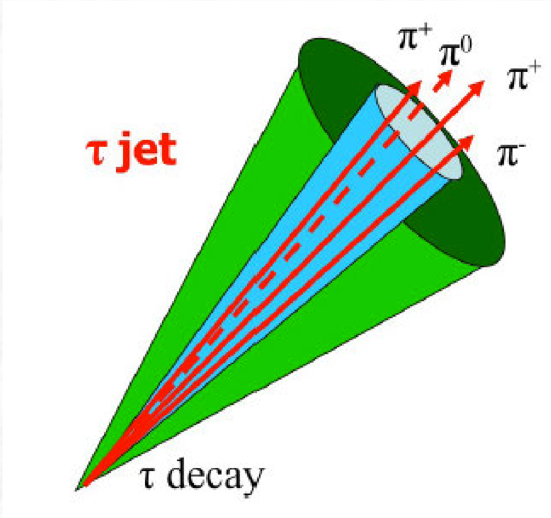
$m_H\ (4\ell) = 125.8 \pm 0.5\ (\text{stat}) \pm 0.2\ (\text{syst})$ GeV

Couplings to quarks and leptons ?



Search for H → $\tau\tau$ and H → bb decays

Why is the search in these decay modes so challenging?

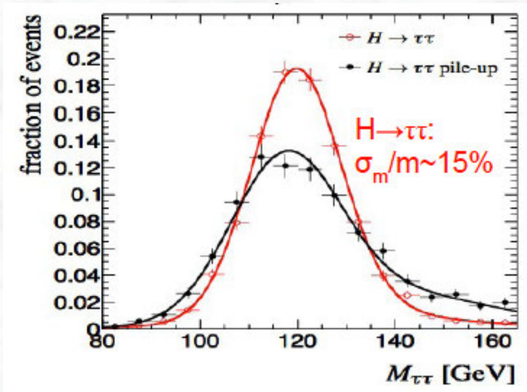


- The τ lepton is the heaviest lepton

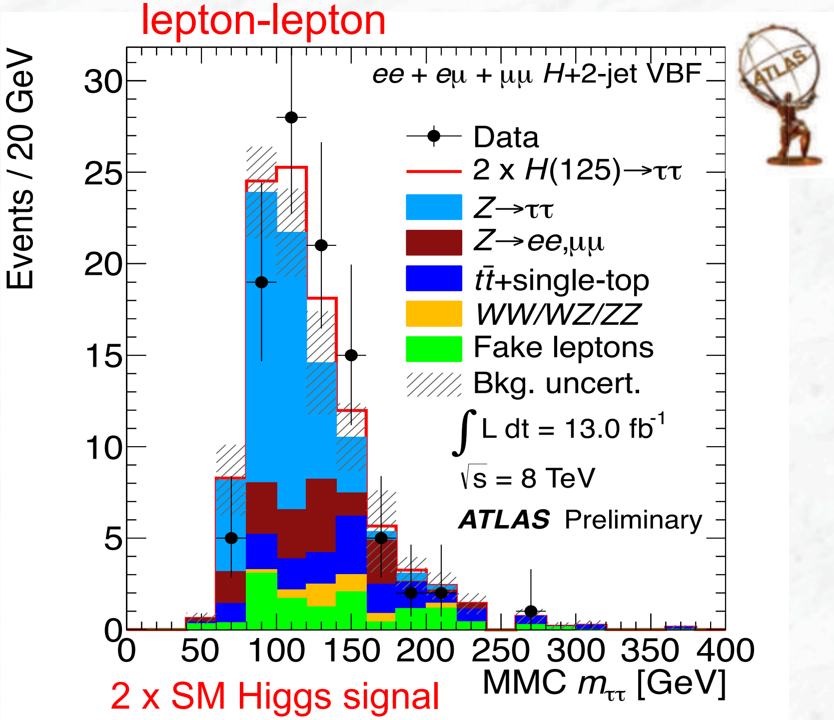
  $m_\tau = 1.78$ GeV /c^2, lifetime 2.9 10^{-13} s

  Decays into hadrons $\tau \rightarrow$ hadrons ν_τ (65%)
  $\tau \rightarrow e\nu_e\nu_\tau,\ \mu\nu_\mu\nu_\tau$ (35%)

- Challenge: distinguish hadronic τ decays from hadronic jet activity

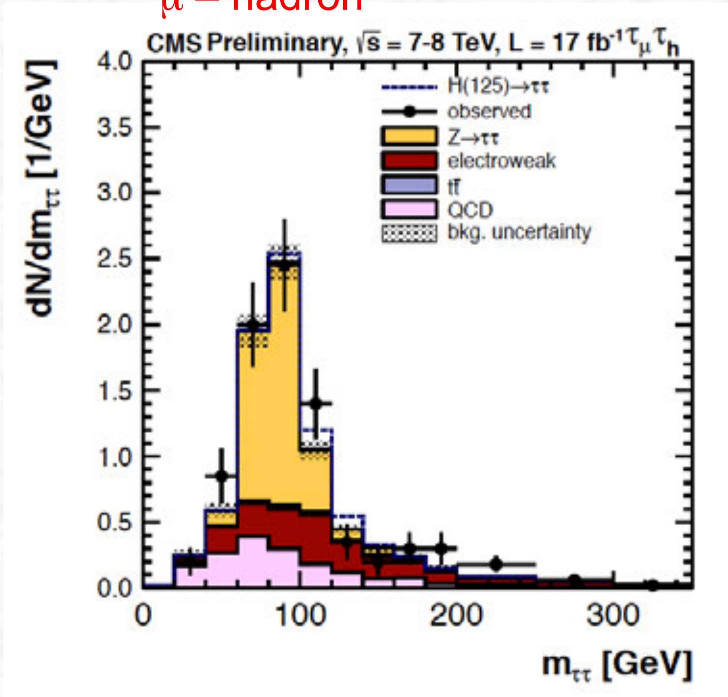


- Neutrinos in the final state, poor mass resolution lepton-lepton



2 x SM Higgs signal

μ – hadron



- Analysis is split into three sub-channels:
  - H → ττ → ℓ νν ℓ νν
  - H → ττ → ℓ νν had ν
  - H → ττ → had ν had ν

- Data set: 13 – 17 fb^{-1}

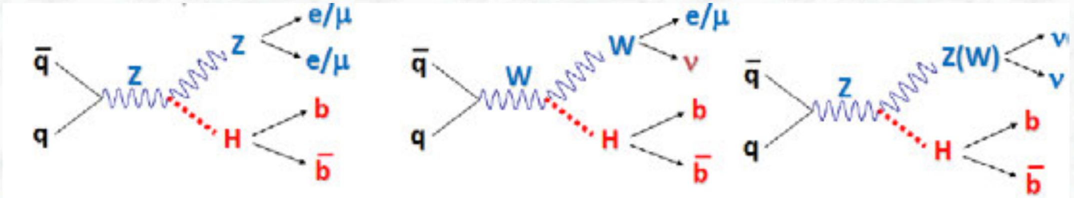
Signal strength (all sub-channels):

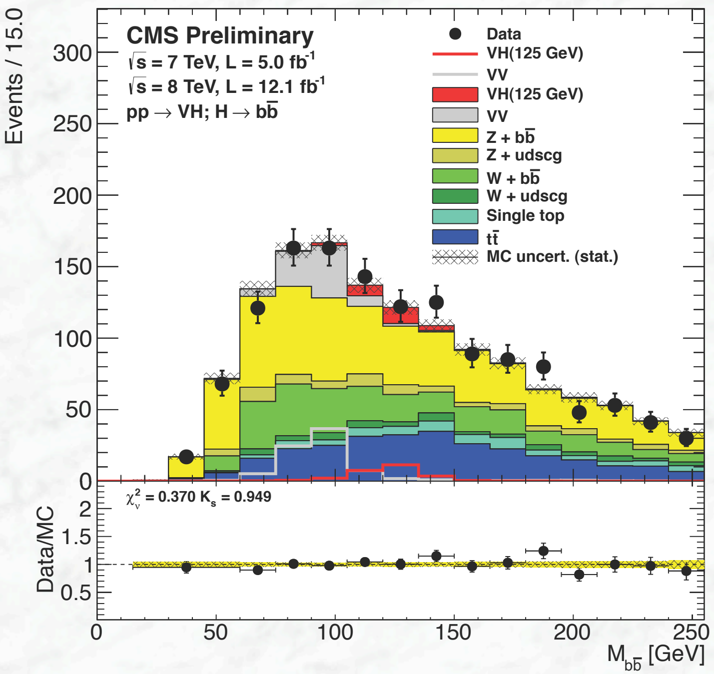
ATLAS: $\mu = 0.7 \pm 0.7$

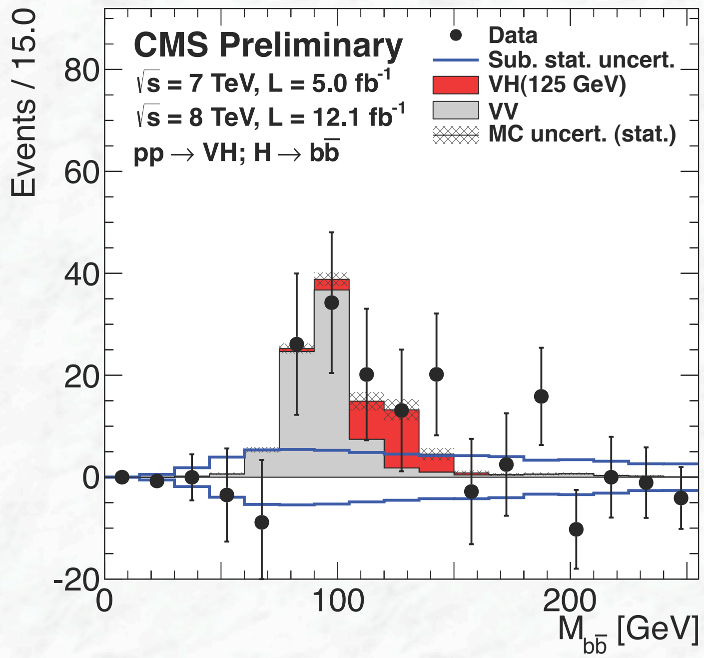
CMS: $\mu = 0.7 \pm 0.5$

More details: “Eingeladener Vortrag” by Stanley Lai (Thursday)

Results on H → bb searches

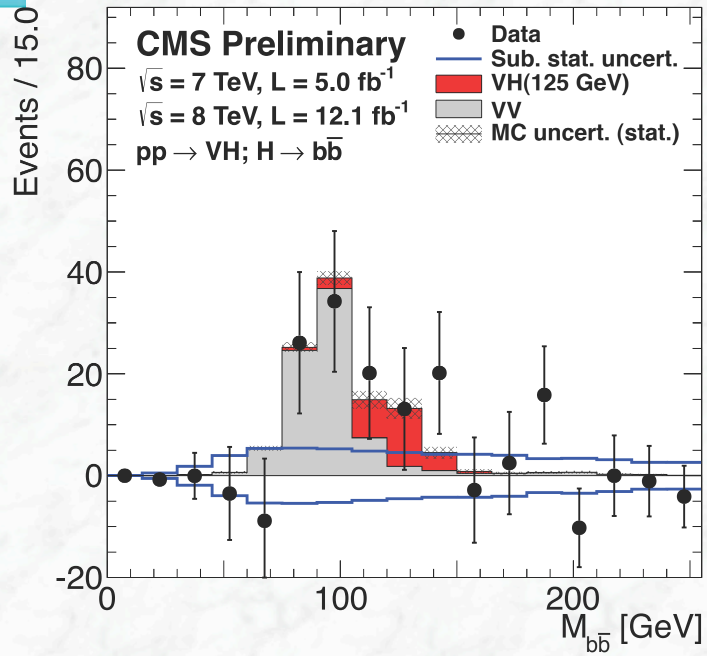


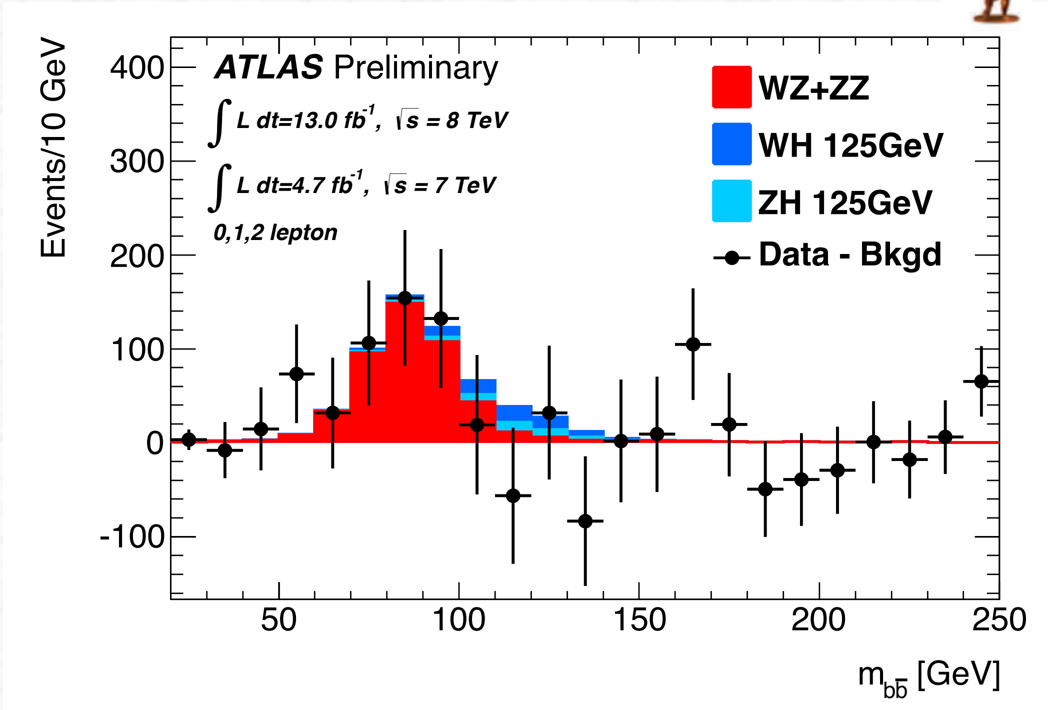




- Small excess is showing up around 125 GeV
- However, the significance is still low !

Results on H → bb from ATLAS



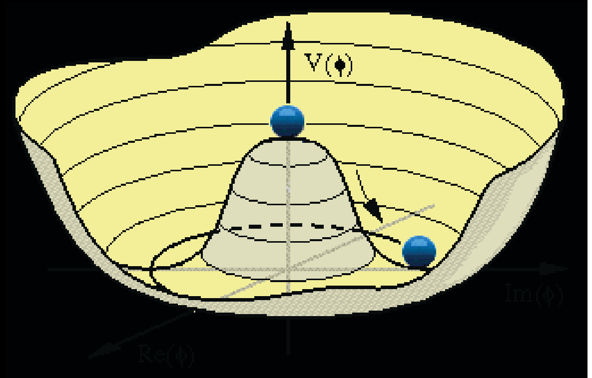


Signal strength:

ATLAS: $\mu = -0.4 \pm 1.0$

CMS: $\mu = 1.3^{+0.7}_{-0.6}$

Is the new particle the Higgs Boson ?



- Production rates ?

  Couplings to bosons and fermions

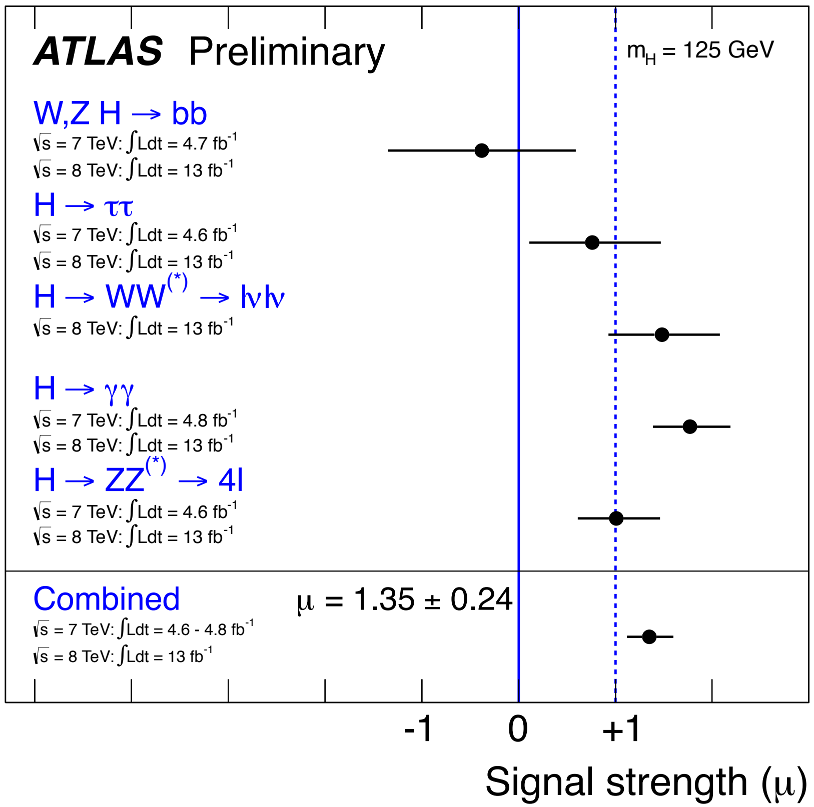
- Spin, J^P quantum number

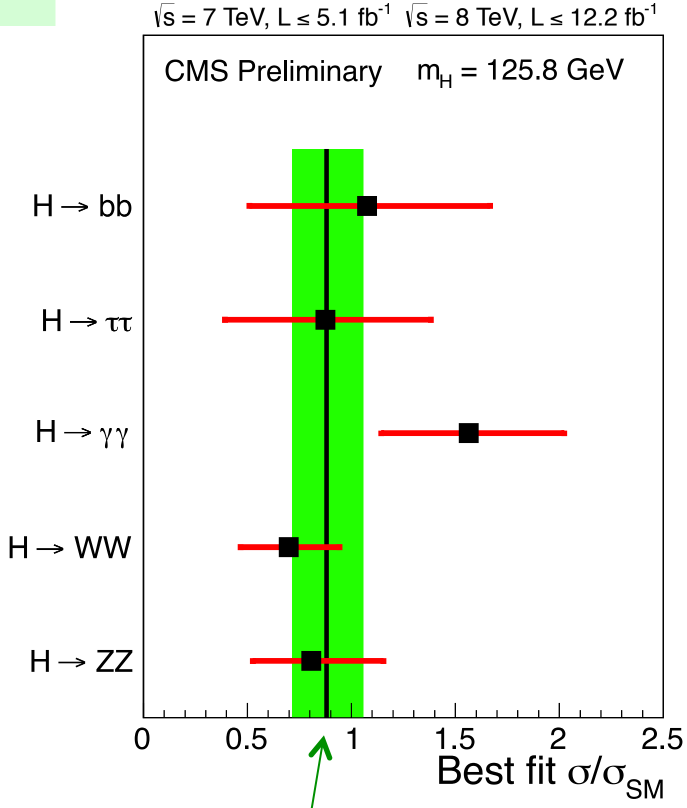
More details: "Eingeladener Vortrag" by Johannes Elmsheuser (Thursday)
"Hauptvortrag" by Thomas Müller (Friday)

Signal strength in individual decay modes

-including new data up to Sept. 2012-

updates expected very soon





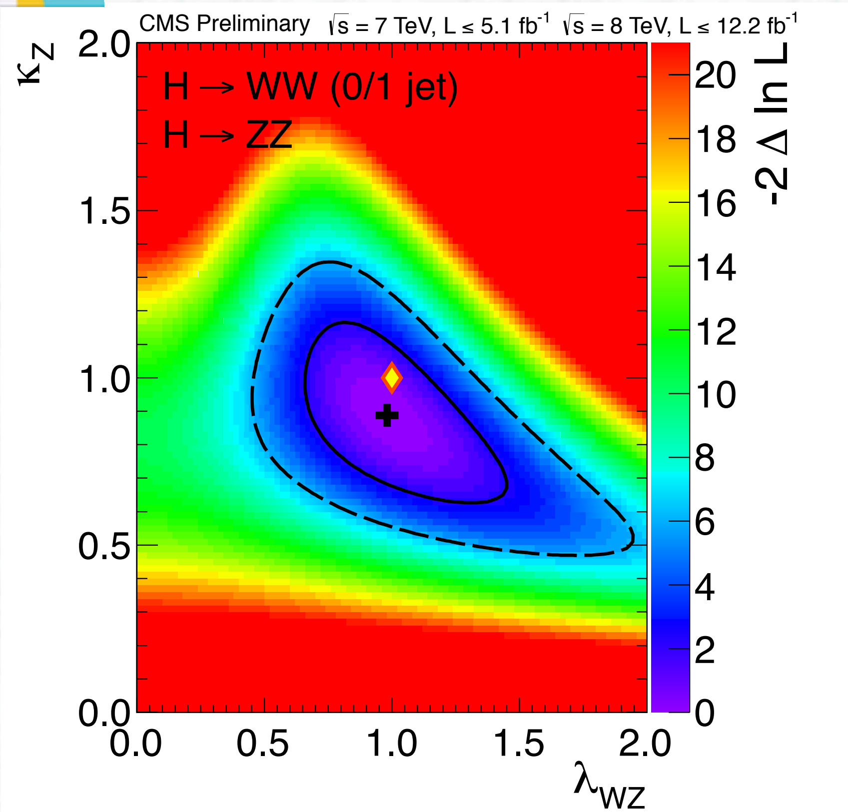
μ = 0.88 ± 0.21

- 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 !

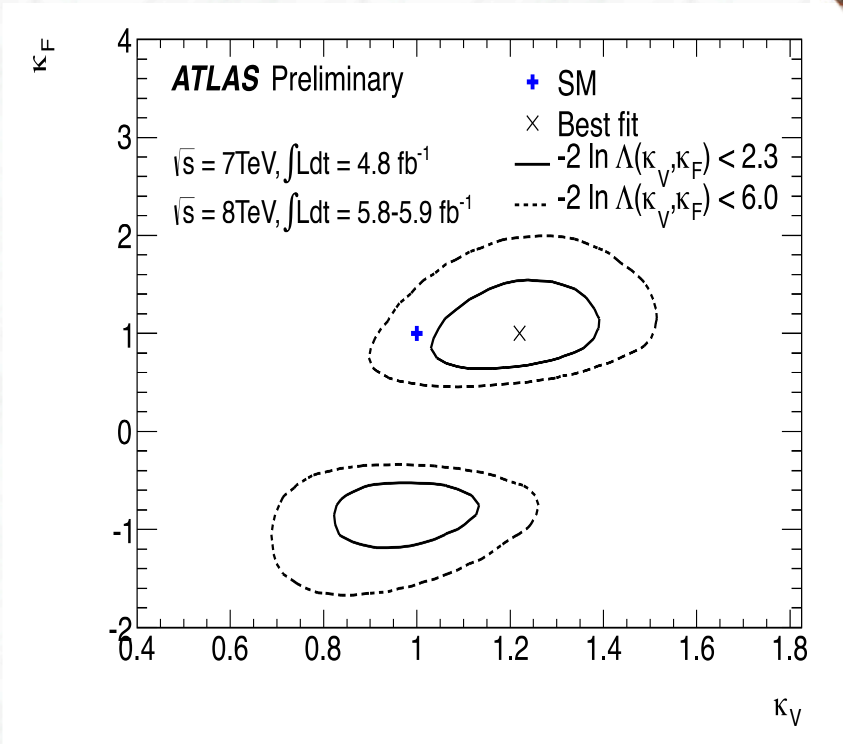
Test of coupling strengths

updates expected very soon

Couplings to W and Z bosons



W,Z versus fermion couplings



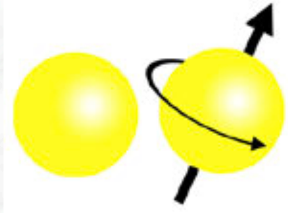
λ_{WZ} = ratio of W/Z coupling strength (normalized to ratio in the SM)

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

Spin and CP



Wolfgang Pauli und Niels Bohr bei der wissenschaftlichen Untersuchung der Kreiselbewegung (1952, anlässlich der Eröffnung des Instituts für Theoretische Physik in Lund / Schweden)

- If Standard Model Higgs boson: $J^P = 0^+$

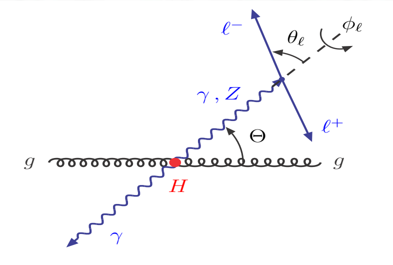
  → strategy is to falsify other hypotheses (0^-, 1^-, 1^+, 2^-, 2^+)

  Spin 1: dis-favoured by observed $H \rightarrow \gamma\gamma$ decays, Landau-Yang theorem

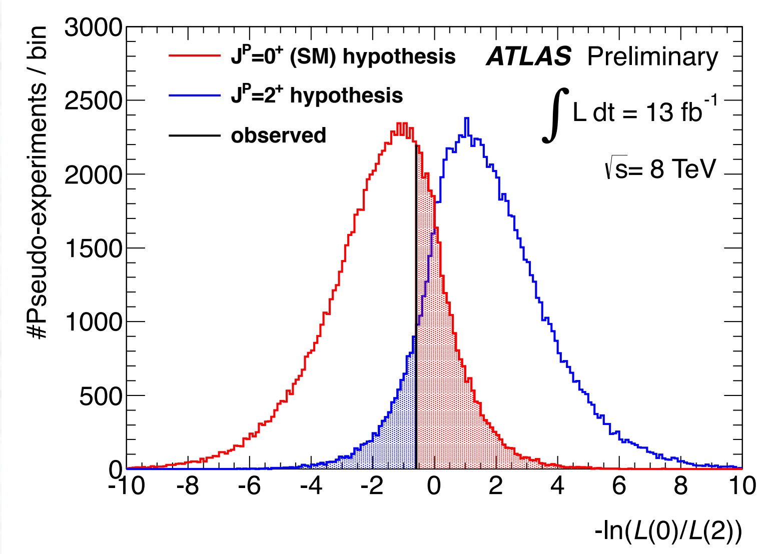
  Spin 2: consider graviton-like tensor, equivalent to a Kaluza-Klein graviton

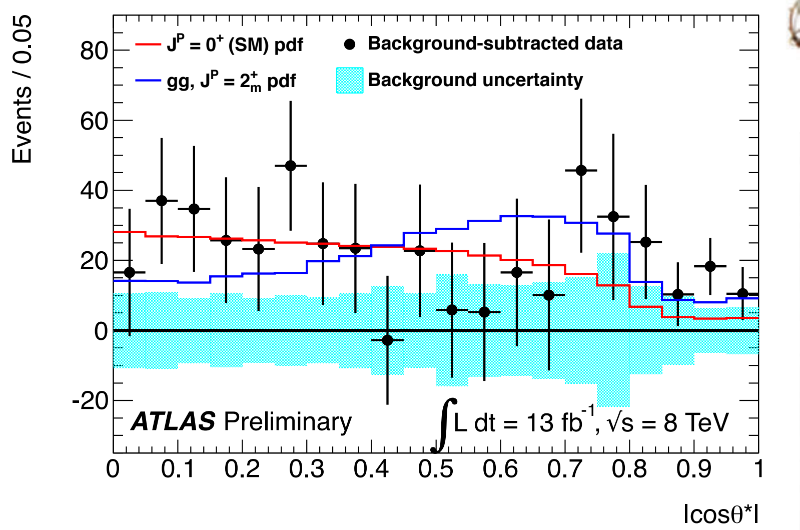
- Angular distributions of final state particles show sensitivity to spin

Spin studies using H → γγ events



Decay angle in the Higgs boson rest frame (Collins-Soper frame)





cos θ* distribution in signal region, after background subtraction

Likelihood hypothesis test of spin-0 versus spin 2:

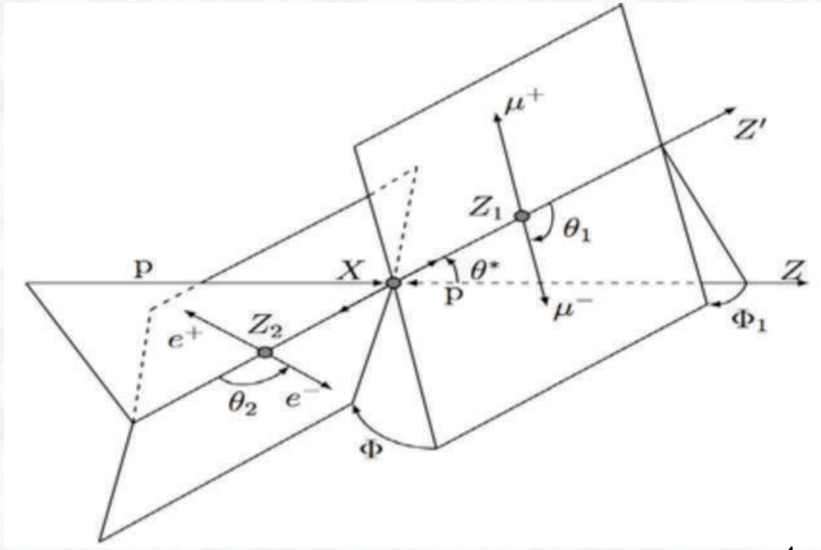
Data favour spin 0,

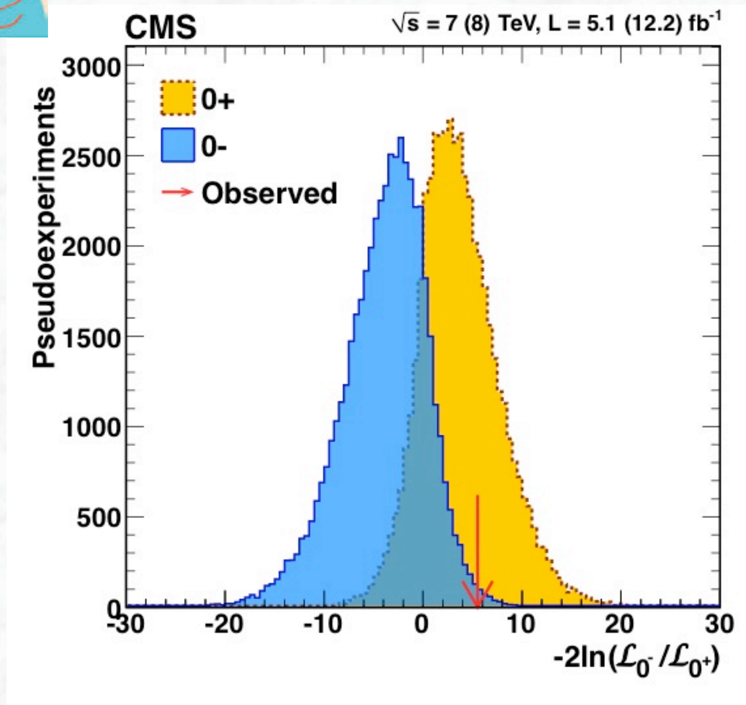
exclude $J^P = 2^+_m$ w.r.t $J^P = 0^+$ with

ATLAS: 1.4σ (p value = 0.12)

Spin studies using H → ZZ$^{(*)}$ → 4 l events

- Sensitive variables:
  - Masses of the two Z bosons
  - Production angle θ^*
  - Four decay angles Φ_1, Φ, θ_1 and θ_2





Updated with full dataset

new

Likelihood hypothesis test of

$J^P = 0^+$ vs. $J^P = 0^-$ ATLAS: 2.8σ (2.7 exp)
CMS: 3.3σ (2.6 exp)

$J^P = 0^+$ vs. $J^P = 2^+_m$ ATLAS: 1.2σ (1.5 exp)
CMS: 2.7σ (1.8 exp)

Data favour $J^P = 0^+$ w.r.t. other J^P configurations (including 0^-, 1^-, 1^+, 2^+)

Conclusions

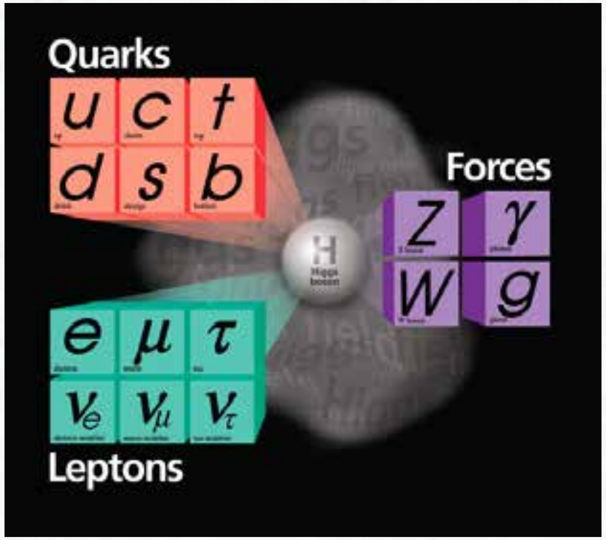
- With the operation of the LHC at high energies, particle physics has entered a new era

- Performance of the LHC and the experiments is superb

- A milestone discovery made in July 2012

Strong evidence that the new particle is the long-sought Higgs boson

- Clear signals in bosonic decays
- Evidence for fermionic decays is building up, but still weak….
- Tensions in some signal/coupling strength (?)
- First evidence for spin 0



- Exciting times ahead of us:
  - Study of the Higgs-like boson itself
  - Search for Physics Beyond the Standard Model