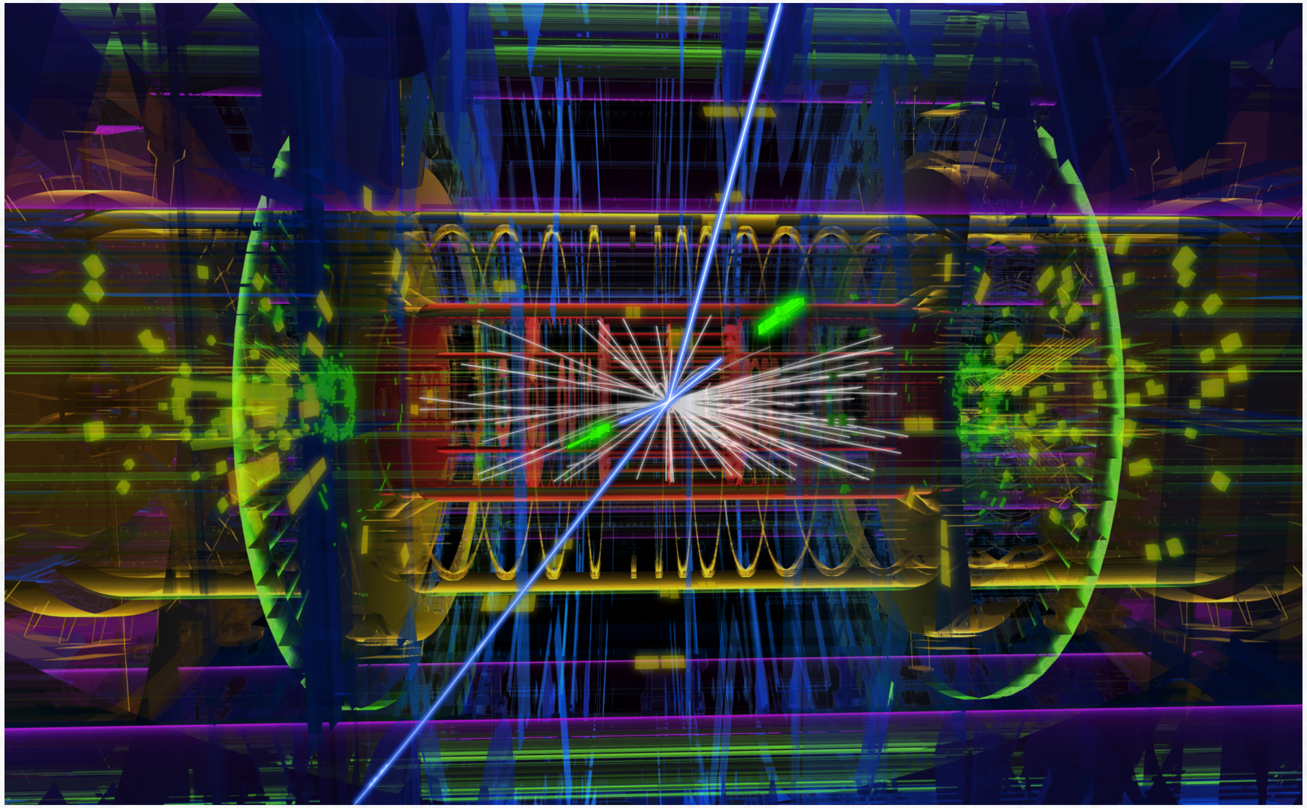
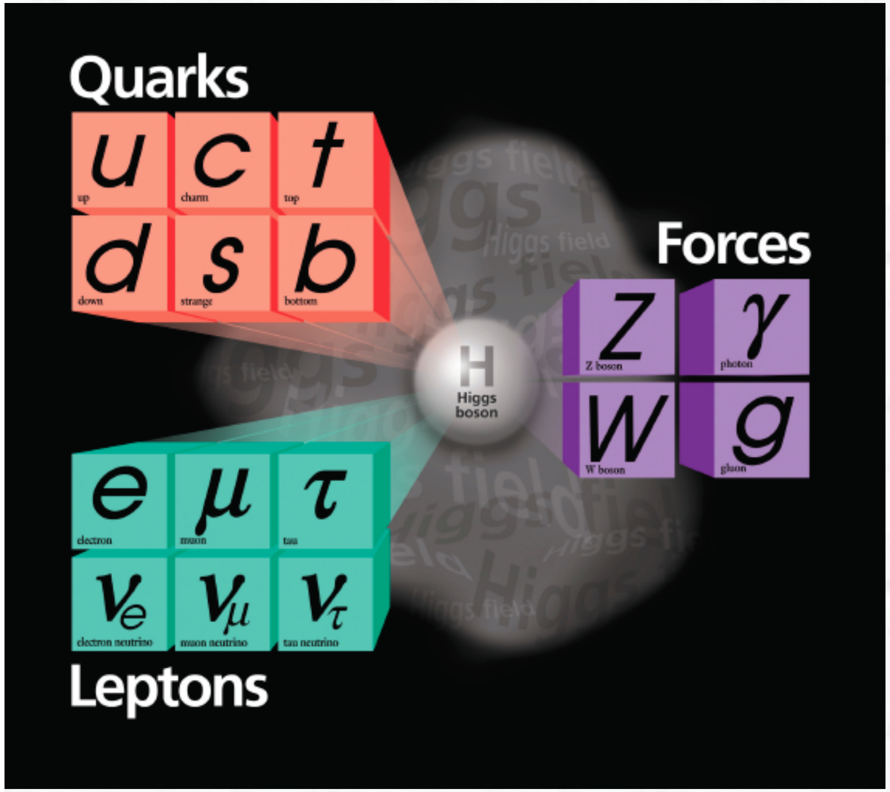
Discovery of a New Boson at the LHC

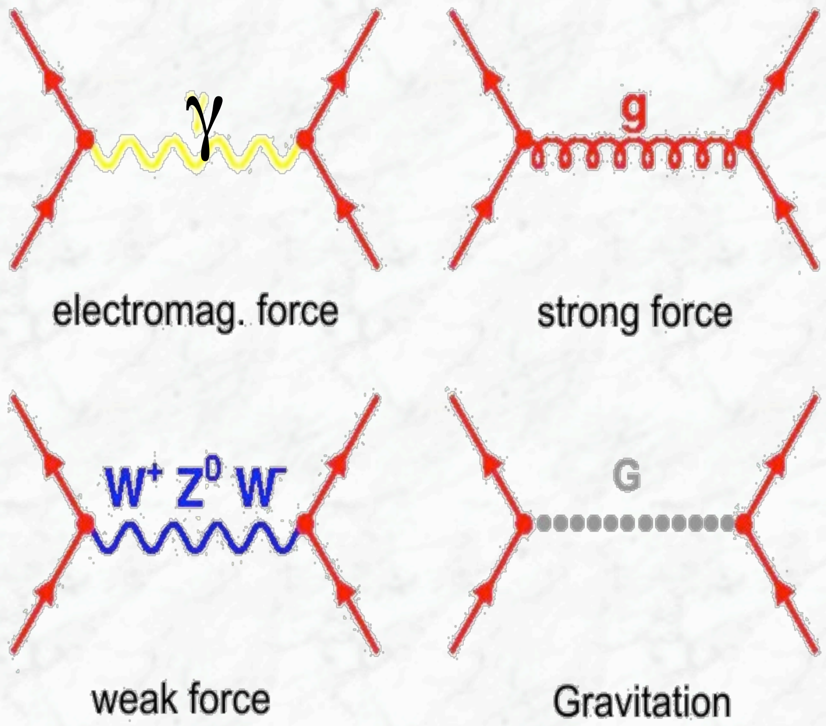
- Or Evidence for the Higgs boson? -



Karl Jakobs
Physikalisches Institut
Universität Freiburg

The Standard Model of Particle Physics





(i) Constituents of matter: quarks and leptons

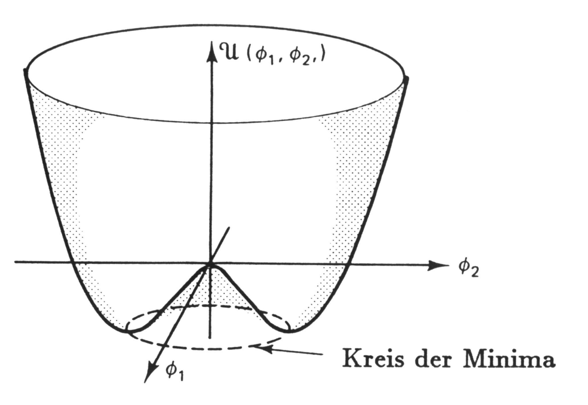
(ii) Four fundamental forces
(described by quantum field theories, except gravitation)

(iii) The Higgs field (problem of mass)

The Higgs mechanism

- Add scalar fields: $$\phi = \frac{1}{\sqrt{2}}\begin{pmatrix}\phi_1 + i\phi_2 \\ \phi_3 + i\phi_4\end{pmatrix} = \begin{pmatrix}\phi^+ \\ \phi^0\end{pmatrix}$$

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



- For $\mu^2 < 0$, $\lambda > 0$, minimum of potential: $$\phi_1^2 + \phi_2^2 + \phi_3^2 + \phi_4^2 = v^2 \qquad v^2 = -\mu^2/\lambda$$
  v = vacuum expectation value $$v = \frac{1}{\sqrt{\sqrt{2}G_F}} = 246 \text{ GeV}$$

- Perturbation theory around ground state:

$$\phi_0(x) = \frac{1}{\sqrt{2}}\begin{pmatrix}0 \\ v + h(x)\end{pmatrix} \Rightarrow$$

3 massive vector fields:
(g = coupling constant, well measured in experiments)

$$m_{W^\pm} = \frac{1}{2}vg \qquad m_Z = \frac{m_W}{\cos\theta_W}$$

1 massless vector field: $$m_\gamma = 0$$

1 massive scalar field: **The Higgs boson H** $$m_H = \sqrt{\lambda v^2}$$

(mass not predicted, < ~1 TeV/c^2)

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)

Why do we need the Higgs boson?

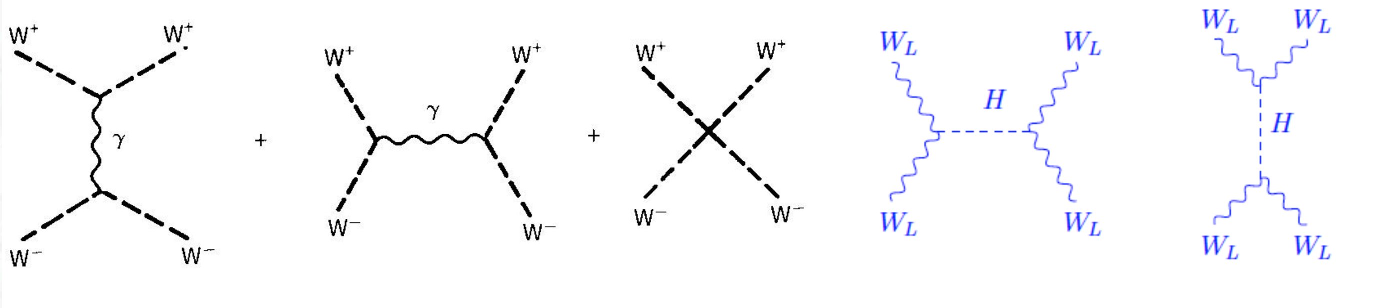
The Higgs boson enters the Standard Model to solve two fundamental problems:

- Masses of the vector bosons W and Z and fermions

Experimental results: $M_W = 80.399 \pm 0.023$ 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)

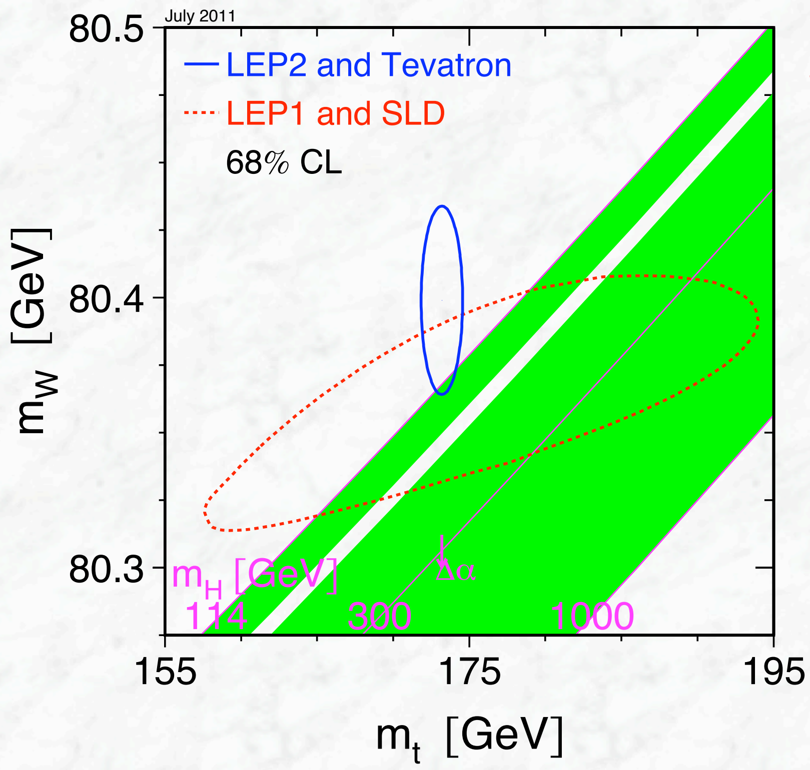


$$-iM(W^+W^- \rightarrow W^+W^-) \sim \frac{s}{M_W^2} \quad \text{for} \quad s \rightarrow \infty$$ (no Higgs boson)

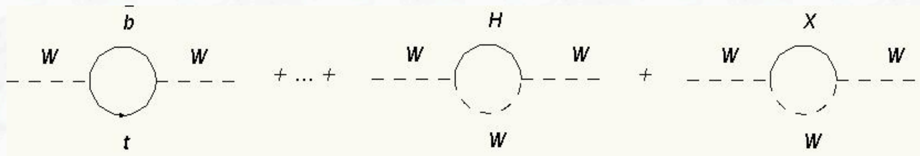
$$-iM(W^+W^- \rightarrow W^+W^-) \sim m_H^2 \quad \text{for} \quad s \rightarrow \infty$$ (with Higgs boson)

Constraints on the Higgs boson mass (before LHC)

- $m_H > 114.4$ GeV/c^2 from direct searches at LEP
- $m_H < 156$ GeV/c^2 .or. $m_H > 177$ GeV/c^2 from direct searches at the Tevatron



July 2011



$m_H = 92^{+34}_{-26}$ GeV/c^2
$m_H < 161$ GeV/c^2 (95 % C.L.)

- Indirect constraints from precision measurements (quantum corrections)

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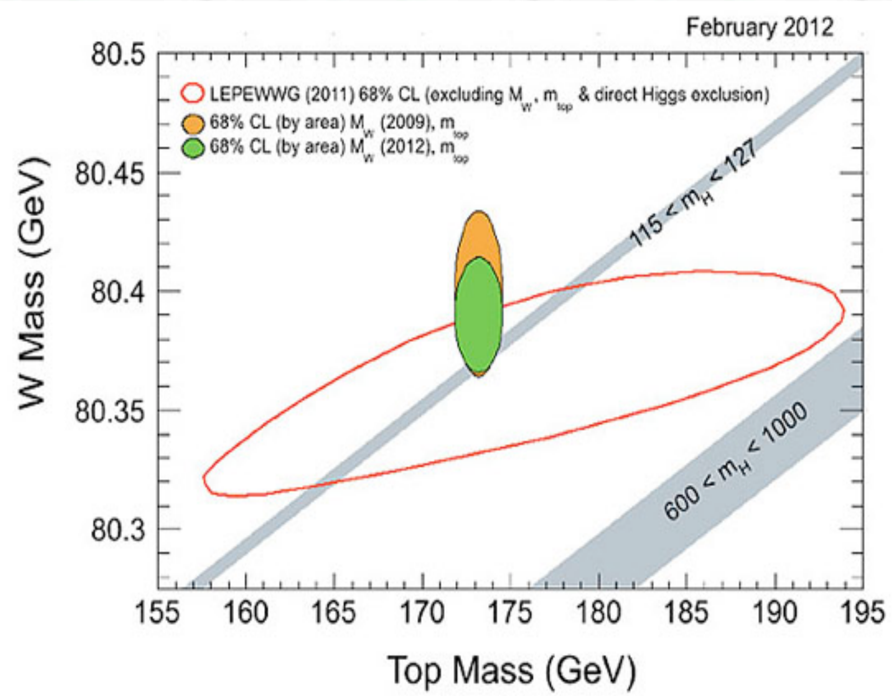
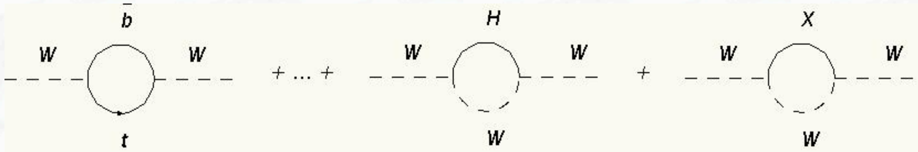


February 2012



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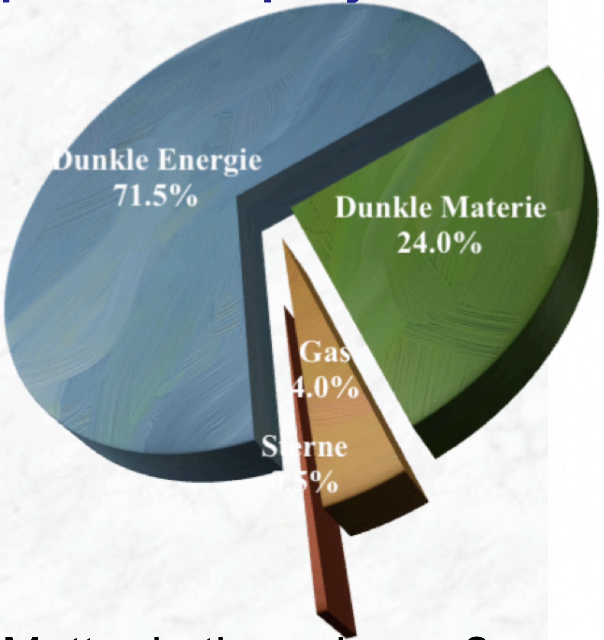
Key questions of particle physics



1. Mass

What is the origin of mass?
Does the Higgs particle exist?

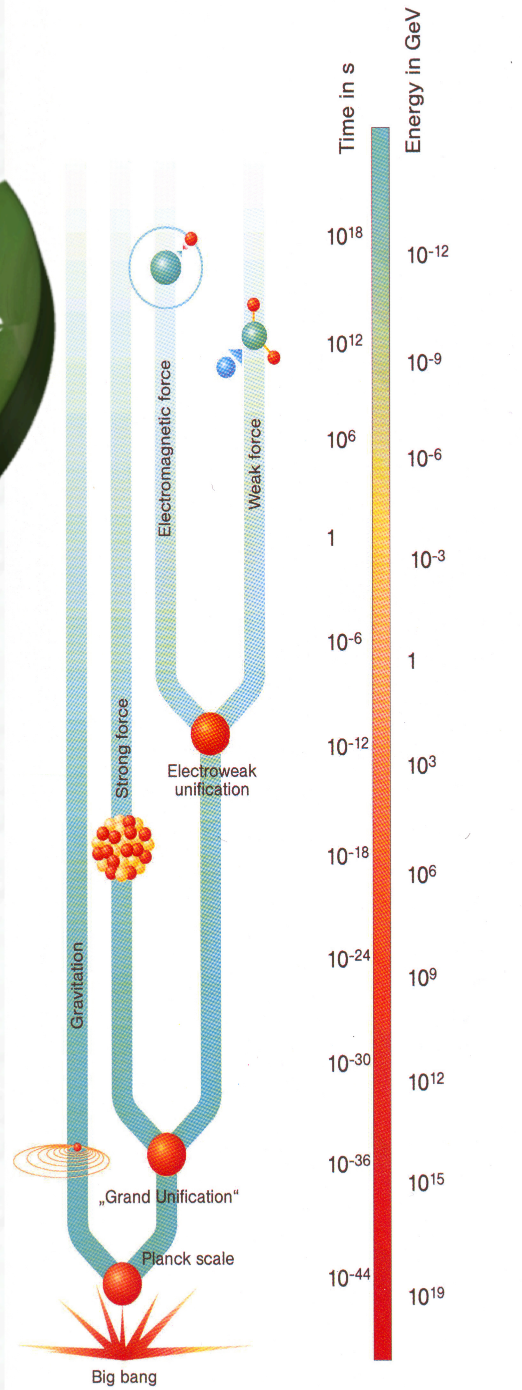
2. Unification

- 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

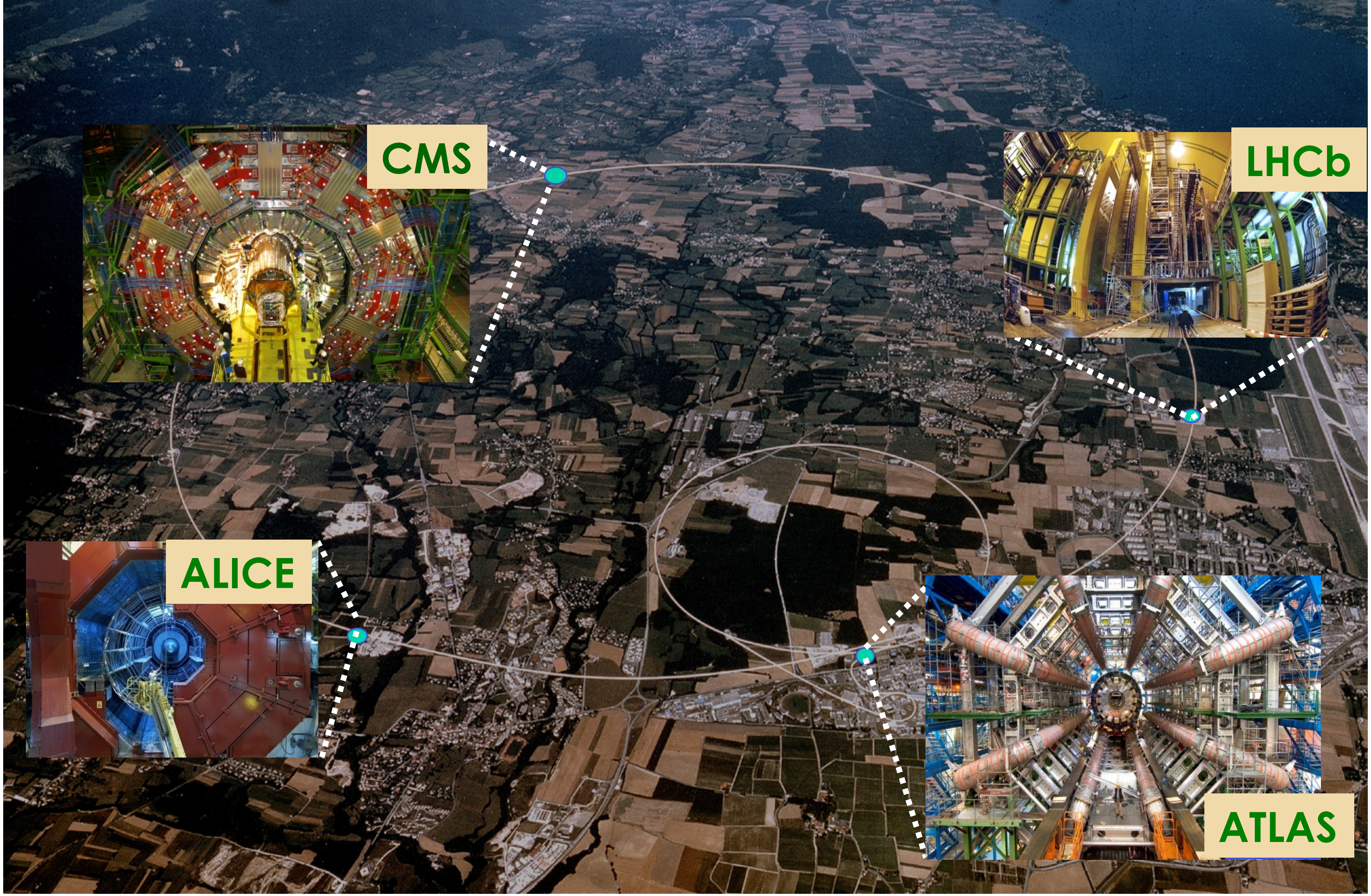
- Why are there three generations of particles?
- What is the origin of the matter-antimatter asymmetry (Origin of CP violation)

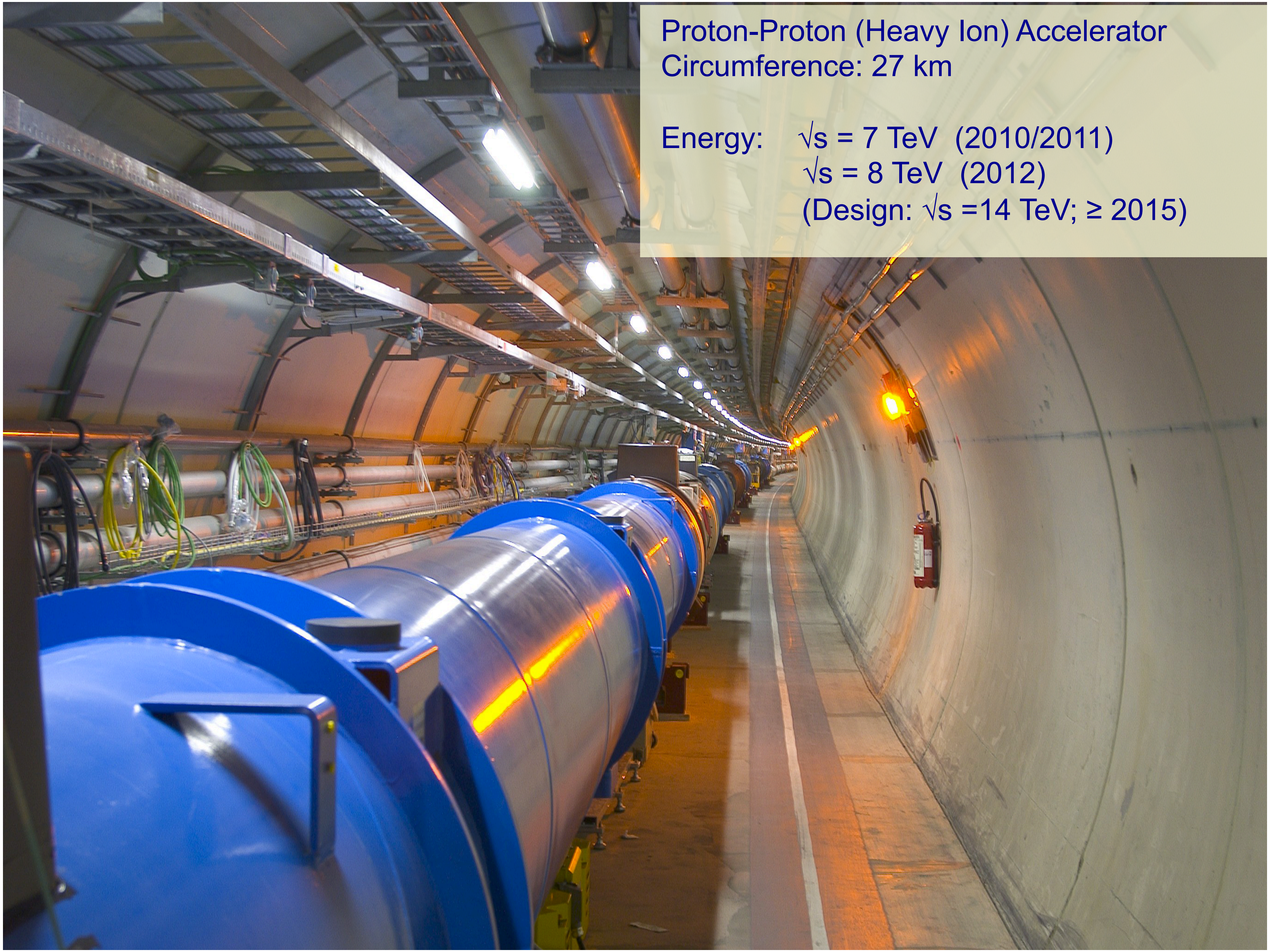
Answers to some of these questions are expected on the TeV energy scale, i.e. at the LHC



Theoretical models
for physics Beyond the
Standard Model

Begin of a new era in particle physics

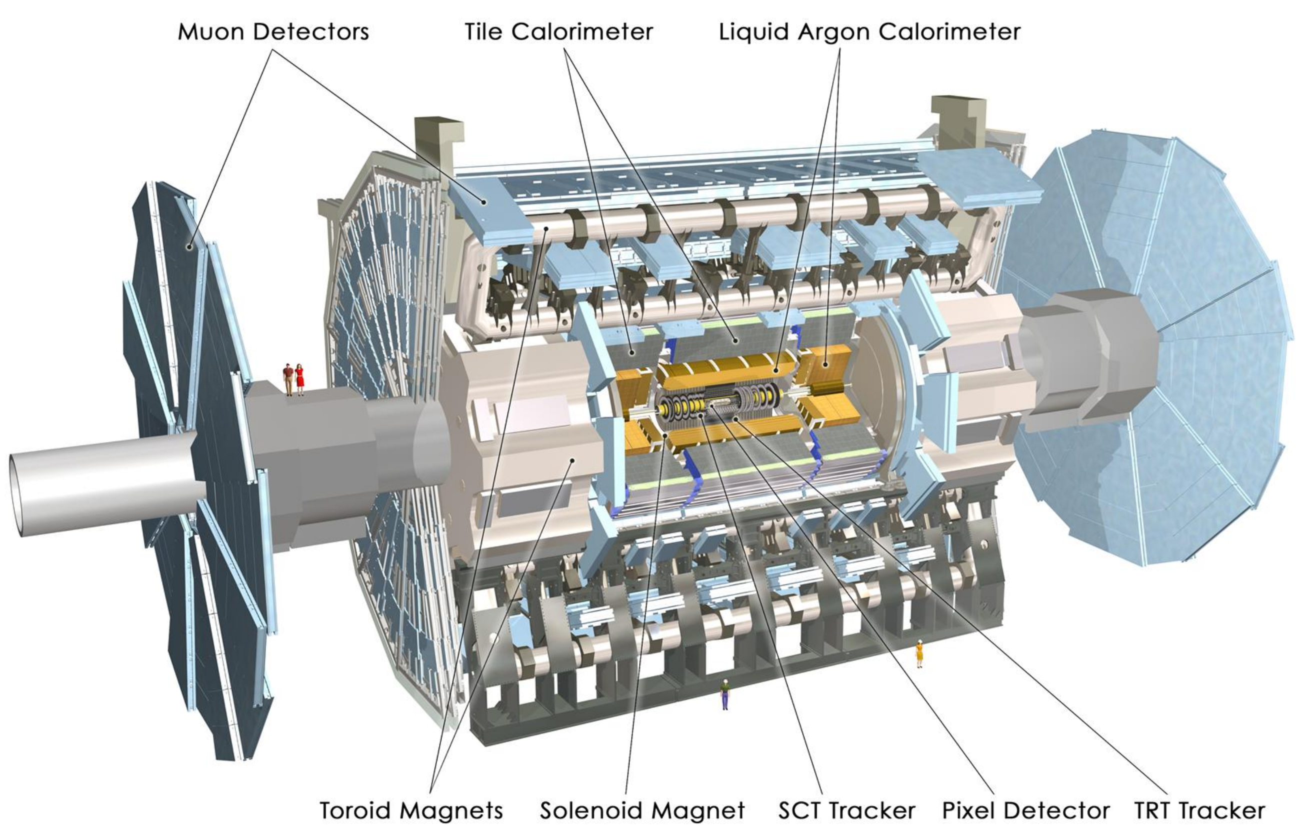




Proton-Proton (Heavy Ion) Accelerator
Circumference: 27 km

Energy: $\sqrt{s}$ = 7 TeV (2010/2011)
$\sqrt{s}$ = 8 TeV (2012)
(Design: $\sqrt{s}$ =14 TeV; ≥ 2015)

The ATLAS experiment



- Solenoidal magnetic field (2T) in the central region (momentum measurement)

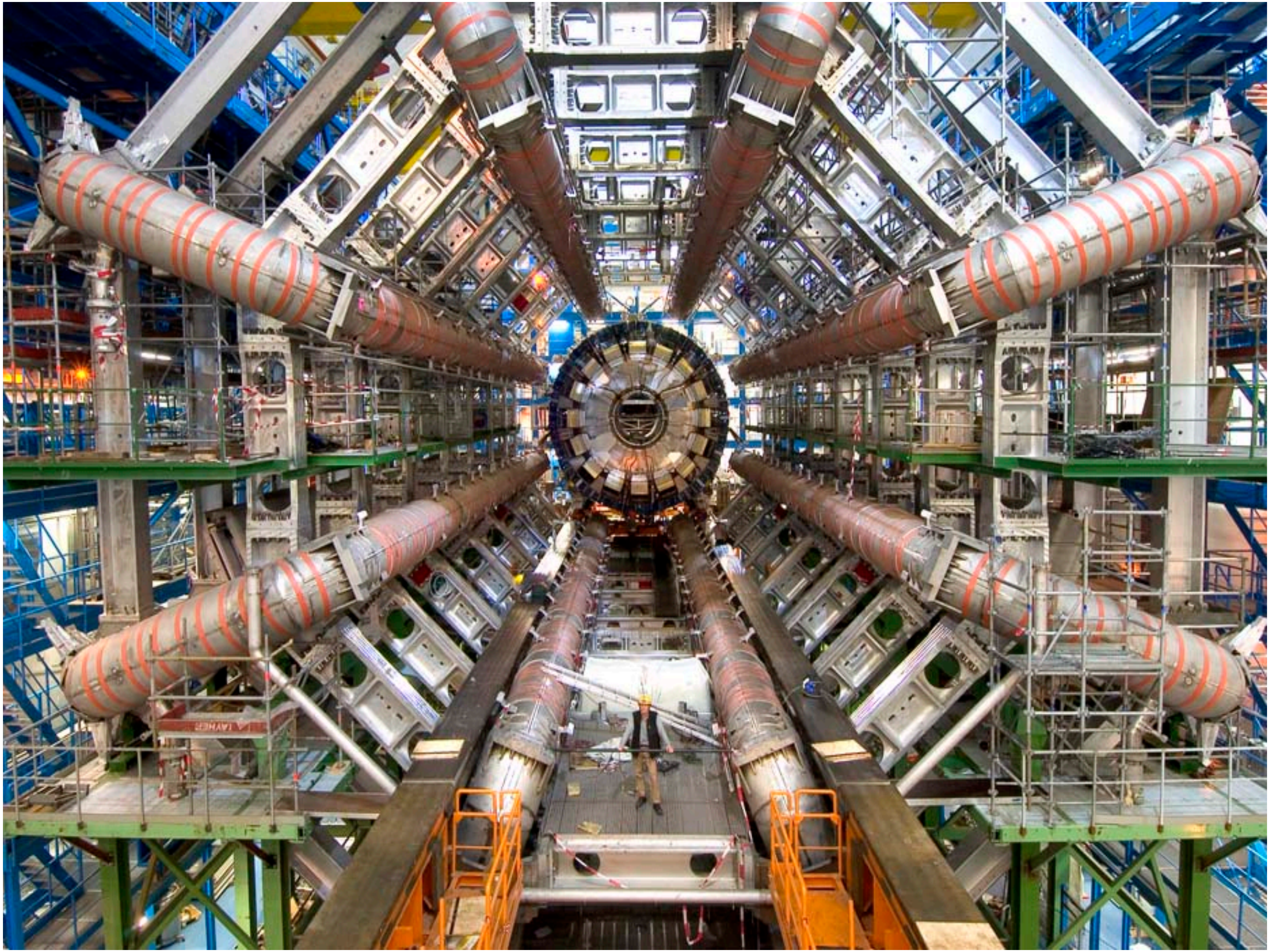
  High resolution silicon detectors:
  - 6 Mio. channels (80 μm x 12 cm)
  - 100 Mio. channels (50 μm x 400 μm)

  space resolution: ~ 15 μm

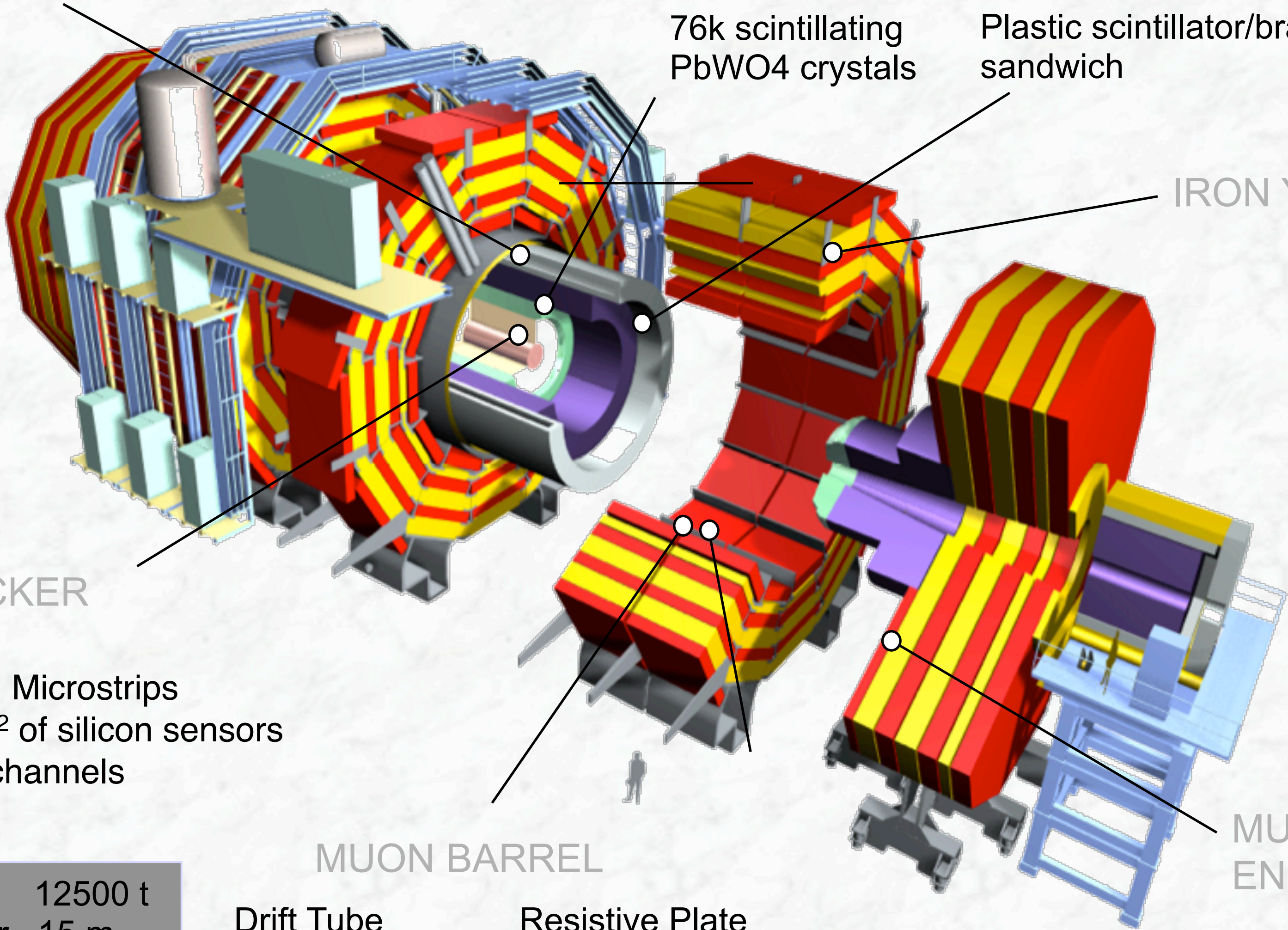
- Energy measurement down to 1° to the beam line

- Independent muon spectrometer (supercond. toroid system)

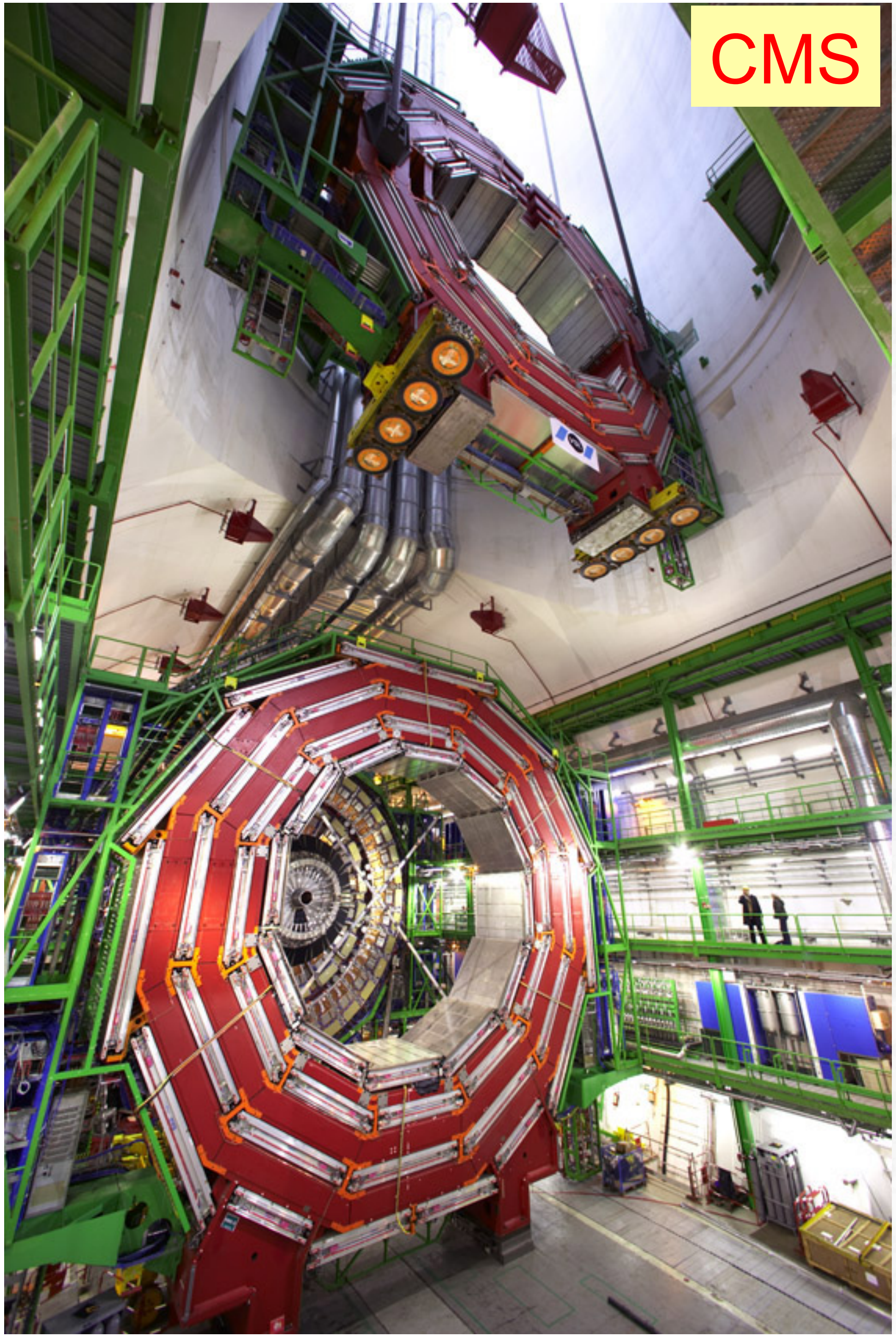
Diameter	25 m
Barrel toroid length	26 m
End-cap end-wall chamber span	46 m
Overall weight	7000 Tons



CMS

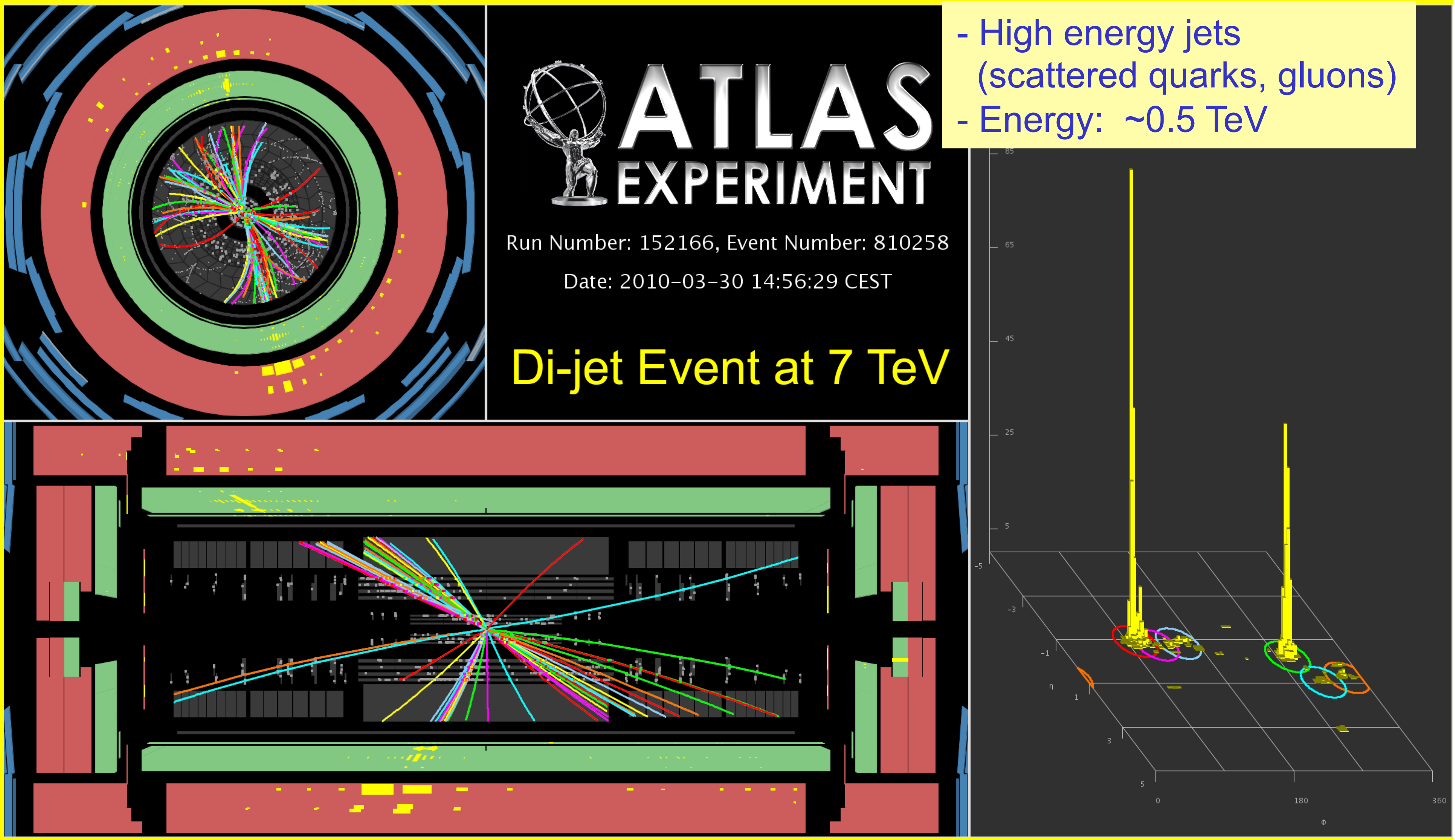


Total weight	12500 t
Overall diameter	15 m
Overall length	21.6 m


CMS

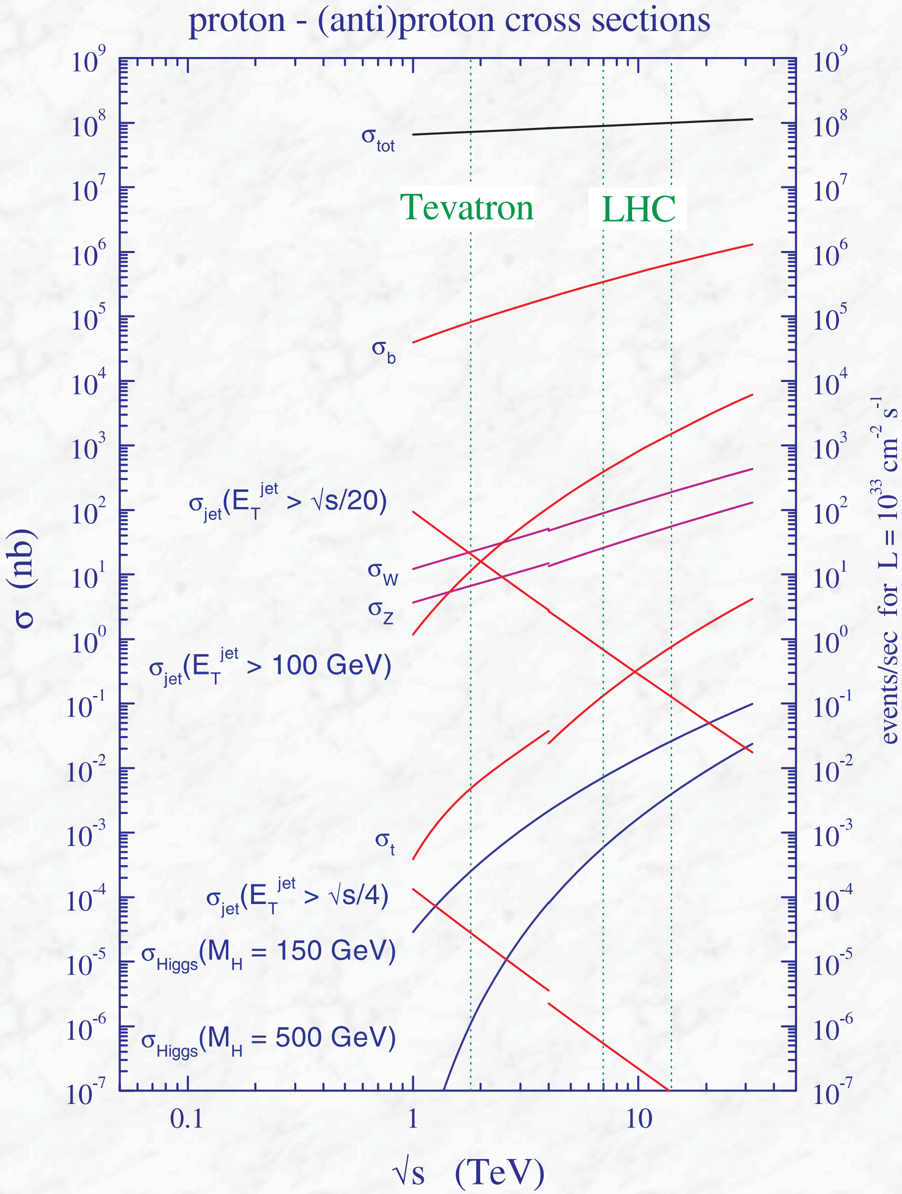
Since 30. March 2010: collisions at 7 TeV

(.... first interesting results appeared soon)



- High energy jets (scattered quarks, gluons)
- Energy: ~0.5 TeV

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:
$\sqrt{s}$ = 14 TeV, L = 10^{34} cm^{-2} s^{-1}:

- Inelastic proton-proton collisions: 10^9 / s

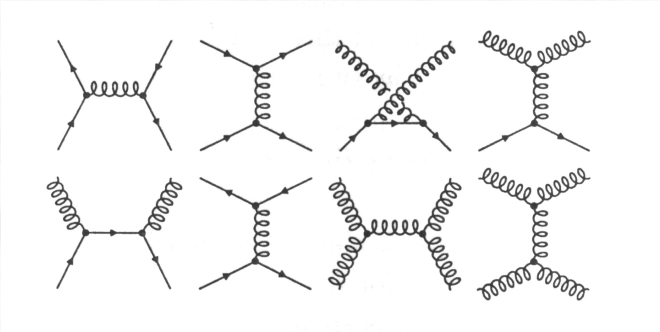
- bb pairs $5\ 10^6$ / s
- tt pairs 8 / s

- W → e ν 150 / s
- Z → e e 15 / s

- **Higgs (150 GeV) 0.2 / s**
- **Gluino, Squarks (1 TeV) 0.03 / s**

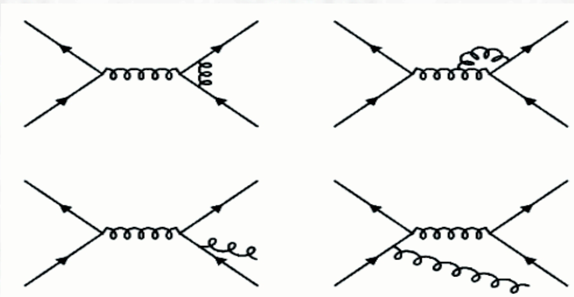
Test of Quantum Chromodynamics

Leading order



- Hard scattering processes (large momentum transfer) are dominated by qq, qg, gg scattering
- Cross sections can be calculated in QCD (perturbation theory)

…some next-to-leading order (NLO) contributions

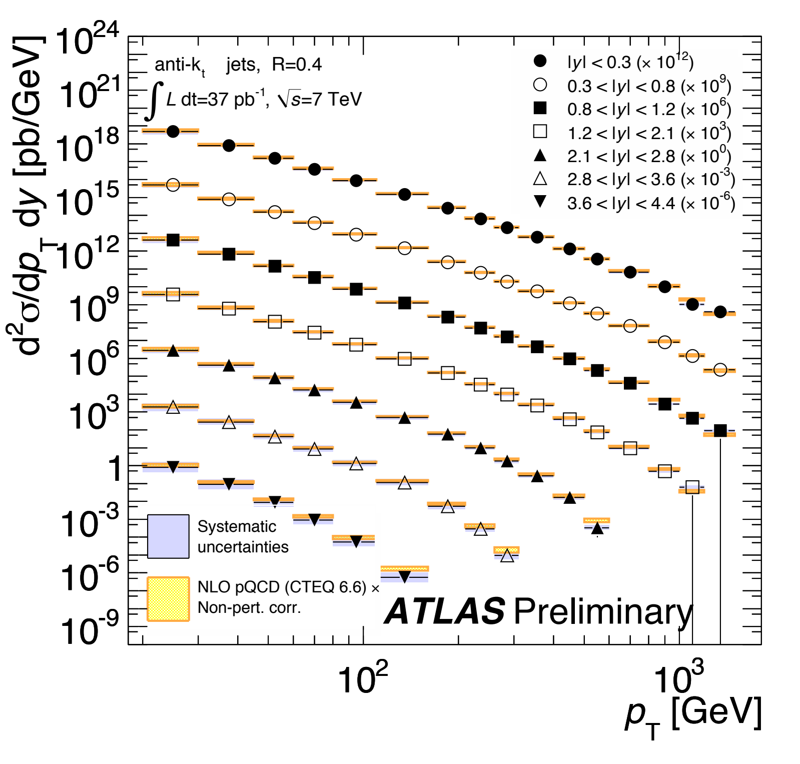


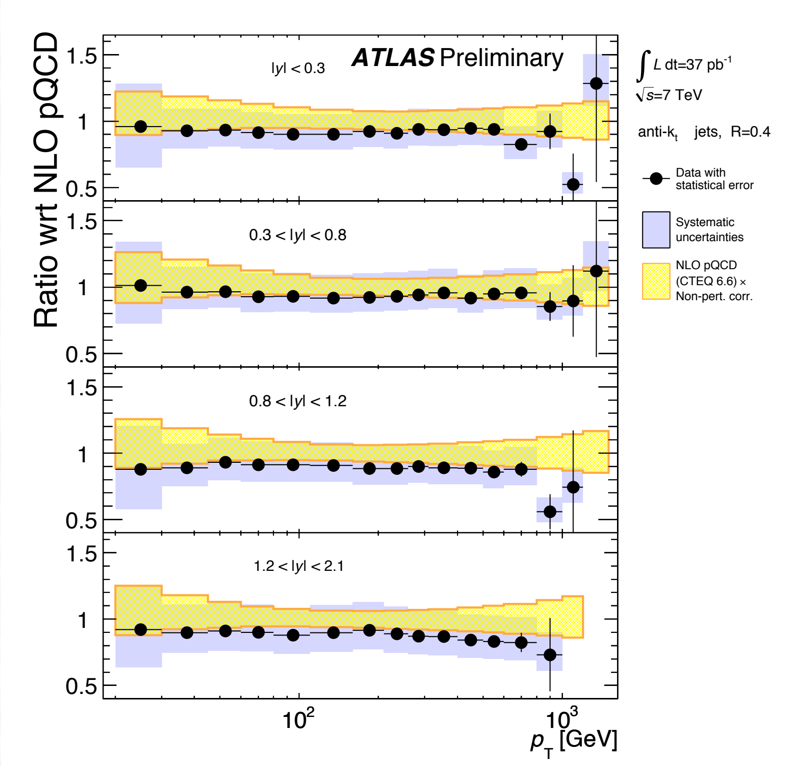
Comparison between experimental data and theoretical predictions constitutes an important test of the theory.

Deviations?

→ Problem in the experiment ?
Problem in the theory (QCD) ?
New Physics, e.g. quark substructure ?

Test of QCD in jet production



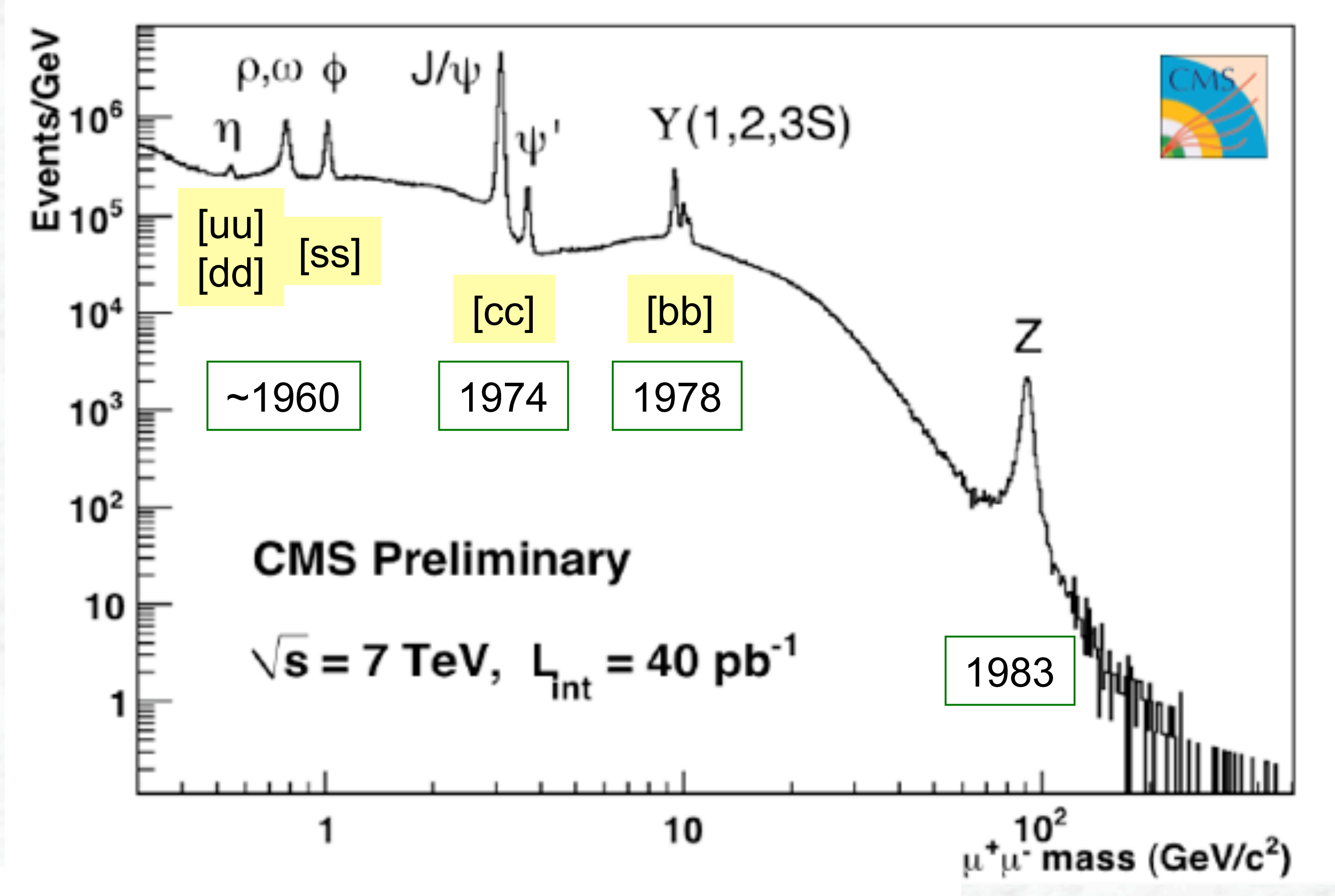


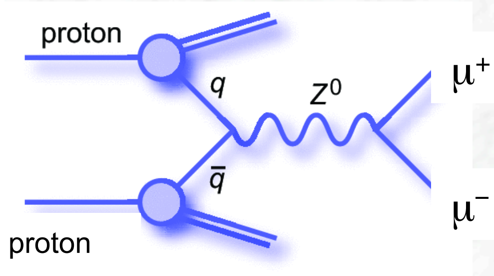
- Double differential cross section in transverse momentum (p_T) and rapidity (y)
- Very good agreement between data and NLO perturbative QCD calculations within the experimental (jet energy measurement) and theoretical uncertainties

rapidity y: $$y = \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right) = \tanh^{-1}\left(\frac{p_z}{E}\right)$$

2010

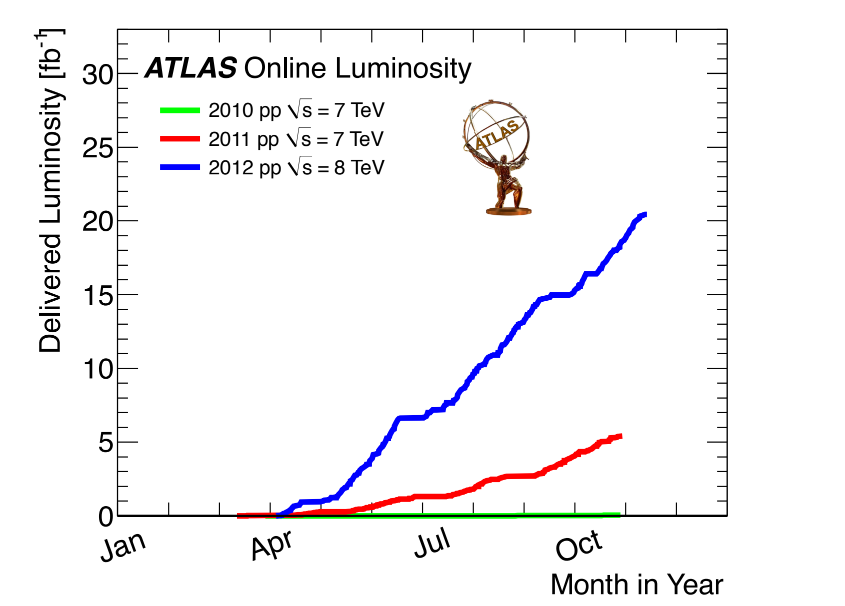
Data corresponding to ~40 pb^{-1} collected
→ re-discovery of the Standard Model





Well known quark-antiquark resonances (bound states) appeared “online”

Data taking in 2011/ 2012

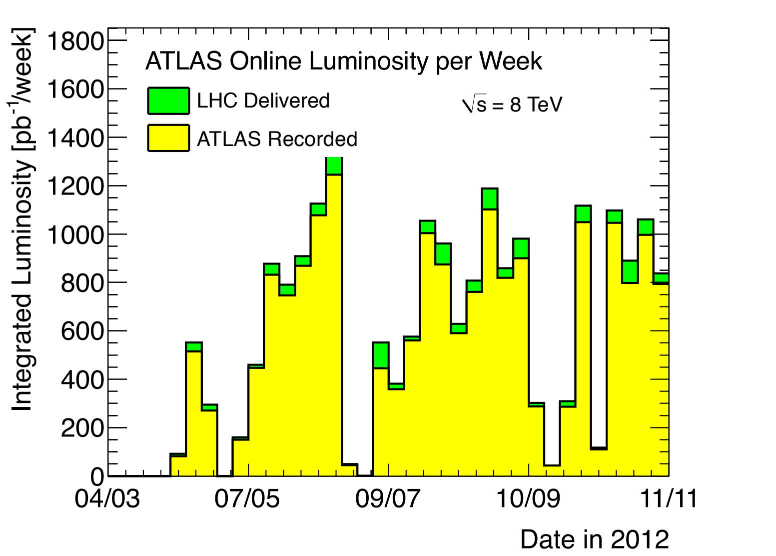


- Excellent LHC performance in 2011and 2012 (far beyond expectations)

- 2011: Peak luminosity seen by ATLAS: $3.6\ 10^{33}\ cm^{-2}\ s^{-1}$

- 2012: running at $\sqrt{s}$ = 8 TeV, Luminosity regularly exceeding $6\ 10^{33}\ cm^{-2}\ s^{-1}$

  So far: integrated luminosity > 20 fb^{-1}

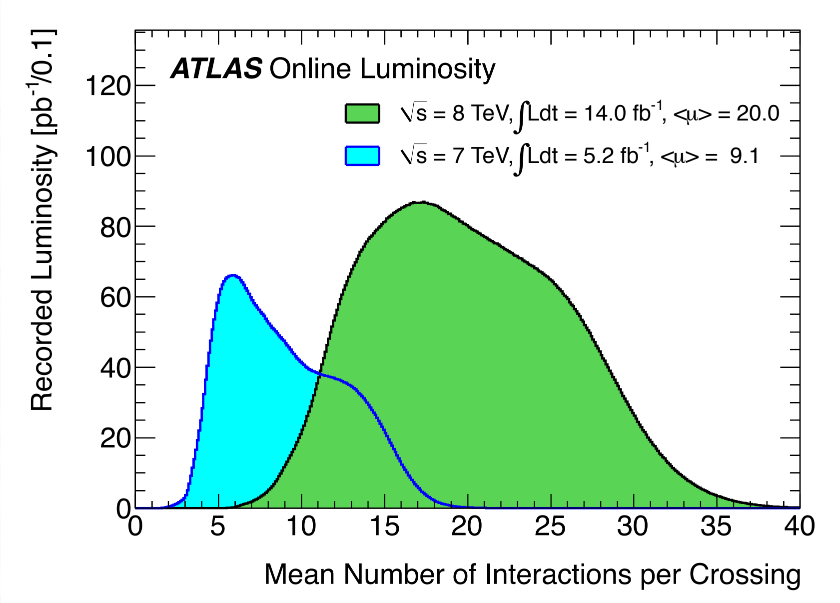


- Excellent performance of the experiments

- Small fraction of non-working detector channels (few per mille → 1-2%)

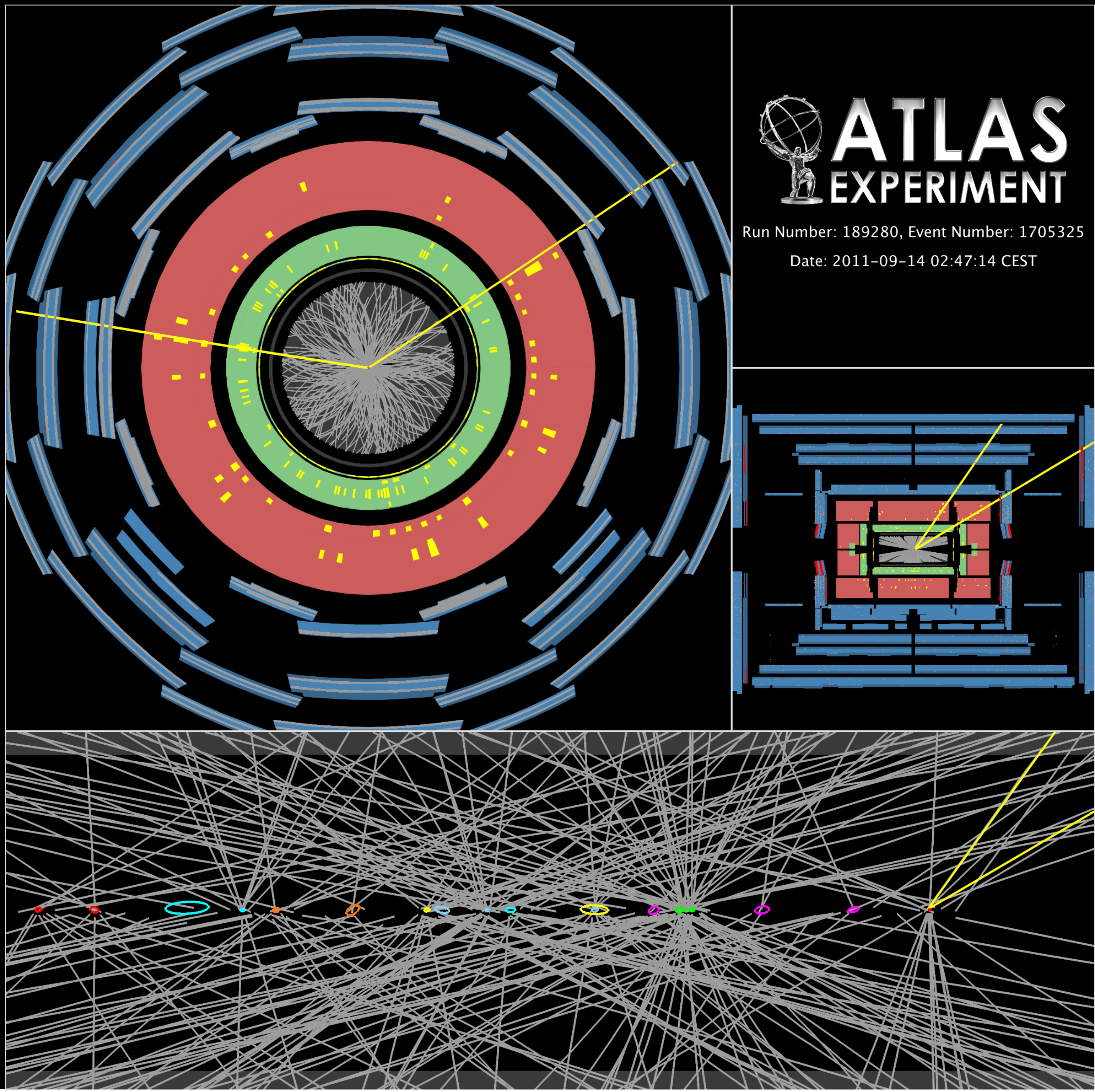
- Data taking efficiency is high: ~93.5%

Running conditions in 2011

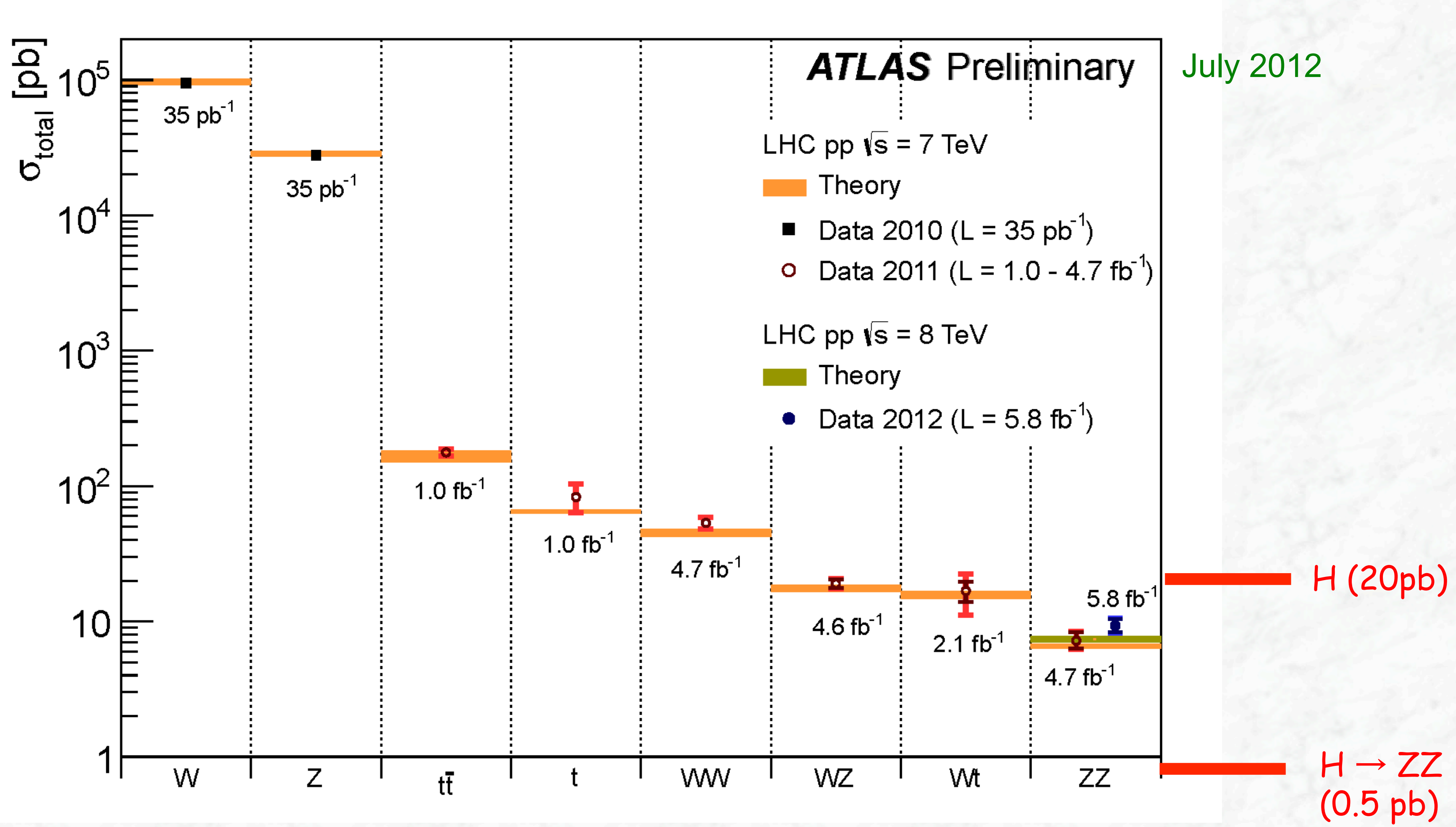


- High peak luminosity and 50 ns bunch spacing → high pile-up
- Superposition of several interactions (reaching more than 20) per crossing
- Very challenging for trigger, computing, reconstruction of physics objects,…

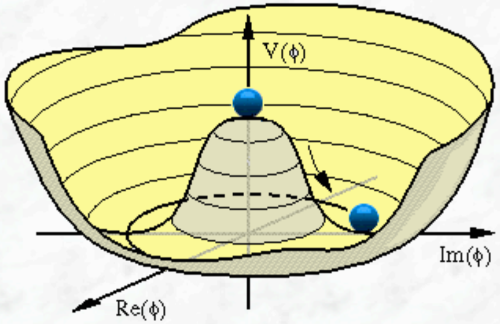
$Z \rightarrow \mu^+ \mu^-$ with 20 superimposed events

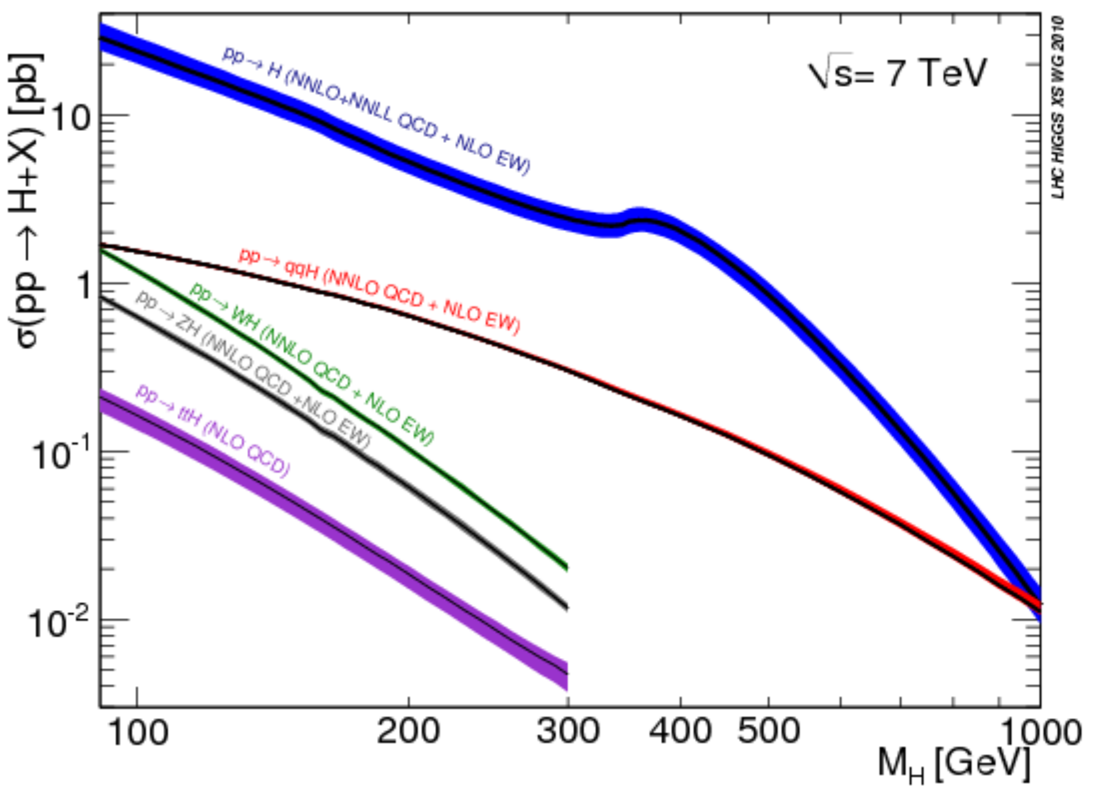


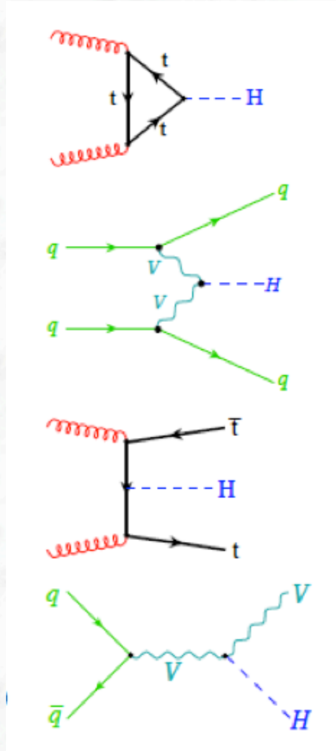
The Standard Model at the LHC



The Search for the Higgs Boson







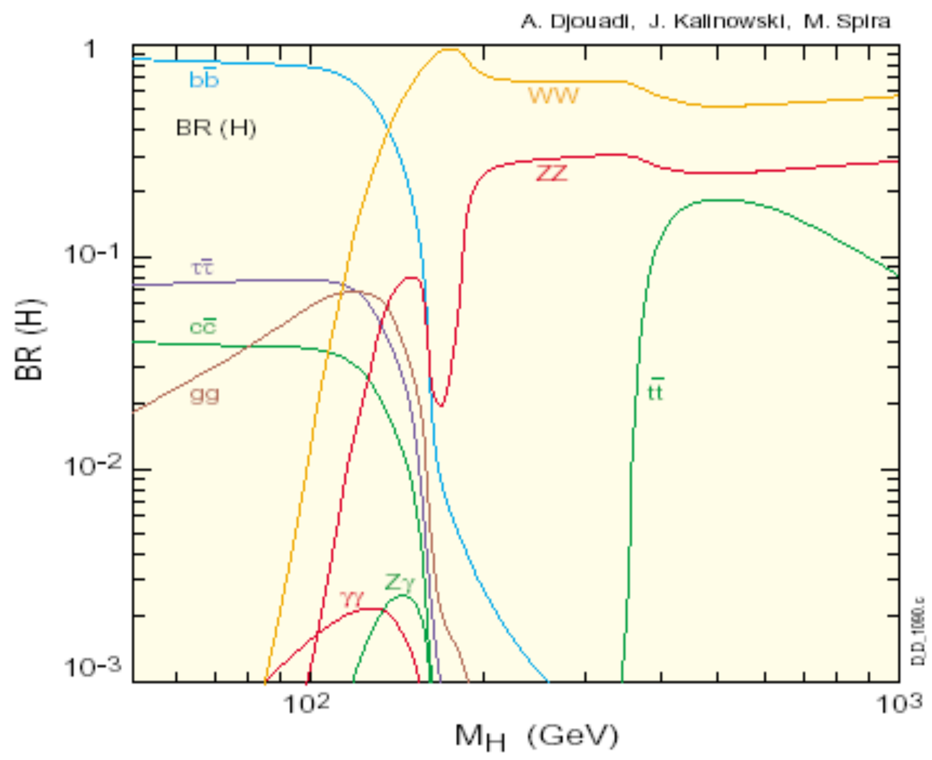
Gluon Fusion

Vector boson fusion

tt associated production

WH/ZH associated production

Useful Higgs Boson Decays at a Hadron Collider



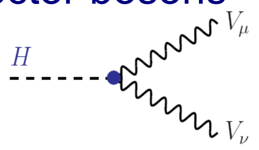
at high mass:
Lepton final states
(via H → WW, ZZ)

at low mass:
Lepton and Photon final states
(via H → WW*, ZZ* and H → γγ)

Tau final states

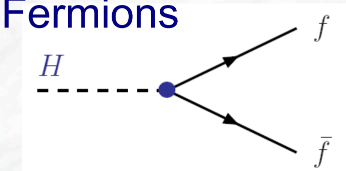
The dominant **bb decay mode** at low mass is only useable, if the Higgs boson is produced in association with a W or Z boson, e.g. pp → WH → ℓν bb

Vector bosons



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

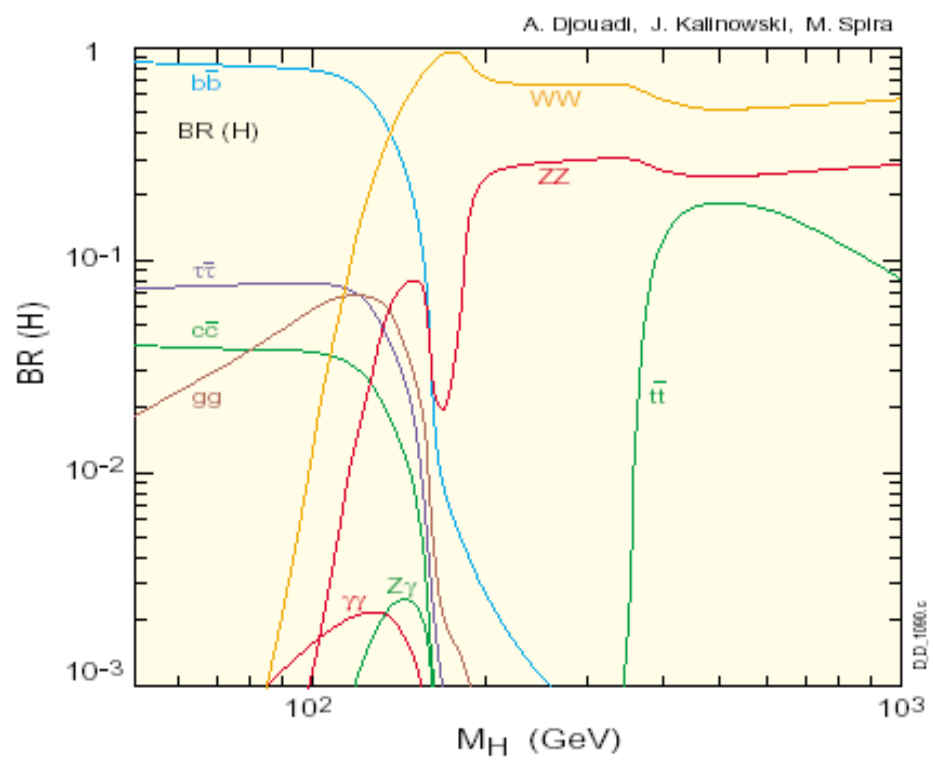
Fermions



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

Important channels: H → WW → ℓν ℓν
H → γγ
H → ZZ → $\ell^+\ell^-$ $\ell^+\ell^-$

Useful Higgs Boson Decays at a Hadron Collider



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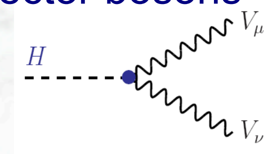

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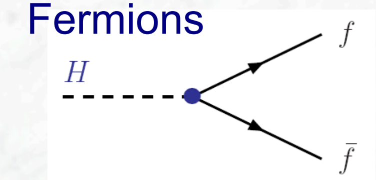

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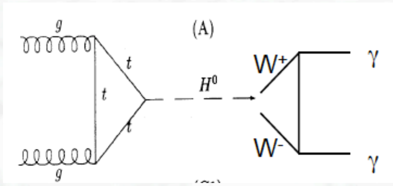

Higgs boson decays in massless particles via higher order processes (small rate)

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.

4. Juli 2012

Frankfurter Allgemeine

Wissen

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Aktuell > Wissen > Physik & Chemie

Erfolg bei Suche nach Higgs-Teilchen

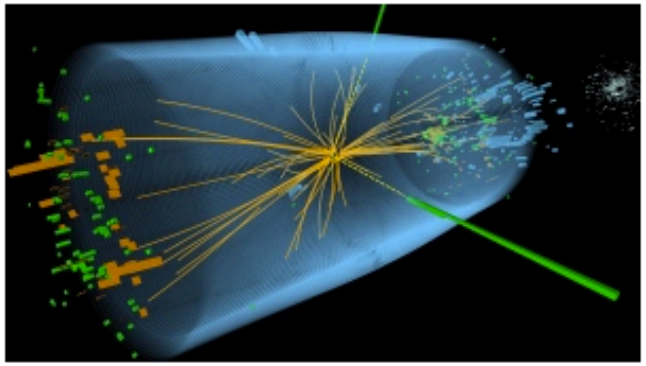
„Eine wissenschaftliche Sensation"

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,



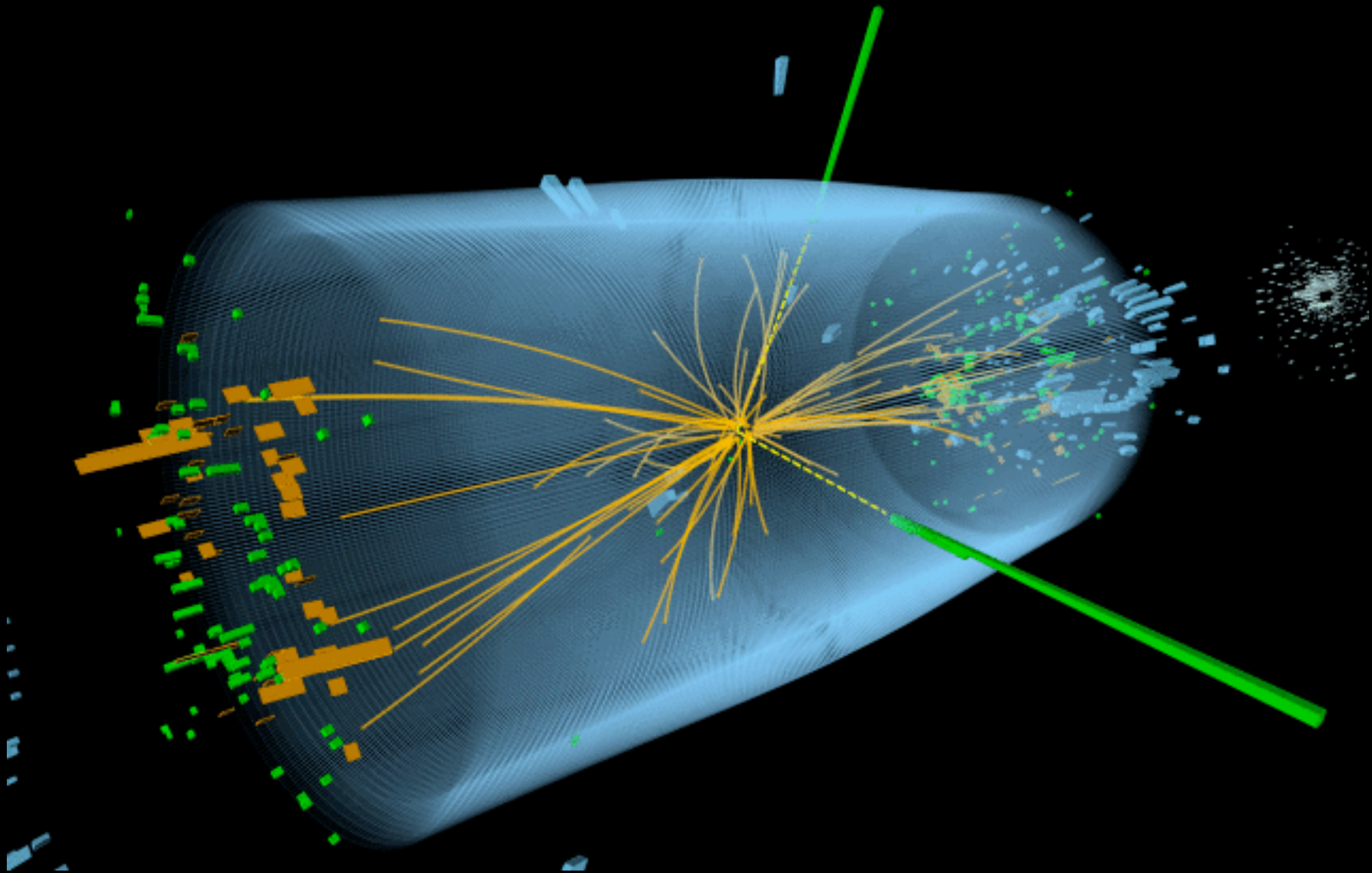
© DAPD

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

…. physicists knew already on the evening before that it would be

worth while to spend the night in front of the CERN auditorium

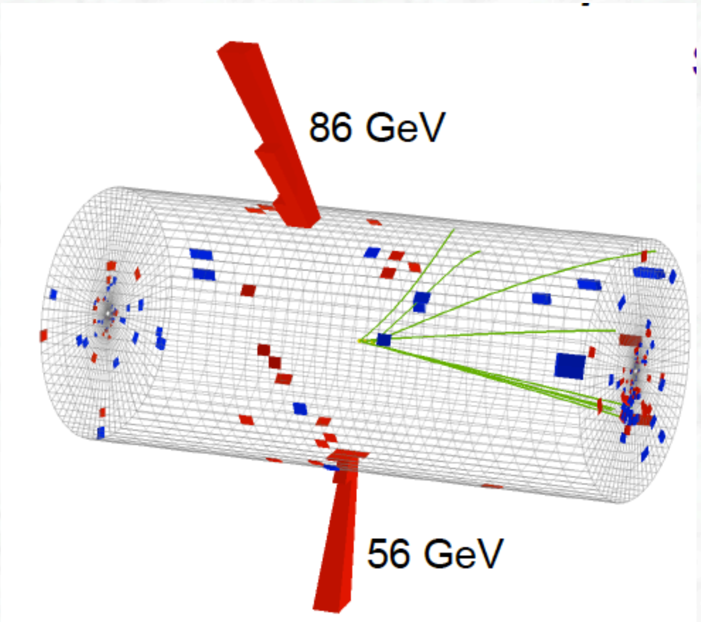
Evidence for the Higgs particle



Expected number of decays in data:
m_H = 125 GeV

~ 480 H → $\gamma\gamma$
~ 30 H → ZZ → 4 ℓ
~ 4400 H → WW → $\ell\nu$ $\ell\nu$

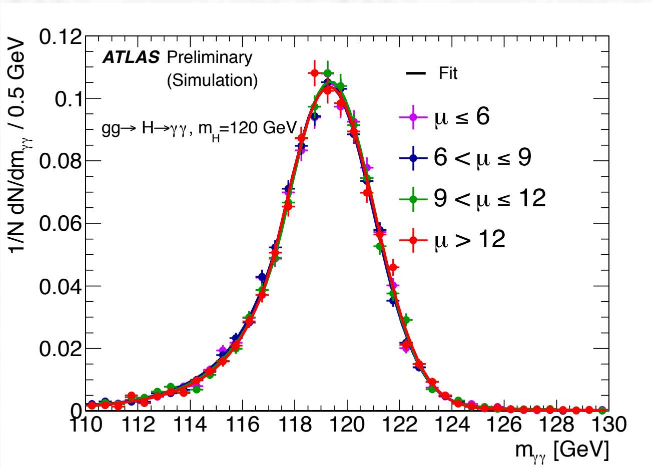
Search for the H → γγ decay



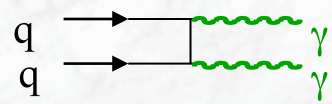
- 2 photons (isolated) with large transverse momenta

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

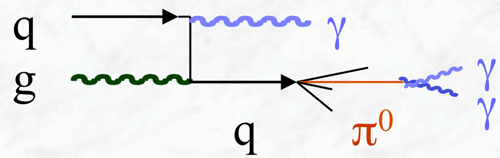
  Both experiments have a good mass resolution
  ATLAS: ~1.7 GeV/c^2 for m_H ~120 GeV/c^2



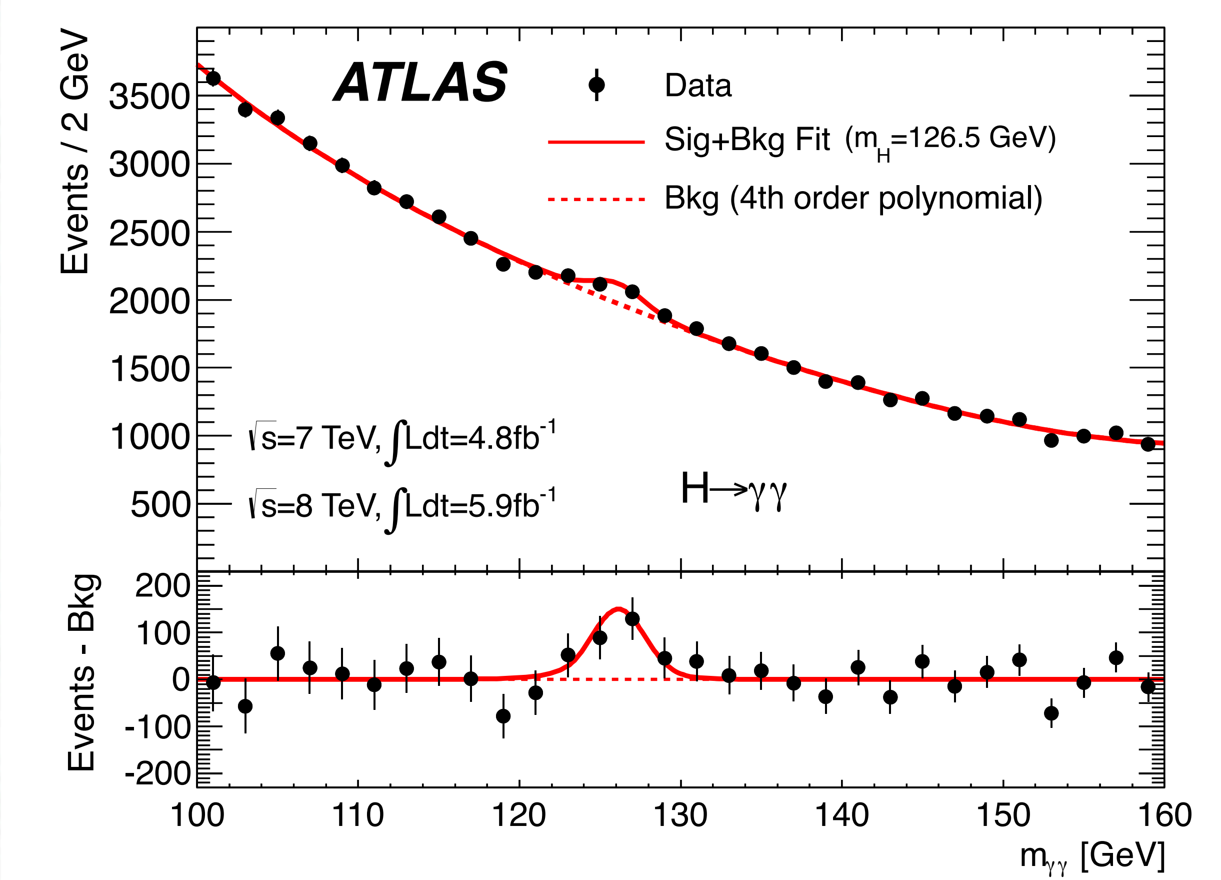
- Challenges:
  - signal-to-background ratio
    (small, but smooth irreducible γγ background)



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

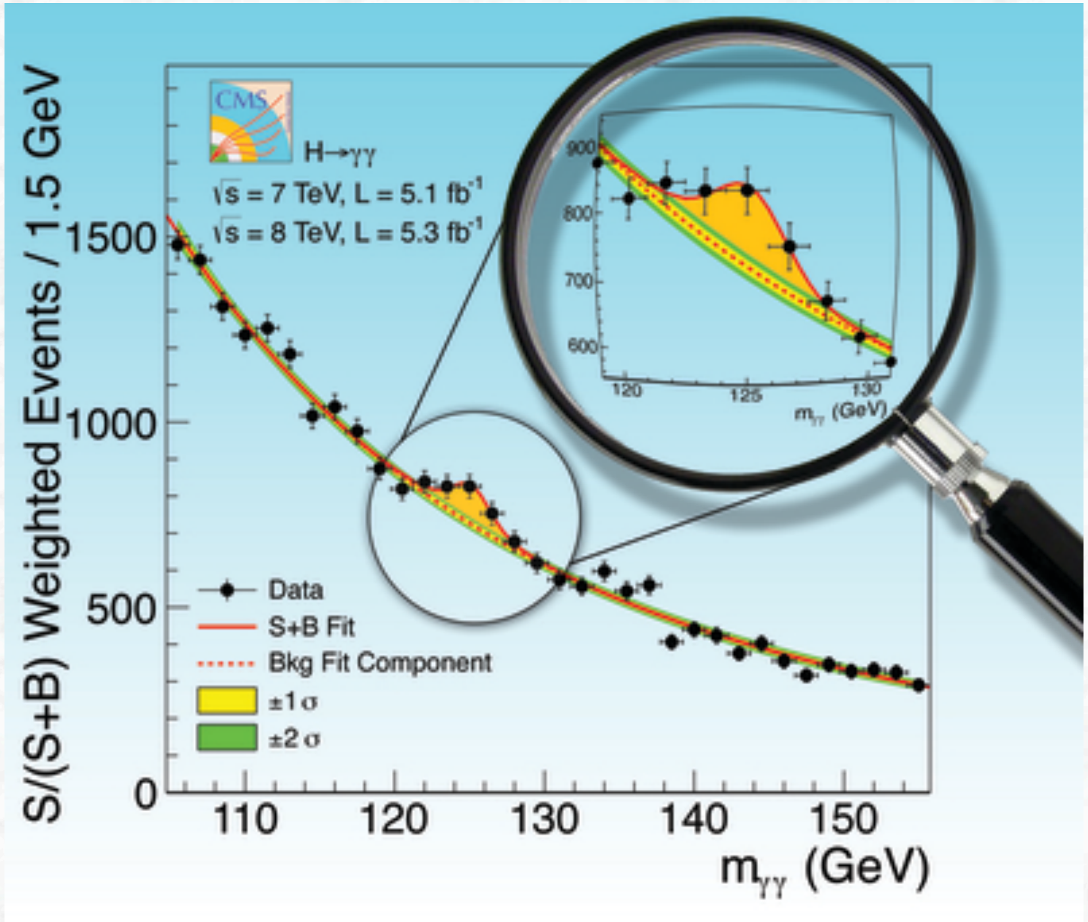


Result of the ATLAS search for H → γγ

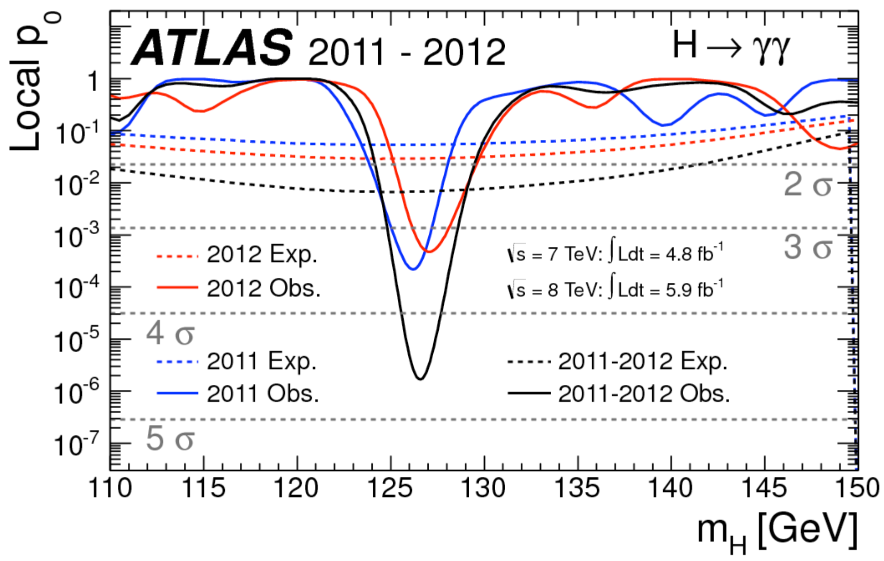


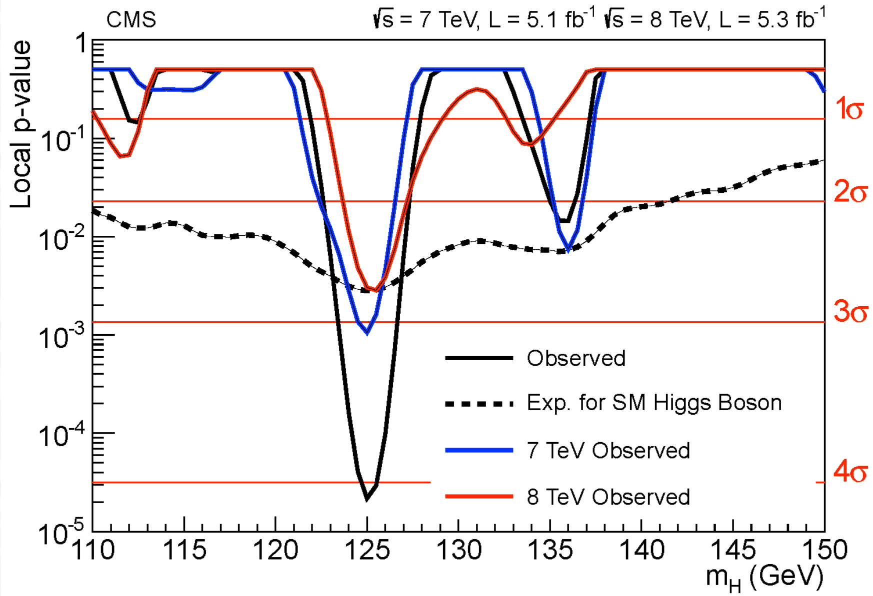
- Background model: exponential / polynomial function, determined directly from data (different models have been used → systematics)

What does the competition see ?



Search for H → γγ: compatibility with background hypothesis



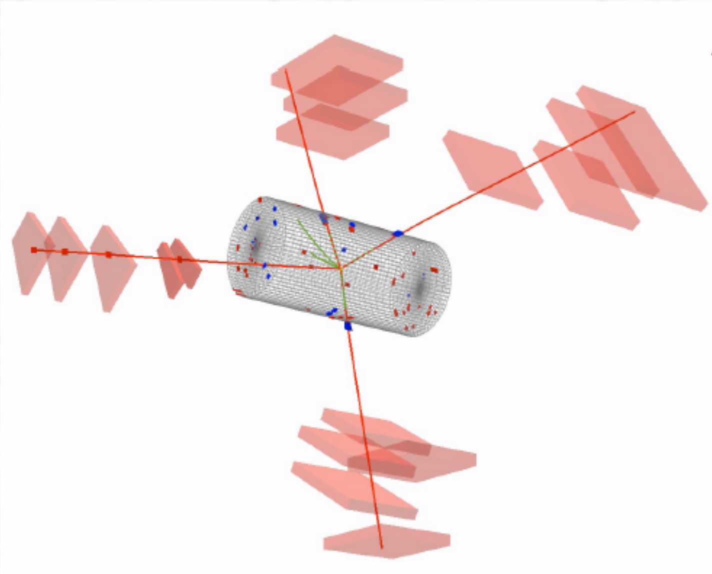


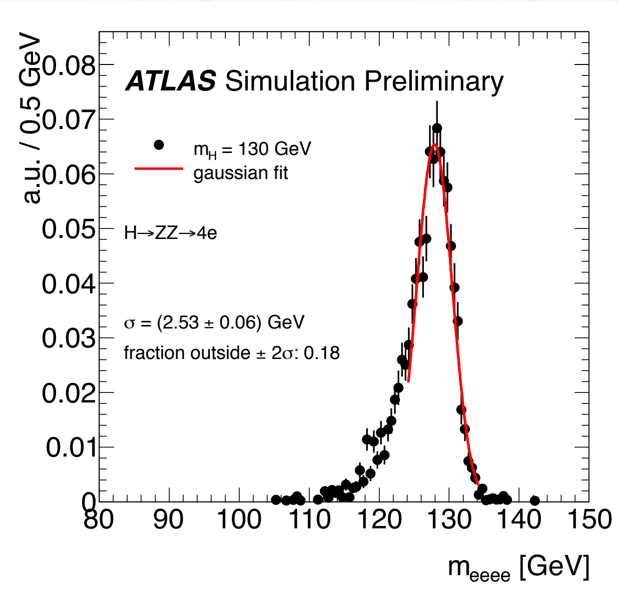
- Maximum deviation from background-only expectation observed for:

	ATLAS		CMS	
	m_H~126 GeV/c^2		m_H ~125 GeV/c^2	
- local p_0-value:	$2 \cdot 10^{-6}$	4.5σ	$2.5 \cdot 10^{-5}$	4.1σ

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

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



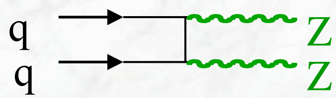


- The "golden mode"
  4 leptons (isolated) with large transverse momenta

- 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

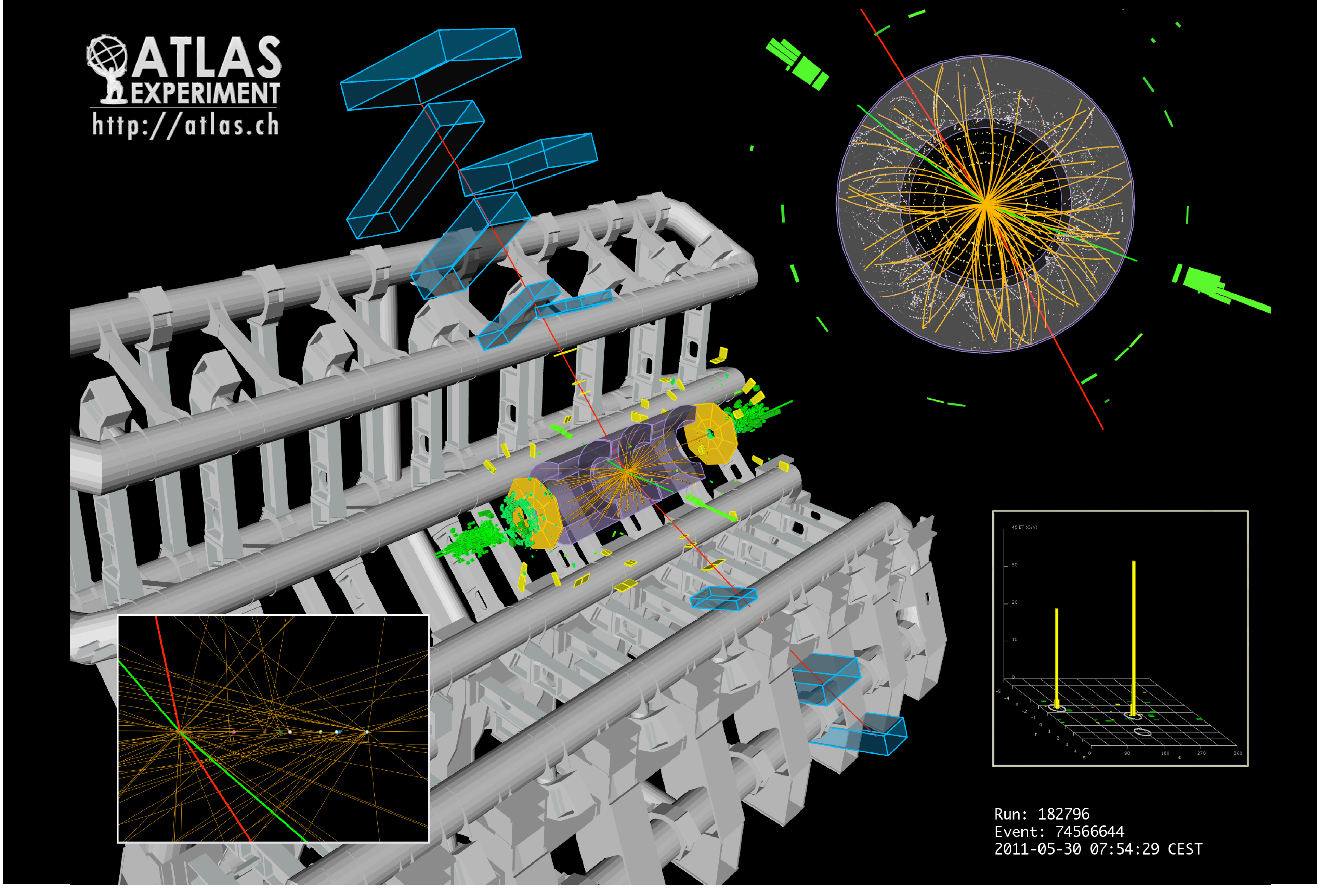
- Low signal rate, but also low background:
  - Mainly from ZZ continuum



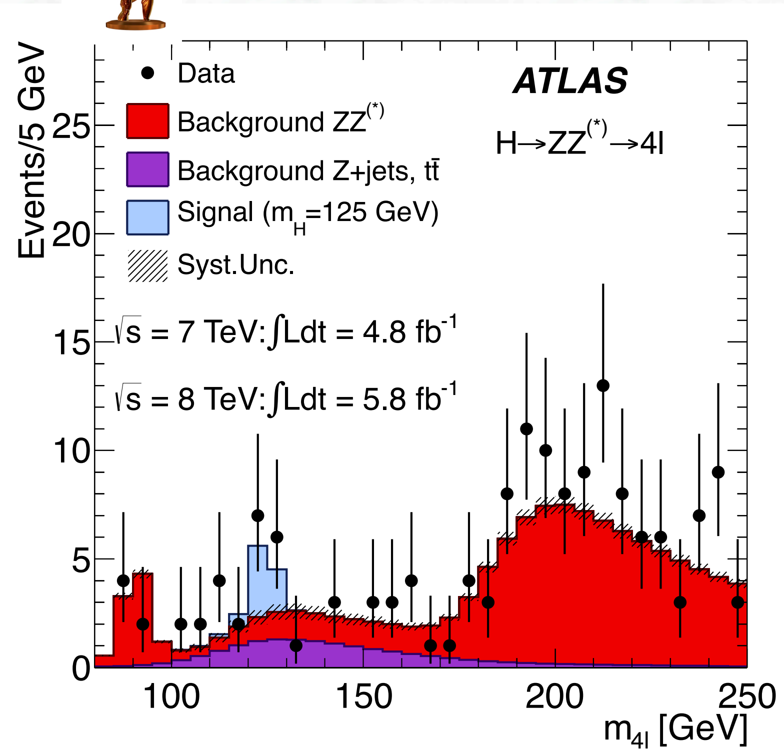
- In addition from tt and Zbb events:
  tt → Wb Wb → ℓν cℓν ℓν cℓν
  Z bb → ℓℓ cℓν cℓν
  however: leptons are non-isolated and do not originate from the primary vertex

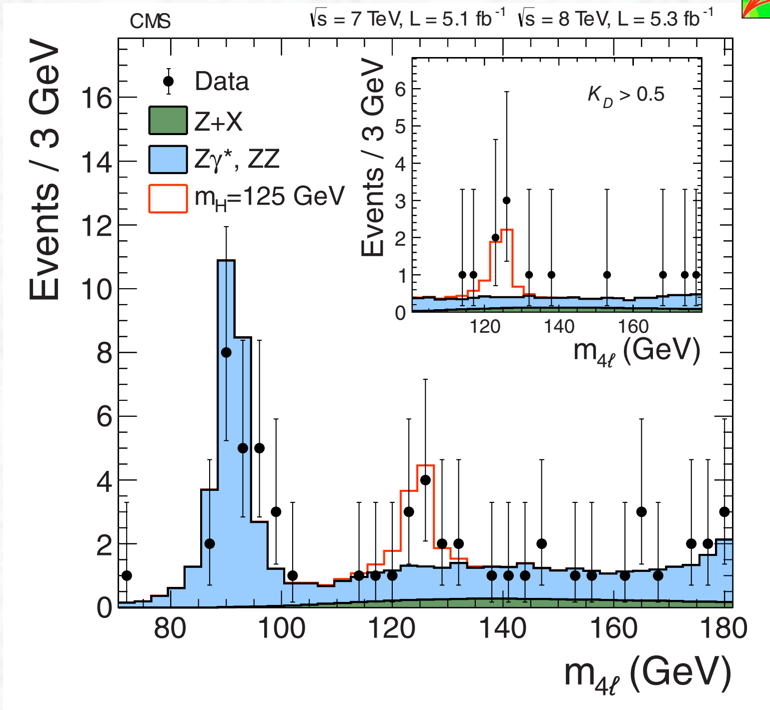
  rejection possible in excellent LHC tracking detectors

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



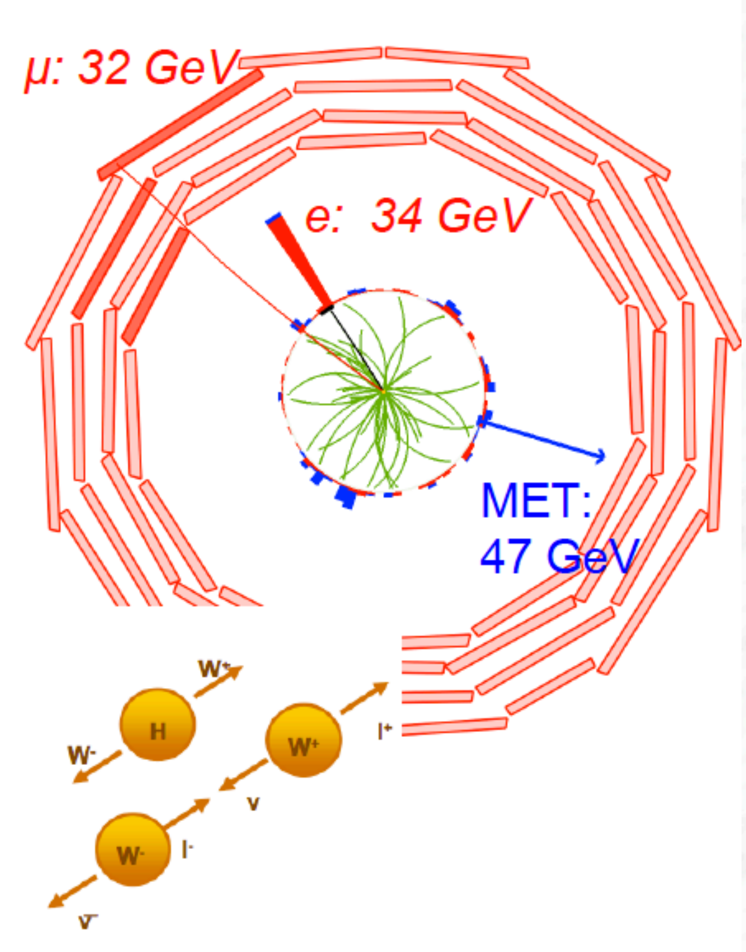
4ℓ invariant mass spectra





- Reducible backgrounds from Z+jets, Zbb, tt giving 2 genuine + 2 fake leptons measured using background-enriched, signal-depleted control regions in data
- Irreducible background from non-resonant continuum ZZ production seem slightly underestimated in NLO Monte Carlo simulation; normalized in high-mass region;

Search for H → WW → ℓν ℓν decay



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

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

- 2 neutrinos

  → large missing transverse energy

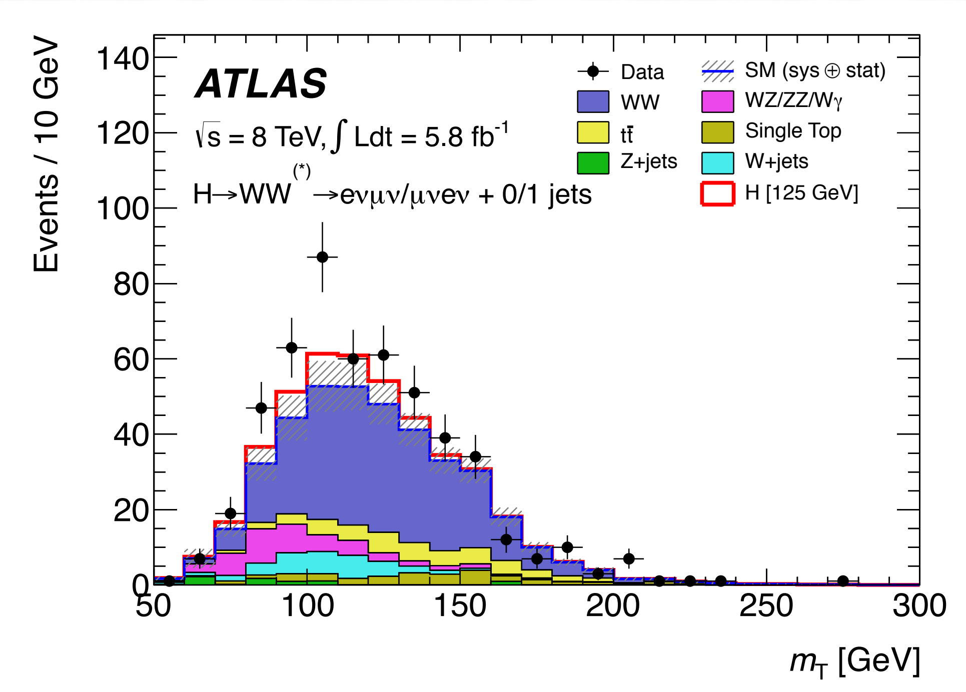
  → Higgs boson mass cannot be reconstructed, use transverse mass

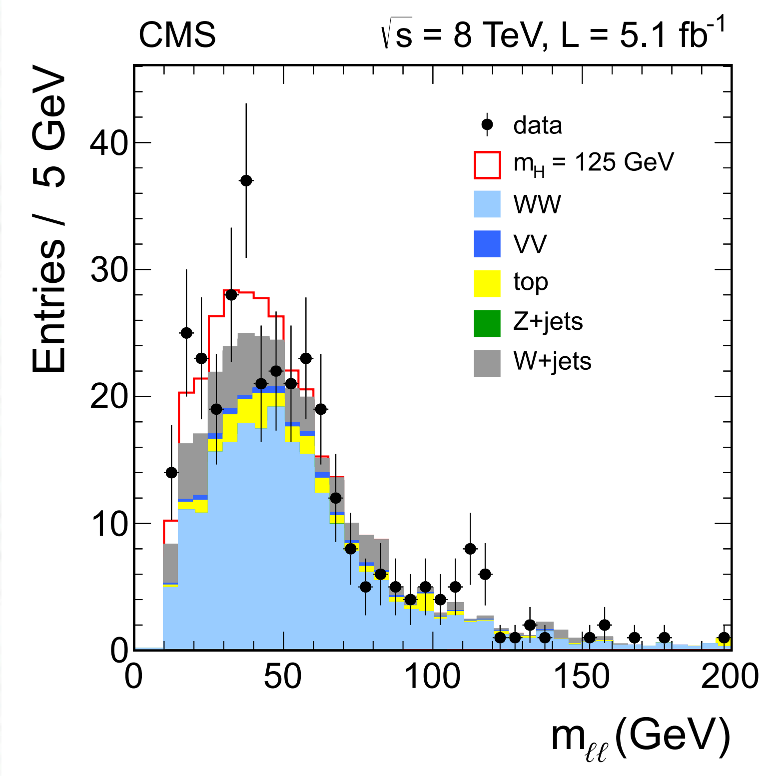
- Highest sensitivity around 160 GeV/c^2

  (nearly 100% H → WW branching ratio)

- Tevatron exclusion is based on this channel

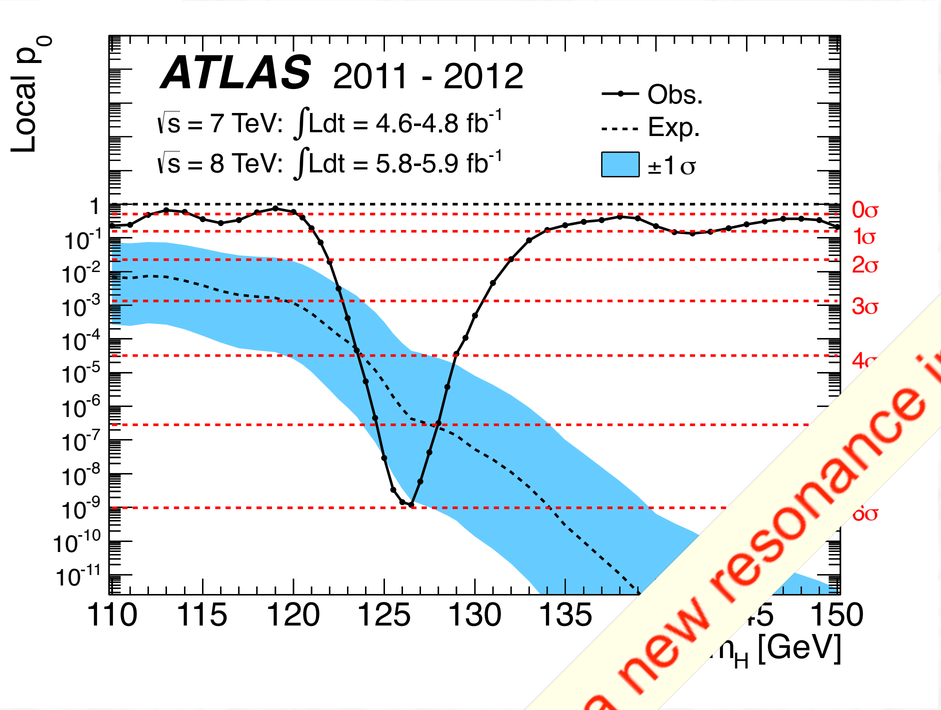
H → WW → ℓν ℓν

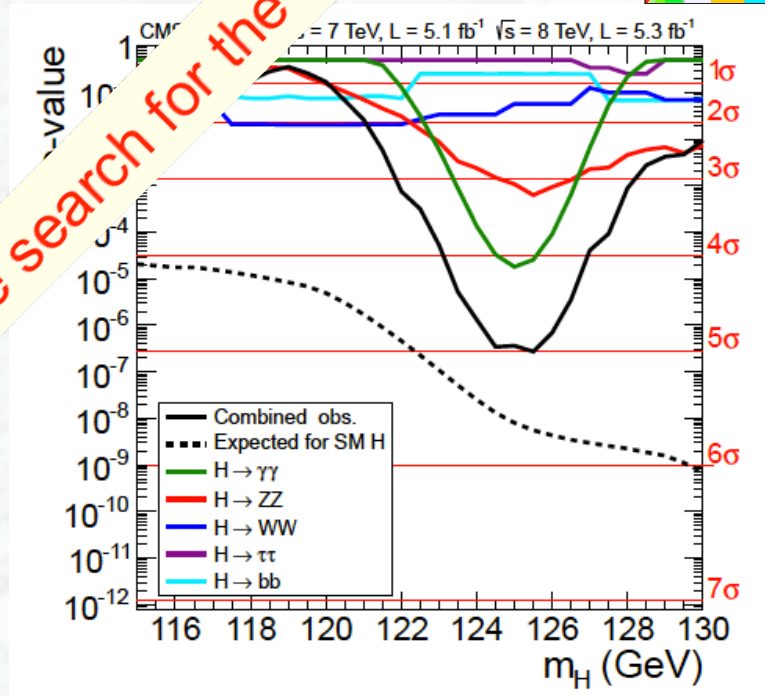




Updated ATLAS analysis (since 4th July) including the 2012 data

Test of background-only hypothesis for the combin[illegible] of the γγ, ZZ, WW, ττ and bb channels -ATLAS and CMS-





Observation of a new resonance in the search for the Higgs boson

Small probabilitie[illegible] background-only hypothesis observed for:

ATLAS: 1[illegible] GeV: 5.9σ (expected for m_H = 126.0 GeV: 5.0 σ)

CMS: [illegible]5.3 GeV: : 5.0σ (expected for m_H = 125.3 GeV: 5.8 σ)

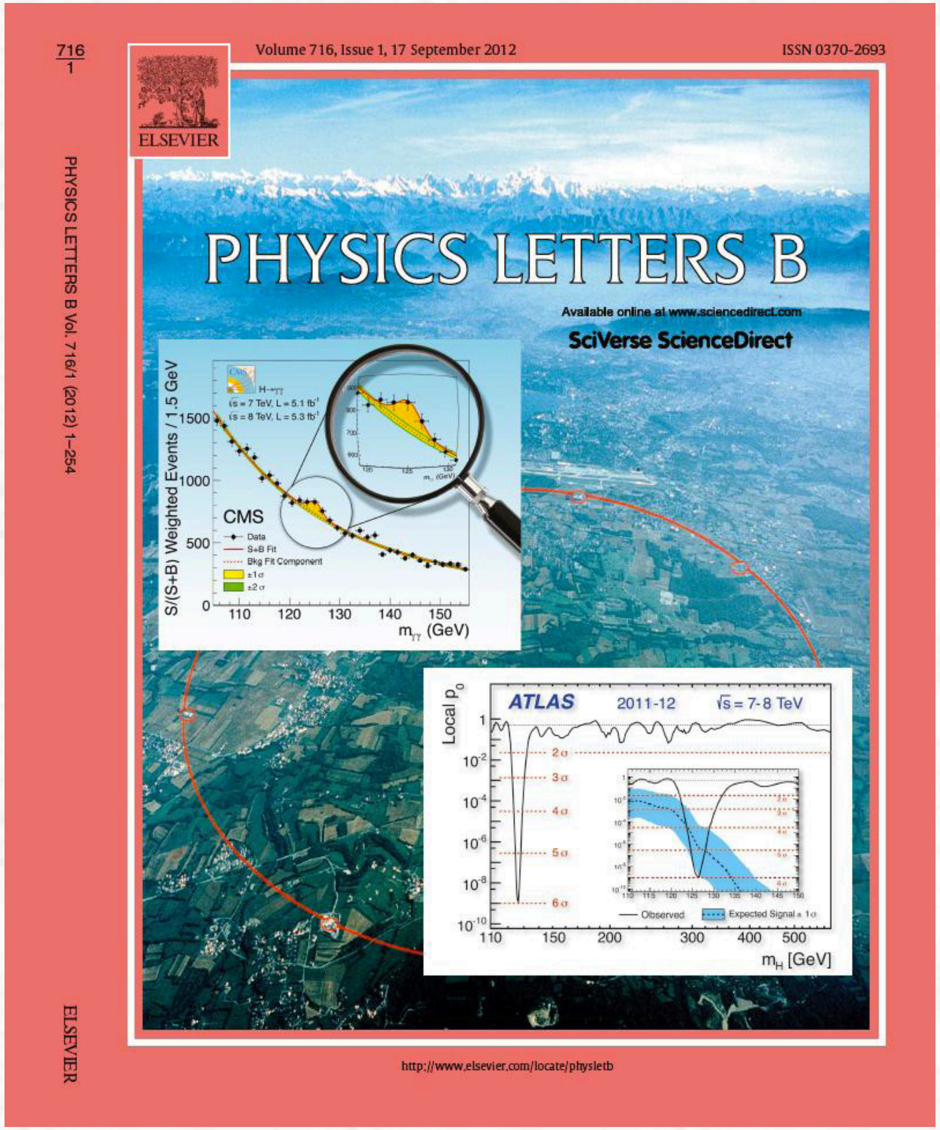
Fabiola Gianotti (CERN) and
Joseph Incandela (UC Santa Barbara)

-spokespersons of the ATLAS and CMS
experiments-

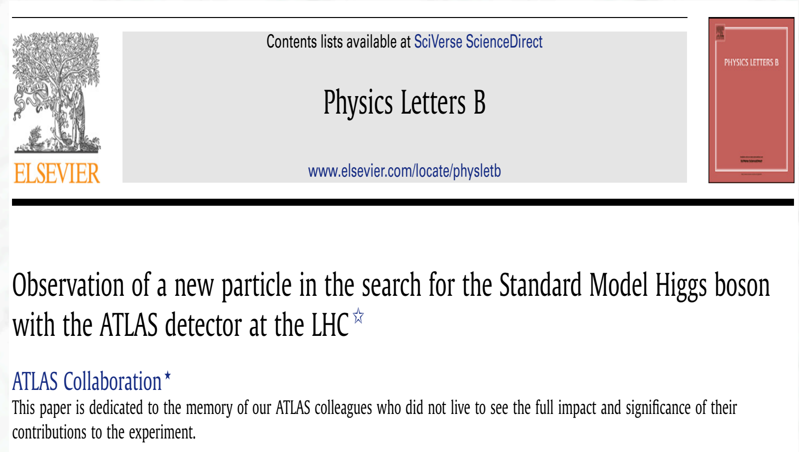
Live transmission to Melbourne

Int. Conference on High Energy Physics

Observation of a New Particle



Submission to PLB on 31. July 2012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Physics Letters B

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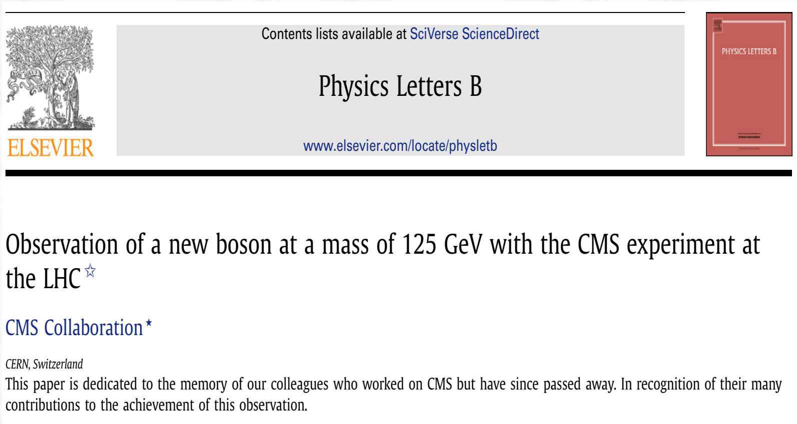
ELSEVIER

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

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ELSEVIER

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

CMS Collaboration *

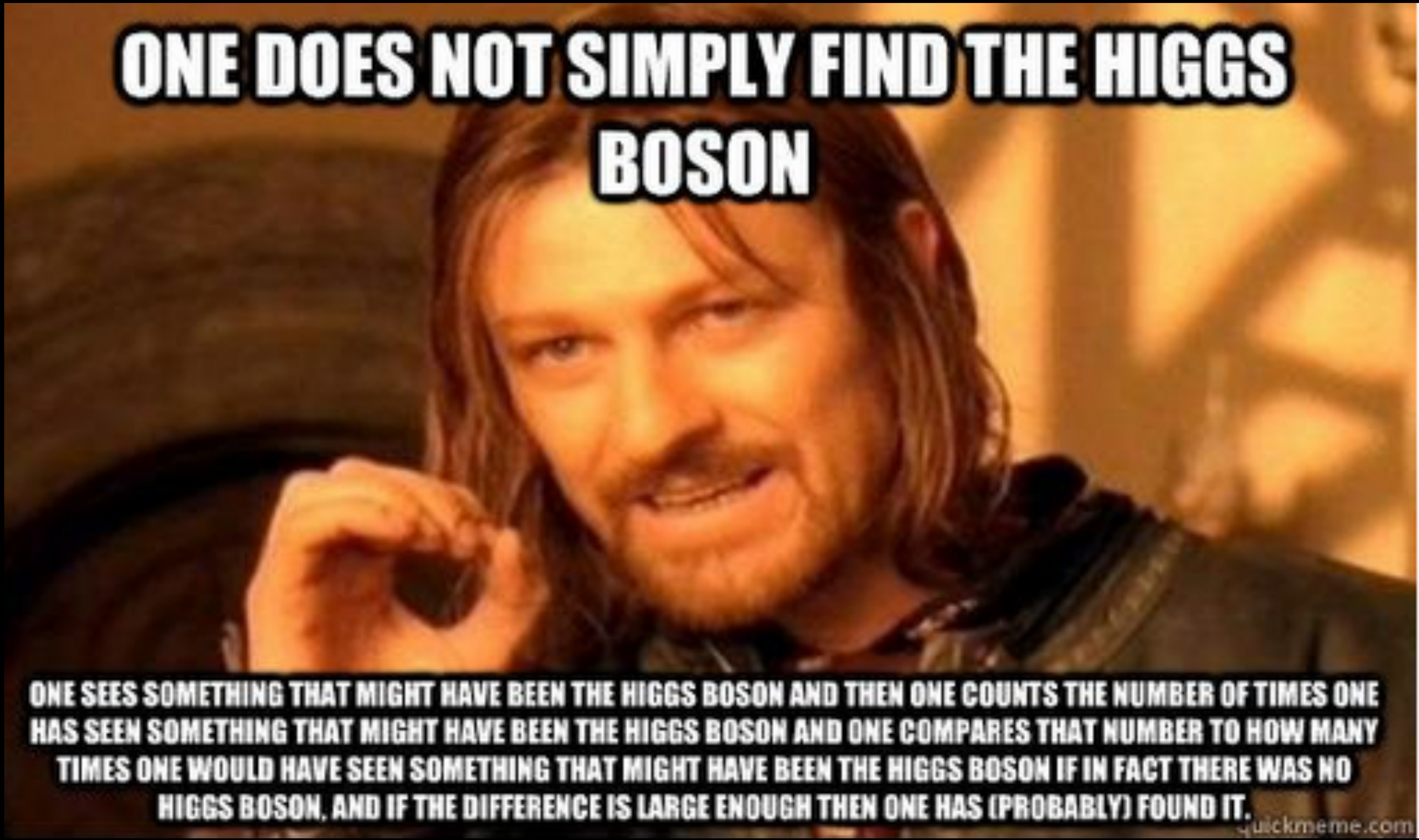
CERN, Switzerland

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

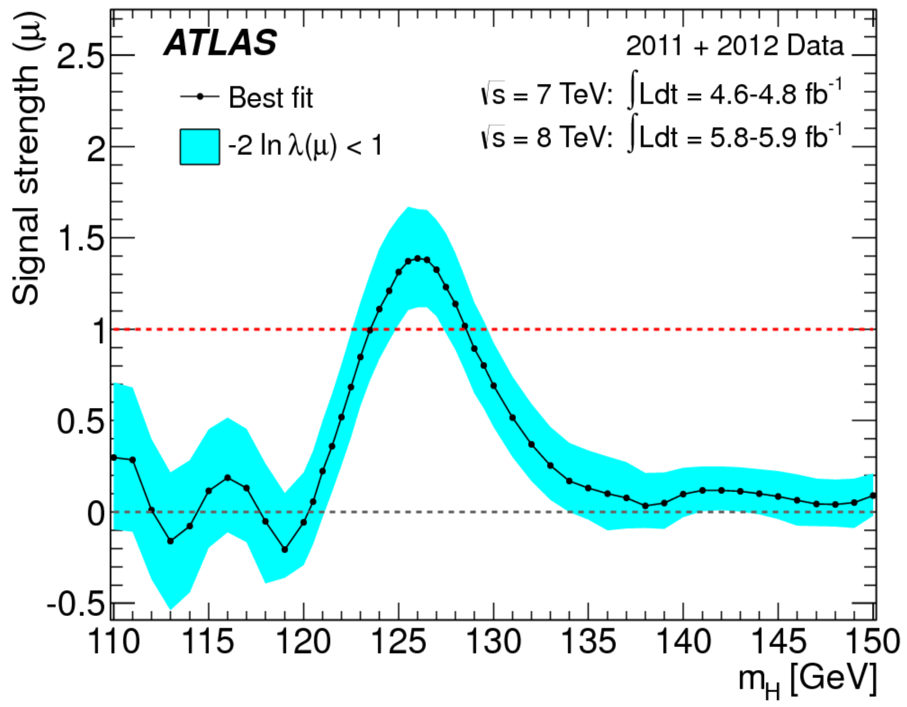
→ a new neutral boson has been discovered

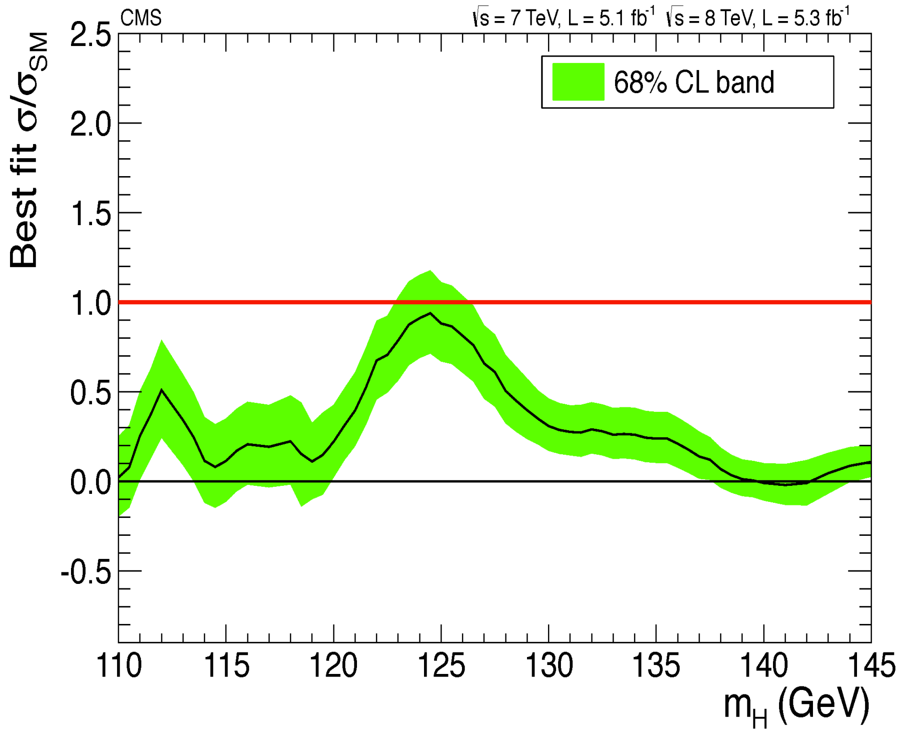
Is it the Higgs Boson ?



Signal strength of the new particle

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





Largest signal strength at m_H= 126.0 GeV

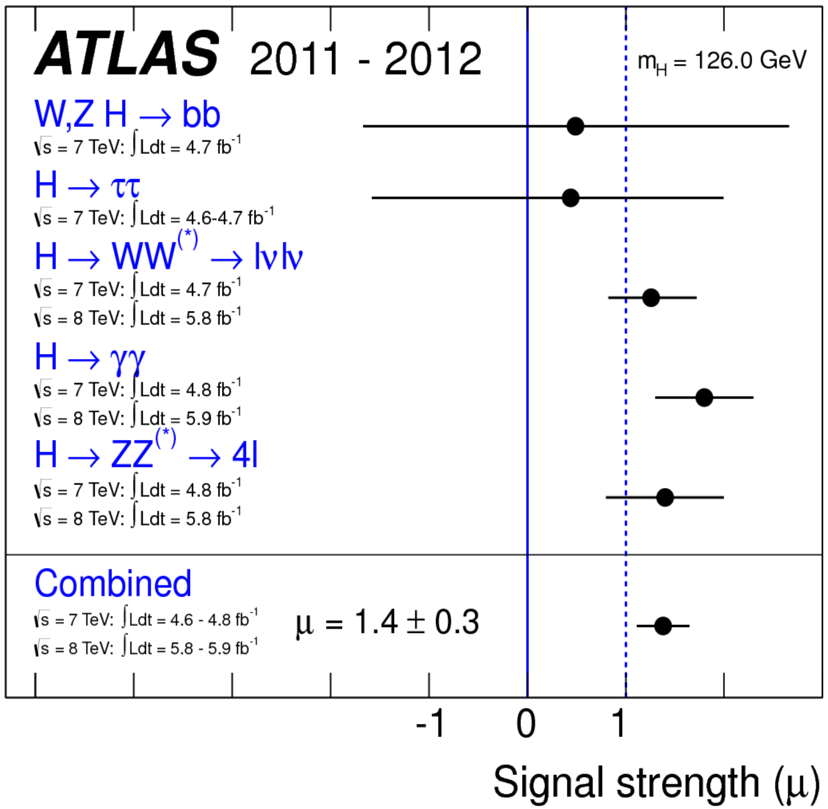
μ = 1.4 ± 0.3

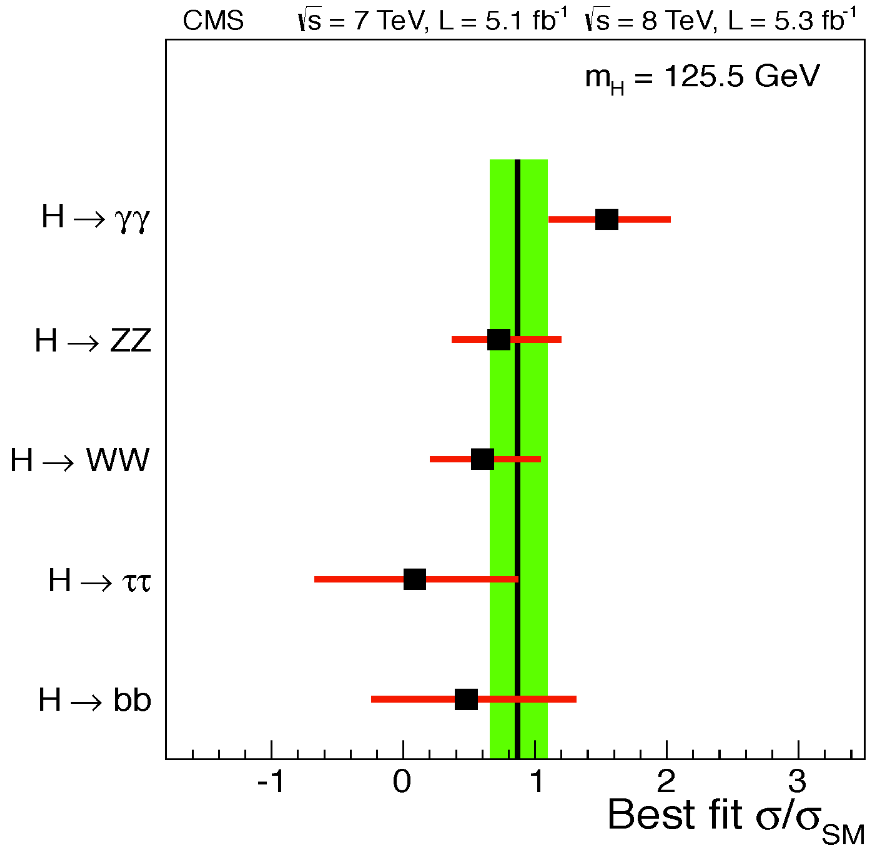
Largest signal strength at m_H= 125.5 GeV

μ = 0.87 ± 0.23

Consistent with expectation in the Standard Model (μ=1)

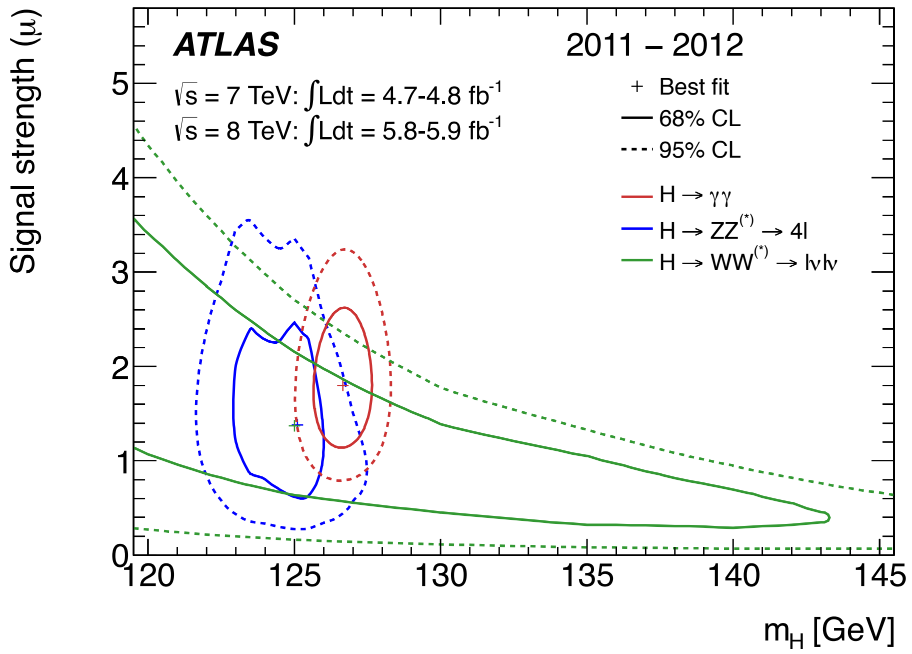
Signal strength in individual decay modes

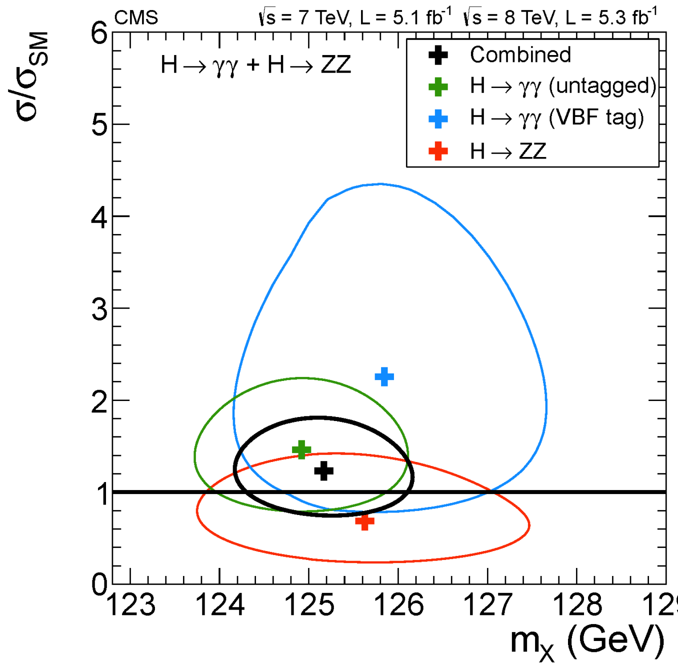




- Data are consistent with the hypothesis of a Standard Model Higgs boson !
- Experimental uncertainties are still too large to get excited about “high” $\gamma\gamma$ and “low” fermionic ($\tau\tau$ and bb) signal strength !

Determination of mass and signal strength





m_H = 126.0 ± 0.4 (stat) ± 0.4 (syst) GeV

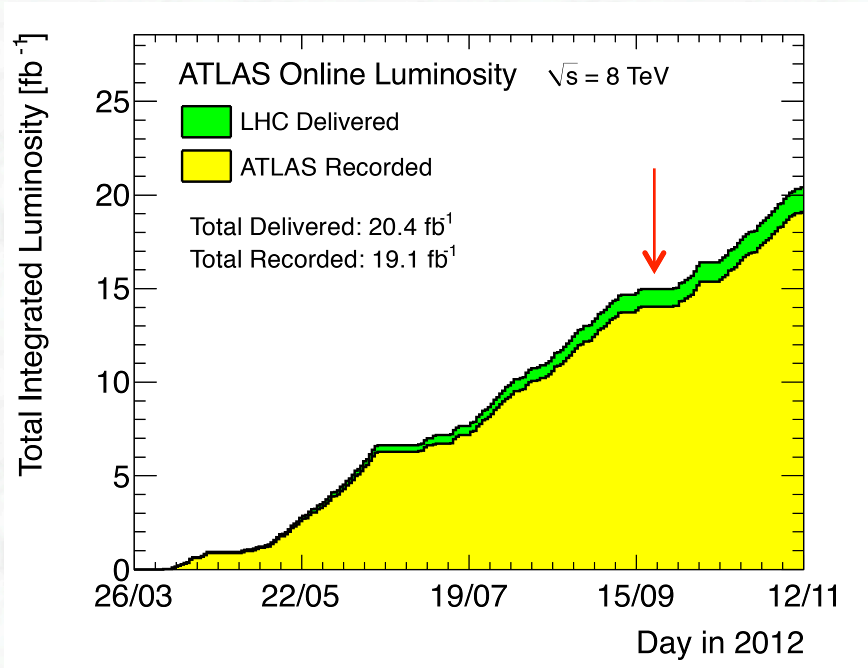
m_H = 125.3 ± 0.4 (stat) ± 0.5 (syst) GeV

What do the new data say?

-2012 data since 4th July-

- Results based on 13 fb^{-1} at $\sqrt{s}$ = 8 TeV have been shown TODAY at the *Hadron Collider Physics Symposium* in Kyoto / Japan

- Focus on $H \rightarrow \tau\tau$ and $H \rightarrow bb$ decays



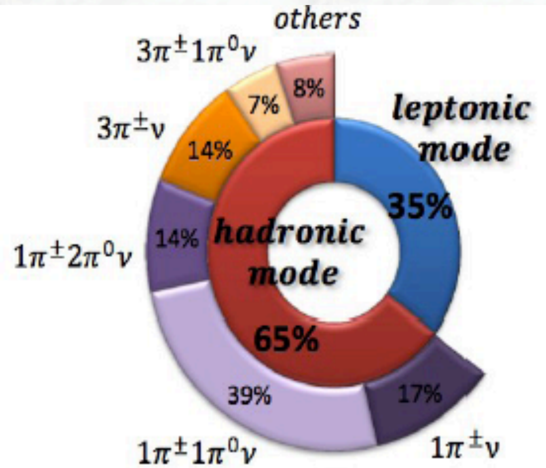
Why is the search in these decay modes so challenging?

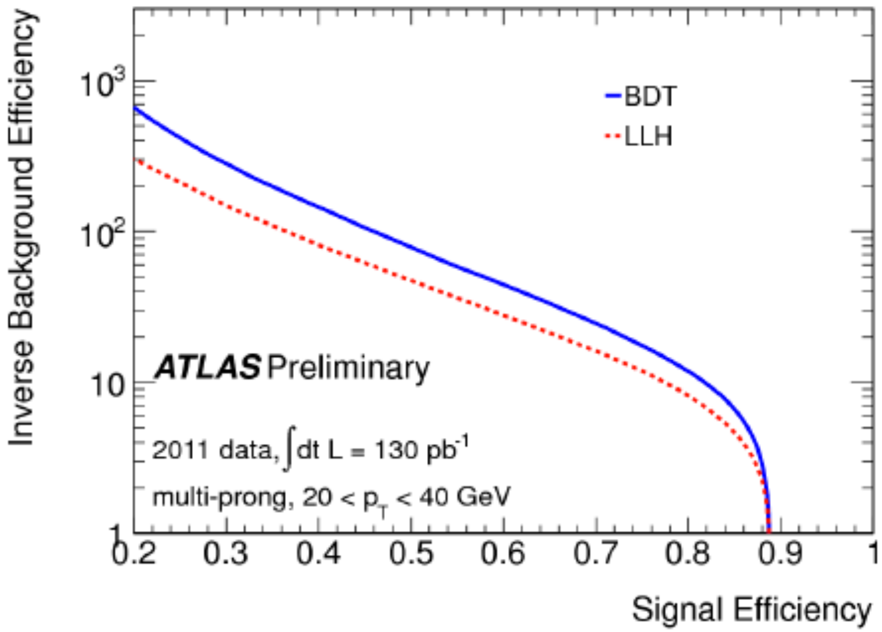
The tau lepton: heaviest lepton observed,

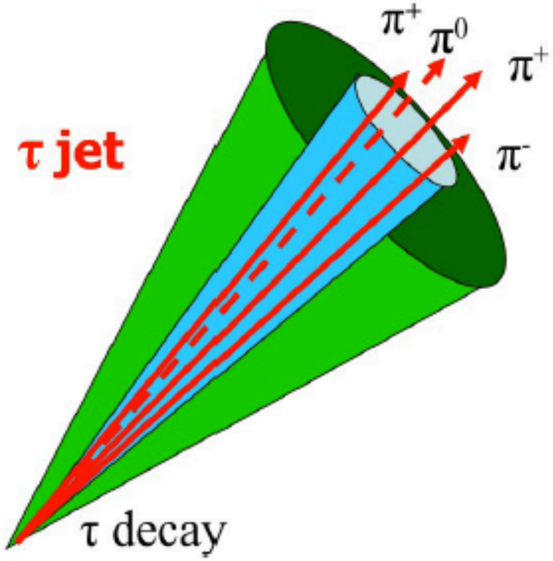
(m_τ = 1.78 GeV, lifetime 2.9×10^{-13} s)

Challenge:

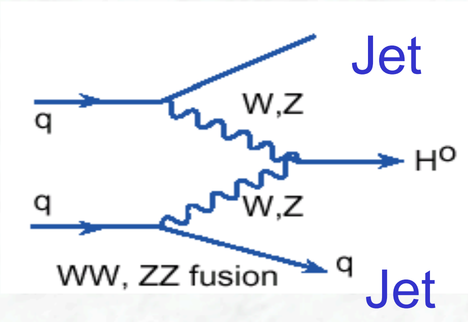
distinguishing hadronic tau decays from hadronic jet activity





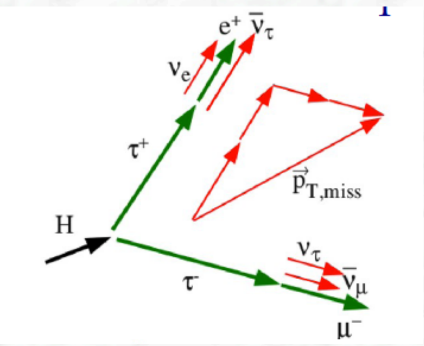


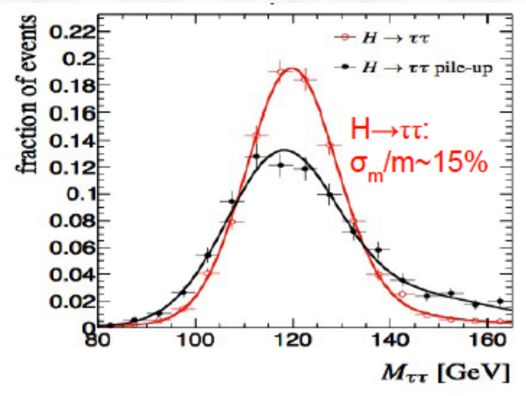
More complications with taus:



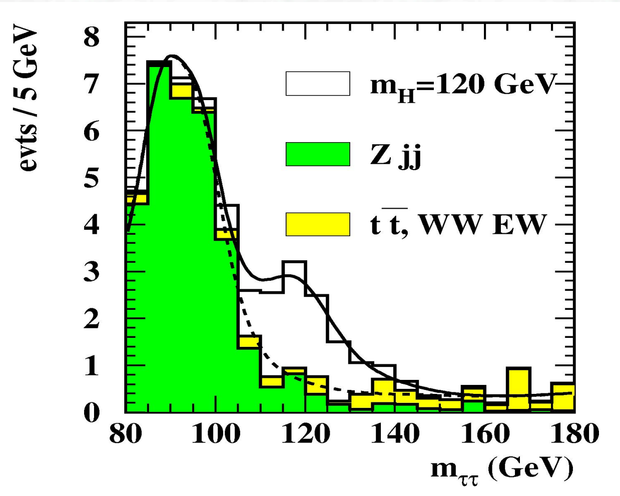
- Small signal rate, compared to large background from jet production via QCD processes
  → smaller vector boson fusion need to be used

- Neutrinos in the final state
  → poor mass resolution





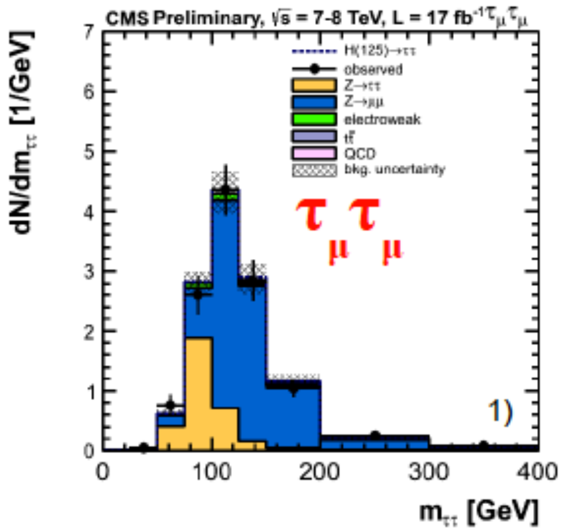
- Small signal in presence of a large $Z \rightarrow \tau\tau$ background

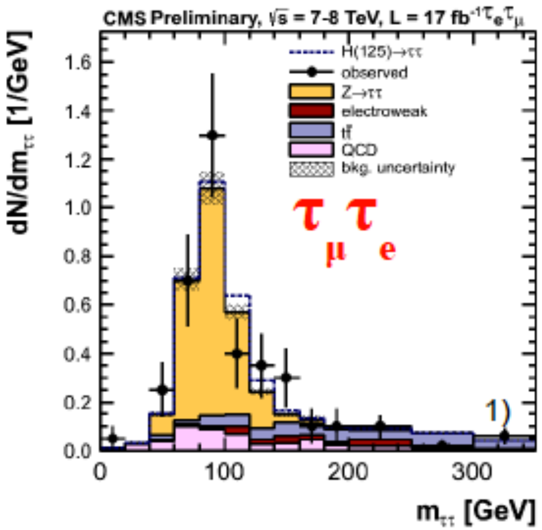


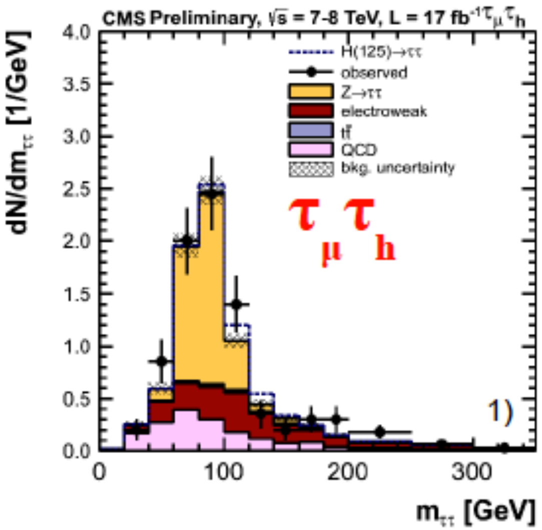
Expected signal

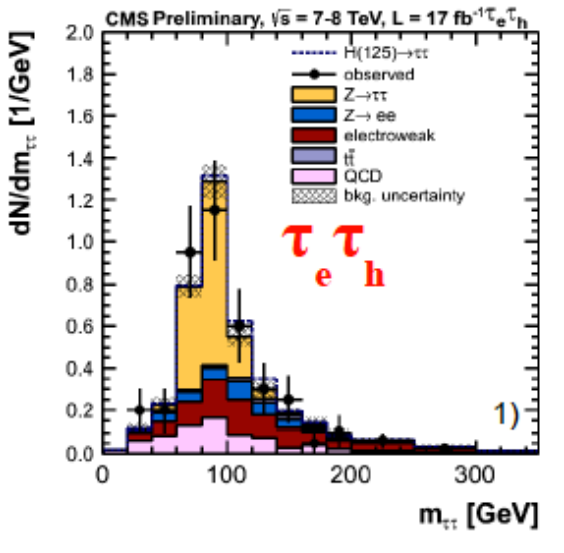
Monte Carlo Simulation !
~50 fb^{-1}

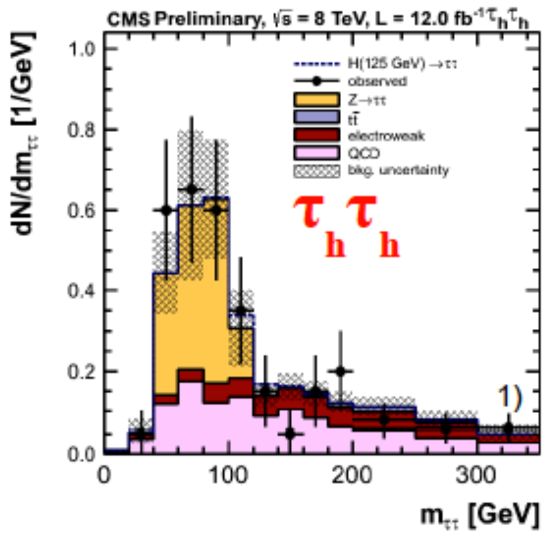
Results based on 17 fb^{-1} data:
(R. Wolf, CMS @ Kyoto)







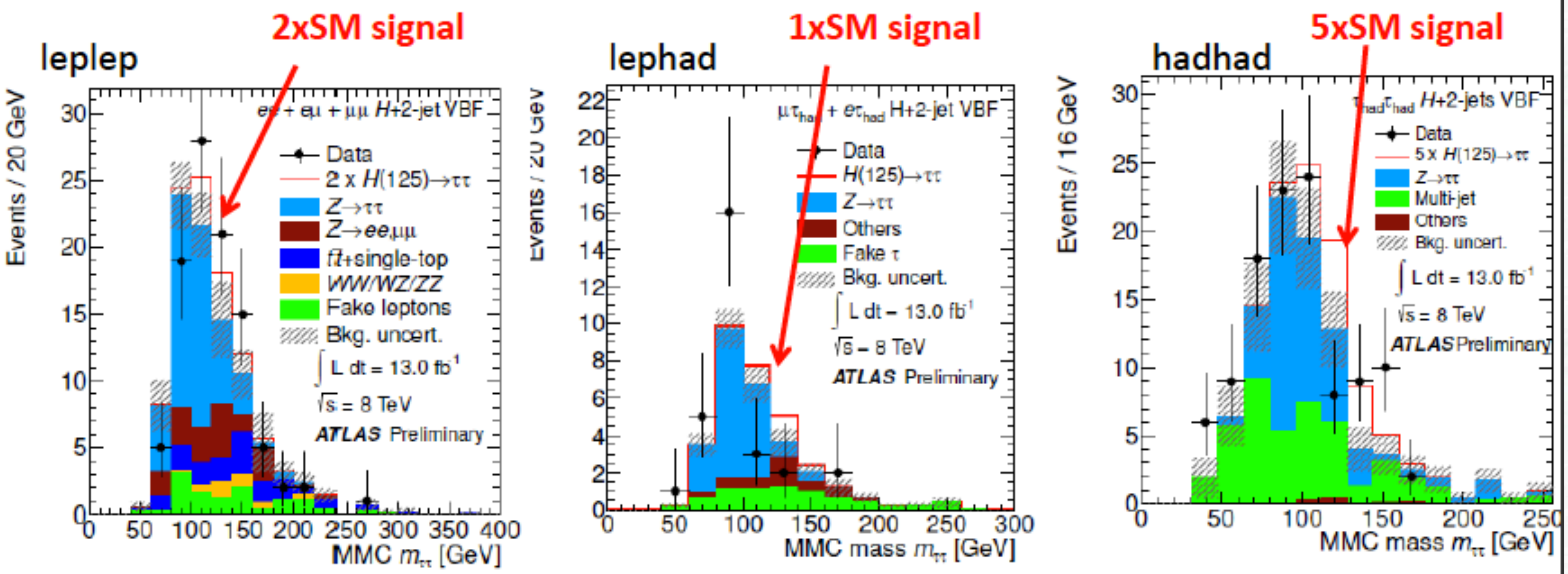




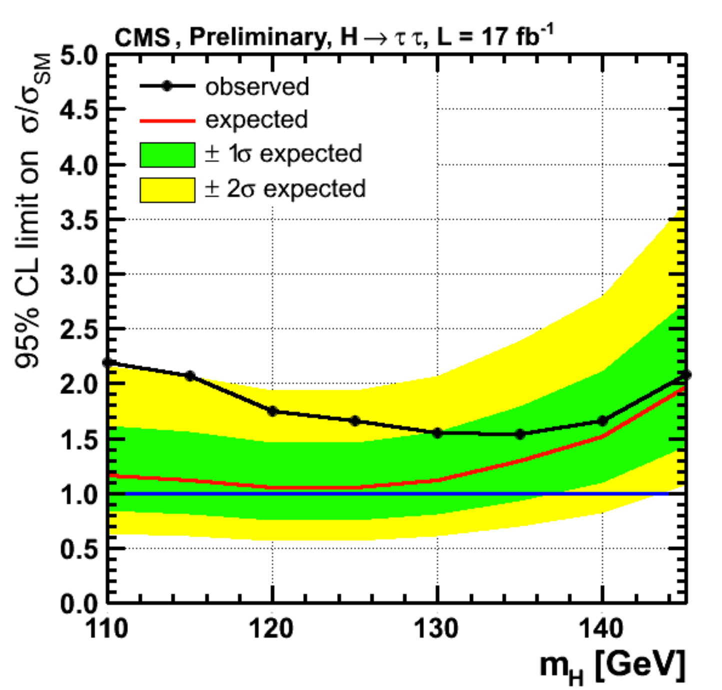
- After template fit (S+B hypothesis).
- Shaded bands: uncert's after fit.

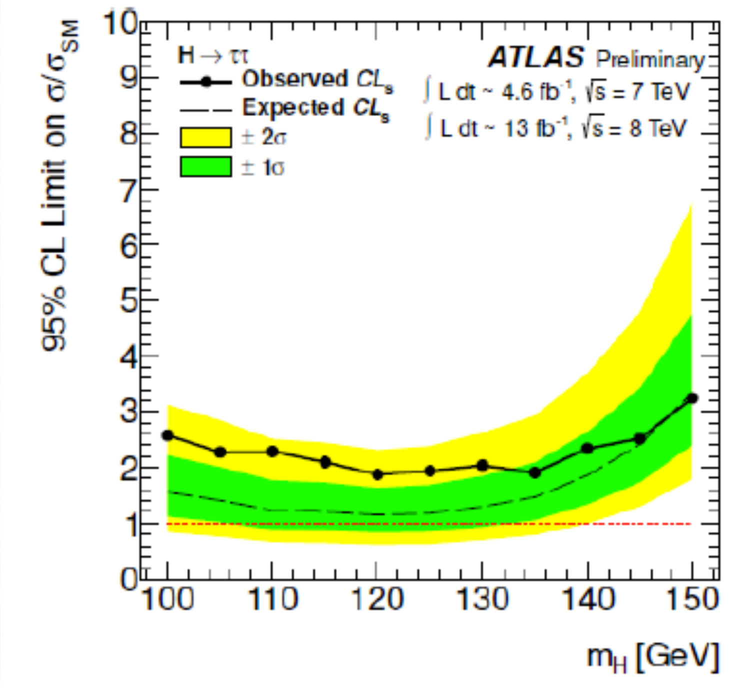
[1] divided by bin width

Results based on 13 fb^{-1} data at $\sqrt{s}$ = 8 TeV:
(K. Nakamura, ATLAS @ Kyoto)



Results of updated H → ττ searches



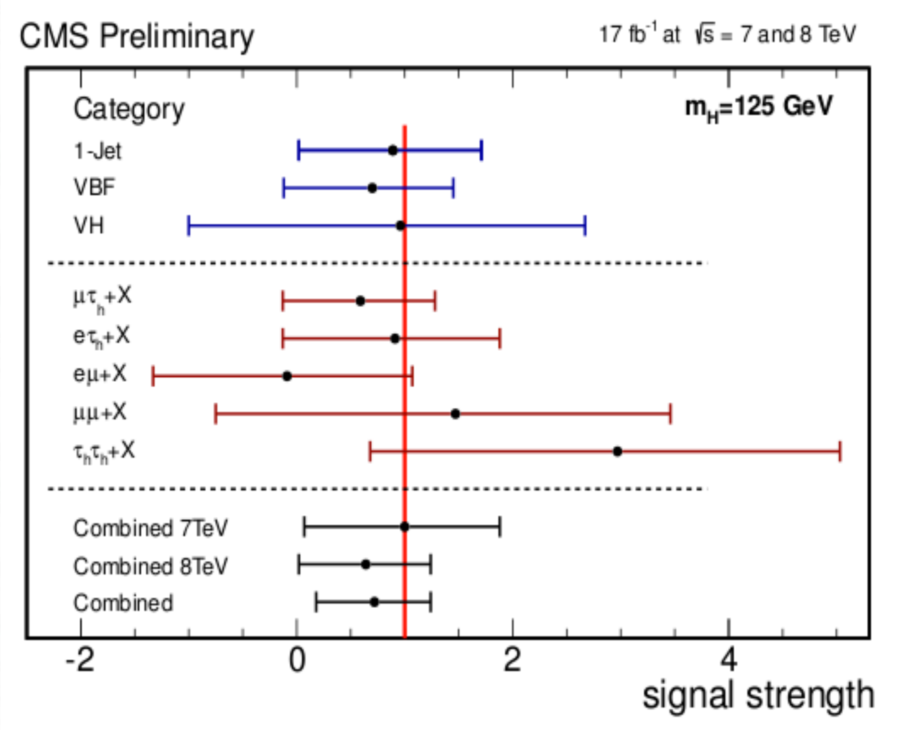


- Sensitivity (125 GeV) = 1.05 σ_{SM}
  Observed limit (125 GeV) = 1.66 σ_{SM}

- Sensitivity (125 GeV) = 1.2 σ_{SM}
  Observed limit (125 GeV) = 1.9 σ_{SM}

- The results of both experiments are compatible with a Higgs boson signal at 125 GeV, but also with the background only hypothesis.

Results of updated H → ττ searches

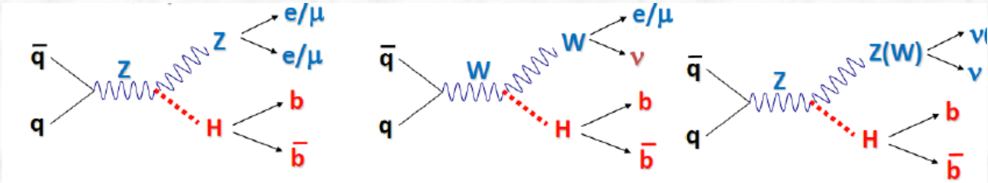


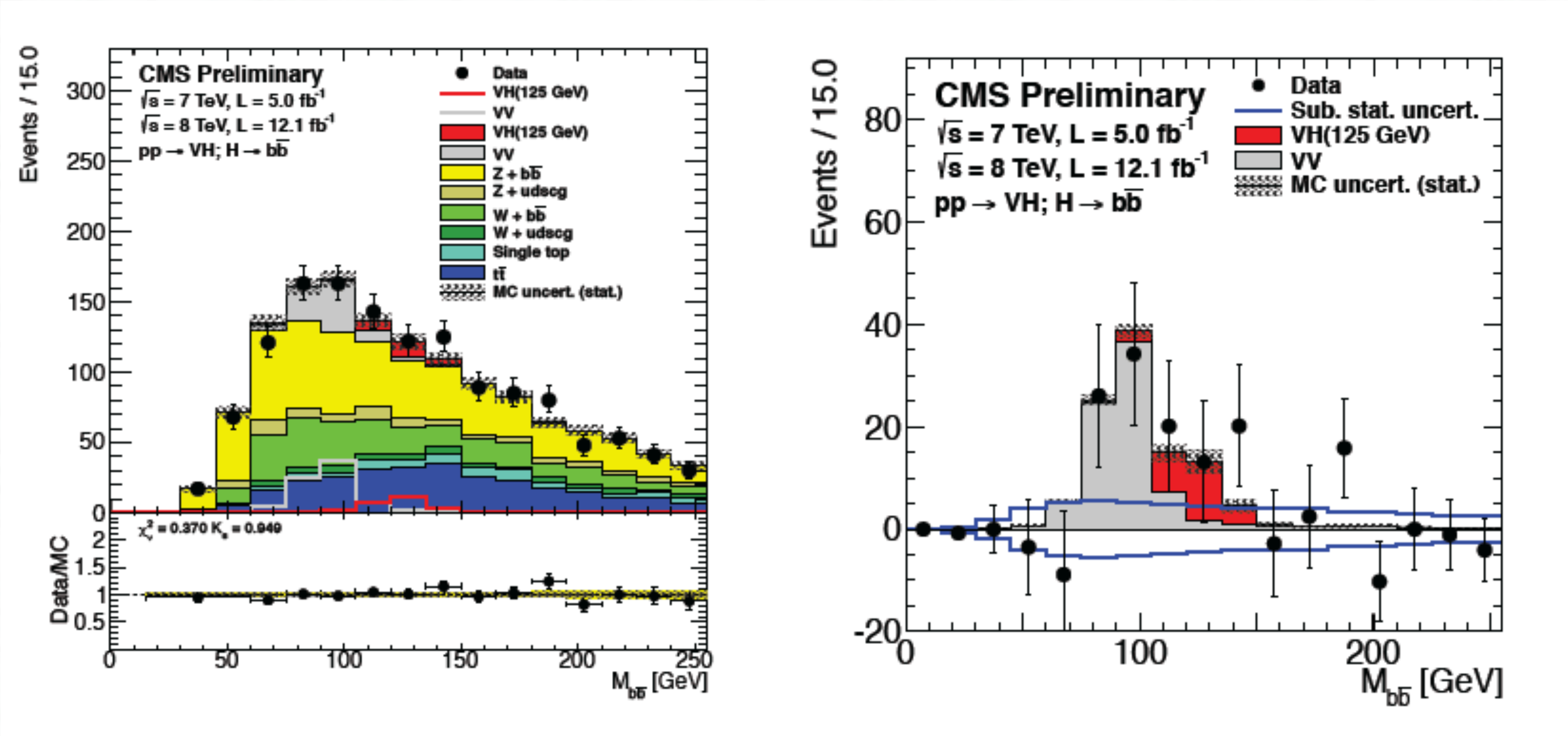
Combined signal strength

CMS: $\mu\,(H \rightarrow \tau\tau) = 0.72 \pm 0.52$

ATLAS: $\mu\,(H \rightarrow \tau\tau) = 0.7 \pm 0.7$

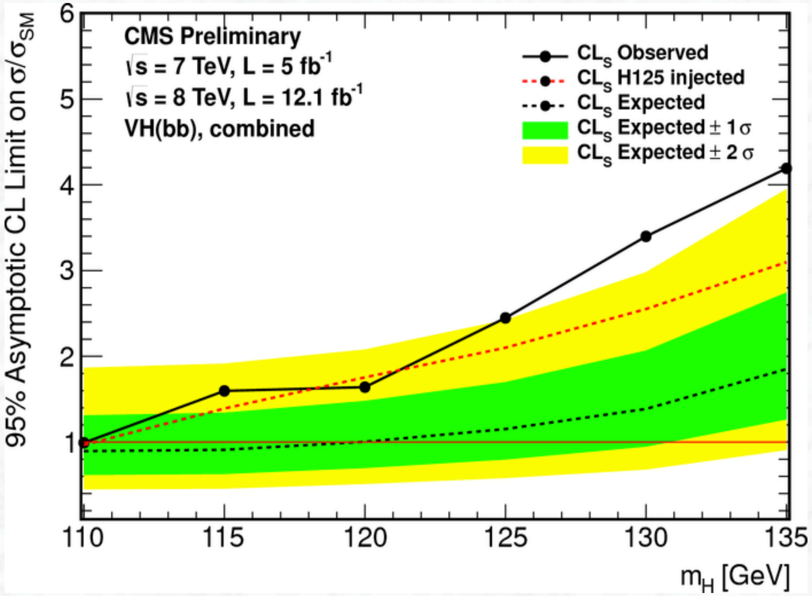
Results on H → bb from CMS

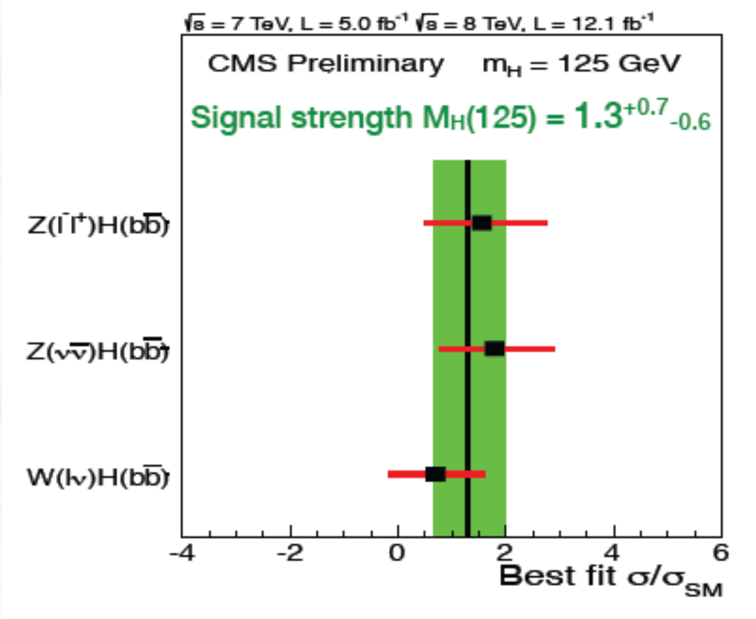




- Small excess is showing up around 125 GeV
- Signal from di-boson production VZ, Z→ bb seen and well described

Results on H → bb





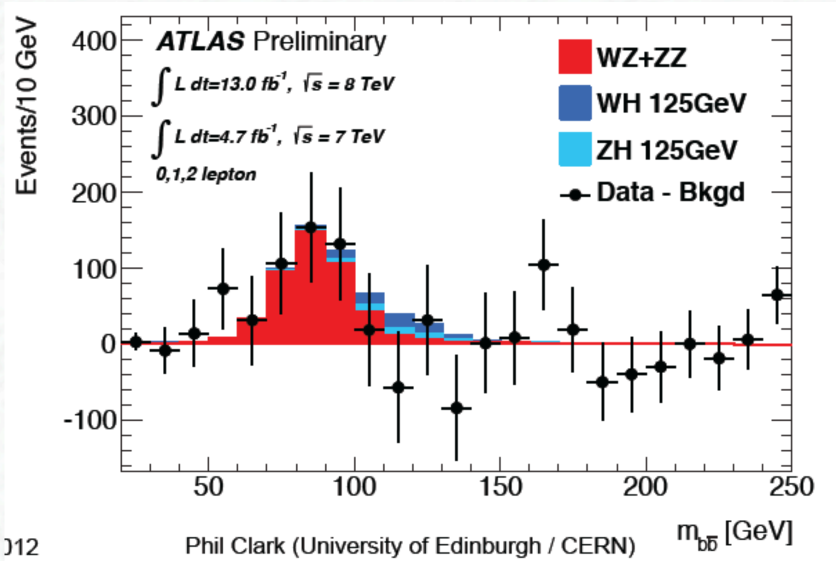
- Observed excess (125 GeV) = 2.2 σ
  Expected (125 GeV) = 2.1 σ

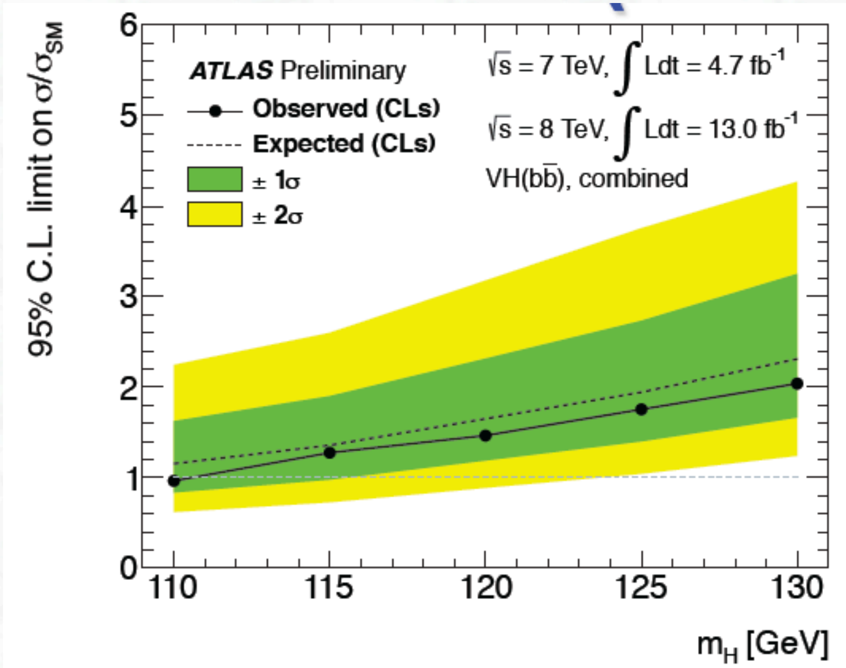
- Compatible with Higgs boson signal at 125 GeV but also with background only hypothesis.

Combined signal strength

μ (H → bb) = $1.3^{+0.7}_{-0.6}$

Results on H → bb from ATLAS



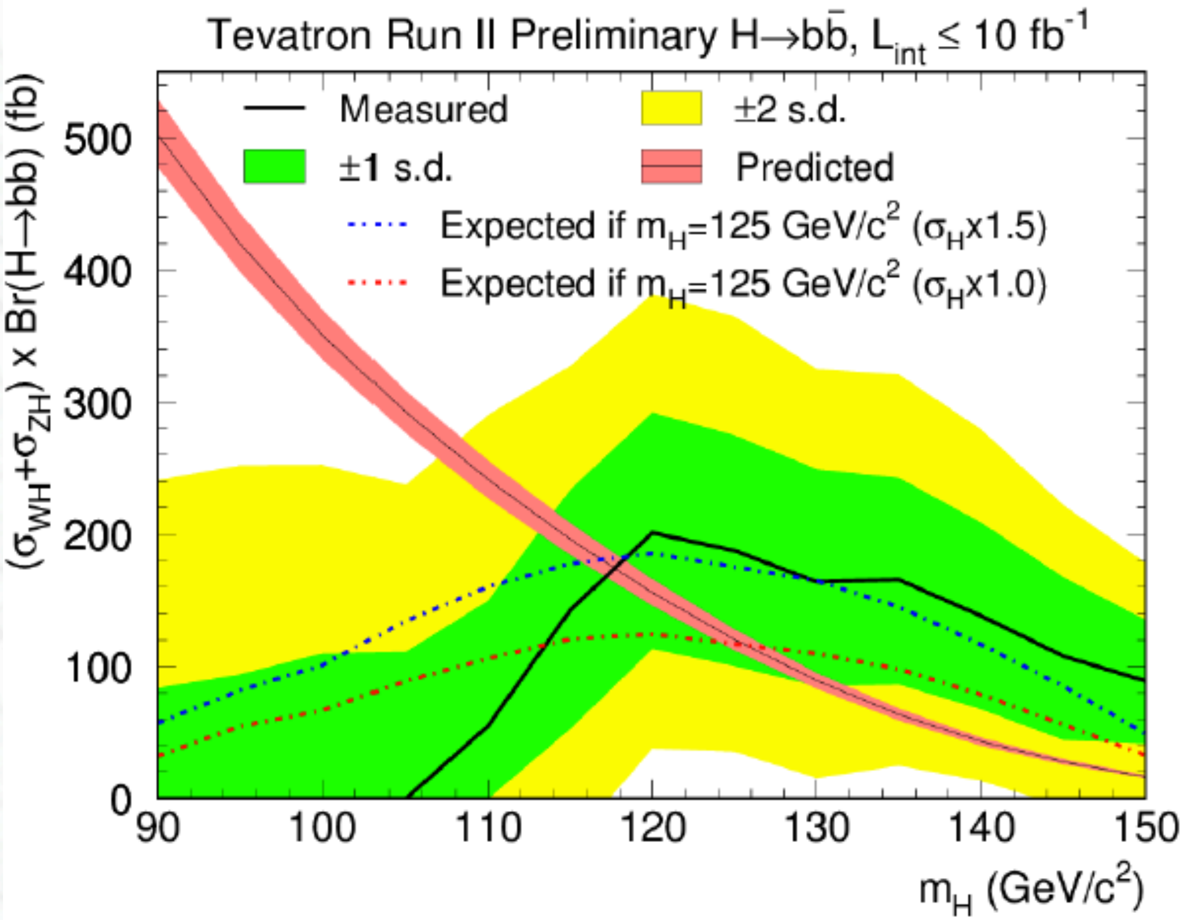


- No excess visible around 125 GeV
- Signal from di-boson production VZ, Z → bb seen

Combined signal strength

μ (H → bb) = -0.4 ± 1.1

Results on H → bb from the Tevatron

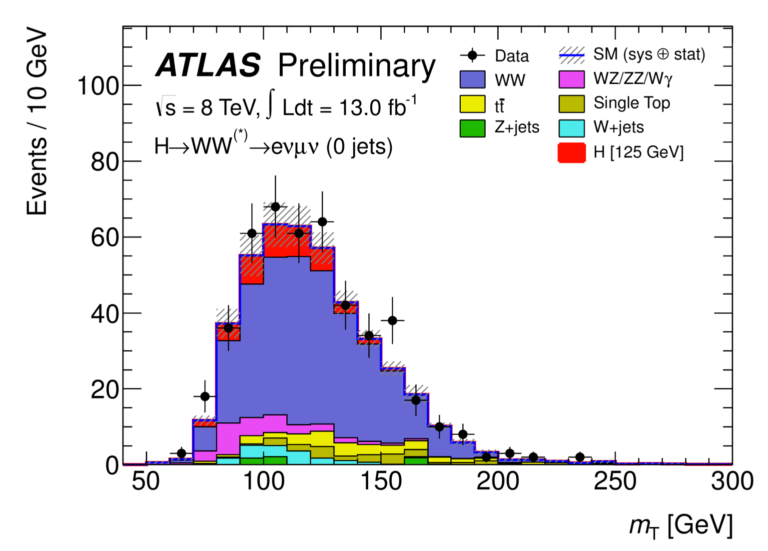


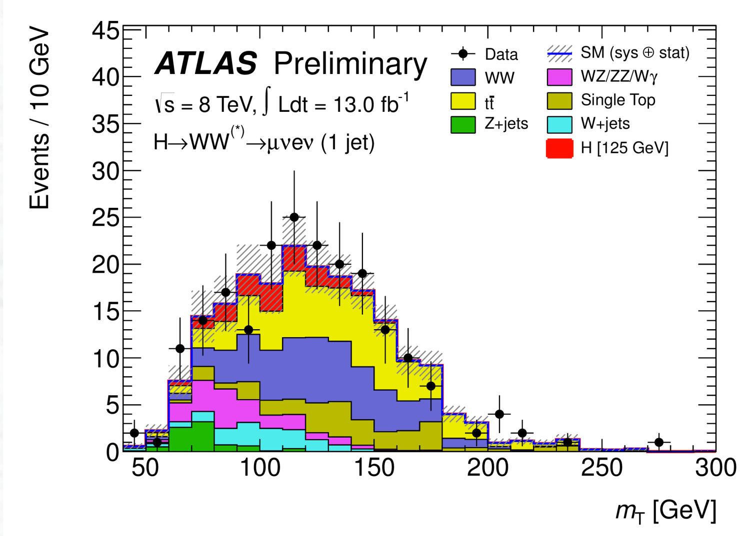
$\mu = 1.56 \pm^{0.72}_{0.73}$

$$(\sigma_{WH}+\sigma_{ZH})\times\mathcal{B}(H\to b\bar{b}) = 0.19\pm0.09\ (\mathrm{stat}+\mathrm{syst})\ \mathrm{pb}.$$

SM expectation : 0.12 ± 0.01 pb

Results on H → WW from ATLAS





assumes SM ratio of production mechanisms

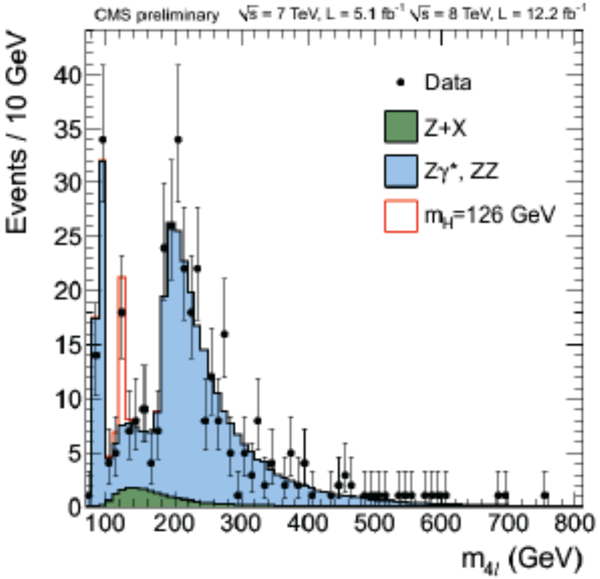
backgrounds & signal acceptance

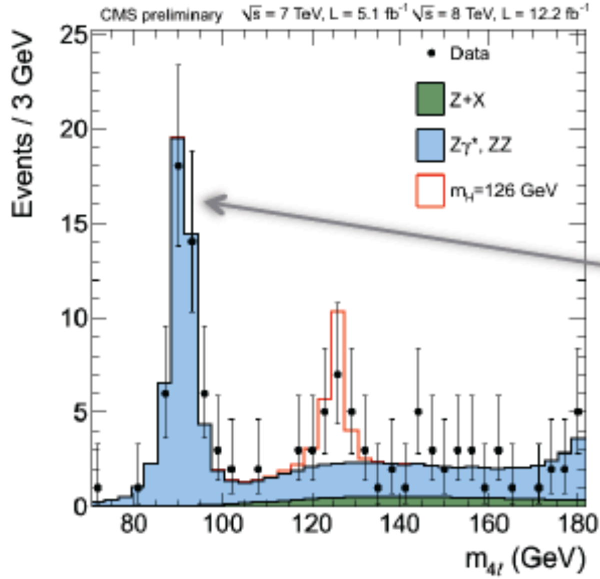
$$\sigma(pp \to H) \cdot Br(H \to WW) = 7.0^{+1.7}_{-1.6}\ (\text{stat})^{+1.7}_{-1.6}\ (\text{theory})^{+1.3}_{-1.3}\ (\text{exp}) \pm 0.3\ (\text{lum})\ \text{pb}$$

SM expectation: $\sigma(pp \to H) \cdot Br(H \to WW) = 4.77 \pm 0.64\ (\text{xsec}) \pm 0.2\ (\text{BR})\ \text{pb}$

LHC Higgs XS WG

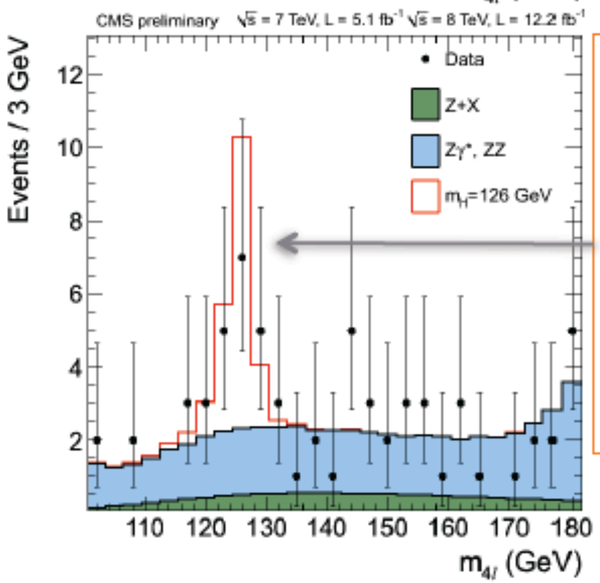
Results on H → ZZ from CMS





Good agreement between predicted and observed ZZ continuum.

Z→4l peak is in place and in agreement with prediction. Fit of the Z→4l peak shows δm~0.4±0.28 GeV and expected resolution.

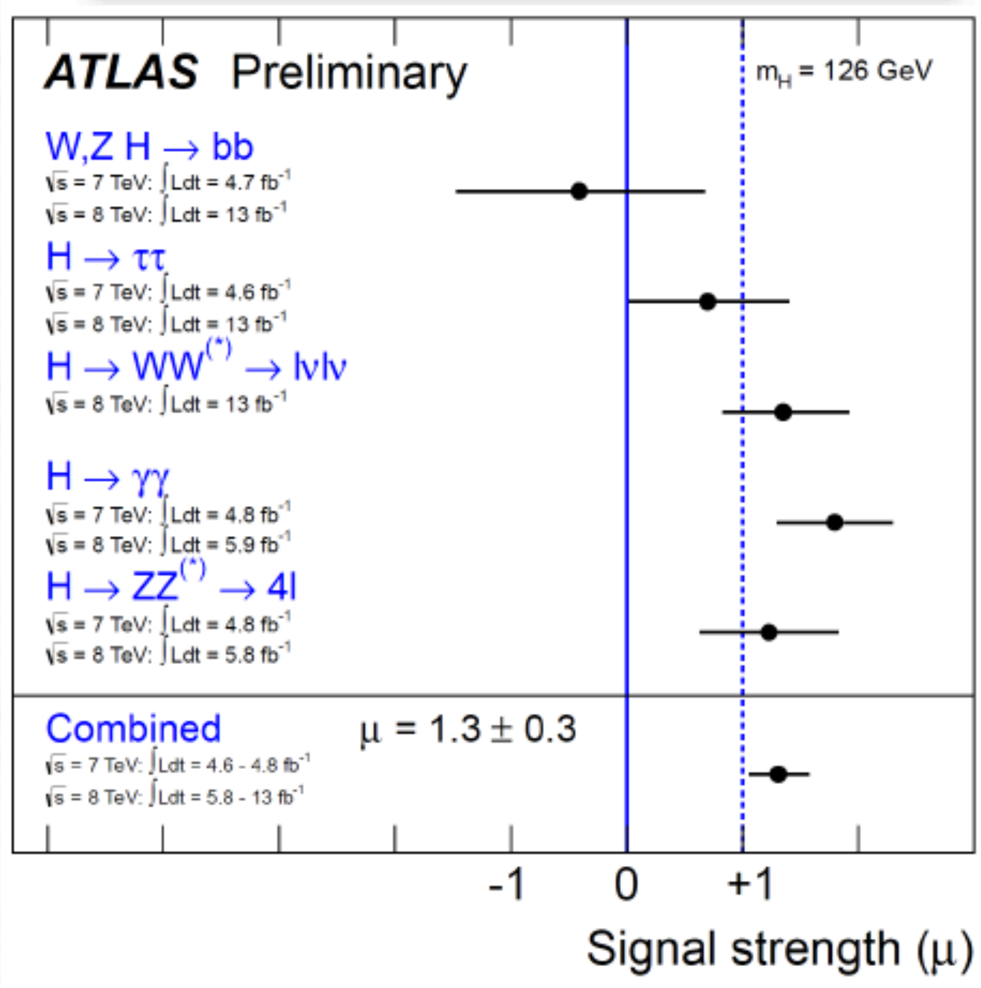


X→ZZ→4l peak is there and increasing in statistics corresponding to luminosity and expectation of H→ZZ→4l

For m(4l) = 121.5..130.5 GeV:

- Expected background: 6.5 events
- Expected signal (m_H=126 GeV): 12.5 events
- Signal:Bckg ~ 2:1!
- Observed: 17 events

Results on Signal strengths including new data



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 many 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 conclusive and more precise 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