Higgs Searches and Properties Measurement with ATLAS

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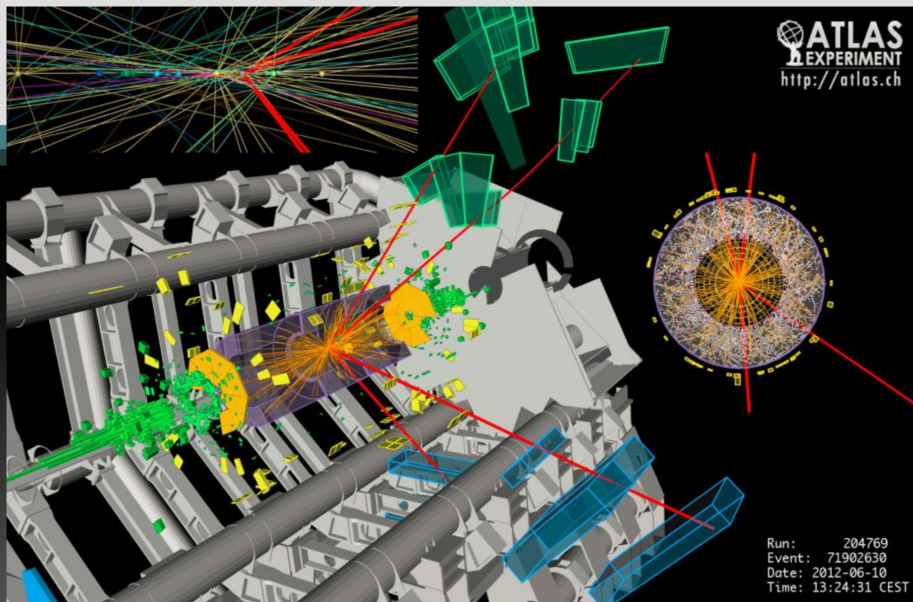


LHEP, Hainan, China, January 11-14, 2013

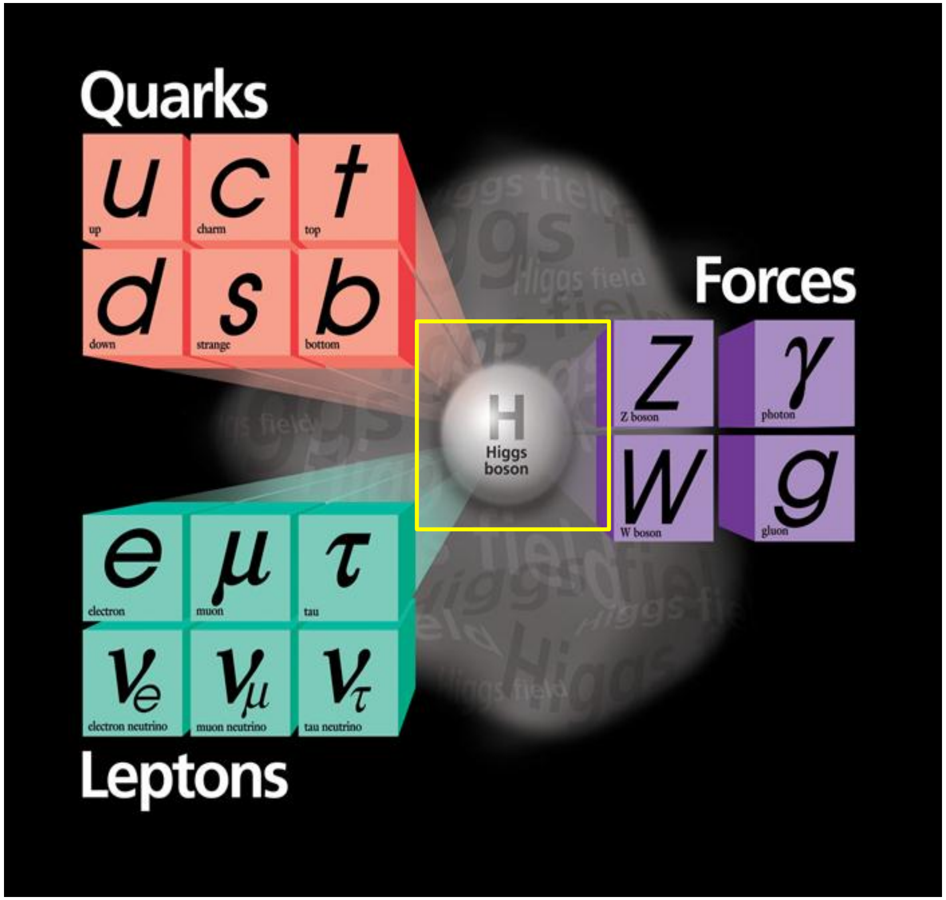
Outline

- Introduction of SM
- Higgs Searches at Tevatron, LEP and EW measurements
- ATLAS Experiment at LHC
- Higgs Production and decays at LHC
- Major challenge for Higgs Searches
- Observation of Higgs-like particle (ICHEP, 5.8fb^{-1} at 8 TeV)
- Update results for Higgs searches (13fb^{-1} at 8 TeV)
- Higgs Properties (Spin, CP, Couplings) Measurements
- Summary and Conclusions

Standard Model of Elementary Particles

- **Elementary Particles**
  > 100 years' discoveries
- The SM is in excellent agreement with the numerous experimental measurements.

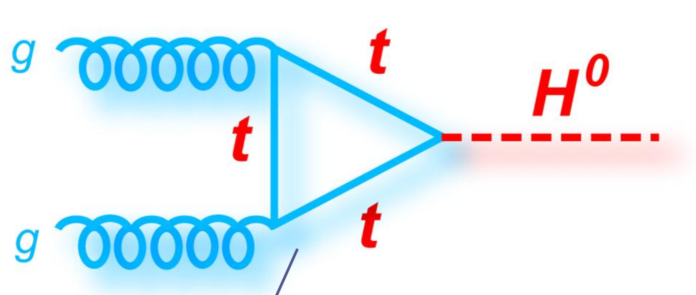
- The only missing SM particle is the Higgs boson which is proposed to responsible for the electroweak symmetry breaking, particles acquire mass when interacting with the Higgs field.

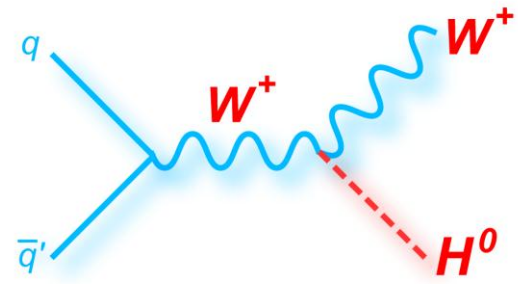


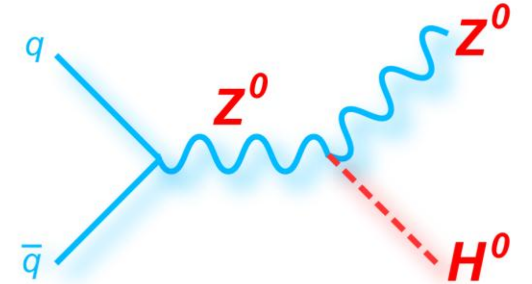
➔ Hunting for the Higgs boson is one of main goals in particle physics (LEP, Tevatron, LHC)

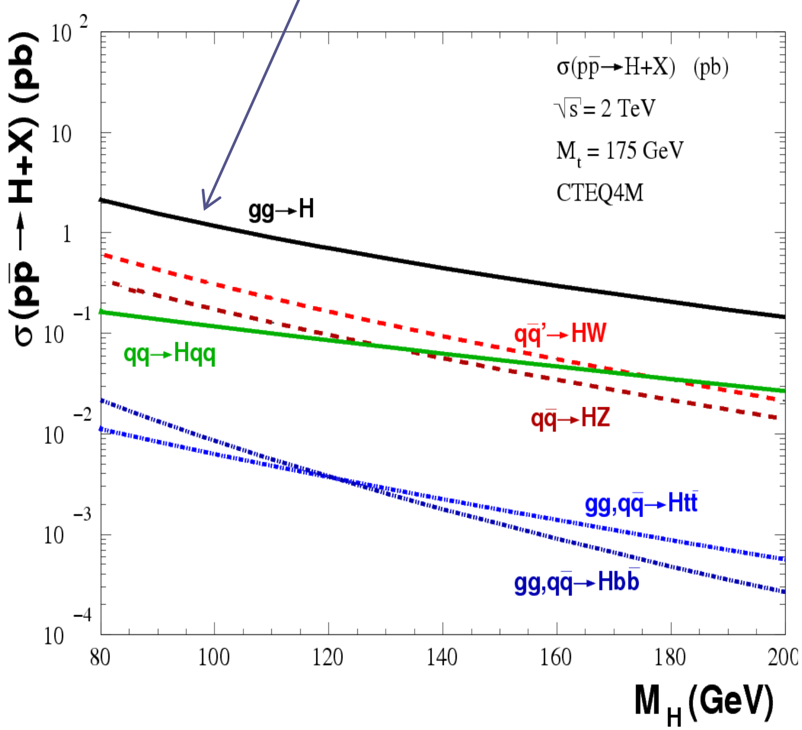
Search for Higgs boson at Tevatron

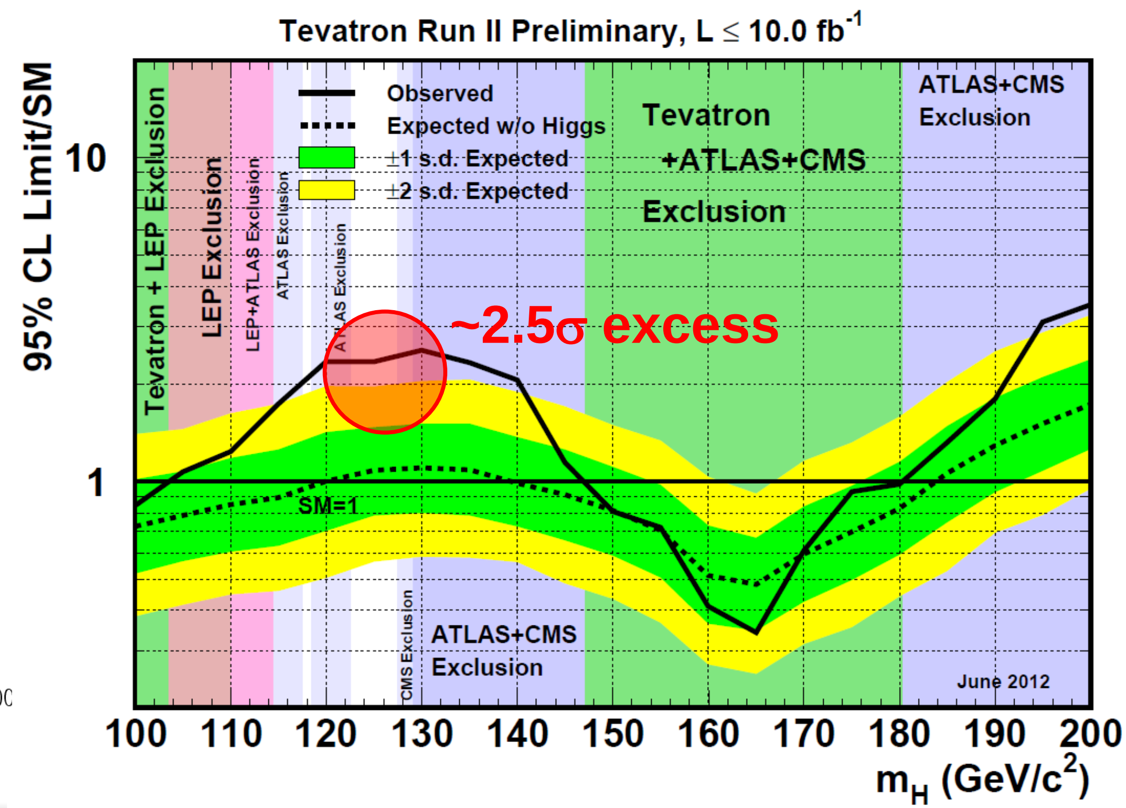
➔ Results (arXiv:1207.0449): 2.5σ excess at m_H=120-130 GeV





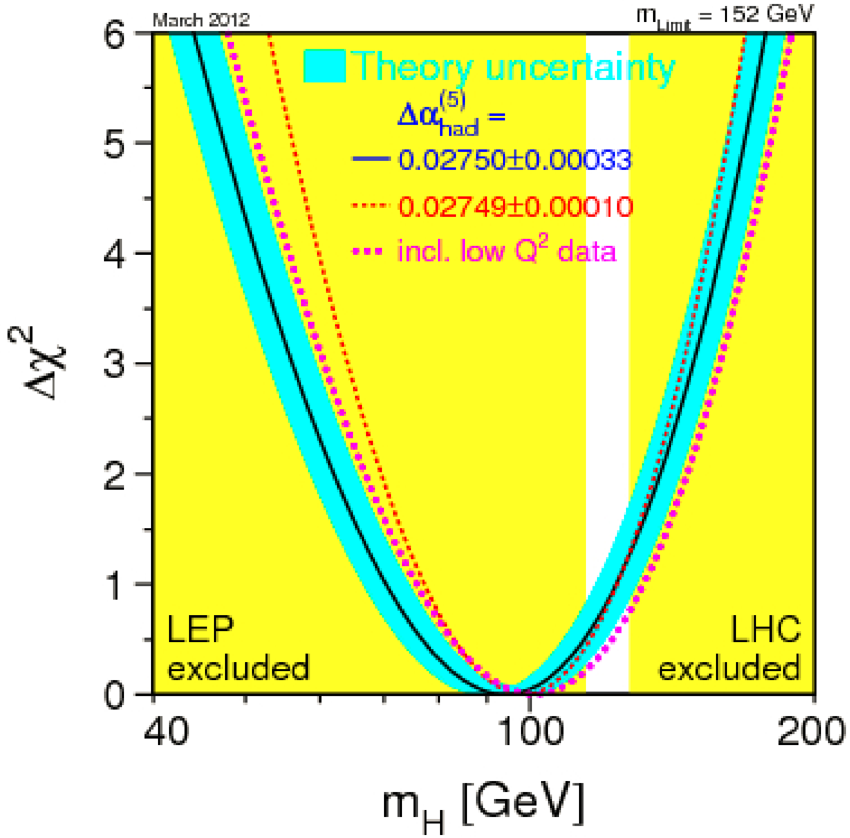


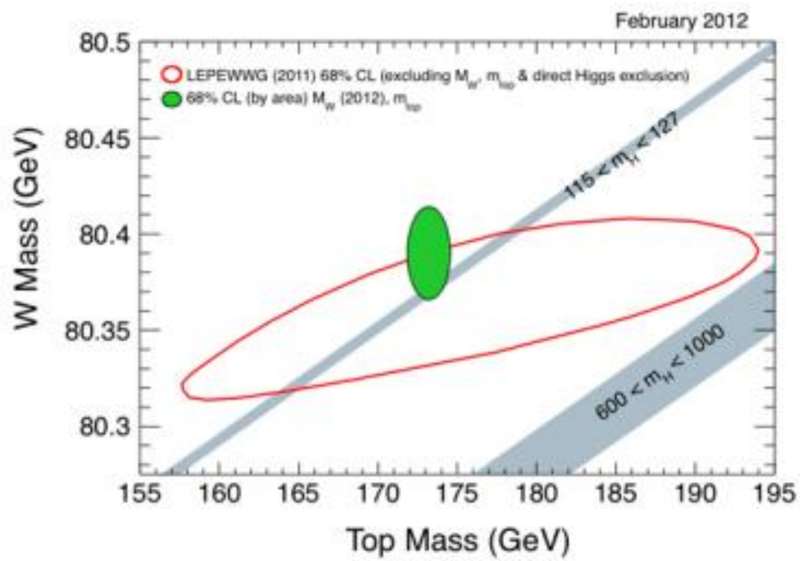


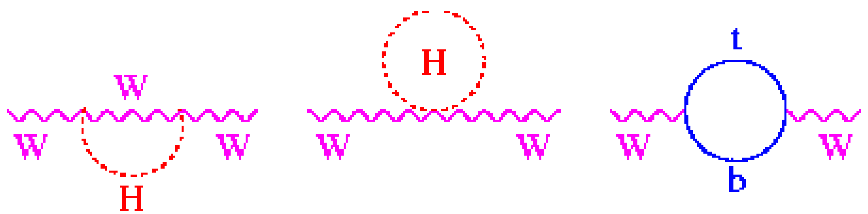


Searches for Higgs Boson at LEP and LHC

- Direct searches at LEP (2000):
  $m_H > 114.4$ GeV @ 95% C.L.
- Direct search at LHC (2012.3)
  $m_H < 127$ GeV @ 95% C.L.
- Precision electroweak data are sensitive to Higgs mass, global fit mass: $m_H = 94^{+29}_{-24}$ GeV



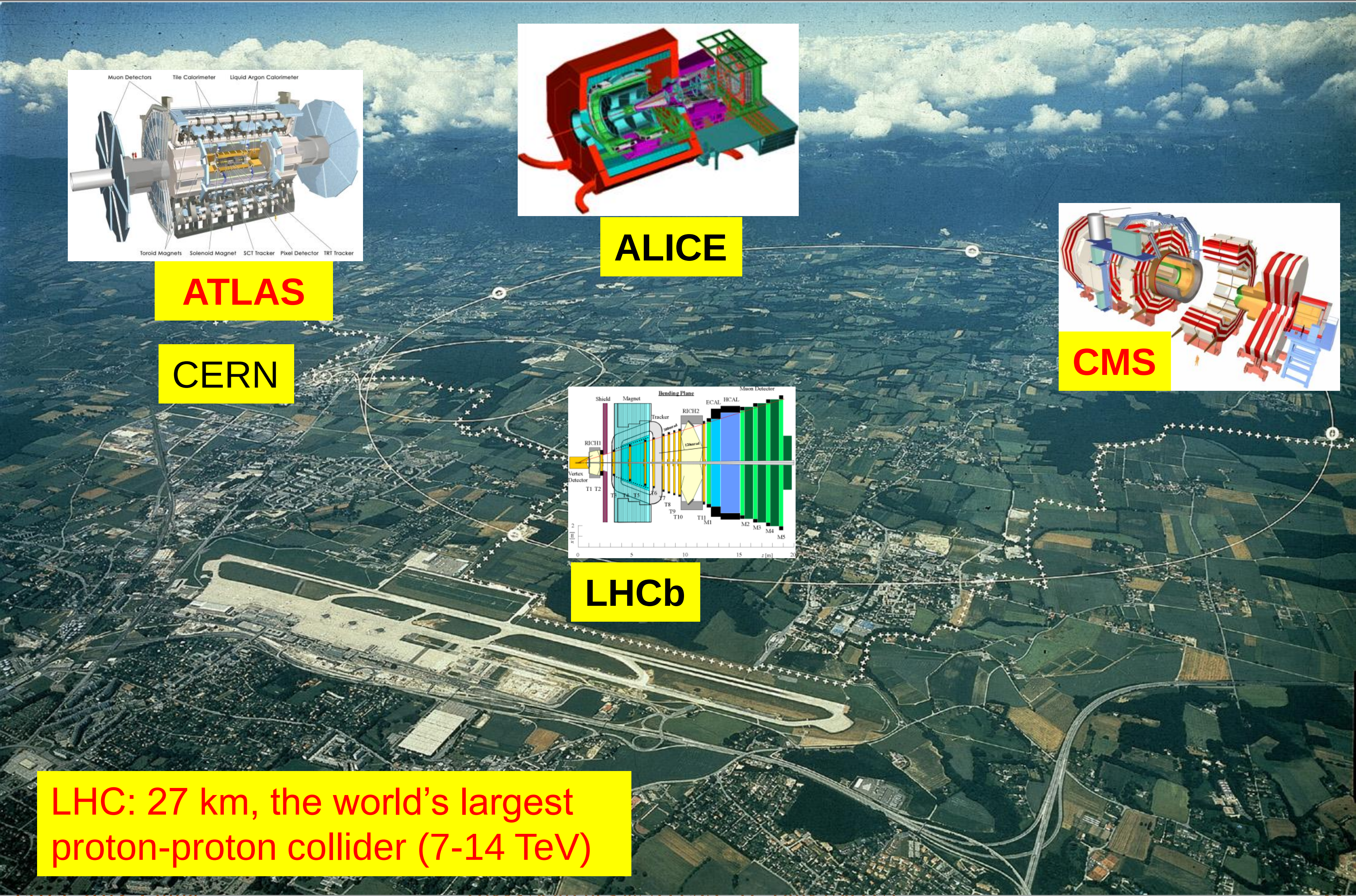




$M^2_W = M^2_Z(1-\sin^2\theta_w)(1+\Delta\rho)$

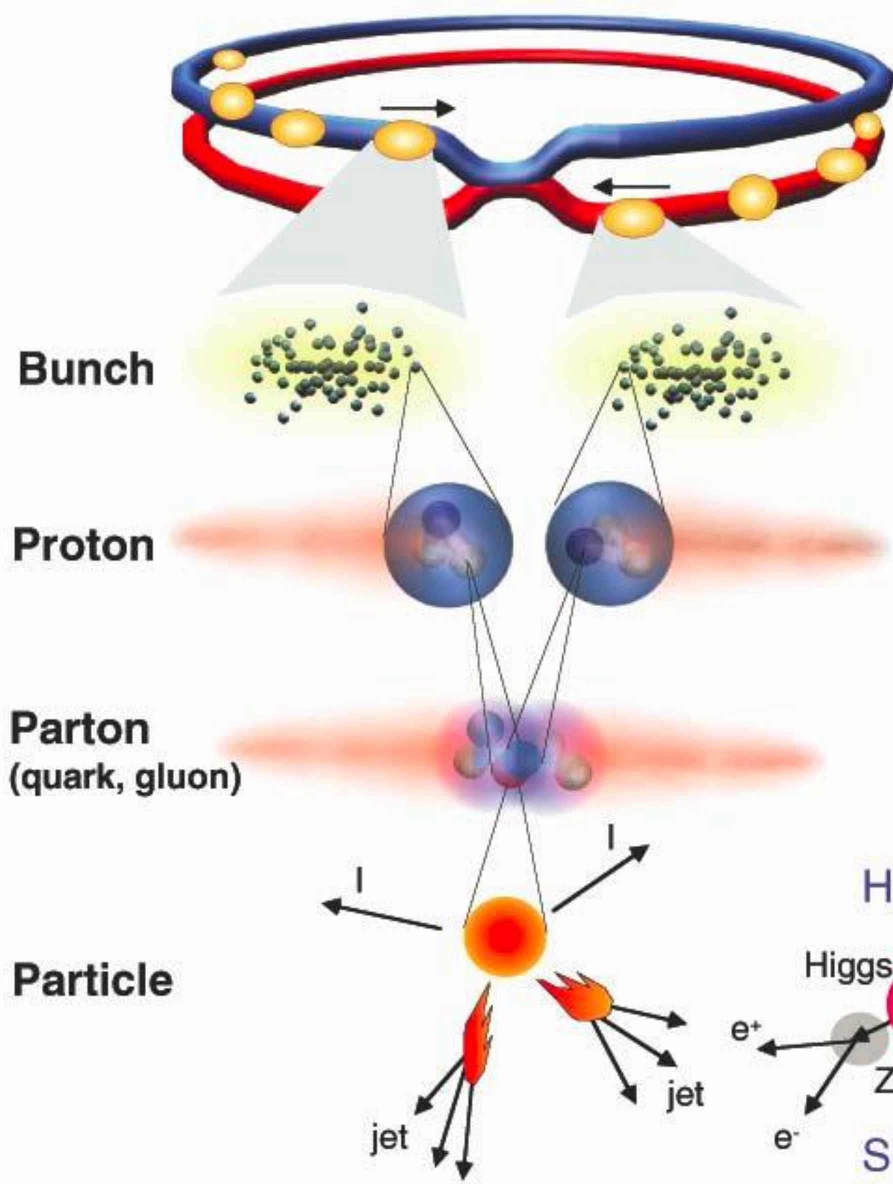
Radiative correction: $\Delta\rho(m_t, m_H, \alpha, \ldots)$

Large Hadron Collider at CERN

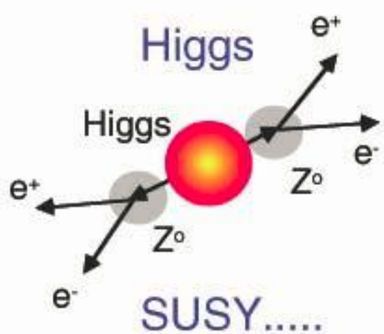


LHC: 27 km, the world's largest proton-proton collider (7-14 TeV)

Proton-proton Collisions at LHC

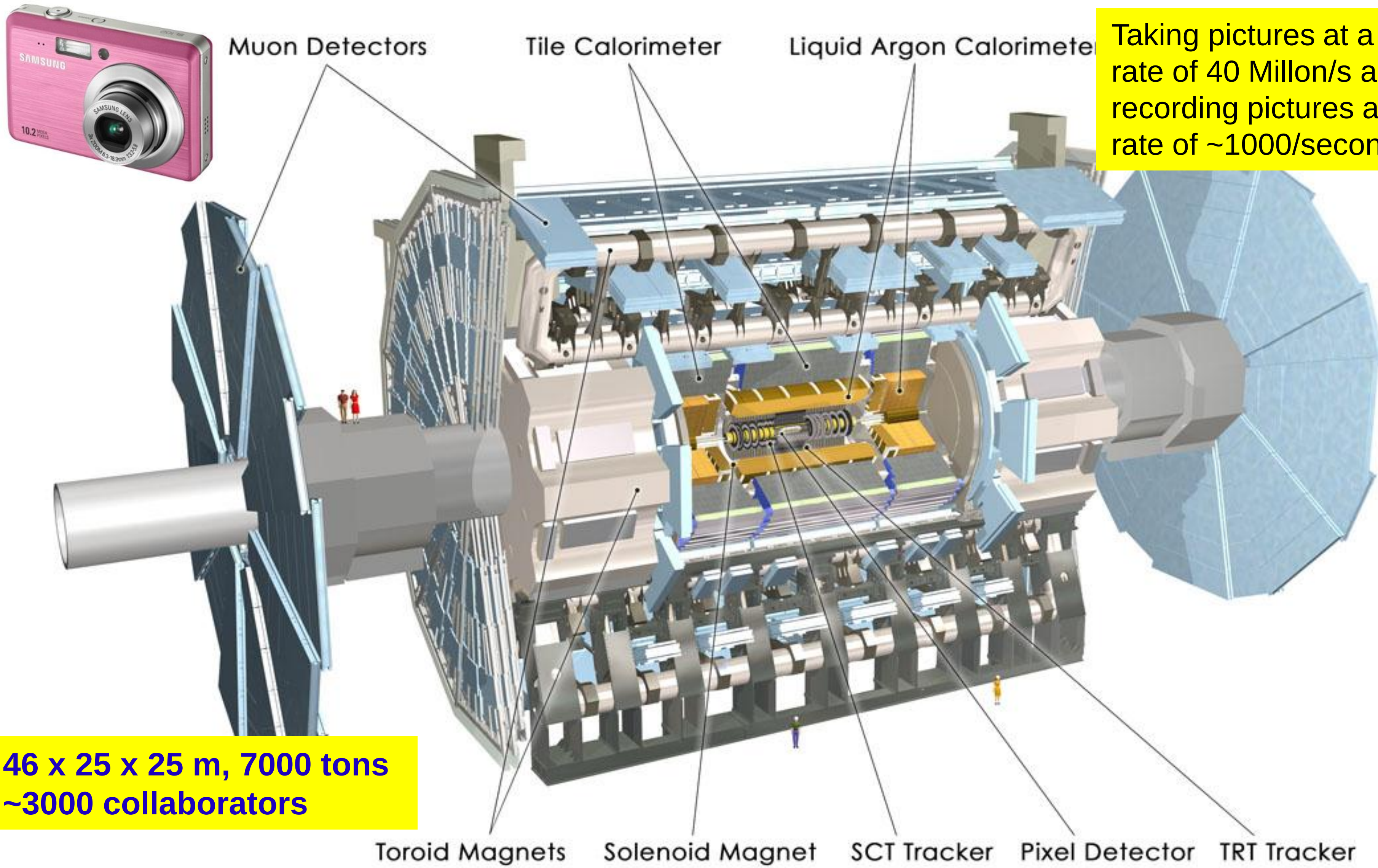


Proton-Proton	2835 bunch/beam
Protons/bunch	10^{11}
Beam energy	7 TeV (7×10^{12} eV)
Luminosity	10^{34} cm^{-2} s^{-1}
Crossing rate	40 MHz
Collisions ≈	10^{7} - 10^{9} Hz



Selection of 1 in 10,000,000,000,000

The ATLAS Detector: Huge Camera

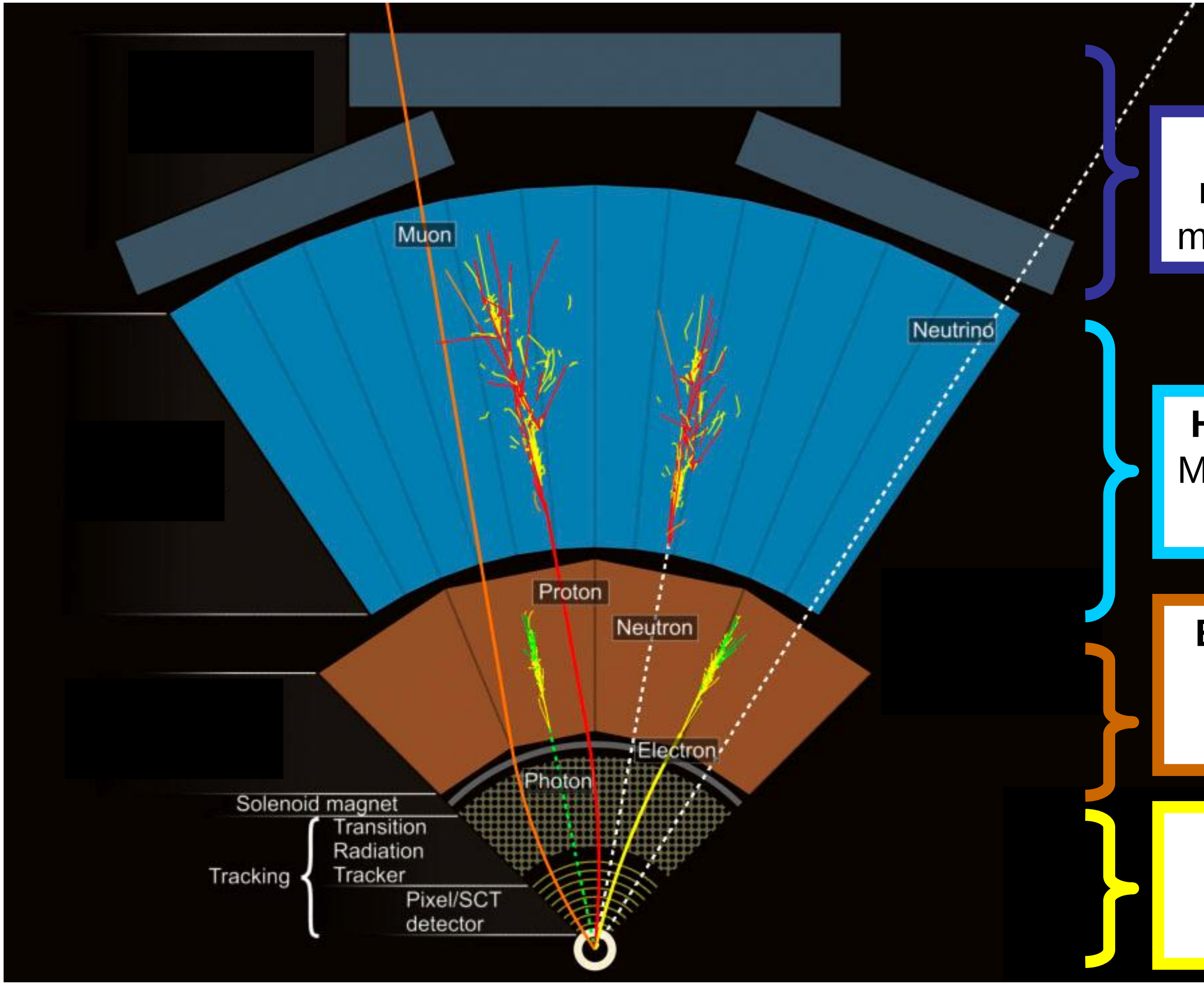


Taking pictures at a rate of 40 Millon/s and recording pictures at a rate of ~1000/second

46 x 25 x 25 m, 7000 tons
~3000 collaborators

Particle Detection

- Different particles have different signatures in detectors



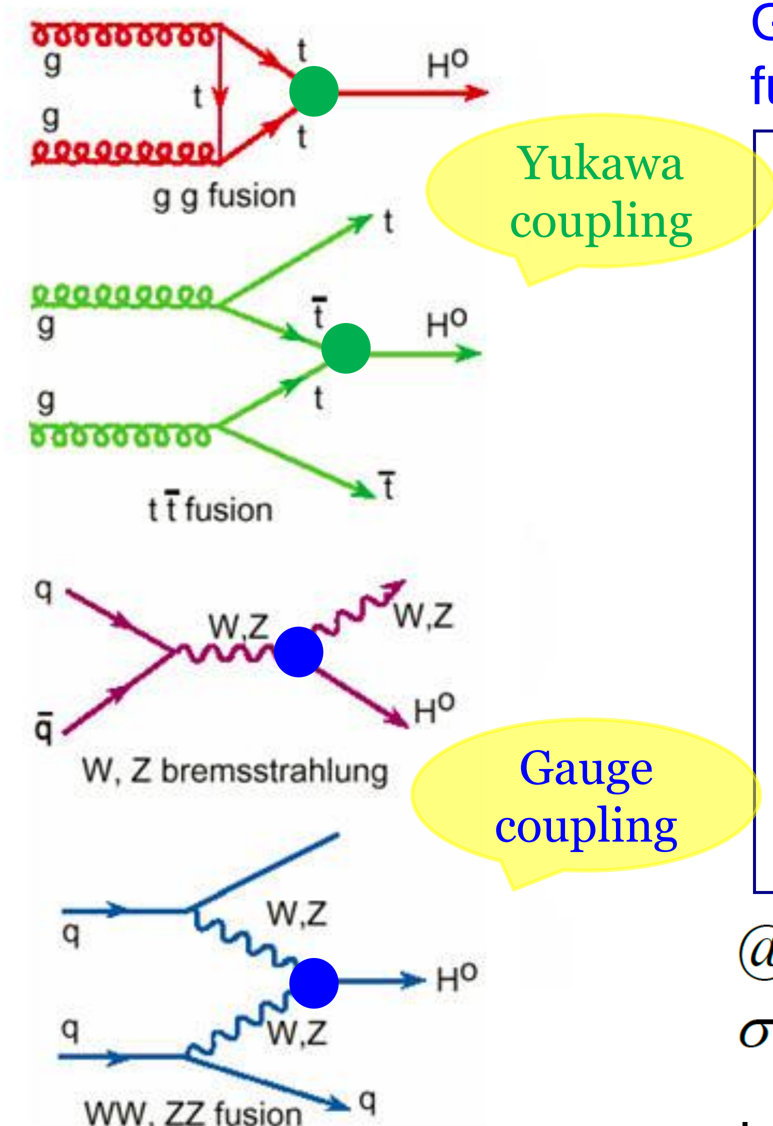
Muon Spectrometer: muon identification and momentum measurement

Hadronic calorimeter: Measurement of jets and missing energy

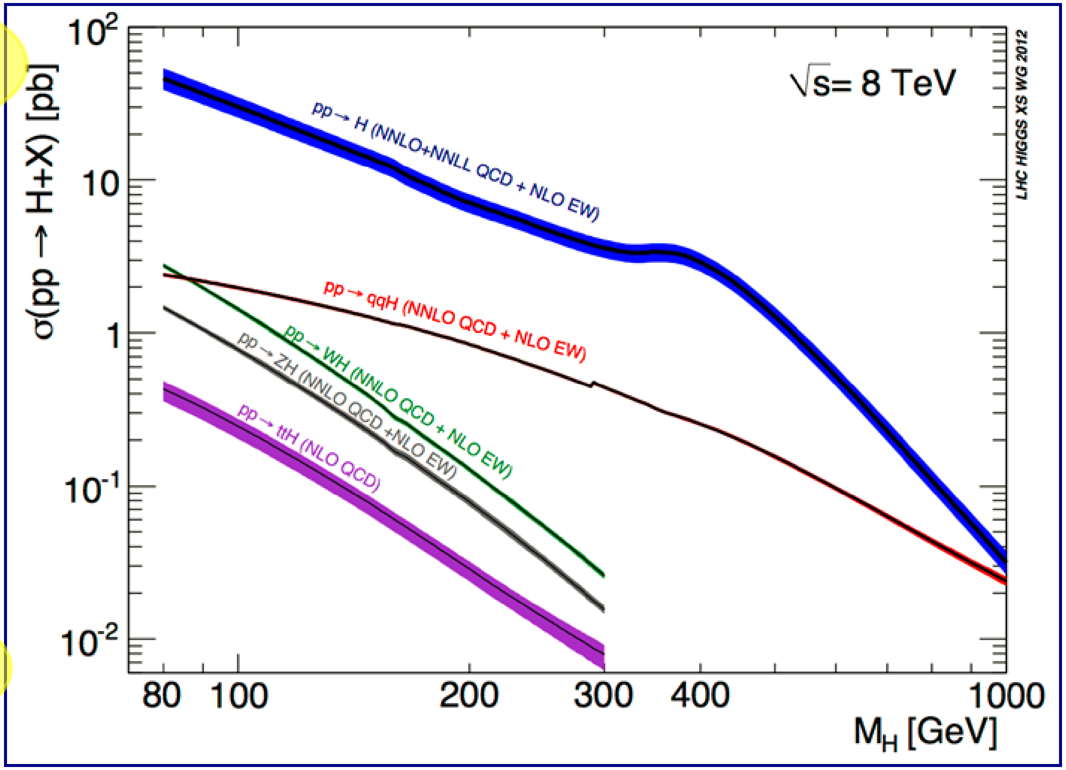
Electromagnetic calo: e/γ identification and energy measurement

Tracking system: Charged particle momentum, vertexing

Higgs Boson Production at LHC



Gluon-gluon fusion gg→H and vector-boson fusion qq→qqH are dominant



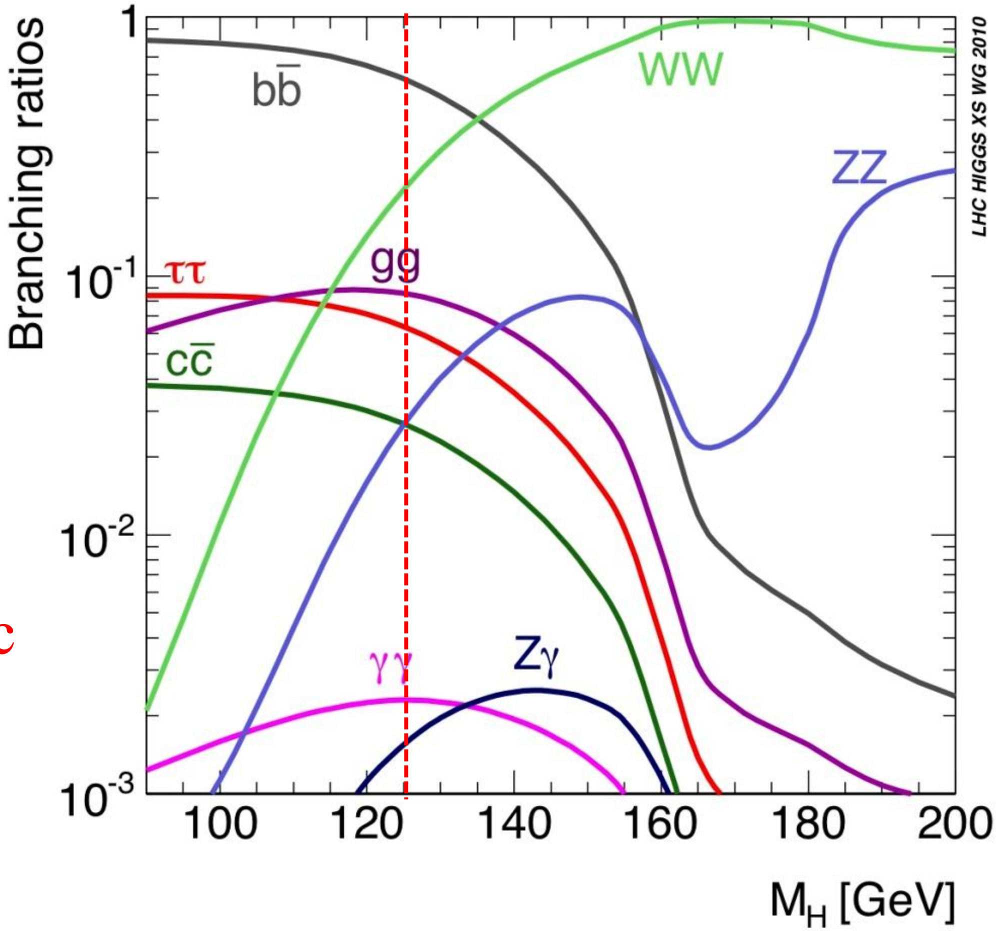
$$@125\ \text{GeV:}\quad \sigma_{ggH} = 19.5\ \text{pb},\ \sigma_{VBF} = 1.6\ \text{pb},$$
$$\sigma_{WH} = 0.70\ \text{pb},\ \sigma_{ZH} = 0.39\ \text{pb},\ \sigma_{ttH} = 0.13\ \text{pb}$$

Inelastic pp cross section at 7 TeV is ~ 60 mb

Higgs Boson Decay

Higgs decay branching ratio at m_H=125 GeV

- bb: 57.7% (huge QCD background)
- WW: 21.5% (easy identification in di-lepton mode, complex background)
- ττ: 6.3% (complex final states with τ leptonic and/or hadronic decays)
- ZZ*: 2.6% ("gold-plated", clean signature of 4-lepton, high S/B, excellent mass peak)
- γγ: 0.23% (excellent mass resolution, high sensitivity)



Higgs boson production rate: 1 out of 10^{12} collision events

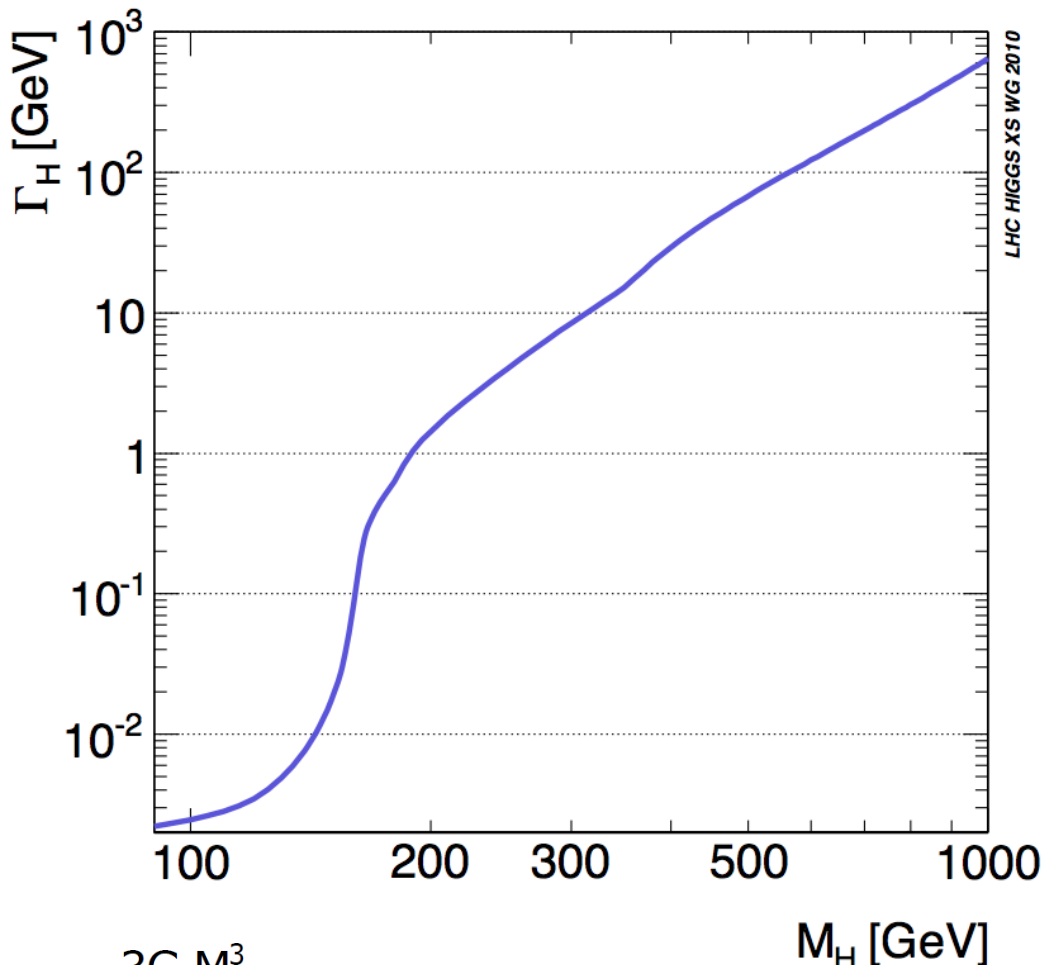
Higgs Boson Width

- **Strong mass dependent**

Γ_H = 3.5 MeV @ 120 GeV
1.4 GeV @ 200 GeV
8.4 GeV @ 300 GeV
68.0 GeV @ 500 GeV

- At low mass region (<200 GeV), detector resolution dominates mass resolution

- At high mass, intrinsic width becomes dominant

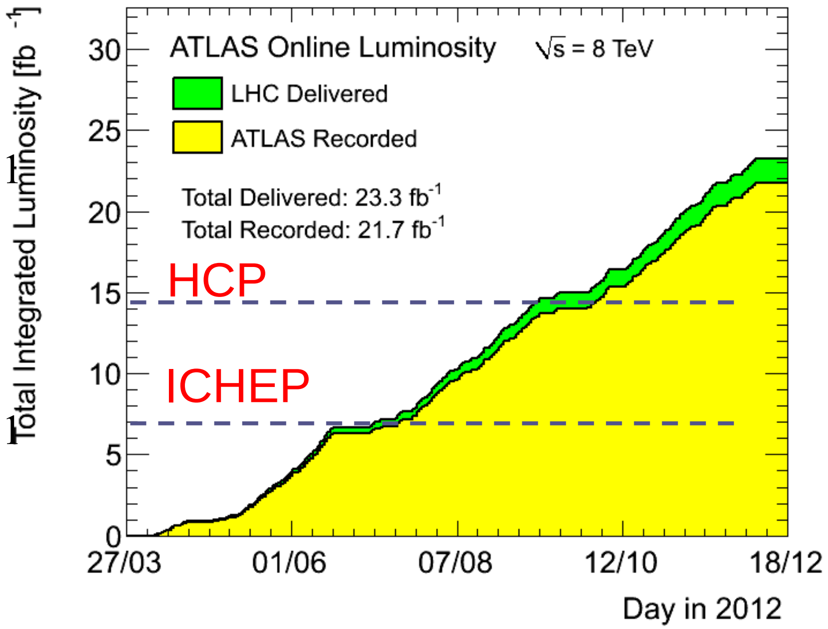


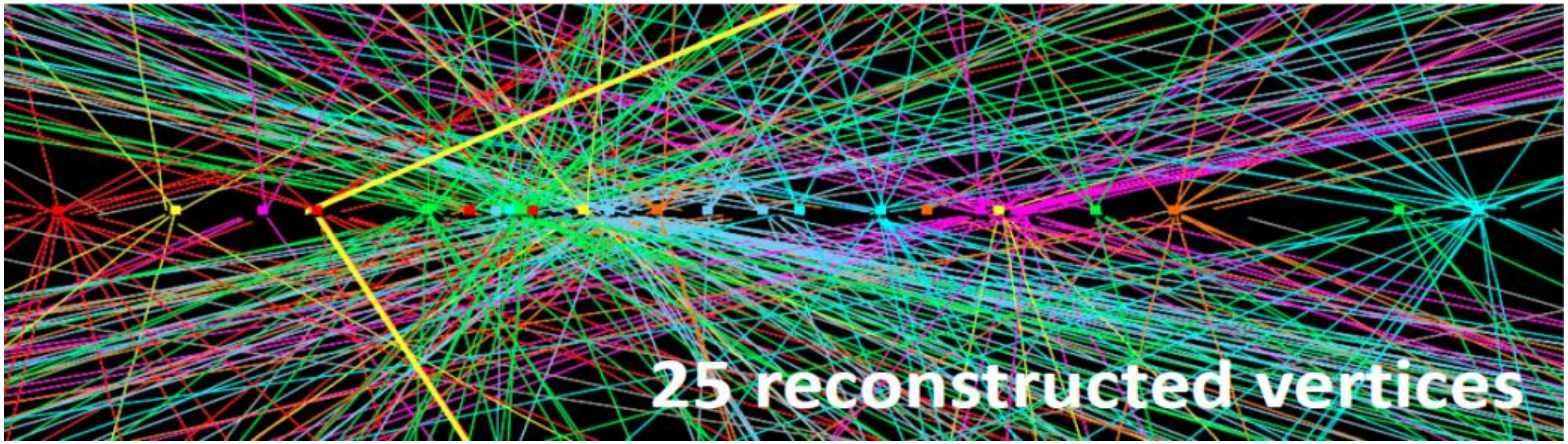
$$\Gamma_H \approx \frac{3G_F M_H^3}{16\pi\sqrt{2}}$$

$$\approx 500\ \text{GeV} \cdot \left(\frac{M_H}{1\ \text{TeV}}\right)^3$$

ATLAS Data Samples

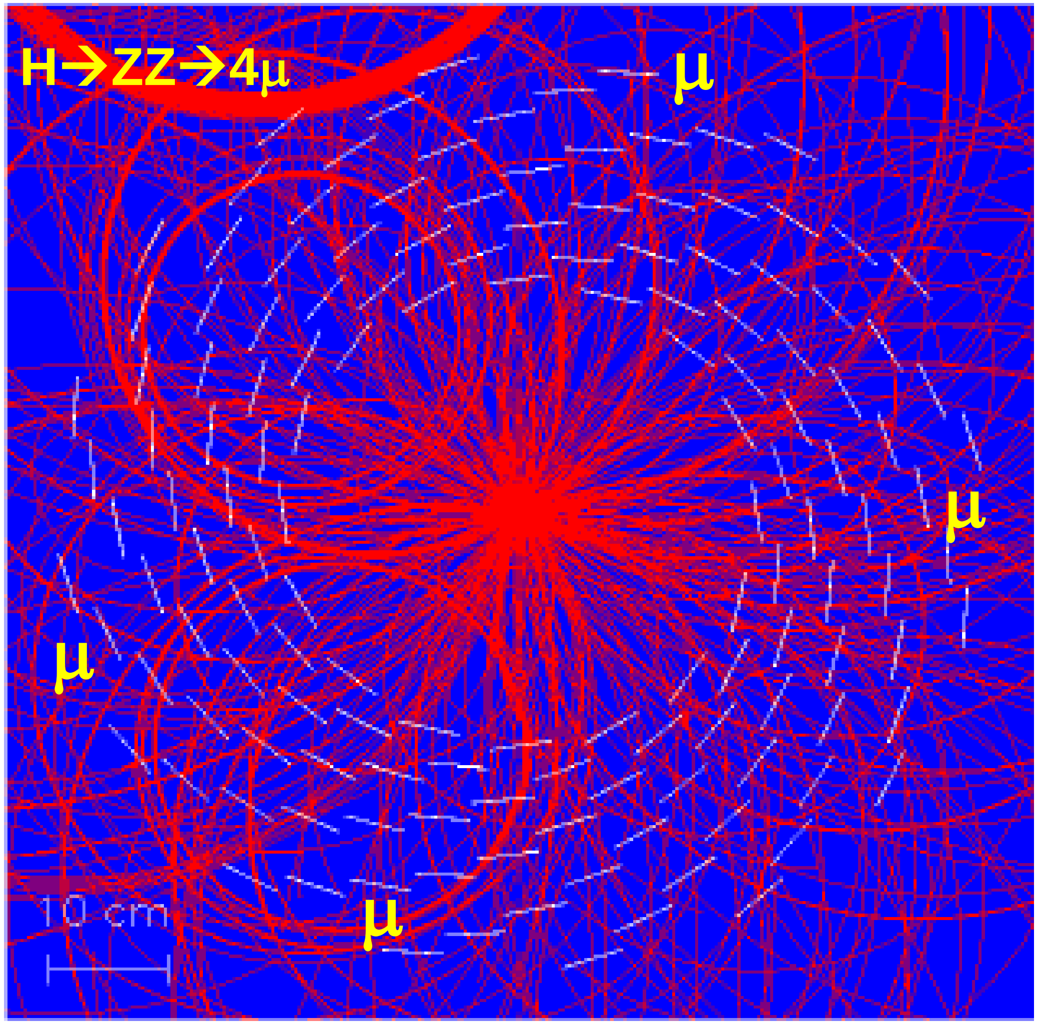
- **7 TeV data samples (2011)**
  - 4.8 fb^{-1} for physics analysis
  - Peak luminosity $3.6 \times 10^{33} cm^{-2}s^{-1}$
- **8 TeV data samples (2012)**
  - 21.7 fb^{-1} for physics analysis
  - Peak luminosity $7.7 \times 10^{33} cm^{-2}s^{-1}$
- **Data-taking efficiency: ~94%**
- **Significant pileup events**



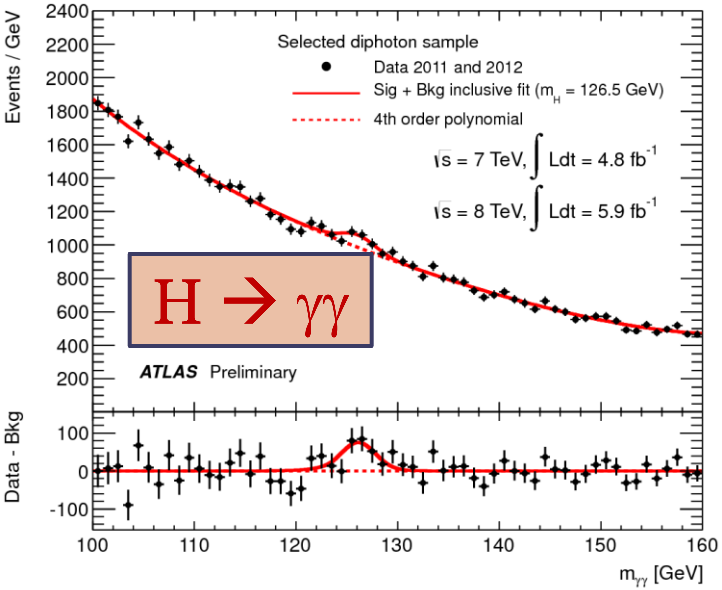


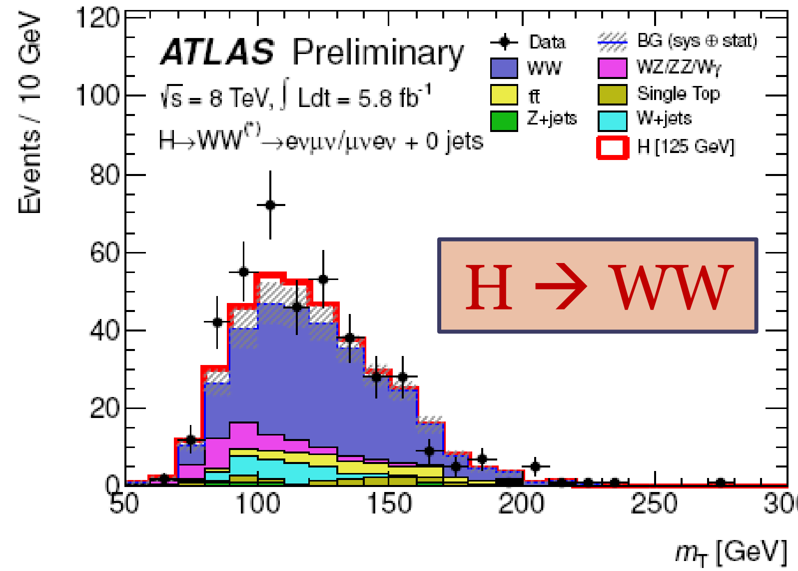
Major Challenge

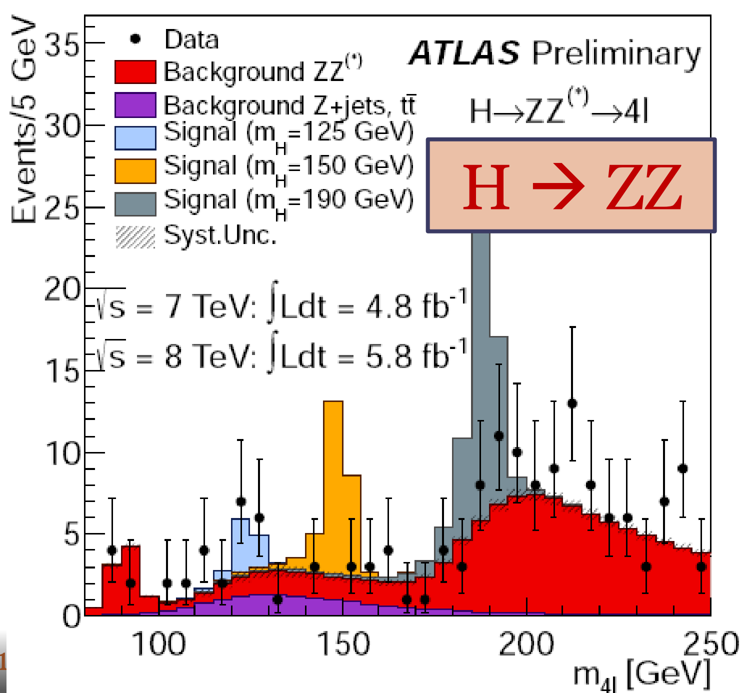
- Large pileup events result in big challenge to the detector, reconstruction and particle identification !

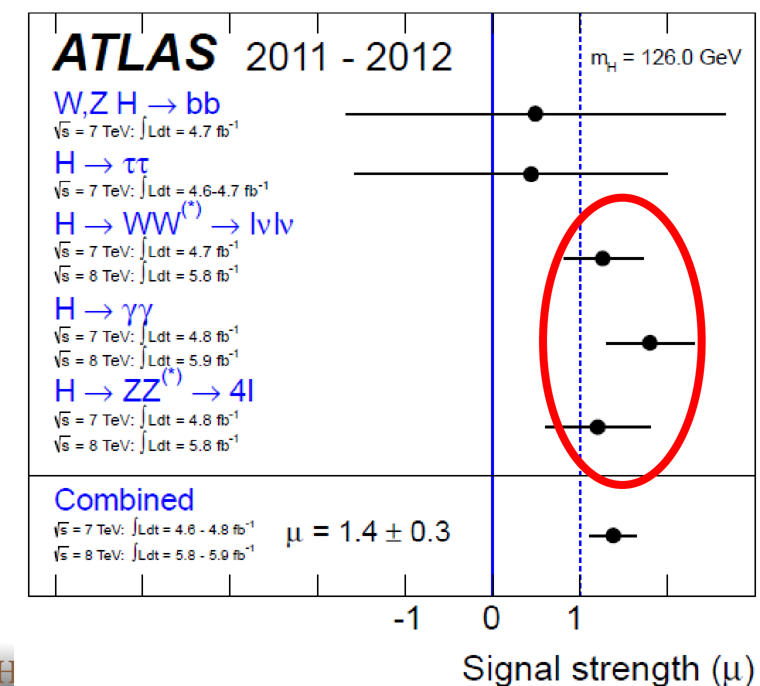


Observation of a new Particle (July 4, 2012)



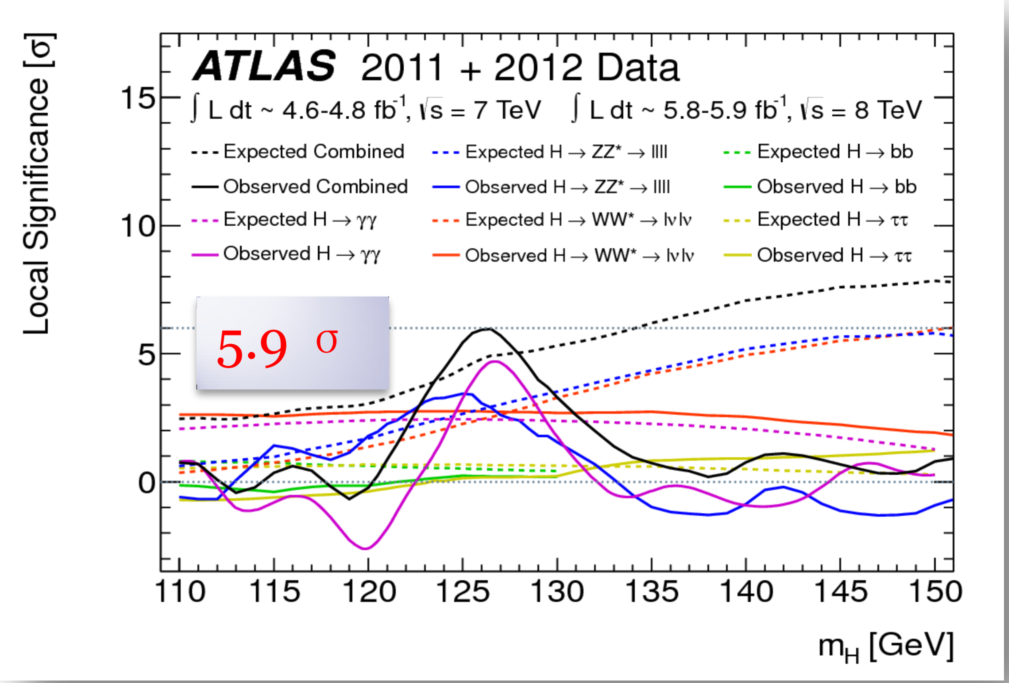


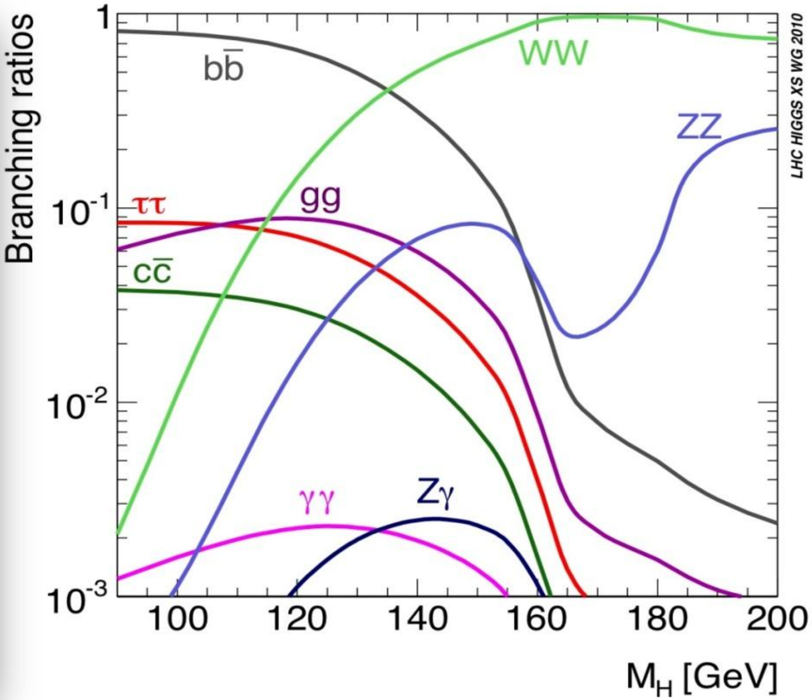




ATLAS Combined Results

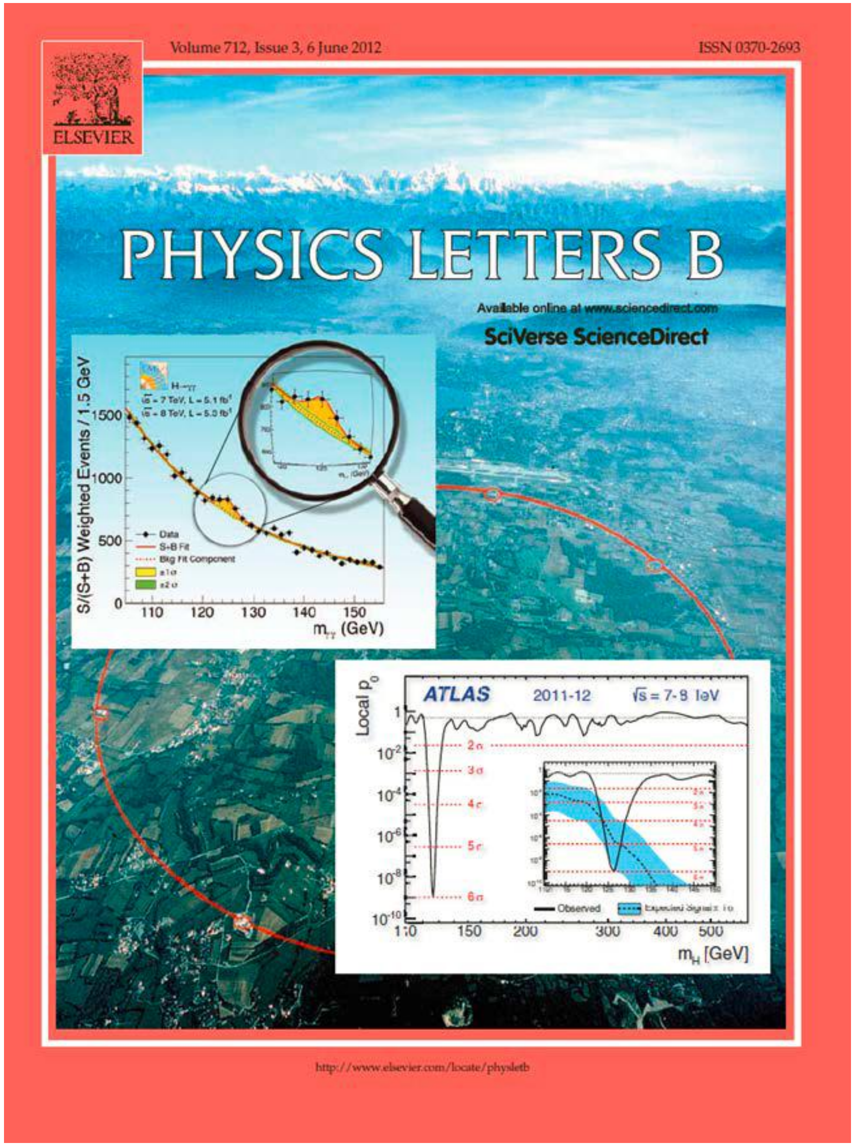
➔ **Discovery of a particle with a local significance of 5.9σ.**





Channel	Fitted m_H	Observed	Expected
H→γγ	126.5 GeV	4.5σ	2.5σ
H→ZZ*→4l	125.0 GeV	3.6σ	2.7σ
H→WW*→lνlν	125.0 GeV	2.8σ	2.3σ
Combined	**126.0 GeV**	**5.9σ**	**4.9σ**

Observation of a new Particle (2012.7.4) !



Phys. Lett. B 716 (2012) 1-29 (ATLAS) **Phys. Lett. B 716 (2012) 30-61 (CMS)**

Update Since July 4, 2012

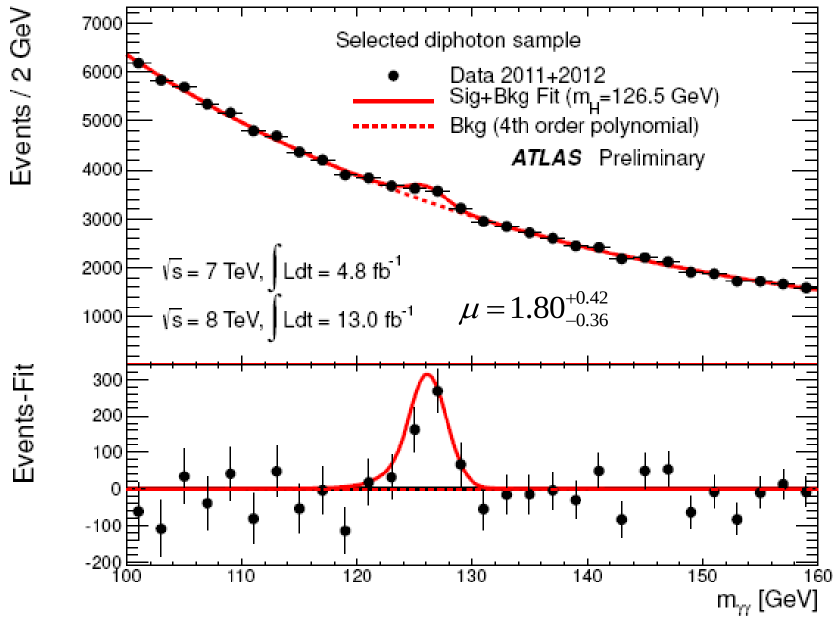
Ref: ATLAS-CONF-2012-170

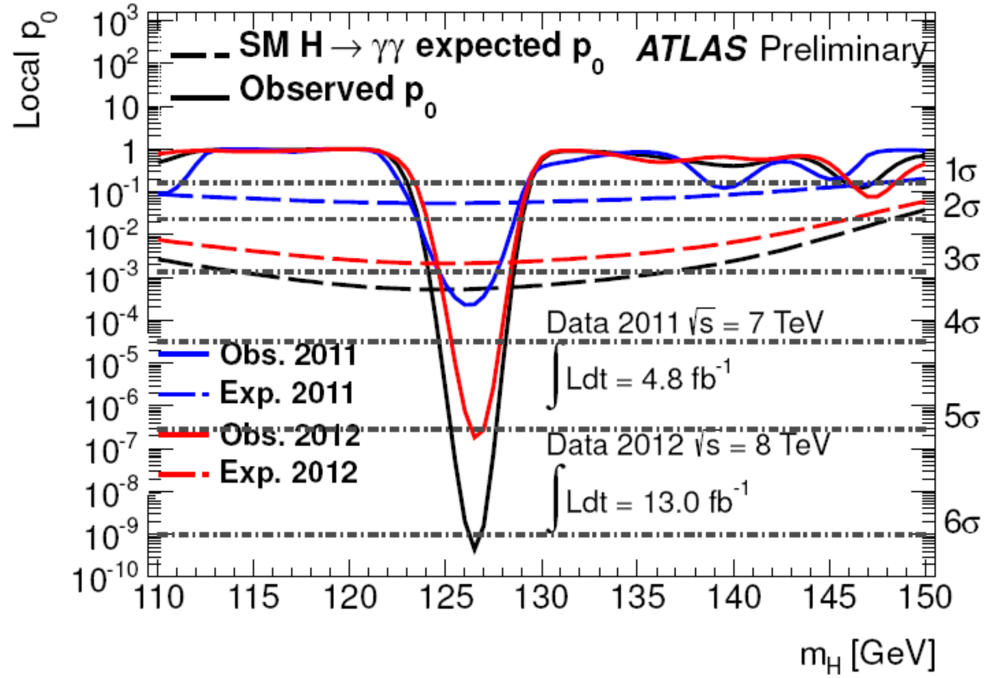
$\sqrt{s}$ = 7 TeV
4.6-4.7 fb^{-1}

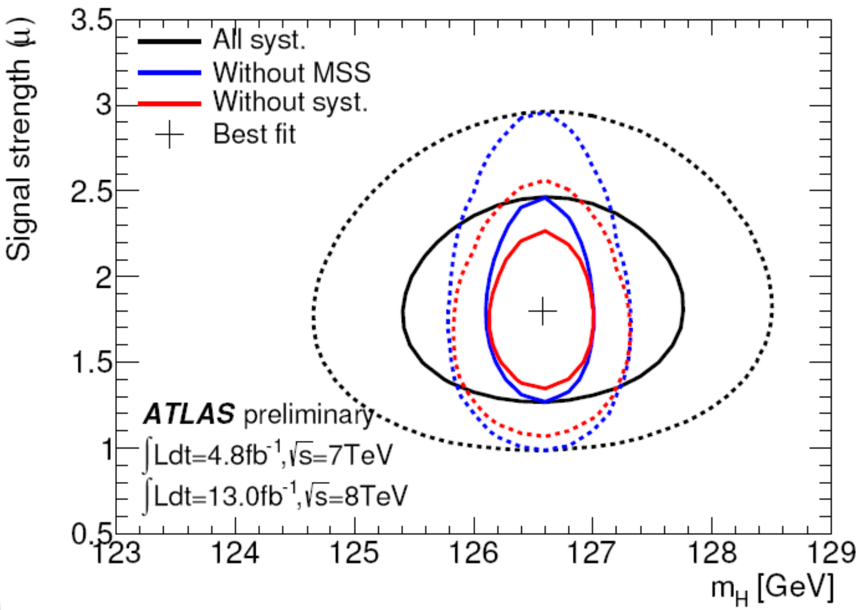
$\sqrt{s}$ = 8 TeV
13 fb^{-1}

Higgs Boson Decay	Subsequent Decay	Sub-Channels	$\int L\,dt$ [fb^{-1}]
		2011 $\sqrt{s}$ =7 TeV	
$H \to ZZ^{(*)}$	4ℓ	$\{4e, 2e2\mu, 2\mu 2e, 4\mu\}$	4.6
$H \to \gamma\gamma$	–	12 categories $\{p_{\mathrm{Tt}} \otimes \eta_\gamma \otimes \text{conversion}\} \oplus \{\text{2-jet VBF}\} \oplus \{\ell\text{-tag, 2-jet VH}\}$	4.8
$H \to \tau\tau$	$\tau_{\mathrm{lep}}\tau_{\mathrm{lep}}$	$\{e\mu\} \otimes \{\text{0-jet}\} \oplus \{\ell\ell\} \otimes \{\text{1-jet, 2-jet, } p_{\mathrm{T},\tau\tau} > 100 \text{ GeV}, VH\}$	4.6
	$\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$	$\{e, \mu\} \otimes \{\text{0-jet, 1-jet, } p_{\mathrm{T},\tau\tau} > 100 \text{ GeV, 2-jet}\}$	4.6
	$\tau_{\mathrm{had}}\tau_{\mathrm{had}}$	$\{\text{1-jet, 2-jet}\}$	4.6
$VH \to Vbb$	$Z \to \nu\nu$	$E_{\mathrm{T}}^{\mathrm{miss}} \in \{120-160, 160-200, \geq 200 \text{ GeV}\} \otimes \{\text{2-jet, 3-jet}\}$	4.6
	$W \to \ell\nu$	$p_{\mathrm{T}}^{W} \in \{< 50, 50-100, 100-150, 150-200, \geq 200 \text{ GeV}\}$	4.7
	$Z \to \ell\ell$	$p_{\mathrm{T}}^{Z} \in \{< 50, 50-100, 100-150, 150-200, \geq 200 \text{ GeV}\}$	4.7
		2012 $\sqrt{s}$ =8 TeV	
$H \to ZZ^{(*)}$	4ℓ	$\{4e, 2e2\mu, 2\mu 2e, 4\mu\}$	13
$H \to \gamma\gamma$	–	12 categories $\{p_{\mathrm{Tt}} \otimes \eta_\gamma \otimes \text{conversion}\} \oplus \{\text{2-jet VBF}\} \oplus \{\ell\text{-tag, 2-jet VH}\}$	13
$H \to WW^{(*)}$	$e\nu\mu\nu$	$\{e\mu, \mu e\} \otimes \{\text{0-jet, 1-jet}\}$	13
$H \to \tau\tau$	$\tau_{\mathrm{lep}}\tau_{\mathrm{lep}}$	$\{\ell\ell\} \otimes \{\text{1-jet, 2-jet, } p_{\mathrm{T},\tau\tau} > 100 \text{ GeV}, VH\}$	13
	$\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$	$\{e, \mu\} \otimes \{\text{0-jet, 1-jet, } p_{\mathrm{T},\tau\tau} > 100 \text{ GeV, 2-jet}\}$	13
	$\tau_{\mathrm{had}}\tau_{\mathrm{had}}$	$\{\text{1-jet, 2-jet}\}$	13
$VH \to Vbb$	$Z \to \nu\nu$	$E_{\mathrm{T}}^{\mathrm{miss}} \in \{120-160, 160-200, \geq 200 \text{ GeV}\} \otimes \{\text{2-jet, 3-jet}\}$	13
	$W \to \ell\nu$	$p_{\mathrm{T}}^{W} \in \{< 50, 50-100, 100-150, 150-200, \geq 200 \text{ GeV}\}$	13
	$Z \to \ell\ell$	$p_{\mathrm{T}}^{Z} \in \{< 50, 50-100, 100-150, 150-200, \geq 200 \text{ GeV}\}$	13

Update of H → γγ



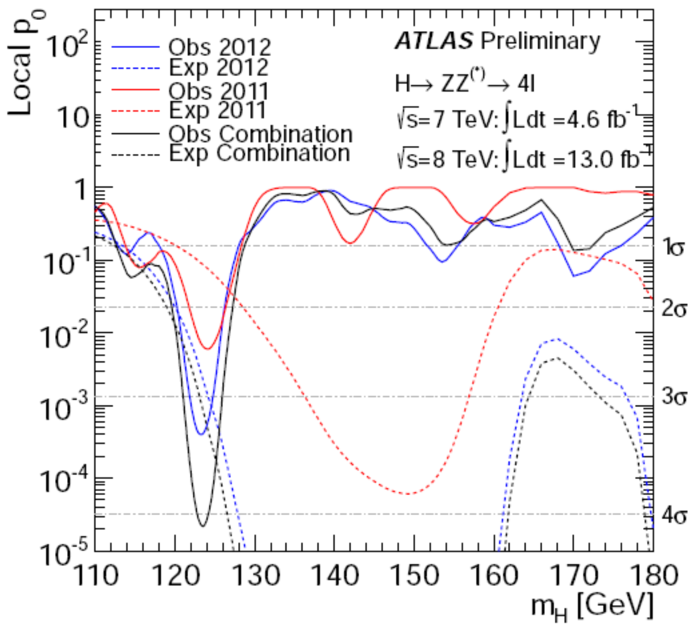


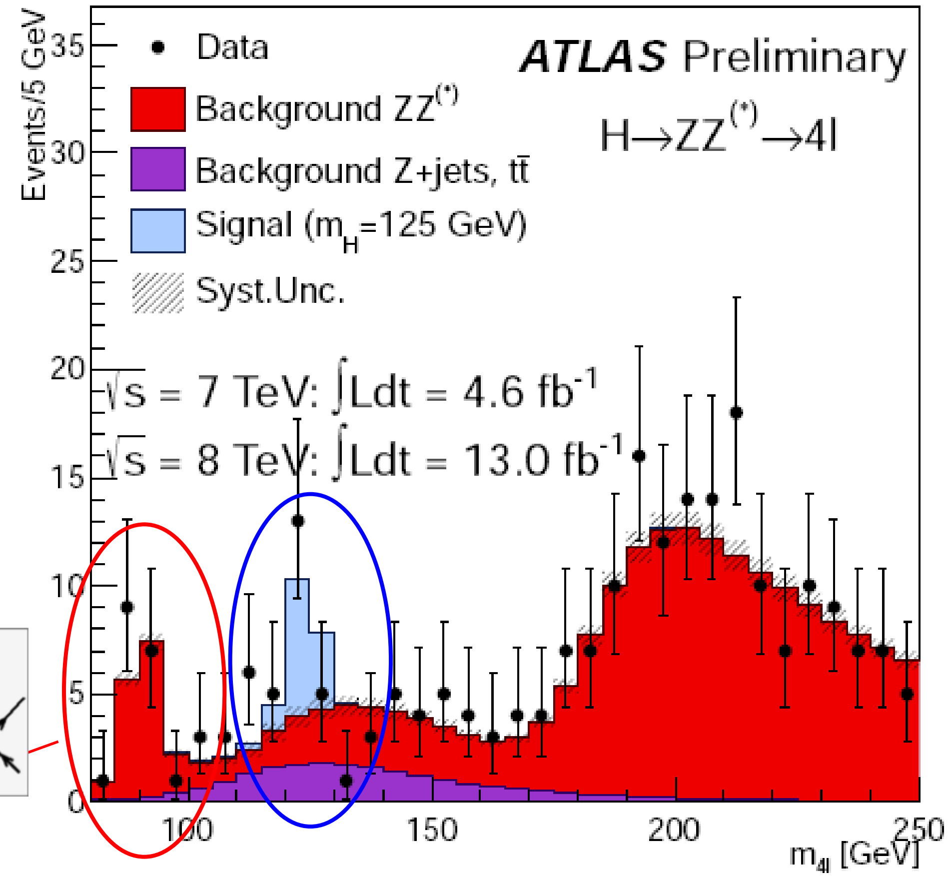


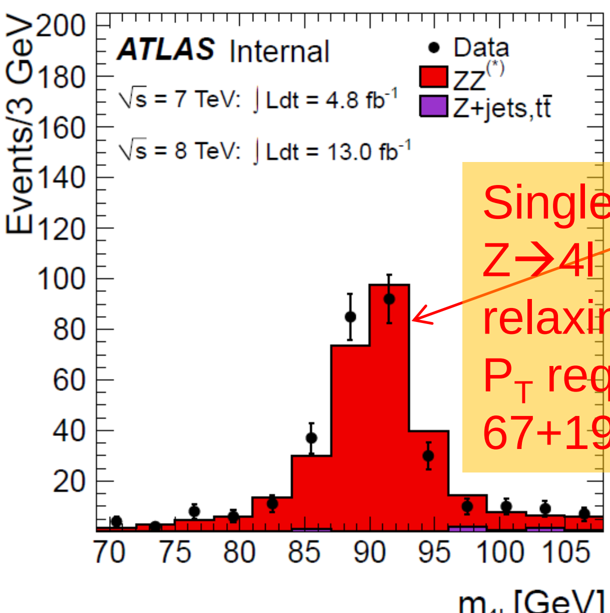
Best fit mass:
M_H = 126.6 ± 0.3(stat) ± 0.7(syst) GeV

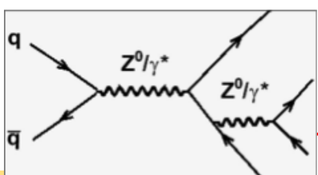
Best fit signal strength:
μ = 1.8 + 0.42 (– 0.36)

Update of H→ZZ*→4l







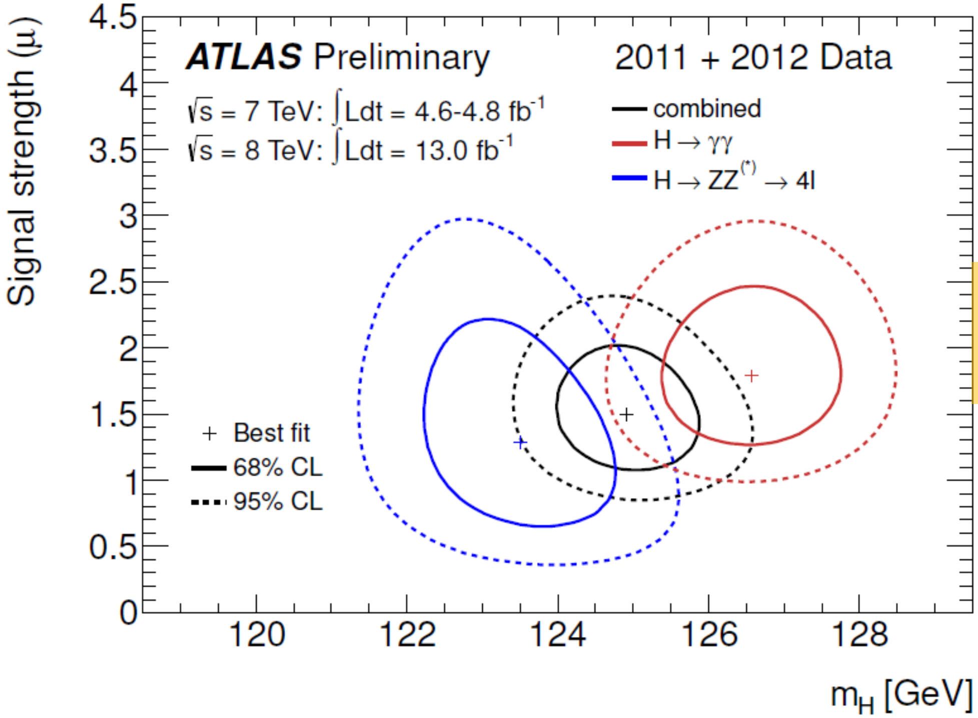


Single resonant Z→4l enhanced by relaxing mass and P_T requirements
67+191=258

Best fit mass:
M_H = 123.5 ±0.9(stat) ± 0.3(syst) GeV

Best fit signal strength:
μ = 1.3 + 0.5 (– 0.4) @ 123.5 GeV
μ = 1.0 ± 0.4 @ 125 GeV

Higgs Mass Measurements

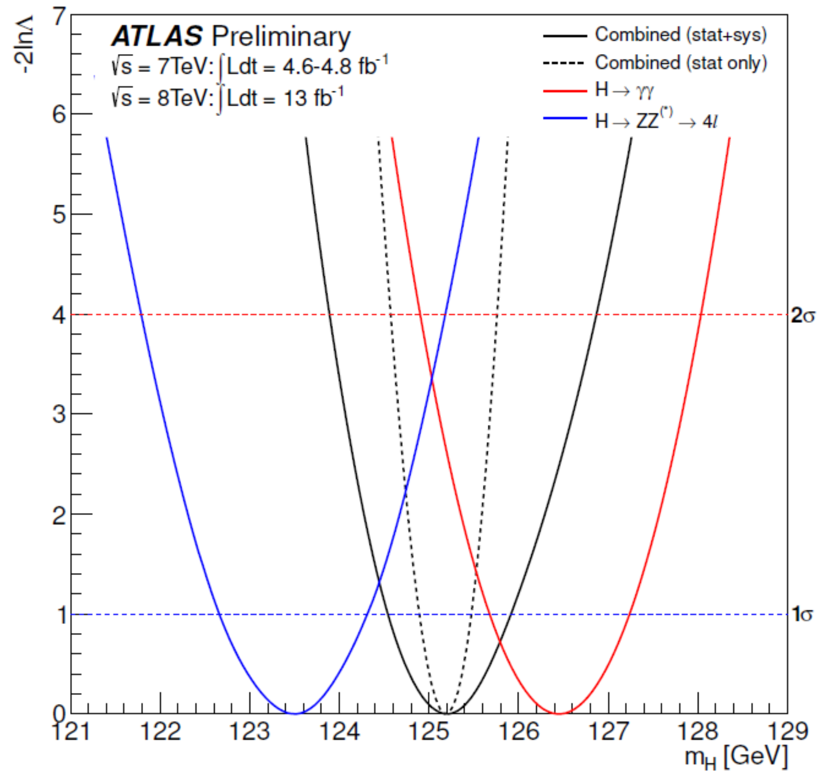


profile likelihood ratio

$$\Lambda(m_H) = \frac{L(m_H\,,\,\hat{\hat{\mu}}_{\gamma\gamma}(m_H)\,,\,\hat{\hat{\mu}}_{4\ell}(m_H)\,,\,\hat{\hat{\theta}}(m_H))}{L(\hat{m}_H, \hat{\mu}_{\gamma\gamma}, \hat{\mu}_{4\ell}, \hat{\theta})}$$

Best fit mass for combination:

M_H = 125.2 ±0.3(stat) ± 0.6(syst) GeV



Best fit mass for H → γγ:

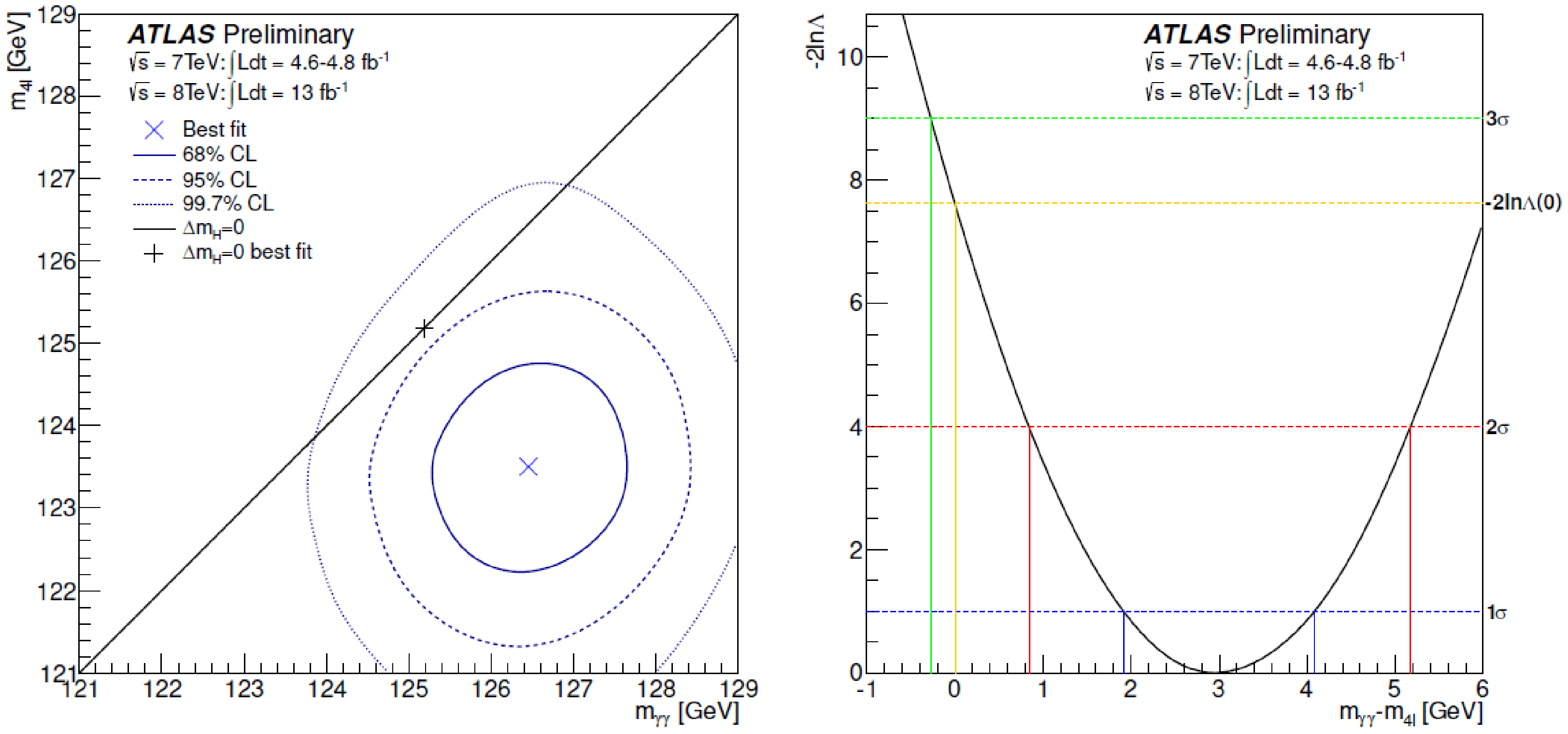
M_H = 126.6 ±0.3(stat) ± 0.7(syst) GeV

Best fit mass for H → ZZ* → 4ℓ:

M_H = 123.5 ±0.9(stat) ± 0.3(syst) GeV

Consistency Check of Higgs Mass Discrepancy

$$\Delta\hat{m}_H = \hat{m}_H^{\gamma\gamma} - \hat{m}_H^{4\ell} = 3.0^{+1.1}_{-1.0}\ \text{GeV} = 3.0 \pm 0.8\,(\text{stat})\ ^{+0.7}_{-0.6}\,(\text{sys})\ \text{GeV}$$

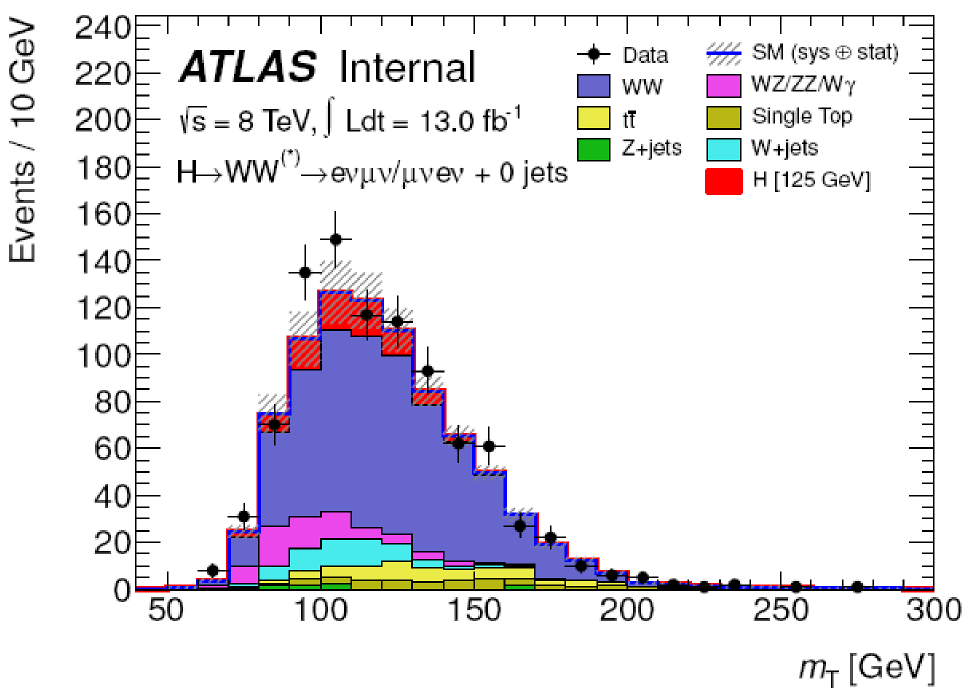


The probability for a single Higgs boson-like particle to produce a value of the Λ test statistic disfavoring the ΔM_H=0 hypothesis more than observed is found to be **0.6% or 2.8σ .**

Update of H → WW* → ℓνℓν

- Final discriminant

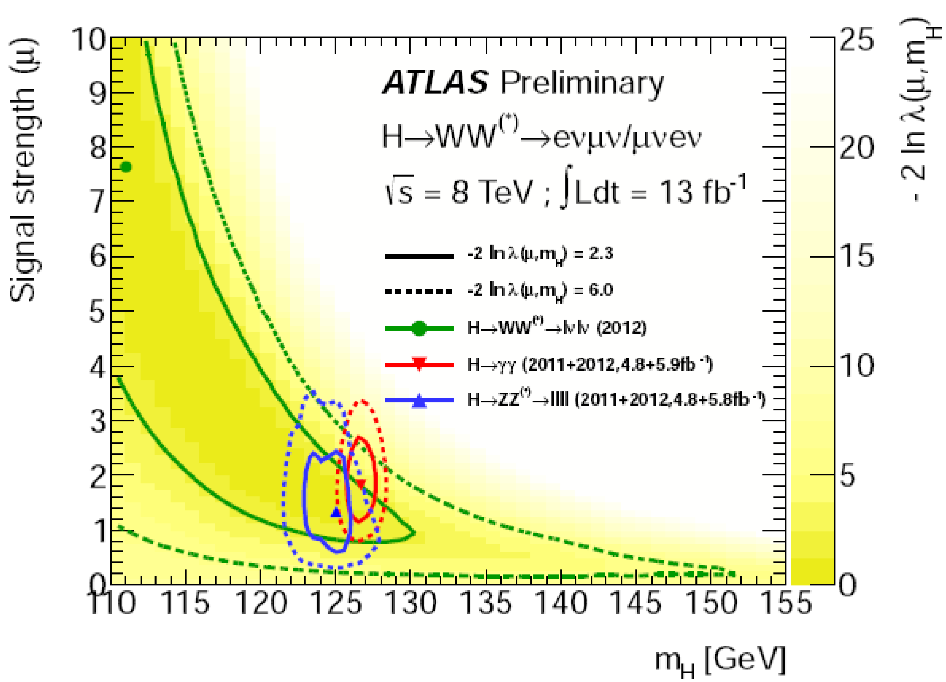
$$m_T = \sqrt{\left(E_T^{\ell\ell} + E_T^{\rm miss}\right)^2 + |\mathbf{p}_T^{\ell\ell} + \mathbf{E}_T^{\rm miss}|^2}$$



Due to spin correlation between W^+ and W^-,
The signal has the following properties:
Large P_T(ll), small m_{ll}, small $\Delta\phi_{ll}$

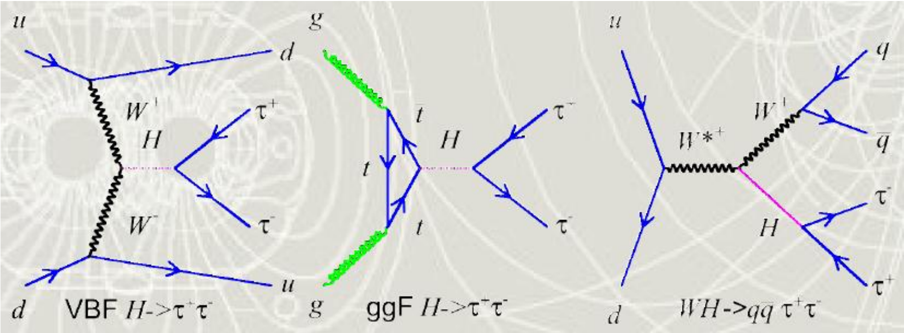
ATLAS best-fit signal strength:
ICHEP(4.7+5.8 fb^{-1}): **μ = 1.3 ±0.5**
2012 (13 fb^{-1}): **μ = 1.5 ± 0.6**

Results for ICHEP: 0/1/2 jets
Results for HCP: 0/1 jet
Major background: SM WW



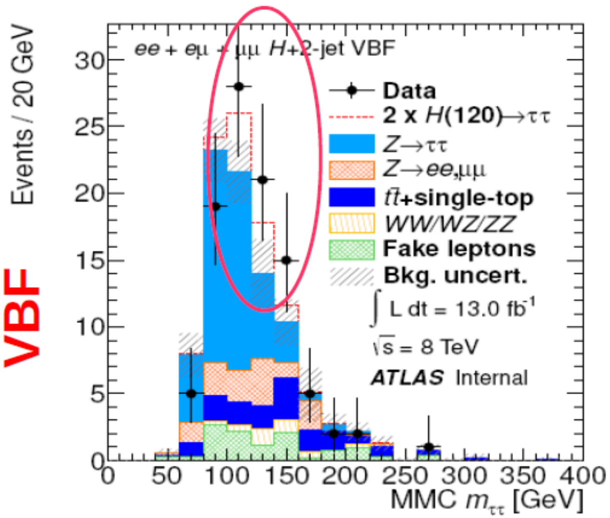
Update of H → ττ

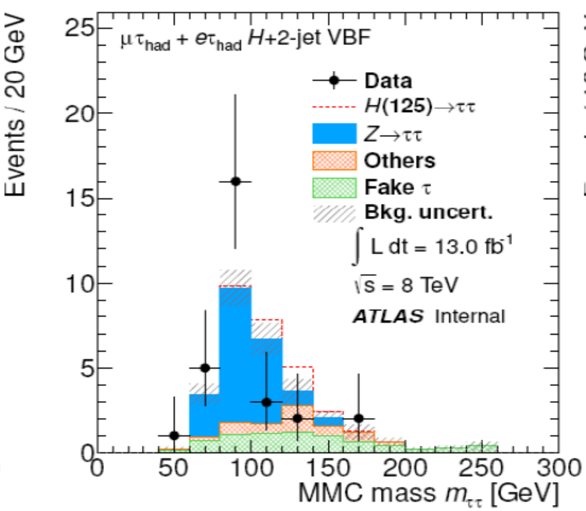
- H → ττ provide an unique opportunity to probe Yukawa coupling which gives mass to quarks and leptons
- It has one the largest branching ratios for low mass Higgs
- Three different ττ decay modes:

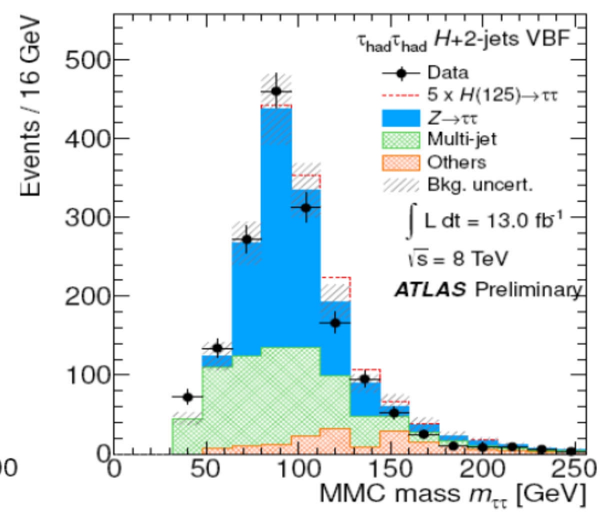


- lep-lep: $\ell\ell 4\nu$: (ee) + eμ + $\mu\mu$
- lep-had: $\ell\tau_{had}3\nu$: $e\tau_{had} + \mu\tau_{had}$
- had-had: $\tau_{had}\tau_{had}\nu\nu$: $\tau_{had}\tau_{had}$

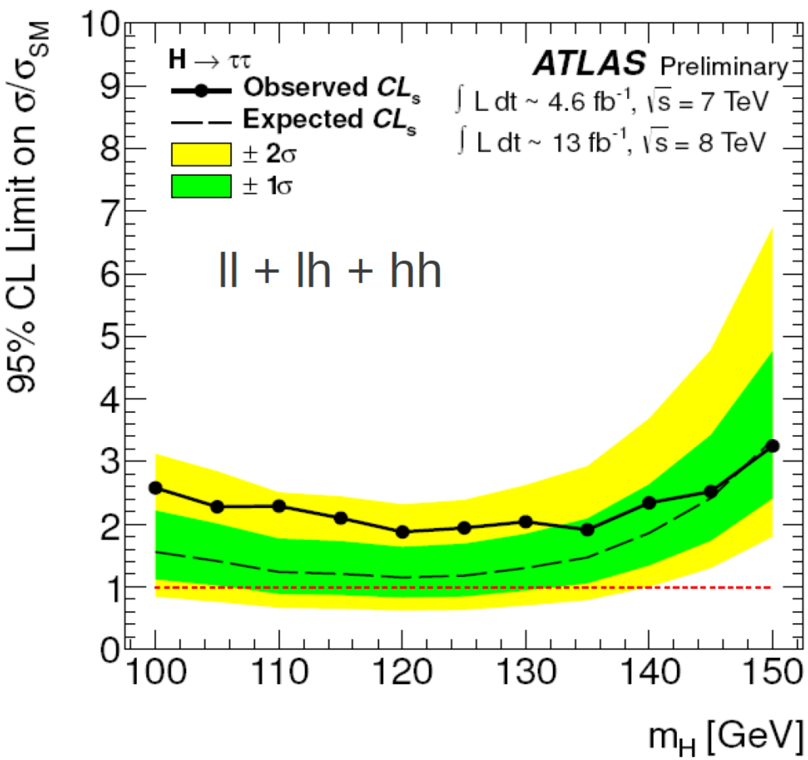
VBF

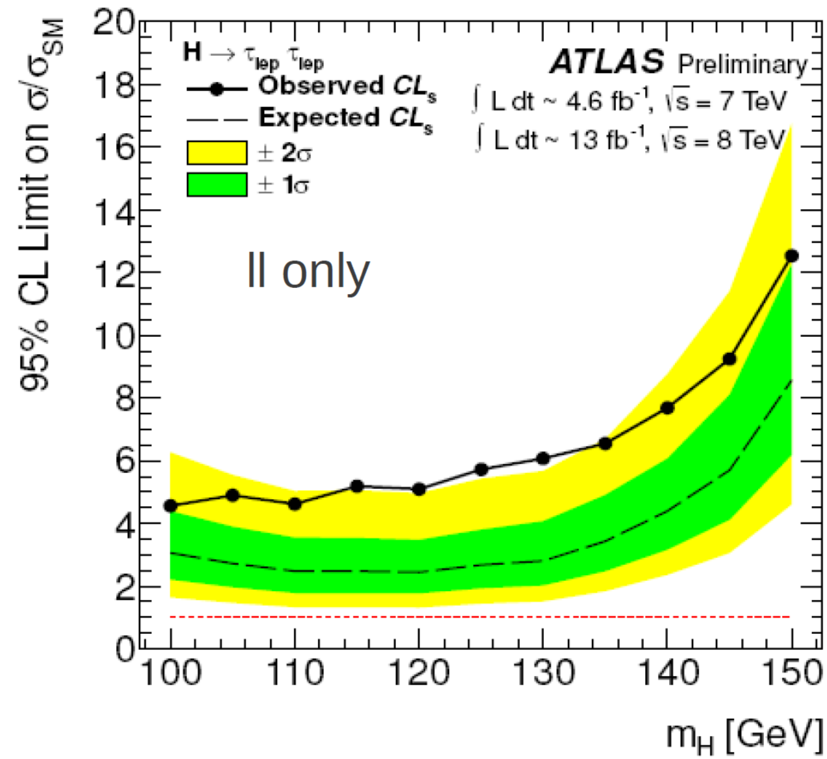






Update of H → ττ

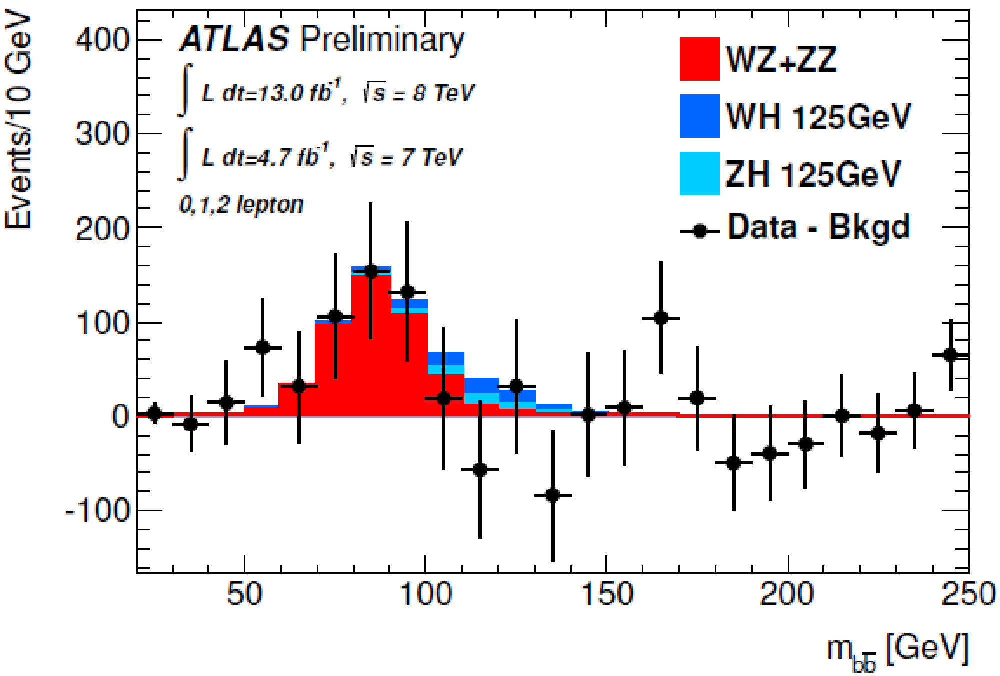


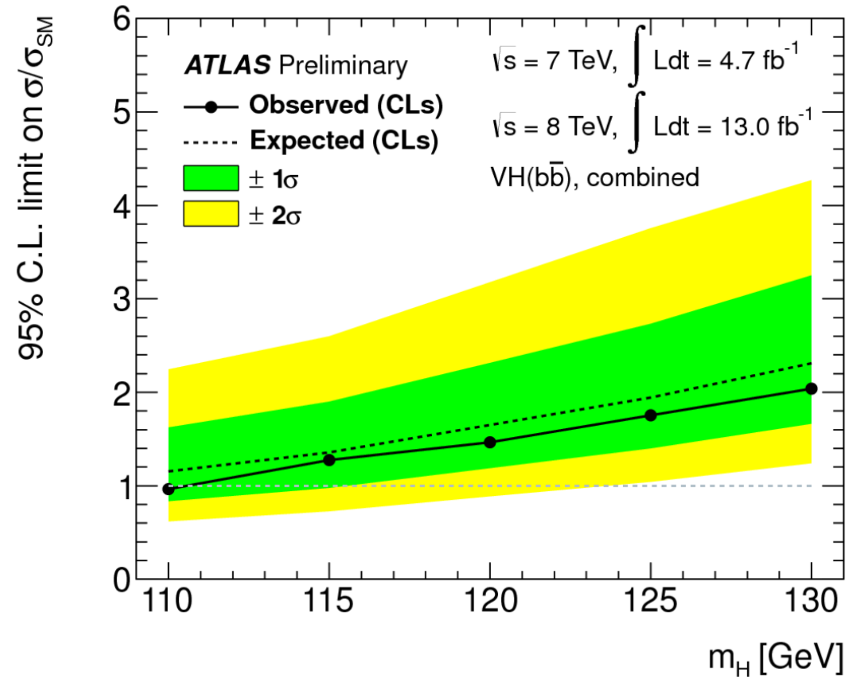


- The largest deviation of observed from expected limit is in the 2-lepton channel.
- The best fitted signal strength @ 125 GeV: **$\mu = 0.8 \pm 0.7$**
- **Due to the presence of MET, the complexity of each subchannel of H→ττ is greater than γγ or ZZ→4l channel.**

Update of H→bb

- Fit invariant mass of M_{bb} distribution
- Validation WZ,ZZ → bb + X: $\mu_{WZ,ZZ} = 1.09 \pm 0.30$ (4.0σ)
- On the Higgs search, data show no excess on top of expected backgrounds, expected limit 1.9 σ/σ_{SM} @ m_H = 125 GeV, the observed limit is 1.8 σ/σ_{SM} , signal strength is **μ= -0.4 ±1.0**

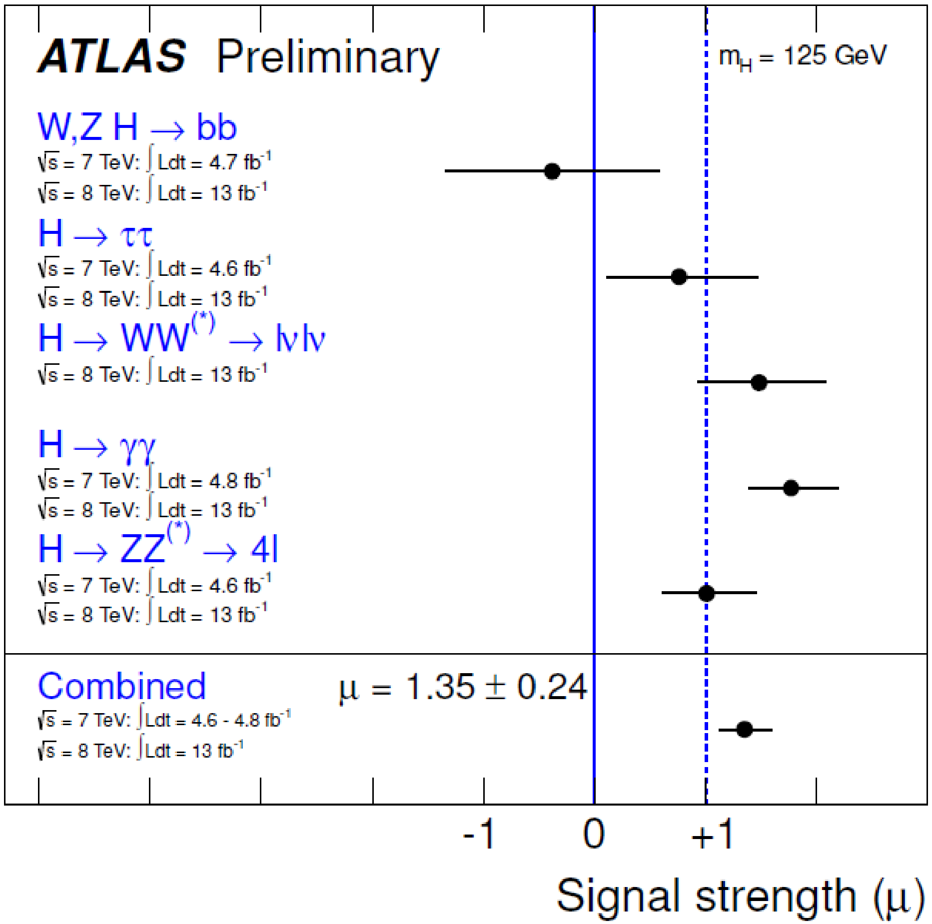


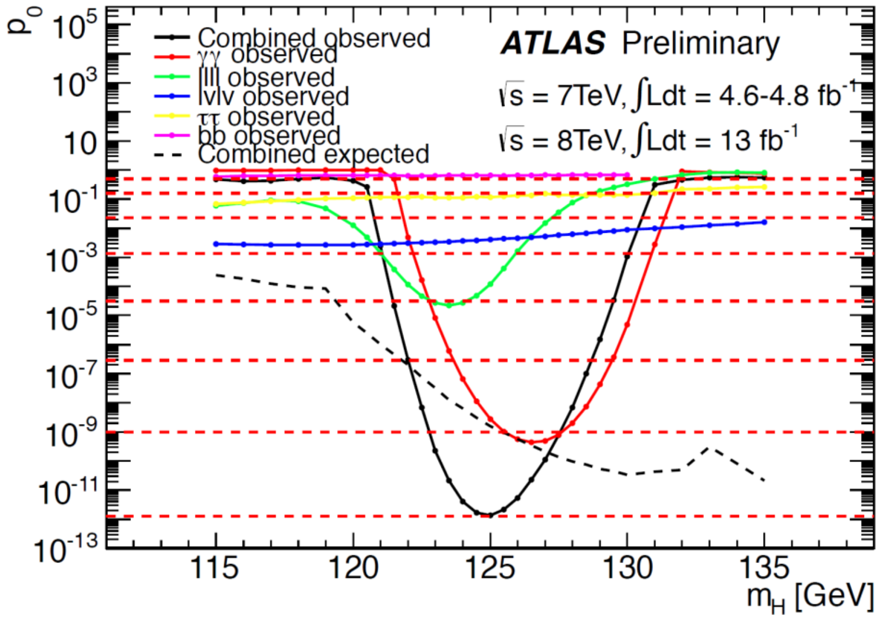


Update of Higgs Signal Strength

➔ **The observed significance is ~ 7.0σ (expected 5.9σ)**

➔ **The signal strength: μ = 1.35 ±0.24**





Higgs Boson Decay	μ (m_H=125 GeV)
$VH \rightarrow Vbb$	−0.4 ± 1.0
$H \rightarrow \tau\tau$	0.8 ± 0.7
$H \rightarrow WW^{(*)}$	1.5 ± 0.6
$H \rightarrow \gamma\gamma$	1.8 ± 0.4
$H \rightarrow ZZ^{(*)}$	1.0 ± 0.4
Combined	1.35 ± 0.24

Is it the SM Higgs ?

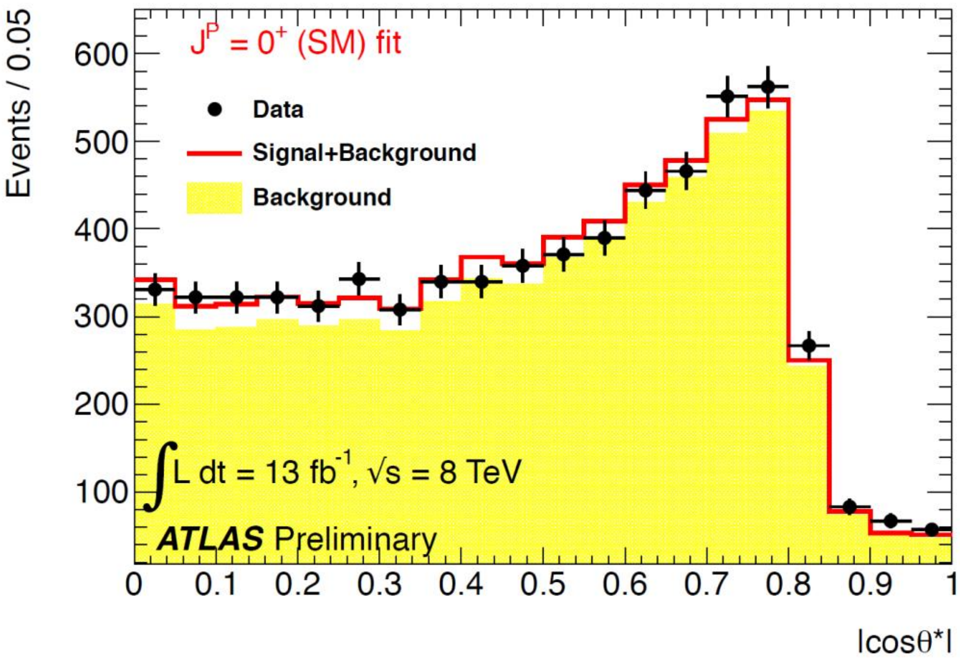
- ❑ Verify the new observed particle
  - ✓ Spin-0 particle
    - ❖ Spin-1: excluded by $H \rightarrow \gamma\gamma$
    - ❖ Spin-2: look at angular correlations

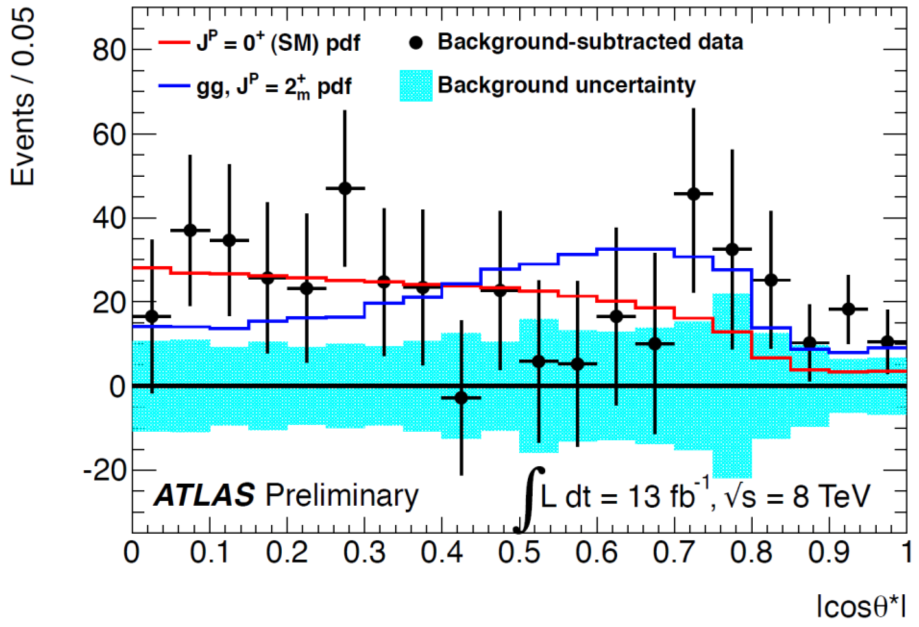
Spin of particle	γγ	ZZ*	ττ	bb
Spin 0	☺	☺	☺	☺
Spin 1	☹	☺	☺	☺
Spin 2	☺	☺	☹	☺
Seen?	Yes	Yes	Not yet	Not yet

  - ✓ CP-nature
    - ❖ SM Higgs CP-even, extended Higgs sectors has CP-odd or mixed states
    - ❖ Look at angular correlations
  - ✓ Couplings
    - ❖ Gauge / Yukawa couplings → g_{vvH}, $g_{ffH} \propto m$
    - ❖ Unitarity in $W_L W_L$ scattering → $g_{WWH} \propto m_W$
    - ❖ Higgs self-couplings, determine shape of Higgs potential via trilinear and quartic couplings, $V = \mu^2|\Phi|^2 + \lambda|\Phi|^4 + \text{constant}$

H → γγ : Spin Analysis

- Using events in signal mass window [123.6, 128.6] GeV
- The photon polar angle in the resonance rest frame |cosθ*| is sensitive to the spin of Higgs.



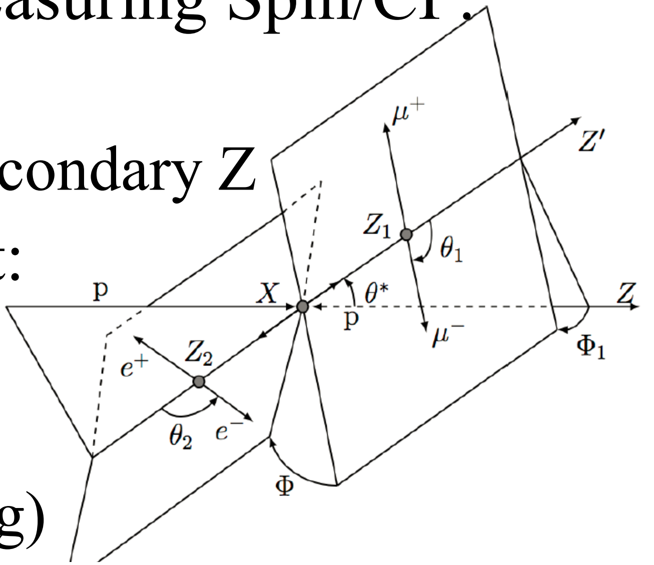


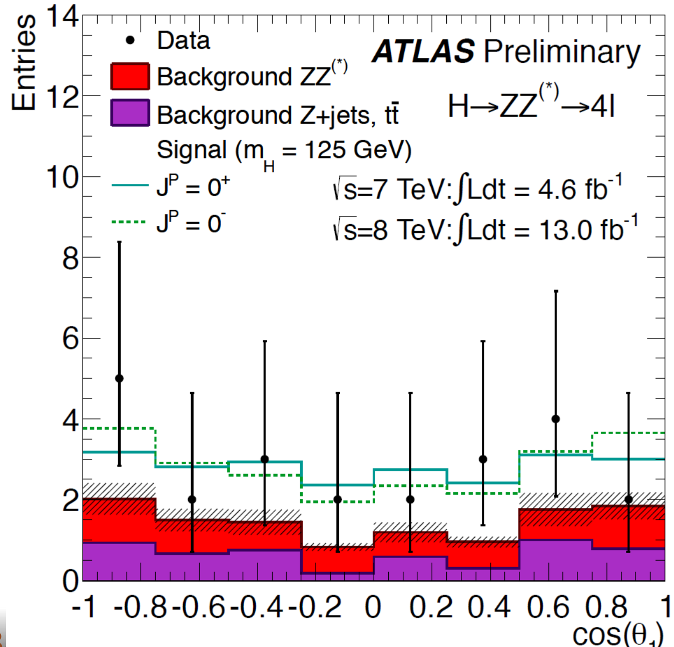
→ Expected separation between spin 0^+ and 2^+ hypotheses is 1.8 σ.

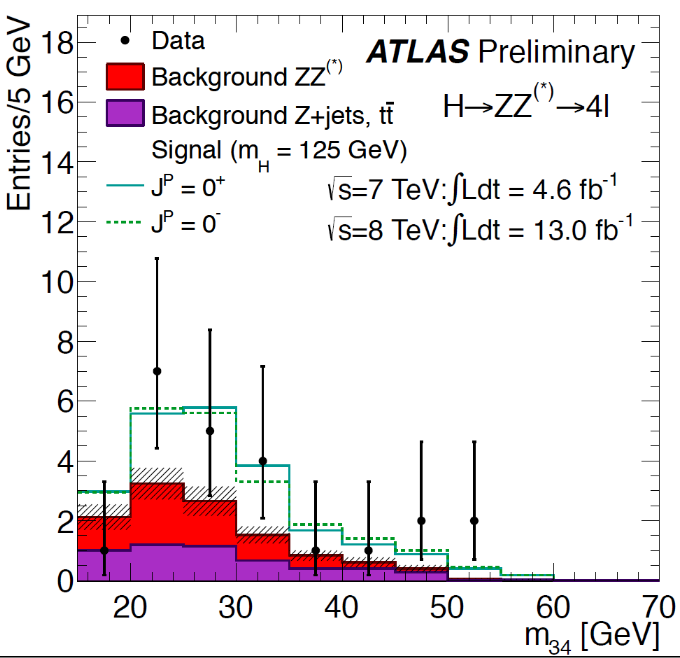
→ Spin 2 hypothesis is disfavored at 91% C.L. (or 1.4σ) assuming 100% gluon-gluon production.

H→ZZ*→4l : Spin and CP

- ❑ Fully reconstructed final state allows measuring Spin/CP:
  - Five kinematic angles (production, decay)
  - Invariant mass of the primary Z and the secondary Z
- ❑ Discriminate 0^+ (SM) hypothesis against:
  - 0^- (CP odd)
  - 2^- (pseudo-tensor)
  - 2^+_m (graviton-like tensor, minimal coupling)

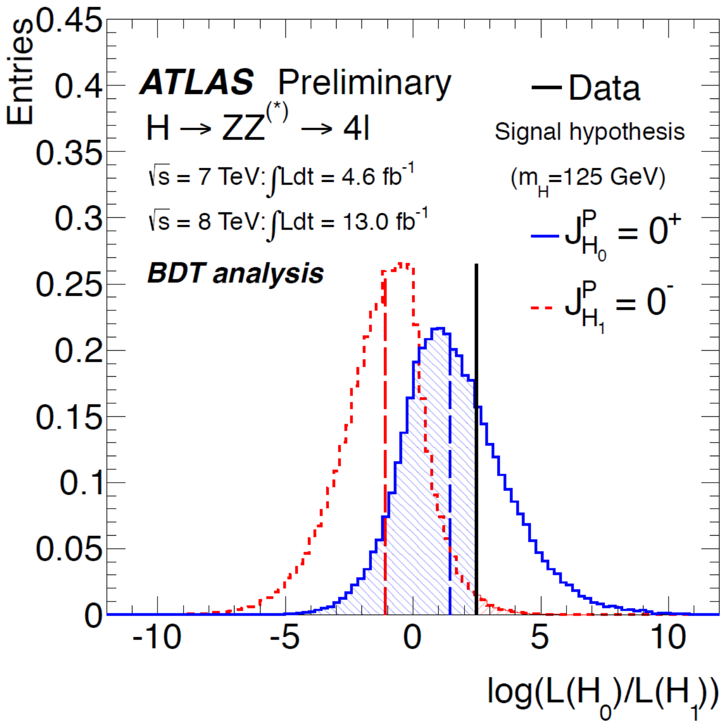


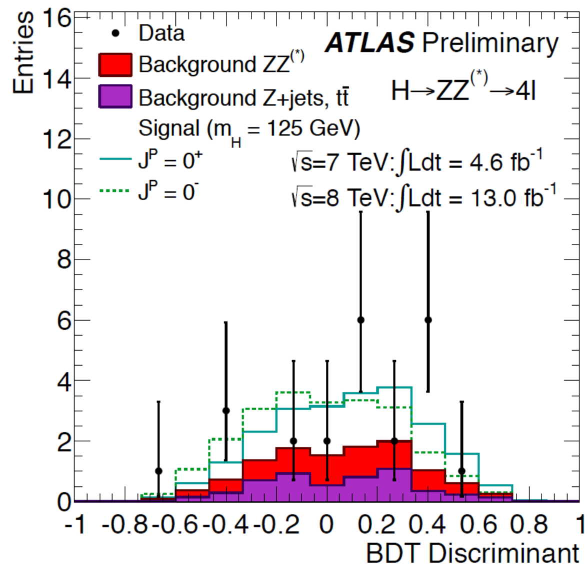


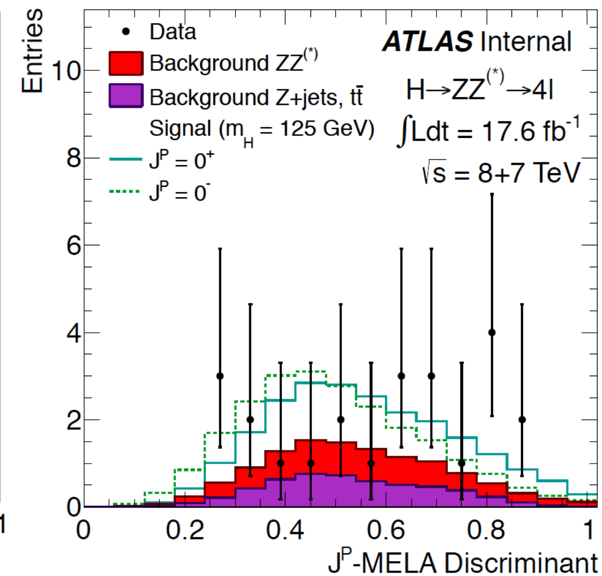


H→ZZ*→4l : Spin and CP

- Two multi-variate discriminants used:
  - – Boosted Decision Trees (BDT)
  - – Matrix-Element calculation for each spin/CP (J^P-MELA)







➔ Data strongly favour 0^+ vs 0^-: 2.7σ

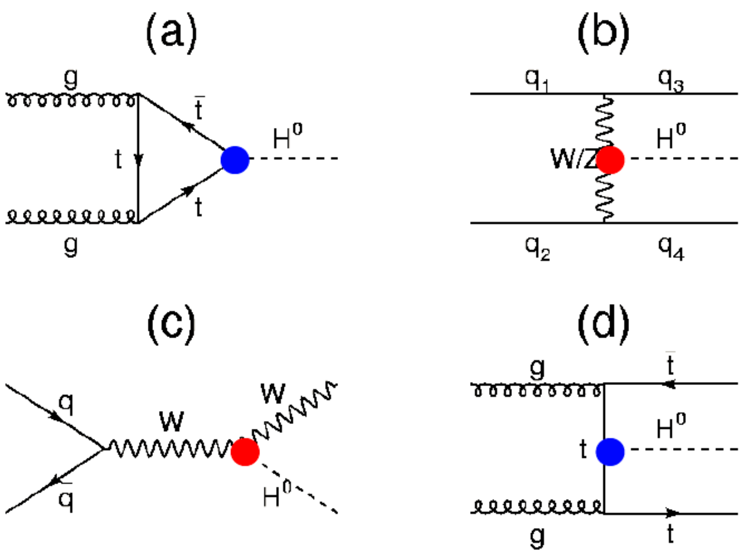
0^- hypothesis is excluded at 99% C.L.

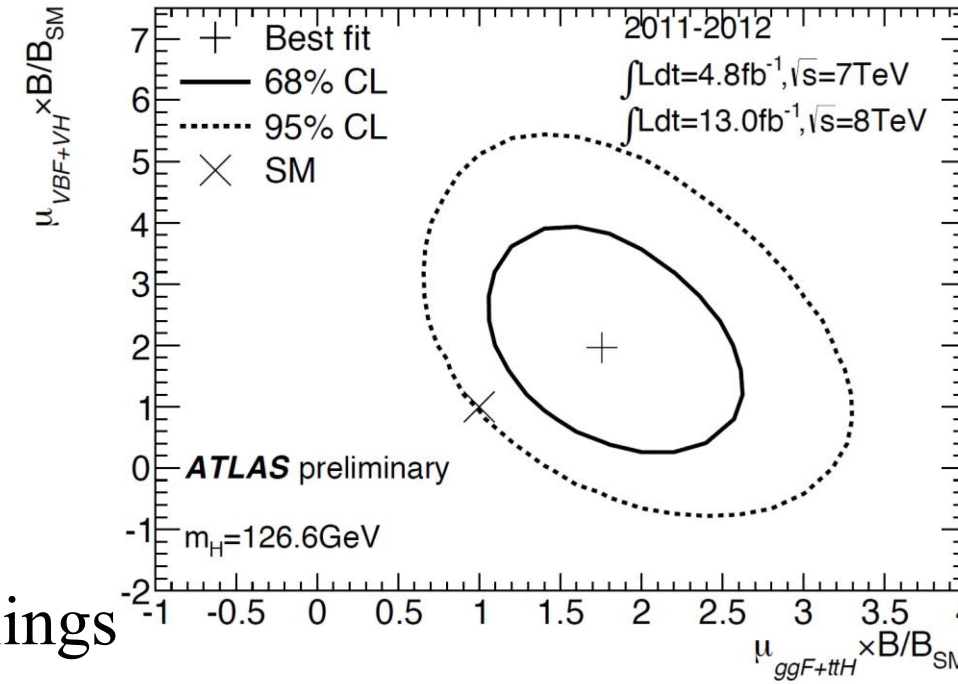
➔ 0^+ vs 2^- : observed separation ~ 2.0σ

➔ 2^+ is excluded at ~85% C.L.

Higgs → γγ

- Observation of H → γγ excludes spin-1

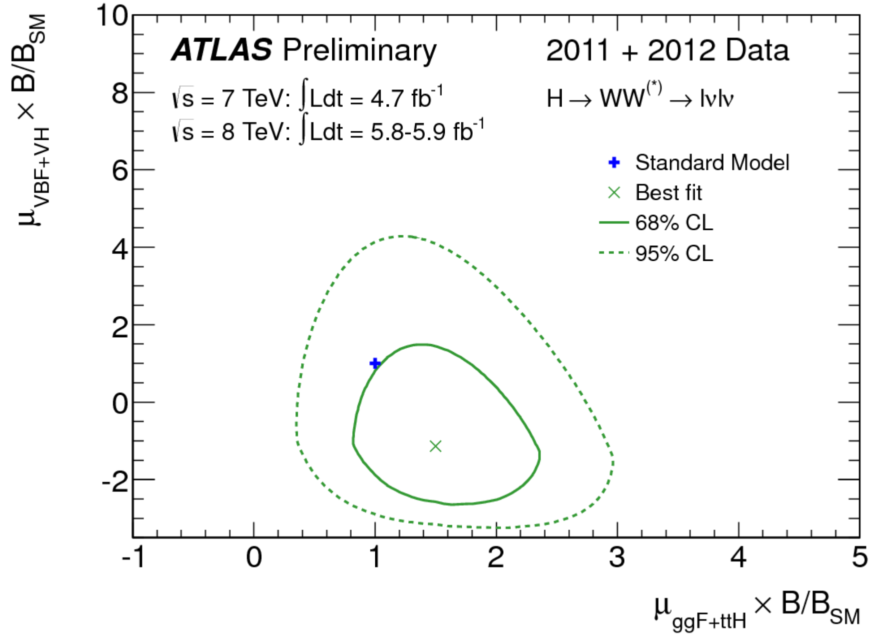


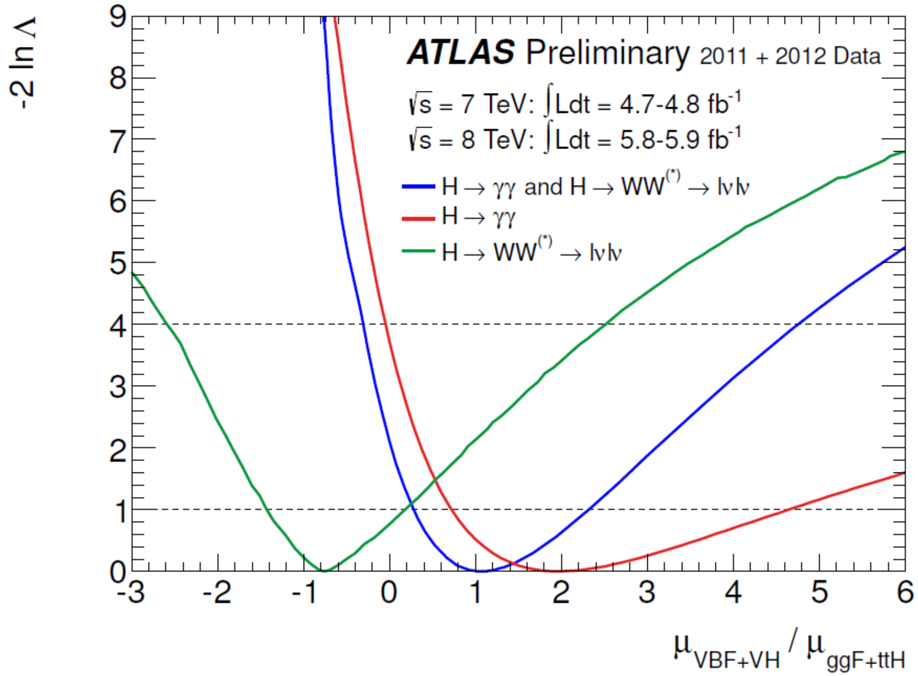


- Higgs has two types of couplings
  - "Gauge" couplings (to bosons)
  - Yukawa couplings (to fermions)
- Explore tension between SM value and observation from different Higgs production modes: μ_{VBF+VH} vs. $\mu_{ggF+ttH}$

Higgs → WW* → lνlν

- ❑ Model independent coupling studies which are directly related to experimental observables. 2D contour: μ_{VBF+VH} vs. $\mu_{ggF+ttH}$
- ❑ H→ZZ*→4l has low statistics and uses inclusive analysis





➔ The signal strength ratios cancel the branching ratios of different channels so that the results can be compared directly.

Measurement of Higgs Couplings

- **Assumptions (LHC HXSWG, arXiv:1209.0040):**
  - The signal observed in different channels originate from a single narrow resonance with mass near 125 GeV.
  - The width of the assumed Higgs boson near 125 GeV is neglected, hence the signal cross section can be decomposed in the following for all channels:

$$(\sigma \cdot \mathrm{BR})\,(ii \to \mathrm{H} \to ff) = \frac{\sigma_{ii} \cdot \Gamma_{ff}}{\Gamma_{\mathrm{H}}}$$

  - Only modifications of couplings strengths are taken into account, while the tensor structure of the couplings is assumed to be same as in the SM prediction (CP-even scalar). **[ATLAS-CONF-2012-127]**

Higgs Coupling Structure

- Depending on the benchmark model, κ_g, κ_γ and κ_H are either functions of other couplings or independent parameters.
- Notation for gg→H→γγ

Zero Width Approximation

$$(\sigma \cdot \mathrm{BR})(gg \to H \to \gamma\gamma) = \sigma_{\mathrm{ggF}} \cdot \frac{\Gamma_{\gamma\gamma}}{\Gamma_H}$$

$$\frac{\sigma_{\mathrm{ggF}}}{\sigma_{\mathrm{ggF}}^{\mathrm{SM}}} = \kappa_g^2 \qquad \frac{\Gamma_{\gamma\gamma}}{\Gamma_{\gamma\gamma}^{\mathrm{SM}}} = \kappa_\gamma^2 \qquad \frac{\Gamma_H}{\Gamma_H^{\mathrm{SM}}} = \kappa_H^2$$

$$= \kappa_g^2 \sigma_{\mathrm{SM}}(gg \to H) \cdot \frac{\kappa_\gamma^2}{\kappa_H^2} \mathrm{BR}_{\mathrm{SM}}(H \to \gamma\gamma)$$

fixed

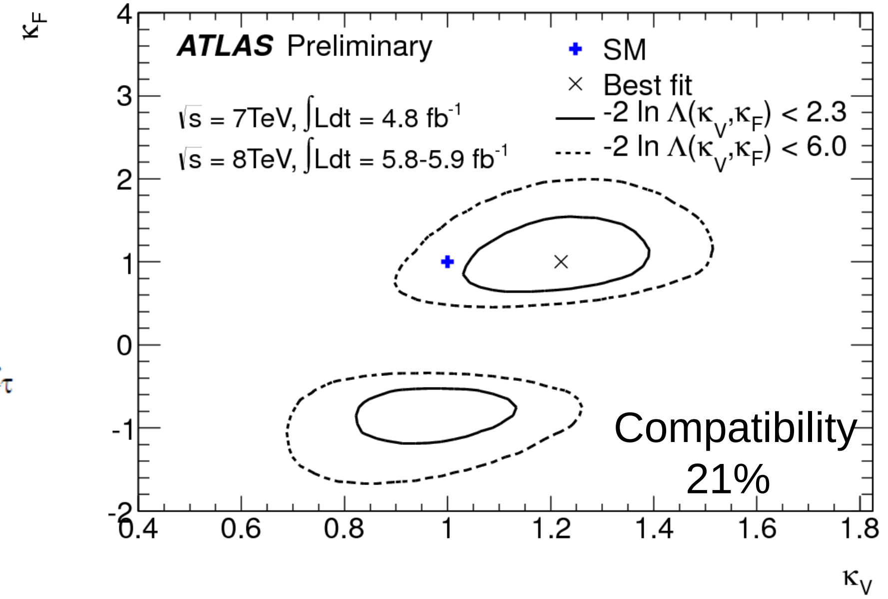
Higgs Couplings

- No BSM particle contributions to gg→H, H→γγ and the total width. Two coupling scale factors κ_F for fermions and κ_V for bosons,

$$\kappa_F = \kappa_t = \kappa_b = \kappa_\tau$$
$$\kappa_V = \kappa_W = \kappa_Z$$

68% CL intervals

$$\kappa_F \in [-1.0, -0.7] \cup [0.7, 1.3]$$
$$\kappa_V \in [0.9, 1.0] \cup [1.1, 1.3]$$

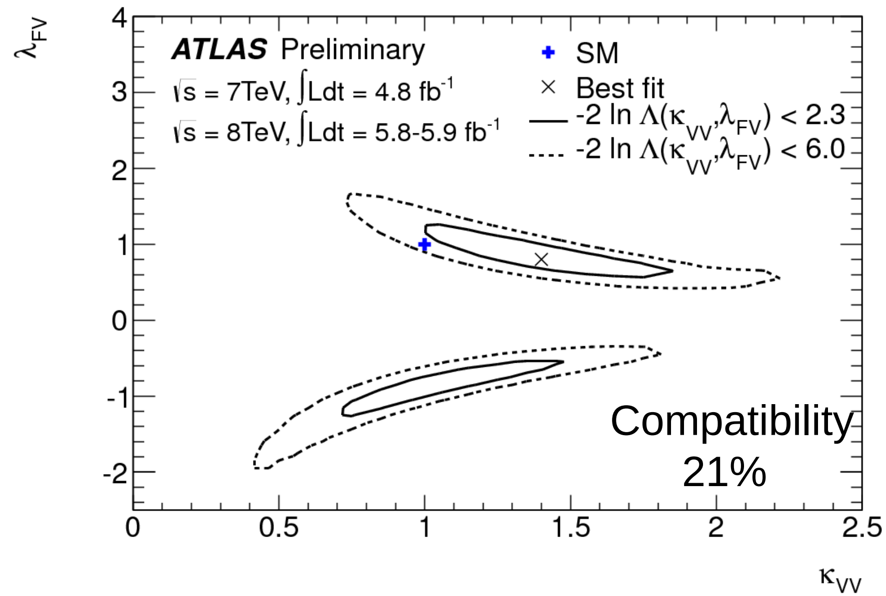


- Same as above, but without the assumption on the total width

$\lambda_{FV}=\kappa_F/\kappa_V$, $\kappa_{VV}=\kappa_V\cdot\kappa_V/\kappa_H$

68% CL intervals

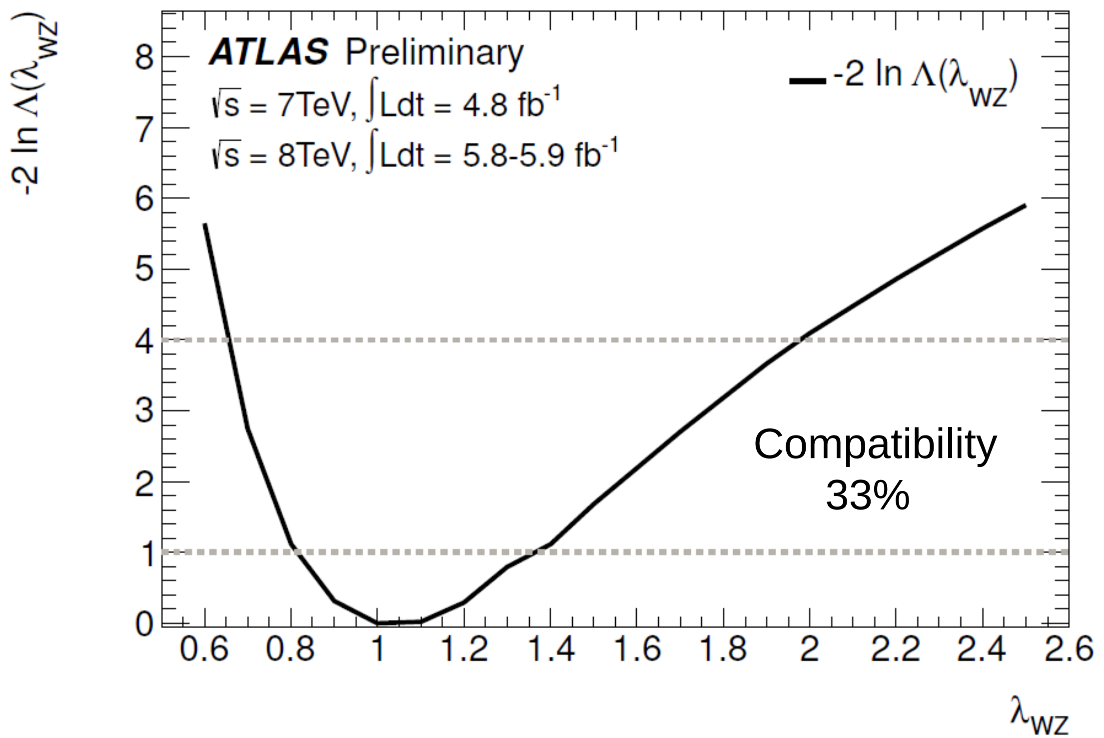
$$\lambda_{FV} \in [-1.1, -0.7] \cup [0.6, 1.1]$$
$$\kappa_{VV} = 1.2^{+0.3}_{-0.6}$$



Probing custodial symmetry of the W/Z Coupling

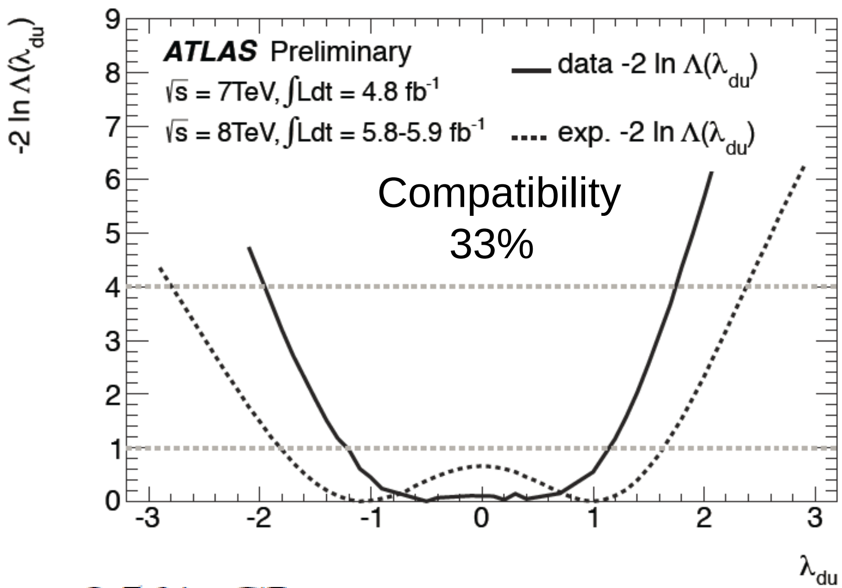
- Similar to previous benchmark model, but $\kappa_V \rightarrow \kappa_W$ and κ_Z, so there are three free parameters κ_W , κ_Z and κ_F. Identical couplings scale factors for the W and Z are required within tight bounds by SU(2) custodial symmetry and ρ parameter.
- The VBF process is parametrized with κ_W and κ_Z according to the Standard Model.

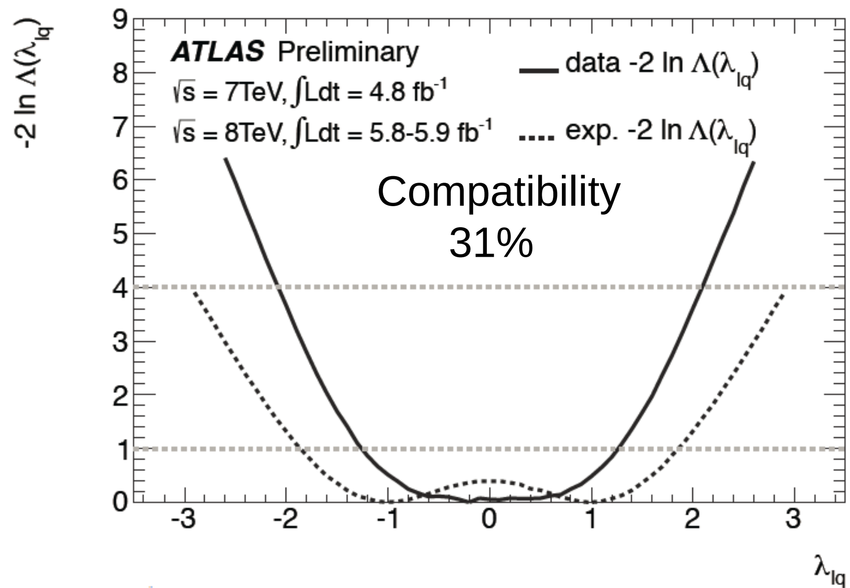
$$\lambda_{WZ} = \frac{\kappa_W}{\kappa_Z} = 1.07^{+0.35}_{-0.27}$$



Probing the up-type and down-type fermion and quark-lepton symmetry

- In many extensions of the SM, the couplings of the light Higgs boson to up-type and down-type fermions differ ($|\lambda_{du}|$).
- The measurement is dominated by channels where we don't observe an excess, $H \rightarrow bb$ ($\mu=-0.4\pm1.0$) and $H \rightarrow \tau\tau$ ($\mu=0.8\pm0.7$).





95% CL

$$\lambda_{du} \in [-2.0, 1.8]$$

$$\lambda_{du} = \frac{\kappa_d}{\kappa_u}$$

95% CL

$$\lambda_{lq} \in [-2.1, 2.1]$$

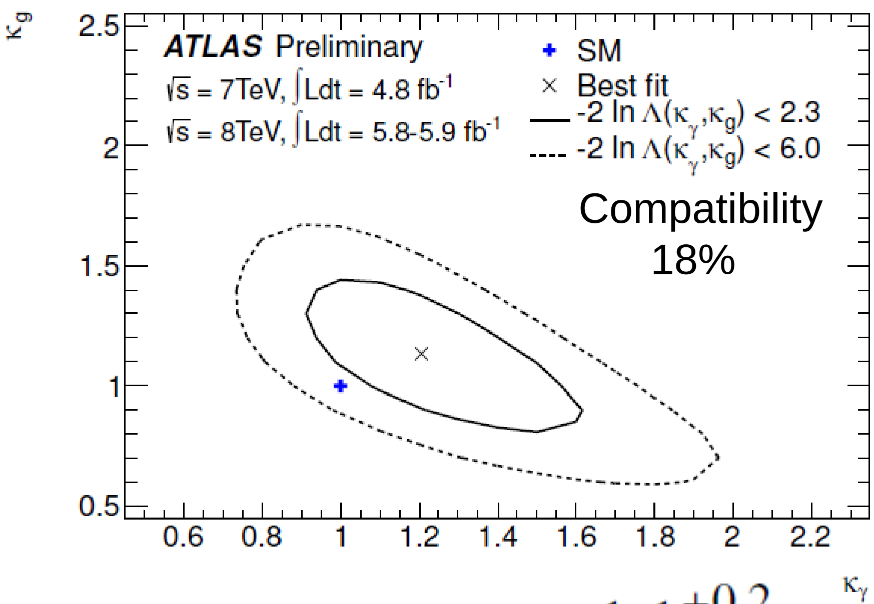
$$\lambda_{lq} = \frac{\kappa_l}{\kappa_q}$$

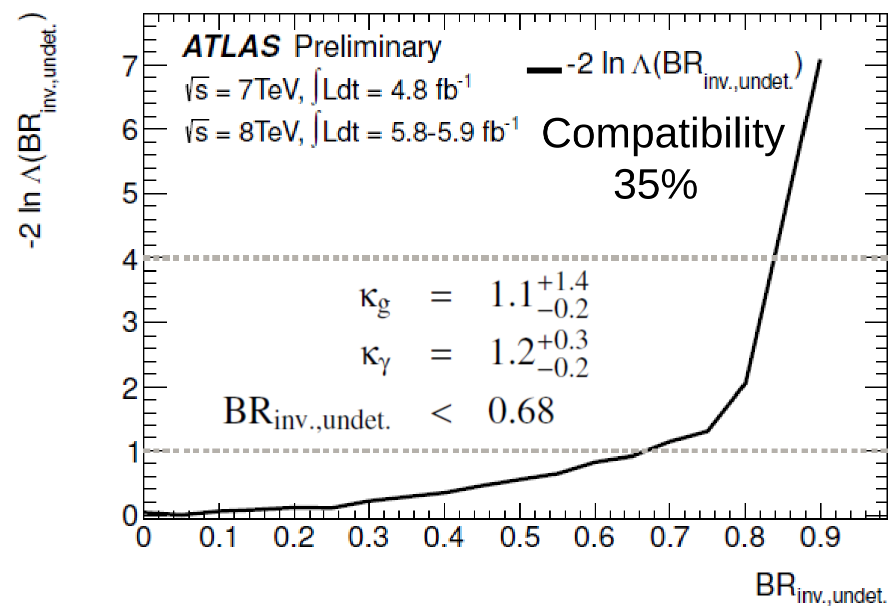
Probing Potential Non-SM Particle Contributions

- For H→γγ and gg→H vertices, effective scale factors κ_γ and κ_g are introduced (two free parameters). Non-SM particles can contribute to H→γγ and gg→H loops or in new final states.

assuming only SM contributions to total width and $\kappa_i = 1$ for all SM particles

no assumption on total width, but $\kappa_i = 1$ for all SM particles





68% CL $\kappa_g = 1.1^{+0.2}_{-0.3}$ $\kappa_\gamma = 1.2^{+0.3}_{-0.2}$

$$\Gamma_H = \frac{\kappa_H^2(\kappa_i)}{(1 - BR_{inv.,undet.})}\Gamma_H^{SM}$$

Summary and Conclusions

- A new Higgs-like particle was observed and confirmed

Mass: m_H = 125.2 ± 0.3 (stat) ± 0.6 (syst) GeV
Signal strength @ 125 GeV : μ = 1.35 ± 0.24

- Higgs decays to $\gamma\gamma$, ZZ* and WW* (Gauge coupling) are established, but H → bb, $\tau\tau$ (Yukawa coupling) still lack of statistics to draw definitive conclusion.
- The spin-1 is excluded due to observation of H→$\gamma\gamma$.
- Spin/CP: data favour 0^+ (spin 0 and CP even, SM)
- Uncertainties of couplings parameters ~20-30% , no significant deviations from SM couplings are observed.

Please stay tuned !

Backup

References

- $H \rightarrow WW \rightarrow e\mu\nu\nu$ — ATLAS-CONF-2012-158
- $H \rightarrow ZZ \rightarrow 4l$, $H \rightarrow \gamma\gamma$, 2011 $H \rightarrow WW$ — Phys. Lett. B 716 (2012) 1-29
- $H \rightarrow \tau\tau$ — ATLAS-CONF-2012-160
- $VH \rightarrow bb + X$ — ATLAS-CONF-2012-161
- $ttH \rightarrow bb + X$ — ATLAS-CONF-2012-135
- $H \rightarrow ZZ \rightarrow ll\nu\nu$ — ATLAS-CONF-2012-016
- $H \rightarrow ZZ \rightarrow lljj$ — ATLAS-CONF-2012-017
- $H \rightarrow WW \rightarrow l\nu jj$ — ATLAS-CONF-2012-018
- MSSM Neutral Higgs — ATLAS-CONF-2012-024
- Charged Higgs — ATLAS-CONF-2012-011, ATLAS-CONF-2011-094

https://twiki.cern.ch/twiki/bin/view/AtlasPublic

H→ZZ*→4l Candidate

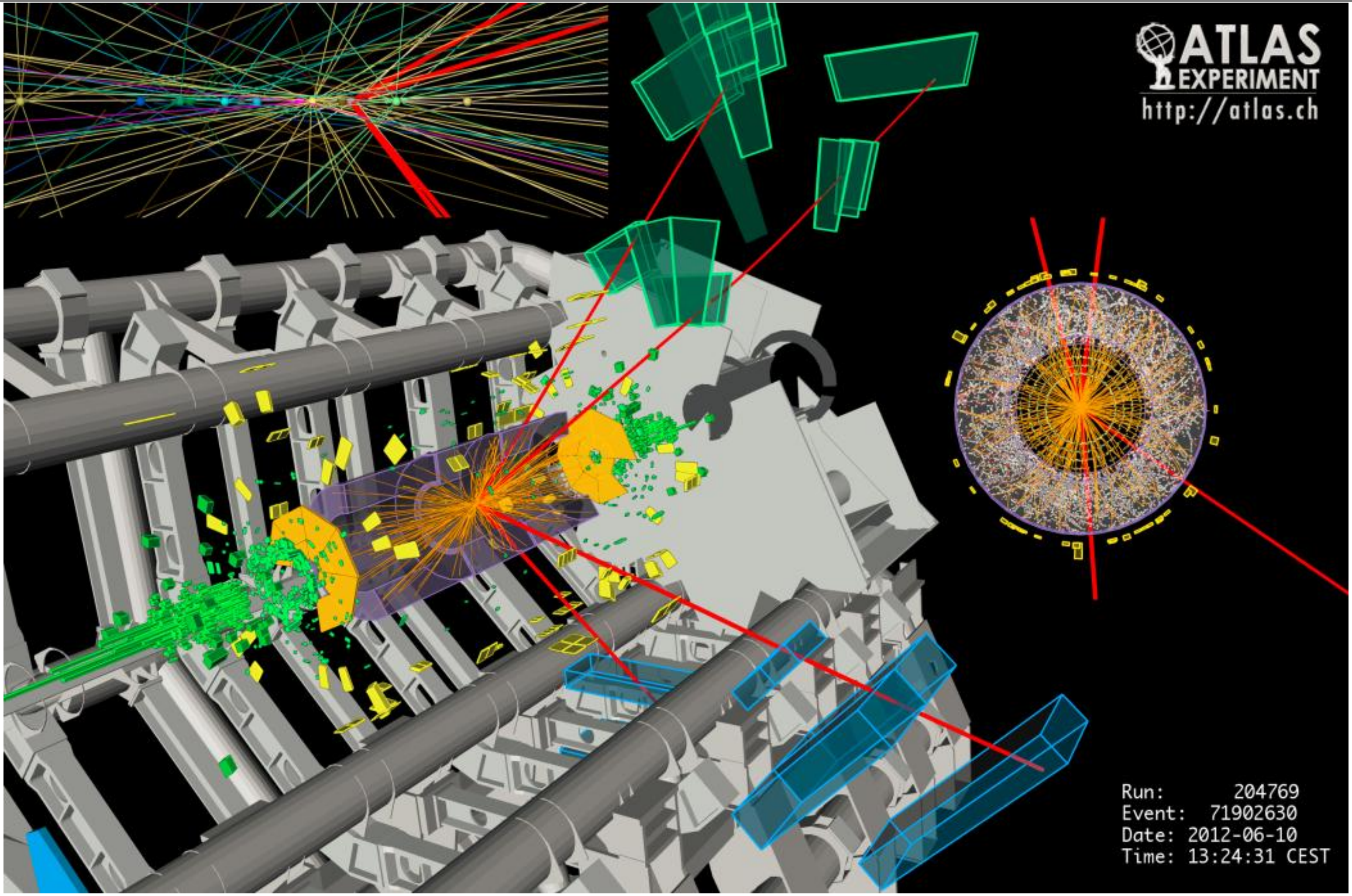
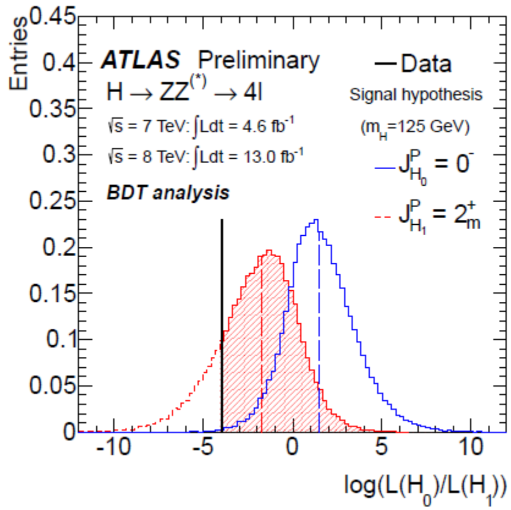
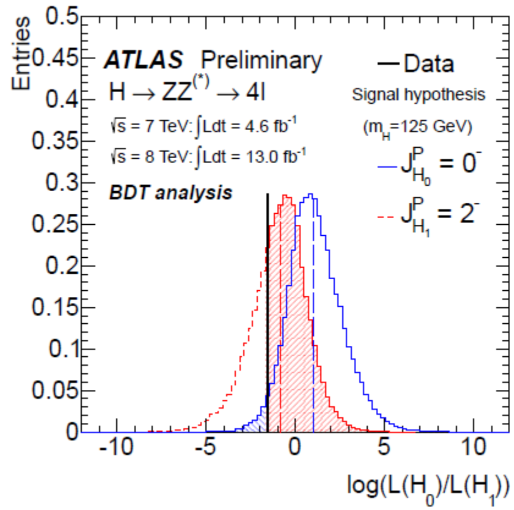


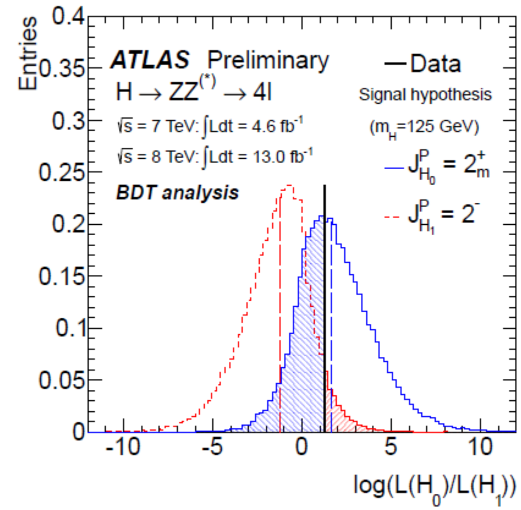
Figure 42: Event display of a 4μ candidate. EventNumber: 71902630 RunNumber: 204769 $m_{4\ell}$ = 125.1 GeV. m_{12} = 86.3 GeV, m_{34} = 31.6 GeV. $\mu_1 : p_T, \eta, \phi$ = 36.1 GeV, 1.29, 1.33. $\mu_2 : p_T, \eta, \phi$ = 47.5 GeV, 0.69, −1.65. $\mu_3 : p_T, \eta, \phi$ = 26.4 GeV, 0.47, −2.51. $\mu_4 : p_T, \eta, \phi$ = 71.7 GeV, 1.85, 1.65. $p_T^{4\ell}$ = 27.0 GeV. E_T^{miss} = 41.8 GeV.


ATLAS Preliminary
H → ZZ(*) → 4l
√s = 7 TeV: ∫Ldt = 4.6 fb-1
√s = 8 TeV: ∫Ldt = 13.0 fb-1
BDT analysis
Data
Signal hypothesis
(mH=125 GeV)
JP H0 = 0-
JP H1 = 2+m
Entries
log(L(H0)/L(H1))

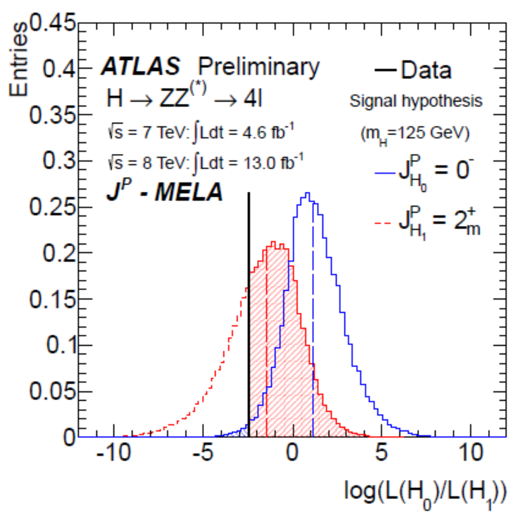
(a)


ATLAS Preliminary
H → ZZ(*) → 4l
√s = 7 TeV: ∫Ldt = 4.6 fb-1
√s = 8 TeV: ∫Ldt = 13.0 fb-1
BDT analysis
Data
Signal hypothesis
(mH=125 GeV)
JP H0 = 0-
JP H1 = 2-
Entries
log(L(H0)/L(H1))

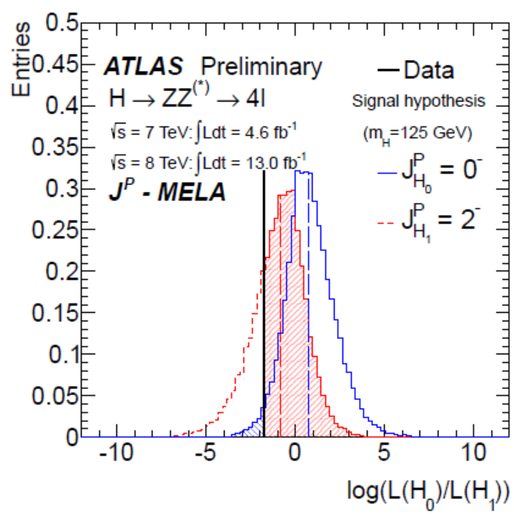
(b)


ATLAS Preliminary
H → ZZ(*) → 4l
√s = 7 TeV: ∫Ldt = 4.6 fb-1
√s = 8 TeV: ∫Ldt = 13.0 fb-1
BDT analysis
Data
Signal hypothesis
(mH=125 GeV)
JP H0 = 2+m
JP H1 = 2-
Entries
log(L(H0)/L(H1))

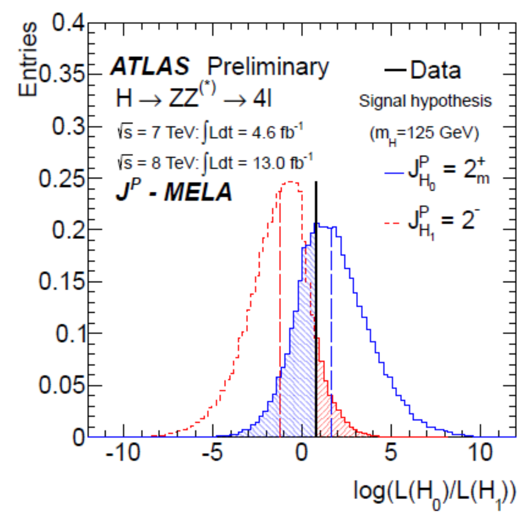
(c)


ATLAS Preliminary
H → ZZ(*) → 4l
√s = 7 TeV: ∫Ldt = 4.6 fb-1
√s = 8 TeV: ∫Ldt = 13.0 fb-1
JP - MELA
Data
Signal hypothesis
(mH=125 GeV)
JP H0 = 0-
JP H1 = 2+m
Entries
log(L(H0)/L(H1))

(d)


ATLAS Preliminary
H → ZZ(*) → 4l
√s = 7 TeV: ∫Ldt = 4.6 fb-1
√s = 8 TeV: ∫Ldt = 13.0 fb-1
JP - MELA
Data
Signal hypothesis
(mH=125 GeV)
JP H0 = 0-
JP H1 = 2-
Entries
log(L(H0)/L(H1))

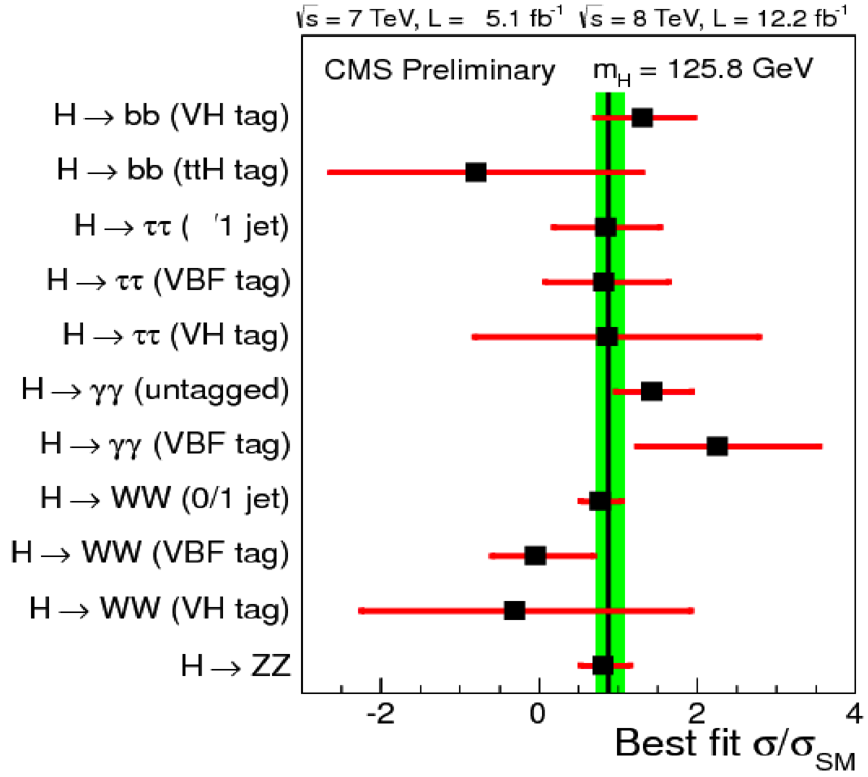
(e)


ATLAS Preliminary
H → ZZ(*) → 4l
√s = 7 TeV: ∫Ldt = 4.6 fb-1
√s = 8 TeV: ∫Ldt = 13.0 fb-1
JP - MELA
Data
Signal hypothesis
(mH=125 GeV)
JP H0 = 2+m
JP H1 = 2-
Entries
log(L(H0)/L(H1))

(f)

CMS Results (HCP, 5.1+12.2 fb^{-1})

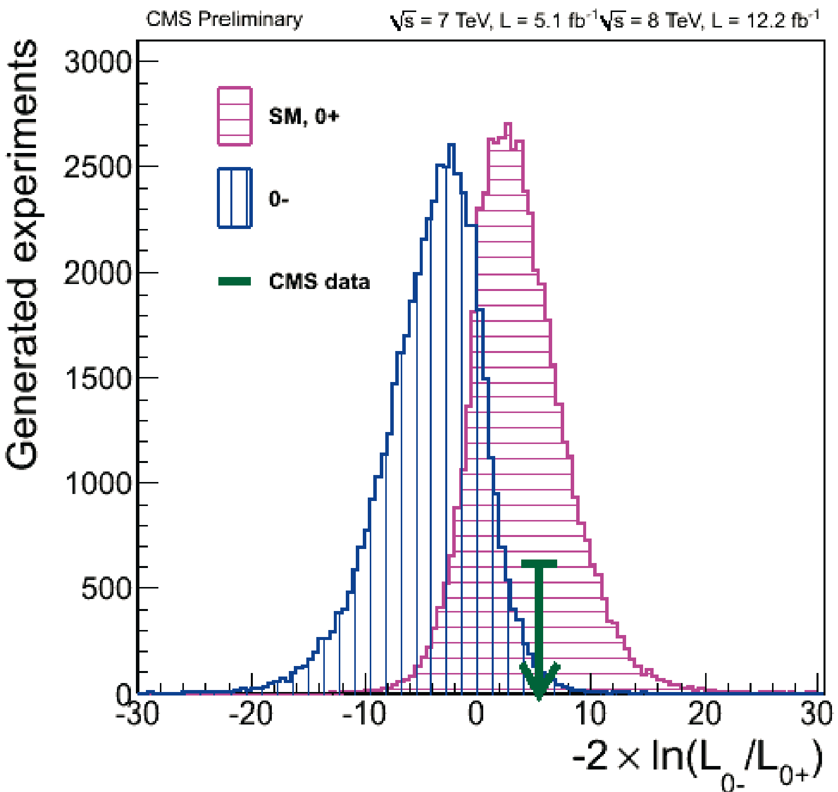
- ❑ m_H = 125.8 ± 0.4(stat) ± 0.4(syst) GeV, 6.9 σ
- ❑ H→ZZ*→4l: m_H=126.2 ± 0.6(stat) ± 0.2(syst) GeV, 4.5σ
- ❑ H→γγ: m_H = 125.1 ± 0.4(stat) ± 0.6(syst) GeV, 4.1σ
- ❑ Signal strength, μ = 0.88 ± 0.21
- ❑ H→γγ: μ=1.56 ± 0.43



CMS Results

- Spin/CP from H→ZZ*→4l
  - 0^+ vs 0^- : 1.93σ expected separation, 0^+ is within 0.53σ
  - 0^- is consistent with observation at 2.45σ level(2.4% CLs)

ITS spin-parity:



0+ vs. 0-:
Expected separation: 1.93 σ
Observed:
0- is consistent with observation within 2.45 σ (2.4% using CLs)
0+ - is within 0.53 σ

Summary

- Tevatron combination on H→$b\bar{b}$ has been updated:
  - CDF ννbb with the latest b-tagger, 14% better sensitivity.
  - DZero lνbb small changes on treatment of scale factors.
- New preliminary result:

$$\sigma(WH+ZH) \times Br(H \rightarrow b\bar{b}) = 0.19 \pm 0.09 \text{ (stat+syst) pb}$$

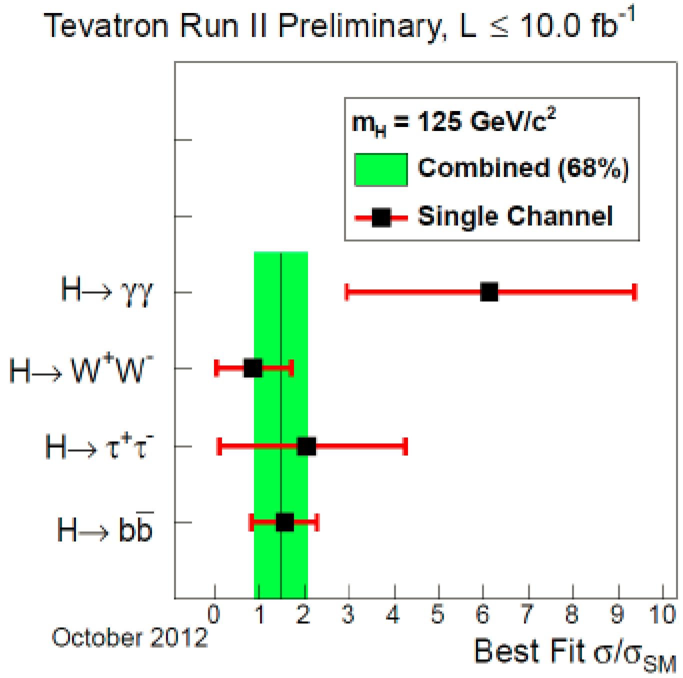
$$\rightarrow \mu = 1.56 \pm^{0.72}_{0.73} \text{ @}M_H\text{=125GeV}$$

Diboson VZ X section measurement

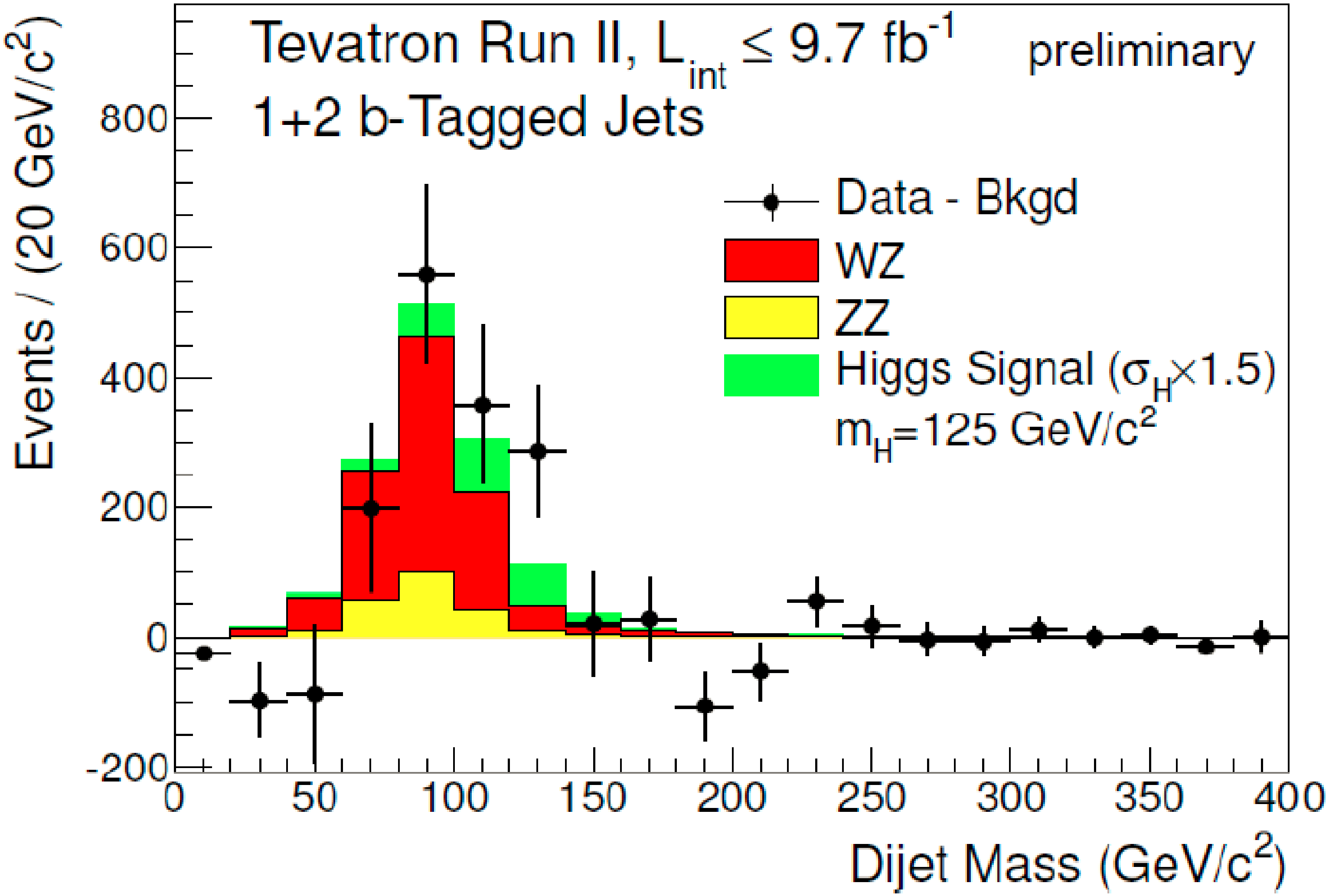
$$\sigma(WZ+ZZ) = 3.0 \pm 0.9 \text{ pb}$$

(NLO exp. : 4.4 ± 0.3 pb)

Submit PRD soon.



- Future
  - Extract Spin information based on kinematics of V+H system (J. Ellis et al. arXiv:1208.6002)

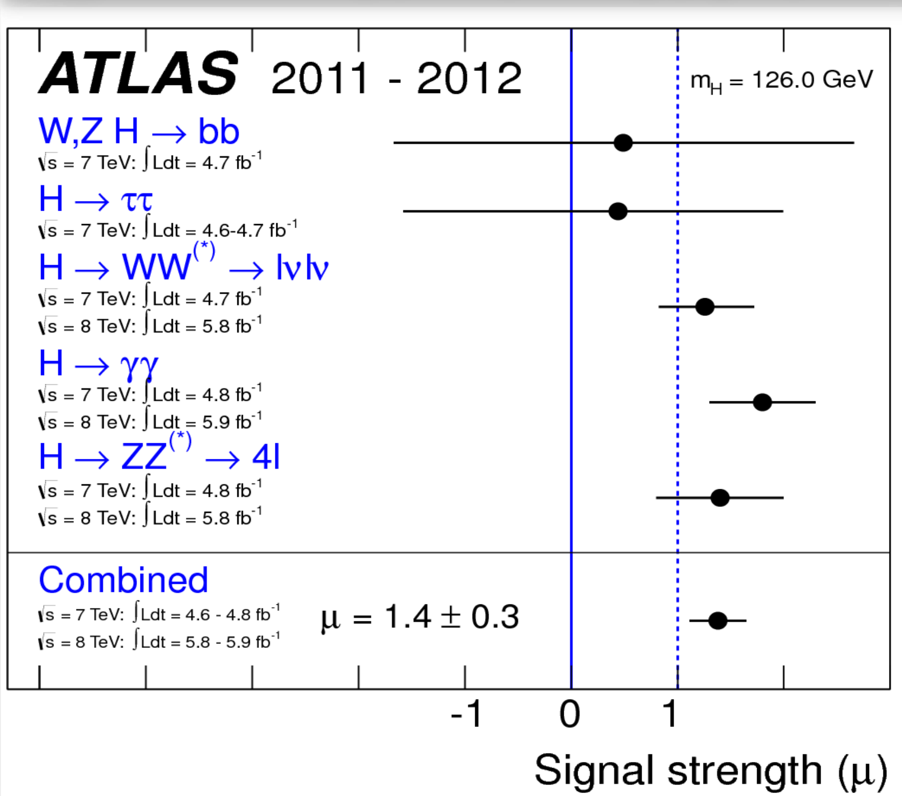


Thank you for your attention.

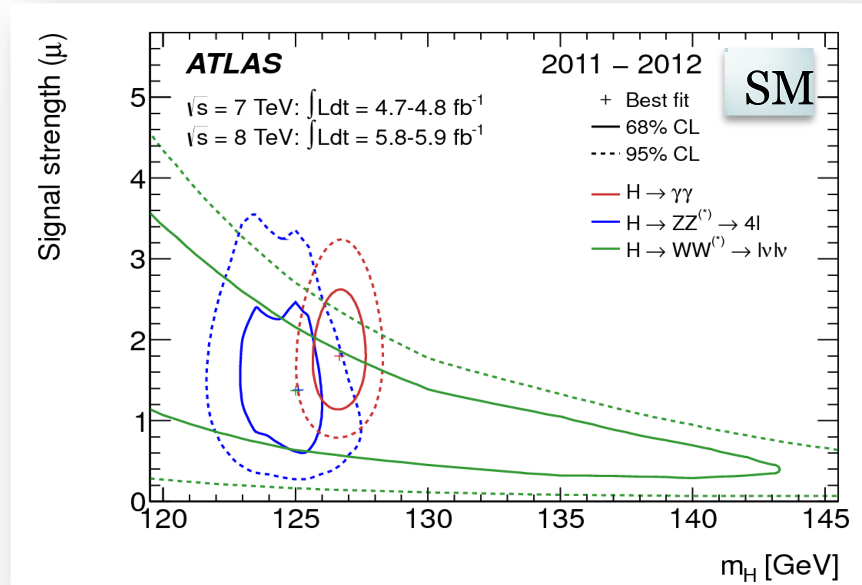
ATLAS Combined Results

- Higgs decays to γγ, ZZ* and WW* are well established, but H → bb, ττ still lack statistics to draw definitive conclusion.

Best–fit Higgs mass:
m_H = 126 ± 0.4 (stat) ± 0.4 (syst) GeV



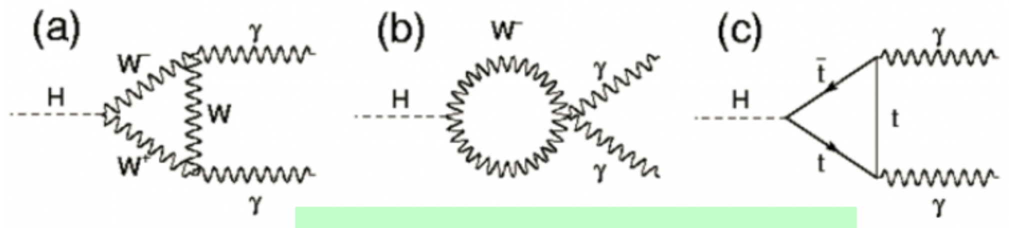
2D likelihood fit: mass vs strength



Best-fit signal strength:
μ = 1.4 ± 0.3

Higgs → γγ

- Very simple signature, but small rate $Br(H\to\gamma\gamma) \sim 2\times10^{-3}$;
- Important decay mode for the low mass region (100-140 GeV)

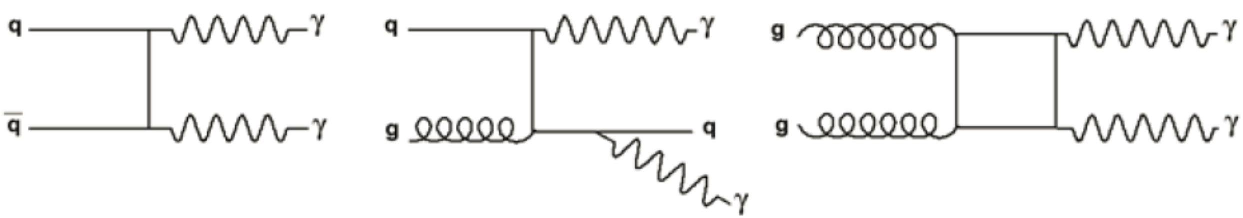


Decay through loops !

$$\sigma_H \times Br(H \to \gamma\gamma) \sim 50 \text{ fb}$$
$$@\ m_H = 125 \text{ GeV}$$

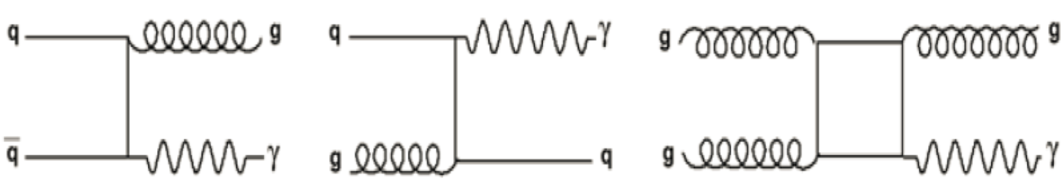
~500 events in 2011+2012 sample!

- Irreducible background from γγ production



$$\sigma(\gamma\gamma) \sim 40 \text{ pb}$$

- Reducible background from γj and jj productions



$$\sigma(\gamma j) \sim 3\times10^{5} \text{ pb}$$
$$\sigma(jj) \sim 6\times10^{8} \text{ pb}$$

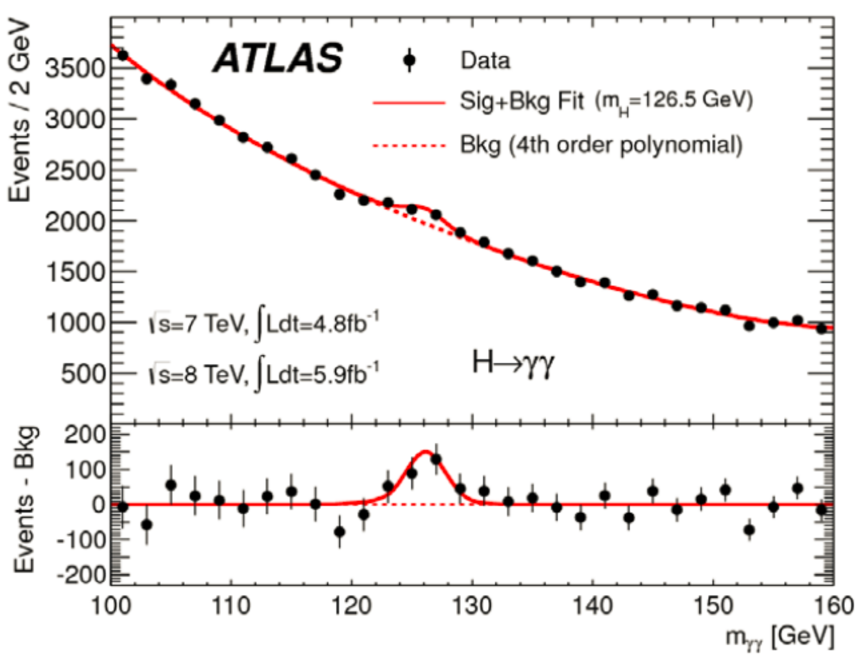
Theoretical uncertainty $\Delta\sigma/\sigma \sim 30\%$, not reliable !

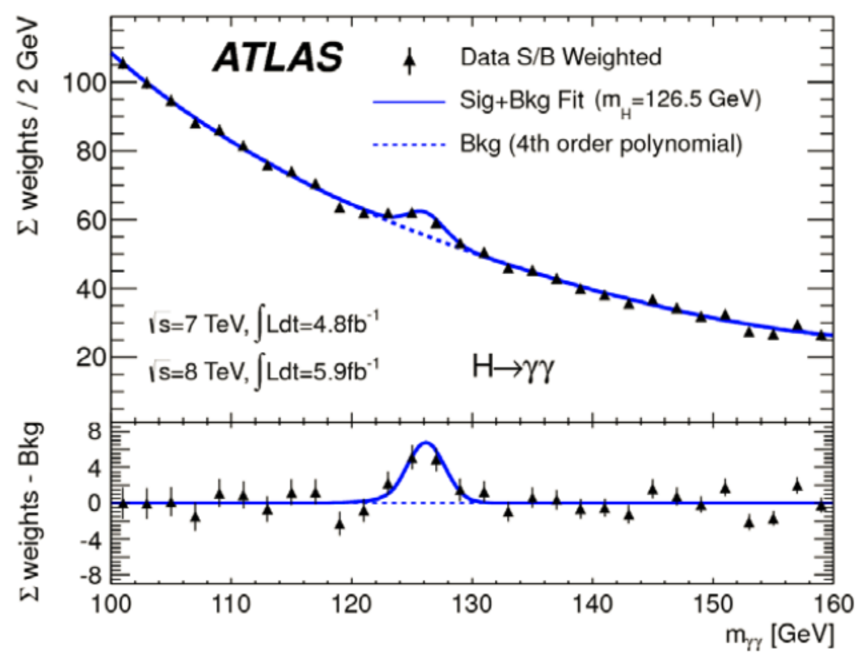
Diphoton mass $m_{\gamma\gamma}$ as the final discriminant variable

$$m^2 = 2E_{\gamma_1}E_{\gamma_2}\left(1-\cos\Delta\phi_{\gamma\gamma}\right)$$

Model signal and background using analytical functions:

- **Signal: Crystal-Ball function (core) + Gaussian (outlier)**
- **Backgrounds: exponentials, polynomials, ...**





A total 59059 events selected, expect ~170 signal events at 126 GeV

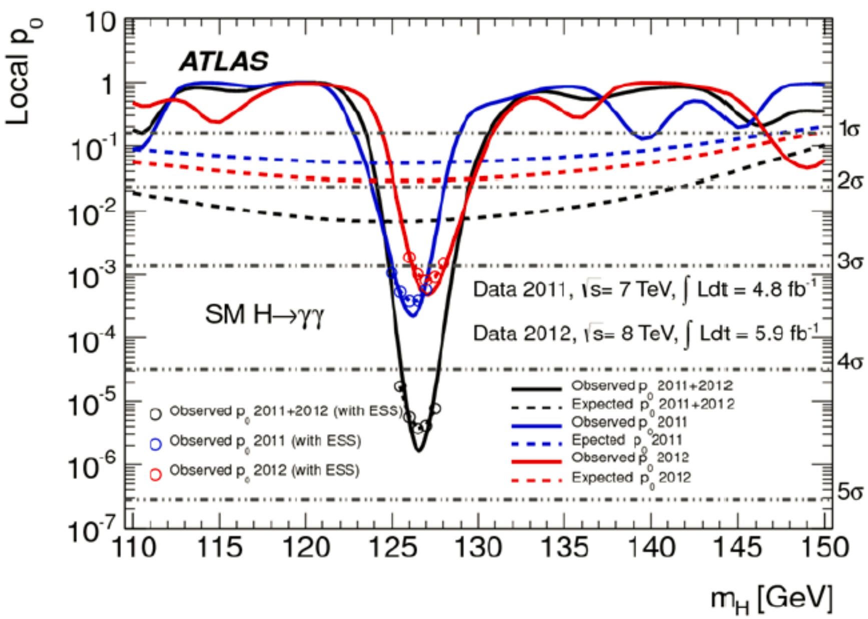
Higgs → γγ

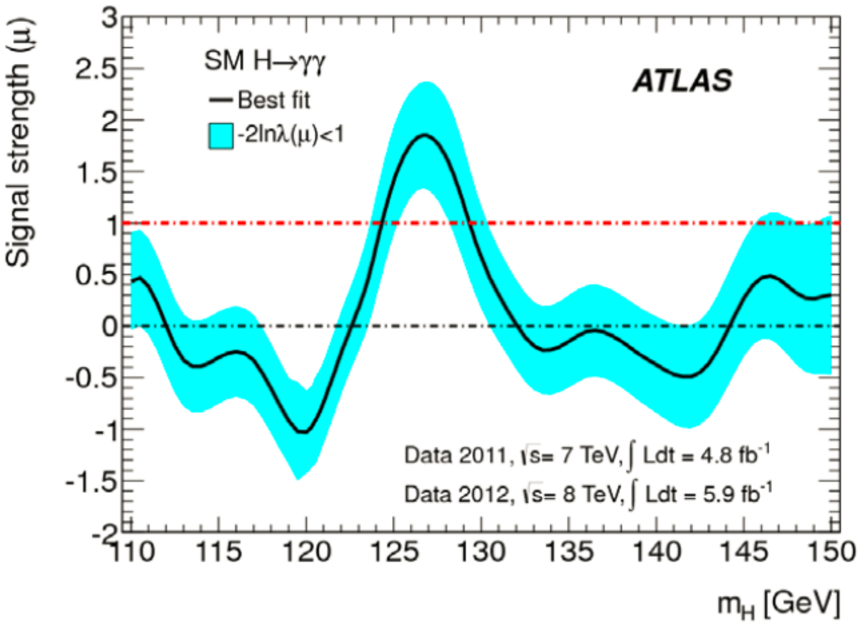
Consistent excesses in both 2011 and 2012 data

Samples	Mass (GeV)	p-value	Obs. Sig.	Exp. Sig.
2011	126	3×10^{-4}	3.4σ	1.6σ
2012	127	5×10^{-4}	3.2σ	1.9σ
Combined	126.5	2×10^{-6}	4.5σ	2.5σ

A minimum p_0 at 126.5 GeV

$$p_0 = 2\times10^{-6} \Rightarrow 4.5\sigma$$



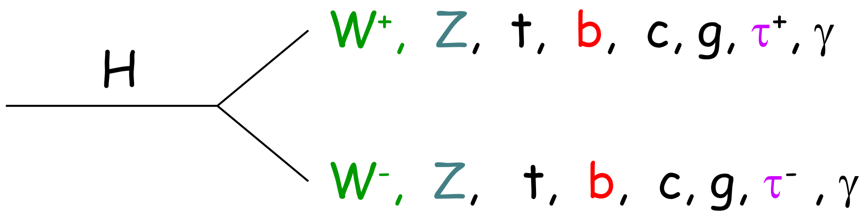


The measured signal strength, the excess relative to the SM expectation, at 126 GeV:

$$\mu = \frac{\sigma\cdot Br}{(\sigma\cdot Br)_{SM}} = 1.8\pm0.5$$

Higgs Boson Decays

The decay properties of the Higgs boson are fixed, **if the mass is known:**



$$\Gamma(H \to f\bar{f}) = N_C \frac{G_F}{4\sqrt{2}\pi} m_f^2(M_H^2)\, M_H$$

$$\Gamma(H \to VV) = \delta_V \frac{G_F}{16\sqrt{2}\pi} M_H^3\, (1 - 4x + 12x^2)\, \beta_V$$

where: $\delta_Z = 1, \delta_W = 2, \quad x = M_V^2/M_V^2, \quad \beta =$ velocity

$$\Gamma(H \to gg) = \frac{G_F\, \alpha_s^2(M_H^2)}{36\sqrt{2}\pi^3} M_H^3 \left[1 + \left(\frac{95}{4} - \frac{7N_f}{6}\right)\frac{\alpha_s}{\pi}\right]$$

$$\Gamma(H \to \gamma\gamma) = \frac{G_F\, \alpha^2}{128\sqrt{2}\pi^3} M_H^3 \left[\frac{4}{3} N_C e_t^2 - 7\right]^2$$

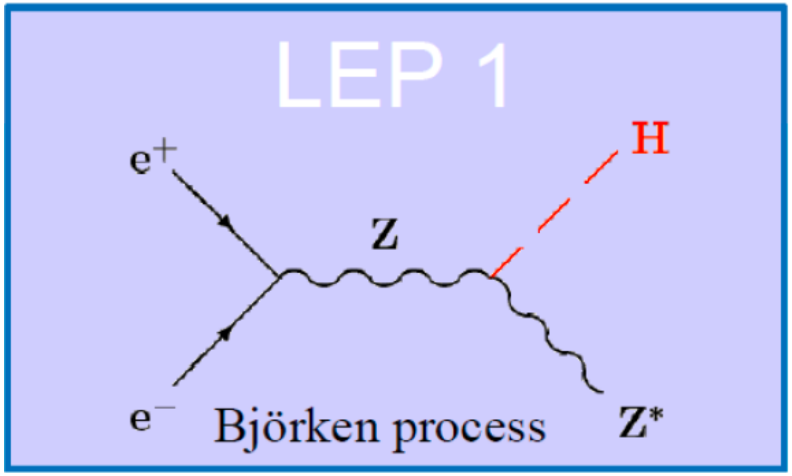
Higgs Boson:

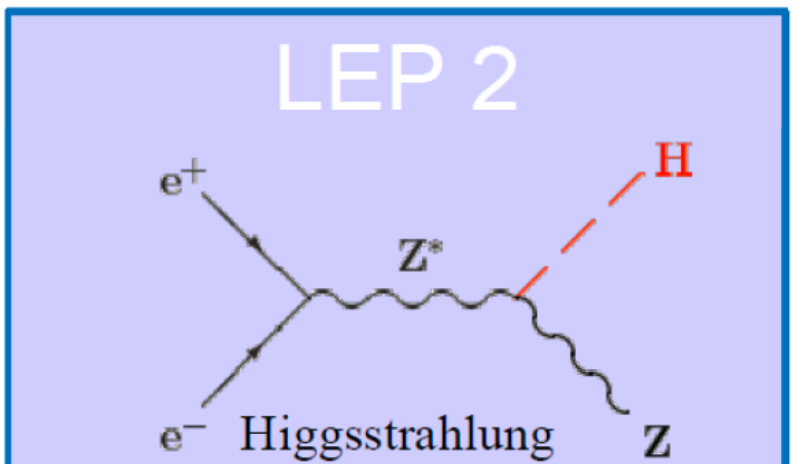
- it couples to particles proportional to their masses
- decays preferentially in the heaviest particles kinematically allowed

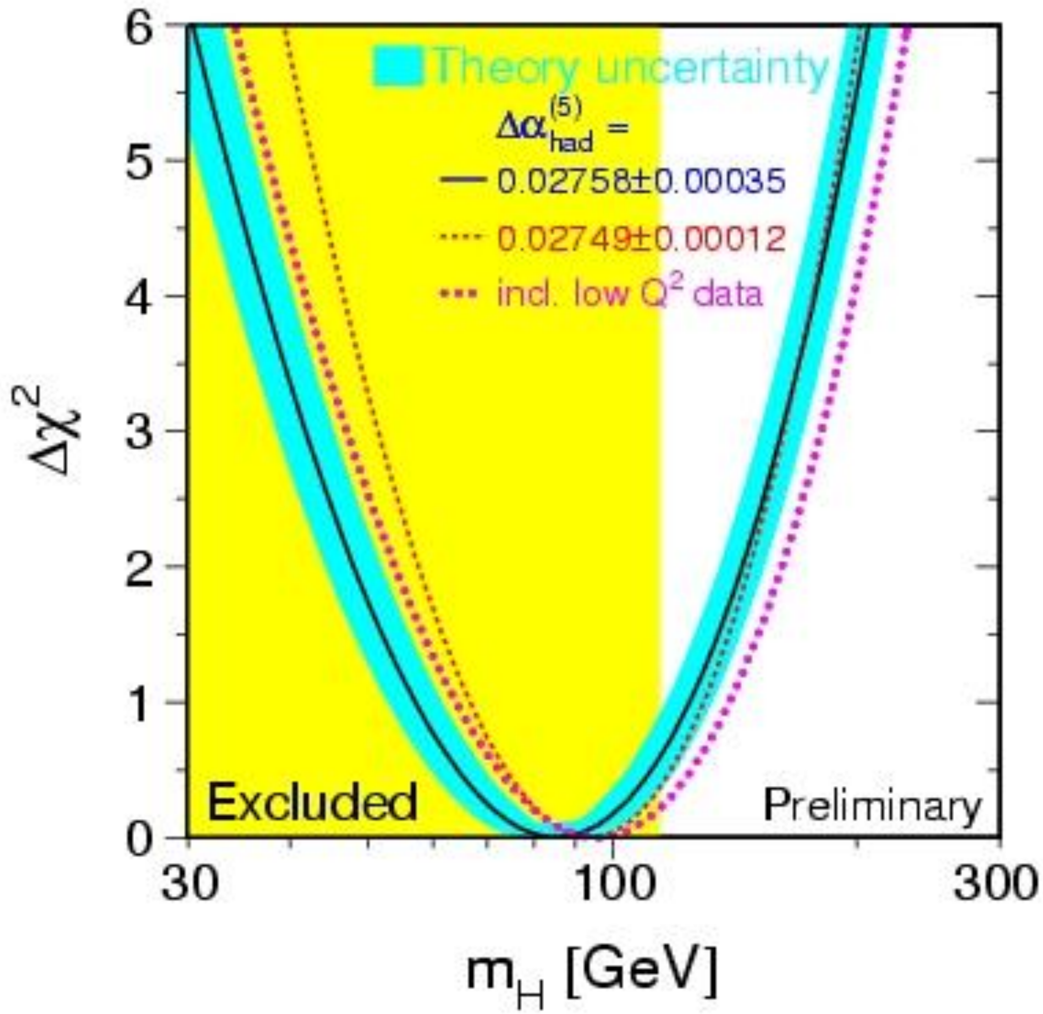
Search for Higgs boson at LEP

➔Results: exclude $m_H < 114.4$ GeV/c^2 at 95% CL

(Physics Letters B 565 (2003) 61-75)







Particle Acceleration and Collision

- Proton-proton collision at LHC