希格斯玻色子的发现和属性测量

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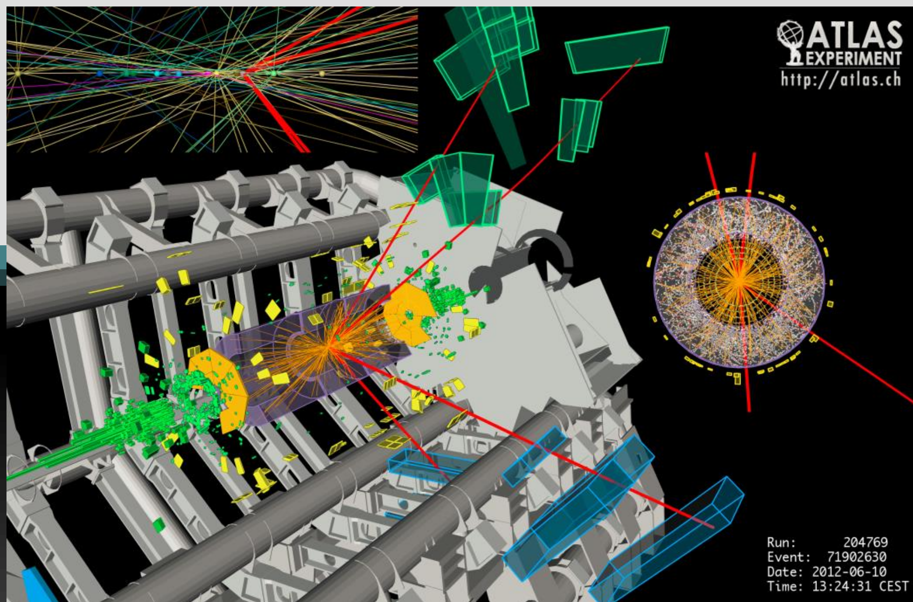


中国物理学会秋季会议
2013年9月13-15日

Outline

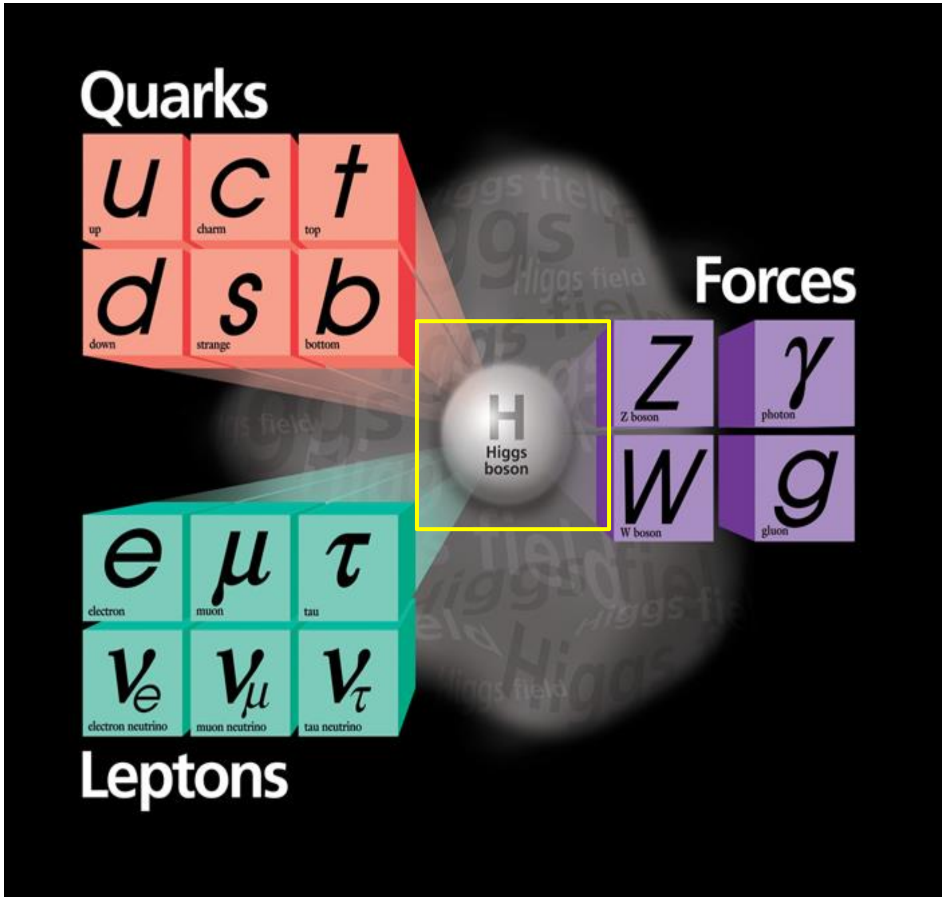
- Brief Introduction of Standard Model
- ATLAS Experiment at LHC
- Higgs Production and decays at LHC
- Major challenge for Higgs Searches
- Observation of Higgs-like particle
- Update results for Higgs searches (20.7fb^{-1} at 8 TeV)
- Higgs Properties (Spin, CP, Couplings) Measurements
- Summary and Conclusions

Standard Model of Elementary Particles

- ❑ **Elementary Particles**

  > 100 years' discoveries

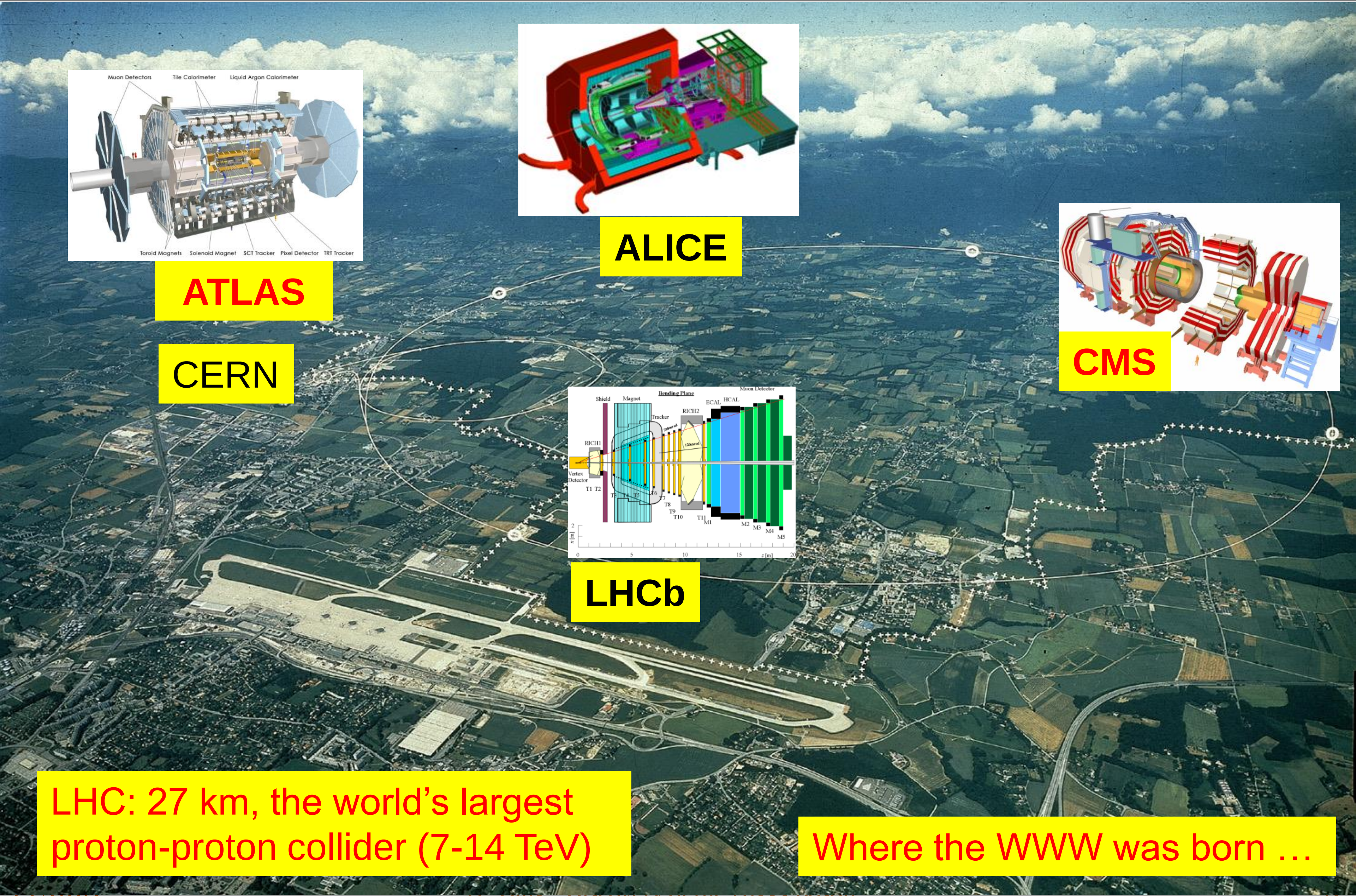
- ❑ The SM is in excellent agreement with the numerous experimental measurements.
- ❑ The only missing SM particle is the Higgs boson which is proposed to responsible for the electroweak symmetry breaking, particles acquire mass when interacting with the Higgs field.



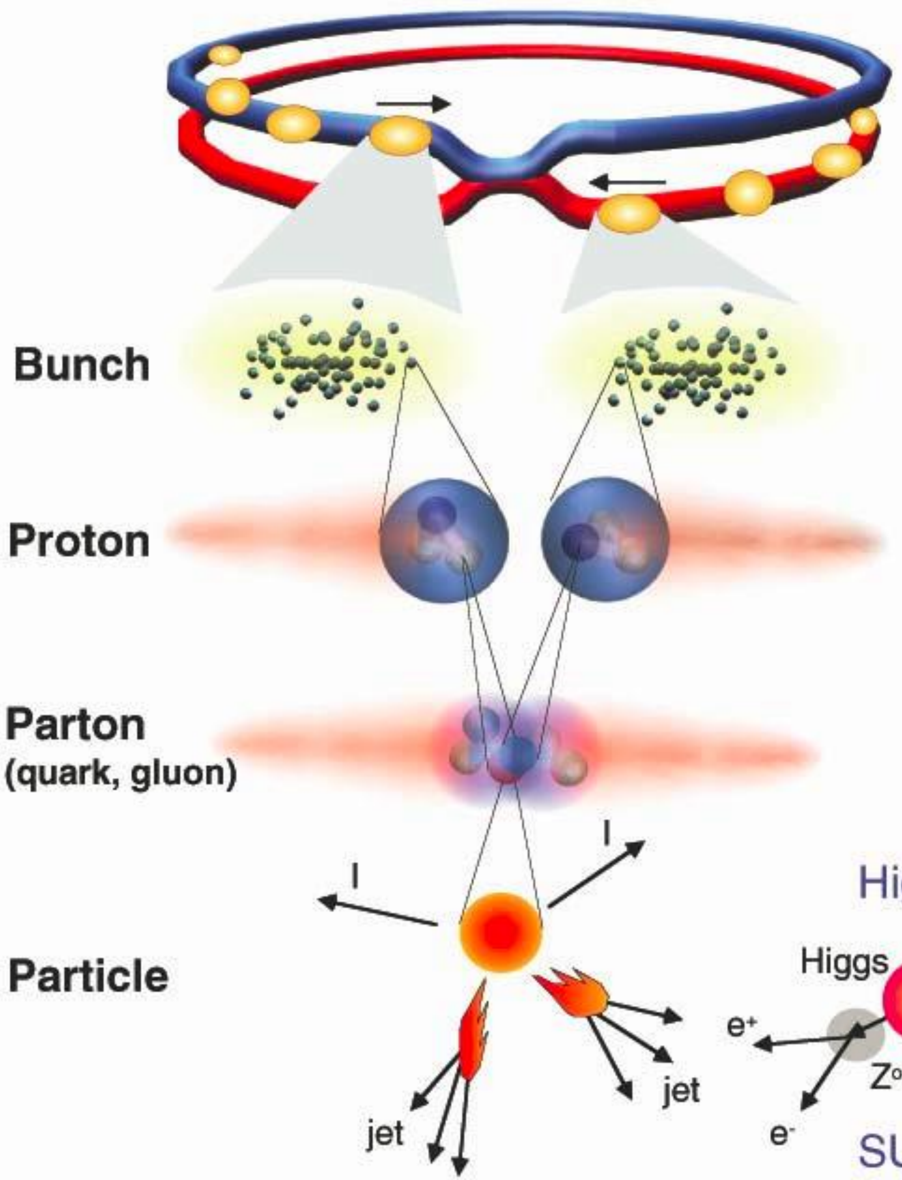
1964: **F. Englert, R. Brout, P. Higgs, G.S. Guralnik, C.R. Hagen and T.W.B. Kibble**

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

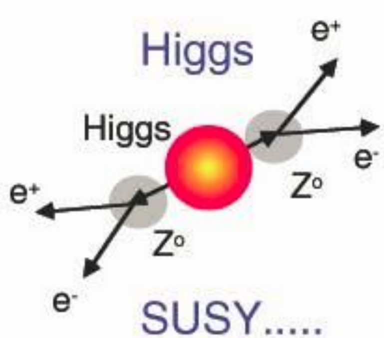
Large Hadron Collider at CERN



Proton-proton Collisions at LHC

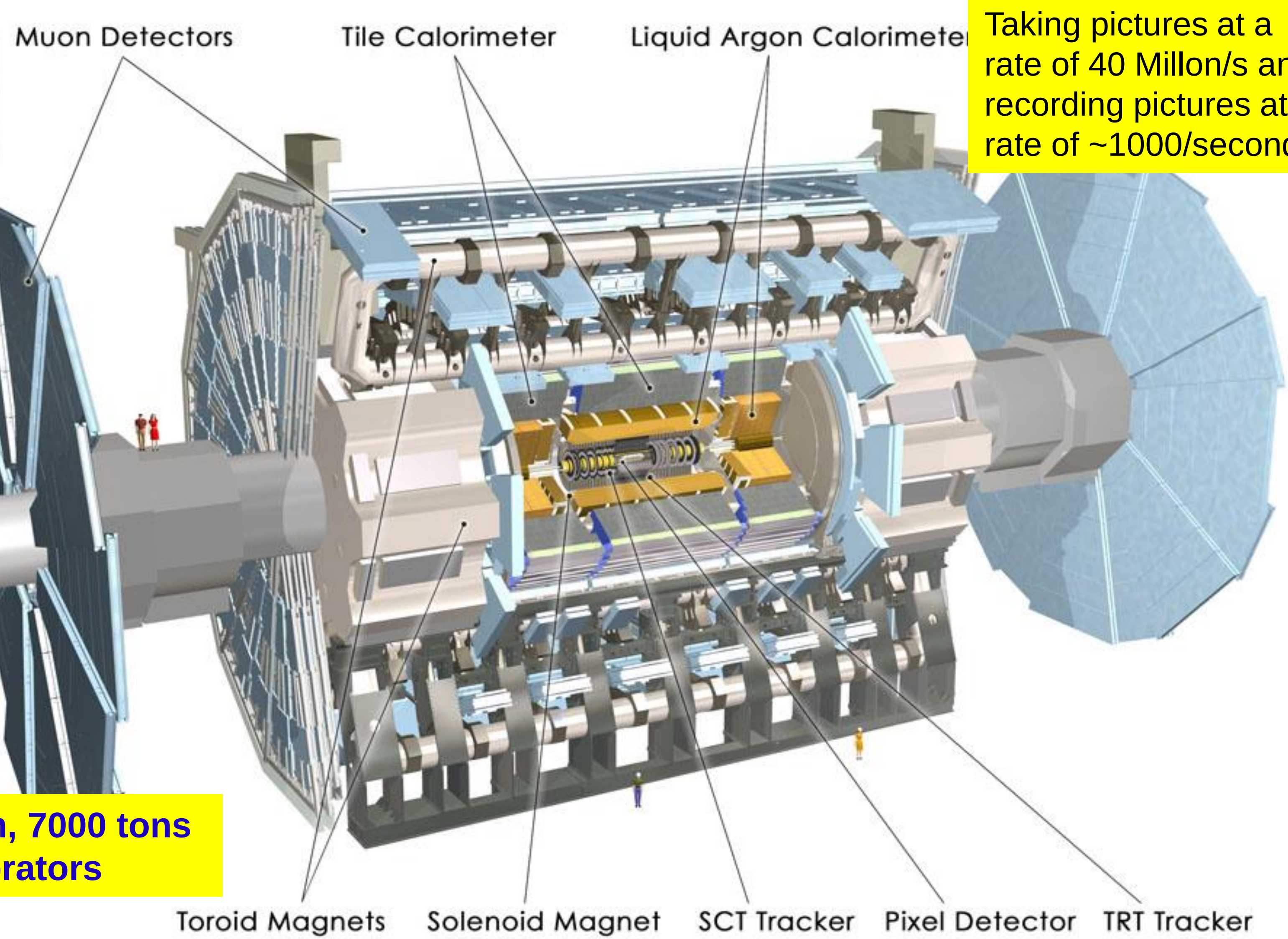


Proton-Proton	2835 bunch/beam
Protons/bunch	10^{11}
Beam energy	7 TeV ($7x10^{12}$ eV)
Luminosity	10^{34} cm^{-2} s^{-1}
Crossing rate	40 MHz
Collisions ≈	10^7 - 10^9 Hz



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

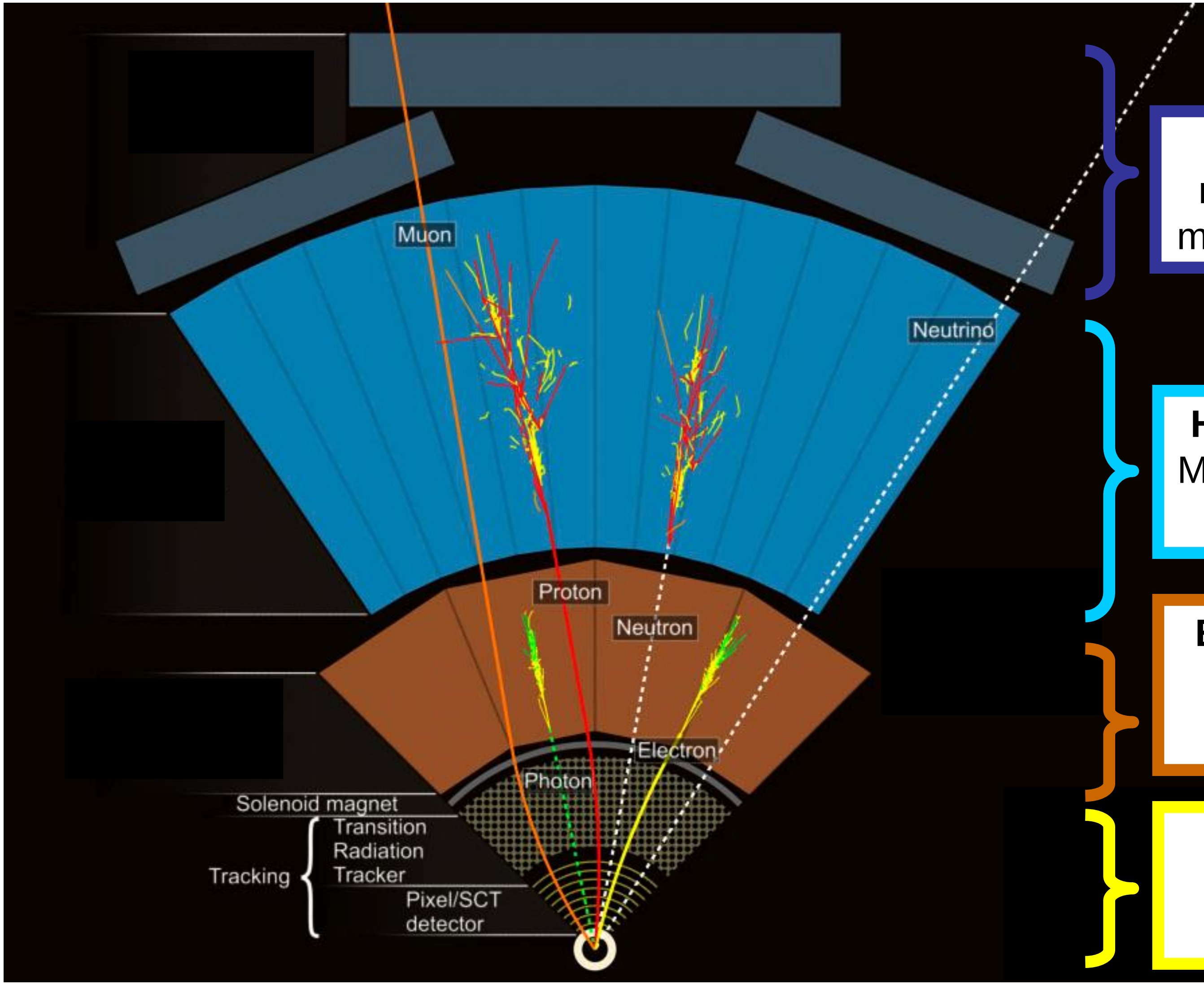
The ATLAS Detector: Huge Camera



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

- Different particles have different signatures in detectors



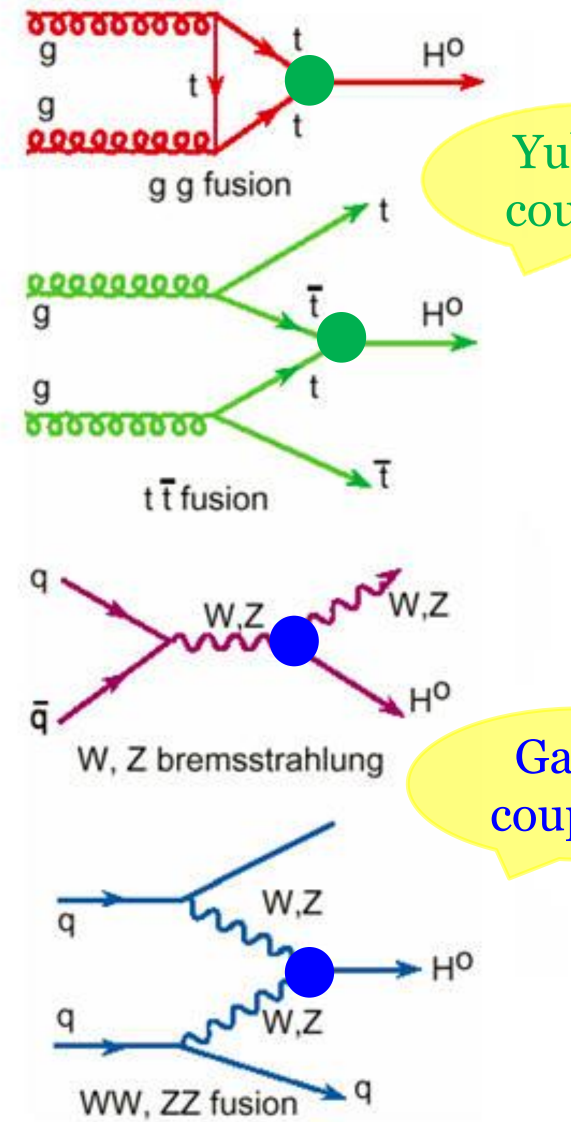
Muon Spectrometer:
muon identification and momentum measurement

Hadronic calorimeter:
Measurement of jets and missing energy

Electromagnetic calo:
e/γ identification and energy measurement

Tracking system:
Charged particle momentum, vertexing

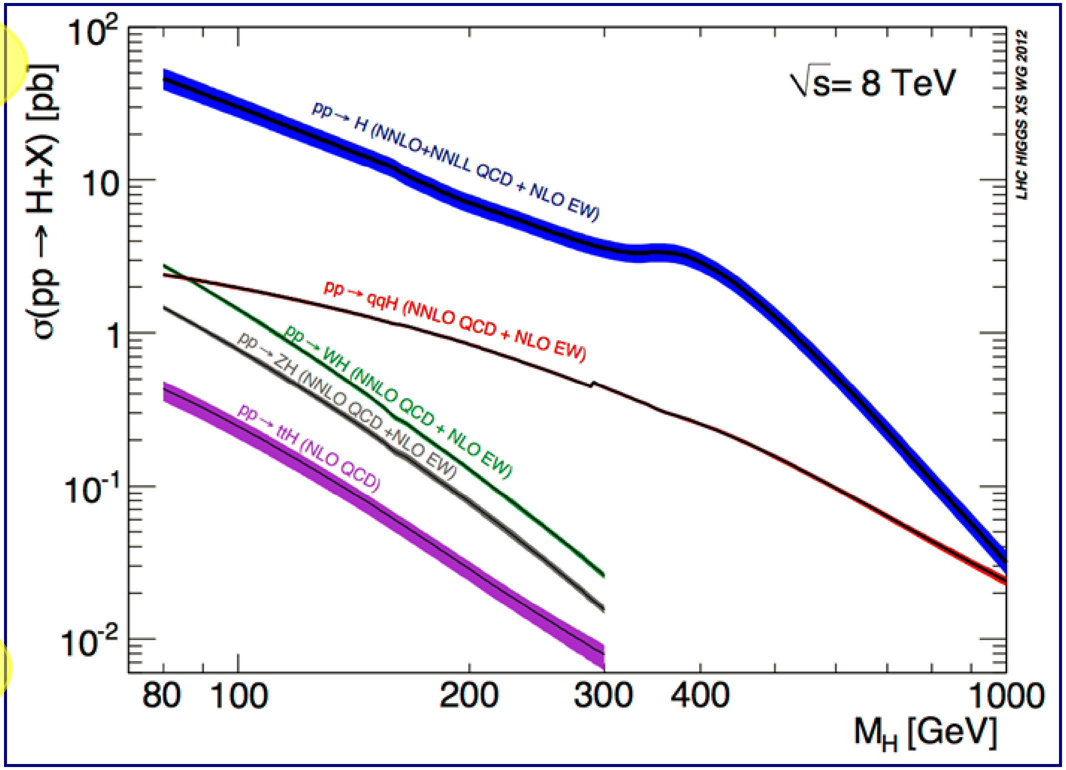
Higgs Boson Production at LHC



Yukawa coupling

Gauge coupling

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



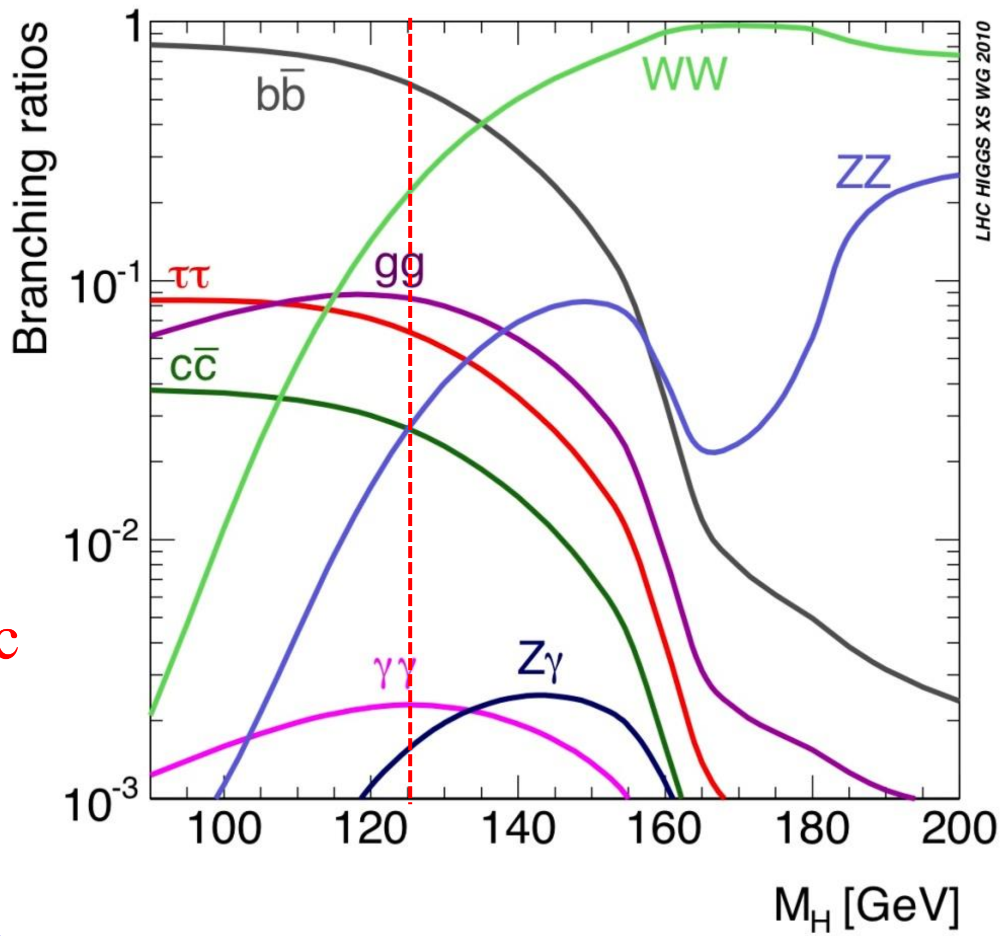
$$@125\text{ GeV:}\ \ \sigma_{ggH} = 19.5\text{ pb},\ \sigma_{VBF} = 1.6\text{ pb},$$
$$\sigma_{WH} = 0.70\text{ pb},\ \sigma_{ZH} = 0.39\text{ pb},\ \sigma_{ttH} = 0.13\text{ pb}$$

Inelastic pp cross section at 7 TeV is ~ 60 mb

Higgs Boson Decay

Higgs decay branching ratio at m_H=125 GeV

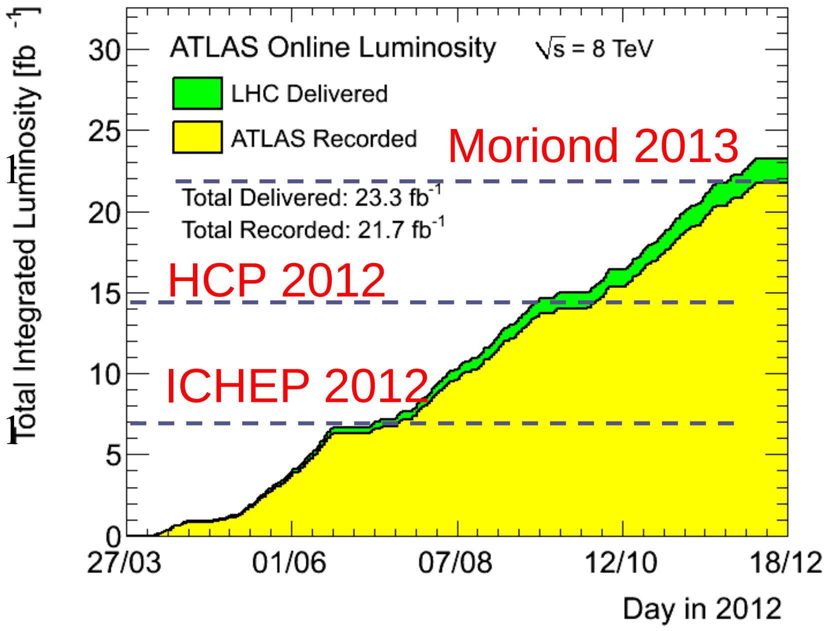
- bb: 57.7% (huge QCD background)
- WW: 21.5% (easy identification in di-lepton mode, complex background)
- ττ: 6.3% (complex final states with τ leptonic and/or hadronic decays)
- ZZ*: 2.6% ("gold-plated", clean signature of 4-lepton, high S/B, excellent mass peak)
- γγ: 0.23% (excellent mass resolution,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

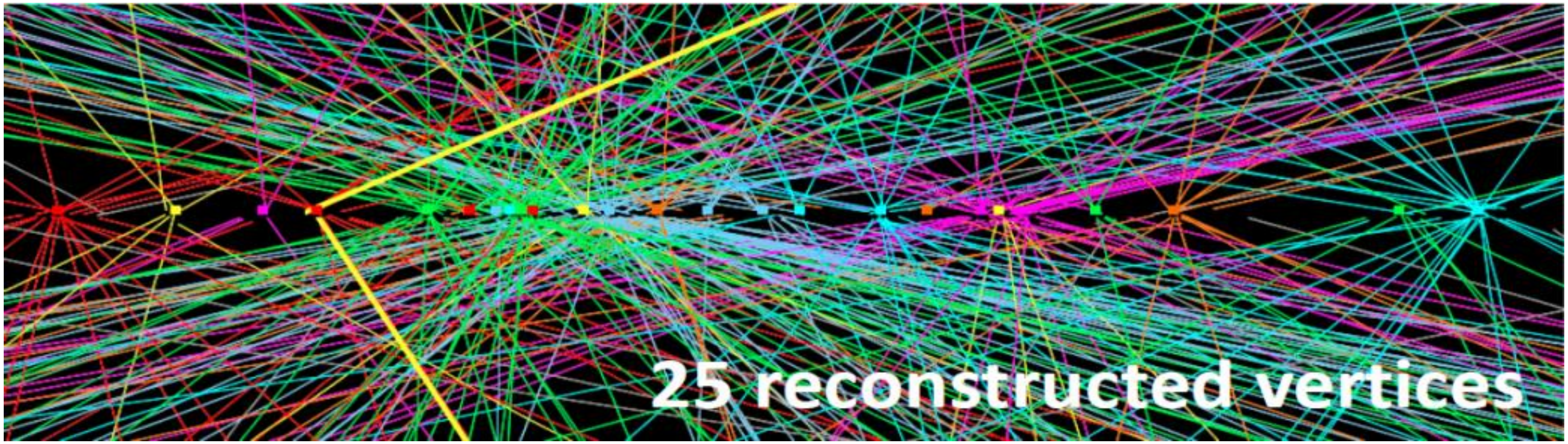


Higgs boson production rate: 1 out of 10^{12} collision events

ATLAS Data Samples

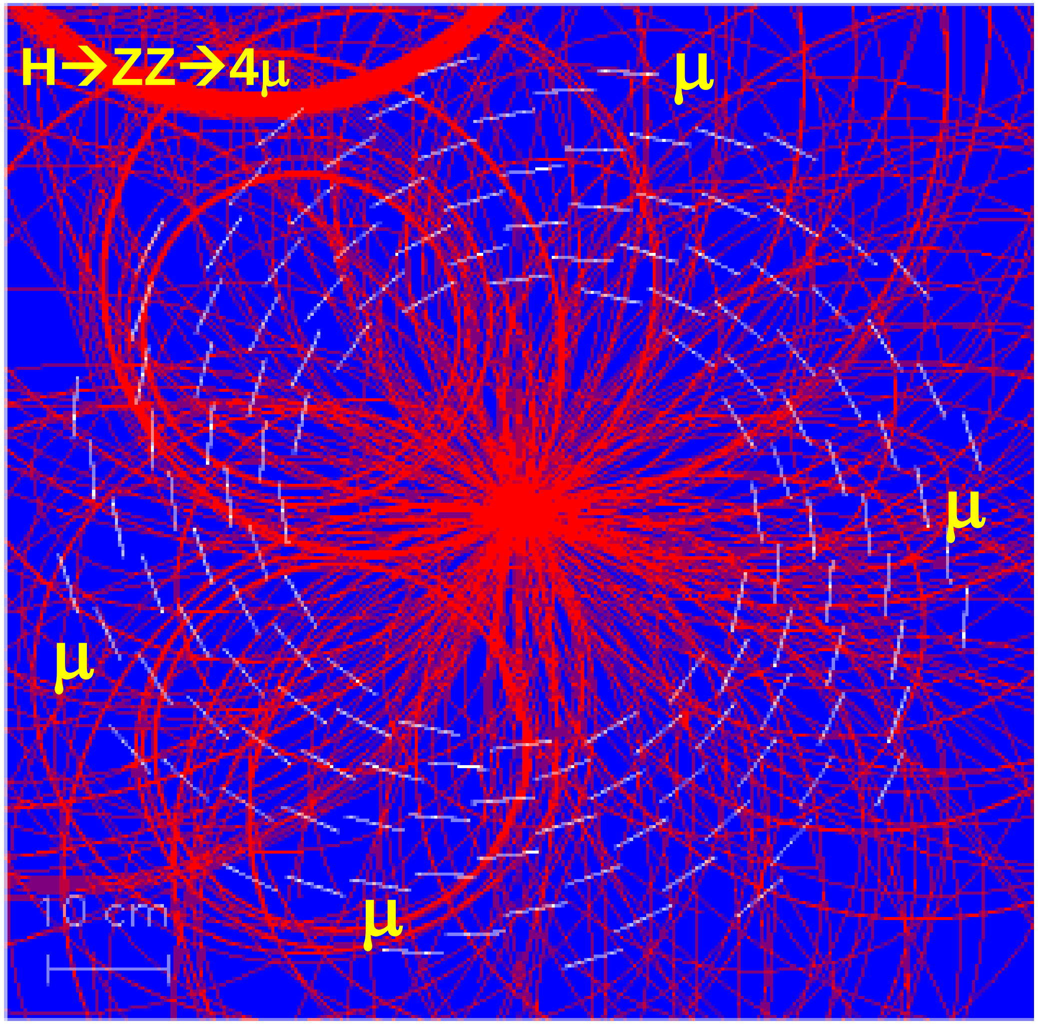
- **7 TeV data samples (2011)**
  - 4.8 fb^{-1} for physics analysis
  - Peak luminosity $3.6 \times 10^{33} cm^{-2}s^{-1}$
- **8 TeV data samples (2012)**
  - 20.7 fb^{-1} for physics analysis
  - Peak luminosity $7.7 \times 10^{33} cm^{-2}s^{-1}$
- **Data-taking efficiency: ~94%**
- **Significant pileup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



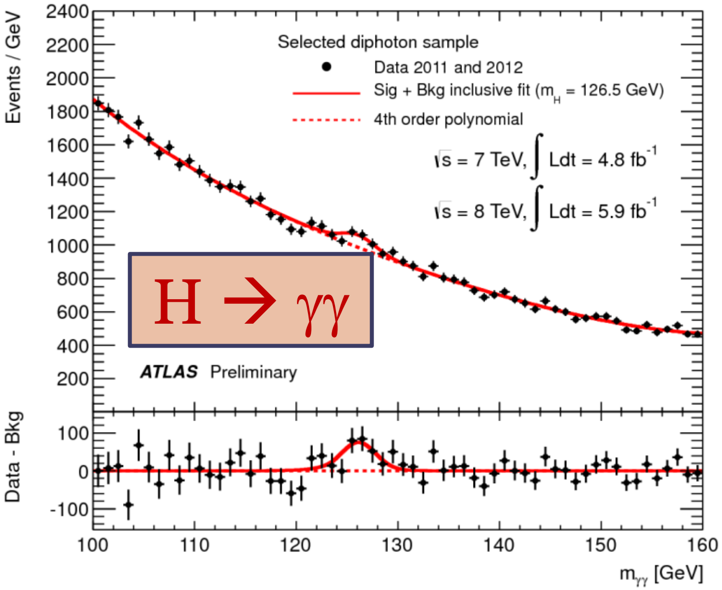


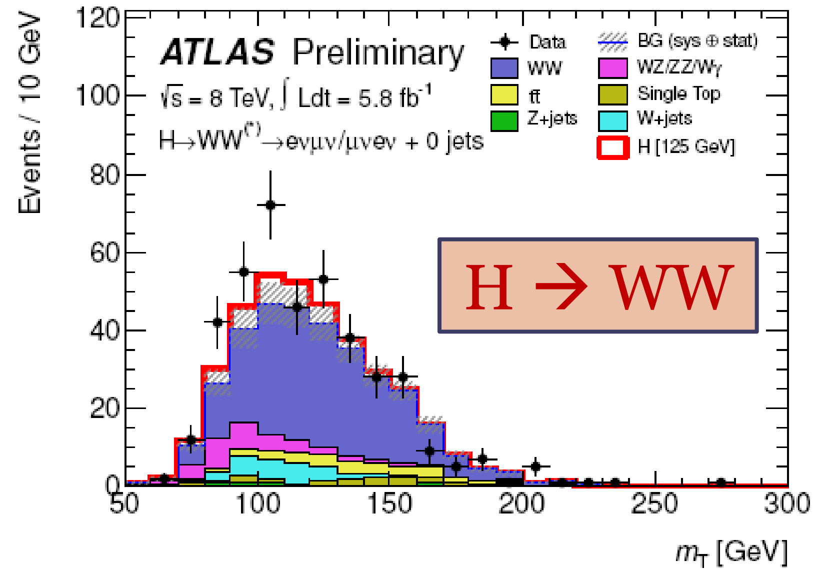
Major Challenge (Large Pileup)

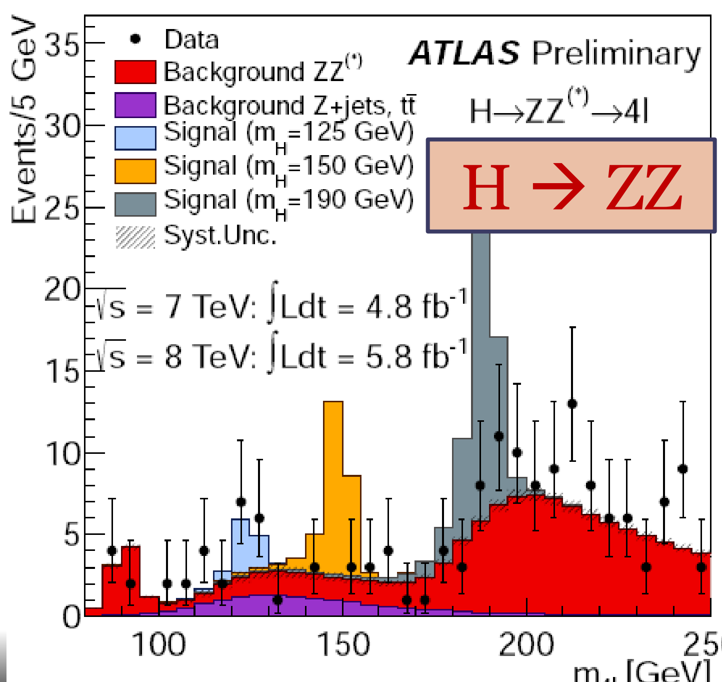
- Large pileup events result in big challenge to the detector, reconstruction and particle identification !

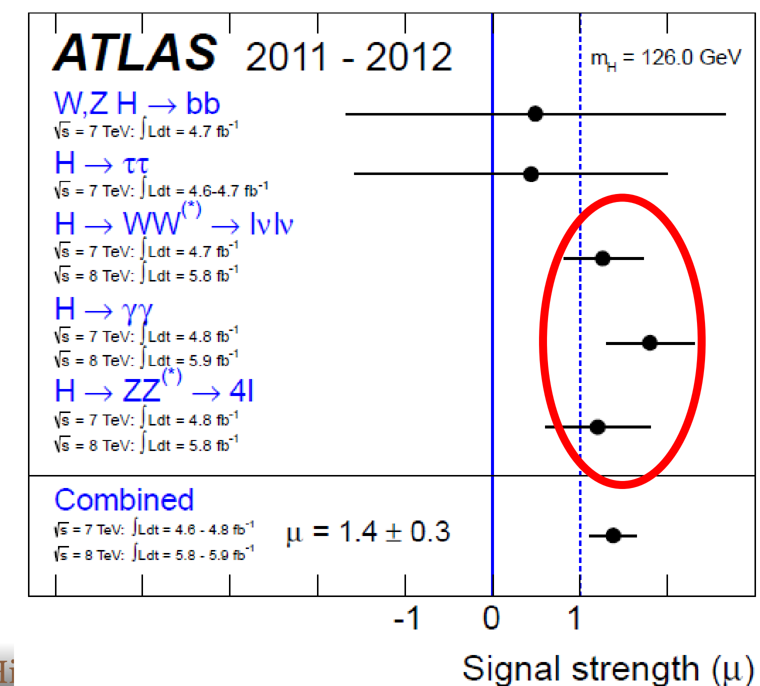


Observation of a new Particle (July 4, 2012)

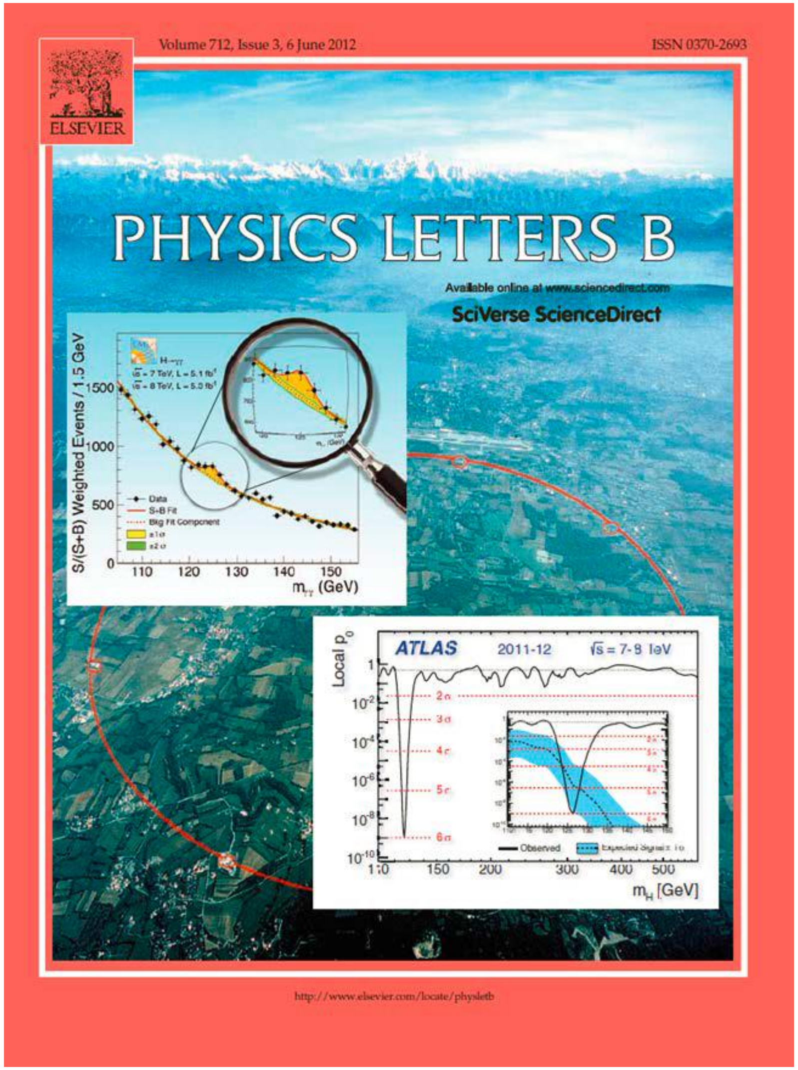








Observation of a new Particle (5σ) !



Phys. Lett. B 716 (2012) 1-29 (ATLAS)

Phys. Lett. B 716 (2012) 30-61 (CMS)

New - After the Higgs Discovery

- **H→ γγ, ZZ*, WW* analysis updates based on full 2011-2012 dataset ($4.6\ fb^{-1}$ @ 7TeV, $20.7\ fb^{-1}$ @ 8TeV)**

- Higgs mass from H→ γγ and H→ZZ*→ 4l
- Signal strengths ($\mu = \sigma/\sigma_{SM}$)
- Sensitivity to vector boson fusion (VBF)
- Higgs Couplings
- Higgs Spin and parity

New ATLAS Higgs Papers

arXiv:1307.1427 Sub. Phys. Lett. B (Mass, Couplings)
arXiv:1307.1432 Sub. Phys. Lett. B (Spin-parity)

New ATLAS Higgs Pub Notes

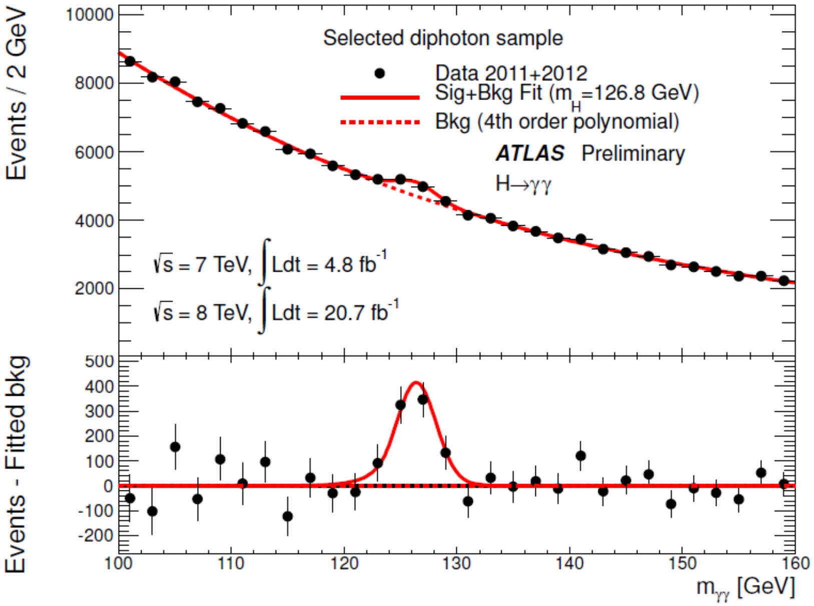
Property measurement:

ATLAS-CONF-2013-012 (γγ)
ATLAS-CONF-2013-013 (ZZ*)
ATLAS-CONF-2013-031 (WW*)
ATLAS-CONF-2013-040 (Spin)
ATLAS-CONF-2013-079 (VH → bb)
ATLAS-CONF-2012-160 (H → ττ)
ATLAS-CONF-2013-075 (WW*)
ATLAS-CONF-2013-029 (γγ)

Searches:

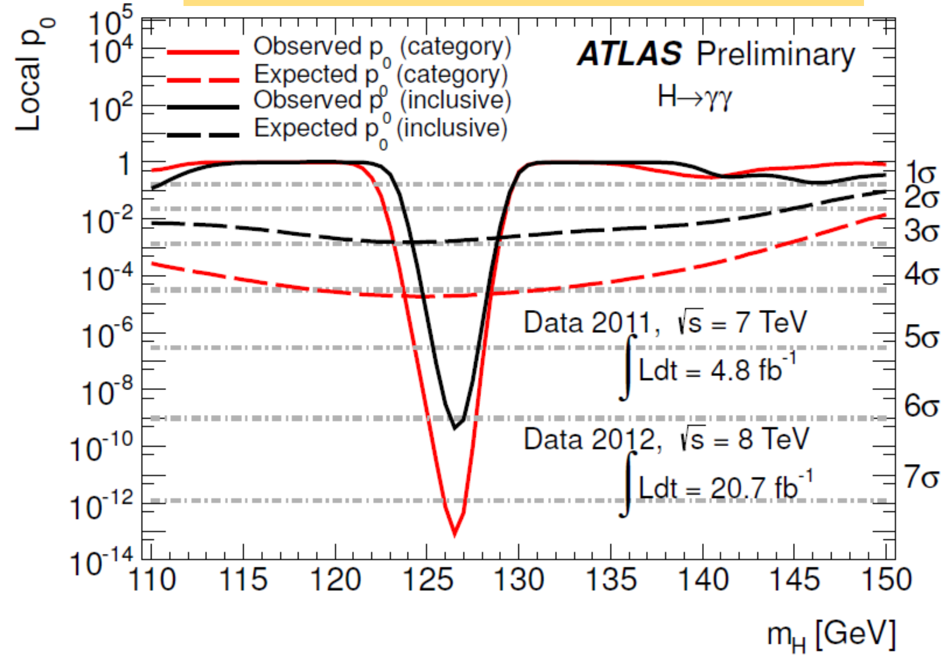
ATLAS-CONF-2013-009(Zγ)
ATLAS-CONF-2013-010(μμ)
ATLAS-CONF-2013-067(HMH→WW)
ATLAS-CONF-2013-072 (diff σ H→γγ)
ATLAS-CONF-2013-075(VH→WW)
ATLAS-CONF-2013-080(tt +H→γγ)
ATLAS-CONF-2013-081(t→cH)

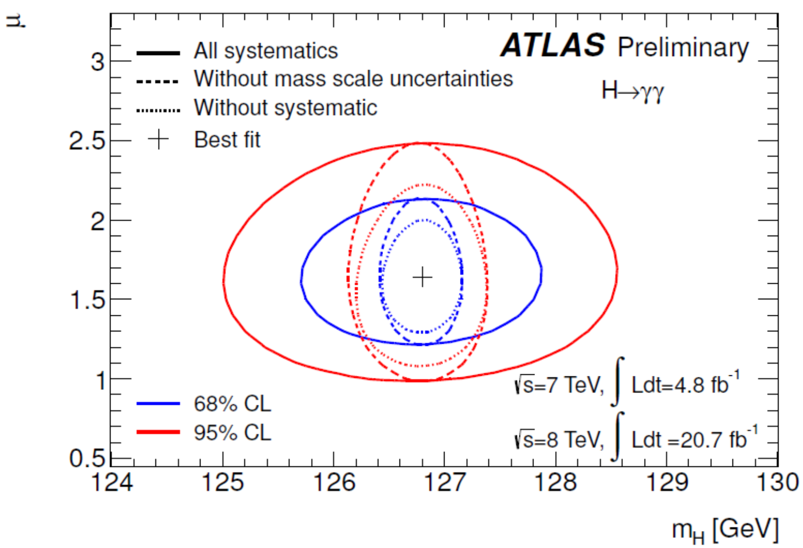
Update of H → γγ



Higgs Significance

- **Expected 4.1σ**
- **Observed 7.4σ**





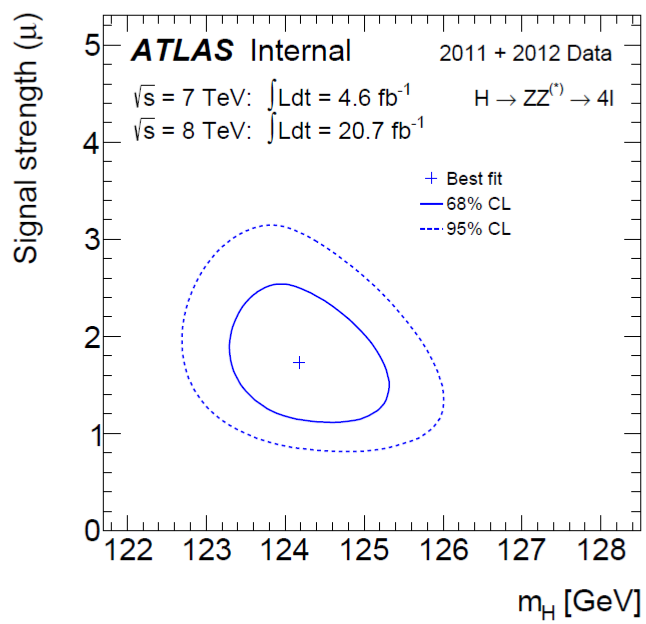
Best fitted mass:

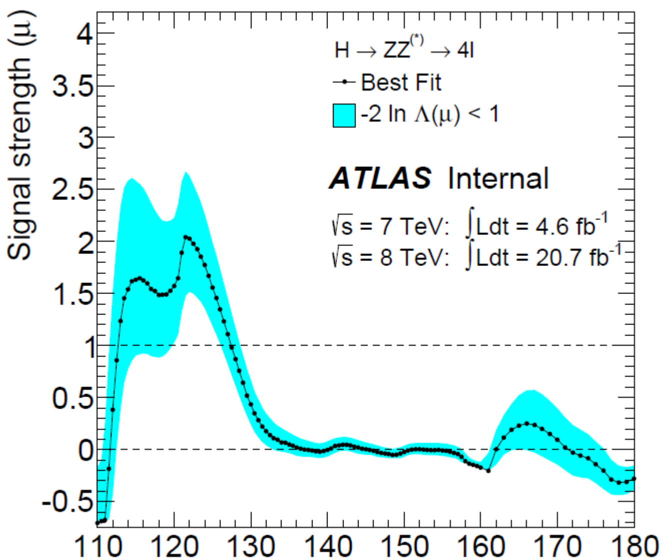
M_H = 126.8 ± 0.2(stat) ± 0.7(syst) GeV

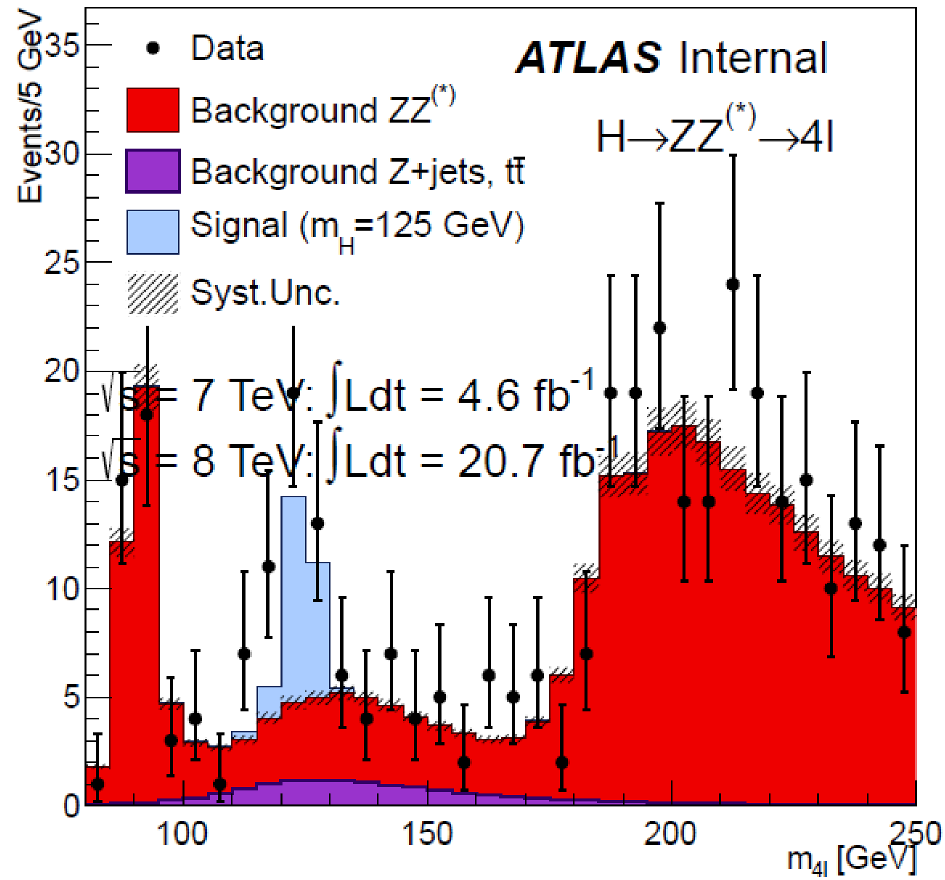
Best fitted Signal strength

$$1.65 \pm 0.24(\mathrm{stat})^{+0.25}_{-0.18}(\mathrm{syst})$$

Update of H→ZZ*→4l







Best fit mass:

M_H = 124.3 ± 0.6(stat) ± 0.3(syst) GeV

Best fit signal strength:

μ = 1.7 + 0.5 (– 0.4) @ 124.3 GeV

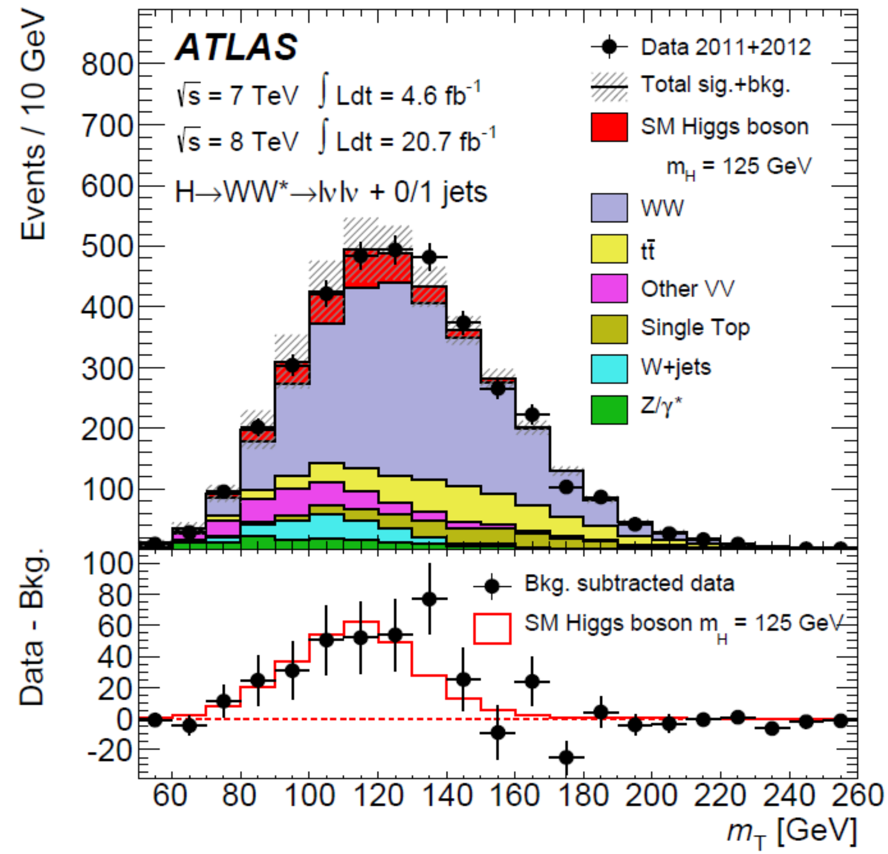
μ = 1.5 ± 0.4 @ 125.5 GeV

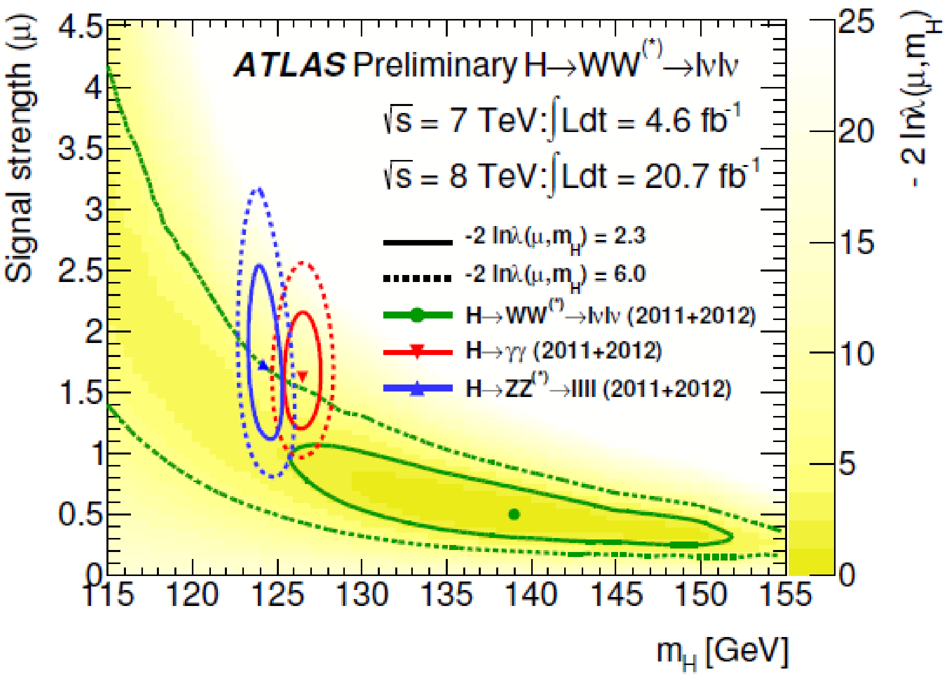
Update of H → WW* → ℓνℓν

- Final discriminant

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

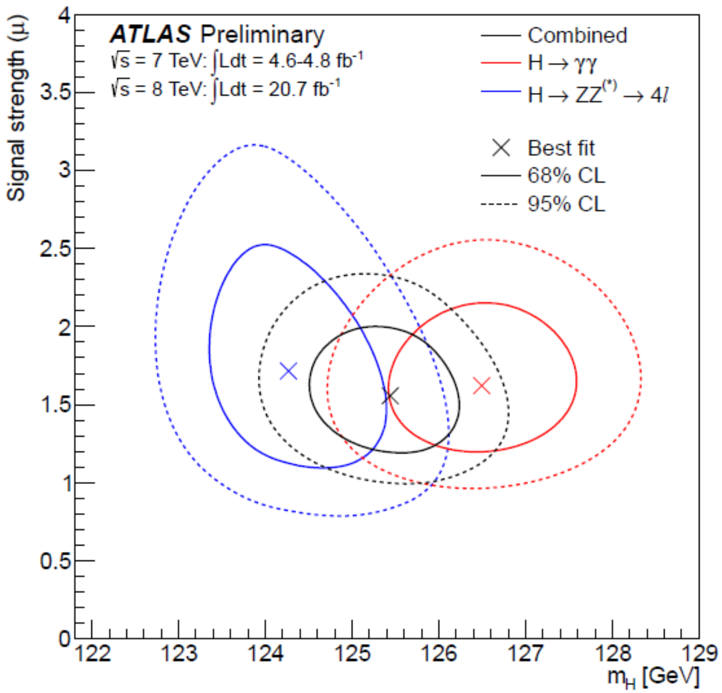
Due to spin correlation between W^+ and W^-,
The signal has the following properties:
Large $P_T(ll)$, small m_{ll}, small $\Delta\phi_{ll}$





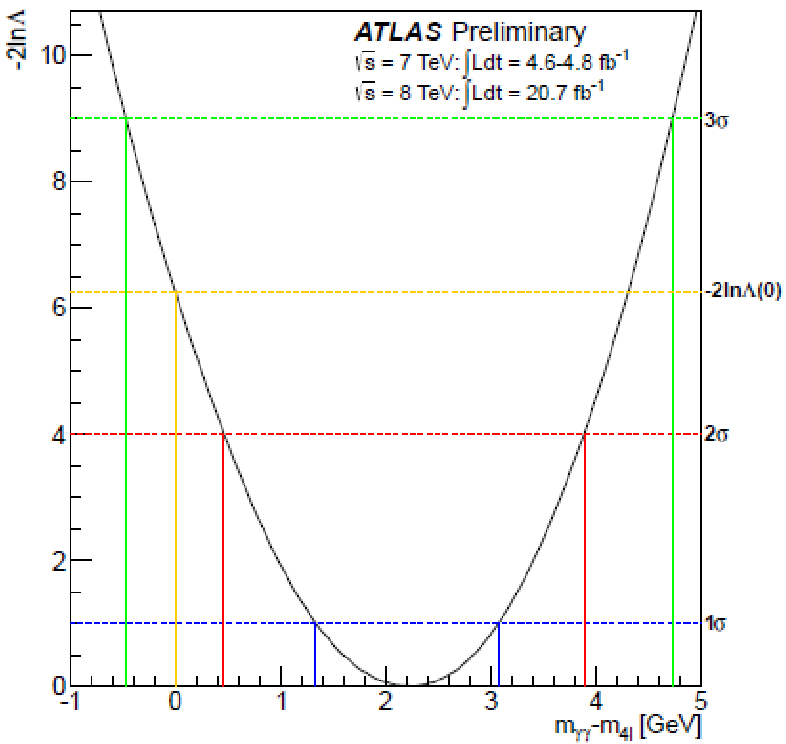
ATLAS best-fit signal strength:
ICHEP(4.6+5.8 fb^{-1}): μ = **1.3 ± 0.5**
2012 (4.6+20.7 fb^{-1}): μ = **1.0 ± 0.3**

Higgs Mass Measurements



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

$$\Delta\hat{m}_H = \hat{m}_H^{\gamma\gamma} - \hat{m}_H^{4\ell} = 2.3^{+0.6}_{-0.7}\,(\text{stat}) \pm 0.6\,(\text{sys})\ \text{GeV}$$



Best fit mass for H → γγ and 4l

M_H (γγ)= 126.6 ±0.2(stat) ± 0.7(syst) GeV

M_H (4l)= 124.3 ±0.6(stat) ± 0.3(syst) GeV

Best fit mass for combination:

ATLAS: 125.5 ±0.2(stat) ± 0.6(syst) GeV

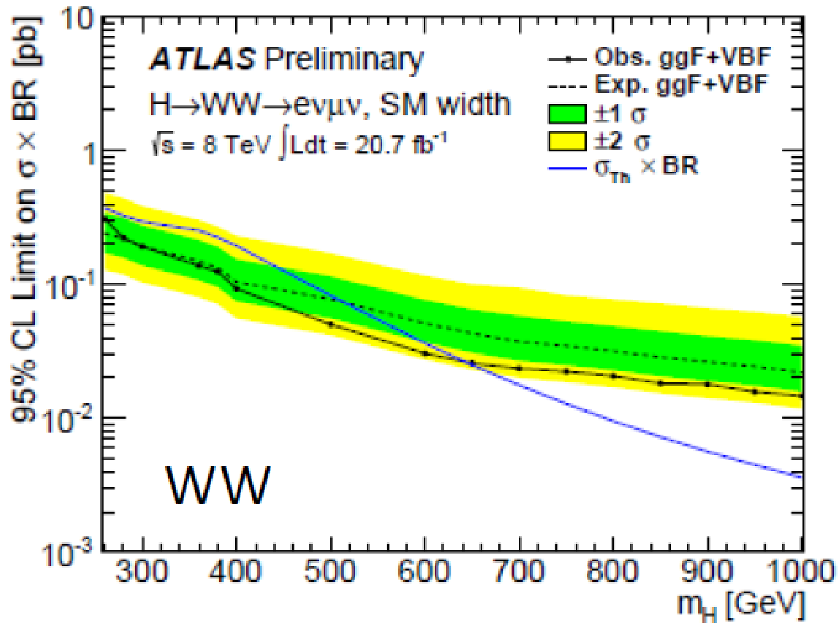
CMS:125.7±0.3(stat) ± 0.3(syst) GeV

Mass compatibility: 1.2%, 2.5σ

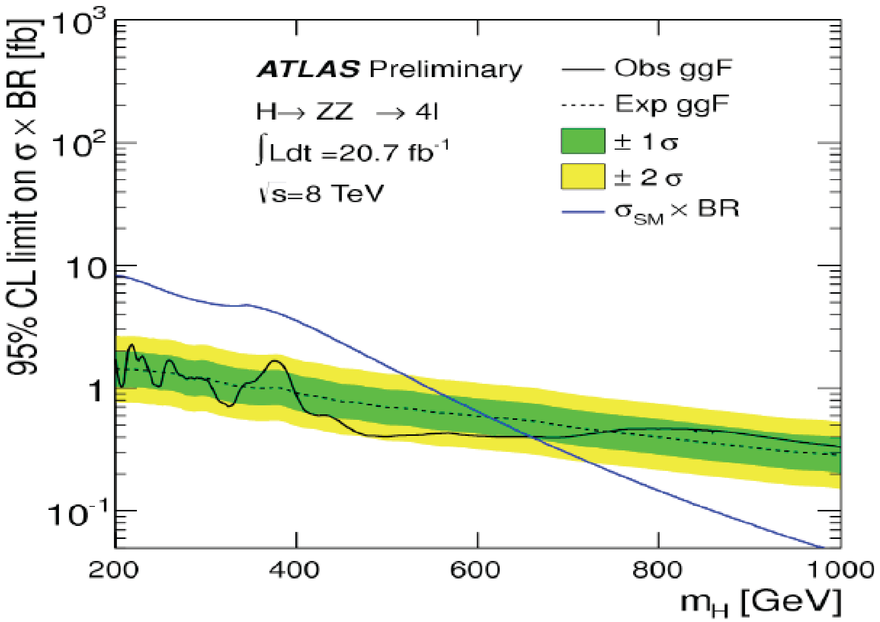
- **Extend the Higgs search to high mass assume SM-like width and decay.**

ATLAS-CONF-2013-067

WW→ lνlν*



ZZ→ 4l*



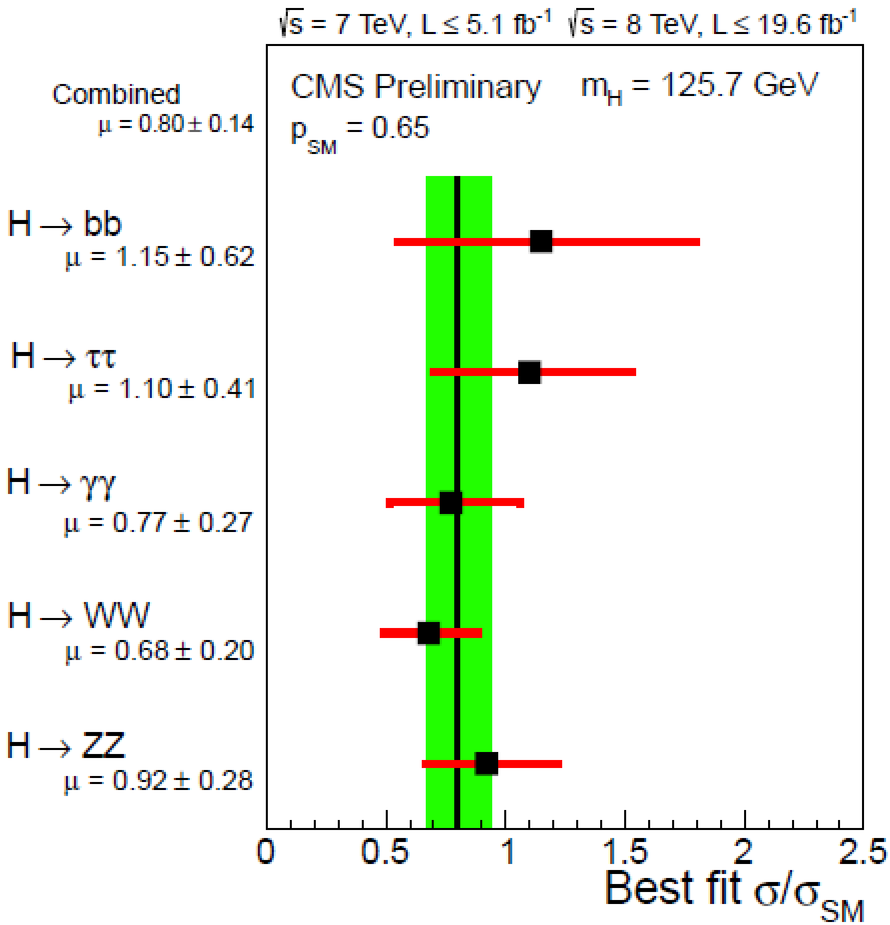
95% C.L. exclusion of a SM-like heavy Higgs up to ~ 650 GeV

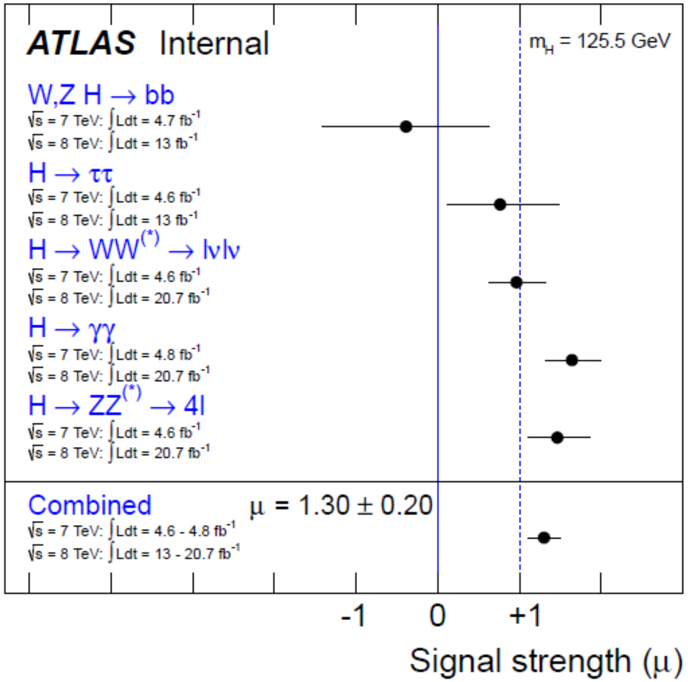
Update of Higgs Signal Strength

➔ **Signal strength: μ = 1.3 ±0.2 (ATLAS)** ATLAS-CONF-2013-034

➔ **μ = 0.8 ±0.14 (CMS)**

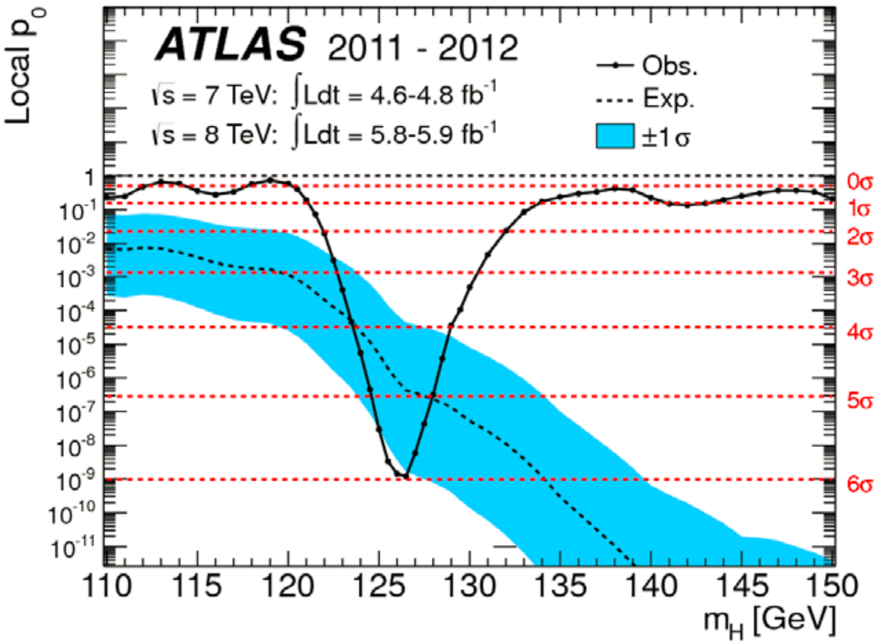
CMS-HIG-13-005





Higgs Boson Decay	μ (m_H=125.5 GeV)
$VH \rightarrow Vbb$	-0.4 ± 1.0
$H \rightarrow \tau\tau$	0.8 ± 0.7
$H \rightarrow WW^{(*)}$	1.0 ± 0.3
$H \rightarrow \gamma\gamma$	1.6 ± 0.3
$H \rightarrow ZZ^{(*)}$	1.5 ± 0.4
Combined	1.30 ± 0.20

Strong Evidence for a New Particle



❑ 2012 ICHEP

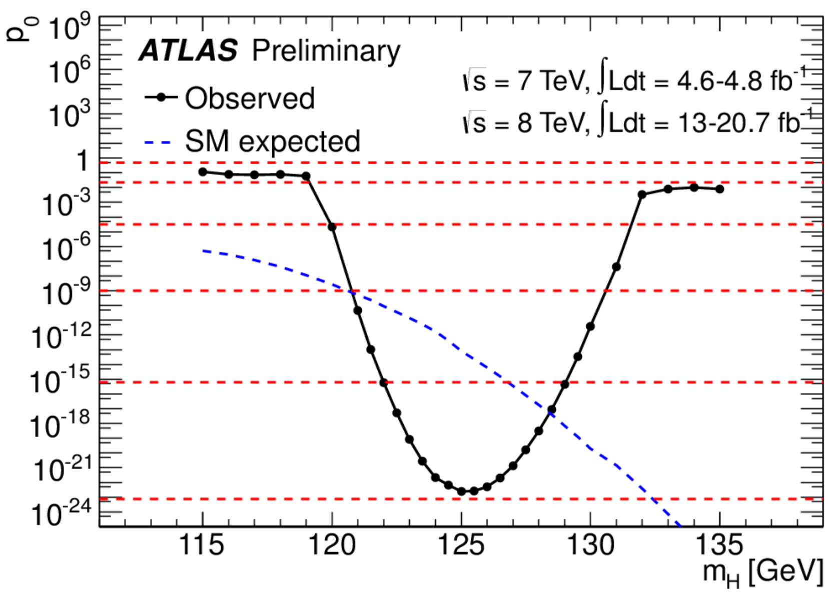
➔ Significance 5.9σ (exp 5.0σ)

➔ M_H=126.0±0.4±0.4 GeV

❑ 2012 Full Datasets

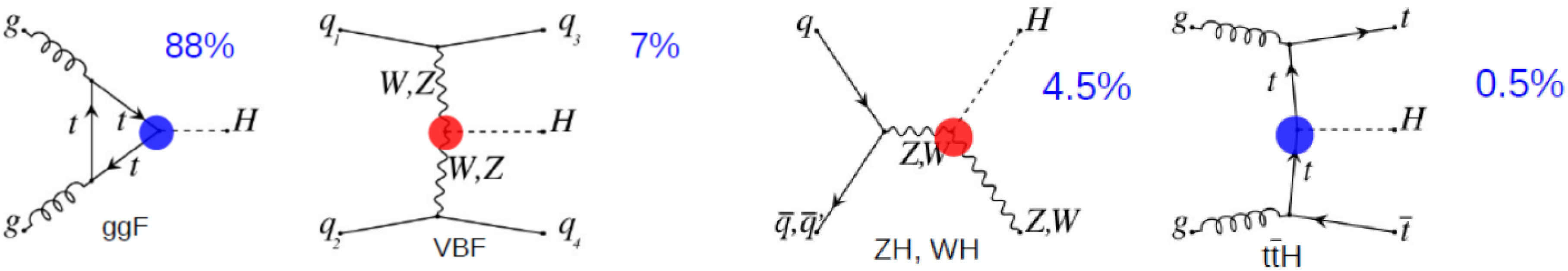
➔ Significance 9.9σ (exp 7.5σ)

➔ M_H=125.5±0.2±0.6 GeV

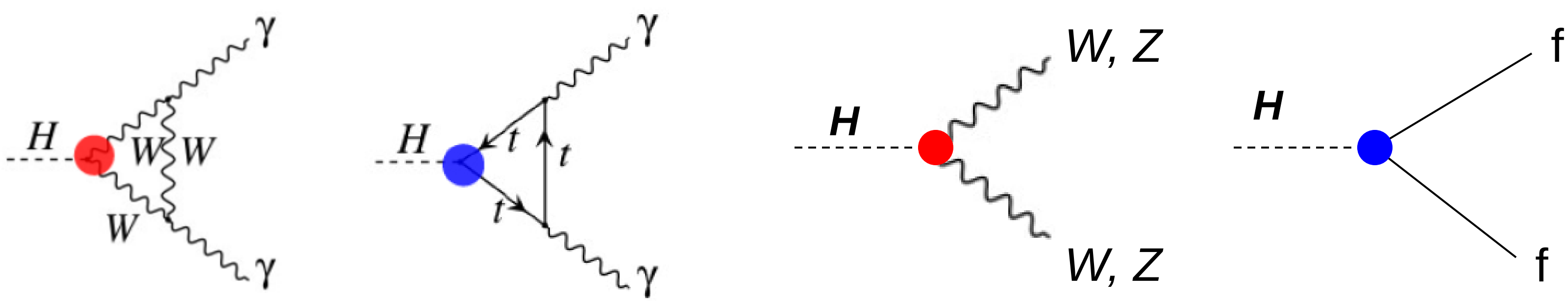


Is it the SM Higgs Boson?

❖ Higgs production (m_H = 125 GeV)



❖ Higgs decays



❖ Couplings (new force!)

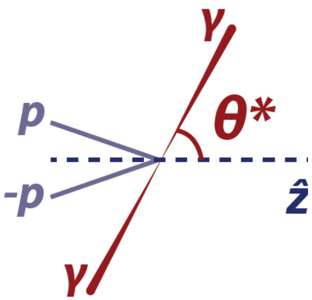
● : fermions
● : vector bosons

g_F (Yukawa coupling) $=\sqrt{2}\times m_F/\nu$
g_V (Gauge coupling) $= 2m_V^2/\nu$
(ν is the vacuum expectation value)

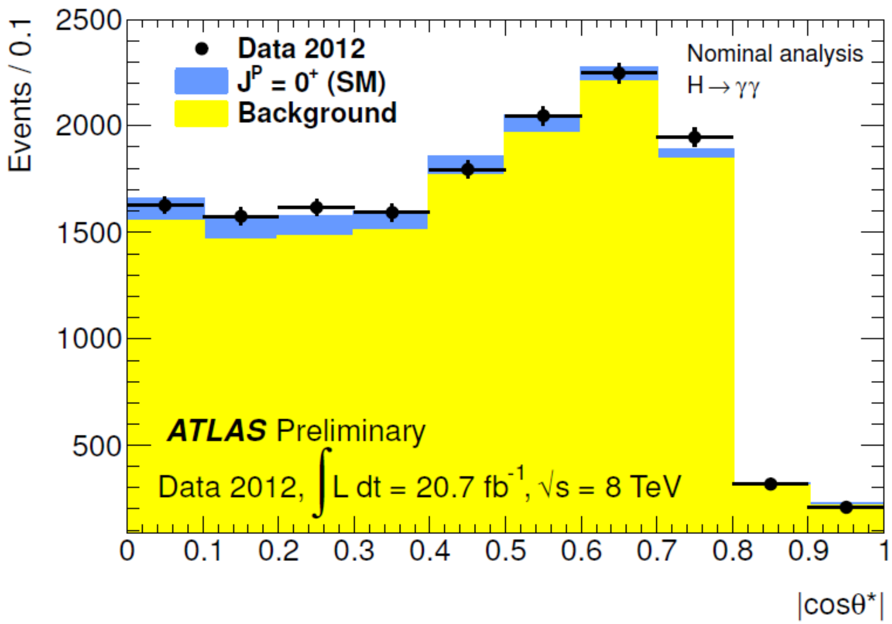
❖ Spin and Parity

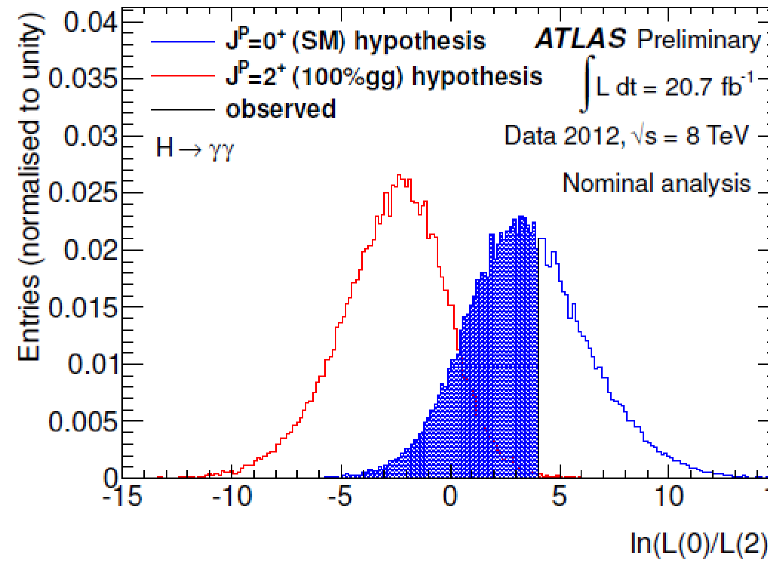
Spin for H → γγ

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



$$\cos\theta^* = \frac{\sinh(\eta_{\gamma_1} - \eta_{\gamma_2})}{\sqrt{1 + \left(p_T^{\gamma\gamma}/m_{\gamma\gamma}\right)^2}} \cdot \frac{2 p_T^{\gamma_1} p_T^{\gamma_2}}{m_{\gamma\gamma}^2}$$



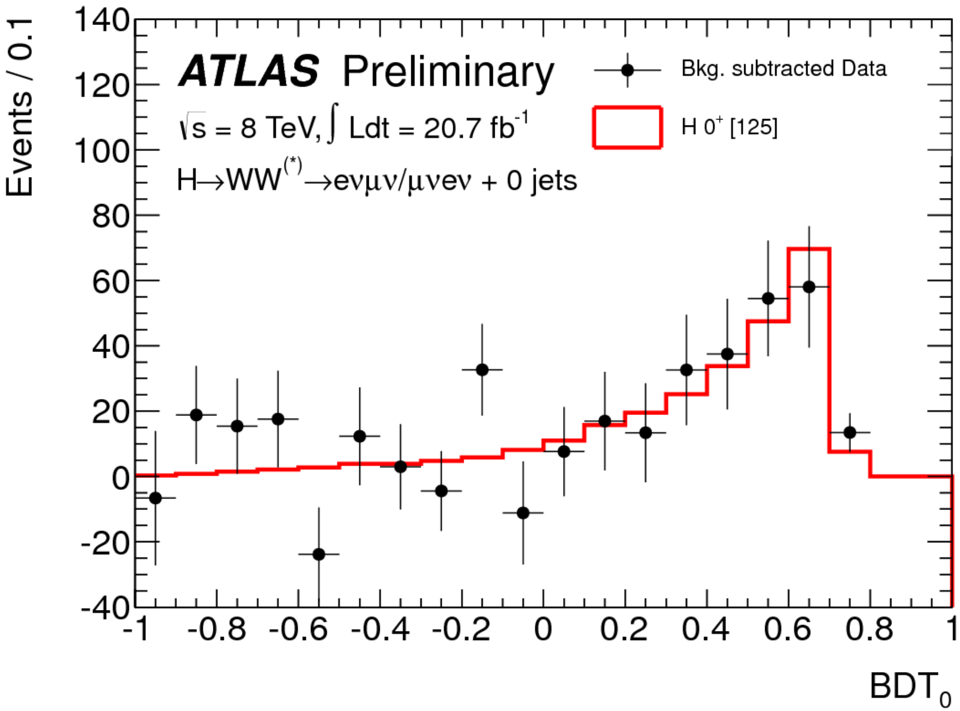


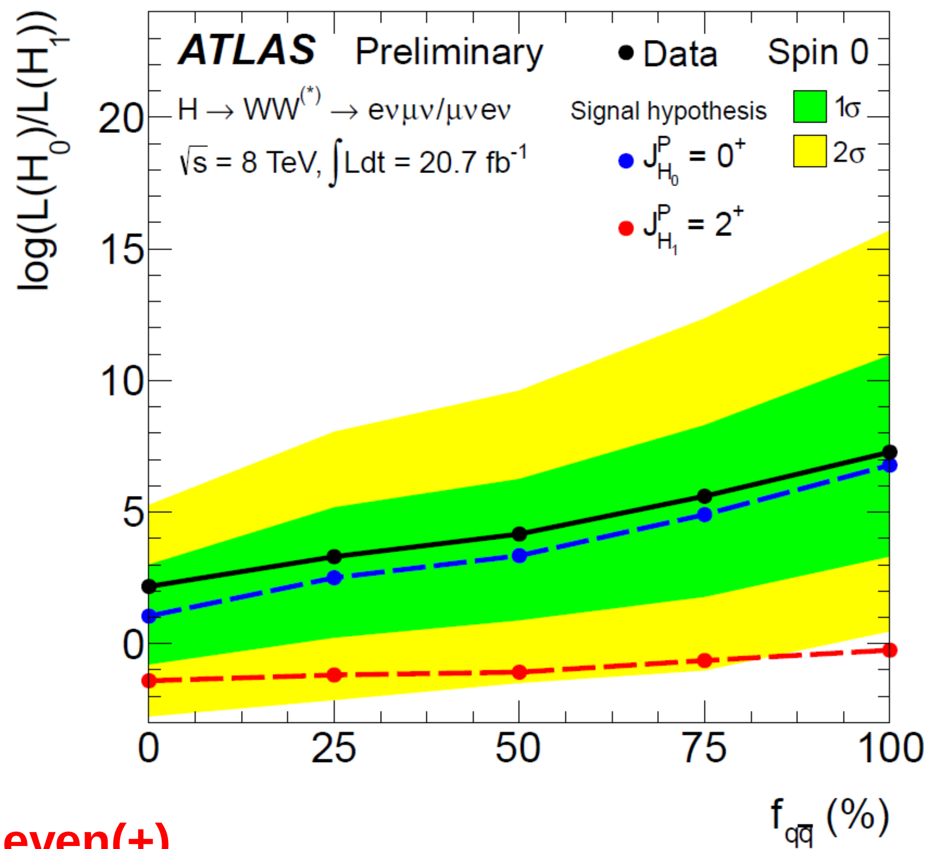
➔ Data agree with spin 0^+ hypothesis $(1\text{-}CL_b) \sim 58.8\%$.

➔ Spin 2 is disfavored at 99.3% C.L. (or 2.9σ).

Spin for H → WW

- Combine several variables in a MVA discriminant (Boosted Decision Trees, BDT)
- Variables used: m_{ll}, P_T^{ll}, $\Delta\varphi_{ll}$, m_T



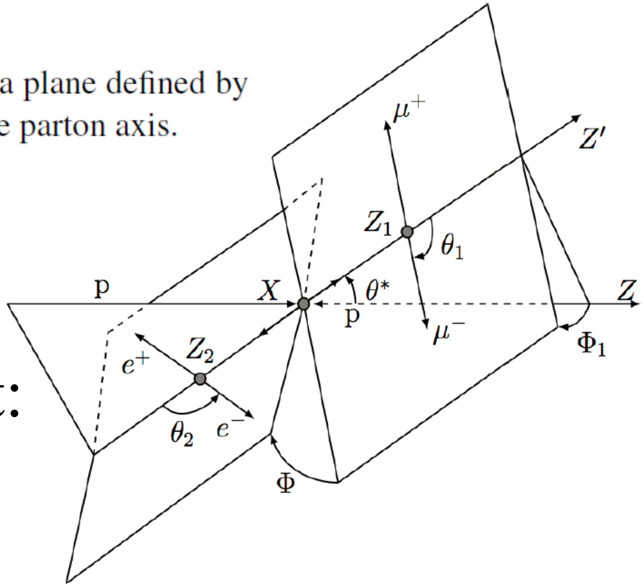


➔ **The ATLAS data favors spin 0 with CP even(+).**

$H \rightarrow ZZ^* \rightarrow 4l$: Spin and CP

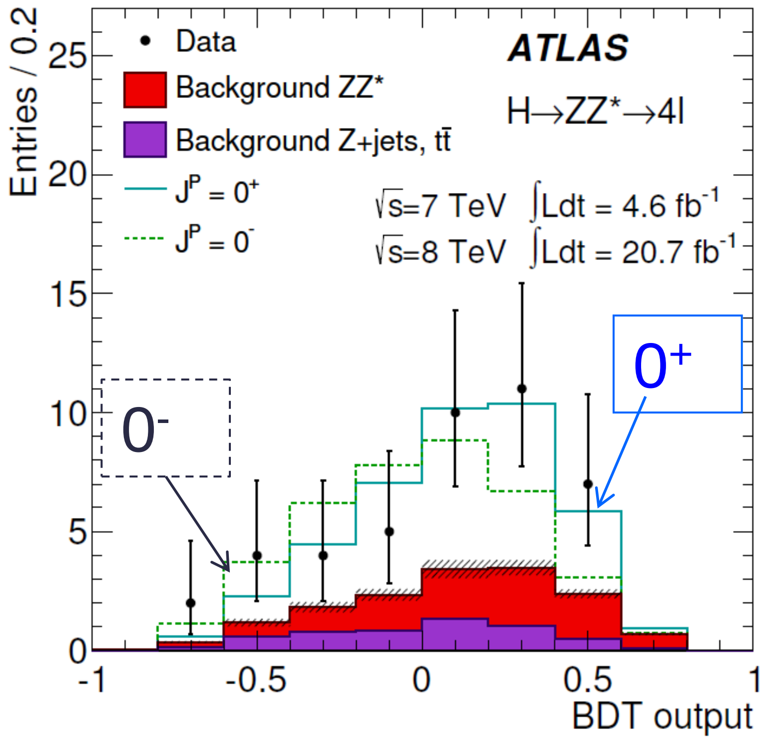
- Fully reconstructed final state allows measuring Spin/CP:
  - Five kinematic angles (production, decay)
  - Invariant mass of the primary Z and the secondary Z

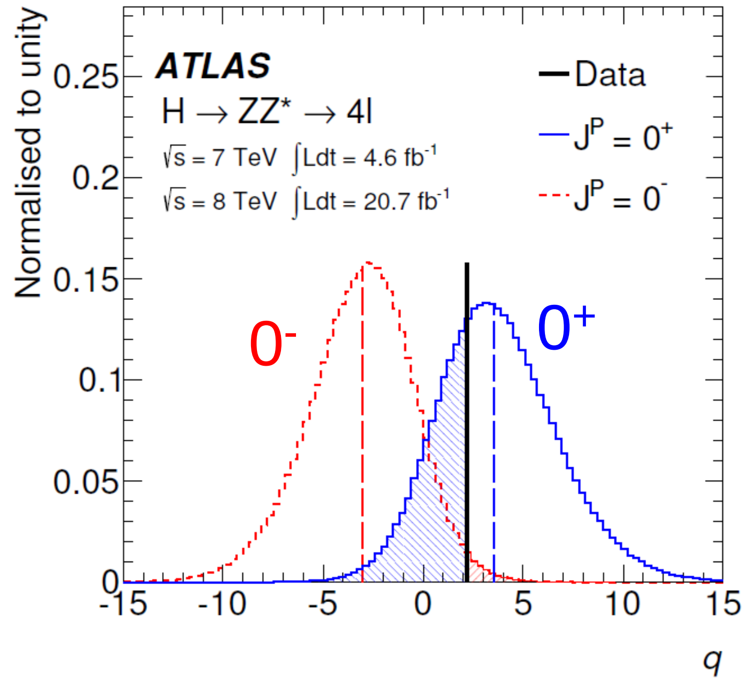
- θ_1 (θ_2) is the angle between the negative final state lepton and the direction of flight of Z_1 (Z_2) in the Z rest frame.
- Φ is the angle between the decay planes of the four final state leptons expressed in the four lepton rest frame.
- Φ_1 is the angle defined between the decay plane of the leading lepton pair and a plane defined by the vector of the Z_1 in the four lepton rest frame and the positive direction of the parton axis.
- θ^* is the production angle of the Z_1 defined in the four lepton rest frame.



- Discriminate 0^+ (SM) hypothesis against:
  - 0^- (CP odd), 1^+, 1^-
  - 2^- (pseudo-tensor)
  - 2^+_m (graviton-like tensor, minimal coupling)

H→ZZ*→4l : Spin and CP





BDT analysis variables:

m_{Z1}, m_{Z2} from Higgs --> ZZ* →4l

\+ production and decay angles

Exclusion (1-CL_s):

Observed 0^- exclusion 97.8%

Observed 1^+ exclusion 99.8%

		BDT analysis			
		tested J^P for an assumed 0^+		tested 0^+ for an assumed J^P	CL_S
		expected	observed	observed*	
0^-	p_0	0.0037	0.015	0.31	0.022
1^+	p_0	0.0016	0.001	0.55	0.002
1^-	p_0	0.0038	0.051	0.15	0.060
2^+_m	p_0	0.092	0.079	0.53	0.168
2^-	p_0	0.0053	0.25	0.034	0.258

Higgs Boson Spin

- Both ATLAS and CMS strongly prefer $J^{PC} = 0^{++}$ over the alternatives
  - Pseudoscalar 0^{-+} and tensor 2^{++} hypotheses have been excluded at ~3σ level by each experiment

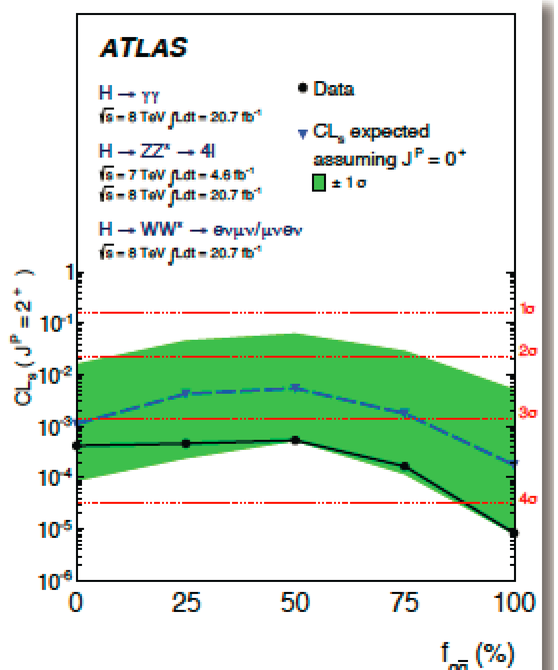
HIG-13-002

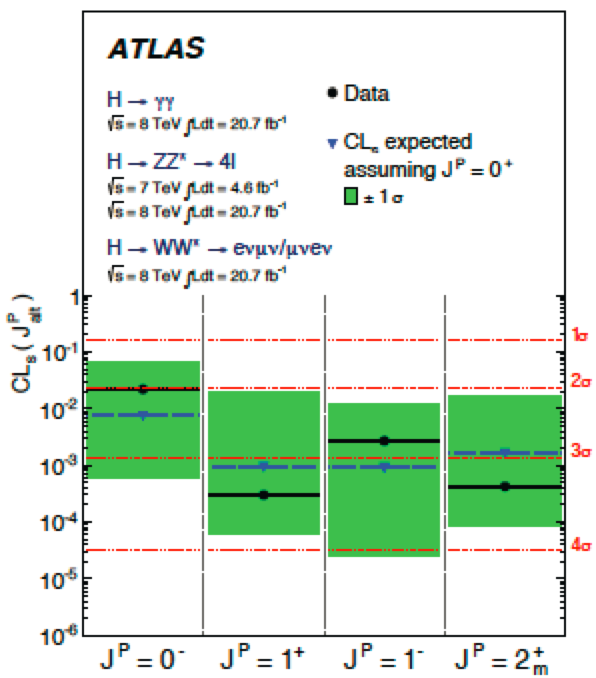
ATLAS Collaboration arXiv:1307.1432

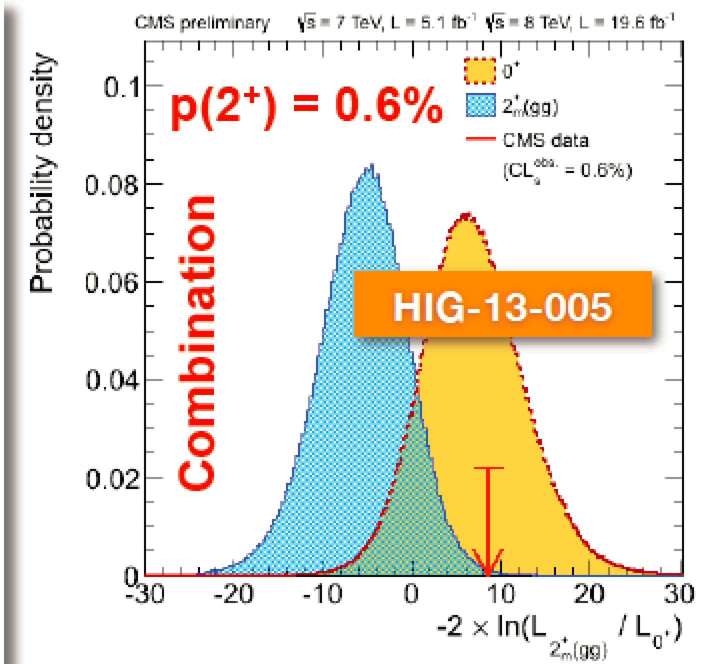
0^- is excluded at 97.8% CL
1^+ is excluded at 99.97% CL
1^- is excluded at 99.7% CL
2^+ is excluded at >99.9% CL

H(ZZ) alone

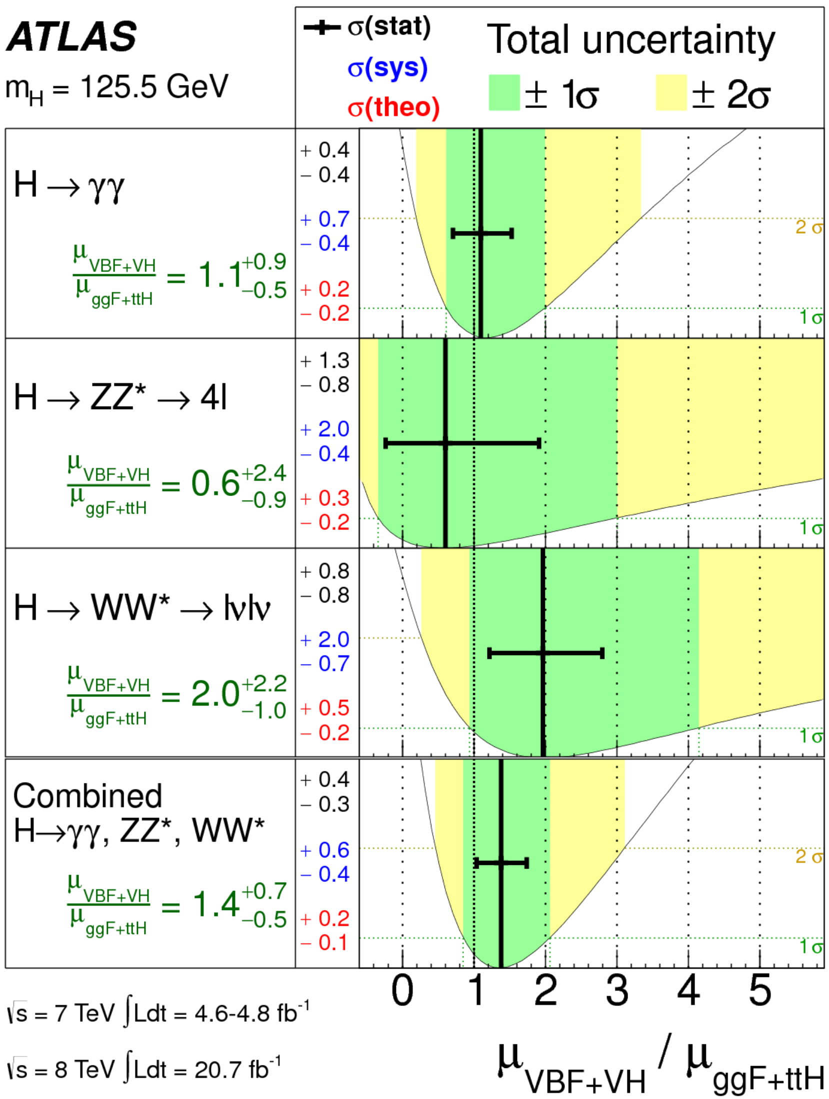
J^P	production	comment	expect (μ=1)	obs. 0^+	obs. J^P	CL_s
0^-	$gg \to X$	pseudoscalar	2.6σ (2.8σ)	0.5σ	3.3σ	0.16%
0^+_h	$gg \to X$	higher dim operators	1.7σ (1.8σ)	0.0σ	1.7σ	8.1%
2^+_{mgg}	$gg \to X$	minimal couplings	1.8σ (1.9σ)	0.8σ	2.7σ	1.5%
$2^+_{mq\bar{q}}$	$q\bar{q} \to X$	minimal couplings	1.7σ (1.9σ)	1.8σ	4.0σ	<0.1%
1^-	$q\bar{q} \to X$	exotic vector	2.8σ (3.1σ)	1.4σ	$>4.0\sigma$	<0.1%
1^+	$q\bar{q} \to X$	exotic pseudovector	2.3σ (2.6σ)	1.7σ	$>4.0\sigma$	<0.1%



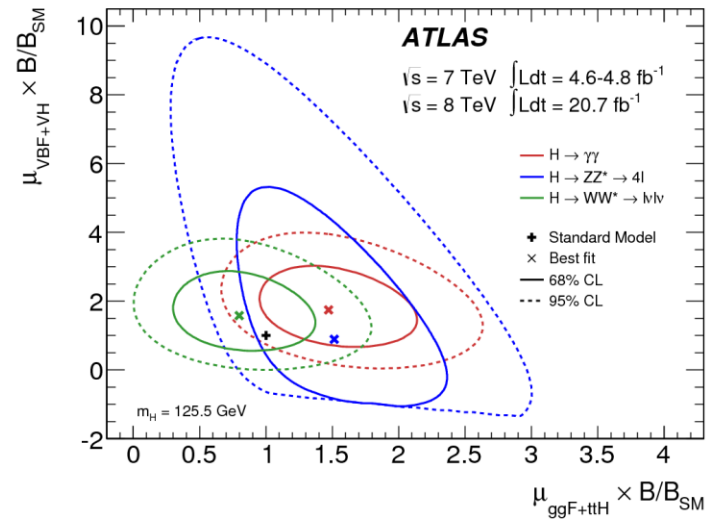


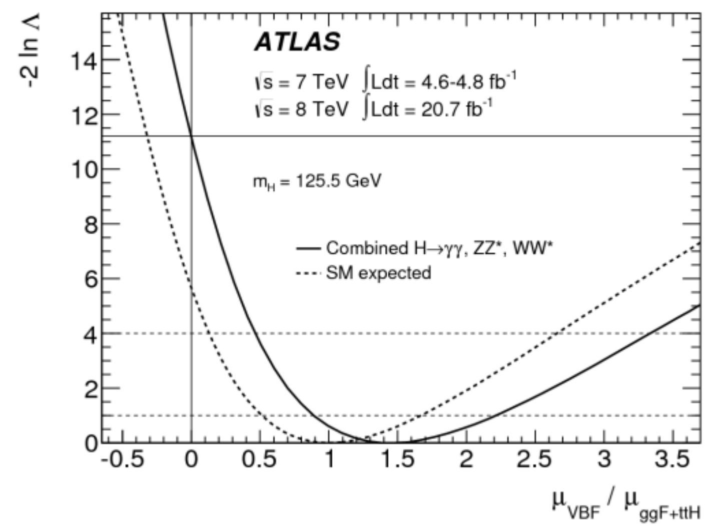


Higgs Production: ggF vs.VBF



μ_{VBF+VH} vs $\mu_{ggF+ttH}$ potentially modified by B/B_{SM}





$\mu_{VBF+VH} / \mu_{ggF+ttH}$ = 1.4+0.4-0.3(stat)+0.6-0.4(sys)

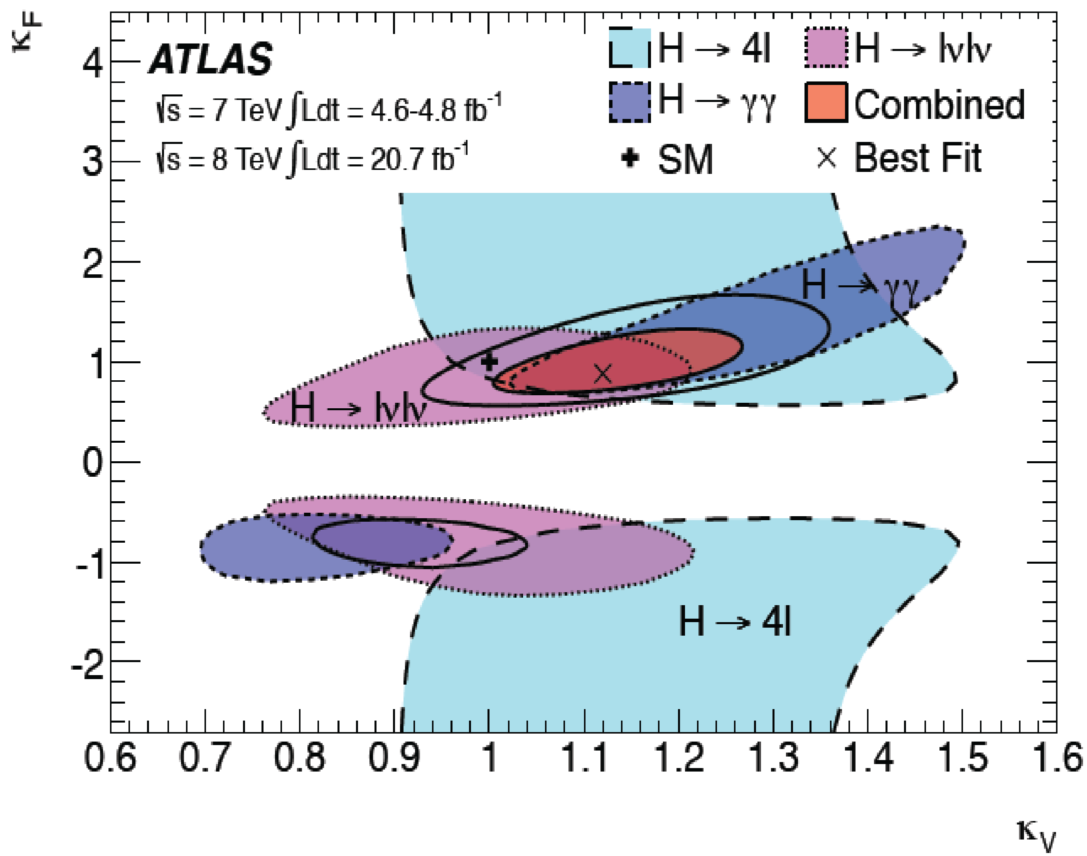
Fermion and Vector Couplings

2-parameter benchmark model:
$\kappa_V = \kappa_W = \kappa_Z$ (>0)
$\kappa_F = \kappa_t = \kappa_b = \kappa_c = \kappa_\tau = \kappa_g$
(Gluon coupling are related to top, b, and their interference in tree level loop diagrams)

Assume no BSM contributions to loops: gg→ H and H→$\gamma\gamma$, and no BSM decays (no invisible decays)

- **κ_F = 0 is excluded (>5σ)**

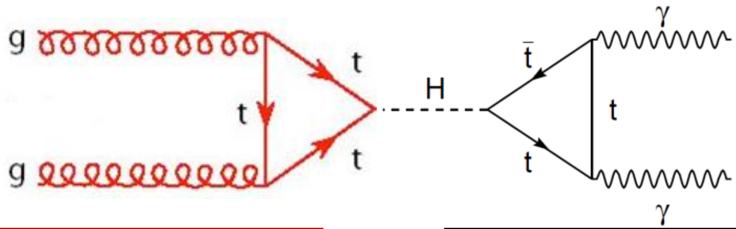
Double minimum from interference between vector(W) and fermion (top) in H→$\gamma\gamma$



Constraints on BSM Loops

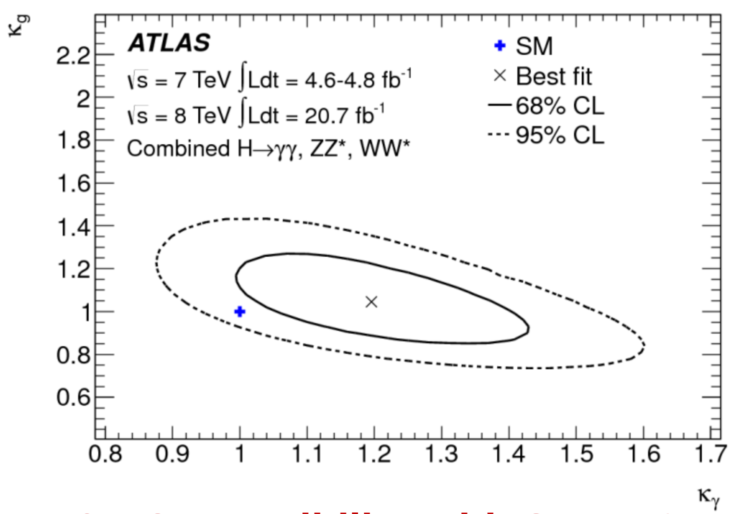
New heavy particles may contribute to loops

- Introduce effective κ_g, κ_γ to allow heavy BSM particles contribute to the loops
- Tree-level couplings: $\kappa_W, \kappa_Z, \kappa_t, \kappa_b$, κ_τ etc set to 1
  - Absorb all difference into loop couplings
  - Indirectly fixed normalization of Higgs width

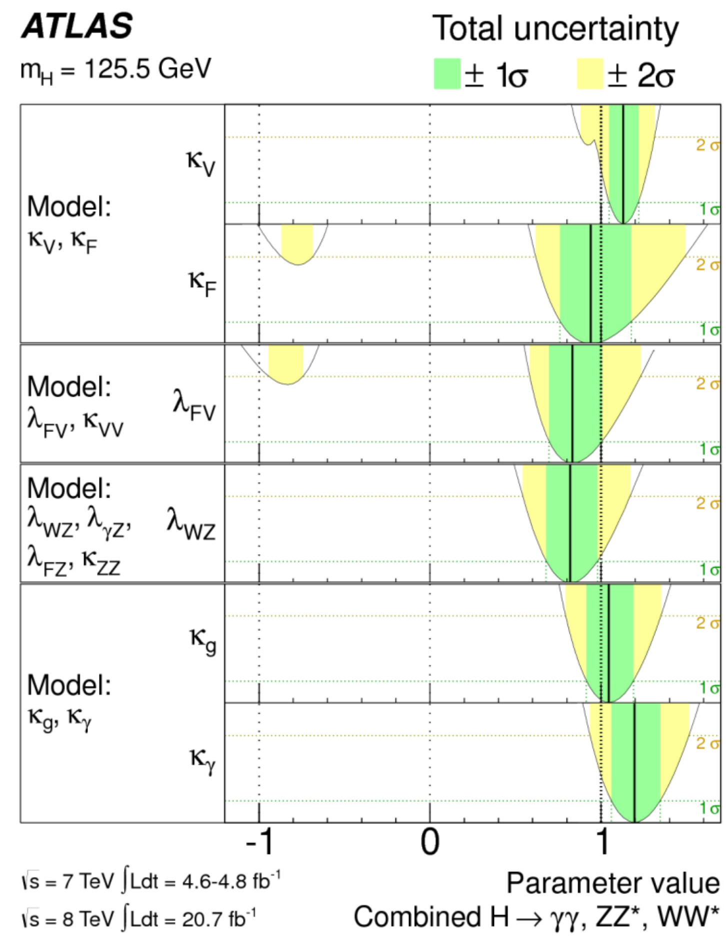


κ_g =1.04 ± 0.14

κ_γ =1.20 ± 0.15



2D Compatibility with SM: 14%



Couplings tested for anomalies w.r.t. fermion and boson, W/Z and vertex loop contributions at ±10-15% precision

Summary and Conclusions

- A SM-like Higgs particle was observed and confirmed

Mass: m_H = 125.5 $\pm$ 0.2 (stat) $\pm$ 0.6 (syst) GeV
Signal strength @ 125.5 GeV : μ = 1.3 $\pm$ 0.2

- Higgs decays to $\gamma\gamma$, ZZ* and WW* (Gauge coupling) are established.
- The spin-1 is excluded due to observation of $H\rightarrow\gamma\gamma$.
- Spin/CP: data favour 0^+ (spin 0 and CP even, SM)
- Uncertainties of couplings parameters ~10-20% , no significant deviations from SM couplings are observed.

Backup Slides

- Higgs couplings: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2013-034
- Higgs mass: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2013-014
- Higgs spin: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2013-040
- $\gamma\gamma$: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2013-012
- $\gamma\gamma$ spin : https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2013-029
- ZZ: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2013-013
- WW: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2013-030
- WW spin: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2013-031
- $\tau\tau$: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2012-160
- bb: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2012-161
- $\mu\mu$: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2013-010
- $Z\gamma$: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2013-009
- $ZH\rightarrow$invisible: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2013-009

Summary of what we know now ?

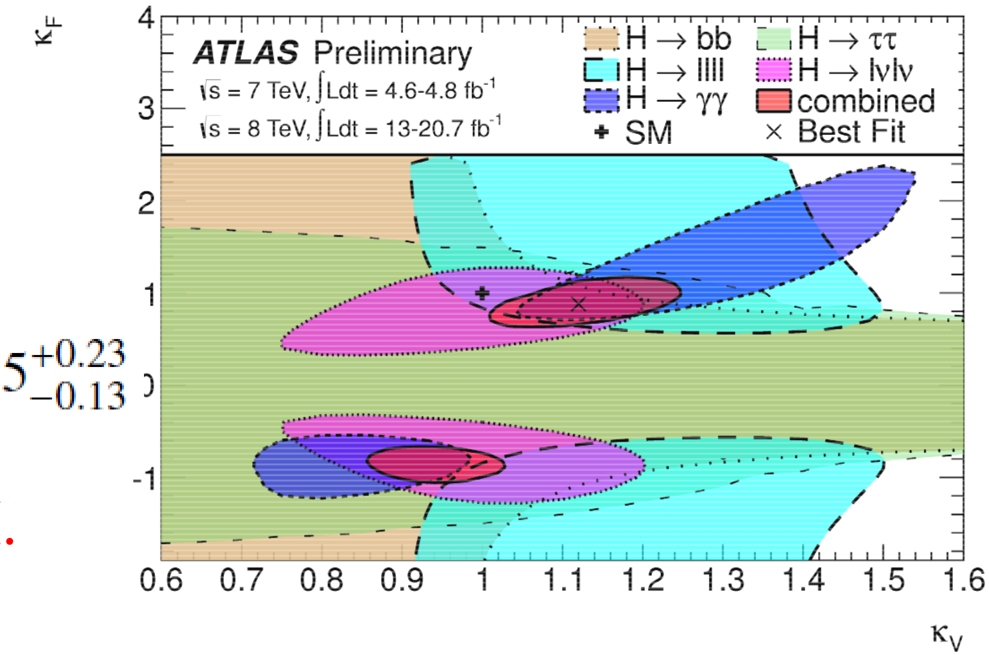
Higgs Mass	**125-126 GeV – agree with SM rough prediction**
Spin	Spin 0 fits well, spin 1 unlikely, spin 2^+ excluded at 99.9%
Parity	Reasonable evidence it is symmetric
Charge	Zero, as it should be
Lifetime	Unknown, but narrow resonance and no obvious flight
Interaction with W/Z	Rates in WW and ZZ look as expected
Interaction with fermions	Direct evidence weak, gluon rate implies ~SM coupling, Tevatron +CMS have evidence for $H \to bb$
Interaction with gluons	Total rate suggest it's as expected
Interaction with photons	1.6 ± 0.2(stat) ± 0.2 (syst), $< 2\sigma$ deviation from SM !
Conclusion	**SM Higgs with reasonable statistical fluctuations**

Fermion and Vector Couplings

- Two coupling scale factors κ_F for fermions and κ_V for bosons

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

- Vector coupling (κ_V) measured in channels (H→γγ, WW, ZZ)
- Fermion coupling (κ_F) measured:
  - Directly in H→bb and H→ττ
  - Indirectly via loop gg→H



- $\lambda_{FV}=\kappa_F/\kappa_V$, $\kappa_{VV}=\kappa_V\cdot\kappa_V/\kappa_H$
  - Measured ratio of fermion to vector couplings: $\lambda_{FV} = 0.85^{+0.23}_{-0.13}$
  - Fermion & vector couplings non-zero, consistent with SM.
  - 2D compatibility of the SM hypothesis with the best fit point is 8%.

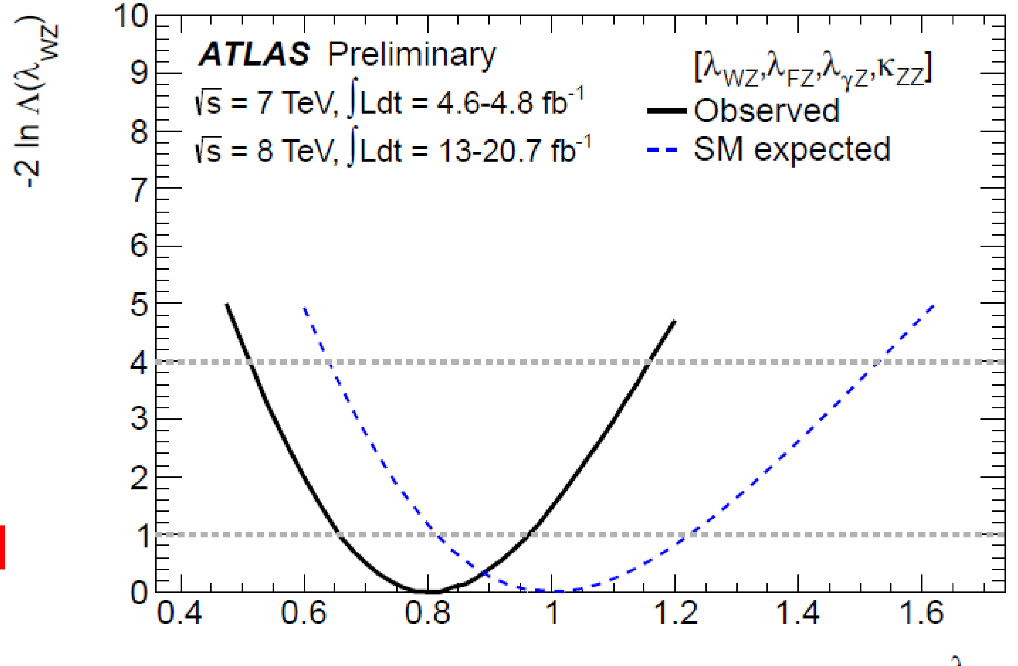
$$\kappa_F \in [-0.88, -0.75] \cup [0.73, 1.07]$$
$$\kappa_V \in [0.91, 0.97] \cup [1.05, 1.21] \quad .$$

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.

$$\lambda_{WZ} = 0.80 \pm 0.15$$
$$\lambda_{\gamma Z} = 1.10 \pm 0.18$$
$$\lambda_{FZ} = 0.74^{+0.21}_{-0.17}$$
$$\kappa_{ZZ} = 1.5^{+0.5}_{-0.4}$$

➢ 4D compatibility of the SM hypothesis with the best fit point is 9%.



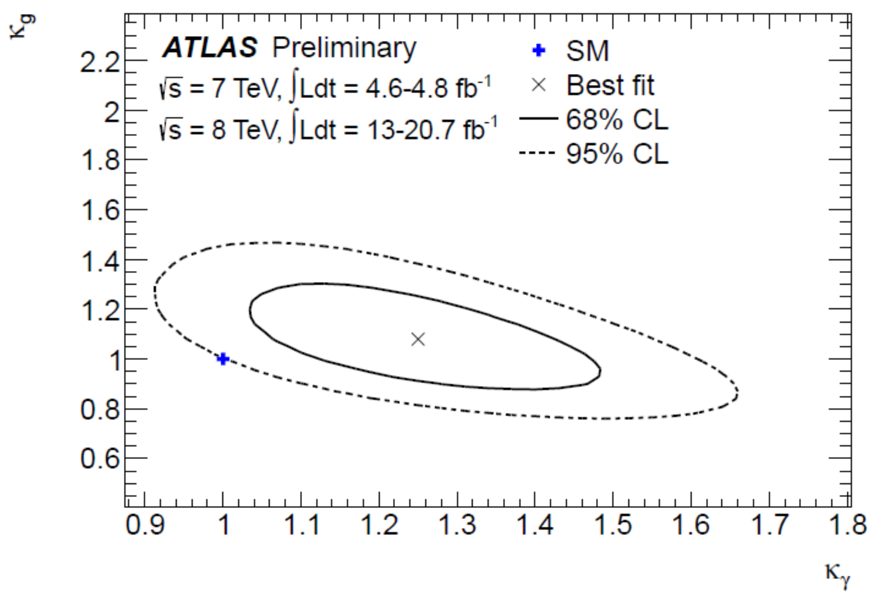
(a)

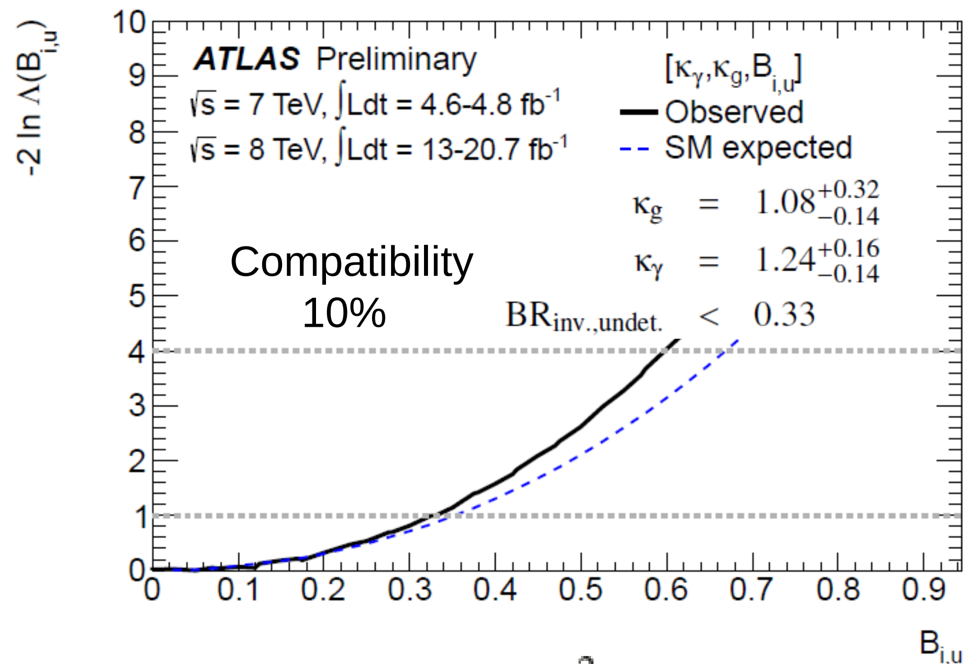
Probing Potential Non-SM Particle Contributions

- 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

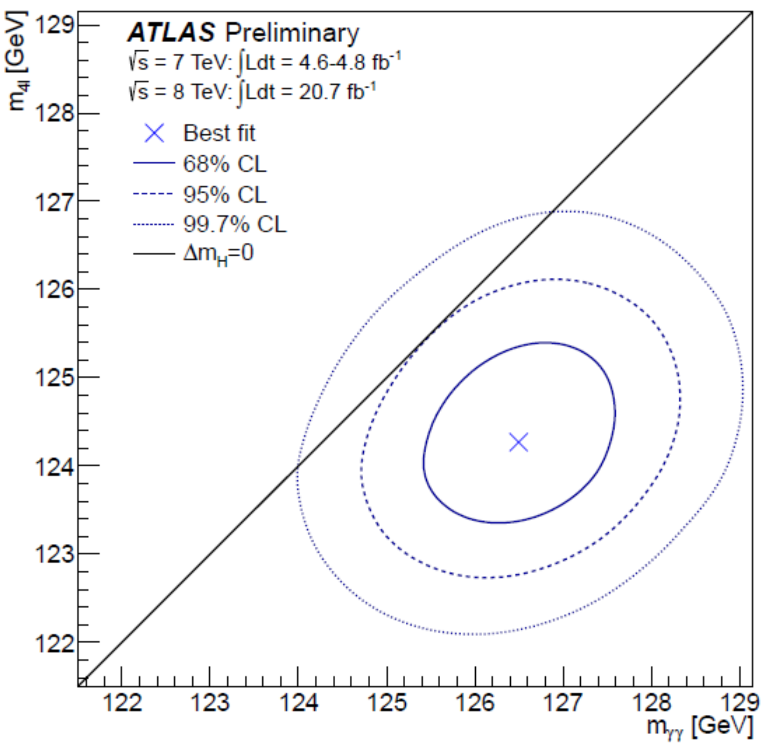
$$\kappa_g = 1.08 \pm 0.14$$

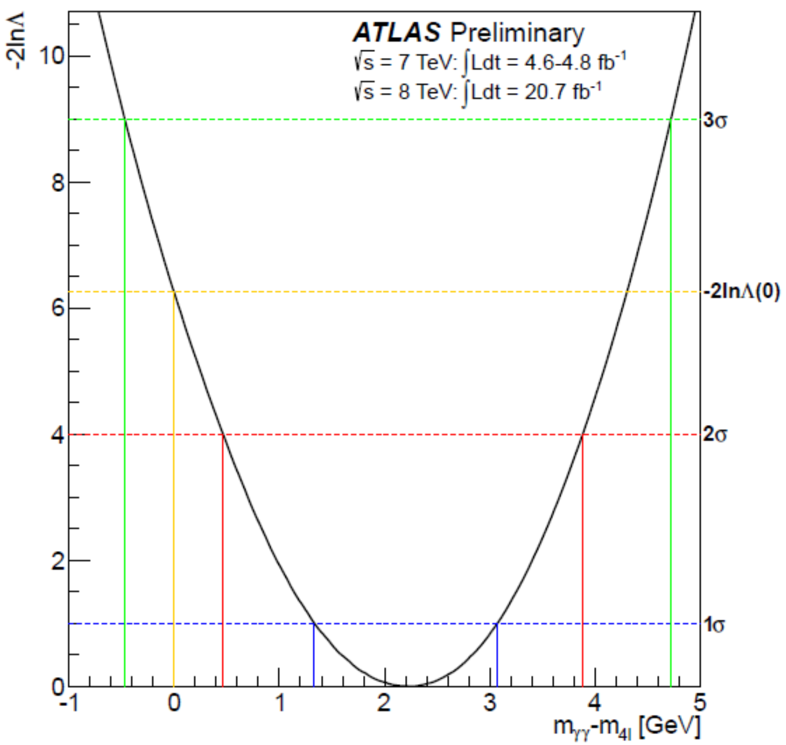
$$\kappa_\gamma = 1.23^{+0.16}_{-0.13}$$

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

Consistency Check of Higgs Mass Discrepancy

$$\Delta\hat{m}_H = \hat{m}_H^{\gamma\gamma} - \hat{m}_H^{4\ell} = 2.3^{+0.6}_{-0.7}\,(\mathrm{stat}) \pm 0.6\,(\mathrm{sys})\ \mathrm{GeV}$$

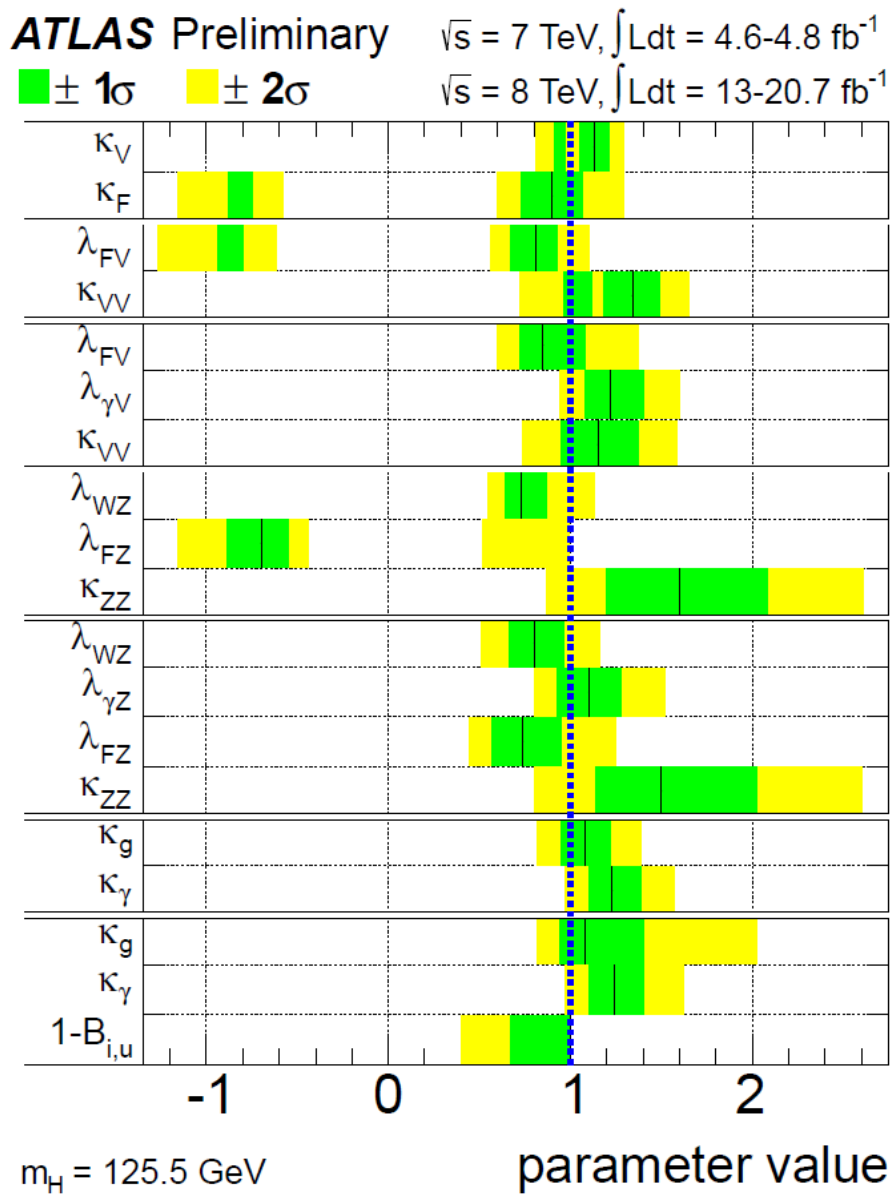




The probability for a single Higgs boson-like particle to produce a value of the Λ test statistic disfavoring the $\Delta M_H=0$ hypothesis more than observed is found to be **1.2% or 2.5σ .**

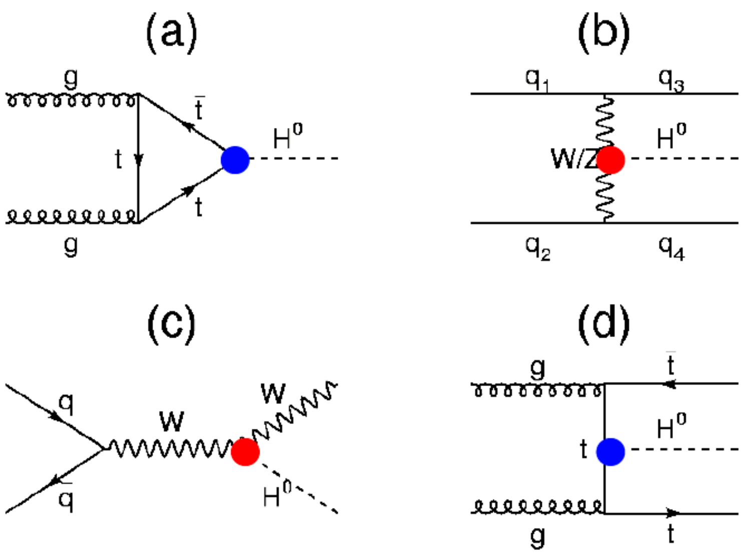
Coupling Measurements

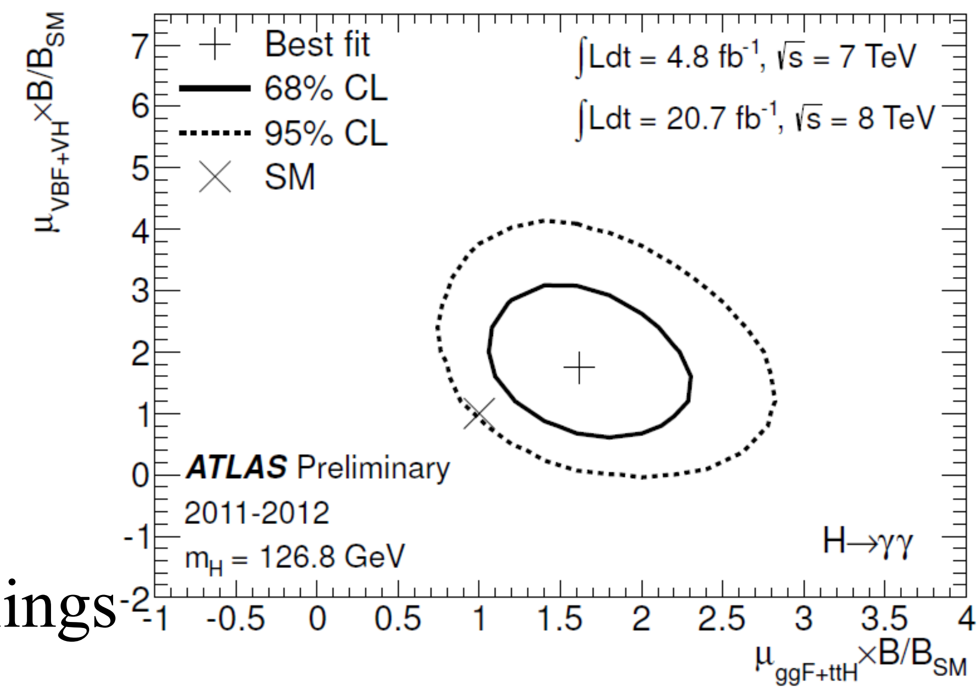
- The compatibility of the measured yields for the studied channels with the prediction for the SM Higgs boson is tested under various benchmark assumptions proving salient features of the couplings.
- For the different tested benchmarks the compatibility with the SM Higgs expectation ranges between 10%-20%.
- **No significant deviation from the SM prediction is observed in any of the fits performed.**



Higgs → γγ

- ❑ Observation of H → γγ excludes spin-1

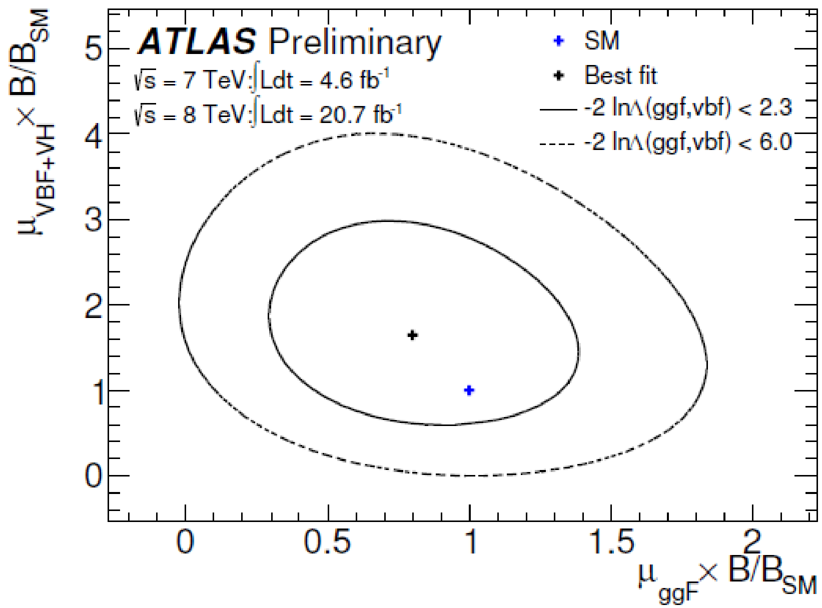


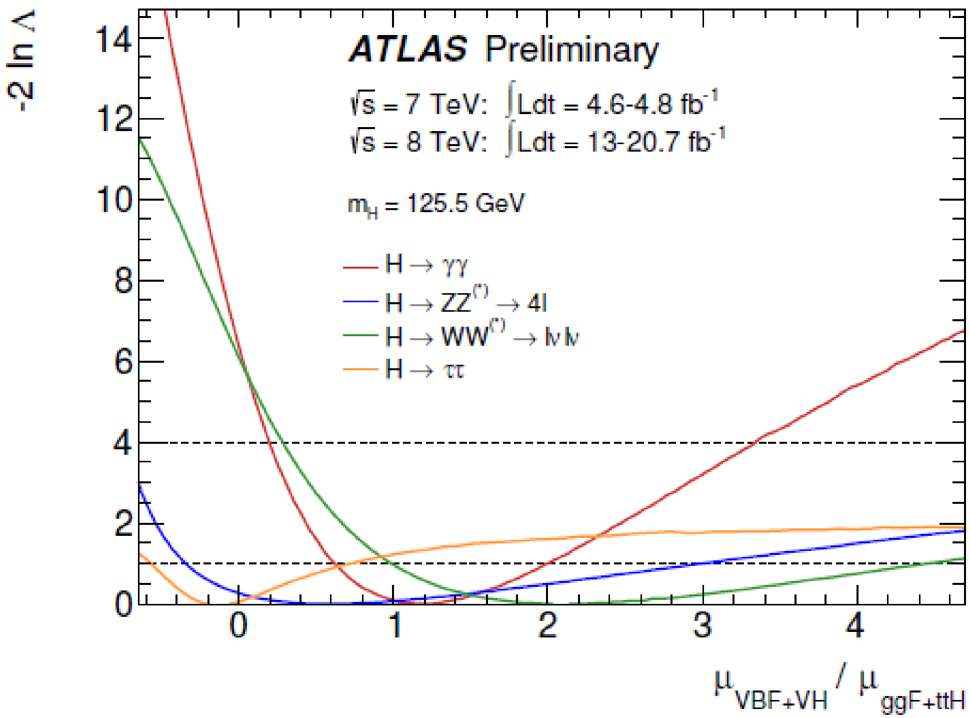


- ❑ Higgs has two types of couplings
  - "Gauge" couplings (to bosons)
  - Yukawa couplings (to fermions)
- ❑ Explore tension between SM value and observation from different Higgs production modes: μ_{VBF+VH} **vs.** $\mu_{ggF+ttH}$

Higgs → WW* → lνlν

- Model independent coupling studies which are directly related to experimental observables.
  2D contour: μ_{VBF+VH} vs. $\mu_{ggF+ttH}$





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

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

H→ZZ*→4l Candidate

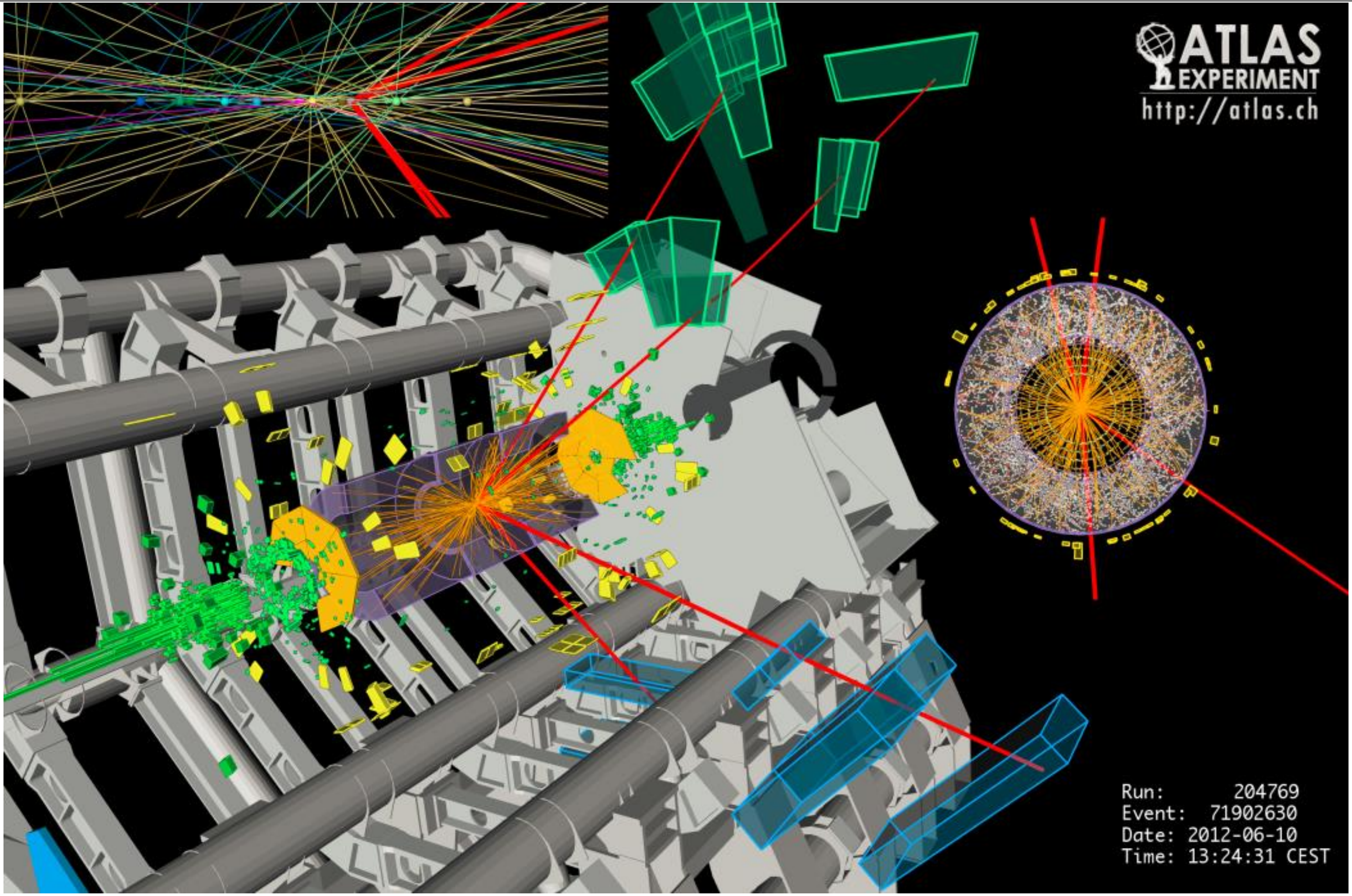
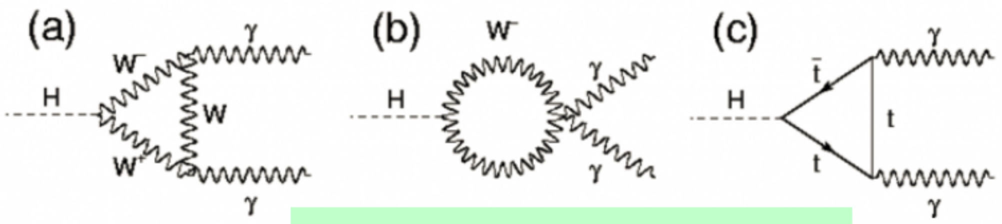


Figure 42: Event display of a 4μ candidate. EventNumber: 71902630 RunNumber: 204769 $m_{4\ell}$ = 125.1 GeV. m_{12} = 86.3 GeV, m_{34} = 31.6 GeV. $\mu_1 : p_{\mathrm{T}}, \eta, \phi$ = 36.1 GeV, 1.29, 1.33. $\mu_2 : p_{\mathrm{T}}, \eta, \phi$ = 47.5 GeV, 0.69, −1.65. $\mu_3 : p_{\mathrm{T}}, \eta,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

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)

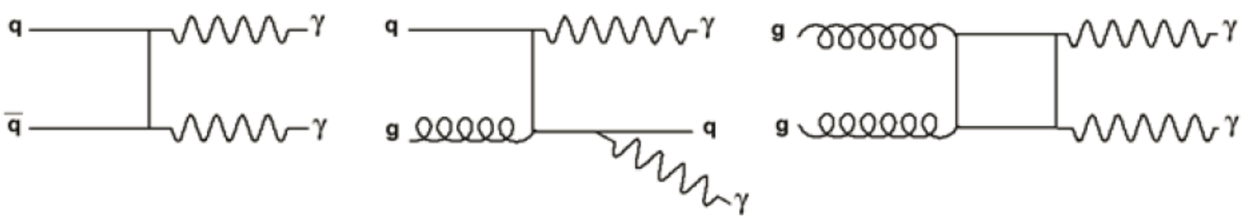


$$\sigma_H \times Br(H \to \gamma\gamma) \sim 50 \text{ fb}$$
$$@\ m_H = 125 \text{ GeV}$$

Decay through loops !

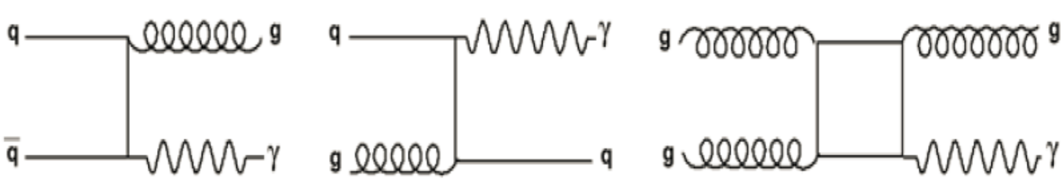
~500 events in 2011+2012 sample!

- Irreducible background from γγ production



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

- Reducible background from γj and jj productions

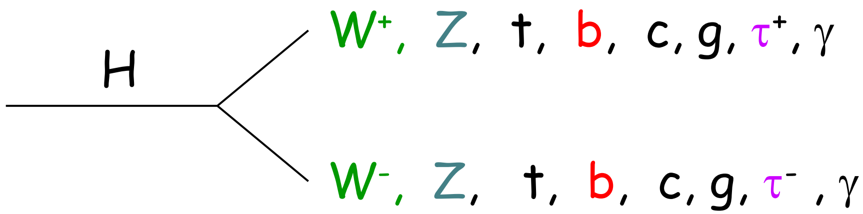


$$\sigma(\gamma j) \sim 3\times10^5 \text{ pb}$$
$$\sigma(jj) \sim 6\times10^8 \text{ pb}$$

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

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

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

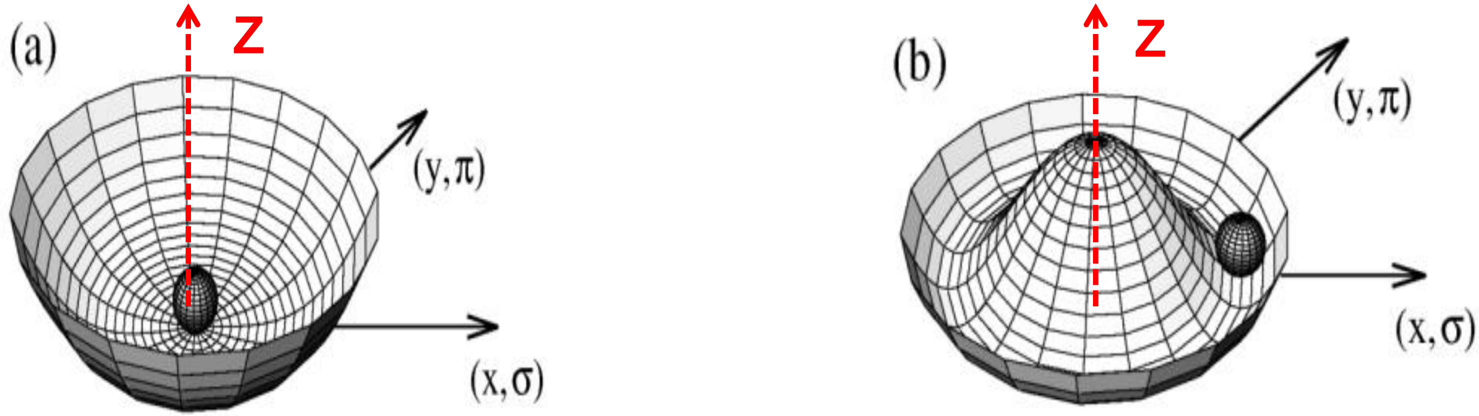
$$\Gamma(H \to \gamma\gamma) = \frac{G_F\, \alpha^2}{128\sqrt{2}\pi^3} M_H^3 \left[\frac{4}{3} N_C e_t^2 - 7\right]^2$$

Higgs Boson:

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

Higgs Mechanism

- The potential in (a) is symmetric
- The potential in (b) the potential is still symmetric,
  but the symmetry of the ground state is spontaneously broken.



- Spontaneously symmetry breaking ➔ Nambu-Goldstone bosons (no spin, mass)

- Peter Higgs showed that Goldstone bosons need not occur when a local symmetry is spontaneously broken in a relativistic theory. Instead, the Goldstone mode provides the third polarisation of a massive vector field. The other mode of the original scalar doublet remains as a massive spin-zero particle – the Higgs boson.

History of the Higgs Search

- 1964 Brout & Englert, Higgs, Guralnik, Hagen & Kibble,
  - Not taken too seriously until...
- 1973 Experimental acceptance of the Standard Model
- 1983 Discovery of W and Z bosons
  - Closely linked to the Higgs boson
- 1993 CERN/LEP1 studies Z's and rules out $m_H<53$ GeV
  - And indirectly excludes $m_H > 300$ GeV
- 2000 CERN/LEP2 lower limit reaches 114.4 GeV
- 2011 CERN/LHC excludes 130-550 GeV
- 2011 Fermilab/Tevatron excludes 156-175 GeV
- 2012 Fermilab/Tevatron observed 2.5σ excess at [120,130]
- **2012.7.4 New particle found at ~125 GeV**
  - **5σ for ATLAS/CMS, consistent with the SM Higgs**

Higgs Boson Width

- **Strong mass dependent**

Γ_H = 3.5 MeV @ 120 GeV

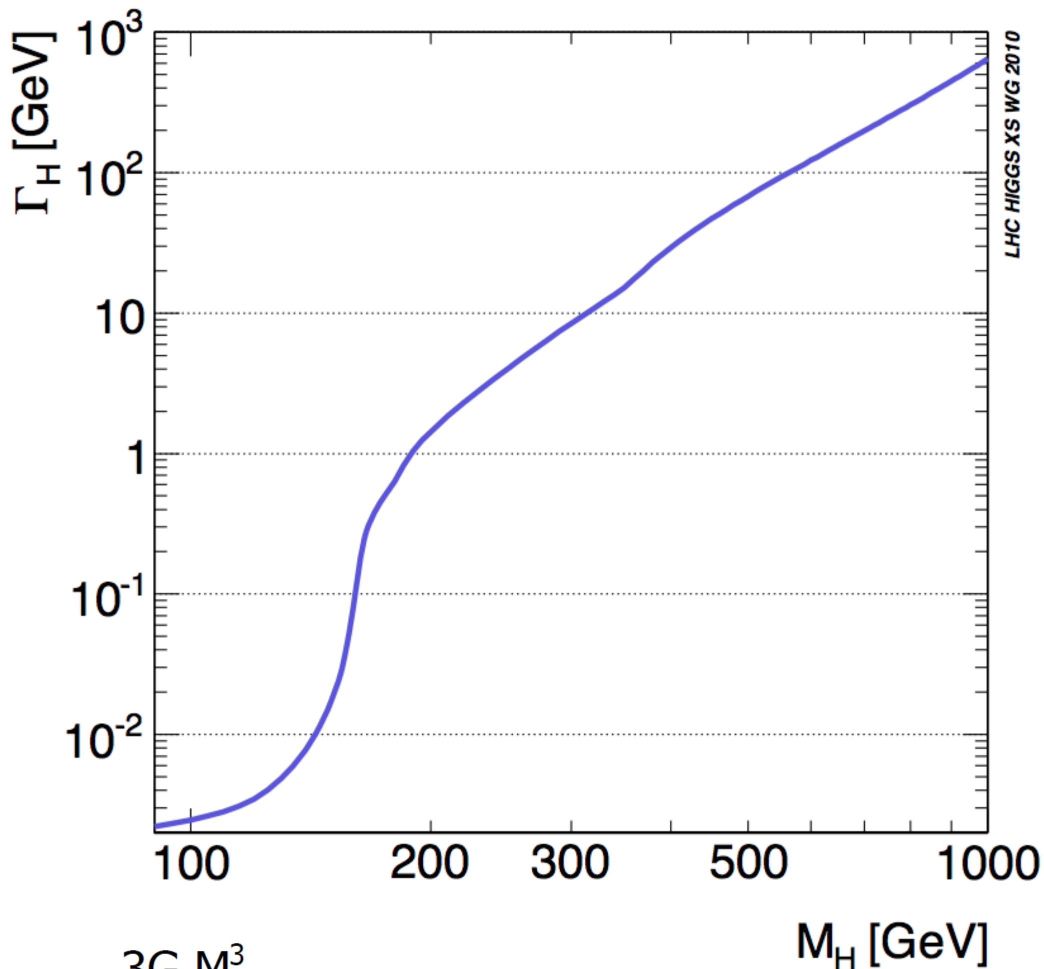
1.4 GeV @ 200 GeV

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

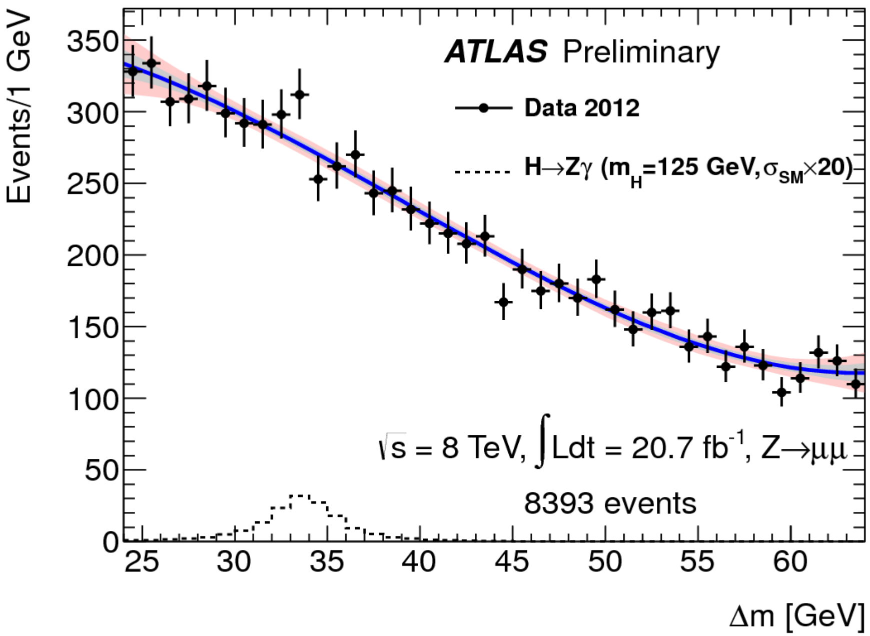


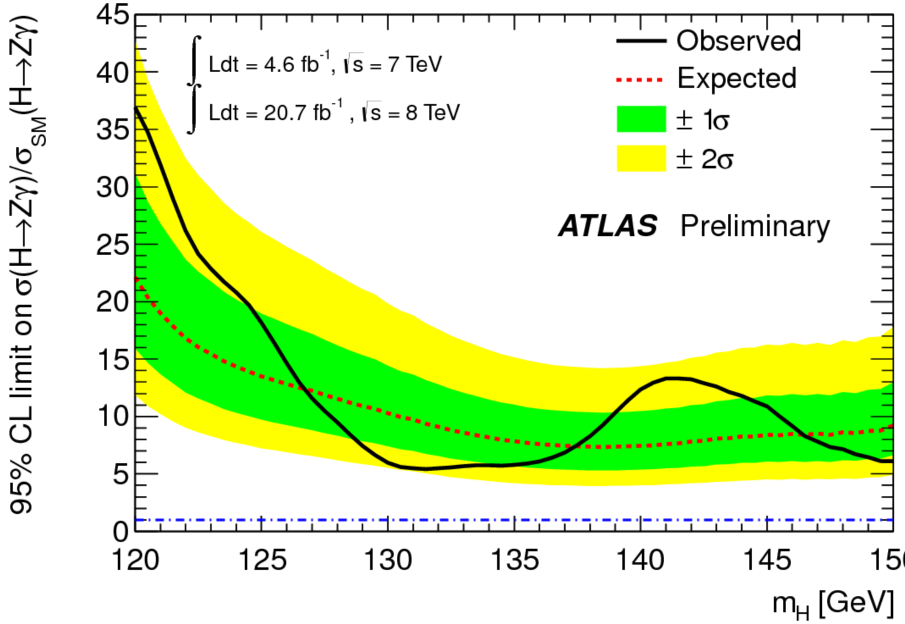
$$\Gamma_H \approx \frac{3G_F M_H^3}{16\pi\sqrt{2}}$$

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

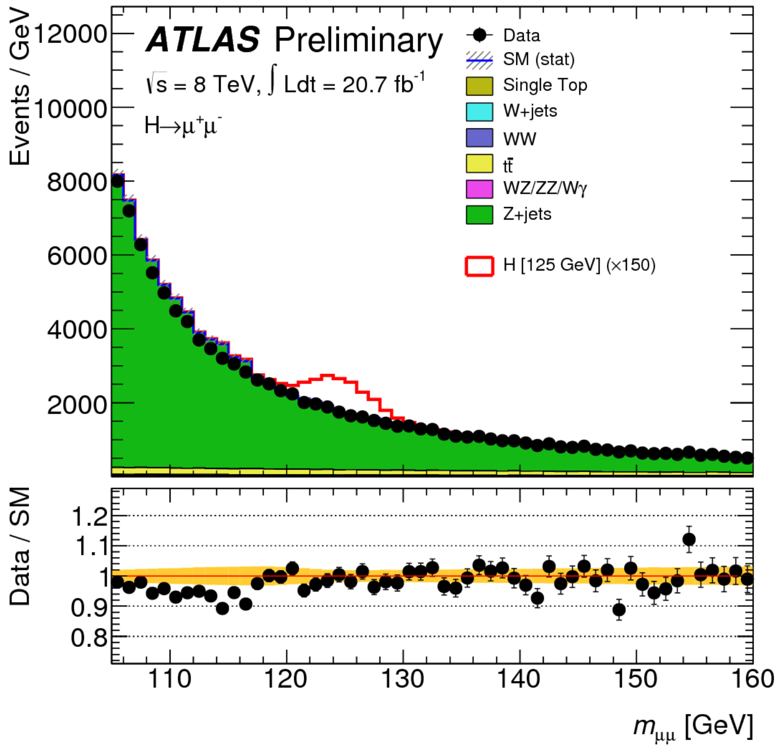
Higgs → Zγ

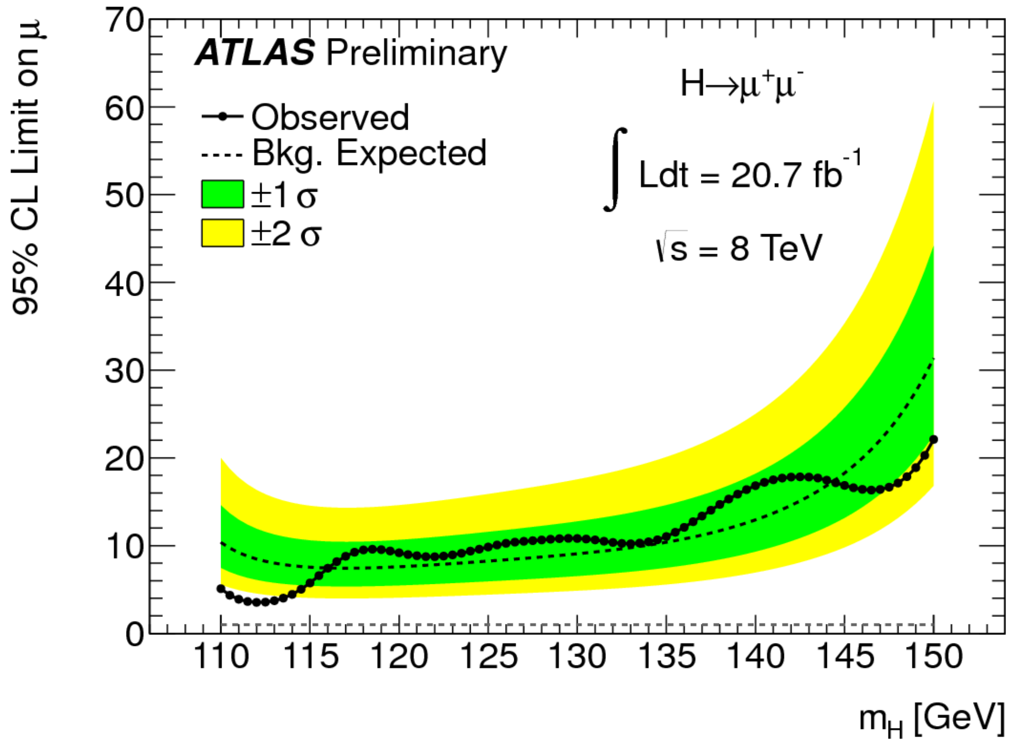
- Loop decay like H→γγ
  - Could be enhanced if radion not Higgs (hep-ph/9907447)
- Four channels combined to make limits
  - ee, μμ at 7 TeV and 8 TeV
  - Observed limit 18 × SM Higgs
  - Expected limit 13 × SM Higgs





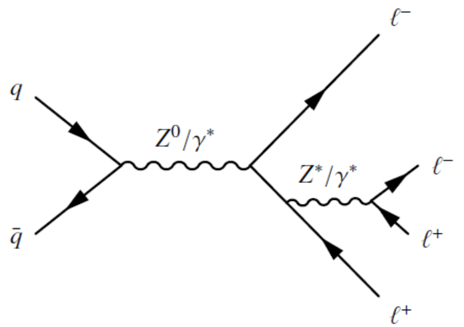
Higgs → μμ



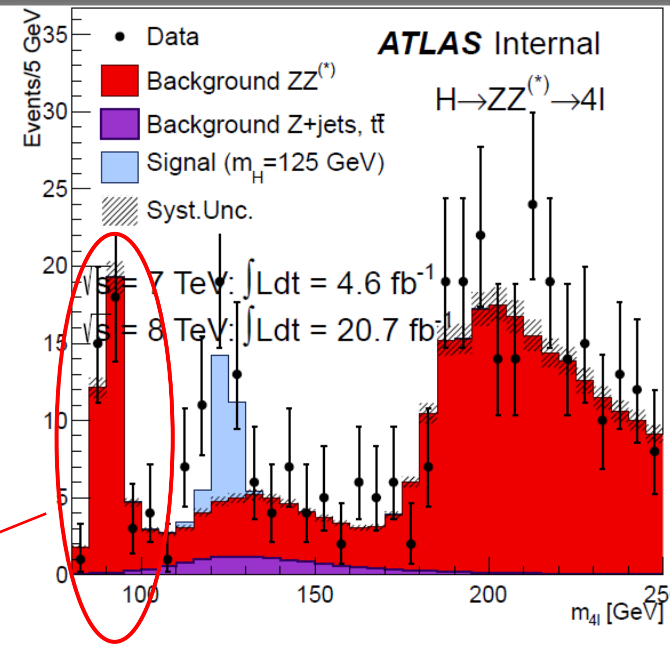


- ➔ Expect suppressed by $(1.7778/0.1056)^2$ ~280 w.r.t. ττ
- ➔ Good efficiency and mass resolution improves things
- But SM sensitivity needs considerably more data
- Observed limit 9.2 × SM
- Expected limit 8.2 × SM

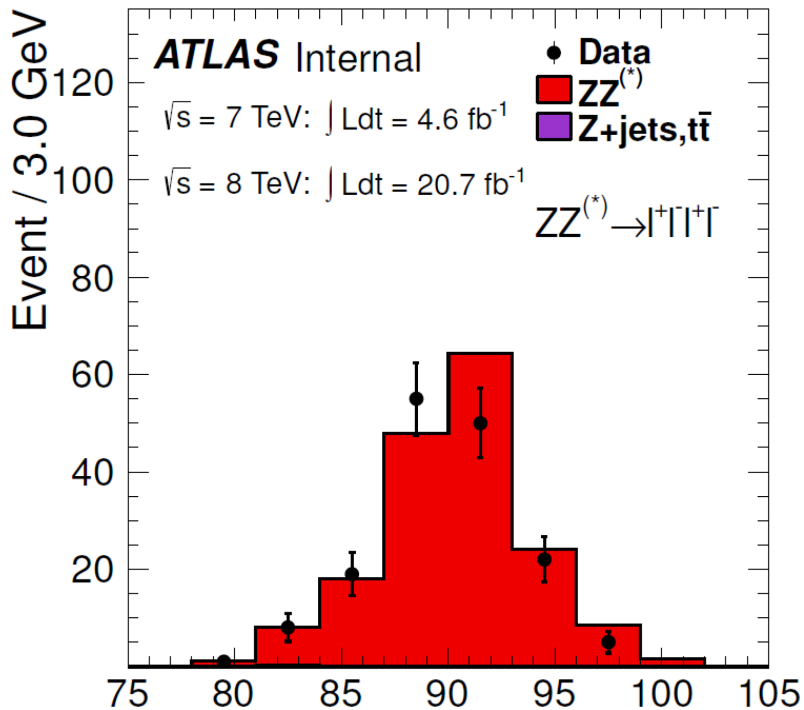
Update of Z→4l

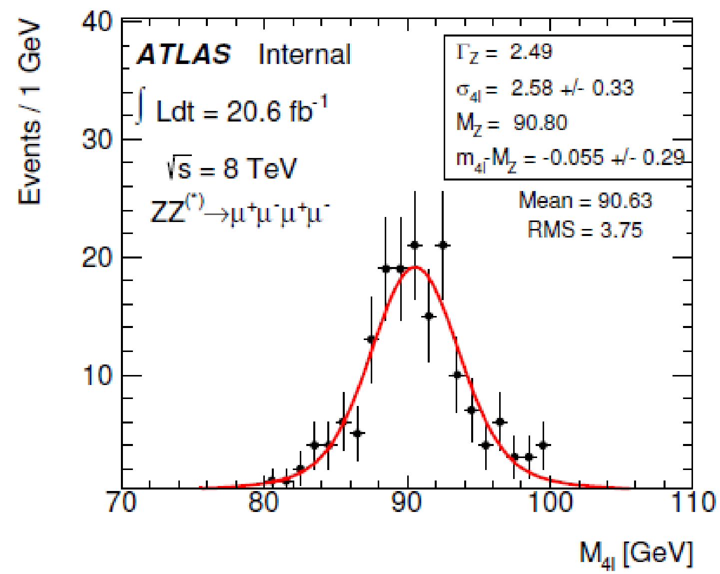


Single resonant Z→4l enhanced by relaxing mass, P_T requirements



BR of Z→4l is measured to be $(4.2 \pm 0.4)\times 10^{-6}$, consistent with SM prediction $(4.37 \pm 0.03)\times 10^{-6}$.





Is it the SM Higgs Boson?

- ❑ 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, $V = \mu^2|\Phi|^2 + \lambda|\Phi|^4 + \text{constant}$

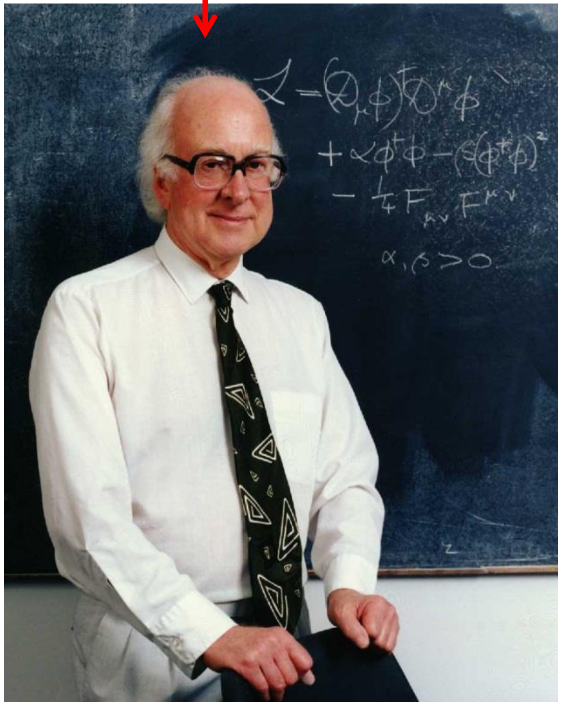
Higgs Mechanism (1964)

- **J. J. Sakurai Prize for Theoretical Particle Physics (2011)**

Peter W. Higgs
Phys. Lett. 12 (1964.9.15) 132
PRL 13 (1964.10.19) 508

F. Englert, R. Brout
PRL 13 (1964.8.31) 321

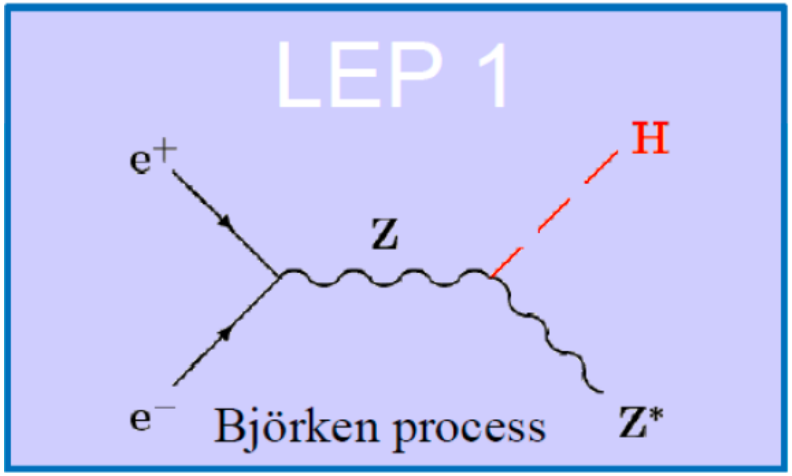
G.S. Guralnik, C.R. Hagen and
T.W.B. Kibble, PRL 13 (1964.11.16) 585

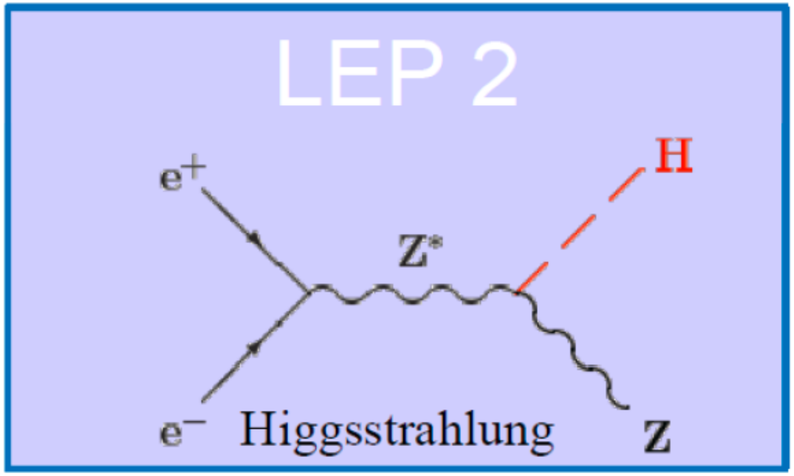


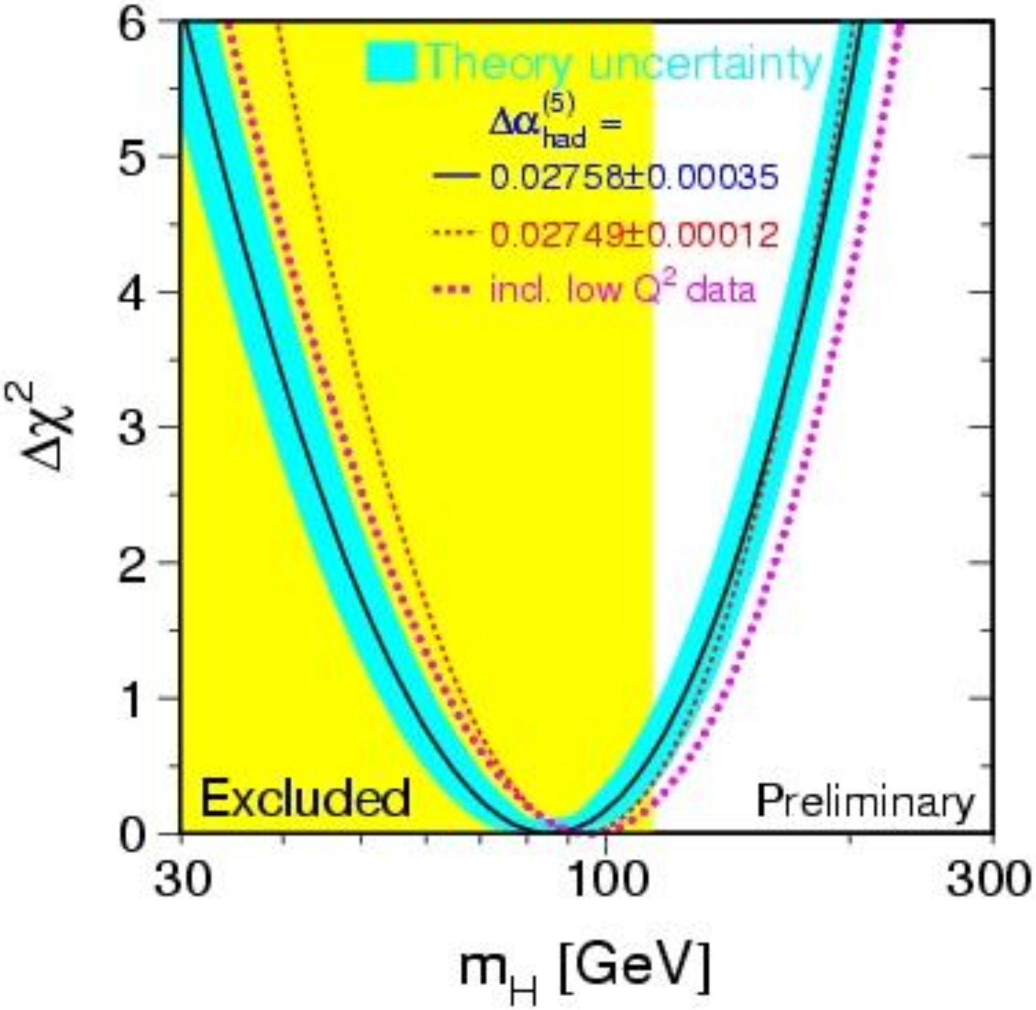
Search for Higgs boson at LEP

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

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

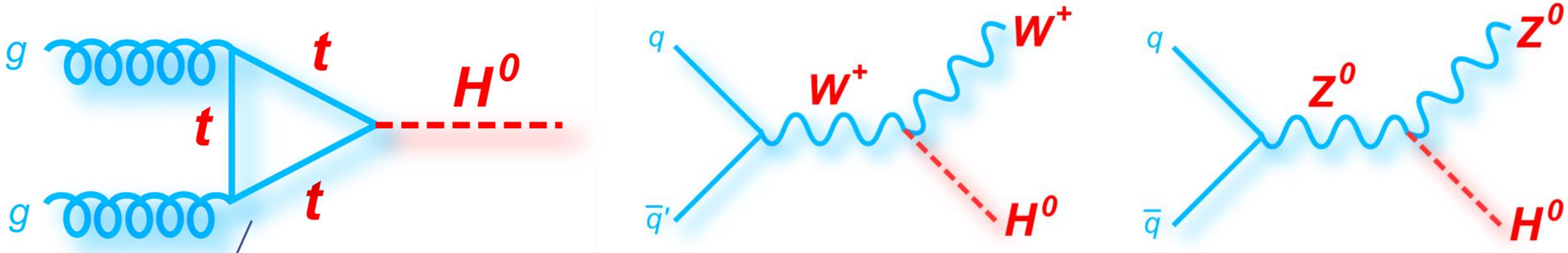


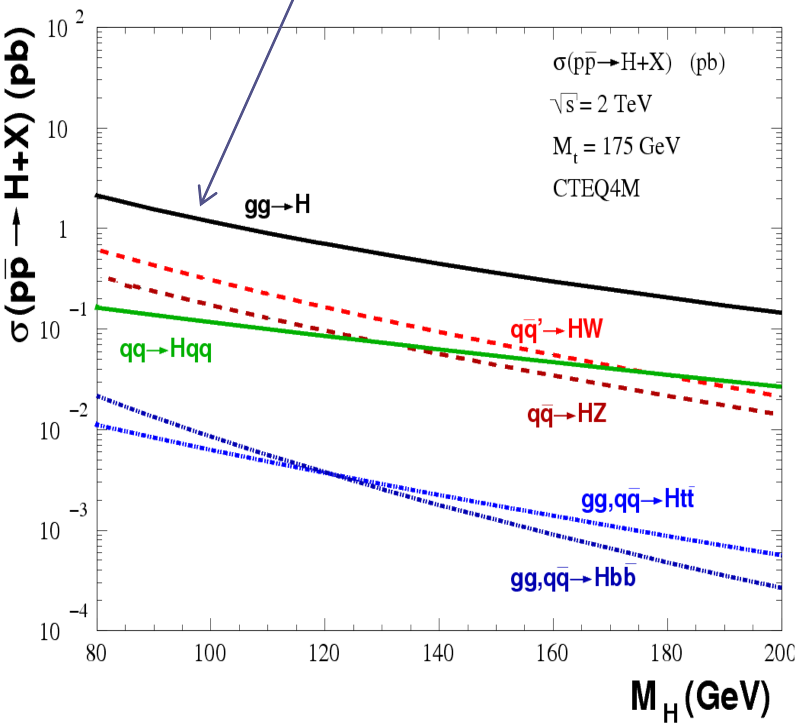


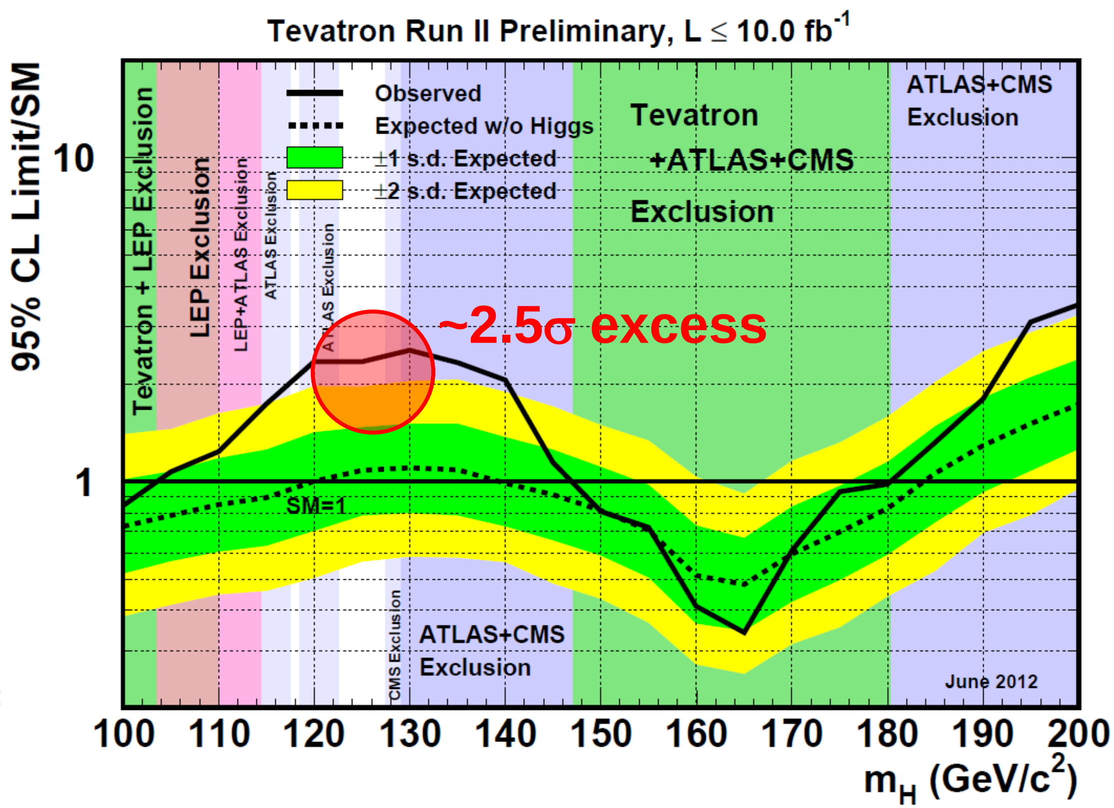


Search for Higgs boson at Tevatron

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

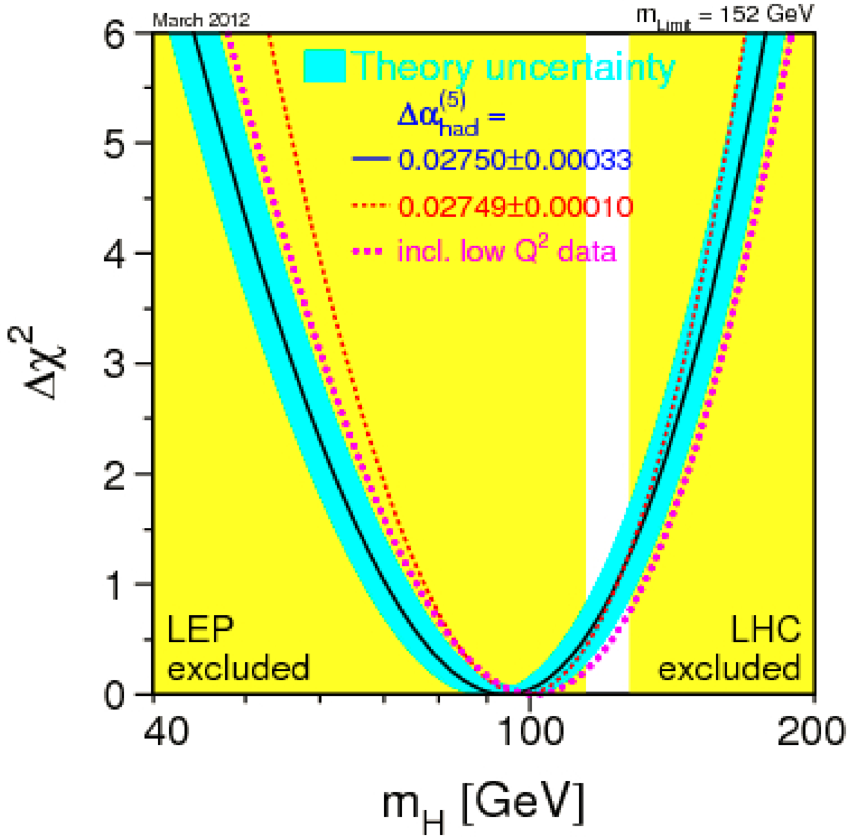


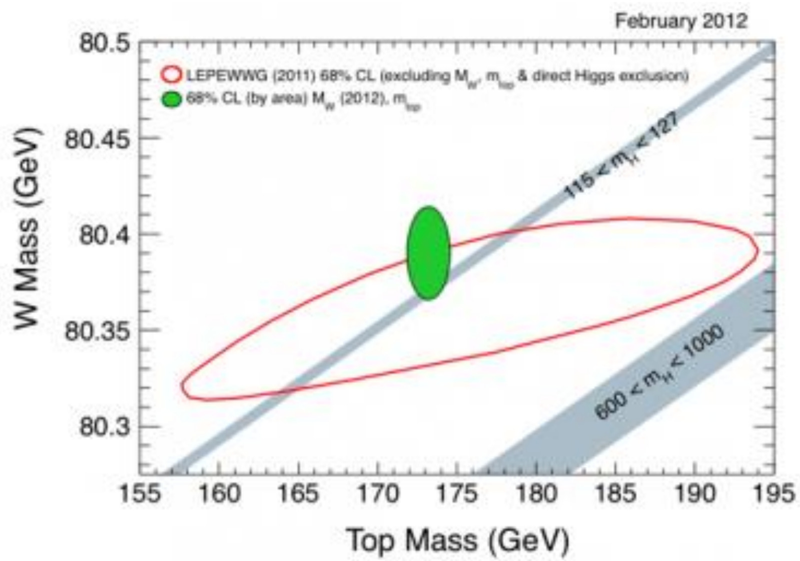


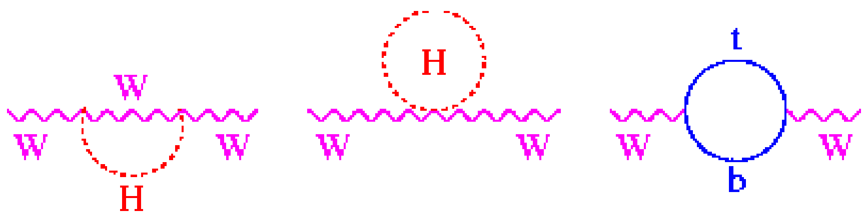


Searches for Higgs Boson at LEP and LHC

- 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



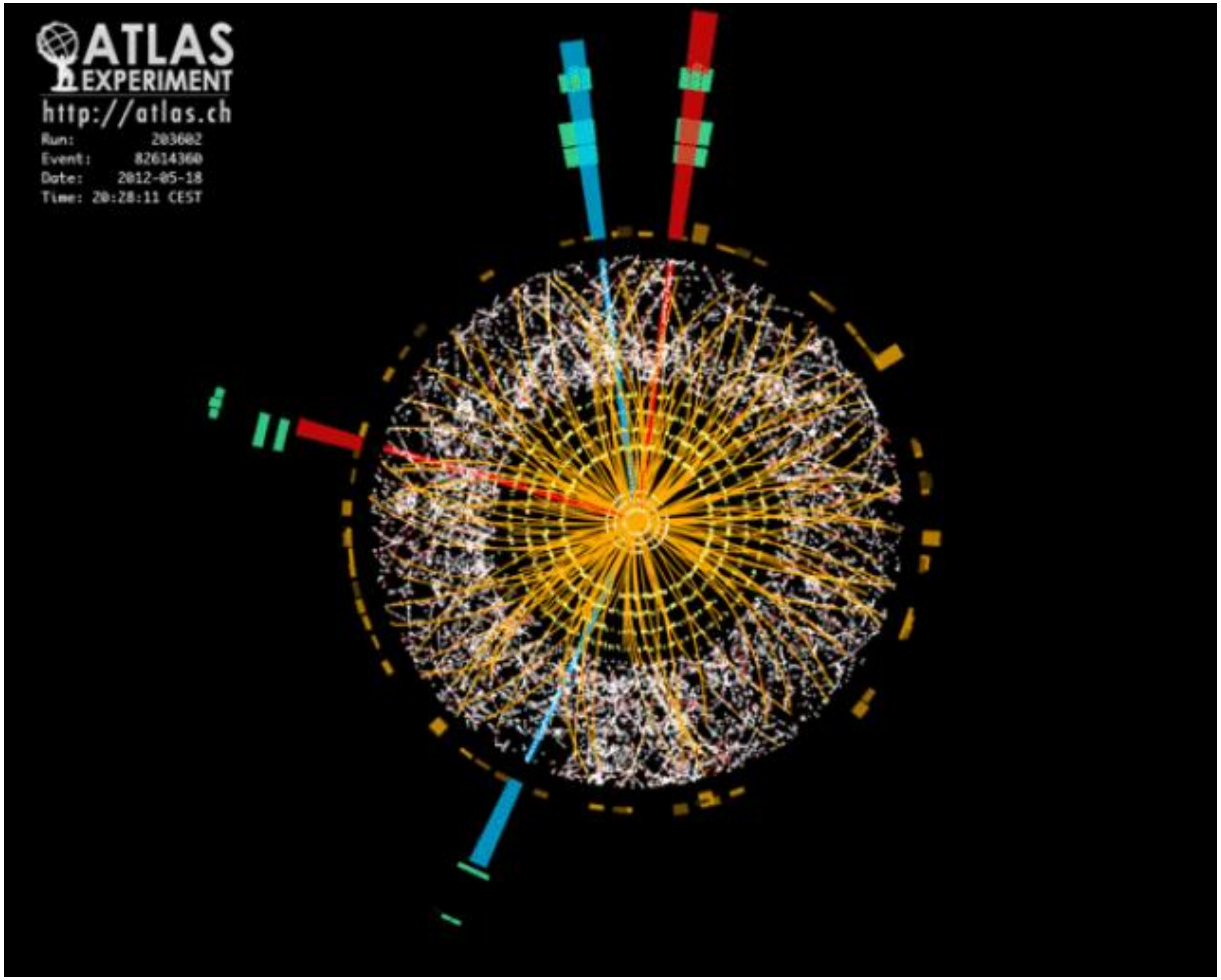




$M^2_W = M^2_Z(1-\sin^2\theta_w)(1+\Delta\rho)$

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

Evolution of Higgs →ZZ* →4l Candidates



Higgs Signal Strength

Signal strength $\mu = \sigma/\sigma_{SM}$

Combination of diboson final states

$H \rightarrow \gamma\gamma$

$H \rightarrow ZZ(^*) \rightarrow 4l$

$H \rightarrow WW(^*) \rightarrow l\nu l\nu$

measured at combined m_H=125.5 GeV

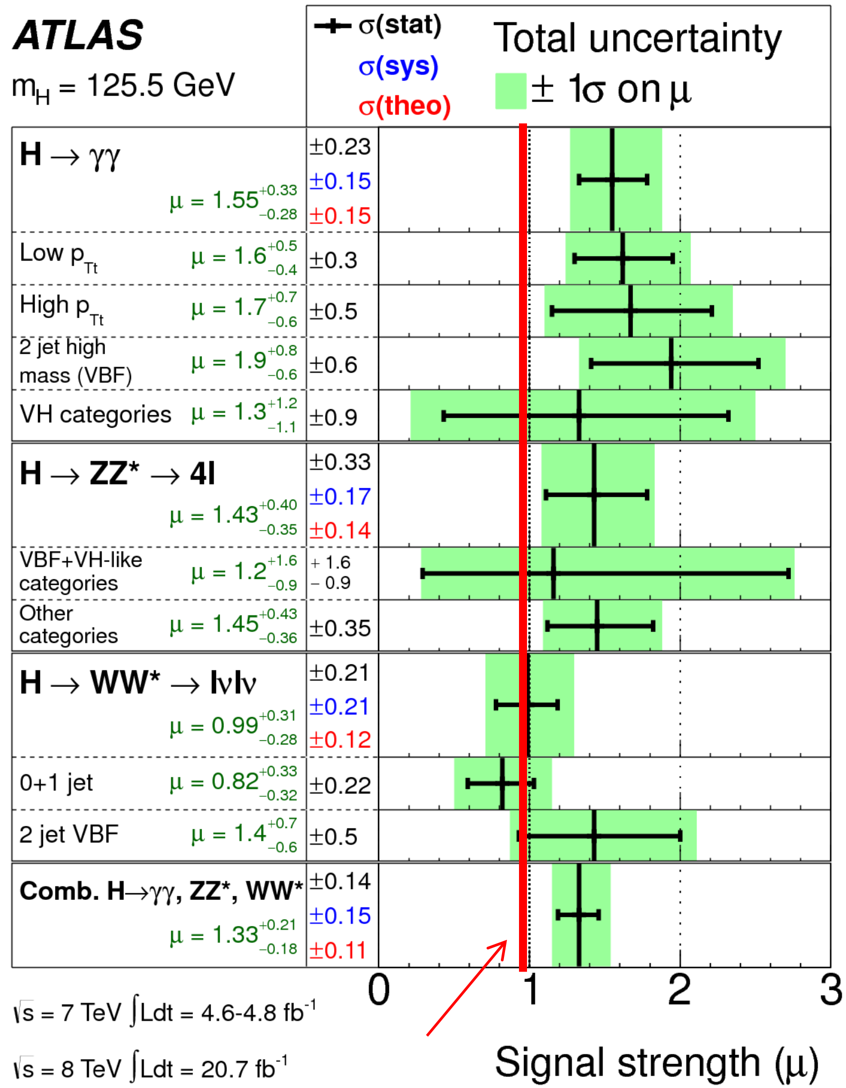
- **Variation due to m_H uncertainty: ±3%**
- **Compatibility with SM (μ=1): 7%**
- **Largest deviation $\mu_{\gamma\gamma}$: 1.9 σ**

Including preliminary μ_{bb}, $\mu_{\tau\tau}$: μ=1.23 ± 0.18

ATLAS also sets preliminary (95%CL) limits:

$H \rightarrow \mu\mu$: μ<9.8 (20.7 fb^{-1})

$H \rightarrow Z\gamma$: μ<18.2 (4.6 fb^{-1} + 20.7 fb^{-1})



μ = 1.33 ± 0.14 (stat) ± 0.15 (sys) ± 0.11 (theo)