Higgs Searches and Properties Measurement with ATLAS

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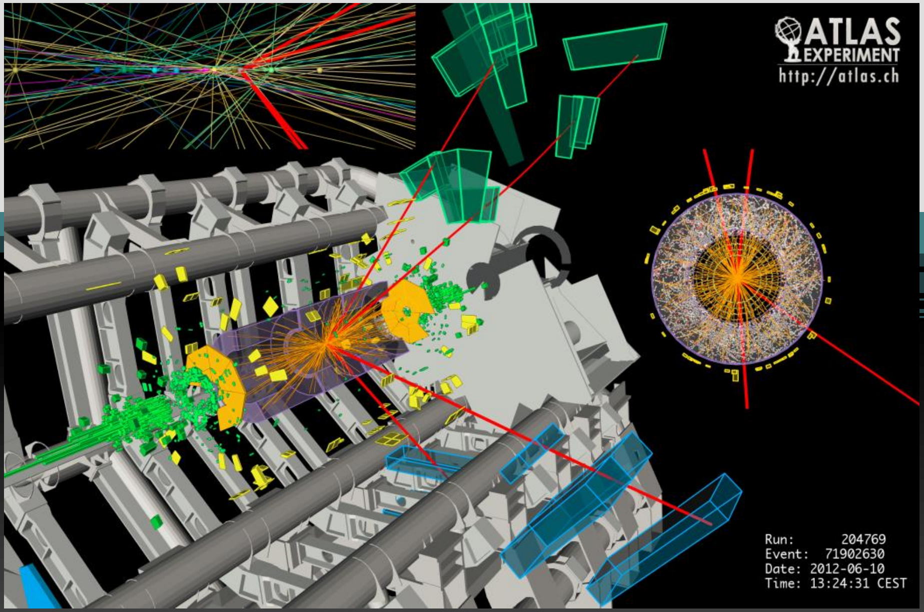


中国科学院大学

June 17, 2013

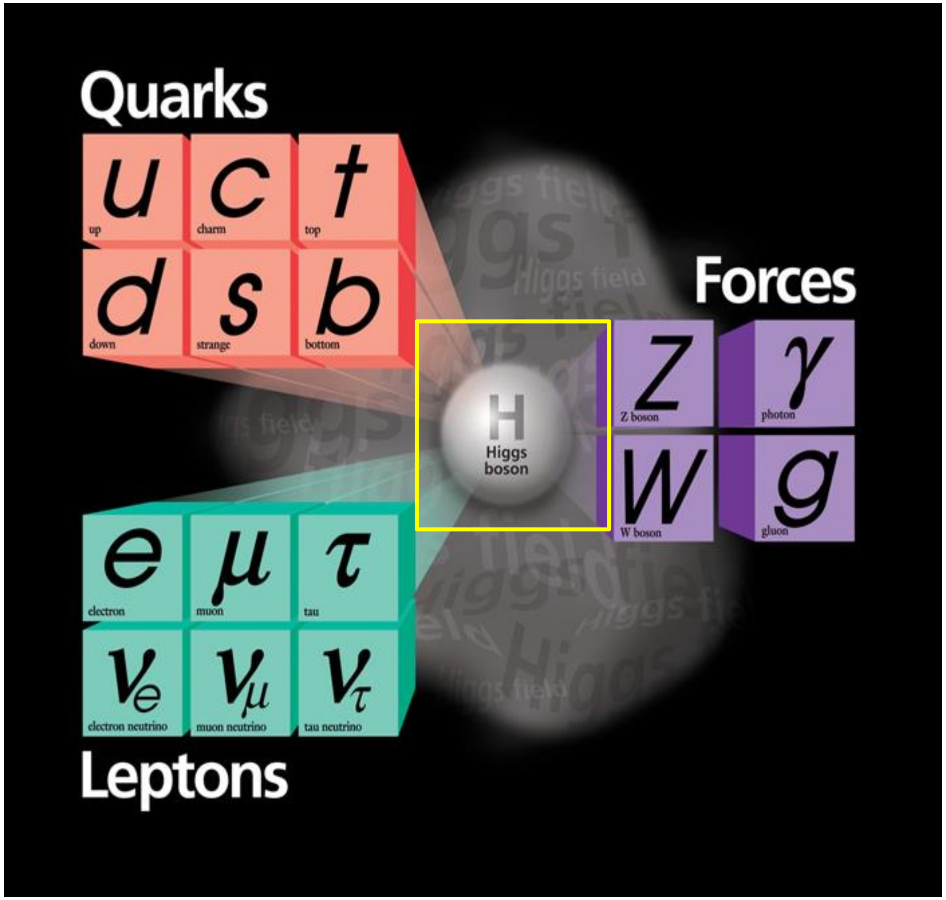
Outline

- 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
- 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.



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

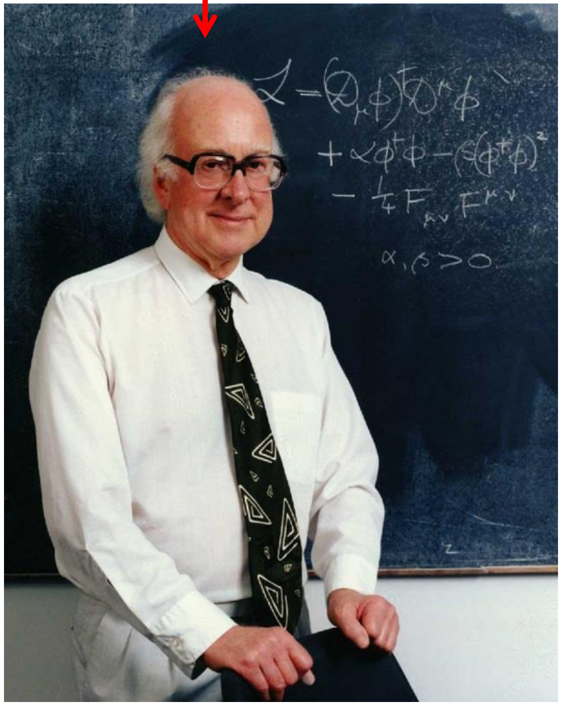
Higgs Mechanism (1964)

➢ **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

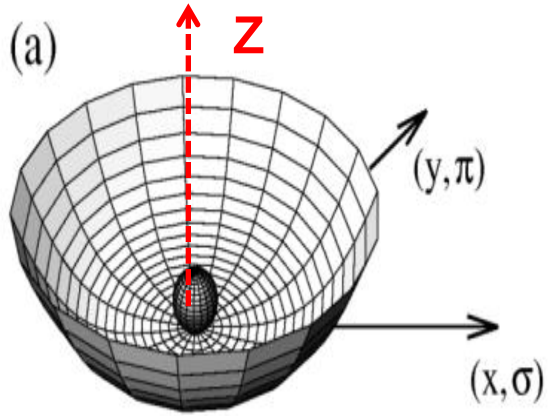
F. Englert, R. Brout
PRL 13 (1964.8.31) 321

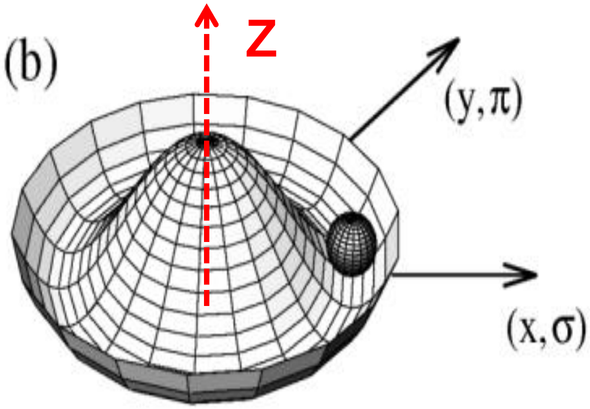
G.S. Guralnik, C.R. Hagen and
T.W.B. Kibble, PRL 13 (1964.11.16) 585



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.

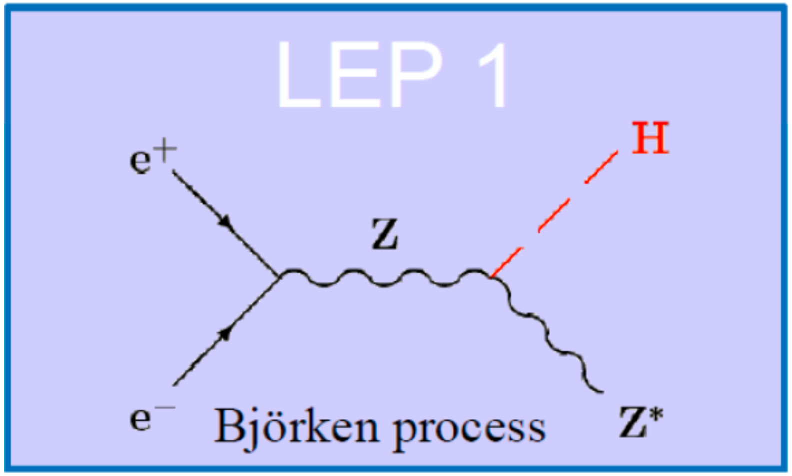
History of the Higgs Search

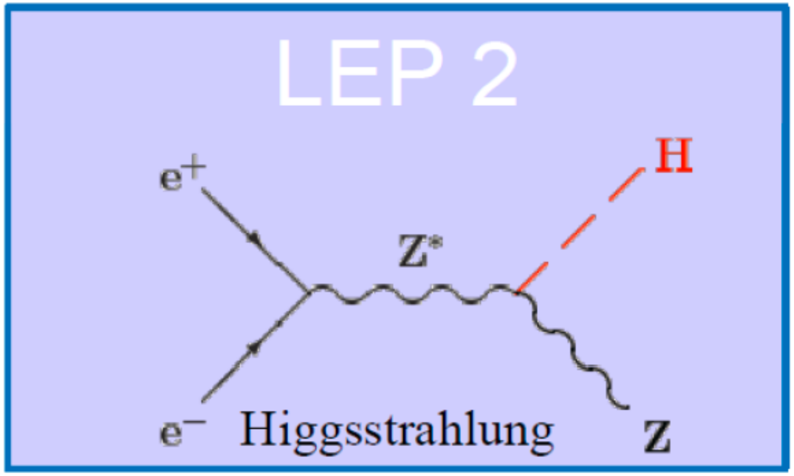
- 1964 Brout & Englert, Higgs, Guralnik, Hagen & Kibble,
  - Not taken too seriously until...
- 1973 Experimental acceptance of the Standard Model
- 1983 Discovery of W and Z bosons
  - Closely linked to the Higgs boson
- 1993 CERN/LEP1 studies Z's and rules out m_H<53 GeV
  - And indirectly excludes 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**

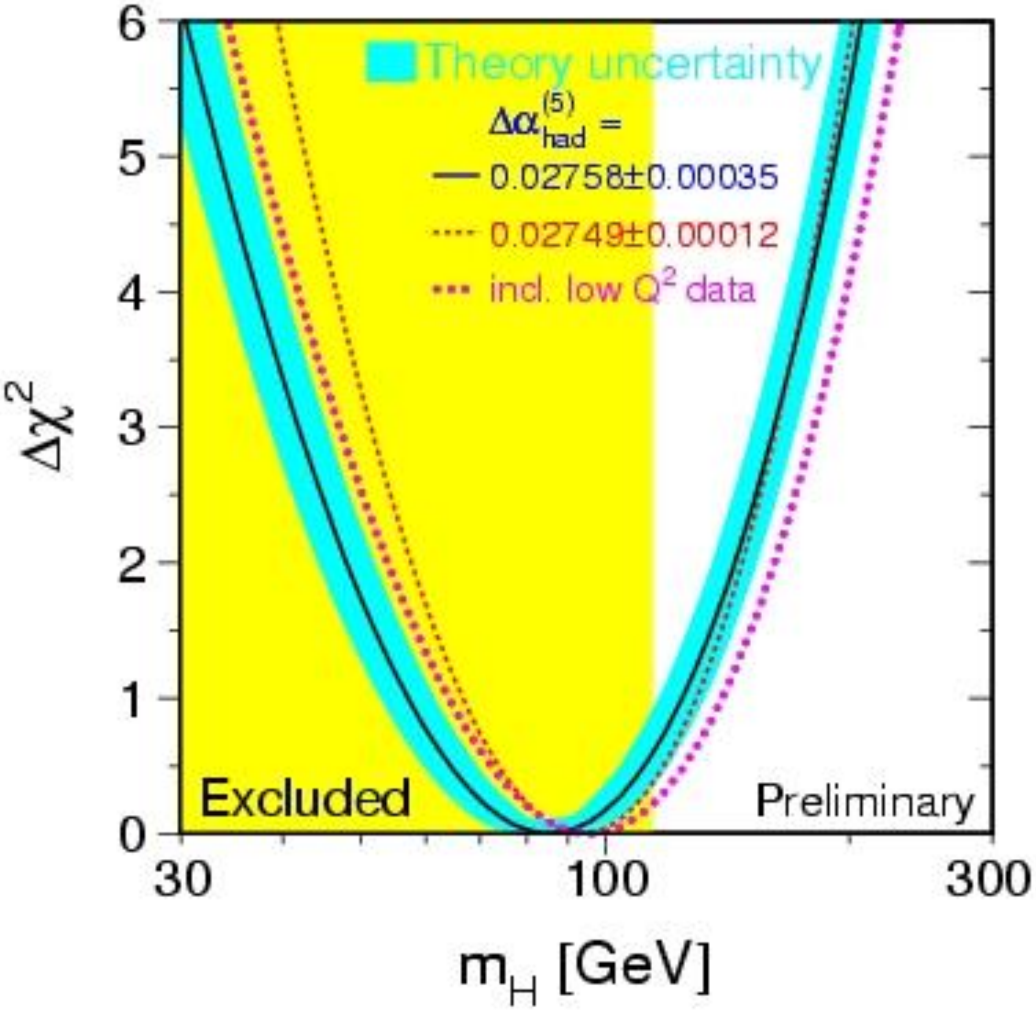
Search for Higgs boson at LEP

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

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

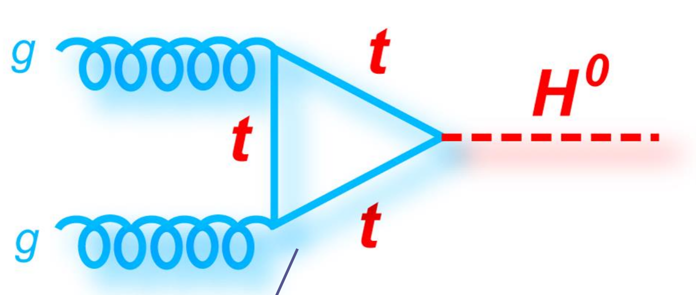


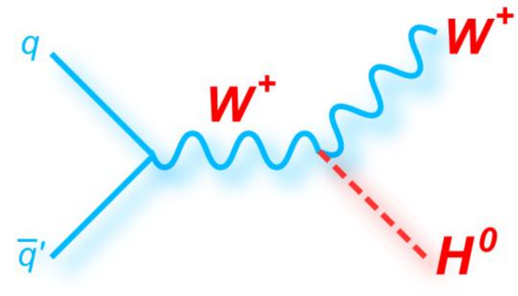


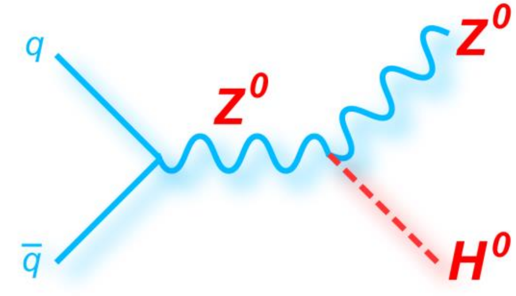


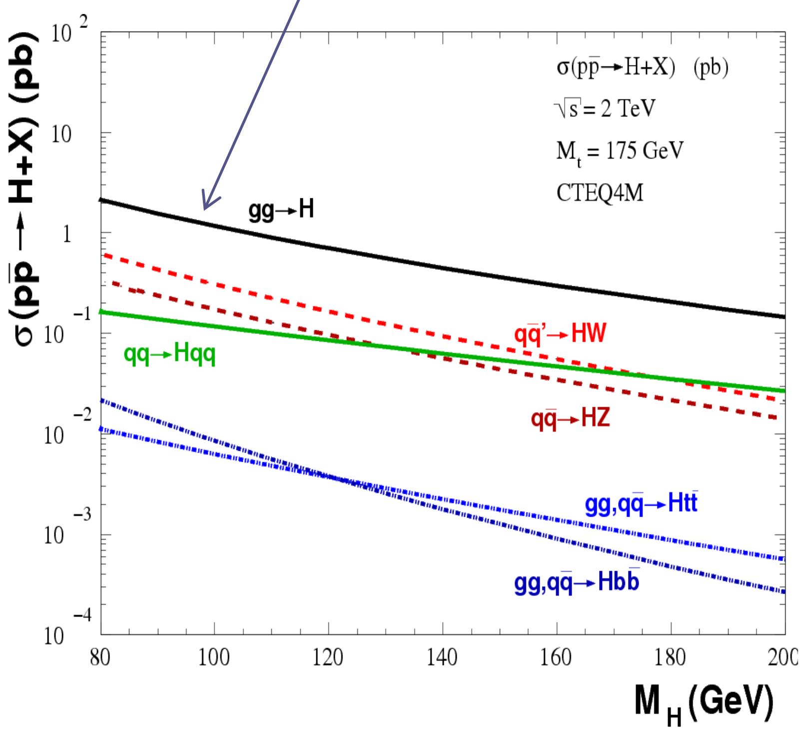
Search for Higgs boson at Tevatron

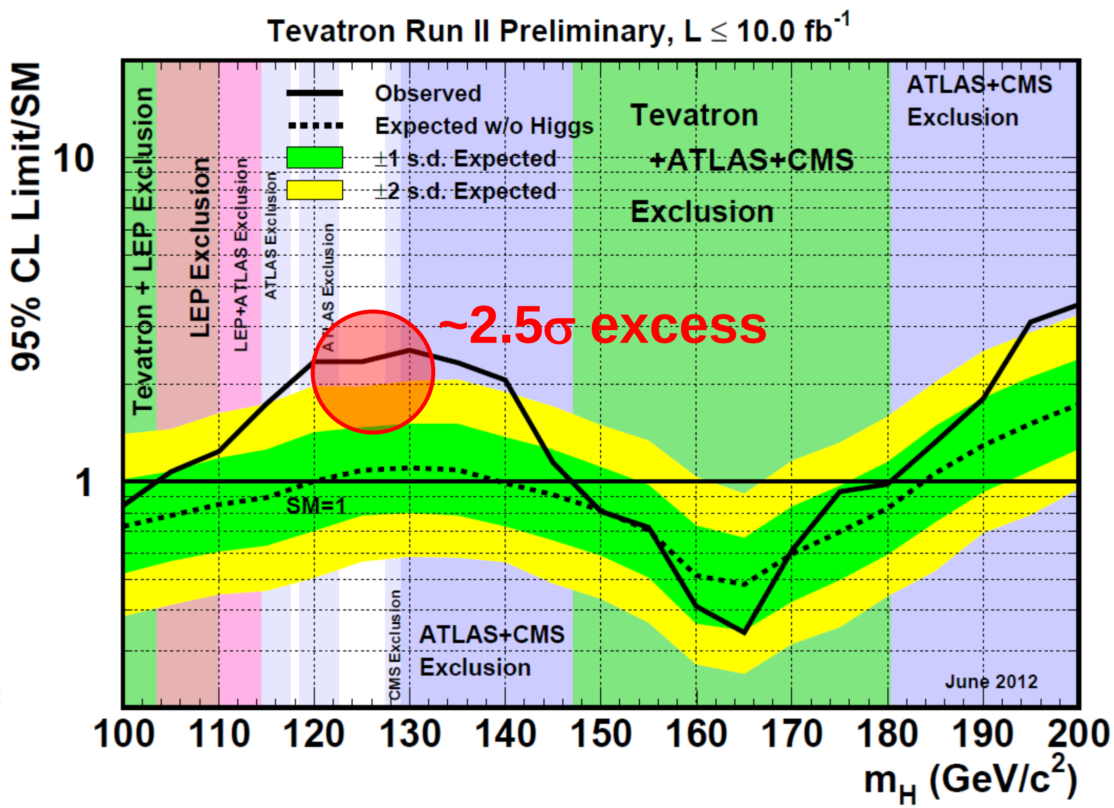
➔ Results (arXiv:1207.0449): 2.5σ excess at m_H=120-130 GeV





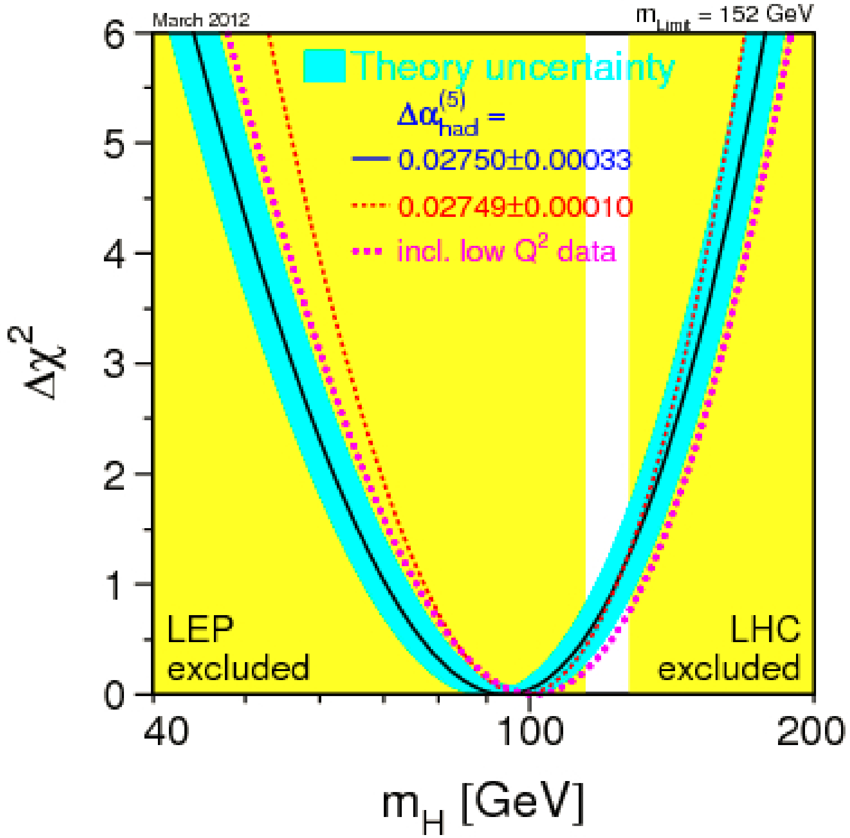


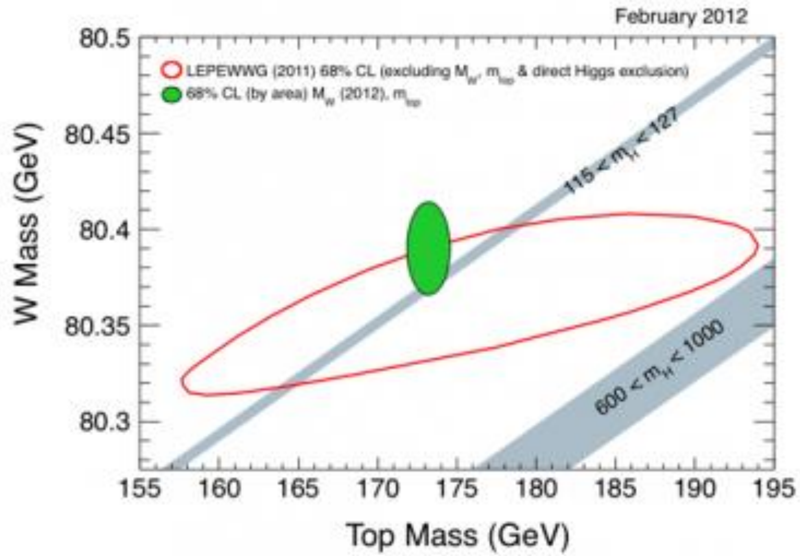


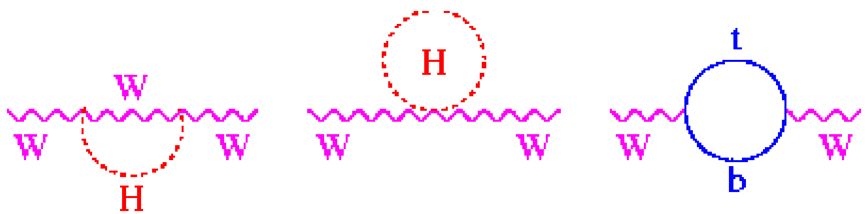


Searches for Higgs Boson at LEP and LHC

- 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



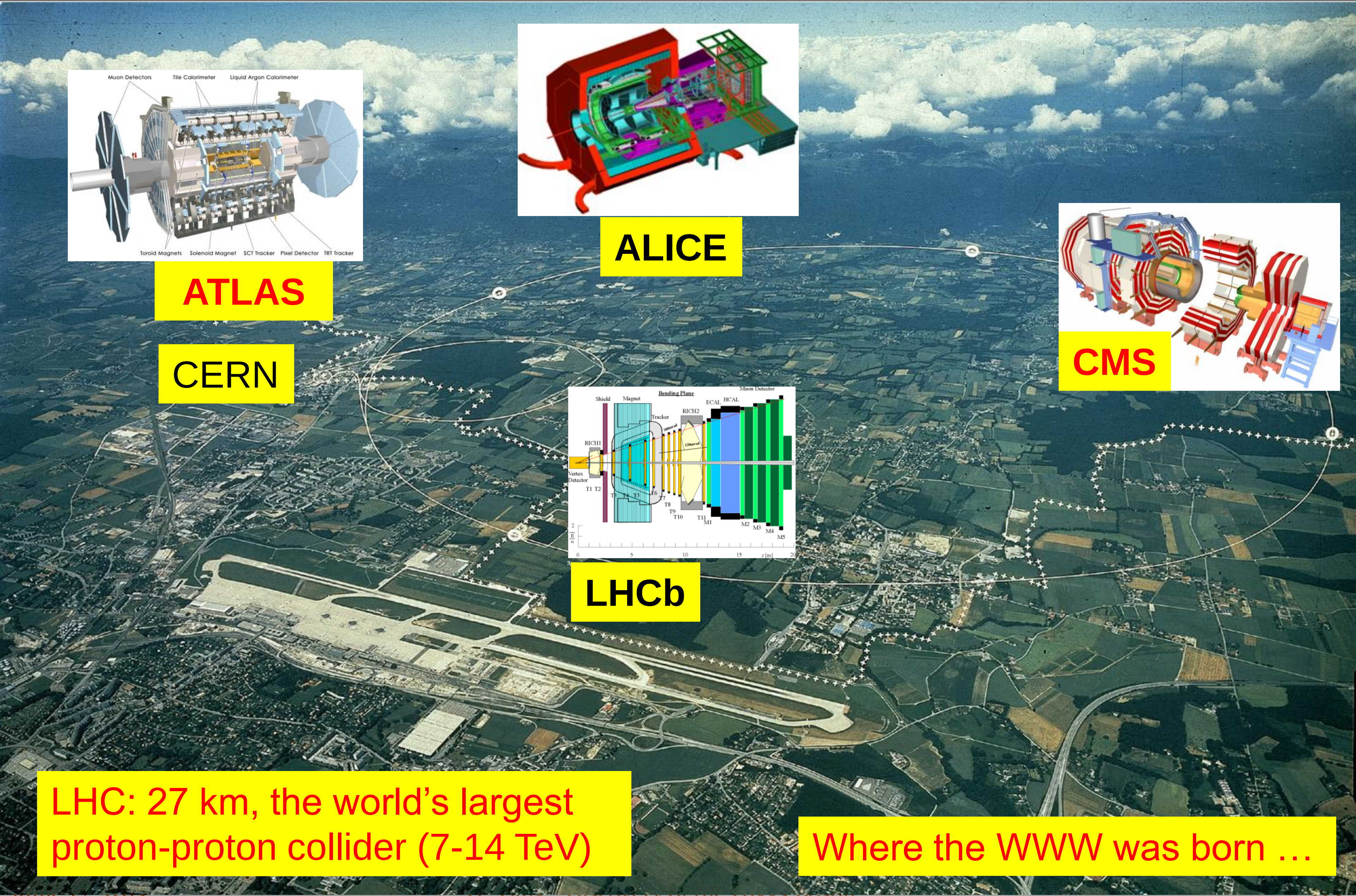




$M^2_W = M^2_Z(1-\sin^2\theta_w)(1+\Delta\rho)$

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

Large Hadron Collider at CERN

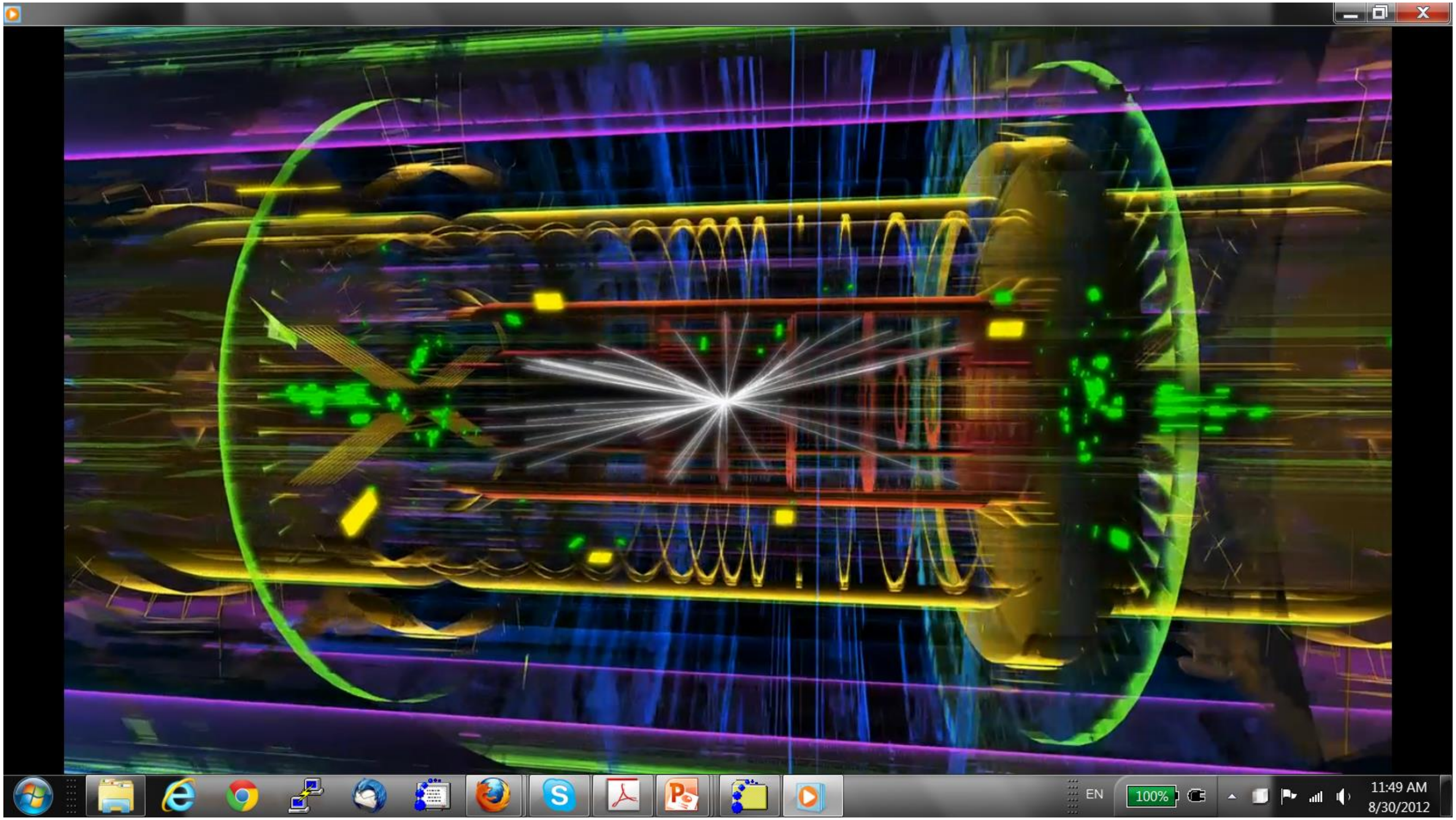


LHC: 27 km, the world's largest proton-proton collider (7-14 TeV)

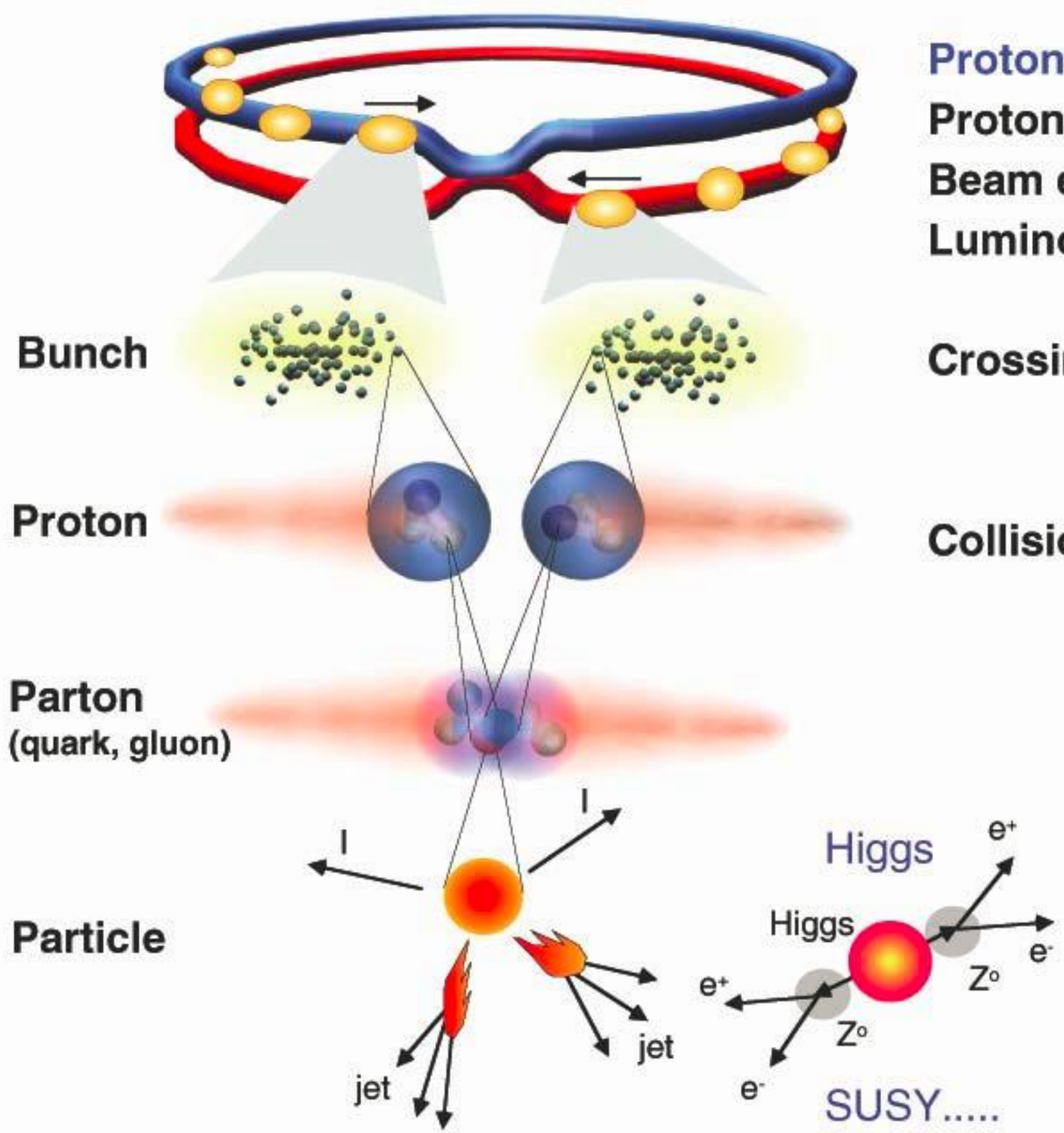
Where the WWW was born …

Particle Acceleration and Collision

- [Proton-proton collision at LHC]



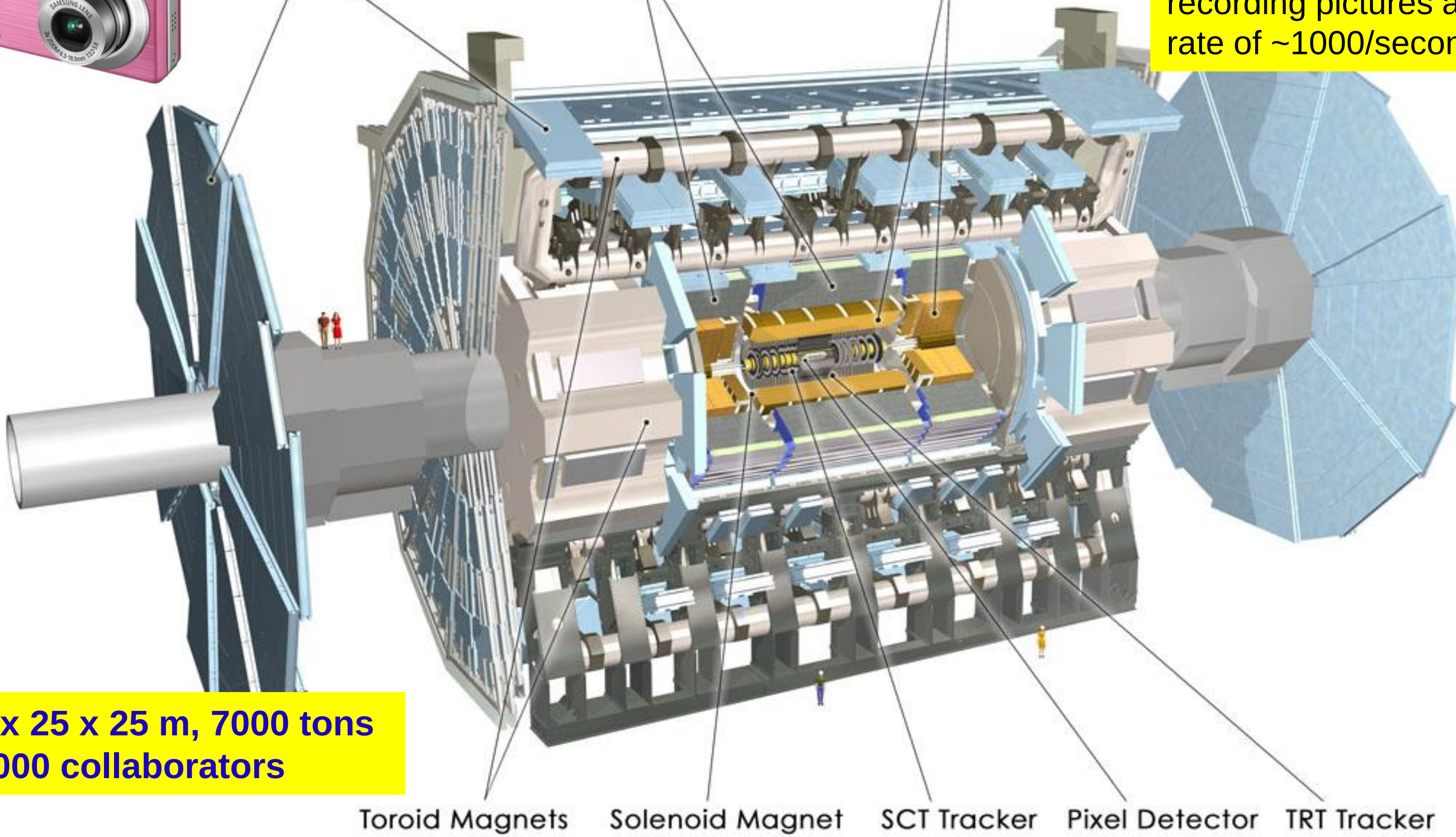
Proton-proton Collisions at LHC



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

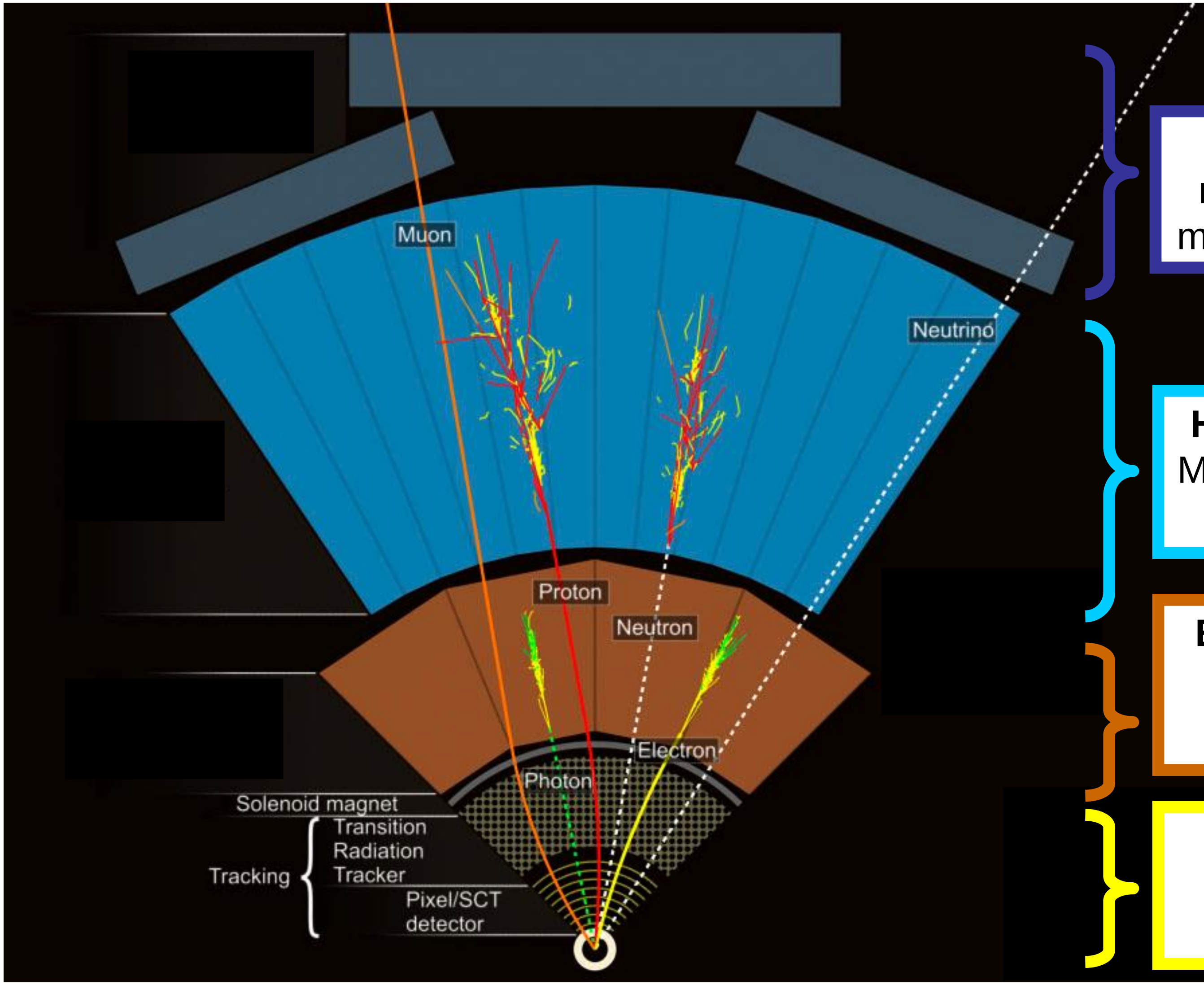


Taking pictures at a rate of 40 Millon/s and recording pictures at a rate of ~1000/second

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

Particle Detection

- Different particles have different signatures in detectors



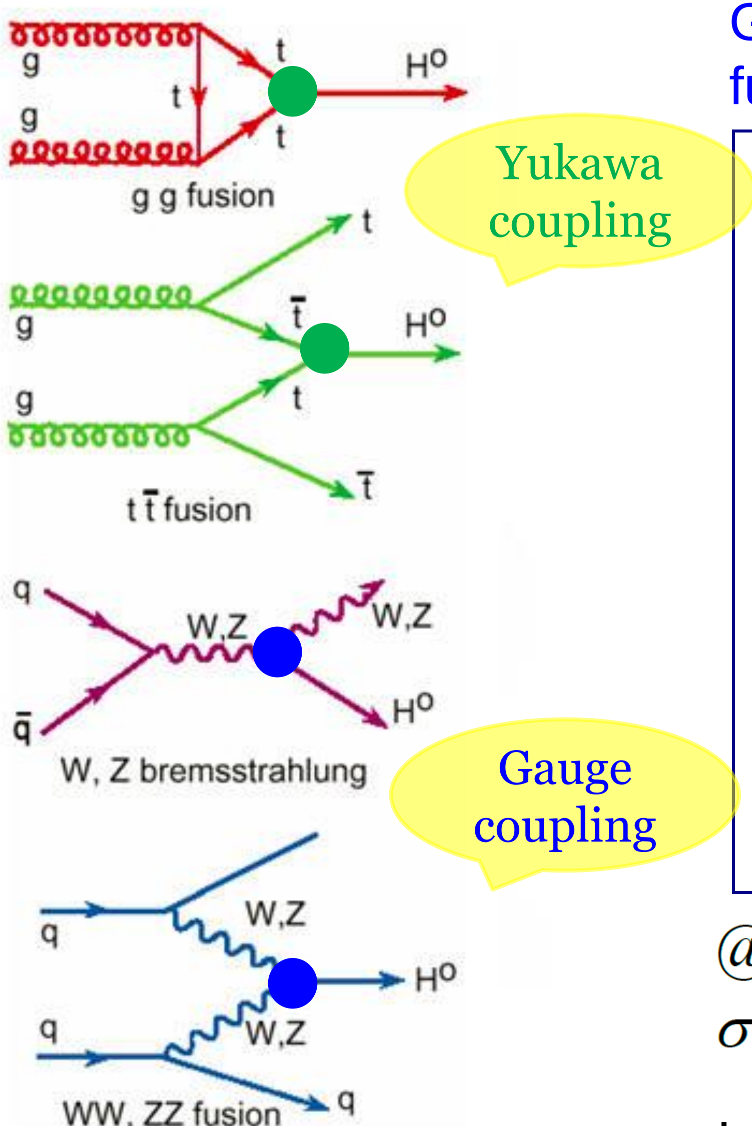
Muon Spectrometer:
muon identification and momentum measurement

Hadronic calorimeter:
Measurement of jets and missing energy

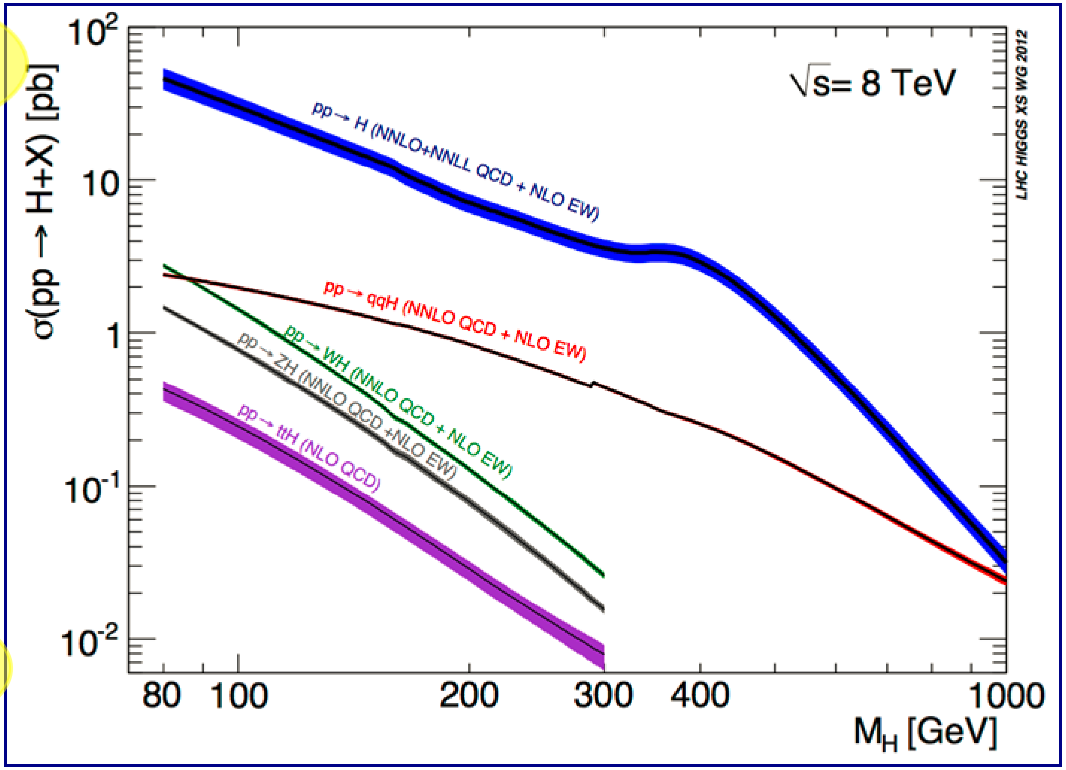
Electromagnetic calo:
e/γ identification and energy measurement

Tracking system:
Charged particle momentum, vertexing

Higgs Boson Production at LHC



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



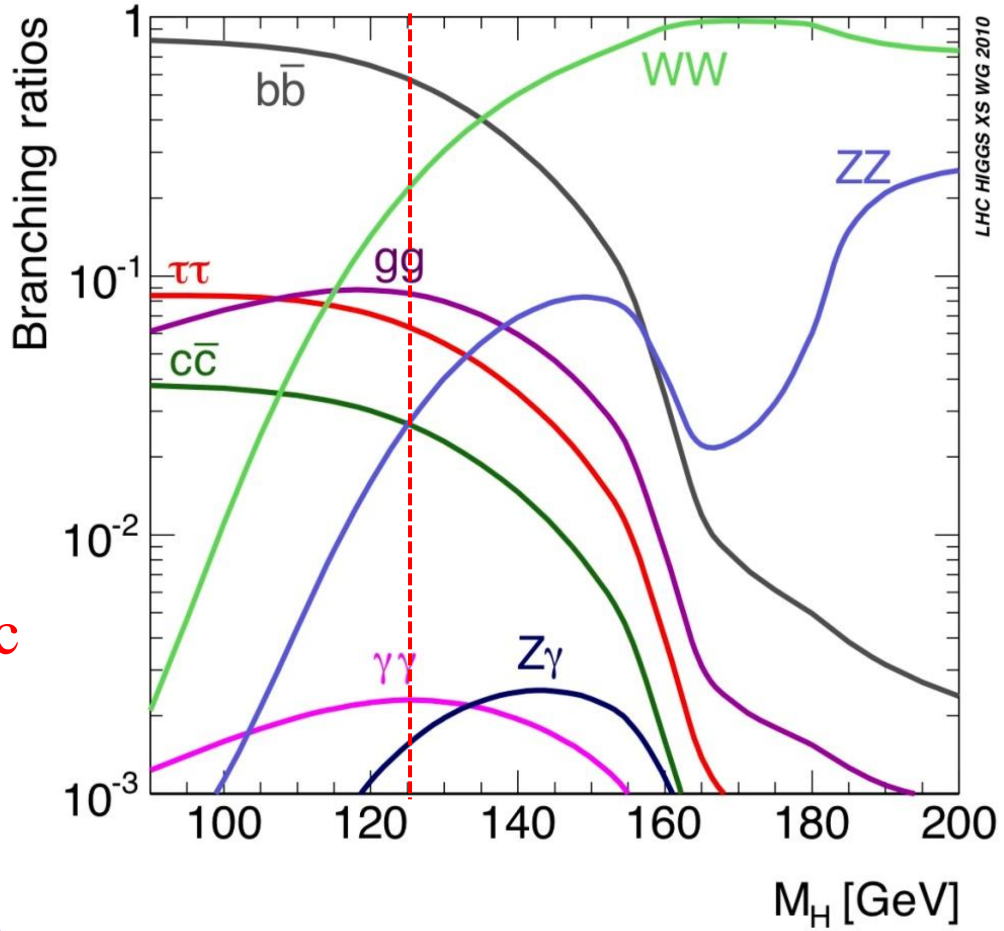
$$@125\ \text{GeV:}\quad \sigma_{ggH} = 19.5\ \text{pb},\ \sigma_{VBF} = 1.6\ \text{pb},$$
$$\sigma_{WH} = 0.70\ \text{pb},\ \sigma_{ZH} = 0.39\ \text{pb},\ \sigma_{ttH} = 0.13\ \text{pb}$$

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

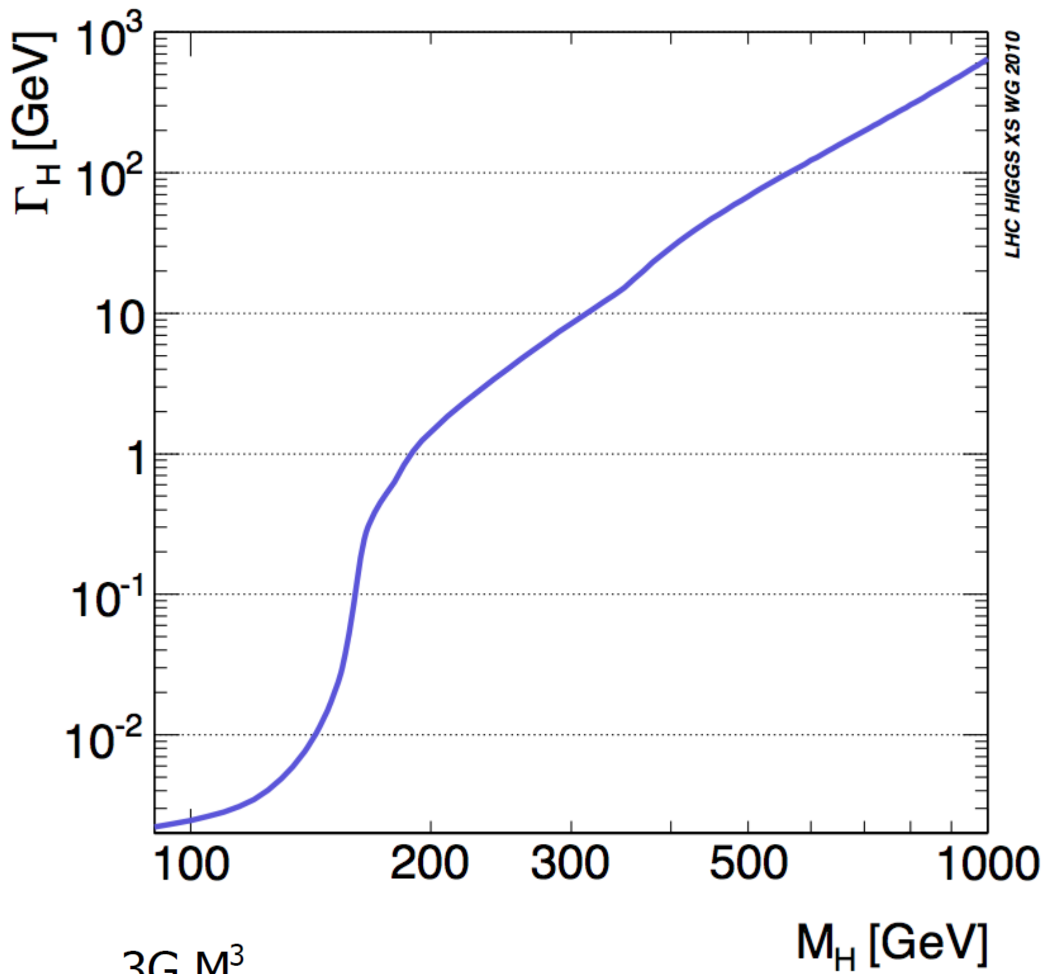
Higgs Boson Width

- **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

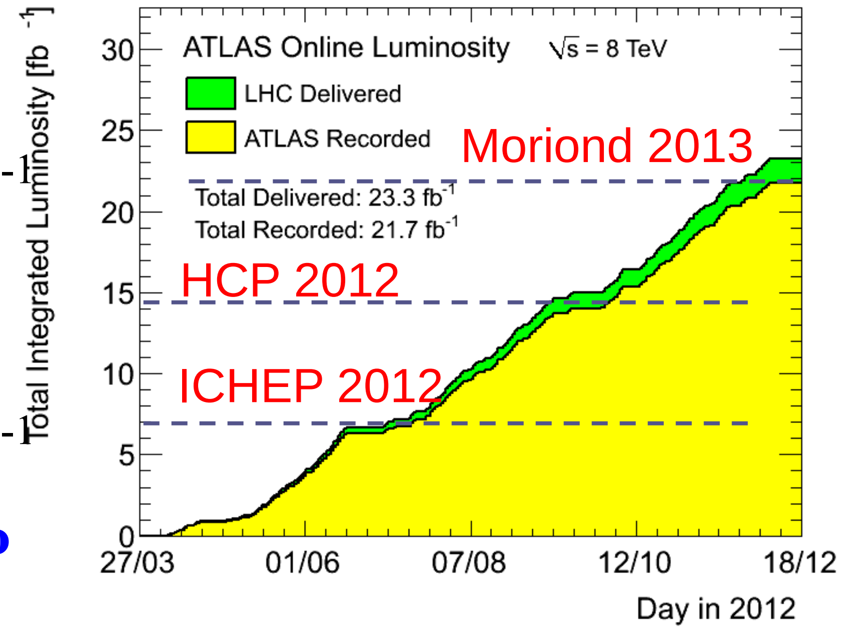


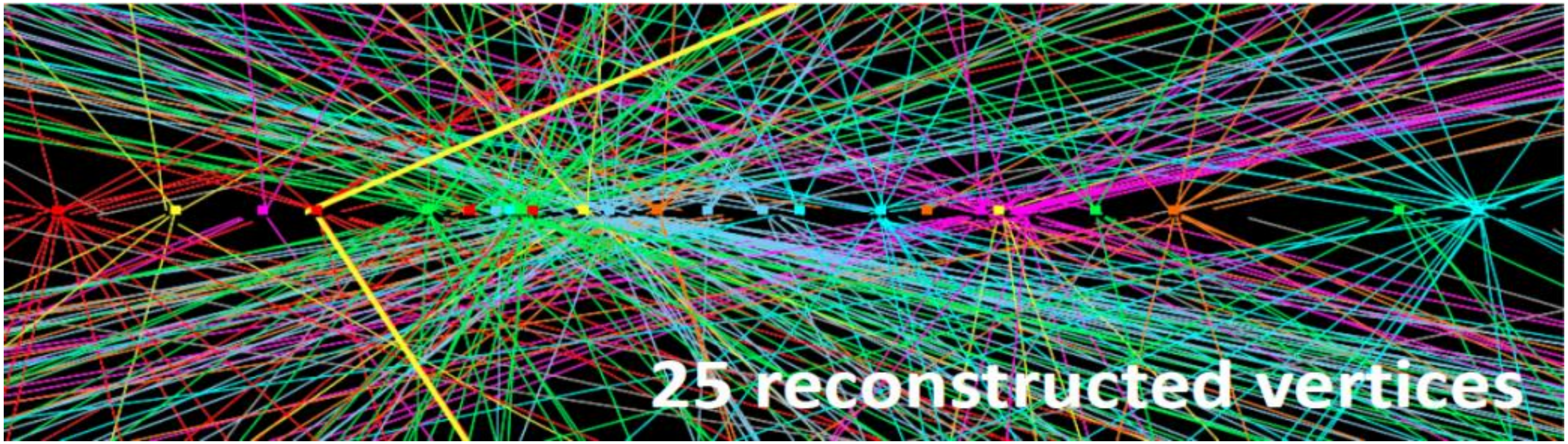
$$\Gamma_H \approx \frac{3G_F M_H^3}{16\pi\sqrt{2}}$$

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

ATLAS Data Samples

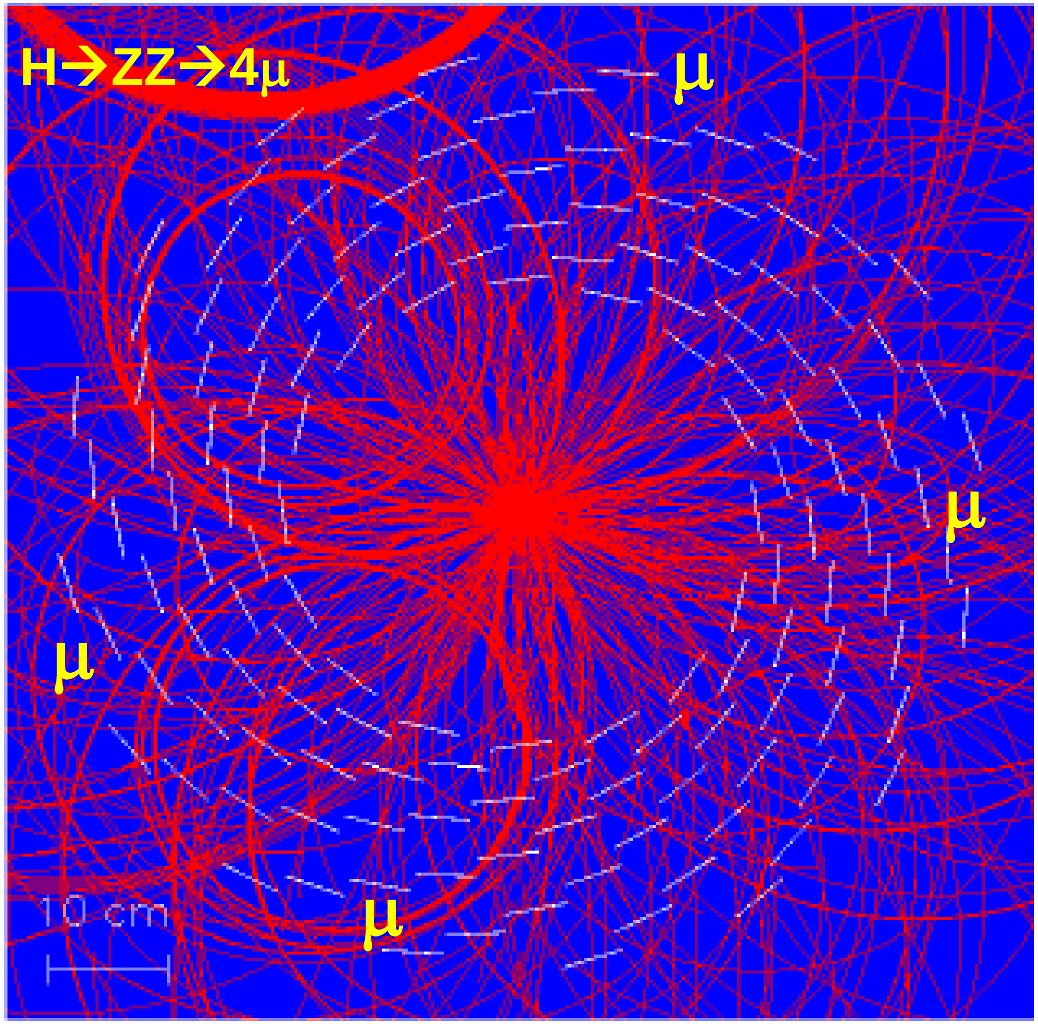
- **7 TeV data samples (2011)**
  - 4.8 fb^{-1} for physics analysis
  - Peak luminosity $3.6 \times 10^{33} cm^{-2}s^{-1}$
- **8 TeV data samples (2012)**
  - 20.7 fb^{-1} for physics analysis
  - Peak luminosity $7.7 \times 10^{33} cm^{-2}s^{-1}$
- **Data-taking efficiency: ~94%**
- **Significant pileup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



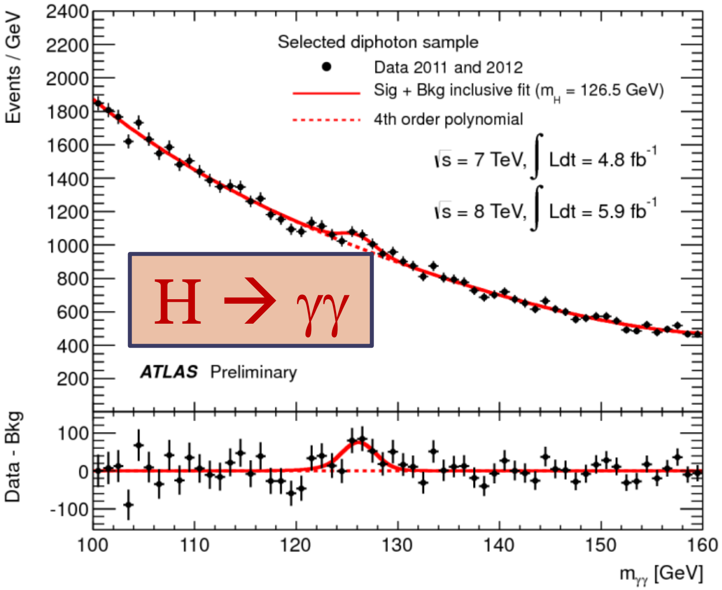


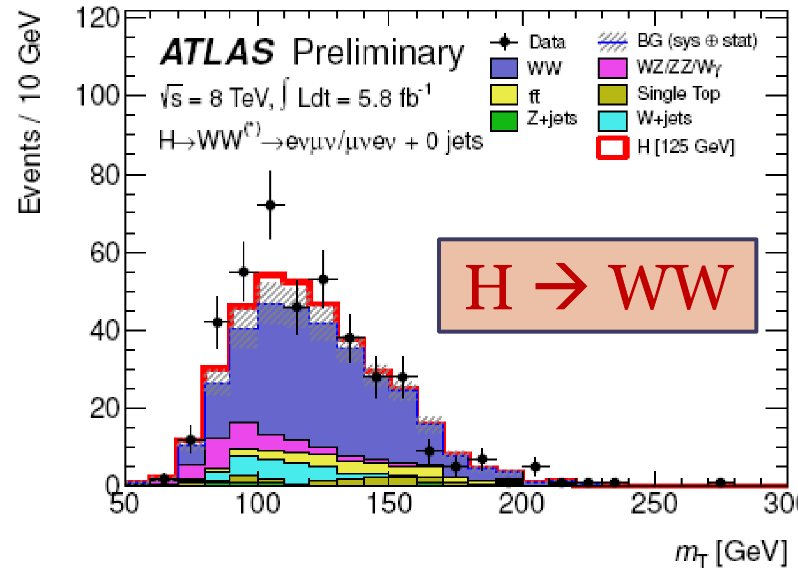
Major Challenge (Large Pileup)

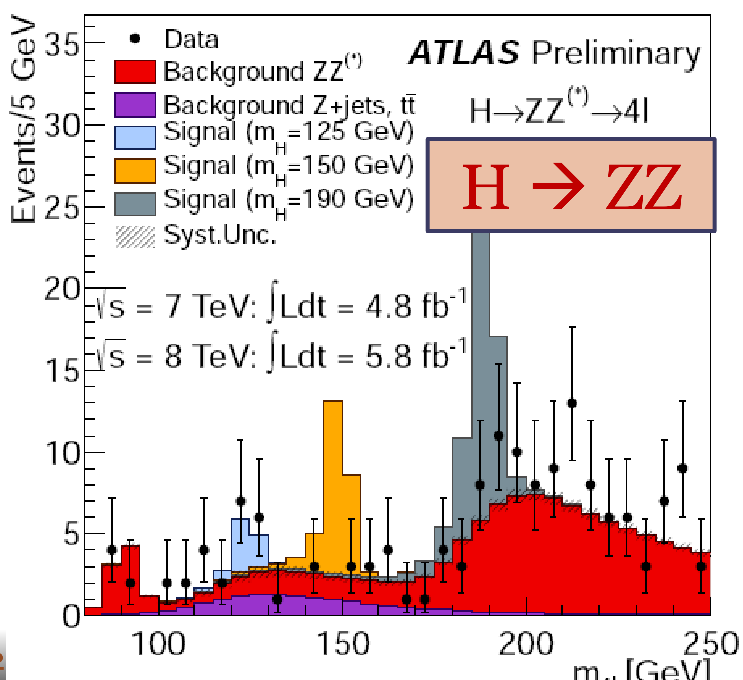
- Large pileup events result in big challenge to the detector, reconstruction and particle identification !

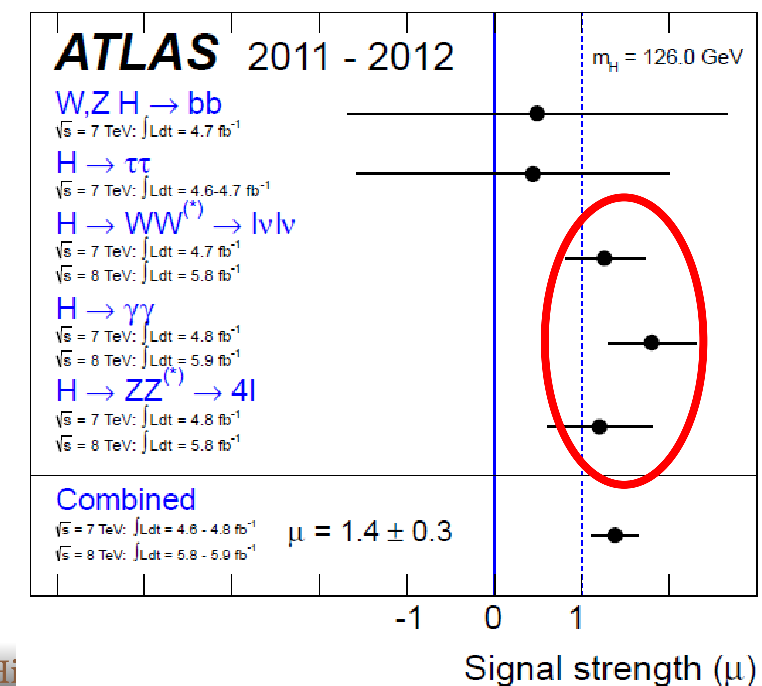


Observation of a new Particle (July 4, 2012)

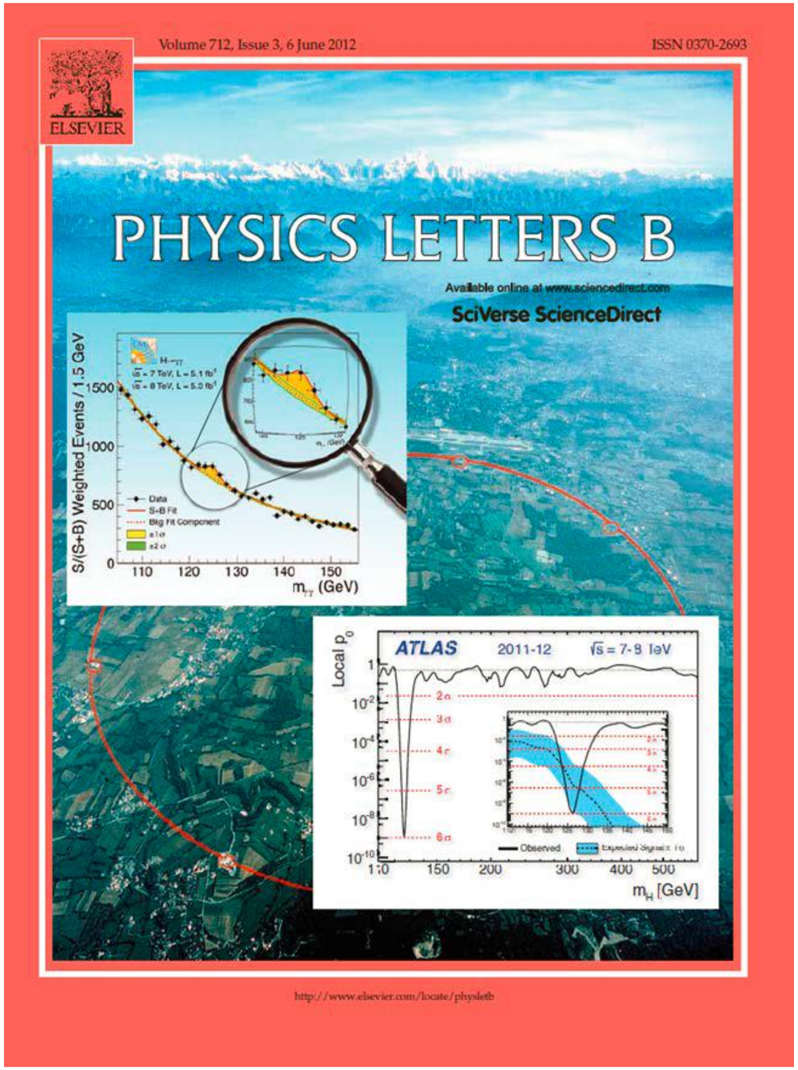








Observation of a new Particle (5σ) !



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

Update Since July 4, 2012

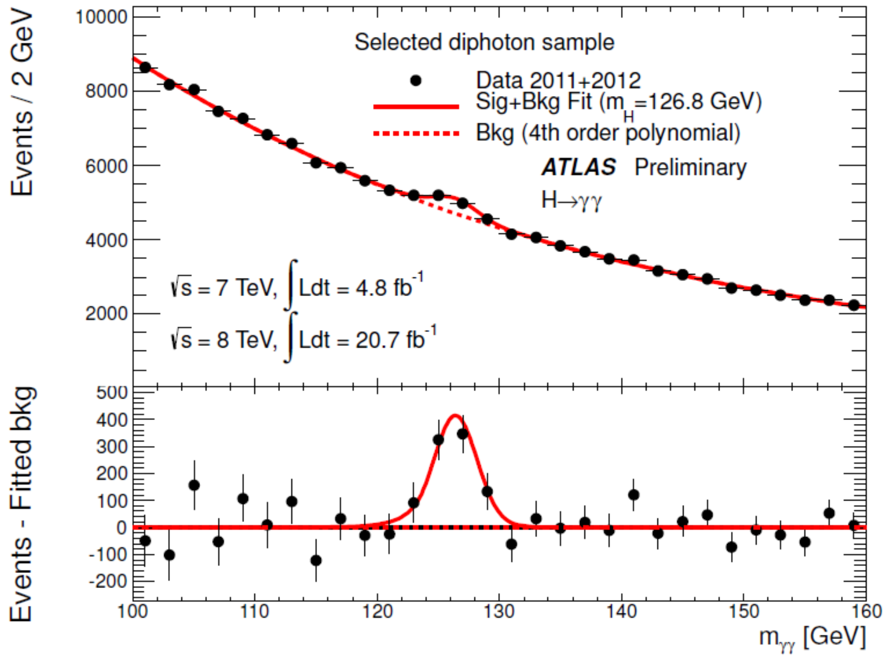
Ref: ATLAS-COM-CONF-2013-035, ATLAS-COM-CONF-2013-025

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

$\sqrt{s}$ = 8 TeV
Full dataset
20.7 fb^{-1} for
$\gamma\gamma$,ZZ,WW

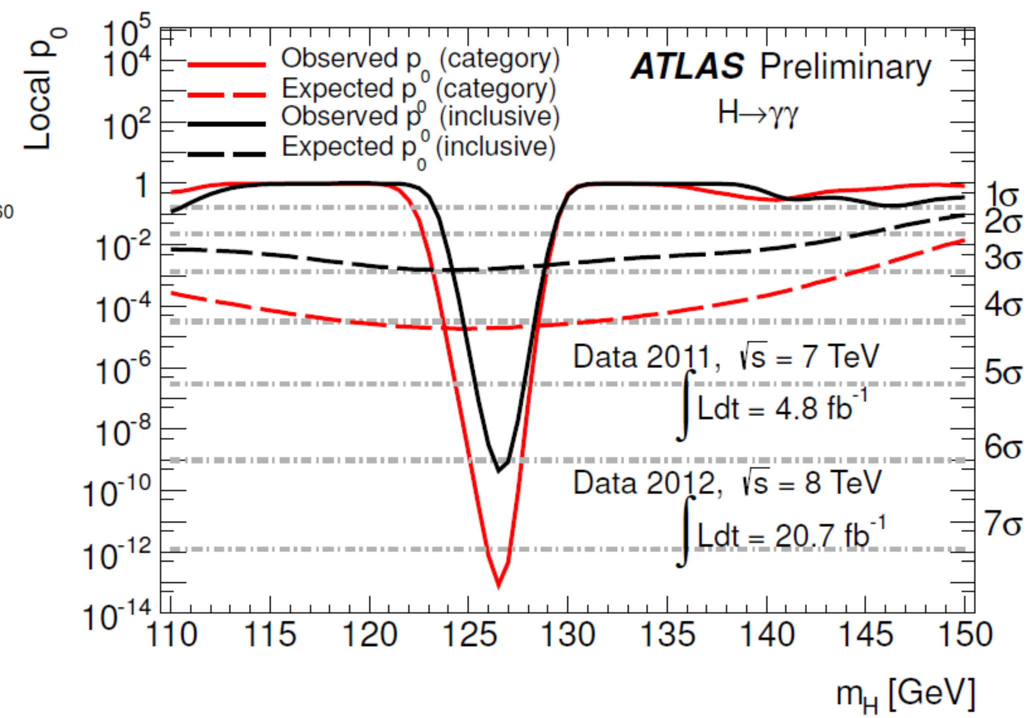
Higgs Boson Decay	Subsequent Decay	Sub-Channels	$\int L\,dt$ [fb^{-1}]	Ref.
		2011 $\sqrt{s}$ =7 TeV		
$H \to ZZ^{(*)}$	4ℓ	$\{4e, 2e2\mu, 2\mu 2e, 4\mu\}$	4.6	[8]
$H \to \gamma\gamma$	–	10 categories $\{p_{Tt} \otimes \eta_\gamma \otimes \text{conversion}\} \oplus \{\text{2-jet VBF}\}$	4.8	[7]
$H \to WW^{(*)}$	$\ell\nu\ell\nu$	$\{ee, e\mu, \mu e, \mu\mu\} \otimes \{\text{0-jet, 1-jet, 2-jet VBF}\}$	4.6	[9]
$H \to \tau\tau$	$\tau_{lep}\tau_{lep}$	$\{e\mu\} \otimes \{\text{0-jet}\} \oplus \{\ell\ell\} \otimes \{\text{1-jet, 2-jet, } p_{T,\tau\tau} > 100 \text{ GeV}, VH\}$	4.6	[10]
	$\tau_{lep}\tau_{had}$	$\{e, \mu\} \otimes \{\text{0-jet, 1-jet, } p_{T,\tau\tau} > 100 \text{ GeV, 2-jet}\}$	4.6	
	$\tau_{had}\tau_{had}$	$\{\text{1-jet, 2-jet}\}$	4.6	
$VH \to Vbb$	$Z \to \nu\nu$	$E_T^{miss} \in \{120-160, 160-200, \geq 200 \text{ GeV}\} \otimes \{\text{2-jet, 3-jet}\}$	4.6	[11]
	$W \to \ell\nu$	$p_T^W \in \{< 50, 50-100, 100-150, 150-200, \geq 200 \text{ GeV}\}$	4.7	
	$Z \to \ell\ell$	$p_T^Z \in \{< 50, 50-100, 100-150, 150-200, \geq 200 \text{ GeV}\}$	4.7	
		2012 $\sqrt{s}$ =8 TeV		
$H \to ZZ^{(*)}$	4ℓ	$\{4e, 2e2\mu, 2\mu 2e, 4\mu\}$	20.7	[8]
$H \to \gamma\gamma$	–	14 categories $\{p_{Tt} \otimes \eta_\gamma \otimes \text{conversion}\} \oplus \{\text{2-jet VBF}\} \oplus \{\ell\text{-tag}, E_T^{miss}\text{-tag, 2-jet VH}\}$	20.7	[7]
$H \to WW^{(*)}$	$\ell\nu\ell\nu$	$\{ee, e\mu, \mu e, \mu\mu\} \otimes \{\text{0-jet, 1-jet, 2-jet VBF}\}$	20.7	[9]
$H \to \tau\tau$	$\tau_{lep}\tau_{lep}$	$\{\ell\ell\} \otimes \{\text{1-jet, 2-jet, } p_{T,\tau\tau} > 100 \text{ GeV}, VH\}$	13	[10]
	$\tau_{lep}\tau_{had}$	$\{e, \mu\} \otimes \{\text{0-jet, 1-jet, } p_{T,\tau\tau} > 100 \text{ GeV, 2-jet}\}$	13	
	$\tau_{had}\tau_{had}$	$\{\text{1-jet, 2-jet}\}$	13	
$VH \to Vbb$	$Z \to \nu\nu$	$E_T^{miss} \in \{120-160, 160-200, \geq 200 \text{ GeV}\} \otimes \{\text{2-jet, 3-jet}\}$	13	[11]
	$W \to \ell\nu$	$p_T^W \in \{< 50, 50-100, 100-150, 150-200, \geq 200 \text{ GeV}\}$	13	
	$Z \to \ell\ell$	$p_T^Z \in \{< 50, 50-100, 100-150, 150-200, \geq 200 \text{ GeV}\}$	13	

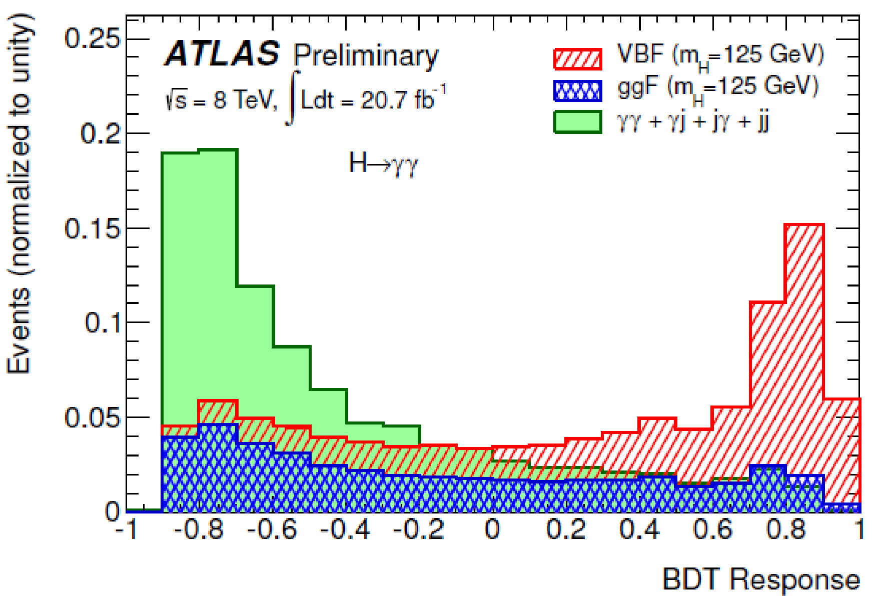
Update of H → γγ



Higgs Significance

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

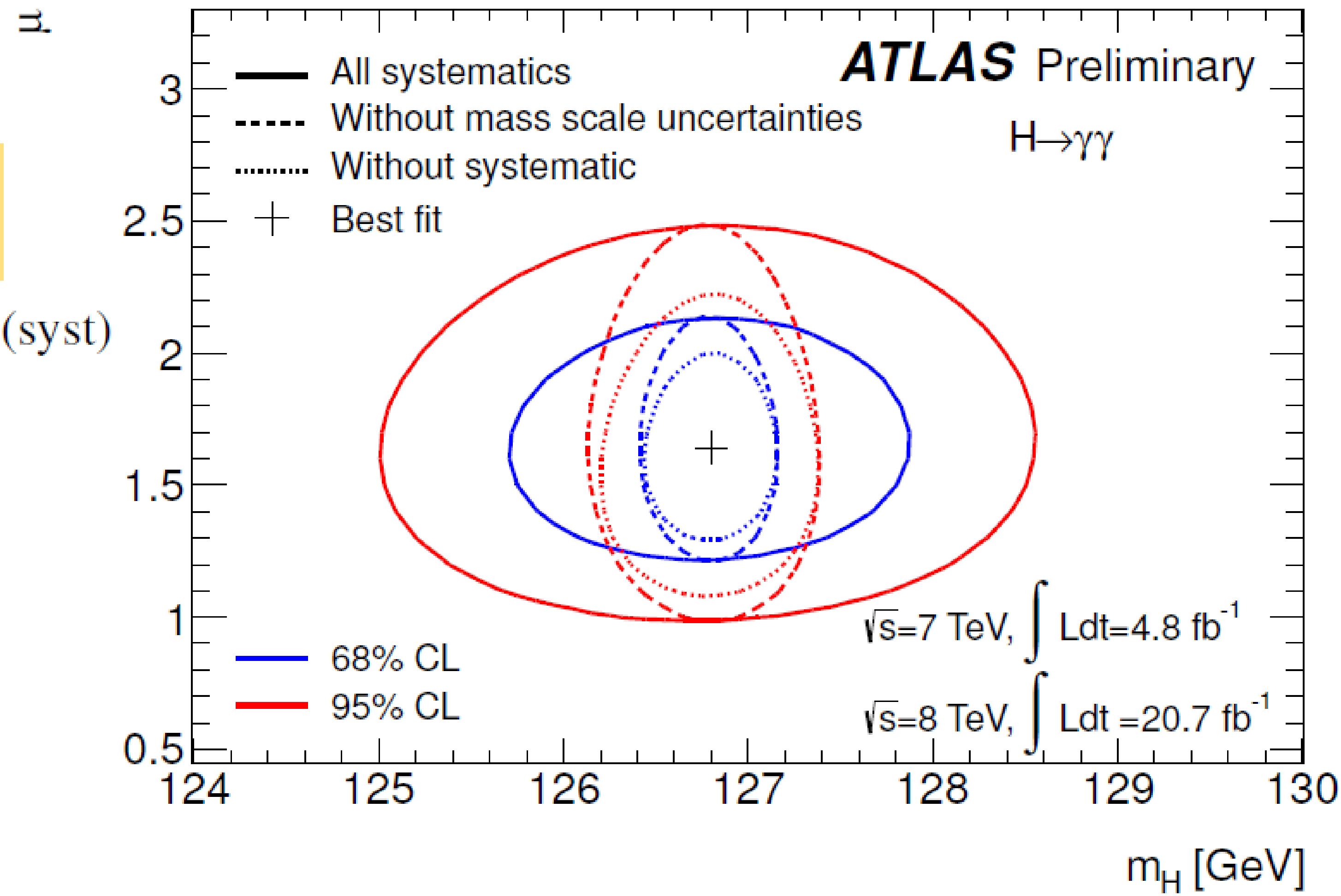




Update of H → γγ

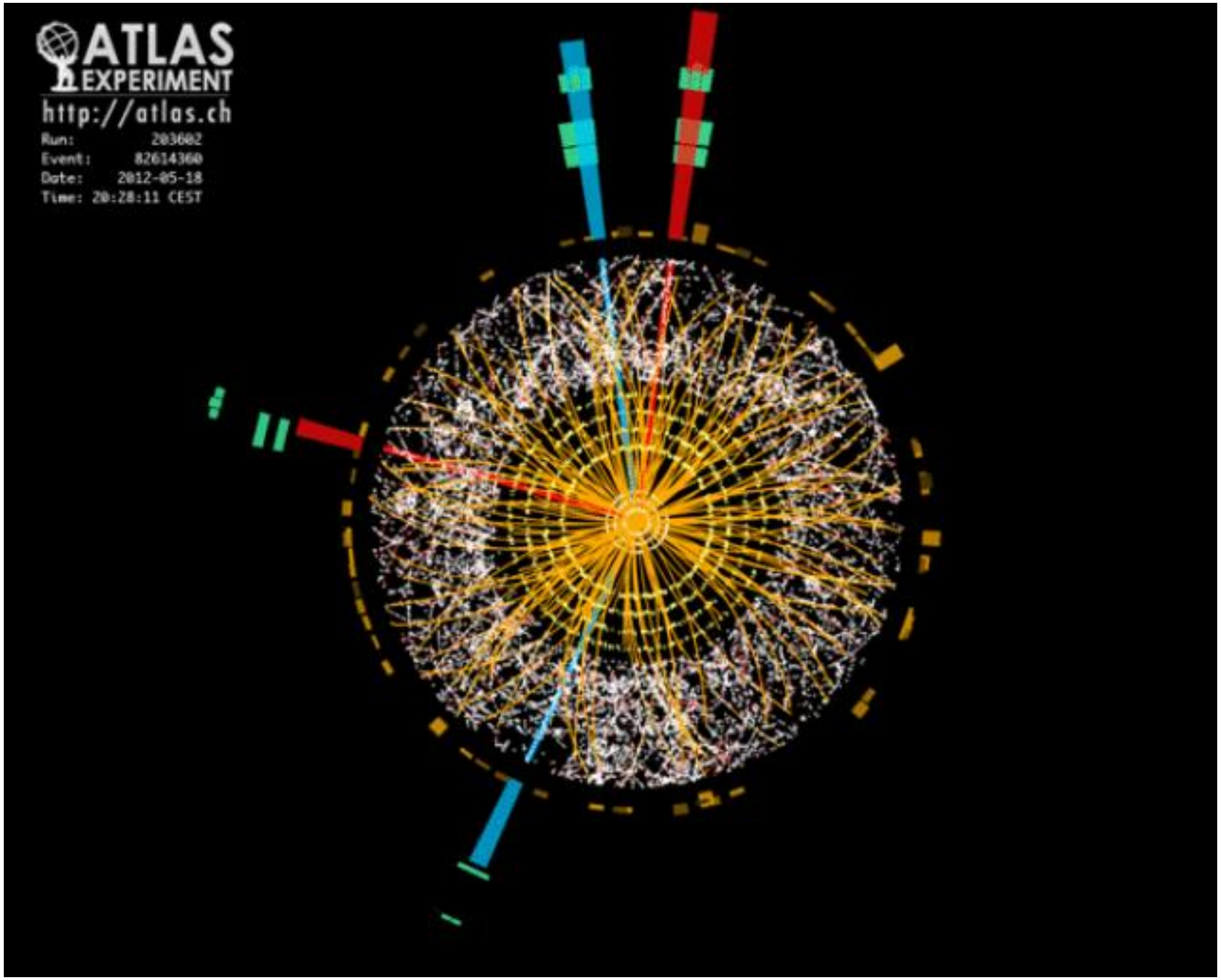
Best fitted Signal strength

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

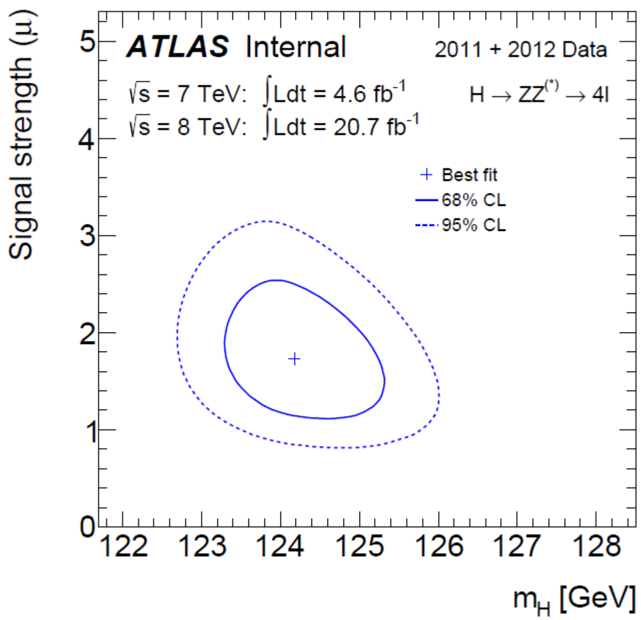


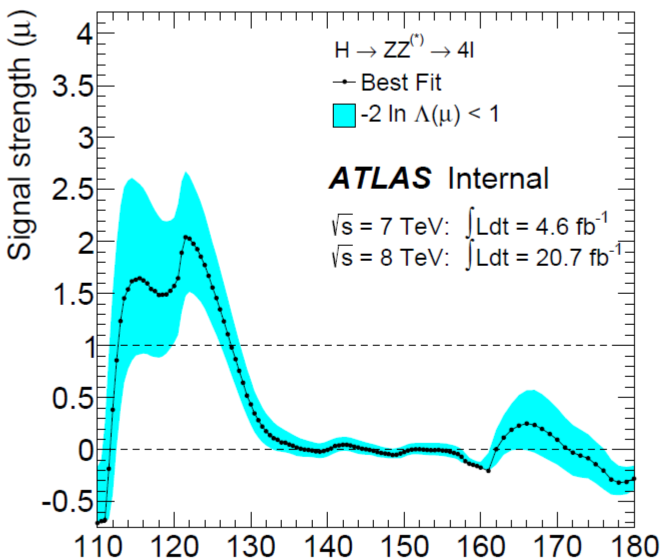
Best fitted mass:
M_H = 126.8 ± 0.2(stat) ± 0.7(syst) GeV

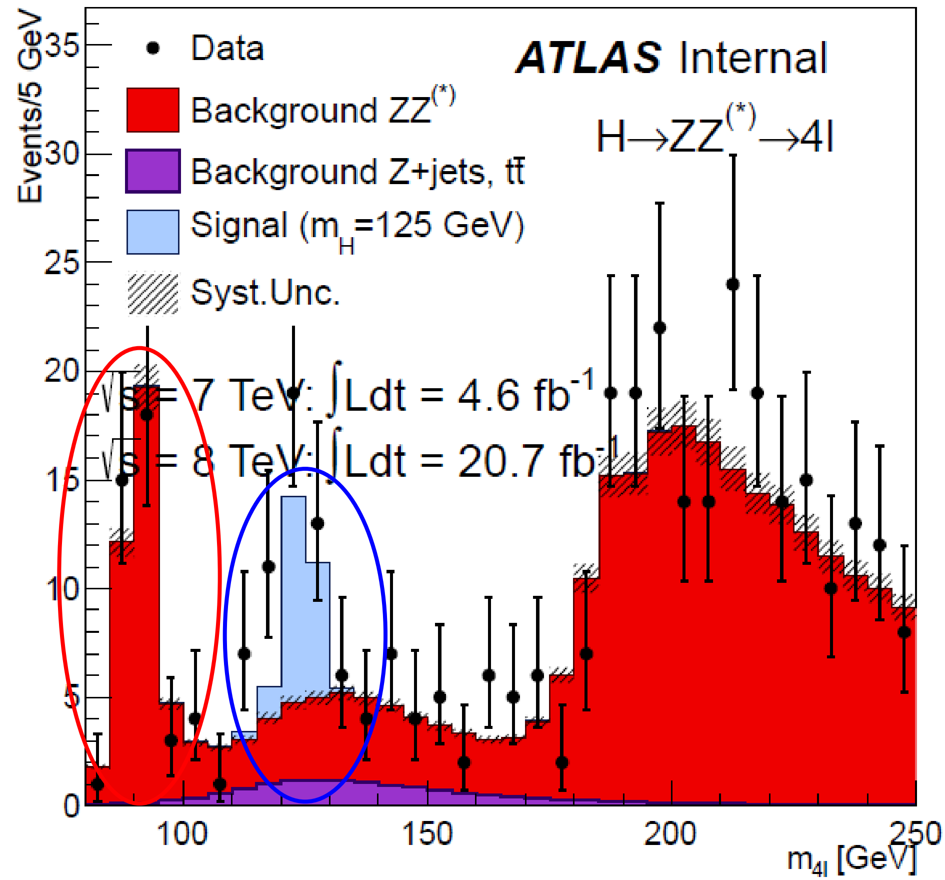
Evolution of Higgs →ZZ* →4l Candidates



Update of H→ZZ*→4l







Best fit mass:

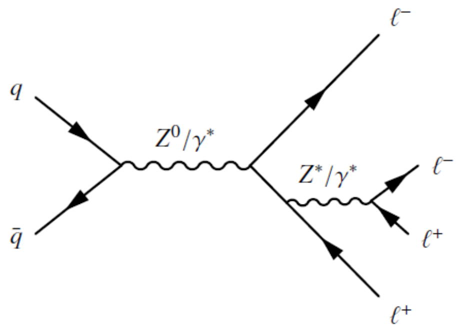
M_H = 124.2 ± 0.6(stat) ± 0.3(syst) GeV

Best fit signal strength:

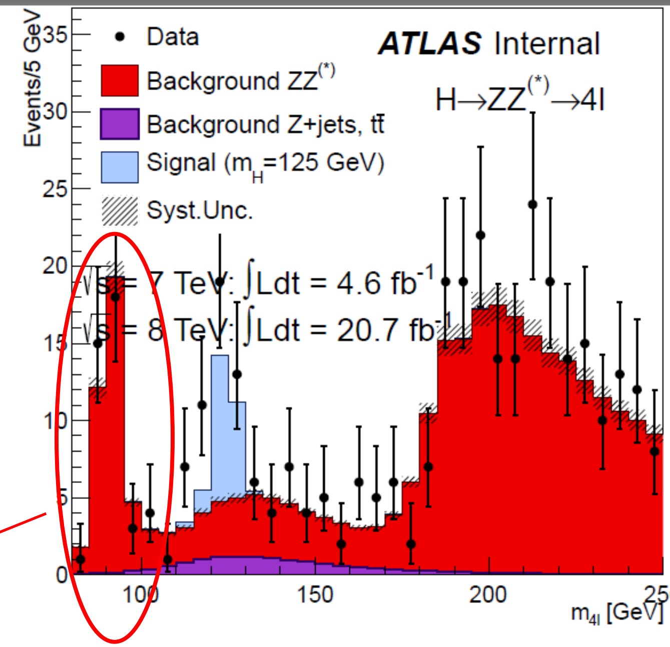
μ = 1.7 + 0.5 (– 0.4) @ 124.2 GeV

μ = 1.5 ± 0.4 @ 125.5 GeV

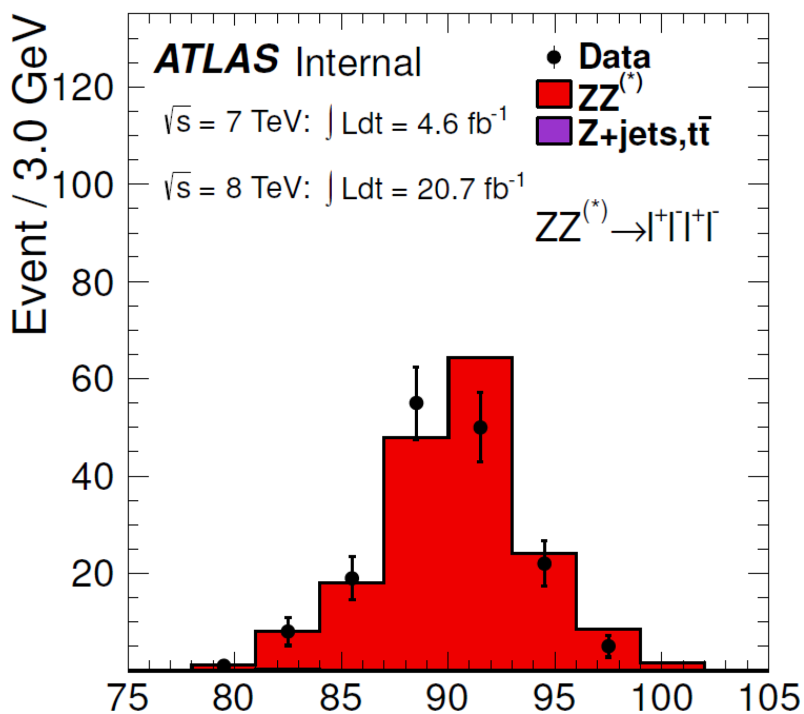
Update of Z→4l

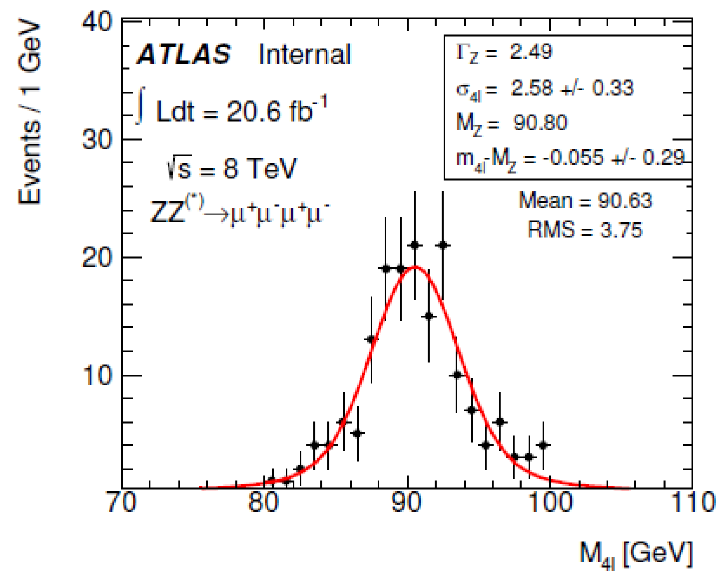


Single resonant Z→4l enhanced by relaxing mass, P_T requirements

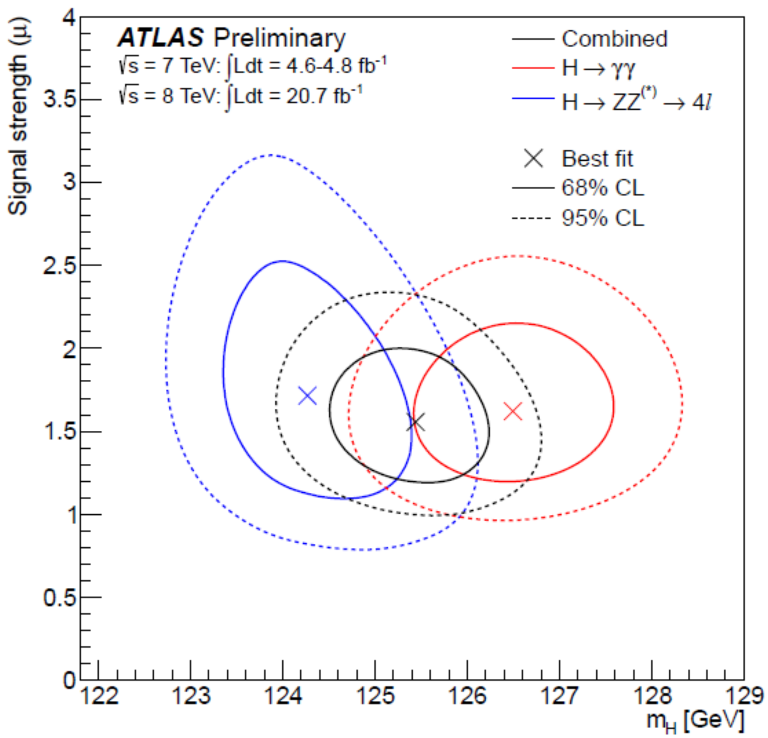


BR of Z→4l is measured to be $(4.2\pm0.4)\times10^{-6}$, consistent with SM prediction $(4.37\pm0.03)\times10^{-6}$.



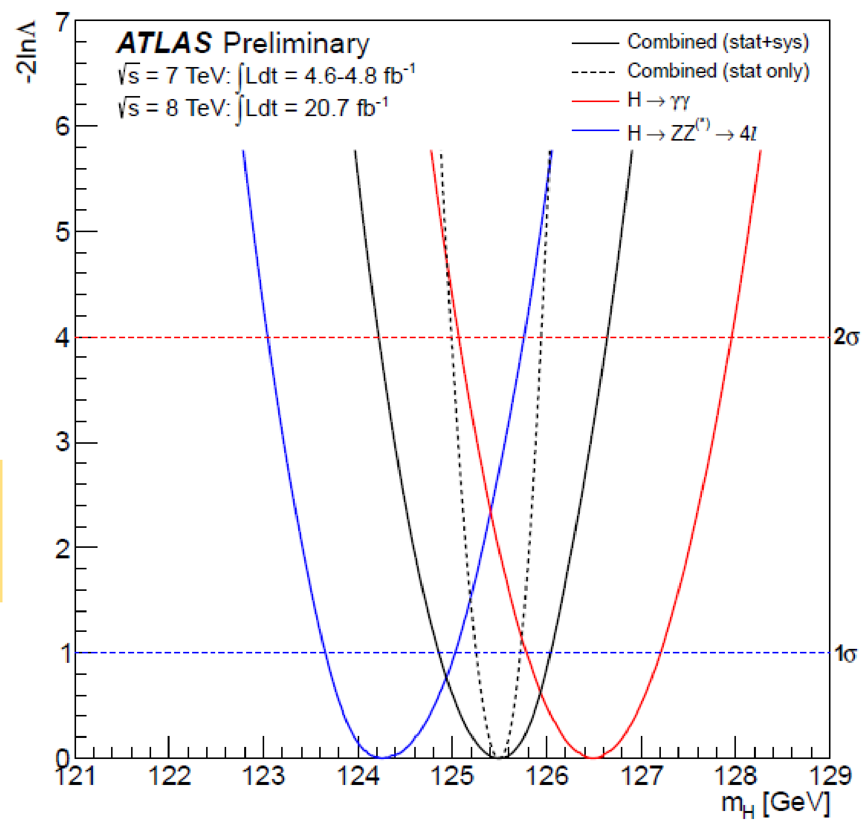


Higgs Mass Measurements



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

Best fit mass for combination:
M_H = 125.5 ±0.2(stat) ± 0.6(syst) GeV

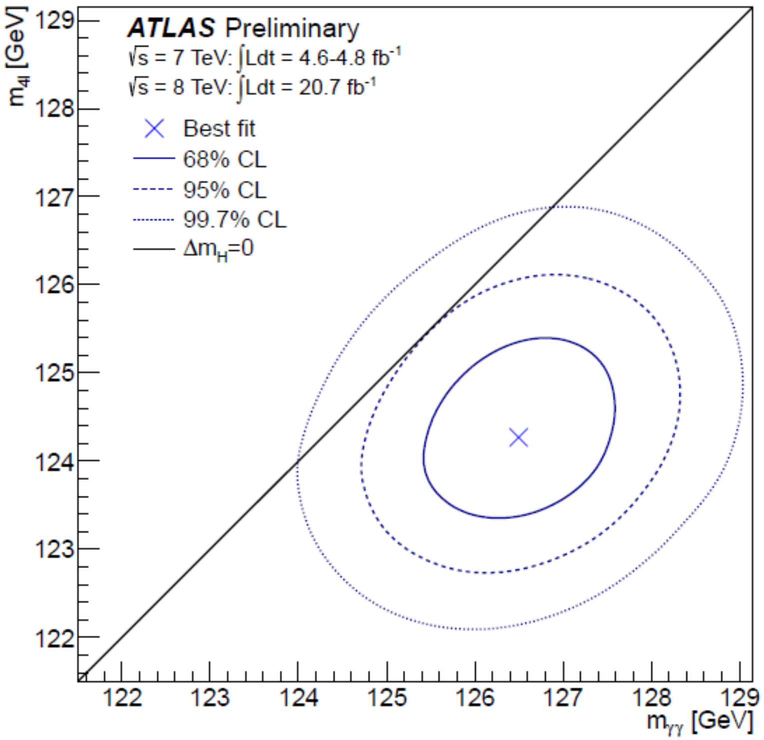


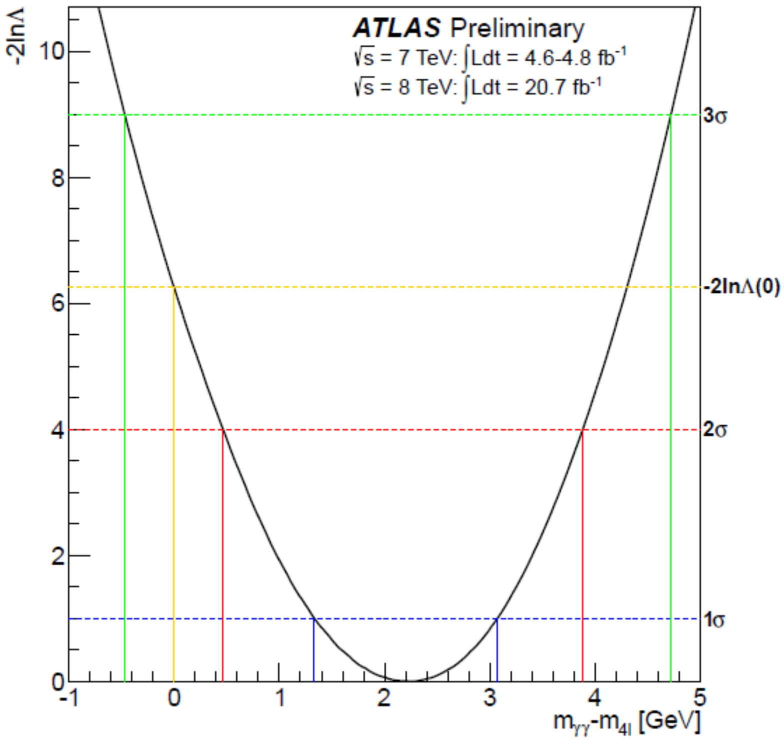
Best fit mass for H → γγ:
M_H = 126.6 ±0.2(stat) ± 0.7(syst) GeV

Best fit mass for H → ZZ* → 4ℓ:
M_H = 124.3 ±0.6(stat) ± 0.3(syst) GeV

Consistency Check of Higgs Mass Discrepancy

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





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 **1.2% or 2.5σ .**

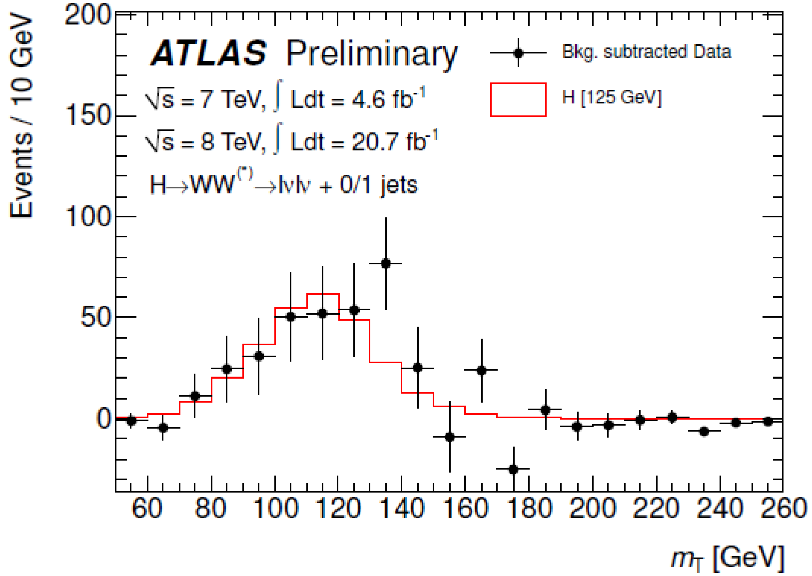
Update of H → WW* → ℓνℓν

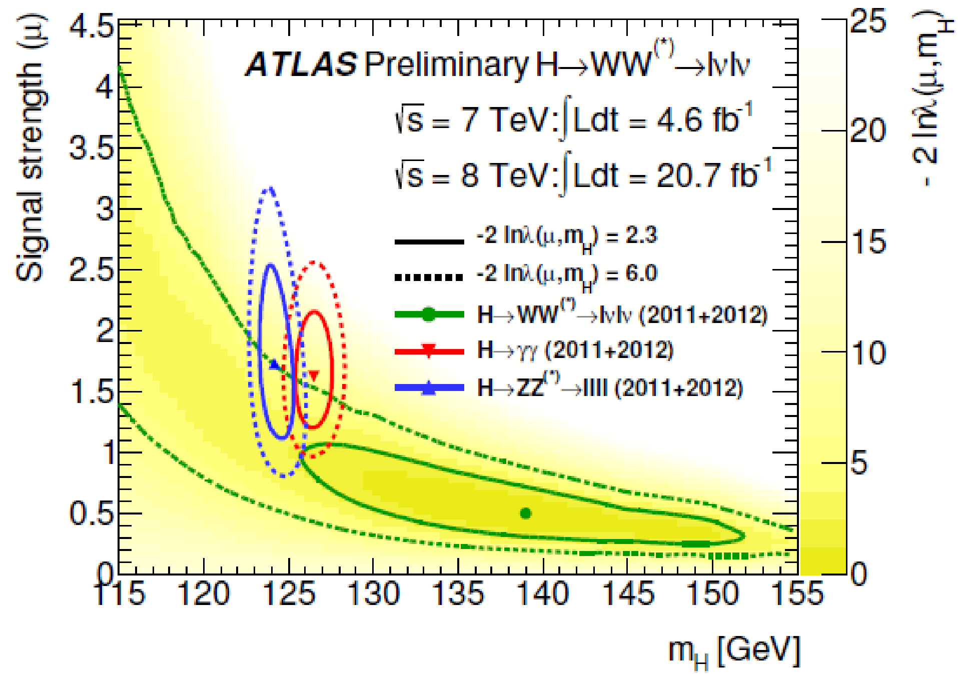
- Final discriminant

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

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**

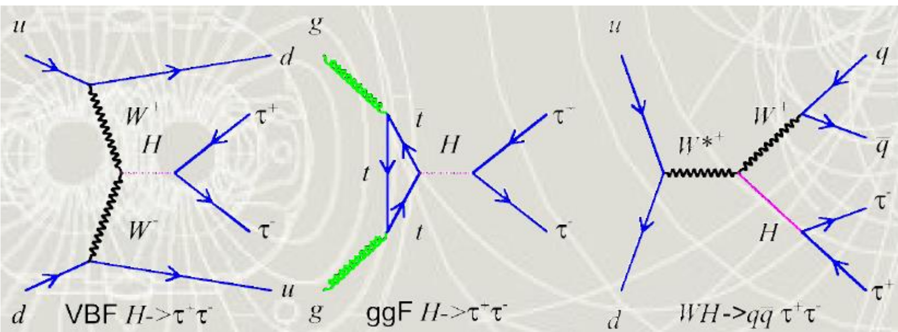




N_{jet}	N_{obs}	N_{bkg}	N_{sig}	N_{WW}	N_{VV}	$N_{t\bar{t}}$	N_t	N_{Z/γ^*}	$N_{W+\text{jets}}$
$=0$	154	161 ± 11	25 ± 5	113 ± 10	12 ± 2	5 ± 1	4 ± 1	6 ± 2	21 ± 5
$=1$	62	47 ± 6	7 ± 2	16 ± 6	5 ± 1	10 ± 3	6 ± 2	5 ± 2	5 ± 1
≥ 2	2	4.6 ± 0.8	1.4 ± 0.2	0.7 ± 0.2	-	0.7 ± 0.5	0.1 ± 0.1	2.4 ± 0.6	0.3 ± 0.1

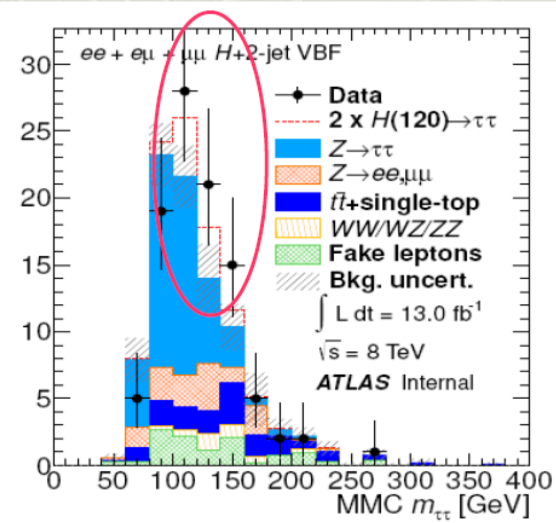
Update of H → ττ

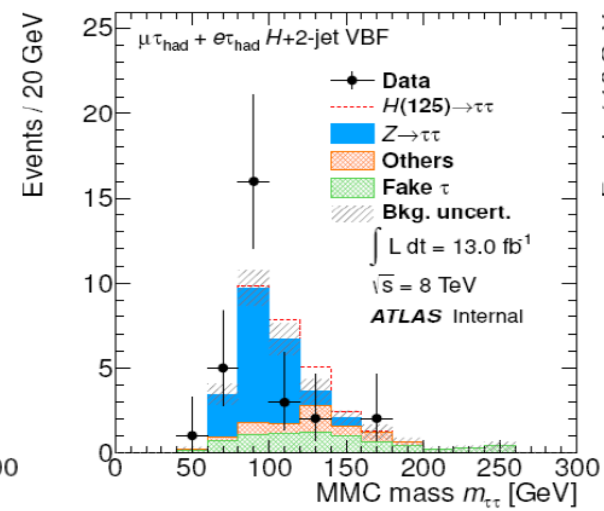
- H → ττ provide an unique opportunity to probe Yukawa coupling which gives mass to quarks and leptons
- It has one the largest branching ratios for low mass Higgs
- Three different ττ decay modes:

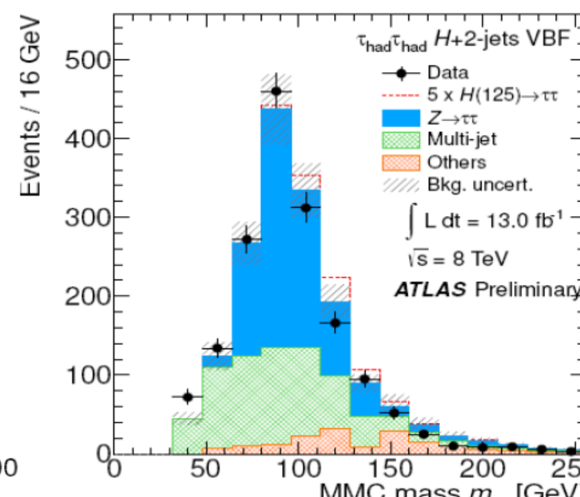


- lep-lep: $\ell\ell 4\nu$: (ee) + eμ + $\mu\mu$
- lep-had: $\ell\tau_{had}3\nu$: eτ_{had} + $\mu\tau_{had}$
- had-had: $\tau_{had}\tau_{had}\nu\nu$: $\tau_{had}\tau_{had}$

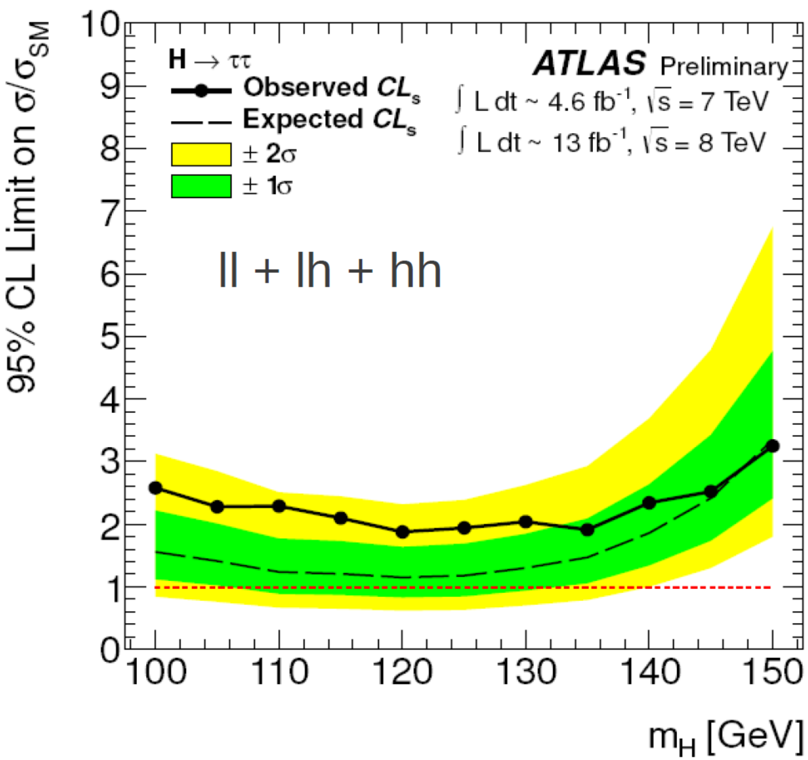
VBF

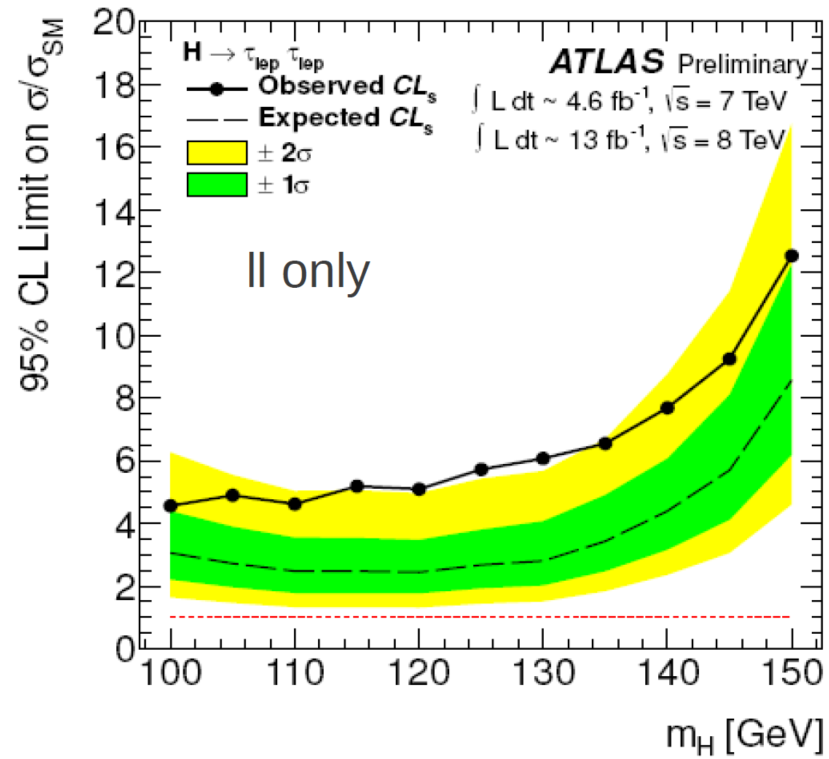






Update of H → ττ

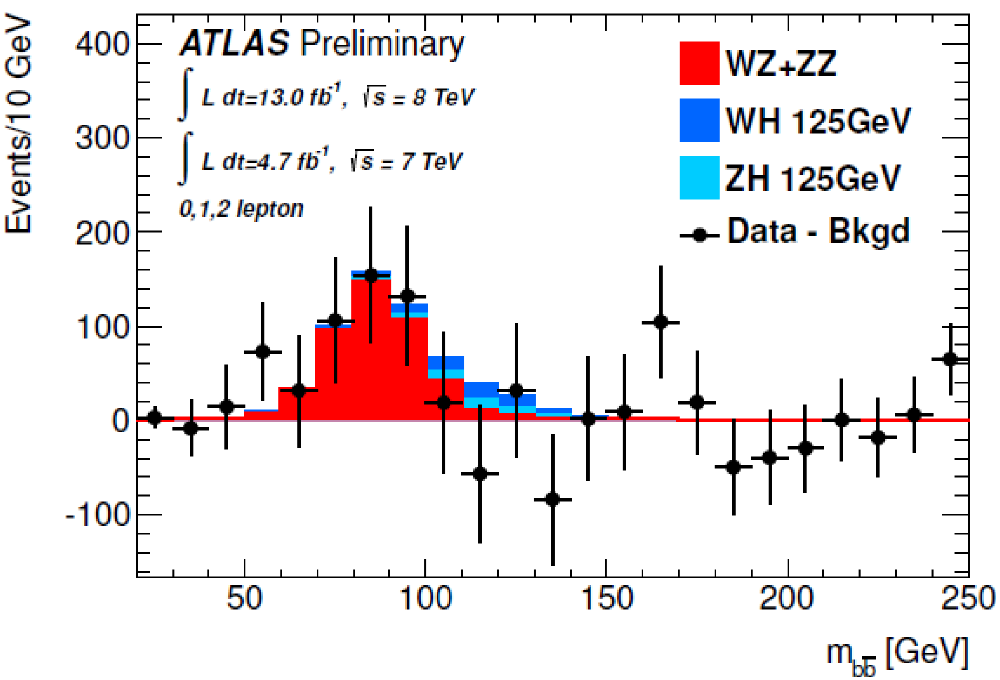


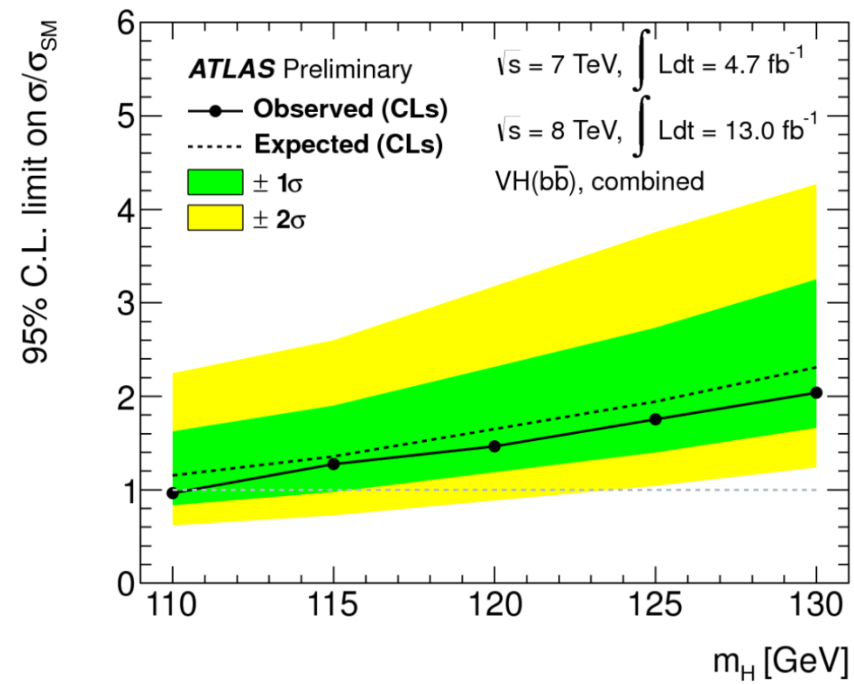


- The largest deviation of observed from expected limit is in the 2-lepton channel.
- The best fitted signal strength @ 125 GeV: **$\mu = 0.8 \pm 0.7$**
- **Due to the presence of MET, the complexity of each subchannel of H→ττ is greater than γγ or ZZ→4l channel.**

Update of H→bb

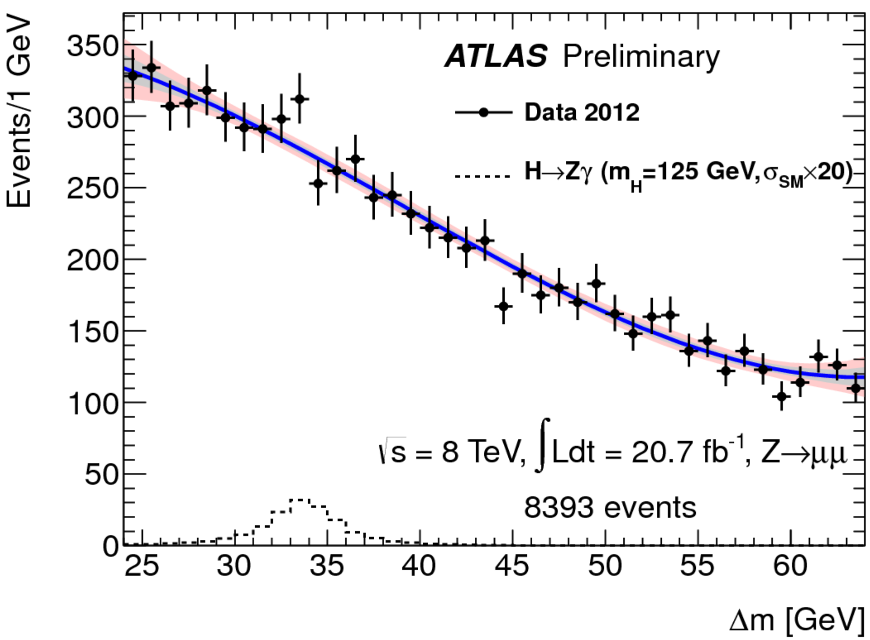
- Fit invariant mass of M_{bb} distribution
- Validation WZ,ZZ → bb + X: $\mu_{WZ,ZZ} = 1.09 \pm 0.30$ (4.0σ)
- On the Higgs search, data show no excess on top of expected backgrounds, expected limit 1.9 σ/σ_{SM} @ m_H = 125 GeV, the observed limit is 1.8 σ/σ_{SM} , signal strength is **$\mu = -0.4 \pm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

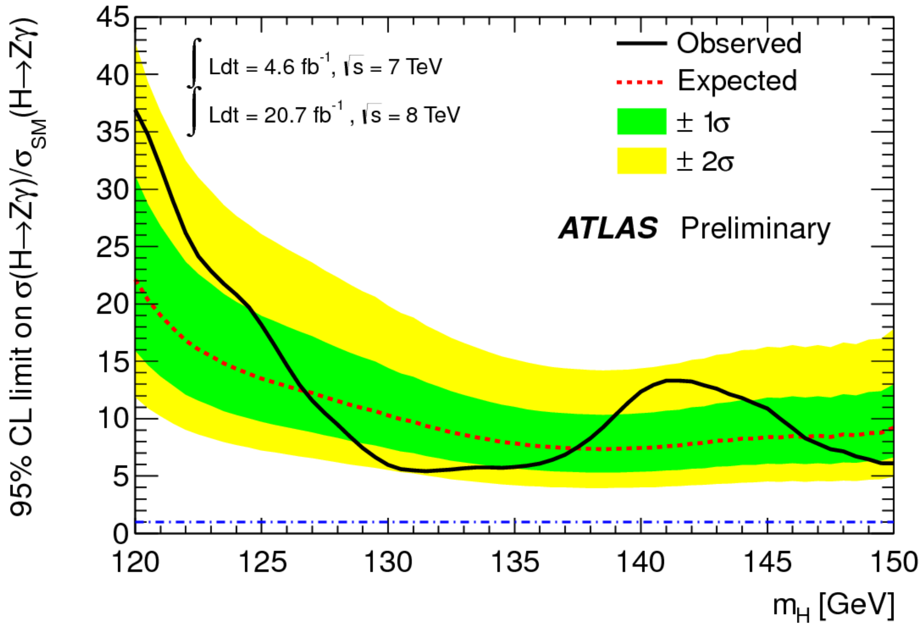




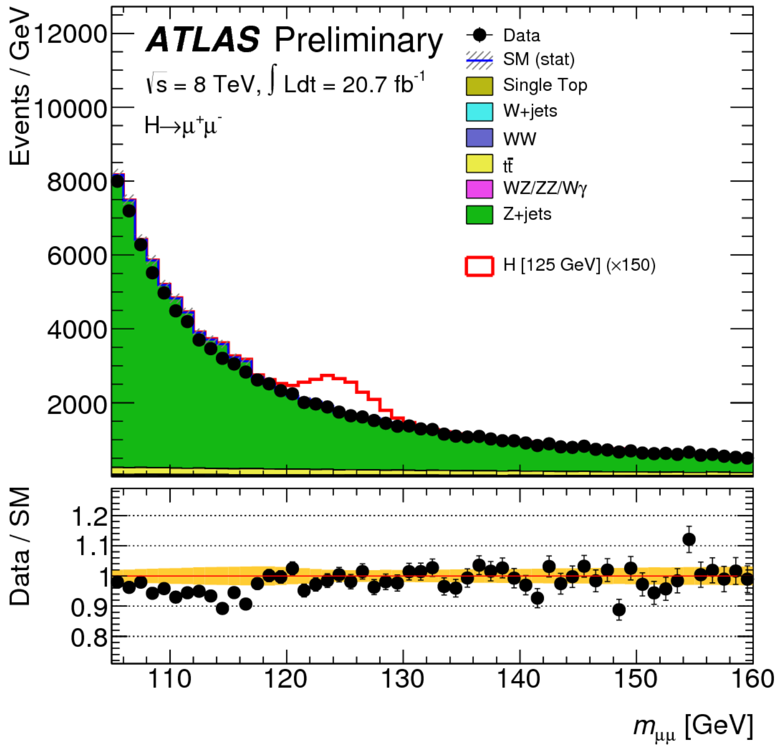
Higgs → Zγ

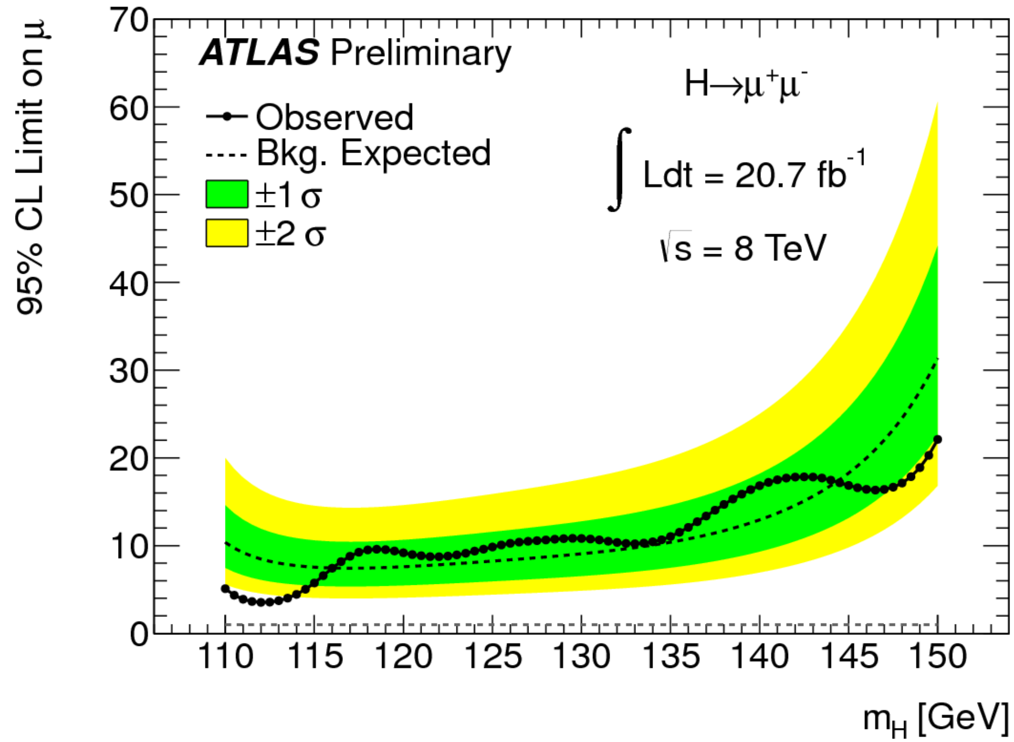
- Loop decay like H→γγ
  - Could be enhanced if radion not Higgs (hep-ph/9907447)
- Four channels combined to make limits
  - ee, μμ at 7 TeV and 8 TeV
  - Observed limit 18 × SM Higgs
  - Expected limit 13 × SM Higgs





Higgs → μμ





➔ Expect suppressed by $(1.7778/0.1056)^2$ ~280 w.r.t. ττ

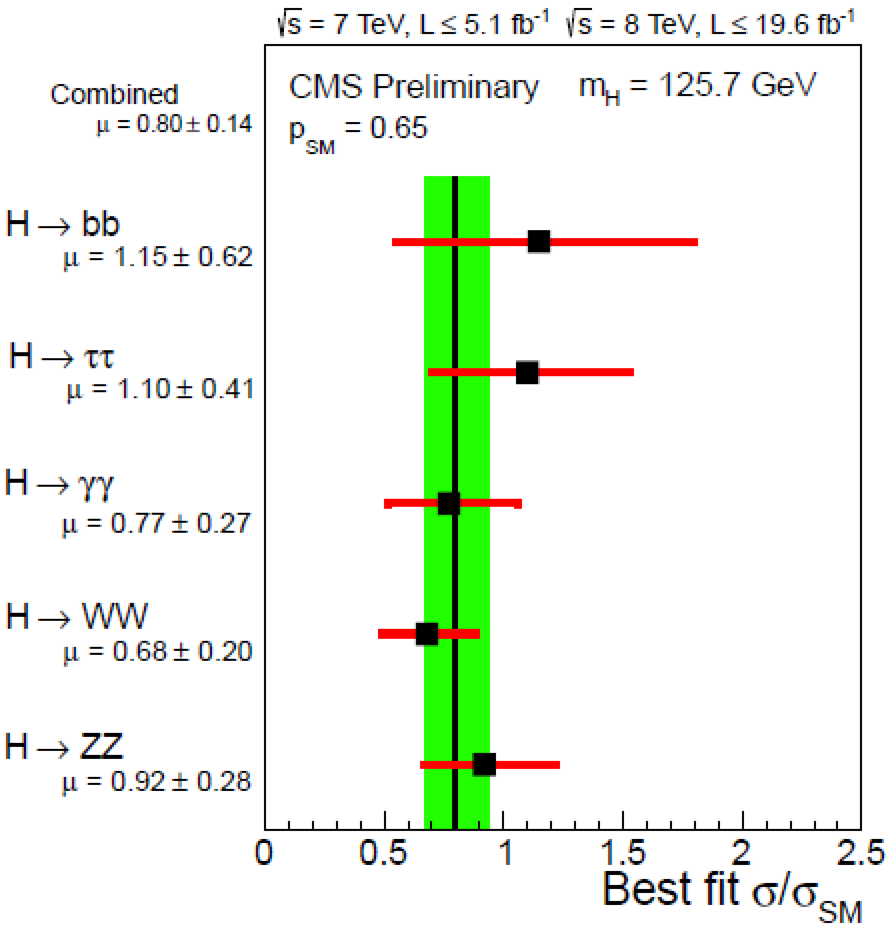
➔ Good efficiency and mass resolution improves things

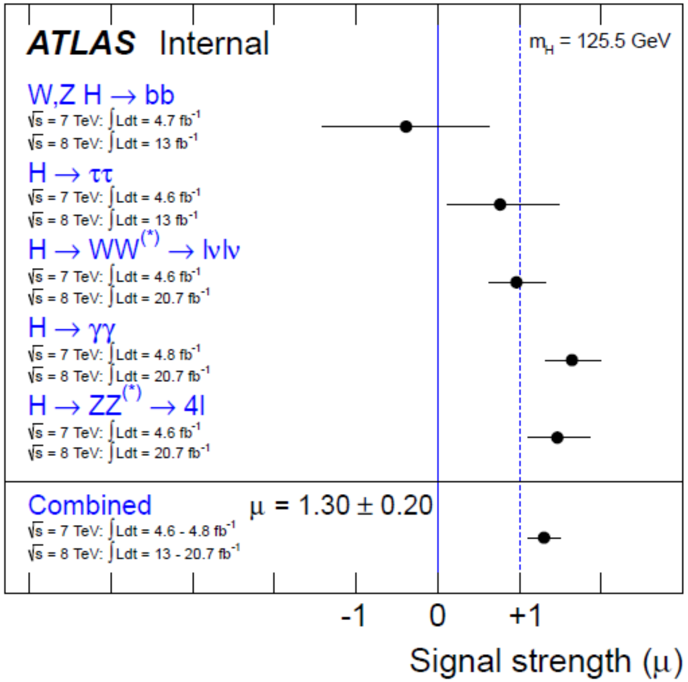
- But SM sensitivity needs considerably more data
- Observed limit 9.2 × SM
- Expected limit 8.2 × SM

Update of Higgs Signal Strength

➔ **Signal strength: μ = 1.3 ±0.2 (ATLAS)**

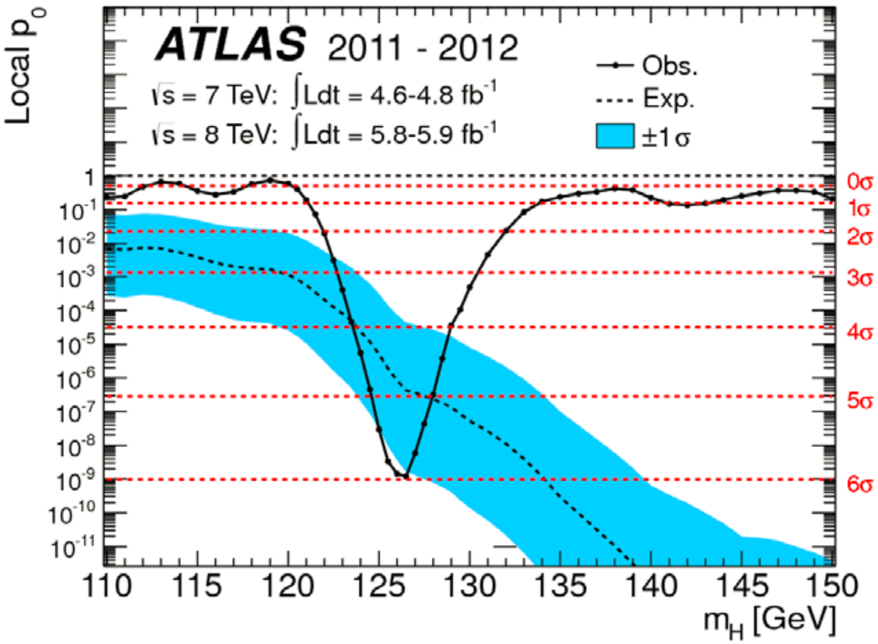
➔ **μ = 0.8 ±0.14 (CMS)**





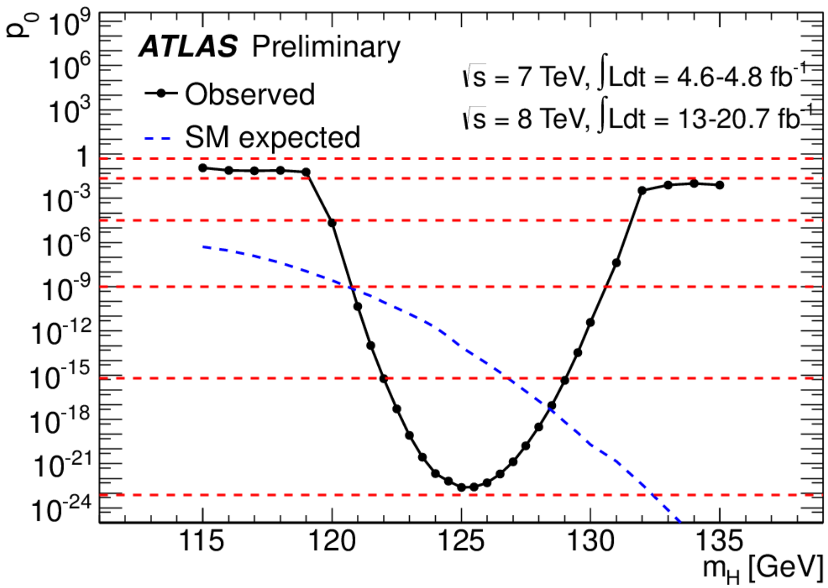
Higgs Boson Decay	μ (m_H=125.5 GeV)
$VH \rightarrow Vbb$	-0.4 ± 1.0
$H \rightarrow \tau\tau$	0.8 ± 0.7
$H \rightarrow WW^{(*)}$	1.0 ± 0.3
$H \rightarrow \gamma\gamma$	1.6 ± 0.3
$H \rightarrow ZZ^{(*)}$	1.5 ± 0.4
Combined	1.30 ± 0.20

Strong Evidence for a New Particle



- ❑ **2012 ICHEP**
  - ➔ Significance 6.0σ (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 ?

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

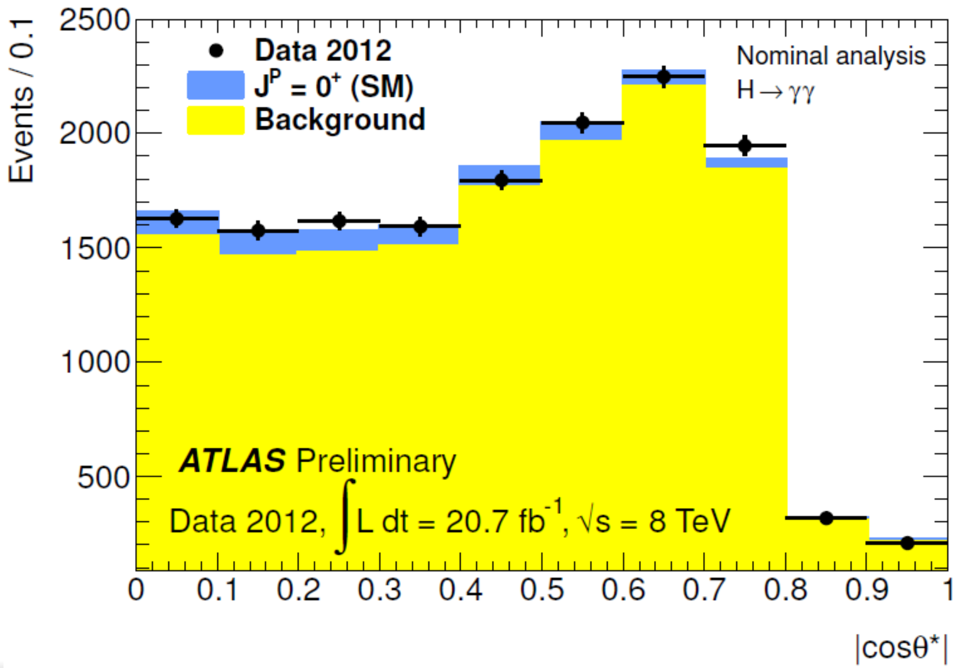
Spin of particle	$\gamma\gamma$	ZZ^*	$\tau\tau$	bb
Spin 0	☺	☺	☺	☺
Spin 1	☹	☺	☺	☺
Spin 2	☺	☺	☹	☺
Seen?	Yes	Yes	Not yet	Not yet

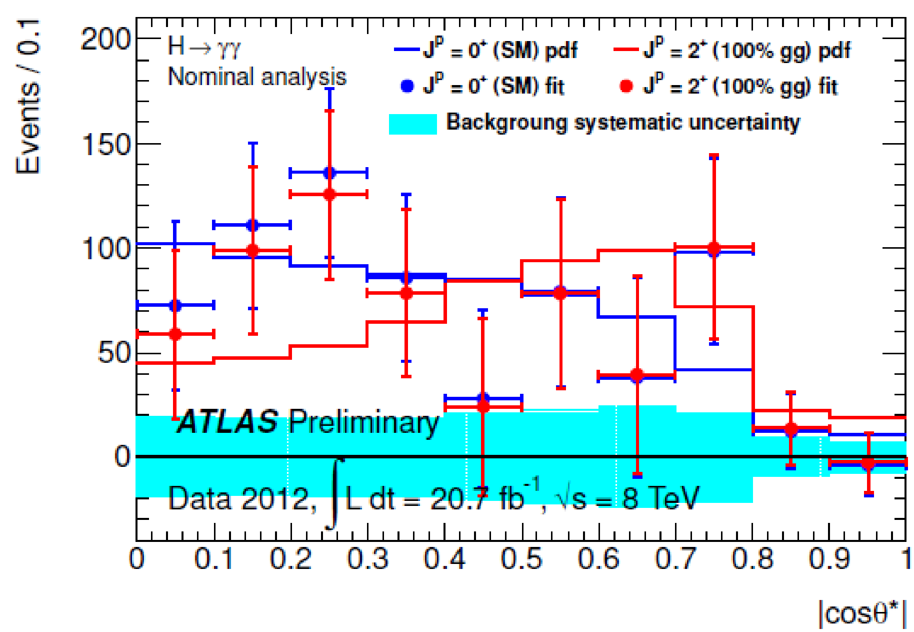
  - ✓ CP-nature
    - ❖ SM Higgs CP-even, extended Higgs sectors has CP-odd or mixed states
    - ❖ Look at angular correlations
  - ✓ Couplings
    - ❖ Gauge / Yukawa couplings → g_{VVH}, $g_{ffH} \propto m$
    - ❖ Unitarity in $W_L W_L$ scattering → $g_{WWH} \propto m_W$
    - ❖ Higgs self-couplings, 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.

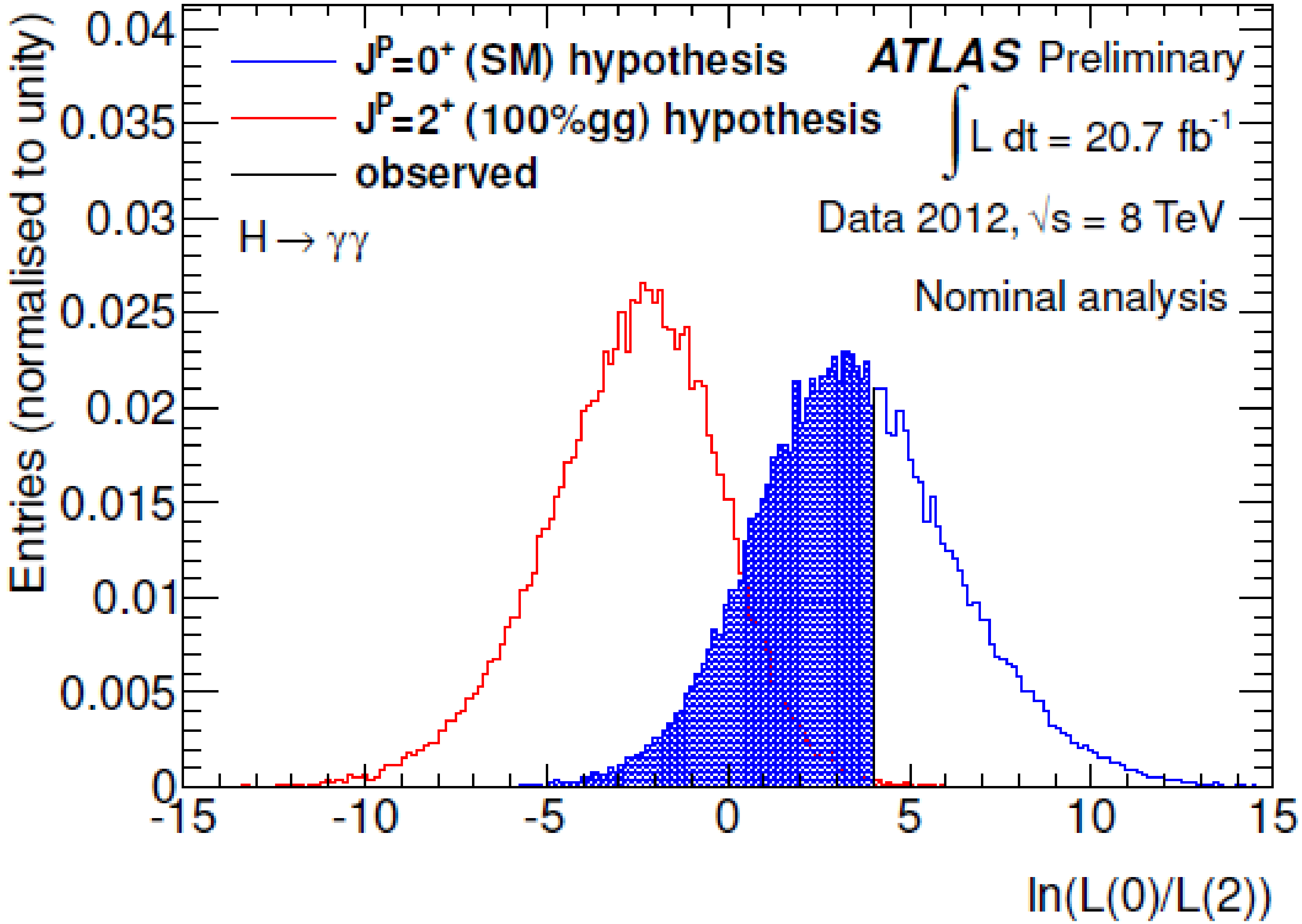
$$\cos\theta^* = \frac{\sinh(\eta_{\gamma_1} - \eta_{\gamma_2})}{\sqrt{1 + \left(p_T^{\gamma\gamma}/m_{\gamma\gamma}\right)^2}} \cdot \frac{2 p_T^{\gamma_1} p_T^{\gamma_2}}{m_{\gamma\gamma}^2}$$





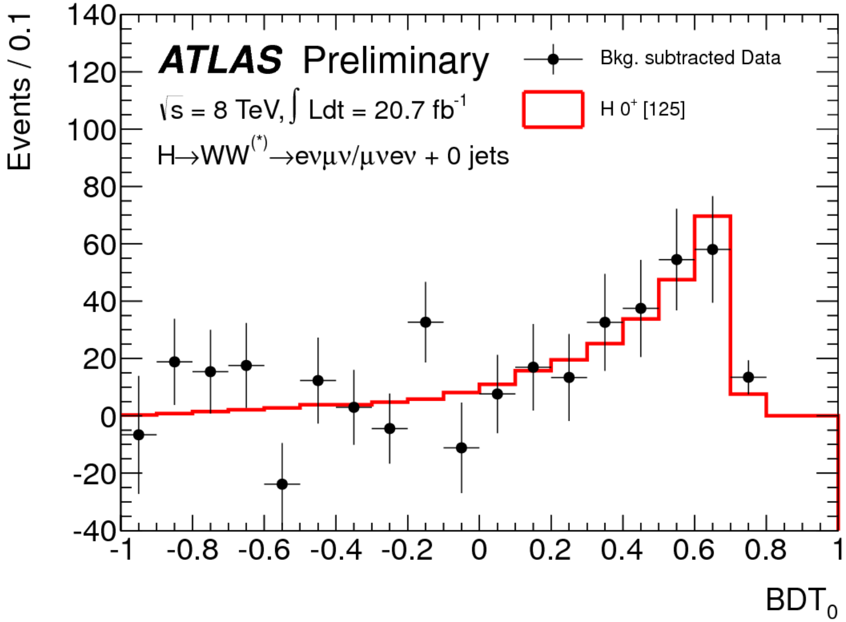
H → γγ : Spin Analysis

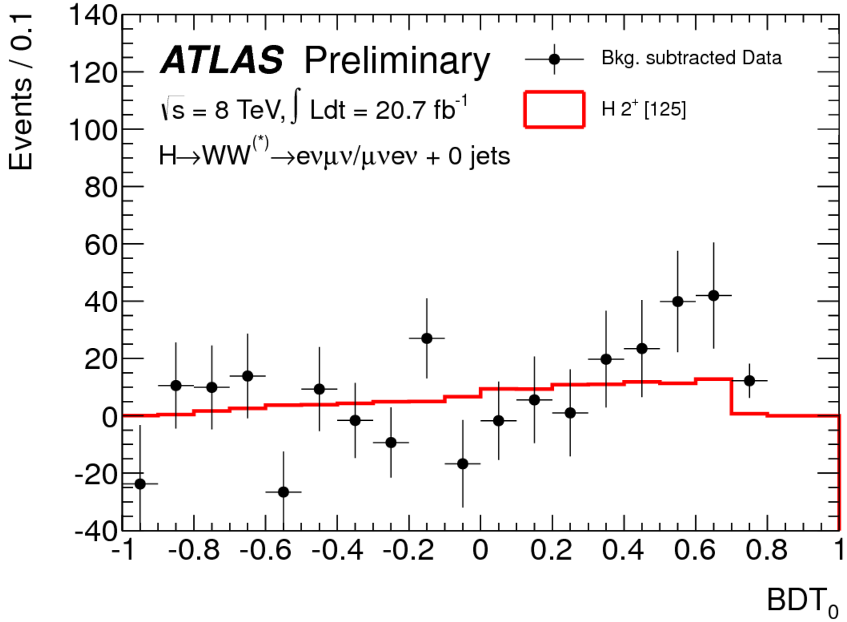
- ➔ Observed data agree with spin 0^+ hypothesis ($1\text{-}CL_b$) ~ 58.8%.
- ➔ Spin 2 hypothesis is disfavored at 99.3% C.L. (or 2.9σ) assuming 100% gluon-gluon production.



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





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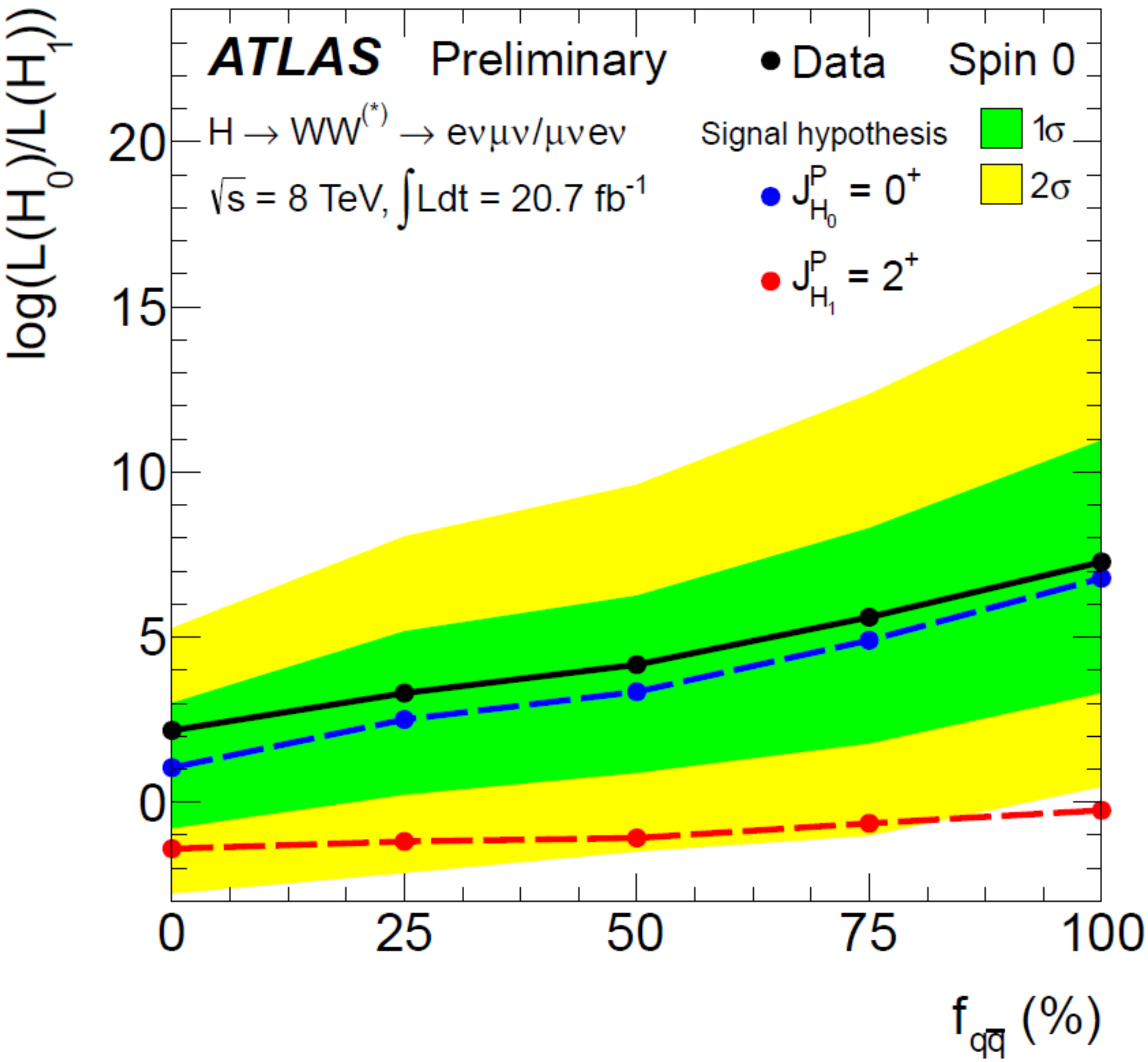
Spin for H → WW

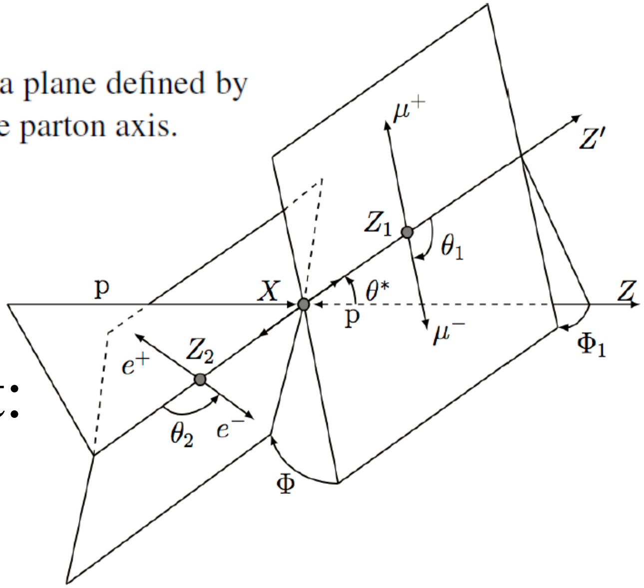
- The ATLAS data favors spin 0 with CP even.



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

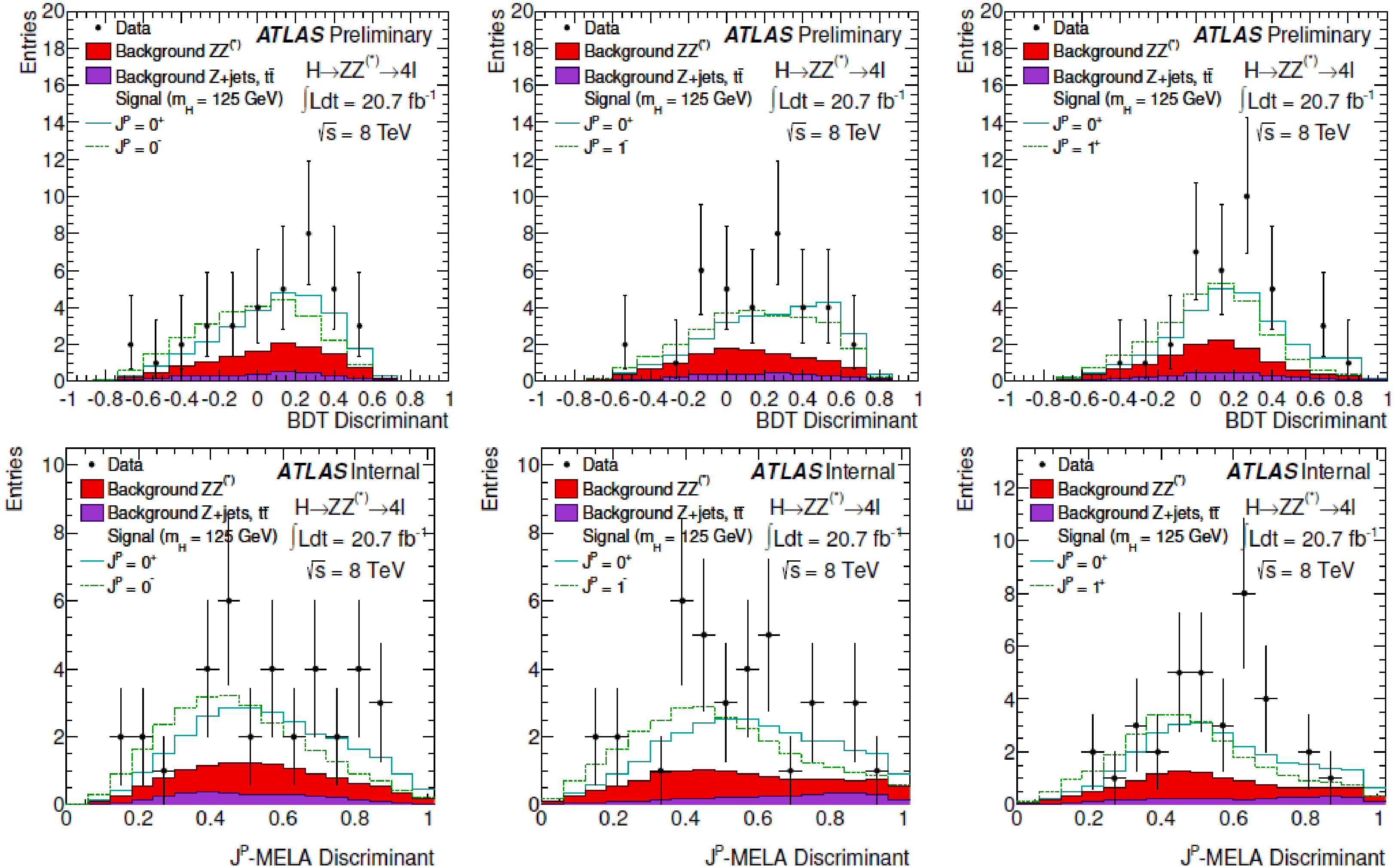
- θ_1 (θ_2) is the angle between the negative final state lepton and the direction of flight of Z_1 (Z_2) in the Z rest frame.
- Φ is the angle between the decay planes of the four final state leptons expressed in the four lepton rest frame.
- Φ_1 is the angle defined between the decay plane of the leading 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

❑ MVA: BDT vs J^P-MELA

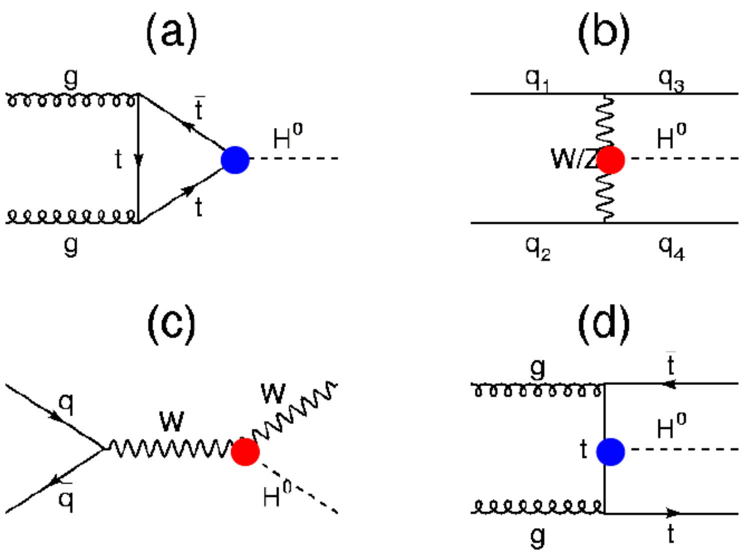


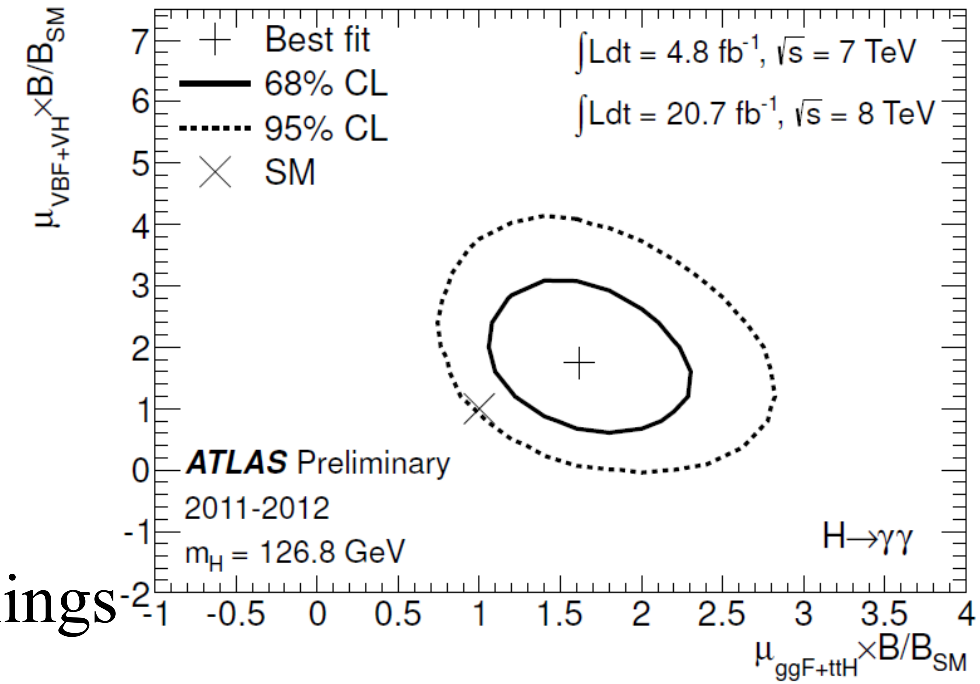
➔ Data favour 0^+ , 0^- hypothesis is excluded at 98.7% C.L. (2.23σ)

➔ 1^+ is excluded at 99% C.L., 2^+ is excluded at ~95.8% C.L. (1.73σ)

Higgs → γγ

- Observation of H → γγ excludes spin-1

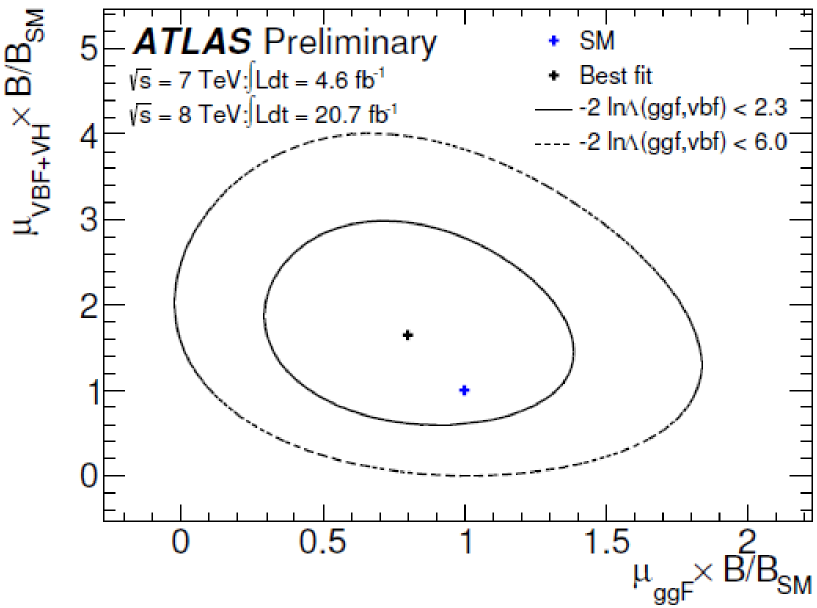


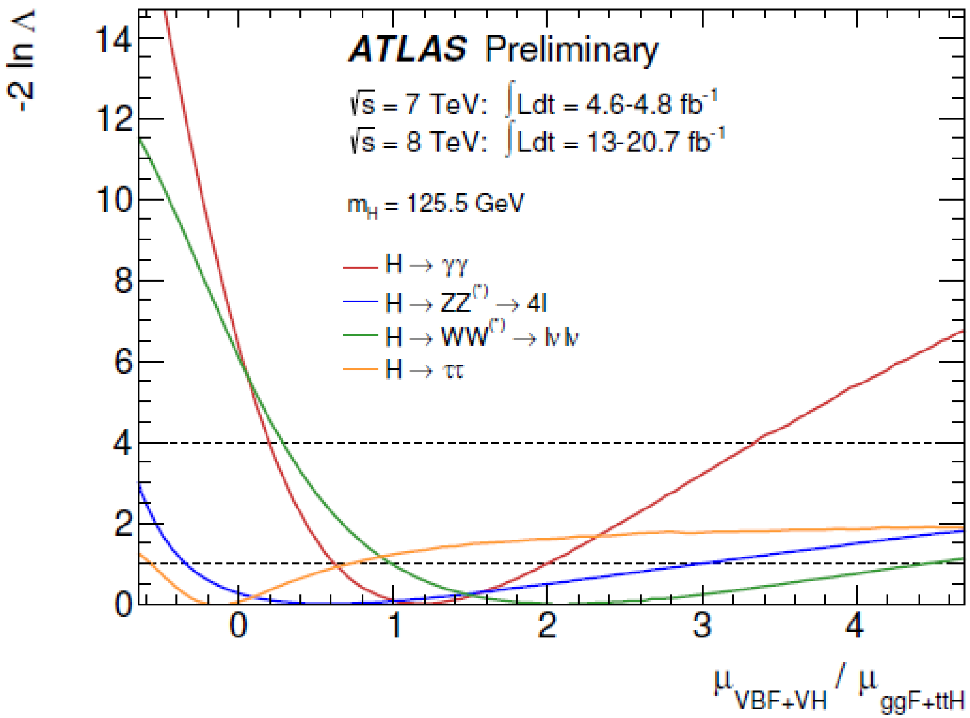


- Higgs has two types of couplings
  - "Gauge" couplings (to bosons)
  - Yukawa couplings (to fermions)
- Explore tension between SM value and observation from different Higgs production modes: μ_{VBF+VH} vs. $\mu_{ggF+ttH}$

Higgs → WW* → lνlν

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



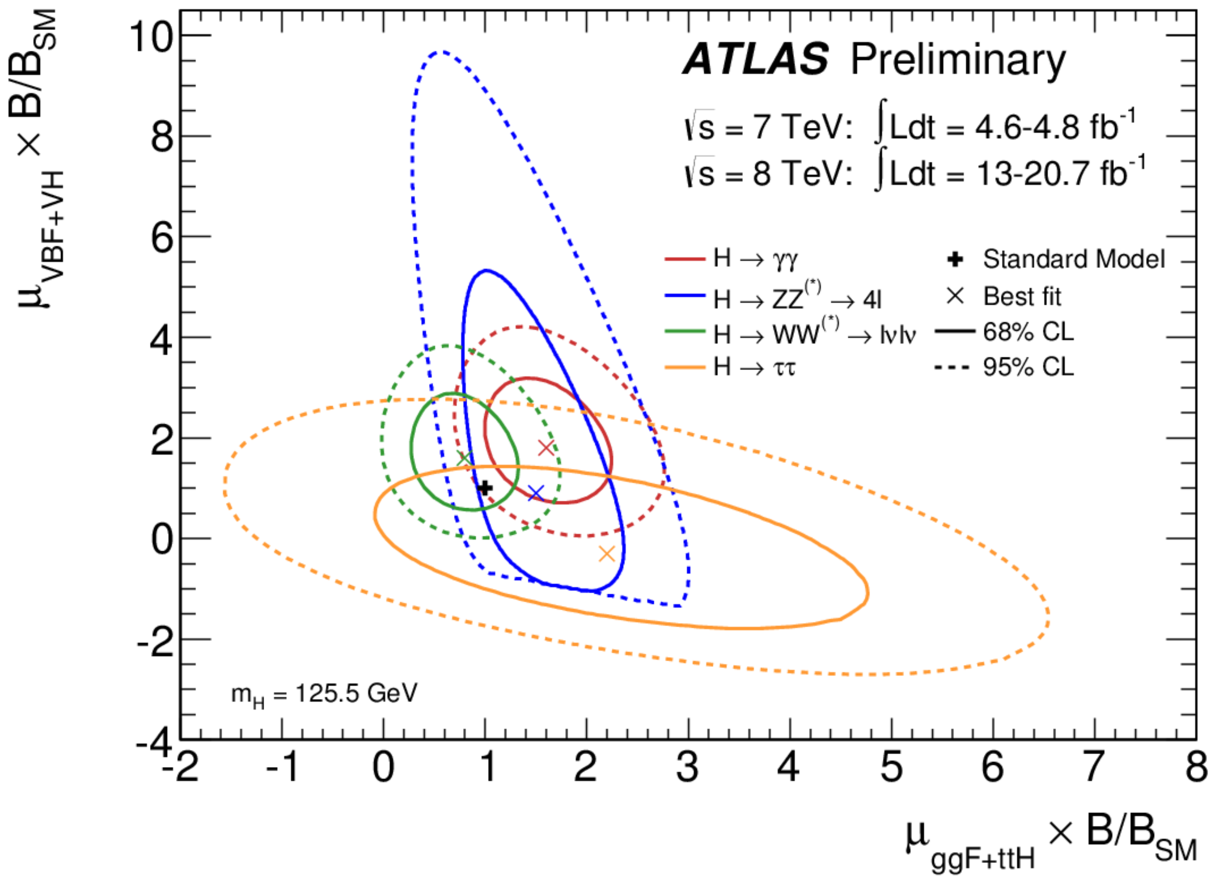


➔The signal strength ratios cancel the branching ratios of different channels so that the results can be compared directly.

Higgs Production: ggF vs.VBF

- A determination of $\mu_{VBF+VH}/\mu_{ggF+ttH}$ provides evidence for VBF production at the 3.1σ level.

$$\mu_{\mathrm{VBF}+VH}/\mu_{\mathrm{ggF}+t\bar{t}H} = 1.2^{+0.7}_{-0.5}$$



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

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

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

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

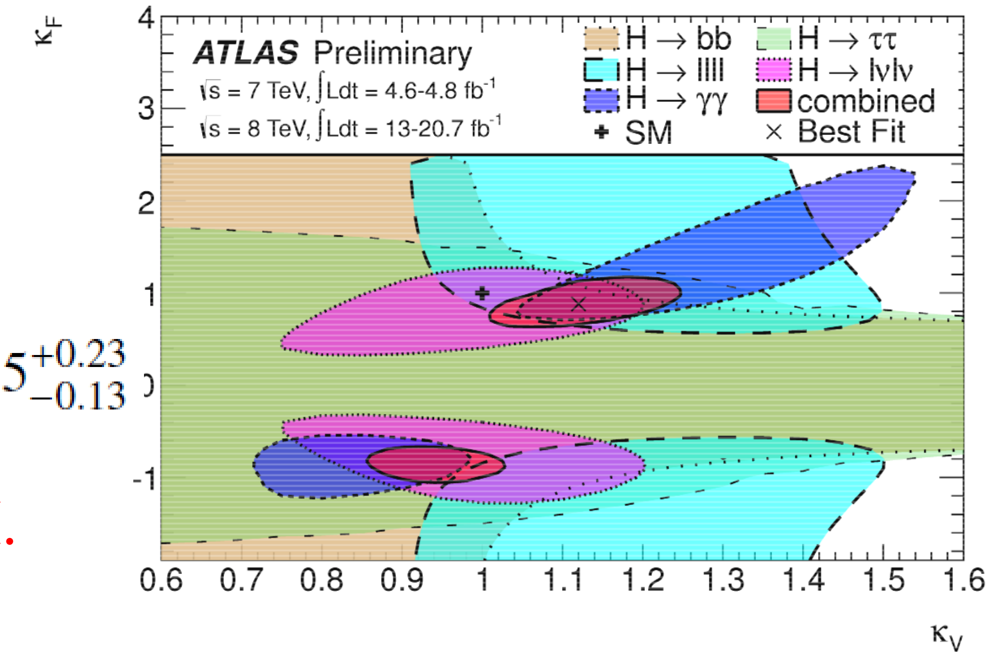
fixed

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.

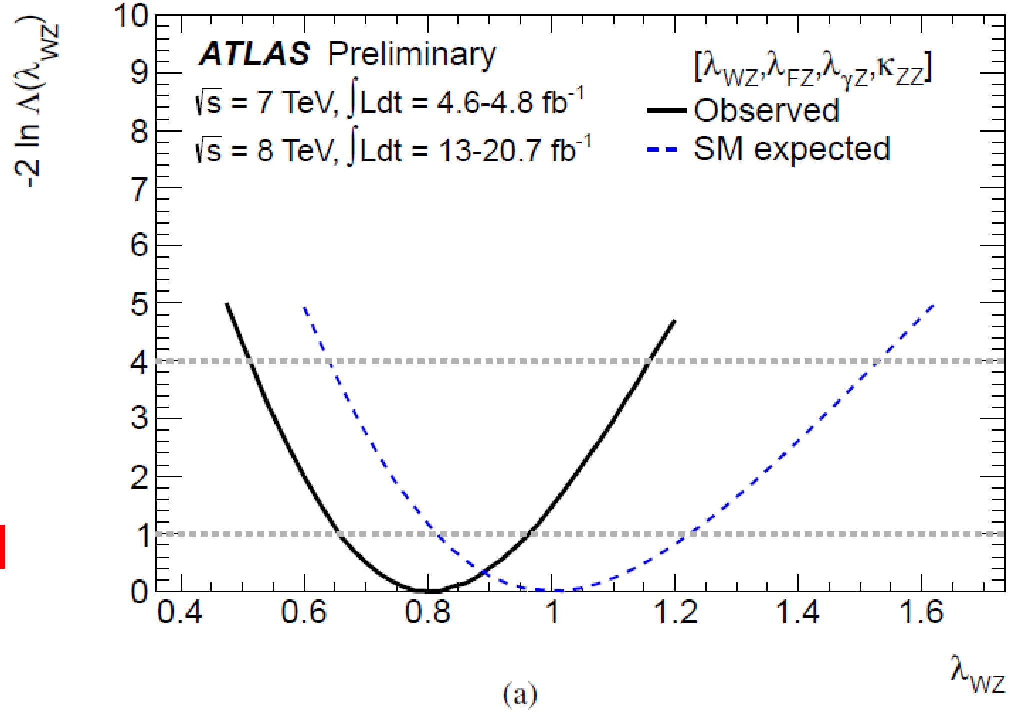
$$\lambda_{WZ} = 0.80 \pm 0.15$$

$$\lambda_{\gamma Z} = 1.10 \pm 0.18$$

$$\lambda_{FZ} = 0.74^{+0.21}_{-0.17}$$

$$\kappa_{ZZ} = 1.5^{+0.5}_{-0.4}$$

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



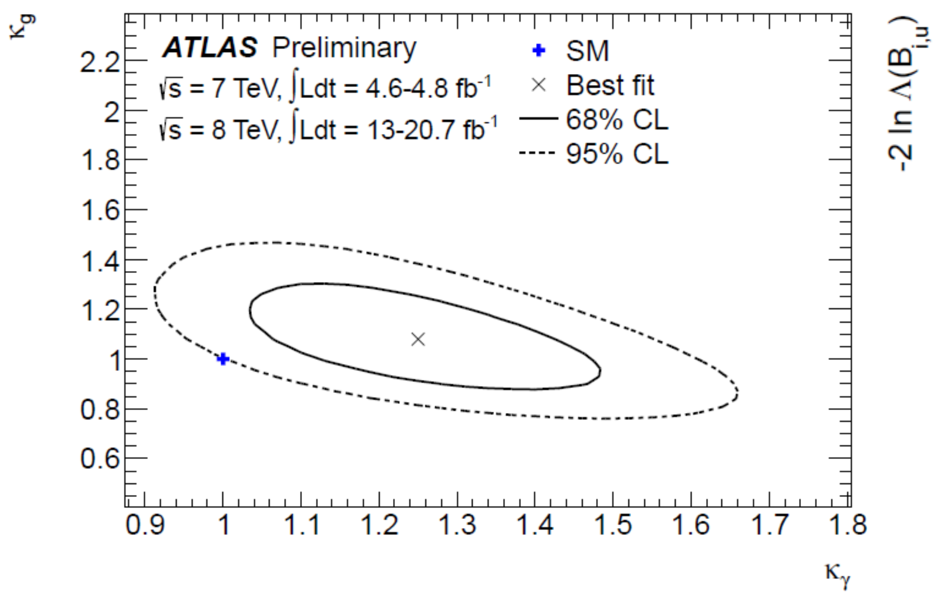
(a)

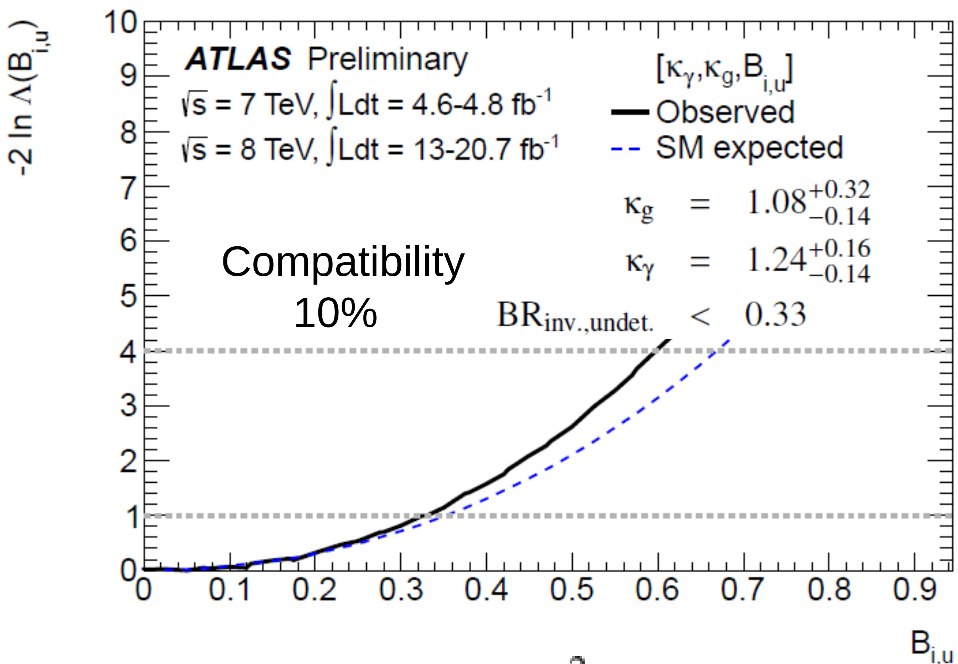
Probing Potential Non-SM Particle Contributions

- 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





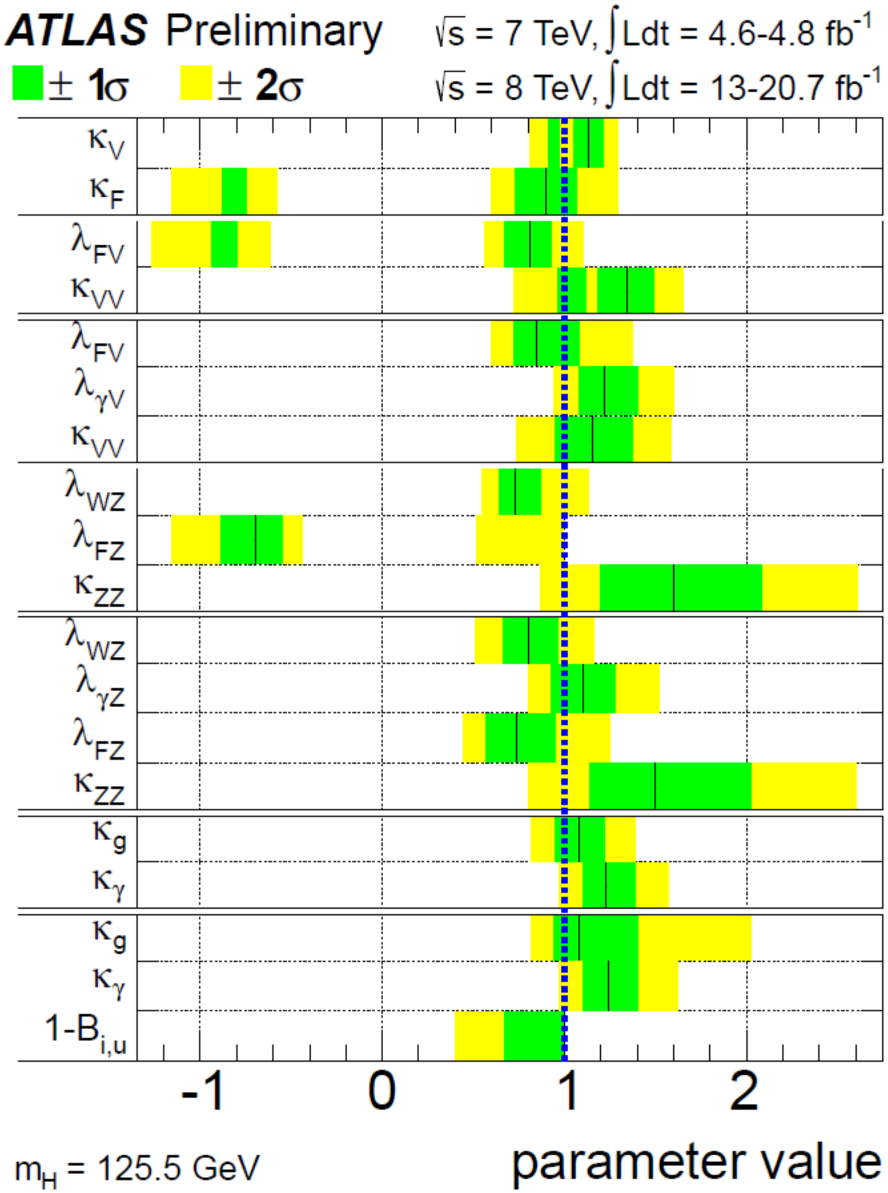
68% CL $\kappa_g = 1.08 \pm 0.14$

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

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

Summary of 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.**



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→bb
Interaction with gluons	Total rate suggest it's as expected
Interaction with photons	1.6 ± 0.2(stat) ± 0.2 (syst), < 2σ deviation from SM !
Conclusion	**SM Higgs with reasonable statistical fluctuations**

Summary and Conclusions

- ❑ A new Higgs-like particle was observed and confirmed

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

- ❑ Higgs decays to $\gamma\gamma$, ZZ* and WW* (Gauge coupling) are established, but H → bb, $\tau\tau$, $\mu\mu$ (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 ~10-20% , no significant deviations from SM couplings are observed.

Please stay tuned !

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

H→ZZ*→4l Candidate

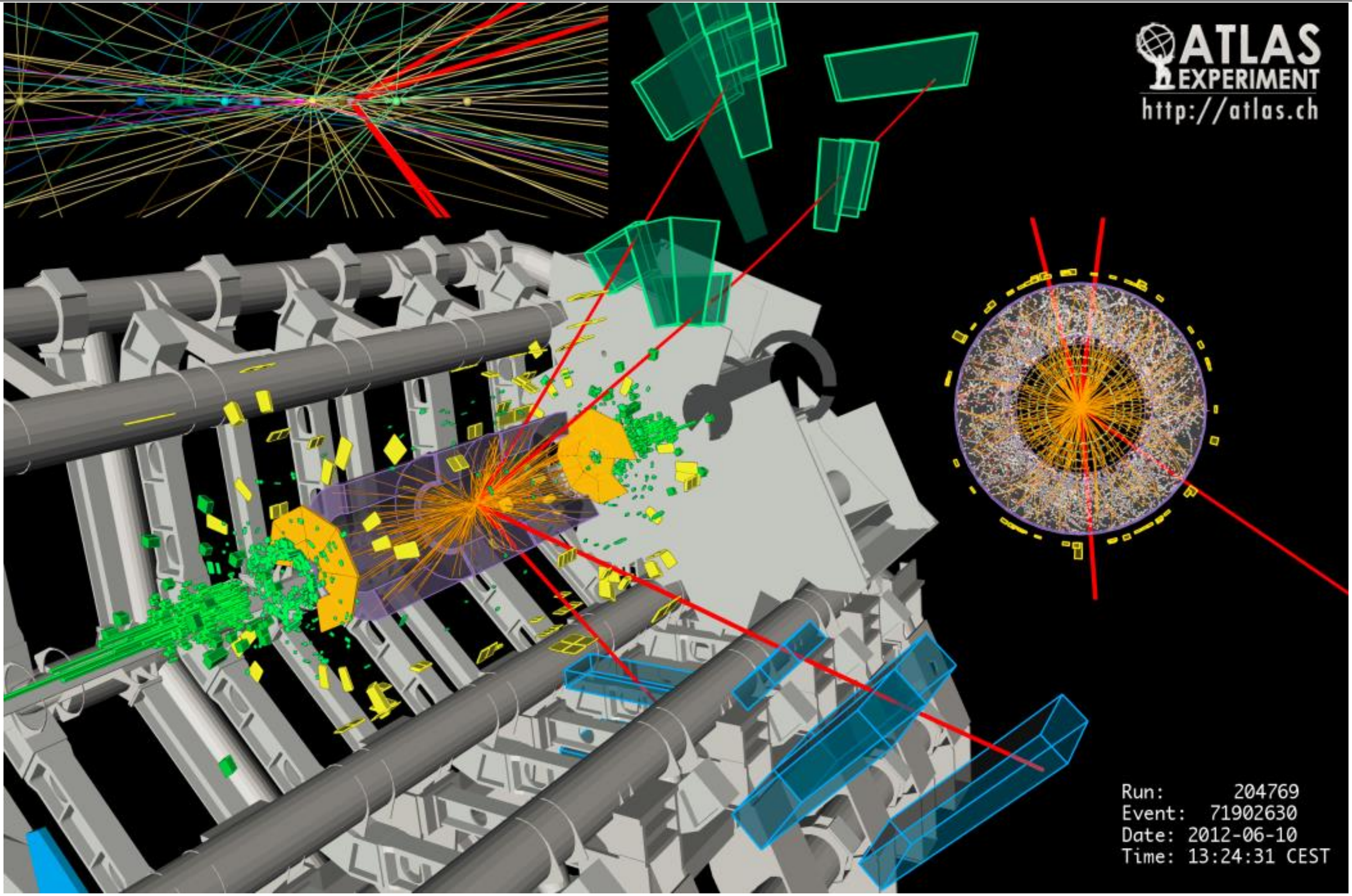
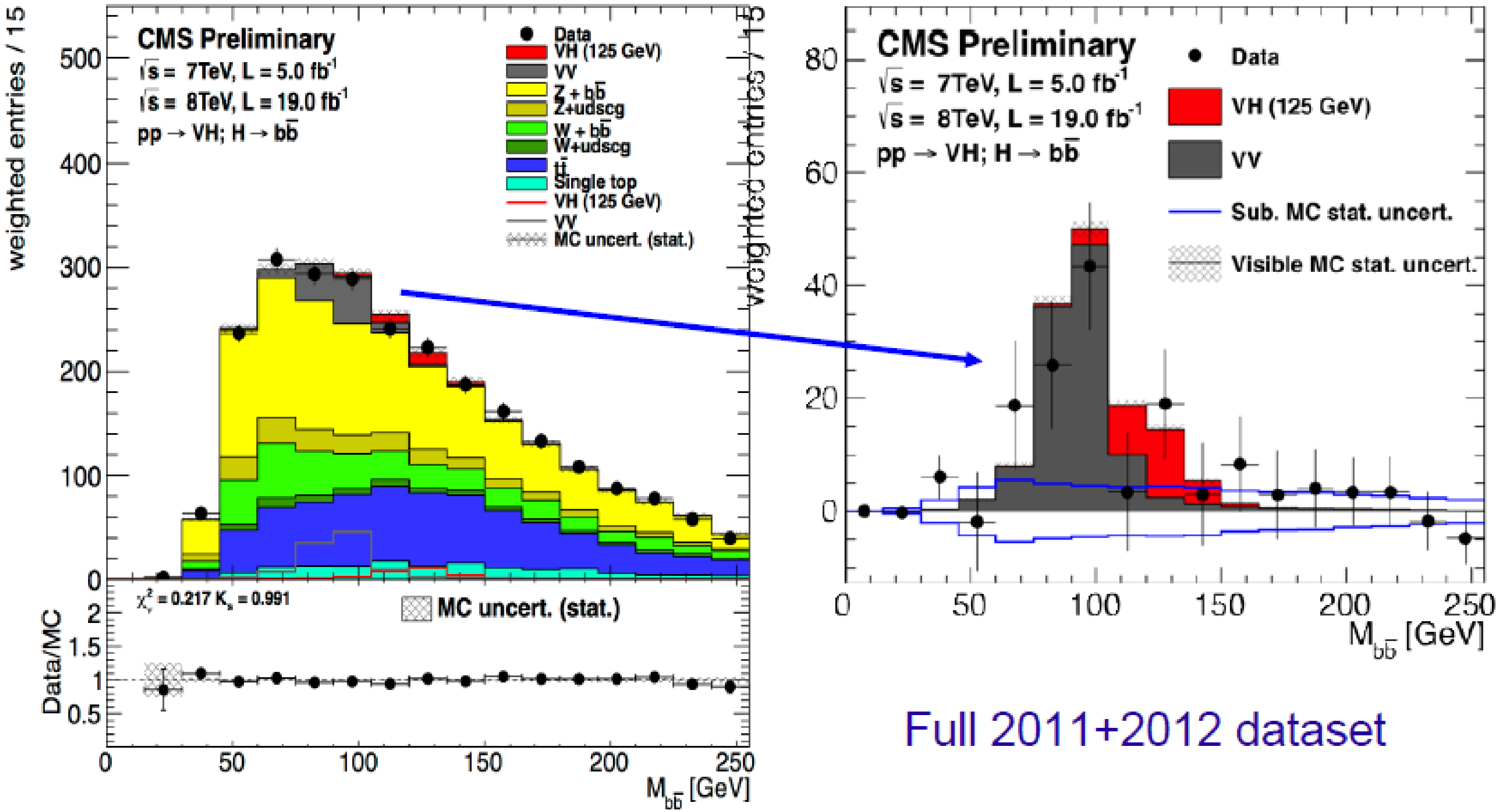


Figure 42: Event display of a 4μ candidate. EventNumber: 71902630 RunNumber: 204769 $m_{4\ell}$ = 125.1 GeV. m_{12} = 86.3 GeV, m_{34} = 31.6 GeV. $\mu_1 : p_{\mathrm{T}}, \eta, \phi$ = 36.1 GeV, 1.29, 1.33. $\mu_2 : p_{\mathrm{T}}, \eta, \phi$ = 47.5 GeV, 0.69, −1.65. $\mu_3 : p_{\mathrm{T}}, \eta,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

Data Summary: VH → Vbb

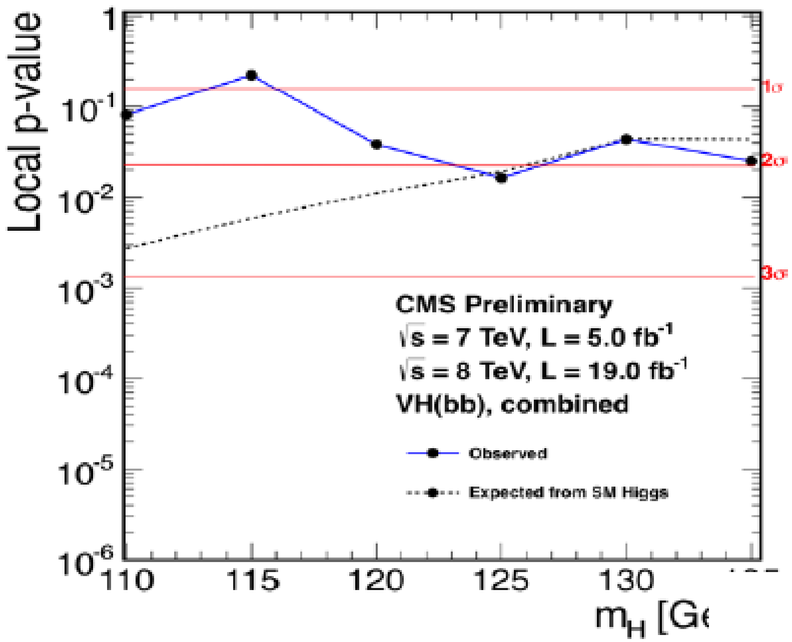


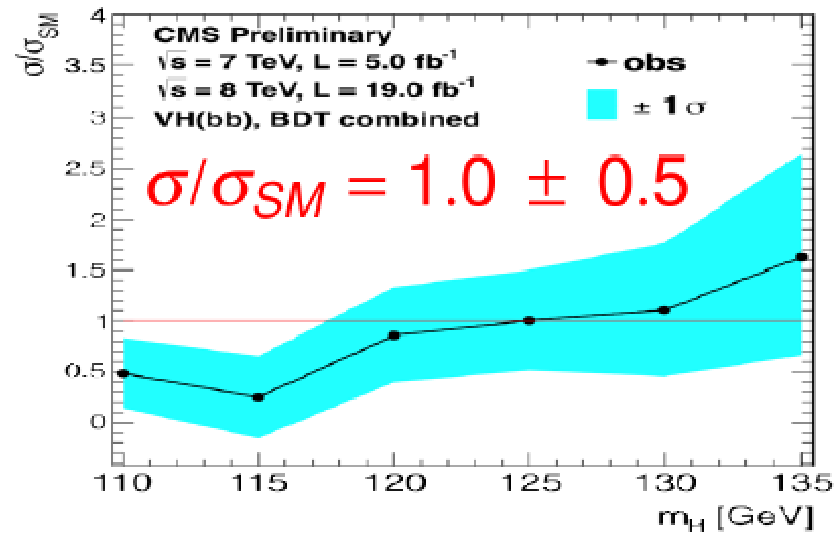
Full 2011+2012 dataset

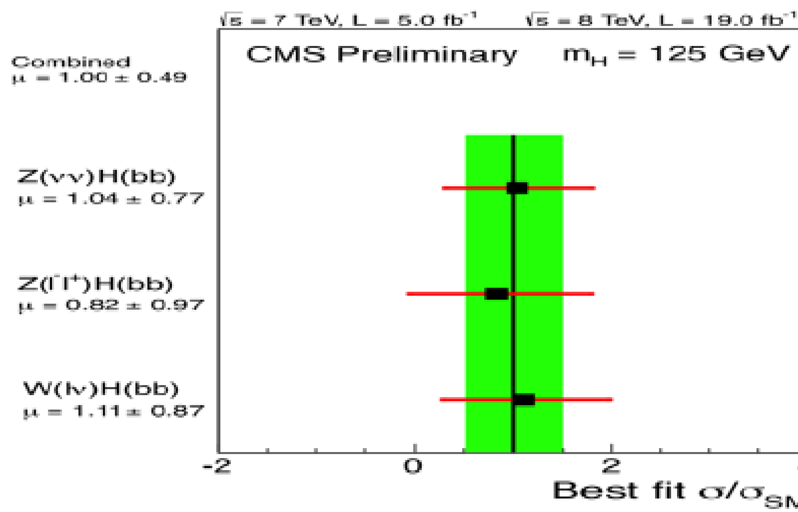
Summary

– seeing diboson production (VV), Higgs excess starting to build up

Results Summary: $H \rightarrow bb$







CMS result

- SM sensitivity reached
- mild excess is observed, channels consistent
- need more data

Summary

- Tevatron combination on $H \rightarrow b\bar{b}$ 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:

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

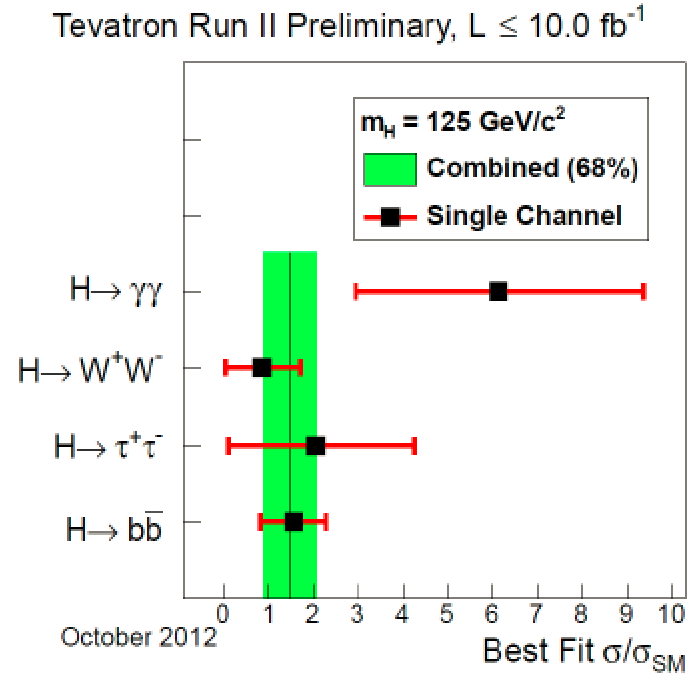
$$\rightarrow \mu = 1.56 \pm^{0.72}_{0.73} \text{ @} M_H = 125\text{GeV}$$

Diboson VZ X section measurement

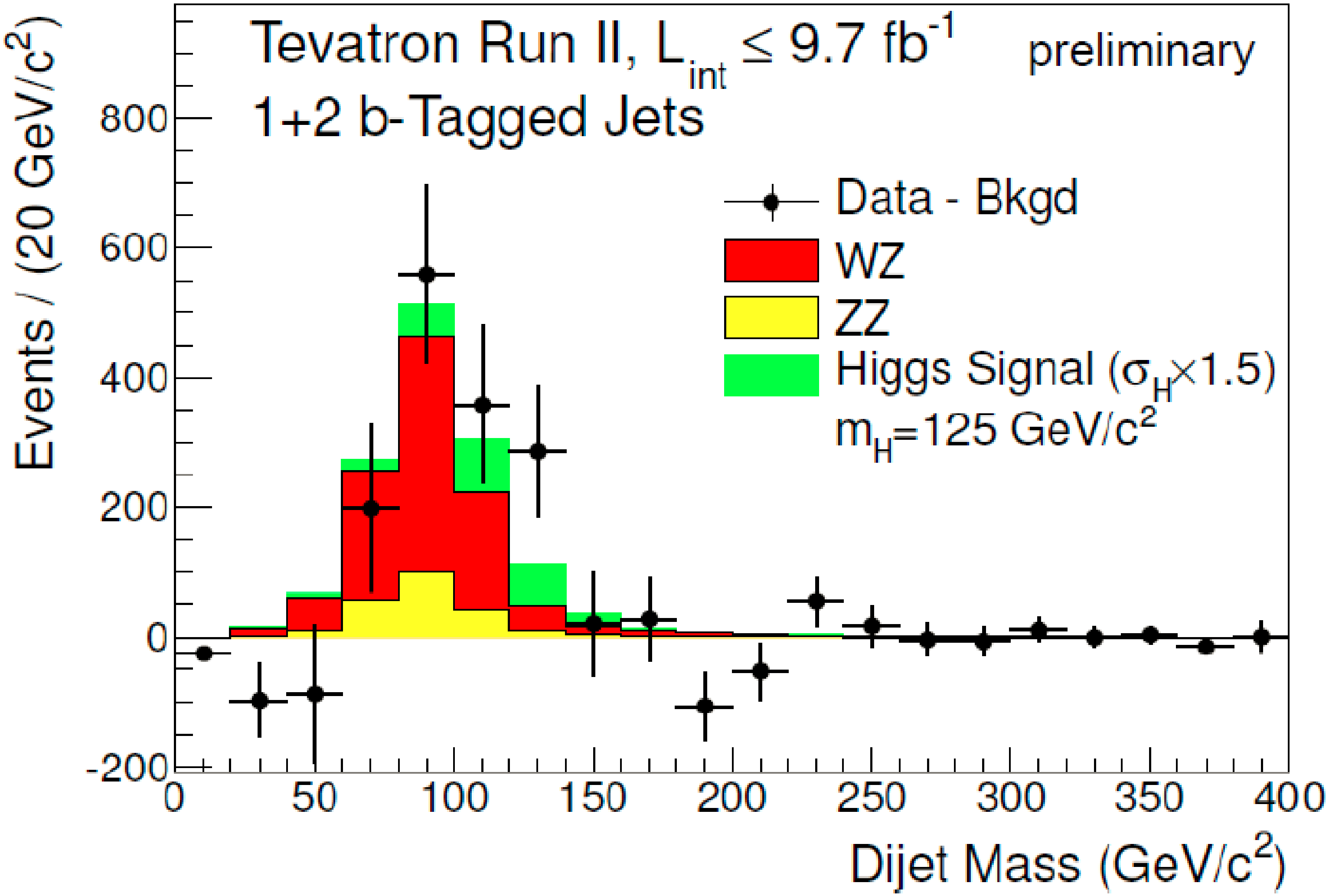
$$\sigma(WZ+ZZ) = 3.0 \pm 0.9 \text{ pb}$$

(NLO exp. : 4.4 ± 0.3 pb)

Submit PRD soon.



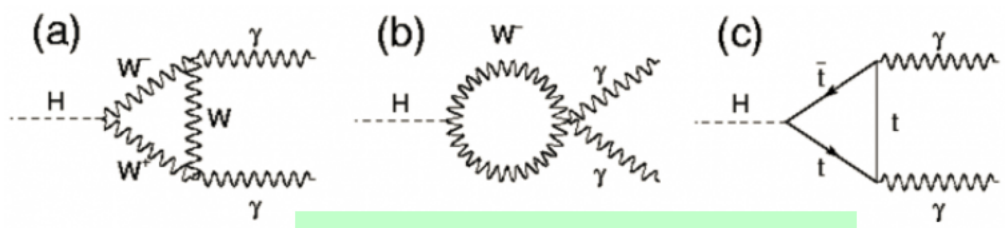
- Future
  - Extract Spin information based on kinematics of V+H system (J. Ellis et al. arXiv:1208.6002)



Thank you for your attention.

Higgs → γγ

- Very simple signature, but small rate Br(H→γγ) ~ 2×10^{-3};
- Important decay mode for the low mass region (100-140 GeV)

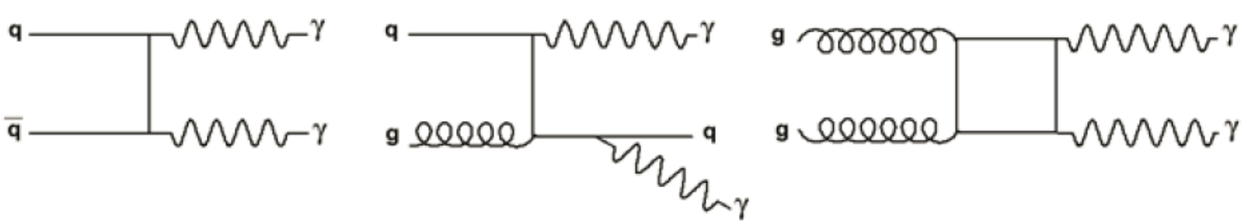


$$\sigma_H \times Br\left(H \rightarrow \gamma\gamma\right) \sim 50 \text{ fb}$$
$$@\ m_H = 125 \text{ GeV}$$

Decay through loops !

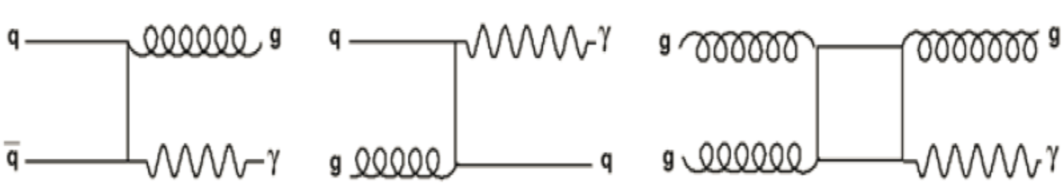
~500 events in 2011+2012 sample!

- Irreducible background from γγ production



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

- Reducible background from γj and jj productions



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

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

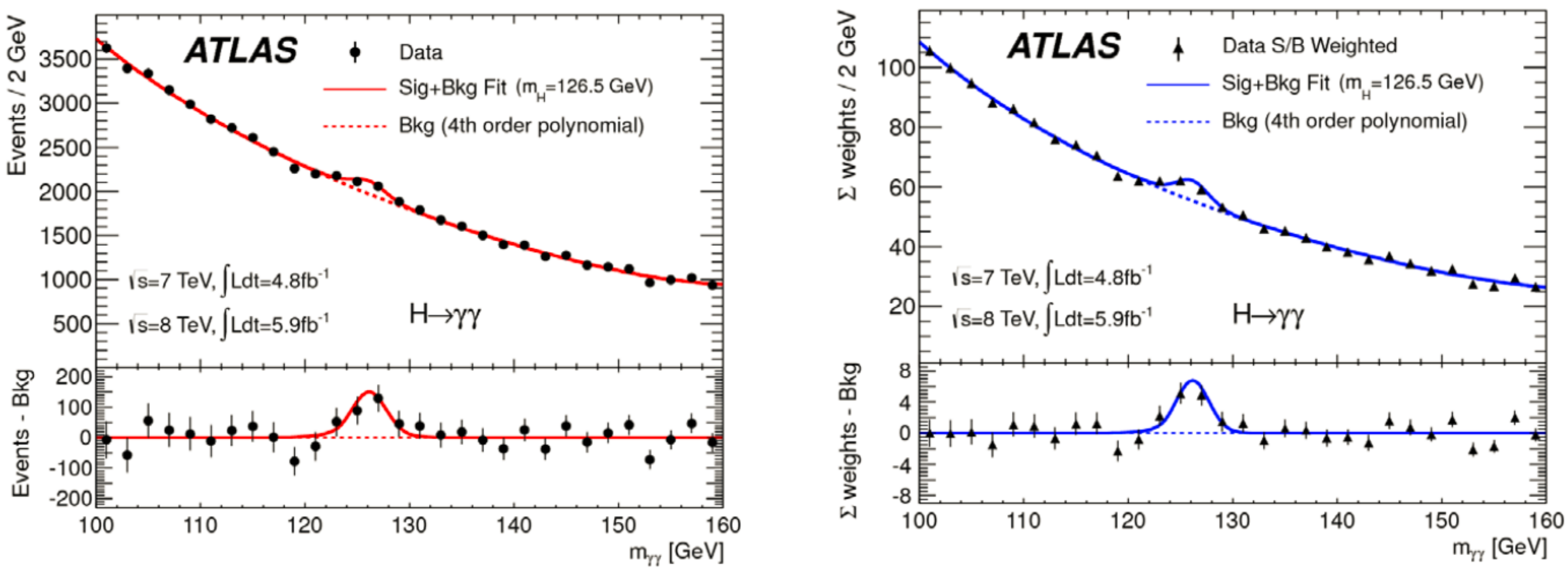
Higgs → γγ

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:

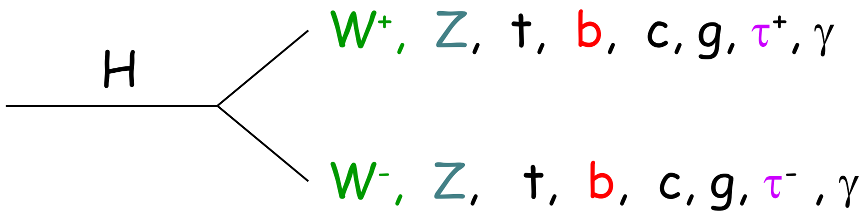
- **Signal: Crystal-Ball function (core) + Gaussian (outlier)**
- **Backgrounds: exponentials, polynomials, ...**



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

Higgs 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: $\delta_Z = 1, \delta_W = 2, \quad x = M_V^2/M_V^2, \quad \beta = \text{velocity}$

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

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

Higgs Boson:

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

Major Challenge (Huge Background)

- ❑ LHC physics is all about Background rejection ($\sim 10^{10}$)

“Every event at a lepton collider is physics; every event at a hadron collider is background”

- By Samuel C.C. Ting