Higgs Properties Measurement based on H→ZZ*→4ℓ with ATLAS

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The 9th Workshop of TeV Physics Working Group
Sun Yat-sen University, Guangzhou, China
May 15-18, 2014

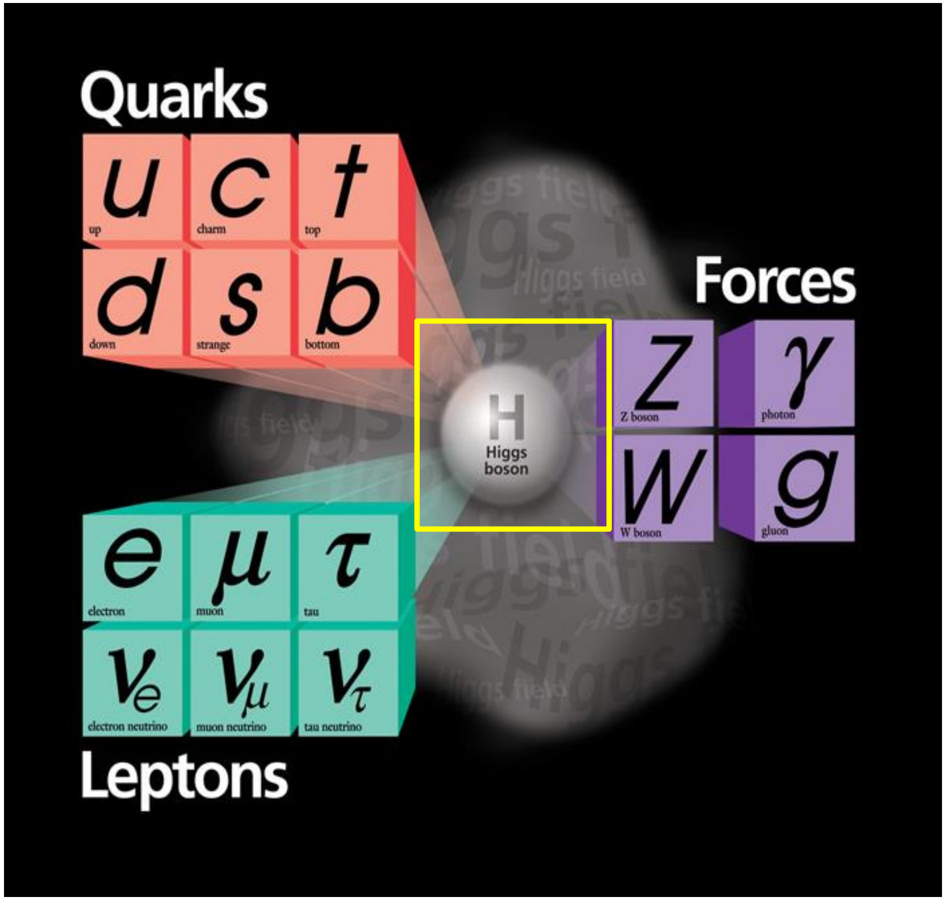
Outline

- Standard Model and Discovery of Higgs Boson
- Higgs Production and Decays at LHC
- Event Selection of H → ZZ* → 4ℓ
- Measurement of Properties : mass, spin, CP, couplings
- Summary

References:

PLB 726 pp.88-119, pp. 120-144
ATLAS-CONF-2013-013
ATLAS-CONF-2013-034
ATLAS-CONF-2014-009

Standard Model and Discovery of the Higgs



Higgs boson is proposed to responsible for the electroweak symmetry breaking, particles acquire mass when interacting with the Higgs field.

➔ The Higgs boson was discovered by ATLAS and CMS at LHC in July, 2012.
➔ F. Englert and P. Higgs won the Nobel Prize in Physics in 2013.

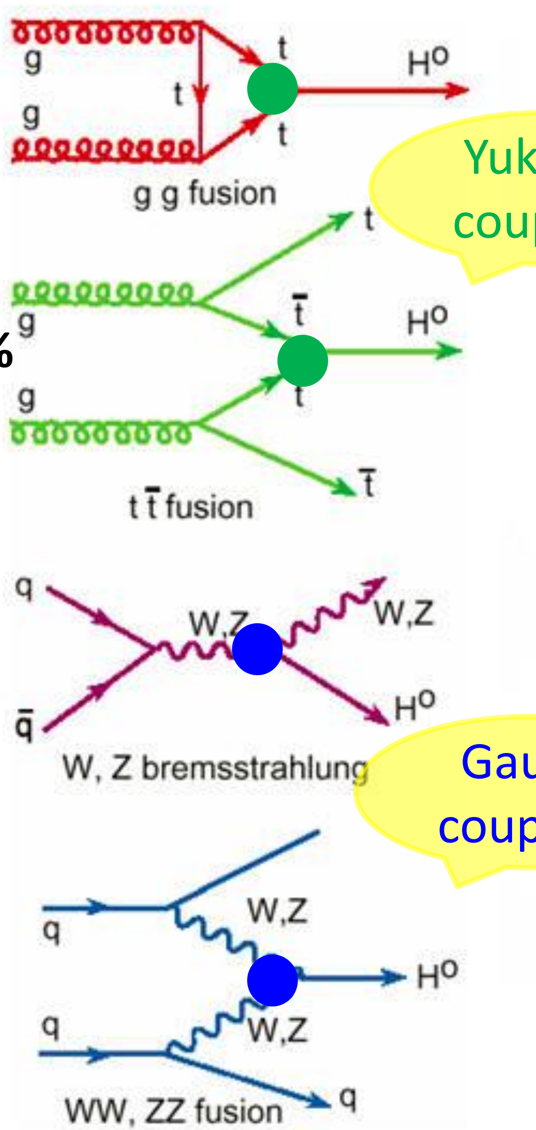
Higgs Boson Production at LHC

87%

0.5%

5%

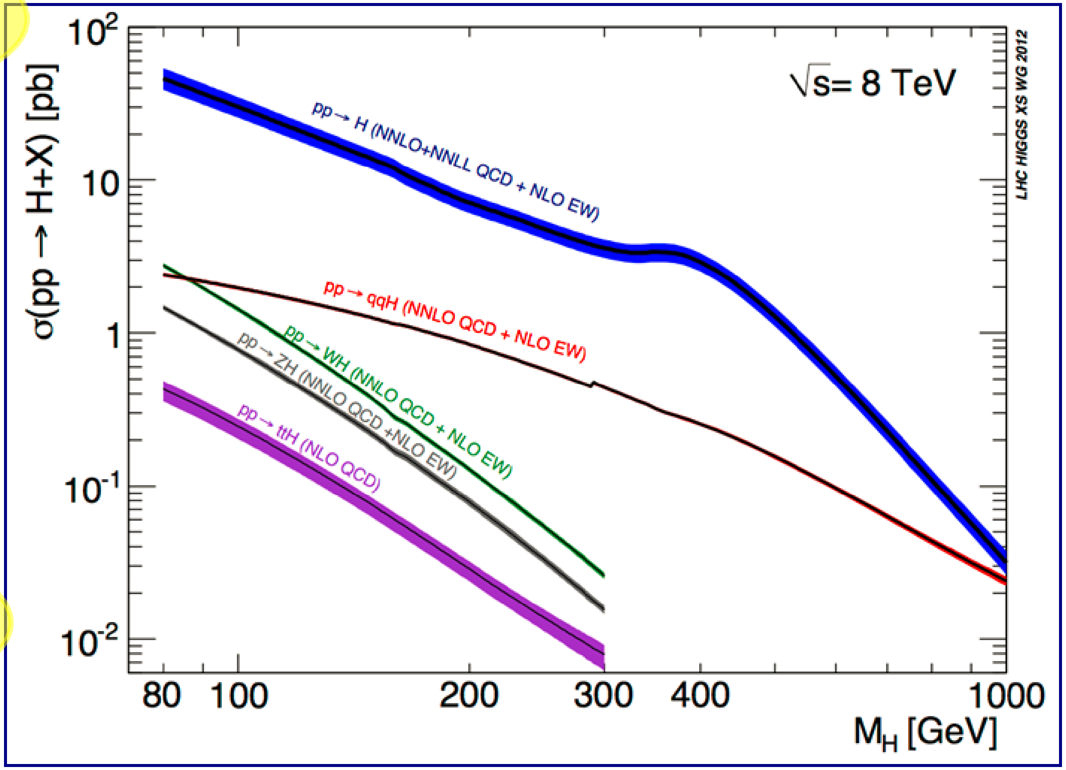
7%



Yukawa coupling

Gauge coupling

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

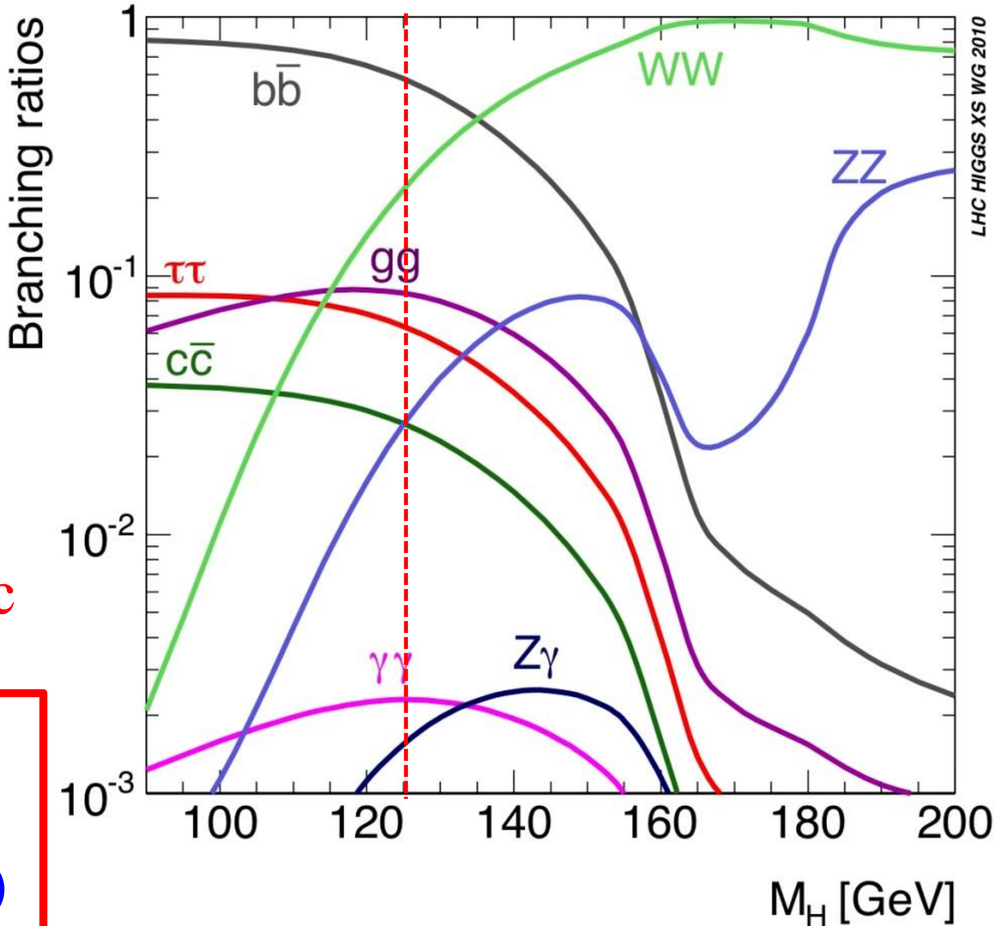


$$@125\text{ GeV: } \sigma_{ggH} = 19.5\text{ pb}, \sigma_{VBF} = 1.6\text{ pb},$$
$$\sigma_{WH} = 0.70\text{ pb}, \sigma_{ZH} = 0.39\text{ pb}, \sigma_{ttH} = 0.13\text{ pb}$$

Higgs Boson Decay

Higgs decay branching ratio at m_H=125 GeV

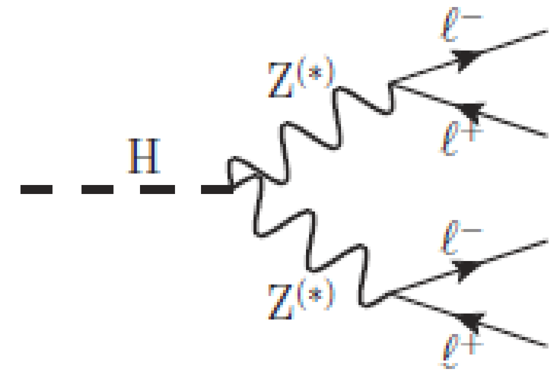
- bb: 57.7% (huge QCD background)
- WW: 21.5% (easy identification in di-lepton mode, complex background)
- ττ: 6.3% (complex final states with τ leptonic and/or hadronic decays)
- ZZ*: 2.6% ("gold-plated", clean signature of 4-lepton, high S/B, excellent mass peak)
- γγ: 0.23% (excellent mass resolution,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



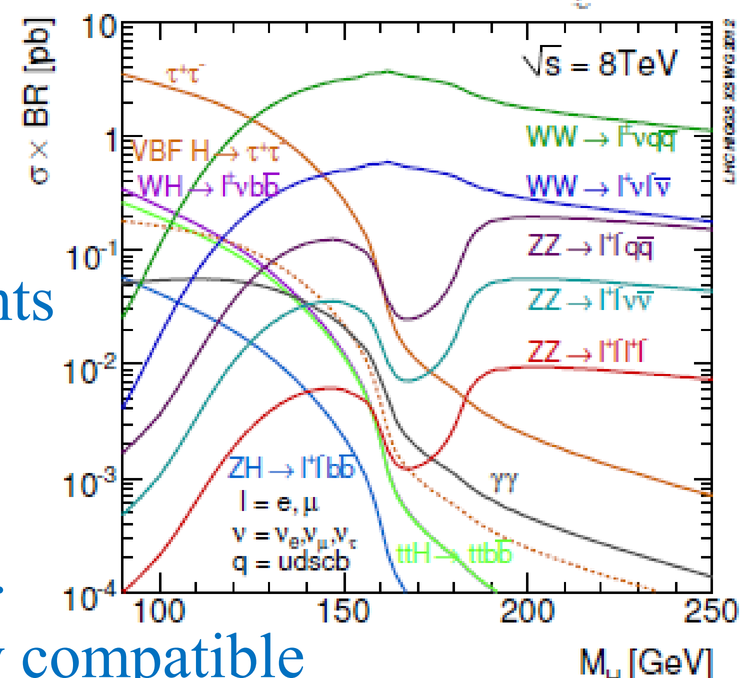
H → ZZ* → 4l production rate: 1 out of 10^{13} collision events

H→ZZ*→4ℓ Overview

- ❑ Extremely clean – "Gold-plated" channel
  - o Fully reconstructed final states
  - o Good mass resolution (~ 1.6-2.4 GeV)
  - o High S/B ratio (~ 1-2)
  - o Low decay branching fraction



- ❑ Currently statistically limited
  - o 4.6 fb^{-1} @ 7 TeV + 20.7 fb^{-1} @ 8 TeV
  - o Expect 68 SM H→ZZ*→4ℓ (e,μ) events



- ❑ Properties measurement
  - o Higgs mass, spin, parity, couplings etc.
  - o Critical to determine whether it is fully compatible with the SM Higgs boson

Event Selection

- Trigger match with single and/or di-lepton trigger
- Four sub-channels: 4e, 2e2μ, 2μ2e, 4μ

Event Pre-selection	
Electrons	
"MultiLepton" quality GSF electrons with $E_{\mathrm{T}} > 7$ GeV and $\|\eta\| < 2.47$	
Muons	
combined or segment-tagged muons with $p_{\mathrm{T}} > 6$ GeV and $\|\eta\| < 2.7$	
Maximum one calo-tagged or standalone muon	
calo-tagged muons with $p_{\mathrm{T}} > 15$ GeV and $\|\eta\| < 0.1$	
standalone muons with $p_{\mathrm{T}} > 6$ GeV, $2.5 < \|\eta\| < 2.7$ and $\Delta R > 0.2$ from closest segment-tagged	
Event Selection	
Kinematic Selection	Require at least one quadruplet of leptons consisting of two pairs of same-flavour opposite-charge leptons fulfilling the following requirements: p_{T} thresholds for three leading leptons in the quadruplet 20, 15 and 10 GeV Leading di-lepton mass requirement 50 GeV $< m_{12} <$ 106 GeV Sub-leading di-lepton mass requirement $m_{threshold} < m_{34} <$ 115 GeV Remove quadruplet if alternative same-flavour opposite-charge di-lepton gives $m_{\ell\ell} < 5$ GeV $\Delta R(\ell, \ell') > 0.10(0.20)$ for all same (different) flavour leptons in the quadruplet.
Isolation	Lepton track isolation ($\Delta R = 0.20$): $\Sigma p_{\mathrm{T}}/p_{\mathrm{T}} < 0.15$ Electron calorimeter isolation ($\Delta R = 0.20$) : $\Sigma E_T/E_T < 0.20$ Muon calorimeter isolation ($\Delta R = 0.20$) : $\Sigma E_T/E_T < 0.30$ Stand-Alone muons calorimeter isolation ($\Delta R = 0.20$) : $\Sigma E_T/E_T < 0.15$
Impact Parameter Significance	Apply impact parameter significance cut to all leptons of the quadruplet. For electrons : $d_0/\sigma_{d_0} < 6.5$ For muons : $d_0/\sigma_{d_0} < 3.5$

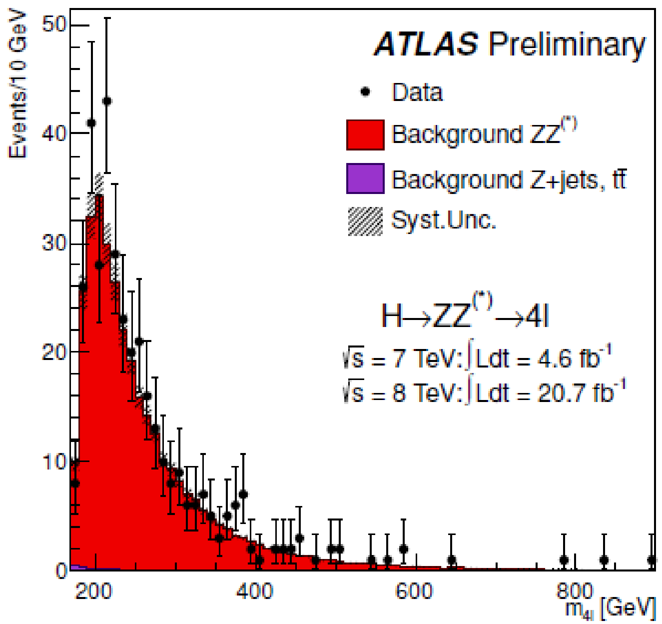
Background Estimation

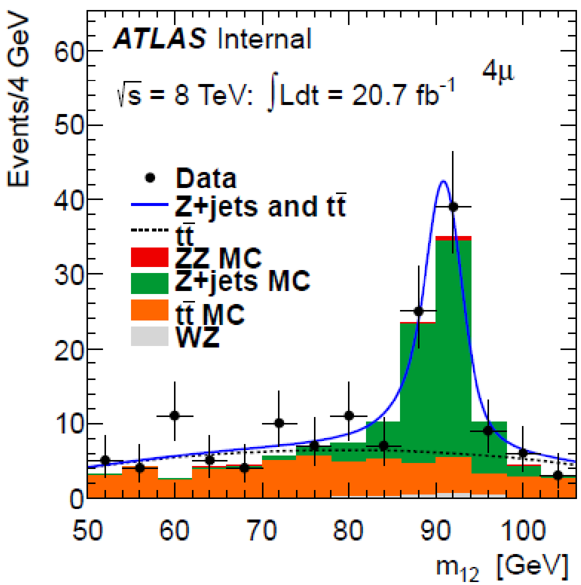
Main background is $ZZ^{(*)}$ production

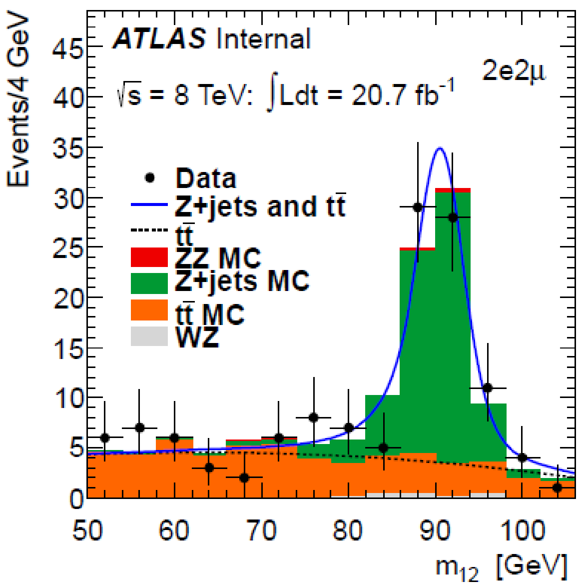
- MC simulation, scaled to theoretical cross section

Reducible backgrounds:

- $Zb\bar{b}$, Z+light jets, $t\bar{t}$
- Estimated using data-driven methods
  - Define background-enriched/signal-depleted control reigions
  - Extrapolate to signal region using transfer factors

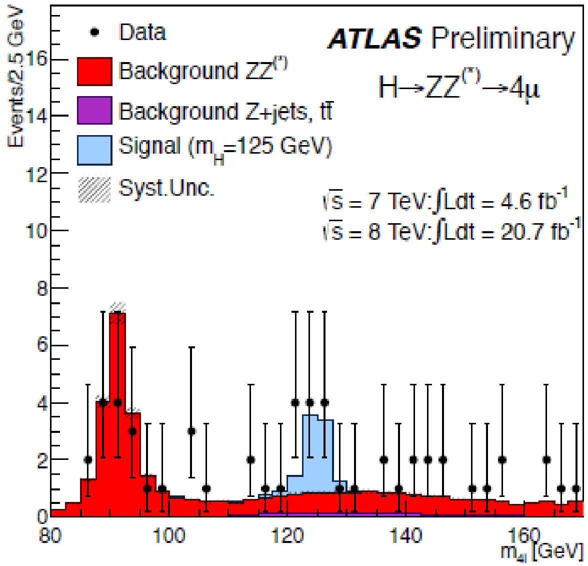




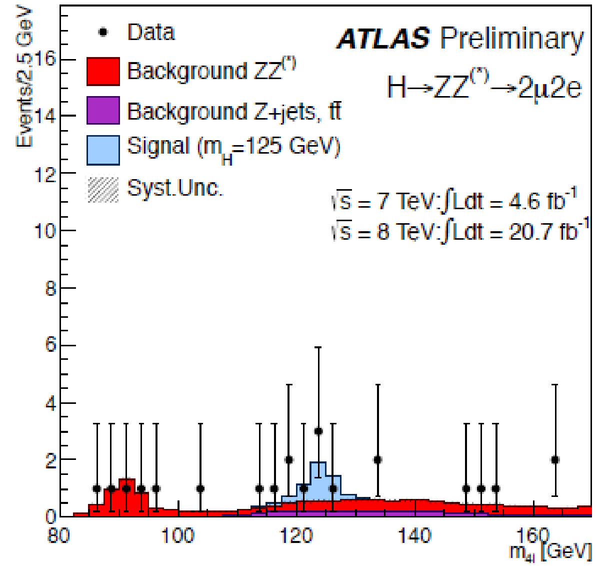


- Estimates agree well with data in control region where isolation and d_0 requirements are removed for subleading pair

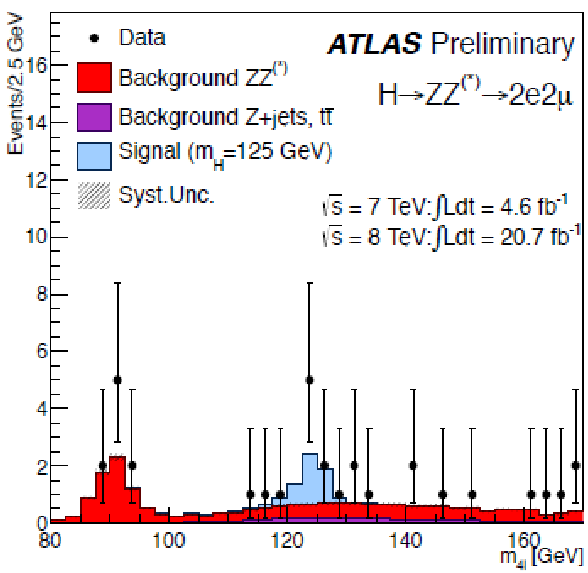
Invariant Mass of 4-lepton

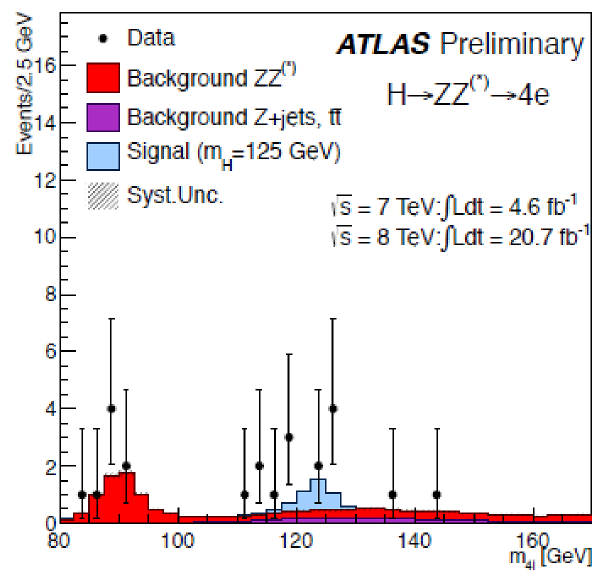


(a)

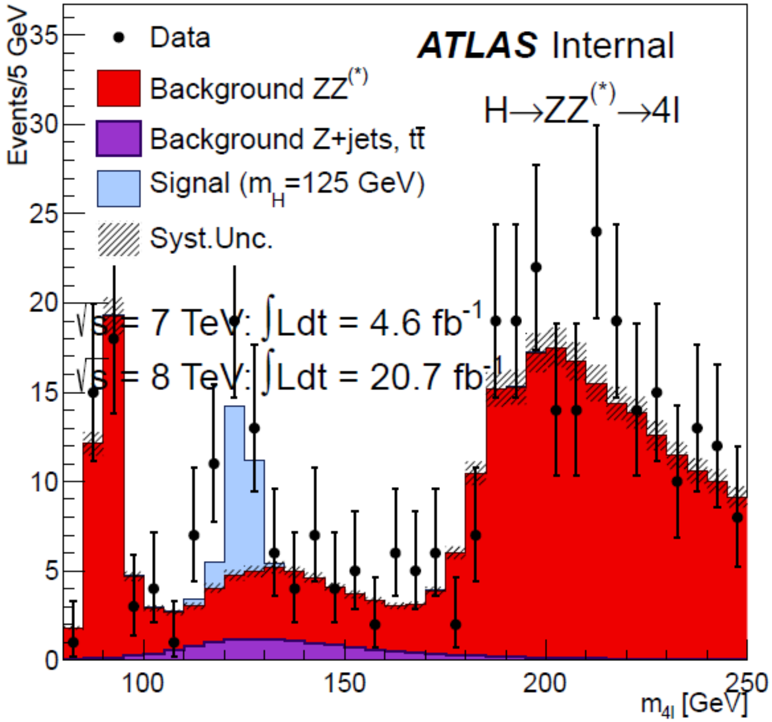


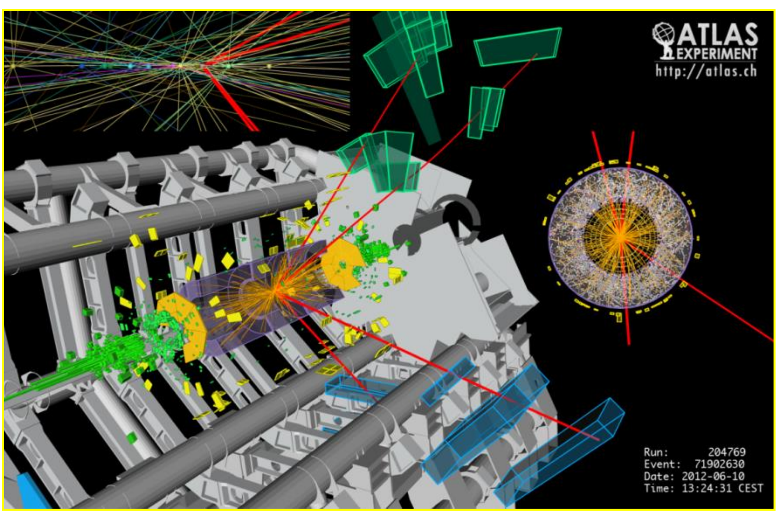
(b)





Selected Higgs Candidates



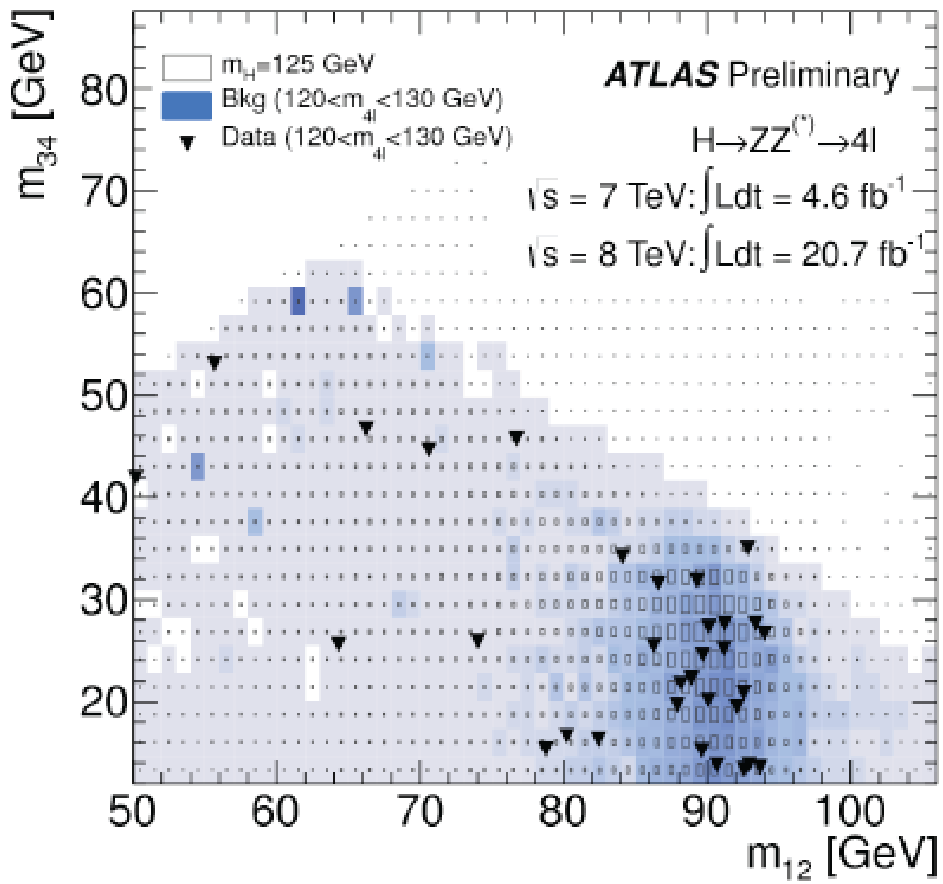


BR(H→ZZ*) = 2.63%, BR(ZZ*→4l)=0.45%

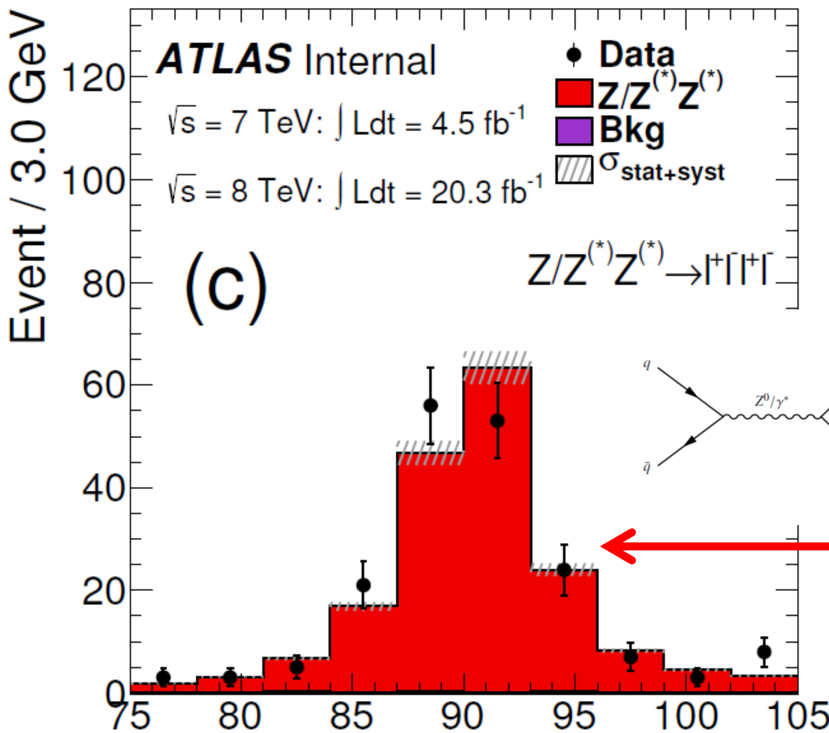
About 68 H→ ZZ*→4l events produced

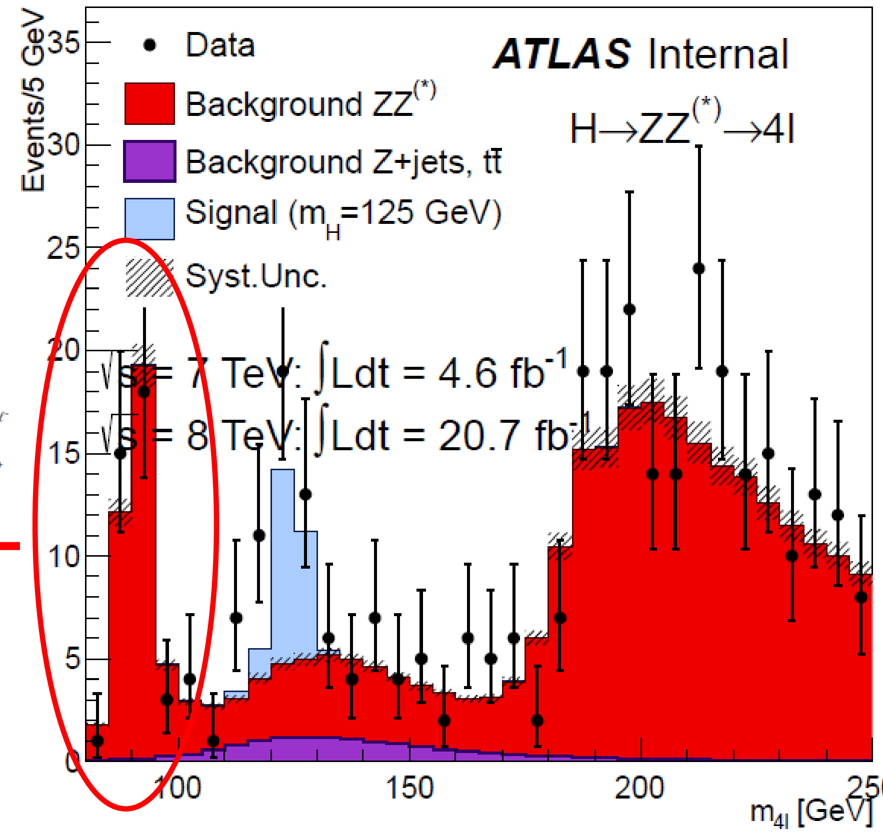
Observed 32 candidates (16 Higgs signal)

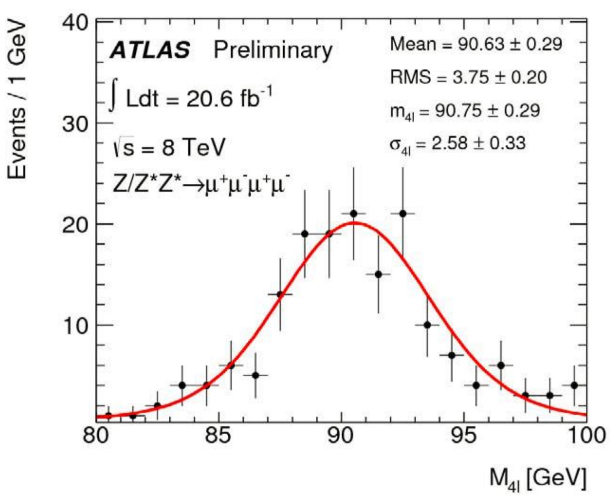
	Signal	ZZ^*	$Z+\text{jets}, t\bar{t}$	Observed
4μ	6.3 ± 0.8	2.8 ± 0.1	0.55 ± 0.15	13
$2e2\mu/2\mu 2e$	7.0 ± 0.6	3.5 ± 0.1	2.11 ± 0.37	13
$4e$	2.6 ± 0.4	1.2 ± 0.1	1.11 ± 0.28	6



H→ZZ*→4ℓ :Mass Calibration



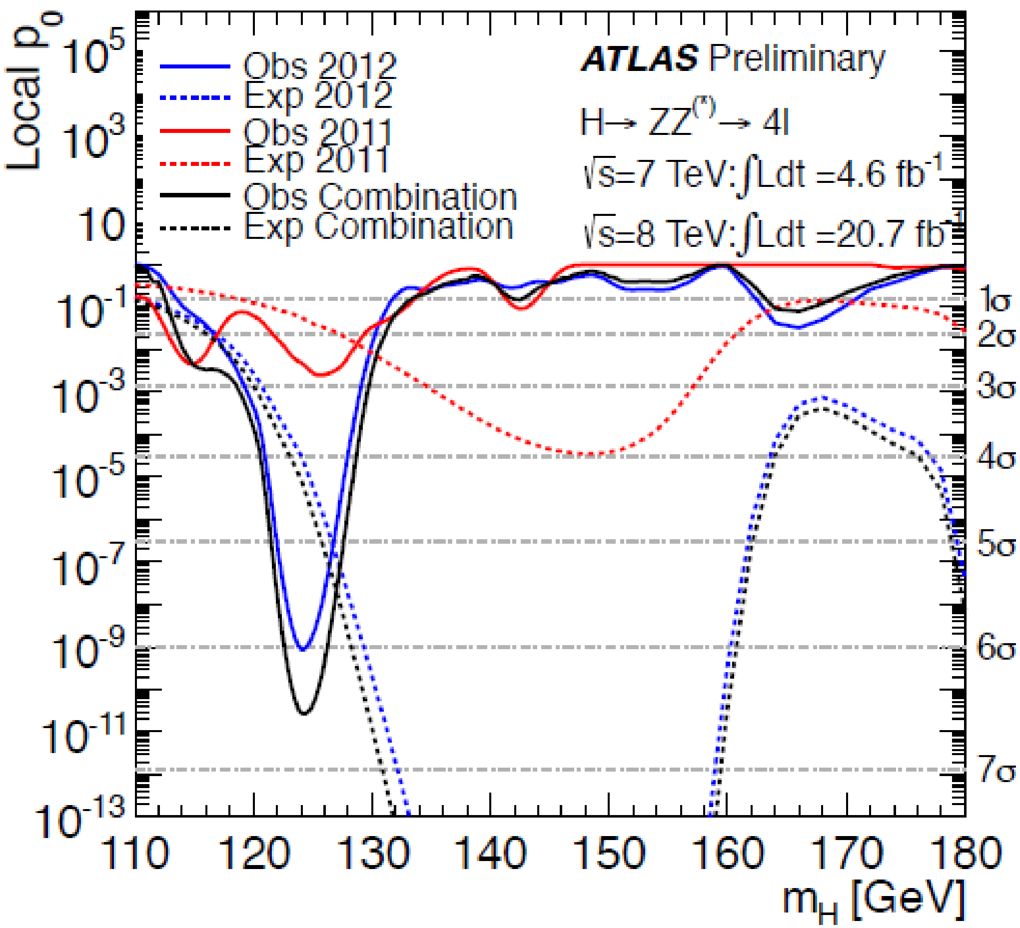




BR(meas.)=(3.20 ± 0.25 ± 0.13) × 10^{-6}
BR(SM NLO)=(3.33 ± 0.01) × 10^{-6}
$\sigma_{(PS)}$=107.3 ± 8.8 ± 4.0 ± 3.0 (fb)
(arXiv:1403.5657,
accepted by PRL on May 7, 2014)

Higgs Detection Significance

data set	observed min p_0	observed significance $[\sigma]$	observed $m_H(p_0)$	expected min $p_0(m_H)$	expected significance $[\sigma]$
$\sqrt{s}$ = 7 TeV	2.5×10^{-3}	2.8	125.6 GeV	3.5×10^{-2}	1.8
$\sqrt{s}$ = 8 TeV	8.8×10^{-10}	6.0	124.1 GeV	2.8×10^{-5}	4.0
combined	2.7×10^{-11}	6.6	124.3 GeV	5.7×10^{-6}	4.4



- ❑ **Signal significance**
  6.6 σ (Measured)
  4.4 σ (Expected)

➔ **> 5σ discovery in H→ZZ*→4ℓ channel**

Higgs Mass Measurement

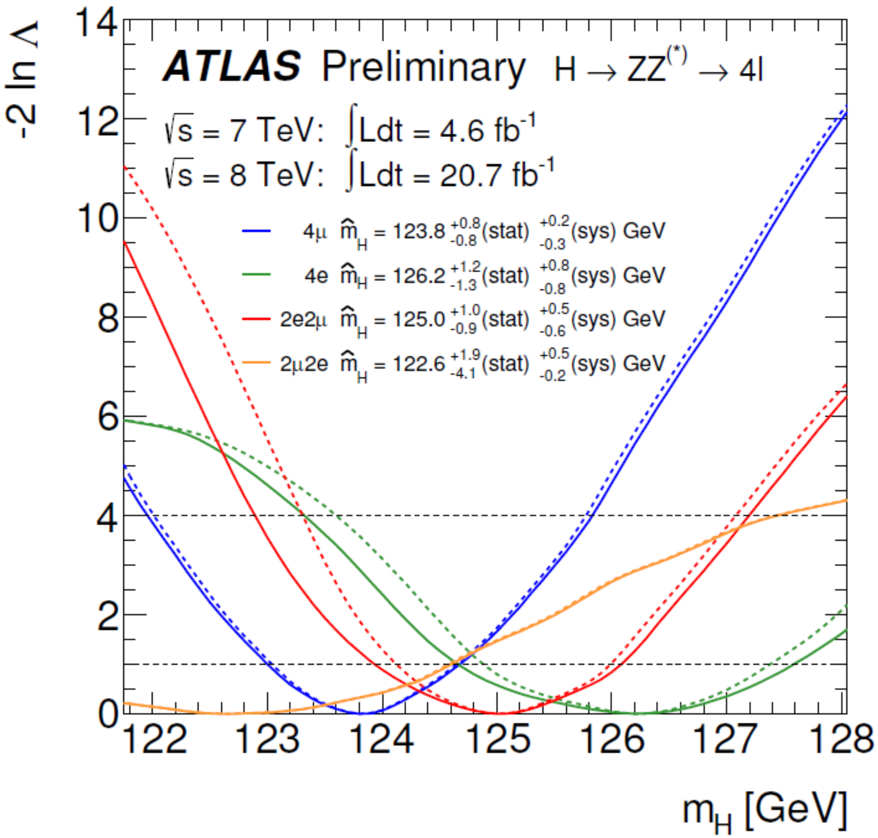
$\hat{m}_H(4\mu) = 123.8^{+0.8}_{-0.8}(\text{stat})^{+0.2}_{-0.3}(\text{sys})$ GeV

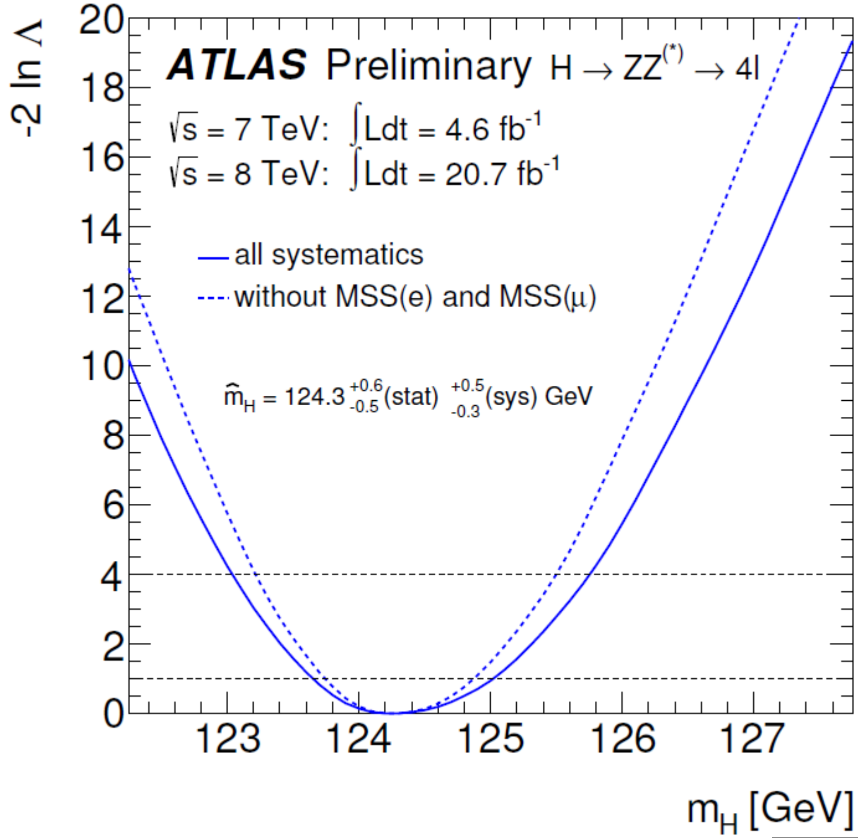
$\hat{m}_H(4e) = 126.2^{+1.2}_{-1.3}(\text{stat})^{+0.8}_{-0.8}(\text{sys})$ GeV

$\hat{m}_H(2e2\mu) = 125.0^{+1.0}_{-0.9}(\text{stat})^{+0.5}_{-0.6}(\text{sys})$ GeV

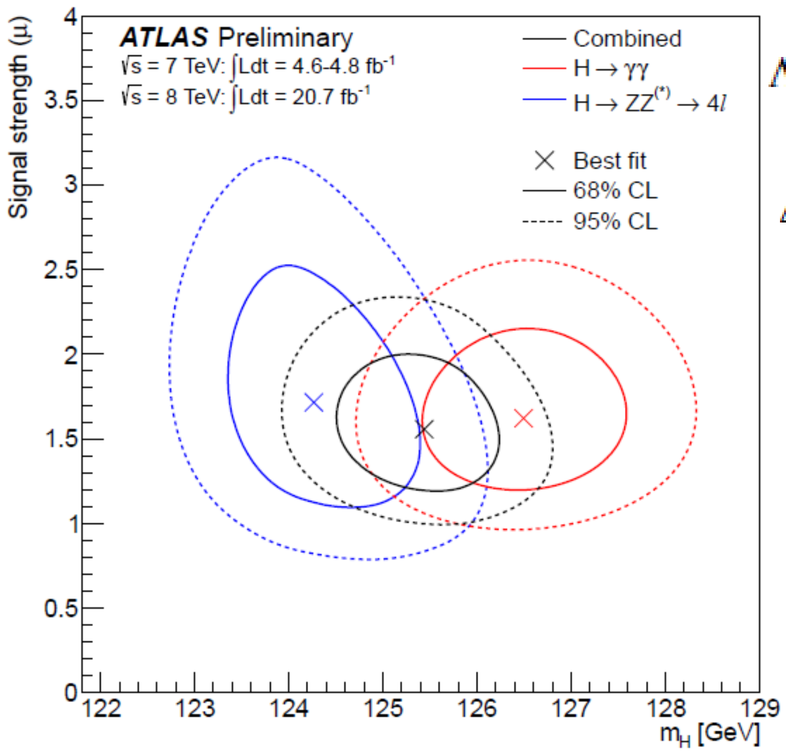
$\hat{m}_H(2\mu 2e) = 122.6^{+1.9}_{-4.1}(\text{stat})^{+0.5}_{-0.2}(\text{sys})$ GeV

$\hat{m}_H(\text{combined}) = 124.3^{+0.6}_{-0.5}(\text{stat})^{+0.5}_{-0.3}(\text{sys})$ GeV



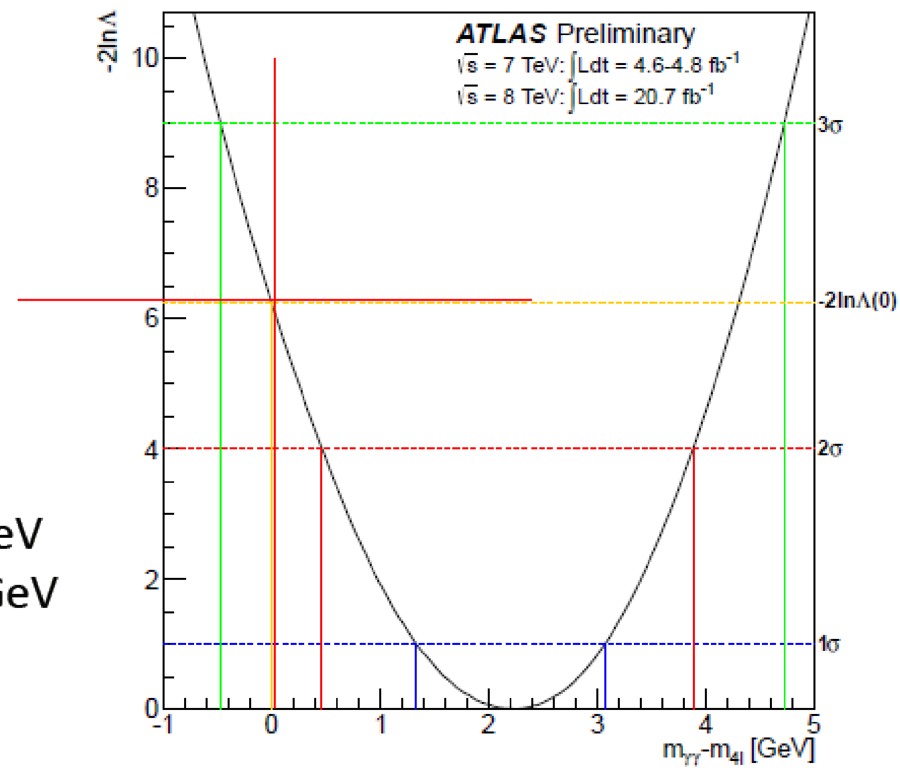


Higgs Mass Measurements



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

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



$H \rightarrow \gamma\gamma$	126.8 ± 0.2 (stat) ± 0.7 (sys) GeV
$H \rightarrow ZZ^* \rightarrow 4l$	$124.3\ ^{+0.6}_{-0.5}$ (stat) $^{+0.5}_{-0.3}$ (sys) GeV

Combined mass

$$m_H = 125.5 \pm 0.2(\text{stat})^{+0.5}_{-0.6}(\text{sys})\ \text{GeV}$$

It is compatible with $\Delta M_H = 0$ at the level of 1.2%, 2.5σ

Measurements of Higgs Signal Strength

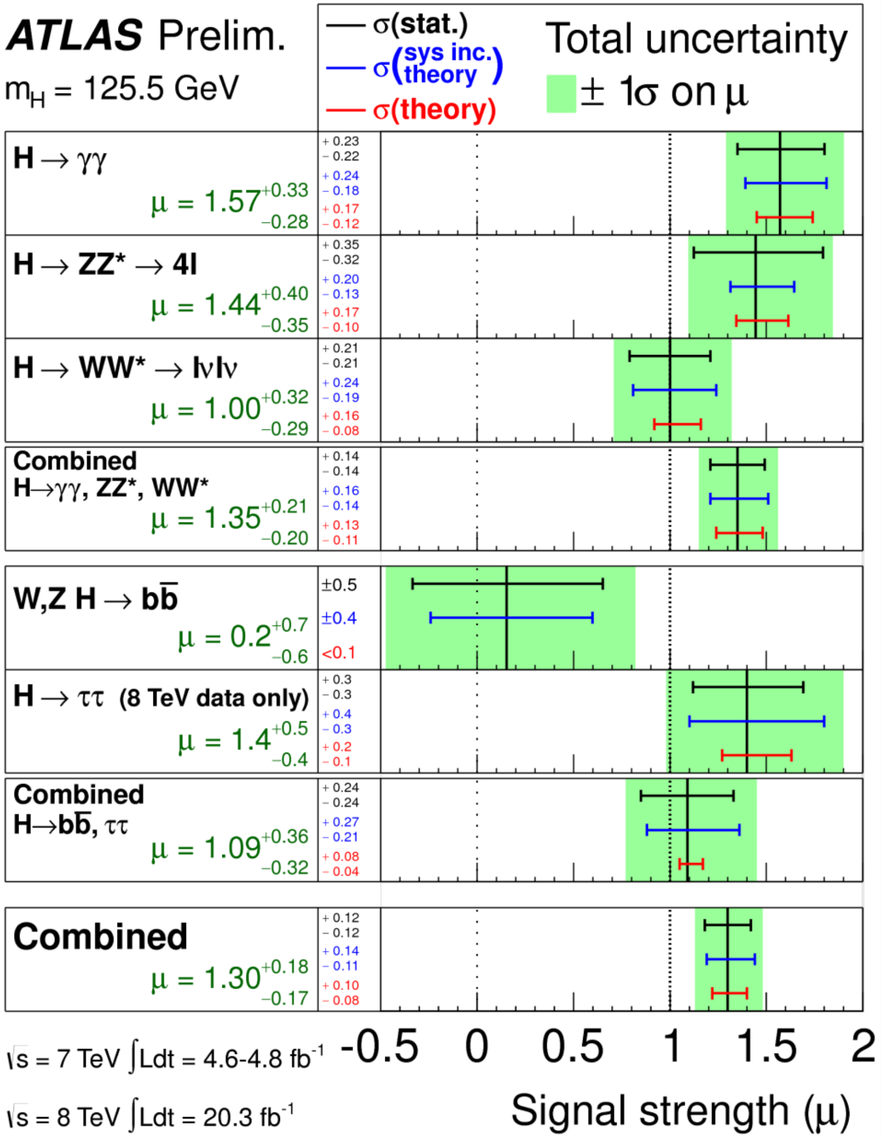
➔ **Signal strength for H➔ZZ*➔4ℓ:**

$\mu = 1.4 \pm 0.4$

➔ **Combined signal strength**

$\mu = 1.3 \pm 0.2$ **(ATLAS)**

$$\mu = \frac{\sigma \times Br}{(\sigma \times Br)_{SM}}$$



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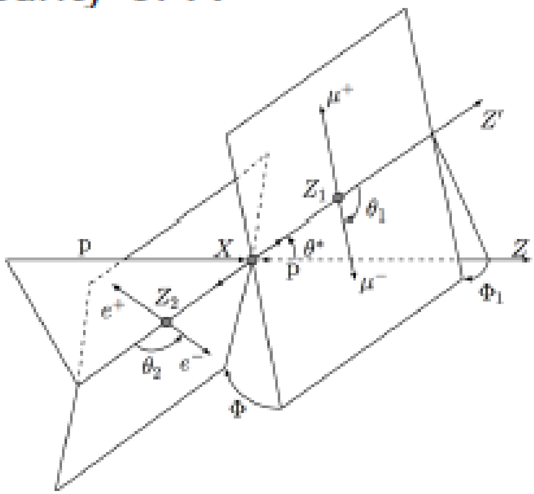
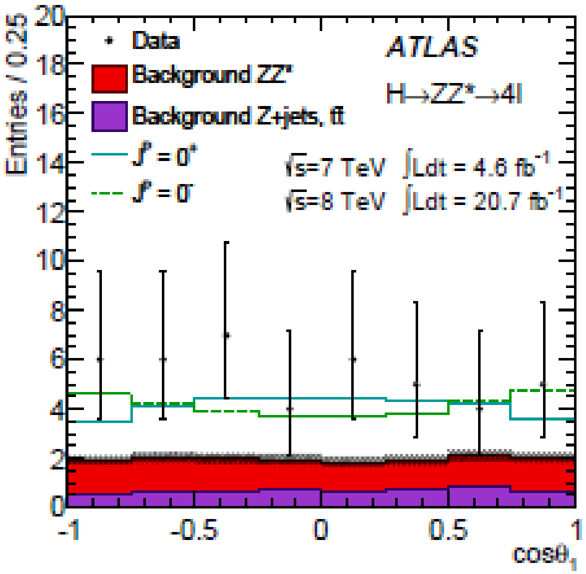
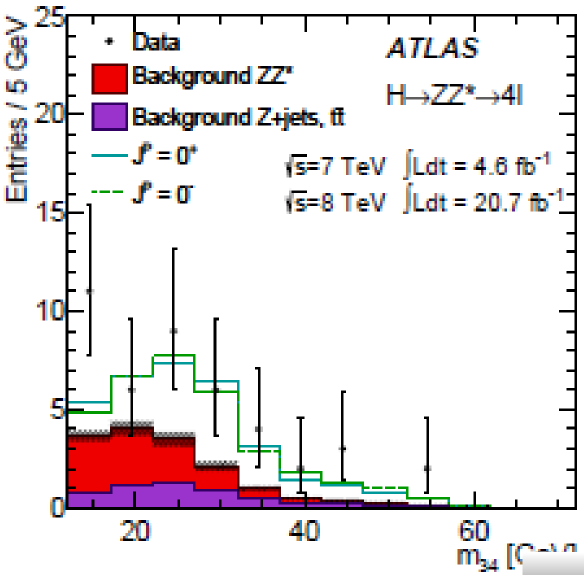
H→ZZ*→4l : Spin and Parity

- In X→ $ZZ^{(*)} \to 4\ell$ decays, m_{Z_1}, m_{Z_2} and the production and decay angles are sensitive to the spin-parity of X

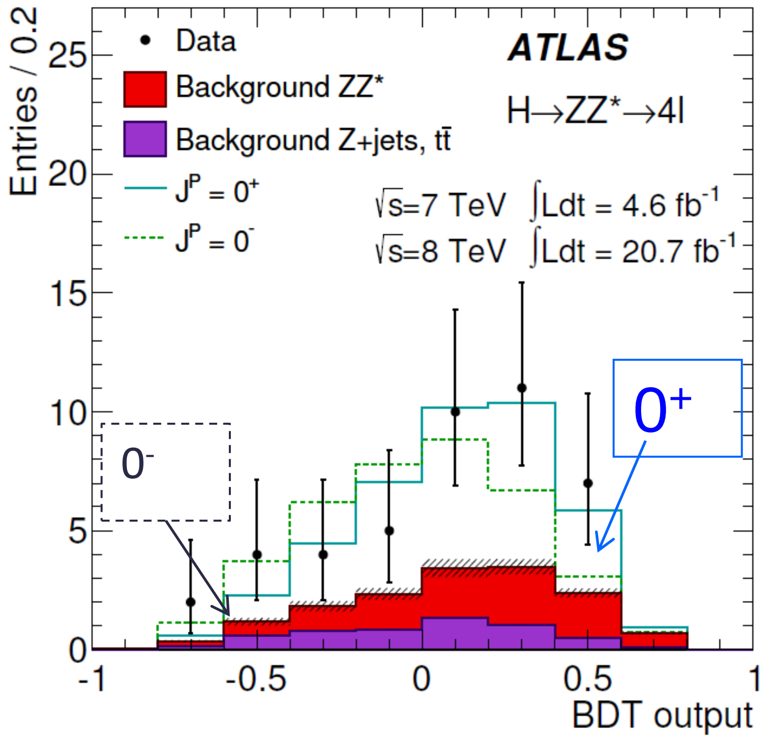


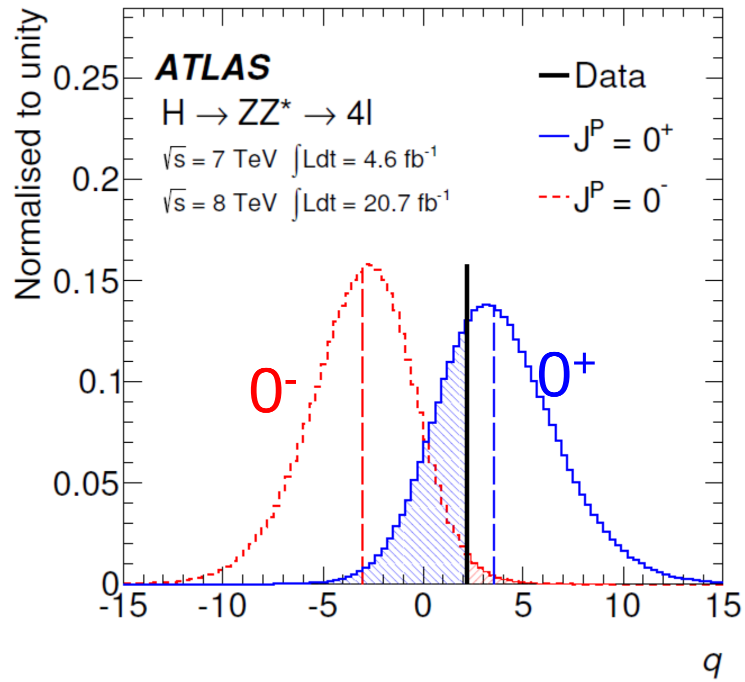


- Construct a discriminant between different hypotheses using two different multivariate techniques:
  - BDT (machine learning)
  - J^P-MELA (use theoretical differential decay rates to construct a matrix element based likelihood ratio)
- Use events in range $115 < m_{4\ell} < 130$ GeV
- Test SM 0^+ hypothesis against alternative hypotheses 0^-, 1^+, 1^-, 2^+_m



H→ZZ*→4l : Spin and Parity





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%

Observed 2^+_m exclusion 83.2%

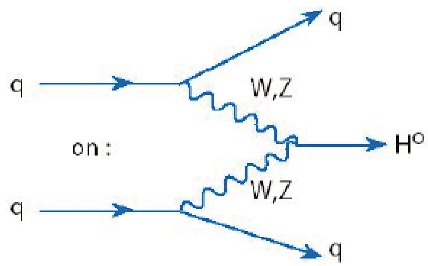
		BDT analysis			
		tested J^P for an assumed 0^+		tested 0^+ for an assumed J^P	CL_S
		expected	observed	observed*	
0^-	p_0	0.0037	0.015	0.31	0.022
1^+	p_0	0.0016	0.001	0.55	0.002
1^-	p_0	0.0038	0.051	0.15	0.060
2^+_m	p_0	0.092	0.079	0.53	0.168
2^-	p_0	0.0053	0.25	0.034	0.258

Probing Higgs Production

- Event characteristics allow measurement of signal strength from different production modes

σ/σ_{Total}

7%



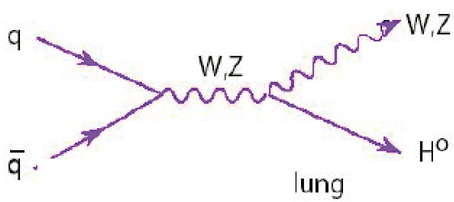
Vector Boson Fusion (VBF)

>= 2 jets with p_T > 25 (30) GeV and
$|\eta|<2.5$ ($2.5 < |\eta| < 4.5$)
$\Delta\eta_{jj} > 3$; $M_{jj} > 350$ GeV
8 observed candidates →

One VBF candidate with
$m_{4\ell}$ = 123.5 GeV

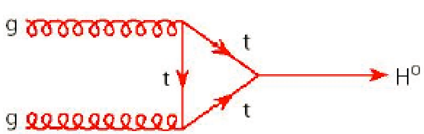
In 120-130 GeV:

5%

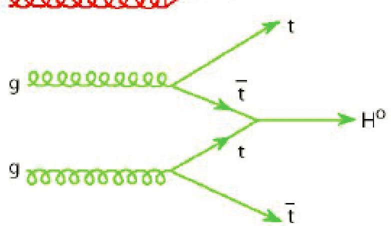


Associated P
Additional lept
1 observe

87%

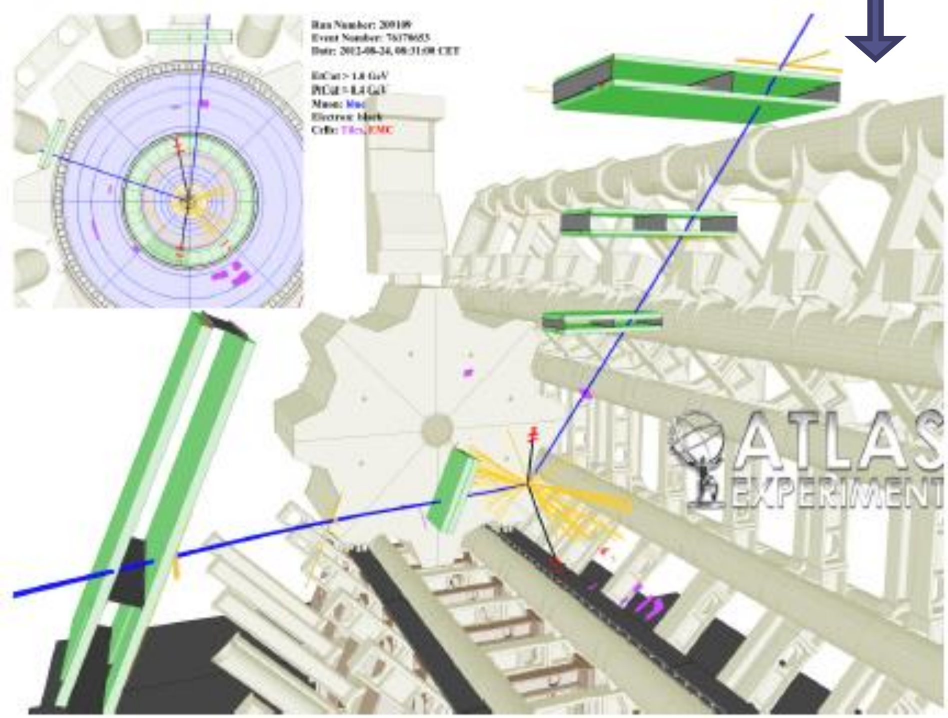


0.5%



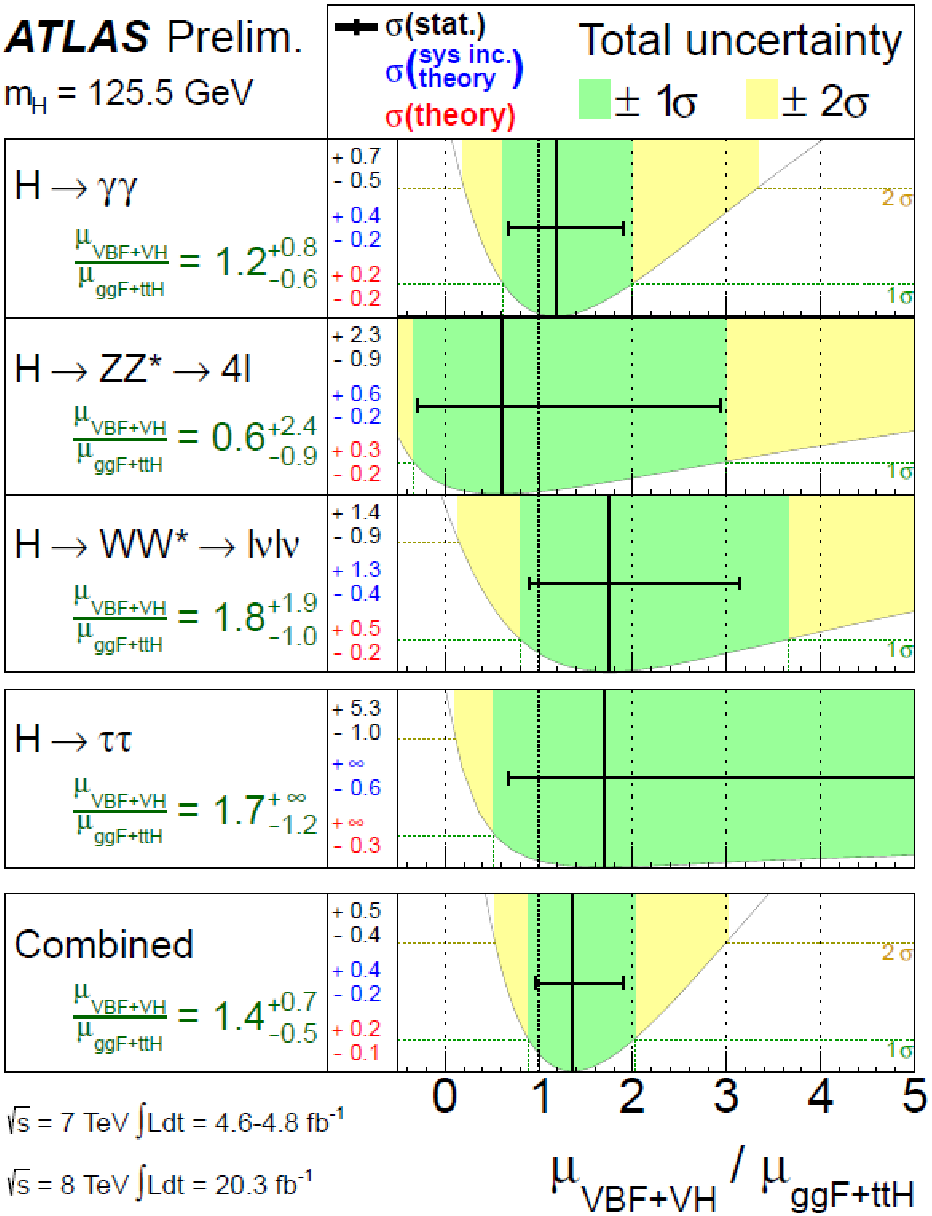
Gluon Gluo

tt Fusi

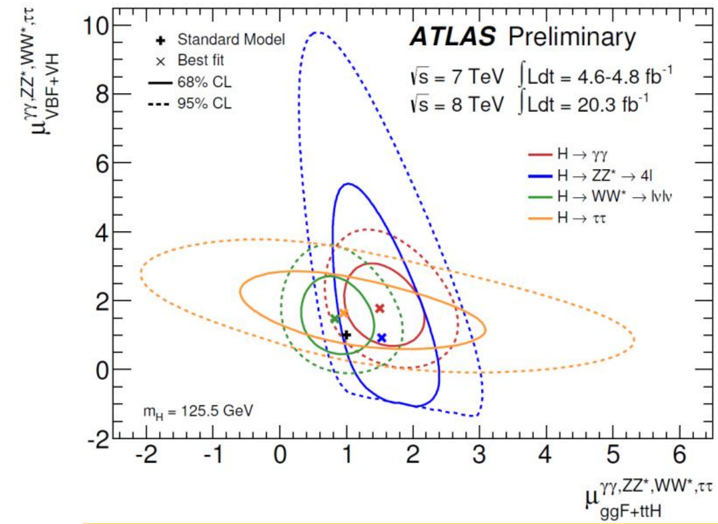


Candidate event with $m_{4\ell}$ = 123.5 GeV in VBF-like category

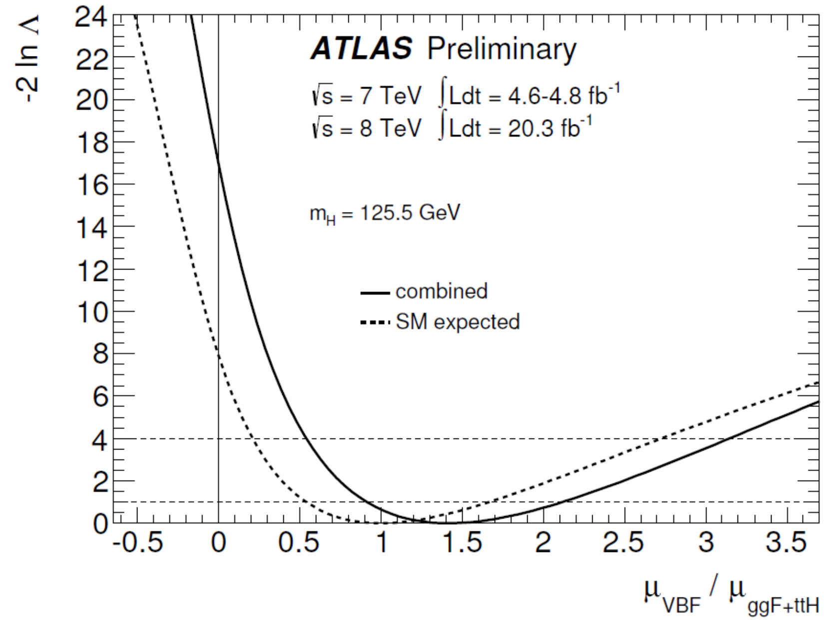
Higgs Production: ggF vs. VBF



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



Compatibility with $\mu_{VBF}=0 \rightarrow 4.1\sigma$



Fermion and Vector Couplings

Coupling scale factors

2-parameter benchmark model:

$\kappa_V = \kappa_W = \kappa_Z$

$\kappa_F = \kappa_t = \kappa_b = \kappa_c = \kappa_\tau = \kappa_g$

(Gluon coupling are related to top, b, and their interference in tree level loop diagrams)

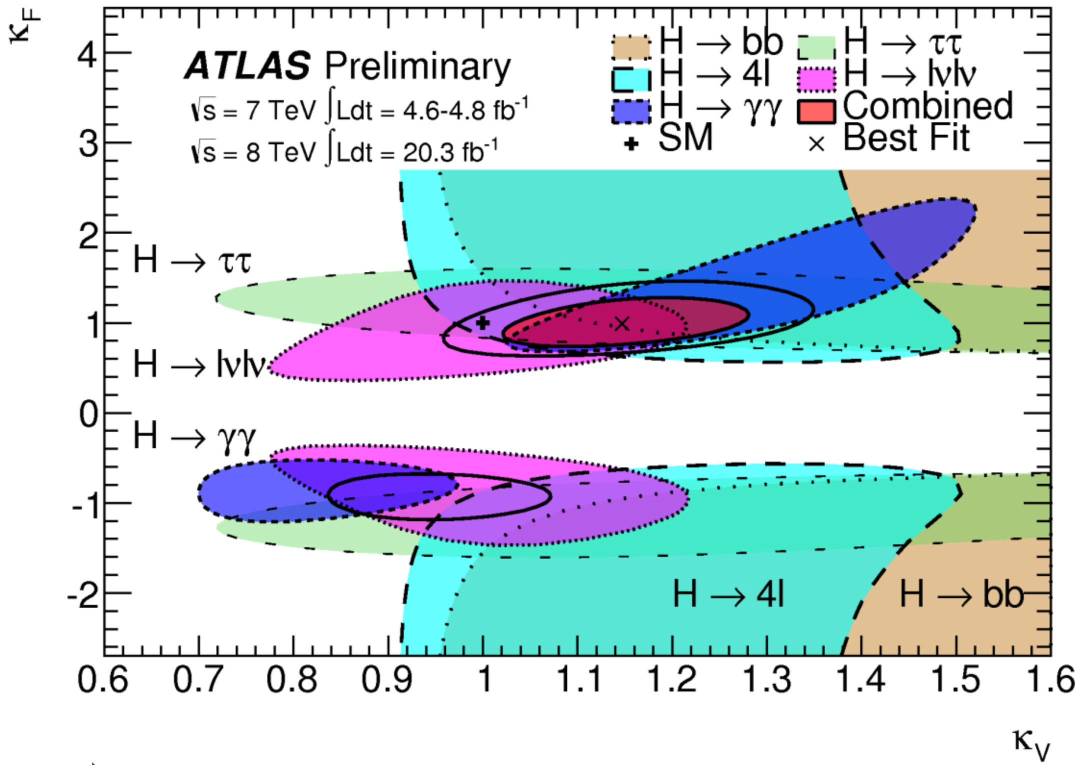
Assume no BSM contributions to loops: gg→ H and no BSM decays (no invisible decays)

$$\kappa_V = 1.15 \pm 0.08$$

$$\kappa_F = 0.99^{+0.17}_{-0.15}.$$

→ κ_F = 0 is excluded (>5σ)

$$\frac{\sigma \cdot B\,(gg \to H \to \gamma\gamma)}{\sigma_{SM}(gg \to H) \cdot B_{SM}(H \to \gamma\gamma)} = \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$$



See Xin Chen's talk for direct evidence of H→ff

Summary

- With 2011 (4.6 fb^{-1} @ 7TeV) and 2012 (20.7 fb^{-1} @ 8 TeV) datasets, the Higgs boson is observed in the $H \to ZZ^* \to 4\ell$ channel with local significance of 6.6σ.
- The best fit mass of the Higgs boson from $H \to ZZ^* \to 4\ell$

$$m_H = 124.3\ ^{+0.6}_{-0.5}(stat)^{+0.5}_{-0.3}(sys)\ \text{GeV}$$

Combined Higgs mass

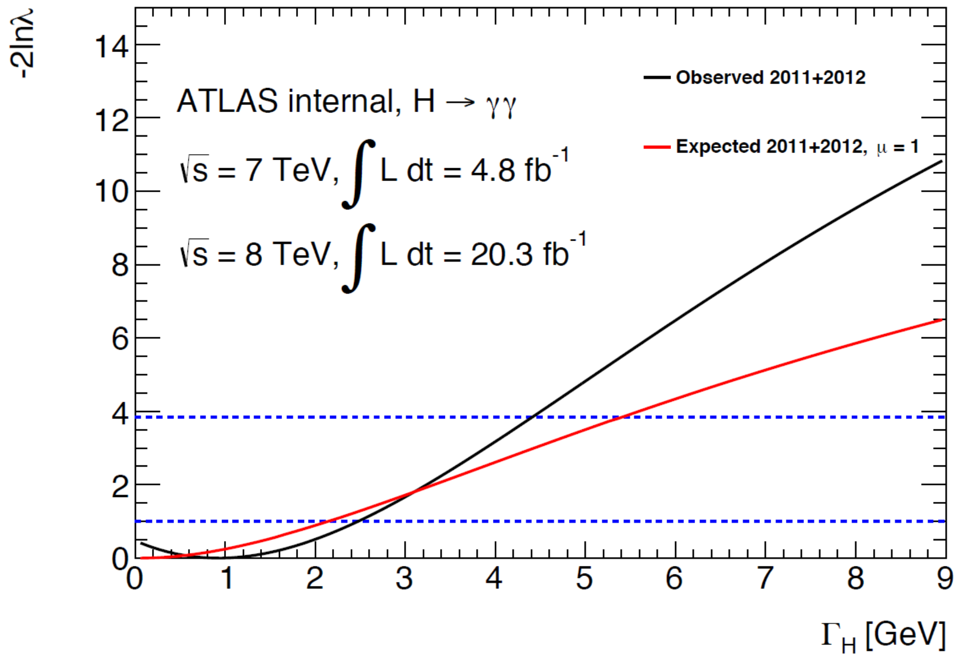
$$m_H = 125.5 \pm 0.2(\text{stat})^{+0.5}_{-0.6}(\text{sys})\ \text{GeV}$$

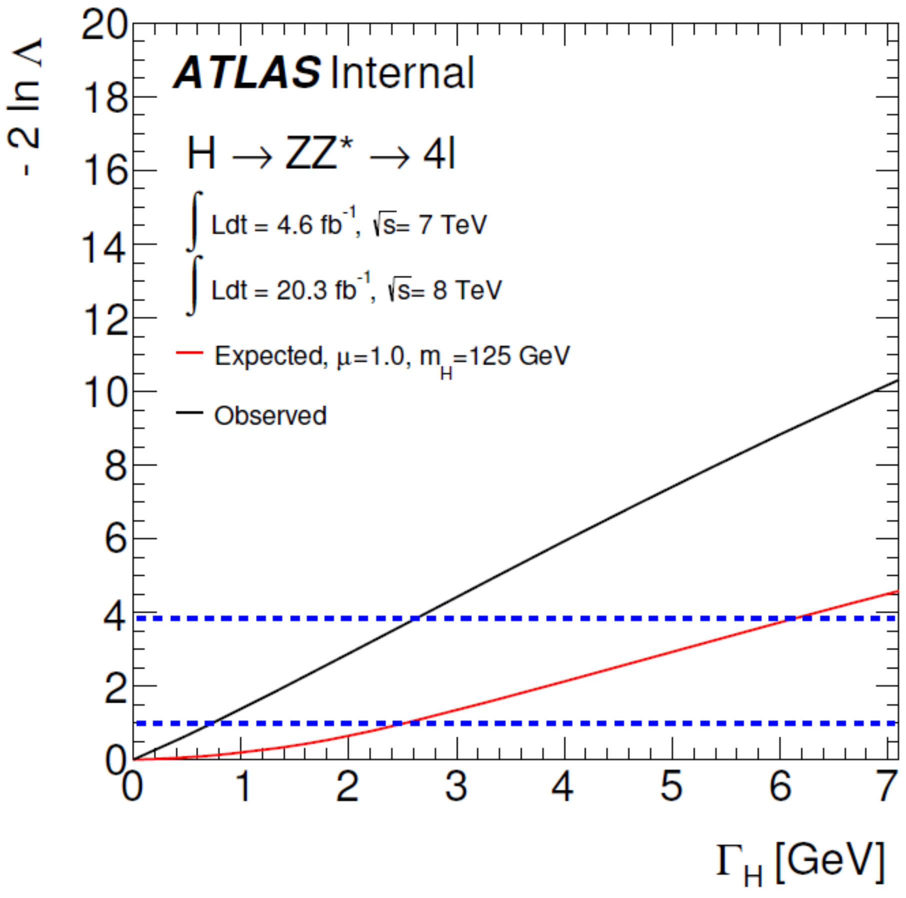
- The ratio of signal strength for bosonic (VBF+VH) and fermionic (ggF+ttH) production modes are measured, evidence of VBF production is 4.1σ.
- The ATLAS data is found to favour the Standard Model Higgs boson $J^P = 0^+$ hypothesis.

Backup

Higgs Width

- Using per-event-error method, direct limit on the total width of the Higgs boson LH < 2.6 GeV @ 95% C.L.





Measurements of Higgs Signal Strength

➔ **Signal strength: μ=1.3±0.2(ATLAS)**
➔ **μ = 0.8 ±0.14 (CMS)**

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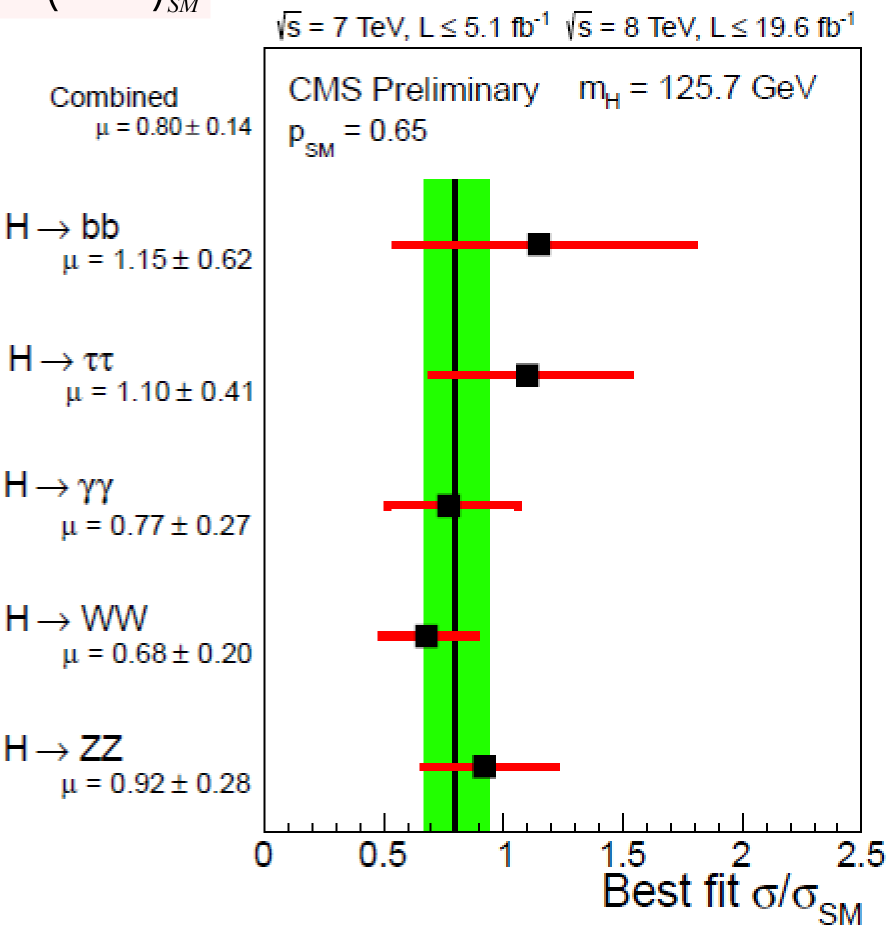
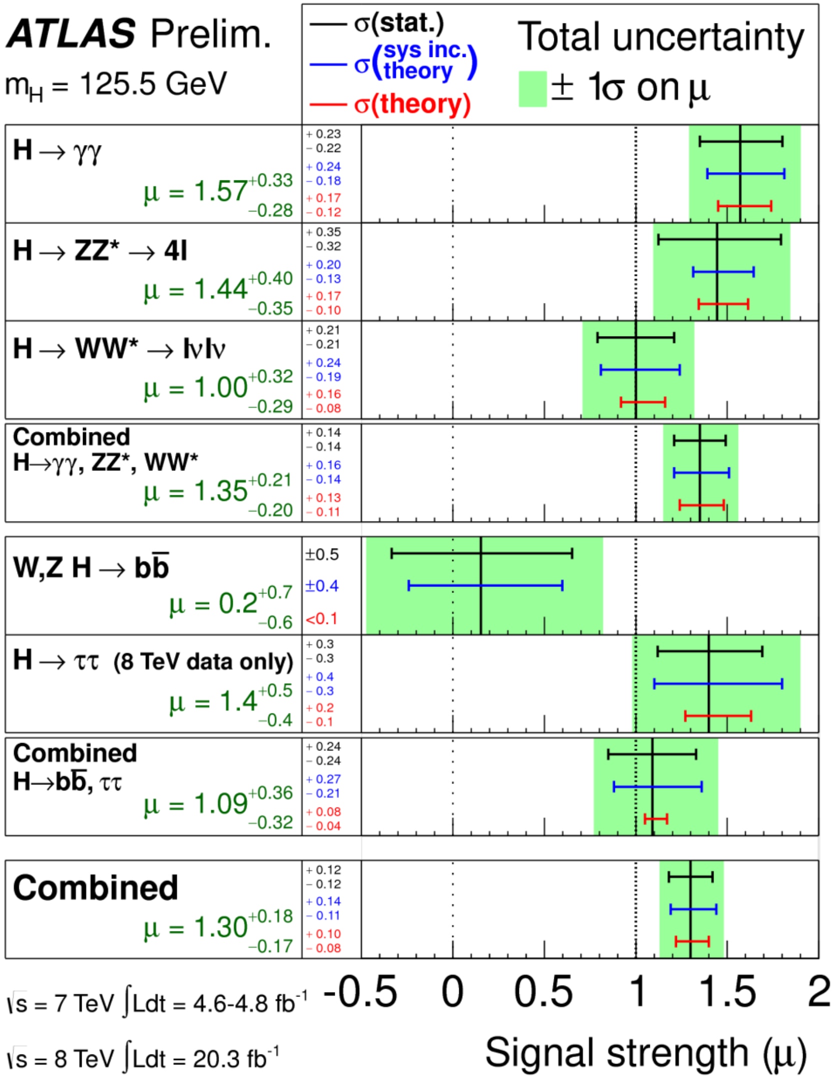
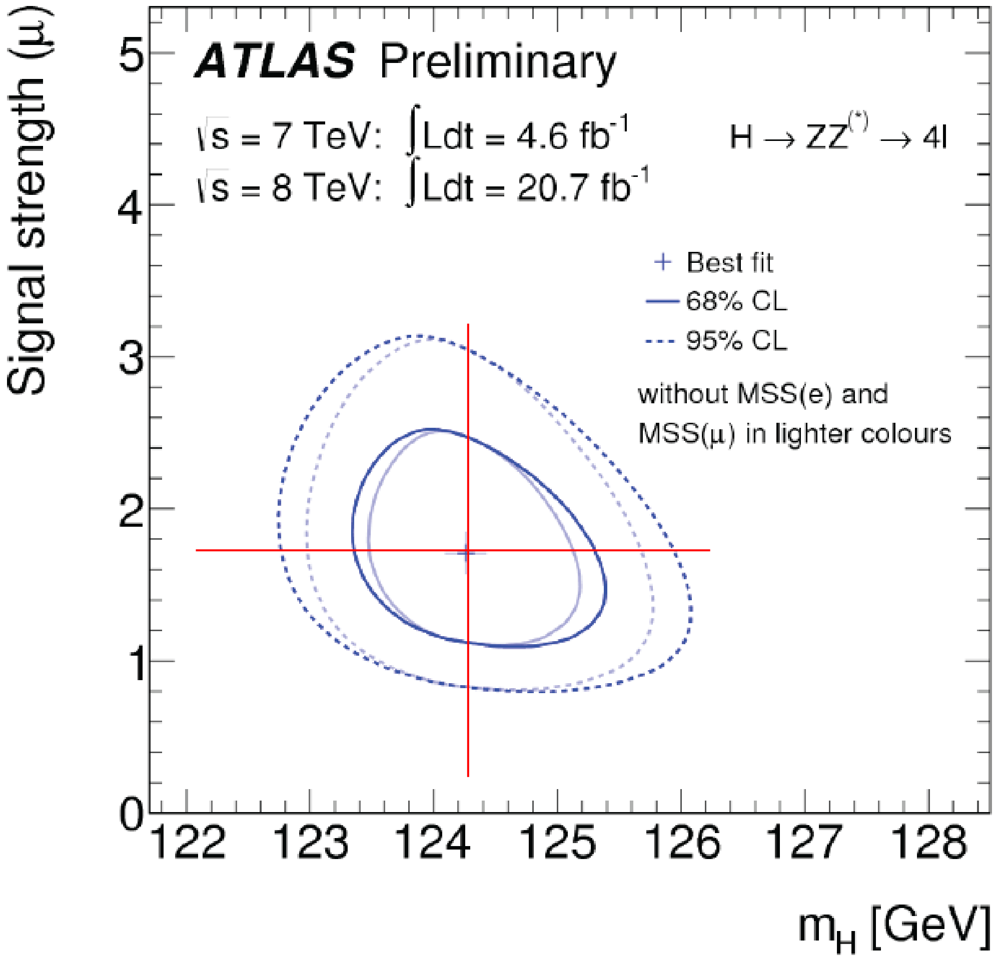
$$\mu = \frac{\sigma \times Br}{(\sigma \times Br)_{SM}}$$

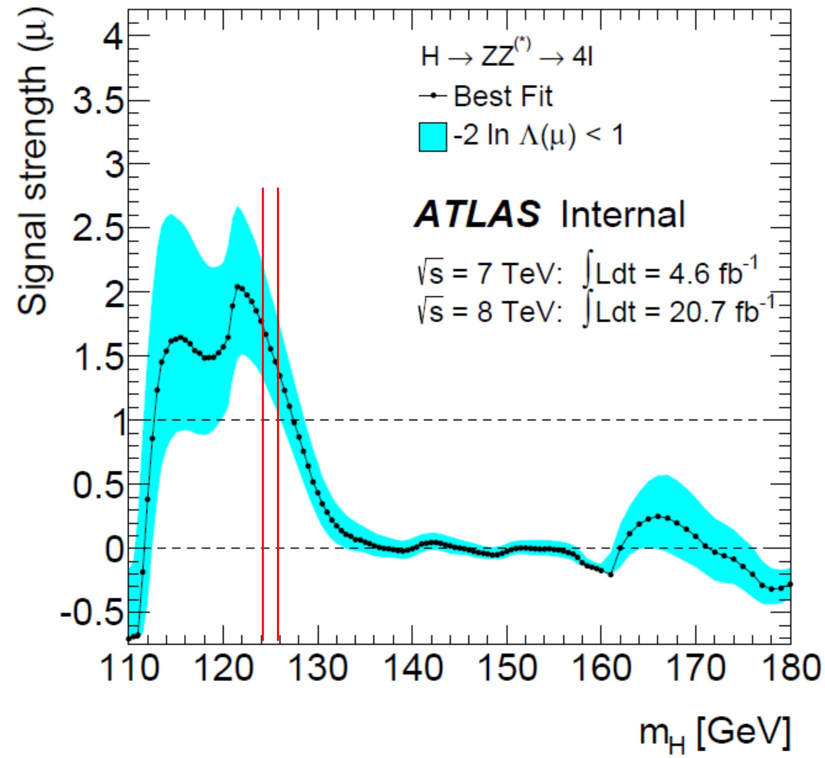
CMS-HIG-13-005





Higgs Mass and Signal Strength





μ = 1.5 ± 0.4 at combined mass m_H = 125.5 GeV

$$M_H = 124.3^{+0.6}_{-0.5}(\mathrm{stat})^{+0.5}_{-0.3}(\mathrm{syst})\ \mathrm{GeV}$$

$$\mu = \sigma_{obs}/\sigma_{SM} = 1.7^{+0.5}_{-0.4}$$

Background Estimation

Table 3: Summary of the estimated numbers of Z + jets and $t\bar{t}$ background events for the 20.7 fb^{-1} of $\sqrt{s}$ = 8 TeV data and for the 4.6 fb^{-1} of $\sqrt{s}$ = 7 TeV data for the full mass range of the analysis after the kinematic selections described in the text. The sub-leading same sign full analysis event counts are given only for $m_{4\ell}$ < 160 GeV to avoid contamination from the irreducible $ZZ^{(*)}$ background with an incorrect charge measurement. Approximately 80% of the reducible background has $m_{4\ell}$ < 160 GeV. The "†" symbol indicates the estimates used for the background normalisation, the others being cross-checks. The first uncertainty is statistical, the second is systematic.

method	estimate at $\sqrt{s}$ = 8 TeV	estimate at $\sqrt{s}$ = 7 TeV
	4μ	4μ
m_{12} fit: Z + jets contribution	$2.4 \pm 0.5 \pm 0.6^{\dagger}$	$0.22 \pm 0.07 \pm 0.02^{\dagger}$
m_{12} fit: $t\bar{t}$ contribution	$0.14 \pm 0.03 \pm 0.03^{\dagger}$	$0.03 \pm 0.01 \pm 0.01^{\dagger}$
$t\bar{t}$ from $e\mu + \mu\mu$	$0.10 \pm 0.05 \pm 0.004$	-
	$2e2\mu$	$2e2\mu$
m_{12} fit: Z + jets contribution	$2.5 \pm 0.5 \pm 0.6^{\dagger}$	$0.19 \pm 0.06 \pm 0.02^{\dagger}$
m_{12} fit: $t\bar{t}$ contribution	$0.10 \pm 0.02 \pm 0.02^{\dagger}$	$0.03 \pm 0.01 \pm 0.01^{\dagger}$
$t\bar{t}$ from $e\mu + \mu\mu$	$0.12 \pm 0.07 \pm 0.005$	-
	$2\mu 2e$	$2\mu 2e$
$\ell\ell + e^{\pm}e^{\mp}$ relaxed cuts	$5.2 \pm 0.4 \pm 0.5^{\dagger}$	$1.8 \pm 0.3 \pm 0.4$
$\ell\ell + e^{\pm}e^{\mp}$ inverted cuts	$3.9 \pm 0.4 \pm 0.6$	-
$3\ell + \ell$ (same-sign)	$4.3 \pm 0.6 \pm 0.5$	$2.8 \pm 0.4 \pm 0.5^{\dagger}$
sub-leading same sign full analysis events	4	0
	$4e$	$4e$
$\ell\ell + e^{\pm}e^{\mp}$ relaxed cuts	$3.2 \pm 0.5 \pm 0.4^{\dagger}$	$1.4 \pm 0.3 \pm 0.4$
$\ell\ell + e^{\pm}e^{\mp}$ inverted cuts	$3.6 \pm 0.6 \pm 0.6$	-
$3\ell + \ell$ (same-sign)	$4.2 \pm 0.5 \pm 0.5$	$2.5 \pm 0.3 \pm 0.5^{\dagger}$
sub-leading same sign full analysis events	3	2

Selected Events

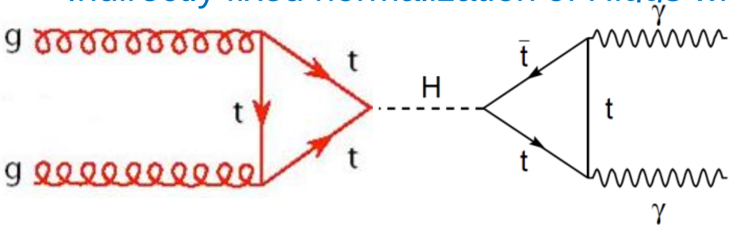
Table 7: The numbers of expected signal events for the m_H=125 GeV hypothesis and background events together with the numbers of observed events, in a window of ±5 GeV around 125 GeV for 20.7 fb^{-1} at $\sqrt{s}$ = 8 TeV and 4.6 fb^{-1} at $\sqrt{s}$ = 7 TeV as well as for their combination.

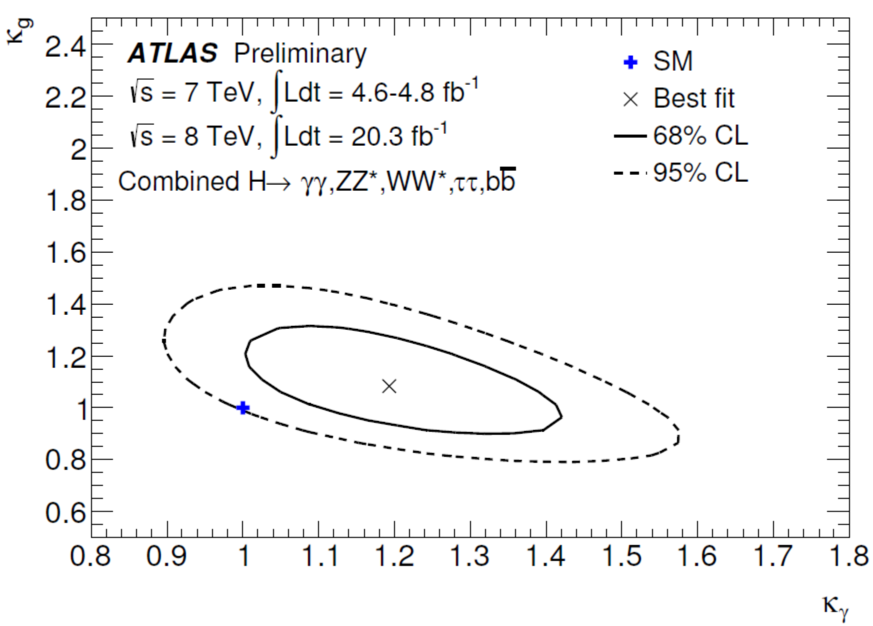
	total signal full mass range	signal	$ZZ^{(*)}$	Z + jets, $t\bar{t}$	S/B	expected	observed
			$\sqrt{s}$ = 8 TeV				
4μ	5.8 ± 0.7	5.3 ± 0.7	2.3 ± 0.1	0.50 ± 0.13	1.9	8.1 ± 0.9	11
$2\mu 2e$	3.0 ± 0.4	2.6 ± 0.4	1.2 ± 0.1	1.01 ± 0.21	1.2	4.8 ± 0.7	4
$2e2\mu$	4.0 ± 0.5	3.4 ± 0.4	1.7 ± 0.1	0.51 ± 0.16	1.5	5.6 ± 0.7	6
$4e$	2.9 ± 0.4	2.3 ± 0.3	1.0 ± 0.1	0.62 ± 0.16	1.4	3.9 ± 0.6	6
total	15.7 ± 2.0	13.7 ± 1.8	6.2 ± 0.4	2.62 ± 0.34	1.6	22.5 ± 2.9	27
			$\sqrt{s}$ = 7 TeV				
4μ	1.0 ± 0.1	0.97 ± 0.13	0.49 ± 0.02	0.05 ± 0.02	1.8	1.5 ± 0.2	2
$2\mu 2e$	0.4 ± 0.1	0.39 ± 0.05	0.21 ± 0.02	0.55 ± 0.12	0.5	1.2 ± 0.1	1
$2e2\mu$	0.7 ± 0.1	0.57 ± 0.08	0.33 ± 0.02	0.04 ± 0.01	1.5	0.9 ± 0.1	2
$4e$	0.4 ± 0.1	0.29 ± 0.04	0.15 ± 0.01	0.49 ± 0.12	0.5	0.9 ± 0.1	0
total	2.5 ± 0.4	2.2 ± 0.3	1.17 ± 0.07	1.12 ± 0.17	1.0	4.5 ± 0.5	5
			$\sqrt{s}$ = 8 TeV and $\sqrt{s}$ = 7 TeV				
4μ	6.8 ± 0.8	6.3 ± 0.8	2.8 ± 0.1	0.55 ± 0.15	1.9	9.6 ± 1.0	13
$2\mu 2e$	3.4 ± 0.5	3.0 ± 0.4	1.4 ± 0.1	1.56 ± 0.33	1.0	6.0 ± 0.8	5
$2e2\mu$	4.7 ± 0.6	4.0 ± 0.5	2.1 ± 0.1	0.55 ± 0.17	1.5	6.6 ± 0.8	8
$4e$	3.3 ± 0.5	2.6 ± 0.4	1.2 ± 0.1	1.11 ± 0.28	1.1	4.9 ± 0.8	6
total	18.2 ± 2.4	15.9 ± 2.1	7.4 ± 0.4	3.74 ± 0.93	1.4	27.1 ± 3.4	32

Constraints on BSM

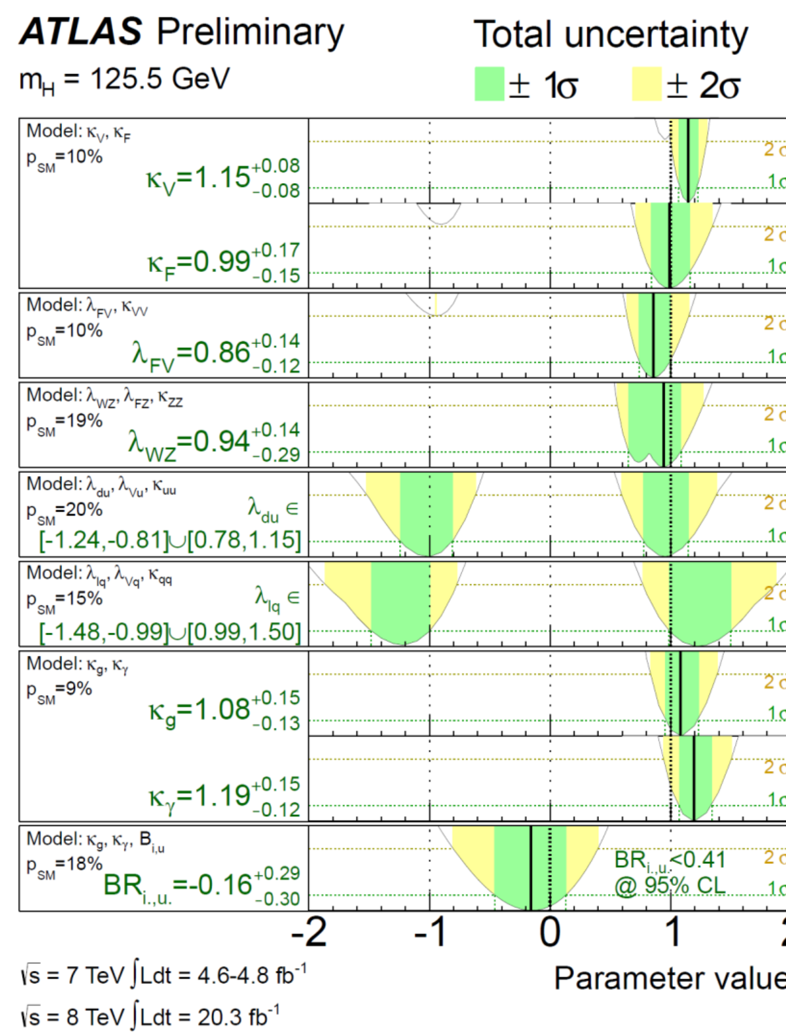
New heavy particles may contribute to loops

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



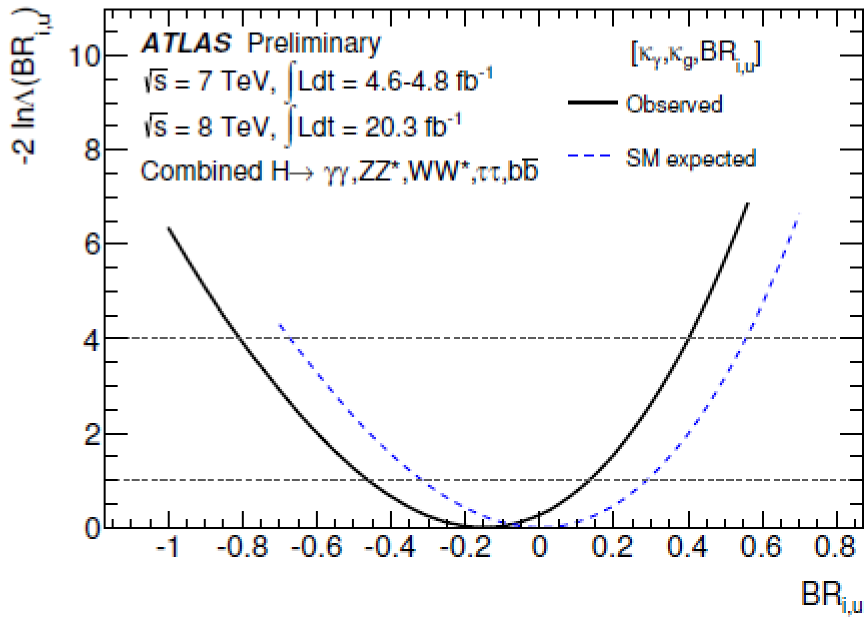


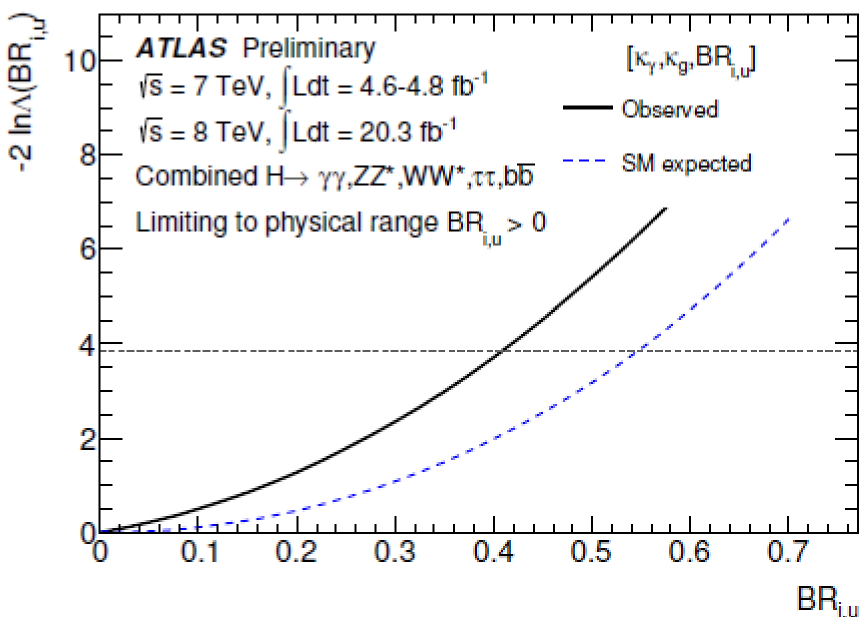
3D Compatibility with SM: 18%



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

Constraints on BSM Loops





New particles may contribute to loops

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

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

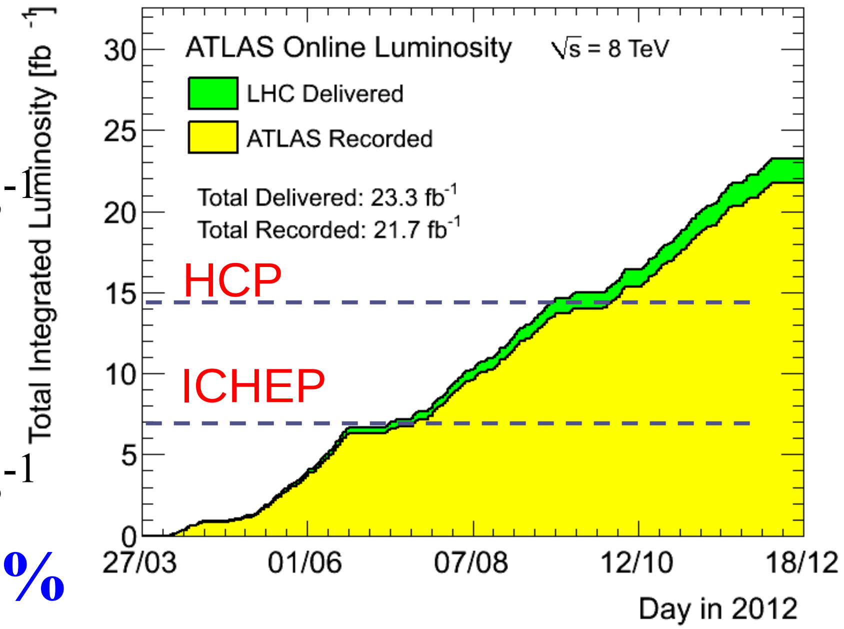
$$\kappa_g = 1.00^{+0.23}_{-0.16}$$

$$\kappa_\gamma = 1.17^{+0.16}_{-0.13}$$

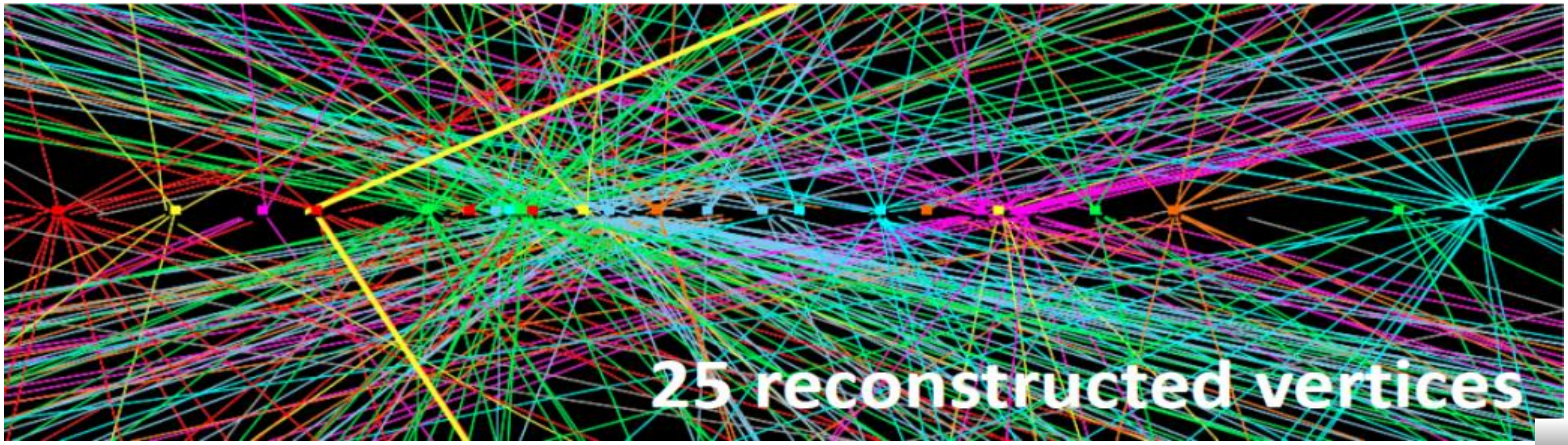
$$BR_{i.,u.} = -0.16^{+0.29}_{-0.30}$$

ATLAS Data Samples

- **7 TeV data samples (2011)**
  - 4.6 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: ~95.5%**

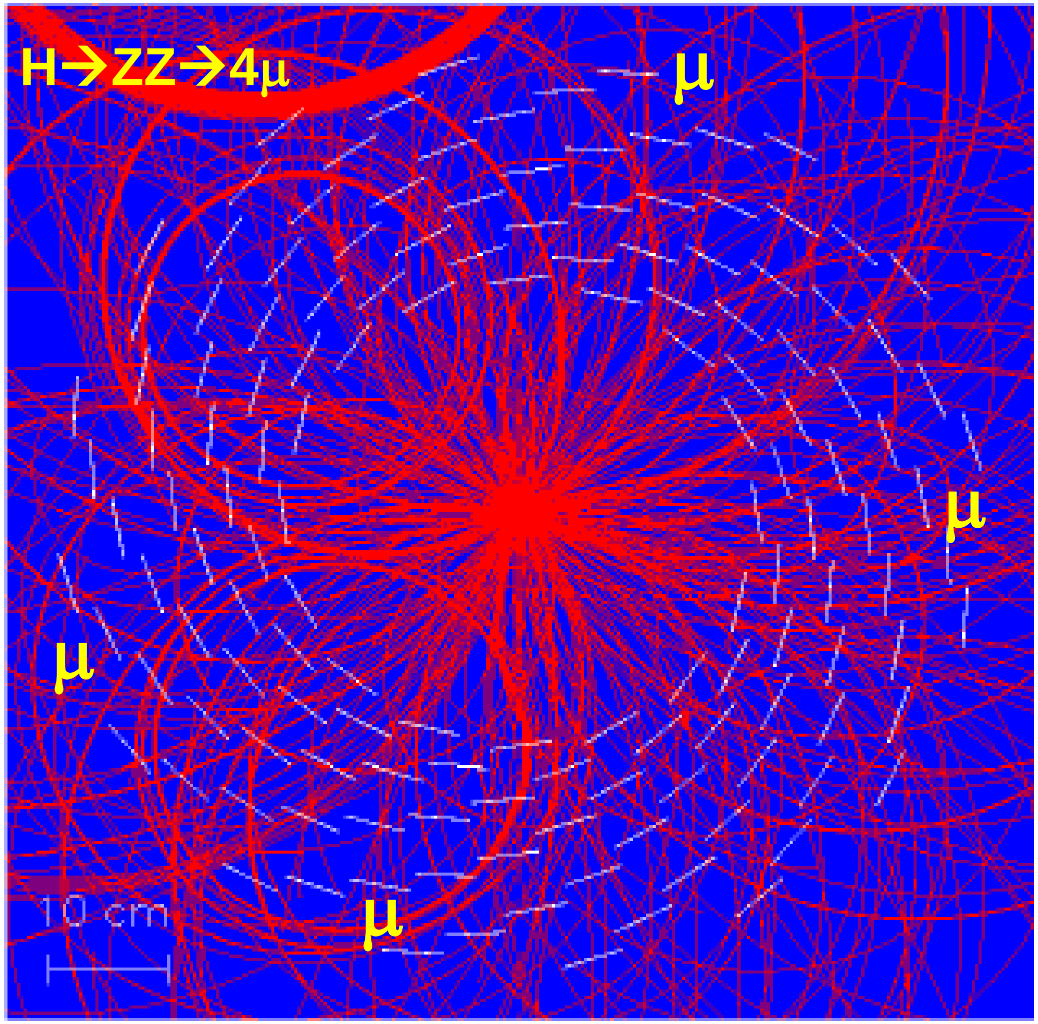


- **Significant pileup events**



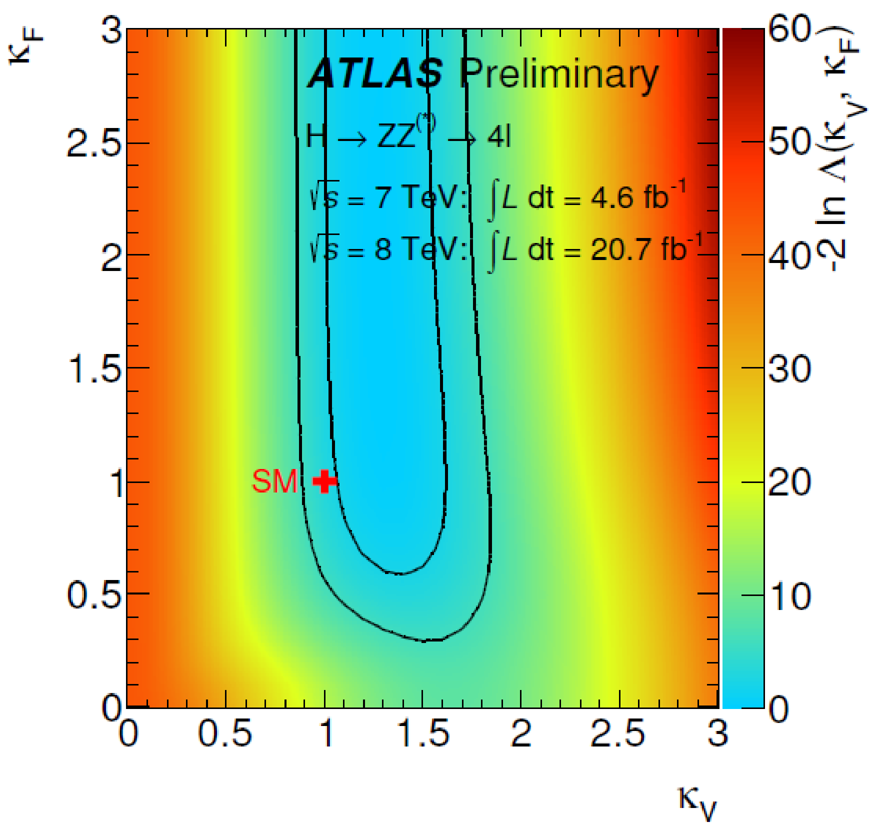
Major Challenge (Large Pileup)

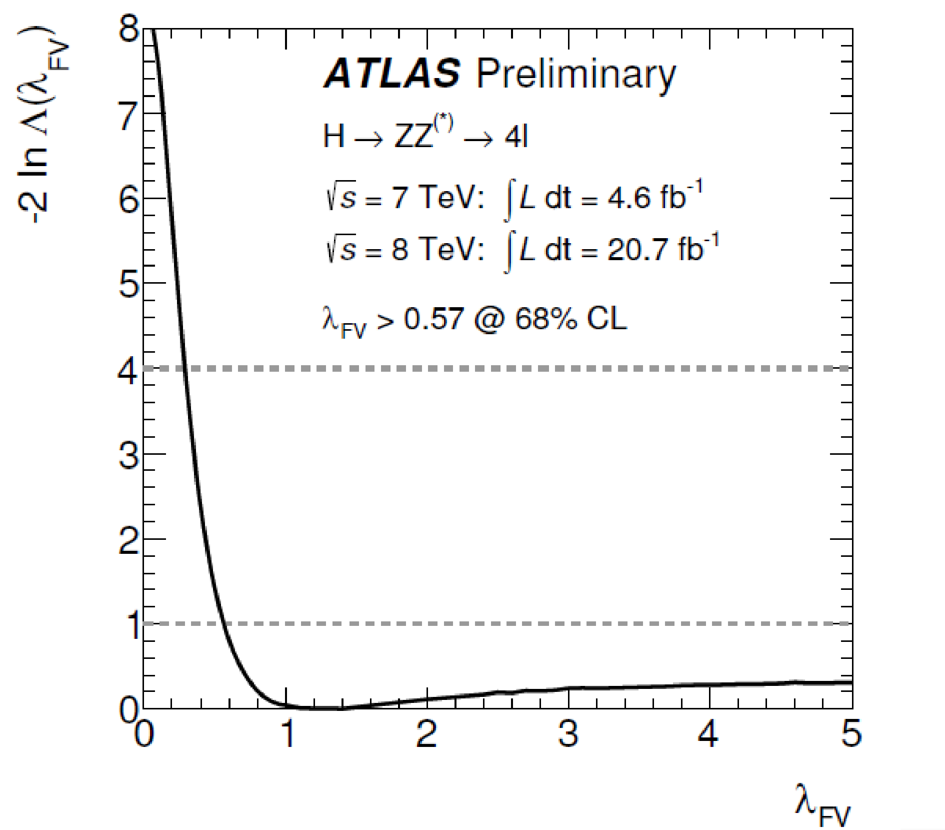
- Large pileup events result in big challenge to the detector, reconstruction and particle identification !!!



Following recommendations in LHCHXSWG-2012-001, probe benchmark model:

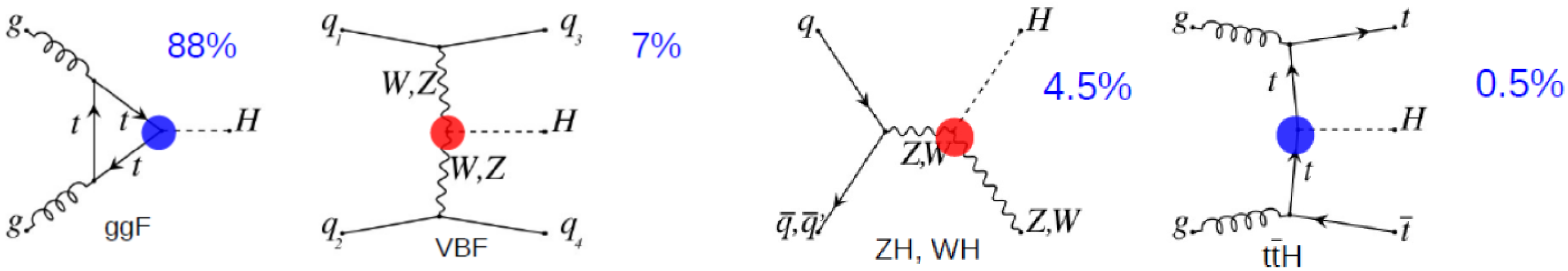
- All fermion couplings modified by single factor k_F
- All massive boson couplings modified by a single factor k_V
- No non-SM contributions to the Higgs total decay width
- The ratio $\lambda_{FV} = k_F / k_V$
  - Assumption on total width is relaxed



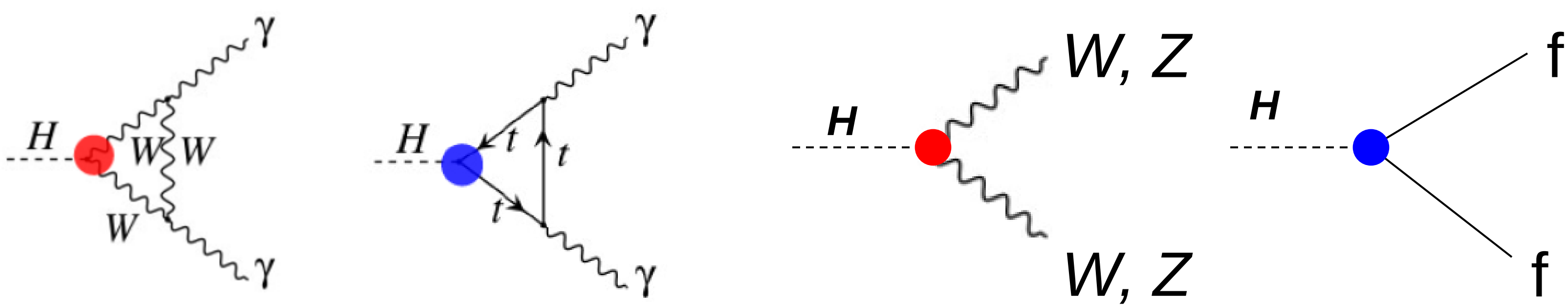


Is it the SM Higgs Boson?

❖ **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)

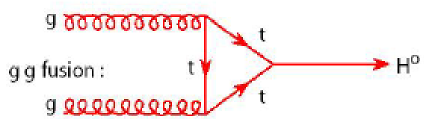
❖ **Spin and Parity**

Coupling Measurements

Coupling strengths κ_i & ratio: $\kappa_F = g_F/g_{F,SM}$, $\kappa_V = g_V/g_{V,SM}$, $\lambda_{ij} = \kappa_i/\kappa_j$

Model	Probed couplings	Parameters of interest	Functional assumptions κ_V	κ_F	κ_g	κ_γ	κ_H	Example: $gg \to H \to \gamma\gamma$
1	Couplings to fermions and bosons	κ_V, κ_F	√	√	√	√	√	$\kappa_F^2 \cdot \kappa_\gamma^2(\kappa_F, \kappa_V)/\kappa_H^2(\kappa_F, \kappa_V)$
2		$\lambda_{FV}, \kappa_{VV}$	√	√	√	√	-	$\kappa_{VV}^2 \cdot \lambda_{FV}^2 \cdot \kappa_\gamma^2(\lambda_{FV}, \lambda_{FV}, \lambda_{FV}, 1)$
3	Custodial symmetry	$\lambda_{WZ}, \lambda_{FZ}, \kappa_{ZZ}$	-	√	√	√	-	$\kappa_{ZZ}^2 \cdot \lambda_{FZ}^2 \cdot \kappa_\gamma^2(\lambda_{FZ}, \lambda_{FZ}, \lambda_{FZ}, \lambda_{WZ})$
4		$\lambda_{WZ}, \lambda_{FZ}, \lambda_{\gamma Z}, \kappa_{ZZ}$	-	√	√	-	-	$\kappa_{ZZ}^2 \cdot \lambda_{FZ}^2 \cdot \lambda_{\gamma Z}^2$
5	Vertex loops	κ_g, κ_γ	=1	=1	-	-	√	$\kappa_g^2 \cdot \kappa_\gamma^2/\kappa_H^2(\kappa_g, \kappa_\gamma)$

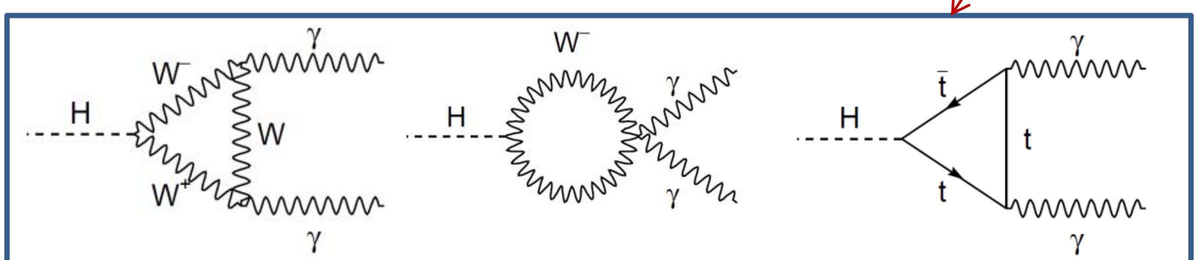
Example $H \to \gamma\gamma$



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

κ_g, κ_γ: loop coupling scale factors

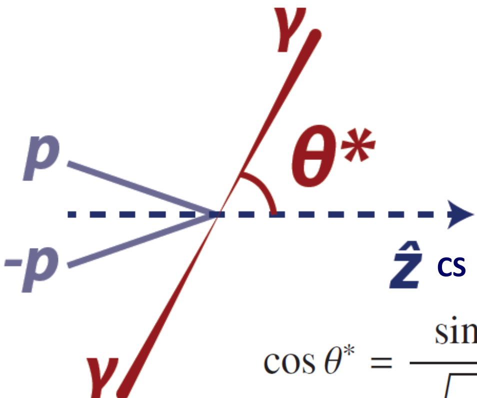
κ_H is the total Higgs width scale factor



$$\kappa_\gamma^2 = |1.28\,\kappa_W - 0.28\,\kappa_t + \ldots|^2$$

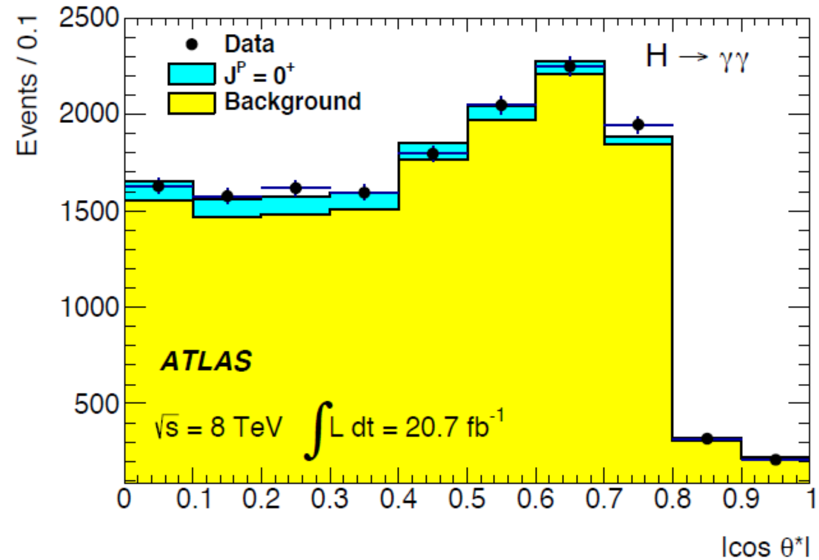
Spin Analysis with H→ γγ

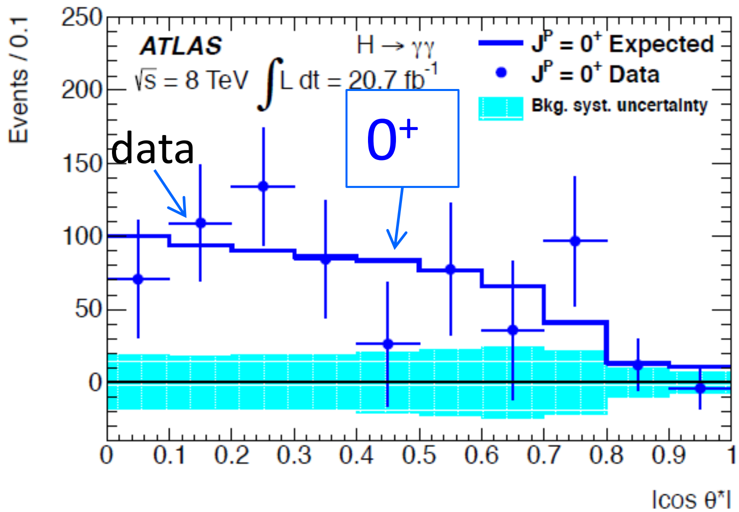
Polar angle θ^* of the photon decay in Collines-Soper frame, along with $m_{\gamma\gamma}$

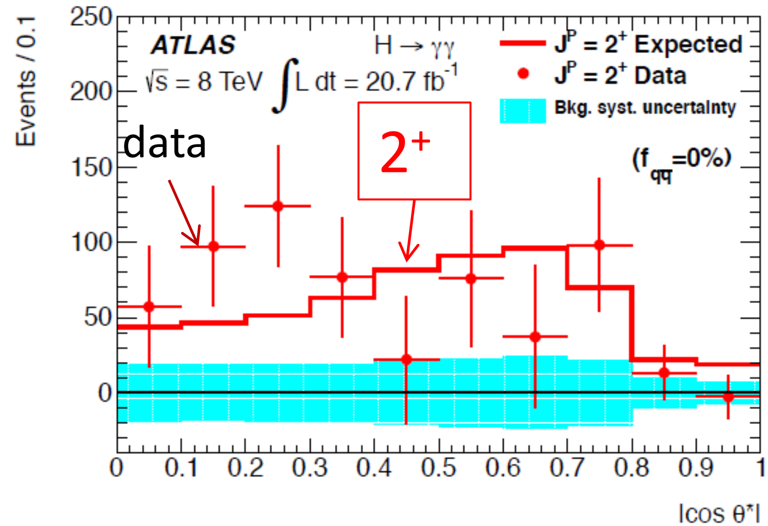


Z_{CS} bisects angle between the momenta of colliding hadrons

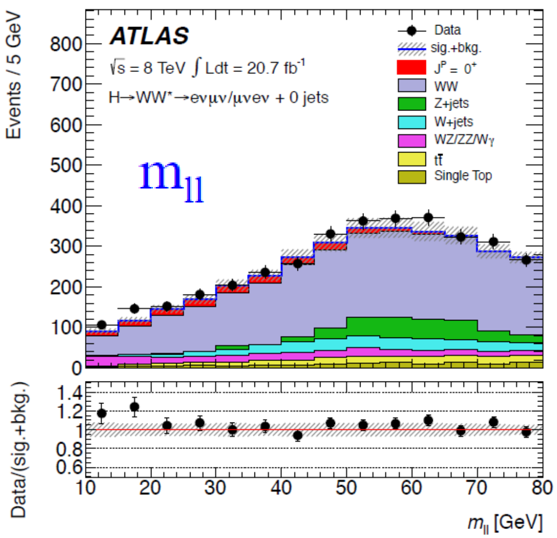
$$\cos\theta^* = \frac{\sinh(\eta_{\gamma_1} - \eta_{\gamma_2})}{\sqrt{1 + \left(p_T^{\gamma\gamma}/m_{\gamma\gamma}\right)^2}} \cdot \frac{2 p_T^{\gamma_1} p_T^{\gamma_2}}{m_{\gamma\gamma}^2}$$

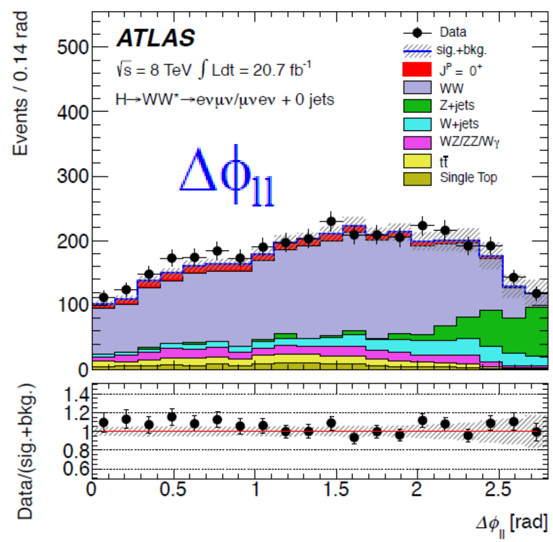


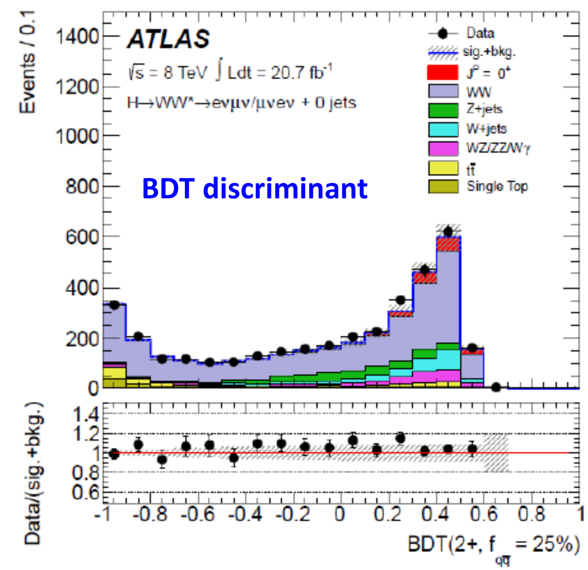




Spin Analysis With H→ WW*

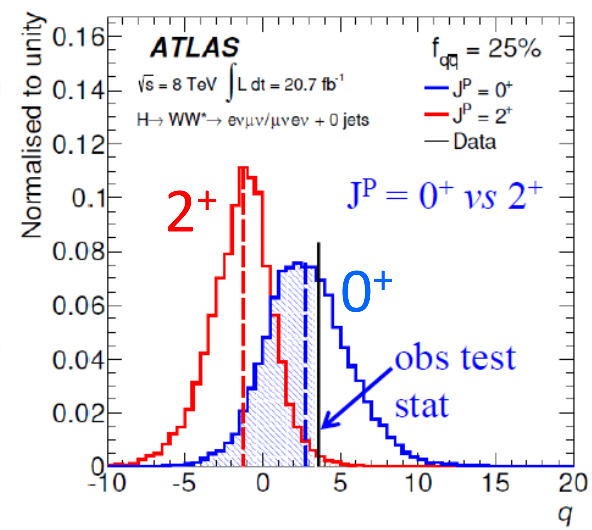






$J^P = 0^+ \; vs \; 2^+$

$f_{q\bar{q}}$	2⁺ assumed Exp. $p_0(J^P = 0^+)$	0⁺ assumed Exp. $p_0(J^P = 2^+)$	Obs. $p_0(J^P = 0^+)$	Obs. $p_0(J^P = 2^+)$	$CL_s(J^P = 2^+)$
100%	0.013	$3.6 \cdot 10^{-4}$	0.541	$1.7 \cdot 10^{-4}$	$3.6 \cdot 10^{-4}$
75%	0.028	0.003	0.586	0.001	0.003
50%	0.042	0.009	0.616	0.003	0.008
25%	0.048	0.019	0.622	0.008	0.020
0%	0.086	0.054	0.731	0.013	0.048



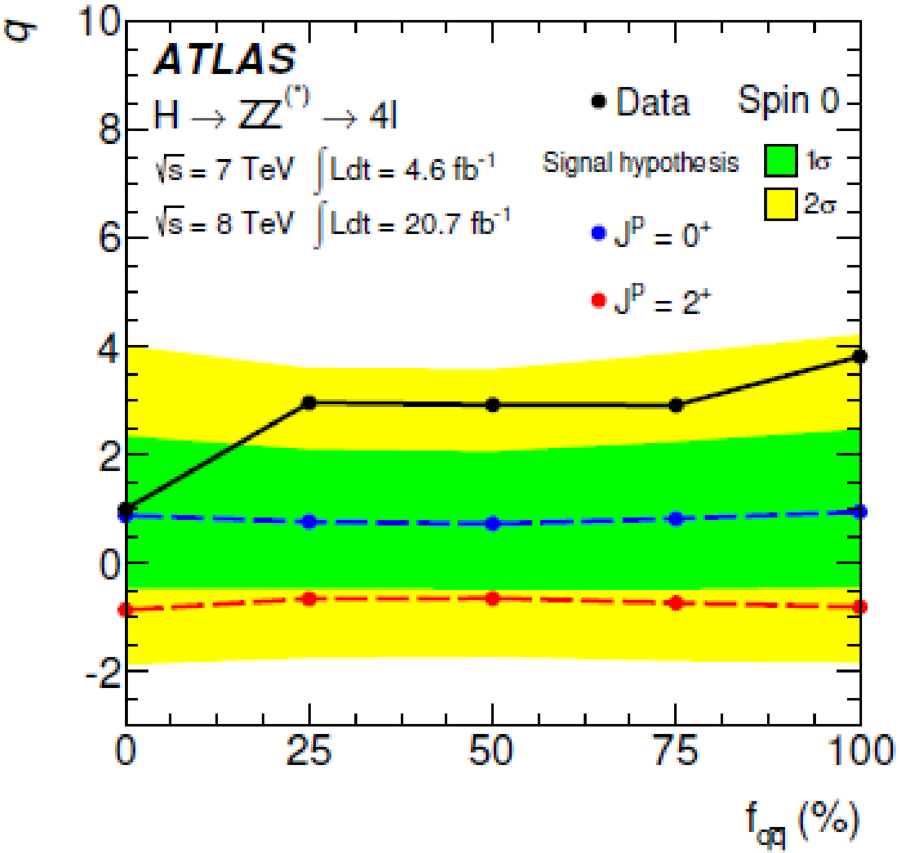
Exclusion **($1-CL_s$):**

Observed 2⁺ (qq=100%) exclusion 99.96%

Observed 2⁺ (qq = 0%) exclusion 95.2%

H→ZZ*→4l : Spin and CP

- For $J^P = 2^+_m$ model:
  - Graviton-like tensor with minimal couplings to SM particles
  - See Phys. Rev. D81 (2010) 075022
  - Production via *gg* or *qq*
- Scan fraction of *qq* production between 0 and 100%
- Sensitivity is stable as a function of $q\bar{q}$ fraction
- Observed exclusion (0^+ vs 2^+_m) at 83.2 CL for 100% ggF produced state



Value of test statistic, q, as a function of the $q\bar{q}$ production fraction, $f_{q\bar{q}}$

ATLAS Trigger

Table 9: Summary of the triggers that are used during the 2012 data taking for the three analysis channels. When multiple chains are indicated, it is intended that the OR among them is requested.

Channel	Single-lepton	Di-lepton
4e	e24vhi_medium1, e60_medium1	2e12Tvh_loose1, 2e12Tvh_loose1_L2StarB(only data)
4μ	mu24i_tight, mu36_tight	2mu13, mu18_mu8_EFFS
$2e2\mu$	4μ OR $4e$ OR e12Tvh_medium1_mu8 OR e24vhi_loose1_mu8	

Table 10: Summary of the triggers that are used during the 2011 data taking. In each data taking period, the OR of single and di-lepton triggers is used to select each signature.

Single-lepton triggers				
Period	B-I	J	K	L-M
4μ	EF_mu18_MG	EF_mu18_MG_medium	EF_mu18_MG_medium	EF_mu18_MG_medium
$4e$	EF_e20_medium	EF_e20_medium	EF_e22_medium	EF_e22vh_medium1
$2e2\mu$	4μ OR $4e$			
Di-lepton triggers				
Period	B-I	J	K	L-M
4μ	EF_2mu10_loose	EF_2mu10_loose	EF_2mu10_loose	EF_2mu10_loose
$4e$	EF_2e12_medium	EF_2e12_medium	EF_2e12T_medium	EF_2e12Tvh_medium
$2e2\mu$	4μ OR $4e$ OR EF_e10_medium_mu6			

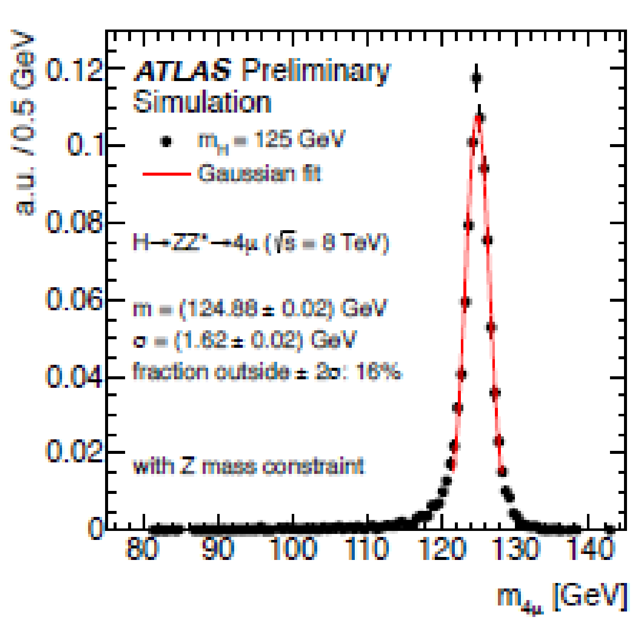
Higgs Production and Decays

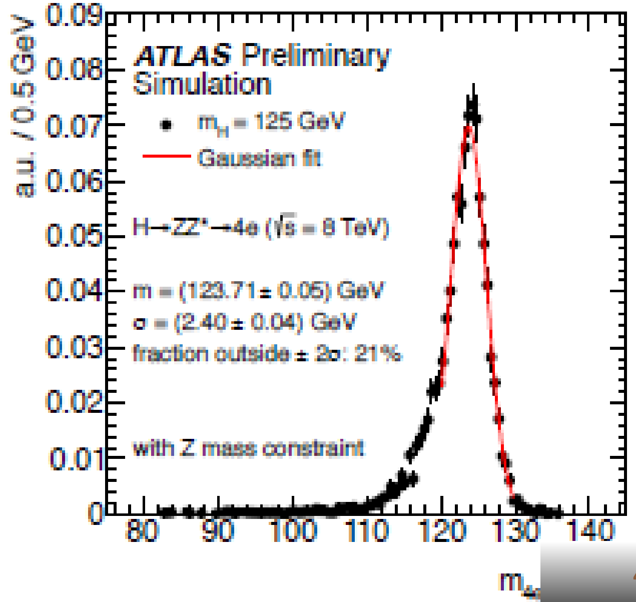
Table 2: Higgs boson production cross sections for gluon fusion, vector-boson fusion and associated production with a W or Z boson in pp collisions at $\sqrt{s}$ of 7 TeV and 8 TeV [11]. The quoted uncertainties correspond to the total theoretical systematic uncertainties with linear sum of QCD scale and PDF+α_s uncertainties. The production cross section for the associated production with a W or Z boson is negligibly small for $m_H > 300$ GeV. The decay branching ratio for $H \to 4\ell$, with $\ell = e$ or μ, is reported in the last column [11].

m_H [GeV]	$\sigma(gg \to H)$ [pb]	$\sigma(qq' \to Hqq')$ [pb]	$\sigma(q\bar{q} \to WH)$ [pb]	$\sigma(q\bar{q} \to ZH)$ [pb]	$\mathrm{BR}\left(H \to ZZ^{(*)} \to 4\ell\right)$ $[10^{-3}]$
			$\sqrt{s} = 7$ TeV		
123	$15.8^{+2.3}_{-2.4}$	1.25 ± 0.03	$0.60^{+0.02}_{-0.03}$	0.33 ± 0.02	0.103
125	15.3 ± 2.3	1.22 ± 0.03	0.57 ± 0.02	0.32 ± 0.02	0.125
127	14.9 ± 2.2	1.20 ± 0.03	0.54 ± 0.02	0.30 ± 0.02	0.148
			$\sqrt{s} = 8$ TeV		
123	20.2 ± 3.0	1.61 ± 0.05	0.73 ± 0.03	0.42 ± 0.02	0.103
125	19.5 ± 2.9	$1.58^{+0.04}_{-0.05}$	0.70 ± 0.03	0.39 ± 0.02	0.125
127	18.9 ± 2.8	1.55 ± 0.05	$0.66^{+0.02}_{-0.03}$	0.37 ± 0.02	0.148

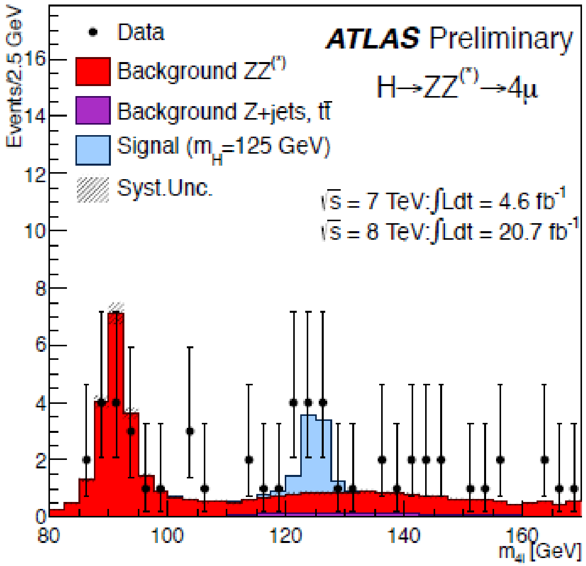
Signal Model

- **Signal templates derived from simulation:**
  - Events generated using POWHEG (NLO generator) + PYTHIA (parton showering)
  - NLO cross sections/branching ratios + QCD/EW corrections
  - Separate templates for each channel used in $m_{4\ell}$ fit
- **Methods added to improve mass resolution:**
  - Final state radiation (FSR) recovery adds photons nearby to muons back into $m_{4\ell}$
    - Correction on 4% of 4μ events with 85% purity
  - Z mass constraint procedure improves resolution by 12-20%
    - Kinematic parameters of leading lepton pair (m_{12}) modified within errors to maximize probability with respect to Z mass PDF
    - Applied to m_{34} if $m_{4\ell}$ > 190 GeV

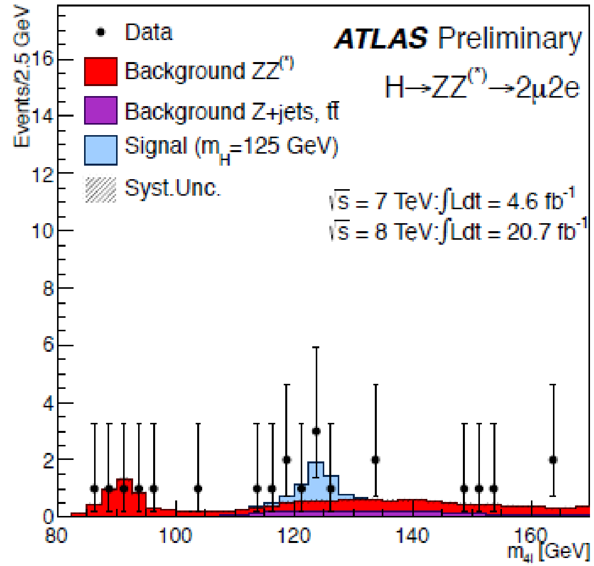




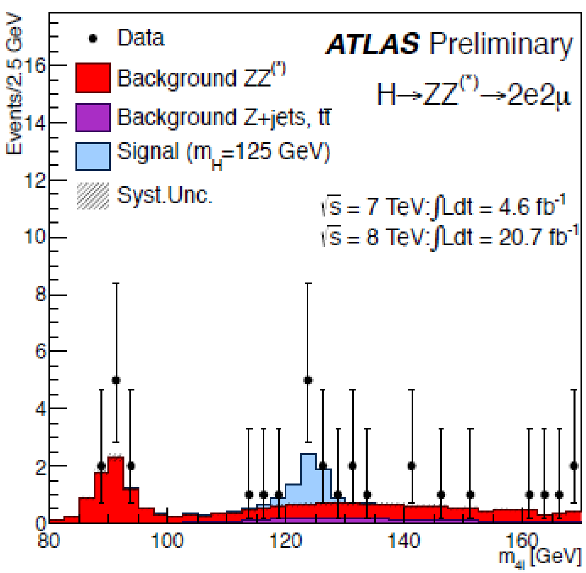
Invariant Mass of 4-lepton

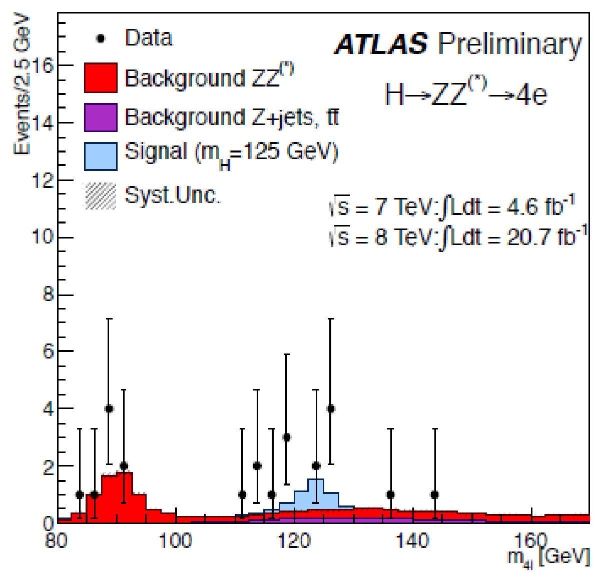


(a)

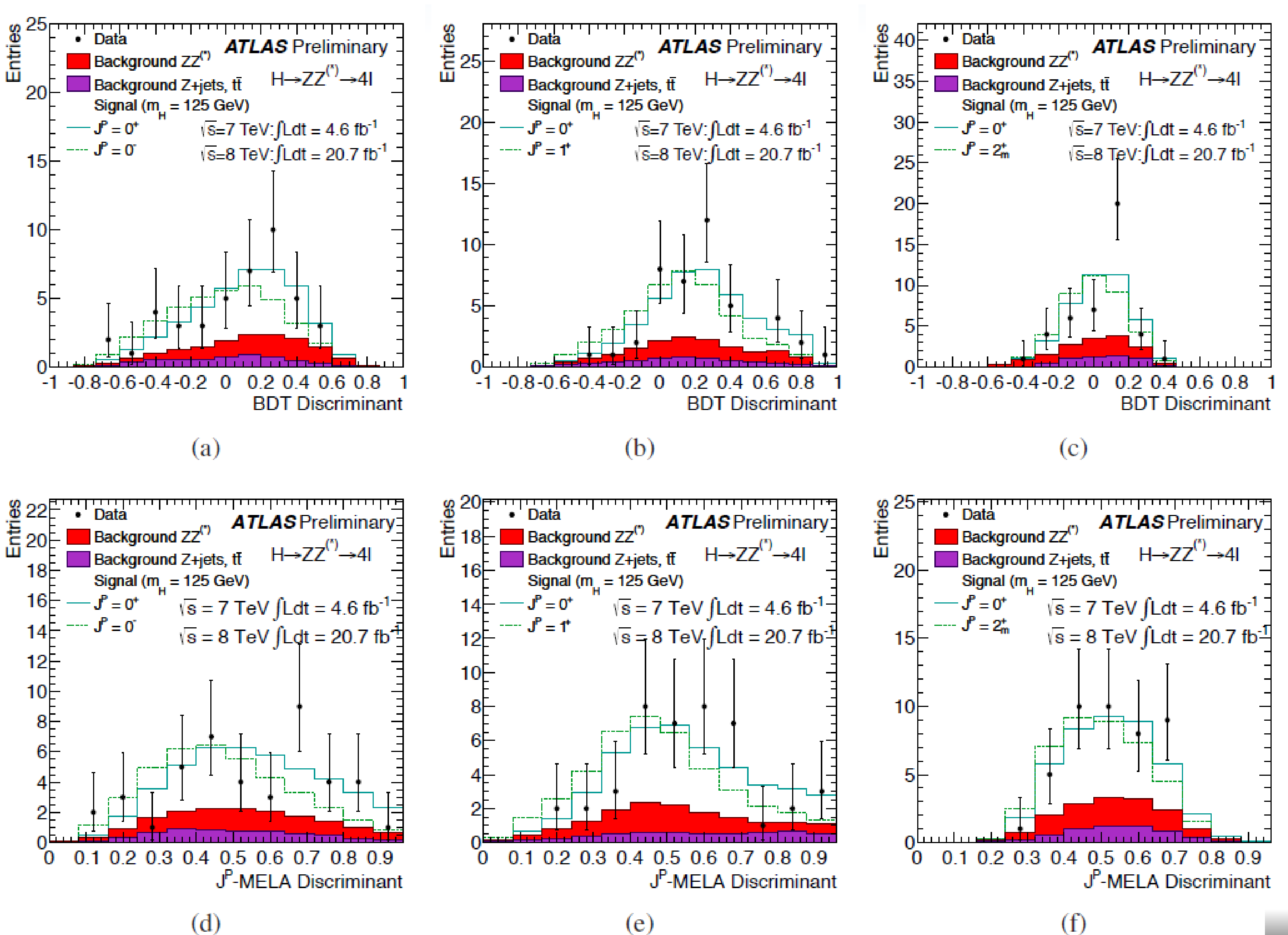


(b)





MVA Discriminant: Higgs Spin and CP



BR of Z → 4ℓ

Branching fraction result uses an error weighted combination of the 7 and 8 TeV results. For $M_{\ell\ell} > 5$ GeV:

Quantity	$\sqrt{s}$	Value
Measured	7 TeV	$(2.67 \pm 0.62\,(\text{stat}) \pm 0.14\,(\text{syst})) \times 10^{-6}$
	8 TeV	$(3.33 \pm 0.27\,(\text{stat}) \pm 0.11\,(\text{syst})) \times 10^{-6}$
	Combined	$(3.20 \pm 0.25\,(\text{stat}) \pm 0.12\,(\text{syst})) \times 10^{-6}$
Expected		$(3.33 \pm 0.01) \times 10^{-6}$

For $M_{\ell\ell} > 4$ GeV

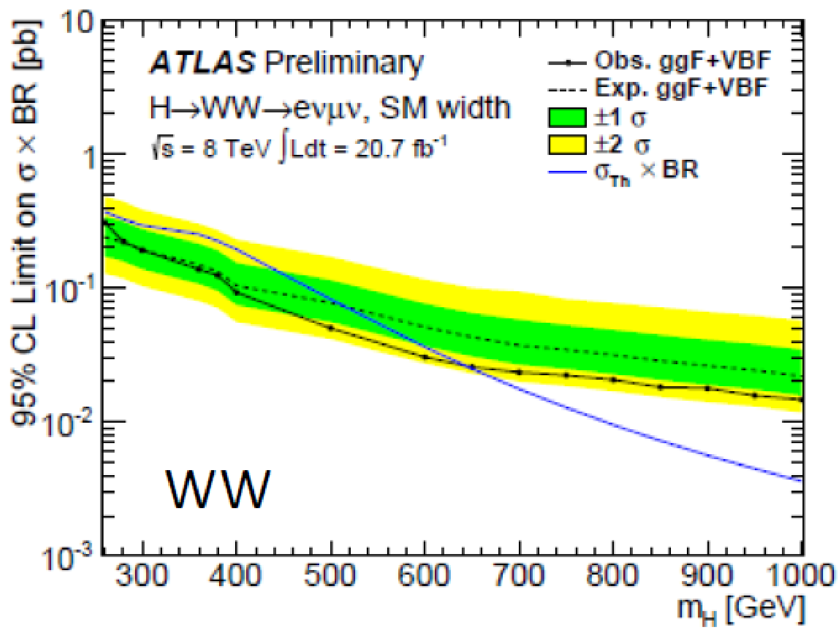
- We observe $(4.31 \pm 0.34\,(\text{stat}) \pm 0.16\,(\text{syst})) \times 10^{-6}$ and expect $(4.50 \pm 0.01) \times 10^{-6}$,
- CMS observes $(4.2^{+0.9}_{-0.8}\,(\text{stat}) \pm 0.2\,(\text{syst})) \times 10^{-6}$ and expects 4.45×10^{-6}.

Search for High Mass H→ ZZ, WW

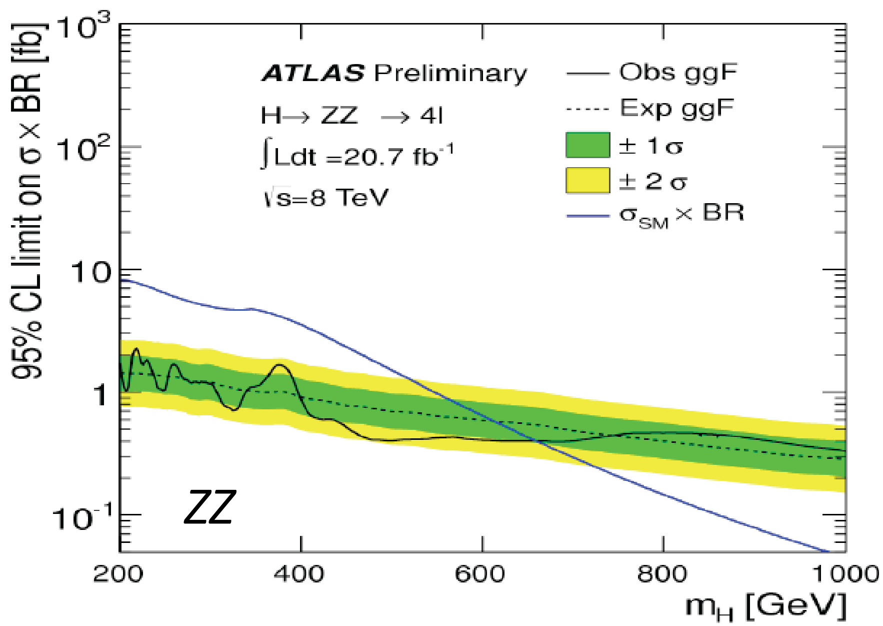
ATLAS-CONF-2013-067

Extend the Higgs search to high mass assume SM-like width, and decay to WW/ZZ

WW → lνlν*

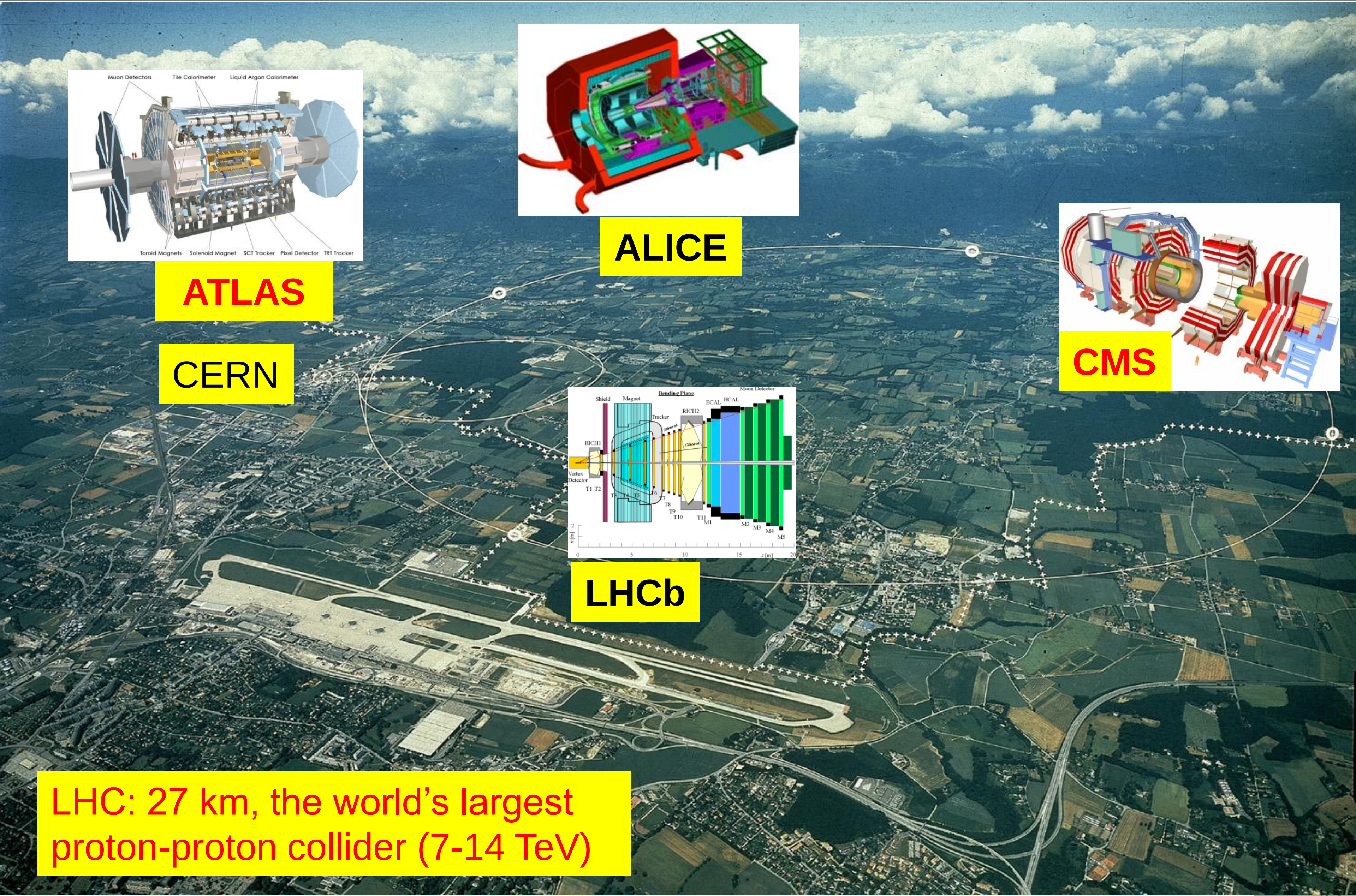


ZZ → 4l*



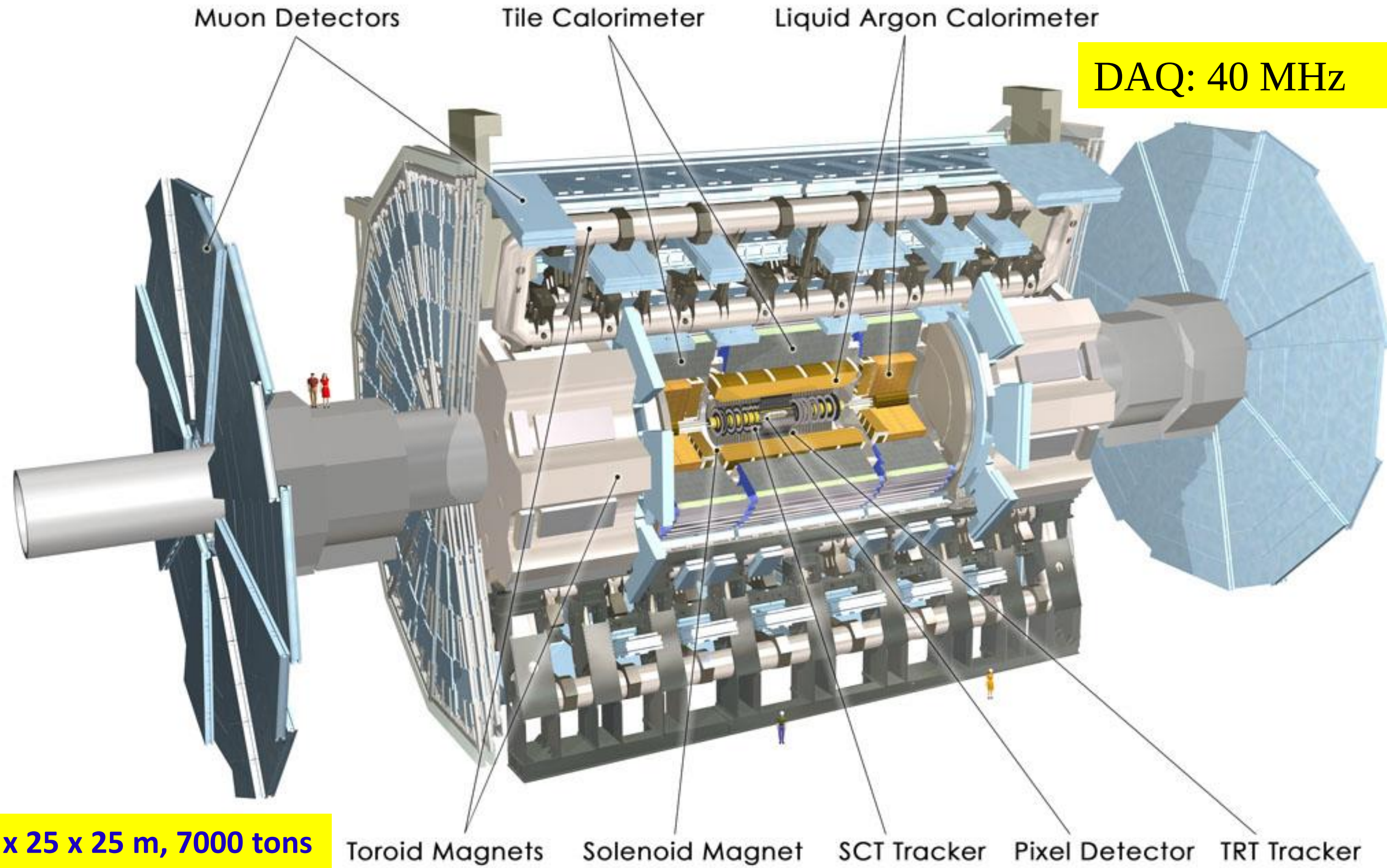
95% C.L. exclusion of a SM-like heavy Higgs up to ~ 650 GeV

Large Hadron Collider at CERN



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

The ATLAS Detector

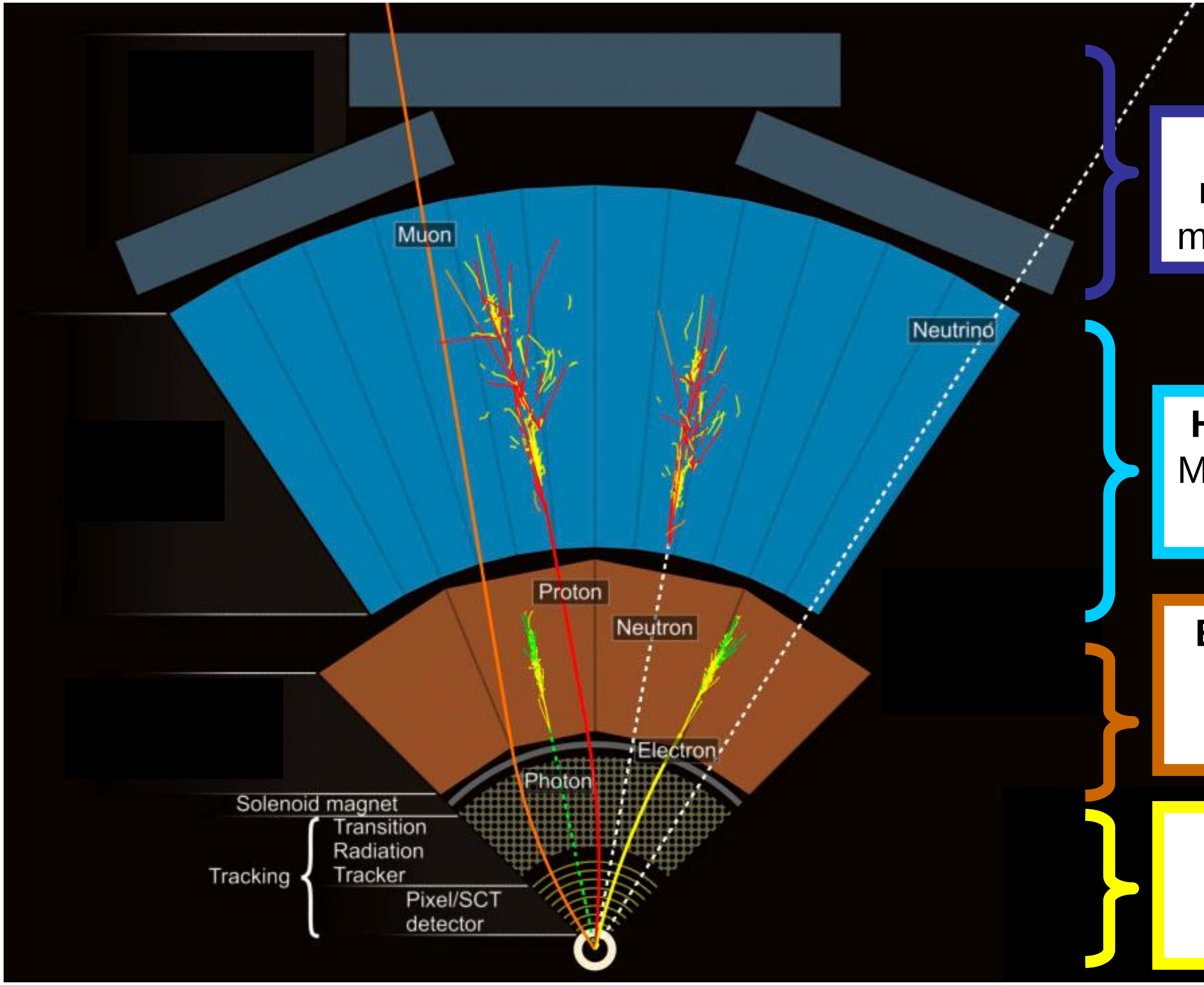


DAQ: 40 MHz

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

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 Width (CMS)

- https://cds.cern.ch/record/1670066/files/HIG-14-002-pas.pdf

The production cross section as a function of m_{ZZ} can be written as:

$$\frac{d\sigma_{gg\to H\to ZZ}}{dm^2_{ZZ}} \propto g^2_{ggH} g^2_{HZZ} \frac{F(m_{ZZ})}{(m^2_{ZZ} - m^2_H)^2 + m^2_H \Gamma^2_H}, \quad (1)$$

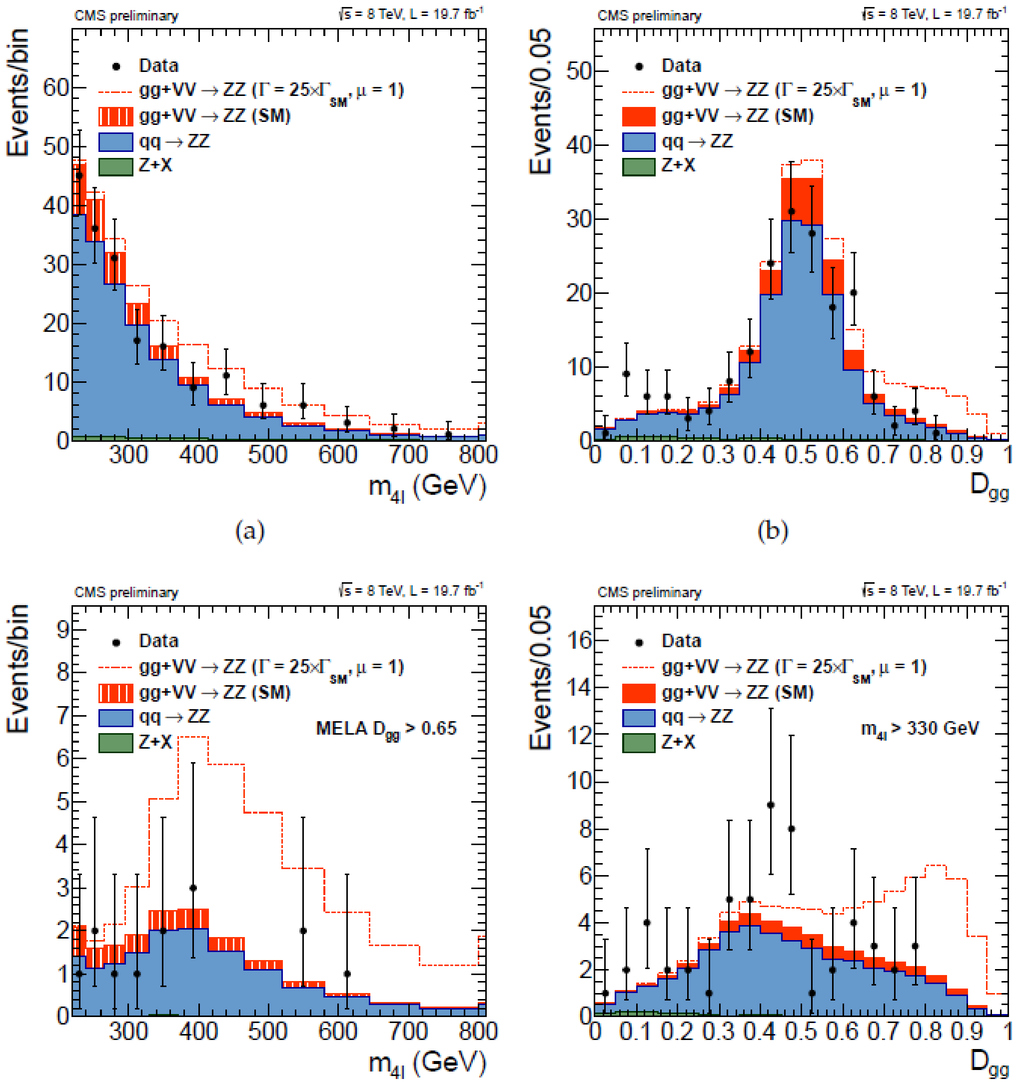
where g_{ggH} (g_{HZZ}) is the coupling constant of the Higgs boson to gluons (to Z bosons), and $F(m_{ZZ})$ is a function which depends on the (virtual) Higgs and Z boson production and decay dynamics. In the resonant and off-shell regions, the integrated cross sections are

$$\sigma^{on-peak}_{gg\to H\to ZZ} \propto \frac{g^2_{ggH} g^2_{HZZ}}{\Gamma_H}, \qquad \sigma^{off-peak}_{gg\to H\to ZZ} \propto g^2_{ggH} g^2_{HZZ}. \quad (2)$$

	4ℓ	$2\ell 2\nu$	Combined
Expected 95% CL limit, r	11.5	10.7	8.5
Observed 95% CL limit, r	6.6	6.4	4.2
Observed 95% CL limit, Γ_H (MeV)	27.4	26.6	17.4
Observed best fit, r	$0.5^{+2.3}_{-0.5}$	$0.2^{+2.2}_{-0.2}$	$0.3^{+1.5}_{-0.3}$
Observed best fit, Γ_H (MeV)	$2.0^{+9.6}_{-2.0}$	$0.8^{+9.1}_{-0.8}$	$1.4^{+6.1}_{-1.4}$

Higgs Width (CMS)

- https://cds.cern.ch/record/1670066/files/HIG-14-002-pas.pdf



(a) (b) (c) (d)