Measurement of properties of the Higgs-like boson in diboson channels on ATLAS

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Outline

- Motivation & overview
- Measurement of resonance mass

  - $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ \rightarrow 4l$

  - combination

- Measurement of signal strength

  - $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ \rightarrow 4l$, $H \rightarrow WW \rightarrow l\nu l\nu$

  - signal strengths in different production modes

- ○ For coupling combinations, see G. Facini's talk in *Higgs 2* parallel session
- Spin/CP (J^P) discrimination

  - $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ \rightarrow 4l$, $H \rightarrow WW \rightarrow l\nu l\nu$

  - combination

- Summary & outlook

Motivation & overview

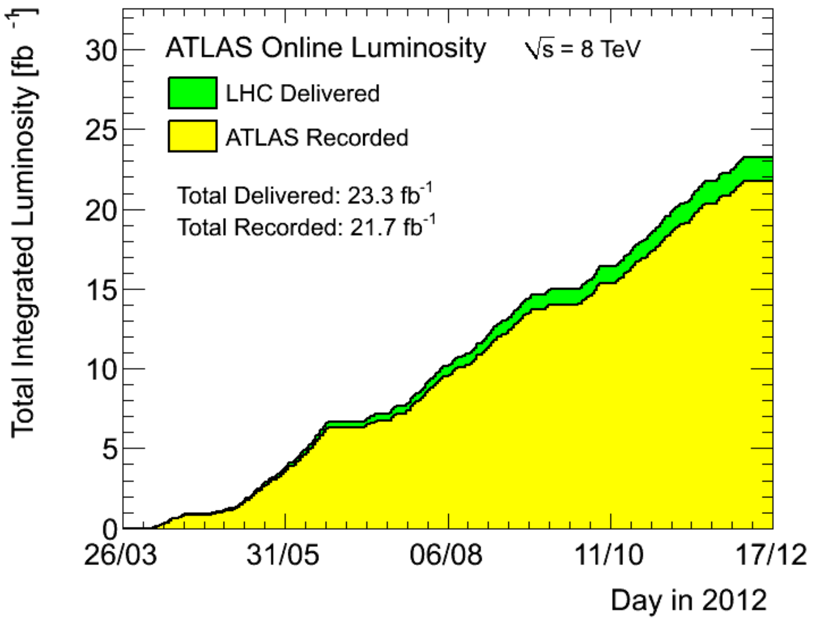
- We have found a new boson in the search for the SM Higgs
- So far confirmed it in the 3 bosonic decay channels: $\gamma\gamma$, *ZZ* and *WW*
- We can already start measuring its properties in these channels

  - mass, couplings, signal strengths in various production modes: measure and compare to expectations from SM

  - J^P quantum numbers: compare expected kinematics of $J^P = 0^+$ signal with those of non-SM hypotheses

- The LHC has given us enough data during 2011-12 to start making fairly strong statements

  - 4.6-4.8 fb^{-1} at 7 TeV, 20.7 fb^{-1} at 8 TeV



Measurement of resonance mass

Mass from high-resolution channels

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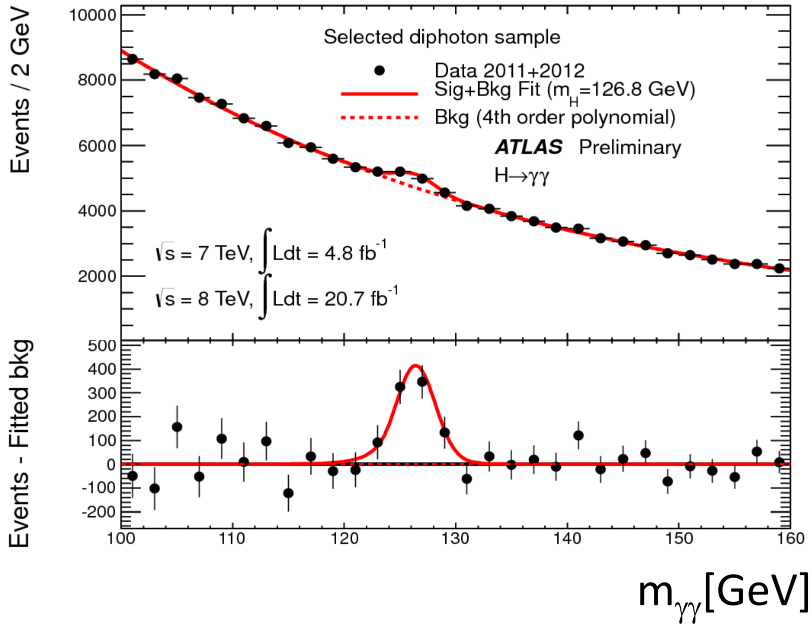

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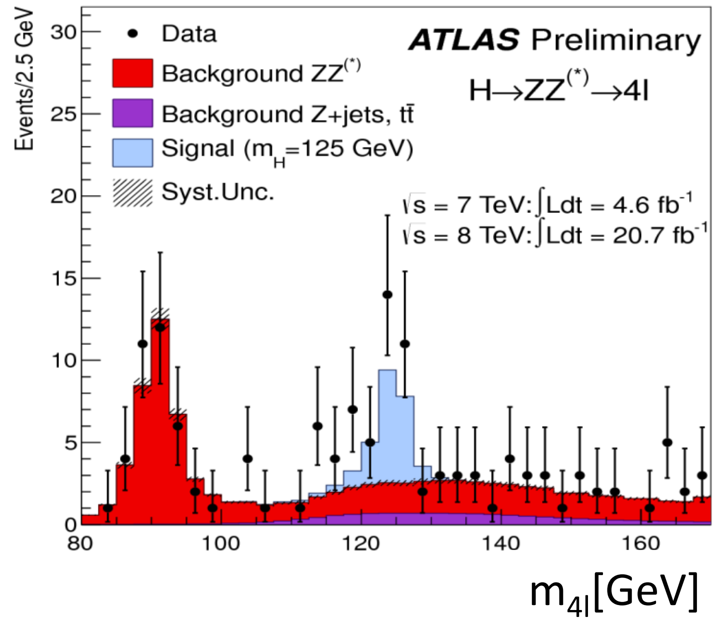

- Use mass m_H as the parameter of interest in likelihood, fit to data

  - signal strength μ (=σ/σ_{SM}) is a free parameter

- Best-fit mass

$H \rightarrow \gamma\gamma$: $$m_H = 126.8 \pm 0.2(\text{stat}) \pm 0.7(\text{syst})\ \text{GeV}$$

$H \rightarrow ZZ \rightarrow 4l$: $$m_H = 124.3^{+0.6}_{-0.5}(\text{stat})^{+0.5}_{-0.3}(\text{syst})\ \text{GeV}$$

Mass: combination of $\gamma\gamma$, $4l$ channels

- From combined fit: $m_H = 125.5 \pm 0.2(\text{stat}) \pm 0.5(\text{syst})\,\text{GeV}$

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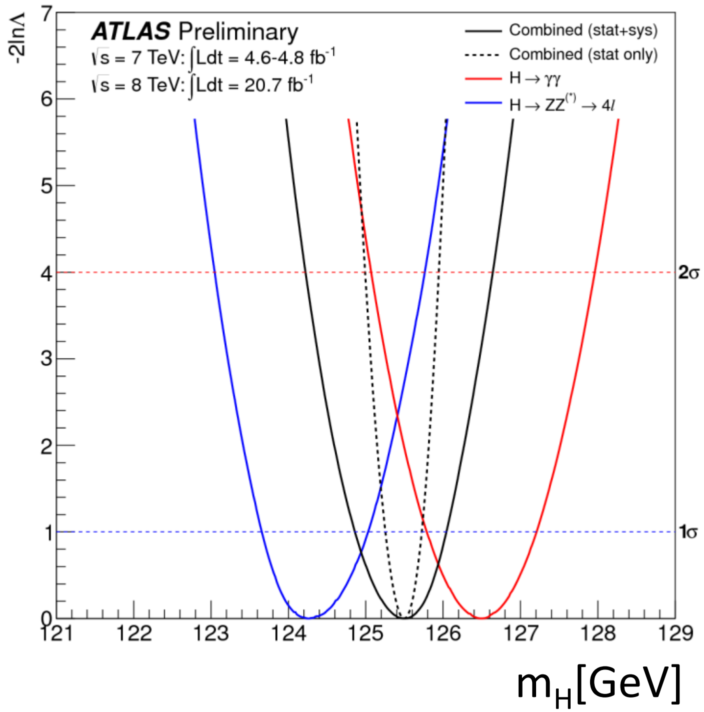
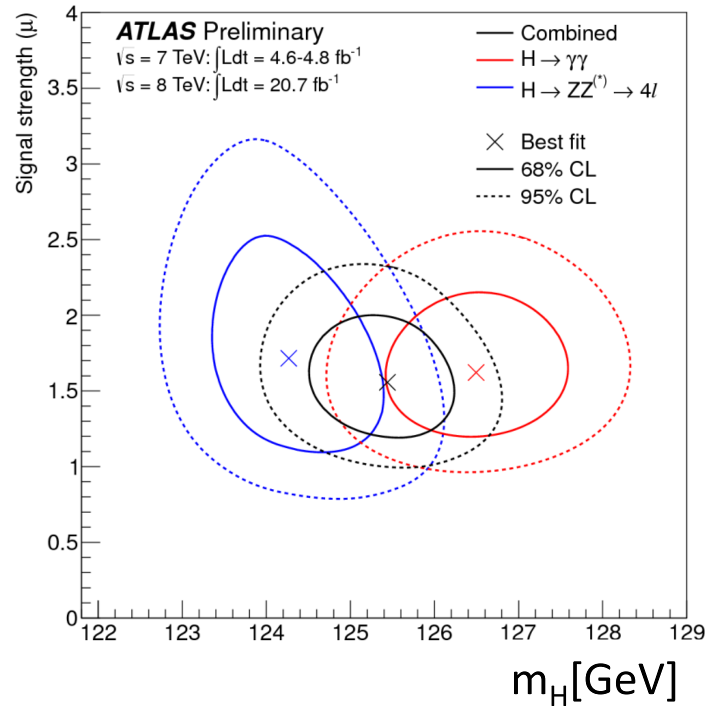




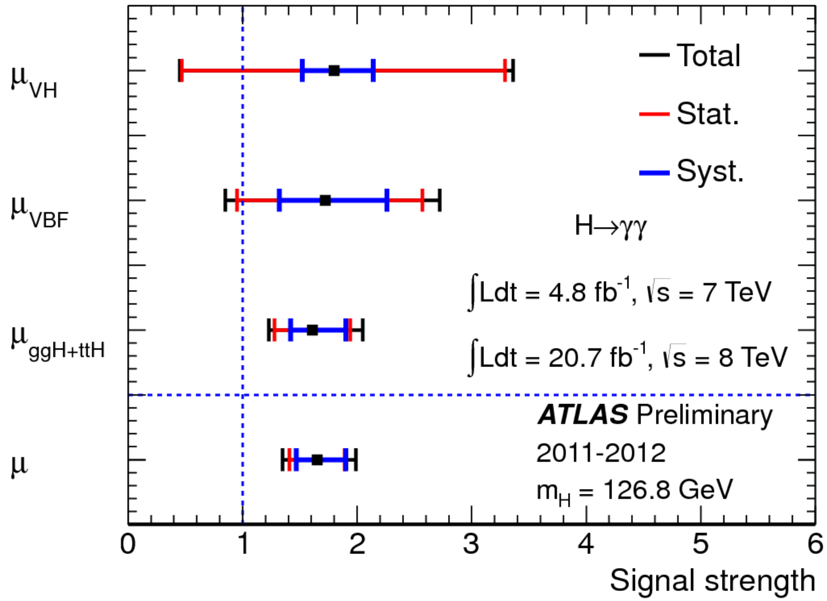
- Mass difference $\Delta m_H(\gamma\gamma - 4l) = 2.3^{+0.6}_{-0.7}(\text{stat}) \pm 0.6(\text{syst})\,\text{GeV}$

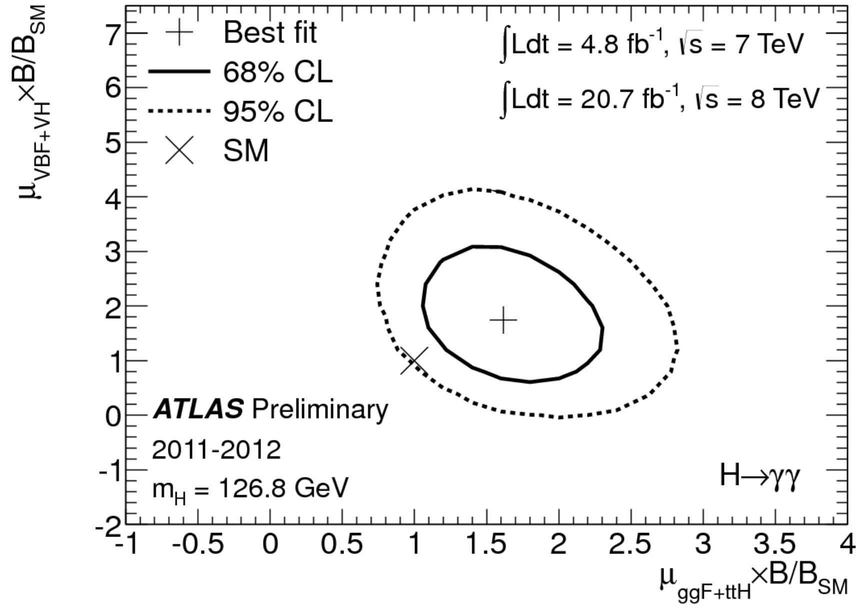
- What is the probability that both channels see the same resonance?

  prob(Δm_H=0) = 1.5% (2.4σ) using ensemble tests

Measurement of signal strengths

$H \rightarrow \gamma\gamma$





- Overall signal strength μ (=σ/σ_{SM}) at 126.8 GeV: $1.65 \pm 0.24(\mathrm{stat})^{+0.25}_{-0.18}(\mathrm{syst})$
- Compatibility with SM expectation: 2.3σ
- At combined mass of 125.5 GeV, μ : 1.6 ± 0.3
- Signal strength is high in all production modes, although consistent with SM expectation in VBF and associated production modes

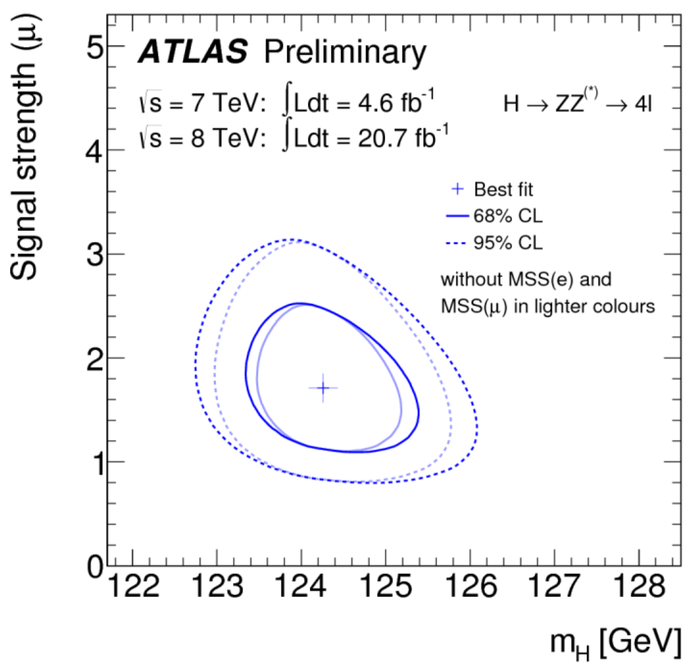
  - can imply presence of new particles in decay loop

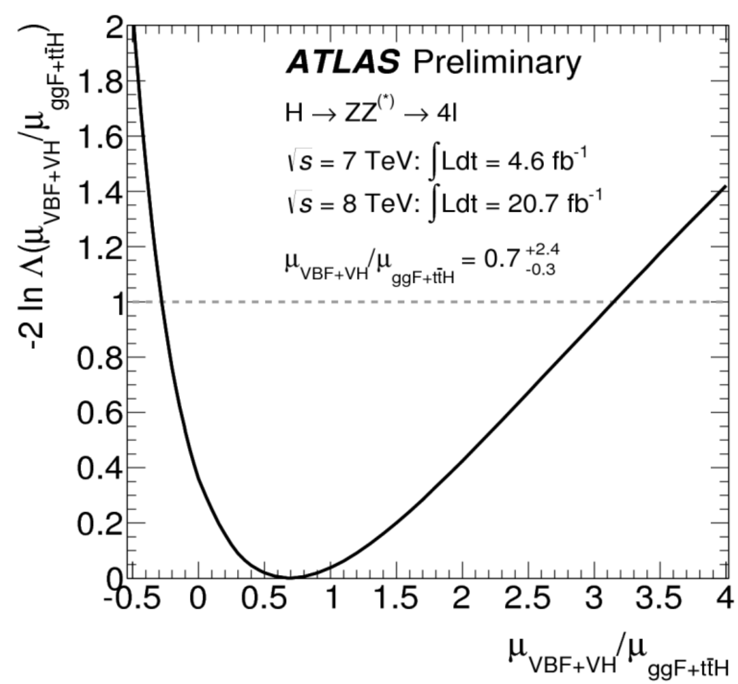
$H \rightarrow ZZ \rightarrow 4l$

- Overall signal strength μ at 124.3 GeV: $1.7^{+0.5}_{-0.4}$
- At 125.5 GeV, μ : 1.5 ± 0.4

Signal strength by production mode at m_H = 124.3 GeV

Quantity	$\mu_{ggF+ttH}$ x B/B_{SM}	μ_{VBF+VH} x B/B_{SM}	μ_{VBF+VH} / $\mu_{ggF+ttH}$
Measured value	$1.8^{+0.8}_{-0.5}$	$1.2^{+3.8}_{-1.4}$	$0.7^{+2.4}_{-0.3}$





$H \rightarrow WW \rightarrow l\nu l\nu$

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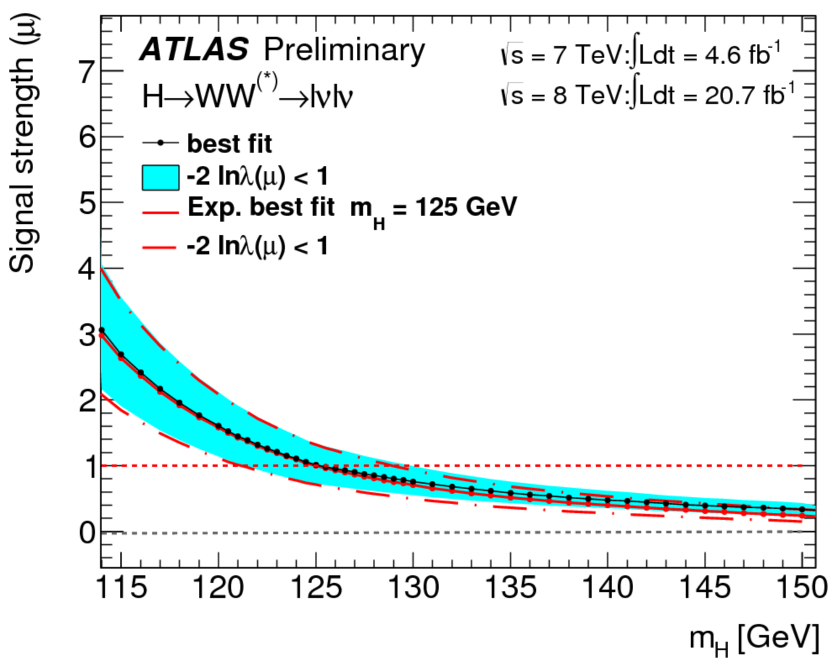
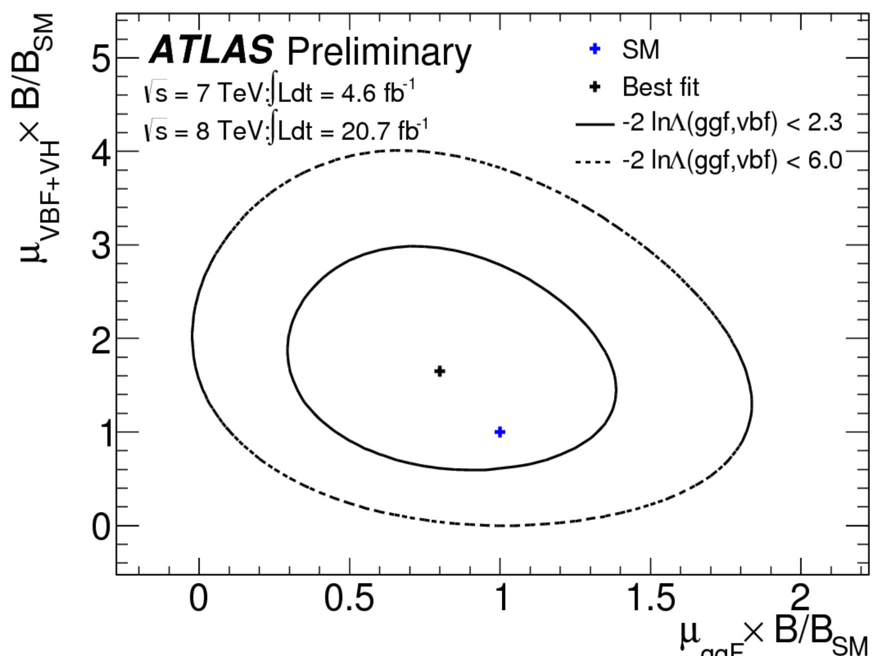
- Overall signal strength μ at 125 GeV: 1.01 ± 0.31
- Excellent agreement with SM!

Signal strength by production mode at m_H = 125.0 GeV

Quantity	μ_{ggF} x B/B_{SM}	μ_{VBF+VH} x B/B_{SM}
Measured value	0.82 $\pm$ 0.24(stat) $\pm$ 0.28(syst)	1.66 $\pm$ 0.67(stat) $\pm$ 0.42(syst)





Spin/CP discrimination

$H \rightarrow ZZ \rightarrow 4l$

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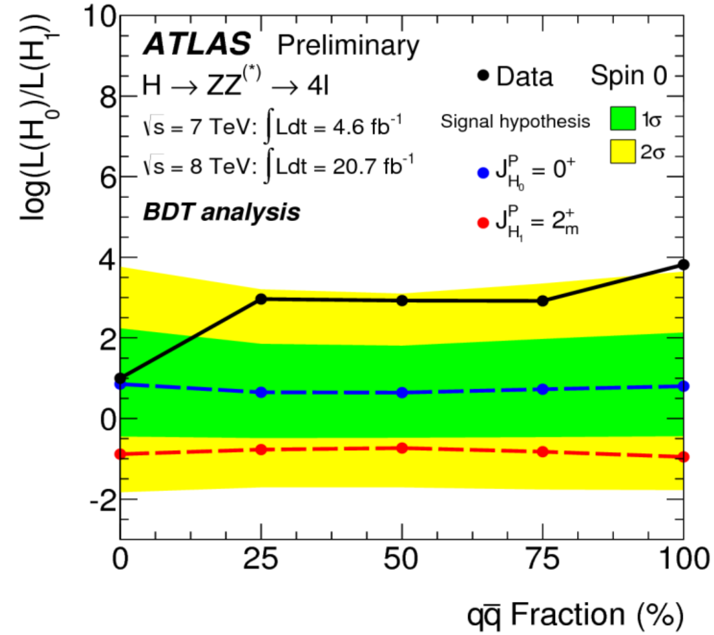
- 4 charged leptons → most sensitive channel for J^P discrimination
- 6 J^P hypotheses tested: 0^+, 0^-, 1^+, 1^-, 2^+, 2^-
- 2^+ can produced via ggF or *qq* annihilation
  - agnostic to production model → do analysis for 5 *gg/qq* → 2^+ fractions in interval [0, 1]
- Boosted Decision Trees (BDTs) used to maximize sensitivity



		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

- 0^- excluded at 97.8% CL
- All 2^+ hypotheses excluded at >83% CL
- SM hypothesis favored in all cases

$H \rightarrow \gamma\gamma$ and $H \rightarrow WW \rightarrow l\nu l\nu$

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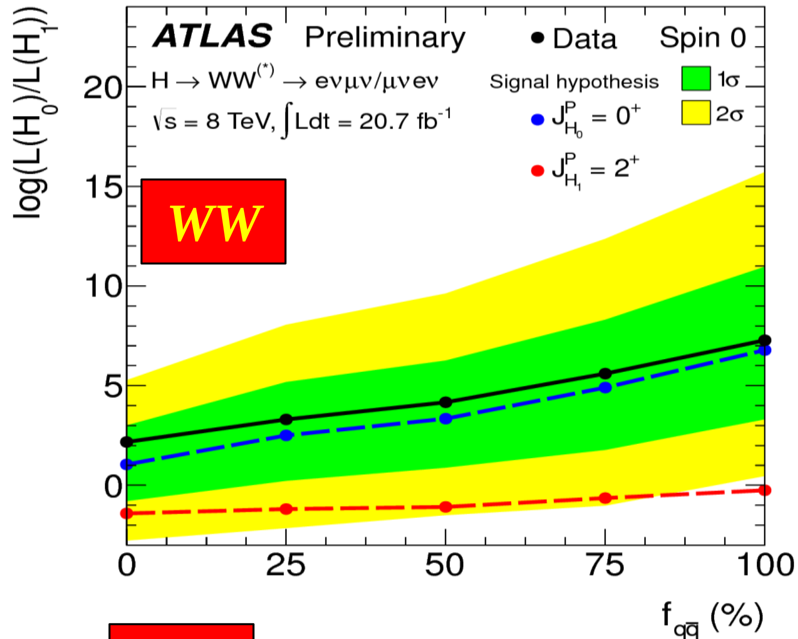
- $J^P = 0^+$ *vs* 2^+ discrimination analysis
- Five 2^+ production models tested, and data does not prefer any of them
- In both channels, data agree closely with SM signal hypothesis



$\gamma\gamma$

$f_{q\bar{q}}$ (%)	Spin hypothesis	p-values (%) expected	p-values (%) observed	$1 - CL_S(2^+)$ (%)
0	0^+	1.2	58.8	99.3
	2^+	0.5	0.3	
25	0^+	6.3	60.2	92.2
	2^+	5.3	3.1	
50	0^+	24.3	75.2	68
	2^+	23.4	7.9	
75	0^+	29.4	88.6	70
	2^+	28.0	3.4	
100	0^+	14.8	79.8	88
	2^+	13.5	2.5	

WW

$f_{q\bar{q}}$	1-CLs (2^+_m)
100%	0.99
75%	0.99
50%	0.98
25%	0.97
0%	0.95

Combination of $J^P = 0^+$ *vs* 2^+ analyses

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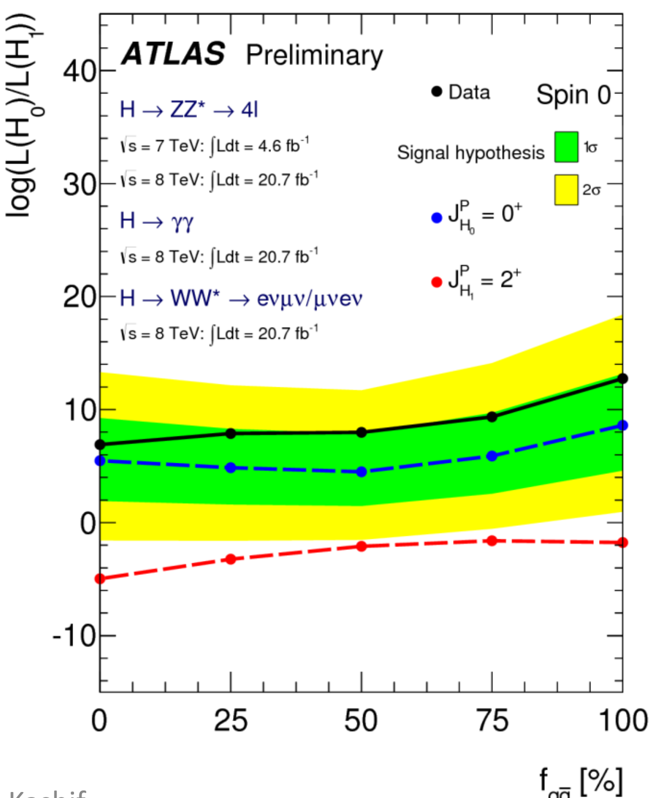
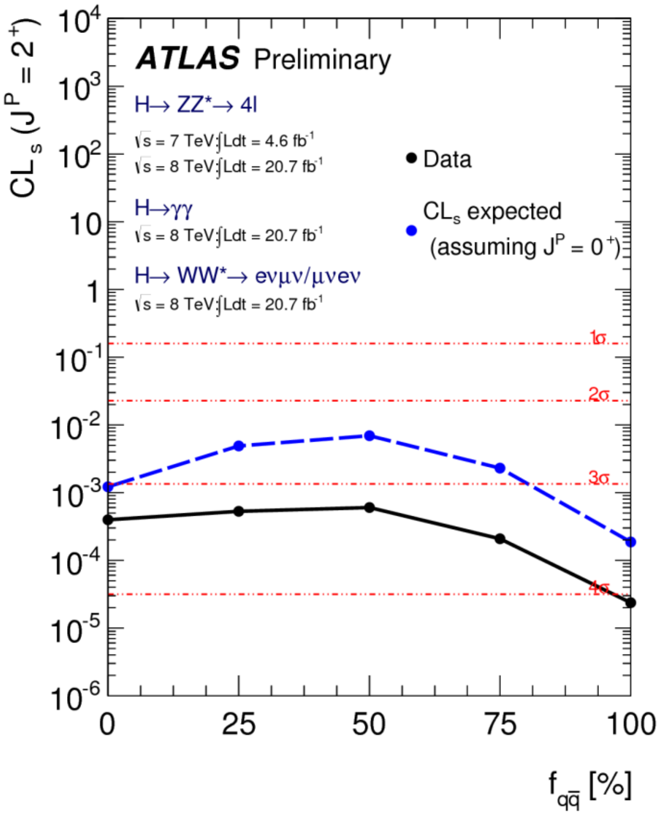
$f_{q\bar{q}}$	Spin-2 assumed exp. $p_0(J^P = 0^+)$	Spin-0 assumed exp. $p_0(J^P = 2^+)$	obs. $p_0(J^P = 0^+)$	obs. $p_0(J^P = 2^+)$	$CL_s(J^P = 2^+)$
100%	$3.4 \cdot 10^{-3}$	$9.4 \cdot 10^{-5}$	0.82	$0.4 \cdot 10^{-5}$	$0.2 \cdot 10^{-4}$
75%	$1.0 \cdot 10^{-2}$	$1.1 \cdot 10^{-3}$	0.82	$3.7 \cdot 10^{-5}$	$2.1 \cdot 10^{-4}$
50%	$1.5 \cdot 10^{-2}$	$3.5 \cdot 10^{-3}$	0.85	$9.1 \cdot 10^{-5}$	$6.0 \cdot 10^{-4}$
25%	$6.8 \cdot 10^{-3}$	$2.4 \cdot 10^{-3}$	0.81	$1.0 \cdot 10^{-4}$	$5.3 \cdot 10^{-4}$
0%	$1.6 \cdot 10^{-3}$	$6.1 \cdot 10^{-4}$	0.65	$1.4 \cdot 10^{-4}$	$4.0 \cdot 10^{-4}$





All 2^+ models excluded at >99.9% CL

Data look *very* SM Higgs-like

Conclusion & outlook

- Measurement of properties of new boson in ATLAS using Run I dataset presented

  - current focus is on bosonic decay channels: $\gamma\gamma$, *ZZ* and *WW*

- Mass from combination of $\gamma\gamma$, *ZZ* channels:

  $125.5 \pm 0.2(\text{stat}) \pm 0.5(\text{syst})\,\text{GeV}$

  - error on mass already <1%, and systematically limited

- Overall signal strength in *WW* channel very SM-like; high in *ZZ*, but still statistically limited

- Signal strength in $\gamma\gamma$ channel is high, consistent w/ SM expectation at 2.3σ

- Spin/CP analyses done in all 3 channels

- $J^P = 2^+$ excluded at >99.9% CL, $J^P = 0^-$ and $1^{+/-}$ excluded at >94% CL

✓ This boson is looking very SM-like, but confirmation in fermionic channels crucial (D. Jamin's talk in this session)

Backup

Systematic uncertainties in $H \rightarrow ZZ \rightarrow 4l$

➢ Mass measurement

- Decay modes involving electrons ($4e$, $2e2\mu$): electron energy scale uncertainty is main contributor

  - 0.4% (0.2%) on measured mass in $4e$ ($2e2\mu$)

- Decay modes involving muons (4μ, $2\mu 2e$): muon momentum scale, resolution uncertainty are main contributors

  - 0.2% (0.1%) on measured mass in 4μ ($2\mu 2e$)

➢ Signal strength measurement

- Decay modes involving electrons: electron ID and reco efficiency

  - at m_{4l} = 125 GeV, impact is 9.4% in $4e$, 8.7% in $2e2\mu$, 2.4% in $2\mu 2e$

- Decay modes involving muons: muon ID and reco efficiency

  - impact is 0.8% in $4e$, 8.7% in $2e2\mu$, 2.4% in $2\mu 2e$

Systematic uncertainties in $H \rightarrow \gamma\gamma$

Table 5: Summary of the impact of systematic uncertainties on the signal yields for the analysis of 8 TeV data.

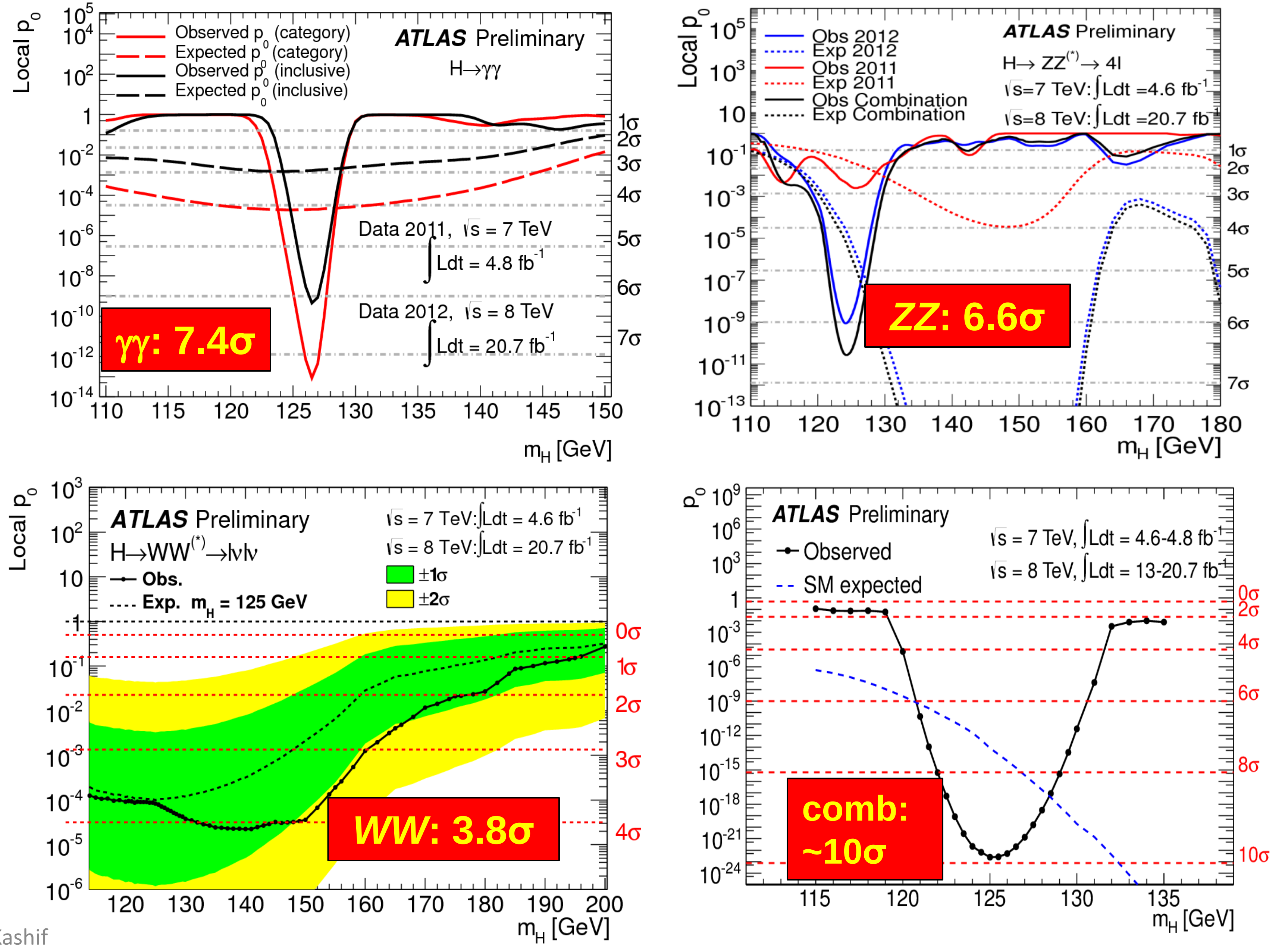
Systematic uncertainties	Value(%)			Constraint
Luminosity	±3.6			
Trigger	±0.5			
Photon Identification	±2.4			Log-normal
Isolation	±1.0			
Photon Energy Scale	±0.25			
Branching ratio	$\pm5.9\% - \pm2.1\%$ (m_H = 110 - 150 GeV)			Asymmetric Log-normal
Scale	ggF: $^{+7.2}_{-7.8}$	VBF: $^{+0.2}_{-0.2}$	WH: $^{+0.2}_{-0.6}$	Asymmetric Log-normal
	ZH: $^{+1.6}_{-1.5}$	ttH: $^{+3.8}_{-9.3}$		
PDF+α_s	ggF: $^{+7.5}_{-6.9}$	VBF: $^{+2.6}_{-2.7}$	WH: ±3.5	Asymmetric Log-normal
	ZH: ±3.6	ttH: ±7.8		
Theory cross section on ggF	Tight high-mass two-jet:	±48		Log-normal
	Loose high-mass two-jet:	±28		
	Low-mass two-jet:	±30		

Systematic uncertainties in $H \rightarrow WW \rightarrow l\nu l\nu$

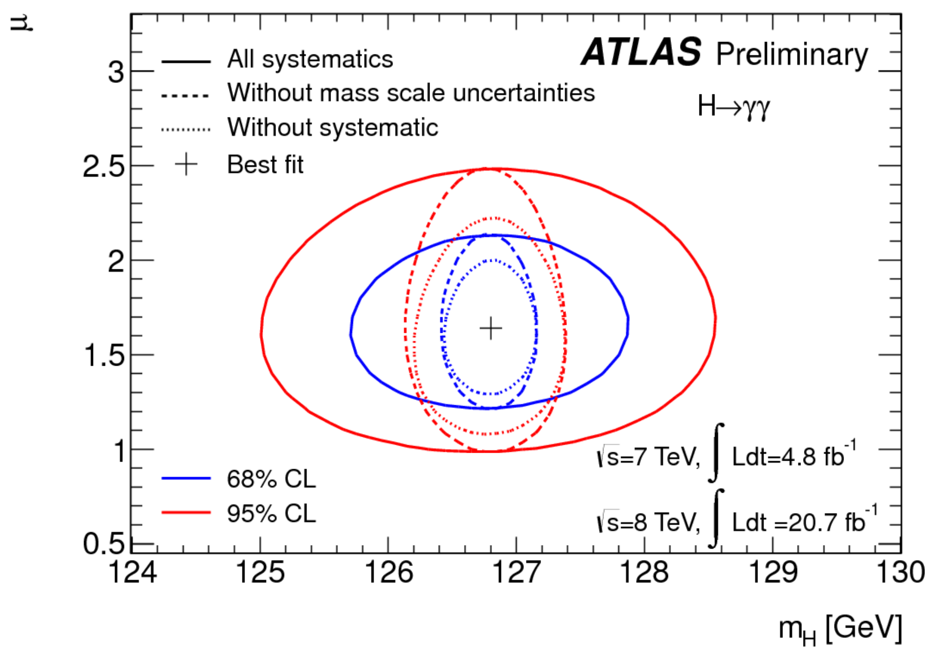
Table 13: Leading uncertainties on the signal strength μ for the combined 7 and 8 TeV analysis.

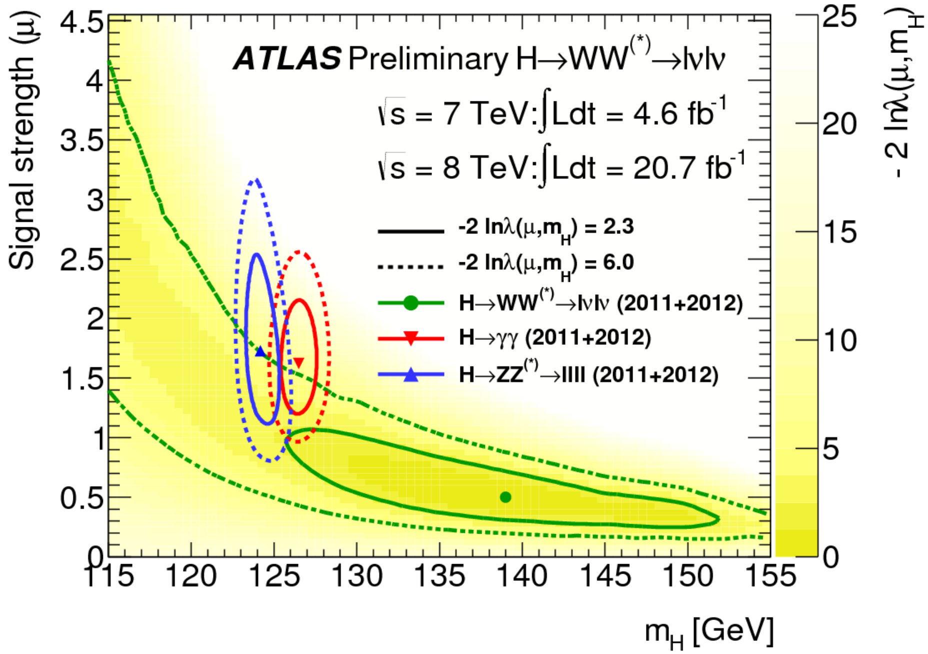
Category	Source	Uncertainty, up (%)	Uncertainty, down (%)
Statistical	Observed data	+21	−21
Theoretical	Signal yield ($\sigma \cdot \mathcal{B}$)	+12	−9
Theoretical	WW normalisation	+12	−12
Experimental	Objects and DY estimation	+9	−8
Theoretical	Signal acceptance	+9	−7
Experimental	MC statistics	+7	−7
Experimental	$W+$ jets fake factor	+5	−5
Theoretical	Backgrounds, excluding WW	+5	−4
Luminosity	Integrated luminosity	+4	−4
Total		+32	−29

Probability of background-only hypothesis



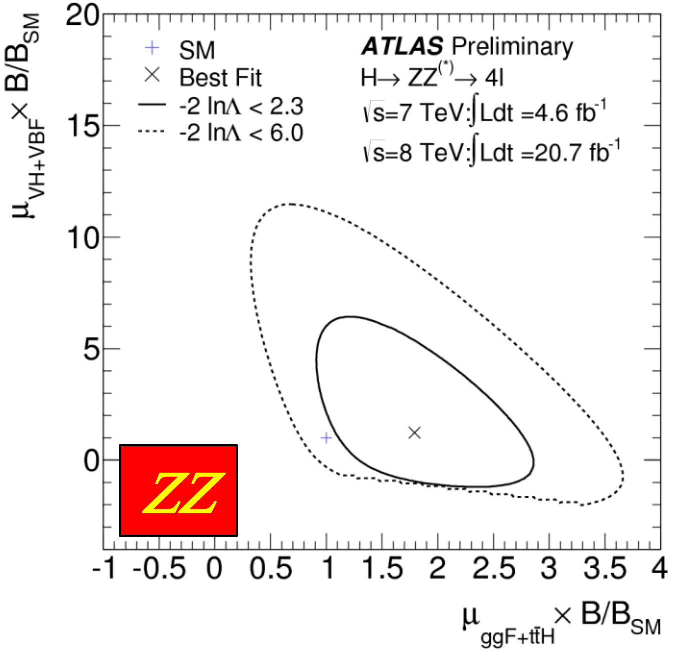
Best-fit μ *vs* mass

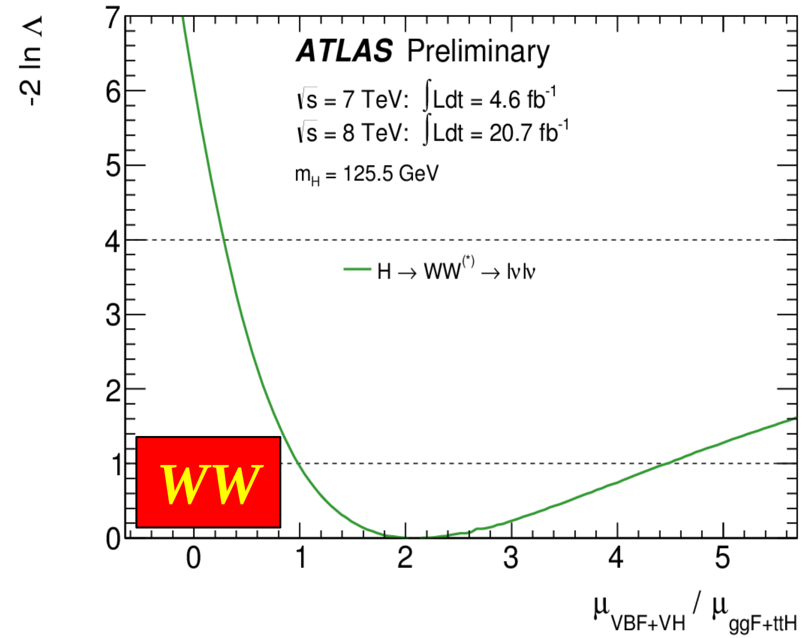


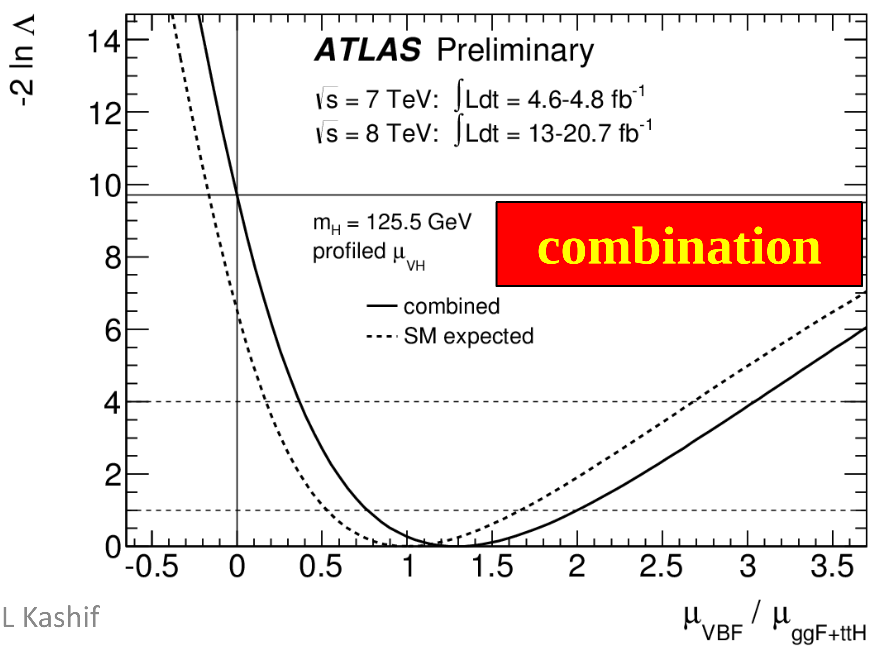


- Poor mass resolution in $H \rightarrow WW \rightarrow l\nu l\nu$
- Agreement with $\gamma\gamma$ and ZZ within 95% CL

$\mu_{ggF+ttH}$, μ_{VBF+VH}

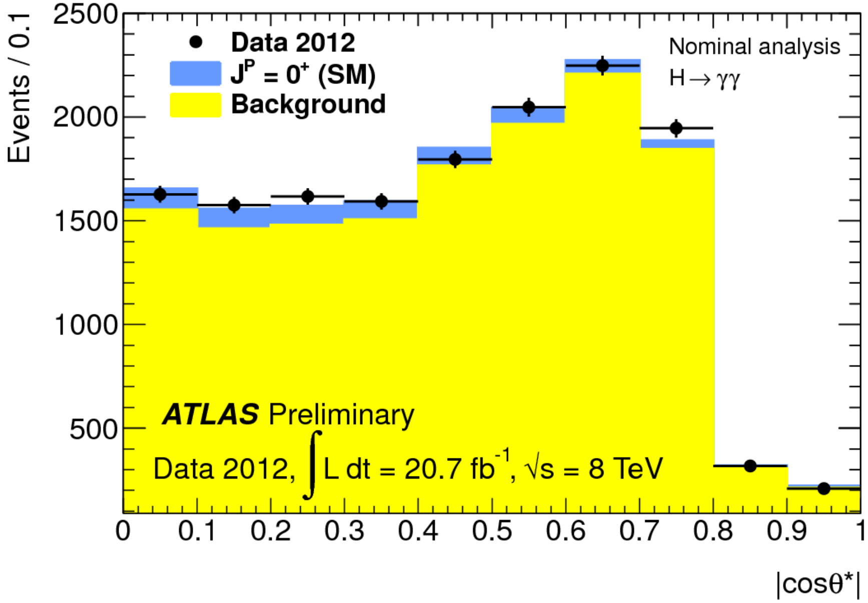




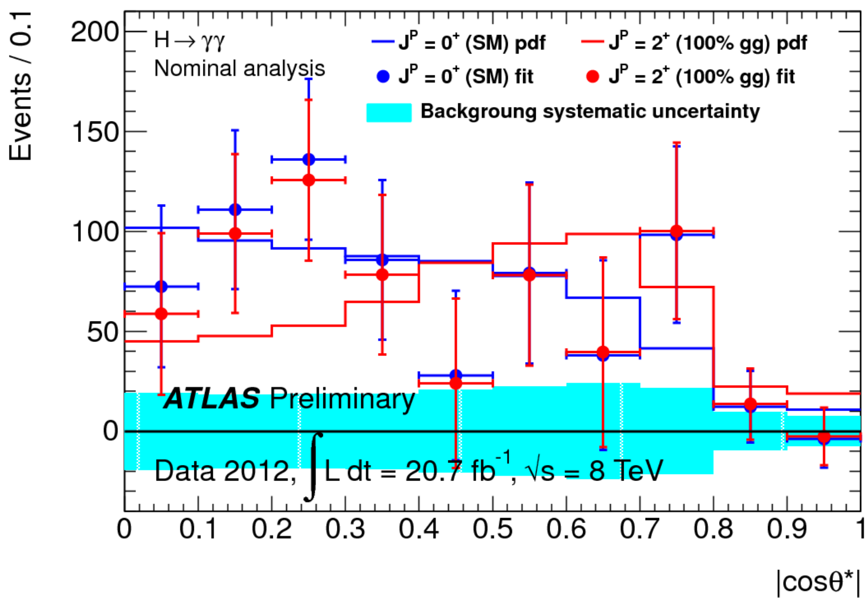


- Combination yields >3σ evidence for VBF production of resonance

Spin discrimination in $H \rightarrow \gamma\gamma$

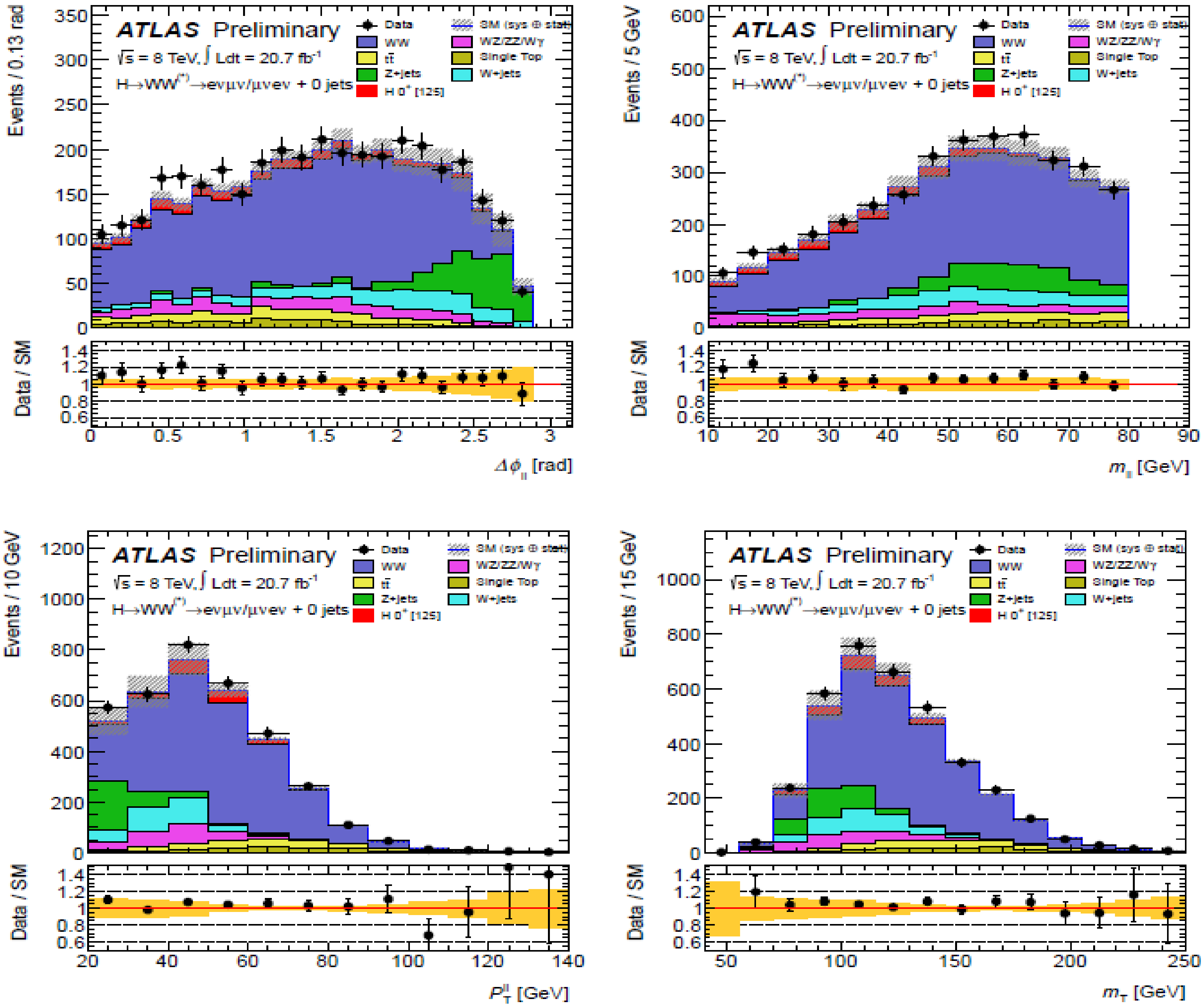


cosθ* distribution in data and from SM signal prediction, overlain on background

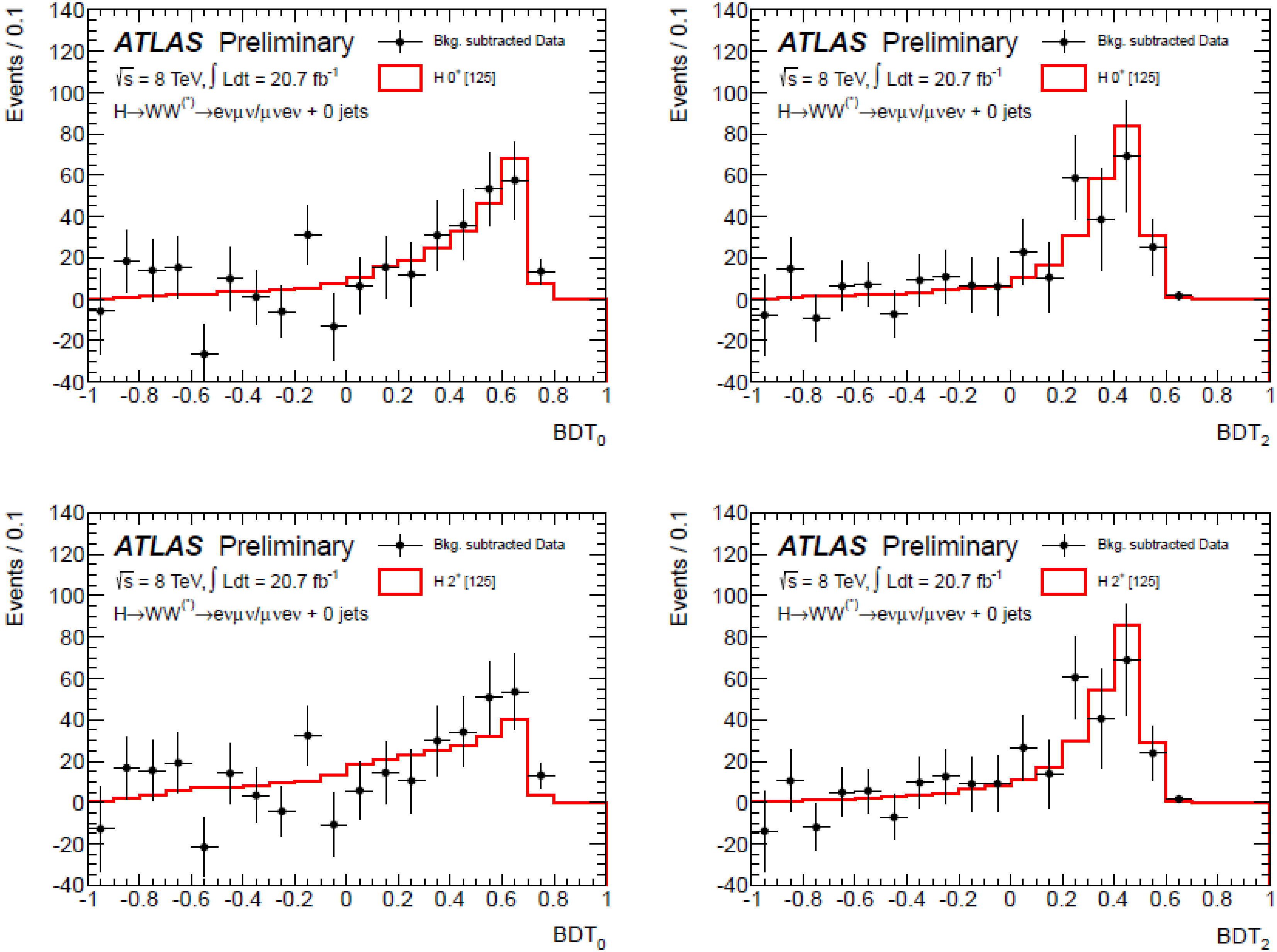


cosθ* distribution in bkg-subtracted data. The two sets of points correspond to the subtraction of the different profiled bkg shapes in the case of the conditional 0^+ and 2^+ fits. The expected PDFs for the two cases are overlain. The cyan band shows the systematics on bkg modeling.

Spin discriminants in *H* → *WW* → *lνlν*

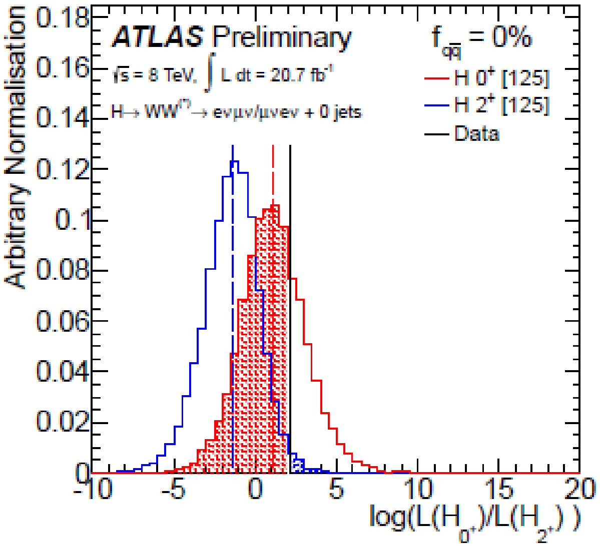


Bkg-subtracted BDT distributions in $H \rightarrow WW \rightarrow l\nu l\nu$

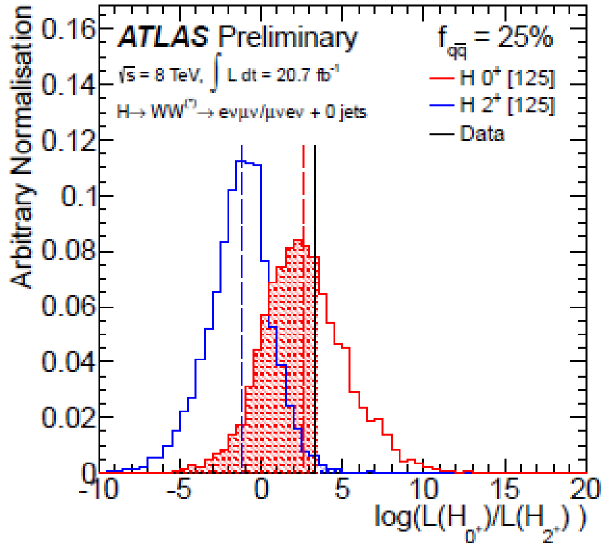


Spin toy distributions in $H \rightarrow WW \rightarrow l\nu l\nu$

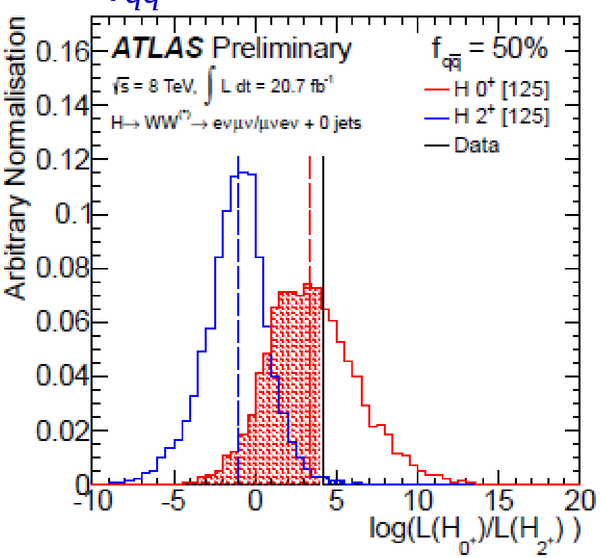
$f_{qq} = 0$



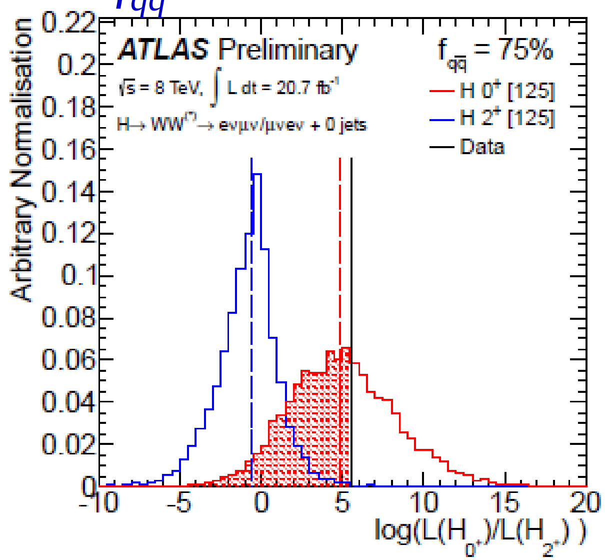
$f_{qq} = 0.25$



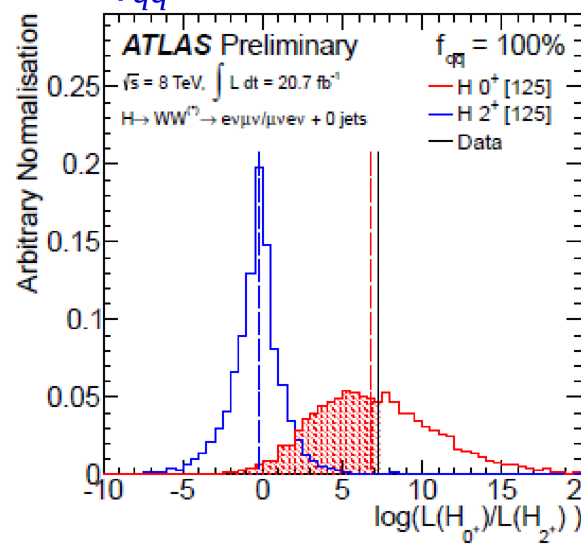
$f_{qq} = 0.5$



$f_{qq} = 0.75$



$f_{qq} = 1$



Spin analyses: statistical treatment

- Same statistical methodology used in individual channels and in combination

- Likelihood defined with the fraction of $J^P = 0^+$ signal as the parameter of interest ε

$$\mathcal{L}(\epsilon, \theta) = \prod_{i}^{N_{bins}} P(N_i | \epsilon \cdot S_i^{0^+}(\theta) + (1-\epsilon) S_i^{2^+_m}(\theta) + B_i(\theta)) \times \prod_{j}^{N_{sys}} \mathcal{A}(\tilde{\theta}_j | \theta_j)$$

- Since have no knowledge of 2^+_m production cross-section, signal strength μ is a floating parameter in fit

- The test statistic q is defined as a ratio of likelihoods

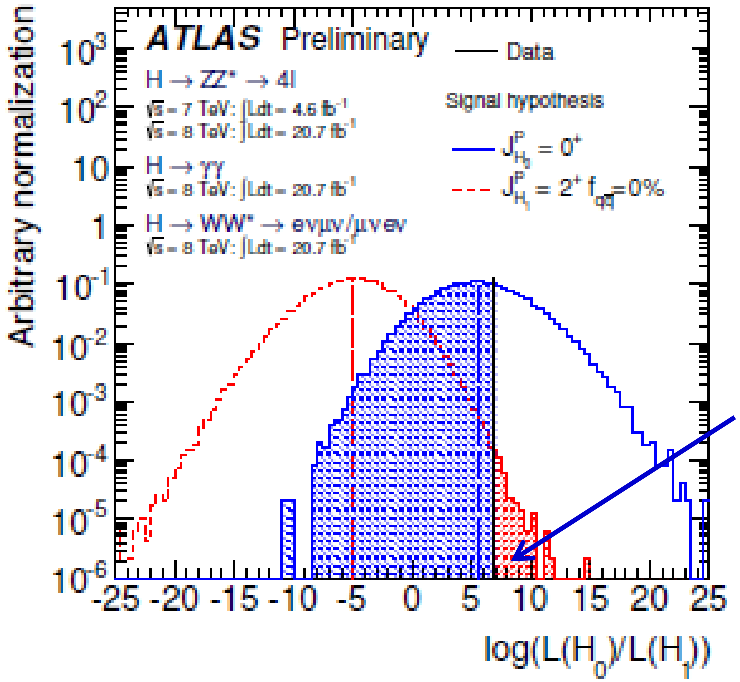
$$q = \ln \frac{L(\varepsilon = 1, \vec{\theta}_{\varepsilon=1})}{L(\varepsilon = 0, \vec{\theta}_{\varepsilon=0})}$$

- Distributions of test statistic obtained using toy MC

  - in toy generation, number of signal and bkg events in each channel is estimated from a fit to data, with all nuisance parameters profiled

Spin analyses: p-values and $\mathrm{CL_s}$

For illustration



Spin-2 rejection test:

obtain expected p-value by integrating over tail of the blue (2^+) distribution to the right of the median of the red (0^+) distribution

obtain observed p-value by integrating over same tail, but this time to the right of the observed test statistic (black vertical line)

Spin-0 rejection test similar, with the direction of integration reversed

- To avoid spurious exclusion of a hypothesis owing to fluctuations in data, normalize p-value using a $\mathrm{CL_s}$ approach

$$\mathrm{CL_s}(J^P = 2^+) = \frac{p_0(J^P = 2^+)}{1 - p_0(J^P = 0^+)}$$

The 2^+ model

- The amplitude for the interaction of a general spin-2 particle with gauge bosons is:

$$A(X \to VV) = \Lambda^{-1} \Big[2g_1^{(2)} t_{\mu\nu} f^{*1,\mu\alpha} f^{*2,\nu\alpha} + 2g_2^{(2)} t_{\mu\nu} \frac{q_\alpha q_\beta}{\Lambda^2} f^{*1,\mu\alpha} f^{*2,\nu,\beta}$$
$$+ g_3^{(2)} \frac{\tilde{q}^\beta \tilde{q}^\alpha}{\Lambda^2} t_{\beta\nu} (f^{*1,\mu\nu} f^{*2}_{\mu\alpha} + f^{*2,\mu\nu} f^{*1}_{\mu\alpha}) + g_4^{(2)} \frac{\tilde{q}^\nu \tilde{q}^\mu}{\Lambda^2} t_{\mu\nu} f^{*1,\alpha\beta} f^{*(2)}_{\alpha\beta}$$
$$+ m_V^2 \left(2g_5^{(2)} t_{\mu\nu} \epsilon_1^{*\mu} \epsilon_2^{*\nu} + 2g_6^{(2)} \frac{\tilde{q}^\mu q_\alpha}{\Lambda^2} t_{\mu\nu} (\epsilon_1^{*\nu} \epsilon_2^{*\alpha} - \epsilon_1^{*\alpha} \epsilon_2^{*\nu}) + g_7^{(2)} \frac{\tilde{q}^\mu \tilde{q}^\nu}{\Lambda^2} t_{\mu\nu} \epsilon_1^* \epsilon_2^* \right)$$
$$+ g_8^{(2)} \frac{\tilde{q}_\mu \tilde{q}_\nu}{\Lambda^2} t_{\mu\nu} f^{*1,\alpha\beta} \tilde{f}^{*(2)}_{\alpha\beta} + g_9^{(2)} t_{\mu\alpha} \tilde{q}^\alpha \epsilon_{\mu\nu\rho\sigma} \epsilon_1^{*\nu} \epsilon_2^{*\rho} q^\sigma + \frac{g_{10}^{(2)} t_{\mu\alpha} \tilde{q}^\alpha}{\Lambda^2} \epsilon_{\mu\nu\rho\sigma} q^\rho \tilde{q}^\sigma \left(\epsilon_1^{*\nu} (q\epsilon_2^*) + \epsilon_2^{*\nu} (q\epsilon_1^*) \right) \Big]$$

(Y. Gao et al., Phys. Rev. D 336 81 (2010) 075022, http://arxiv.org/pdf/1001.3396.pdf)

- At least 10 couplings → large number of possible models depending on which couplings are non-zero

- In our case, all 3 channels use a simplified scenario

  - for *gg* production of 2^+, all couplings except g_1 are zero, with $g_1 = 1$

  - for bosonic decays, $g_1 = g_5 = 1$, all other couplings zero

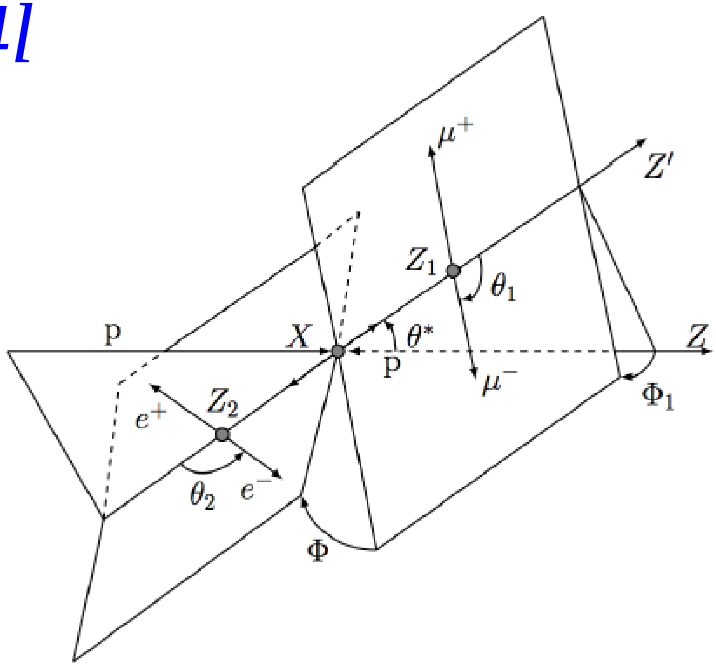
  - for *qq* production, only $\rho_1 = 1$ in Eq. 10 in above reference

$H \rightarrow ZZ \rightarrow 4l$

ATLAS-CONF-2013-013

- 4 charged leptons → most sensitive channel for J^P discrimination
- 6 J^P hypotheses tested: 0^+, 0^-, 1^+, 1^-, 2^+, 2^-
- 2^+ can produced via ggF or *qq* annihilation

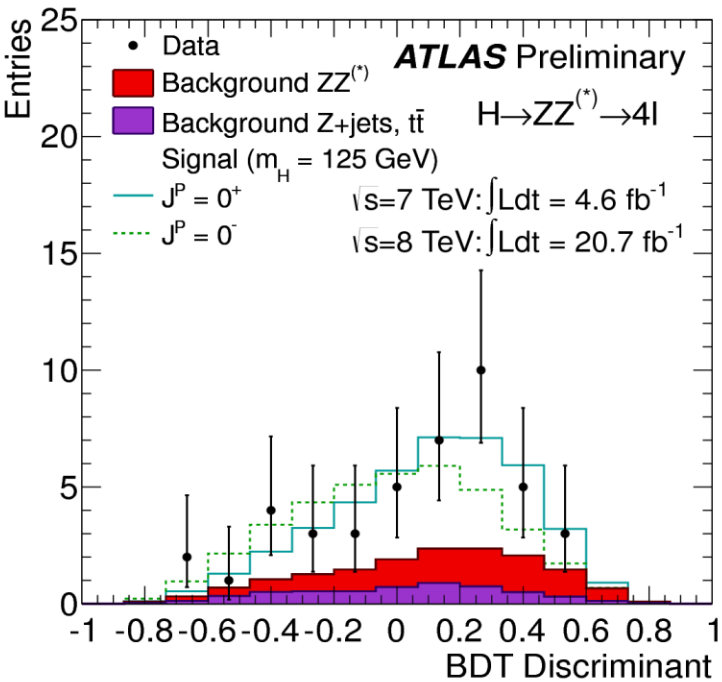
  - agnostic to production model → do analysis for 5 *gg/qq* → 2^+ fractions in interval [0, 1]



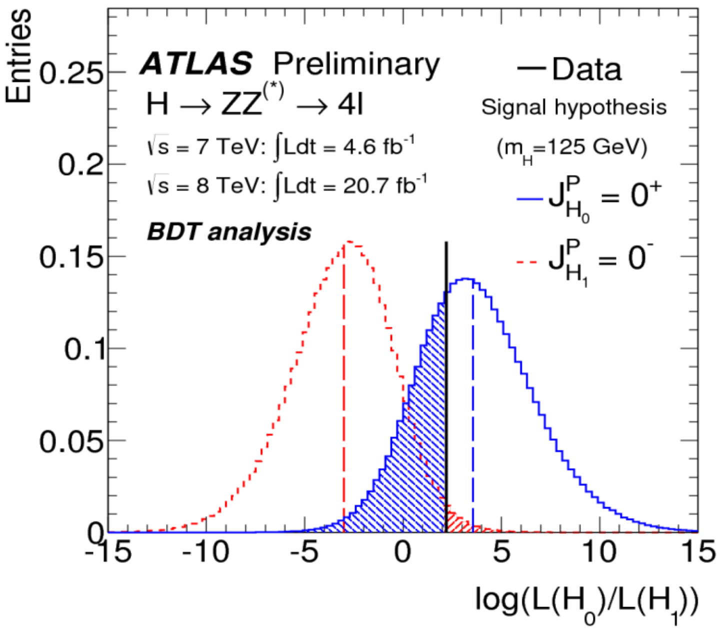
- Selected events in range $115 < m_{4l} < 130$ GeV used
- Boosted Decision Trees (BDTs) trained to maximize sensitivity

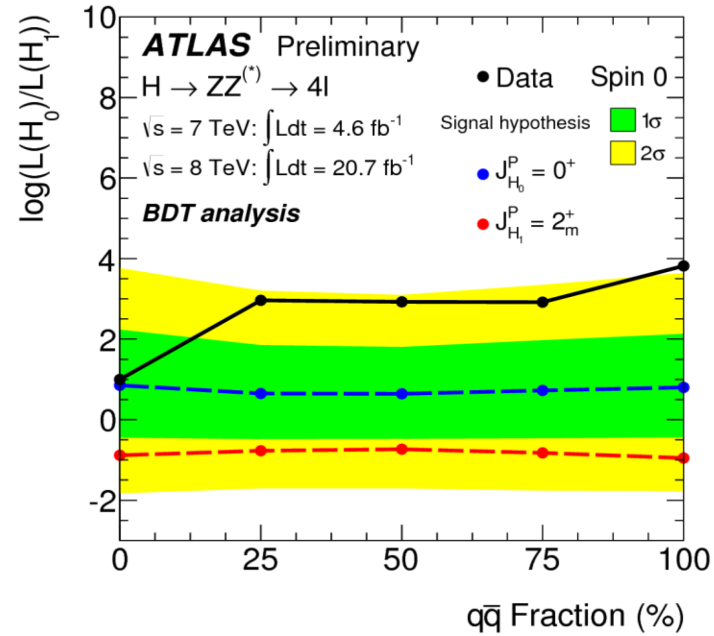
  - Φ, θ_1, θ_2, m_{12}, m_{34} used to train BDT for 0^+ *vs* 0^- discrimination

  - for other hypotheses, Φ_1 and θ^* used in addition



$H \rightarrow ZZ \rightarrow 4l$ (cont'd)





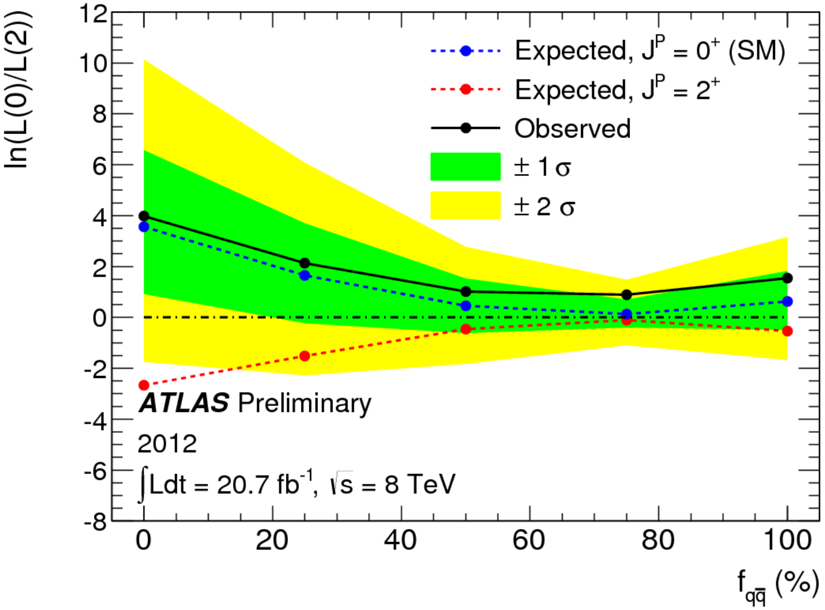
		BDT analysis			
		tested J^P for an assumed 0^+		tested 0^+ for an assumed J^P	$\mathrm{CL_S}$
		expected	observed	observed*	
0^-	p_0	0.0037	0.015	0.31	0.022
1^+	p_0	0.0016	0.001	0.55	0.002
1^-	p_0	0.0038	0.051	0.15	0.060
2^+_m	p_0	0.092	0.079	0.53	0.168
2^-	p_0	0.0053	0.25	0.034	0.258

- 0^- excluded at 97.8% CL
- All 2^+ hypotheses excluded at >83% CL
- SM signal hypothesis is strongly favored in all cases

Spin: $H \to \gamma\gamma$

ATLAS-CONF-2013-029

- $J^P = 0^+$ *vs* 2^+ discrimination analysis
- Five 2^+ production models tested, as in *ZZ* channel
- Two variables used to separate signal from bkg, and to test J^P hypotheses:
  - $\gamma\gamma$ invariant mass, $m_{\gamma\gamma}$
  - polar angle distribution of photons with respect to z-axis of Collins-Soper frame, $|\cos\theta^*|$
- Only 8 TeV data used
- 2^+ hypothesis with 100% *gg* fraction rejected at >99% CL
- Data prefer SM signal hypothesis



$f_{q\bar{q}}$ (%)	Spin hypothesis	p-values (%) expected	p-values (%) observed	$1 - CL_S(2^+)$ (%)
0	0^+	1.2	58.8	99.3
	2^+	0.5	0.3	
25	0^+	6.3	60.2	92.2
	2^+	5.3	3.1	
50	0^+	24.3	75.2	68
	2^+	23.4	7.9	
75	0^+	29.4	88.6	70
	2^+	28.0	3.4	
100	0^+	14.8	79.8	88
	2^+	13.5	2.5	

Spin: $H \rightarrow WW \rightarrow l\nu l\nu$

ATLAS-CONF-2013-031

- $J^P = 0^+$ *vs* 2^+ discrimination analysis
- 2 BDTs trained

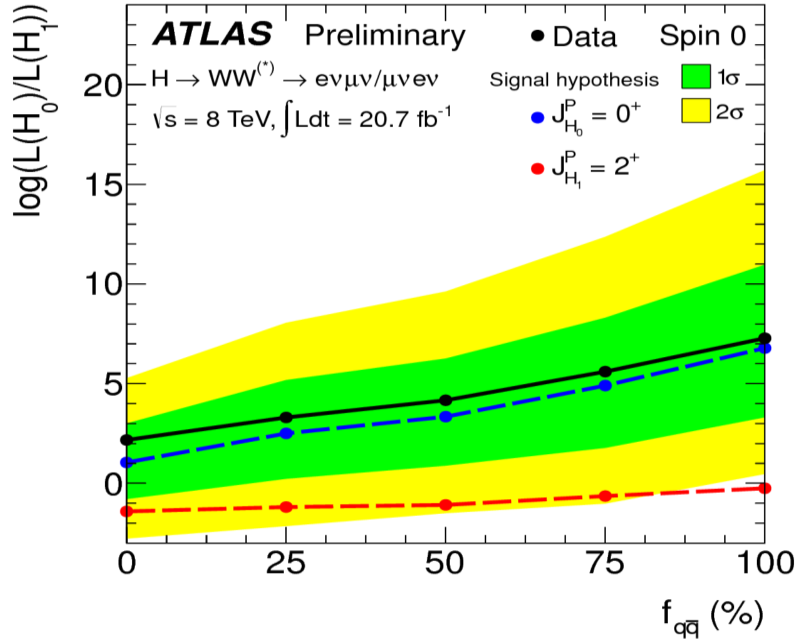
  - one BDT to separate 0^+ signal from bkg, the other to separate 2^+ signal from bkg

  - 2D BDT output fit to data
- Training variables: $\Delta\phi_{ll}$, m_{ll}, pT_{ll}, m_T

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

- Different lepton flavor, 0-jet channel used

  - only 8 TeV data used at this point
- 2^+ hypothesis rejected at 95% CL or better in all cases
- As in the other two channels, data prefer SM signal hypothesis



$f_{q\bar{q}}$	1-CLs (2^+_m)
100%	0.99
75%	0.99
50%	0.98
25%	0.97
0%	0.95