Spin/CP Combination in ATLAS

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on behalf on the ATLAS Collaboration

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Outline

- Analyses aim to examine the Higgs Spin/CP nature[1]:
  - Test pure BSM spin-0 and spin-2 models against the Standard Model
  - Constrain possible SM and BSM mixing of Spin-0 boson
  - Extend previous publication[2] with updated spin-2 results and HVV EFT approach

- Combine results from all sensitive vector boson channels:
  - $H \rightarrow ZZ^* \rightarrow 4l$, $H \rightarrow WW^* \rightarrow e\nu\mu\nu$ ($+\leqq 1$jet)[3] and $H \rightarrow \gamma\gamma$
  - ZZ* and WW* are used to examine both spin-0 and spin-2 models, whereas γγ contributes to spin-2

1: Study of the spin and parity of the Higgs boson in di-boson decays with the ATLAS detector

2: Evidence for the spin-0 nature of the Higgs boson using ATLAS data

3: Determination of spin and parity of the Higgs boson in the $WW^* \rightarrow e\nu\mu\nu$ decay channel with the ATLAS detector

Models

- Classification framework proposed in '<u>A framework for Higgs characterisation</u>'*
  - SM without Higgs plus generic boson described with EFT. (EFT scale here chosen to Λ=1 TeV)

$$\mathcal{L}_{HC,J} = \mathcal{L}_{SM-H} + \mathcal{L}_J$$

- <u>Spin-0</u>: a) Testing SM against pure BSM scalar (0^+_h) and pseudo-scalar (0^-)

  b) Constrain continuum of BSM / SM couplings: $(\tilde{\kappa}_{AVV}/\kappa_{SM}) \cdot \tan\alpha$, $\tilde{\kappa}_{HVV}/\kappa_{SM}$ (CP-odd / CP-even)

$\left(\tilde{\kappa}_X = \frac{1}{4}\frac{\nu}{\Lambda}\kappa_X\right)$

$$\begin{aligned}\mathcal{L}_0^V = & \left\{\cos(\alpha)\kappa_{\rm SM}\left[\tfrac{1}{2}g_{HZZ}Z_\mu Z^\mu + g_{HWW}W^+_\mu W^{-\mu}\right]\right. \\ & -\tfrac{1}{4}\tfrac{1}{\Lambda}\left[\cos(\alpha)\kappa_{HZZ}Z_{\mu\nu}Z^{\mu\nu} + \sin(\alpha)\kappa_{AZZ}Z_{\mu\nu}\tilde{Z}^{\mu\nu}\right] \\ & \left.-\tfrac{1}{2}\tfrac{1}{\Lambda}\left[\cos(\alpha)\kappa_{HWW}W^+_{\mu\nu}W^{-\mu\nu} + \sin(\alpha)\kappa_{AWW}W^+_{\mu\nu}\tilde{W}^{-\mu\nu}\right]\right\}X_0\end{aligned}$$

J^P	Model	Values of tensor couplings			
		$\kappa_{\rm SM}$	κ_{HVV}	κ_{AVV}	α
0^+	SM Higgs boson	1	0	0	0
0^+_h	BSM spin-0 CP-even	0	1	0	0
0^-	BSM spin-0 CP-odd	0	0	1	$\pi/2$

WW*, ZZ*

- <u>Test SM against graviton-like spin-2</u>. Including only quark and gluon couplings in production
  - Others estimated to be insignificant: $\sigma_{EW}/\sigma_{QCD} \cong 0.03\%$

Spin-2

Values of spin-2 quark and gluon couplings		$p_{\rm T}^X$ selections (GeV)	
$\kappa_q = \kappa_g$	Universal couplings	–	–
$\kappa_q = 0$	Low light-quark fraction	< 300	< 125
$\kappa_q = 2\kappa_g$	Low gluon fraction	< 300	< 125

WW*, ZZ*, γγ

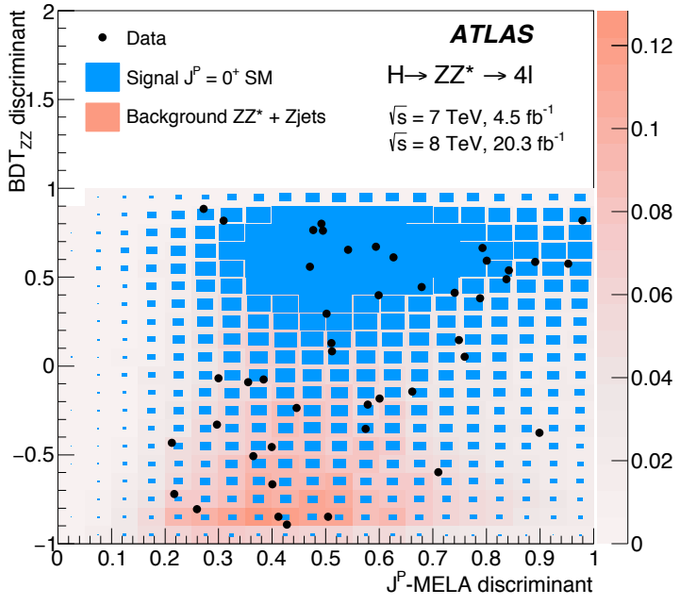
- Testing SM against three spin-2 coupling configurations: κ_q/κ_g = 0,1 and 2

*JHEP11(2013)043

Hypothesis discrimination

- Different approaches used in final states

H→ZZ*→4l

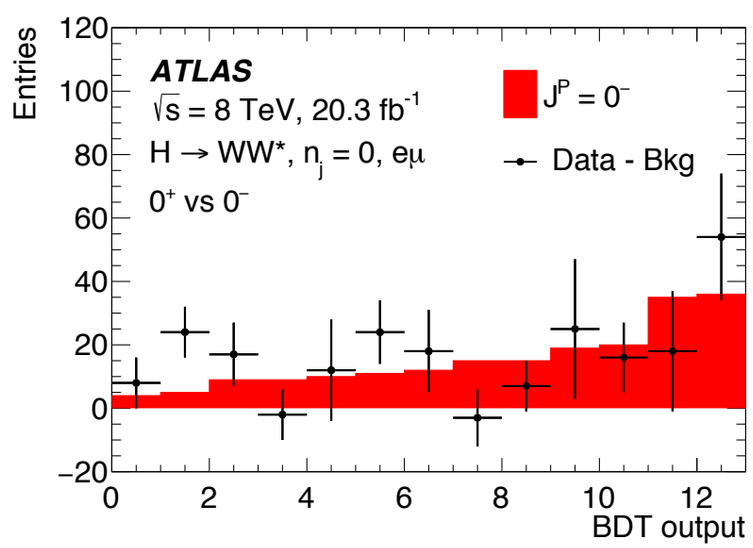


Possible to fully reconstruct final state

Discriminants constructed from BSM, SM matrix elements

BDT suppresses backgrounds

H→WW*→eνμν



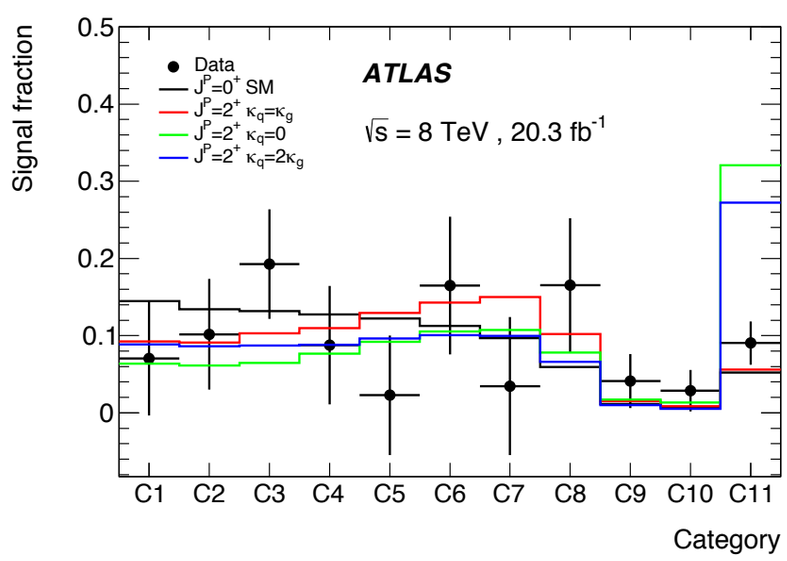
Each test based on two BDTs:

Spin-0: SM vs Bkg.+ SM vs Alt.
0 Jet category

Spin-2: SM vs Bkg + Alt. vs Bkg.
0+1 Jet categories

BDTs trained on lepton kinematics and MET

H→γγ



Discriminant based on polar angle, $|\cos(\theta^*)|$

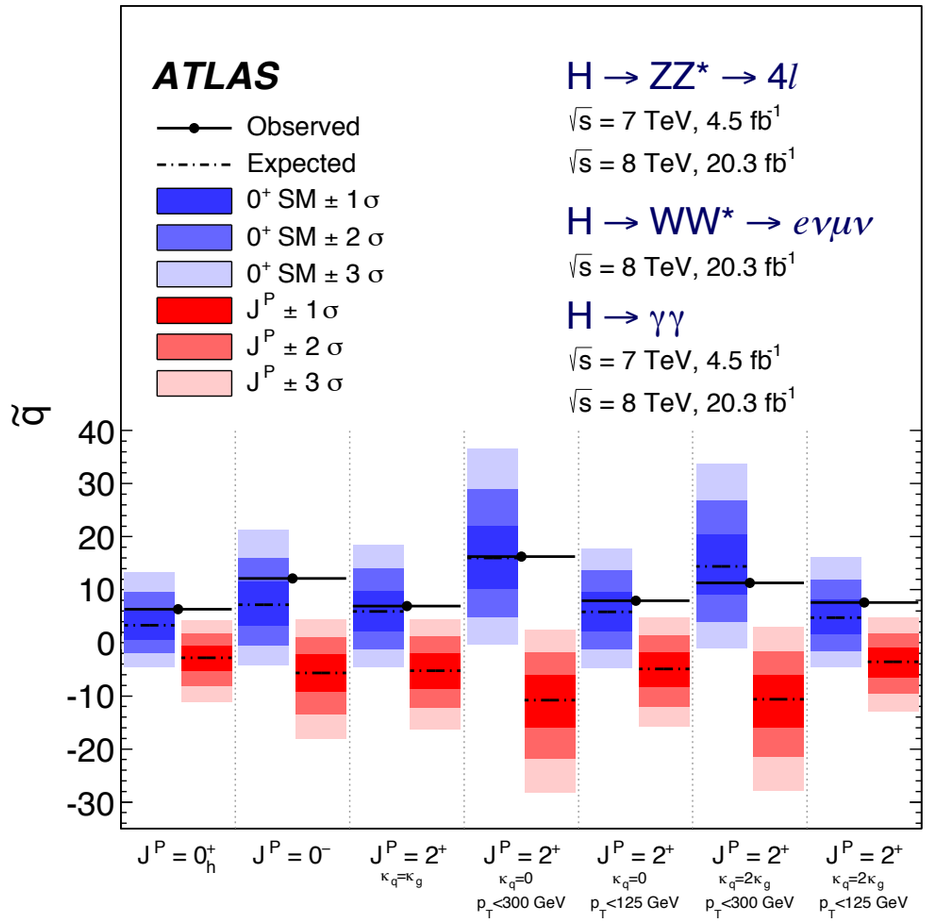
10 categories from 0 to 1

Extend with 11th category with $p_T \in [125, 300]$ GeV

Per-category $m_{\gamma\gamma}$-fit determines signal fraction

Results-I: Fixed hypotheses

- Tests examining the Spin/CP nature of the Higgs boson:
  - Spin-0: CP-even BSM and pseudo-scalar
  - Spin-2: Universal couplings and $\kappa_q/\kappa_g = 0$ and 2
- Combining diboson final states: WW*, ZZ* and γγ
- Exclusion determined from CL_S : $CL_S(J^P_{alt}) = \dfrac{p(J^P_{alt})}{1 - p(J^P_{SM})}$

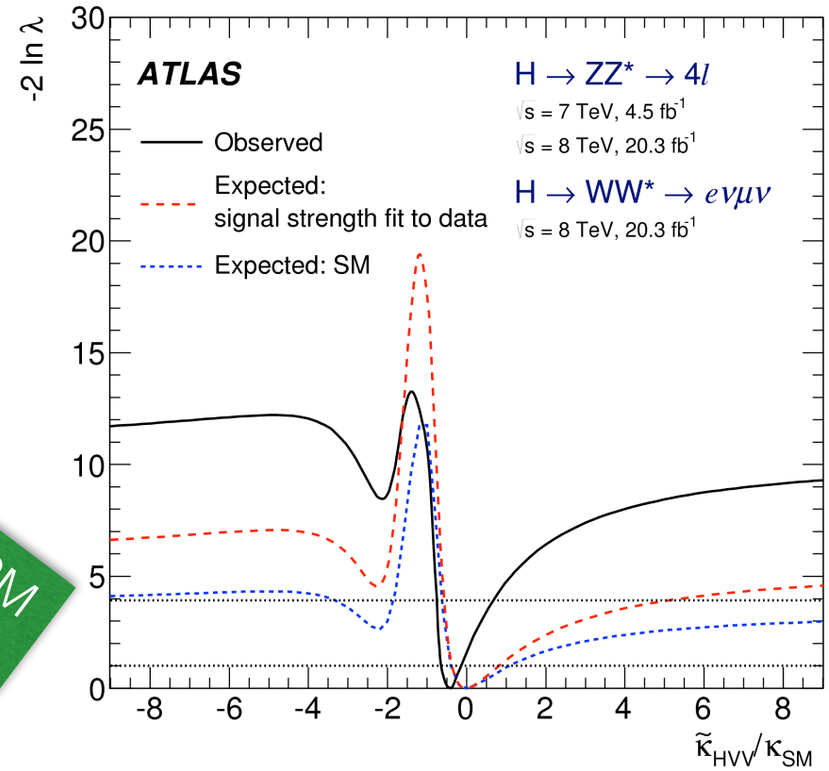


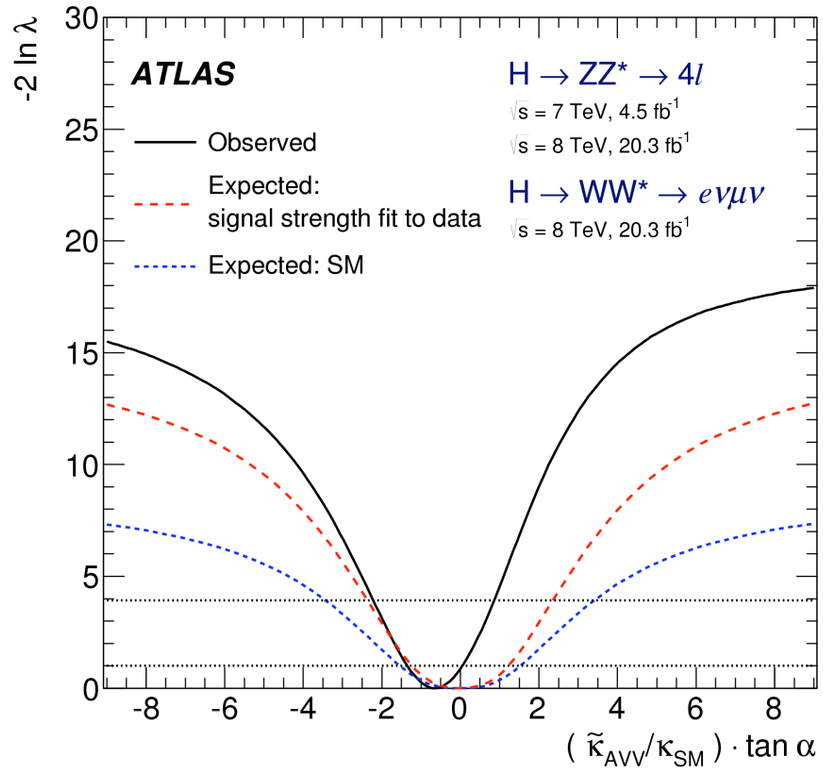
	Tested Hypothesis	$p^{\text{alt}}_{\text{exp},\mu=1}$	$p^{\text{alt}}_{\text{exp},\mu=\hat{\mu}}$	$p^{\text{SM}}_{\text{obs}}$	$p^{\text{alt}}_{\text{obs}}$	Obs. CL_s (%)
ZZ+WW	0^+_h	$2.5 \cdot 10^{-2}$	$4.7 \cdot 10^{-3}$	0.85	$7.1 \cdot 10^{-5}$	$4.7 \cdot 10^{-2}$
ZZ+WW	0^-	$1.8 \cdot 10^{-3}$	$1.3 \cdot 10^{-4}$	0.88	$< 3.1 \cdot 10^{-5}$	$< 2.6 \cdot 10^{-2}$
γγ	$2^+(\kappa_q = \kappa_g)$	$4.3 \cdot 10^{-3}$	$2.9 \cdot 10^{-4}$	0.61	$4.3 \cdot 10^{-5}$	$1.1 \cdot 10^{-2}$
γγ	$2^+(\kappa_q = 0;\ p_{\text{T}} < 300GeV)$	$< 3.1 \cdot 10^{-5}$	$< 3.1 \cdot 10^{-5}$	0.52	$< 3.1 \cdot 10^{-5}$	$< 6.5 \cdot 10^{-3}$
γγ	$2^+(\kappa_q = 0;\ p_{\text{T}} < 125GeV)$	$3.4 \cdot 10^{-3}$	$3.9 \cdot 10^{-4}$	0.71	$4.3 \cdot 10^{-5}$	$1.5 \cdot 10^{-2}$
γγ	$2^+(\kappa_q = 2\kappa_g;\ p_{\text{T}} < 300GeV)$	$< 3.1 \cdot 10^{-5}$	$< 3.1 \cdot 10^{-5}$	0.28	$< 3.1 \cdot 10^{-5}$	$< 4.3 \cdot 10^{-3}$
γγ	$2^+(\kappa_q = 2\kappa_g;\ p_{\text{T}} < 125GeV)$	$7.8 \cdot 10^{-3}$	$1.2 \cdot 10^{-3}$	0.80	$7.3 \cdot 10^{-5}$	$3.7 \cdot 10^{-2}$

SM is favoured and alternative models excluded > 95%CL_S

Results-II: Spin-0 coupling ratios

CP-Even BSM Contribution





CP-Odd Contribution

- Combined fit performed on ZZ* and WW* final states

- Results translated to effective BSM cross section fraction

Ratio	Best-fit value	95% CL Exclusion Regions	
Combined	Observed	SM Expectation	Observed
$\tilde{\kappa}_{HVV}/\kappa_{\mathrm{SM}}$	-0.48	$(-\infty,-0.55]\bigcup[4.80,\infty)$	$(-\infty,-0.73]\bigcup[0.63,\infty)$
$f_{g2}\cdot\cos\phi_{g2}$		$[-1,-0.096]\bigcup[0.89,1]$	$[-1,-0.16]\bigcup[0.12,1]$
$(\tilde{\kappa}_{AVV}/\kappa_{\mathrm{SM}})\cdot\tan\alpha$	-0.68	$(-\infty,-2.33]\bigcup[2.30,\infty)$	$(-\infty,-2.18]\bigcup[0.83,\infty)$
$f_{g4}\cdot\cos\phi_{g4}$		$[-1,-0.44]\bigcup[0.43,1]$	$[-1,-0.41]\bigcup[0.090,1]$

Data in agreement with Standard Model expectations

Conclusions and outlook

- Analysis of Higgs Spin/CP nature:
  - Pure BSM CP-even scalar (0^+_h) and pseudo-scalar (0^-) excluded in favour of SM
  - SM furthermore favoured over spin-2 models with different κ_q/κ_g coupling configurations
    - Spin-0 BSM/SM coupling ratio fits indicate that data is agreement with SM
- Looking forward to Run-II:
  - Continue development of EFT approach to study HVV interaction
  - Add different Higgs production mechanisms
  - Simultaneous fit of couplings

Backup

Models - Expanded

$$\mathcal{L}_{HC,J} = \mathcal{L}_{SM-H} + \mathcal{L}_J$$

Spin-0

$$\begin{aligned}\mathcal{L}_0^V = & \left\{\cos(\alpha)\kappa_{\rm SM}\left[\tfrac{1}{2}g_{HZZ}Z_\mu Z^\mu + g_{HWW}W_\mu^+ W^{-\mu}\right]\right. \\ & -\tfrac{1}{4}\tfrac{1}{\Lambda}\left[\cos(\alpha)\kappa_{HZZ}Z_{\mu\nu}Z^{\mu\nu} + \sin(\alpha)\kappa_{AZZ}Z_{\mu\nu}\tilde{Z}^{\mu\nu}\right] \\ & \left.-\tfrac{1}{2}\tfrac{1}{\Lambda}\left[\cos(\alpha)\kappa_{HWW}W_{\mu\nu}^+ W^{-\mu\nu} + \sin(\alpha)\kappa_{AWW}W_{\mu\nu}^+ \tilde{W}^{-\mu\nu}\right]\right\} X_0\end{aligned}$$

J^P	Model	Values of tensor couplings			
		$\kappa_{\rm SM}$	κ_{HVV}	κ_{AVV}	α
0^+	SM Higgs boson	1	0	0	0
0_h^+	BSM spin-0 CP-even	0	1	0	0
0^-	BSM spin-0 CP-odd	0	0	1	$\pi/2$

Spin-2

$$\mathcal{L}_2 = -\frac{1}{\Lambda}\left[\sum_V \kappa_V \mathcal{T}_{\mu\nu}^V X^{\mu\nu} + \sum_f \kappa_f \mathcal{T}_{\mu\nu}^f X^{\mu\nu}\right]$$

Values of spin-2 quark and gluon couplings		$p_{\rm T}^X$ selections (GeV)	
$\kappa_q = \kappa_g$	Universal couplings	–	–
$\kappa_q = 0$	Low light-quark fraction	< 300	< 125
$\kappa_q = 2\kappa_g$	Low gluon fraction	< 300	< 125

Per final state results

Tested Hypothesis	$H \to \gamma\gamma$				
	$p^{\text{alt}}_{\text{exp},\mu=1}$	$p^{\text{alt}}_{\text{exp},\mu=\hat{\mu}}$	$p^{\text{SM}}_{\text{obs}}$	$p^{\text{alt}}_{\text{obs}}$	Obs. CL_s (%)
$2^+(\kappa_q = \kappa_g)$	0.13	$7.5 \cdot 10^{-2}$	0.13	0.34	39
$2^+(\kappa_q = 0;\ p_\text{T} < 300GeV)$	$4.3 \cdot 10^{-4}$	$< 3.1 \cdot 10^{-5}$	0.16	$2.9{\cdot}10^{-4}$	$3.5{\cdot}10^{-2}$
$2^+(\kappa_q = 0;\ p_\text{T} < 125GeV)$	$9.4 \cdot 10^{-2}$	$5.6{\cdot}10^{-2}$	0.23	0.20	26
$2^+(\kappa_q = 2\kappa_g;\ p_\text{T} < 300GeV)$	$9.1 \cdot 10^{-4}$	$< 3.1 \cdot 10^{-5}$	0.16	$8.6{\cdot}10^{-4}$	0.10
$2^+(\kappa_q = 2\kappa_g;\ p_\text{T} < 125GeV)$	0.27	0.24	0.20	0.54	68
Tested Hypothesis	$H \to WW^* \to e\nu\mu\nu$				
	$p^{\text{alt}}_{\text{exp},\mu=1}$	$p^{\text{alt}}_{\text{exp},\mu=\hat{\mu}}$	$p^{\text{SM}}_{\text{obs}}$	$p^{\text{alt}}_{\text{obs}}$	Obs. CL_s (%)
0^+_h	0.31	0.29	0.91	$2.7{\cdot}10^{-2}$	29
0^-	$6.4{\cdot}10^{-2}$	$3.2{\cdot}10^{-2}$	0.65	$1.2{\cdot}10^{-2}$	3.5
$2^+(\kappa_q = \kappa_g)$	$6.4{\cdot}10^{-2}$	$3.3{\cdot}10^{-2}$	0.25	0.12	16
$2^+(\kappa_q = 0;\ p_\text{T} < 300GeV)$	$1.5{\cdot}10^{-2}$	$4.0{\cdot}10^{-3}$	0.55	$3.0{\cdot}10^{-3}$	0.6
$2^+(\kappa_q = 0;\ p_\text{T} < 125GeV)$	$5.6{\cdot}10^{-2}$	$2.9{\cdot}10^{-2}$	0.42	$4.4{\cdot}10^{-2}$	7.5
$2^+(\kappa_q = 2\kappa_g;\ p_\text{T} < 300GeV)$	$1.5{\cdot}10^{-2}$	$4.0{\cdot}10^{-3}$	0.52	$3.0{\cdot}10^{-3}$	0.7
$2^+(\kappa_q = 2\kappa_g;\ p_\text{T} < 125GeV)$	$4.4{\cdot}10^{-2}$	$2.2{\cdot}10^{-2}$	0.69	$7.0{\cdot}10^{-3}$	2.2
Tested Hypothesis	$H \to ZZ^* \to 4\ell$				
	$p^{\text{alt}}_{\text{exp},\mu=1}$	$p^{\text{alt}}_{\text{exp},\mu=\hat{\mu}}$	$p^{\text{SM}}_{\text{obs}}$	$p^{\text{alt}}_{\text{obs}}$	Obs. CL_s (%)
0^+_h	$3.2 \cdot 10^{-2}$	$5.2 \cdot 10^{-3}$	0.80	$3.6 \cdot 10^{-4}$	0.18
0^-	$8.0 \cdot 10^{-3}$	$3.6 \cdot 10^{-4}$	0.88	$1.2 \cdot 10^{-5}$	$1.0{\cdot}10^{-2}$
$2^+(\kappa_q = \kappa_g)$	$3.3 \cdot 10^{-2}$	$5.7 \cdot 10^{-4}$	0.91	$3.6 \cdot 10^{-5}$	$4.0{\cdot}10^{-2}$
$2^+(\kappa_q = 0;\ p_\text{T} < 300GeV)$	$3.9 \cdot 10^{-2}$	$9.0 \cdot 10^{-3}$	0.95	$2.7 \cdot 10^{-5}$	$5.4{\cdot}10^{-2}$
$2^+(\kappa_q = 0;\ p_\text{T} < 125GeV)$	$4.6 \cdot 10^{-2}$	$1.1 \cdot 10^{-2}$	0.93	$3.0 \cdot 10^{-5}$	$4.3{\cdot}10^{-2}$
$2^+(\kappa_q = 2\kappa_g;\ p_\text{T} < 300GeV)$	$4.6 \cdot 10^{-2}$	$1.1 \cdot 10^{-2}$	0.66	$3.3 \cdot 10^{-3}$	0.97
$2^+(\kappa_q = 2\kappa_g;\ p_\text{T} < 125GeV)$	$5.0 \cdot 10^{-2}$	$1.3 \cdot 10^{-2}$	0.88	$3.2 \cdot 10^{-4}$	0.27

Per final state results, tensor structure

Coupling ratio	Best-fit value	95% CL Exclusion Regions	
$H \to ZZ^* \to 4\ell$	Observed	Expected	Observed
$\tilde{\kappa}_{HVV}/\kappa_{\mathrm{SM}}$	-0.2	$(-\infty, -0.75] \bigcup [6.95, \infty)$	$(-\infty, -0.75] \bigcup [2.45, \infty)$
$(\tilde{\kappa}_{AVV}/\kappa_{\mathrm{SM}}) \cdot \tan\alpha$	-0.8	$(-\infty, -2.95] \bigcup [2.95, \infty)$	$(-\infty, -2.85] \bigcup [0.95, \infty)$

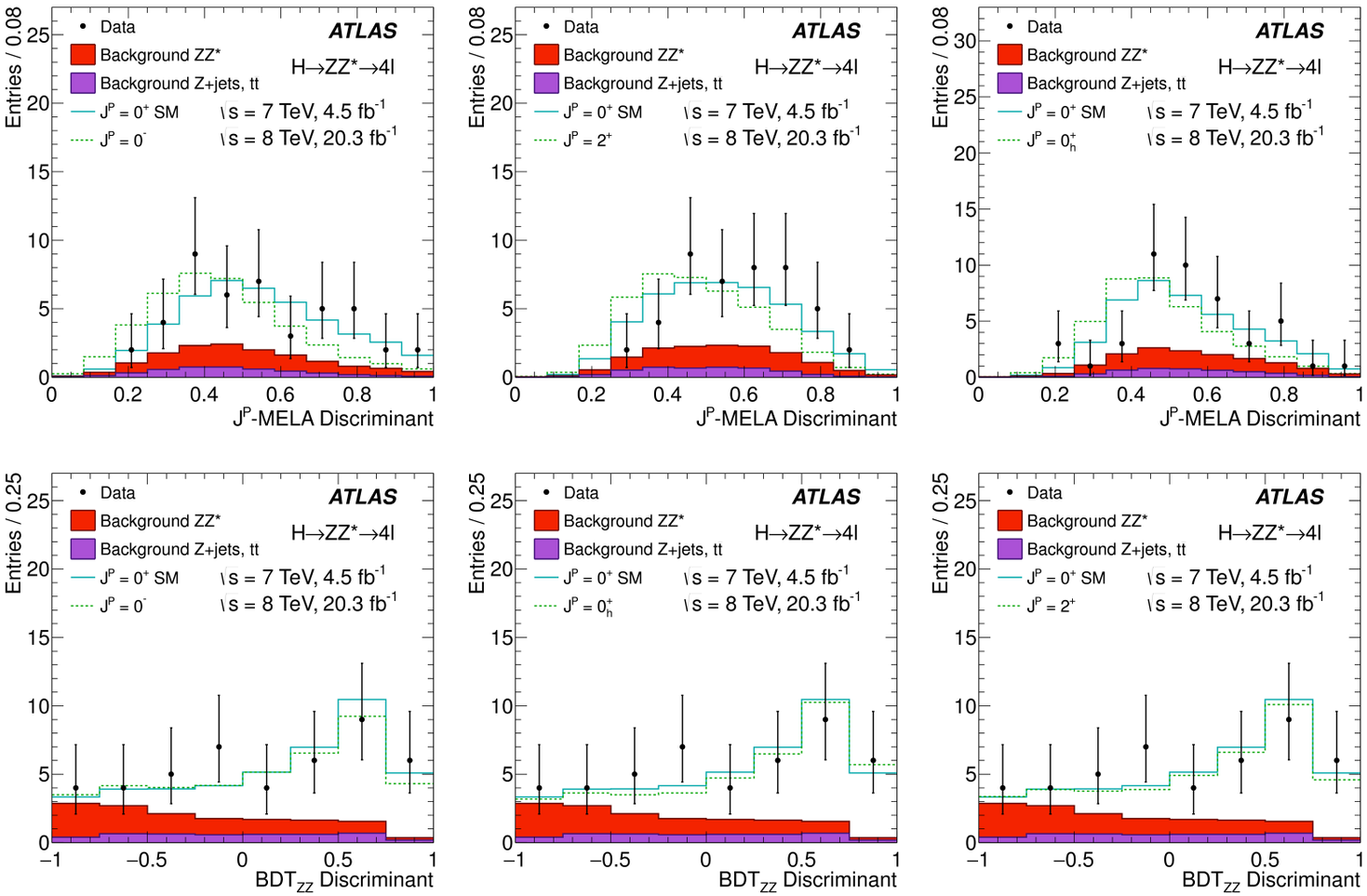
Coupling ratio	Best-fit value	95% CL Exclusion Regions	
$H \to WW^* \to e\nu\mu\nu$	Observed	Expected	Observed
$\tilde{\kappa}_{HVV}/\kappa_{\mathrm{SM}}$	-1.3	$[-1.2, -0.7]$	$(-\infty, -2.2] \bigcup [-1, -0.85] \bigcup [0.4, \infty)$
$(\tilde{\kappa}_{AVV}/\kappa_{\mathrm{SM}}) \cdot \tan\alpha$	-0.2	n.a.	$(-\infty, -6] \bigcup [5, \infty)$

$H \to ZZ^* \to 4l$

- Background discriminant from production related observables:
  η_{4l}, $p_{T,4l}$, m_{4l}, $\cos(\theta^*)$ and Φ_1

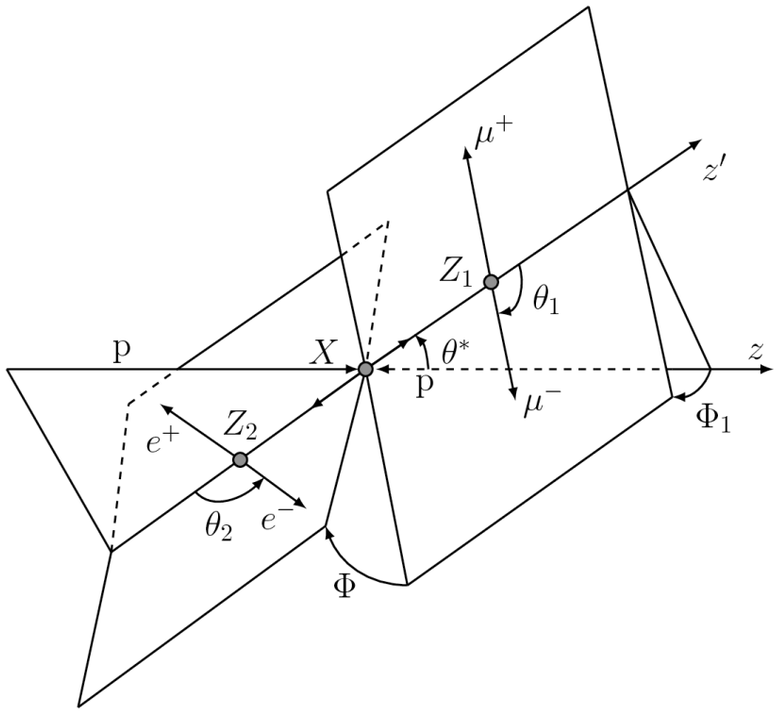
$$J^P - MELA = \frac{P(H_1)}{P(H_1) + P(H_2)}$$

Hypothesis tests Discriminants



	SM Signal	ZZ^*	$t\bar{t}, Z+\text{jets}$	Observed
		$\sqrt{s} = 7$ TeV		
4μ	1.02±0.10	0.65±0.03	0.14±0.06	3
$2\mu 2e$	0.47±0.05	0.29±0.02	0.53±0.12	1
$2e2\mu$	0.64±0.06	0.45±0.02	0.13±0.05	2
$4e$	0.45±0.04	0.26±0.02	0.59±0.12	2
Total	2.58±0.25	1.65±0.09	1.39±0.26	8
		$\sqrt{s} = 8$ TeV		
4μ	5.81±0.58	3.36±0.17	0.97±0.18	13
$2\mu 2e$	3.00±0.30	1.59±0.10	0.52±0.12	8
$2e2\mu$	3.72±0.37	2.33±0.11	0.84±0.14	9
$4e$	2.91±0.29	1.44±0.09	0.52±0.11	7
Total	15.4 ±1.5	8.72±0.47	2.85±0.39	37

Normalisations



$H \to ZZ^* \to 4l$

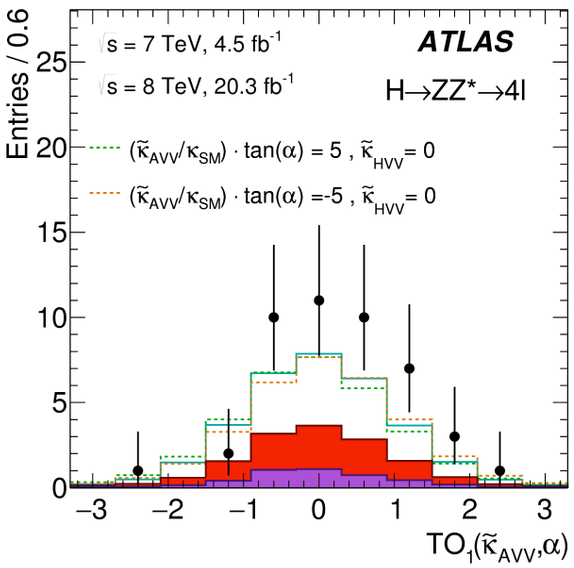
- Background discriminant from production related observables:
  η_{4l}, $p_{T,4l}$, m_{4l}, $\cos(\theta^*)$ and Φ_1

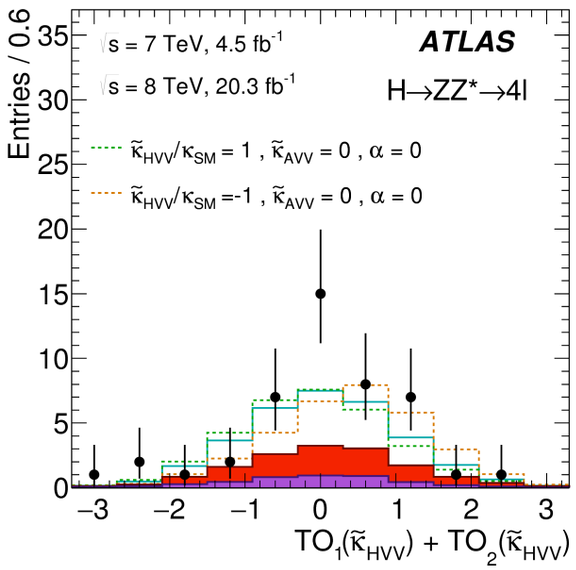
$$O_1(\kappa_{HVV}) = \frac{2\Re[\mathrm{ME}(\kappa_{SM}\neq 0;\, \kappa_{HVV},\kappa_{AVV}=0;\, \alpha=0)^* \cdot \mathrm{ME}(\kappa_{HVV}\neq 0;\, \kappa_{SM},\kappa_{AVV}=0;\, \alpha=0)]}{|\mathrm{ME}(\kappa_{SM}\neq 0;\, \kappa_{HVV},\kappa_{AVV}=0;\, \alpha=0)|^2},$$

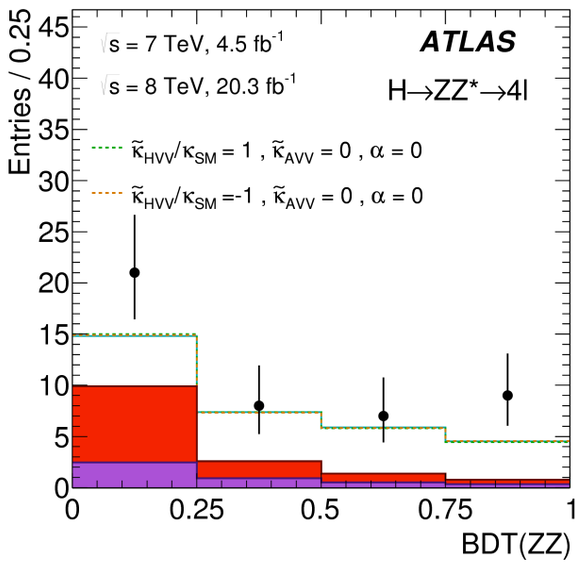
$$O_2(\kappa_{HVV}) = \frac{|\mathrm{ME}(\kappa_{HVV}\neq 0;\, \kappa_{SM},\kappa_{AVV}=0;\, \alpha=0)|^2}{|\mathrm{ME}(\kappa_{SM}\neq 0;\, \kappa_{HVV},\kappa_{AVV}=0;\, \alpha=0)|^2},$$

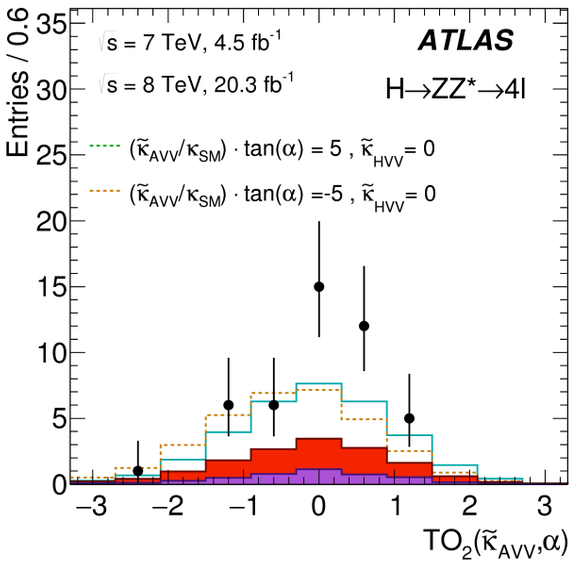
$$O_1(\kappa_{AVV},\alpha) = \frac{2\Re[\mathrm{ME}(\kappa_{SM}\neq 0;\, \kappa_{HVV},\kappa_{AVV}=0;\, \alpha=0)^* \cdot \mathrm{ME}(\kappa_{AVV}\neq 0;\, \kappa_{SM},\kappa_{HVV}=0;\, \alpha=\pi/2)]}{|\mathrm{ME}(\kappa_{SM}\neq 0;\, \kappa_{HVV},\kappa_{AVV}=0;\, \alpha=0)|^2},$$

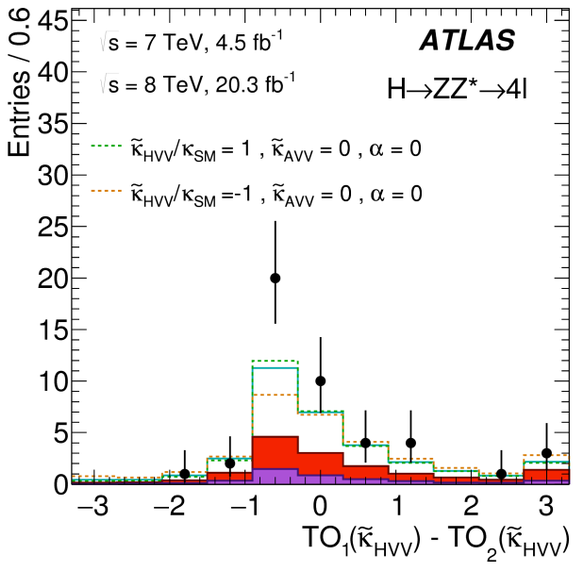
$$O_2(\kappa_{AVV},\alpha) = \frac{|\mathrm{ME}(\kappa_{AVV}\neq 0;\, \kappa_{SM},\kappa_{HVV}=0;\, \alpha=\pi/2)|^2}{|\mathrm{ME}(\kappa_{SM}\neq 0;\, \kappa_{HVV},\kappa_{AVV}=0;\, \alpha=0)|^2}.$$

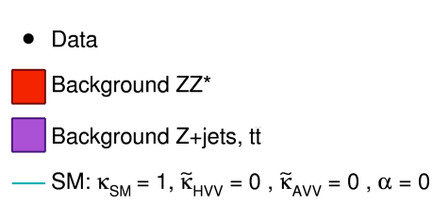








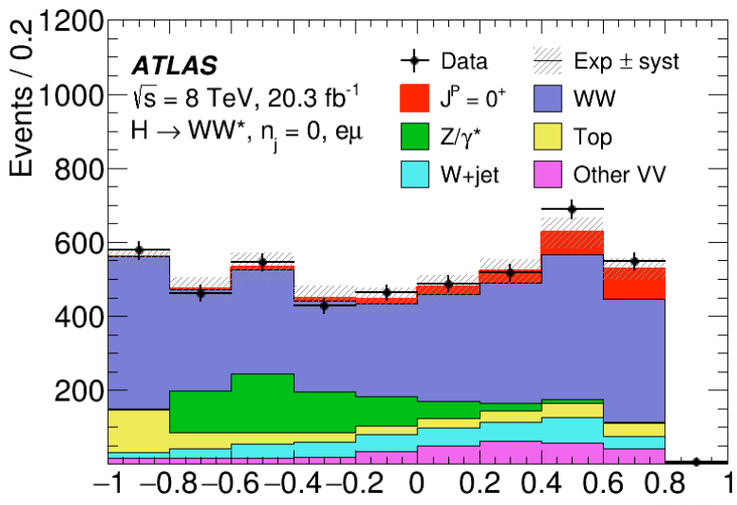


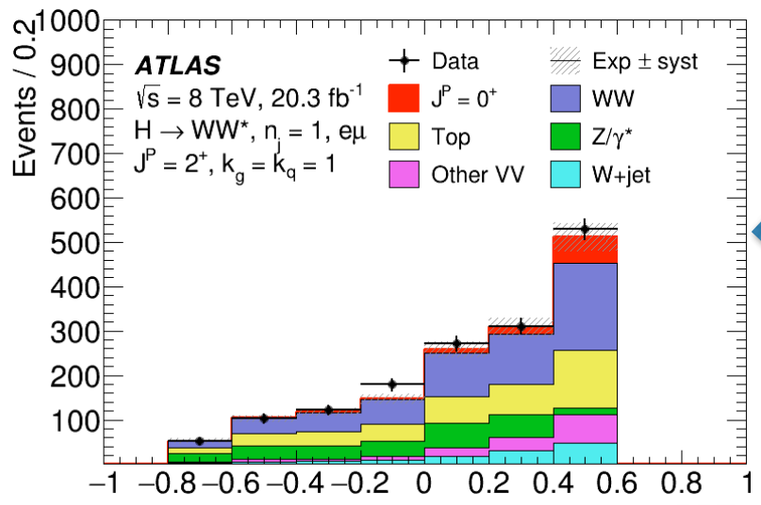


Tensor structure fit discriminants

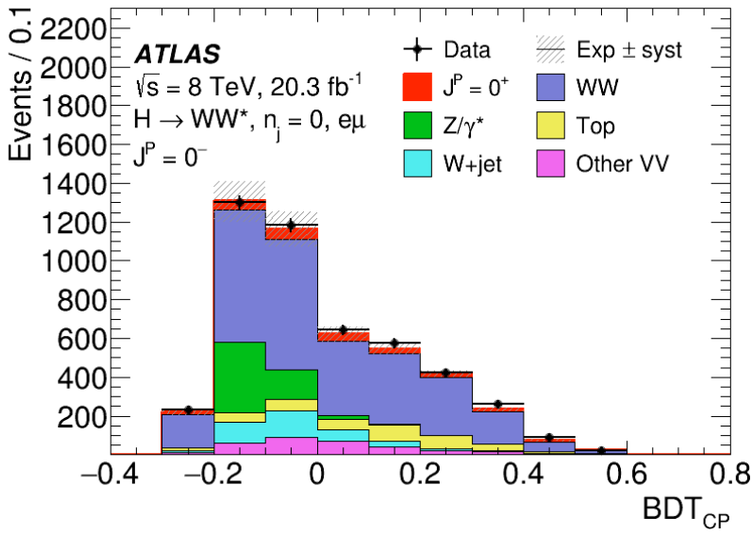
$H \rightarrow WW^* \rightarrow 4l$

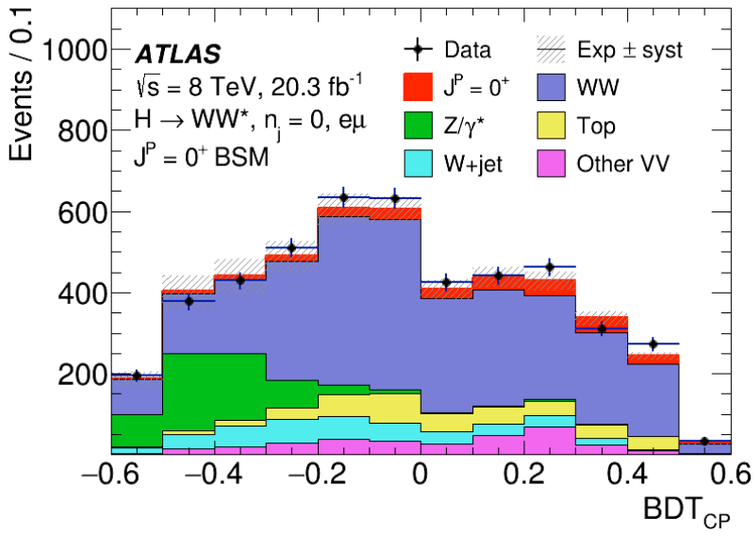
- Spin-2 tests training parameters: pTll, mll, ΔΦll, mT
- SM vs 0+h Training parameters: pTll, mll, ΔΦll, pmiss
- SM vs 0- Training parameters: mll, pTl1 -0.5pTl2 + 0.5pTmiss, ΔpT, ΔΦll





Spin-2, UC

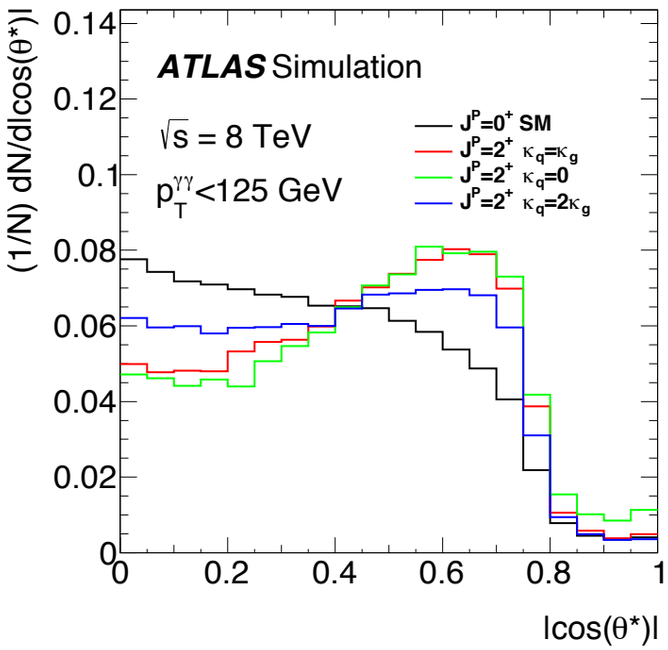


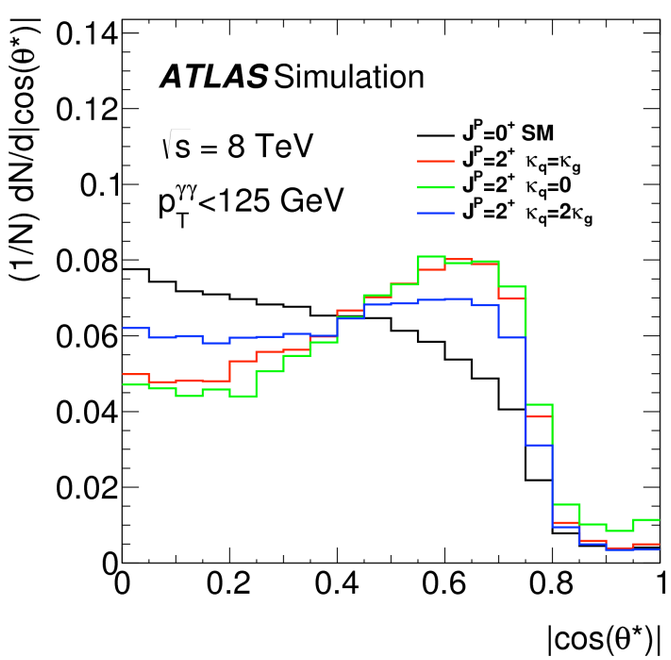


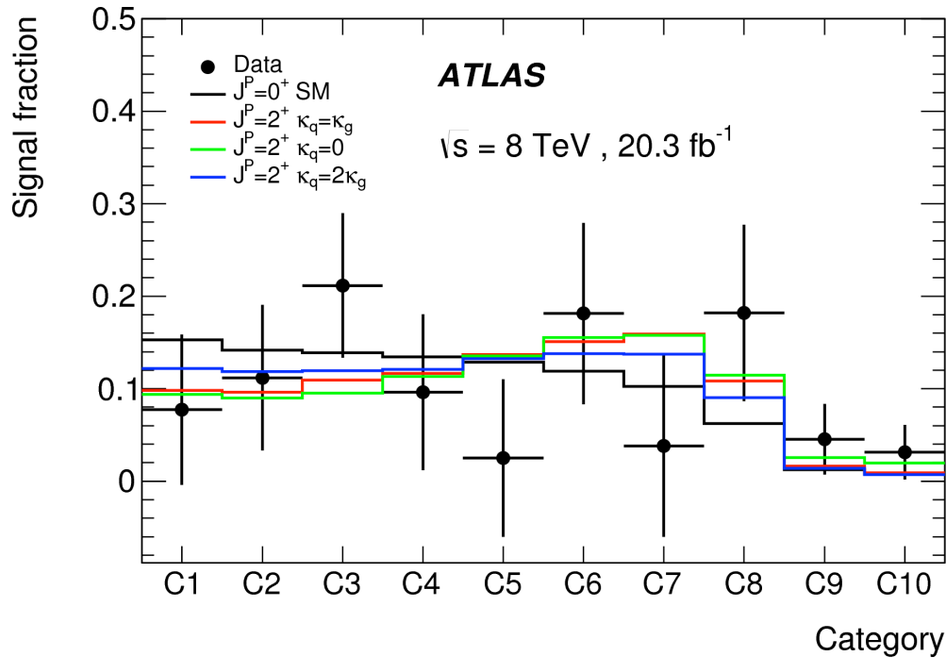
Spin-0

	N_{ggF}	N_{WW}	$N_{t\bar{t}}$	N_t	$N_{\mathrm{DY},\tau\tau}$	$N_{W+\mathrm{jets}}$	N_{VV}	$N_{\mathrm{DY,SF}}$	N_{bkg}	Data	Data/N_{bkg}
0j SR	218	2796	235	135	515	366	311	32	4390	4730	1.08 ± 0.02
1j SR:	77	555	267	103	228	123	131	5.8	1413	1569	1.11 ± 0.03
1j SR: $p_{\mathrm{T}}^{\mathrm{H}} < 300$ GeV	77	553	267	103	228	123	131	5.8	1411	1567	1.11 ± 0.03
1j SR: $p_{\mathrm{T}}^{\mathrm{H}} < 125$ GeV	76	530	259	101	224	121	128	5.8	1367	1511	1.11 ± 0.03

H→γγ







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

$\Delta\eta^{\gamma\gamma}$: Separation in pseudorapidity between the two photons

- Category normalisation from fitting function:

$$f^{[c]}(m_{\gamma\gamma}|J) = \frac{n_B^{[c]} f_B^{[c]}(m_{\gamma\gamma}) + (n_J^{[c]} + n_{\text{bias}}^{[c]}) f_S^{[c]}(m_{\gamma\gamma})}{n_B^{[c]} + n_J^{[c]} + n_{\text{bias}}^{[c]}}$$

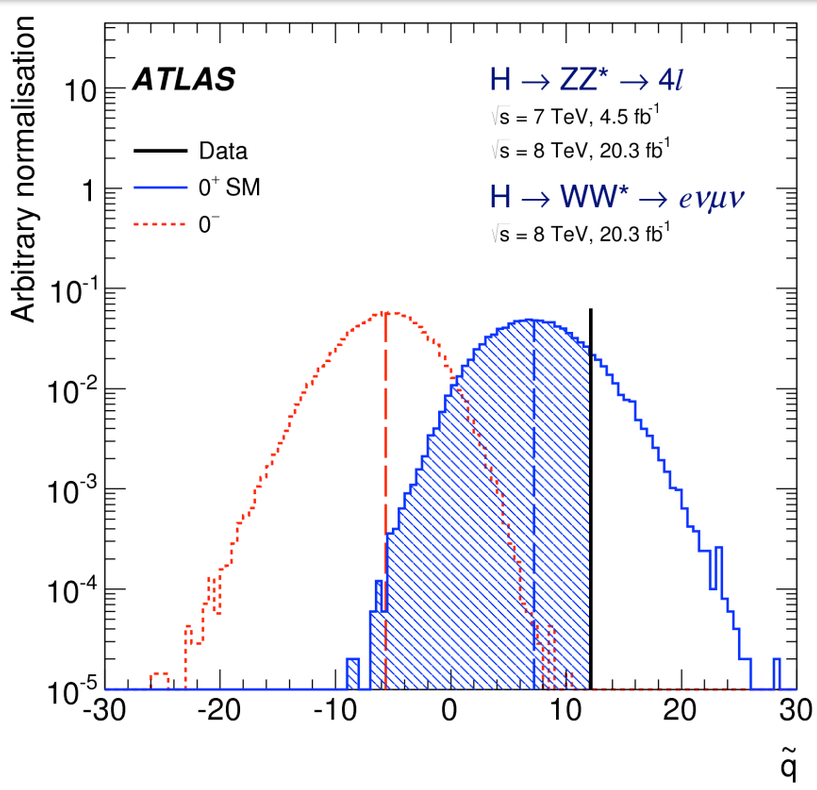
- $f_S^{[c]}(m_{\gamma\gamma})$: Chrystal Ball + Gaussian

- $f_B^{[c]}(m_{\gamma\gamma})$: Exponential of first or second degree polynomial

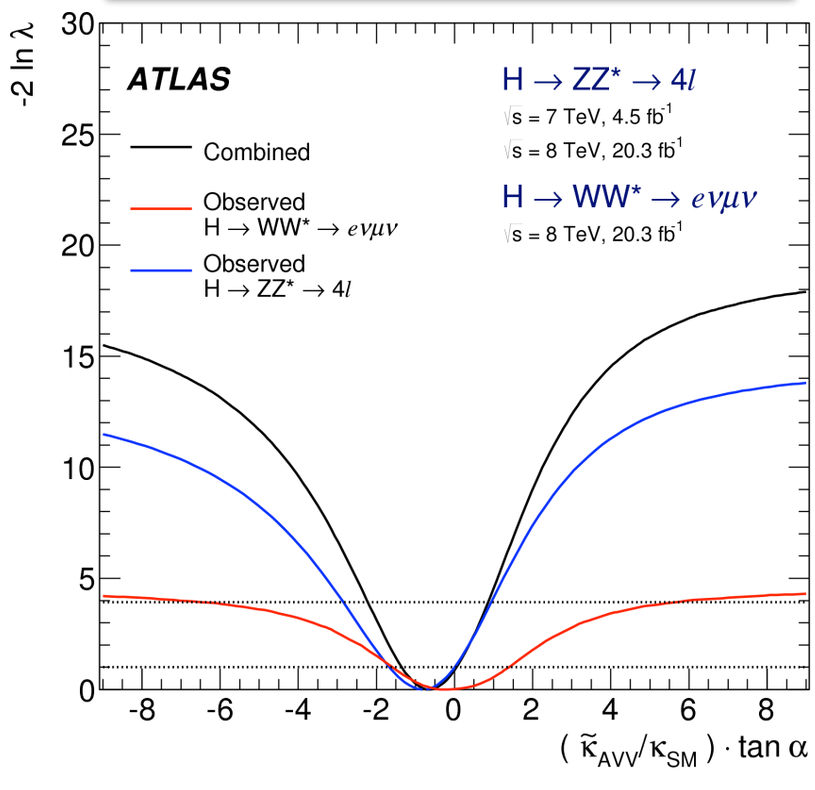
Combination

- Construct combined likelihood model including all final states
- Common systematic uncertainties are identified and correlated between final states
  - WW*, ZZ*: Luminosity, VV background renormalisation+factorisation scale and parton density function
  - ZZ*, γγ: E-Cal resolution model

Ratio of SM/BSM likelihoods exclude pure spin-0 and spin-2 models



Profiled likelihood scan limits coupling ratios



Coupling ratios to effective cross section fraction

$$f_{gi} = \frac{|g_i|^2\sigma_i}{|g_1|^2\sigma_1 + |g_2|^2\sigma_2 + |g_4|^2\sigma_4}, \ \phi_i = \arg\left(\frac{g_i}{g_1}\right).$$

$$f_{g_i} = \frac{r_{i1}^2}{1 + r_{i1}^2}; \quad (i = 2, 4),$$

Assuming one BSM coupling

$$r_{21}^2 = \frac{\sigma_{HVV}}{\sigma_{\rm SM}}\left(\frac{\tilde{k}_{HVV}}{k_{\rm SM}}\right)^2, \ \text{and} \ r_{41}^2 = \frac{\sigma_{AVV}}{\sigma_{\rm SM}}\left(\frac{\tilde{k}_{AVV}}{k_{\rm SM}}\right)^2 \tan^2\alpha.$$

Cross section fractions from MadGraph5_aMC@NLO

$$\sigma_{AVV}/\sigma_{\rm SM} = 0.143 \qquad \sigma_{HVV}/\sigma_{\rm SM} = 0.349$$

References

- Study of the spin and parity of the Higgs boson in diboson decays with the ATLAS detector
  http://arxiv.org/abs/1506.05669

- Determination of spin and parity of the Higgs boson in the WW* →evμv decay channel with the ATLAS detector
  http://dx.doi.org/10.1140/epjc/s10052-015-3436-3

- A framework for Higgs characterisation
  http://link.springer.com/article/10.1007%2FJHEP11%282013%29043