Spin, Anomalous Couplings, CP structure

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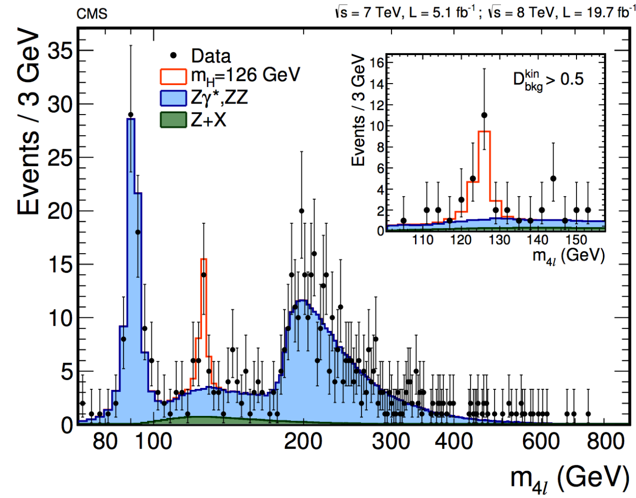
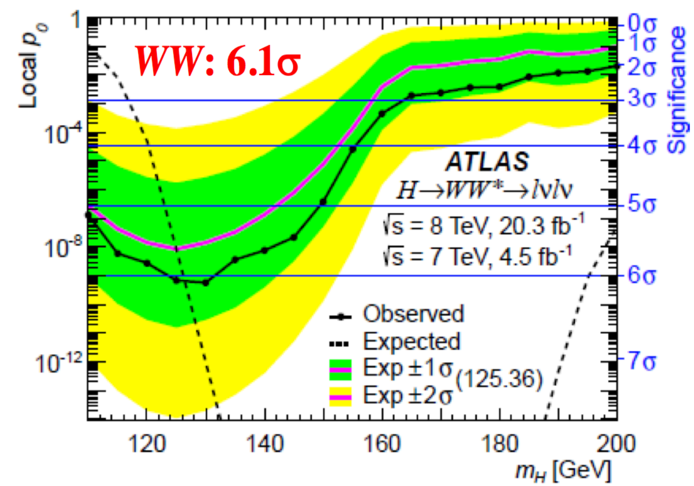
Introduction

- In 2012 we discovered the Higgs boson
- But is it really **"The"** Higgs boson?
  - It is a neutral particle with a known mass that decays as the SM Higgs would
- Study fundamental properties

  → **Spin, anomalous couplings and CP structure**
- ATLAS and CMS have extended studies of the spin-parity properties of the Higgs boson:
  - full LHC Run-1 dataset, 7 and 8 TeV
  - **H→ZZ, H→WW, H → γγ** decay channels





ATLAS-CONF-2015-008
18 March 2015
arXiv:1503.03643
12 March 2015

arXiv:1411.3441
13 Nov 2014

Two kind of analyses

- **Straightforward:** Test of **different BSM spin and CP hypotheses**
  → Exotic spin-1 or spin-2, BSM 0^- 0^+_h
- **More complicated:** study of the tensor structure of the HVV interactions setting **limits on anomalous couplings** under spin-0 assumption

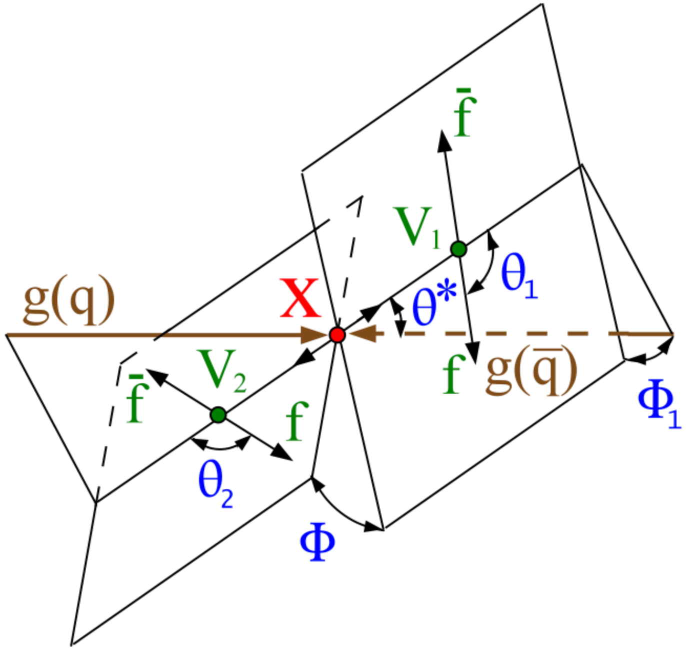
- ATLAS and CMS perform:
  - **Hypothesis testing** → Different J^{CP} models are compared with the SM versus the data and ruled out individually
  - **Parameter estimation** → where different parameters related to anomalous couplings are measured
- Rely on simulation of the alternative hypotheses, done with:
  - **MadGraph5_aMC@NLO, POWHEG+JHUGen (ATLAS)**
  - **POWHEG+JHUGen (CMS)**

Kinematic variables

- The analysis is done via the study of the **kinematic distributions of the decay products**
  - Determined by the tensor structure of the HVV interactions
  - The number of kinematic variables available depends on the Higgs decay → determines the strategy followed in each channel

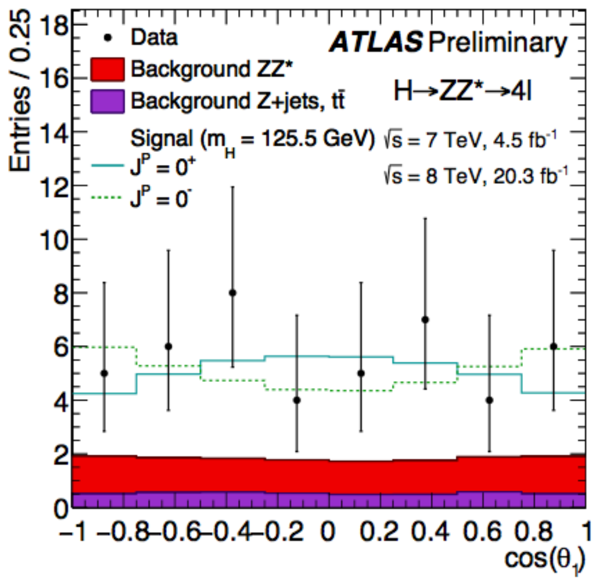
Production:
gg/qq/any
Decay:
$ZZ/Z\gamma^{*}/\gamma^{*}\gamma^{*} \rightarrow 4l$, $WW \rightarrow 2l2\nu$, and $\gamma\gamma$

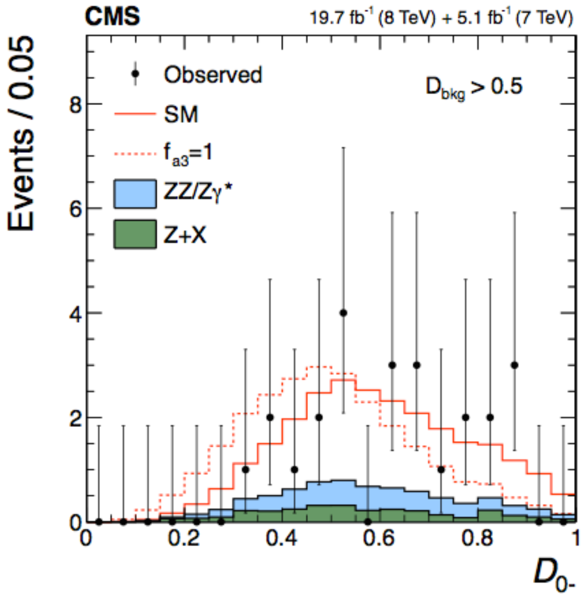
Two production angles:
θ^{*} and Φ_1 in the X rest frame
Three decay angles:
θ_1, θ_2, and Φ in the V rest frames



H→ZZ→4l

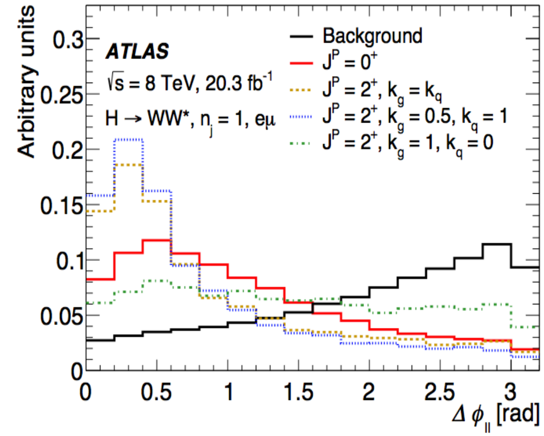
- **The complete final state can be reconstructed** → **Full kinematic information accessible** → Best sensitivity
- 8 kinematic variables: 5 angles : $\theta^*, \theta_1, \theta_2, \Phi, \Phi_1$; 3 masses: m_{Z1}, m_{Z2}, m_{4l}



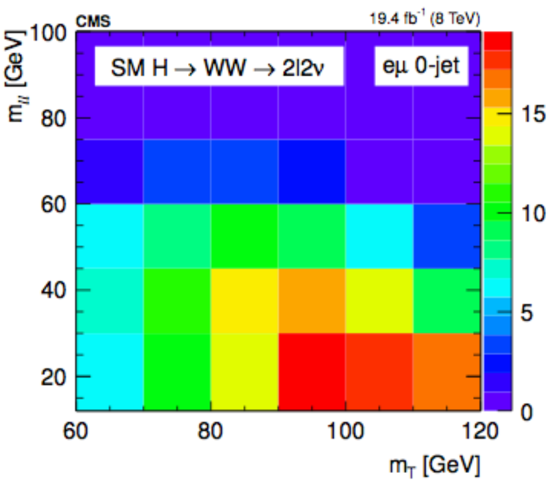


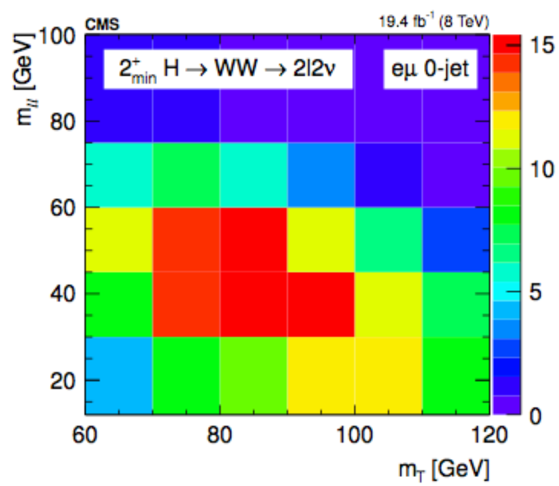
- The information is condensed in a set of discriminants based on:
  - **Matrix Element** calculations, such as the Matrix Element Likelihood Approach (MELA) or **BDT** discriminants trained with simulation

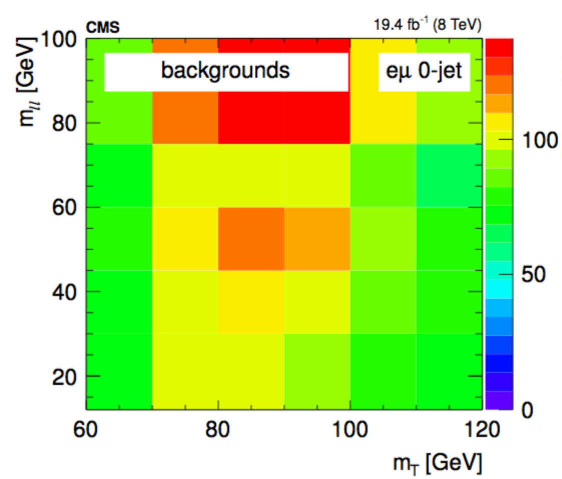
H→WW→2l2ν



- Two lepton final state (eμ), two neutrinos
  → **full final state cannot be reconstructed**
- Rely on limited set kinematics
  - **m_{ll}, m_T** (CMS) - **m_{ll} , $\Delta\phi_{ll}$, p_T^{ll}, m_T** (ATLAS)
- The analysis is performed using
  - **2D templates** (legacy SM analysis) (CMS)
  - **BDT** trained using input variables (different BDTs for SM signal/ background, BSM signal/background, SM signal/BSM signal) (ATLAS)



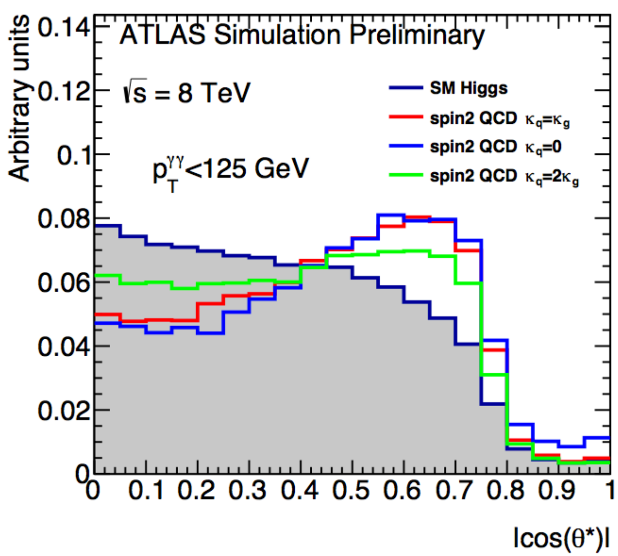


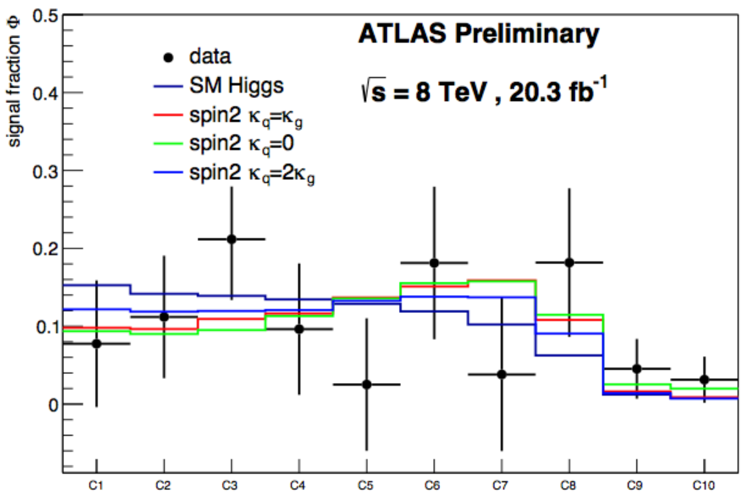


H→γγ

- Only a single kinematic variable encodes the spin information
  - **cosθ* :** cosine of scattering angle in the Collins-Soper frame
- Both ATLAS and CMS use the same variable and follow their respective legacy H→γγ analyses

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





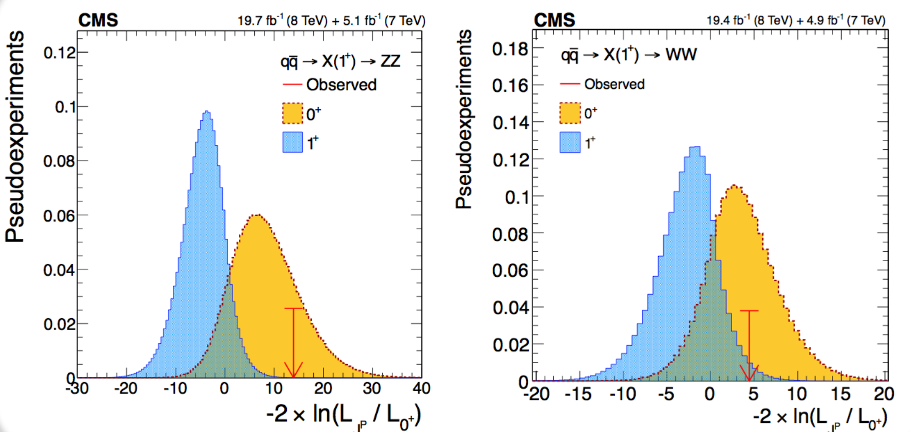
Spin studies

- The main sensitivity comes from **H→ZZ→4l** channel
  - H→WW and H→γγ also used and combined

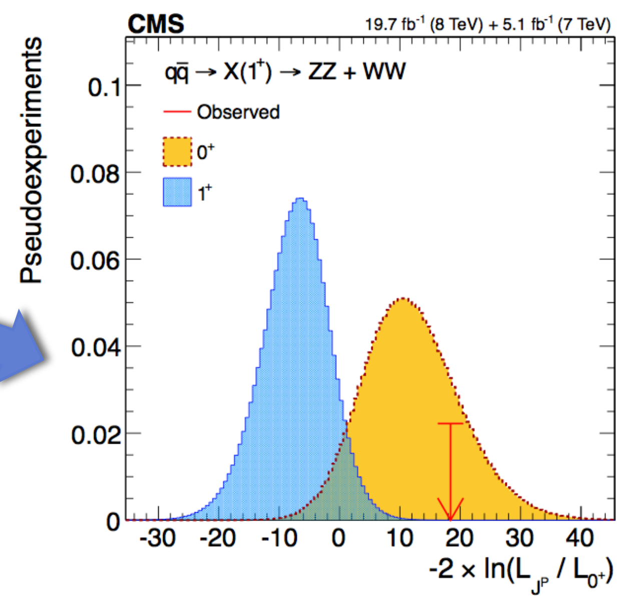
- Hypothesis testing of SM against:
  - All mixtures of spin-1 states
    - 1^+, 1^- and mixed, qq produced
  - Several individual spin-2 models
    - Comprehensive set of benchmark states
    - qq, gg produced
  - Spin-0
    - Pure pseudoscalar 0^- and pure scalar with higher order corrections 0^+_h
- Test statistic used to quantify the consistency of the two models with data

Spin-1

- J=1 not allowed for X→$\gamma\gamma$ by the Landau-Yang theorem
- Spin-1 models tested anyway experimentally
  - under the hypothesis that the excess in WW and ZZ is not the same resonance as $\gamma\gamma$

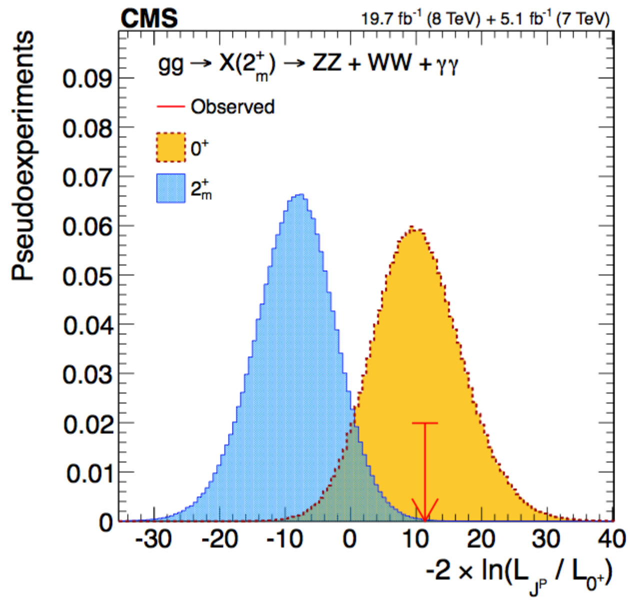


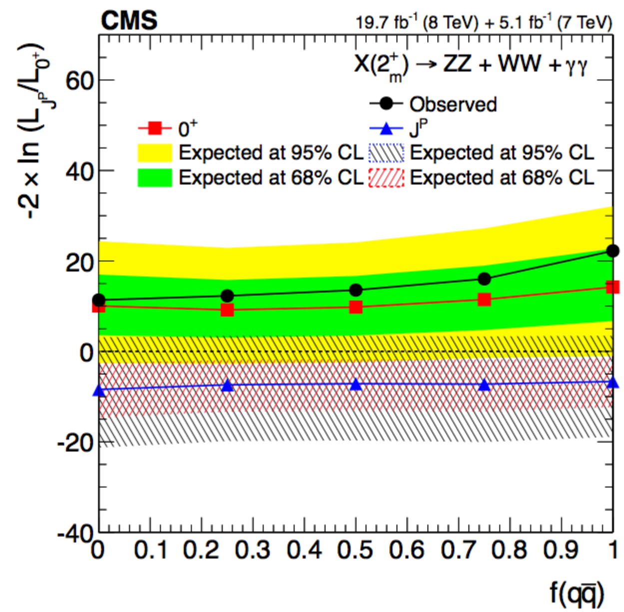
pseudovector 1^+



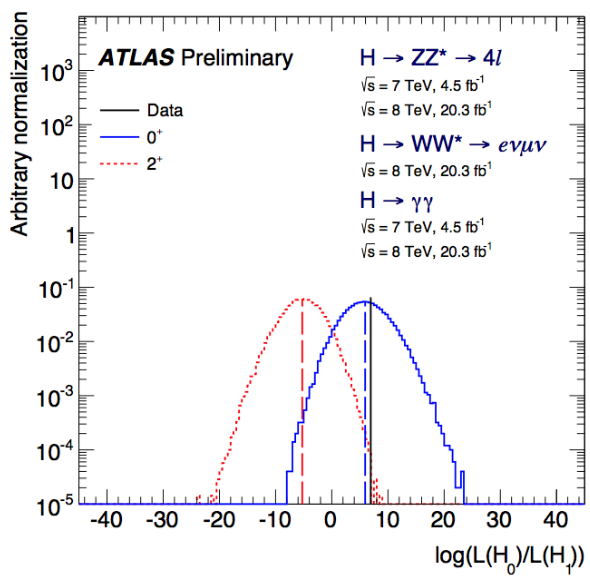
Spin-2

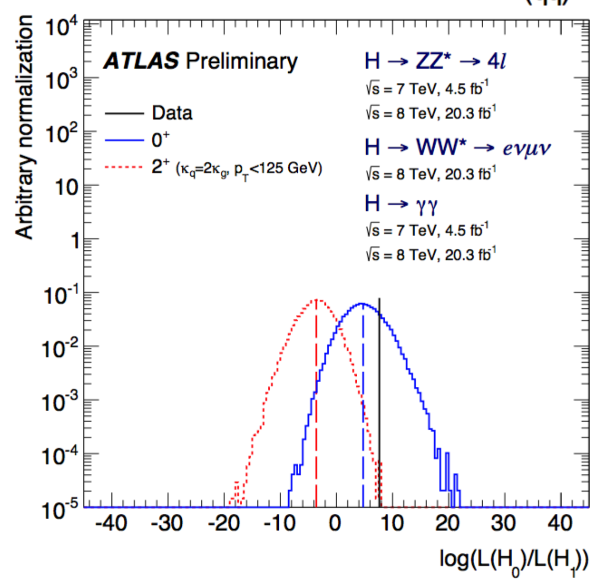
X→ZZ+WW+γγ combination for 2^+_m model: graviton-like with minimal couplings



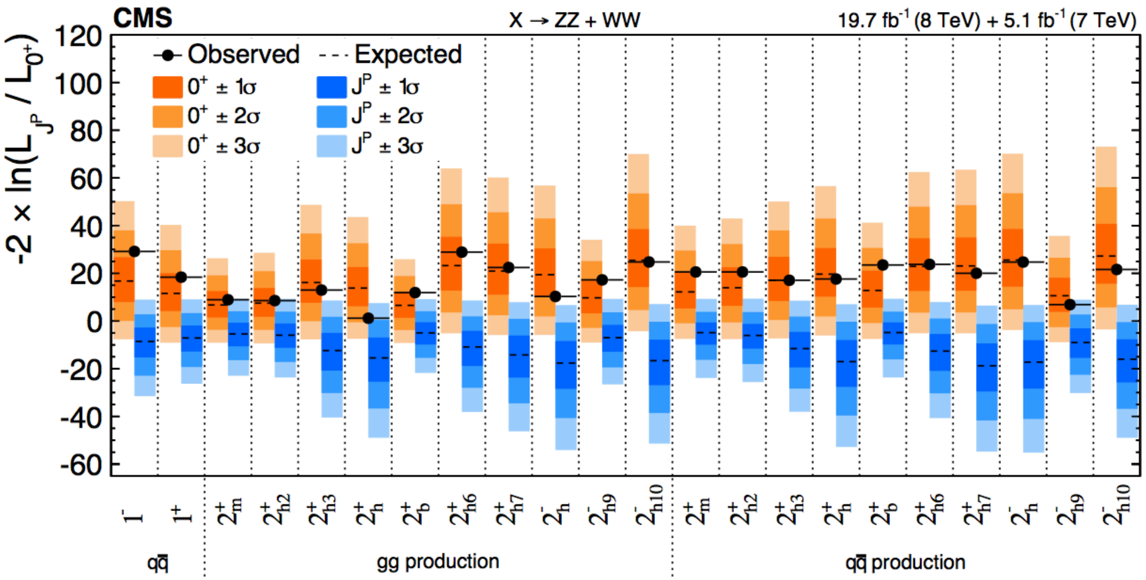


X→ZZ+WW+γγ combination for 2^+ model for universal and non-universal couplings





Exotic Spin Results



J^P Model	J^P Prod.	Expected $X \to ZZ$	Expected $X \to WW$	Expected $X \to \gamma\gamma$	Expected (μ=1)	Obs. 0^+	Obs. J^P	CL_s
2^+_m	gg	1.9σ	1.8σ	$1.6\ \sigma$	3.0σ (3.7σ)	-0.2σ	$+3.3\sigma$	0.13%
2^+_m	$q\bar{q}$	1.7σ	2.7σ	$1.2\ \sigma$	3.3σ (4.4σ)	-0.9σ	$+4.7\sigma$	0.001%

All spin-1 hypotheses excluded at > 99.999% CL , Spin-2 boson 2^+_m, excluded at a 99.87% CL, other spin-2 hypotheses excluded at a ≥99% CL

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

All considered non-SM spin hypotheses excluded at > 99% CL in favor of the SM

Anomalous Couplings

- **Both ATLAS and CMS exclude all the exotic spin 1 and 2 hypotheses tested at 99%CL or higher**
- **The new boson has spin 0**
  - Pure pseudoscalar hypothesis, 0^-, ruled out
  - It appears to be compatible with the $\mathbf{J^{CP}=0^{++}}$ SM state
- It still could be a mixture of CP states → the couplings to gauge bosons could have small **anomalous components**
  - We need **to study the tensor structure of the HVV interaction**
- Hypothesis testing is not sufficient → **parameter measurement**
  - ATLAS and CMS follow similar routes while measuring slightly different parameters

Spin-0: CMS

- The decay amplitude for a spin-0 boson to a pair of V bosons can be described as:

$$A(\mathrm{HV_1V_2}) \sim \left[a_1^{\mathrm{V_1V_2}} + \underbrace{\frac{\kappa_1^{\mathrm{V_1V_2}} q_{\mathrm{V1}}^2 + \kappa_2^{\mathrm{V_1V_2}} q_{\mathrm{V2}}^2}{\left(\Lambda_1^{\mathrm{V_1V_2}}\right)^2}}_{\substack{\Lambda_1 \text{ term} \\ \text{leading momentum expansion}}} \right] m_{\mathrm{V}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^* + \underbrace{a_2^{\mathrm{V_1V_2}} f_{\mu\nu}^{*(\mathrm{V_1})} f^{*(\mathrm{V_2}),\mu\nu}}_{\substack{a_2 \text{ term} \\ \text{CP even state}}} + \underbrace{a_3^{\mathrm{V_1V_2}} f_{\mu\nu}^{*(\mathrm{V_1})} \tilde{f}^{*(\mathrm{V_2}),\mu\nu}}_{\substack{a_3 \text{ term} \\ \text{CP odd state}}}$$

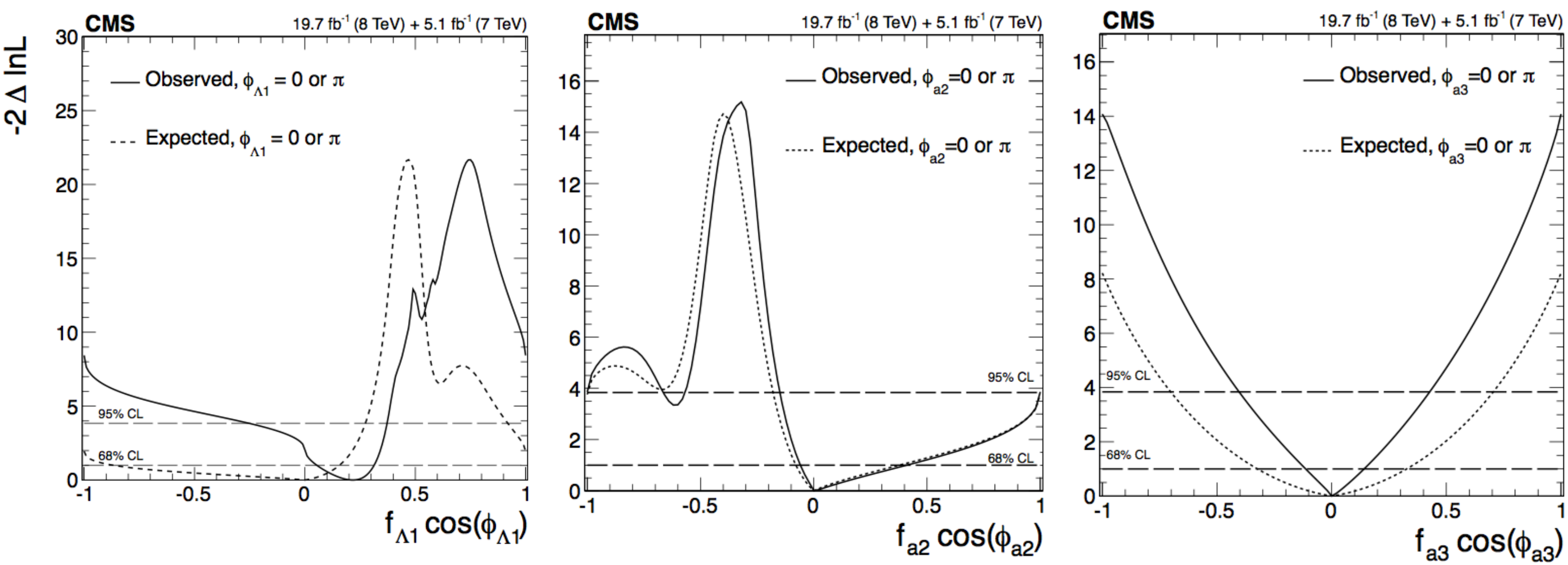
- We choose a parameterization that relates cross sections fractions (**f_{a2}**, **f_{a3}**, **$f_{\Lambda 1}$**) to a_2, a_3, and **Λ_1**

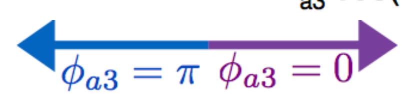
$$f_{a3} = \frac{|a_3|^2\sigma_3}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda 1}/\left(\Lambda_1\right)^4 + \dots}, \qquad \phi_{a3} = \arg\left(\frac{a_3}{a_1}\right)$$

- σ_i in each case corresponds to $a_i = 1$ and $a_{j\neq I} = 0$
- **$f_{a1} = 1 - f_{a2} - f_{a3} - f_{\Lambda 1} - \dots$** is the SM contribution → expected to dominate
- For a **measured value of f_x** → possible to extract the ratio a_i/a_1

Likelihood scans of f_x

- **Likelihood scans for the three effective fractions** for $H \to ZZ \to 4l$ (most sensitive channel) in the most representative scenario
  - Couplings constrained to be real, other couplings fixed to the SM





Full set of scans available, e.g. allowing complex phases. fitting more than one parameter at a time …
→ all consistent with the SM

cosϕ term allows for a signed quantity
cosϕ= −1 (π) or +1 (0)

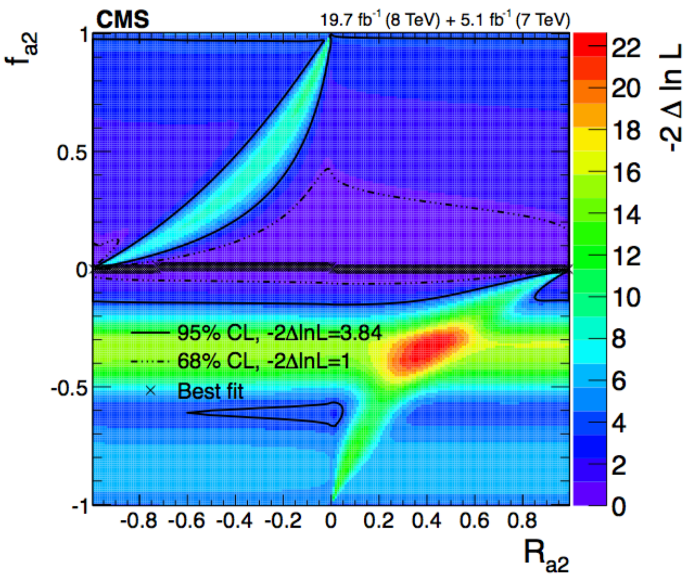
H→ZZ and H→WW combination

- General relationship between HWW and HZZ couplings

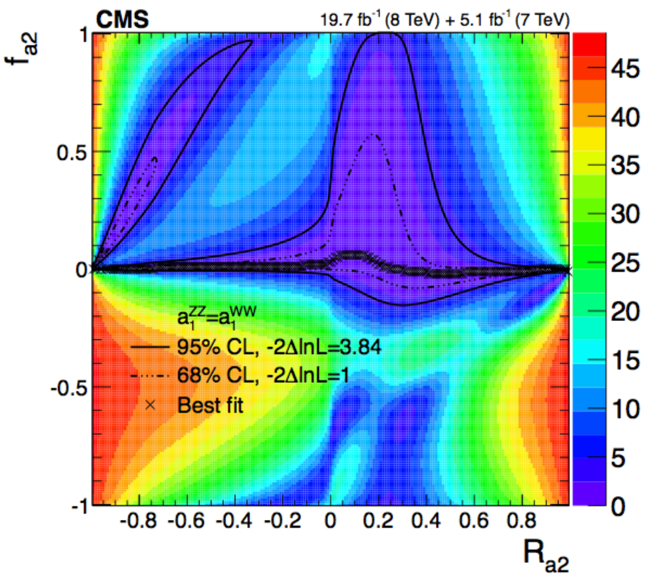
$$r_{ai} = \frac{a_i^{WW}/a_1^{WW}}{a_i/a_1} \quad r_{ai}\ [-\infty, +\infty] \longrightarrow R_{ai} = \frac{r_{ai}|r_{ai}|}{1+r_{ai}^2} \quad R_{ai}\ [-1,+1]$$

- f_{ai} can then be written as a function of f_{ai}^{WW} via R_{ai}
- Two scenarios for combination: arbitrary relationship between a_1 for W and Z or custodial symmetry

$a_1^{WW} \neq a_1^{ZZ}$

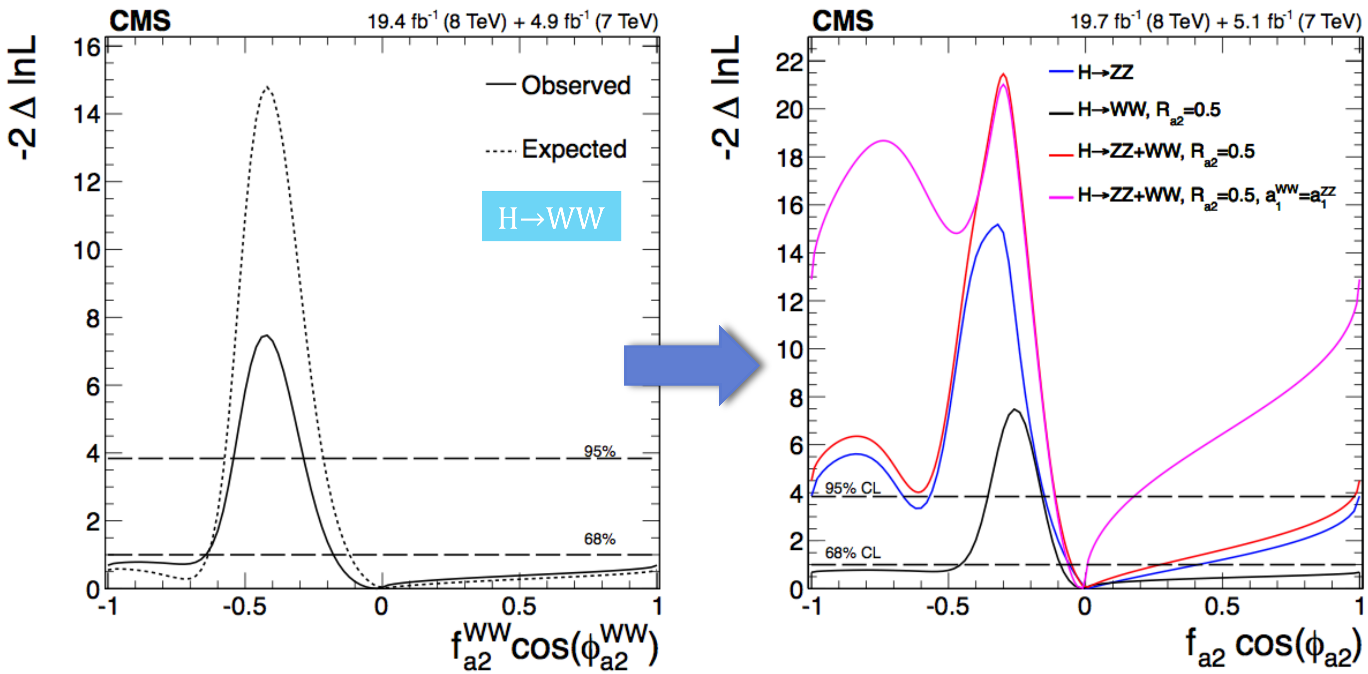


$a_1^{WW} = a_1^{ZZ}$



H→WW and H→ZZ combination

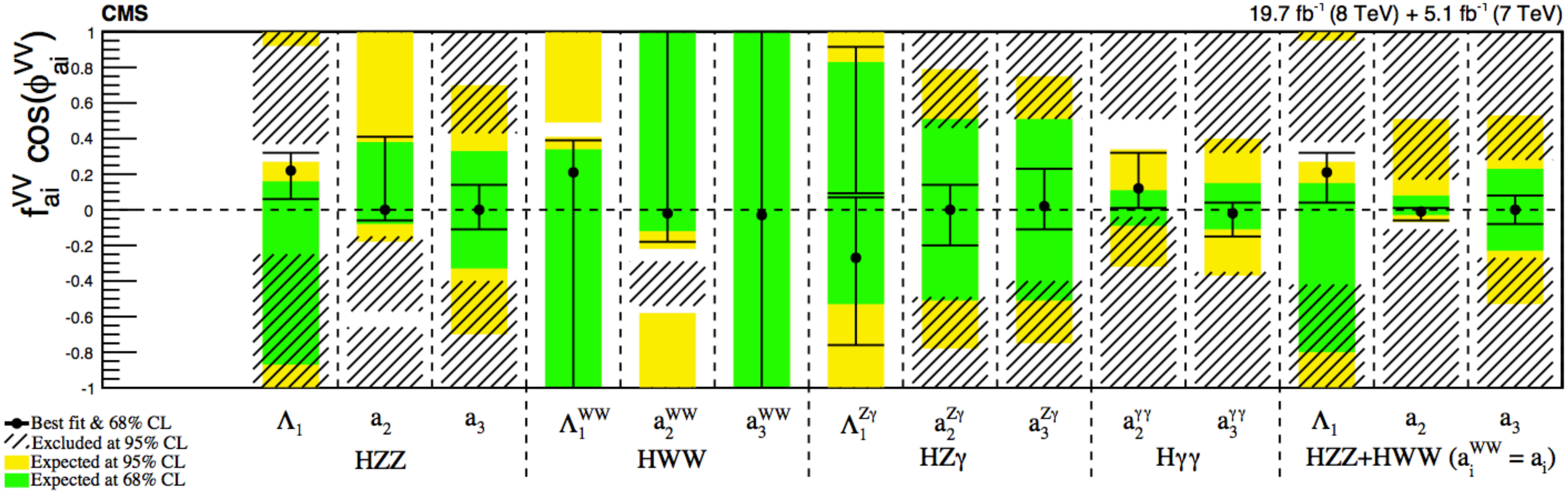
- We pick R_{a2}=0.5 (r_{a2}=1) for illustration purposes



- Not assuming custodial symmetry the combination is close to the sum of the two individual curves
- In the custodial symmetry scenario a greater exclusion is achieved because the yields are related

Summary of anomalous couplings

- **Allowed confidence level intervals** for anomalous coupling parameters assuming real coupling ratios (π or 0)



Parameter	Observed	Expected
$(\Lambda_1 \sqrt{\lvert a_1 \rvert}) \cos(\phi_{\Lambda_1})$	$[-\infty, -100\,\mathrm{GeV}] \cup [103\,\mathrm{GeV}, \infty]$	$[-\infty, 43\,\mathrm{GeV}] \cup [116\,\mathrm{GeV}, \infty]$
a_2/a_1	$[-0.58, 0.76]$	$[-0.45, 1.67]$
a_3/a_1	$[-1.54, 1.57]$	$[-2.65, 2.65]$

- Assuming custodial symmetry: **pure 0_h^+ (related to f_{a2}) excluded at 99.93% CL and pure 0^- (related to f_{a3}) excluded at 99.99% CL**

Spin-0: ATLAS

- Equivalent approach → **Spin-0 Lagrangian** can be written with a slightly different parametrization as :

$$\mathcal{L}_0^V = \underbrace{\left\{c_\alpha \kappa_{\mathrm{SM}} \left[\tfrac{1}{2} g_{HZZ} Z_\mu Z^\mu + g_{HWW} W_\mu^+ W^{-\mu}\right]\right.}_{\text{SM}} - \frac{1}{4}\frac{1}{\Lambda}\left[\underbrace{c_\alpha \kappa_{HZZ} Z_{\mu\nu} Z^{\mu\nu}}_{\text{BSM CP-even}} + \underbrace{s_\alpha \kappa_{AZZ} Z_{\mu\nu} \tilde{Z}^{\mu\nu}}_{\text{BSM CP-odd}}\right] \left. - \frac{1}{2}\frac{1}{\Lambda}\left[c_\alpha \kappa_{HWW} W_{\mu\nu}^+ W^{-\mu\nu} + s_\alpha \kappa_{AWW} W_{\mu\nu}^+ \tilde{W}^{-\mu\nu}\right]\right\} X_0$$

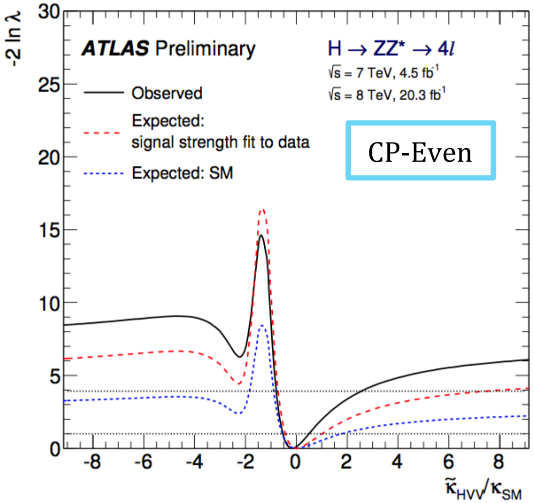
- Here, the **coupling constants** κ_{SM}, κ_{HVV}, κ_{AVV} and the **mixing angle α** determine the J^P status of the Higgs:

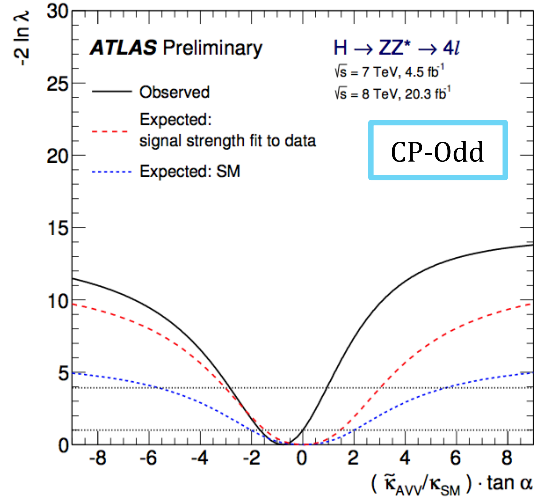
J^P	Model	Choice of tensor couplings			
		κ_{SM}	κ_{HVV}	κ_{AVV}	α
0^+	Standard Model Higgs boson	1	0	0	0
0_h^+	BSM spin-0 CP-even	0	1	0	0
0^-	BSM spin-0 CP-odd	0	0	1	$\pi/2$

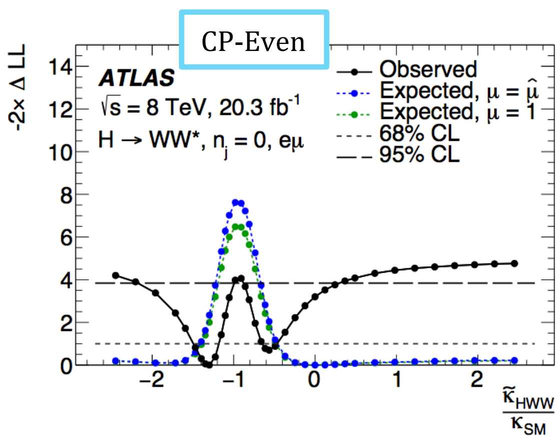
- The measurement is done by fitting **coupling ratios** to the discriminant observables for H → WW and H → ZZ processes and their combination, assuming one BSM coupling at the time

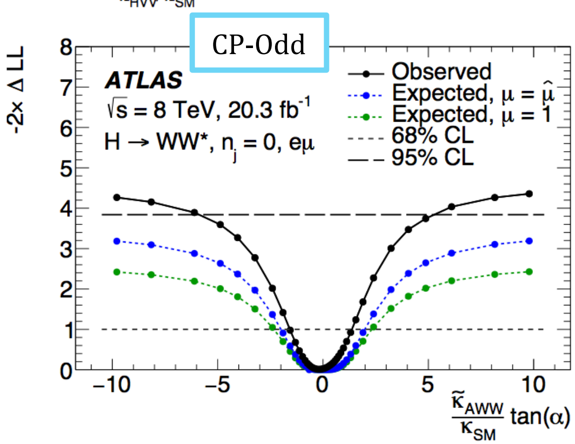
Coupling ratios

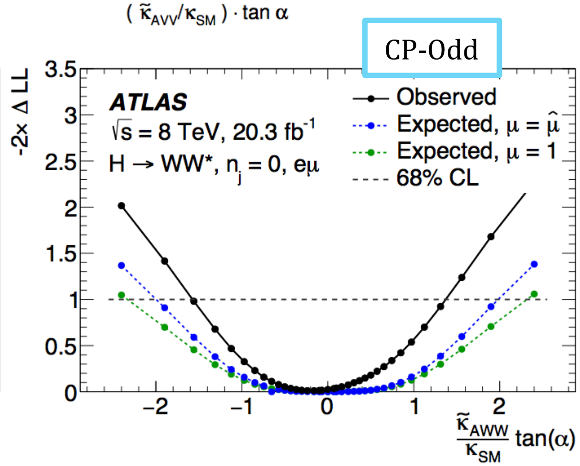
Coupling ratio	Best fit value		95% CL Exclusion Regions	
$H \to ZZ^* \to 4\ell$	Expected	Observed	Expected	Observed
$\tilde{\kappa}_{HVV}/\kappa_{SM}$	0.0	−0.2	$(-\infty, -0.75] \bigcup [6.95, \infty)$	$(-\infty, -0.75] \bigcup [2.45, \infty)$
$(\tilde{\kappa}_{AVV}/\kappa_{SM}) \cdot \tan\alpha$	0.0	−0.8	$(-\infty, -2.95] \bigcup [2.95, \infty)$	$(-\infty, -2.85] \bigcup [0.95, \infty)$





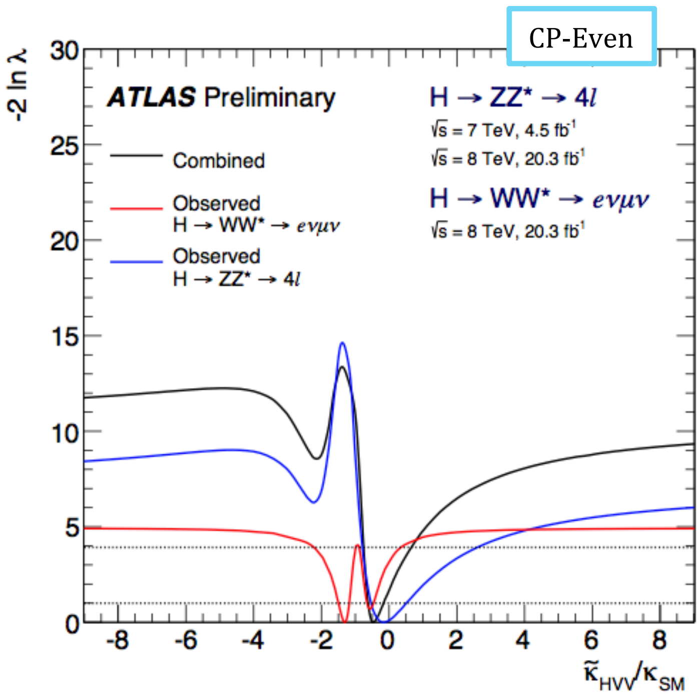


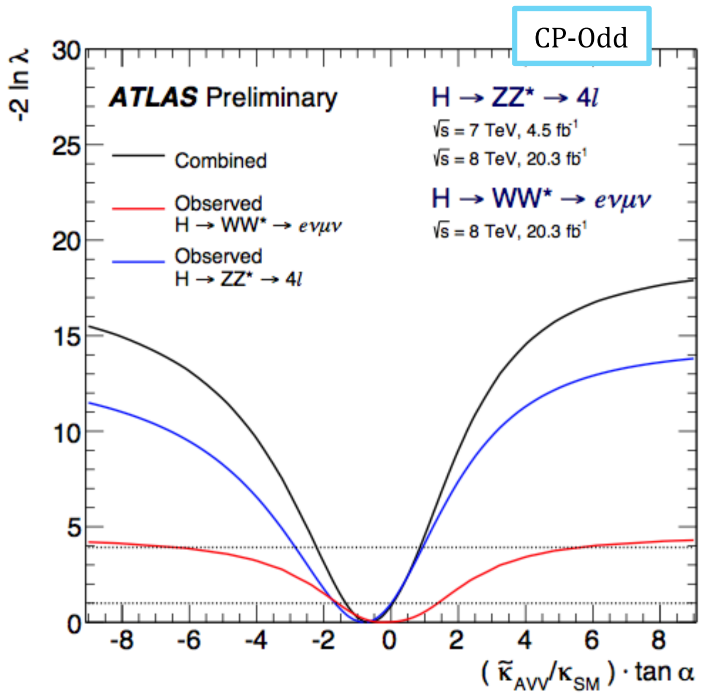




Coupling ratios: Combination

Coupling ratio	Best fit value		95% CL Exclusion Regions	
Combined	Expected	Observed	Expected	Observed
$\tilde{\kappa}_{HVV}/\kappa_{SM}$	0.0	−0.48	$(-\infty,-0.55]\bigcup[4.80,\infty)$	$(-\infty,-0.73]\bigcup[0.63,\infty)$
$(\tilde{\kappa}_{AVV}/\kappa_{SM})\cdot\tan\alpha$	0.0	−0.68	$(-\infty,-2.33]\bigcup[2.30,\infty)$	$(-\infty,-2.18]\bigcup[0.83,\infty)$





Effective cross sections

- ATLAS also provides the results in terms of effective cross section fractions in the same way as CMS, using the equivalent f_{gi} parameters:

$$f_{gi} = \frac{|g_i|^2\sigma_i}{|g_1|^2\sigma_1 + |g_2|^2\sigma_2 + |g_4|^2\sigma_4}, \quad \phi_i = \arg\left(\frac{g_i}{g_1}\right) \qquad f_{g_i} = \frac{r_{i1}^2}{1 + r_{i1}^2}; \quad (i = 2, 4)$$

- **The coupling ratios relate to the effective cross section fractions as**

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

Observed 95% CL limits		
$H \to WW^* \to e\nu\mu\nu$		
$f_{g2} < 0.053$ for $\phi_{g2} = 0$	and	$f_{g2} < 0.20$; $0.26 < f_{g2} < 0.63$ for $\phi_{g2} = \pi$
$f_{g4} < 0.78$ for $\phi_{g4} = 0$	and	$f_{g4} < 0.84$ for $\phi_{g4} = \pi$
$H \to ZZ^* \to 4\ell$		
$f_{g2} < 0.68$ for $\phi_{g2} = 0$	and	$f_{g2} < 0.16$ for $\phi_{g2} = \pi$
$f_{g4} < 0.11$ for $\phi_{g4} = 0$	and	$f_{g4} < 0.54$ for $\phi_{g4} = \pi$
Combination of $H \to ZZ^* \to 4\ell$ and $H \to WW^* \to e\nu\mu\nu$		
$f_{g2} < 0.12$ for $\phi_{g2} = 0$	and	$f_{g2} < 0.16$ for $\phi_{g2} = \pi$
$f_{g4} < 0.090$ for $\phi_{g4} = 0$	and	$f_{g4} < 0.41$ for $\phi_{g4} = \pi$

$f_{g2} = f_{a2}$, $f_{g4} = f_{a3}$

Parameter	CMS	ATLAS
	H→ZZ	
$f_{a2} = f_{g2}$	[-0.66, -0.57] U [0.15, 1.00]	[-0.16, 0.68]
$f_{a3} = f_{g4}$	[-0.40, 0.43]	[-0.54, 0.11]
$f_{\Lambda 1}$	[-0.25, 0.37]	
	H→WW	
$f_{a2}^{WW} = f_{g2}^{WW}$	[-1.00, -0.54] U [-0.29, 1.00]	[-0.63, -0.26] U [-0.20, 0.053]
$f_{a3}^{WW} = f_{g4}^{WW}$	[-1.00, 1.00]	[-0.84, 0.78]
$f_{\Lambda 1}^{WW}$	[-1.00, 1.00]	
	H→ZZ and H→WW Combination ($a_i^{ZZ}=a_i^{WW}$)	
$f_{a2} = f_{g2}$	[-0.11,0.17]	[-0.16, 0.12]
$f_{a3} = f_{g4}$	[-0.27, 0.28]	[-0.41, 0.090]
$f_{\Lambda 1}$	[-0.42, 0.38]	
	H→Zγ*→4l	
$f_{a2}^{Z\gamma} = f_{g2}^{Z\gamma}$	[-0.49, 0.46]	
$f_{a3}^{Z\gamma} = f_{g4}^{Z\gamma}$	[-0.40, 0.51]	
$f_{\Lambda 1}^{Z\gamma}$	[-1.00, 1.00]	
	H→γ*γ*→4l	
$f_{a2}^{\gamma\gamma} = f_{g2}^{\gamma\gamma}$	[-0.04, 0.51]	
$f_{a3}^{\gamma\gamma} = f_{g4}^{\gamma\gamma}$	[-0.35, 0.32]	

Summary

- Study of the **spin, parity, and anomalous HVV couplings of the Higgs boson** by ATLAS and CMS using the full **LHC Run-1** dataset
  - **$H \to ZZ$**, **$H \to WW$**, and **$H \to \gamma\gamma$** decays
  - Based on kinematic variables
- Exotic scenarios with spin-1 and -2 have been ruled out at 99%CL or higher → **The Higgs boson has spin 0**
- Pure pseudoscalar 0^- and pure 0^+_h have also been ruled out
  - The Higgs still can be in a **mixed CP** state → anomalous contributions
- Tensor structure of the HVV interactions studied under the spin-0 assumption
  - Via parameter measurement → coupling ratios and effective cross sections

No signs of deviations from the SM with the data available
The Higgs boson is compatible with the SM hypotheses $J^{CP} = 0^{++}$
If it is exactly the SM Higgs, only Run-2 data will tell!