Studio di spin e parità del bosone di Higgs in decadimenti bosonici con l'esperimento ATLAS

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Introduction and outline

Discovery of new boson announced July 4th, 2012: to confirm it is a Standard Model (SM) Higgs boson we must measure its mass and properties, and in particular to confirm it is a CP-even spin-0 particle ($J^P = 0^+$).

Analyses aim to examine the Higgs Spin/CP nature:

- 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 with updated spin-2 results and HVV EFT approach
- Combine results from all sensitive vector boson channels $H \rightarrow ZZ^* \rightarrow 4l$, $H \rightarrow WW^* \rightarrow e\nu\mu\nu$ (+≦1jet) and $H \rightarrow \gamma\gamma$: ZZ^* and WW^* are used to examine both spin-0 and spin-2 models, whereas $\gamma\gamma$ contributes to spin-2

Details of the analyses can be found in: ATLAS-CONF-2015-008
(https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2015-008/
arXiv: http://arxiv.org/pdf/1506.05669v1.pdf)

Spin-CP: Theoretical Models

- Classification framework proposed in 'A framework for Higgs characterisation' JHEP11(2013)043
- SM without Higgs plus generic boson described with EFT (EFT scale here chosen to Λ=1 TeV):

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

Spin 0

- **Test pure BSM spin-0 and spin-2 models against the Standard Model**
- **Constrain possible SM and BSM mixing of Spin-0 boson:**

CP-odd $(\tilde{\kappa}_{AVV}/\kappa_{SM})\cdot\tan\alpha$ and CP-even $(\kappa_{HVV}/\kappa_{SM})$ with $\tilde{\kappa}_x = \frac{1}{4}\frac{v}{\Lambda}\kappa_x$

$$L_0^V = \Big\{ c_\alpha \kappa_{SM}\Big[\frac{1}{2} g_{HZZ} Z_\mu Z^\mu + g_{HWW} W_\mu^+ W^{-\mu}\Big]$$

$$-\frac{1}{4}\frac{1}{\Lambda}\Big[c_\alpha \kappa_{HZZ} Z_{\mu\nu} Z^{\mu\nu}\Big] - \frac{1}{2}\frac{1}{\Lambda}\Big[c_\alpha \kappa_{HWW} W_{\mu\nu}^+ W^{-\mu\nu}\Big]$$

$$-\frac{1}{4}\frac{1}{\Lambda}\Big[s_\alpha \kappa_{HWW} Z_{\mu\nu} \tilde{Z}^{\mu\nu}\Big] - \frac{1}{2}\frac{1}{\Lambda}\Big[s_\alpha \kappa_{HWW} W_{\mu\nu}^+ \tilde{W}^{+-}\Big]\Big\} X_0$$

SM Higgs

BSM CP-even coupling

CP-odd coupling

cα = cosα, sα = sinα
Λ=cut-off scale
α = Mixing angle

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	$\pi/2$

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Spin 2

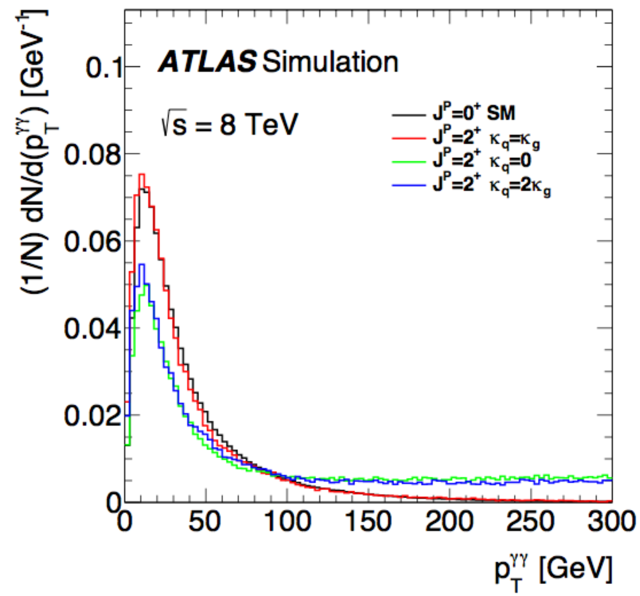
- **Test SM against graviton-like spin-2. Including only quark and gluon couplings in production**
- **Others estimated to be insignificant: $\sigma_{EW}/\sigma_{QCD} \cong 0.03\%$**
- **Testing SM against three spin-2 coupling configurations: κ_q/κ_g = 0,1 and 2**

$$L_0^V = \frac{1}{\Lambda}\left[\sum_{V=W,Z,\gamma} \kappa_V X^{\mu\nu} T^V_{\mu\nu} + \sum_{F=q,l} \kappa_f X^{\mu\nu} T^f_{\mu\nu}\right]$$

X: spin-2 field tensor
T: energy-momentum tensor

Non-universal coupling scenario shows unitarity violating behavior (high p_T^X tail) → study some benchmarks with p_T^X cut-off

Choice of QCD couplings		p_T^X cut-off (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



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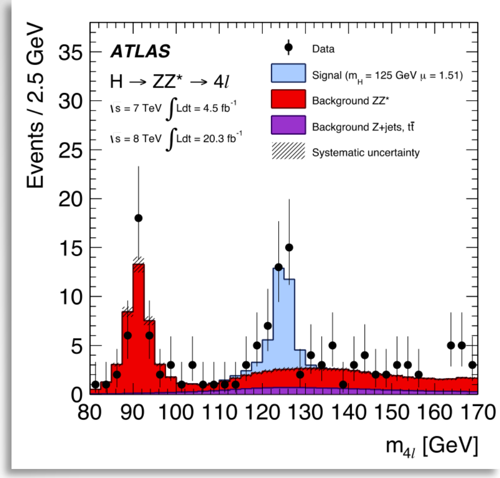
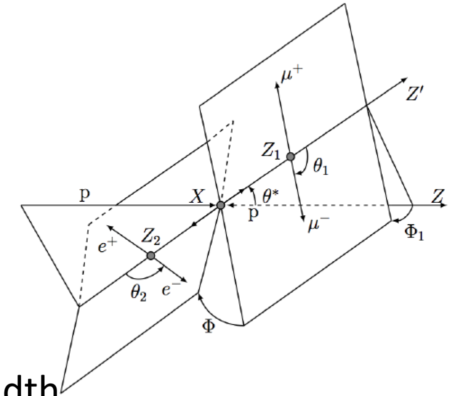


H→ZZ*→4l

Golden channel

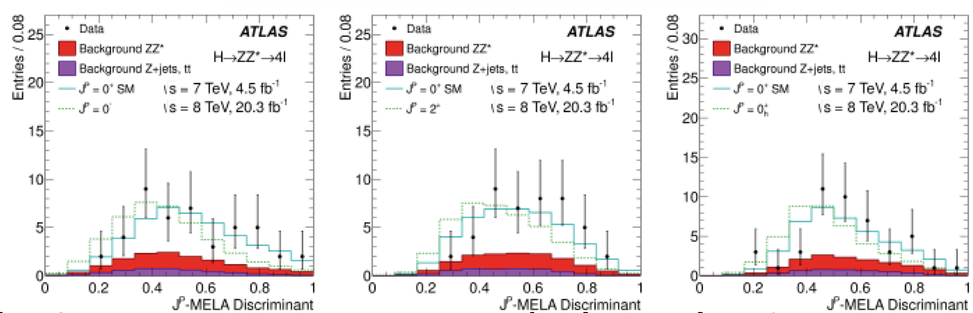
- Small rate;
- Cleanest final state;
- S/B ~ 2;
- BR (ZZ)=2.3%
- fully reconstructed mass;
- Ideal to study: mass, spin, parity, couplings, width,..
- **Backgrounds:** irreducible ZZ* and reducible Z+jets, tt



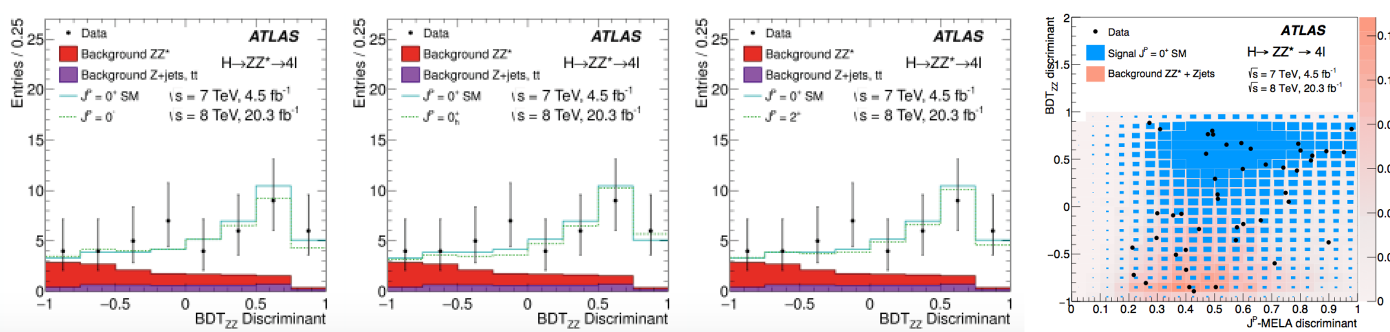
Spin-CP measurement: Hypothesis tests Discriminants

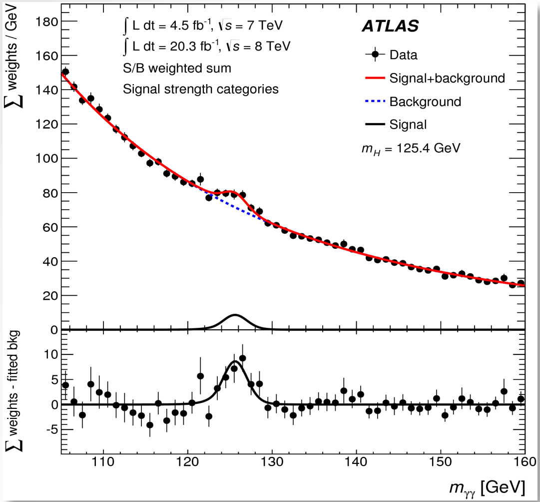
◇ **Exploits full lepton kinematics, matrix element based discriminant (J^P-MELA):**

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



◇ **Analysis uses multivariate (MV) discriminant against ZZ* (BDT_{ZZ}):** discriminant from production related observables (η_{4l}, $p_{T,4l}$, m_{4l}, $\cos(\theta^*)$ and Φ_1)

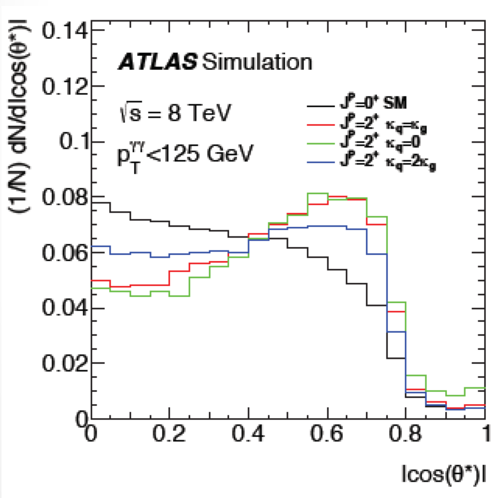


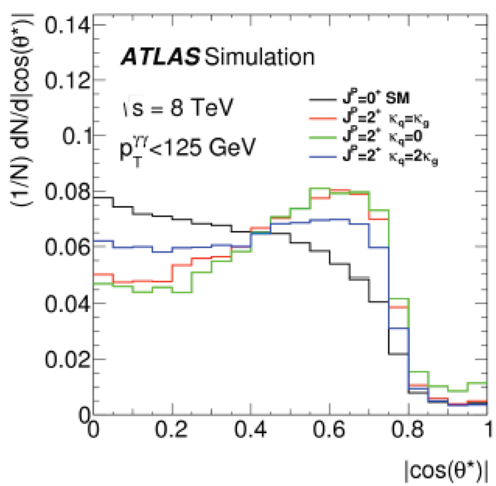


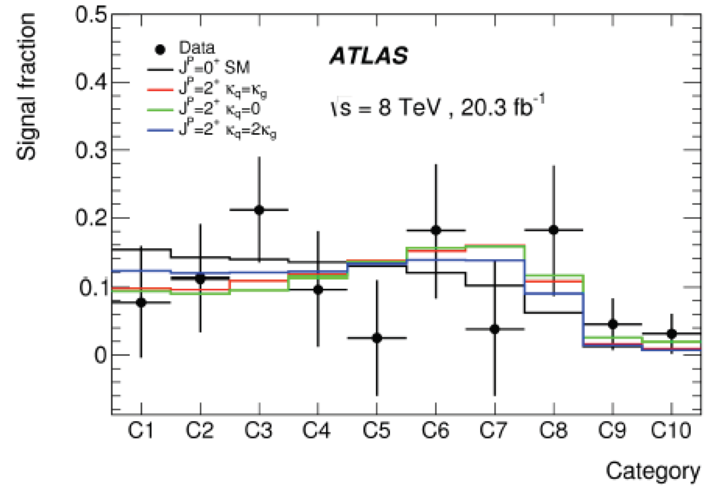
$H \rightarrow \gamma\gamma$

BR=0.23%, but clean peak in $m_{\gamma\gamma}$
S/B = 3%

- ◇ **Signal:** 2 good quality, isolated, high p_T photons
- ◇ **Backgrounds:** Irreducible γγ (80%), reducible γj, jj (20%);
- ◇ Small S/B needs excellent detector performance;







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

(in Collins-Soper frame)
$\Delta\eta_{\gamma\gamma}$: Separation in pseudorapidity between the two photons

ATLAS-CONF-2015-008: http://arxiv.org/pdf/1506.05669v1.pdf

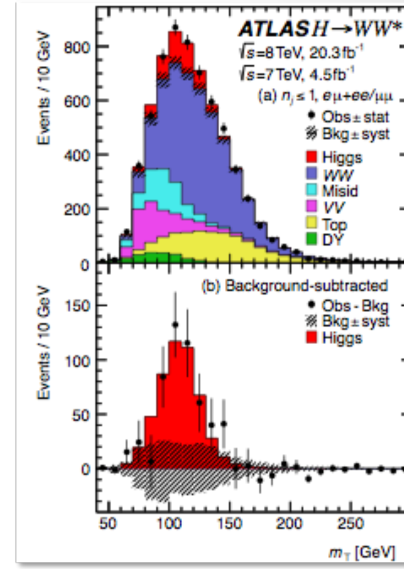
H→WW*→eν μ ν

Signal:
- 2 oppositely charged leptons l = e, μ
- Large E_T^{miss} from undetected νs
- Small opening angle between l^+ and l^-

Backgrounds:
- Dominant: WW, tt
- Drell-Yan, W + jets, small: Z → ττ, Wγ, Wll, ZZ, QCD

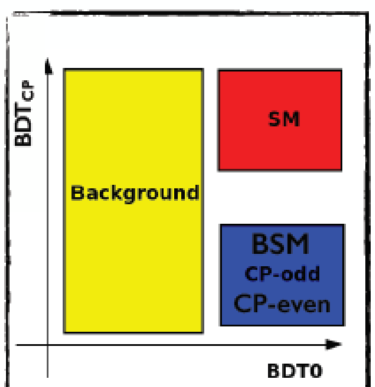
Events categorised according to lepton flavour final state and Njets

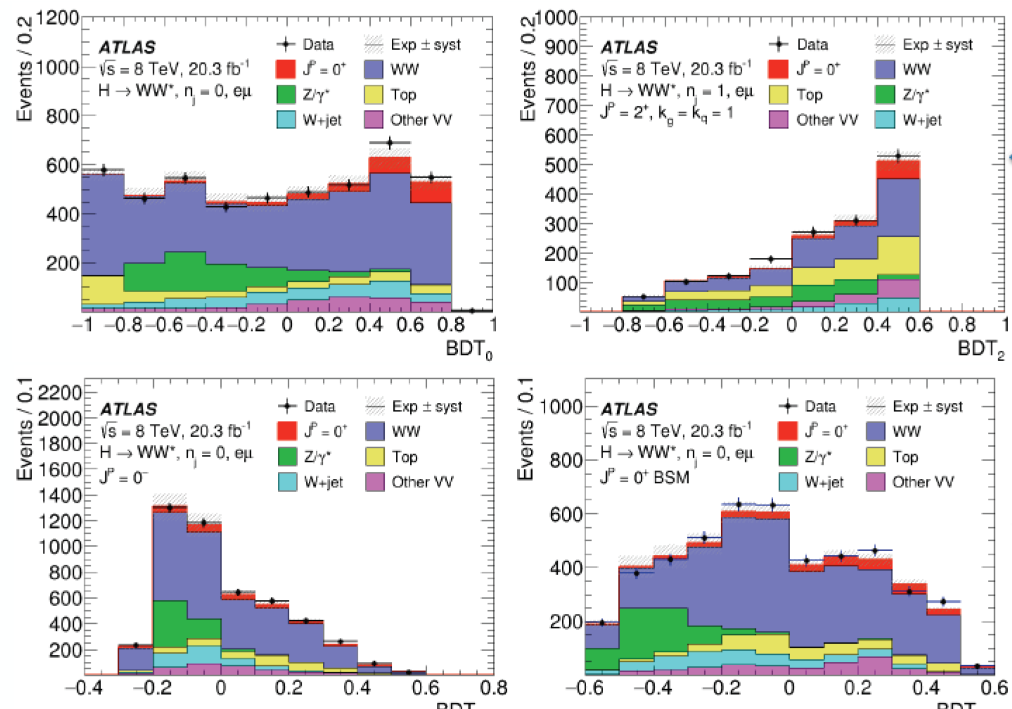
BR (WW)=22%
lvlv main mode
S/B=0.1-0.4
Non-resonant



Spin-CP measurement: Boosted Decision Trees (BDTs) used as discriminats in WW*

- Spin-2 tests training parameters: p_{Tll}, m_{ll}, $\Delta\Phi_{ll}$, m_T
- SM vs 0^+_h Training parameters: p_{Tll}, m_{ll}, $\Delta\Phi_{ll}$, p_{miss}
- SM vs 0^- Training parameters: m_{ll}, $p_{Tl1} - 0.5p_{Tl2} + 0.5p_{Tmiss}$, Δp_T, $\Delta\Phi_{ll}$





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Fixed Hypotheses Results

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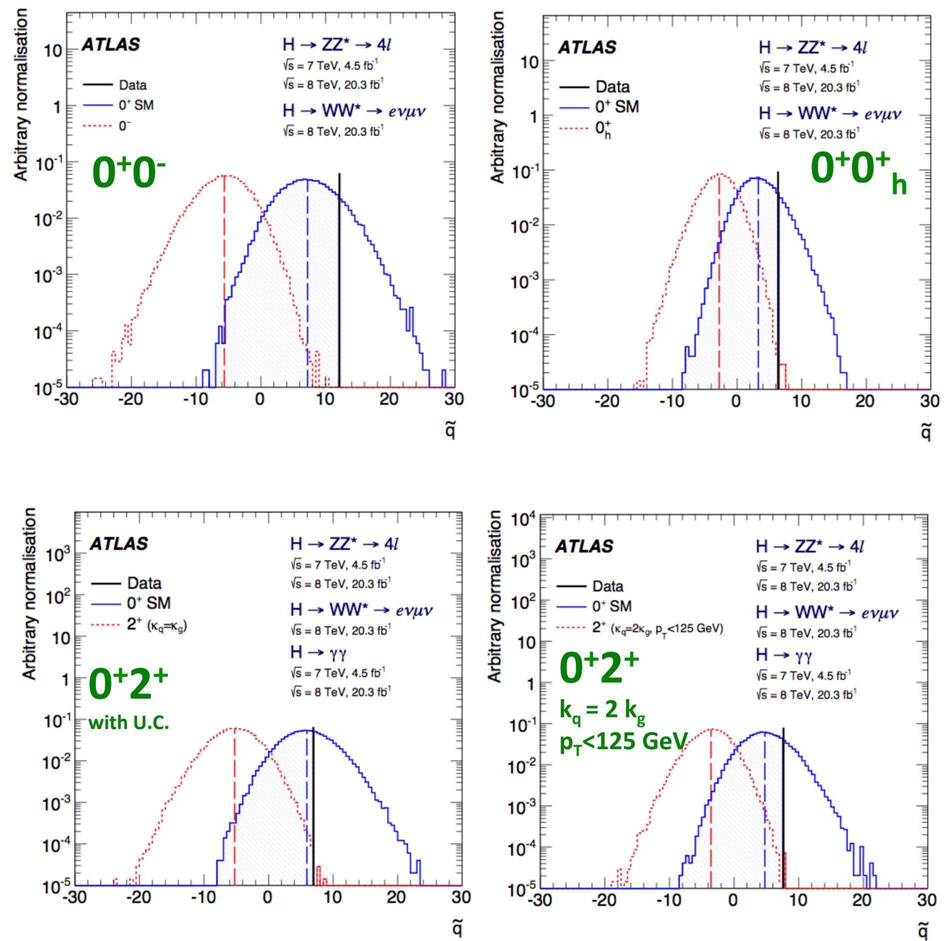
Performed using $H \rightarrow ZZ^* \rightarrow 4l$, $H \rightarrow \gamma\gamma$ and $H \rightarrow WW^* \rightarrow l\nu l\nu$ channels

The Standard Model (SM) Higgs boson hypothesis has been tested against several alternative spin and parity models.

- **Two non-SM spin-0:**
  - ◇ pure BSM CP-odd (0^-)
  - ◇ BSM CP-even (0^+_h): scalar with higher-dimension operators



- **Spin-2 models:**
  - ◇ 2^+ with universal coupling
  - ◇ Two benchmark models ($k_q = 0$ and $k_q = 2\,k_g$) with non-universal couplings to fermions and vector bosons and with two p_T cutoff 125 GeV and 300 GeV

Fixed Hypotheses Results

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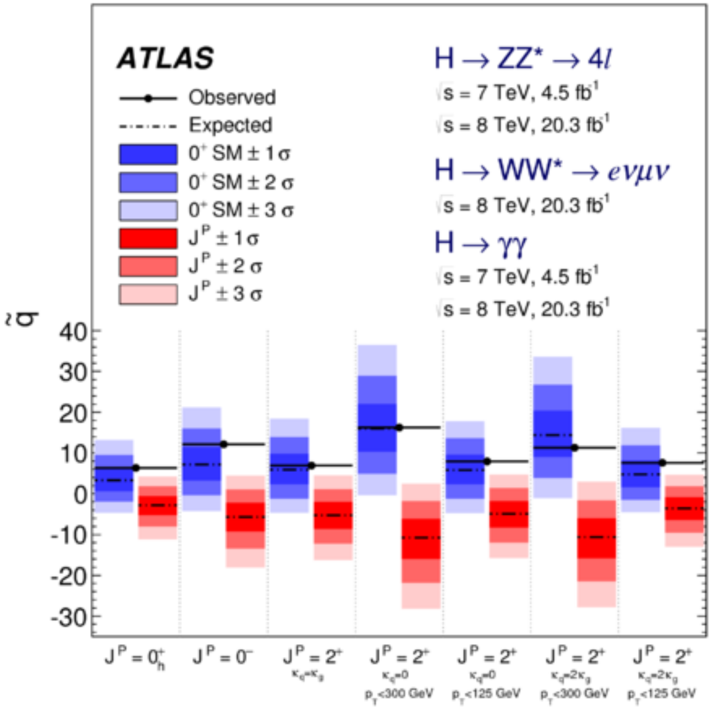


SM Higgs boson hypothesis favoured and alternative models excluded >95% CL

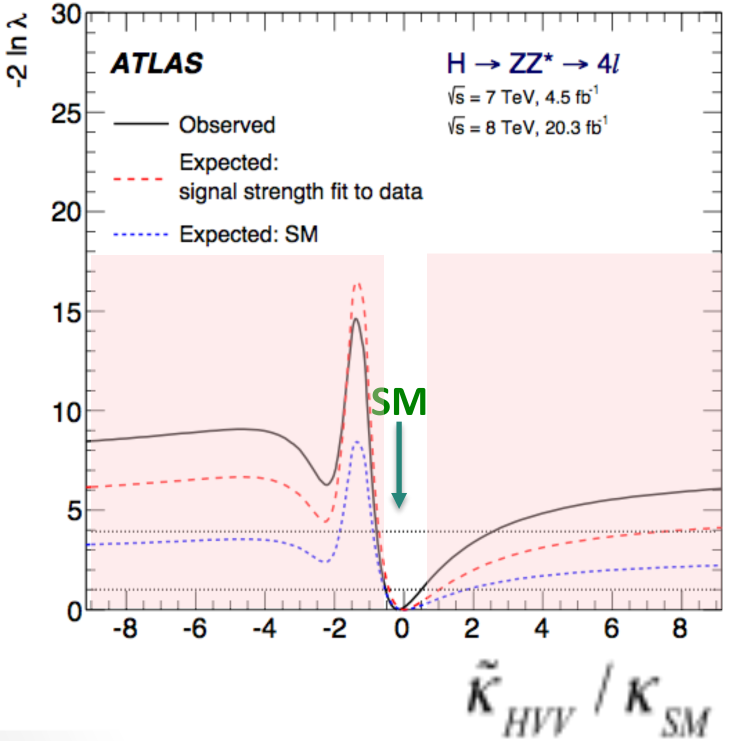
Tested Hypothesis	$p^{ALT}_{exp,\mu=1}$	$p^{ALT}_{exp,\mu=\hat{\mu}}$	p^{SM}_{obs}	p^{ALT}_{obs}	Obs. CL$_S$ (%)
0^+_h	$2.5 \cdot 10^{-2}$	$4.7 \cdot 10^{-3}$	0.85	$7.1 \cdot 10^{-5}$	$4.7 \cdot 10^{-2}$
0^-	$1.8 \cdot 10^{-3}$	$1.3 \cdot 10^{-4}$	0.88	$< 3.1 \cdot 10^{-5}$	$< 2.6 \cdot 10^{-2}$
2^+	$4.3 \cdot 10^{-3}$	$2.9 \cdot 10^{-4}$	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	$7.3 \cdot 10^{-5}$	$3.7 \cdot 10^{-2}$

Spin-0 coupling ratios in HVV

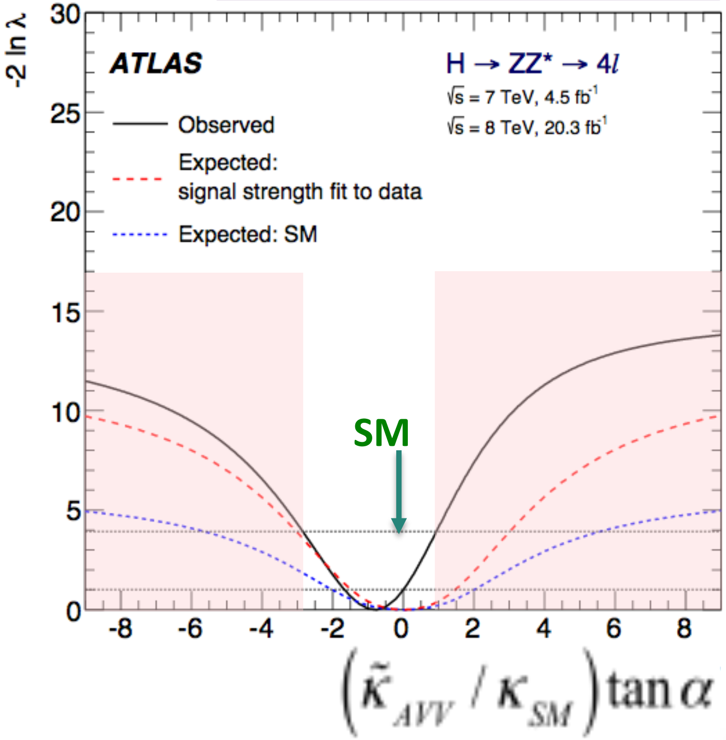
ATLAS-CONF-2015-008: http://arxiv.org/pdf/1506.05669v1.pdf

Set limit on BSM coupling and mixing angle in CP even (or odd) mixing scenarios using the $H\to ZZ^*\to 4l$ and $H\to WW^*\to l\nu l\nu$ decays.

BSM CP-even cotribution



BSM CP-odd contribution



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

No CP violation in Higgs sector is observed

Conclusions

Final Run-I Higgs Spin-CP analyses on the:

- 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
- Details of the results can be found in: ATLAS-CONF-2015-008 - http://arxiv.org/pdf/1506.05669v1.pdf
- ***Looking forward to Run-II:***
  - Continue development of EFT approach to study HVV interaction
  - Add different Higgs production mechanisms
  - Simultaneous fit of couplings

All ATLAS results in the public page:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults

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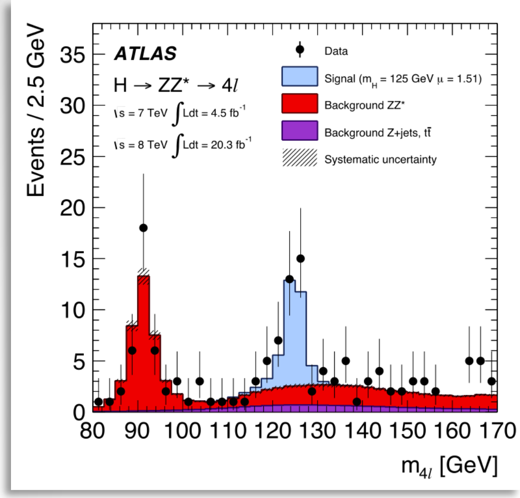
References

- "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 $WW^* \to e\nu\mu\nu$ 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
- Previous publication: "Evidence for the spin-0 nature of the Higgs boson using ATLAS data" Phys. Lett. B 726 (2013), pp. 120-144

H→ZZ*→4l

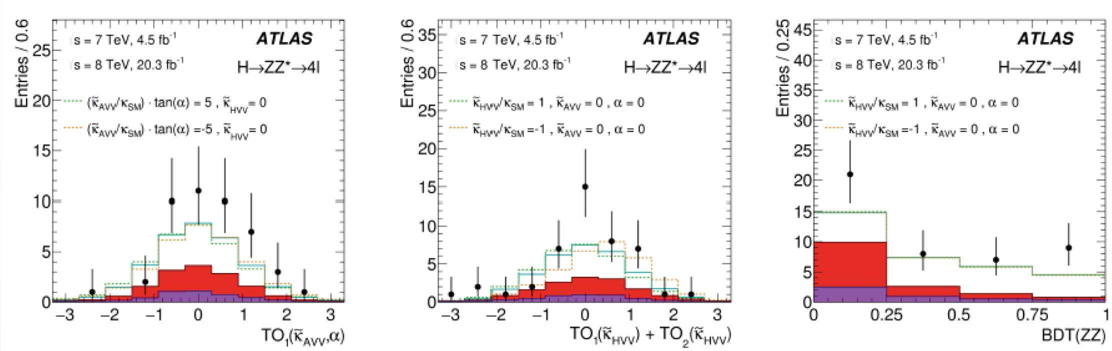


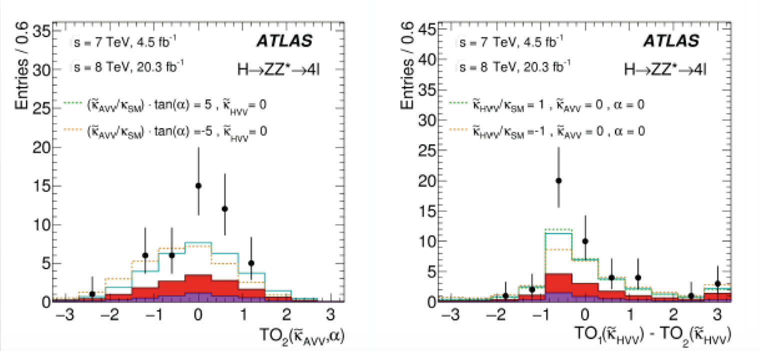
Golden channel

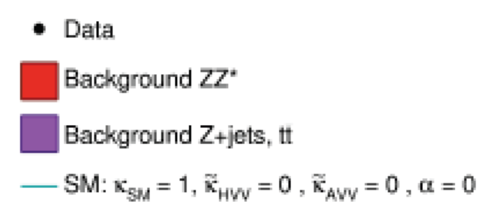
- Small rate;
- Cleanest final state;
- S/B ~ 2;
- BR (ZZ)=2.3%
- fully reconstructed mass;
- Ideal to study: mass, spin, parity, couplings, width,..

	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

Spin-CP measurement: Tensor structure fit discriminants







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

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

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

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

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