Individual and Combined Measurements of the Spin and Parity Properties of the Higgs boson using the ATLAS Detector

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on behalf of the ATLAS collaboration

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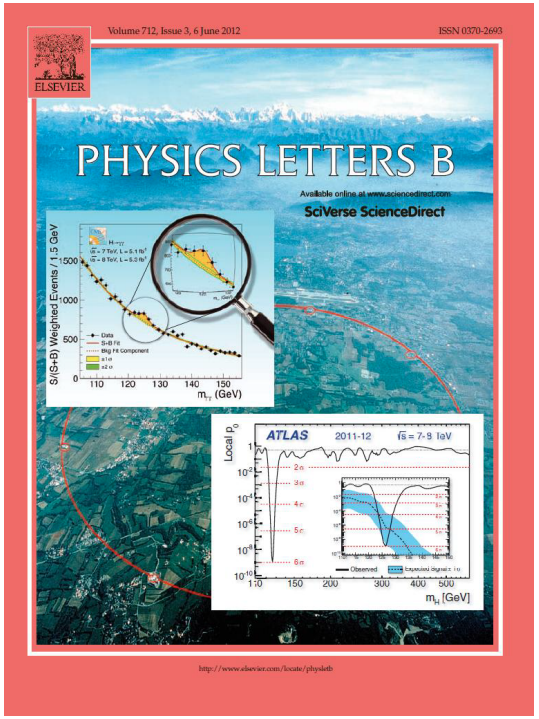
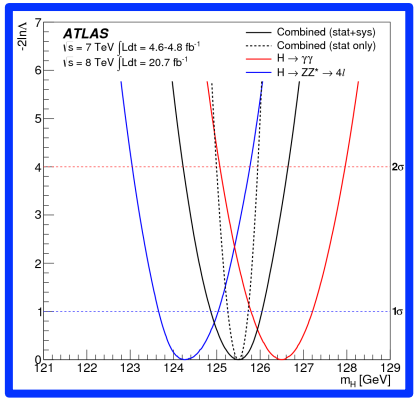
Introduction

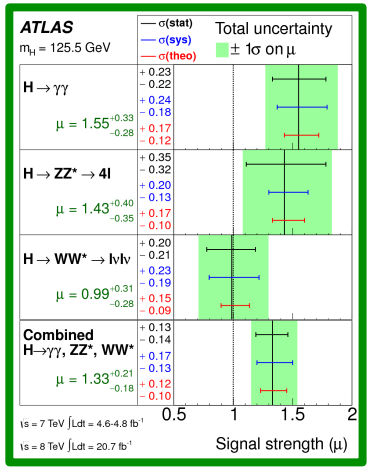
- **ATLAS and CMS experiments announced the discovery of a new boson at LHC on 4 July 2012**

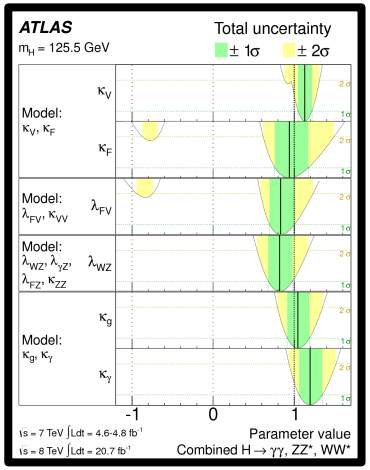
- **The main experimental challenge after the discovery:**
  - **Is this particle the SM Higgs boson, responsible for the EW symmetry breaking mechanism?**
    - **Couplings to bosons and fermions as expected in SM**
    - **Quantum numbers as predicted in the SM: $J^P=0^+$**

- **Experimental answer by measuring the properties of this boson:**
  - **Mass**
  - **Rates**
  - **Couplings**
  - **Spin-parity**







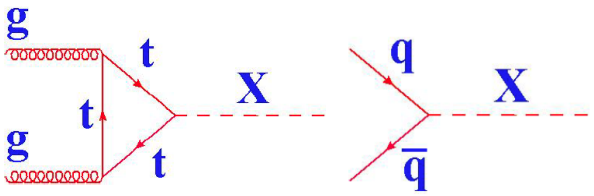


Spin and parity determination

- **Production** and **decay** kinematics of the new boson sensitive to **spin** and **parity**
  - Bosonic decay channels (**ZZ,WW,γγ**) used for the spin and parity determination
- Specific benchmark models tested against the SM $J^P = 0^+$

	ZZ^*	WW^*	$\gamma\gamma$
0^-	✓	-	-
$1^+,1^-$	✓	✓	-
2^+	✓	✓	✓

- $J^P=0^-$: pseudoscalar, no CP mixing
  - ggF production mechanism
- $J^P=1^+,1^-$: exotic vector and pseudovector.
  - $q\bar{q}$ production mechanism
  - Landau-Yang theorem: On-shell X(J=1) $\not\rightarrow \gamma\gamma$
  - Worth testing with other decay modes

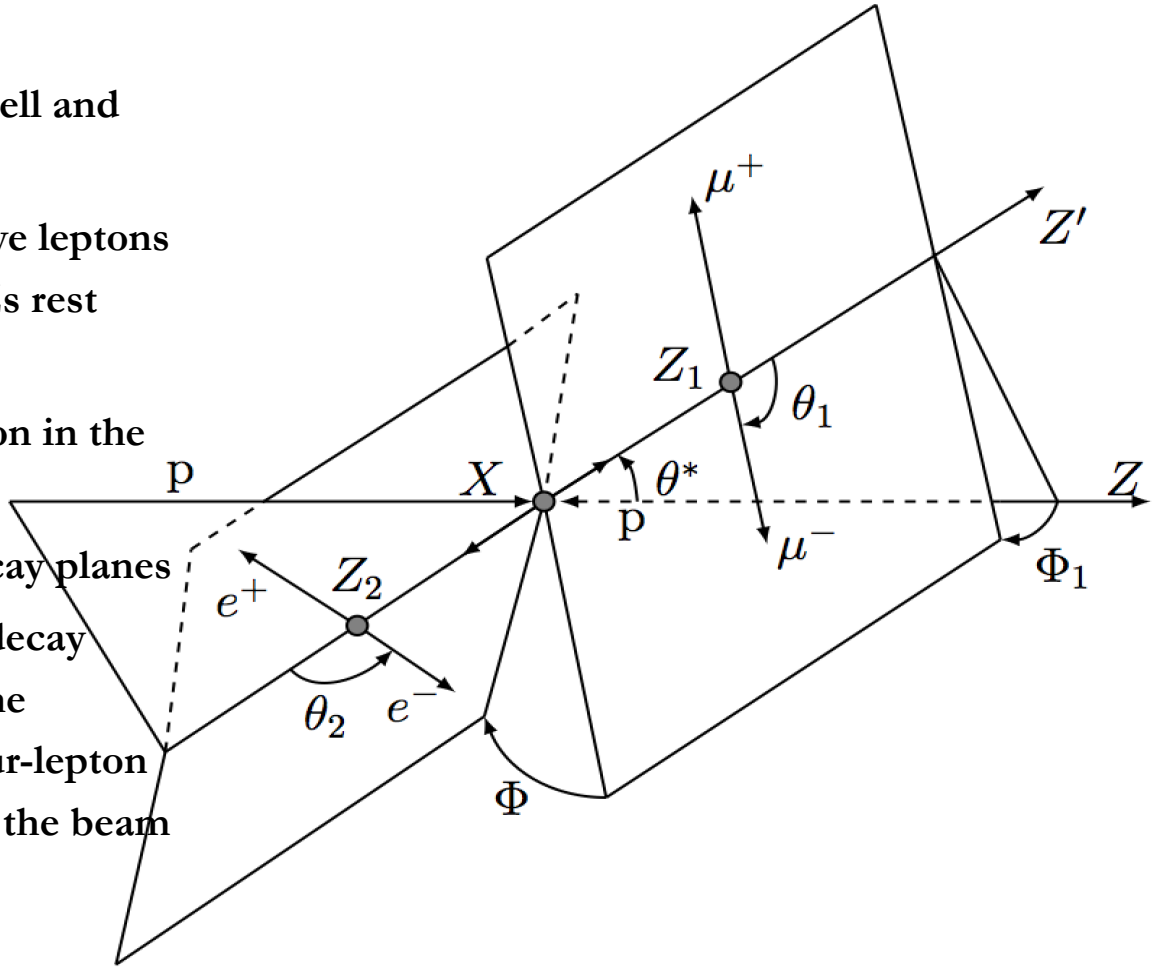


- $J^P=2^+$: graviton–inspired tensor with minimal couplings to SM particles
  - Both gg fusion and $q\bar{q}$ production
  - Observables sensitive to qqbar production fraction $f_{q\bar{q}}$ → different polarizations along collision axis selected
  - Exclusion can be studied as function of the $f_{q\bar{q}}$

Spin-parity measurement in $H \to ZZ^* \to 4l$

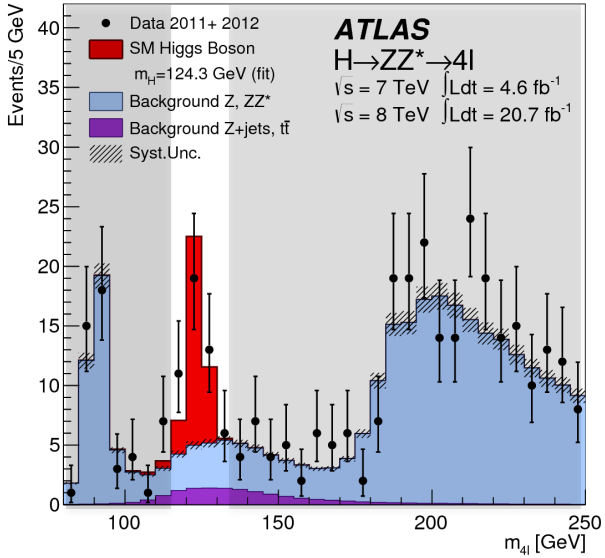
- **Golden Channel : high S/B (~1) , full final state reconstruction**
  - Access to the spin and parity of the underlying resonance
  - Used to test all alternative hypothesis considered against the SM ($J^P=0^+$)

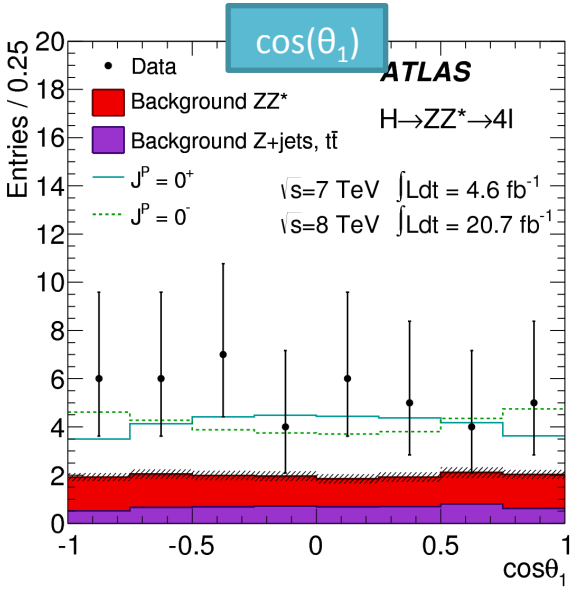
- **Discriminating variables:**
  - m_{Z1} , m_{Z2} masses of the on-shell and off-shell Z bosons
  - θ_1 and θ_2 angles of the negative leptons defined in the corresponding Zs rest frame.
  - θ^* angle of the on-shell Z boson in the Higgs rest frame
  - φ angle between the two Z decay planes
  - φ_1 angle angle between the Z_1 decay plane and a plane defined by the momentum of the Z_1 in the four-lepton rest frame and the direction of the beam axis

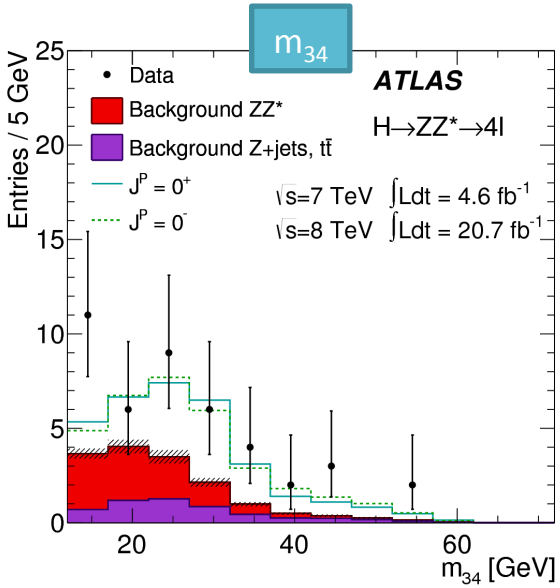


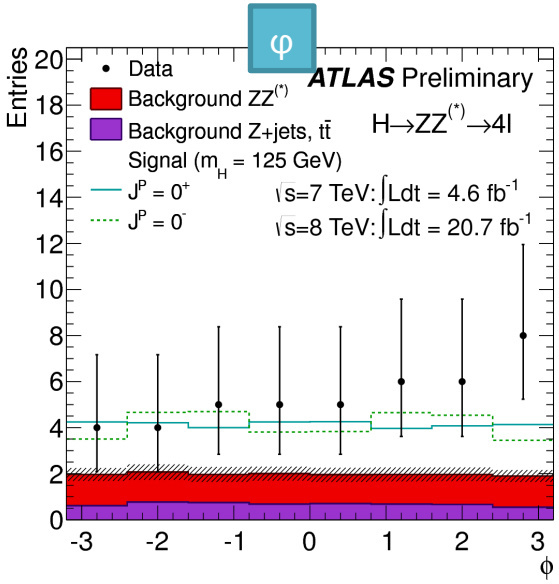
Spin-parity measurement in $H \to ZZ^* \to 4l$

- Events within $115 < m_{4l} < 130$ GeV considered
  - 43 data candidates ($\sqrt{s}$=7TeV and $\sqrt{s}$=8TeV full datasets used)
- Same selection as in the rate analysis
- Background: from full simulation (irreducible ZZ^*) and from control regions ($t\bar{t}$,Z+jet)



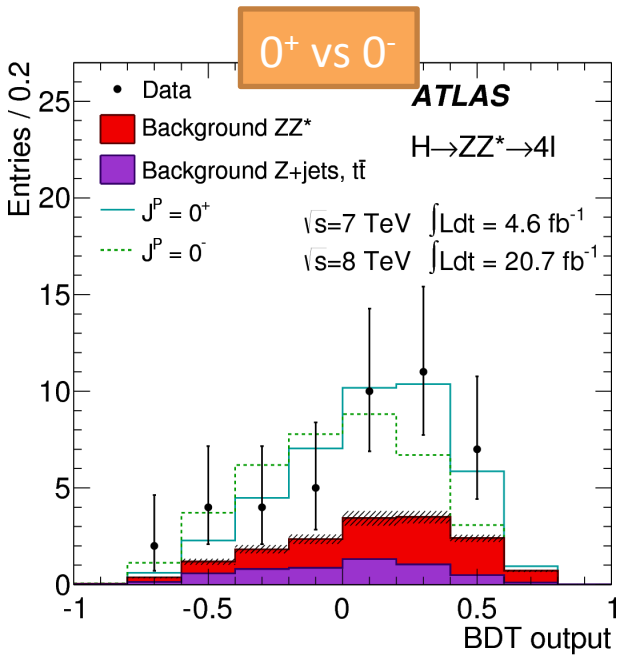


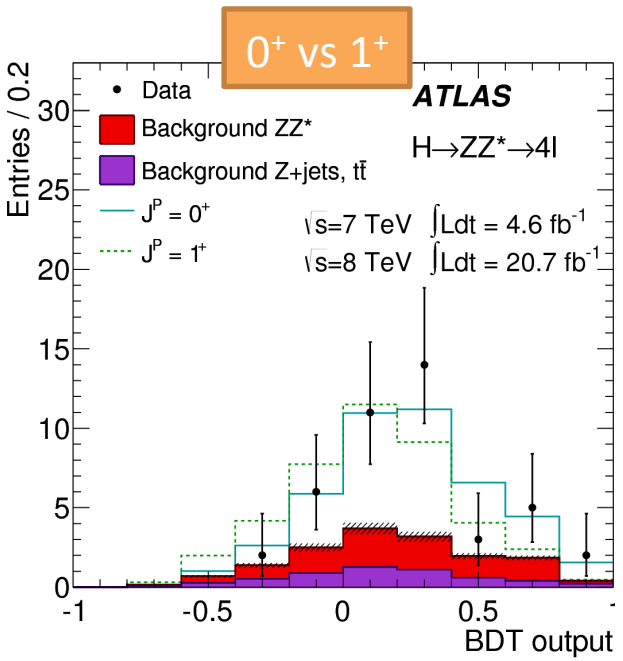


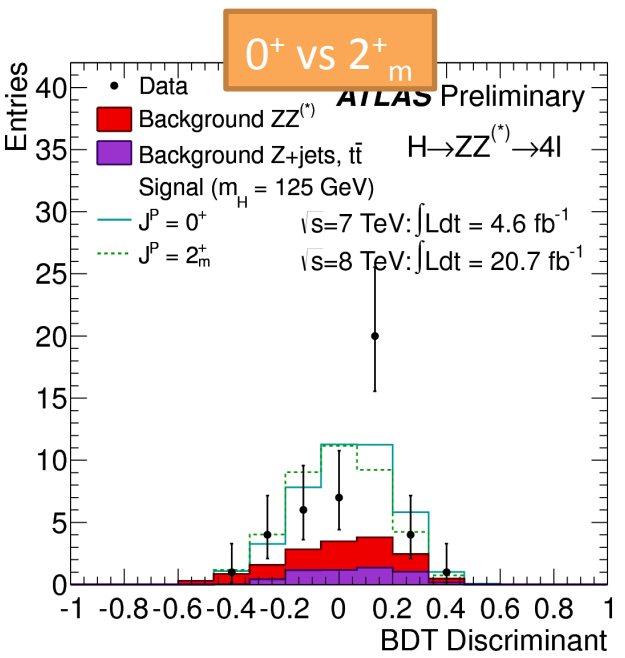


Spin-parity measurement in H→ ZZ*→4l

- Multivariate discriminant based on Boosted Decision Tree trained using J^P- discriminating variables to separate pairs of different J^P hypotheses
  - Similar results obtained using a ME discriminant based approach

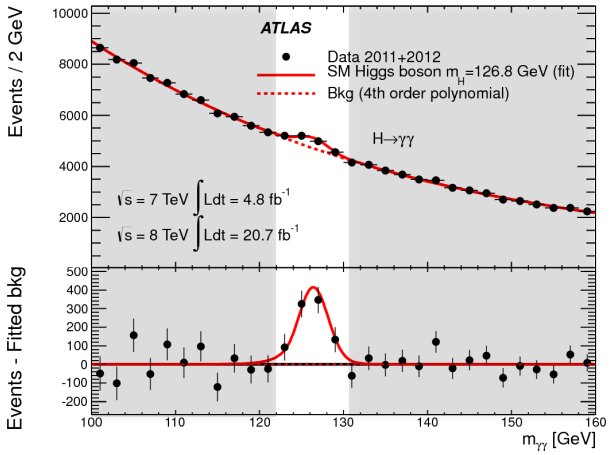


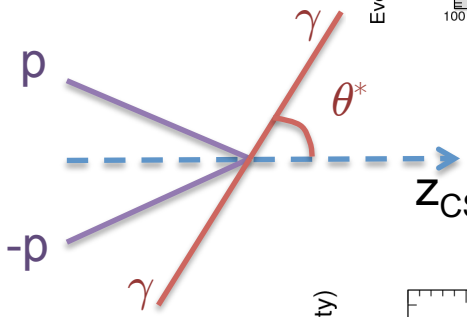




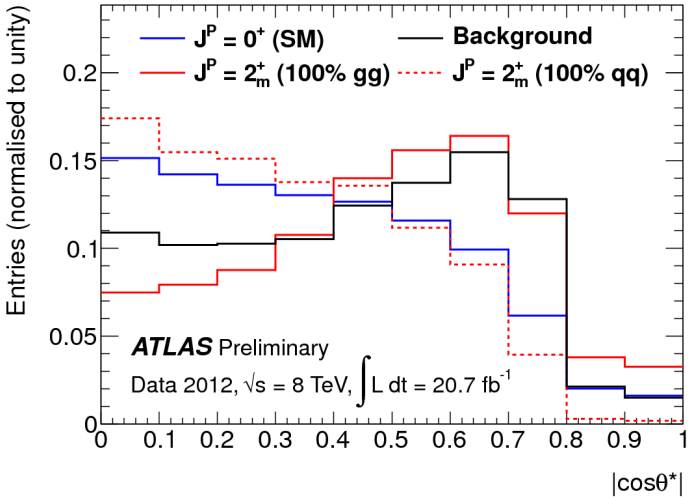
Spin Measurement in H→ γ γ

- Sensitive to the spin of the Higgs, S/B~3%
  - 2 photons with E_T> 35 , 25 GeV
- Signal region:
  - 122<$m_{\gamma\gamma}$<130 GeV
- SM compared to $J^P=2^+$
- Discriminating variable: $|\cos\theta^*|$
  - Polar angle of the photon wrt z axis of Collins-Soper frame
  - Correlations between $m_{\gamma\gamma}$ and $|\cos\theta^*|$ reduced by $p_{T\gamma 1}/m_{\gamma\gamma}$ >0.35 and $p_{T\gamma 2}/m_{\gamma\gamma}$ >0.25 cuts
- Background shape from sidebands



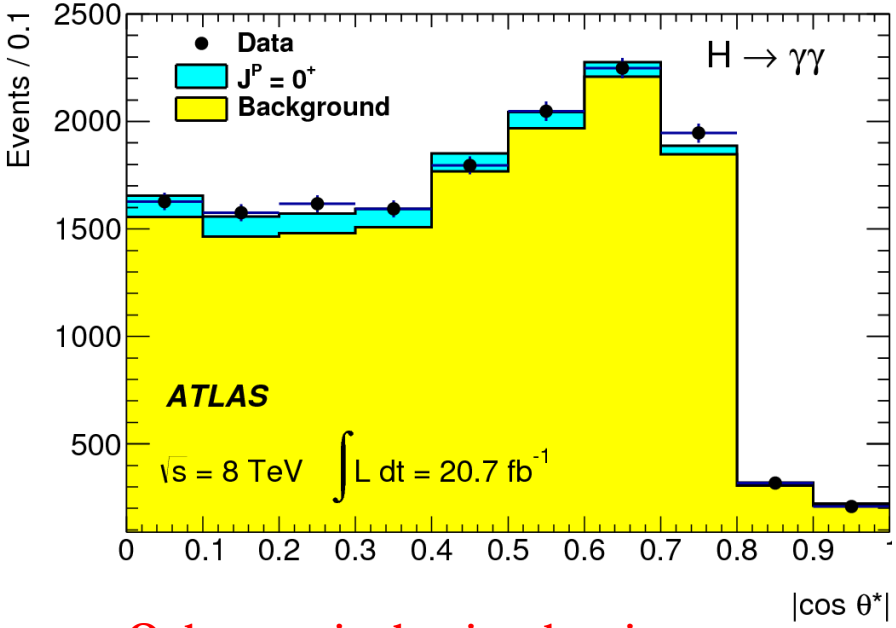


$$|\cos\theta^*| = \frac{|\sinh(\Delta\eta^{\gamma\gamma})|}{\sqrt{1+(p_T^{\gamma\gamma}/m_{\gamma\gamma})^2}} \frac{2p_T^{\gamma 1}p_T^{\gamma 2}}{m_{\gamma\gamma}^2}$$



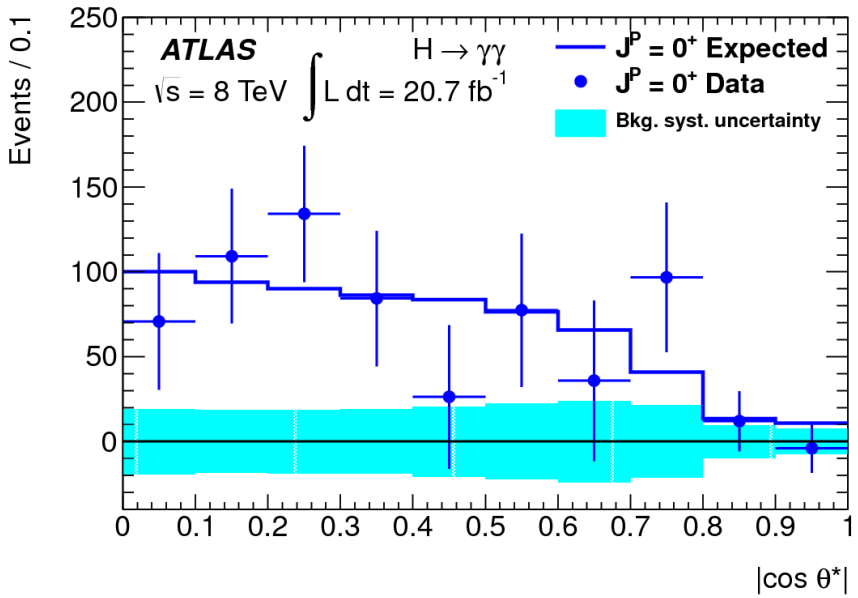
Spin Measurement in H→ γ γ

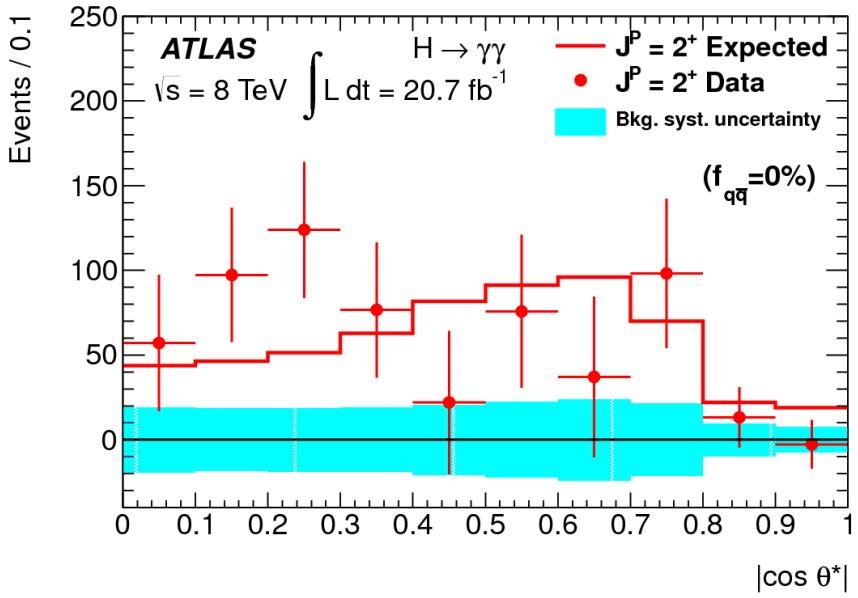
- $|\cos\theta^*|$ distribution before and after background subtraction



Only event in the signal region

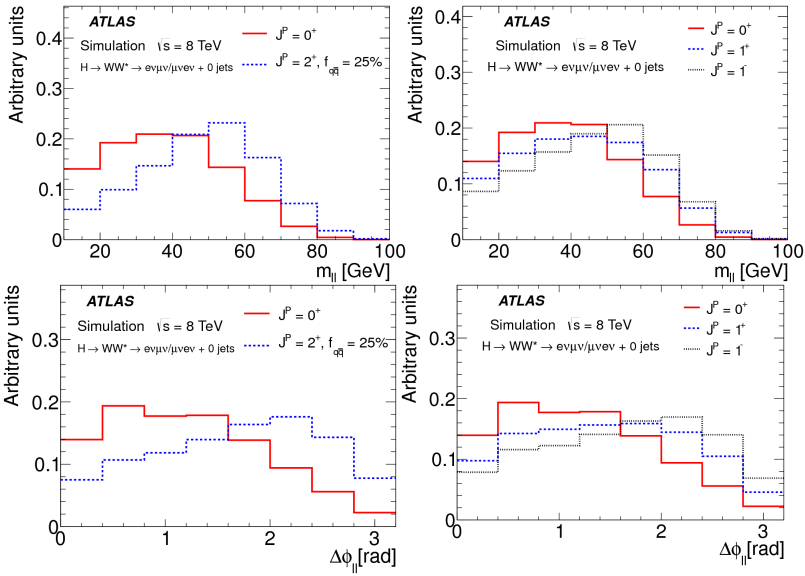
$-122 < m_{\gamma\gamma} < 130$ GeV



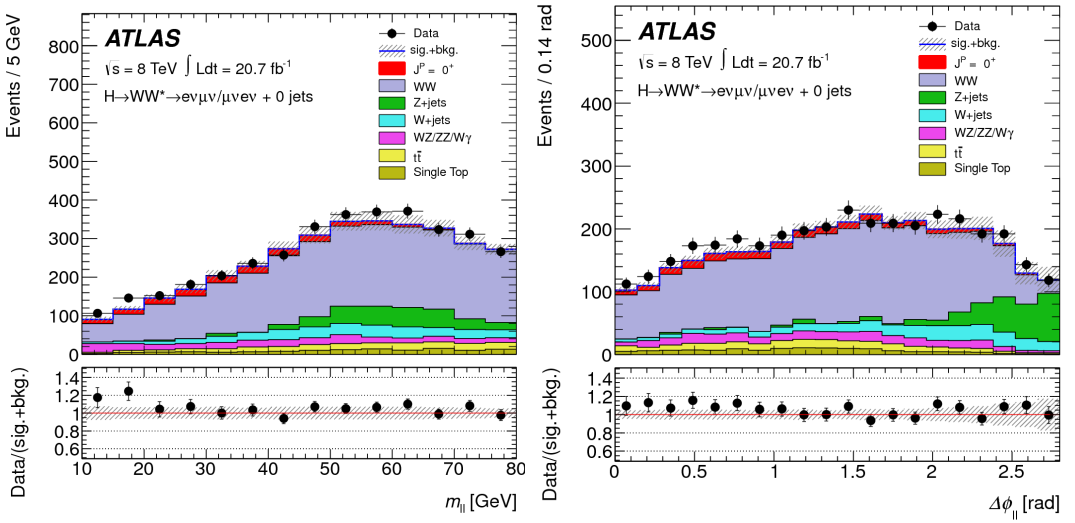


Spin Measurement in H→WW*→lvlv

- Analysis restricted to e/μ final state
  - Smaller bkg wrt same flavour final state
- Preselection
  - $p_T(l)$>25,15 GeV, $|\eta(l)|$<2.5, 0-jets
- Main backgrounds:
  - Z+jets,tt, t, WW, W+jets
  - Reduced with: $E_{T,miss}$>20 GeV, m_{ll}<80 GeV, p_{Tll}>20 GeV, $\Delta\phi_{ll}$< 2.8

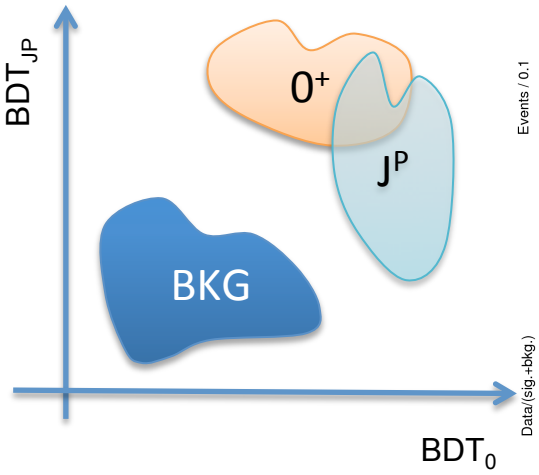


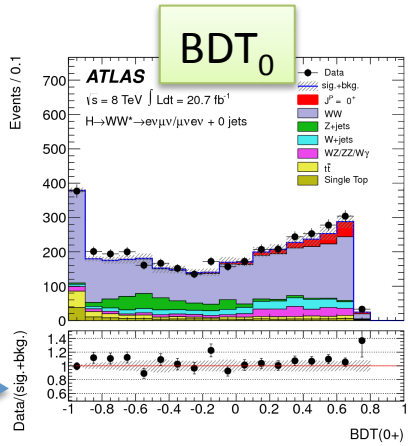
- Spin correlations between decay products shapes angular distributions
- Sensitive variables to various J^P:
  - M_{ll}, $\Delta\phi_{ll}$, $p_{T,ll}$, $E^{miss}_{T,rel}$

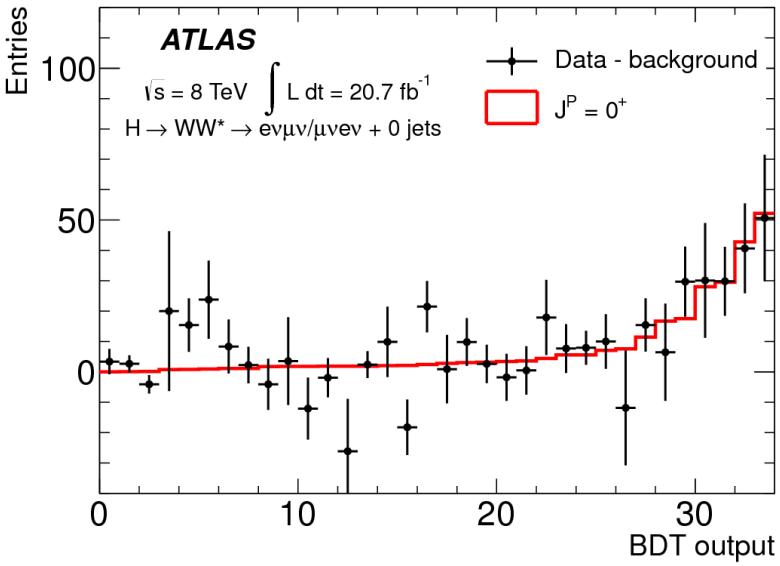


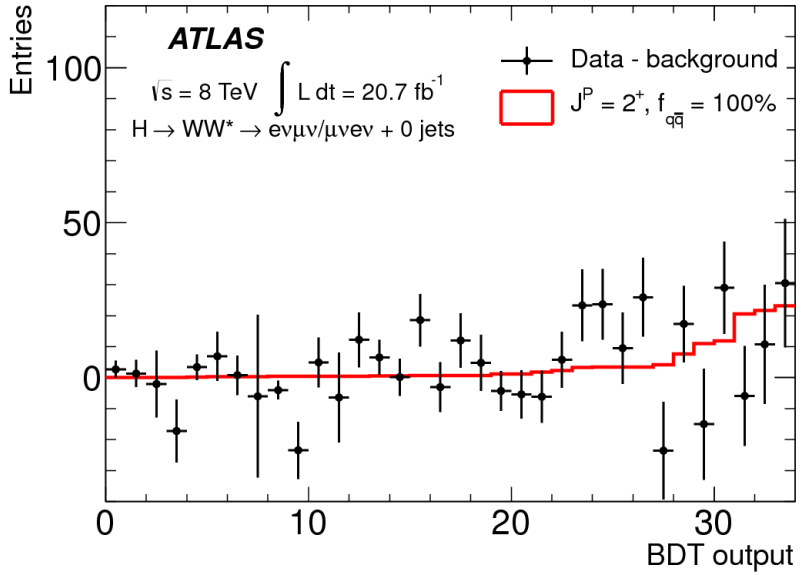
Spin Measurement in H→WW*→lvlv

- **Discrimination between SM 0^+ and other J^P hypotheses ($J^P=1^+,1^-\ 2^+$) performed with a 2D-fit of two BDTs**
  - **BDT_0 (SM 0^+ vs bkg) and BDT_{JP} (alternative J^P vs bkg)**
  - **M_{ll},$\Delta\phi_{ll}$, $p_{T,ll}$, m_T, used for the BDT training**









Results

Statistical Treatment

- **Two hypotheses testing: SM ($J^P=0^+$) vs = 0^- , 1^- , 1^+ , 2^+**
- **Observables sensitive to spin and parity used to create a binned likelihood J^P dependent**

Expected signal events — Nuisance Parameters constraints

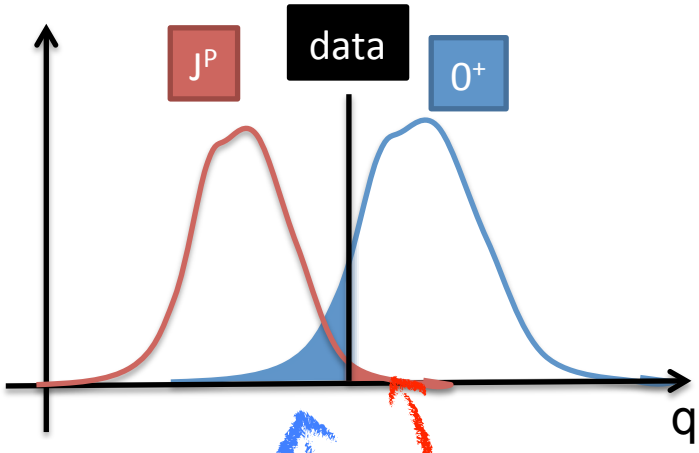
$$\mathcal{L}(J^P, \mu, \boldsymbol{\theta}) = \prod_j^{N_{\text{chann.}}} \prod_i^{N_{\text{bins}}} P\left(N_{i,j} \mid \mu_j \cdot S_{i,j}^{(J^P)}(\boldsymbol{\theta}) + B_{i,j}(\boldsymbol{\theta})\right) \times \mathcal{A}_j(\boldsymbol{\theta})$$

Signal rate for each channel — Expected background events

- **Test statistic to distinguish two J^P hypothesis based on ratio of profiled likelihoods**

$$q = \log \frac{\mathcal{L}(J^P = 0^+, \hat{\hat{\mu}}_{0^+}, \hat{\hat{\theta}}_{0^+})}{\mathcal{L}(J^P_{\text{alt}}, \hat{\hat{\mu}}_{J^P_{\text{alt}}}, \hat{\hat{\theta}}_{J^P_{\text{alt}}})}$$

- **Pseudo experiments used to extract the test statistic distribution**
- **Exclusion of alternative hypothesis wrt SM evaluated in terms of CLs**



$$\text{CL}_s(J^P_{\text{alt}}) = \frac{p_0(J^P_{\text{alt}})}{1 - p_0(0^+)}$$

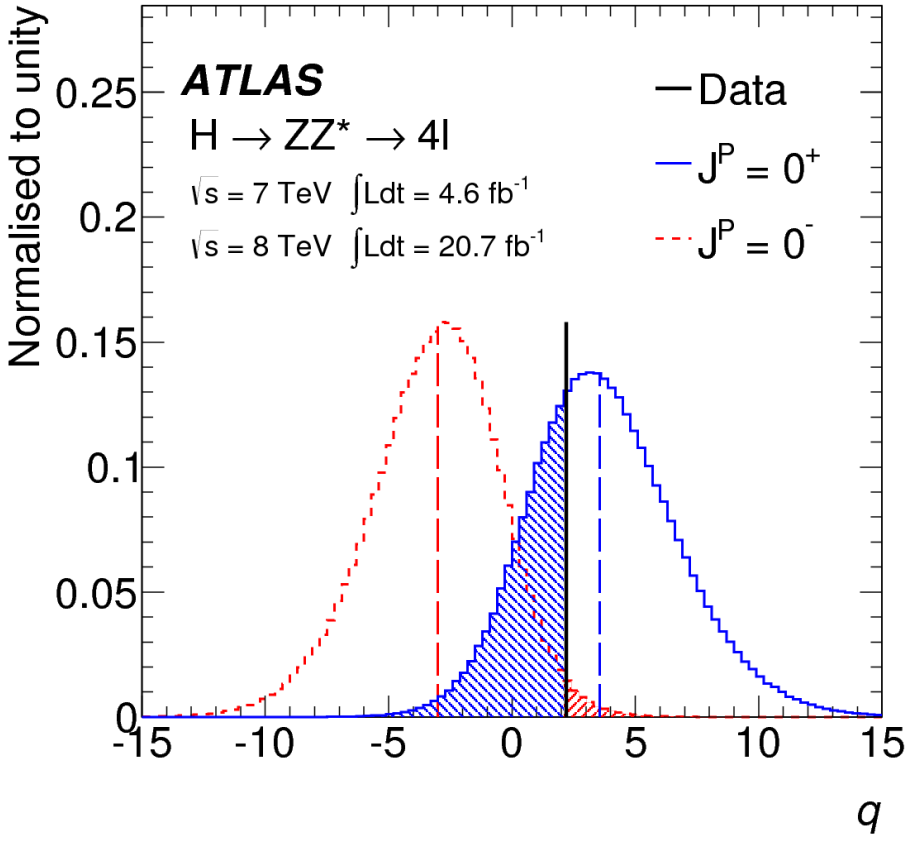
Standard Model $J^P=0^+$ vs $J^P=0^-$

- $H \rightarrow ZZ^* \rightarrow 4l$ channel only

	ZZ^*	WW^*	$\gamma\gamma$
0^-	✓	-	-
$1^+,1^-$	✓	✓	-
2^+	✓	✓	✓

- Data in agreement with $J^P=0^+$ hypothesis

- $J^P=0^-$ hypothesis of the observed resonance excluded @ 97.8% CL
  - expected exclusion: 99.6%

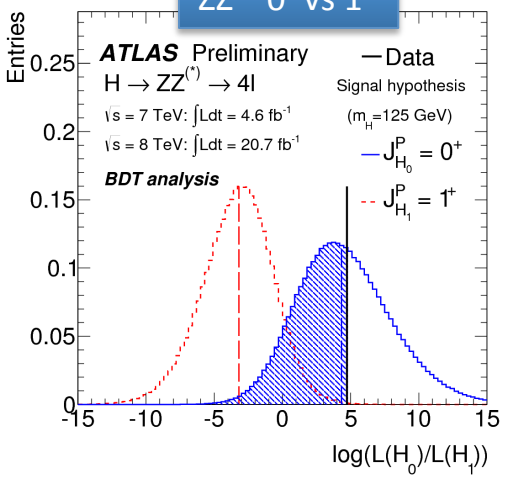


Channel	0^- assumed Exp. $p_0(J^P=0^+)$	0^+ assumed Exp. $p_0(J^P=0^-)$	Obs. $p_0(J^P=0^+)$	Obs. $p_0(J^P=0^-)$	$CL_s(J^P=0^-)$
$H \rightarrow ZZ^*$	$1.5 \cdot 10^{-3}$	$3.7 \cdot 10^{-3}$	0.31	0.015	0.022

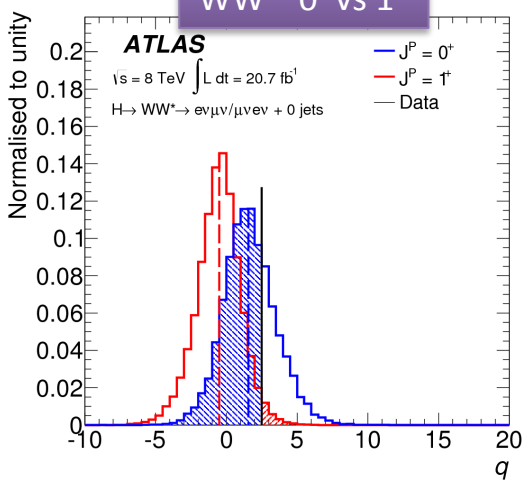
Standard Model $J^P=0^+$ vs $J^P=1^+, 1^-$

- **$H\to ZZ^*\to 4l$ and $H\to WW^*\to l\nu l\nu$ combination**

ZZ 0^+ vs 1^+



WW 0^+ vs 1^+



	ZZ^*	WW^*	$\gamma\gamma$
0^-	✓	-	-
$1^+,1^-$	✓	✓	-
2^+	✓	✓	✓

Channel	1^+ assumed Exp. $p_0(J^P=0^+)$	0^+ assumed Exp. $p_0(J^P=1^+)$	Obs. $p_0(J^P=0^+)$	Obs. $p_0(J^P=1^+)$	$CL_s(J^P=1^+)$
$H\to ZZ^*$	$4.6\cdot10^{-3}$	$1.6\cdot10^{-3}$	0.55	$1.0\cdot10^{-3}$	$2.0\cdot10^{-3}$
$H\to WW^*$	0.11	0.08	0.70	0.02	0.08
Combination	$2.7\cdot10^{-3}$	$4.7\cdot10^{-4}$	0.62	$1.2\cdot10^{-4}$	$3.0\cdot10^{-4}$

$J^P=1^+$ exclusion

H→ZZ*→4l : 99.8% CL
H→WW*→lνlν : 92% CL
Combined : 99.97% CL

Channel	1^- assumed Exp. $p_0(J^P=0^+)$	0^+ assumed Exp. $p_0(J^P=1^-)$	Obs. $p_0(J^P=0^+)$	Obs. $p_0(J^P=1^-)$	$CL_s(J^P=1^-)$
$H\to ZZ^*$	$0.9\cdot10^{-3}$	$3.8\cdot10^{-3}$	0.15	0.051	0.060
$H\to WW^*$	0.06	0.02	0.66	0.006	0.017
Combination	$1.4\cdot10^{-3}$	$3.6\cdot10^{-4}$	0.33	$1.8\cdot10^{-3}$	$2.7\cdot10^{-3}$

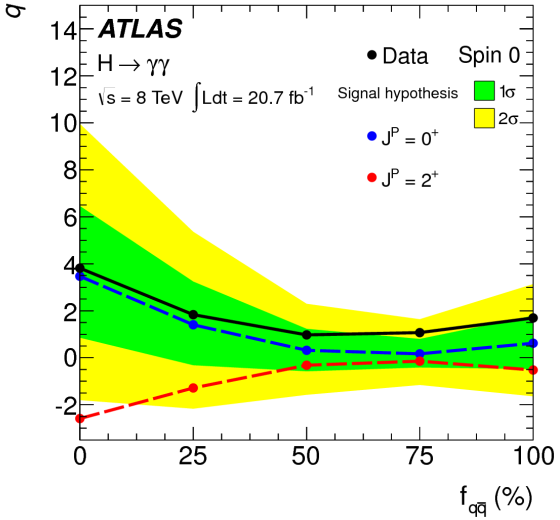
$J^P=1^-$ exclusion

H→ZZ*→4l : 94% CL
H→WW*→lνlν : 98% CL
Combined : 99.7% CL

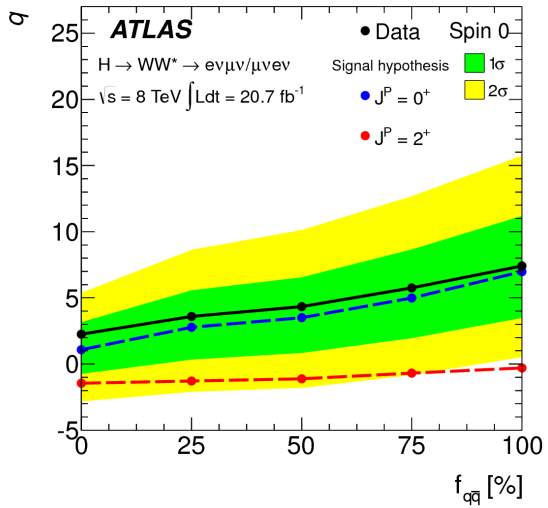
- **Spin 1 hypothesis ($J^P=1^+$ and 1^-) excluded @ more than 99.7% CL**

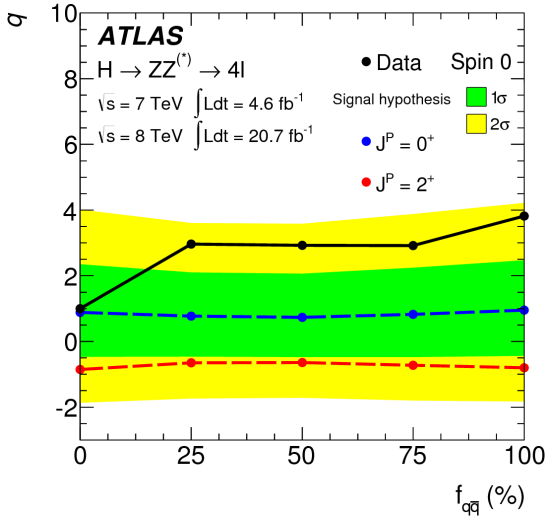
Standard Model $J^P=0^+$ vs $J^P=2^+$

- **Exclusion of the $J^P=2^+$ studied as function of $q\bar{q}/gg$ production mechanism fraction**
- **In minimal model 2^+_m production dominated by ggF @ LO in QCD**
  - **$f_{q\bar{q}}=4\%$**
- **All studied channels contribute**
  - **Complementary sensitivities as function of $f_{q\bar{q}}$**

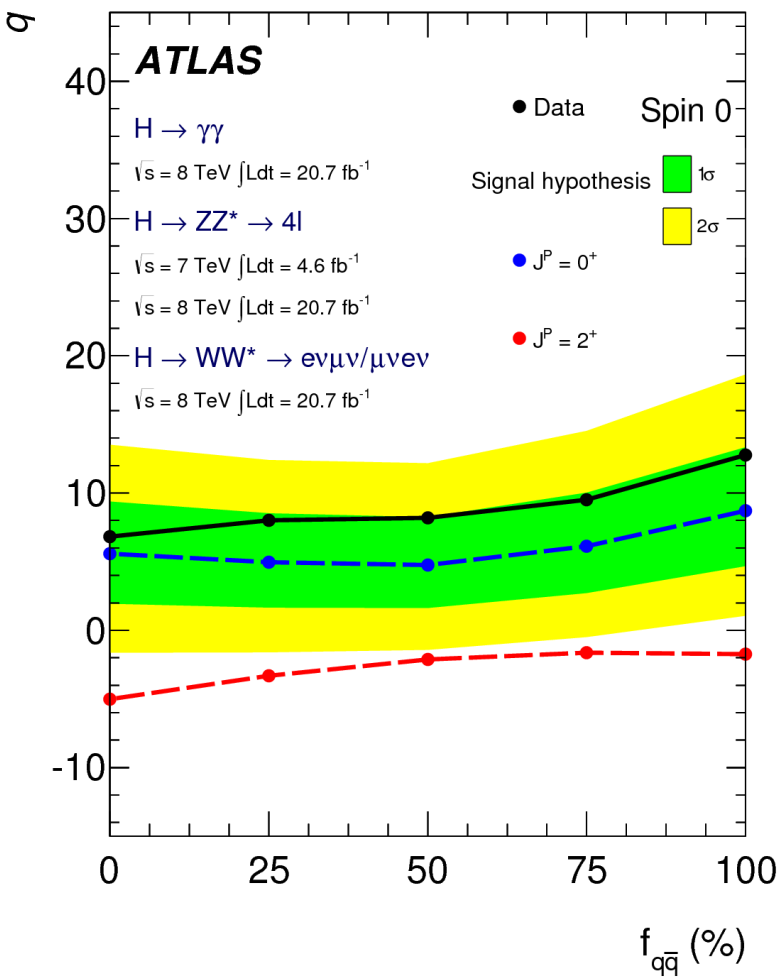


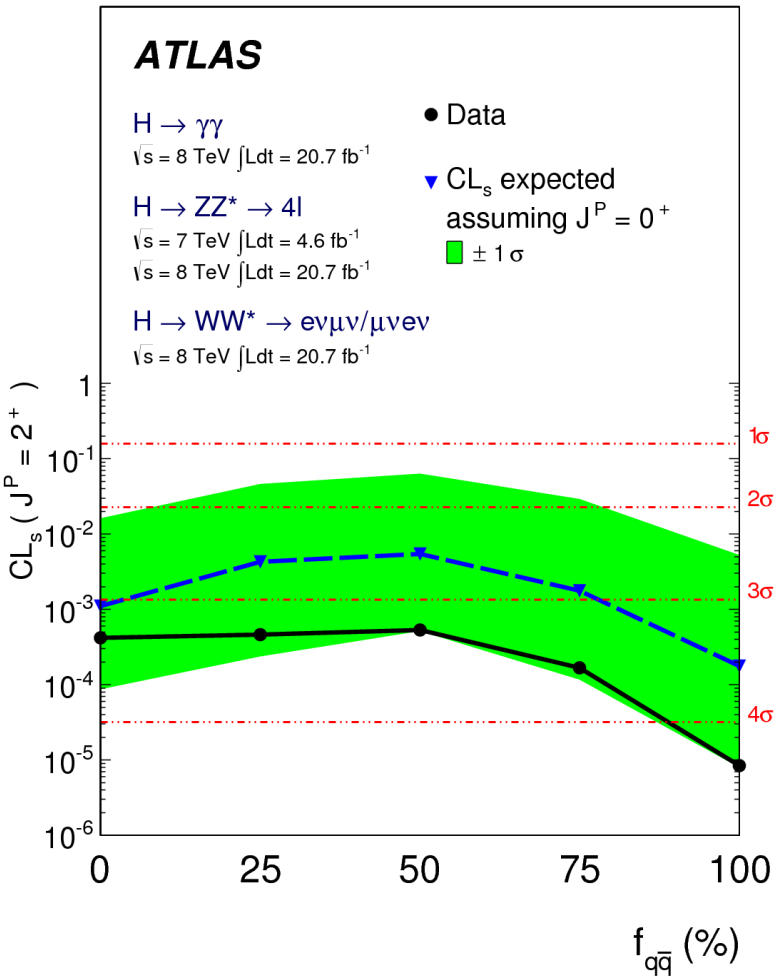
	ZZ*	WW*	γγ
0^-	✓	-	-
$1^+,1^-$	✓	✓	-
2^+	✓	✓	✓





Standard Model $J^P=0^+$ vs $J^P=2^+$

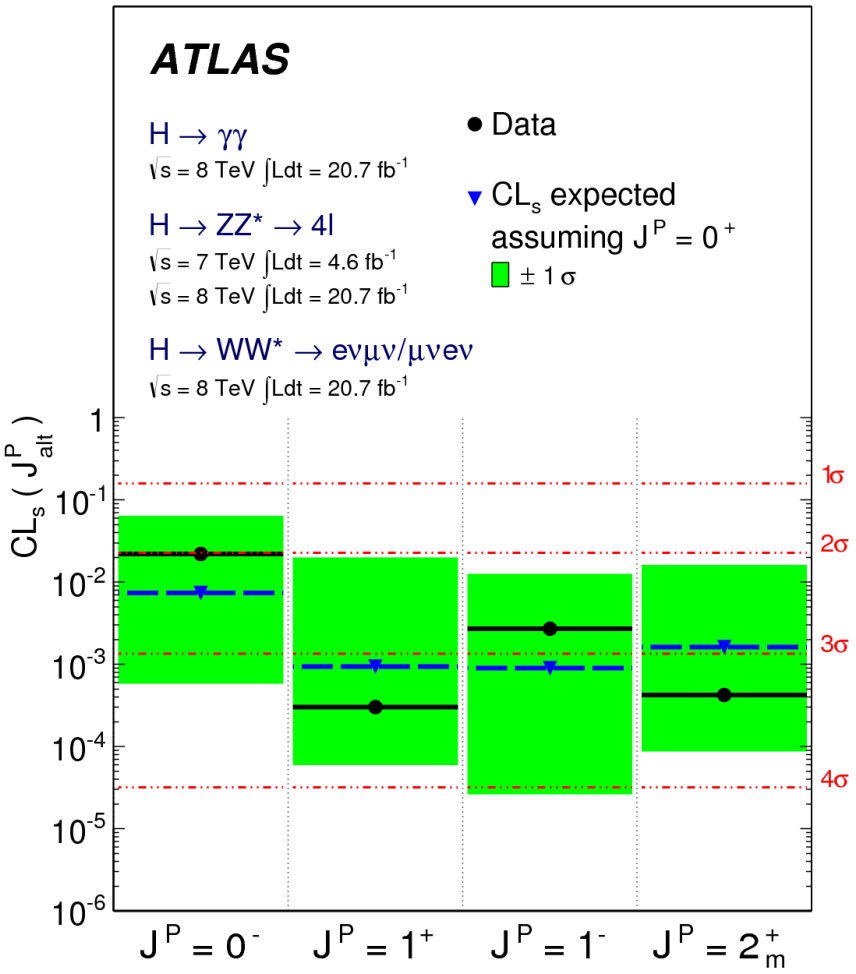




- **ATLAS combined exclusions (γγ, WW*→ lνlν, ZZ*→ 4l) for $J^P=2^+$:**
  - **$J^P=2^+$(100% gg) hypothesis excluded at >99.9% CL**
  - **$J^P=2^+$(100% $q\bar{q}$) hypothesis excluded at >99.9% CL**

Conclusions

- Great performances of ATLAS and CM experiments @ LHC
  - Discovery of new boson
- Full RUN1 datasets used to study the properties of this new particle
  - Is this the Higgs Boson of SM?
- Quantum numbers studied with 3 diboson channels
  - $H \to \gamma\gamma$, $H \to WW^* \to l\nu l\nu$, $H \to ZZ^* \to 4l$
- Data favor the SM $J^P=0^+$ against the alternative hypotheses tested
  - $J^P=0^-$ excluded at 98.7% CL
  - $J^P=1^+,1^-$ excluded at > 99.7% CL
  - $J^P=2^+$ excluded at > 99.9% CL for all $gg/q\bar{q}$ production fraction tested



Backup

References

- "Measurements of the properties of the Higgs-like boson in the four lepton decay channel with the ATLAS detector using 25 fb^{-1} of proton-proton collision data"
  - ATLAS-CONF-2013-013
- "Study of the spin properties of the Higgs-like boson in the H → WW(*) → e ν μ ν channel with 21 fb^{-1} of $\sqrt{s}$ = 8 TeV data collected with the ATLAS detector"
  - ATLAS-CONF-2013-031
- "Study of the spin of the Higgs-like boson in the two photon decay channel using 20.7 fb^{-1} of pp collisions collected at sqrt(s) = 8 TeV with the ATLAS detector"
  - ATLAS-CONF-2013-029
- "Study of the spin of the new boson with up to 25 fb^{-1} of ATLAS data"
  - ATLAS-CONF-2013-040
- "Evidence for the spin-0 nature of the Higgs boson using ATLAS data"
  - Phys. Lett. B 726 (2013), pp. 120-144