# Couplings to fermions and bosons

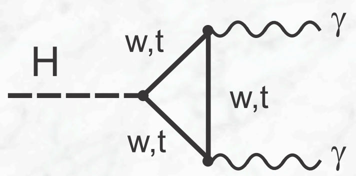
- Assume only one scale factor for fermion and vector couplings:

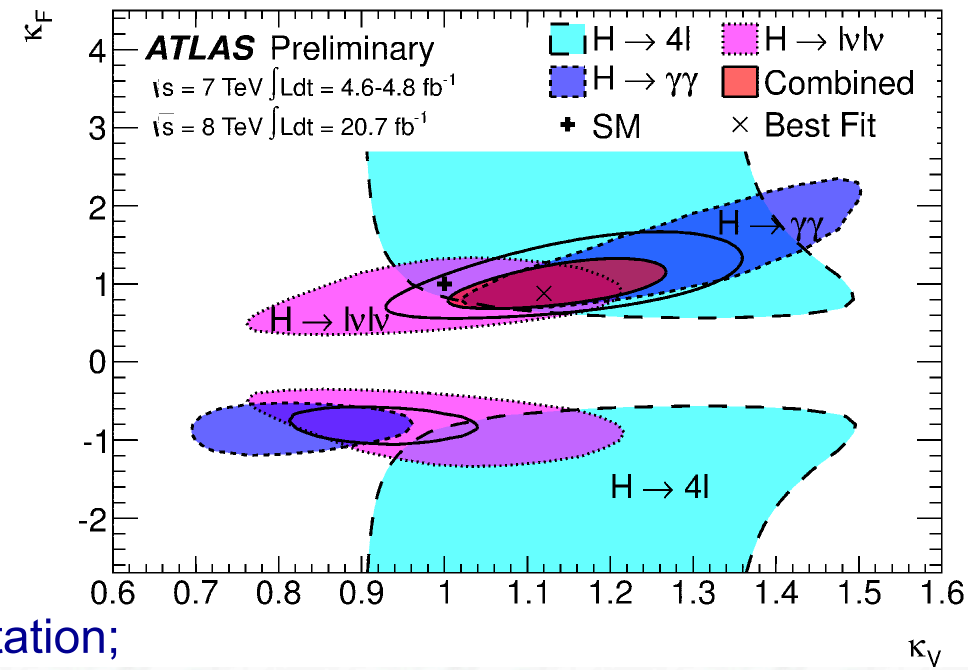
  $\kappa_V = \kappa_W = \kappa_Z$

  $\kappa_F = \kappa_t = \kappa_b = \kappa_\tau$

- Assume that H → $\gamma\gamma$ and gg → H loops and the total Higgs boson width depend only on $\kappa_V$ and $\kappa_F$ (no contributions from physics beyond the Standard Model)

- Sensitivity to relative sign between $\kappa_F$ and $\kappa_V$ only from interference term in H → $\gamma\gamma$ decays (assume $\kappa_V$ > 0)




Results:

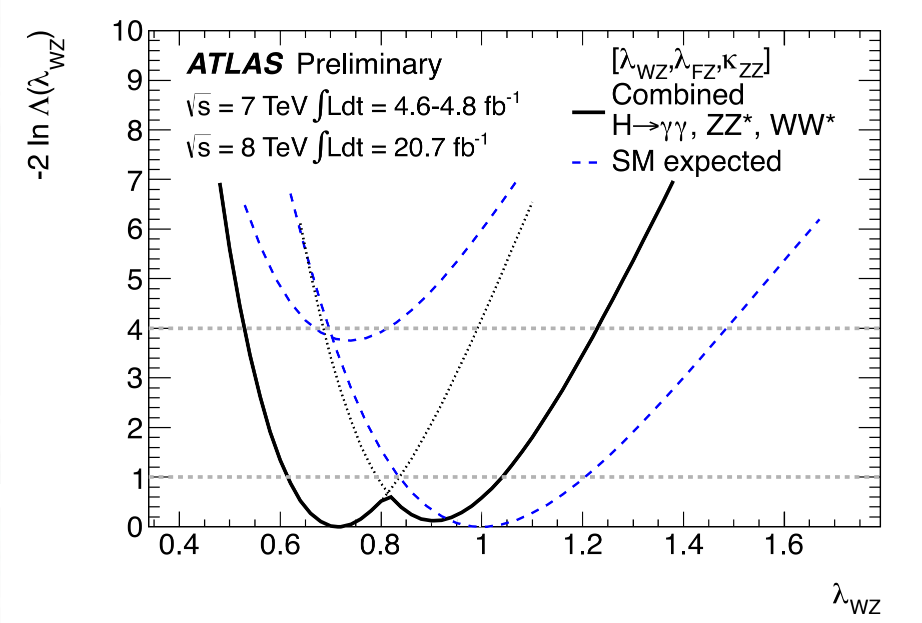
- Data consistent with the SM expectation;
  Two-dimensional consistency: 12%

- 68% CL intervals: $\kappa_F \in [0.76, 1.18]$ $\kappa_V \in [1.05, 1.22]$

# Ratio of couplings to the W and Z bosons

- Custodial symmetry requires $\lambda_{WZ} := \kappa_W/\kappa_Z = 1$

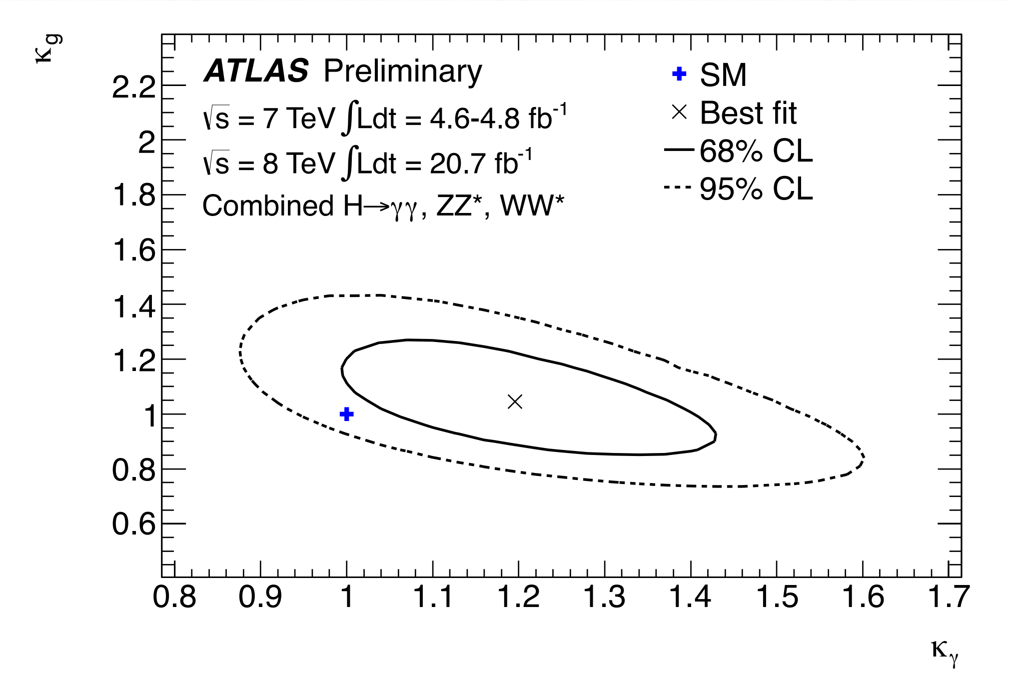
- Sensitivity via VBF and VH production and H → WW and H → ZZ rates




68% CL intervals: $\lambda_{WZ} \in [0.61, 1.04]$

# Constraints on production and decay loops

- Test on contributions from other particles contributing to loop-induced processes
- Assume nominal couplings for all SM particles $\kappa_i = 1$
  and that the new particles do not contribute to the Higgs boson width
- Introduce effective scale factors $\kappa_g$ and $\kappa_\gamma$

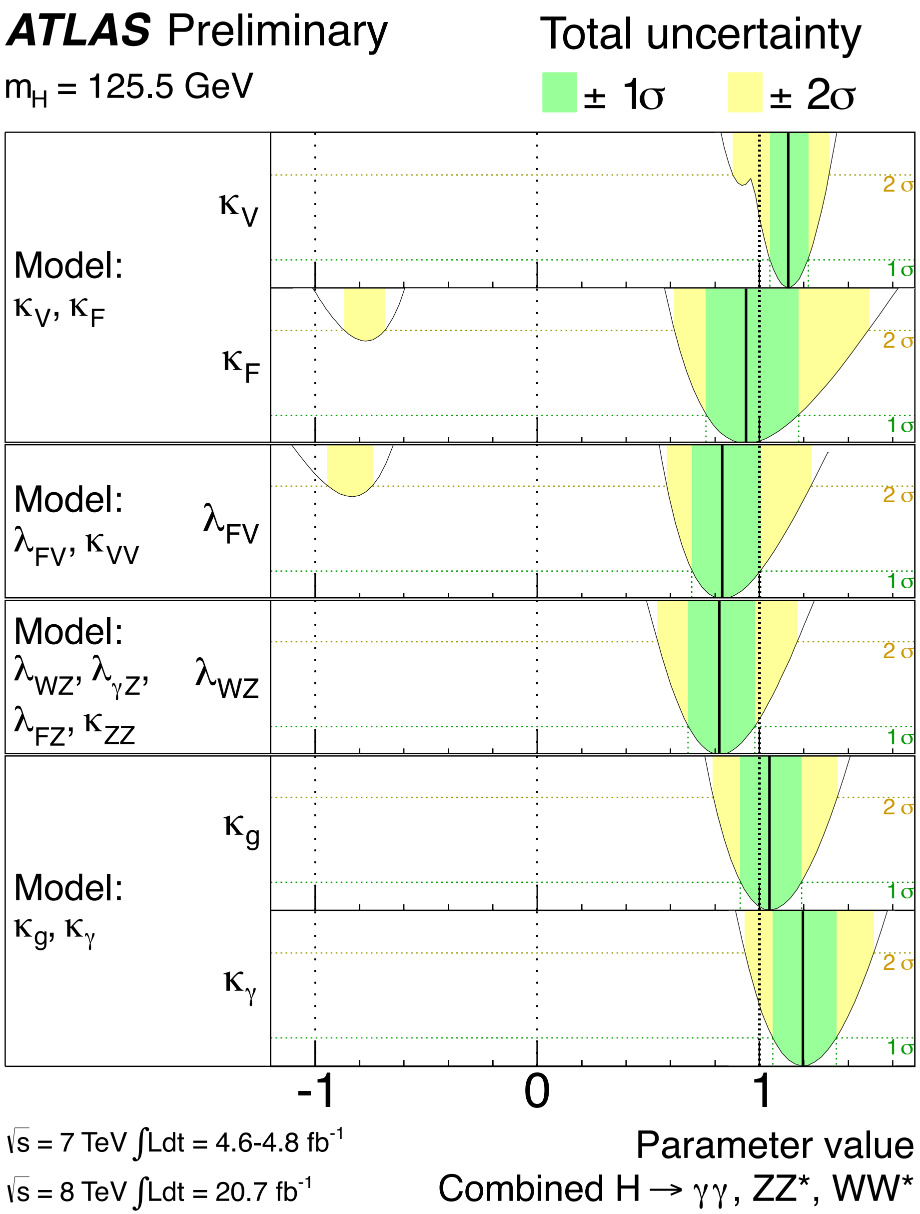



Best fit values:

$\kappa_g = 1.04 \pm 0.14$

$\kappa_\gamma = 1.20 \pm 0.15$

# Summary of coupling scale factor measurements




$$\lambda_{FV} = \kappa_F / \kappa_V$$

$$\kappa_{VV} = \kappa_V \kappa_V / \kappa_H$$

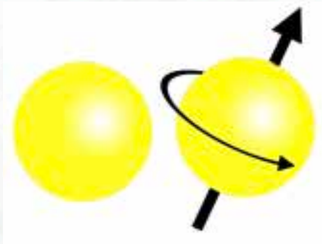
If assumption of no contributions from new particles to the Higgs boson width is relaxed, only the ratio of $k_F/k_V$ can be measured

Extended fit, decouple $H \rightarrow \gamma\gamma$ event rate from the measurement of $\lambda_{WZ}$

- $\kappa_V$ constrained at ±10% level
- Couplings to fermions indirectly observed (5σ)
- $\kappa_W/\kappa_Z$ found to be consistent with one
- No evidence for significant anomalous contributions to the $gg \rightarrow H$ and $H \rightarrow \gamma\gamma$ loops

  (for fixed nominal couplings of SM particles and no BSM contributions to Higgs width)

# Spin and Parity



*Wolfgang Pauli and Niels Bohr studying the motion of a gyro (1952, at the opening of the institute for theoretical physics in Lund /Sweden)*

Standard Model Higgs boson: $J^P = 0^+$

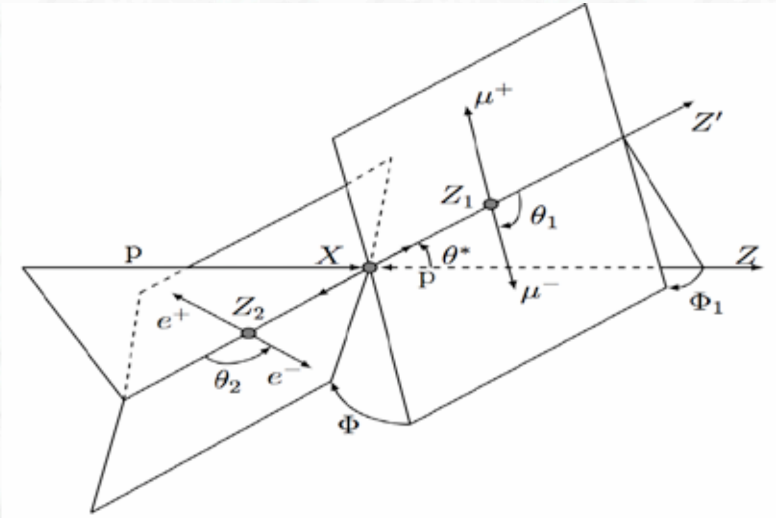
→ strategy is to falsify other hypotheses ($0^-$, $1^-$, $1^+$, $2^-$, $2^+$)

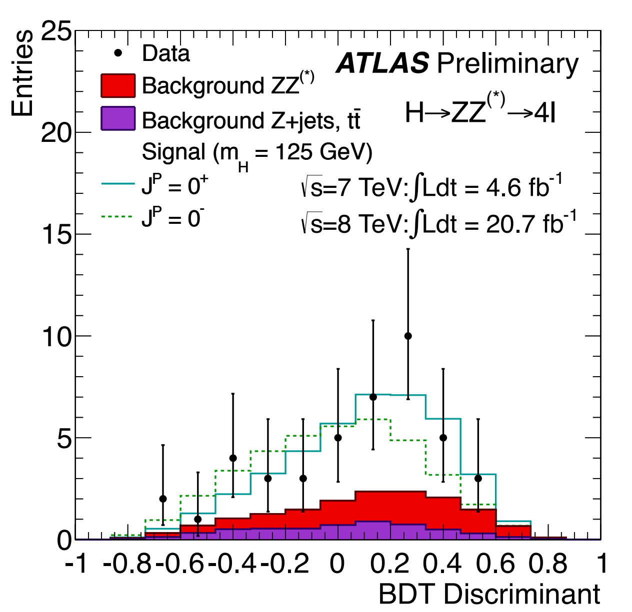
and demonstrate consistency with the $0^+$ hypothesis

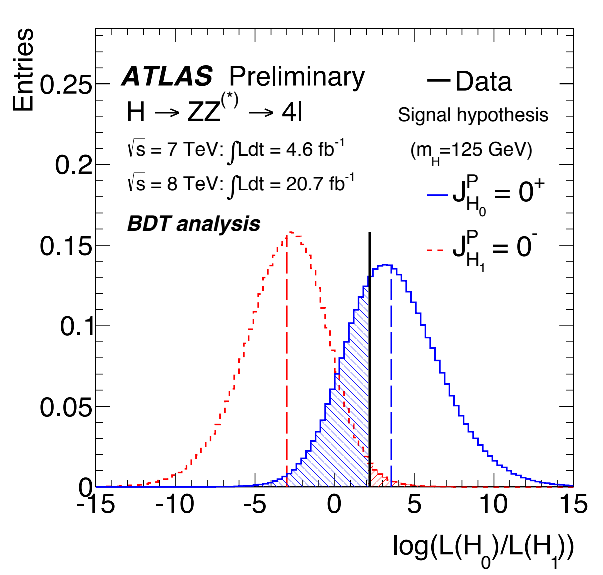
Spin 1: strongly dis-favoured by observed $H \rightarrow \gamma\gamma$ decays, Landau-Yang theorem

# $J^P = 0^-$ versus $J^P=0^+$ (H → ZZ$^{(*)}$ → 4ℓ events)

- Sensitive variables:
  - Masses of the two Z bosons
  - Production angle $\theta^*$
  - Four decay angles $\Phi_1$, $\Phi$, $\theta_1$ and $\theta_2$
- Perform multivariate analysis
  (Boosted decision tree, similar sensitivity using matrix-element method)



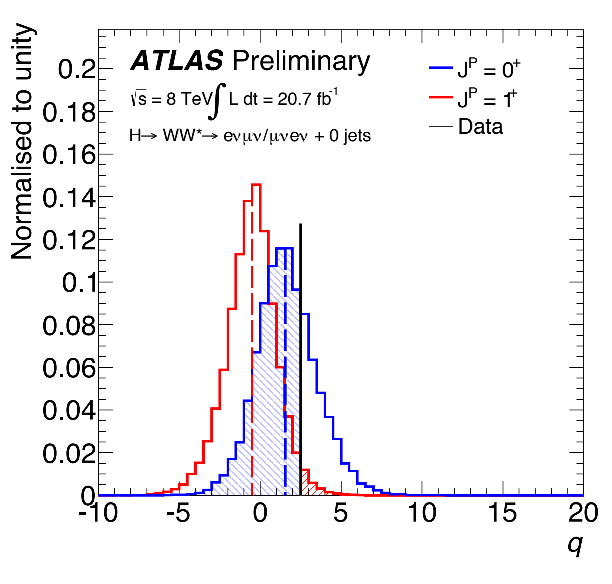



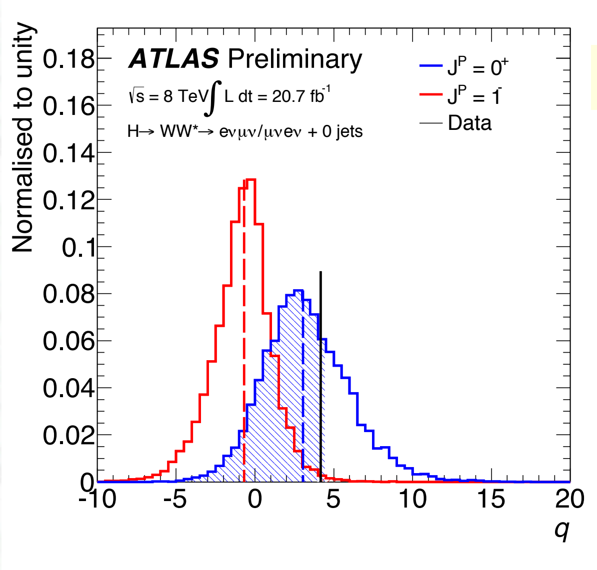




Exclude $J^P=0^-$ (vs. $0^+$) with 97.8% CL

# $J^P = 1^{+/-}$ versus $J^P=0^+$ (H → ZZ* and H → WW* events)

- H → ZZ*, as before: BDT separation based on masses and angles
- H → WW*: $m_{\ell\ell}$, $\Delta\phi_{\ell\ell}$, $p_T(\ell\ell)$, $m_T$ carry information on spin, combine these variables using a BDT analysis




H → WW*

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

q = test statistics to discriminate between two spin hypotheses

| | $p_0$ ($0^+$) | CL ($1^+$) Exclusion | $p_0$ ($0^+$) | CL ($1^-$) Exclusion |
|---|---|---|---|---|
| H → ZZ* | 0.55 | 99.8% | 0.1 | 94% |
| H → WW* | 0.70 | 92% | 0.66 | 98% |
| Combination | 0.62 | 99.97% | 0.33 | 99.7% |

# $J^P = 2^+$ versus $J^P=0^+$ ($H \rightarrow \gamma\gamma$, $H \rightarrow ZZ^*$, and $H \rightarrow WW^*$ events)

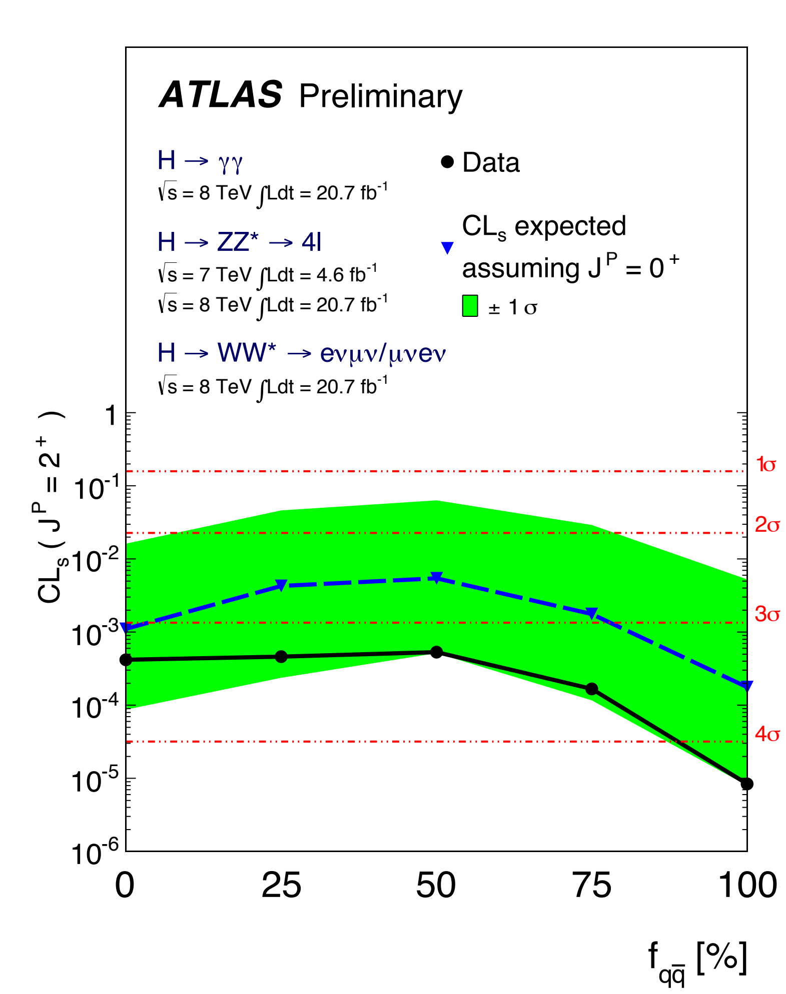
- Spin 2: consider graviton-like tensor, equivalent to a Kaluza-Klein graviton

  (Y. Gao et al, Phys. Rev. D81 (2010) 075022)

- Production via gluon fusion and qq annihilation possible;
  Studies are performed as a function of the qq annihilation fraction ($f_{qq}$)

- Specific model $2^+_m$:
  minimal couplings to SM particles

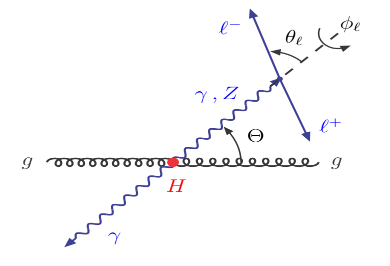
  ($f_{qq}$ = 4% at LO, however, large uncertainties)




- Observed exclusion (combination of $\gamma\gamma$, $ZZ^*$ and $WW^*$) of $J^P = 2^+$ (versus the SM $J^P = 0^+$) exceeds 99.9%, independent of $f_{qq}$;
  Complementary behaviour of the different channels

# Example: H → γγ contribution

Use decay angle w.r.t. collision axis in the Collins-Soper frame



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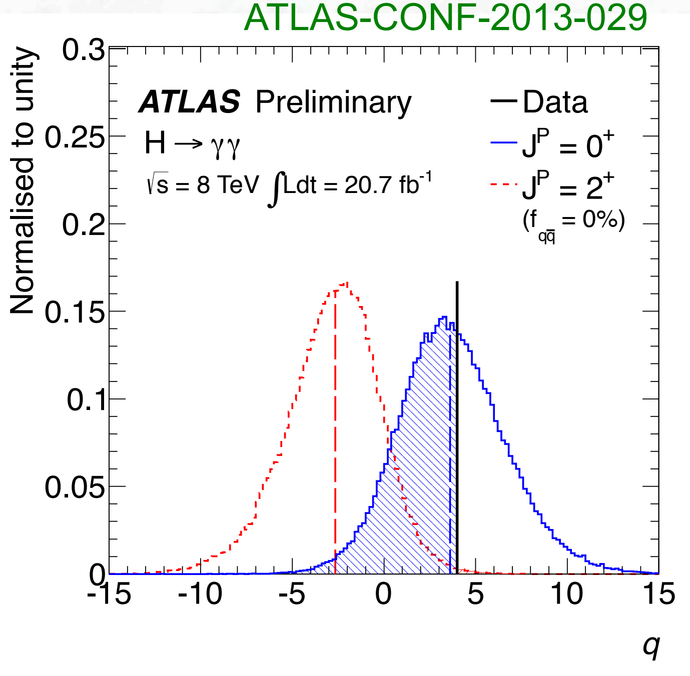


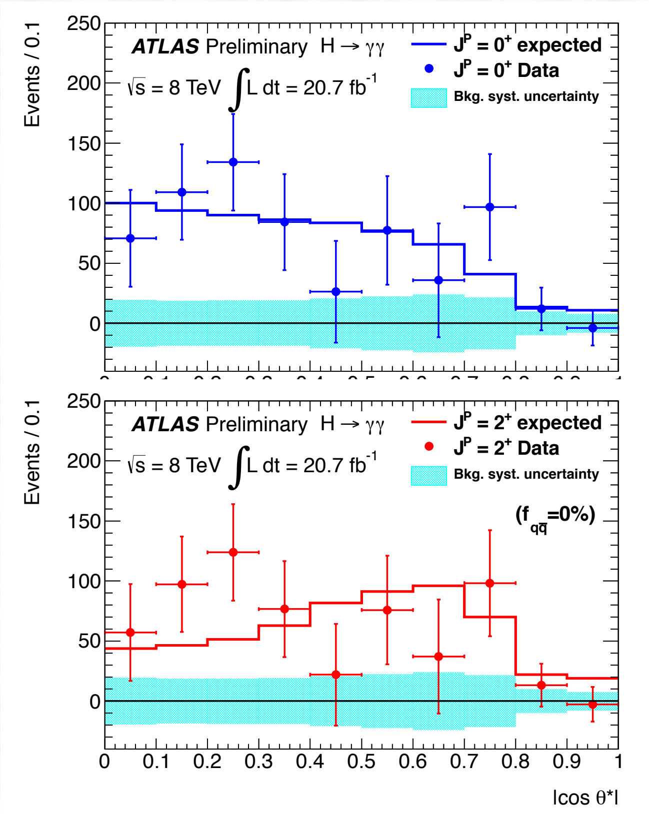


cos θ* distribution in signal region, after background subtraction

Exclude $J^P=2^+$ (produced via gluon fusion, $f_{qq}= 0$) (vs. $0^+$) via H → γγ decays with 99.3% CL

# Conclusions

- A milestone discovery announced in July 2012
- Signals have been impressively confirmed with additional data; discovery phase has turned into the measurement phase
- ATLAS data are consistent with the expectations for the Standard Model Higgs boson (within present uncertainties)

  - Production rates and coupling strengths
  - Evidence for VBF production
  - Evidence for spin-0 ($0^-$ disfavoured)

- Exciting times ahead of us to study the Higgs boson with higher precision (> 2015) and look for surprises (deviations? more Higgs bosons? …)