Measurements of Higgs Boson spin and CP at the LHC

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In the next 15 minutes

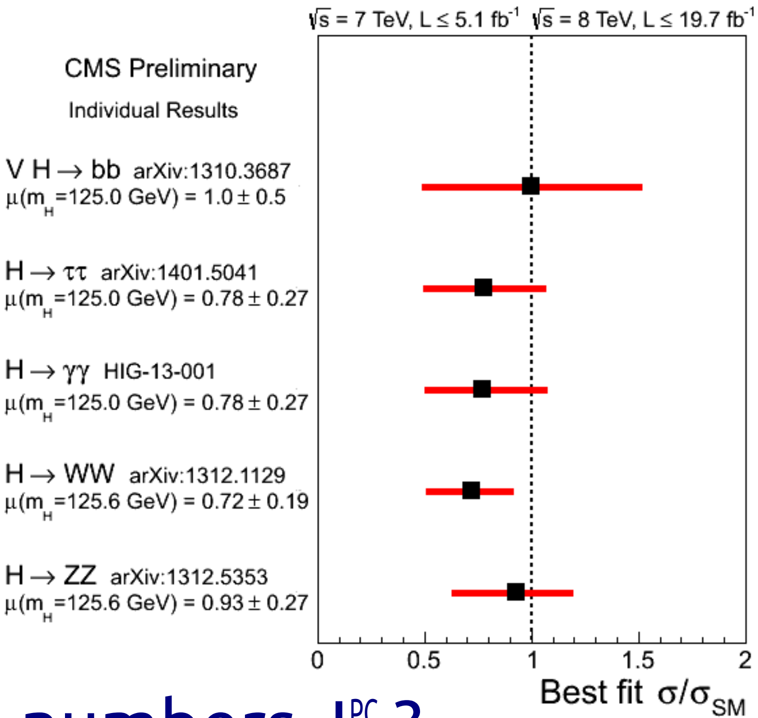
- If ATLAS and CMS can say about:

  higgs boson == The Higgs boson

- Through the 3 giants
  - $H \rightarrow ZZ \rightarrow 4l$
  - $H \rightarrow WW \rightarrow 2l2\nu$
  - $H \rightarrow \gamma\gamma$
- And their combination

Motivation

- July 2012: new resonance discovered by CMS and ATLAS collaborations
  [Phys.Lett. B716 (2012); Phys.Lett. B716 (2012)]
- Couplings and signal strength compatible with the SM Higgs boson:
  - μ = 1.33 ± 0.20 (ATLAS)
  - μ = 0.80 ± 0.14 (CMS)

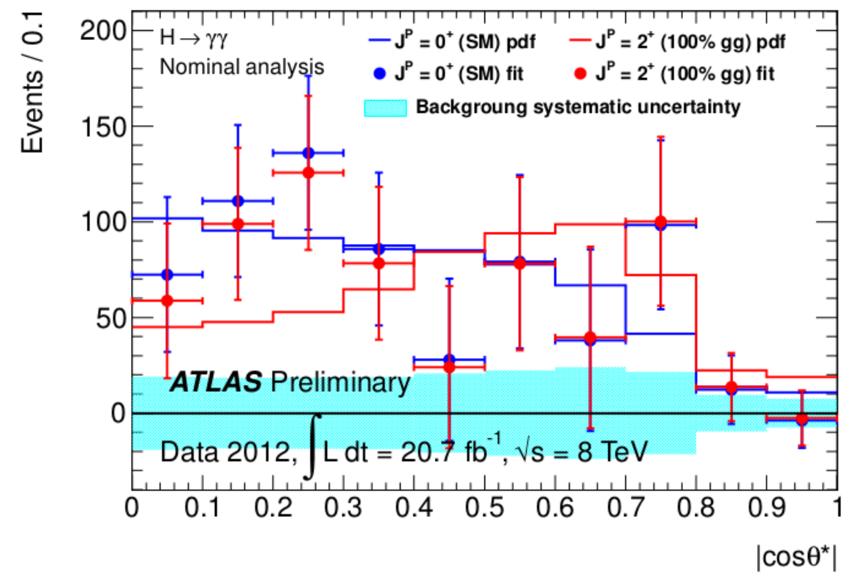


What are the new particle's quantum numbers J^{PC} ?

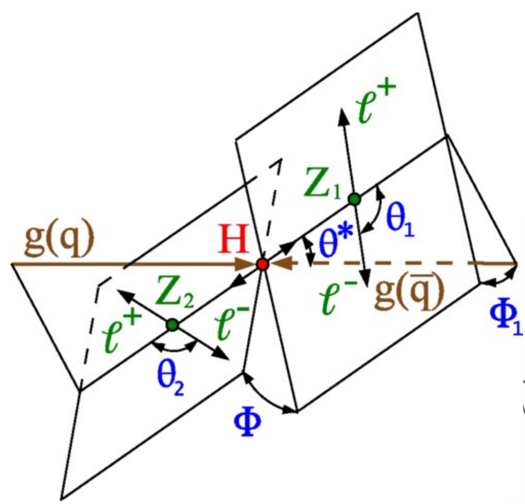
- SM predicts J^{PC} = 0
  - Observation in diphoton implies C=1 and disfavors J=1 due to Landau-Yang
    - ZZ, WW channels can test spin-1 hypothesis for independent confirmation and mixtures
  - Observation in WW favors J=0 (biased selection)
  - Observation in ZZ, WW disfavor P=-1
- Next step is to test the 0^+ hypothesis against alternative models

Spin and parity strategy - observables

- For each channel, find observables
    - discriminate between the SM and the alternative hypotheses
- We test spin-parity → angles interesting
- Different channels → different kinematic properties

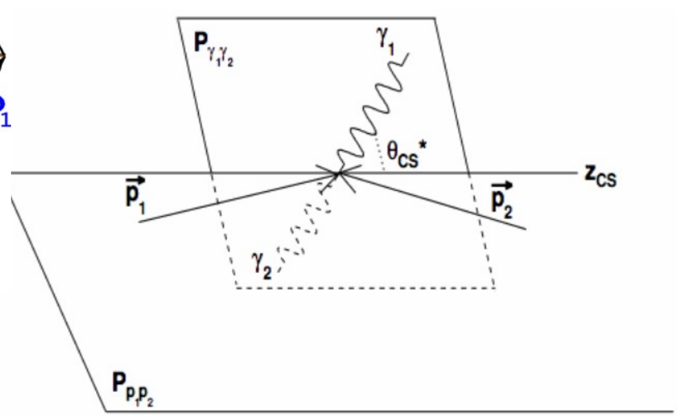


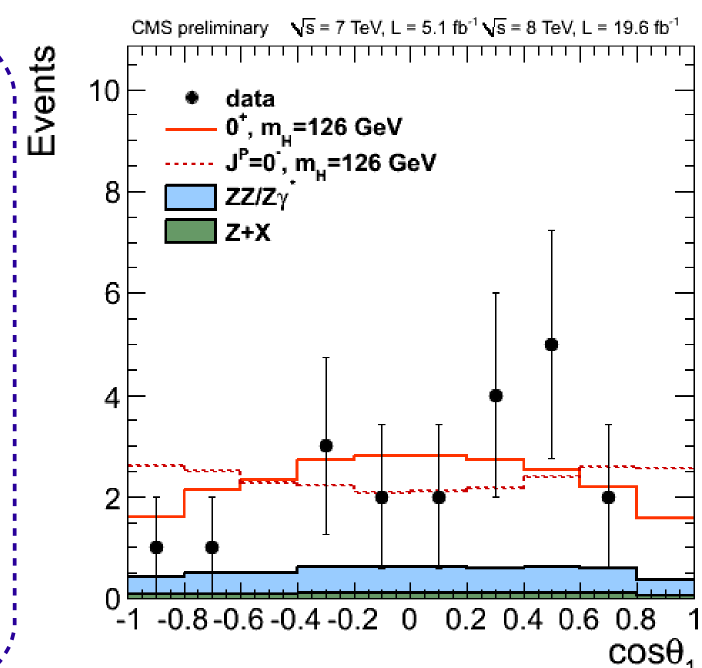
Angles



H → ZZ → 4l

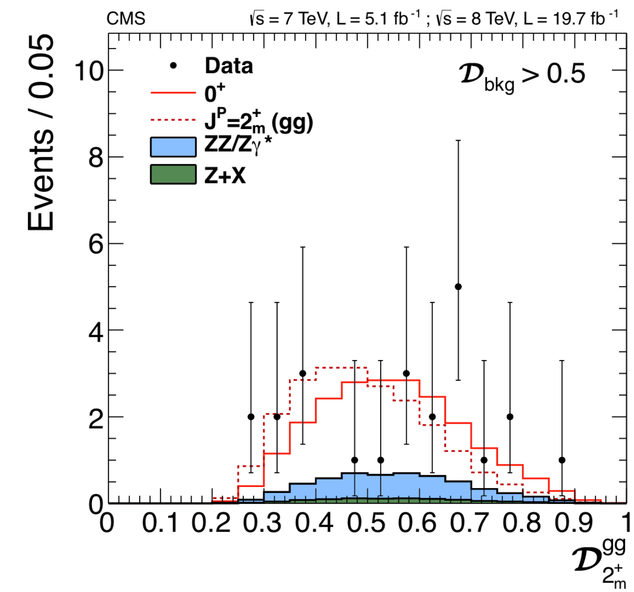
H → γγ



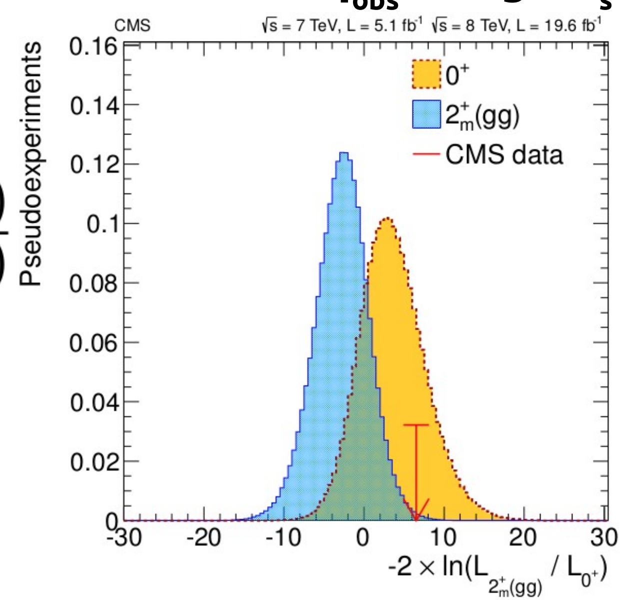


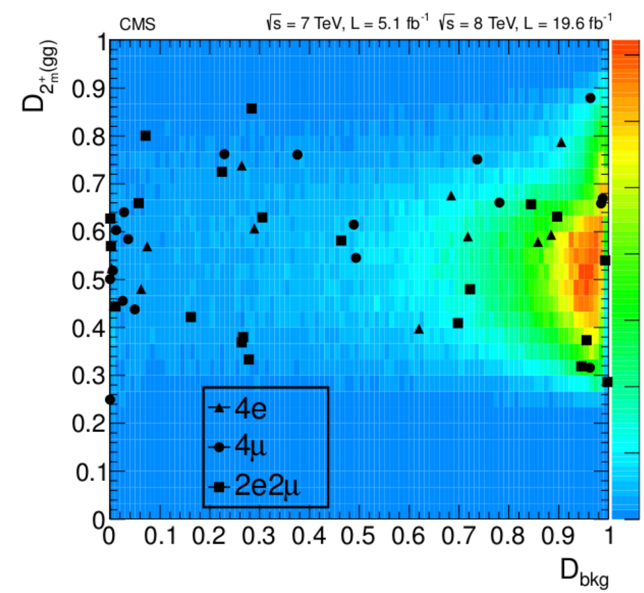
Spin and parity strategy – likelihood

- for good discrimination - looking at a single variable is usually not enough
- From simulations (and control regions), obtain the distributions for background, signal and alternative hypotheses events in the space of the discriminating variables → likelihood distributions for signals/models
- Pseudo-experiments to generate the distribution of the test statistics
- **$q = -2 \log(L_{SM}/L_{JP})$** under the SM/alternative hypothesis
- Compare with results observed in the data **q_{obs}** using **CL_s**



$$CL_s = \frac{P(q \geq q_{obs} \,|\, S_2 + B)}{P(q \geq q_{obs} \,|\, S_1 + B)}$$





Tested models

- Many models tested
- New models tests pipelined for summer conferences

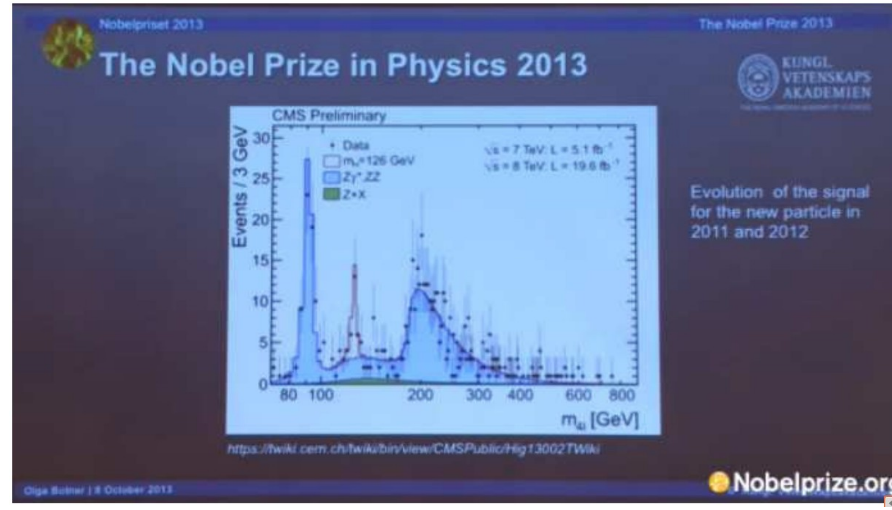
ATLAS		
J^P	prod	channel
0^-	any	ZZ
1^-	any	ZZ,WW
1^+	any	ZZ,WW
2^+_m	gg	ZZ,WW,$\gamma\gamma$
2^+_m	$q\bar{q}$	ZZ,WW,$\gamma\gamma$
2^+_m	any	ZZ,WW,$\gamma\gamma$

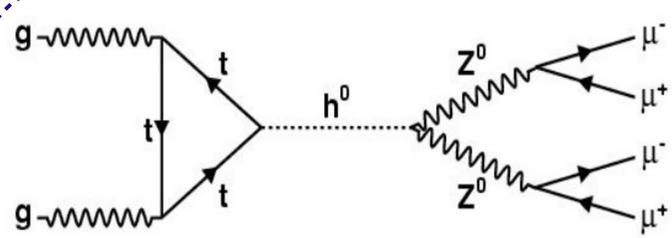
CMS			
J^P	prod	channel	
0^-	any	ZZ,WW	pseudoscalar
0^+_h	any	ZZ	scalar high dim op
1^-	$q\bar{q}$	ZZ	
1^-	any	ZZ	
1^+	$q\bar{q}$	ZZ	
1^+	any	ZZ	
2^+_m	gg	ZZ,WW,$\gamma\gamma$	grav, min. coupl.
2^+_m	$q\bar{q}$	ZZ,WW,$\gamma\gamma$	grav, min. coupl.
2^+_{m}	any	ZZ,WW,$\gamma\gamma$	grav, min. coupl.
2^+_b	gg	ZZ	RS grav, SM in bulk
2^+_h	gg	ZZ	tensor high dim op
2^-_h	gg	ZZ	pseudo-tensor

$H \rightarrow ZZ \rightarrow 4$ leptons

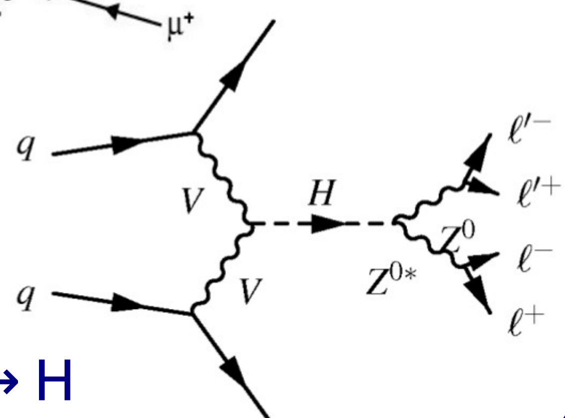
H → ZZ → 4l in a nutshell

- Narow resonance → events in m_{4l} window:
  - [115 – 130] GeV ATLAS
  - [106 – 141] GeV CMS
- 5 angles and 2 masses fully describe the
- H→ZZ→ 4l decay
- Sensitive to both, spin and parity
- Golden channel to probe the 0^- hypothesis



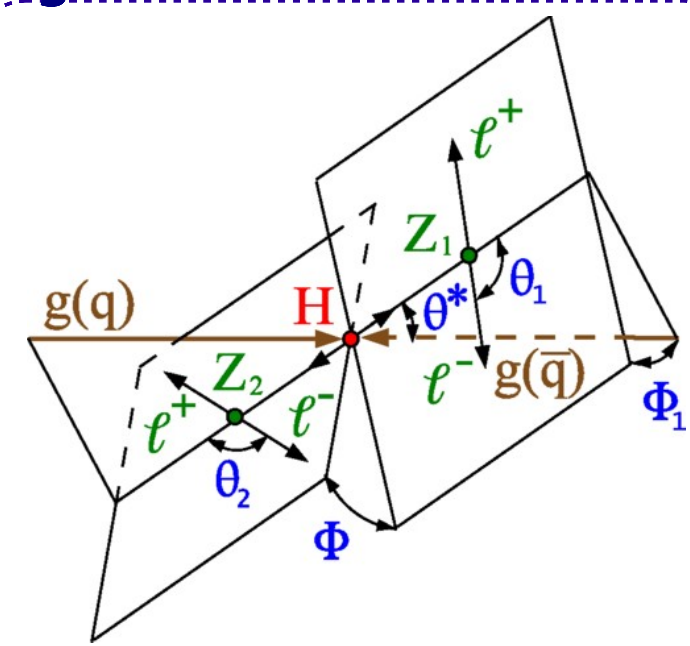


gg → H



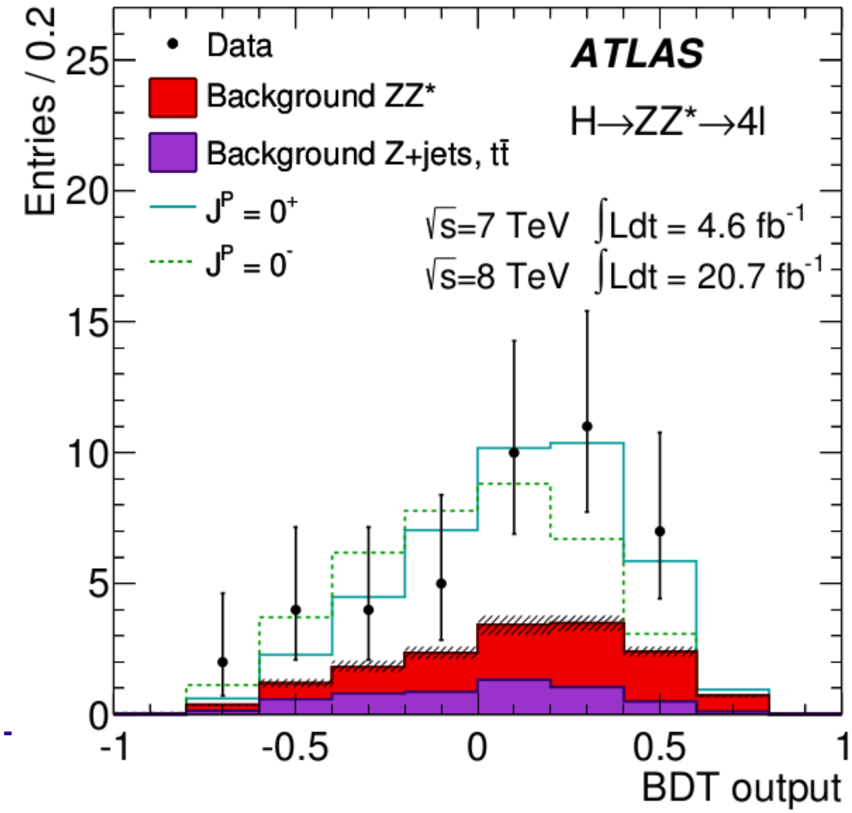
qq → H

Angles



H → ZZ → 4l @ATLAS

- BDT approach using the 5+2 kinematic variables
- Split in 4 final states (4e, 4μ, 2e2μ, 2μ2e) to increase sensitivity
- 2 different mass regions:
  - high S/B in [121-127]
  - low S/B in [115-12] and [127-130]
- 5 different qq fractions tested for spin-2



$f_{q\bar{q}}$	Spin-2 assumed exp. $p_0(J^P = 0^+)$	Spin-0 assumed exp. $p_0(J^P = 2^+)$	obs. $p_0(J^P = 0^+)$	obs. $p_0(J^P = 2^+)$	$CL_s(J^P = 2^+)$
100%	0.102	0.082	0.962	0.001	0.026
75%	0.117	0.099	0.923	0.003	0.039
50%	0.129	0.113	0.943	0.002	0.035
25%	0.125	0.107	0.944	0.002	0.036
0%	0.099	0.092	0.532	0.079	0.169

J = 2 f_{qq} CL_s

		tested J^P for an assumed 0^+		tested 0^+ for an assumed J^P	CL_s
		expected	observed	observed*	
0^-	p_0	0.0037	0.015	0.31	0.022
1^+	p_0	0.0016	0.001	0.55	0.002
1^-	p_0	0.0038	0.051	0.15	0.060

J = 1,2 CL_s

H → ZZ → 4l @CMS

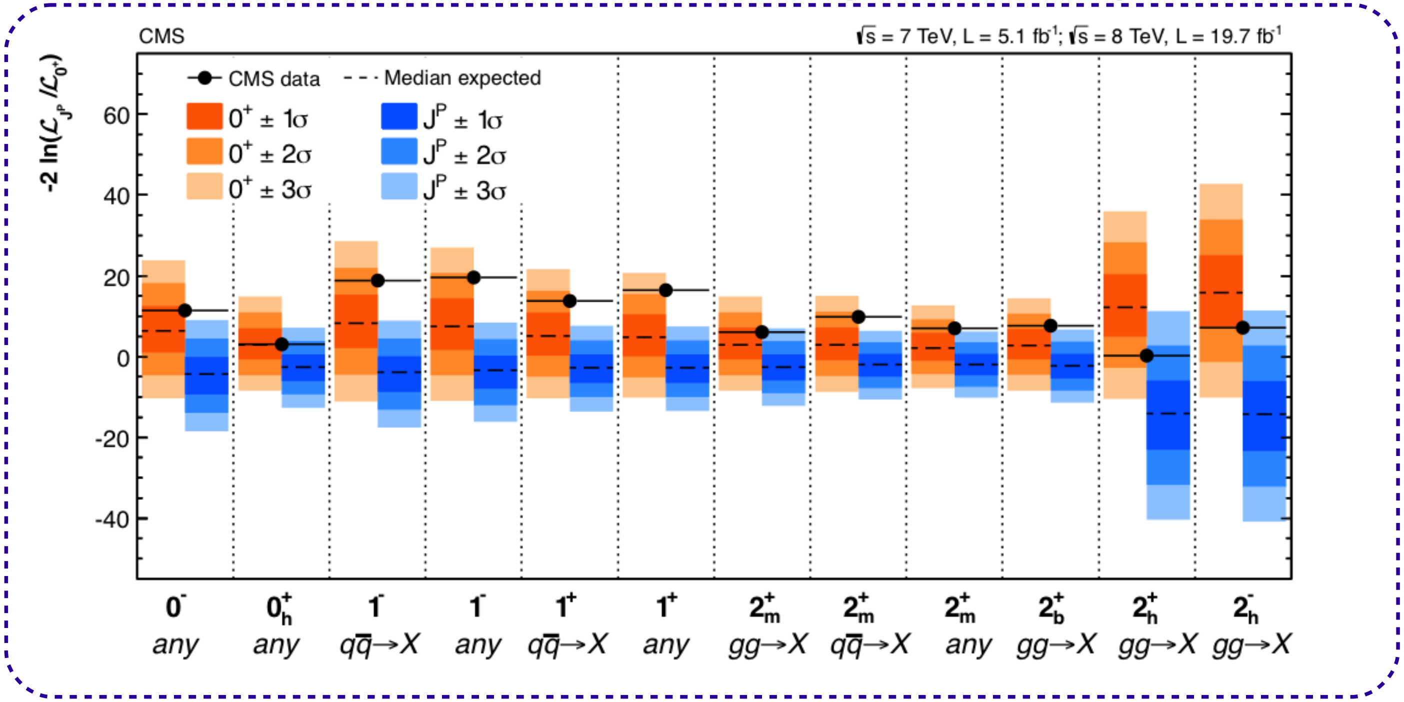
- Matrix Element Likelihood approach compresses kinematic information into 1D discrimants

$$D_{\text{bkg}} = \left[1 + \frac{P^{\text{kin}}_{\text{bkg}}(m_1, m_2, \Omega | m_{4l}) \times P^{\text{mass}}_{\text{bkg}}(m_{4l})}{P^{\text{kin}}_{0+}(m_1, m_2, \Omega | m_{4l}) \times P^{\text{mass}}_{\text{sig}}(m_{4l})}\right]^{-1}$$

$$D_{J^P} = \left[1 + \frac{P^{\text{kin}}_{J^P}(m_1, m_2, \Omega | m_{4l})}{P^{\text{kin}}_{0+}(m_1, m_2, \Omega | m_{4l})}\right]^{-1}$$

- Using 2D templates (D_{JP}, D_{bkg}) to build likelihoods for 0^+ and J^P

- 9 models were tested and excluded + 3 prod. indep. models (1^-, 1^+, 2^+)



$H \rightarrow ZZ \rightarrow 4l$ @CMS

- 9 models were tested and excluded + 3 prod. indep. models (1^-, 1^+, 2^+)

J^P model	J^P production	Expected ($\mu = 1$)	Obs. 0^+	Obs. J^P	CL_s
0^-	any	2.4σ (2.7σ)	-1.0σ	$+3.8\sigma$	0.05%
0^+_h	any	1.7σ (1.9σ)	-0.3σ	$+2.1\sigma$	4.5%
1^-	$q\bar{q} \rightarrow X$	2.7σ (2.7σ)	-1.4σ	$+4.7\sigma$	0.002%
1^-	any	2.5σ (2.6σ)	-1.8σ	$+4.9\sigma$	0.001%
1^+	$q\bar{q} \rightarrow X$	2.1σ (2.3σ)	-1.5σ	$+4.1\sigma$	0.02%
1^+	any	2.0σ (2.1σ)	-2.1σ	$+4.8\sigma$	0.004%
2^+_m	$gg \rightarrow X$	1.9σ (1.8σ)	-1.1σ	$+3.0\sigma$	0.9%
2^+_m	$q\bar{q} \rightarrow X$	1.7σ (1.7σ)	-1.7σ	$+3.8\sigma$	0.2%
2^+_m	any	1.5σ (1.5σ)	-1.6σ	$+3.4\sigma$	0.7%
2^+_b	$gg \rightarrow X$	1.6σ (1.8σ)	-1.4σ	$+3.4\sigma$	0.5%
2^+_h	$gg \rightarrow X$	3.8σ (4.0σ)	$+1.8\sigma$	$+2.0\sigma$	2.3%
2^-_h	$gg \rightarrow X$	4.2σ (4.5σ)	$+1.0\sigma$	$+3.2\sigma$	0.09%

$H \rightarrow ZZ \rightarrow 4l$ @CMS – parameter f_{a3}

- Most general spin-0 boson decay amplitude:

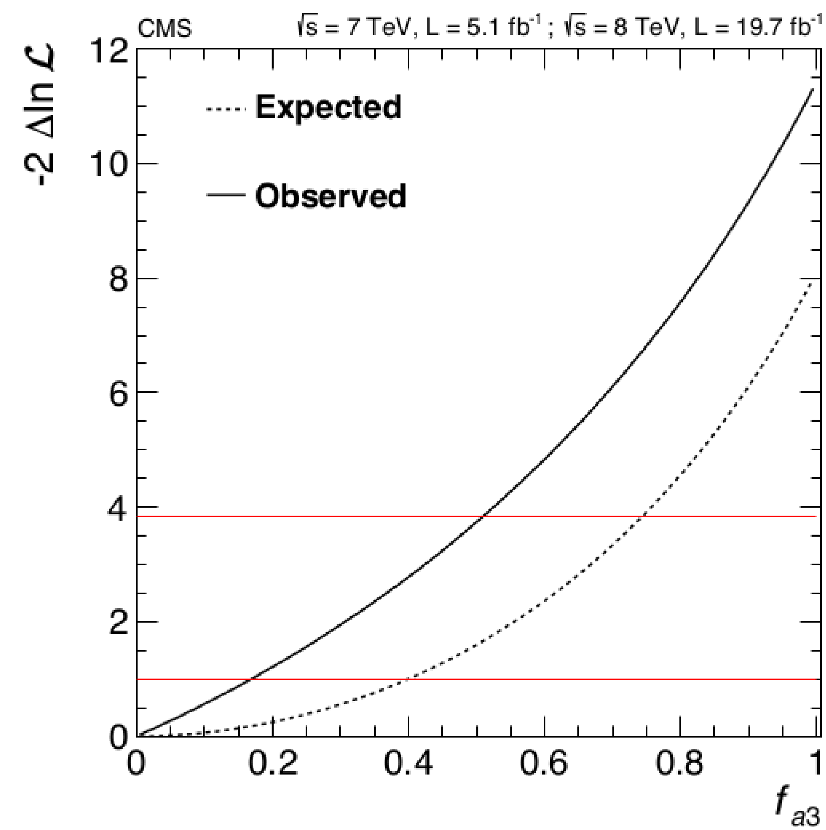
$$A(H \rightarrow ZZ) = v^{-1}\epsilon_1^*\epsilon_2^* \left(a_1 g_{\mu\nu} m_Z^2 + a_2 q_\mu q_\nu + a_3 \epsilon_{\mu\nu\alpha\beta} q_1^\alpha q_2^\beta \right)$$

$|a_1|^2\sigma_3$ $|a_2|^2\sigma_2$ $|a_3|^2\sigma_3$

$$f_{a3} = \frac{|a_3|^2\sigma_3}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3}$$

- CP violation in case $0 < f_{a3} < 1$
- Interference is negligible
  - neglect $|a_2|^2\sigma_2$
- Use shape of D_{0-} as it depends on f_{a3}
- Set a limit on CP violating contributions to HZZ coupling

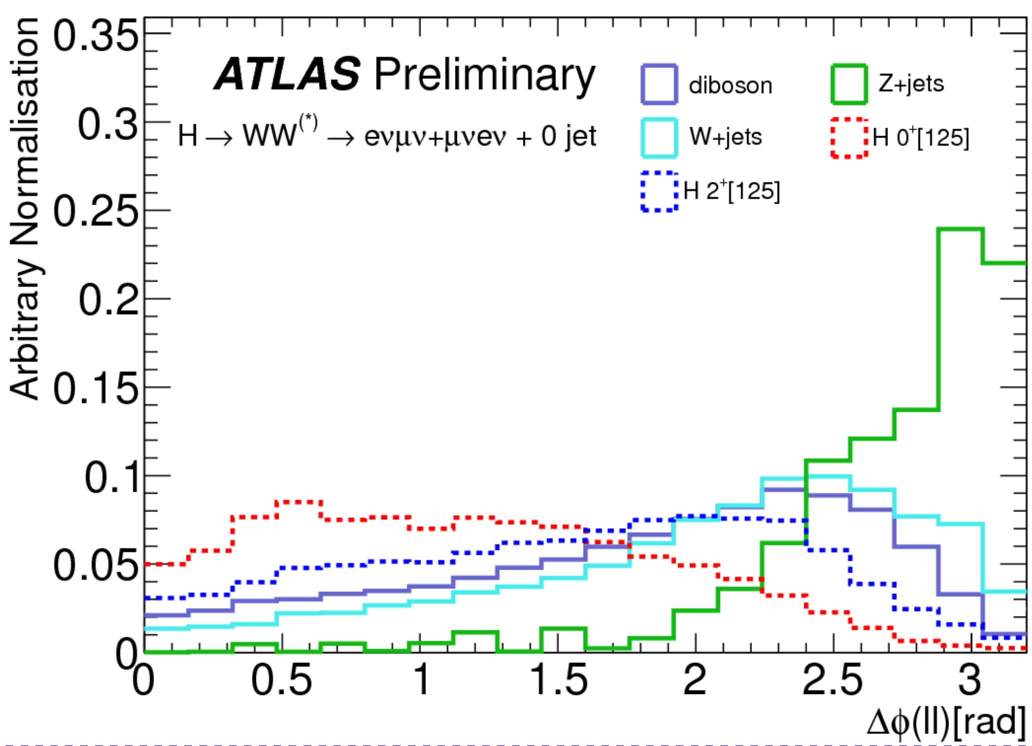
  $f_{a3} < 0.51$ at 95%



$H \rightarrow WW \rightarrow 2l2\nu$

H → WW → 2l2ν in a nutshell

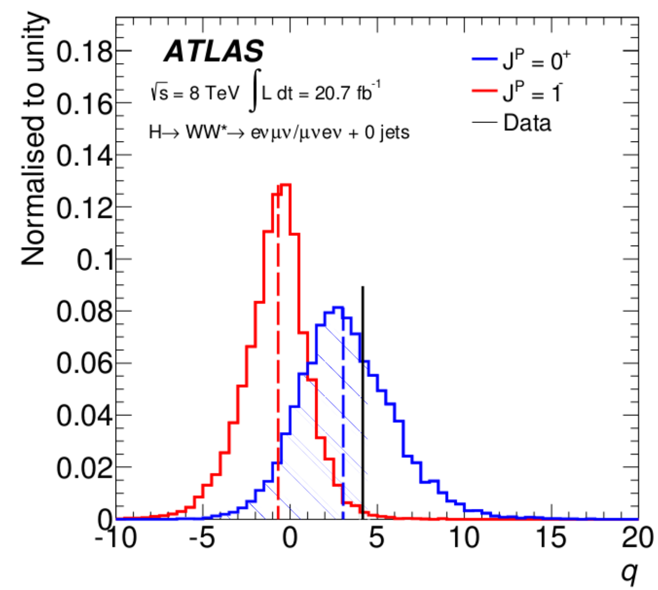
- neutrinos in the final states → low mass resolution
- Low signal, high background → challenging selection
- Can discriminate between spin-0 and spin-2
- key variables: $\Delta\Phi_{ll}$, m_{ll} , p_T^{ll} , m_T
- Most of the sensitivity comes from H → WW → $e\nu_e\, \mu\nu_\mu$



H → WW → 2l2ν @ATLAS

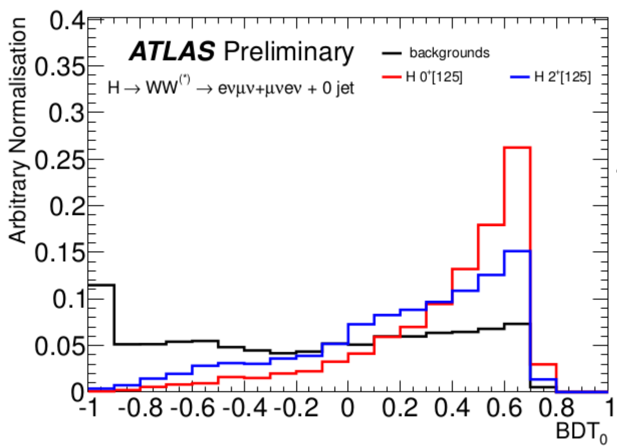
- softer selection wrt nominal:
  - MET > 20 GeV,
  - 0 jets,
  - p_T^{ll} > 20 GeV,
  - m_{ll} < 80 GeV, $\Delta\Phi_{ll}$ < 2.8
- The four discriminating variables are input to BDT

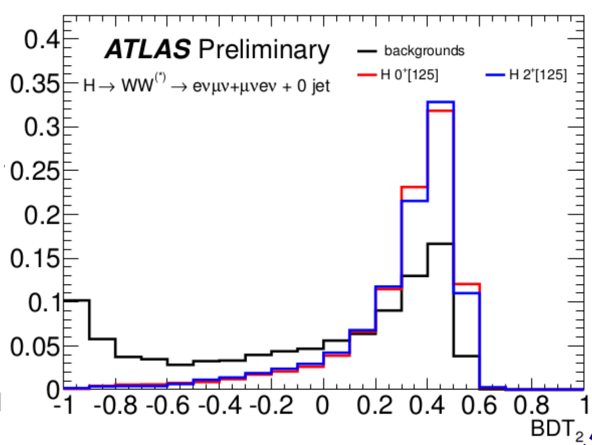
J=1



- 2D fit of the J=0 and J=2 BDT discriminants
- Same approach used for J=1
  - 1^+ excluded at 92% CL,
  - 1^- excluded at 98.3% CL

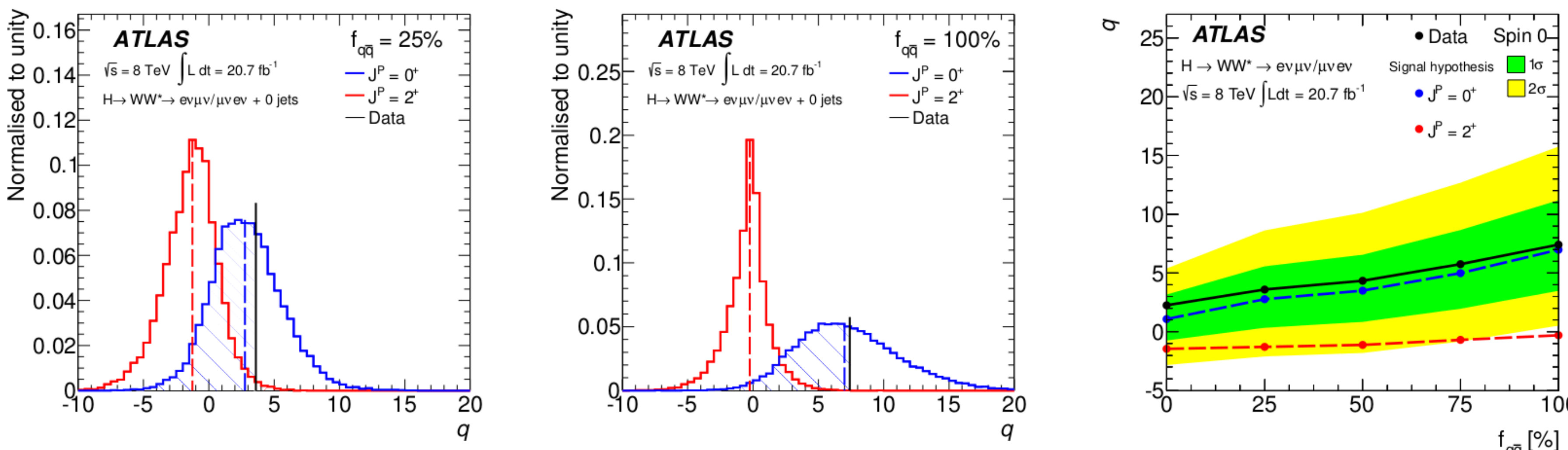
BDT





H → WW → 2l2ν @ATLAS – Spin-2

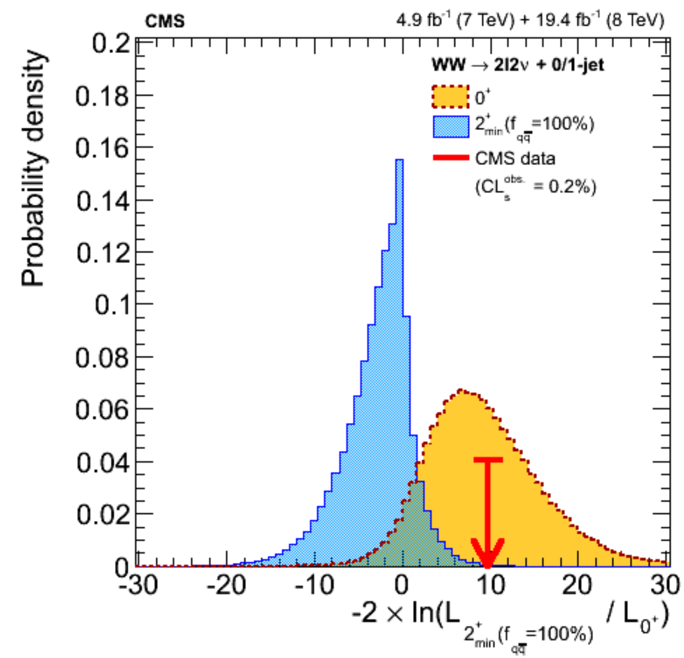
- Different qq fractions tested for spin-2
- Highest rejection for the 100% qq case
- Good agreement between spin-0 and data,
    - 100% qq rejected at > 99% CL



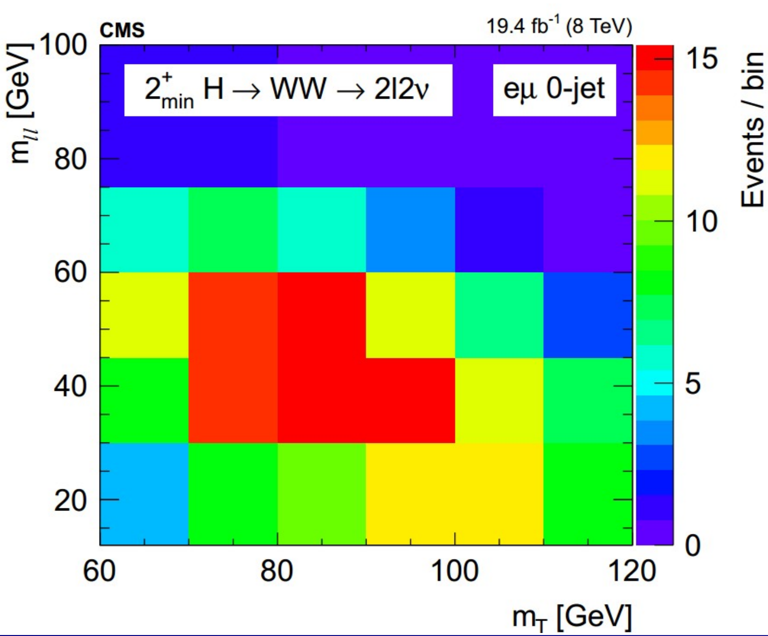
$f_{q\bar{q}}$	$N_{fit}(0^+)$	$N_{fit}(2^+_m)$	exp. $p_0(0^+)$	exp. $p_0(2^+_m)$	obs. $p_0(0^+)$	obs. $p_0(2^+_m)$	1-CL$_S$ (2^+_m)
100%	270^{+100}_{-80}	110^{+110}_{-90}	0.013	0.005	0.543	0.005	0.99
75%	250^{+100}_{-80}	170^{+110}_{-100}	0.034	0.007	0.591	0.005	0.99
50%	250^{+100}_{-80}	230^{+140}_{-100}	0.035	0.012	0.619	0.007	0.98
25%	260^{+110}_{-80}	260^{+130}_{-110}	0.048	0.019	0.613	0.010	0.97
0%	260^{+100}_{-80}	320^{+130}_{-110}	0.091	0.057	0.725	0.014	0.95

H → WW → 2l2ν @CMS

- Used to test 0^+ against 0^- or minimal coupling 2^+_{min} (graviton-like)
- Events in 0 or 1 jet categories
- Similar to ZZ analysis, 2-dimensional templates based on mll and m_T distributions
- Different qq fractions tested



2^+, 0 jets cat.



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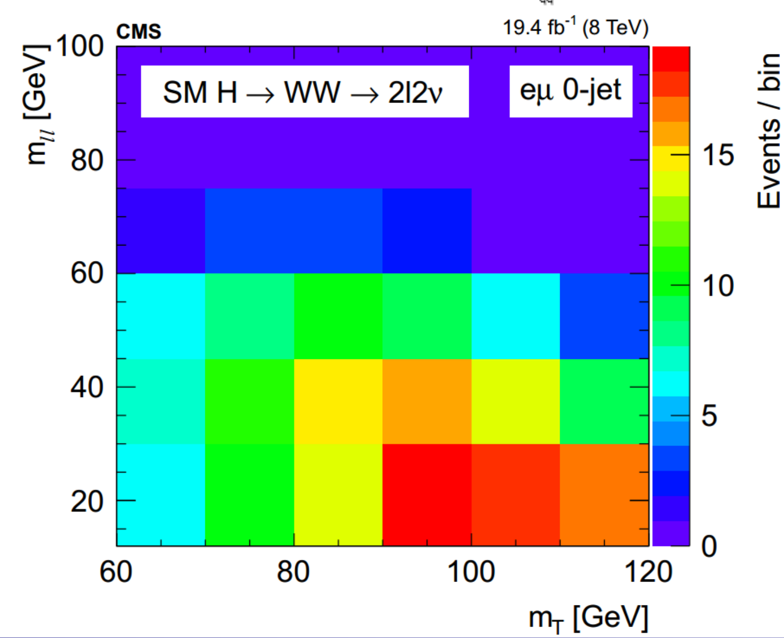
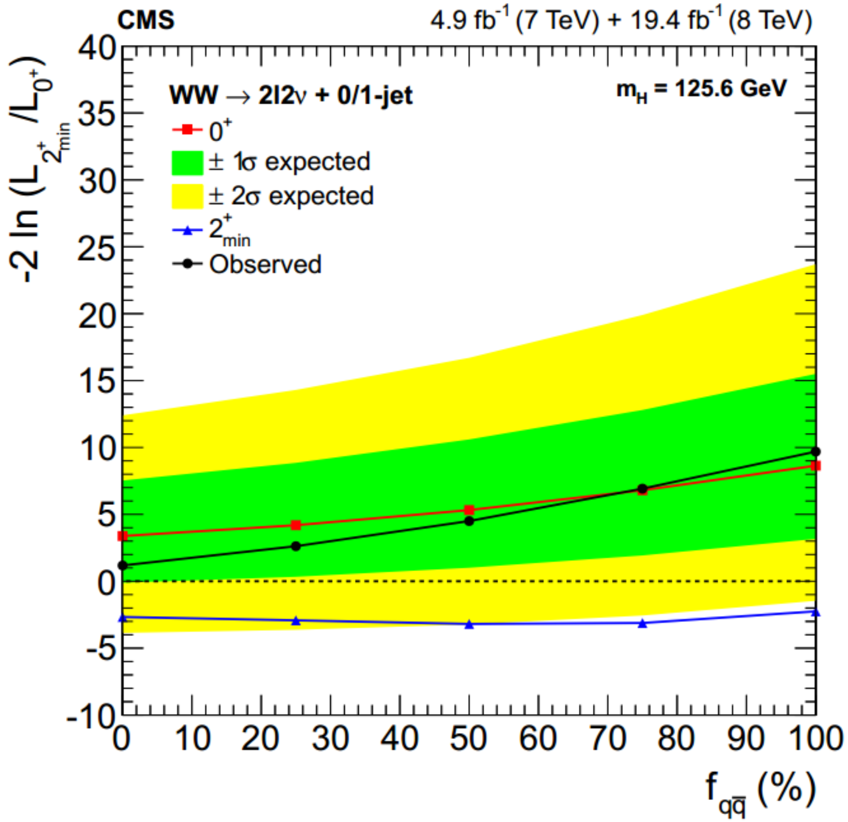


H → WW → 2l2ν @CMS



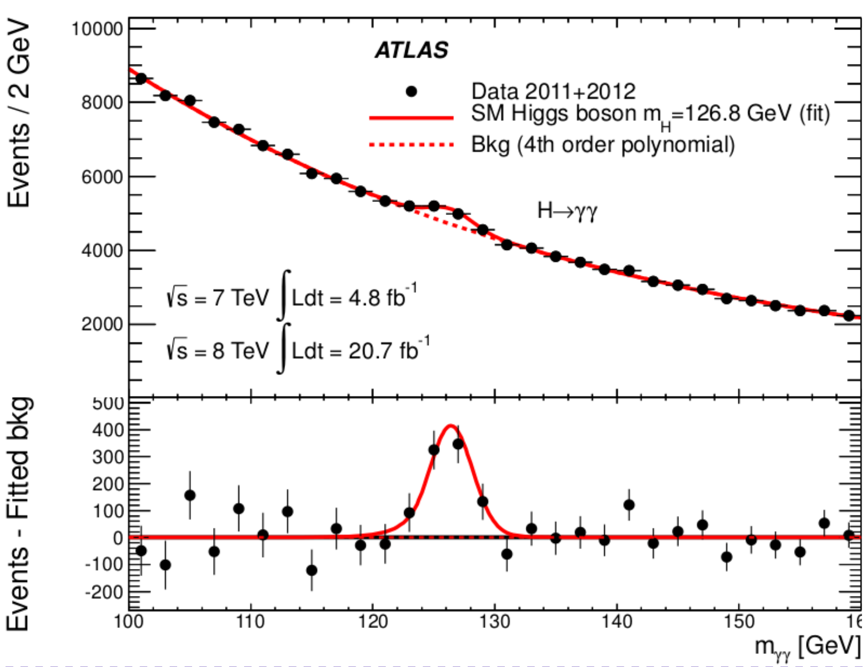
- agreement between 0+ and data,
- 100% qq rejected at 99% CL

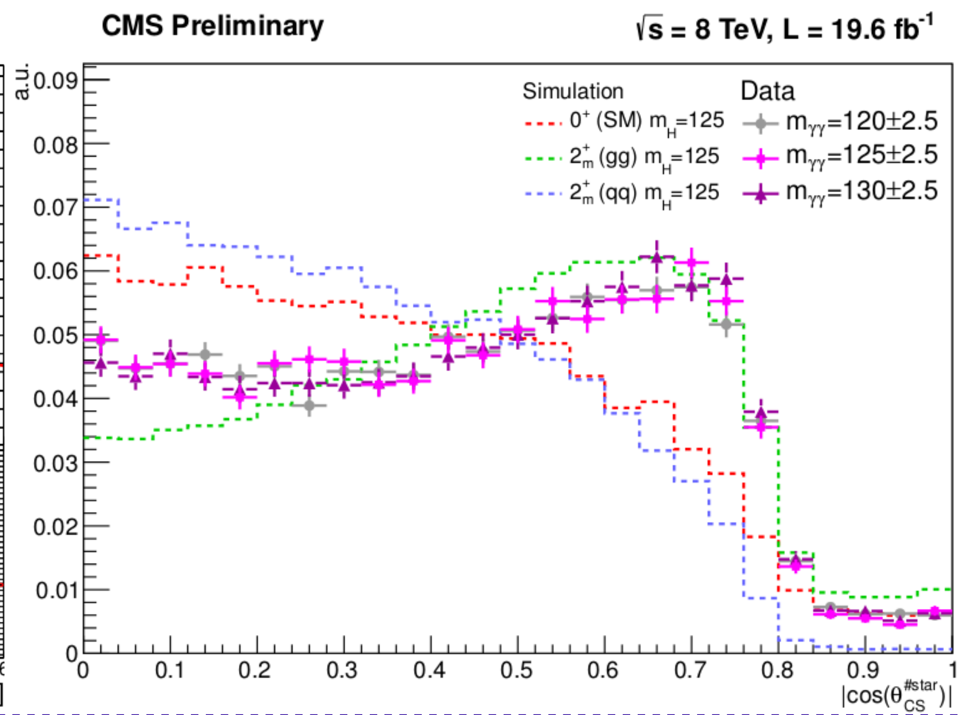
J^P model	J^P production	Expected ($\sigma/\sigma_{SM} = 1$)	obs. 0^+	obs. J^P	CL_s
2^+_{min}	$f_{q\bar{q}}$=0%	1.8σ (2.6σ)	+0.6σ	+1.2σ	16.3%
2^+_{min}	$f_{q\bar{q}}$=50%	2.3σ (3.2σ)	+0.2σ	+2.1σ	3.3%
2^+_{min}	$f_{q\bar{q}}$=100%	2.9σ (3.9σ)	-0.2σ	+3.1σ	0.2%
0^-	any	0.8σ (1.1σ)	-0.5σ	+1.2σ	34.7%

$H \rightarrow \gamma\gamma$

H → γγ in a nutshell

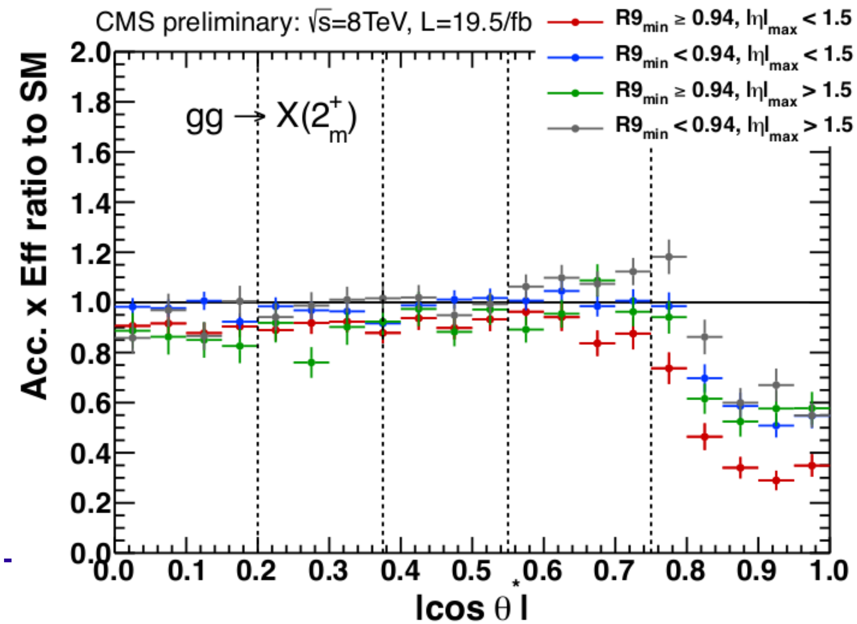
- Decay of spin-1 particles to γγ forbidden by Landau-Yang.
- Observation excludes pure spin-1 states → test spin-2 models
- Most powerful discriminant : polar angle θ^*
- cos θ^* uniform in spin-0, depends on the qq fraction for spin-2
- Discrimination power degrades increasing the qq fraction
  - Most sensitive to pure gg production mechanism

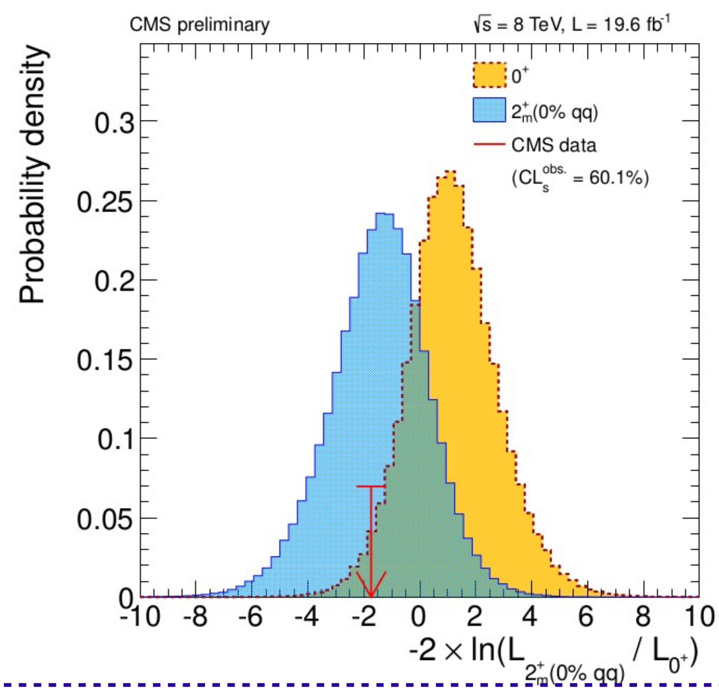


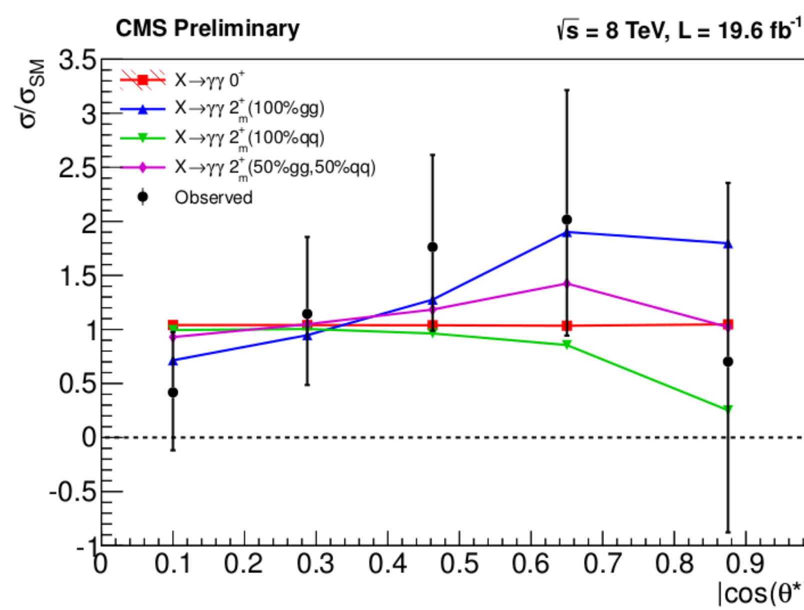


H → γγ @CMS

- Only 8 TeV samples finalized at the moment
- Dataset divided in 5 bins of cos θ* and 4 categories of purity ($R9_{min}$ and $|\eta|_{max}$)
- Total of 20 fits of $m_{\gamma\gamma}$
- Comparison of 0^- vs $gg \rightarrow 2^+_m$ and $qq \rightarrow 2^+_m$
- Results not conclusive yet, updates arriving

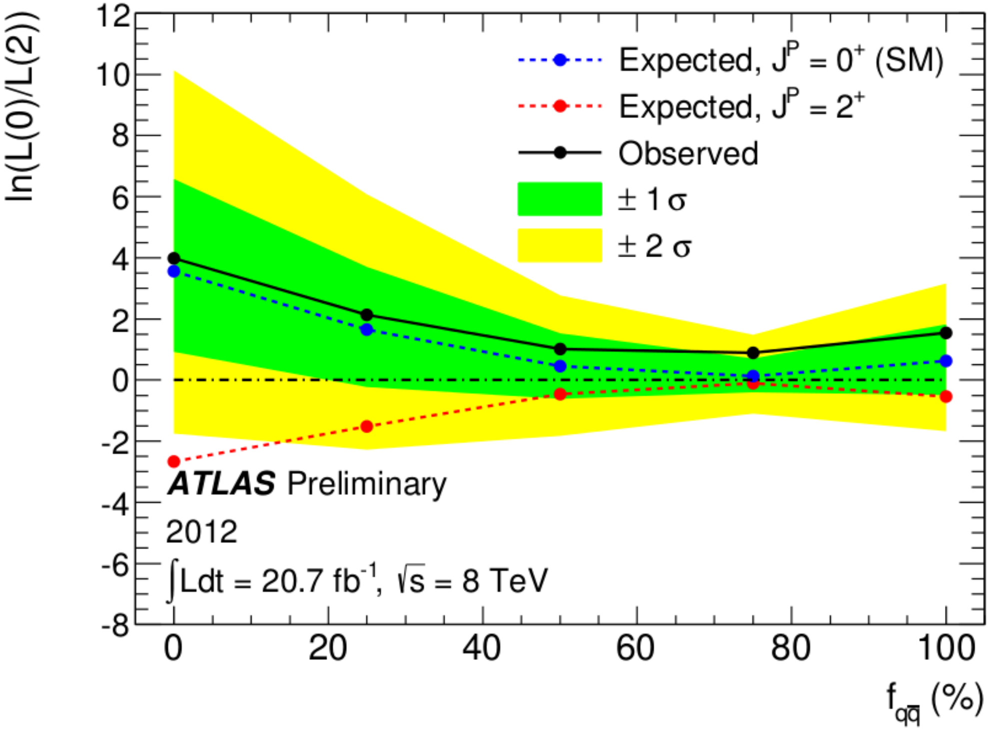






H → γγ @ATLAS

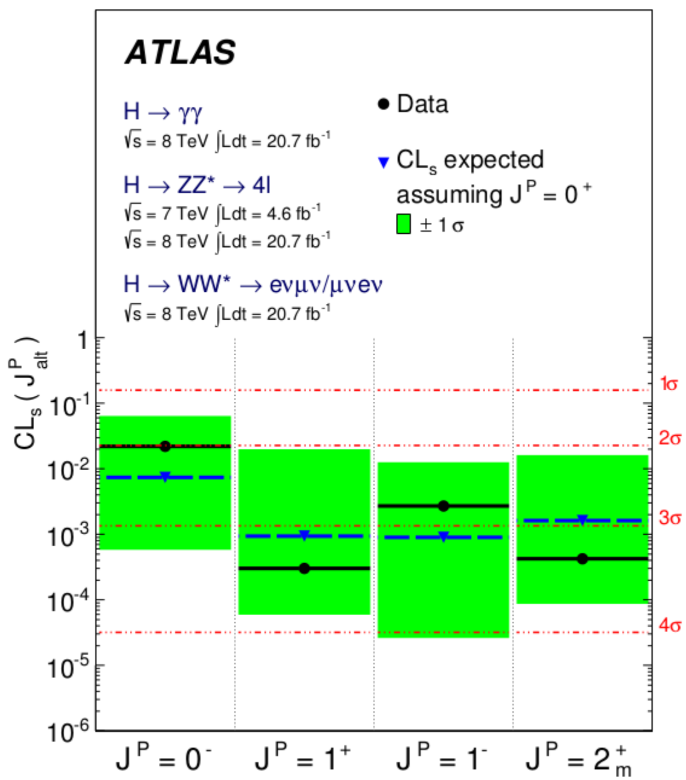
- Good rejection power between 0^+ and 2^+ when 100% gg
- Less powerful in the qq case
- Cuts optimized to minimize the correlation between $m_{\gamma\gamma}$ and cos θ^*
- Alternative: simultaneous fits of mγγ in bins of cos θ^* gives compatible results
- 0% qq spin-2 excluded at 99.3% CL

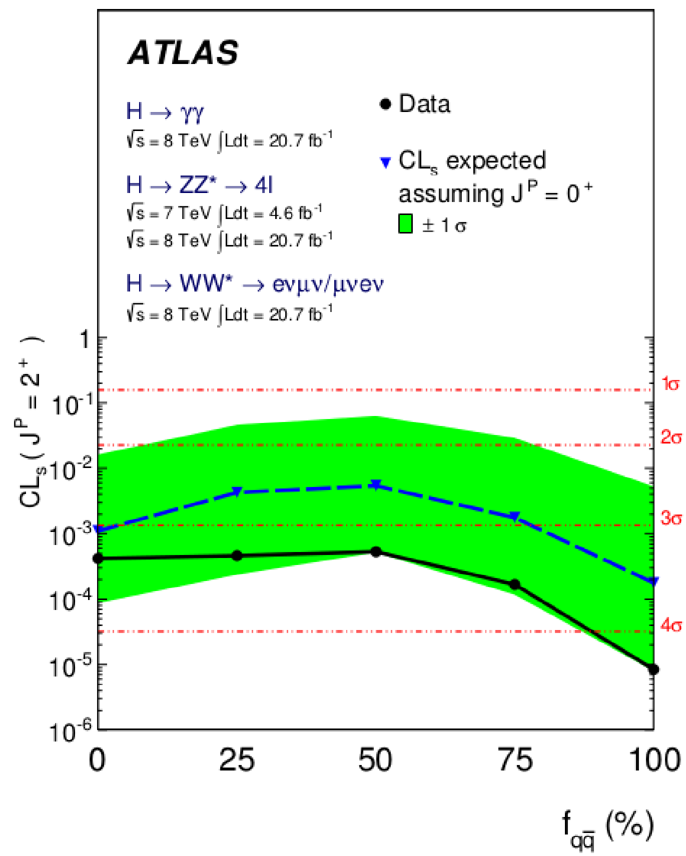


$f_{q\bar{q}}$	Spin-2 assumed exp. $p_0(J^P = 0^+)$	Spin-0 assumed exp. $p_0(J^P = 2^+)$	obs. $p_0(J^P = 0^+)$	obs. $p_0(J^P = 2^+)$	$CL_s(J^P = 2^+)$
100%	0.148	0.135	0.798	0.025	0.124
75%	0.319	0.305	0.902	0.033	0.337
50%	0.198	0.187	0.708	0.076	0.260
25%	0.052	0.039	0.609	0.021	0.054
0%	0.012	0.005	0.588	0.003	0.007

Combination from ATLAS

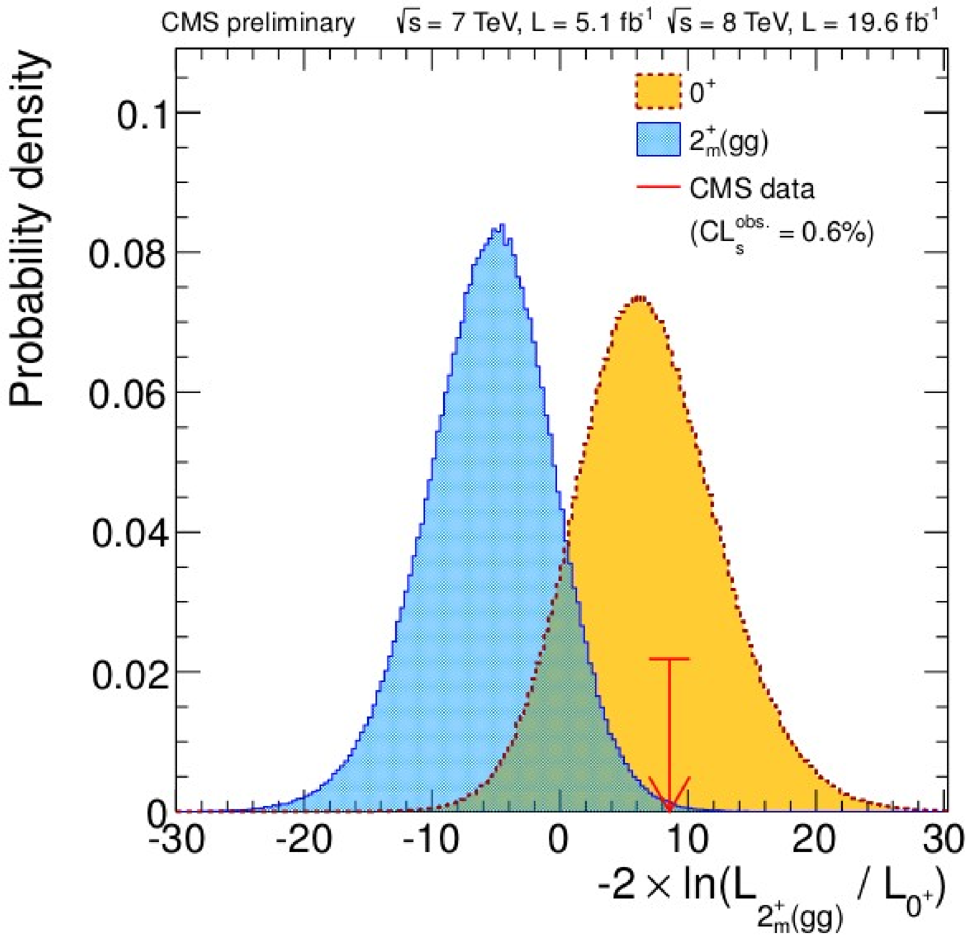
- 0^- hypothesis excluded at 97.8% CL in the ZZ channel
- 1^+ hypothesis excluded at 99.97% CL by the combined ZZ+WW analysis
- 1^- hypothesis excluded at 99.7% CL by the combined ZZ+WW analysis
- Tested 2^+ excluded at 99.9% CL by the combined ZZ+WW+γγ analysis





CMS results

- Negative parity excluded at 99.96% CL in ZZ channel
- Spin-1 excluded at > 99.9% in the ZZ channel
- 2^+_m model excluded at 99.4% by the combined WW+ZZ analysis
- Other spin-2 (2+ , 2+ , 2−) models excluded at more 97% CL in ZZ
- Mixture studies are the next big goal for summer conferences
  - CMS already set a limit on CP-odd contribution fa3 < 0.51 at 95%



Conclusions

- Both CMS and ATLAS results show SM (0+) state highly favored against alternative pure J^P states
- The two experiments show good agreement and consistent and complementary results
- Best knowledge from both experiments allows to exclude all tested hypotheses of $J^P = 0^-$, J = 1 and J = 2 states with CL > 99.9%

Next

- put more stringent constraints on the allowed mixture
- But a limit on the fraction of CP-odd contributions to the cross-section fa3 < 0.51 has already been set by CMS
- In the future, extend the analyses to VBF, VH, ttH, $H \to \tau\tau$, …
- Combination between the experiments

References

- ATLAS results:
  - $H \rightarrow ZZ$
    - ATLAS-CONF-2013-013
  - $H \rightarrow WW$
    - ATLAS-CONF-2013-031
    - Phys. Lett. B 08, 026
  - $H \rightarrow \gamma\gamma$
    - ATLAS-CONF-2013-029
  - Combination
    - ATLAS-CONF-2013-040
    - arXiv:1307.1432

- CMS results:
  - $H \rightarrow ZZ$
    - Phys. Rev. D 89, 092007
  - $H \rightarrow WW$
    - CMS-PAS-HIG-13-023
    - JHEP 01 (2014) 096
  - $H \rightarrow \gamma\gamma$
    - CMS-PAS-HIG-13-016
  - Combination
    - CMS-PAS-HIG-13-005

Thank you!

List of discriminants used by CMS

TABLE II. List of observables and kinematic discriminants used for signal versus background separation and studies of the properties of the observed resonance. The alternative hypotheses for $J = 0$ are independent of the production mechanism without the need of integrating out the production angles $\cos\theta^*$ and Φ_1.

Discriminant	Note
	Observables used for the signal-strength measurement
$m_{4\ell}$	Four-lepton invariant mass, main background discrimination.
$\mathcal{D}^{\rm kin}_{\rm bkg}$	Discriminate SM Higgs boson against ZZ background.
$\mathcal{D}_{\rm jet}$	Linear discriminant, uses jet information to identify VBF topology.
$p_{\rm T}^{4\ell}$	$p_{\rm T}$ of the 4ℓ system, discriminates between production mechanisms.
	Observables used in the spin-parity hypothesis testing
$\mathcal{D}_{\rm bkg}$	Discriminates SM Higgs boson against ZZ background, includes $m_{4\ell}$.
$\mathcal{D}_{1^-}$	Exotic vector (1^-), $q\bar{q}$ annihilation.
$\mathcal{D}_{1^+}$	Exotic pseudovector (1^+), $q\bar{q}$ annihilation.
$\mathcal{D}^{gg}_{2^+_{\rm m}}$	Graviton-like with minimal couplings $(2^+_{\rm m})$, gluon fusion.
$\mathcal{D}^{q\bar{q}}_{2^+_{\rm m}}$	Graviton-like with minimal couplings $(2^+_{\rm m})$, $q\bar{q}$ annihilation.
$\mathcal{D}^{gg}_{2^+_{\rm b}}$	Graviton-like with SM in the bulk $(2^+_{\rm b})$, gluon fusion.
$\mathcal{D}^{gg}_{2^+_{\rm h}}$	Tensor with higher-dimension operators $(2^+_{\rm h})$, gluon fusion.
$\mathcal{D}^{gg}_{2^-_{\rm h}}$	Pseudotensor with higher-dimension operators $(2^-_{\rm h})$, gluon fusion.
	Production-independent observables used in the spin-parity hypothesis testing
$\mathcal{D}_{0^-}$	Pseudoscalar (0^-), discriminates against SM Higgs boson.
$\mathcal{D}_{0^+_{\rm h}}$	Non-SM scalar with higher-dimension operators $(0^+_{\rm h})$.
$\mathcal{D}^{\rm dec}_{\rm bkg}$	Discriminates against ZZ background, includes $m_{4\ell}$, excludes $\cos\theta^*$, Φ_1.
$\mathcal{D}^{\rm dec}_{1^-}$	Exotic vector (1^-), decay-only information.
$\mathcal{D}^{\rm dec}_{1^+}$	Exotic pseudovector (1^+), decay-only information.
$\mathcal{D}^{\rm dec}_{2^+_{\rm m}}$	Graviton-like with minimal couplings $(2^+_{\rm m})$, decay-only information.