מכון ויצמן למדע
WEIZMANN INSTITUTE OF SCIENCE

LHC Run-I: Scalar boson Spin/CP Results

„Physics at LHC and Beyond“ in Quy Nhon (Vietnam)

(14.08.2014)

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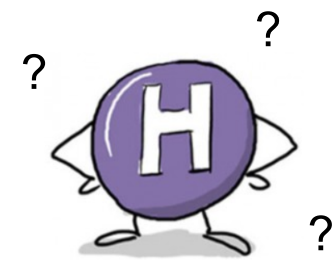
for the ATLAS & CMS Collaborations

Introduction



- **Discovery of a new boson announced on 4th of July 2012**

  [Phys. Lett. B 716 (2012) 1-29], [Phys. Lett. B 716 (2012) 30]

  → Is it a CP-even spin-0 particle as predicted by the SM ($J^P = 0^+$)?

- Landau-Yang theorem: Massive spin-1 particle cannot interact with 2 massless identical bosons (which forbids the decay to $\gamma\gamma$, and also the production of a spin-1 resonance in ggF)

  [Dokl. Akad. Nauk Ser. Fiz. 60 (1948) 207], [Phys. Rev. 77, 242 (1950)]

  → The observation of $H \to \gamma\gamma$ already disfavores spin-1 hypothesis, but we test spin/CP without prejudice (eg. $\gamma\gamma$ and 4l peaks might not originate from the same particle)

References:

- ATLAS:
  - Spin/CP paper [Phys. Lett. B 726 (2013), 120-144] ($\gamma\gamma$, 4l, lνlν, Combination)
  - Couplings paper [Phys. Lett. B 726 (2013) 88]

- CMS:
  - $H \to WW \to l\nu l\nu$: Paper [JHEP01 (2014) 096], Preliminary note [CMS-PAS-HIG-12-014]
  - $H \to \gamma\gamma$: Paper [arXiv:1407.0558]
  - $H \to$ 4l: Paper [Phys. Rev. D 89, 092007], Preliminary note [CMS-PAS-HIG-14-012]

- Theory:

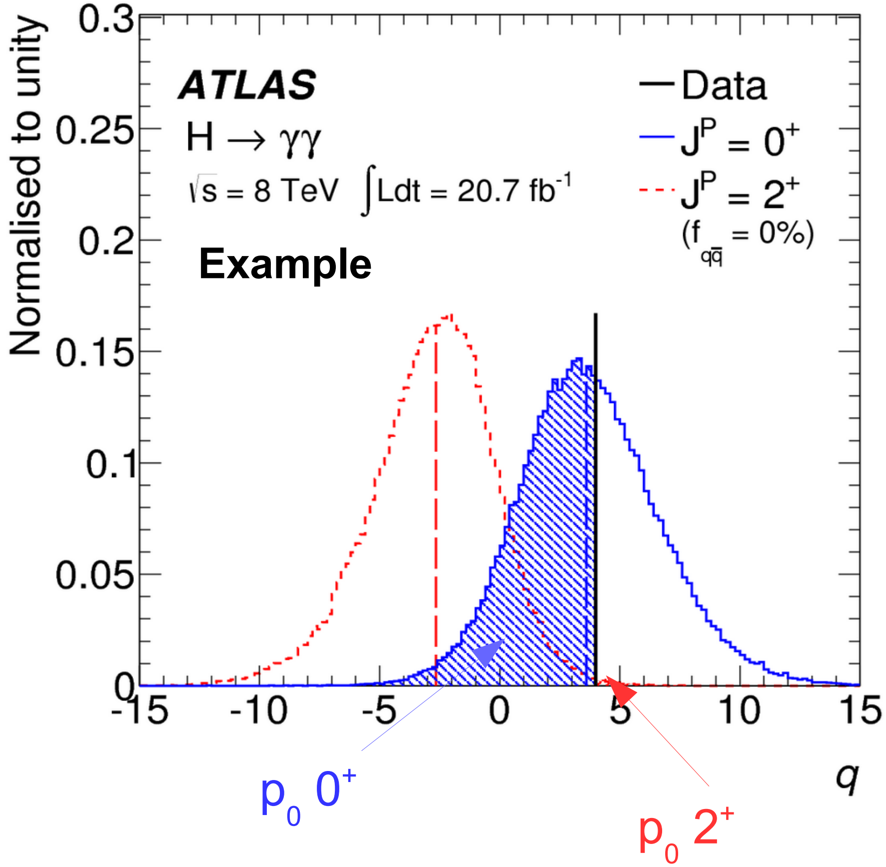
  [Phys. Rev. D 81 (2010) 075022], [Phys. Rev. D 86, 095031], [Phys. Rev. D 89 (2014) 035007]

Hypothesis testing: Compatibility of the data with 0^+ vs...

$J^P = 0^-$: Pseudo-scalar

$J^P = 1^+, 1^-$: Vector and pseudo-vector

various **$J^P = 2^{+/-}$**: Graviton-inspired tensor and pseudo-tensor models



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

$$\mathrm{CL_s}(J^P_{\mathrm{alt}}) = \frac{p_0(J^P_{\mathrm{alt}})}{1 - p_0(0^+)}$$

CL = 1 - CLs

95% exclusion corresponds to CLs=5%

Decay Amplitudes of Spin-1 and Spin-2:

Spin-1: $$A(X_{J=1} \to VV) = \underbrace{b_1 \left[(\epsilon_1^* q)\,(\epsilon_2^* \epsilon_X) + (\epsilon_2^* q)\,(\epsilon_1^* \epsilon_X) \right]}_{\text{vector particle}} + \underbrace{b_2 \epsilon_{\alpha\mu\nu\beta} \epsilon_X^{\alpha} \epsilon_1^{*\mu} \epsilon_2^{*\nu} \tilde{q}^{\beta}}_{\text{pseudo-vector}}$$

→ effective fraction $f_{b2} = \dfrac{|b_2|^2 \sigma_2}{|b_1|^2 \sigma_1 + |b_2|^2 \sigma_2}$ to test mixtures of parity states vs. SM

Spin-2: $$\begin{aligned} A(X_{J=2} \to V_1 V_2) = \Lambda^{-1} \Bigg[& 2c_1 t_{\mu\nu} f^{*1,\mu\alpha} f^{*2,\nu\alpha} + 2c_2 t_{\mu\nu} \frac{q_\alpha q_\beta}{\Lambda^2} f^{*1,\mu\alpha} f^{*2,\nu,\beta} \\ & + c_3 \frac{\tilde{q}^\beta \tilde{q}^\alpha}{\Lambda^2} t_{\beta\nu} \left(f^{*1,\mu\nu} f^{*2}_{\mu\alpha} + f^{*2,\mu\nu} f^{*1}_{\mu\alpha} \right) + c_4 \frac{\tilde{q}^\nu \tilde{q}^\mu}{\Lambda^2} t_{\mu\nu} f^{*1,\alpha\beta} f^{*(2)}_{\alpha\beta} \\ & + m_V^2 \left(2c_5 t_{\mu\nu} \epsilon_1^{*\mu} \epsilon_2^{*\nu} + 2c_6 \frac{\tilde{q}^\mu q_\alpha}{\Lambda^2} t_{\mu\nu} \left(\epsilon_1^{*\nu} \epsilon_2^{*\alpha} - \epsilon_1^{*\alpha} \epsilon_2^{*\nu} \right) + c_7 \frac{\tilde{q}^\mu \tilde{q}^\nu}{\Lambda^2} t_{\mu\nu} \epsilon_1^* \epsilon_2^* \right) \\ & + c_8 \frac{\tilde{q}^\mu \tilde{q}^\nu}{\Lambda^2} t_{\mu\nu} f^{*1,\alpha\beta} \tilde{f}^{*(2)}_{\alpha\beta} + c_9 t^{\mu\alpha} \tilde{q}_\alpha \epsilon_{\mu\nu\rho\sigma} \epsilon_1^{*\nu} \epsilon_2^{*\rho} q^\sigma \\ & + \frac{c_{10} t^{\mu\alpha} \tilde{q}_\alpha}{\Lambda^2} \epsilon_{\mu\nu\rho\sigma} q^\rho \tilde{q}^\sigma \left(\epsilon_1^{*\nu} (q \epsilon_2^*) + \epsilon_2^{*\nu} (q \epsilon_1^*) \right) \Bigg] , \end{aligned}$$

If c_1 and c_5 non-zero: $\mathbf{J^P = 2_m^+}$: Graviton with minimal couplings to SM particles

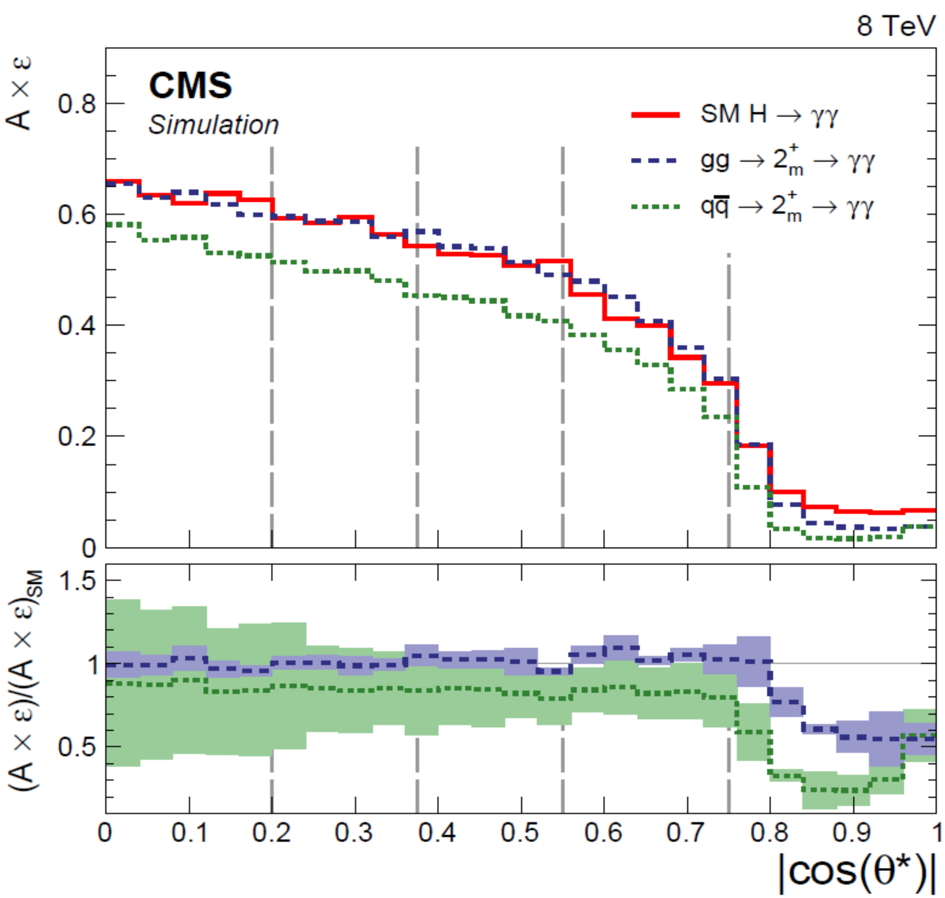
If $c_1 \ll c_5$: $\mathbf{J^P = 2_b^+}$: Graviton in an ED model where SM fields can propagate into the bulk

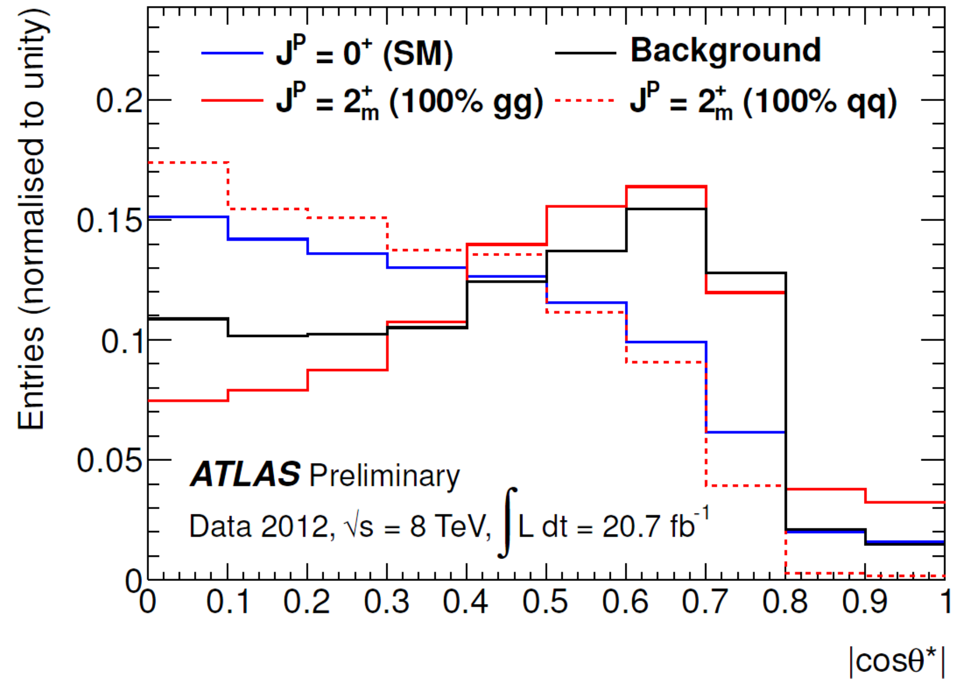
If other c_i non-zero: $\mathbf{J^P = 2_h^{+/-}}$: Spin-2 models with higher-dimension operators

Discriminating Spin-0 from Spin-2:

- Polar angular distribution of the photons in the resonance rest frame |cosθ*| [Phys. Rev. D 16, 2219]:

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





|cosθ*| distribution for a scalar is flat, kinematic cuts shape the distribution

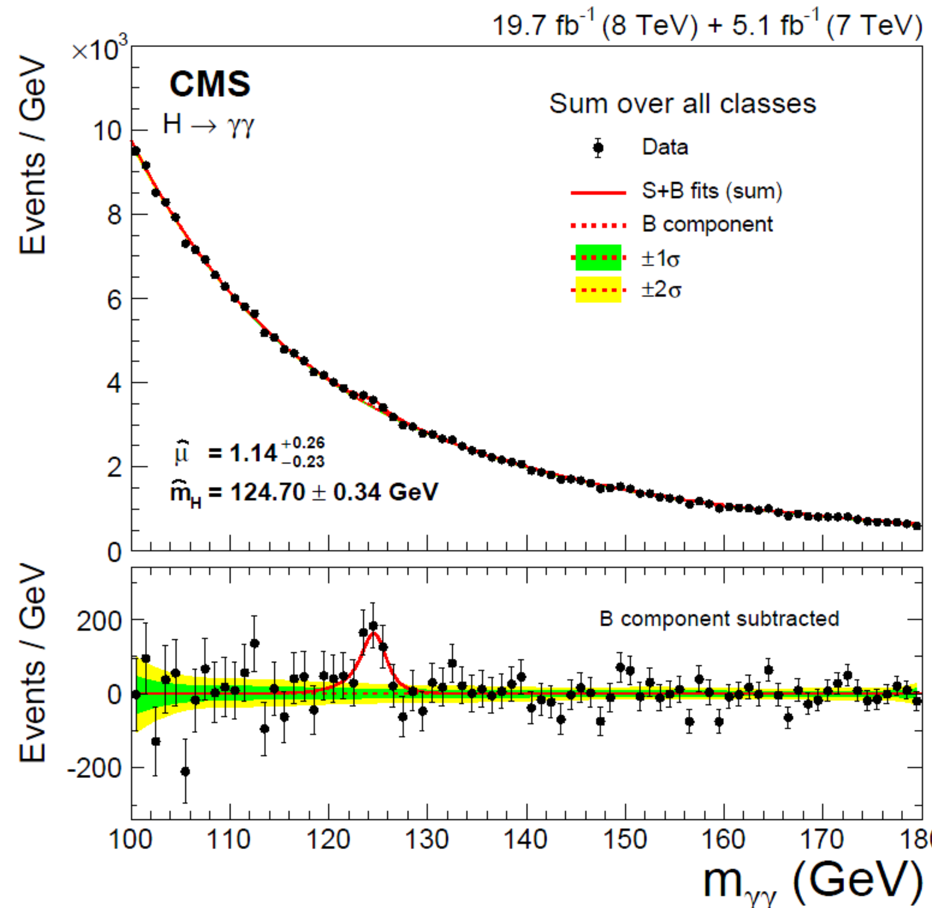
Spin-2 particle polarization depends on initial state helicities, results given as a function of the production fractions (ggF or $q\bar{q}$).

Signal models:

- Spin-0: Powheg+Pythia,
- Spin-2: JHU (LO generator), in case of ggF: $p_{T,\gamma\gamma}$ reweighted to that of Powheg

Event selection ATLAS:

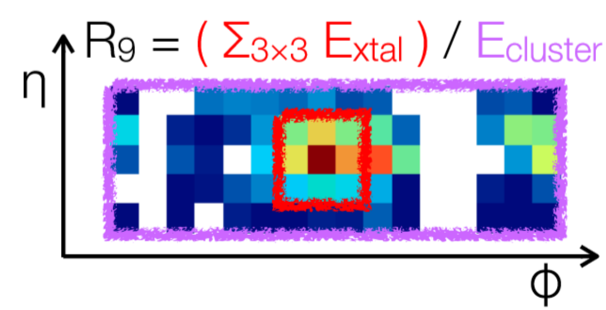
- 2 isolated well-identified photons
- relative pT cuts: $p_{T,1} > 0.35 * m_{\gamma\gamma}$, $p_{T,2} > 0.25 * m_{\gamma\gamma}$ to minimize correlations between $|\cos\theta^*|$ and $m_{\gamma\gamma}$
- 14977 selected data events, 14300 estimated bkg events, 370 expected Higgs boson events
- not categorized for the spin-analysis



Event selection CMS:

- two photons, $p_{T,1} > 33$ GeV, $p_{T,2} > 25$ GeV
- photon identification based on BDT (shower shape variables, isolation, energy densities)

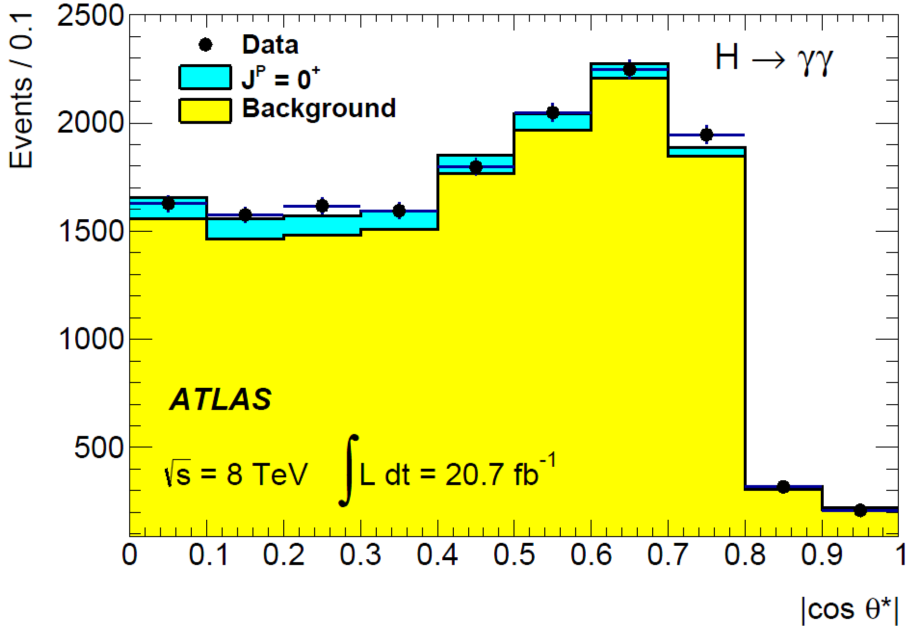
- 4 categories based on $|\eta|$ and R_9 variable:
  Both photons in the barrel and both R_9>0.94
  Both photons in the barrel, at least one R_9<0.94
  At least one photon in the endcap and both R_9>0.94
  At least one photon in the endcap, at least one R_9<0.94



Unconverted photons have large R_9

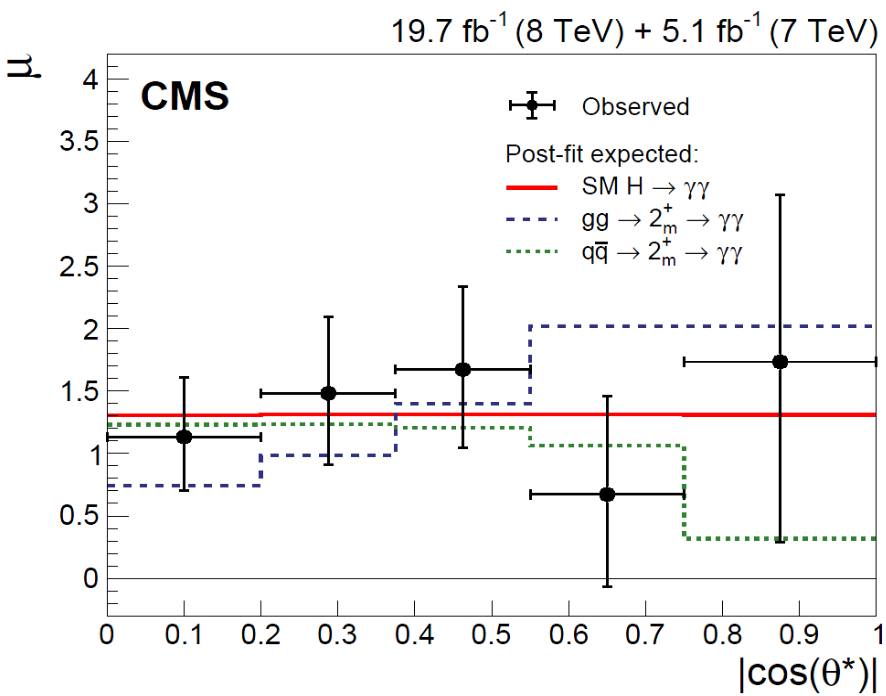
Analysis ATLAS:

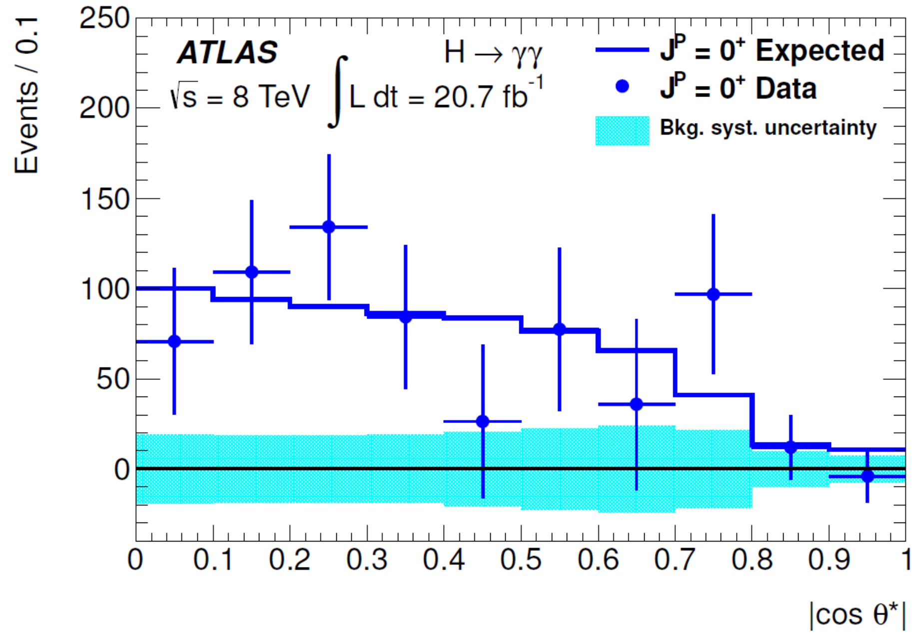
- Background $|\cos\theta^*|$ shape from data from mass sidebands 105–122 GeV and 130-160 GeV
- Residual correlations between $m_{\gamma\gamma}$ and $|\cos\theta^*|$ at most 2%, treated as uncertainties
- Simultaneous fit to signal region ($m_{\gamma\gamma}$) and two sidebands ($m_{\gamma\gamma} \times |\cos\theta^*|$)



Analysis CMS:

- Divide each category into five $|\cos\theta^*|$ bins
- Fit $m_{\gamma\gamma}$ in each $|\cos\theta^*|$ bin

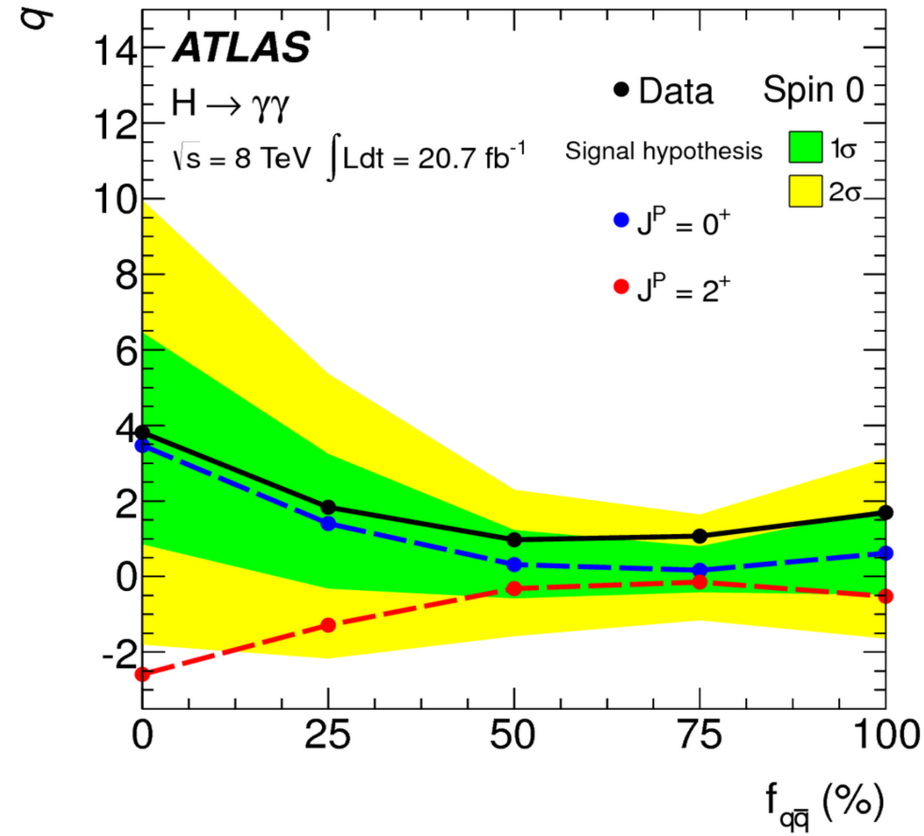


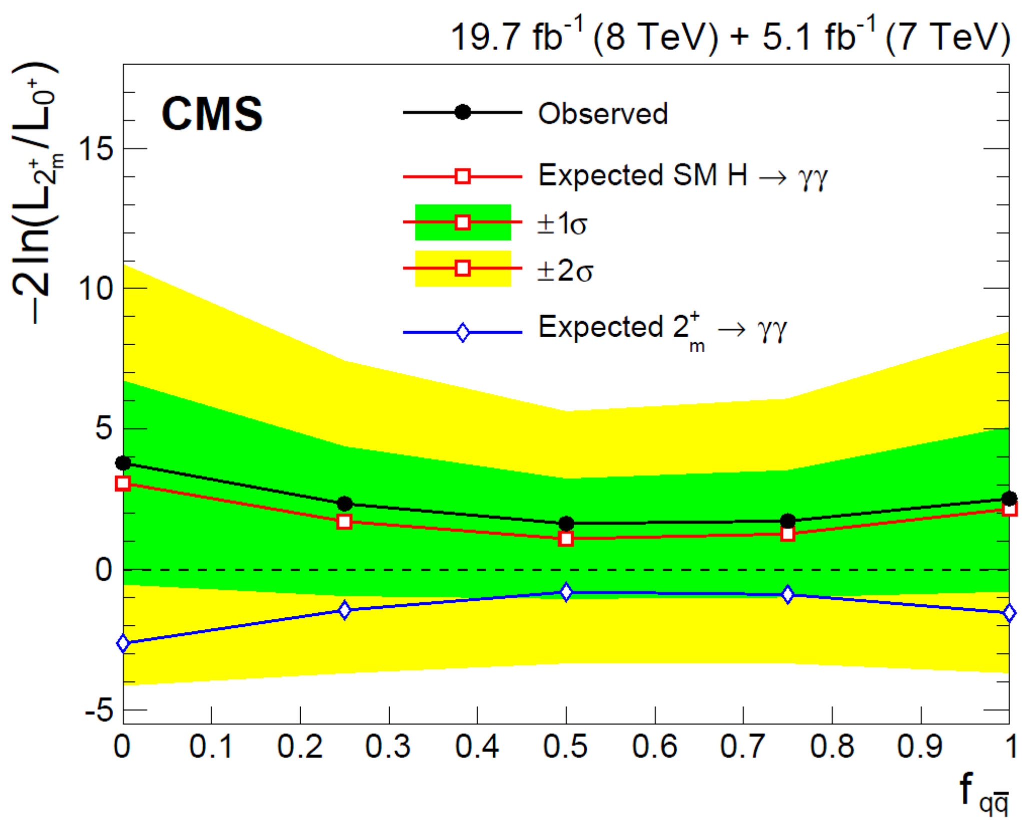


Results: $H \to \gamma\gamma$

ATLAS:

$f_{q\bar{q}}$	Obs. p_0 0^+	Obs. p_0 2^+	CLs 2^+
100%	0.798	0.025	0.124
75%	0.902	0.033	0.337
50%	0.708	0.076	0.260
25%	0.609	0.021	0.054
0%	0.588	0.003	0.007





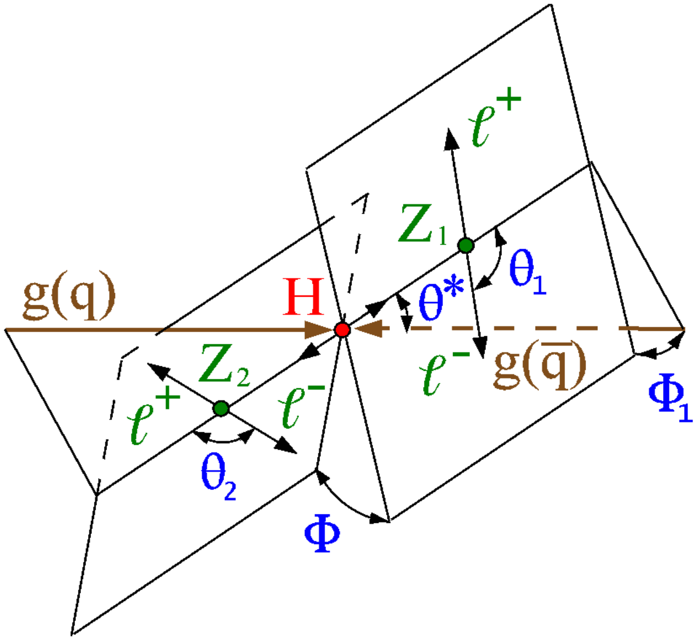
CMS:

$f_{q\bar{q}}$	Expected CLs	Observed CLs
1	0.17	0.15
0.75	0.31	0.25
0.5	0.36	0.29
0.25	0.22	0.17
0	0.08	0.06

→ 2^+ hypotheses disfavored by the data.

Discriminating variables:

- masses of the 2 reconstructed Z bosons, and m_{4l}
- 5 decay angles: θ_1, θ_2, Φ, Φ_1, θ^*

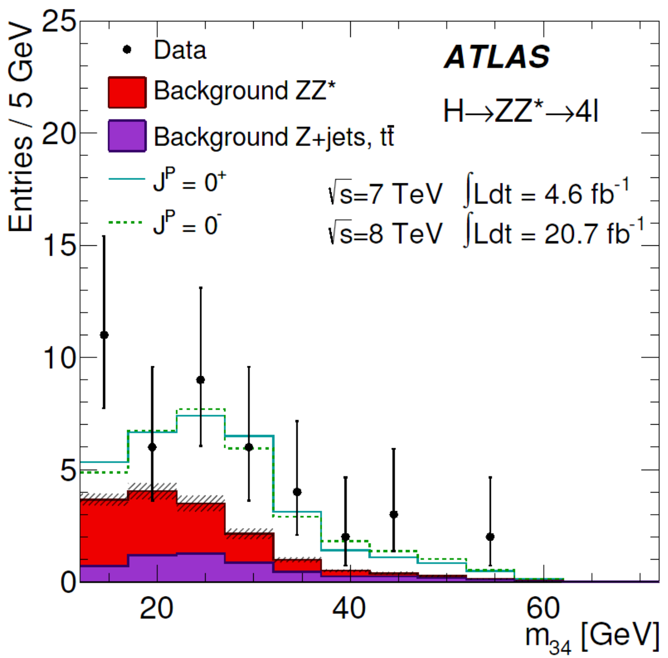


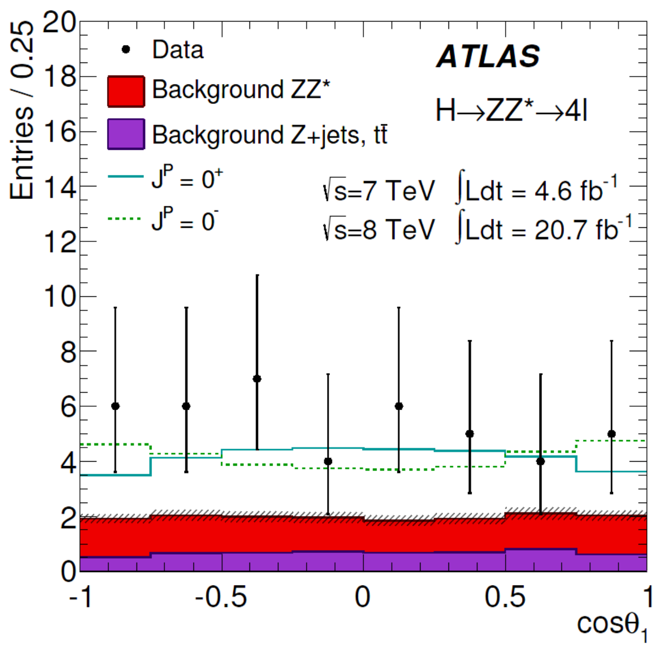
Event selection: [Phys. Lett. B 726 (2013) 88]

- 2 pairs of same-flavor opposite-charge isolated leptons
- Signal region: $115 < m_{4l} < 130$ GeV
- 43 selected data events, 16 expected bkg events, 18 expected signal events

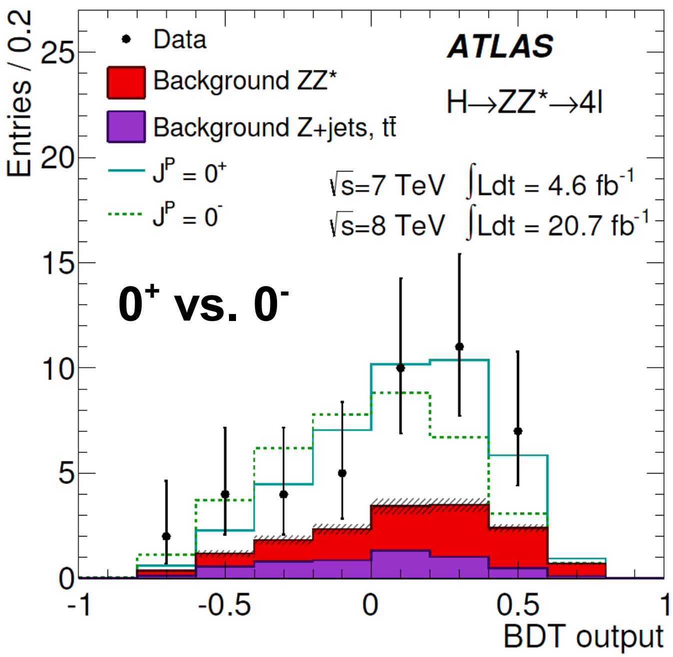
Analysis:

- 2 masses and 5 angles combined into a BDT to separate 0^+ from alternative
- BDT output evaluated in separate signal regions: one with high S/B (121-127 GeV) and two low S/B regions (115-121 GeV,127-130 GeV)
- BDT-outputs used as observable in the likelihood fit





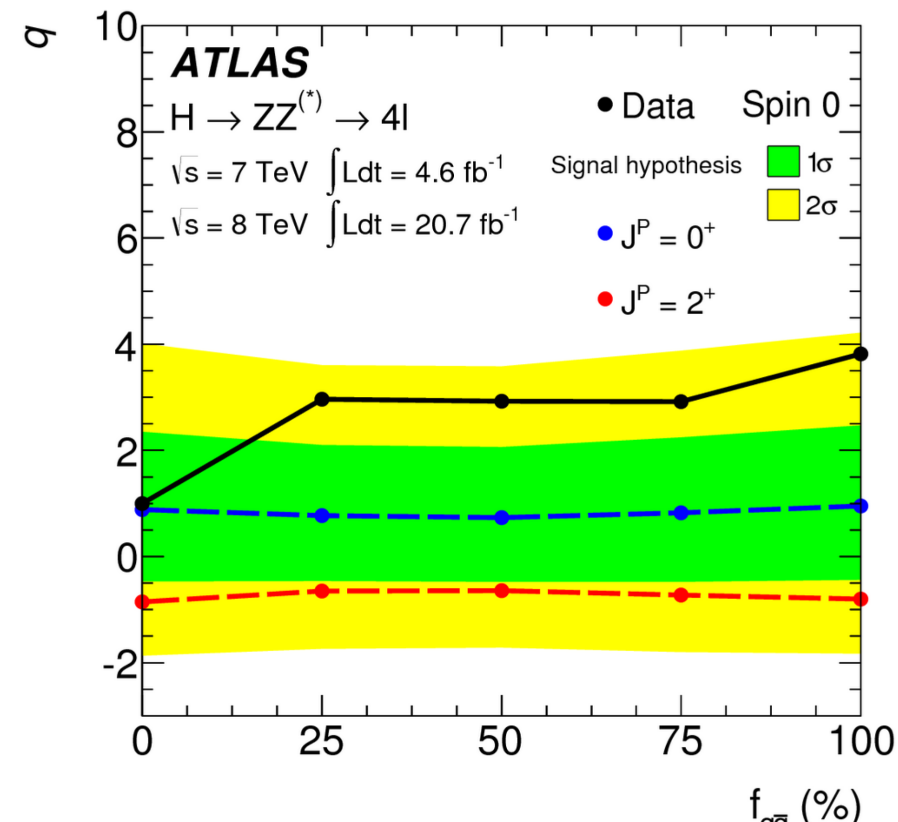
BDT output example:



Results:

Alternative	Obs. p_0 0^+	Obs. p_0 alt	CLs alt
0^-	0.31	0.015	0.022
1^+	0.55	0.001	0.002
1^-	0.15	0.051	0.060

$f_{q\bar{q}}$	Obs. p_0 0^+	Obs. p_0 2^+	CLs 2^+
100%	0.962	0.001	0.026
75%	0.923	0.003	0.039
50%	0.943	0.002	0.035
25%	0.944	0.002	0.036
0%	0.532	0.079	0.169



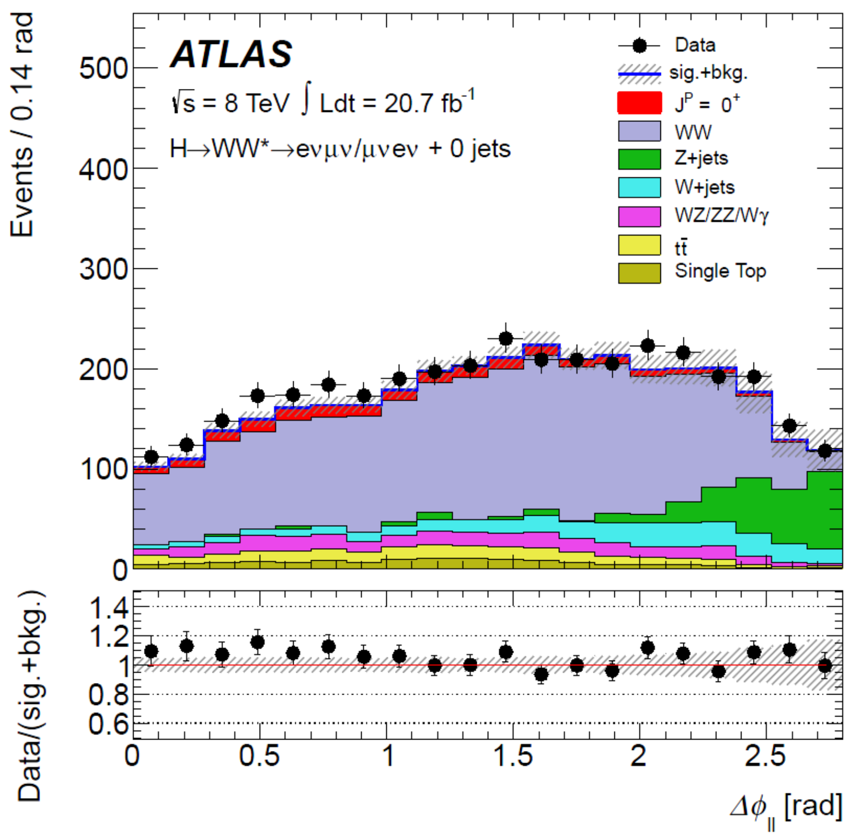
→ Data favores the 0^+ hypothesis over any other hypothesis

ATLAS: $H \to WW \to e\nu\mu\nu$

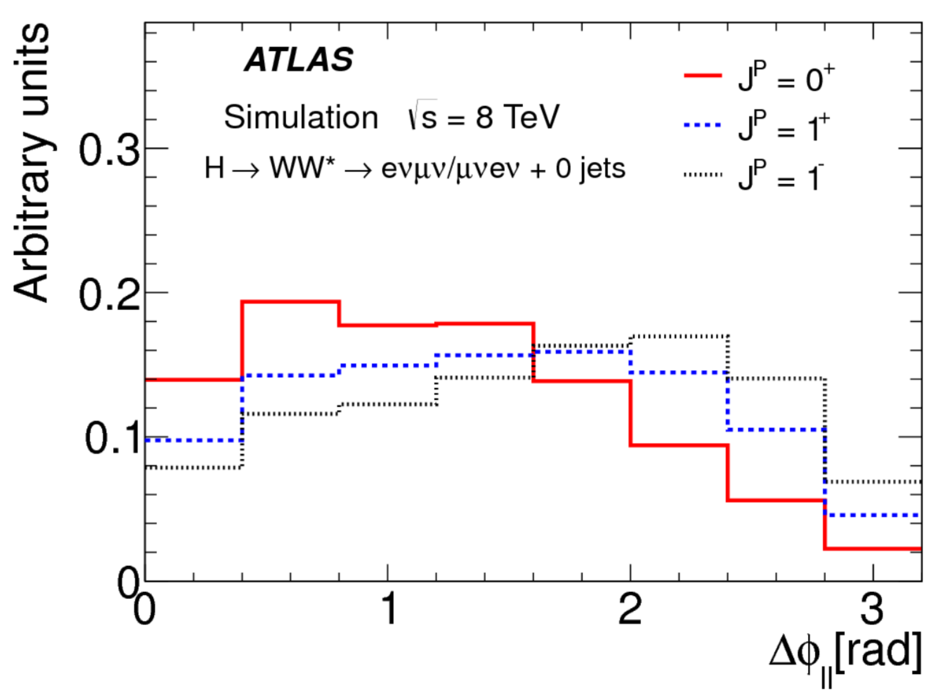
Event selection:
- 2 high pT opposite-flavor leptons (25 GeV, 15 GeV)
- Veto on high pT jets, cuts on m_{ll}, $p_{T,ll}$, $\Delta\phi_{ll}$
- 3615 data events selected, 3300 expected bkg events, 170 expected signal events

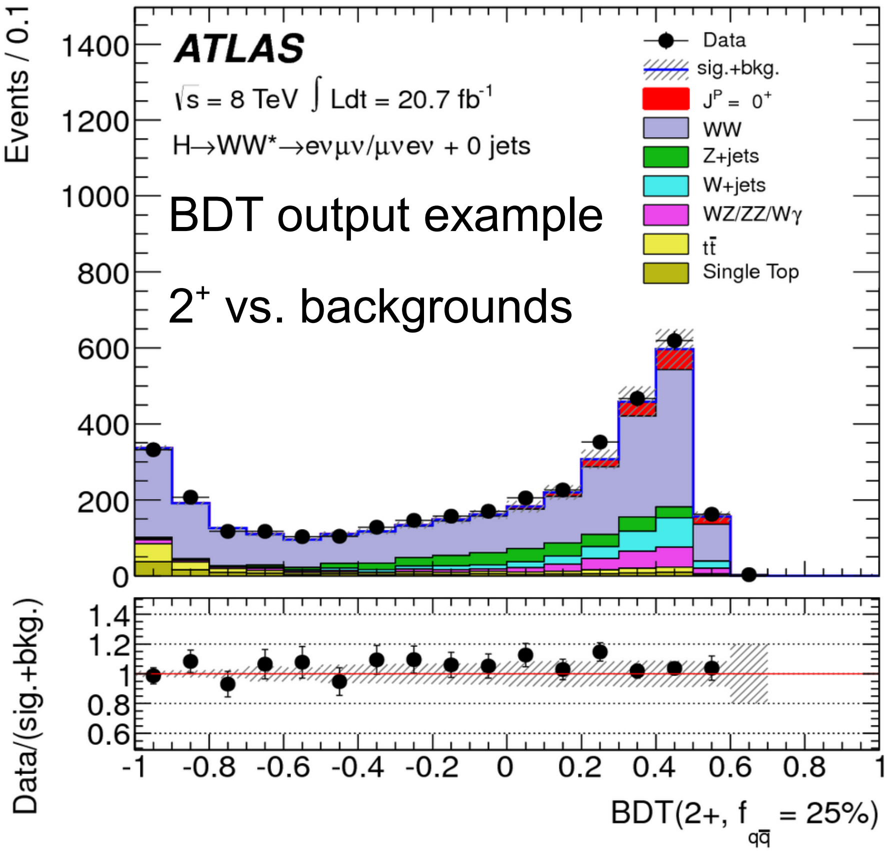
All major backgrounds estimated from data in control regions [Phys. Lett. B 726 (2013) 88]

Analysis:
- BDT combining m_{ll}, $\Delta\Phi_{ll}$, $p_{T,ll}$ and m_T $\quad m_T^2 = 2p_T^{\ell\ell}E_T^{\mathrm{miss}}(1-\cos\Delta\phi(\ell\ell,\vec{E}_T^{\mathrm{miss}}))$
- 2 BDT classifiers: One for 0^+ vs. bkg, the other for the J^P alternative vs. bkg
- 2D BDT output used in the likelihood fit



Discrimination example:



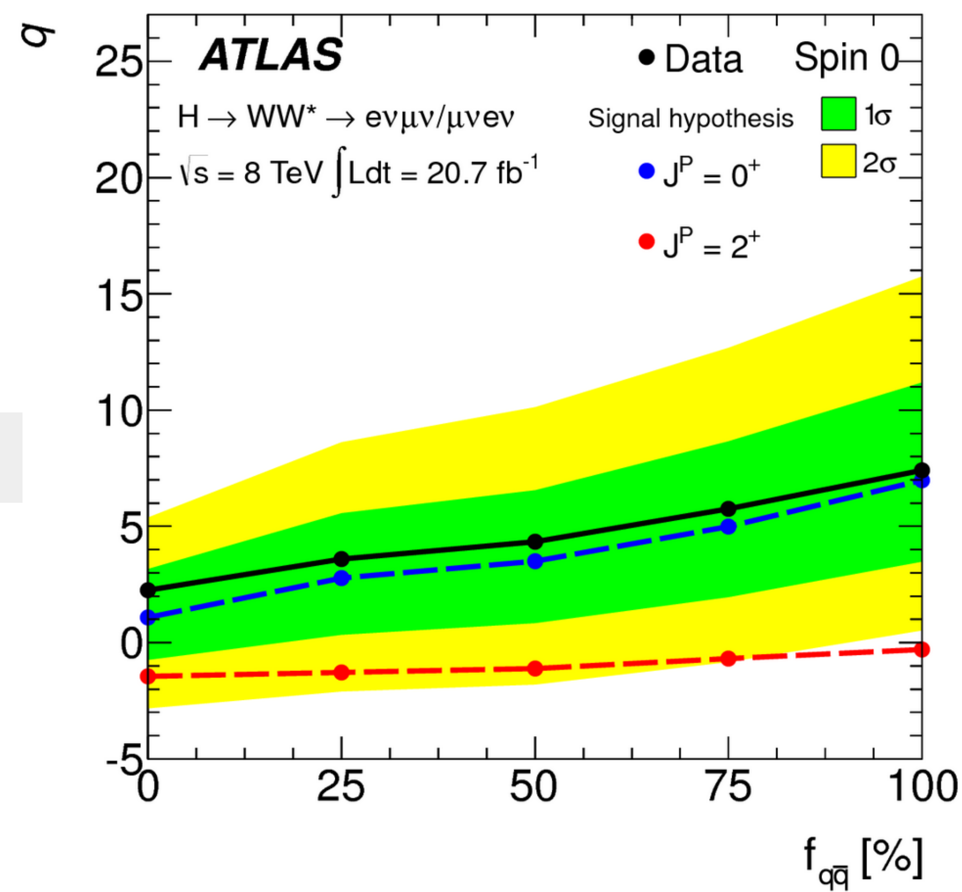


Results:

Alternative	Obs. p_0 0^+	Obs. p_0 alt	CLs alt
1^+	0.70	0.02	0.08
1^-	0.66	0.006	0.017

→ 0^+ preferred by the data over any other hypothesis

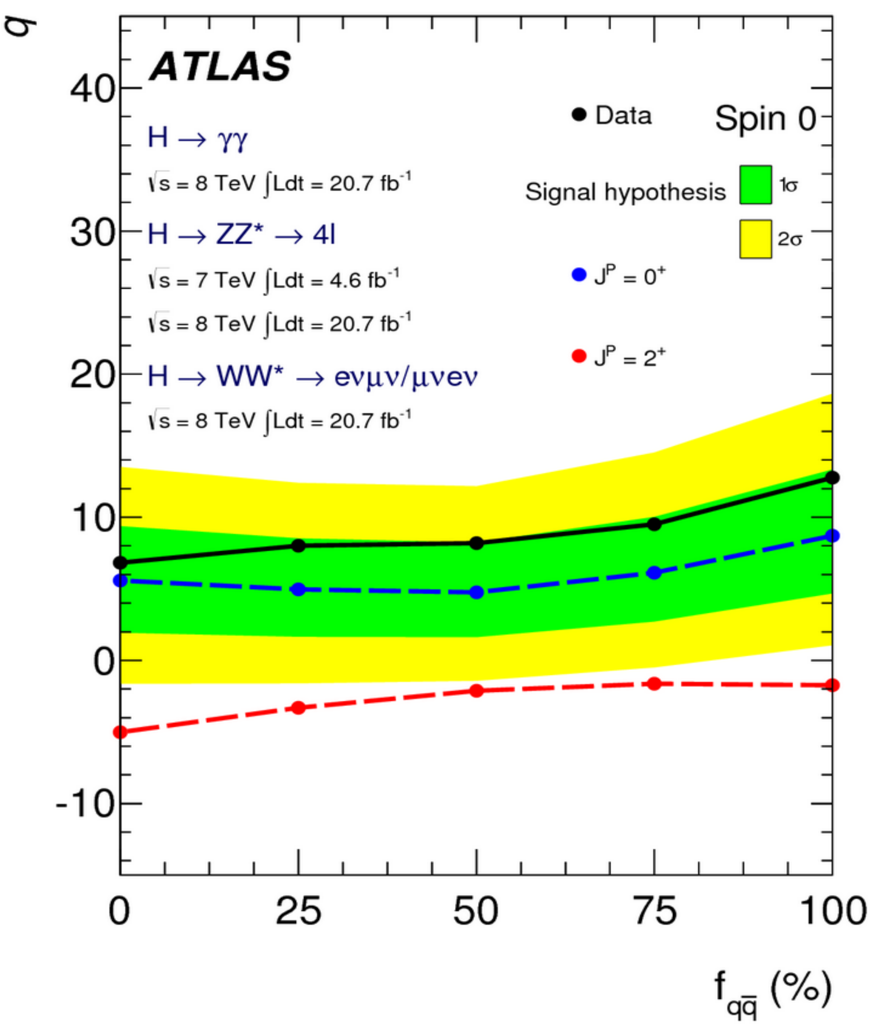
$f_{q\bar{q}}$	Obs. p_0 0^+	Obs. p_0 2^+	CLs 2^+
100%	0.541	0.0001	0.0004
75%	0.586	0.001	0.003
50%	0.616	0.003	0.008
25%	0.622	0.008	0.020
0%	0.731	0.013	0.048



ATLAS: Combination ($\gamma\gamma$, $e\nu\mu\nu$, 4l)

- Higgs boson mass m_H = 125.5 GeV, signal strength μ profiled and not correlated across channels
- Result insensitive to variations of m_H by its uncertainty of 0.6 GeV
- Systematic uncertainties included, their impact on the combined result is less than 0.3σ

Results:

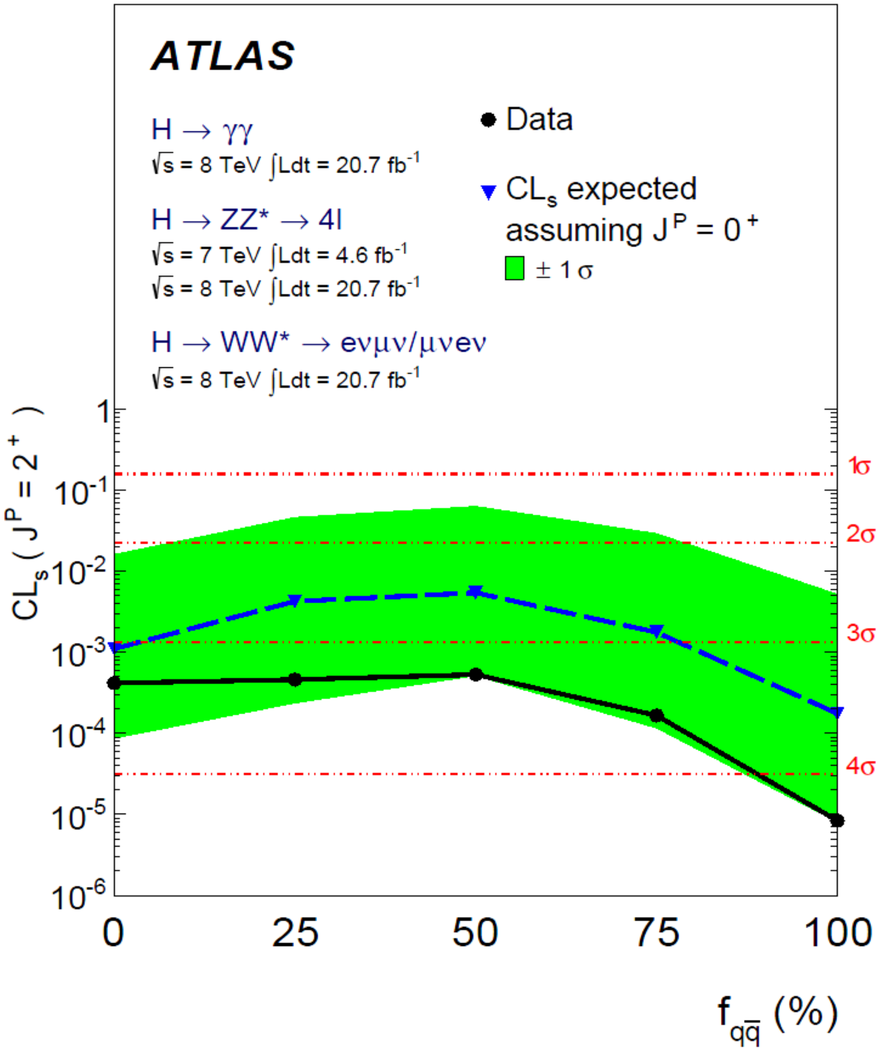


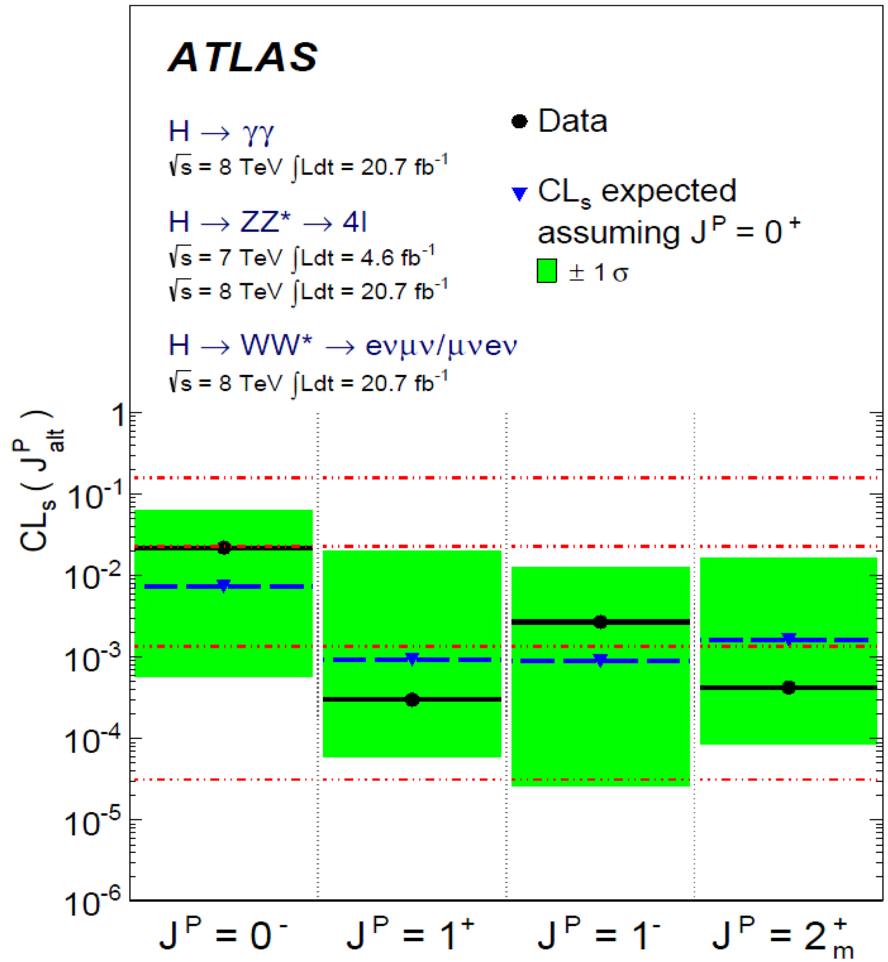
Alternative	Obs. p_0 0^+	Obs. p_0 alt	CLs alt
1^+	0.62	$1.2\cdot10^{-4}$	$3.0\cdot10^{-4}$
1^-	0.33	$1.8\cdot10^{-3}$	$2.7\cdot10^{-3}$

$f_{q\bar{q}}$	Obs. p_0 0^+	Obs. p_0 2^+	CLs 2^+
100%	0.81	$1.6\cdot10^{-6}$	$0.8\cdot10^{-5}$
75%	0.81	$3.2\cdot10^{-5}$	$1.7\cdot10^{-4}$
50%	0.84	$8.6\cdot10^{-5}$	$5.3\cdot10^{-4}$
25%	0.80	$0.9\cdot10^{-4}$	$4.6\cdot10^{-4}$
0%	0.63	$1.5\cdot10^{-4}$	$4.2\cdot10^{-4}$

ATLAS: Combination (γγ, eνμν, 4l)

Combined CLs values of any alternative wrt. 0^+:





4% $q\bar{q}$, 96% ggF

→ 0^- rejected (from 4l channel alone) at 97.8% CL

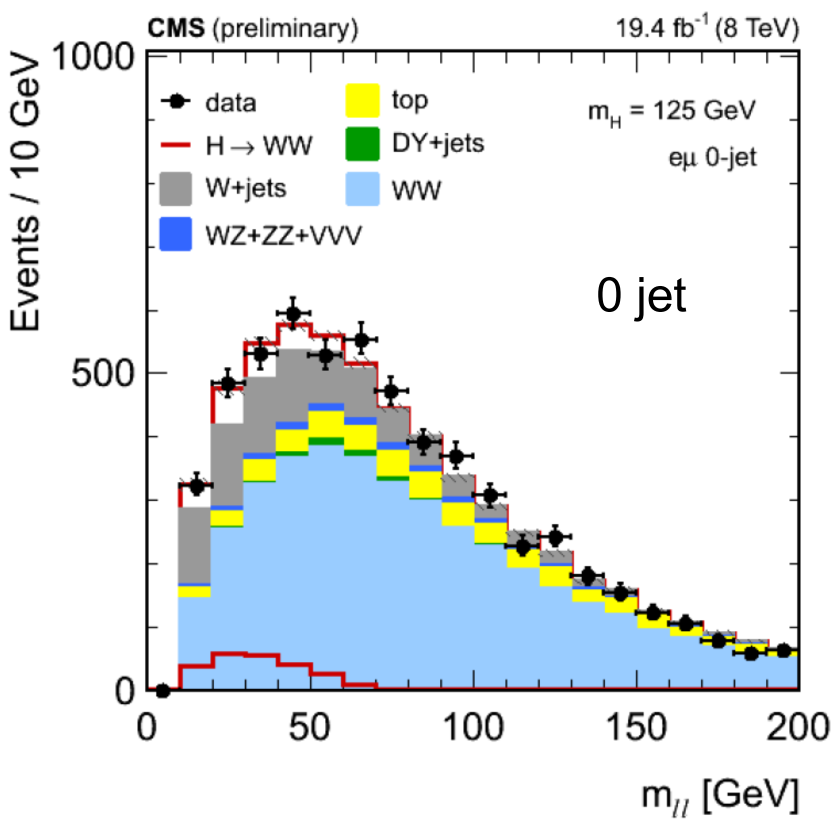
→ 1^+ and 1^- rejected (from combination of WW and ZZ) at 99.7% CL

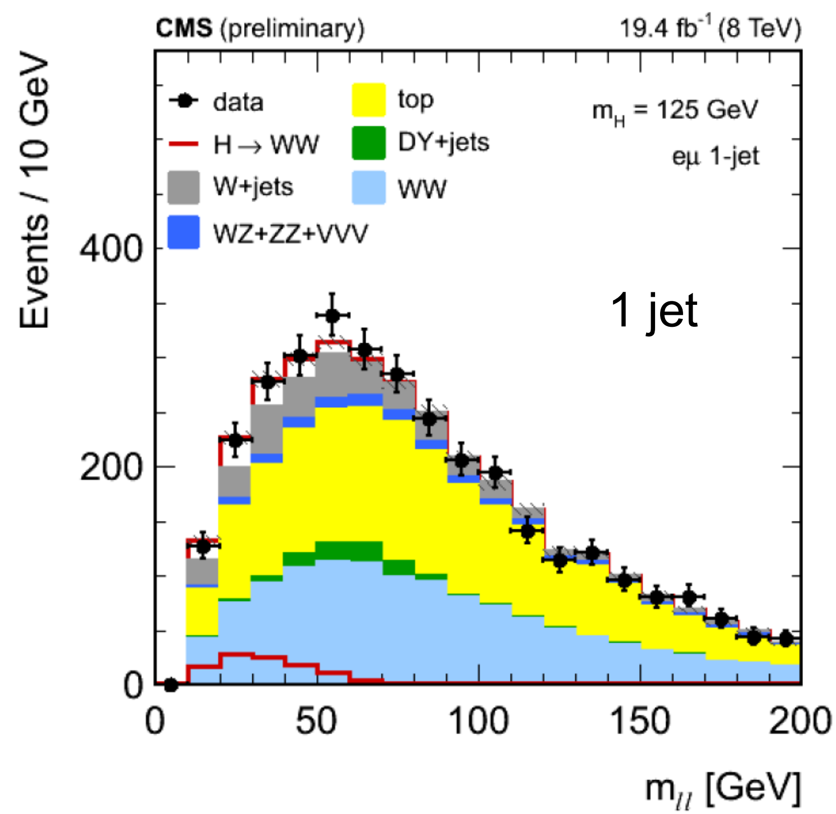
→ 2^+ rejected at 99.9% CL from combining ZZ, WW and γγ

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

Event selection:

- Particle flow algorithm used to reconstruct all particles in the event
- 2 high p_T (20 GeV and 10 GeV), isolated and opposite-charged leptons required, lepton efficiencies determined from data from $Z \rightarrow ll$ decays
- 0 or 1 high-p_T jet required (p_T > 30 GeV in $|\eta|$ < 4.7)
- m_{ll} > 12 GeV, $p_{T,ll}$ > 30 GeV, missing E_T > 20 GeV



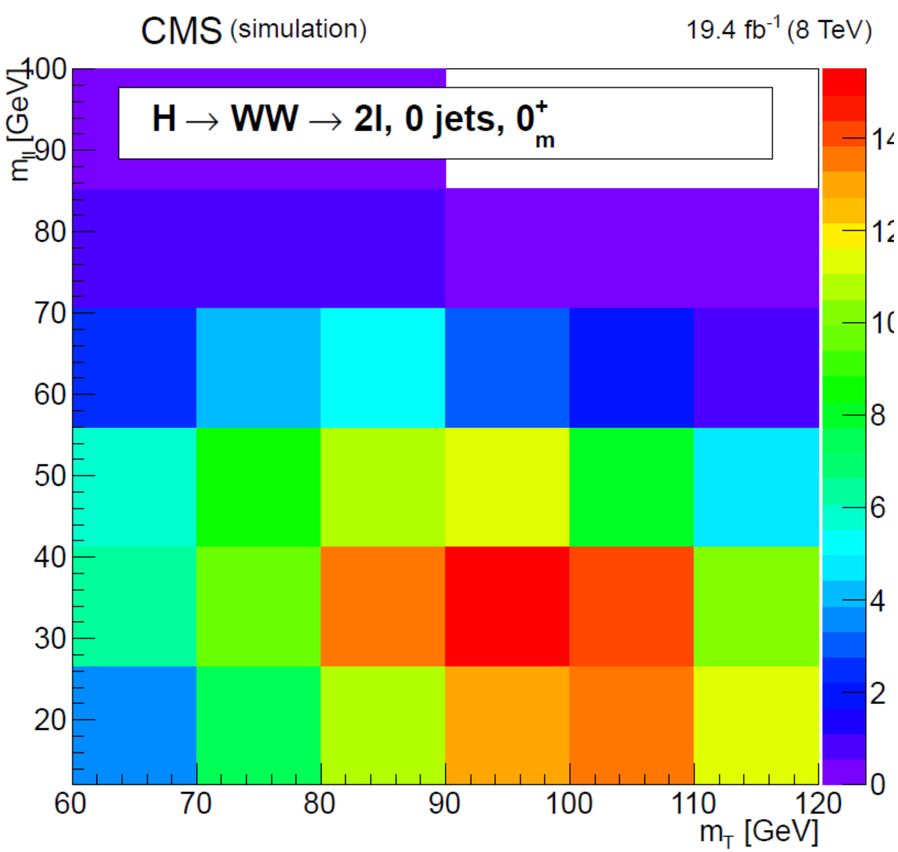


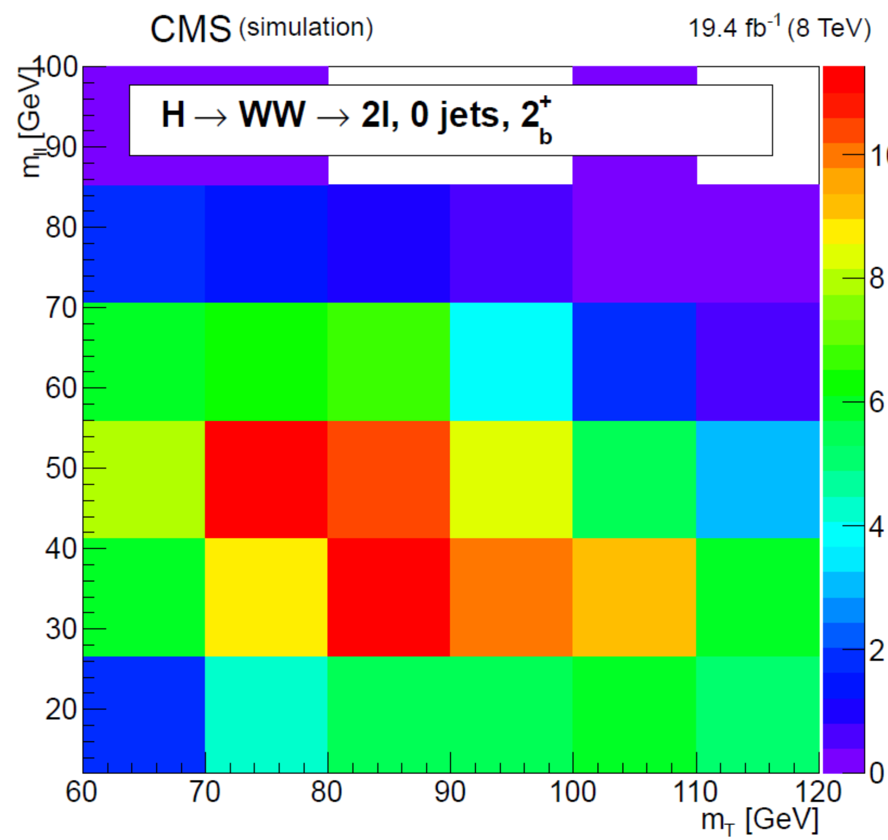
Signal: JHU used to generated spin-0/1/2 signals, ggF spin-0 production with Powheg (NLO)

Discriminants: m_{ll} and m_T

2D templates for 0-jet and 1-jet categories used in the likelihood fit

0-jet category signal templates shown here:





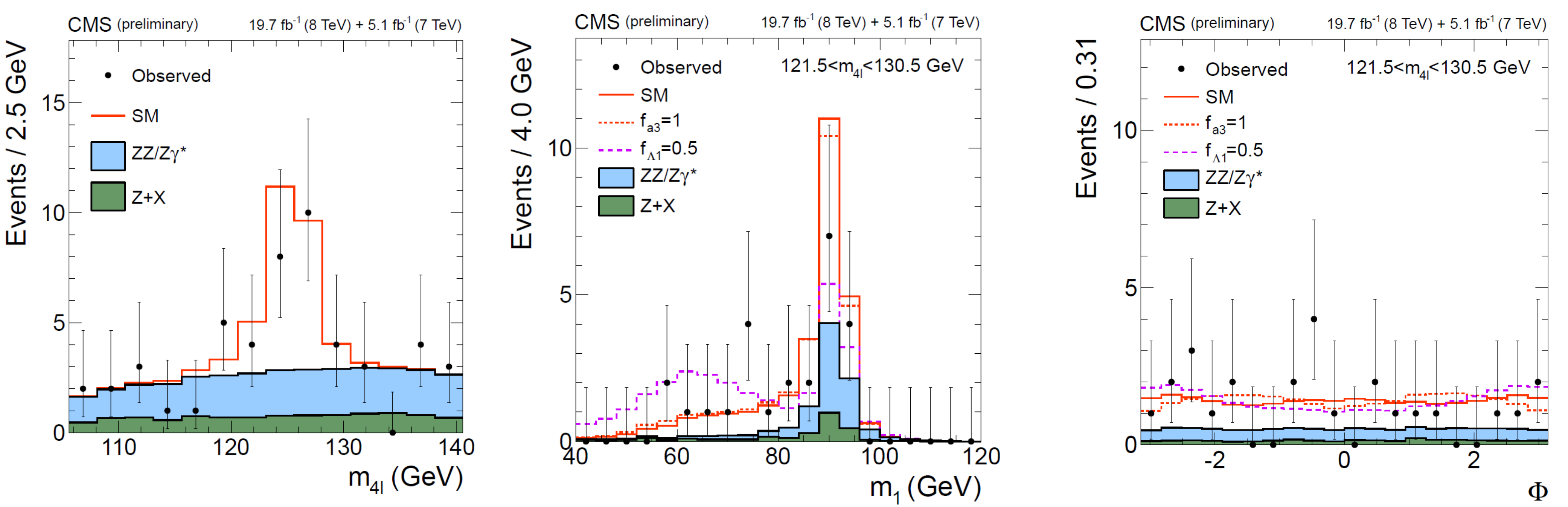
Event selection:

- 2 pairs of same-flavor opposite-charged isolated leptons, one lepton with p_T > 20 GeV, another one with p_T > 10 GeV
- 40 < m_{Z1} < 120 GeV and 12 < m_{Z2} < 120 GeV (m_{Z1} closer to nominal Z mass than m_{Z2})
- Signal region: 105.6 < m_{4l} < 140.6 GeV

→ 50 data event selected, 20 expected signal and 36 expected background events

Observables: 3 masses (m_{4l}, m_{Z1}, m_{Z2}), 5 angles (θ_1, θ_2, Φ, Φ_1, θ^*)

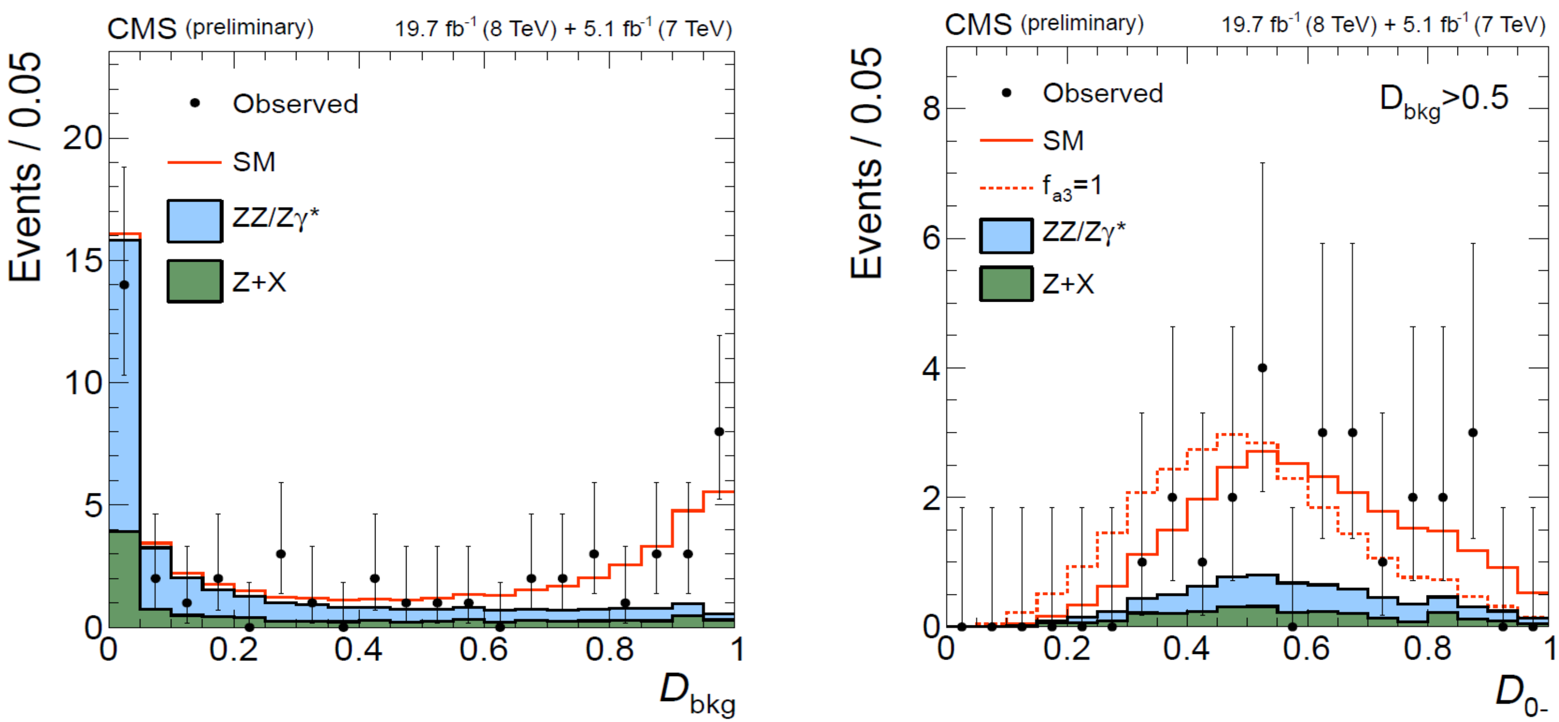
→ They discriminate signal from background and the various signal hypothesis from each other



CMS: H → 4l (H → ZZ / Zγ*/ γ*γ* → 4l)

Kinematic discriminant approach (KD method), using MELA and MEKD packages

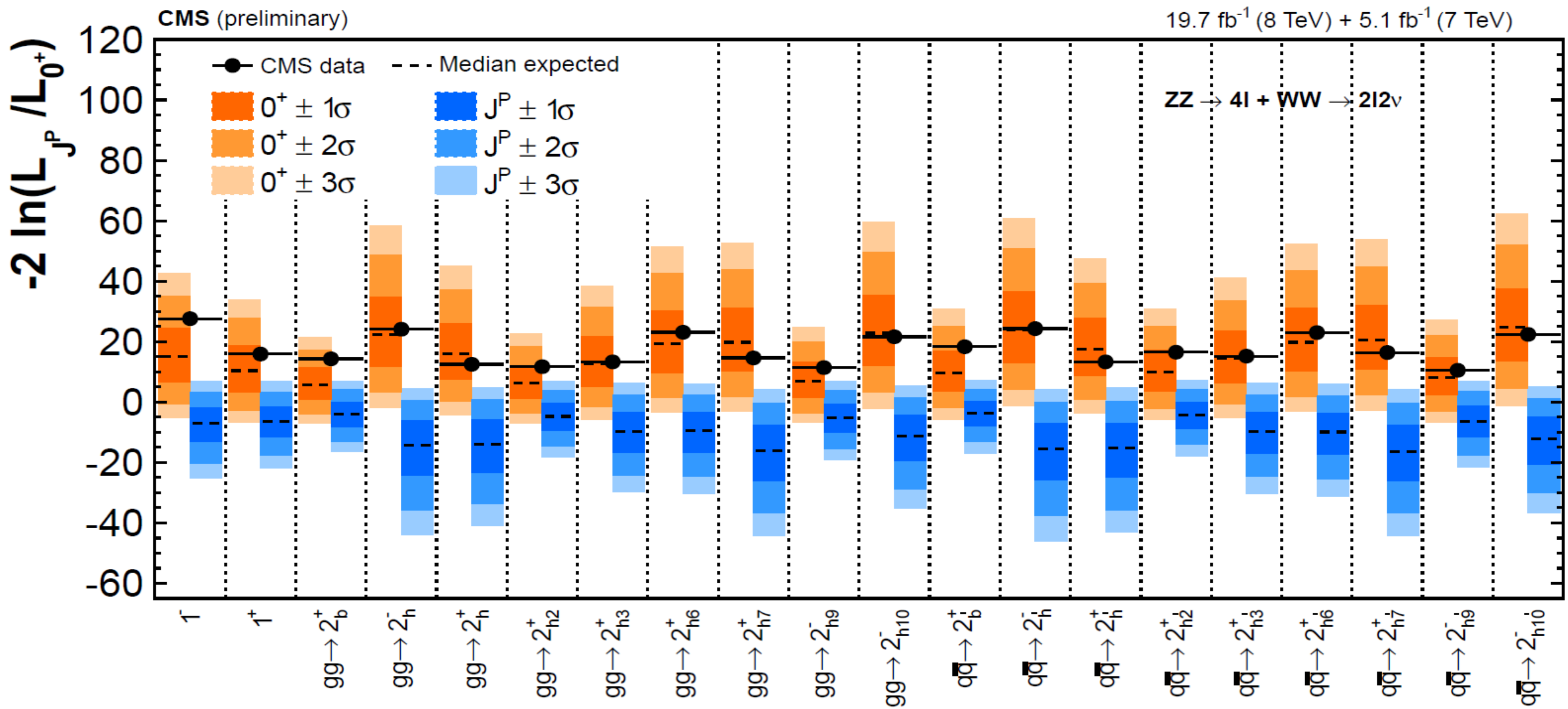
- Computing probabilities for an event from the matrix element as a function of the observables, using JHU for signal and MCFM for backgrounds
- Various kinematic discriminants are built to discriminate hypotheses, eg. 0^+ vs. backgrounds, pure CP states vs. Interferences etc,
- Additional KD observables constructed for exotic signal models (eg. higher dim operators)



Multidimensional distribution method (MD method):

- 8-dimensional likelihood fit (3 masses, 5 angles), using either analytical expression (eg. signal, $q\bar{q}$ → ZZ) or histogram templates on generator level (eg. Z+jets and gg → ZZ) as inputs
- usage of transfer functions to model the detector response

CMS: Hypothesis Testing, Combined Results (lνlν, 4l)



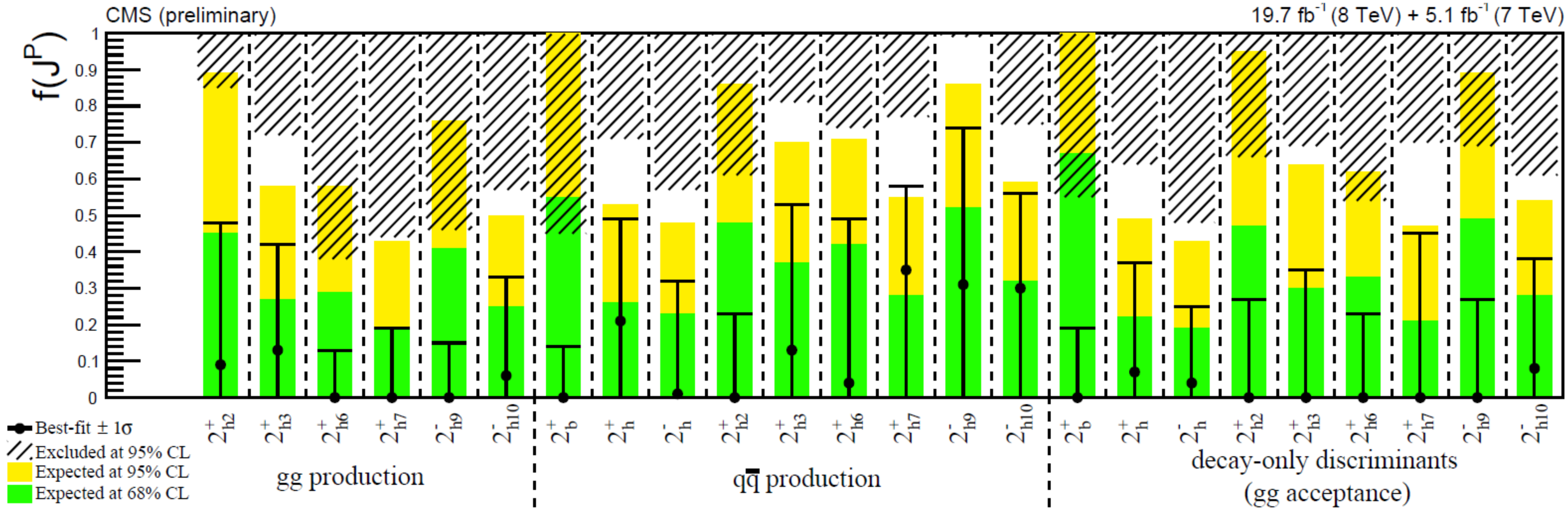
Alternative	Obs. p_0 0^+	Obs. p_0 alt
1^-	-1.3σ	4σ
1^+	-0.7σ	3.9σ
$gg \rightarrow 2$	-1.5σ-0.5σ	3.4σ-4.0σ
$q\bar{q} \rightarrow 2$	-1.2σ-0.5σ	3.2σ-4.0σ

→ Data compatibel with 0^+ hypotheses

→ Any alternative excluded with at least 99.9% CL.

Search for nearby, non-interfering $2^{+/-}$ states:

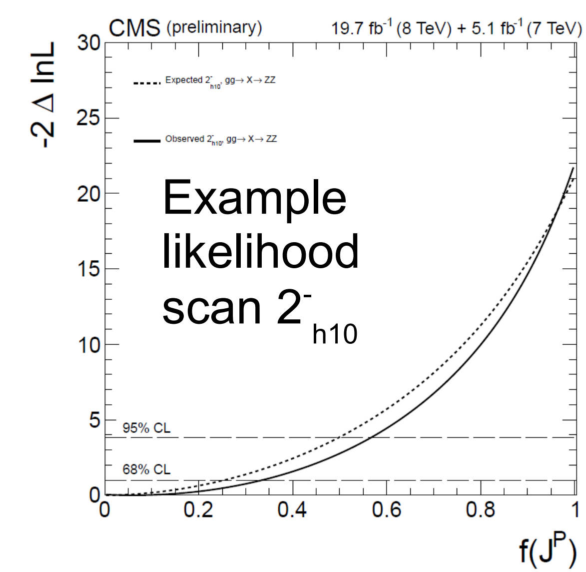
Fractional cross section: $$f\left(J^{CP}\right) = \frac{\sigma_{J^{CP}}}{\sigma_{0_m^+} + \sigma_{J^{CP}}}$$



Probes for the presence of a 2nd particle in the mass peak of the 4l signal region. However, masses separated such that there is no interference with the 0^+ resonance

→ Observations compatibel with f = 0

→ 95% limits on f set depending on the model of the 2nd resonance



Results on non-interfering spin-1 states in the backup

CMS: Results (4l, WW) Testing Spin-1 Mixtures

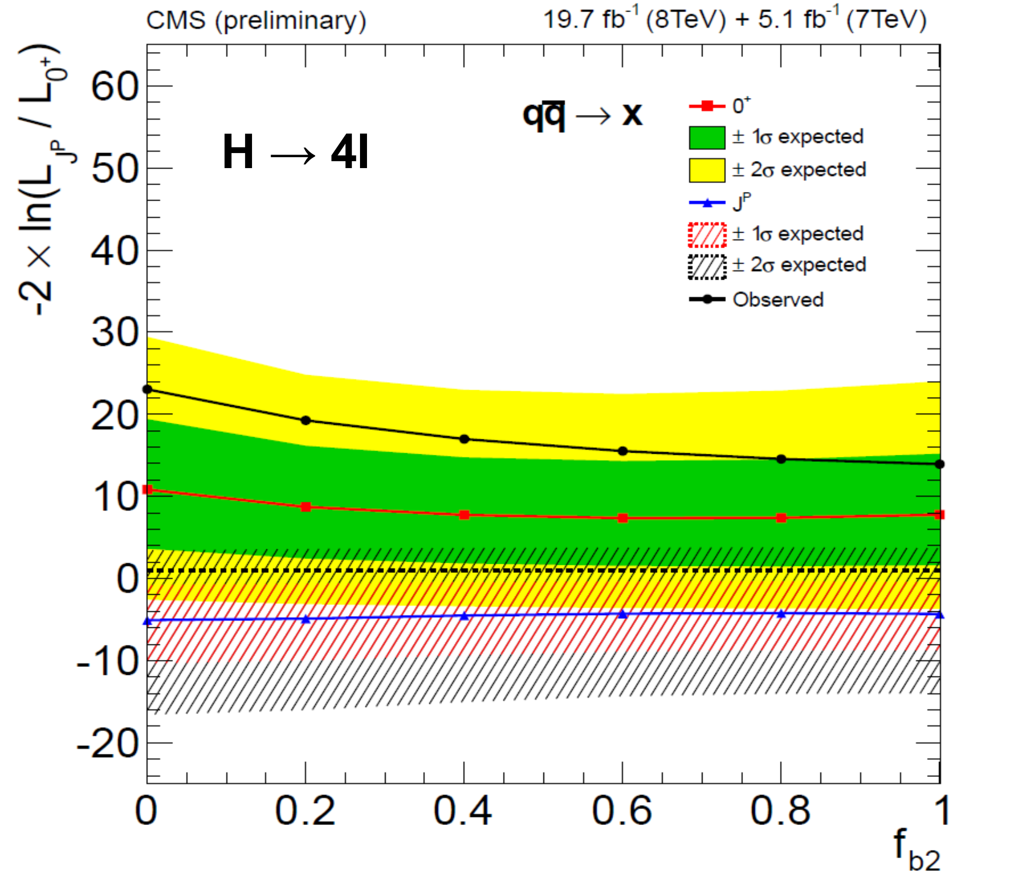
Testing pure and mixed spin-1 states:

$$A(X_{J=1} \to VV) = b_1 \left[(\epsilon_1^* q)(\epsilon_2^* \epsilon_X) + (\epsilon_2^* q)(\epsilon_1^* \epsilon_X) \right] + b_2 \epsilon_{\alpha\mu\nu\beta} \epsilon_X^{\alpha} \epsilon_1^{*\mu} \epsilon_2^{*\nu} \tilde{q}^{\beta}$$

$$f_{b2} = \frac{|b_2|^2 \sigma_2}{|b_1|^2 \sigma_1 + |b_2|^2 \sigma_2}$$

H $\to$ 4l results:

f_{b2}	Obs. p_0 0^+	Obs. p_0 alt	CLs alt
0 (**1**$^-$)	-1.4σ	$>4.5\sigma$	<0.01%
0.2	-1.4σ	4.6σ	<0.01%
0.4	-1.3σ	4.4σ	<0.01%
0.6	-1.2σ	4.1σ	0.01%
0.8	-1.0σ	3.9σ	0.02%
1 (**1**$^+$)	-0.8σ	3.8σ	0.04%



H $\to$ WW results:

J^P model	J^P production	Expected ($\sigma/\sigma_{SM}=1$)	Observed 0^+	Observed J^P	CLs
1^-	$q\bar{q} \to$ H	1.8σ (2.9σ)	-0.2σ	2.1σ	3.9%
1_{Mix}	$q\bar{q} \to$ H	1.6σ (2.6σ)	-0.1σ	1.7σ	8.7%
1^+	$q\bar{q} \to$ H	1.5σ (2.3σ)	0.1σ	1.4σ	14.0%

f_{b2}=0 means pseudo-vector 1^-, f_{b2}=1 means pure vector 1^+, 1_{MIX} means f_{b2}=0.5

Probing the tensor structure of the Spin-0 interaction

see also ICHEP talk from E. DiMarco

Decay amplitude of spin-0 particle → WW:

SM tree level + leading momentum expansion. Λ_1: scale of new physics

$$A(X_{J=0} \to WW) \sim v^{-1}\left(\left[a_1^{WW} - e^{i\phi_{\Lambda_1}}\frac{q_1^2+q_2^2}{\left(\Lambda_1^{WW}\right)^2}\right] m_W^2 \epsilon_1^* \epsilon_2^* + \underbrace{a_2^{WW} f_{\mu\nu}^{*(W)} f^{*(W),\mu\nu}}_{a_2 \text{ terms: CP-even scalar (not participating in EWSB)}} + \underbrace{a_3^{WW} f_{\mu\nu}^{*(W)} \tilde{f}^{*(W),\mu\nu}}_{a_3 \text{ terms: CP-odd scalar}}\right)$$

If particles in the loop are heavy, couplings will be real (in general complex).

Equivalent to an effective field theory Langrangian.

Analysis fits for the terms of the expansion: a_2, a_3, Λ_1

Couplings are converted into effective cross section fractions (anomalous coupling parameters):

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

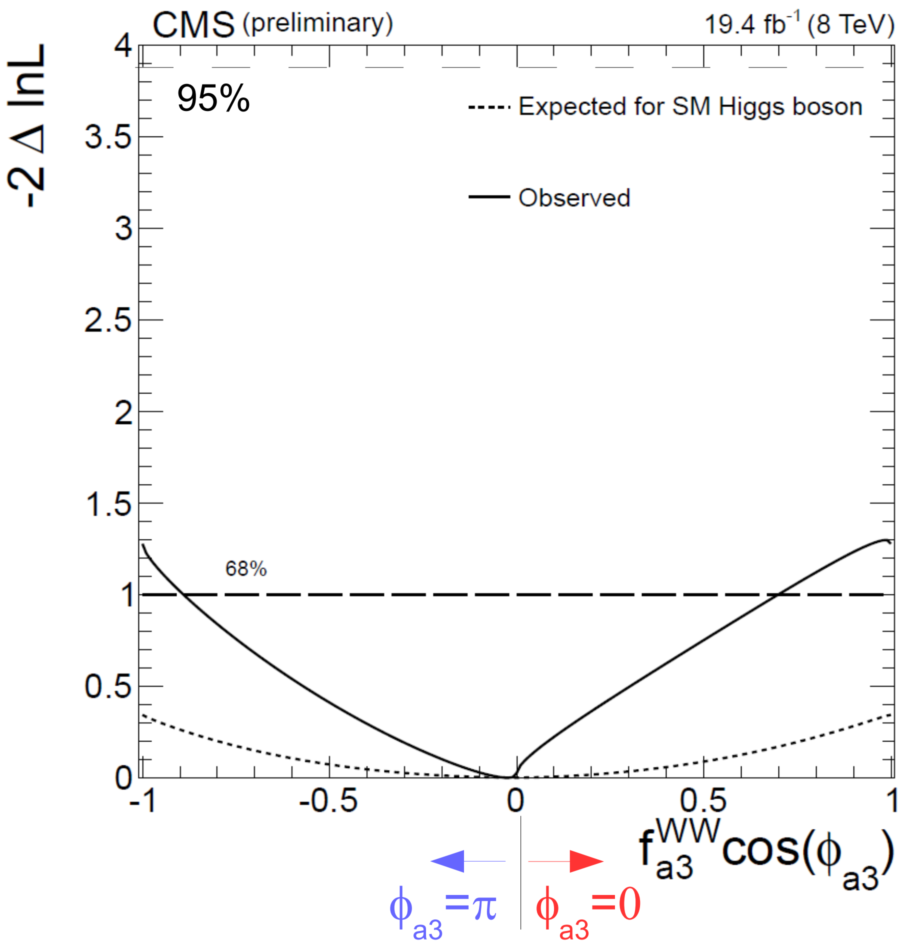
$$f_{a2} = \frac{|a_2|^2\sigma_2}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda_1}/\left(\Lambda_1\right)^4} \qquad \phi_{a2} = \arg\left(\frac{a_2}{a_1}\right)$$

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

σ_i is cross section of process corresponding to a_i=1and $a_{i\neq j}\neq 0$

$\sigma_{\Lambda 1}$ is effective cross section of process corresponding to Λ_1>0, $a_{j\neq\Lambda 1}$=0

Measurement of anomalous coupling parameters in H → WW:



Signal component of the likelihood:

$$\mathcal{L}^i_{f_{a3}^{WW}} = (1 - f_{a3}^{WW})\mathcal{L}^i_{0+} + f_{a3}^{WW}\mathcal{L}^i_{0-} + \sqrt{(1 - f_{a3}^{WW})f_{a3}^{WW}}\mathcal{L}^i_{int}$$

SM coupling anomalous c. Interference

Observed best-fit value of f_{a3} compatibel with 0 (within 0.16σ)

The pure CP-odd states disfavored with 1.13σ

→ No CP-odd contribution observed, in agreement with the SM theory.

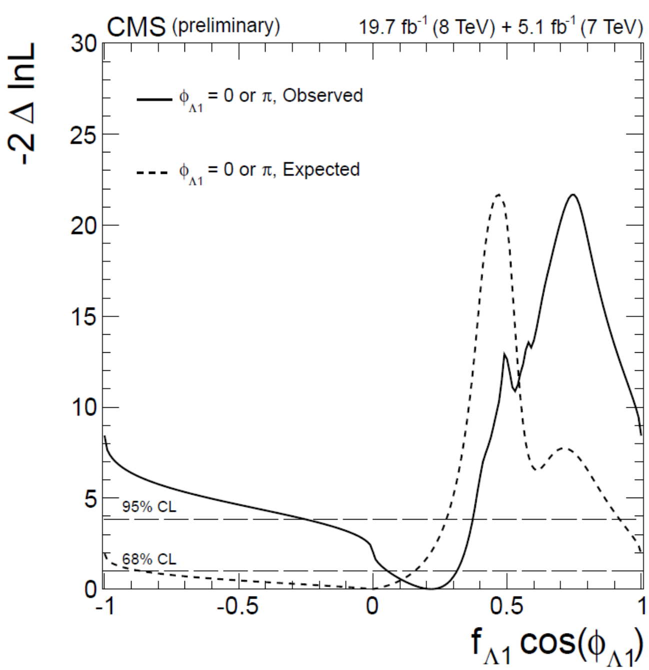
$$f_{a3}^{WW} = \frac{|a_3|^2\sigma_3}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \sigma_4/\Lambda_1{}^4} \; ; \; \phi_{a3} = \arg\left(\frac{a_3}{a_1}\right)$$

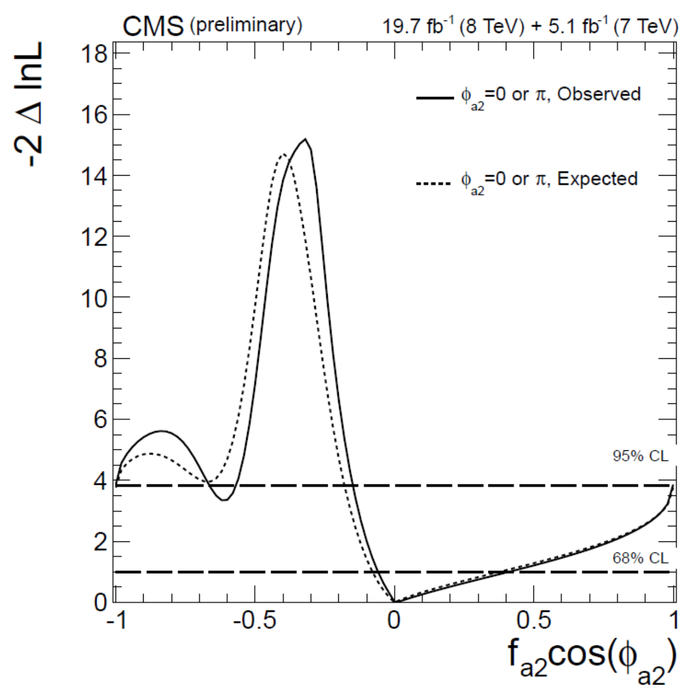
„Fraction of a CP-odd contribution to the total production cross section of the new boson“

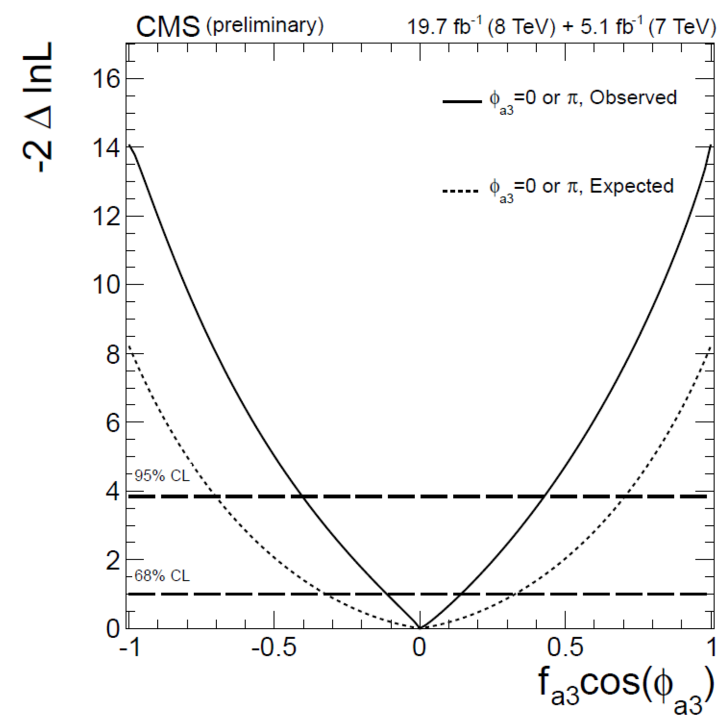
CMS: Measuring Anomalous Couplings of Spin-0

Measurement of anomalous coupling parameters in H → 4l:

Assuming coupling ratios a_2/a_1 and a_3/a_1 are real, $\phi_{\Lambda 1} = 0$ or π, and all other parameters are fixed to their SM values (plots with profiled parameters in the backup)







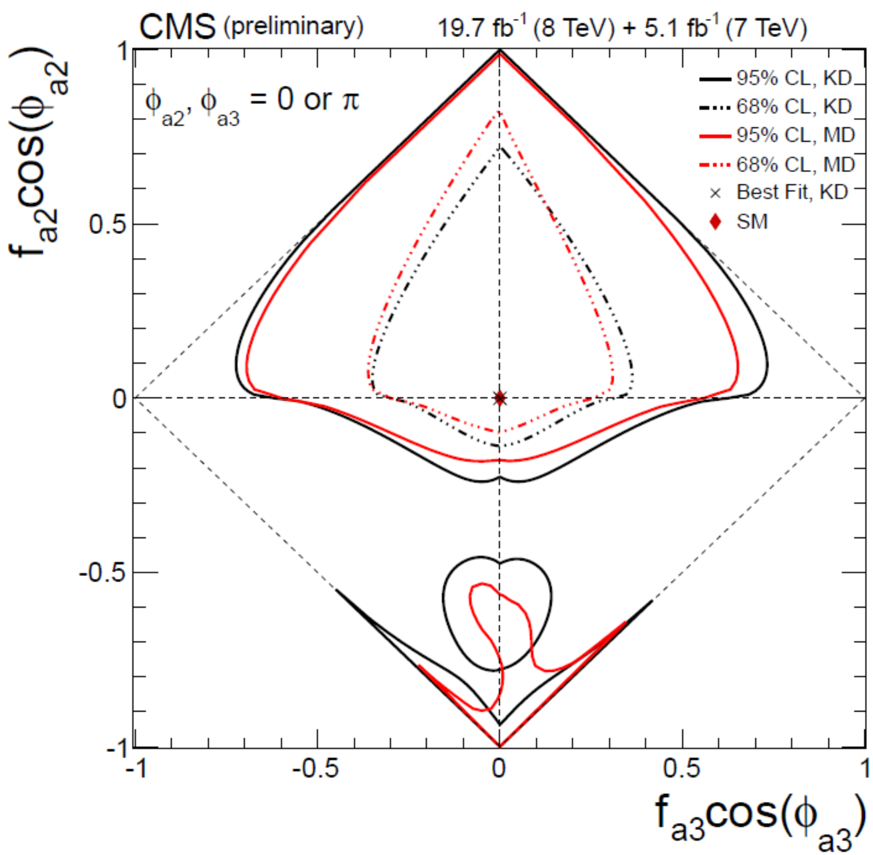
Allowed 95% CL intervals:

Parameter	Observed	Expected
$f_{\Lambda 1}\cos(\phi_{\Lambda 1})$	[-0.25,0.37]	[-1.00,0.27] & [0.92,1.00]
$f_{a2}\cos(\phi_{a2})$	[-0.66,-0.57] & [-0.15,1.00]	[-0.18,1.00]
$f_{a3}\cos(\phi_{a3})$	[-0.40,0.43]	[-0.70,0.70]

Probing 4l for the presence of 2 anomalous couplings simultaneously:

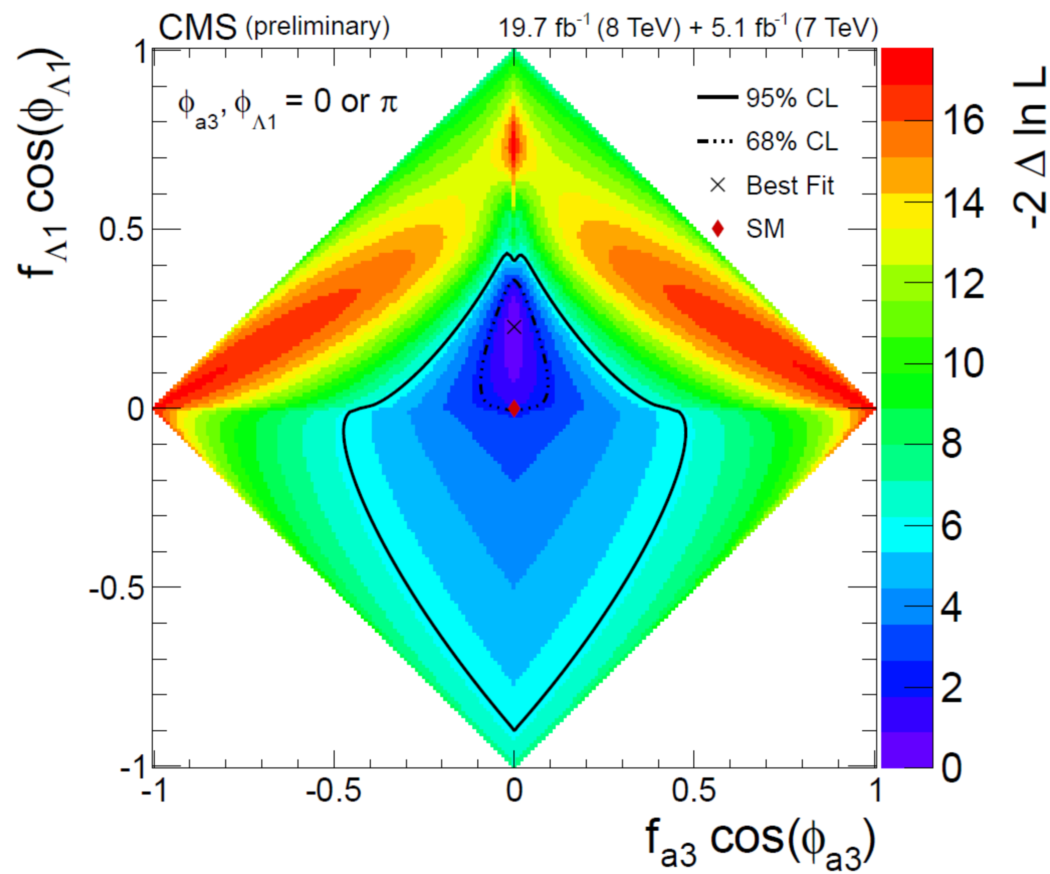
Examples:

Likelihood scan contours:



Assuming a_2/a_1 and a_3/a_1 ratios are real

2D likelihood scan values:



Amplitudes constrained to be real

95% CL. exclusion for $\Delta \ln L > 5.99$

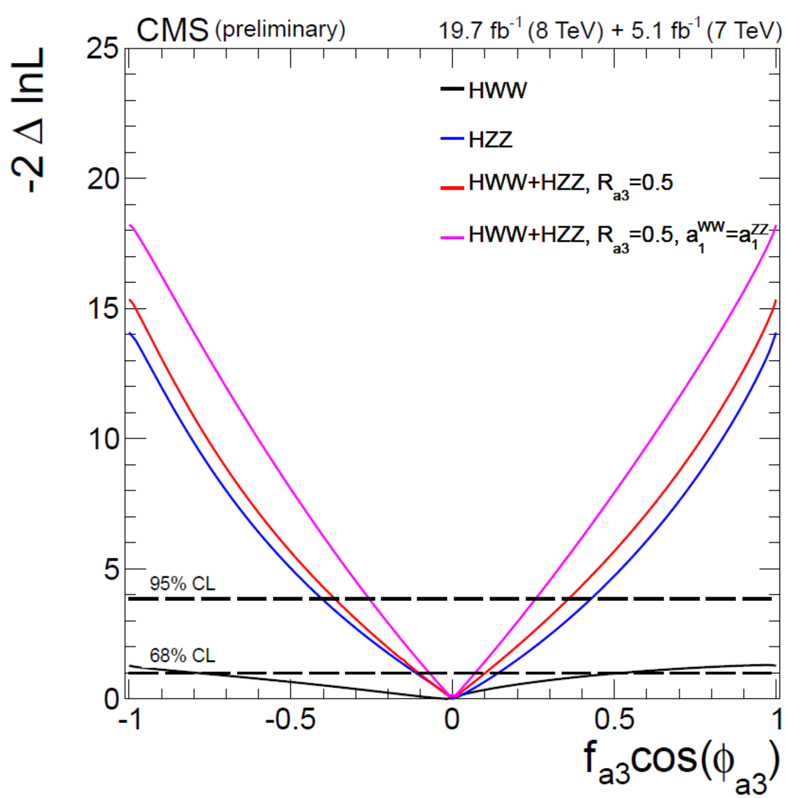
Measurement of anomalous coupling parameters combined for WW and 4l:

$$r_{ai} = \frac{a_i^{WW}/a_1^{WW}}{a_i^{ZZ}/a_1^{ZZ}}$$

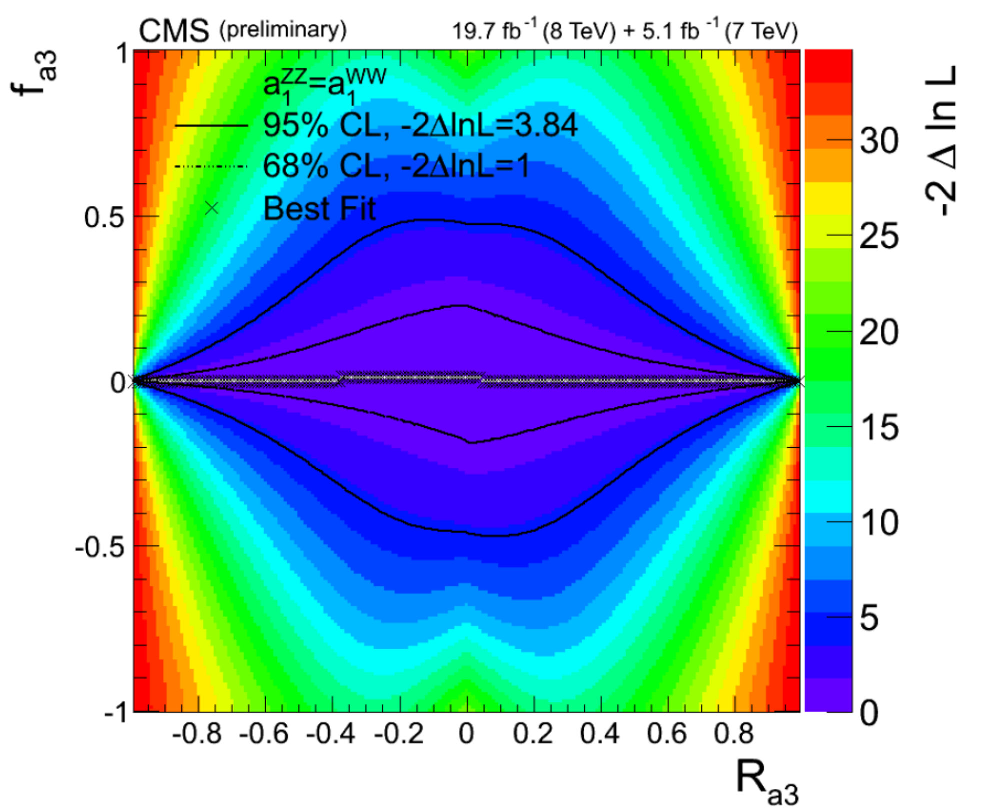
- General relation: $a_1^{WW} \neq a_1^{ZZ}$ $\rightarrow a_i^{WW}/a_1^{WW} = r_{ai} * (a_i^{ZZ}/a_1^{ZZ})$
- Assuming custodial symmetry: $a_1^{WW} = a_1^{ZZ}$ $\rightarrow a_i^{ZZ} = r_{ai} * a_i^{WW}$
  $\rightarrow$ stronger exclusions due to relation between WW and ZZ yields

$$R_{ai} = \frac{r_{ai}|r_{ai}|}{1 + r_{ai}^2}$$

Conditional combined scan of f_{a3} for R_{ai}=0.5 (r_{ai}=1):



Conditional scan of f_{a3} vs. R_{a3} when $a_1^{WW}=a_1^{ZZ}$:



Summary

- Both ATLAS and CMS carried out various Spin/CP studies using the bosonic decay modes
- The SM CP-even scalar hypothesis is preferred over any other tested model:

CL. Exclusions:

J^P	ATLAS	CMS
0^-	97.8%	>99.9%
1^-	>99.9%	>99.9%
1^+	99.7%	>99.9%
$gg \rightarrow 2^{+/-}$	>99.9%	>99.9%
$q\bar{q} \rightarrow 2^{+/-}$	>99.9%	>99.9%

- CMS set limits on the anomalous couplings for spin-0 (here for $H \rightarrow 4l$ assuming coupling ratios are real):

Allowed 95% CL intervals:

Parameter	Observed	Expected
$f_{\Lambda 1}\cos(\phi_{\Lambda 1})$	[-0.25,0.37]	[-1.00,0.27] & [0.92,1.00]
$f_{a2}\cos(\phi_{a2})$	[-0.66,-0.57] & [-0.15,1.00]	[-0.18,1.00]
$f_{a3}\cos(\phi_{a3})$	[-0.40,0.43]	[-0.70,0.70]

→ **All observations are compatible with the SM expectations $J^P=0^+$**

Backup

CMS models:

J^P	mode	production couplings	decay couplings
0_m^+	$gg \to X \to W^+W^-$	(any) $a_2^{(0)} \neq 0$	$a_1^{(0)} \neq 0$
0_h^+	$gg \to X \to W^+W^-$	(any) $a_2^{(0)} \neq 0$	$a_2^{(0)} \neq 0$
$0_{\Lambda 1}^+$	$gg \to X \to W^+W^-$	(any) $a_2^{(0)} \neq 0$	$\Lambda_1 \neq \infty$
0^-	$gg \to X \to W^+W^-$	(any) $a_3^{(0)} \neq 0$	$a_3^{(0)} \neq 0$
1^+	$q\bar{q} \to X \to W^+W^-$	$\rho_2^{(1)}$ or $\rho_1^{(1)} \neq 0$	$b_2 \neq 0$
1^-	$q\bar{q} \to X \to W^+W^-$	$\rho_1^{(1)}$ or $\rho_2^{(1)} \neq 0$	$b_1 \neq 0$
2_m^+	$gg \to X \to W^+W^-$	$c_1 \neq 0$	$c_1 = c_5 \neq 0$
2_{h2}^+	$gg \to X \to W^+W^-$	$c_2 \neq 0$	$c_2 \neq 0$
2_{h3}^+	$gg \to X \to W^+W^-$	$c_3 \neq 0$	$c_3 \neq 0$ i
2_h^+	$gg \to X \to W^+W^-$	$c_4 \neq 0$	$c_4 \neq 0$
2_b^+	$gg \to X \to W^+W^-$	$c_1 \neq 0$	$c_1 \ll c_5 \neq 0$
2_{h6}^+	$gg \to X \to W^+W^-$	$c_1 \neq 0$	$c_6 \neq 0$
2_{h7}^+	$gg \to X \to W^+W^-$	$c_1 \neq 0$	$c_7 \neq 0$
2_h^-	$gg \to X \to W^+W^-$	$c_8 \neq 0$	$c_8 \neq 0$
2_{h9}^-	$gg \to X \to W^+W^-$	$c_8 \neq 0$	$c_9 \neq 0$
2_{h10}^-	$gg \to X \to W^+W^-$	$c_8 \neq 0$	$c_{10} \neq 0$
2_m^+	$q\bar{q} \to X \to W^+W^-$	$\rho_1^{(2)}$ or $\rho_2^{(2)} \neq 0$	$c_1 = c_5 \neq 0$
2_{h2}^+	$q\bar{q} \to X \to W^+W^-$	$\rho_1^{(2)}$ or $\rho_2^{(2)} \neq 0$	$c_2 \neq 0$
2_{h3}^+	$q\bar{q} \to X \to W^+W^-$	$\rho_1^{(2)}$ or $\rho_2^{(2)} \neq 0$	$c_3 \neq 0$
2_h^+	$q\bar{q} \to X \to W^+W^-$	$\rho_1^{(2)}$ or $\rho_2^{(2)} \neq 0$	$c_4 \neq 0$
2_b^+	$q\bar{q} \to X \to W^+W^-$	$\rho_1^{(2)}$ or $\rho_2^{(2)} \neq 0$	$c_1 \ll c_5 \neq 0$
2_{h6}^+	$q\bar{q} \to X \to W^+W^-$	$\rho_1^{(2)}$ or $\rho_2^{(2)} \neq 0$	$c_6 \neq 0$
2_{h7}^+	$q\bar{q} \to X \to W^+W^-$	$\rho_1^{(2)}$ or $\rho_2^{(2)} \neq 0$	$c_7 \neq 0$
2_h^-	$q\bar{q} \to X \to W^+W^-$	$\rho_1^{(2)}$ or $\rho_2^{(2)} \neq 0$	$c_8 \neq 0$
2_{h9}^-	$q\bar{q} \to X \to W^+W^-$	$\rho_1^{(2)}$ or $\rho_2^{(2)} \neq 0$	$c_9 \neq 0$
2_{h10}^-	$q\bar{q} \to X \to W^+W^-$	$\rho_1^{(2)}$ or $\rho_2^{(2)} \neq 0$	$c_{10} \neq 0$

Decay amplitudes for X → WW

Spin-0: $$A(H\to WW)=v^{-1}\left(\left[a_1-e^{i\varphi_{\Lambda 1}}\frac{q_1^2+q_2^2}{(\Lambda_1)^2}\right]m_W^2\epsilon_1^*\epsilon_2^*+a_2f_{\mu\nu}^{*(1)}f^{*(2),\mu\nu}+a_3f_{\mu\nu}^{*(1)}\tilde{f}^{*(2),\mu\nu}\right)$$

Spin-1: $$A(X_{J=1}\to VV)=b_1\left[(\epsilon_1^*q)(\epsilon_2^*\epsilon_X)+(\epsilon_2^*q)(\epsilon_1^*\epsilon_X)\right]+b_2\epsilon_{\alpha\mu\nu\beta}\epsilon_X^\alpha\epsilon_1^{*\mu}\epsilon_2^{*\nu}\tilde{q}^\beta$$

Spin-2: $$\begin{aligned}A(X_{J=2}\to V_1V_2)=\Lambda^{-1}\Bigg[&2c_1t_{\mu\nu}f^{*1,\mu\alpha}f^{*2,\nu\alpha}+2c_2t_{\mu\nu}\frac{q_\alpha q_\beta}{\Lambda^2}f^{*1,\mu\alpha}f^{*2,\nu,\beta}\\&+c_3\frac{\tilde{q}^\beta\tilde{q}^\alpha}{\Lambda^2}t_{\beta\nu}(f^{*1,\mu\nu}f^{*2}_{\mu\alpha}+f^{*2,\mu\nu}f^{*1}_{\mu\alpha})+c_4\frac{\tilde{q}^\nu\tilde{q}^\mu}{\Lambda^2}t_{\mu\nu}f^{*1,\alpha\beta}f^{*(2)}_{\alpha\beta}\\&+m_V^2\left(2c_5t_{\mu\nu}\epsilon_1^{*\mu}\epsilon_2^{*\nu}+2c_6\frac{\tilde{q}^\mu q_\alpha}{\Lambda^2}t_{\mu\nu}\left(\epsilon_1^{*\nu}\epsilon_2^{*\alpha}-\epsilon_1^{*\alpha}\epsilon_2^{*\nu}\right)+c_7\frac{\tilde{q}^\mu\tilde{q}^\nu}{\Lambda^2}t_{\mu\nu}\epsilon_1^*\epsilon_2^*\right)\\&+c_8\frac{\tilde{q}^\mu\tilde{q}^\nu}{\Lambda^2}t_{\mu\nu}f^{*1,\alpha\beta}\tilde{f}^{*(2)}_{\alpha\beta}+c_9t^{\mu\alpha}\tilde{q}_\alpha\epsilon_{\mu\nu\rho\sigma}\epsilon_1^{*\nu}\epsilon_2^{*\rho}q^\sigma\\&+\frac{c_{10}t^{\mu\alpha}\tilde{q}_\alpha}{\Lambda^2}\epsilon_{\mu\nu\rho\sigma}q^\rho\tilde{q}^\sigma\left(\epsilon_1^{*\nu}(q\epsilon_2^*)+\epsilon_2^{*\nu}(q\epsilon_1^*)\right)\Bigg],\end{aligned}$$

Assuming exact chiral symmetry in the limit of vanishing fermion masses:

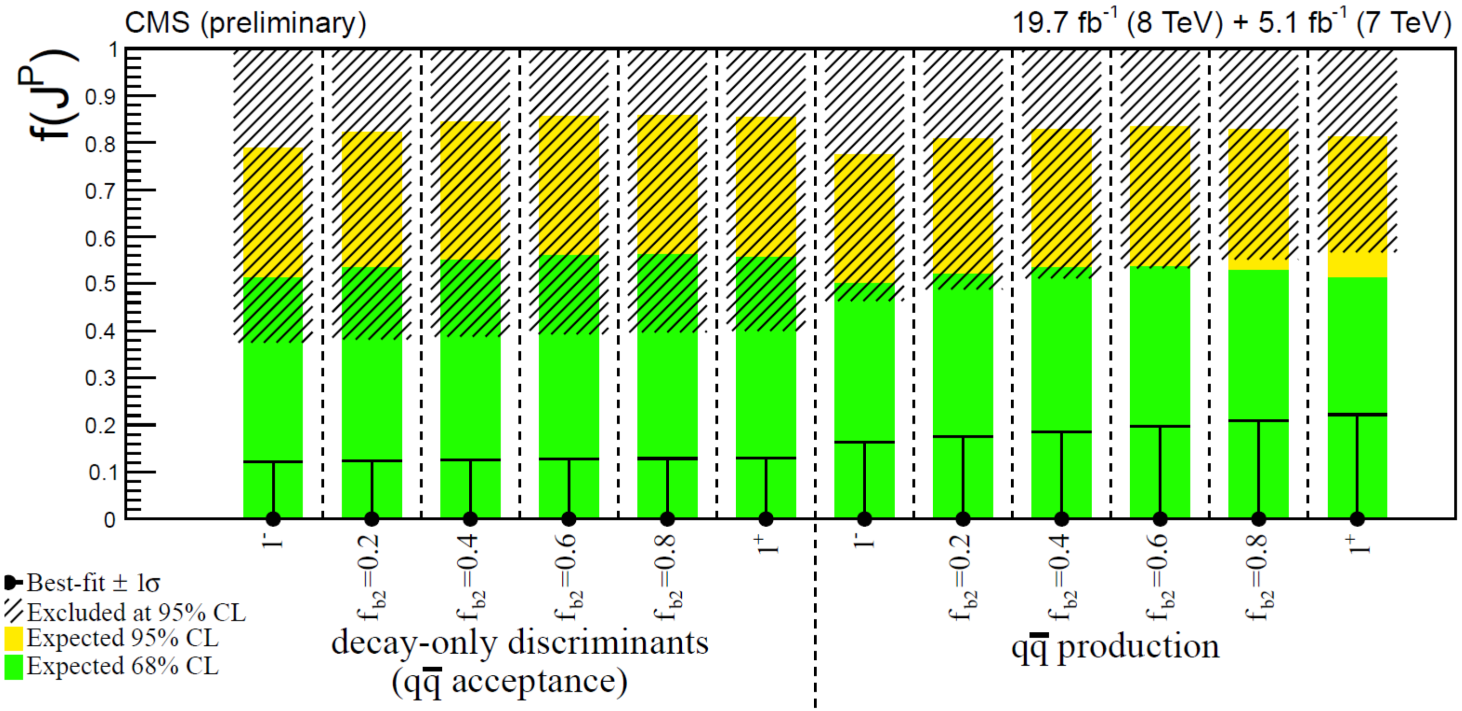
$$A(X_{J=0}f\bar{f})=\frac{m_f}{v}\bar{u}_2\left(\rho_1+\rho_2\gamma_5\right)u_1$$

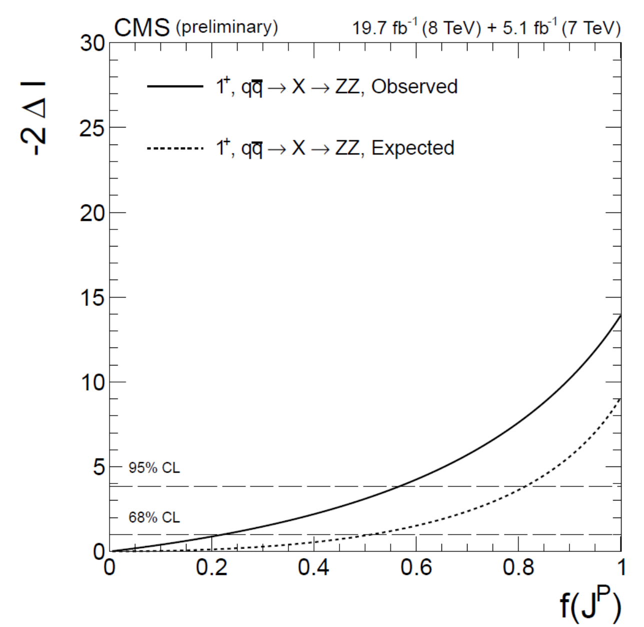
$$A(X_{J=1}f\bar{f})=\epsilon^\mu\bar{u}_2\left(\gamma_\mu\left(\rho_1^{(1)}+\rho_2^{(1)}\gamma_5\right)+\frac{m_f\tilde{q}_\mu}{\Lambda^2}\left(\rho_3^{(1)}+\rho_4^{(1)}\gamma_5\right)\right)u_1\,,$$

$$A(X_{J=2}f\bar{f})=\frac{1}{\Lambda}t^{\mu\nu}\bar{u}_2\left(\gamma_\mu\tilde{q}_\nu\left(\rho_1^{(2)}+\rho_2^{(2)}\gamma_5\right)+\frac{m_f\tilde{q}_\mu\tilde{q}_\nu}{\Lambda^2}\left(\rho_3^{(2)}+\rho_4^{(2)}\gamma_5\right)\right)u_1$$

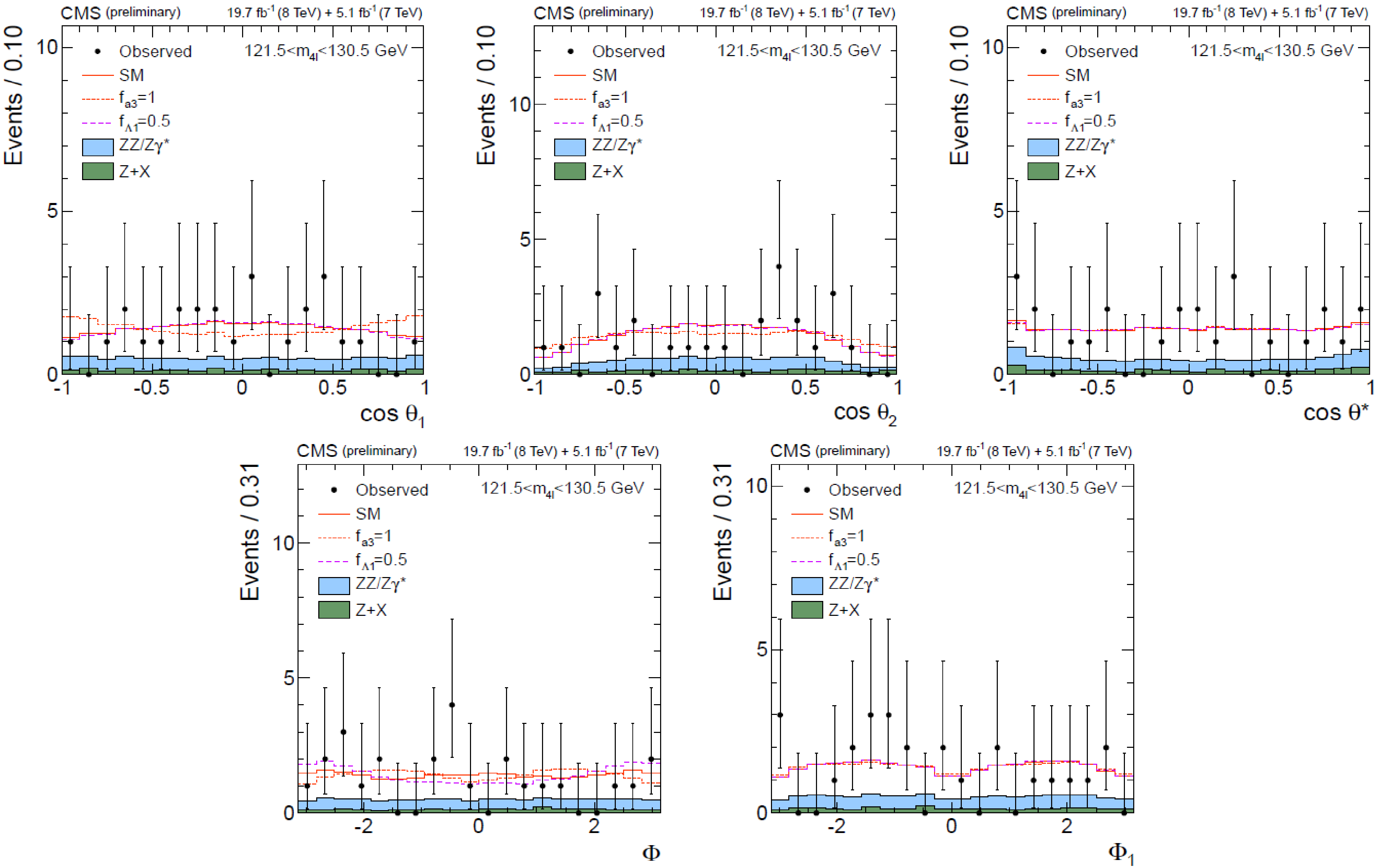
More CMS Results using H → 4l probing Spin-1:

Non-interfering states:





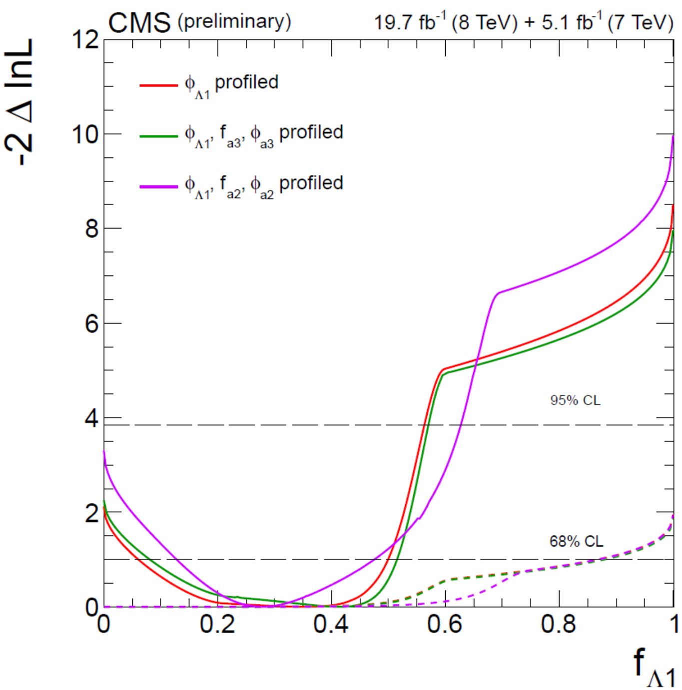
CMS H → 4l Angular Variables

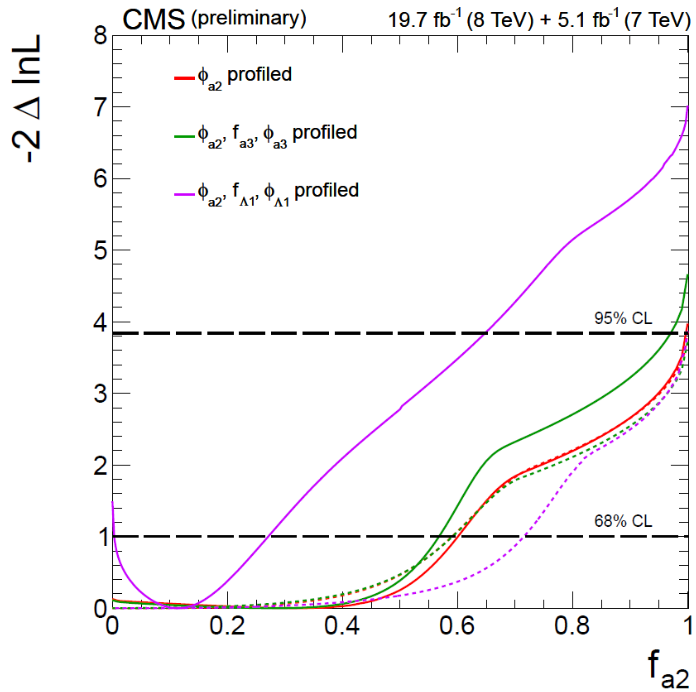


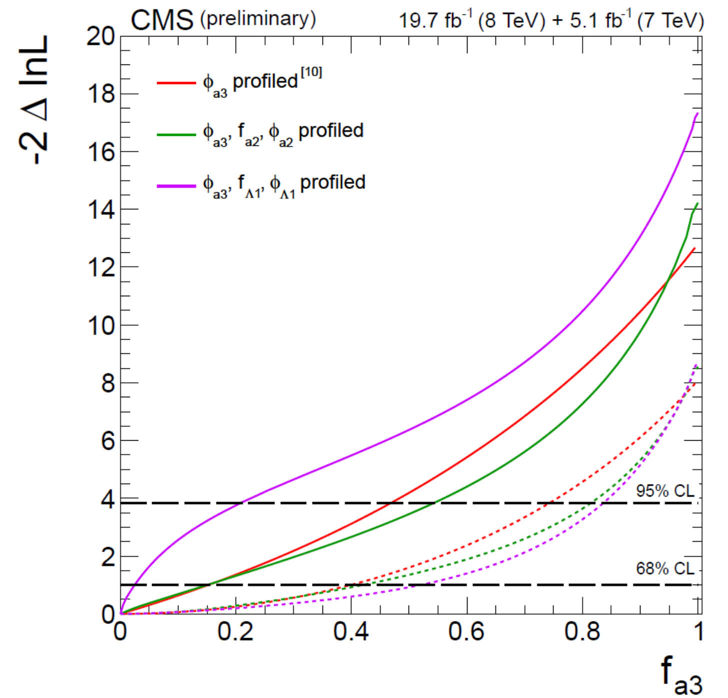
CMS combined results WW+ZZ:

J^P model	J^P production	Expected (μ=1)	Obs. 0^+	Obs. J^P
1^-	$q\bar{q} \to X$	3.3σ ($>4.0\ \sigma$)	-1.3σ	$>4.0\sigma$
1^+	$q\bar{q} \to X$	2.8σ ($3.6\ \sigma$)	-0.7σ	$+3.9\sigma$
2^+_{b}	$gg \to X$	2.1σ ($2.9\ \sigma$)	-1.5σ	$+3.9\sigma$
2^+_{h}	$gg \to X$	3.9σ ($>4.0\ \sigma$)	$+0.4\sigma$	$+3.6\sigma$
2^-_{h}	$gg \to X$	$>4.0\sigma$ ($>4.0\ \sigma$)	-0.1σ	$>4.0\sigma$
2^+_{h2}	$gg \to X$	2.3σ ($3.0\ \sigma$)	-0.9σ	$+3.4\sigma$
2^+_{h3}	$gg \to X$	3.3σ ($3.9\ \sigma$)	-0.1σ	$+3.6\sigma$
2^+_{h6}	$gg \to X$	3.8σ ($>4.0\ \sigma$)	-0.4σ	$>4.0\sigma$
2^+_{h7}	$gg \to X$	$>4.0\sigma$ ($>4.0\ \sigma$)	$+0.5\sigma$	$+3.9\sigma$
2^-_{h9}	$gg \to X$	2.4σ ($3.1\ \sigma$)	-0.7σ	$+3.4\sigma$
2^-_{h10}	$gg \to X$	$>4.0\sigma$ ($>4.0\ \sigma$)	$+0.1\sigma$	$>4.0\sigma$
2^+_{b}	$q\bar{q} \to X$	2.6σ ($3.8\ \sigma$)	-1.2σ	$>4.0\sigma$
2^+_{h}	$q\bar{q} \to X$	4.0σ ($>4.0\ \sigma$)	$+0.5\sigma$	$+3.7\sigma$
2^-_{h}	$q\bar{q} \to X$	$>4.0\sigma$ ($>4.0\ \sigma$)	0.0σ	$>4.0\sigma$
2^+_{h2}	$q\bar{q} \to X$	2.7σ ($3.8\ \sigma$)	-0.9σ	$>4.0\sigma$
2^+_{h3}	$q\bar{q} \to X$	3.4σ ($>4.0\ \sigma$)	-0.1σ	$+3.8\sigma$
2^+_{h6}	$q\bar{q} \to X$	3.9σ ($>4.0\ \sigma$)	-0.3σ	$>4.0\sigma$
2^+_{h7}	$q\bar{q} \to X$	$>4.0\sigma$ ($>4.0\ \sigma$)	$+0.4\sigma$	$+4.0\sigma$
2^-_{h9}	$q\bar{q} \to X$	2.7σ ($3.3\ \sigma$)	-0.4σ	$+3.2\sigma$
2^-_{h10}	$q\bar{q} \to X$	$>4.0\sigma$ ($>4.0\ \sigma$)	$+0.2\sigma$	$>4.0\sigma$

Measurement of anomalous coupling parameters in H → 4l:







Measurement of anomalous coupling parameters in H → 4l and H → WW combined: