HIGGS SPIN-PARITY AND HVV COUPLINGS WITH CMS

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INTRODUCTION

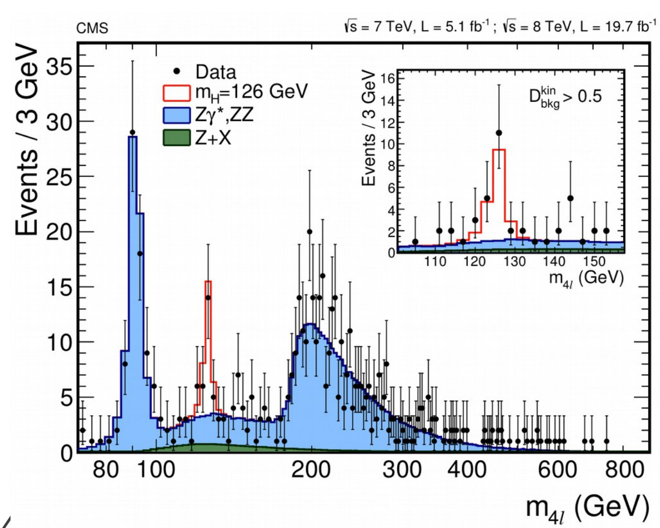
- Talk based on recent results (November)
  - ↳ http://arxiv.org/abs/1411.3441
  - ↳ https://twiki.cern.ch/twiki/bin/view/CMSPublic/Hig14018PaperTwiki
- Previous results → spin-parity properties consistent with scalar SM Higgs
- Now: refined and extended studies
  - ↳ 10 spin-2 hypotheses, with various assumptions on production
  - ↳ Analysis of mixed spin-1 (1+/1-) states
  - ↳ 11 anomalous HVV (V=Z,W,γ) couplings constrained, under spin-0 assumption
- Combination of results in three channels
  - ↳ H→ZZ→4l, H→WW→2l2ν, H→$\gamma\gamma$
- Run-1 legacy results on Higgs spin-parity and coupling structure with H→VV

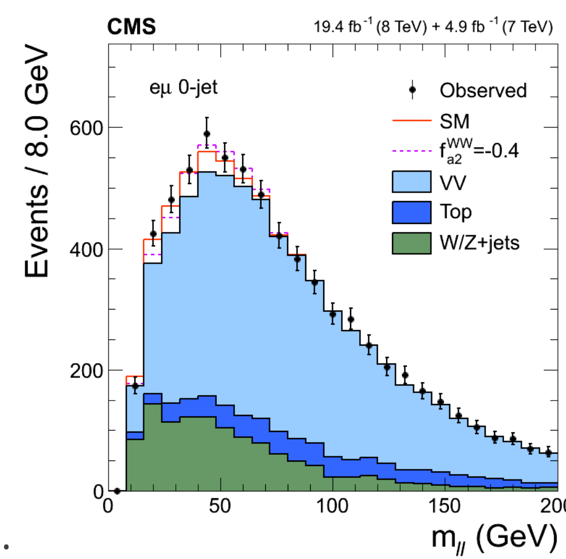
SPIN AND PARITY MEASUREMENTS

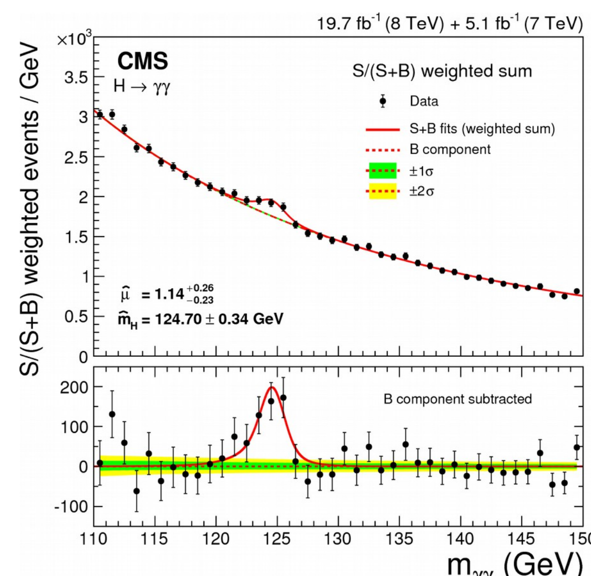
- Spin-parity state and tensor structure probed with kinematic information

Covered measurements

	$ZZ \rightarrow 4l$	$WW \rightarrow 2l2\nu$	$\gamma\gamma$
J=1	Pure states, Non-interfering mixture	Pure states	Forbidden
J=2	Pure states, Non-interfering mixture	Pure states	Pure states
J=0	Real couplings, Complex couplings	Real couplings	No







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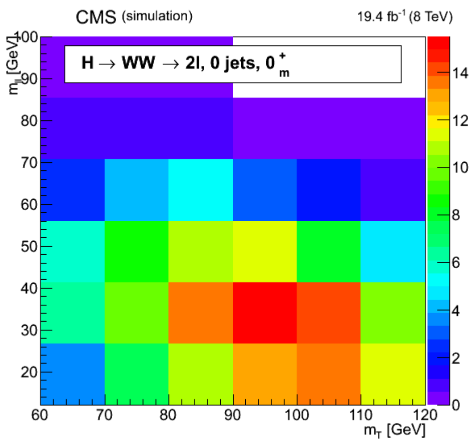
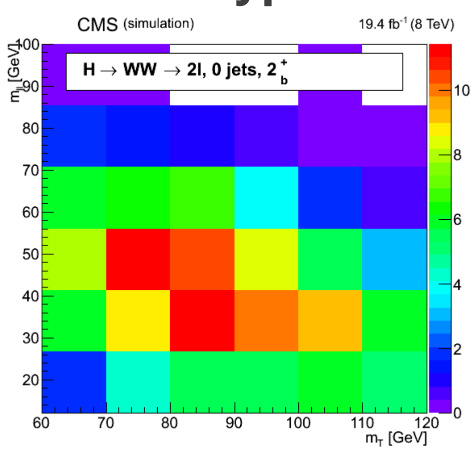
- H→WW→2l2ν: kinematics described by leptons momenta and MET
  - ↳ [M_T, m_{ll}] 2D pdf

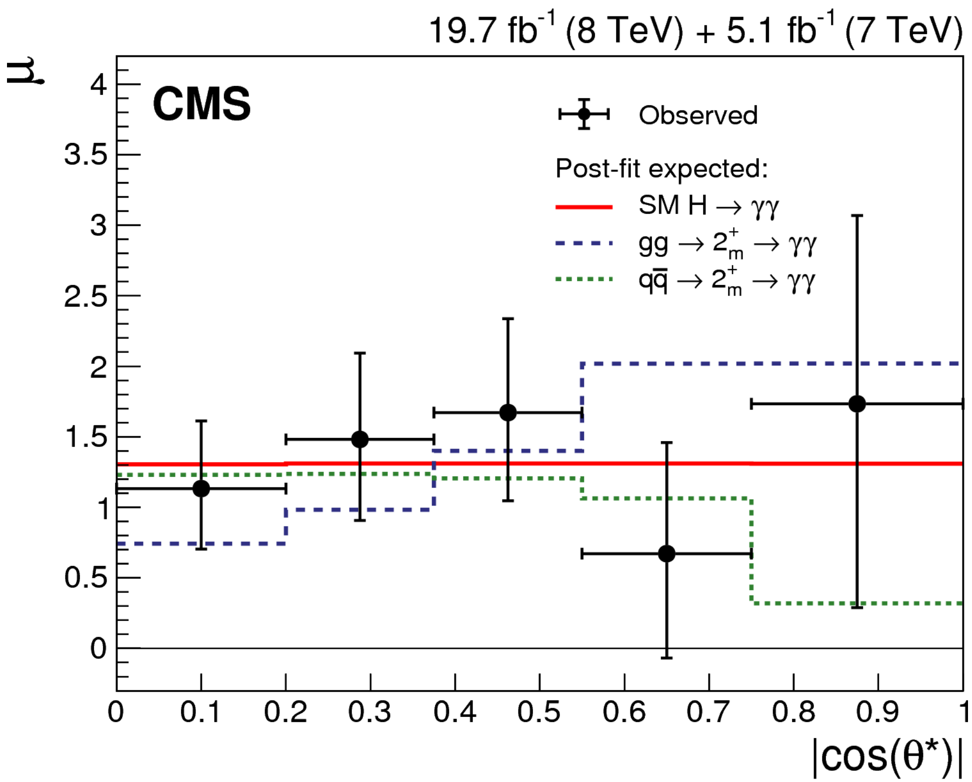
Hypothesis 0^+ (SM)



Alternative hypothesis 2^+_b

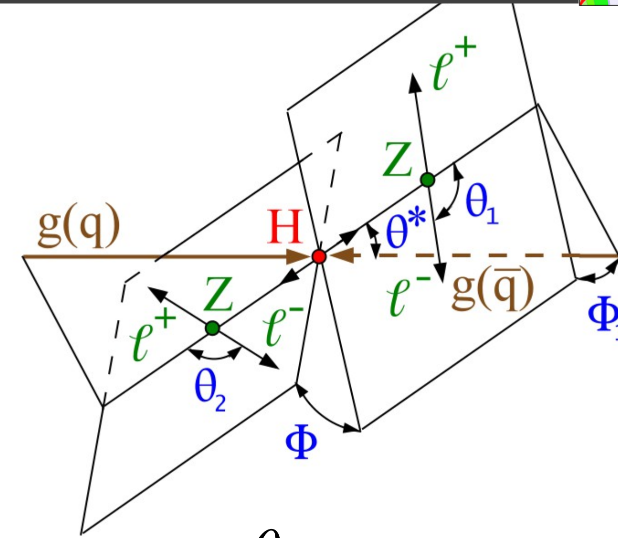


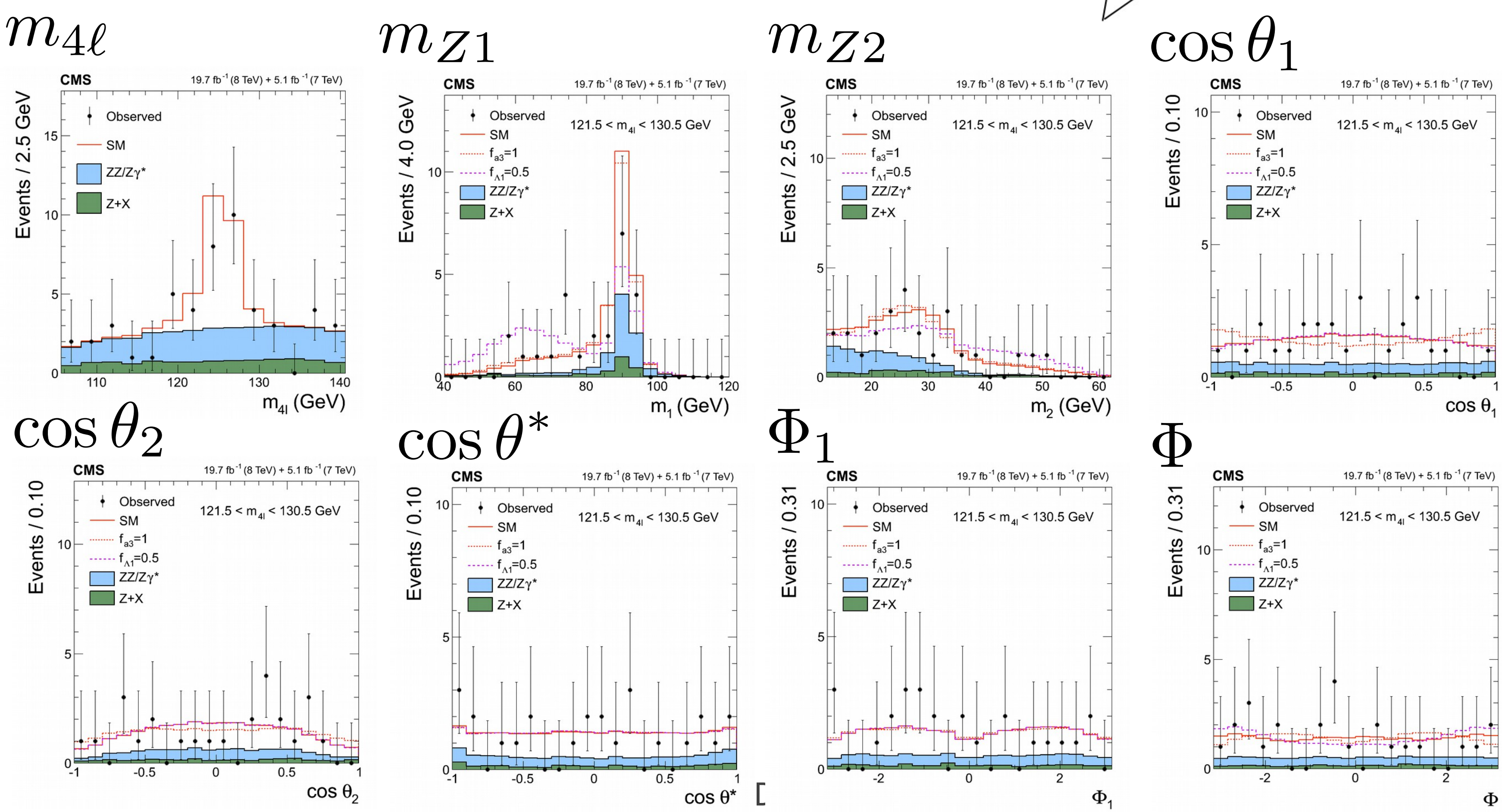
- H→γγ: scattering angle in the Collins-Soper frame
  - ↳ Fit signal strength in different cos(θ*) bins



SPIN-PARITY: H→ZZ→4L OBSERVABLES

- Kinematics description with 8 independent variables
  - ↳ Possible to use all simultaneously in a 8-dimension fit
    - – Done for some of the measurements of the spin-0 tensor structure
    - – "8D" (or "MD") method



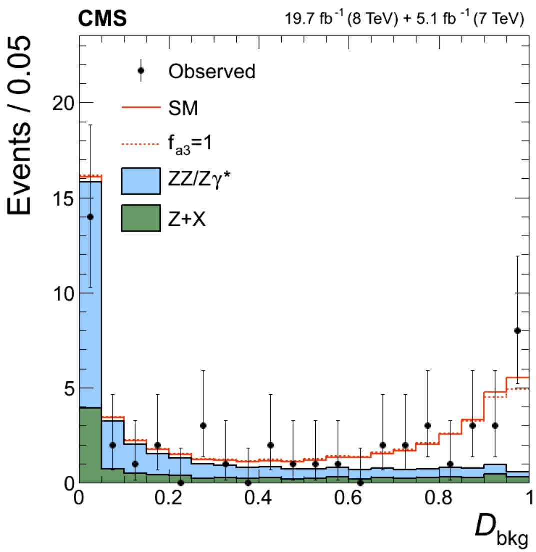


SPIN-PARITY: H→ZZ→4L KINEMATIC DISCRIMINANTS

- These variables can also be optimally condensed into kinematic discriminants (using the MELA package, and cross-checked with MEKD)
  - ↳ Each one probes specific pieces of amplitudes
  - ↳ 2D or 3D pdfs for multiple parameter fits
  - ↳ “KD” method (all HZZ results obtained with this method)

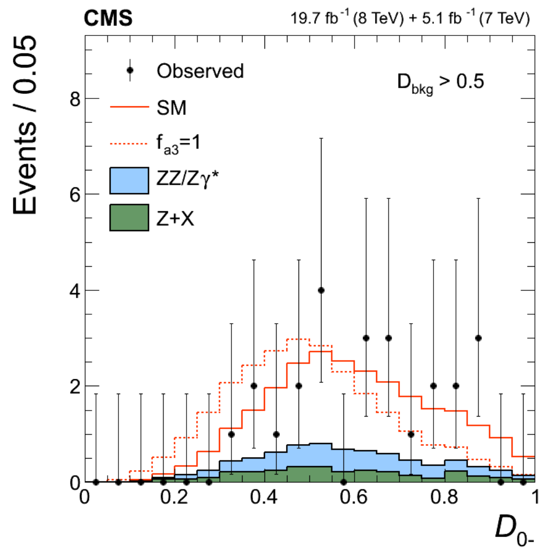
$$D_{\rm bkg} = \frac{P_{\rm SM}}{P_{\rm SM} + P_{\rm bkg}}$$

Discriminates 0^+ SM from background



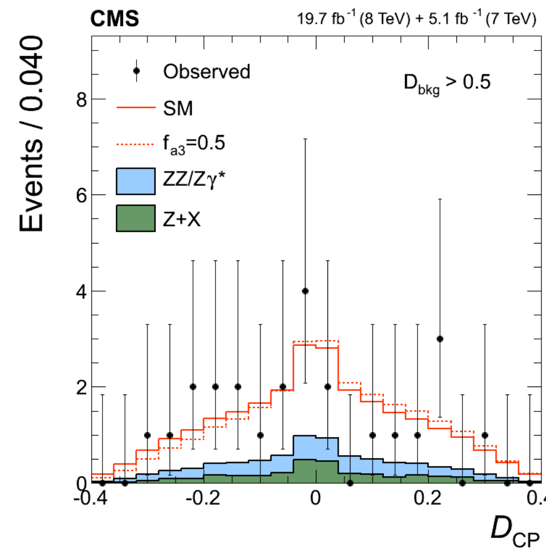
$$D_{J^P} = \frac{P^{\rm kin}_{\rm SM}}{P^{\rm kin}_{\rm SM} + P^{\rm kin}_{\rm JP}}$$

Discriminates 0^+ SM from alternative J^P pure state



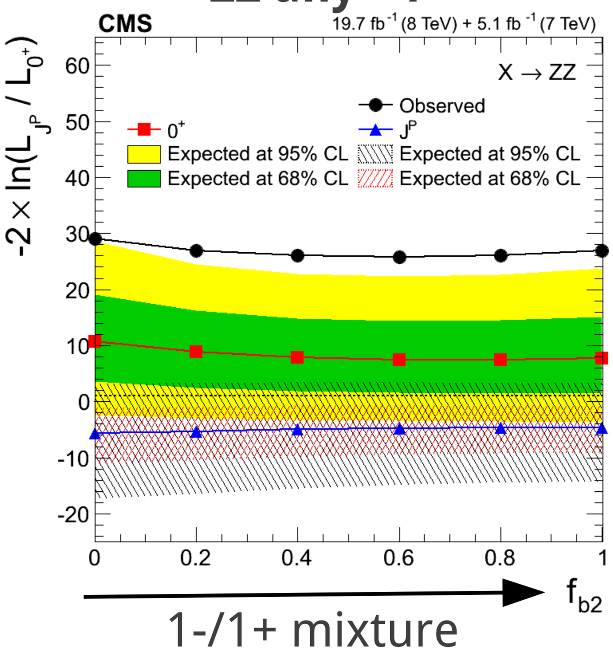
$$D_{\rm int} = \frac{P^{\rm kin}_{{\rm SM}+J^P} - P^{\rm kin}_{J^P} - P^{\rm kin}_{\rm SM}}{P^{\rm kin}_{\rm SM} + P^{\rm kin}_{\rm JP}}$$

Discriminates pure states from interference

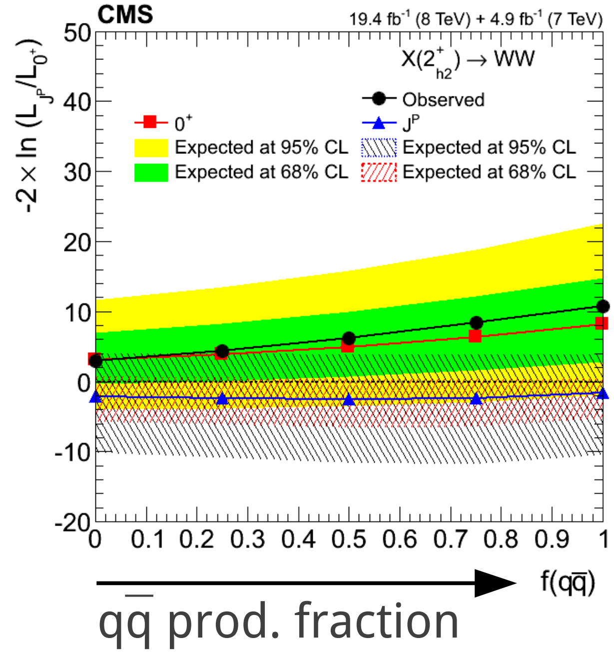


SPIN-PARITY: HYPOTHESIS TESTING

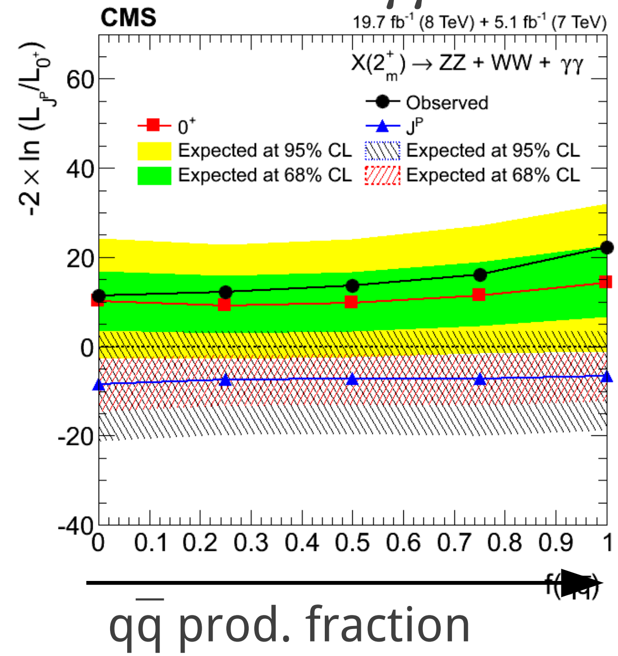
ZZ any→1



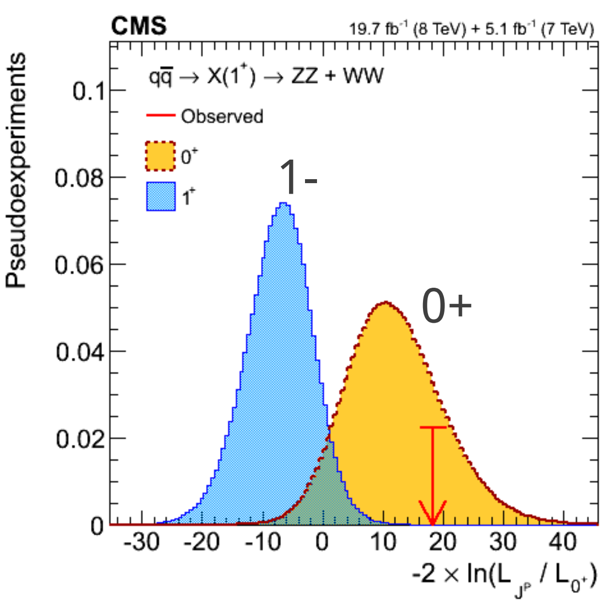
WW 2h+

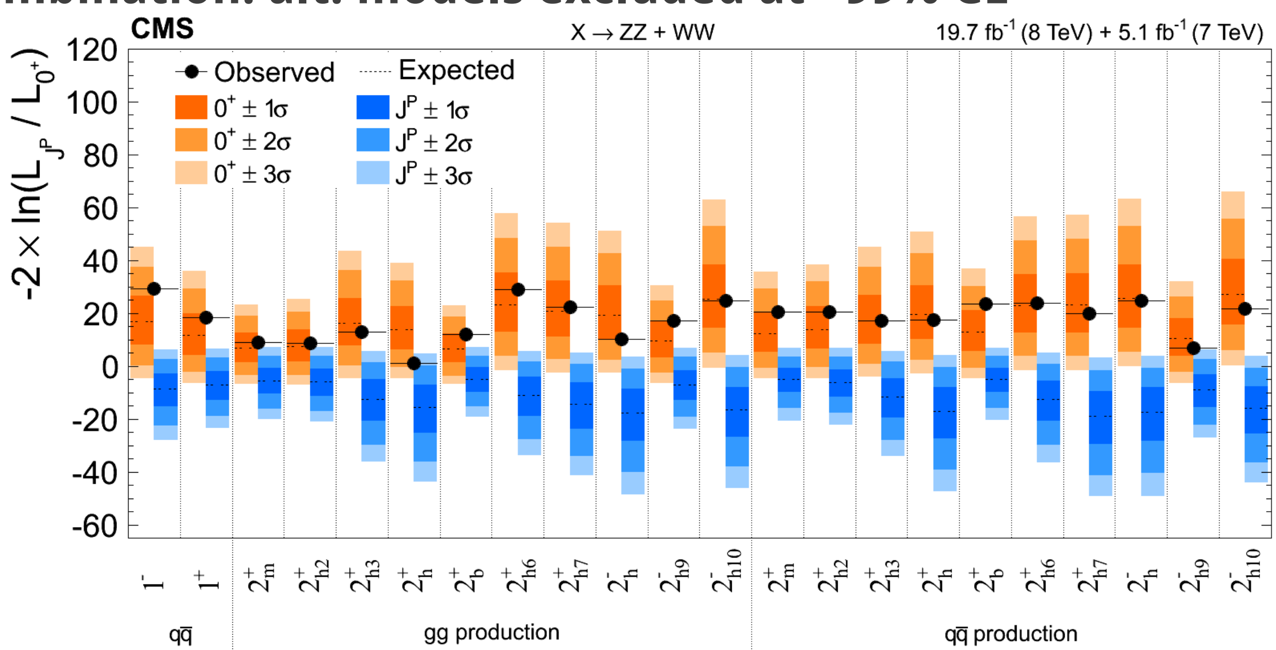


ZZ+WW+γγ 2m+



ZZ + WW combination: alt. models excluded at >99% CL

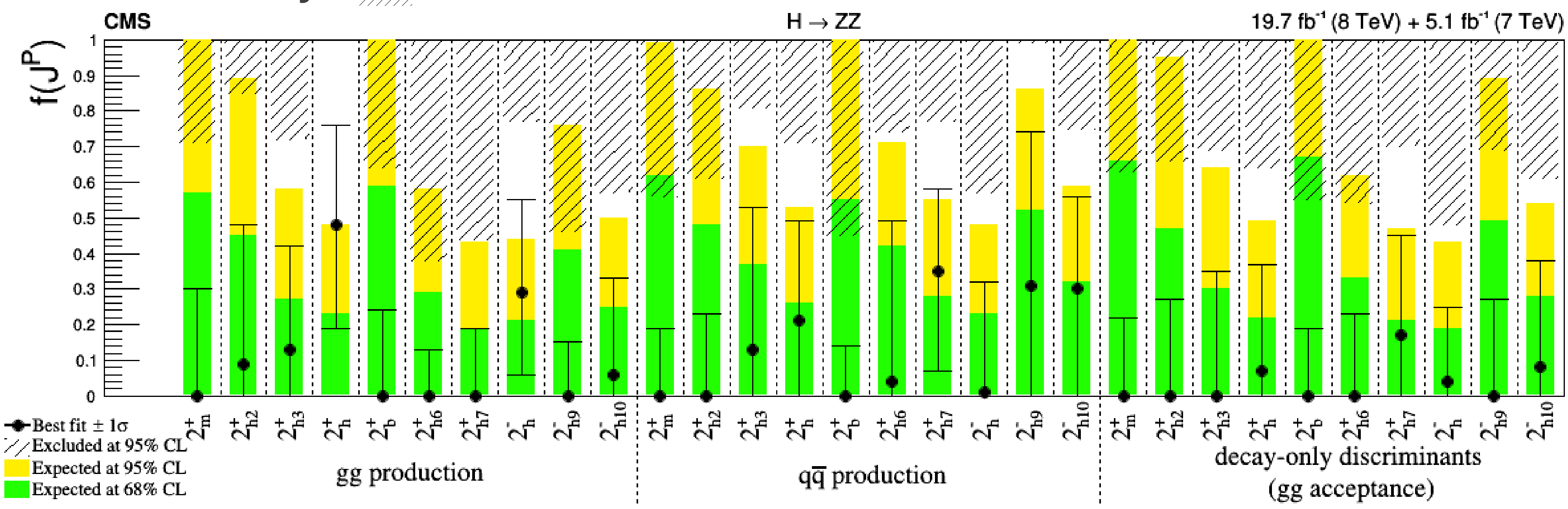




SPIN-PARITY: DEGENERATE STATE FRACTIONS

- Search for two nearby states with different spin-parity numbers
  - ↳ Not possible to resolve these two using the 4l mass
  - ↳ But the presence of a second state can be inferred from decay kinematics
- Measurement of the fraction of the alternative state
  - ↳ $$f(J^P) = \frac{\sigma_{J^P}}{\sigma_{0_m^+} + \sigma_{J^P}}$$
  - ↳ All fractions consistent with 0

ZZ only 95%CL exclusion



ANOMALOUS HVV COUPLINGS

- Spin-0 decay amplitude
  - ↳ Complex and momentum dependent couplings (up to q^2 terms)
  - ↳ q^4 and higher orders neglected → valid only for small deviations from the SM

$$A(H \to VV) \sim \left(a_1 - e^{i\phi_{\Lambda_1}} \frac{q_1^2 + q_2^2}{(\Lambda_1)^2} \right) m_V^2 \epsilon_1^* \epsilon_2^* + a_2 f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3 f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

- a_1: SM tree level CP-even contribution
- $e^{i\phi_{\Lambda_1}} \frac{q_1^2 + q_2^2}{(\Lambda_1)^2}$: Leading momentum expansion, Λ_1 = scale of new physics
- a_2 term: Higher-order CP-even contribution (loop-suppressed in SM)
- a_3 term: CP-odd contribution (loop-suppressed in SM)

- Results reported in terms of effective cross-section fractions + phase

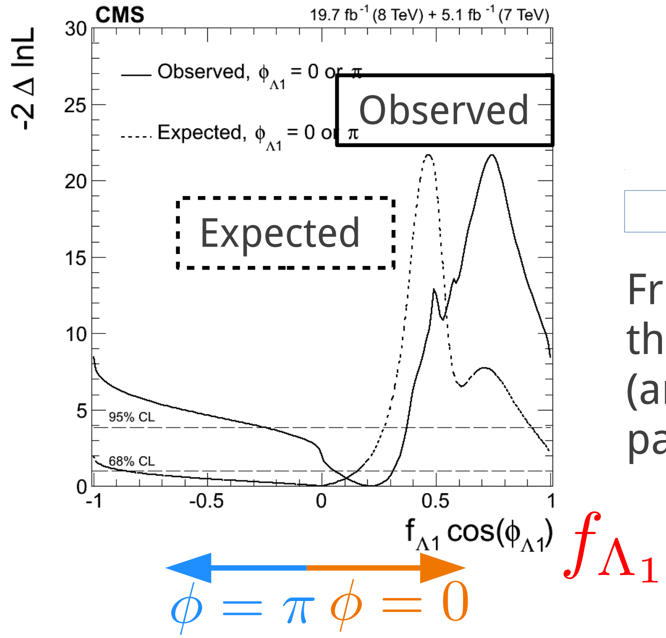
$$f_{a_3} = \frac{|a_3|^2 \sigma_3}{|a_1|^2 \sigma_1 + |a_2|^2 \sigma_2 + |a_3|^2 \sigma_3 + \sigma_4/\Lambda_1{}^4}$$

$$\phi_{a_3} = \arg\left(\frac{a_3}{a_1}\right) = 0, \pi, \text{any}$$

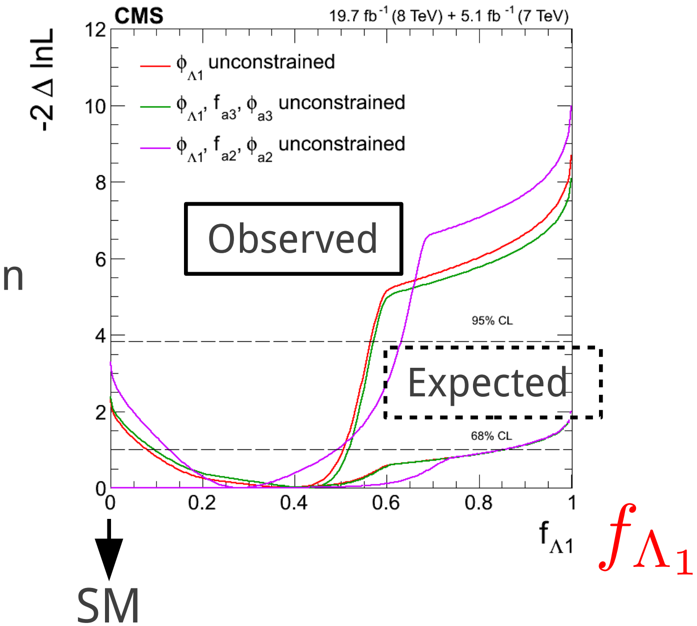
Similar for other parameters

SPIN-0 TENSOR STRUCTURE: HZZ ONLY

- Anomalous couplings fitted separately, with or without constraint on the phase

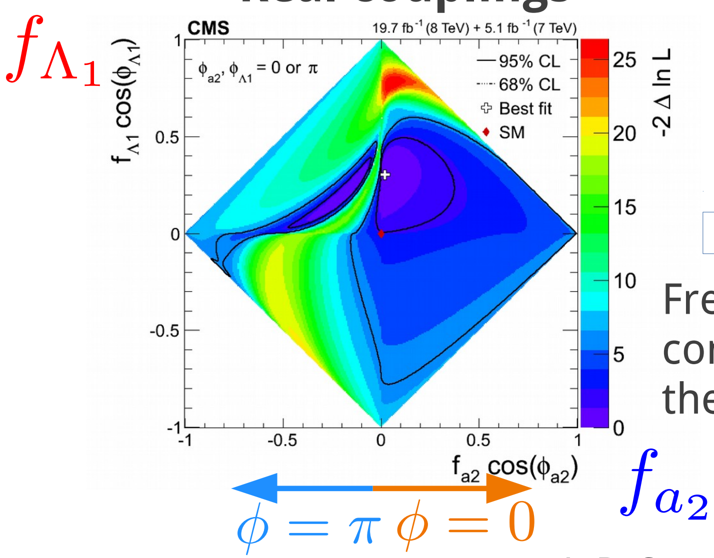


Free condition on the phase (and other parameters)



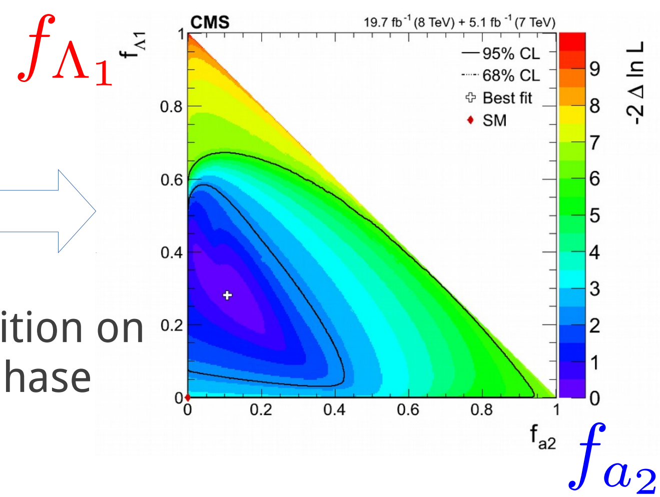
- Also simultaneous fits of pairs of anomalous couplings

Real couplings



Free condition on the phase

Profiled phase

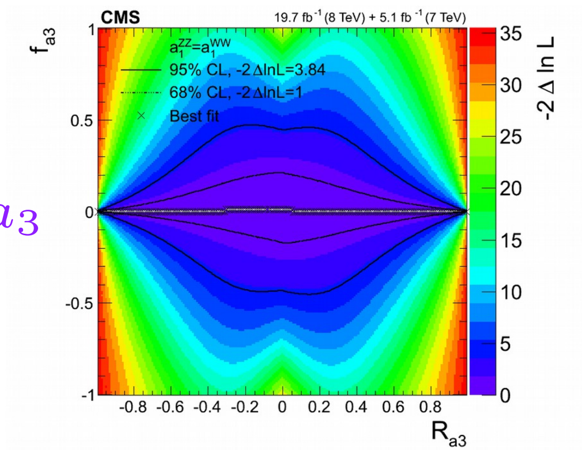


- 2 scenarios for the combination
  - ↳ Custodial symmetry or not

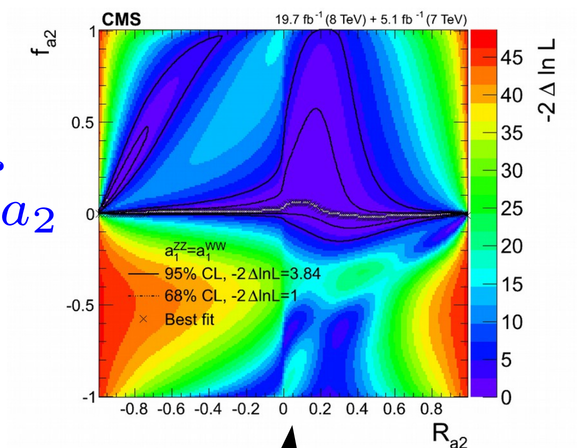
$$a_1^{ZZ} = a_1^{WW} \qquad a_1^{ZZ} \neq a_1^{WW}$$

In these scans the assumption of custodial symmetry is made

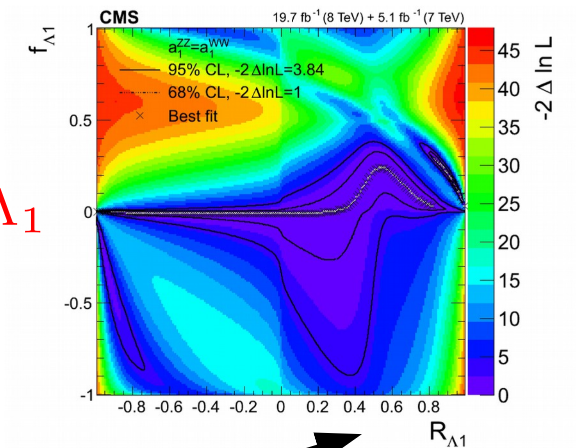
f_{a_3}



f_{a_2}



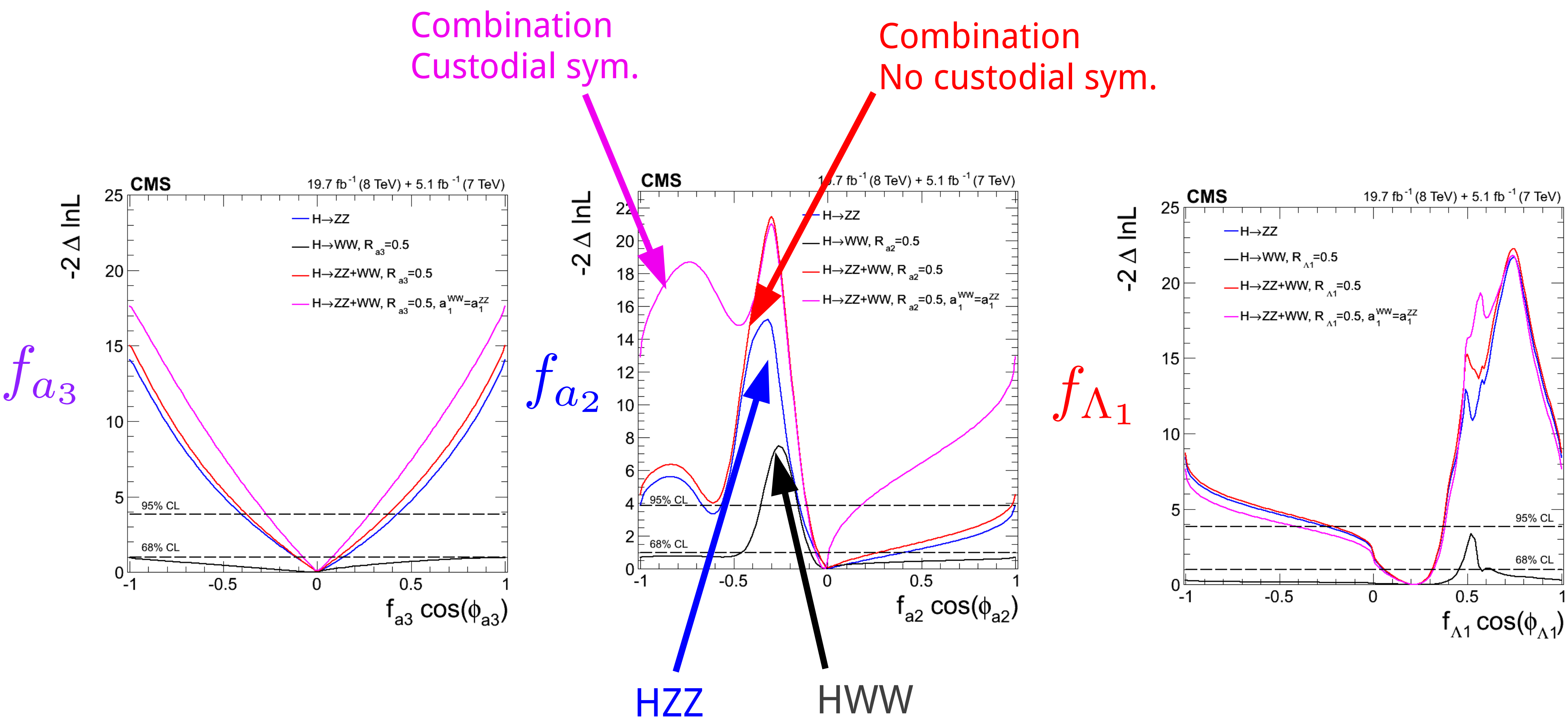
f_{Λ_1}



$$r_{a_i} = \frac{a_i^{WW}/a_1^{WW}}{a_i^{ZZ}/a_1^{ZZ}} \Rightarrow R_{a_i} = \frac{r_{a_i}|r_{a_i}|}{1+r_{a_i}^2}$$ (bounded)

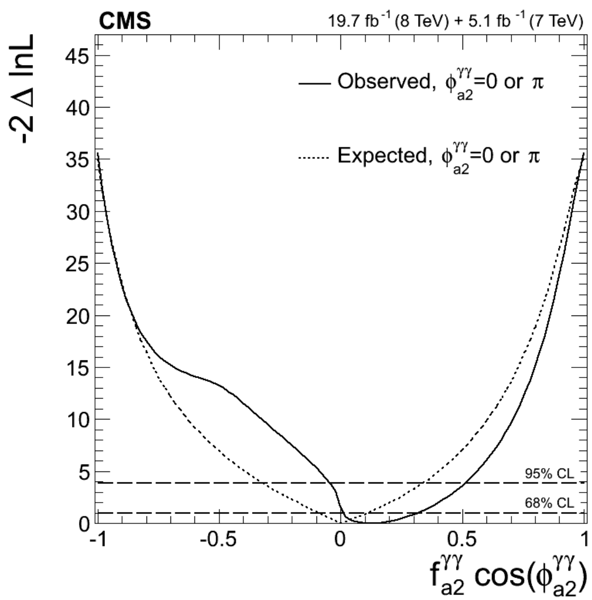
SPIN-0 TENSOR STRUCTURE: HZZ AND HWW

- 1D slice of r_{ai}
  - ↳ $r_{a_i} = 1 \ \left(a_i^{WW}/a_1^{WW} = a_i^{ZZ}/a_1^{ZZ}\right)$
- Assuming custodial symmetry: yields in H → WW and in H→ZZ are related
  - ↳ Brings tighter constraints

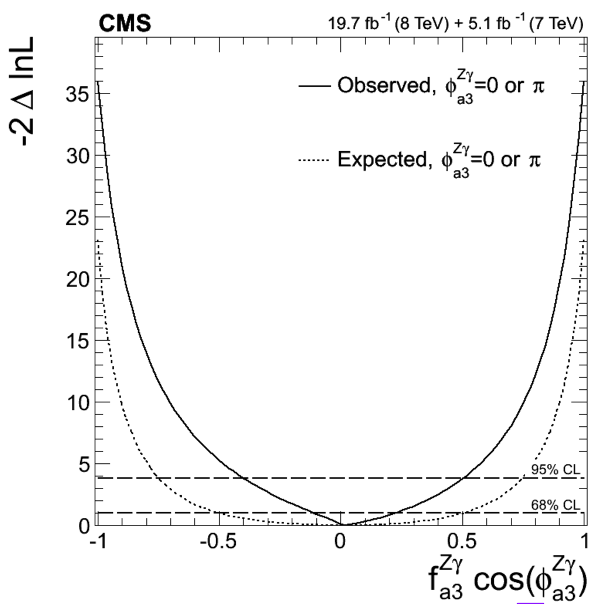


SPIN-0 TENSOR STRUCTURE: HZγ AND Hγγ (4L CHANNEL)

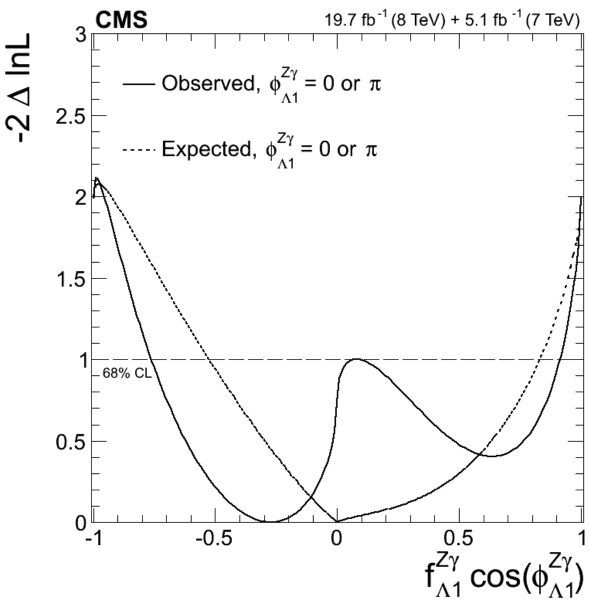
- HZγ and Hγγ couplings constrained using off-shell gauge bosons decaying in 4l
  - ↳ Feasibility study, more relevant for the HL-LHC (currently much better measured with on-shell gauge bosons)
- CP properties of these couplings can be (directly) probed in the 4l channel
  - ↳ Attractive thanks to large kinematic shape differences + interference effects [arXiv:1404.1336]



$f_{a_2}^{\gamma\gamma}$



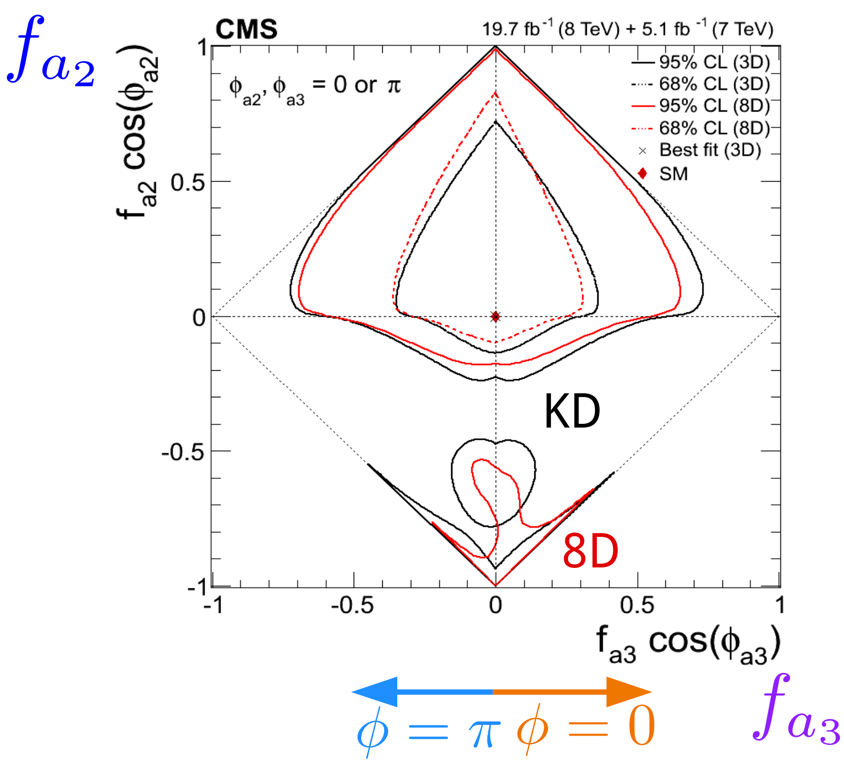
$f_{a_3}^{Z\gamma}$

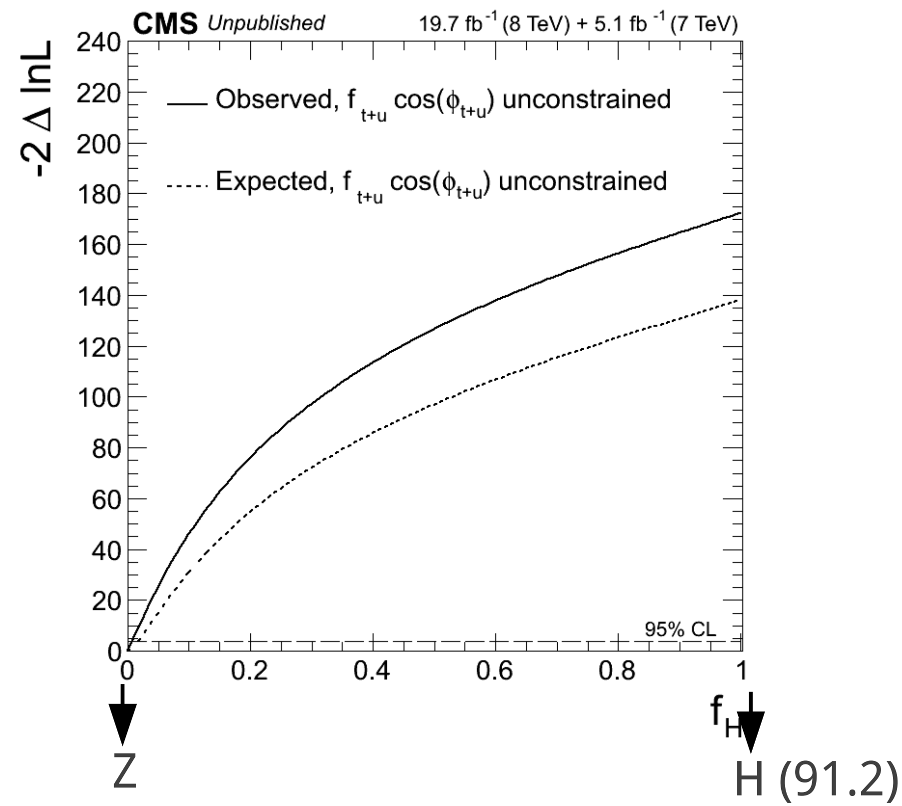


$f_{\Lambda_1}^{Z\gamma}$

$$f_{a_i}^{V\gamma} = \frac{|a_i^{V\gamma}|^2\,\sigma_i^{V\gamma}}{|a_1|^2\,\sigma_1 + |a_i^{V\gamma}|^2\,\sigma_i^{V\gamma} + \ldots} \qquad \phi_{a_i}^{V\gamma} = \arg\left(\frac{a_i^{V\gamma}}{a_1}\right)$$

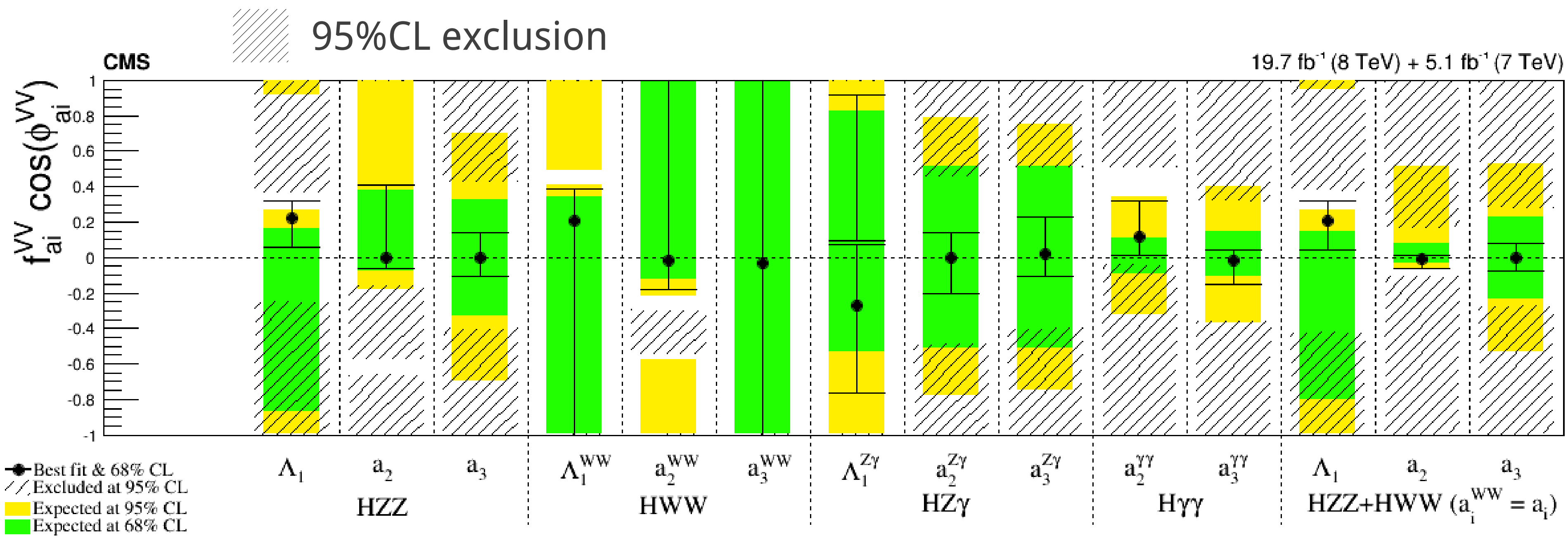
- With 2 independent methods for ZZ
  - ↳ 3D fit with kinematic discriminants
    - – Baseline method
  - ↳ 8D fit
- Compatible results between the two methods
- Using the Z→4l candle
  - ↳ Z vs Higgs (91.2) fraction
- Tight constraint on the Higgs fraction in the Z peak





SUMMARY

- Wide range of spin-2 models excluded at >99% CL
  - ↳ With and without assumption on production mechanism
- Any mixed-parity spin-1 state excluded at >99.999% CL
- With hypothesis of a spin-0 boson
  - ↳ Interaction of the Higgs with ZZ, Zγ, γγ, WW investigated
  - ↳ Limits on 11 anomalous contributions are set
- All observations consistent with the expectations for the minimal Higgs boson



BACKUP

SPIN-1 AND SPIN-2 HVV DECAY AMPLITUDES

Spin-1:

$$A(X_{J=1} \to V_1 V_2) \sim \underbrace{b_1 \left[\left(\epsilon^*_{V_1} q\right) \left(\epsilon^*_{V_2} \epsilon_X\right) + \left(\epsilon^*_{V_2} q\right) \left(\epsilon^*_{V_1} \epsilon_X\right) \right]}_{\text{Vector}} + \underbrace{b_2 \epsilon_{\alpha\mu\nu\beta} \epsilon^{\alpha}_{X} \epsilon^{*\mu}_{V_1} \epsilon^{*\nu}_{V_2} \tilde{q}^{\beta}}_{\text{Pseudo-vector}}$$

Spin-2:

$$A(X_{J=2} \to V_1 V_2) \sim \Lambda^{-1} \Big[2c_1 t_{\mu\nu} f^{*1,\mu\alpha} f^{*2,\nu\alpha} + 2c_2 t_{\mu\nu} \frac{q_\alpha q_\beta}{\Lambda^2} f^{*1,\mu\alpha} f^{*2,\nu\beta}$$

$$+ c_3 \frac{\tilde{q}^\beta \tilde{q}^\alpha}{\Lambda^2} t_{\beta\nu} \left(f^{*1,\mu\nu} f^{*2}_{\mu\alpha} + f^{*2,\mu\nu} f^{*1}_{\mu\alpha} \right) + c_4 \frac{\tilde{q}^\nu \tilde{q}^\mu}{\Lambda^2} t_{\mu\nu} f^{*1,\alpha\beta} f^{*(2)}_{\alpha\beta}$$

$$+ m_V^2 \left(2c_5 t_{\mu\nu} \epsilon^{*\mu}_{V_1} \epsilon^{*\nu}_{V_2} + 2c_6 \frac{\tilde{q}^\mu q_\alpha}{\Lambda^2} t_{\mu\nu} \left(\epsilon^{*\nu}_{V_1} \epsilon^{*\alpha}_{V_2} - \epsilon^{*\alpha}_{V_1} \epsilon^{*\nu}_{V_2} \right) + c_7 \frac{\tilde{q}^\mu \tilde{q}^\nu}{\Lambda^2} t_{\mu\nu} \epsilon^*_{V_1} \epsilon^*_{V_2} \right)$$

$$+ c_8 \frac{\tilde{q}^\mu \tilde{q}^\nu}{\Lambda^2} t_{\mu\nu} f^{*1,\alpha\beta} \tilde{f}^{*(2)}_{\alpha\beta} + c_9 t^{\mu\alpha} \tilde{q}_\alpha \epsilon_{\mu\nu\rho\sigma} \epsilon^{*\nu}_{V_1} \epsilon^{*\rho}_{V_2} q^\sigma$$

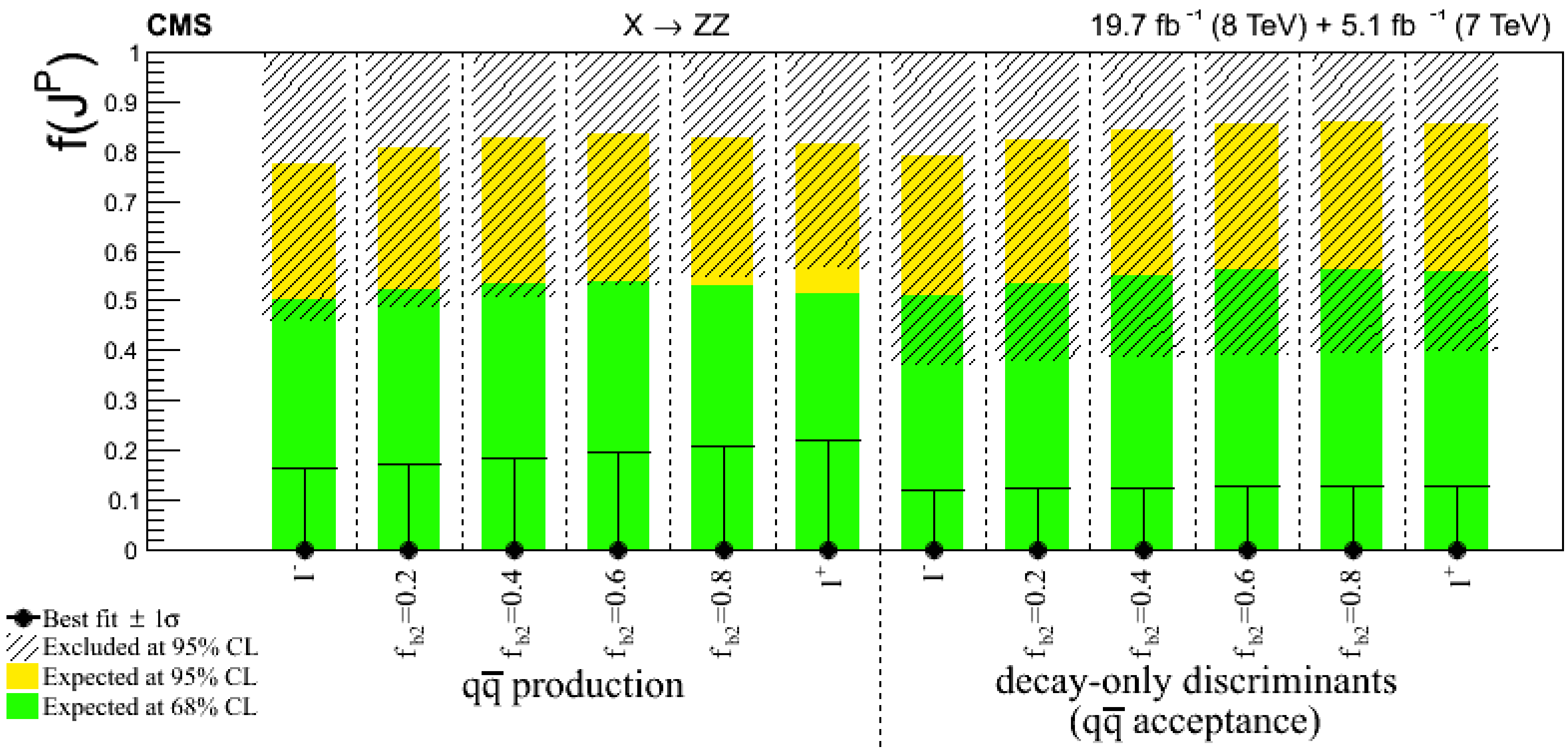
$$+ \frac{c_{10} t^{\mu\alpha} \tilde{q}_\alpha}{\Lambda^2} \epsilon_{\mu\nu\rho\sigma} q^\rho \tilde{q}^\sigma \left(\epsilon^{*\nu}_{V_1} (q \epsilon^*_{V_2}) + \epsilon^{*\nu}_{V_2} (q \epsilon^*_{V_1}) \right) \Big] ,$$

- 2_m^+: KK Graviton-like with minimal couplings
  - ↳ c1 = c5 ≠ 0
- 2_b^+: KK Graviton-like with SM in the bulk
  - ↳ c5 ≠ 0 for X→ZZ and c1 ≠ 0 for gg→X
- 2_h^+: BSM tensor with higher dimension operators
  - ↳ c4 ≠ 0
- 2_h^-: BSM pseudo-tensor with higher dimension operators
  - ↳ c8 ≠ 0

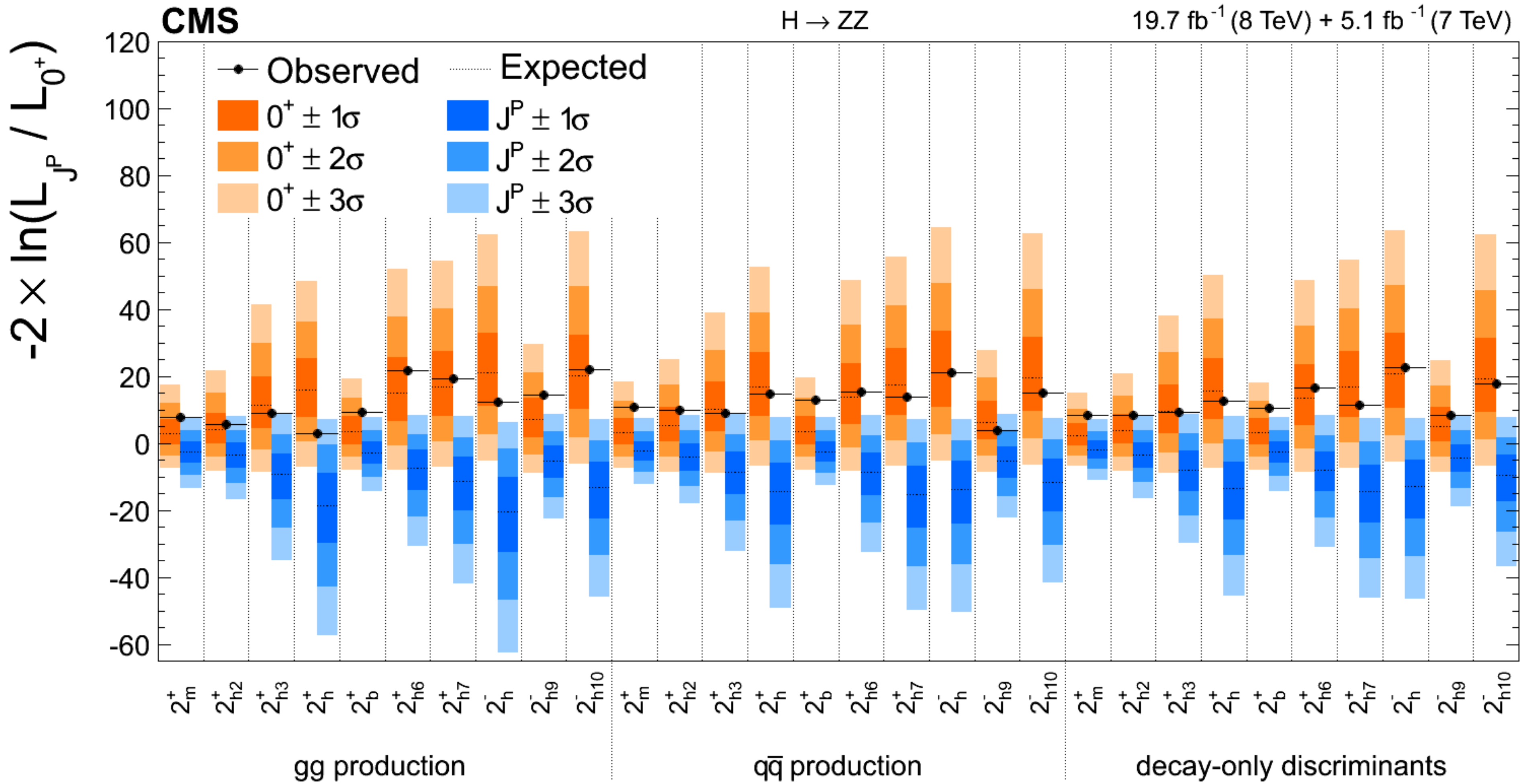
SM COUPLING VALUES

	a_1	q^2/Λ_1^2	a_2	a_3
HZZ(WW)	2	$10^{-3} - 10^{-2}$	$10^{-3} - 10^{-2}$	$< 10^{-10}$
HZγ	-	$10^{-3} - 10^{-2}$	~ 0.0035	$< 10^{-10}$
H$\gamma\gamma$	-	-	$\sim$ -0.004	$< 10^{-10}$

SPIN-1 MIXTURE HZZ

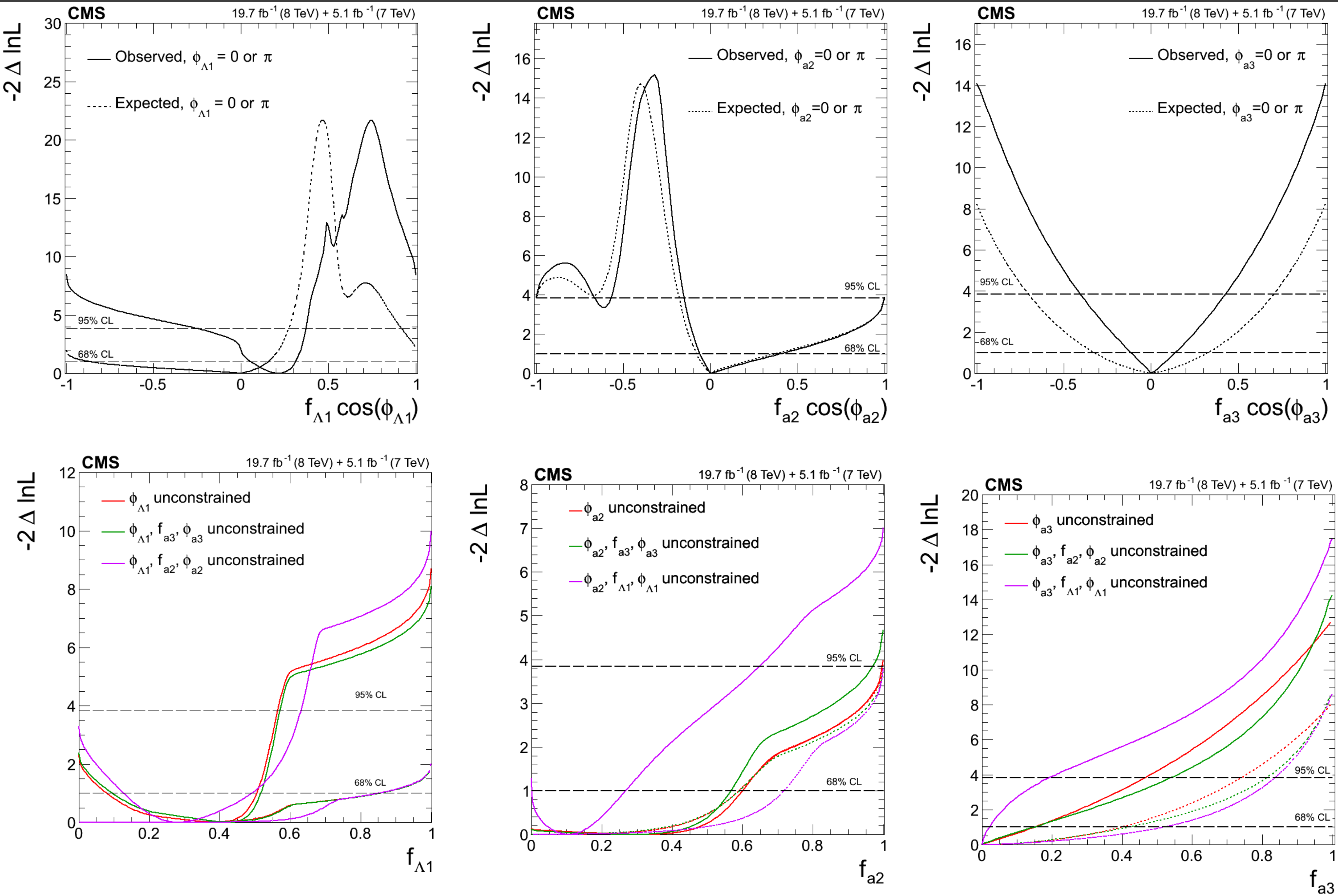


SPIN-2 HZZ



CMS
H → ZZ
19.7 fb^{-1} (8 TeV) + 5.1 fb^{-1} (7 TeV)
$-2 \times \ln(L_{J^P} / L_{0^+})$
Observed
Expected
$0^+ \pm 1\sigma$
$0^+ \pm 2\sigma$
$0^+ \pm 3\sigma$
$J^P \pm 1\sigma$
$J^P \pm 2\sigma$
$J^P \pm 3\sigma$
2^+_m 2^+_{h2} 2^+_{h3} 2^+_h 2^+_b 2^+_{h6} 2^+_{h7} 2^-_h 2^-_{h9} 2^-_{h10}
gg production
$q\bar{q}$ production
decay-only discriminants

SINGLE PARAMETER HZZ



TWO PARAMETERS HZZ