Constraints on CP-violating couplings of the Higgs boson using its decay to fermions in the CMS experiment

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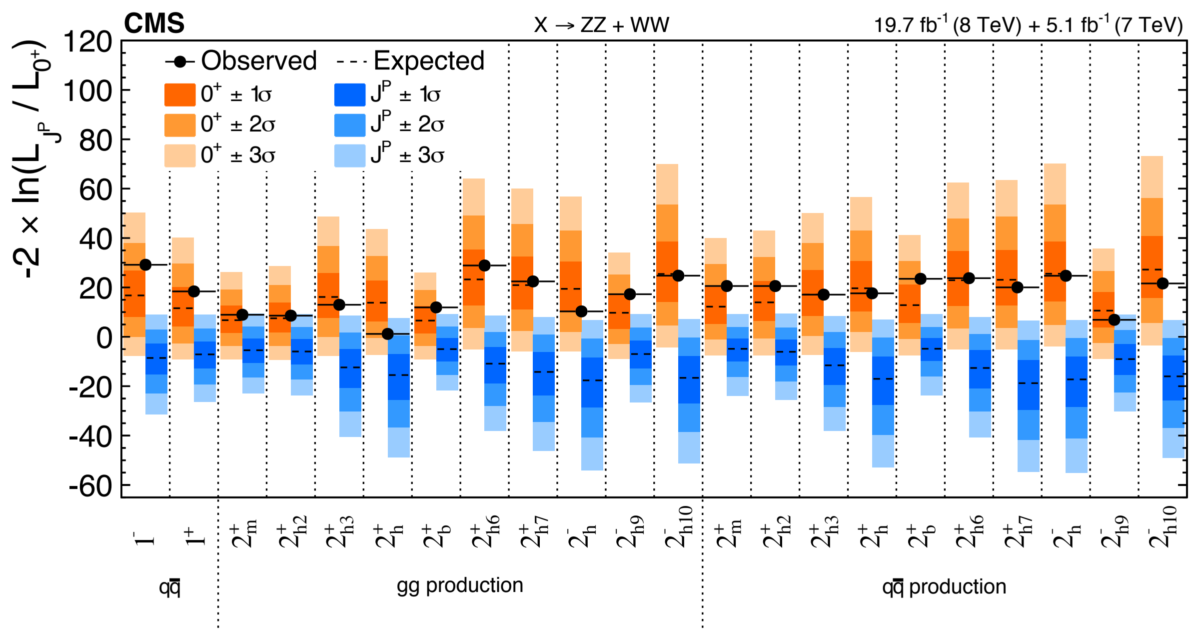
Higgs quantum numbers

J^{CP}

J=1,2 excluded with H(125)^0
=> J=0

CP measurements

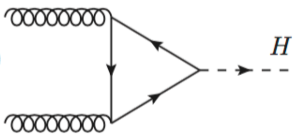
PRD 92 (2015) 012004



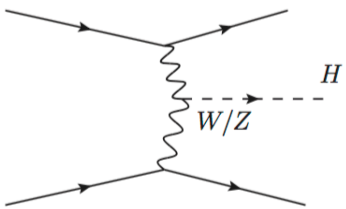
Higgs couplings, production and decay

production

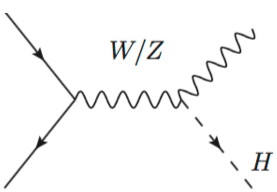
ggH (a)



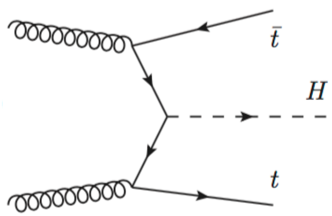
VBF (b)



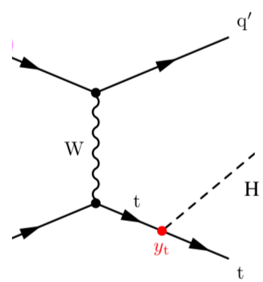
WH/ZH (c)



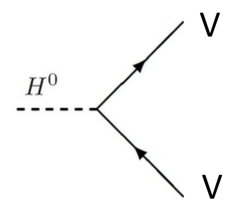
ttH

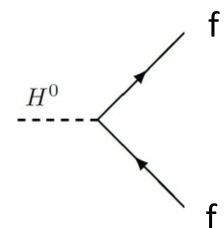


tH



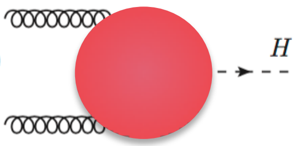
decay

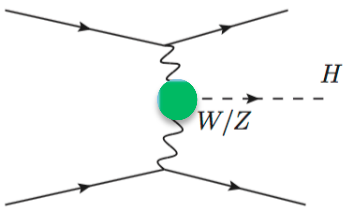


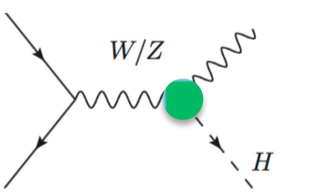


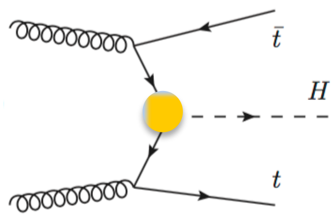
Higgs couplings, production and decay

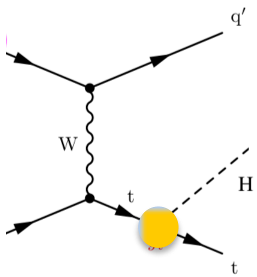
production

ggH


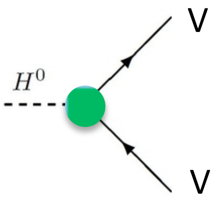
VBF


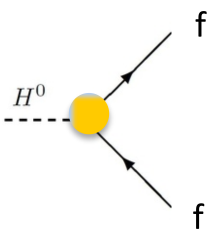
WH/ZH


ttH


tH


decay





coupling	production	decay
Hgg	ggH	-
Hff	ttH, tH	H->bb, H->ττ …
HVV	VBF, VH	H->VV

ggH, ffH and VVH sensitivity

expected precision of spin and CP-mixture measurements:

arXiv:1310.8361

Collider E (GeV) $\mathcal{L}$ (fb^{-1})	pp 14,000 300	pp 14,000 3,000	e^+e^- 250 250	e^+e^- 350 350	e^+e^- 500 500	e^+e^- 1,000 1,000	$\gamma\gamma$ 126 250	$\mu^+\mu^-$ 126	target (theory)
spin-2^+_m	$\sim 10\sigma$	$\gg 10\sigma$	$>10\sigma$	$>10\sigma$	$>10\sigma$	$>10\sigma$			$>5\sigma$
$VVH^\dagger$	0.07	0.02	✓	✓	✓	✓	✓	✓	$< 10^{-5}$
$VVH^\ddagger$	$4{\cdot}10^{-4}$	$1.2{\cdot}10^{-4}$	$7{\cdot}10^{-4}$	$1.1{\cdot}10^{-4}$	$4{\cdot}10^{-5}$	$8{\cdot}10^{-6}$	–	–	$< 10^{-5}$
$VVH^\diamond$	$7{\cdot}10^{-4}$	$1.3{\cdot}10^{-4}$	✓	✓	✓	✓	–	–	$< 10^{-5}$
ggH	0.50	0.16	–	–	–	–	–	–	$< 10^{-2}$
$\gamma\gamma H$	–	–	–	–	–	–	0.06	–	$< 10^{-2}$
$Z\gamma H$	–	✓	–	–	–	–	–	–	$< 10^{-2}$
$\tau\tau H$	✓	✓	0.01	0.01	0.02	0.06	✓	✓	$< 10^{-2}$
ttH	✓	✓	–	–	0.29	0.08	–	–	$< 10^{-2}$
$\mu\mu H$	–	–	–	–	–	–	–	✓	$< 10^{-2}$

† estimated in $H \to ZZ^*$ decay mode

‡ estimated in $V^* \to HV$ production mode

$^\diamond$ estimated in $V^*V^* \to H$ (VBF) production mode

ggH and ffH experimental measurements are more challenging than VVH measurements

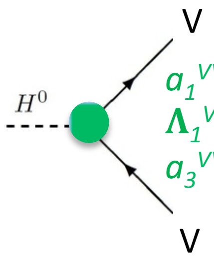
- **the focus with current LHC data is on VVH measurement**

VVH couplings and parameters

Generic spin-0 HVV scattering amplitude:

$$A(\mathrm{HVV}) \sim \left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_{\mathrm{V1}}^2 + \kappa_2^{\mathrm{VV}} q_{\mathrm{V2}}^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2} \right] m_{\mathrm{V1}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^* + a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

tree level scalar (0^+) — higher order scalar (0^+_h) — pseudoscalar (0^-)



a_1^{VV}, a_2^{VV}, (CP)
Λ_1^{VV}, Λ_Q^{VV} (CP)
a_3^{VV} (~~CP~~)

$$f_{a3} = \frac{|a_3|^2 \sigma_3}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda 1} / (\Lambda_1)^4 + \ldots}, \qquad \phi_{a3} = \arg\left(\frac{a_3}{a_1}\right)$$

σ_i defined in decay

a_3 anomalous couplings: mixture of scalar and pseudo-scalar

there are also other parametrizations

Anomalous couplings (a_i , Λ_I) are universal parameters of nature

- However it is **more convenient to measure the effective cross-section ratios** (f_{ai}) rather than the anomalous couplings themselves
  - ⇒ **Measure fractions in defined convention with unique meaning along different channels**

f_{a3} = fractional pseudoscalar cross section

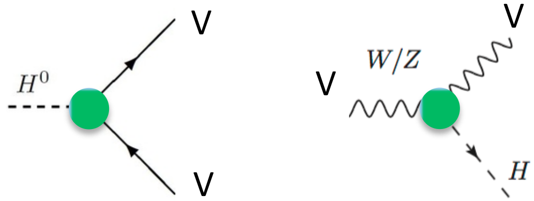
- value **0 < |f_{a3}| < 1** would indicate CP violation, with a possible mixture of scalar and pseudoscalar states
- **f_{a3} = 1 would indicate that the H boson is a pure pseudoscalar resonance**

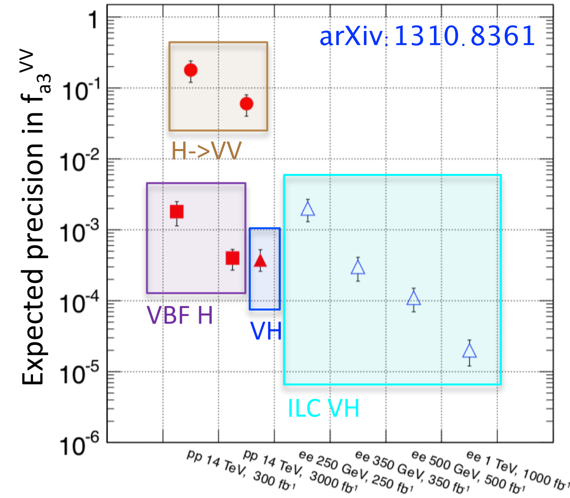
CMS HVV coupling measurements

Final state	Anomalous coupling HVV analysis sensitivity		Energy (lumi/fb^{-1})	reference	
	In production	In decay			
VBF H(->4l), W(->jj)H(->4l), Z(->jj)H(->4l)	✓	✓	**13 TeV** (38.6 for VBF H, 35.9 for VH)	PLB 775 (2017) 1, CMS_PAS_HIG_17_011	
VH(->bb)	✓	-	8 TeV (19.7)	=>	Combination: PLB 759 (2016) 672, CMS_HIG_14_035
H -> WW, ZZ, $Z\gamma^*$, $\gamma^*\gamma^*$	✘	✓	8 TeV (19.7) 7 TeV (5.1)	PRD 92 (2015) 012004, CMS_HIG_14_018	

VH(->bb) (Run1 data)

The high mass of V* in VH makes it a powerful channel for constraining f_{a3}

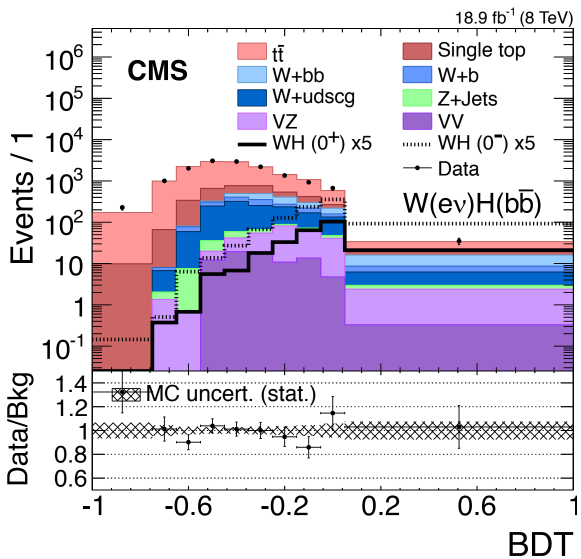




The **interference contributions** to the BDT discriminant and m(VH) distributions are negligible and ignored in the VH channels.

Measurement is performed using 2D templates:

- BDT discriminant (to separate from background)
- **m(VH): observable sensitive to kinematic features of pseudoscalar**



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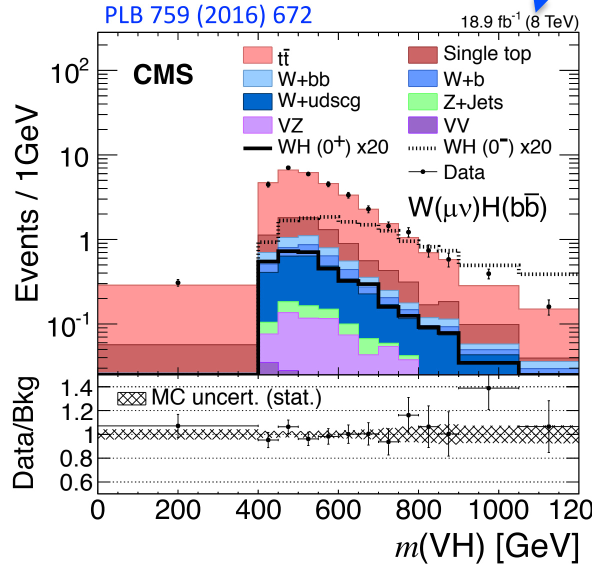
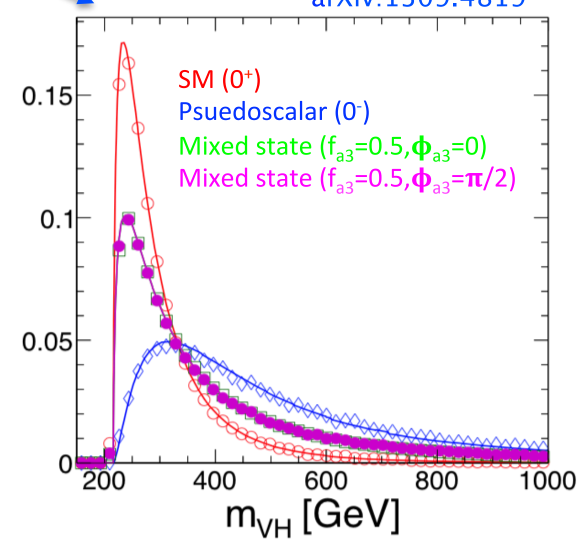


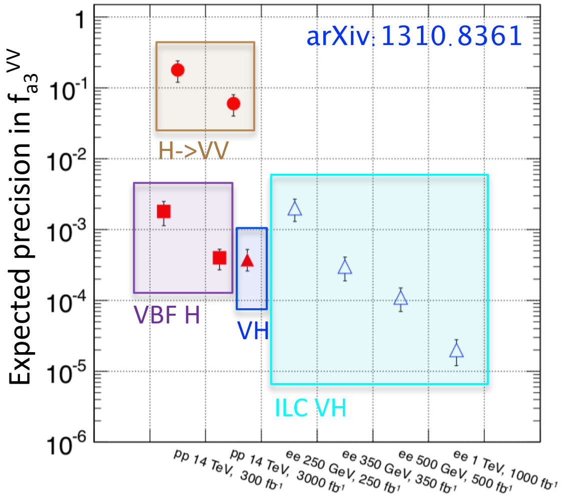
arXiv:1309.4819



=> Results are combined with H->VV

VH(->bb) + H(->VV) results (Run1 data)

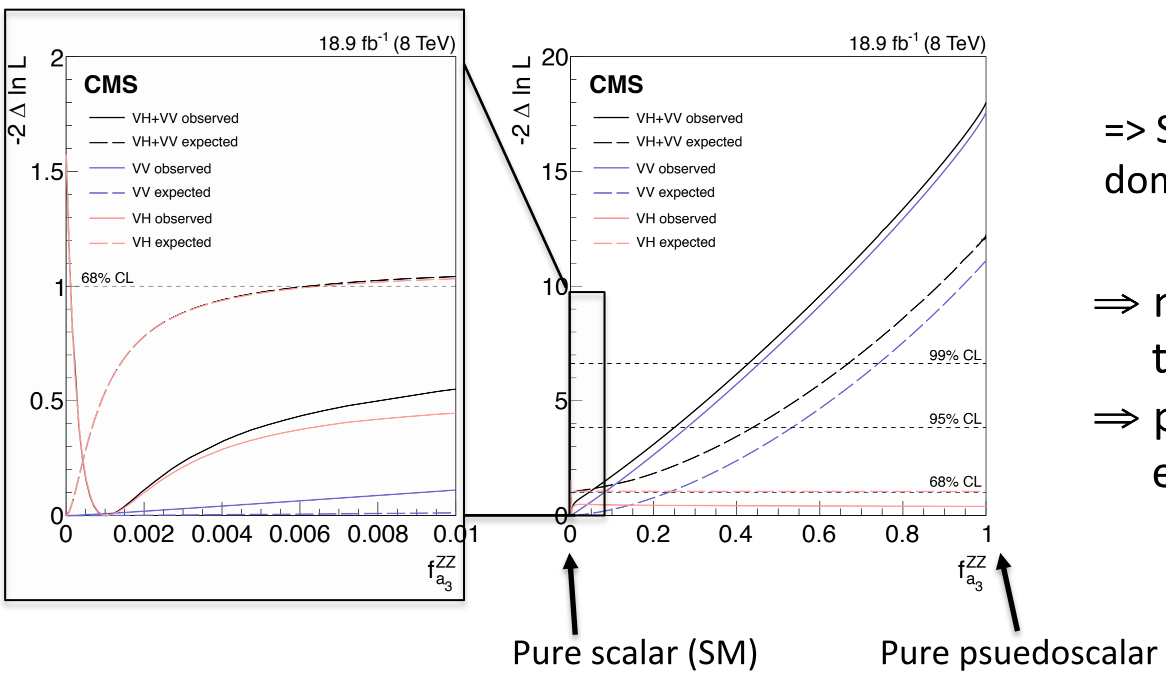
The high mass of V* in VH makes it a powerful channel for constraining f_{a3}



- yields of signal events are expressed with two unconstrained parameters μ_V (VBF and VH production) and μ_F (ggH and ttH production)

  μ = observed signal yield/expected SM signal yield

- μ_V and μ_F are floating freely in the fit
  - sensitivity to anomalous couplings is in a difference in shape, not overall yield



=> Sensitivity at low f_{a3} dominated by ZH channel

⇒ no significant deviation from the SM (f_{a3}=0)

⇒ pure pseudoscalar (f_{a3}=1) excluded at 99.8% CLs

Sensitive observables

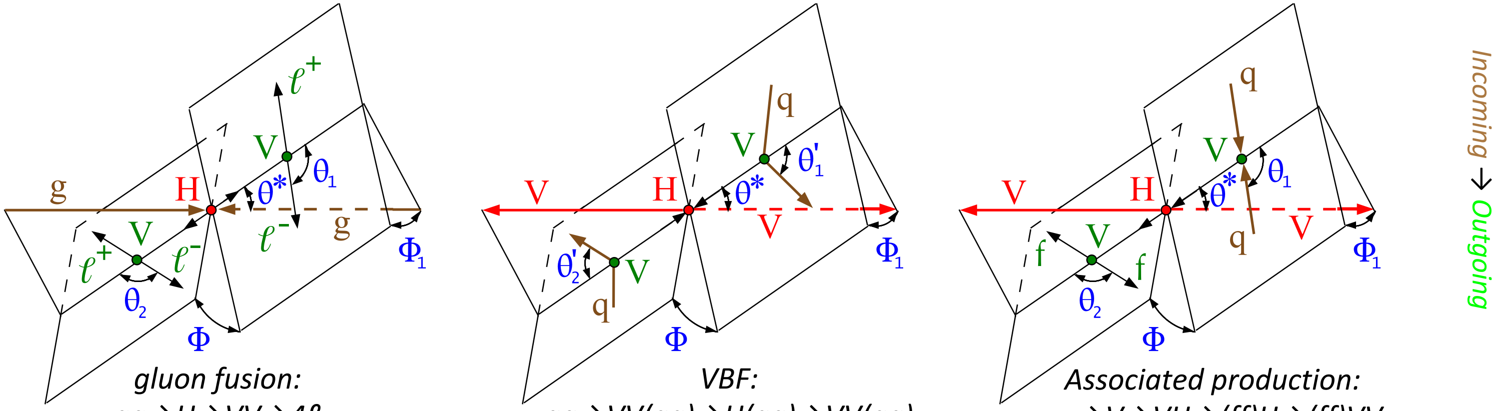
Single kinematic observable:
m(VH), …

MELA package (**M**atrix **E**lement **L**ikelihood **A**pproach):
Using full kinematic

- **Build discriminant for process A vs process B from ME bases probabilities**
- Discriminant: ratio of probabilities
    - Distinguish contributions: SM, BSM, interference
- Optimal observable: $D = P_A / (P_A + P_B)$

H→VV:
five angles + m(VV) fully characterize either the production or the decay chain

angles are defined in either the H or V boson rest frames



gluon fusion:
gg→H→VV→4ℓ

VBF:
qq→VV(qq)→H(qq)→VV(qq)

Associated production:
qq→V→VH→(ff)H→(ff)VV

Sensitive observables

Single kinematic observable:
m(VH), …

MELA package (**M**atrix **E**lement **L**ikelihood **A**pproach):
Using full kinematic

- **Build discriminant for process A vs process B from ME bases probabilities**
- Discriminant: ratio of probabilities
  - Distinguish contributions: SM, BSM, interference
- Optimal observable: $D = P_A / (P_A + P_B)$

H→4l measurement is performed using 3D MELA templates:

To separate higgs signal from background

$$D_{bkg} = \frac{P_{sig}}{P_{sig} + P_{bkg}}$$

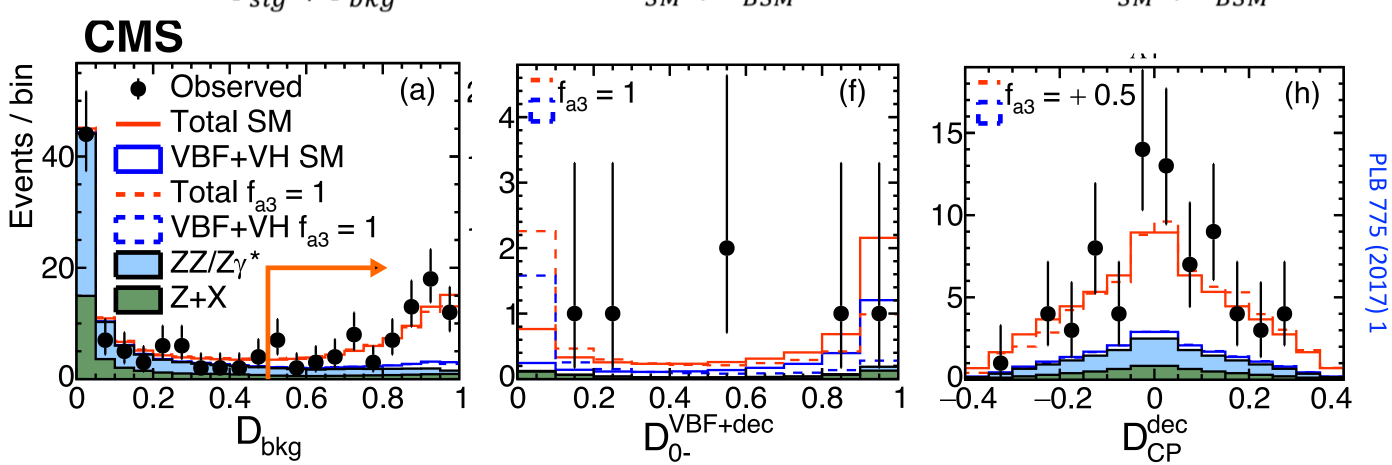
To separate scalar from pseudoscalar

$$D_{BSM} = \frac{P_{SM}}{P_{SM} + P_{BSM}}$$

To separate interference term from signal

$$D_{int} = \frac{P_{SM+BSM} - P_{SM} - P_{BSM}}{P_{SM} + P_{BSM}}$$

P_{SM} and P_{BSM} include production and decay information

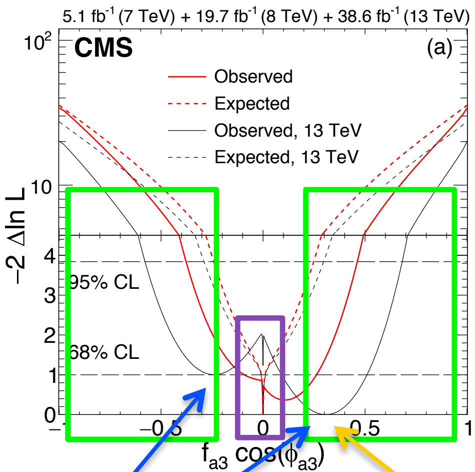


Observables are optimized to be most sensitive to observe CP violation in HVV vertex, hence little sensitivity to ffH and ggH coupling.

H->4l results (Run1+Run2)

Sensitivity from decay

Sensitivity from VBF production

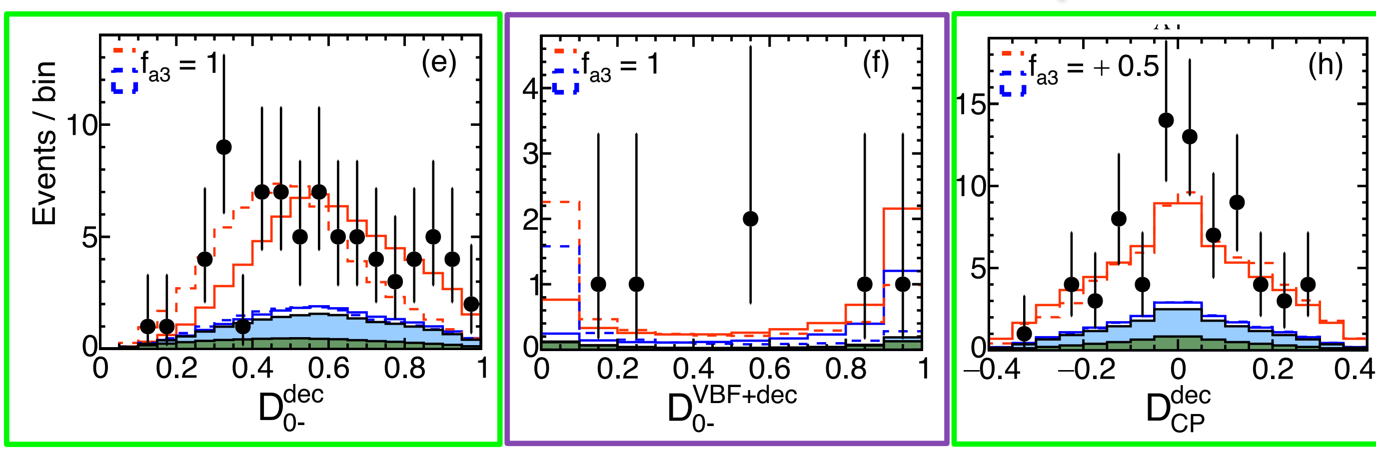


- primary sensitivity from decay
- production (low statistics) is sensitive to smaller couplings
  - with more data, the production information will be much more important

Small asymmetry in D_{CP}^{dec} in positive direction

Fluctuation toward low and high values of D_{0-}^{dec}

=> no significant deviation from the SM (f_{a3}=0)



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Result summary (Run1)

Measurements with and without assuming the SM ratio of the coupling strengths of the Higgs boson to top and bottom quarks (e.g. tyle I 2HDM)

Channel	Parameter	Expected	Observed	CL: (68%) [95%]
Correlated μ parameters				
WH + H $\to$ WW	$f_{a3}^{WW}\cos\phi_{a_3}$	0 (-0.0012, 0.0012) [-0.0027, 0.0027]	-0.0027 (-0.0053, -0.00082)$\cup$(0.00084, 0.0053) [-0.0098, 0.0098]	
ZH + H $\to$ ZZ	$f_{a3}^{ZZ}\cos\phi_{a_3}$	0 (-0.0014, 0.0014) [-0.0034, 0.0034]	0.0011 (-0.0028, 0.0029) [-0.0055, 0.0056]	
VH + H $\to$ VV	$f_{a3}^{ZZ}\cos\phi_{a_3}$	0 (-0.00049, 0.00050) [-0.0011, 0.0011]	0.0012 (-0.0021, -0.00044)$\cup$(0.00047, 0.0021) [-0.0033, 0.0034]	
Uncorrelated μ parameters				
WH + H $\to$ WW	$f_{a3}^{WW}\cos\phi_{a_3}$	0 (0, 1) [0, 1]	-0.00088 (-0.46, 0.20) [0, 1]	
ZH + H $\to$ ZZ	$f_{a3}^{ZZ}\cos\phi_{a_3}$	0 (-0.20, 0.21) [-0.65, 0.66]	0.0067 (-0.13, 0.16) [-0.42, 0.44]	
VH + H $\to$ VV	$f_{a3}^{ZZ}\cos\phi_{a_3}$	0 (-0.0060, 0.0062) [-0.44, 0.44]	0.0010 (-0.039, -0.00011)$\cup$(0.00011, 0.043) [-0.24, 0.25]	

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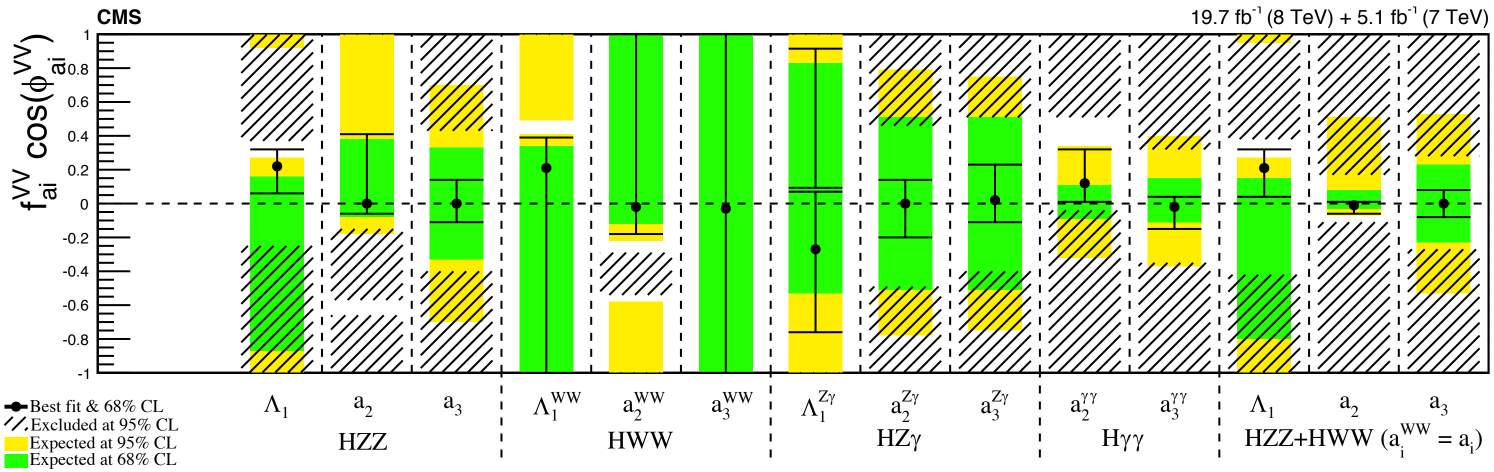

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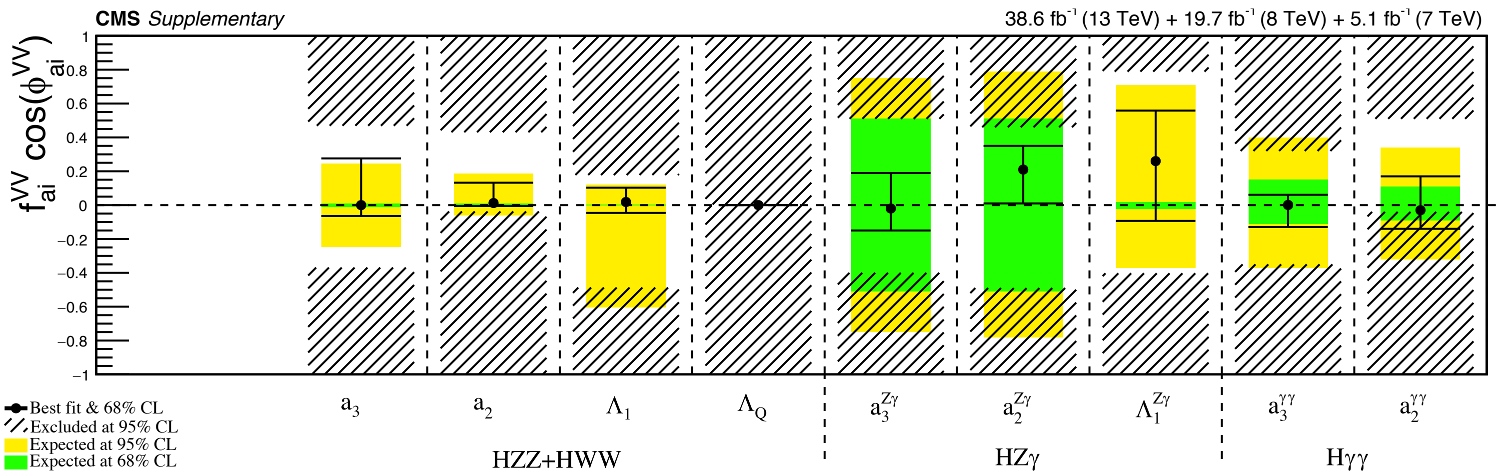
Result summary (Run1+Run2)



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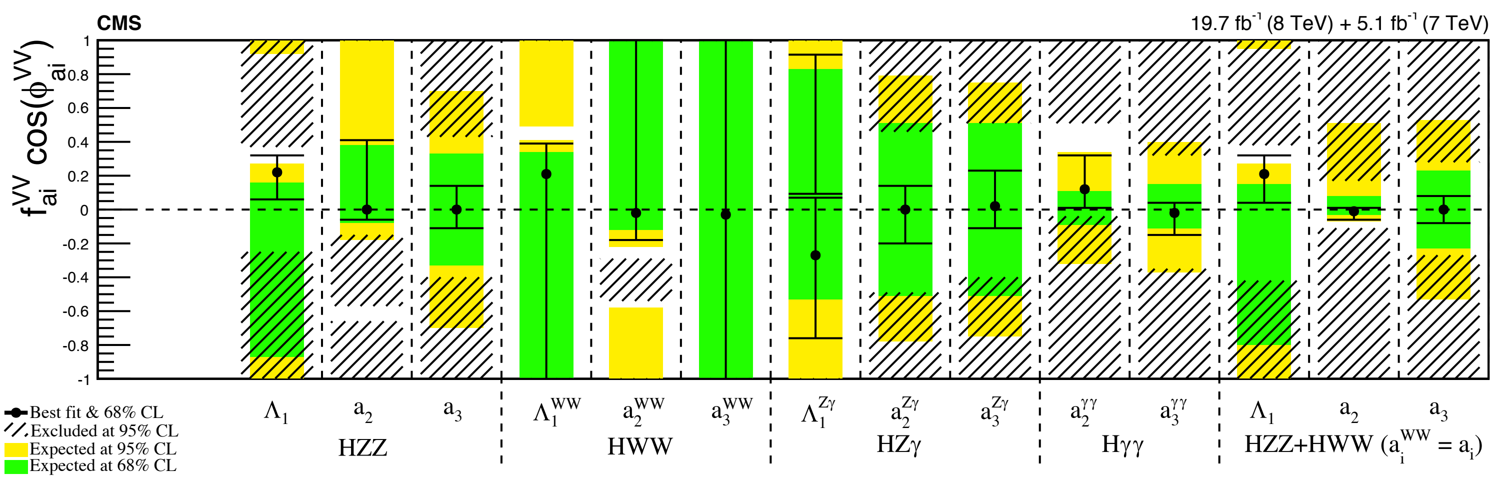

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Conclusions

J^{CP}

Very sure that the Higgs Boson is spin-0

CP measurements: search for small deviations

Testing the CP nature of Higgs is one of the important tasks after its discovery

- Testing the HVV coupling structure
  - Pseudo-scalar coupling is expected to be subdominant
  - Pure pseudoscalar ($J^{CP}=0^-$) hypothesis is excluded
  - No significant CP mixing effect is observed and limits are set on the CP-odd terms in the effective coupling approach
  - Now the focus is on search for small deviations
- Tree level couplings to quarks and leptons (prospects)
  - CP-even and CP-odd couplings induced at the same order
  - Experimental challenges for the test of the CP invariance

Backup

H->4l results

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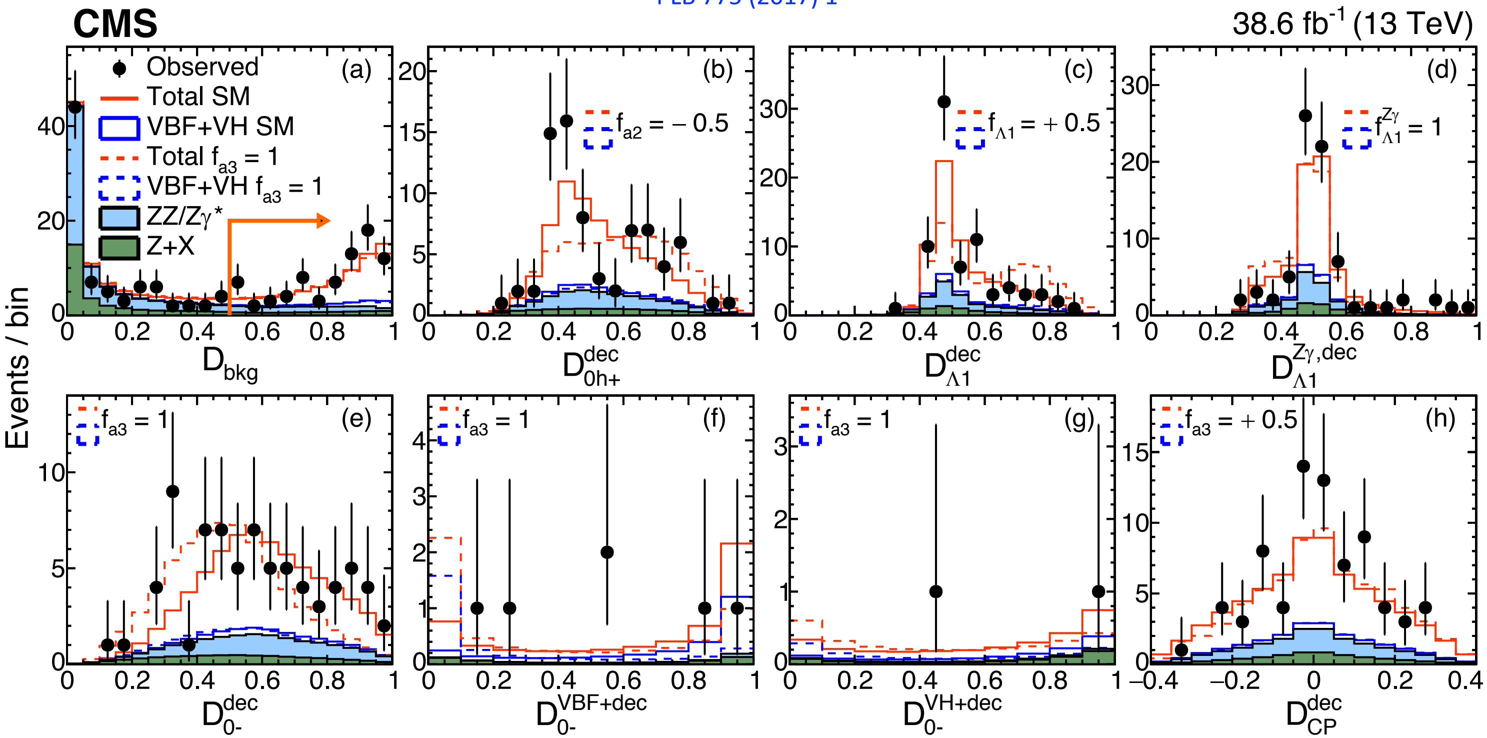

H->4l results

List of discriminants

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Table 3: Summary of three production categories in analysis of the H $\to 4\ell$ events. The discriminants $\mathcal{D}$ based on the matrix element likelihood calculations are defined for each category of events as discussed in text. Three BSM models are considered in definition of the categories: $f_{a3} = 1$, $f_{a2} = 1$, $f_{\Lambda 1} = 1$, and $f_{\Lambda 1}^{Z\gamma} = 1$. Three observables (abbreviated as obs.) are listed for each analysis and for each category. The $\mathcal{D}_{0h+}$ discriminant is used in the $f_{\Lambda 1}$ and $f_{\Lambda 1}^{Z\gamma}$ measurements to allow a two-parameter fit together with f_{a2} at a later time.

category	VBF 2 jet-tagged	VH hadronic-tagged	Untagged
target	$qq'VV \to qq'H \to (jj)(4\ell)$	$q\bar{q} \to VH \to (jj)(4\ell)$	$H \to 4\ell$
selection	$\mathcal{D}_{2jet}^{VBF}$ or $\mathcal{D}_{2jet}^{VBF,BSM} > 0.5$	$\mathcal{D}_{2jet}^{ZH}$ or $\mathcal{D}_{2jet}^{ZH,BSM}$ or $\mathcal{D}_{2jet}^{WH}$ or $\mathcal{D}_{2jet}^{WH,BSM} > 0.5$	not VBF-jets not VH-jets
f_{a3} obs.	$\mathcal{D}_{bkg}, \mathcal{D}_{0-}^{VBF+dec}, \mathcal{D}_{CP}^{VBF}$	$\mathcal{D}_{bkg}, \mathcal{D}_{0-}^{VH+dec}, \mathcal{D}_{CP}^{VH}$	$\mathcal{D}_{bkg}, \mathcal{D}_{0-}^{dec}, \mathcal{D}_{CP}^{dec}$
f_{a2} obs.	$\mathcal{D}_{bkg}, \mathcal{D}_{0h+}^{VBF+dec}, \mathcal{D}_{int}^{VBF}$	$\mathcal{D}_{bkg}, \mathcal{D}_{0h+}^{VH+dec}, \mathcal{D}_{int}^{VH}$	$\mathcal{D}_{bkg}, \mathcal{D}_{0h+}^{dec}, \mathcal{D}_{int}^{dec}$
$f_{\Lambda 1}$ obs.	$\mathcal{D}_{bkg}, \mathcal{D}_{\Lambda 1}^{VBF+dec}, \mathcal{D}_{0h+}^{VBF+dec}$	$\mathcal{D}_{bkg}, \mathcal{D}_{\Lambda 1}^{VH+dec}, \mathcal{D}_{0h+}^{VH+dec}$	$\mathcal{D}_{bkg}, \mathcal{D}_{\Lambda 1}^{dec}, \mathcal{D}_{0h+}^{dec}$
$f_{\Lambda 1}^{Z\gamma}$ obs.	$\mathcal{D}_{bkg}, \mathcal{D}_{\Lambda 1}^{Z\gamma,VBF+dec}, \mathcal{D}_{0h+}^{VBF+dec}$	$\mathcal{D}_{bkg}, \mathcal{D}_{\Lambda 1}^{Z\gamma,VH+dec}, \mathcal{D}_{0h+}^{VH+dec}$	$\mathcal{D}_{bkg}, \mathcal{D}_{\Lambda 1}^{Z\gamma,dec}, \mathcal{D}_{0h+}^{dec}$

Production × decay

Production-only

Decay-only

H->4l results

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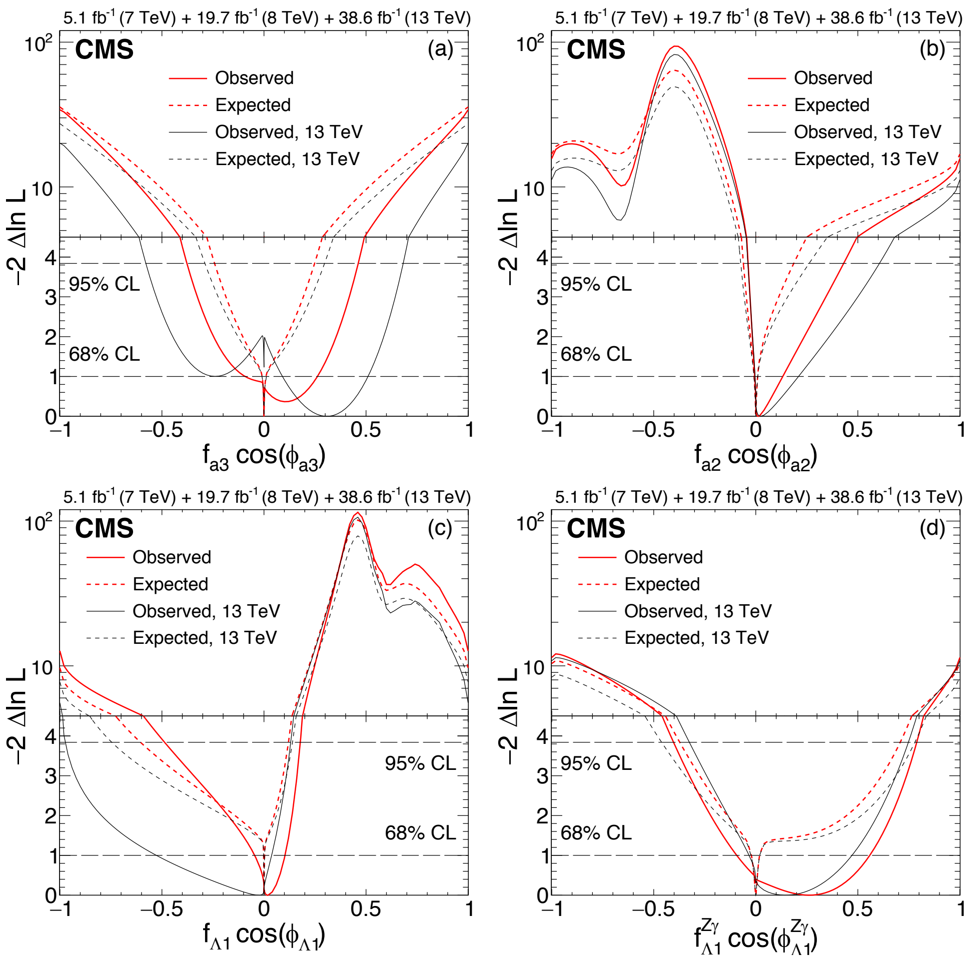

Spin 2 measurements

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The corresponding XVV amplitude is used to describe the $X \to ZZ$ and WW, as well as $gg \to X$, processes

$$A(X_{J=2}VV) \sim \Lambda^{-1} \Big[2c_1^{VV} t_{\mu\nu} f^{*1,\mu\alpha} f^{*2,\nu}{}_{\alpha} + 2c_2^{VV} t_{\mu\nu} \frac{q_\alpha q_\beta}{\Lambda^2} f^{*1,\mu\alpha} f^{*2,\nu\beta}$$
$$+ c_3^{VV} t_{\beta\nu} \frac{\tilde{q}^\beta \tilde{q}^\alpha}{\Lambda^2} (f^{*1,\mu\nu} f^{*2}_{\mu\alpha} + f^{*2,\mu\nu} f^{*1}_{\mu\alpha}) + c_4^{VV} t_{\mu\nu} \frac{\tilde{q}^\nu \tilde{q}^\mu}{\Lambda^2} f^{*1,\alpha\beta} f^{*2}_{\alpha\beta}$$
$$+ m_V^2 \left(2c_5^{VV} t_{\mu\nu} \epsilon_{V1}^{*\mu} \epsilon_{V2}^{*\nu} + 2c_6^{VV} t_{\mu\nu} \frac{\tilde{q}^\mu q_\alpha}{\Lambda^2} (\epsilon_{V1}^{*\nu} \epsilon_{V2}^{*\alpha} - \epsilon_{V1}^{*\alpha} \epsilon_{V2}^{*\nu}) + c_7^{VV} t_{\mu\nu} \frac{\tilde{q}^\mu \tilde{q}^\nu}{\Lambda^2} \epsilon_{V1}^{*} \epsilon_{V2}^{*} \right)$$
$$+ c_8^{VV} t_{\mu\nu} \frac{\tilde{q}^\mu \tilde{q}^\nu}{\Lambda^2} f^{*1,\alpha\beta} \tilde{f}^{*2}_{\alpha\beta}$$
$$+ m_V^2 \left(c_9^{VV} t^{\mu\alpha} \frac{\tilde{q}_\alpha \epsilon_{\mu\nu\rho\sigma} \epsilon_{V1}^{*\nu} \epsilon_{V2}^{*\rho} q^\sigma}{\Lambda^2} + c_{10}^{VV} t^{\mu\alpha} \frac{\tilde{q}_\alpha \epsilon_{\mu\nu\rho\sigma} q^\rho \tilde{q}^\sigma \left(\epsilon_{V1}^{*\nu} (q\epsilon_{V2}^*) + \epsilon_{V2}^{*\nu} (q\epsilon_{V1}^*) \right)}{\Lambda^4} \right) \Big], \quad (11)$$

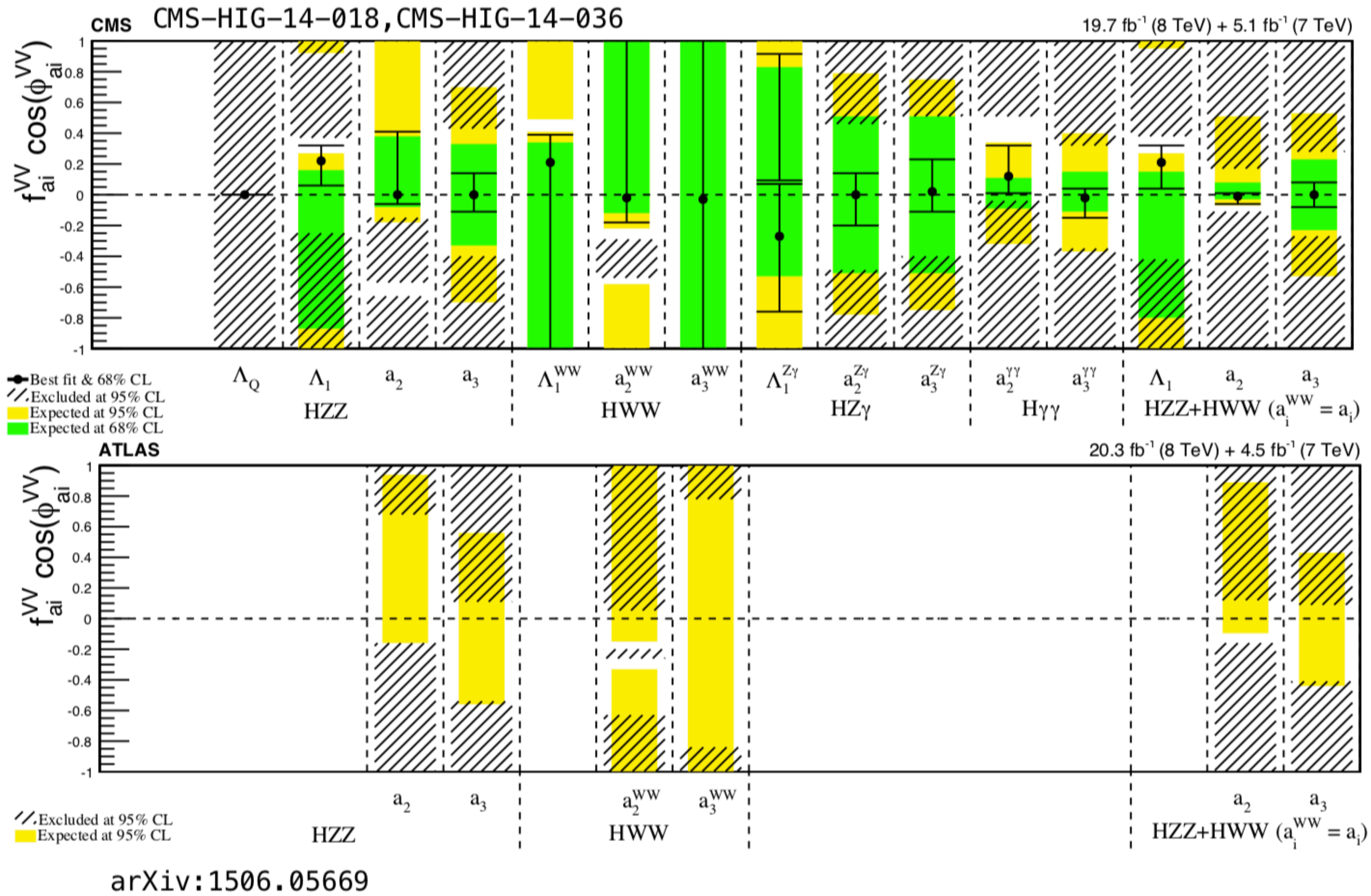
Table 2: List of spin-two models with the production and decay couplings of an exotic X particle. The subscripts m (minimal couplings), h (couplings with higher-dimension operators), and b (bulk) distinguish different scenarios.

J^P Model	$gg \to X$ Couplings	$q\bar{q} \to X$ Couplings	$X \to VV$ Couplings
2_m^+	$c_1^{gg} \neq 0$	$\rho_1 \neq 0$	$c_1^{VV} = c_5^{VV} \neq 0$
2_{h2}^+	$c_2^{gg} \neq 0$	$\rho_1 \neq 0$	$c_2^{VV} \neq 0$
2_{h3}^+	$c_3^{gg} \neq 0$	$\rho_1 \neq 0$	$c_3^{VV} \neq 0$
2_h^+	$c_4^{gg} \neq 0$	$\rho_1 \neq 0$	$c_4^{VV} \neq 0$
2_b^+	$c_1^{gg} \neq 0$	$\rho_1 \neq 0$	$c_1^{VV} \ll c_5^{VV} \neq 0$
2_{h6}^+	$c_1^{gg} \neq 0$	$\rho_1 \neq 0$	$c_6^{VV} \neq 0$
2_{h7}^+	$c_1^{gg} \neq 0$	$\rho_1 \neq 0$	$c_7^{VV} \neq 0$
2_h^-	$c_8^{gg} \neq 0$	$\rho_2 \neq 0$	$c_8^{VV} \neq 0$
2_{h9}^-	$c_8^{gg} \neq 0$	$\rho_2 \neq 0$	$c_9^{VV} \neq 0$
2_{h10}^-	$c_8^{gg} \neq 0$	$\rho_2 \neq 0$	$c_{10}^{VV} \neq 0$

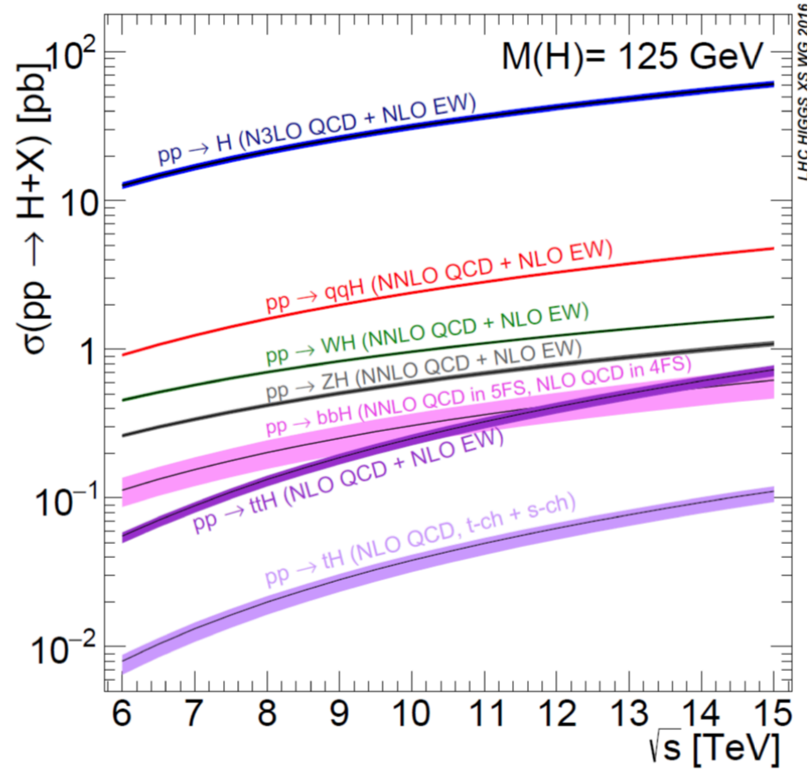
Comparison to ATLAS measurements

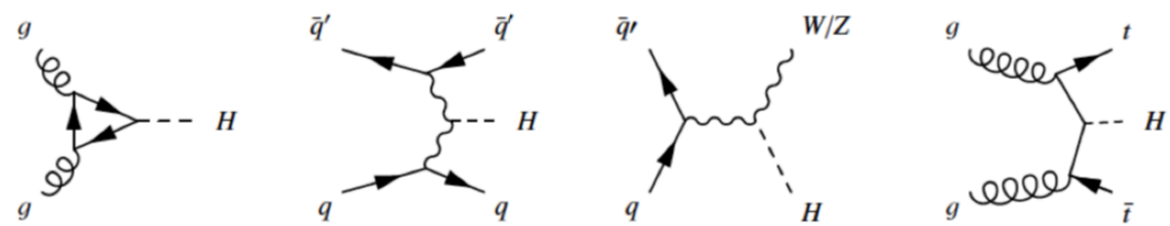
CMS:

ATLAS:



Higgs production at LHC





(a) $gg \to H$ (b) VBF (c) VH (d) $t\bar{t}H$

87%	7%	5%	<1%