Probing CP structure of the Higgs boson couplings with the CMS experiment

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Introduction

- The main motivation to look for CP-violation (CPV) in the Higgs sector is matter-antimatter asymmetry in Universe
  - CPV one of Sakharov conditions

    (for dynamical generation of baryon asymmetry)
  - CPV present in the Standard Model (via CKM) not sufficient

    => new sources needed
- Search for anomalous, i.e. not predicted by SM, CP-odd terms in couplings of the Higgs boson – CPV via interference effects with CP-even terms
  - Also presence of other CP-even anomalous terms probed

Sources of CPV

[Not exhaustive list]

- Higgs – gauge boson couplings (CP-odd term)

$$c_{VV} H_{phys} F_{\mu\nu} \widetilde{F}^{\mu\nu}$$, where $$\widetilde{F}_{\mu\nu} \equiv \frac{1}{2} \epsilon_{\mu\nu\rho\sigma} F^{\rho\sigma}$$ (dual tensor)

- Higgs Yukawa couplings

$$|c_f| \frac{m_f}{v} \bar{f} (\cos\varphi_f + i\gamma_5 \sin\varphi_f) f H_{phys}$$

- Higgs – scalar coupling

CP-violating terms in the scalar potential

$$V_H \sim -(m_{12}^2 \Phi_1^\dagger \Phi_2 + H.c.) + [\frac{1}{2}\lambda_5 (\Phi_1^\dagger \Phi_2)^2 + \lambda_6 (\Phi_1^\dagger \Phi_1)(\Phi_1^\dagger \Phi_2) + \lambda_7 (\Phi_2^\dagger \Phi_2)(\Phi_1^\dagger \Phi_2) + H.c.]$$

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- ~~Higgs – scalar coupling~~

CP-violating terms in the scalar potential

$$V_H \sim -\left(m_{12}^2 \Phi_1^\dagger \Phi_2 + H.c. \right) + \left[\frac{1}{2} \lambda_5 \left(\Phi_1^\dagger \Phi_2 \right)^2 + \lambda_6 \left(\Phi_1^\dagger \Phi_1 \right) \left(\Phi_1^\dagger \Phi_2 \right) + \lambda_7 \left(\Phi_2^\dagger \Phi_2 \right) \left(\Phi_1^\dagger \Phi_2 \right) + H.c. \right]$$

It requires additional Higgs fields and will not be discussed today

Sources of CPV: H-gauge coupling

- Higgs – gauge boson couplings (CP-odd term)

$$c_{VV} H_{phys} F_{\mu\nu} \widetilde{F}^{\mu\nu}$$

  - Effective, non-renormalisable, operator – can be generated by exchange of BSM particles => suppressed by BSM scale Λ as $1/\Lambda^2$

@ LHC: accessible vertices:

  - HZZ/HWW – VBF & VH production and H→ZZ/WW decays
  - HZγ/Hγγ – H→Zγ/γγ decays (including γ*→2ℓ)
  - Hgg – ggF production
    - Can be treated effective interaction as Hγγ or split to elementary Yukawa couplings (assuming loop content, e.g. t quark dominance)
    - ggF + 2 jets topology used

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@ LHC: accessible vertices:

  - HZZ/HWW – VBF & VH production and H→ZZ/WW decays
  - HZγ/Hγγ – H→Zγ/γγ decays (including γ*→2ℓ)

- Studies concentrated (until now) on the H→4ℓ decay and VBF production modes
  - Clear signature,
  - Access to the full kinematics

  => I will focus on this today

Sources of CPV: H-gauge coupling

- Higgs – gauge boson couplings (CP-odd term)

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@ LHC: accessible vertices:

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  - ~~Hgg – ggF production~~

  - Work well advanced, but not public results, yet
    - ggF + 2 jets topology (access to full kinematics)
    - Several Higgs decay modes

    => Not discussed today

    - Results expected this Summer

HVV amplitude

$$A(HZZ/HWW) \sim \left[a_1 + \frac{q_{V1}^2 + q_{V2}^2}{\Lambda_1^2} + \frac{(q_{V1}+q_{V2})^2}{\Lambda_Q^2} \right] m_V^2 \epsilon_{V1}^* \epsilon_{V2}^* + a_2 f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3 f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

m_V, q_V, ε_V – mass, 4-momentum and polarization of V boson,

$f^{\mu\nu} = \varepsilon_V^{\mu} q^{\nu} - \varepsilon_V^{\mu\nu} q^{\mu}$ – field strength tensor

- SM: $a_1 \neq 0$, other 0 (at tree level)
- a_3 – CP-odd term (others CP-even) => CPV via interference
- assumed $a_i \equiv a_i^{ZZ} = a_i^{WW}$ – relevant for VBF and W/ZH production
  - It is possible to recalculate to have other relation
- Constant and real couplings assumed (sensible for $m_{BSM} >> m_H$)

cf. CMS Collaboration, Phys. Rev. D 92, 012004 (2015)

Sources of CPV: Yukawa coupling

NCBJ

Higgs Yukawa couplings

$$|c_f|\frac{m_f}{v}\bar{f}\left(\cos\varphi_f + i\gamma_5 \sin\varphi_f\right) f H_{phys}$$

@ LHC: accessible vertices:

- $H\tau\tau$ – $H \rightarrow \tau\tau$ decays:
  - Study correlation of τ^+ and τ^- spins
    - Difficult as tau momenta not accessible, but visible decay products retain (part) of the correlation
- Htt – ttH production:
  - Study kinematics of the process
  - Several decay modes can be used
  - – Htt also present in the loop of ggF production

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@ LHC: accessible vertices:

- Hττ – H → ττ decays:
  - Study correlation of τ^+ and τ^- spins
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  - Work well advanced, but public results expected this Summer

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Sources of CPV: Yukawa coupling

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$$|c_f|\frac{m_f}{v}\bar{f}\left(\cos\varphi_f + i\gamma_5\sin\varphi_f\right)f\,H_{phys}$$

@ LHC: accessible vertices:

- ~~Hττ – H→ττ decays:~~
  - Study correlation of τ^+ and τ^- spins
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  - Work well advanced, but public results expected this Summer

    => Not discussed today
- Htt – ttH production:
  - Study kinematics of the process
  - Several decay modes can be used
    - Htt also present in the loop of ggF production
  - Results with the H→γγ decay submitted recently to journal

    => Discussed this talk

Htt amplitude

$$A(Htt) \sim -\frac{m_t}{v}\bar{\psi}_t\left(\kappa_t + i\tilde{\kappa}_t\gamma_5\right)\psi_t$$

- In SM: $\kappa_t = 1\,(\text{CP-even}),\ \tilde{\kappa}_t = 0\,(\text{CP-odd})$
- Unlike in HVV CP-even and CP-odd couplings both arise at the same order in q^2

Parametrisation

- We measure couplings in terms of fractions:

$$f_{ai} = \frac{|a_i|^2 \sigma_i}{\sum_j |a_j|^2 \sigma_j},$$

with σ_i − cross section for $a_i = 1, a_{k \neq i} = 0$

HVV coupling: $\sigma_i (H \rightarrow 2e2\mu)$

- In Htt we drop σ to avoid PDF dependence:

$$f_{CP}^{Htt} = \frac{|\tilde{k}_t|^2}{|k_t|^2 + |\tilde{k}_t|^2}$$

- Finally:

$$\varphi_{ai} = \arg\left(\frac{a_i}{a_1}\right), \text{i.e. relative phase of } a_i,$$

which is 0 or π for real couplings

$$\Rightarrow \cos(\varphi_{ai}) = \text{sgn}(a_{ai} / a_1)$$

Likelihood-based discriminants

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MELA (Matrix Element Likelihood Analysis):

- Neyman-Pearson lemma: best observable to distinguish two hypotheses – signal (*sig*) and alternative (*alt*) is:

$$D_{alt} = \frac{P_{sig}}{P_{sig} + P_{alt}}, \ 0 \leqslant D_{alt} \leqslant 1$$

where *P* depend on event kinematics.

alt can be alternative production process (to categorise events), background (non-Higgs process) or anomalous coupling a_i model:

$$D^{VBF,VH} = \frac{P^{VBF,VH}}{P^{VBF,VH} + P^{ggF}} \qquad D_{bkg} = \frac{P_{sig}}{P_{sig} + P_{bkg}} \qquad D_{ai} = \frac{P_{ai}}{P_{ai} + P_{SM}}$$

- To account for interference D_{int} is defined

$$D_{\text{int}} = \frac{P_{\text{int}}}{2\sqrt{P_{ai} P_{SM}}}, \ -1 \leqslant D_{\text{int}} \leqslant 1$$

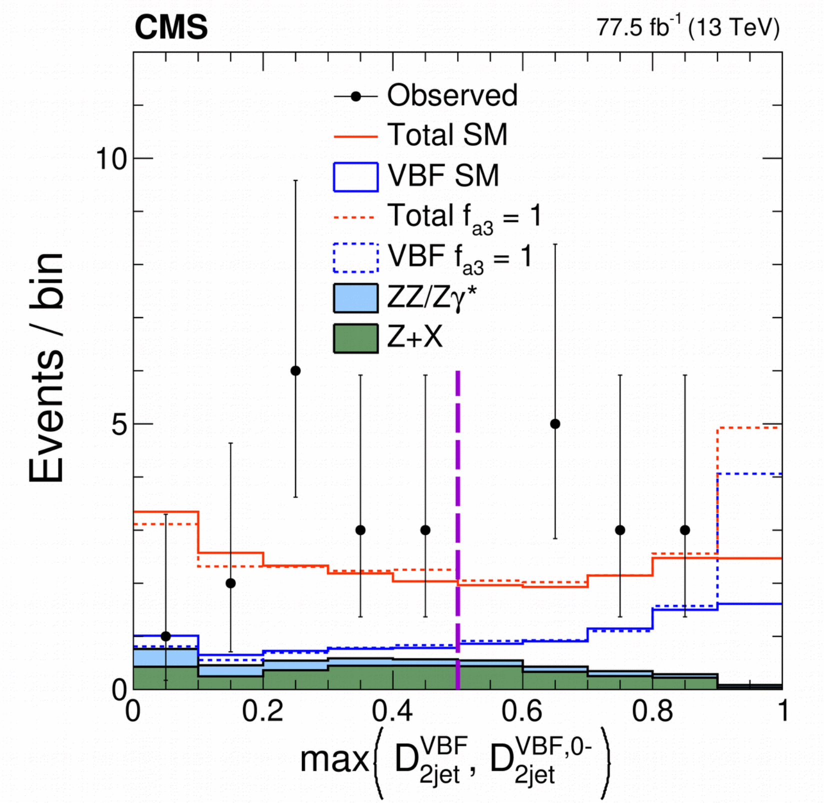
cf. CMS Collaboration, Phys. Rev. D 99, 112003 (2019)

Probing structure of HVV couplings

Probing HVV

Two Higgs decay modes used:

- **$H \rightarrow 4\ell$:** 2e2μ, 4e, 4μ
  - on-shell $105 < m_{4\ell} < 140$ GeV
  - off-shell $m_{4\ell} > 220$ GeV
  - Categories (production) using MELA (only 2016-2017 data)
    - VBF-tagged
    - VH-tagged
    - untagged (rest)

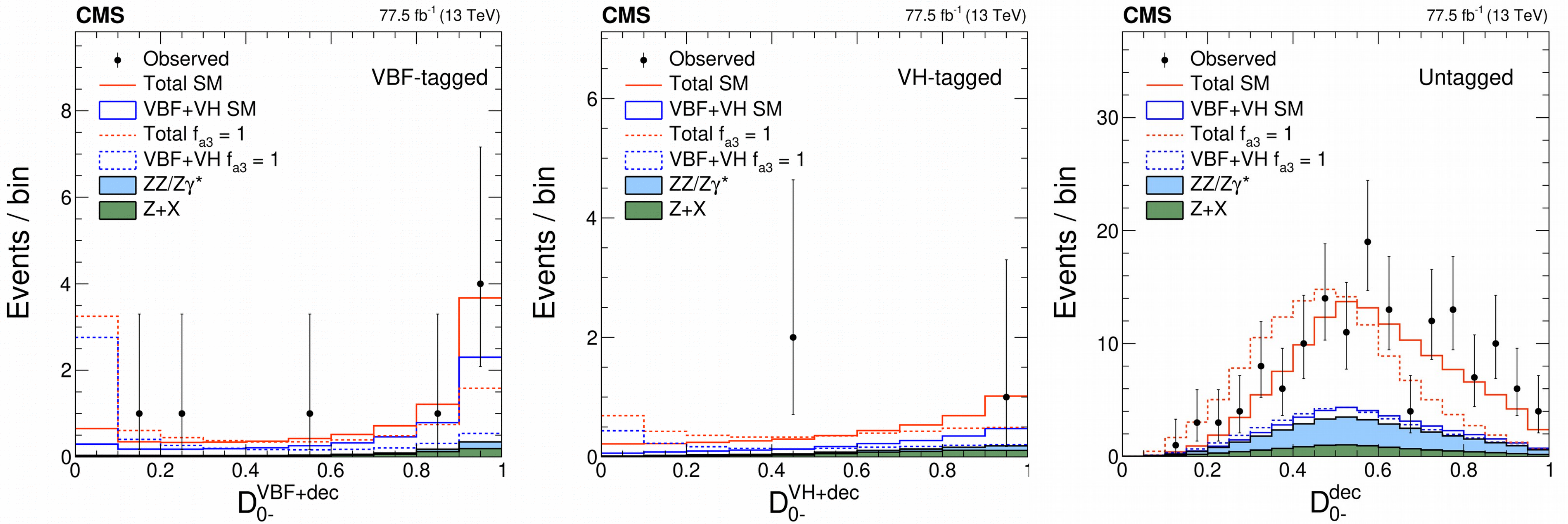


- **$H \rightarrow \tau\tau$:** $\tau_h\tau_h$, $\mu\tau_h$, $e\tau_h$, eμ
  - Categories (production) using kinematic cuts
    - VBF category (2-jet, high m_{jj}, ...)
    - boosted category (1-jet or 2-jets no-VBF)
    - 0-jets category

cf. CMS Collaboration, Phys. Rev. D 99, 112003 (2019)
cf. CMS Collaboration, 1903.06973

Probing HVV with $H \to 4\ell$ at CMS

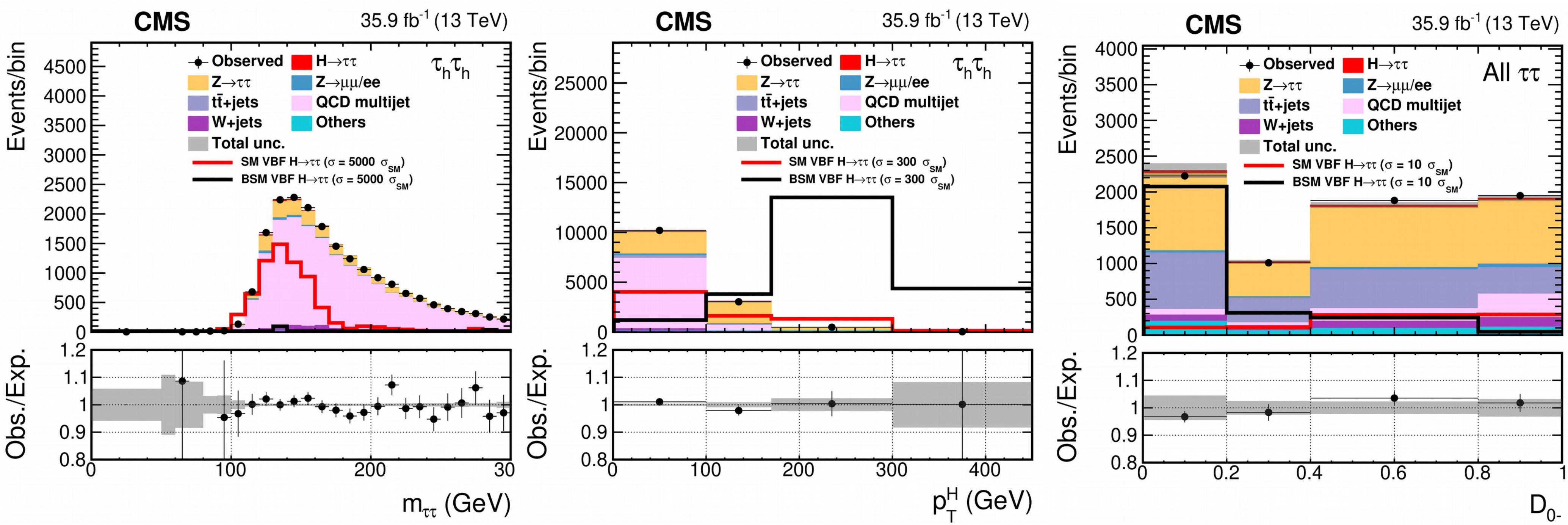
- Each anomalous coupling tested separately (here focus on f_3)
- Production (when available) + decay info used
  - Simultaneous fit of D_{bkg}, D_{0-} (a_3 contr.), D_{CP} ($a_1 - a_3$ interf.) and signal strength modifiers μ_F, μ_V
    - Usage of μ_F, μ_V prevents that excess in VBF/VH categories is interpreted as presence of BSM coupling
- Used 80.2/fb (13TeV) + 5.1/fb (7TeV) + 19.7/fb (8TeV)



cf. CMS Collaboration, Phys. Rev. D 99, 112003 (2019)

Probing HVV with H → ττ

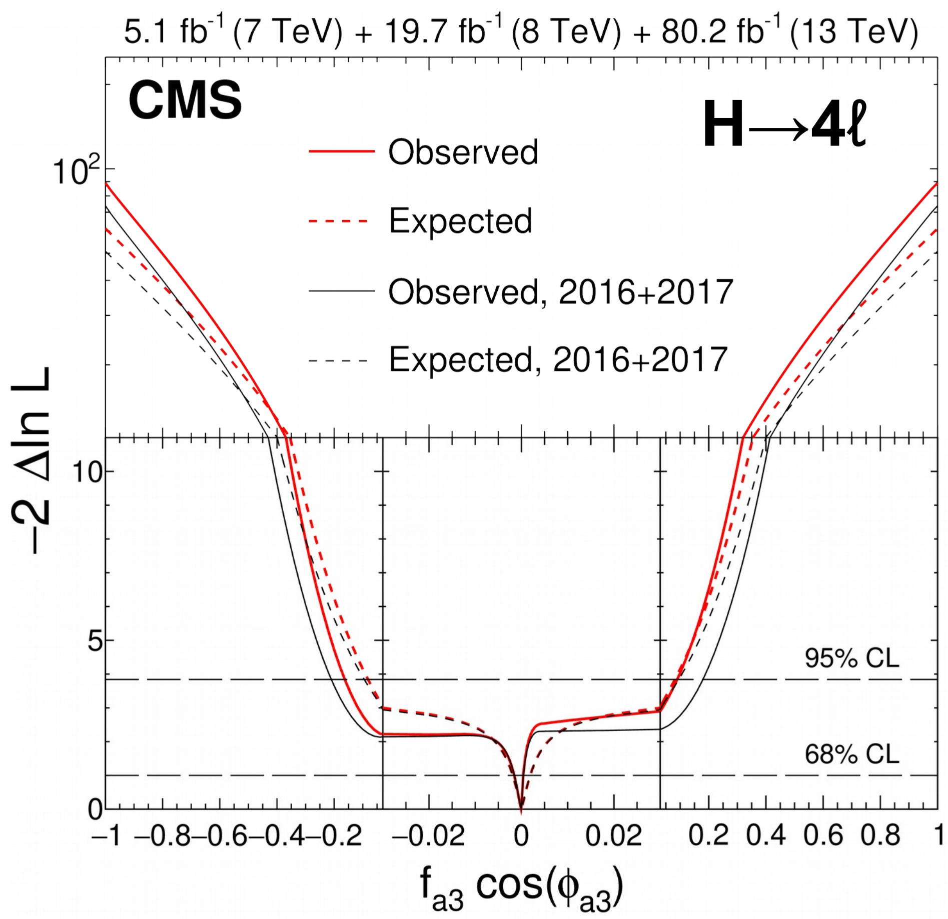
- Production info + H kinematics
  - $m_{\tau\tau}$ (+ other quantity deepened on channel) in 0-jets category
  - $m_{\tau\tau}$, p_T^H in boosted category (1-jet or >1 jet no-VBF)
  - $m_{\tau\tau}$, m_{jj}, D_{0-} (a_3 contr.), D_{CP} ($a_1 - a_3$ interf.) in VBF category and signal strength modifiers μ_F, μ_V
- Used 35.9/fb (13TeV)

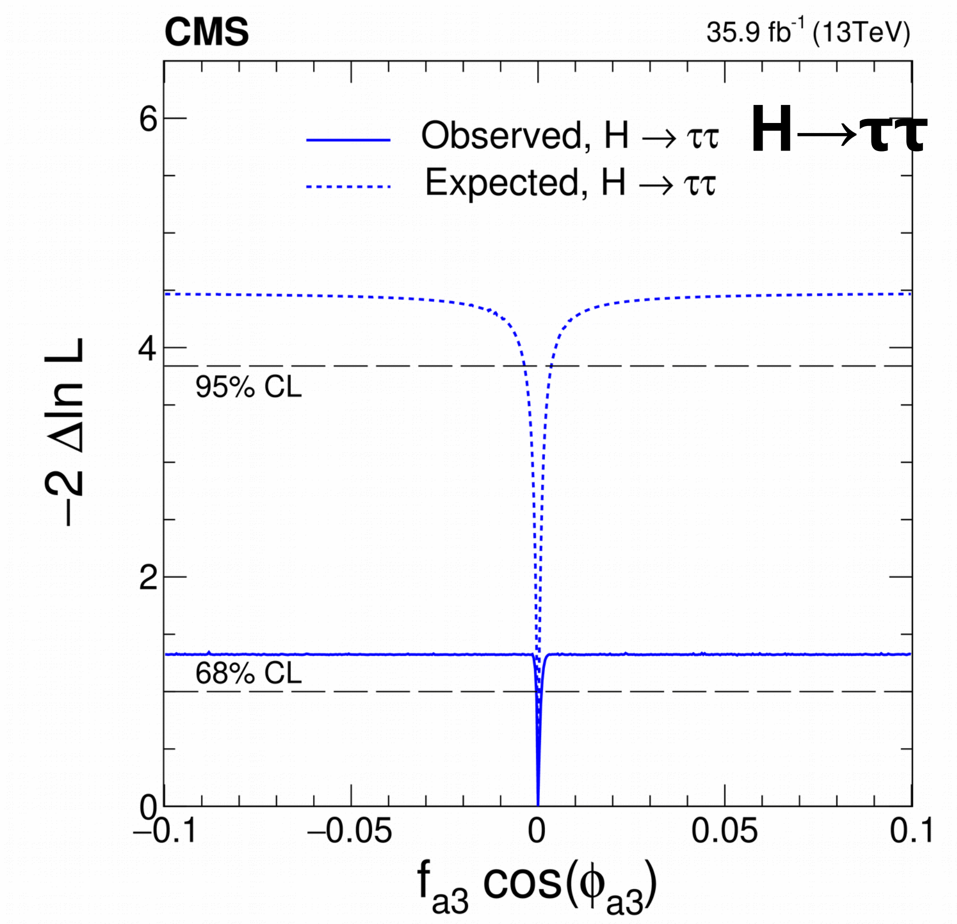


cf. CMS Collaboration, 1903.06973

Results

- Production dominates low f_{ai}, while decay high f_{ai}

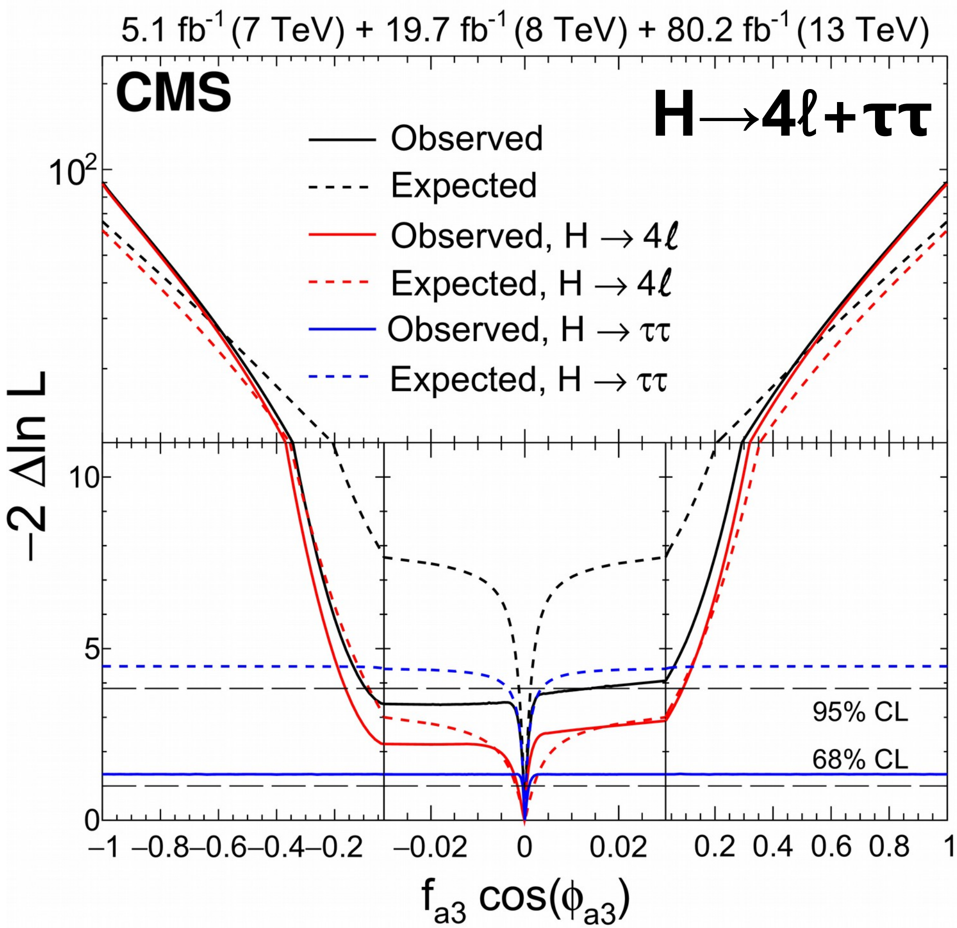




cf. CMS Collaboration, Phys. Rev. D 99, 112003 (2019)

cf. CMS Collaboration, 1903.06973

Results: on-shell combination



Parameter	Observed / (10^{-3})		Expected / (10^{-3})	
	68% CL	95% CL	68% CL	95% CL
$f_{a3}\cos(\phi_{a3})$	0.00 ± 0.27	$[-92, 14]$	0.00 ± 0.23	$[-1.2, 1.2]$
$f_{a2}\cos(\phi_{a2})$	$0.08^{+1.04}_{-0.21}$	$[-1.1, 3.4]$	$0.0^{+1.3}_{-1.1}$	$[-4.0, 4.2]$
$f_{\Lambda 1}\cos(\phi_{\Lambda 1})$	$0.00^{+0.53}_{-0.09}$	$[-0.4, 1.8]$	$0.00^{+0.48}_{-0.12}$	$[-0.5, 1.7]$
$f_{\Lambda 1}^{Z\gamma}\cos(\phi_{\Lambda 1}^{Z\gamma})$	$0.0^{+1.1}_{-1.3}$	$[-6.5, 5.7]$	$0.0^{+2.6}_{-3.6}$	$[-11, 8.0]$

f_{ai} agree with 0 (SM) with $10^{-3} - 10^{-2}$ precision at 95% CL

95%CL

Parameter	Observed	Expected
a_3/a_1	$[-0.81, 0.31]$	$[-0.090, 0.090]$
a_2/a_1	$[-0.055, 0.097]$	$[-0.11, 0.11]$
$(\Lambda_1\sqrt{\lvert a_1\rvert})\cos(\phi_{\Lambda 1})$ (GeV)	$[-\infty, -650] \cup [440, \infty]$	$[-\infty, -610] \cup [450, \infty]$
$(\Lambda_1^{Z\gamma}\sqrt{\lvert a_1\rvert})\cos(\phi_{\Lambda 1}^{Z\gamma})$ (GeV)	$[-\infty, -400] \cup [420, \infty]$	$[-\infty, -360] \cup [390, \infty]$

a_i/a_1 agree with 0 (SM) with 10^{-1} precision

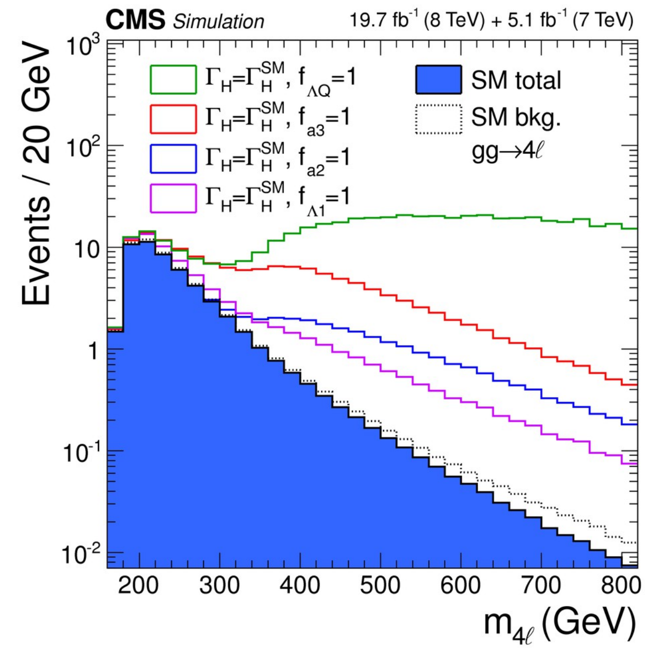
cf. CMS Collaboration, Phys. Rev. D 99, 112003 (2019)

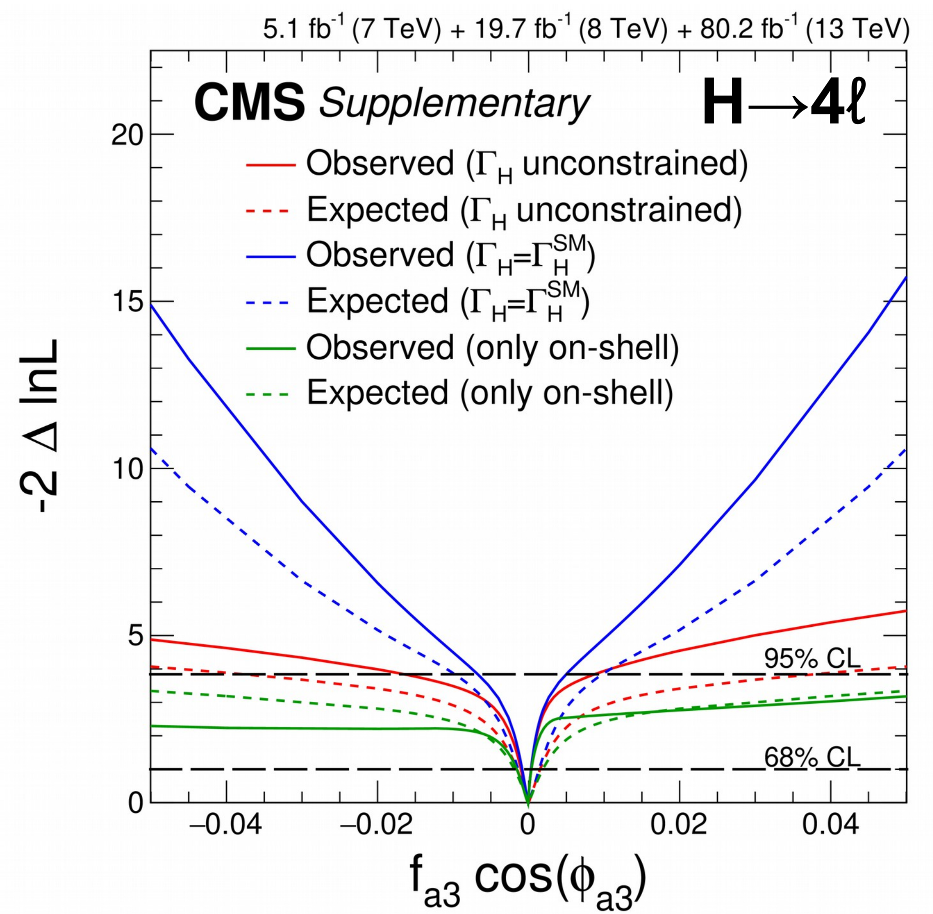
cf. CMS Collaboration, 1903.06973

Results: on-shell & off-shell comb.

- Anomalous couplings cause increase of off-shell events
- Results depend on assumed Γ_H

Phys. Rev. D 92, 072010 (2015)





cf. CMS Collaboration, Phys. Rev. D 99, 112003 (2019)

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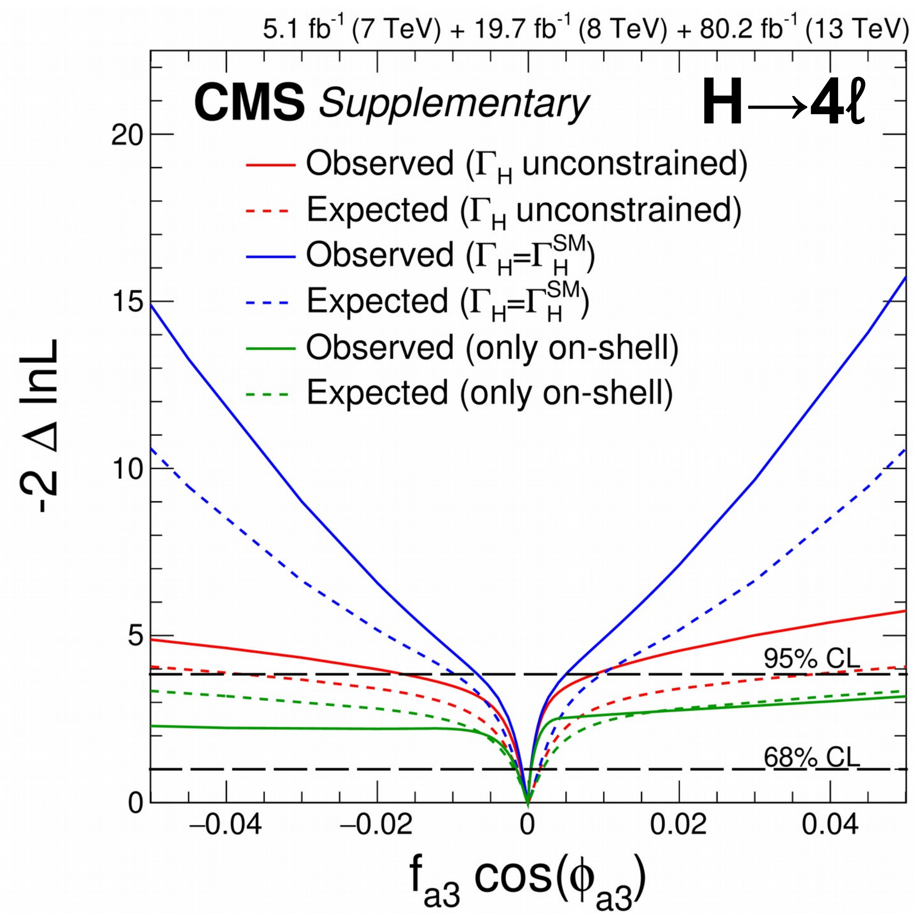


68% CL [95% CL]

Parameter	Scenario	Observed	Expected
$f_{a3}\cos(\phi_{a3})$	on-shell	$-0.0001^{+0.0004}_{-0.0015}$ $[-0.163, 0.090]$	$0.0000^{+0.0019}_{-0.0019}$ $[-0.082, 0.082]$
	any Γ_H	$0.0000^{+0.0003}_{-0.0010}$ $[-0.0165, 0.0087]$	$0.0000^{+0.0015}_{-0.0015}$ $[-0.038, 0.038]$
	$\Gamma_H=\Gamma_H^{SM}$	$0.0000^{+0.0003}_{-0.0009}$ $[-0.0067, 0.0050]$	$0.0000^{+0.0014}_{-0.0014}$ $[-0.0098, 0.0098]$
$f_{a2}\cos(\phi_{a2})$	on-shell	$0.0004^{+0.0026}_{-0.0006}$ $[-0.0055, 0.0234]$	$0.0000^{+0.0030}_{-0.0023}$ $[-0.021, 0.035]$
	any Γ_H	$0.0004^{+0.0026}_{-0.0006}$ $[-0.0035, 0.0147]$	$0.0000^{+0.0019}_{-0.0017}$ $[-0.015, 0.021]$
	$\Gamma_H=\Gamma_H^{SM}$	$0.0005^{+0.0025}_{-0.0006}$ $[-0.0029, 0.0129]$	$0.0000^{+0.0012}_{-0.0016}$ $[-0.010, 0.012]$
$f_{\Lambda1}\cos(\phi_{\Lambda1})$	on-shell	$0.0002^{+0.0030}_{-0.0009}$ $[-0.209, 0.089]$	$0.0000^{+0.0012}_{-0.0006}$ $[-0.059, 0.032]$
	any Γ_H	$0.0001^{+0.0015}_{-0.0006}$ $[-0.090, 0.059]$	$0.0000^{+0.0013}_{-0.0007}$ $[-0.017, 0.019]$
	$\Gamma_H=\Gamma_H^{SM}$	$0.0001^{+0.0015}_{-0.0005}$ $[-0.016, 0.068]$	$0.0000^{+0.0013}_{-0.0006}$ $[-0.015, 0.018]$
$f_{\Lambda1}^{Z\gamma}\cos(\phi_{\Lambda1}^{Z\gamma})$	on-shell	$0.0000^{+0.3554}_{-0.0087}$ $[-0.17, 0.61]$	$0.0000^{+0.0091}_{-0.0100}$ $[-0.098, 0.343]$

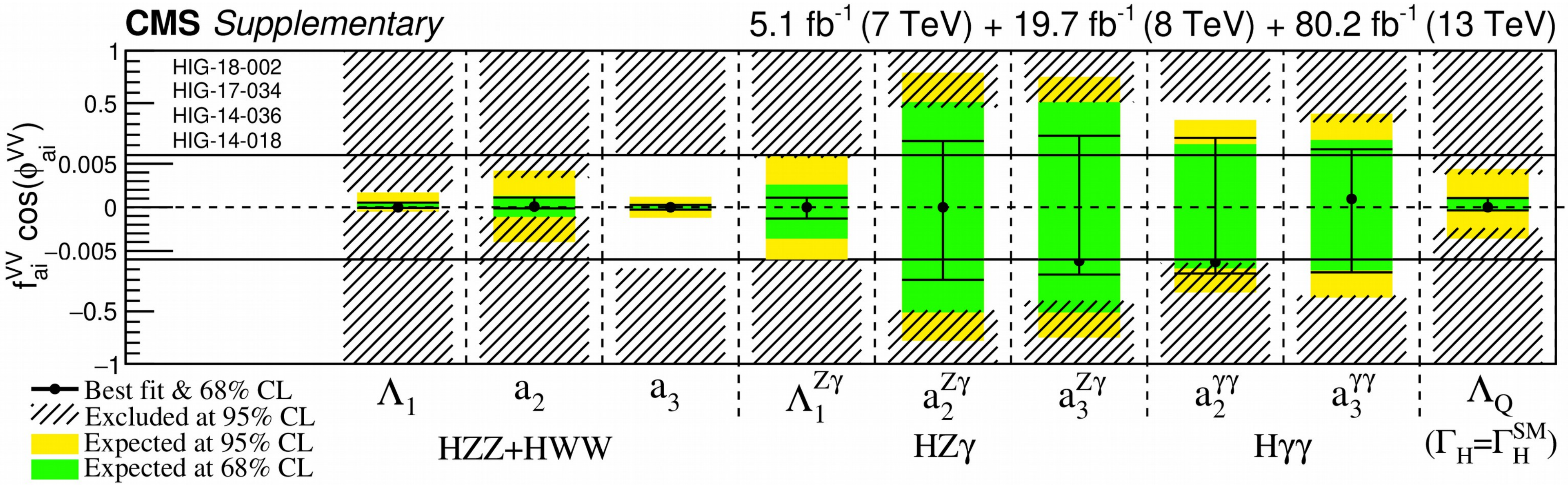
95%CL

Parameter	Scenario	Observed	Expected
a_3/a_1	on-shell	$[-1.13, 0.80]$	$[-0.76, 0.76]$
	any Γ_H	$[-0.33, 0.24]$	$[-0.50, 0.50]$
	$\Gamma_H=\Gamma_H^{SM}$	$[-0.21, 0.18]$	$[-0.25, 0.25]$
a_2/a_1	on-shell	$[-0.12, 0.26]$	$[-0.24, 0.31]$
	any Γ_H	$[-0.098, 0.202]$	$[-0.21, 0.25]$
	$\Gamma_H=\Gamma_H^{SM}$	$[-0.089, 0.189]$	$[-0.17, 0.18]$
$(\Lambda_1\sqrt{\lvert a_1\rvert})\cos(\phi_{\Lambda1})$ (GeV)	on-shell	$[-\infty, -130]\cup[160, \infty]$	$[-\infty, -180]\cup[210, \infty]$
	any Γ_H	$[-\infty, -160]\cup[180, \infty]$	$[-\infty, -250]\cup[240, \infty]$
	$\Gamma_H=\Gamma_H^{SM}$	$[-\infty, -250]\cup[170, \infty]$	$[-\infty, -260]\cup[250, \infty]$
$(\Lambda_1^{Z\gamma}\sqrt{\lvert a_1\rvert})\cos(\phi_{\Lambda1}^{Z\gamma})$ (GeV)	on-shell	$[-\infty, -170]\cup[100, \infty]$	$[-\infty, -200]\cup[130, \infty]$

cf. CMS Collaboration, Phys. Rev. D 99, 112003 (2019)

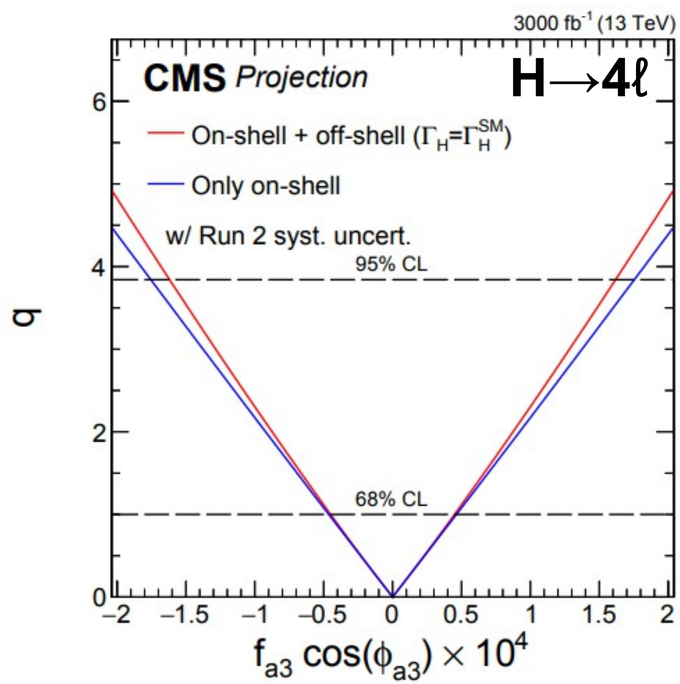
HVV: summary & outlook

cf. CMS Collaboration, 1903.06973



- Analysis of full Run-2 dataset of ~135/fb is ongoing
- During Run-3 (starting 2021) additional ~150/fb at 14TeV expected
- HL-LHC with 3/ab
  - Constrain f_{ai} to 10^{-4} level

    $f_{a3}\cos(\varphi_{a3})$ in $[-1.6,1,6]\times10^{-4}$



CMS-FTR-18-011

Probing structure of Htt coupling

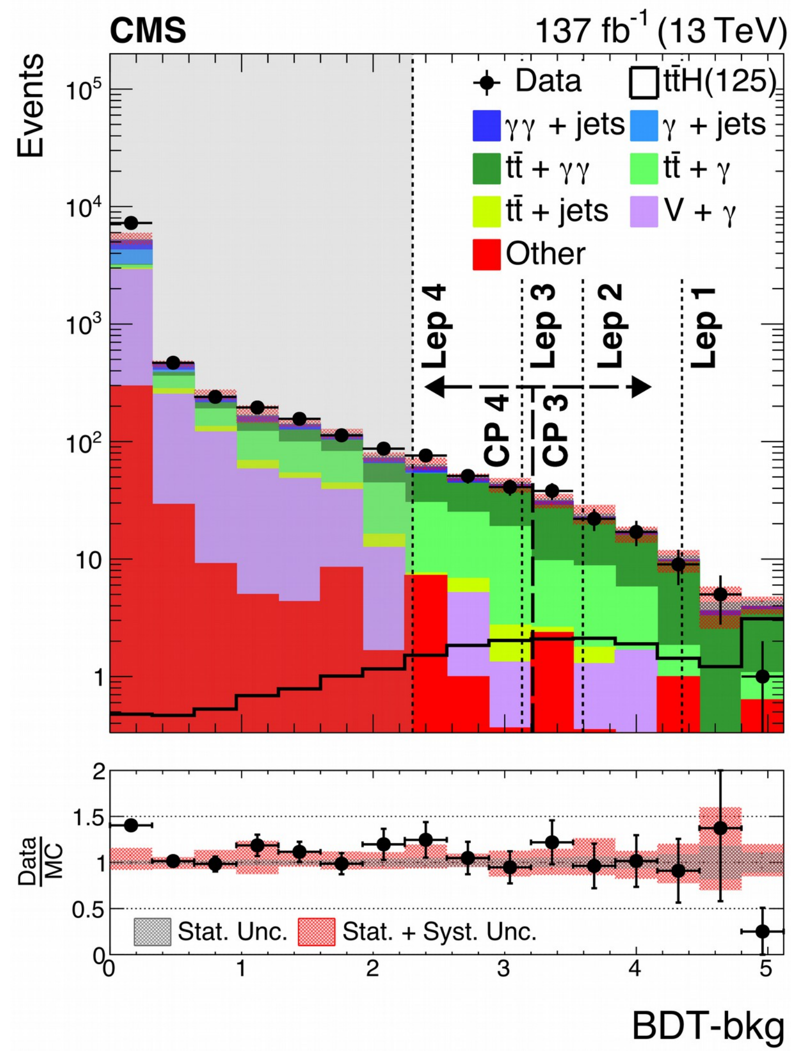
Htt coupling: analysis strategy

$H \rightarrow \gamma\gamma$ decay (full Run-2 dataset of 137/fb):

- Two high-p_T islated photons + jets and leptons
- Two independent topologies:

Hadronic:
- $N_{lep} = 0$
- $N_{jet} \geq 3$, $N_{b\text{-}tag} \geq 1$
- $m_{\gamma\gamma} > 100$ GeV

Leptonic:
- $N_{lep} \geq 0$
- $N_{jet} \geq 1$
- $m_{\gamma\gamma} > 100$ GeV

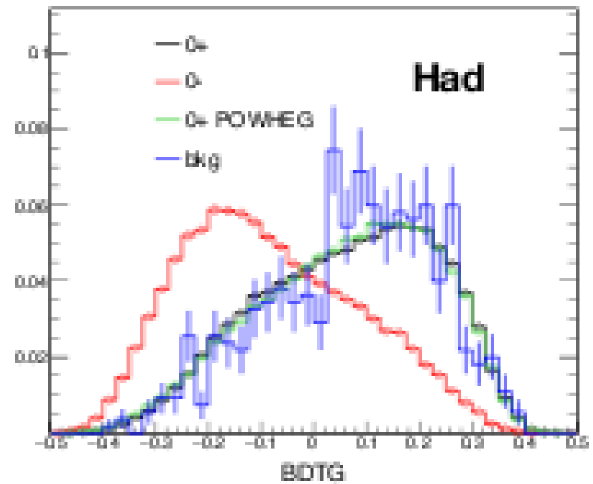


- BDT-bkg discriminant (one for each category) to distinguish ttH signal from background (inc. other Higgs production modes)
  - Exploits event kinematics (excl. $m_{\gamma\gamma}$), photon-ID and b-tagging quality
  - Two signal enriched regions (for each category) for CP measurement

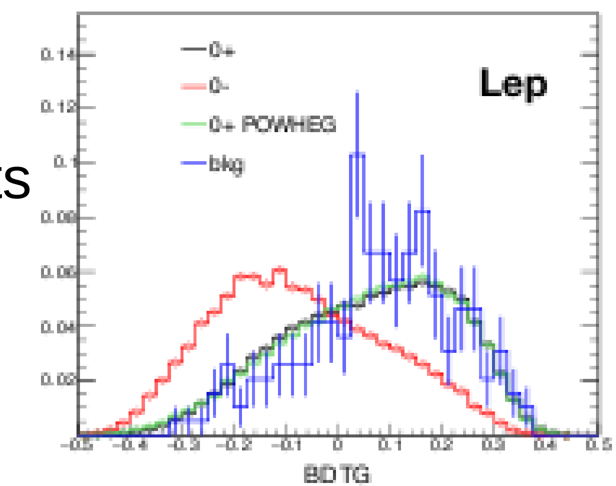
cf. CMS Collaboration, 1903.06973

Probing Htt coupling

- **D_{0-}** to distinguish betheeen CP-even (0^+) and CP-odd (0^-) coupling
  => dedicated BDT instead of ME-based likelihood
  - Performence proven to be as for ME-based discriminant, but more handy in complex toplology thanks to shorter evaluation time / event



- **D_{0-}** trained using
  - Kinenametics of γγ-pair: p_T/m, cos(φ), rapidity,
  - 4-momenta and b-tag score of 6 leading (in p_T) jets
  - Number of leptons and 4-momentum of leading lepton (if present)



- Not correlated with BDT-bkg
- Discriminant sensitive to CP-even – CP-odd interfernece (**D_{CP}**) not defined due to unknown flavours of light jets

cf. CMS Collaboration, 1903.06973

Probing Htt coupling

- Parameters of interest – signal strenght (μ) and fractional contribution of CP-odd component ($|f_{CP}|$) – extracted in simultaneus fit of $m_{\gamma\gamma}$ in 12 event categories
  - 2 toplogies x 2 BDT-bkg regions x 3 D_{0-} bins
- The $m_{\gamma\gamma}$ distribution in data modeled by sum of two contributions
  - Signal peak (Cristal-Ball+Gauss, from MC)
  - Non-resonant background (shape from $m_{\gamma\gamma}$ sidebands)

cf. CMS Collaboration, 1903.06973

The $m_{\gamma\gamma}$ distributions

- Fit of $m_{\gamma\gamma}$ simultaneusly in 6 categories in **hadronic** topology
  - Similar for leptonic topology

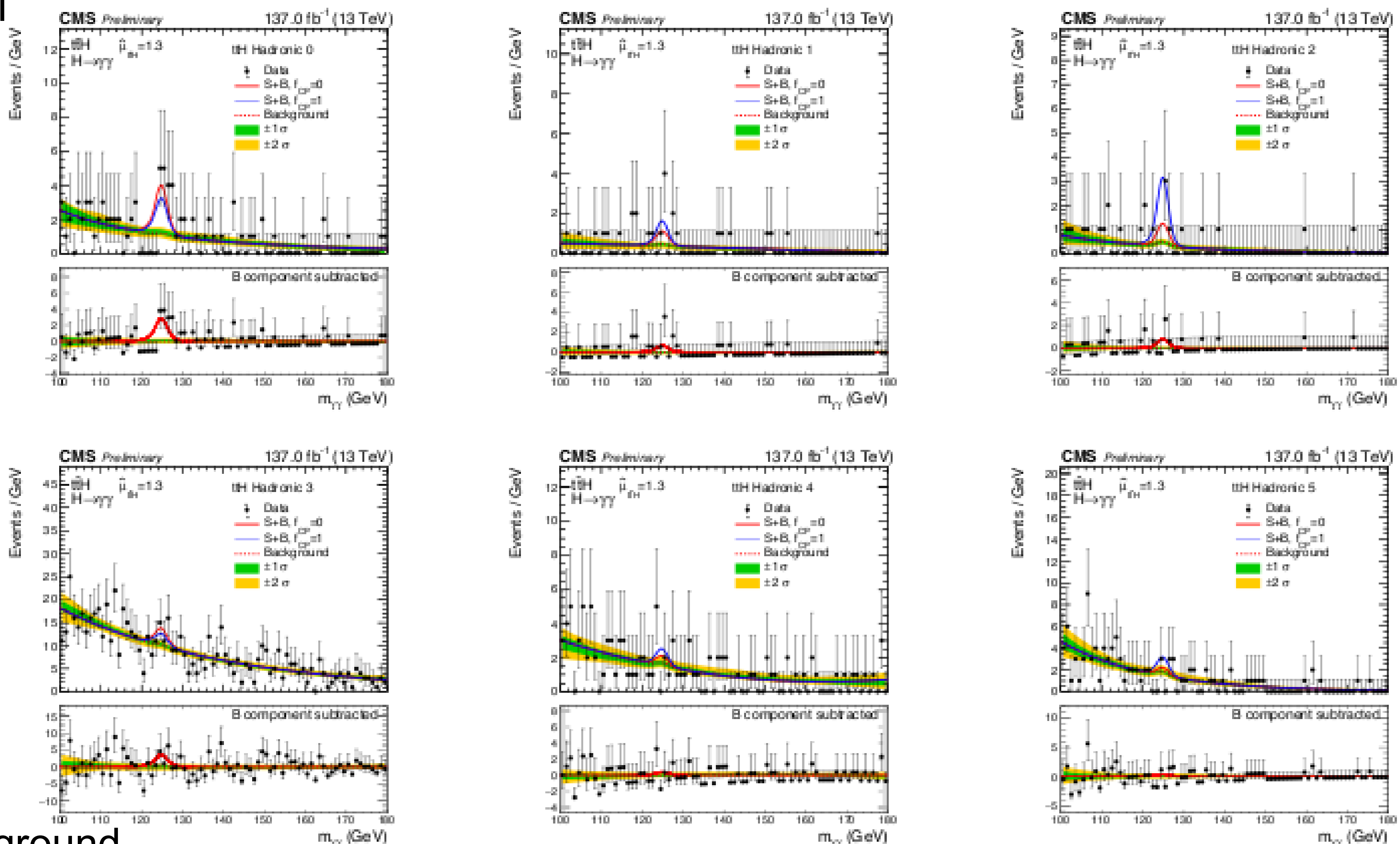
0^+ —— D_{0-} ——► 0^-

signal

▲

BDT-bkg

background

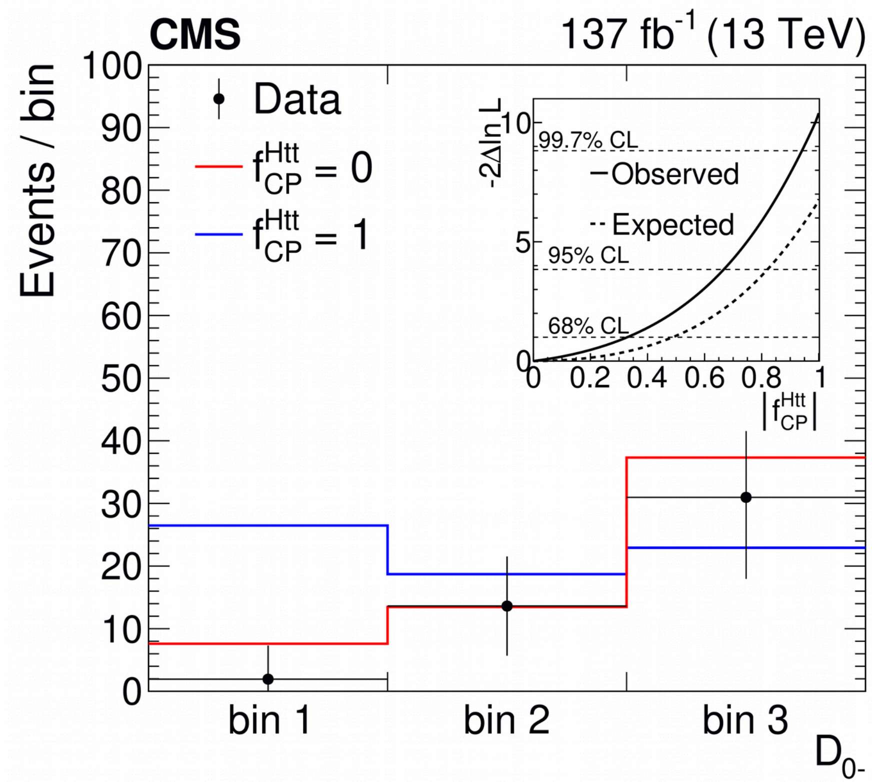


cf. CMS Collaboration, 1903.06973

Htt coupling: results

- Data agree with CP-even coupl. (0^+):
  - $|f_{CP}| = 0.00 \pm 0.32$ (exp: 0.00 ± 0.50)
  - $|f_{CP}| < 0.66$ at 95% CL (exp: <0.83)
- Pure CP-odd coupling (0^-) excluded at 3.2σ (exp: 2.5σ)
- Measured constrains tighter than expected because of signal rate above expectatioins:

$$\mu = 1.39^{+0.37}_{-0.30}$$



Number of events weighted by S/(S+B) in three bins of D_{0-}.

The leptonic and hadronic, and BDT-bkg categories combined in the mass range $115 < m_{\gamma\gamma} < 135$ GeV and the background contribution subtracted.

cf. CMS Collaboration, 1903.06973

Summary

CP violation in Higgs sector an appealing opportunity

Searches performed to date focus on HVV coupling

- Handy experimental setup thanks to purity of the $H \to 4\ell$ decay and VBF production process, and possibility to access 4-momenta of all particles

Current precision in probing CP-odd HVV coupling (wrt SM one) at $\sim 10^{-3}$ level

- Precision at $<10^{-4}$ level expected with 3/fb of HL-LHC

but no hint of CP violation observed (yet?)

First probing CP structure of Hff couplings with ttH, $H \to \gamma\gamma$ are on the place

- Fractional contribution of CP-odd component is measured to be 0.00 ± 0.33 (pure CP-odd excluded at 3.2σ)

Measurements with other decay modes and with $H \to \tau\tau$ decays using full Run-2 dataset of 137/fb are ongoing => results this Summer

THANK YOU!

HVV parametrisation (CMS)

$$A(\mathrm{HVV}) \sim \left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_1^2 + \kappa_2^{\mathrm{VV}} q_2^2}{(\Lambda_1^{\mathrm{VV}})^2}\right] m_{\mathrm{V}1}^2 \epsilon_{\mathrm{V}1}^* \epsilon_{\mathrm{V}2}^* + a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2)\mu\nu} + a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2)\mu\nu},$$

m_V, q_V, ε_V – mass, 4-momentum and polarization of V boson,

$f^{\mu\nu}=\varepsilon_V^{\mu} q^{\nu} - \varepsilon_V^{\mu\nu} q^{\mu}$ – field strength tensor

- In SM only $a_1^{ZZ}\neq0$ and $a_1^{WW}\neq0$ at tree level, assumed $a_1 \equiv a_1^{ZZ} = a_1^{WW}$
- a_3 – CP-odd => CPV via interference with CP-even
- Assuming constant and real couplings (sensible for $m_{BSM} >> m_H$) it is eqiv. to eff. Lagrangian:

$$L(\mathrm{HVV}) \sim a_1 \frac{m_Z^2}{2} \mathrm{H} Z^{\mu} Z_{\mu} - \frac{\kappa_1}{(\Lambda_1)^2} m_Z^2 \mathrm{H} Z_{\mu} \Box Z^{\mu} - \frac{1}{2} a_2 \mathrm{H} Z^{\mu\nu} Z_{\mu\nu} - \frac{1}{2} a_3 \mathrm{H} Z^{\mu\nu} \tilde{Z}_{\mu\nu}$$
$$+ a_1^{\mathrm{WW}} m_W^2 \mathrm{H} W^{+\mu} W_{\mu}^{-} - \frac{1}{(\Lambda_1^{\mathrm{WW}})^2} m_W^2 \mathrm{H} \left(\kappa_1^{\mathrm{WW}} W_{\mu}^{-} \Box W^{+\mu} + \kappa_2^{\mathrm{WW}} W_{\mu}^{+} \Box W^{-\mu}\right)$$
$$- a_2^{\mathrm{WW}} \mathrm{H} W^{+\mu\nu} W_{\mu\nu}^{-} - a_3^{\mathrm{WW}} \mathrm{H} W^{+\mu\nu} \tilde{W}_{\mu\nu}^{-}$$
$$+ \frac{\kappa_2^{Z\gamma}}{\left(\Lambda_1^{Z\gamma}\right)^2} m_Z^2 \mathrm{H} Z_{\mu} \partial_{\nu} F^{\mu\nu} - a_2^{Z\gamma} \mathrm{H} F^{\mu\nu} Z_{\mu\nu} - a_3^{Z\gamma} \mathrm{H} F^{\mu\nu} \tilde{Z}_{\mu\nu} - \frac{1}{2} a_2^{\gamma\gamma} \mathrm{H} F^{\mu\nu} F_{\mu\nu} - \frac{1}{2} a_3^{\gamma\gamma} \mathrm{H} F^{\mu\nu} \tilde{F}_{\mu\nu},$$

cf. CMS Collaboration, Phys. Rev. D 92, 012004 (2015)

Htt sig. enhancement (BDT-bkg)

- BDT discriminant (one for each topology) to distinguish ttH, H→γγ signal from background: tt+X (X=γγ, γ+jet, jets), γγ, W/Z+γ, but also H→γγ from production modes other than ttH
  - QCD background (γ+jets) in the hadronic topology estimated from collision data ("fake rate" method), other processes taken for MC simulation

BDT-bkg input features

Hadronic only Leptonic only

Category	Features		
Photon Kinematics	$\gamma_1\ p_T/m_{\gamma\gamma}$	$\gamma_1\ \eta$	γ_1 Pixel Seed Veto
	$\gamma_2\ p_T/m_{\gamma\gamma}$	$\gamma_2\ \eta$	γ_2 Pixel Seed Veto
	Max γ ID MVA	Min γ ID MVA	
Jet Kinematics	Jet 1 p_T	Jet 1 η	Jet 1 b-tag score
	Jet 2 p_T	Jet 2 η	Jet 2 b-tag score
	Jet 3 p_T	Jet 3 η	Jet 3 b-tag score
	Jet 4 p_T	Jet 4 η	Jet 4 b-tag score
	Max b-tag score	2nd max b-tag score	
	N_{jets}	H_T	
DiPhoton Kinematics	$p_T^{\gamma\gamma}/m_{\gamma\gamma}$	$Y_{\gamma\gamma}$	$\lvert\cos(\Delta\phi)_{\gamma\gamma}\rvert$
	$\Delta R_{\gamma\gamma}$	$\lvert\cos(\text{helicity angle}(\theta))\rvert$	
Lepton Kinematics	lepton p_T	lepton η	$N_{\text{leptons (tight ID)}}$
Event-level Kinematics	E_T^{miss}		
Di-photon/$t\bar{t}+\gamma\gamma$ suppression	dedicated DNNs (more on next slide)		
Top background suppression	Top tagger BDT (more on next slide)		

Improves BDT-bkg performance by ~5% (each) in terms of expected significance

ATLAS analyses

HVV parametrisation (ATLAS)

- ATLAS uses (a bit) different parametrisation of eff. Lagrangian (JHEP 11 (2013) 043)

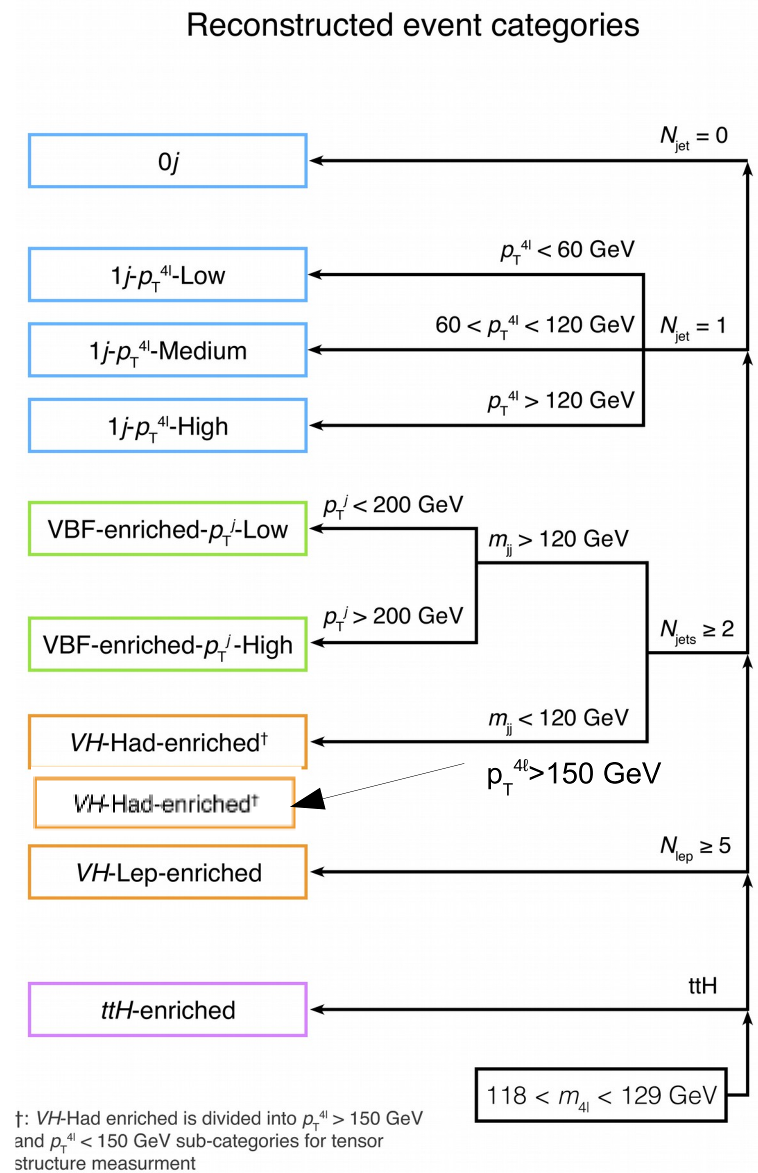
$$\mathcal{L}_0^V = \Big\{ \kappa_{SM} \Big[\frac{1}{2} g_{HZZ} Z_\mu Z^\mu + g_{HWW} W_\mu^+ W^{-\mu} \Big] \\ - \frac{1}{4} \big[\kappa_{Hgg} g_{Hgg} G_{\mu\nu}^a G^{a,\mu\nu} + \tan\alpha\, \kappa_{Agg} g_{Agg} G_{\mu\nu}^a \tilde{G}^{a,\mu\nu} \big] \\ - \frac{1}{4} \frac{1}{\Lambda} \big[\kappa_{HZZ} Z_{\mu\nu} Z^{\mu\nu} + \tan\alpha\, \kappa_{AZZ} Z_{\mu\nu} \tilde{Z}^{\mu\nu} \big] \\ - \frac{1}{2} \frac{1}{\Lambda} \big[\kappa_{HWW} W_{\mu\nu}^+ W^{-\mu\nu} + \tan\alpha\, \kappa_{AWW} W_{\mu\nu}^+ \tilde{W}^{-\mu\nu} \big] \Big\} \mathcal{X}_0$$

- $\tan\alpha\kappa_{AVV}$ (V=g,Z,W) CP-odd couplings ($=a_3^{VV}$)
- Λ cut-off energy (BSM scale), 1 TeV in this study
- Anomalous coupling assumed to be same for ZZ and WW:
  - $\kappa_{HVV} \equiv \kappa_{HZZ} = \kappa_{HWW}$, $\kappa_{AVV} \equiv \kappa_{AZZ} = \kappa_{AWW}$
- α (redundant parameter) set $\pi/4$, so that $\tan\alpha\kappa_{AVV}$ => κ_{AVV}

Probing HVV with H → 4ℓ at ATLAS

- Events divided onto 10 categories
  - cross-section measurement in phase-space regions populated by different processes
  - on-shell: $118 < m_{4\ell} < 129$ GeV
- Presence of anomalous HVV couplings will cause different event distributions across categories compared to SM

  => use event yields to probe HVV couplings
- 36.1/fb of 13TeV data used



ATLAS Collaboration, JHEP 03 (2018) 095

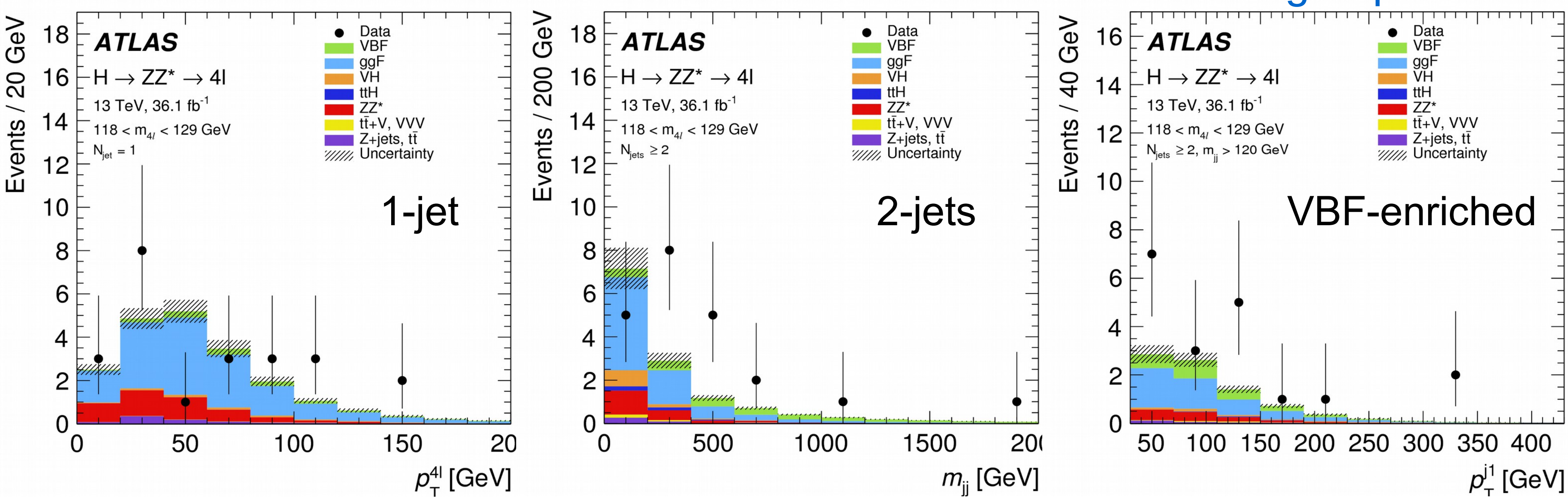
$H \rightarrow 4\ell$ event yields at ATLAS

Reconstructed event category	Signal	ZZ^* background	Other backgrounds	Total expected	Observed
$0j$	26.8 ± 2.5	13.7 ± 1.0	2.23 ± 0.31	42.7 ± 2.7	49
$1j$-$p_T^{4\ell}$-Low	8.8 ± 1.1	3.1 ± 0.4	0.53 ± 0.07	12.5 ± 1.2	12
$1j$-$p_T^{4\ell}$-Med	5.4 ± 0.7	0.88 ± 0.12	0.38 ± 0.05	6.7 ± 0.7	9
$1j$-$p_T^{4\ell}$-High	1.47 ± 0.24	0.139 ± 0.022	0.045 ± 0.007	1.65 ± 0.24	3
VBF-enriched-p_T^{j}-Low	6.3 ± 0.8	1.08 ± 0.32	0.40 ± 0.04	7.7 ± 0.9	16
VBF-enriched-p_T^{j}-High	0.58 ± 0.10	0.093 ± 0.032	0.054 ± 0.006	0.72 ± 0.10	3
VH-Had-enriched-$p_T^{4\ell}$-Low	2.9 ± 0.5	0.63 ± 0.16	0.169 ± 0.021	3.7 ± 0.5	3
VH-Had-enriched-$p_T^{4\ell}$-High	0.64 ± 0.09	0.029 ± 0.008	0.0182 ± 0.0022	0.69 ± 0.09	0
VH-Lep-enriched	0.318 ± 0.019	0.049 ± 0.008	0.0137 ± 0.0019	0.380 ± 0.020	0
ttH-enriched	0.39 ± 0.04	0.014 ± 0.006	0.07 ± 0.04	0.47 ± 0.05	0
Total	54 ± 4	19.7 ± 1.5	3.9 ± 0.5	77 ± 4	95

Excess in both VBF-enriched categories

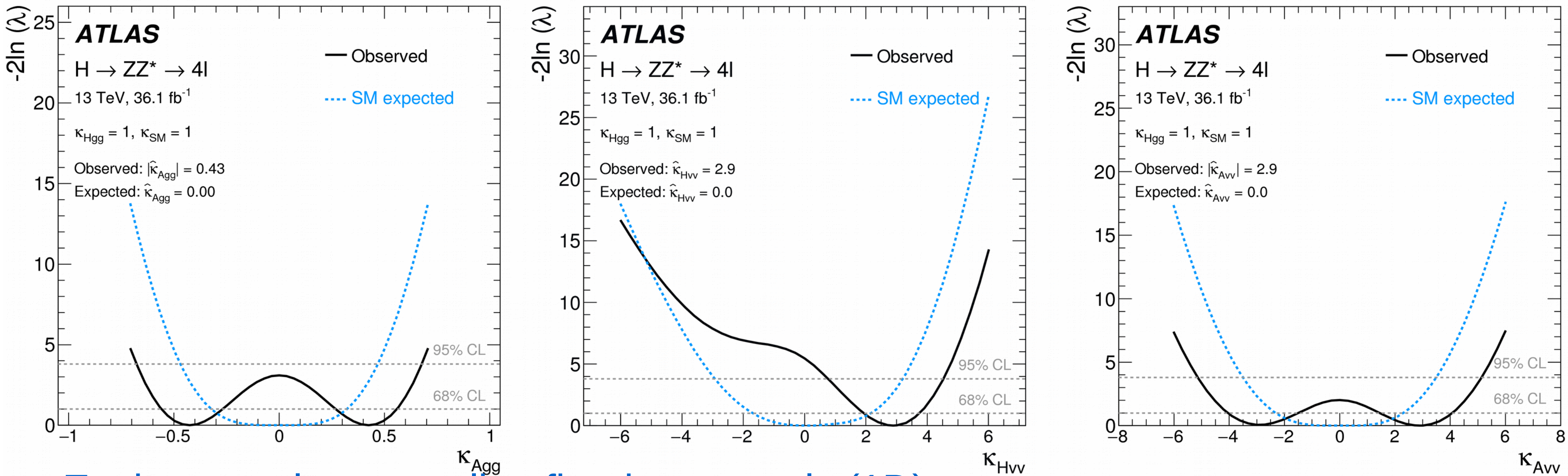
No events in 2 VH- and ttH-enriched categories

Global excess of events translating to μ=1.28



ATLAS Collaboration, JHEP 03 (2018) 095

ATLAS 1D results



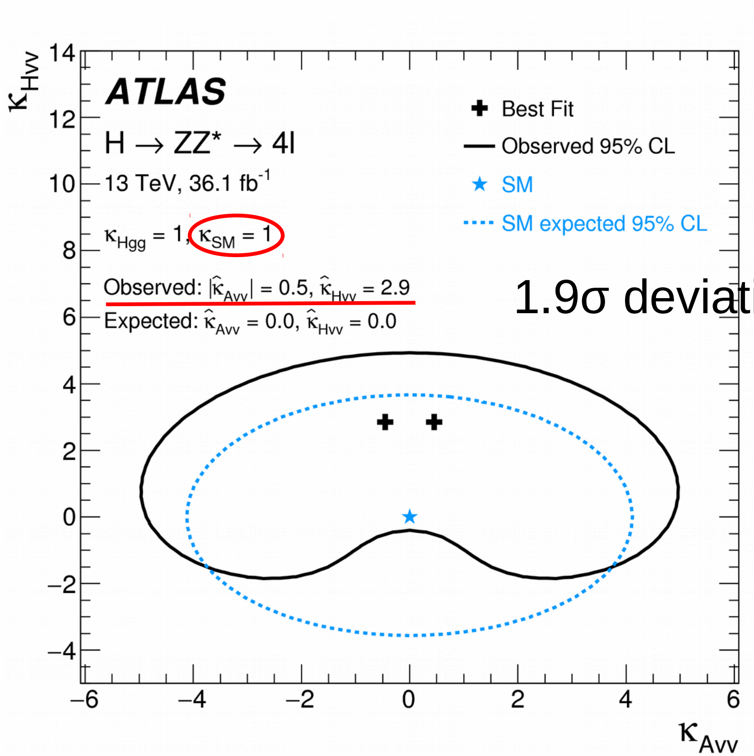
- Each anomalous coupling fitted separately (1D)
- Excess of events results on no-zero central values of BSM couplings
  - esp. when κ_{SM} fixed at 1

95%CL

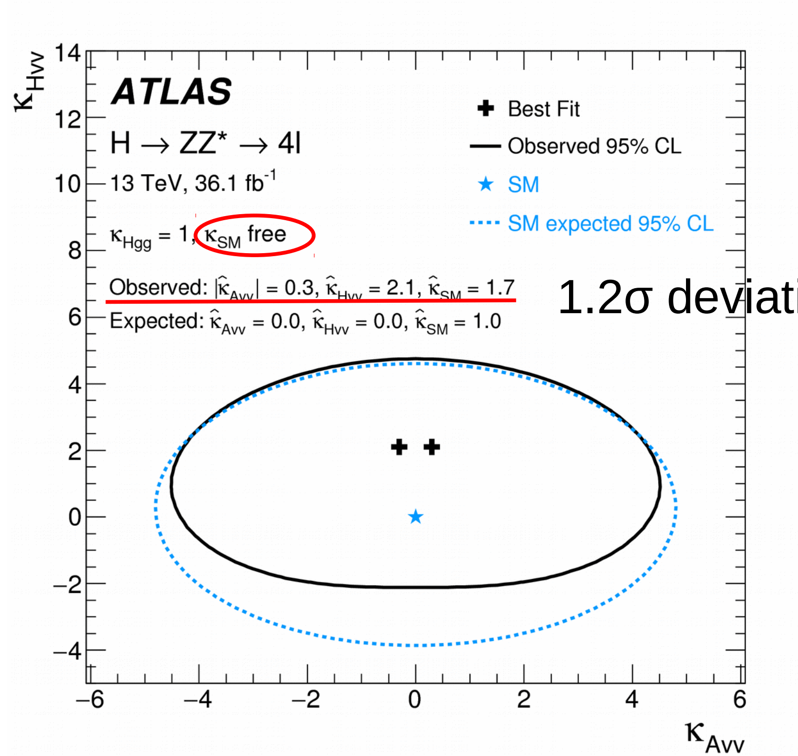
BSM coupling $\kappa_{\rm BSM}$	Fit configuration	Expected conf. inter.	Observed conf. inter.	Best-fit $\hat{\kappa}_{\rm BSM}$	Best-fit $\hat{\kappa}_{\rm SM}$	Deviation from SM
κ_{Agg}	$(\kappa_{Hgg}=1,\ \kappa_{\rm SM}=1)$	$[-0.47, 0.47]$	$[-0.68, 0.68]$	± 0.43	-	1.8σ
κ_{HVV}	$(\kappa_{Hgg}=1,\ \kappa_{\rm SM}=1)$	$[-2.9, 3.2]$	$[0.8, 4.5]$	2.9	-	2.3σ
κ_{HVV}	$(\kappa_{Hgg}=1,\ \kappa_{\rm SM}\ \text{free})$	$[-3.1, 4.0]$	$[-0.6, 4.2]$	2.2	1.2	1.7σ
κ_{AVV}	$(\kappa_{Hgg}=1,\ \kappa_{\rm SM}=1)$	$[-3.5, 3.5]$	$[-5.2, 5.2]$	± 2.9	-	1.4σ
κ_{AVV}	$(\kappa_{Hgg}=1,\ \kappa_{\rm SM}\ \text{free})$	$[-4.0, 4.0]$	$[-4.4, 4.4]$	± 1.5	1.2	0.5σ

ATLAS Collaboration, JHEP 03 (2018) 095

ATLAS 2D results



1.9σ deviation



1.2σ deviation

- The best-fit values of κ_{HVV} similar to the ones for 1D-fit, while one of κ_{AVV} are closer to SM prediction
- Overall agreement with SM within 2σ

ATLAS Collaboration, JHEP 03 (2018) 095

CP via VBF H→ττ (ATLAS)

- Parametrisation eff. Lagrangian used in measurement VBF H→ττ:

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \tilde{g}_{HAA} H \tilde{A}_{\mu\nu} A^{\mu\nu} + \tilde{g}_{HAZ} H \tilde{A}_{\mu\nu} Z^{\mu\nu} + \tilde{g}_{HZZ} H \tilde{Z}_{\mu\nu} Z^{\mu\nu} + \tilde{g}_{HWW} H \tilde{W}^{+}_{\mu\nu} W^{-\mu\nu}$$

  which can be expressed using two dimensionless couplings:

$$\tilde{g}_{HAA} = \frac{g}{2m_W}(\tilde{d}\sin^2\theta_W + \tilde{d}_B\cos^2\theta_W) \qquad \tilde{g}_{HAZ} = \frac{g}{2m_W}\sin 2\theta_W(\tilde{d} - \tilde{d}_B)$$

$$\tilde{g}_{HZZ} = \frac{g}{2m_W}(\tilde{d}\cos^2\theta_W + \tilde{d}_B\sin^2\theta_W) \qquad \tilde{g}_{HWW} = \frac{g}{m_W}\tilde{d},$$

- Different processes in VBF cannot be distinguished
  => arbitrary choice of $\tilde{d} = \tilde{d}_B$
  => $\tilde{g}_{HAA} = \tilde{g}_{HZZ} = \frac{1}{2}\tilde{g}_{HWW} = \frac{g}{2m_W}\tilde{d}$ and $\tilde{g}_{HAZ} = 0$

ATLAS Collaboration, ATLAS-CONF-2019-050

CP via VBF H→ττ: optimal obs.

$$\mathcal{M} = \mathcal{M}_{\text{SM}} + \tilde{d} \cdot \mathcal{M}_{\text{CP-odd}}$$

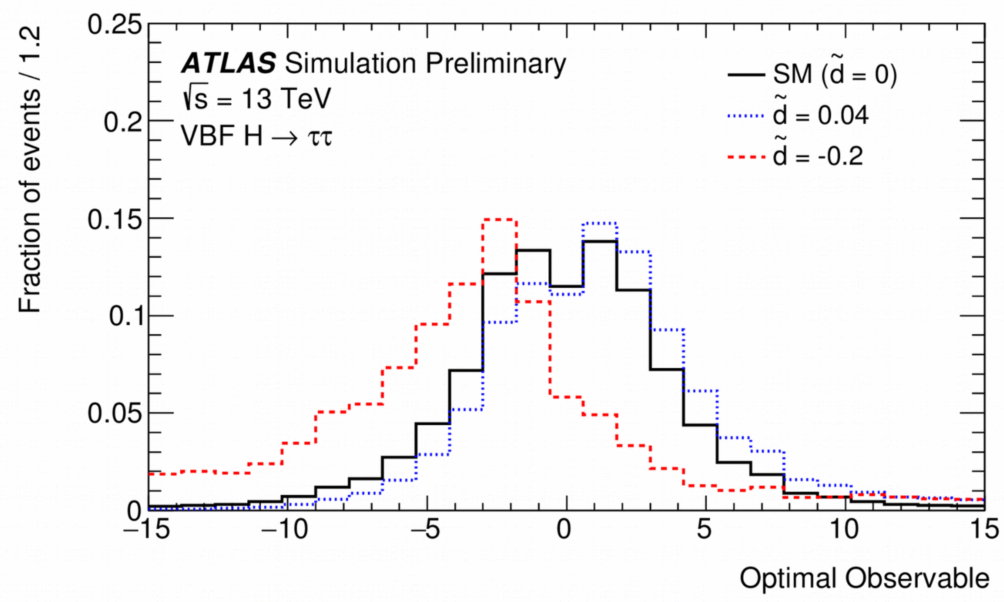
$$|\mathcal{M}|^2 = |\mathcal{M}_{\text{SM}}|^2 + \tilde{d} \cdot 2\,\text{Re}(\mathcal{M}^*_{\text{SM}} \mathcal{M}_{\text{CP-odd}}) + \tilde{d}^2 \cdot |\mathcal{M}_{\text{CP-odd}}|^2$$

=> Optimal observable

$$\mathcal{OO} = \frac{2\,\text{Re}(\mathcal{M}^*_{\text{SM}} \mathcal{M}_{\text{CP-odd}})}{|\mathcal{M}_{\text{SM}}|^2}$$

- full phase-space information in 1d observable for small $\tilde{d}$
- $\langle OO \rangle \neq 0$: sign of CPV (neglecting rescattering effects)

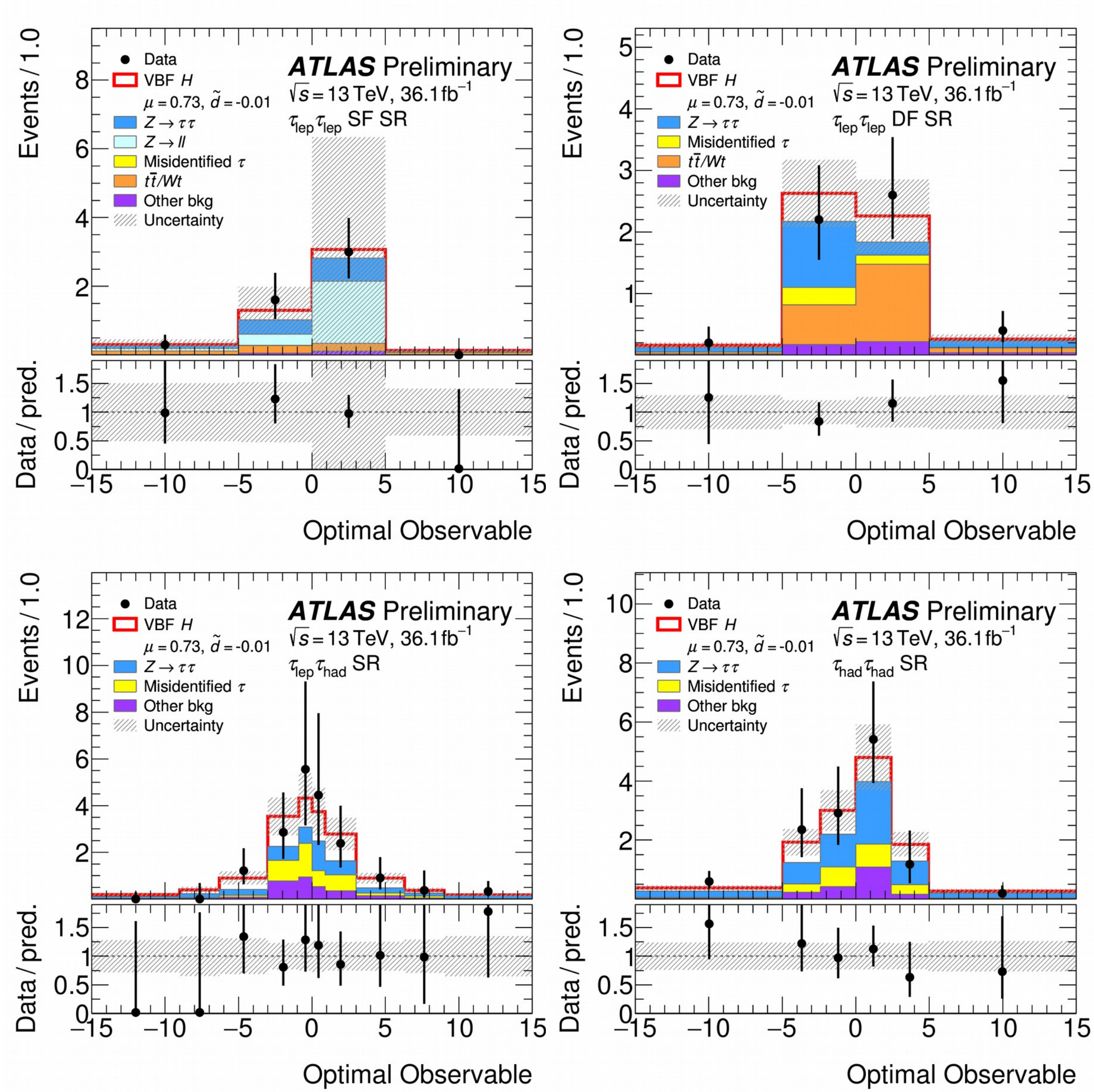
- *OO* computed using ME from HAWK using
  - 4-momenta of 2 tagging jets
  - 4-momentum of H, i.e. ττ system (estimated with MMC)



ATLAS Collaboration, ATLAS-CONF-2019-050

CP via VBF H→ττ: *OO* distributions

- All possible decay modes used: ℓℓ SF, ℓℓ DF, $\ell\tau_h$, $\tau_h\tau_h$



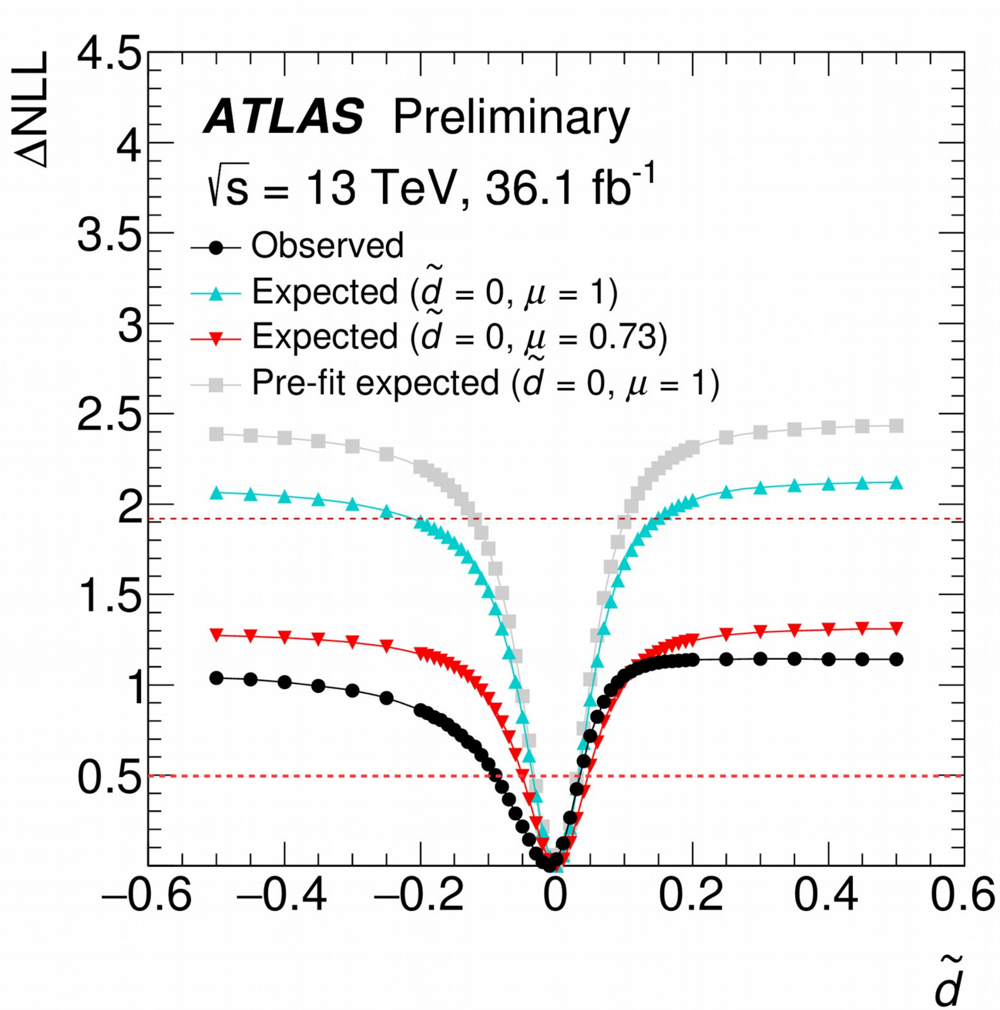
- VBF events selected with dedicated BDTs
(on top of loose preselection)

- Observed mean values of *OO* consistent with SM (<*OO*>=0)
=> no evidence of CPV

Channel	⟨Optimal Observable⟩
$\tau_{lep}\tau_{lep}$ SF	-0.54 ± 0.72
$\tau_{lep}\tau_{lep}$ DF	0.71 ± 0.81
$\tau_{lep}\tau_{had}$	0.74 ± 0.78
$\tau_{had}\tau_{had}$	-1.13 ± 0.65
Combined	-0.19 ± 0.37

ATLAS Collaboration, ATLAS-CONF-2019-050

CP via VBF H → ττ: results



- Value of d˜ obtained with max-likelihood (simultaneously in 4 final states and 7 control regions)

	expected ($\mu = 1$)	observed
68 % CL	[−0.035, 0.033]	[−0.090, 0.035]
95 % CL	[−0.21, 0.15]	-

- Best fit, d˜= -0.01 with signal strength μ = 0.73

  Consistent with SM => no evidence of CPV

  - Observed looser than expected due to event yields smaller than expected (μ=0.73)

ATLAS Collaboration, ATLAS-CONF-2019-050

ATLAS – CMS comparison

- Comparing expressions for eff. Lagrangians one gets

$$f_3 = \frac{|\tilde{d}|^2}{\frac{\sigma_3}{\sigma_1} + |\tilde{d}|^2} \text{ and } \cos(\varphi_3) = sgn(\tilde{d})$$

and

$$\tilde{d} = \frac{v}{4\Lambda} \hat{\kappa}_{AVV} \equiv \frac{v}{4\Lambda} \frac{\kappa_{AVV}}{\kappa_{SM}}$$

This allows to compare sensitivity of different measurements, e.g. expressed as sgn f_3 (some differences in assumption and meaning of exp.)

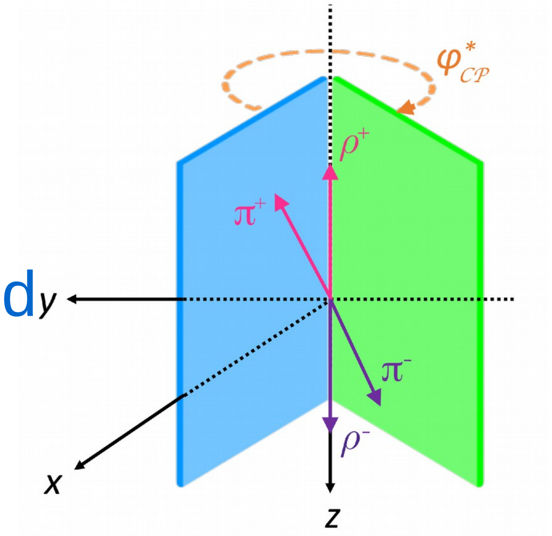
Process	Exp. 68% CL (10^{-3})	Exp. 95% CL (10^{-3})	Obs. 68% CL (10^{-3})	Obs. 95% CL (10^{-3})
$H \to 4\ell + \tau\tau$ (CMS)	[-0.23, 0.23]	[-1.2, 1.2]	[-0.27, 0.27]	[-92, 14]
$H \to 4\ell$ (ATLAS)	[-3.5, 3.5]	[-18.3, 18.3]	not provided	[-8.2, 8.2]
$H \to \tau\tau$ (ATLAS)	[-0.19, 0.017]	[-6.9, 6.7]	[-1.27, 0.19]	not excluded

Testing Yukawa coupling with $H \rightarrow \tau\tau$ at HL-LHC with ATLAS

CP in H $\rightarrow\tau\tau$ decay: observables

Directions of the tau hadronic decay products maintain strong correlation to the tau spin direction – several options to exploit:

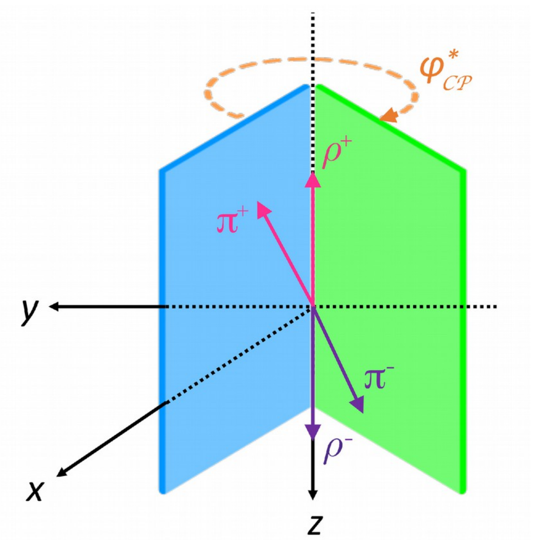
- Correlation between planes defined by charged and neutral pions in $\tau^{\pm}\rightarrow\rho^{\pm}\nu\rightarrow\pi^{\pm}\pi^{0}\upsilon$ decay
  - Br~25%
  - Quantities measured with reasonable precision
  - **Used in the following study**
- Correlation between planes with fully reconstructed $\tau^{\pm}\rightarrow a_1^{\pm}\nu\rightarrow\pi^{\pm}\pi^{\pm}\pi^{\pm}\upsilon$ decay
  - Br~10%
  - Usage of PV, SV and kin. fit
- Correlation between planes with charged particle and its IP (1-prong decays incl. leptonic ones)
  - High resolution of PV and IP required
- Combinations of planes defined in above ways



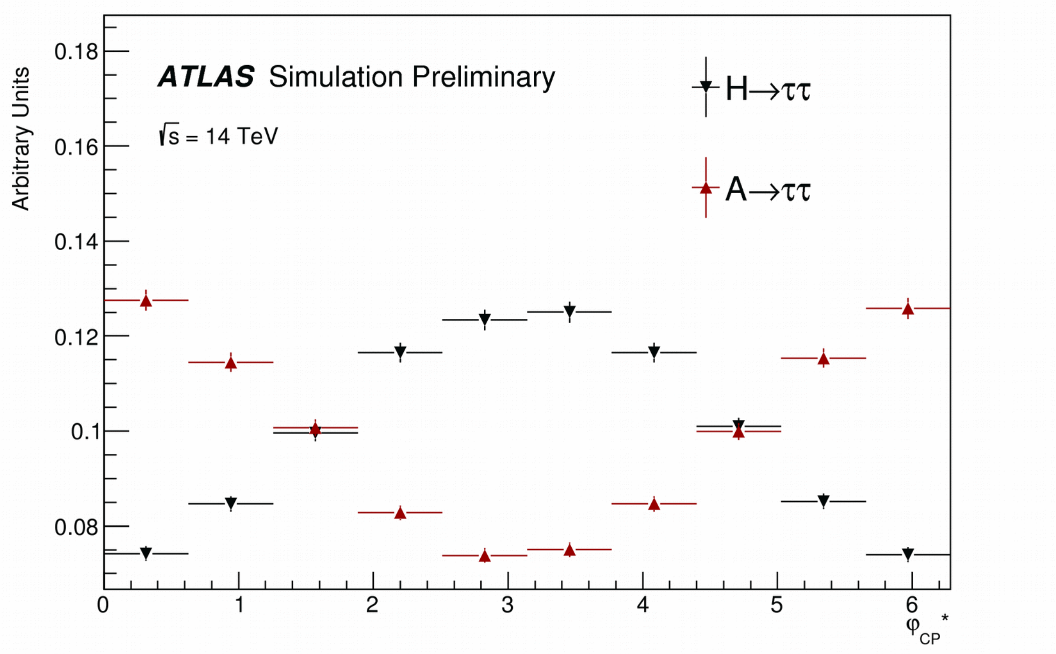
ATLAS Collaboration, ATL-PHYS-PUB-2019-008

CP in H → ττ decay: observable

- Correlation between planes defined by charged and neutral pions in $\tau^{\pm} \rightarrow \rho^{\pm}\nu \rightarrow \pi^{\pm}\pi^{0}\upsilon$ decay
  - Br~25% (=> ~6% of H → ττ)
  - Quantities measured with reasonable precision



Generator Level



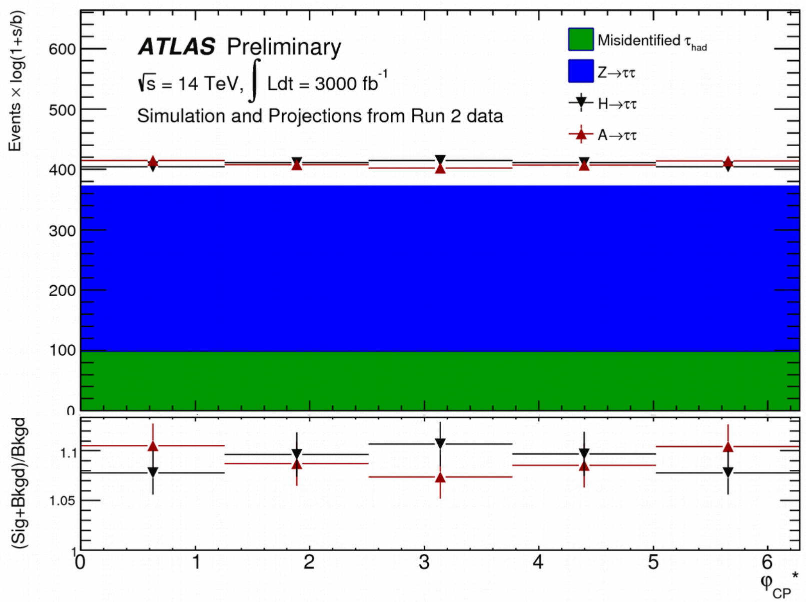
ATLAS Collaboration, ATL-PHYS-PUB-2019-008

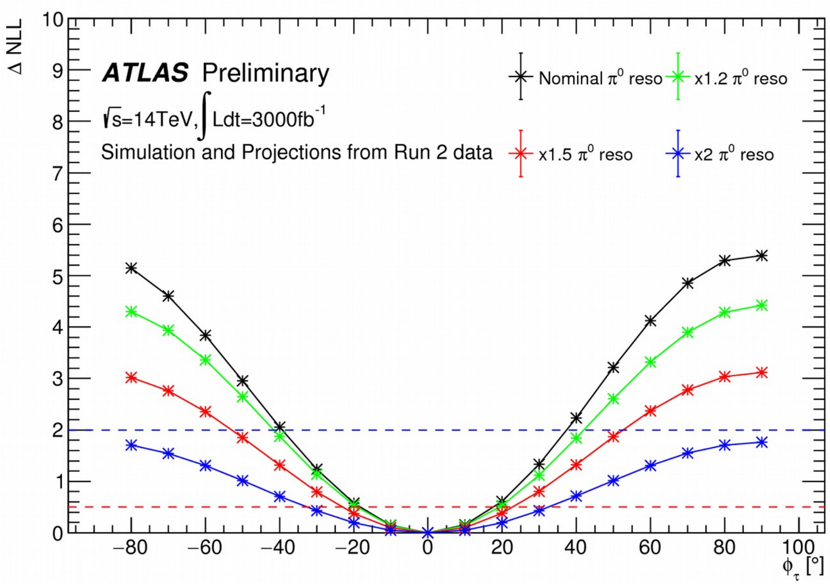
CP in H $\rightarrow \tau\tau$ decay: extrapolation

- Prospect study based on the H $\rightarrow \tau\tau$ cross-section measurements with 36.1/fb at 13 TeV data (ATLAS: Phys. Rev. D 99 (2019), 072001)
  - Signal events produced at 14 TeV with smeared $\pi^{\pm}$ and π^{0} resolutions
  - Background assumed to be flat
    - Proven for irreducible Z $\rightarrow \tau\tau$
    - No reason for correlations in background with fakes taus
  - Same event selection as in 13TeV analysis
  - Events yields extrapolated from 13TeV
    - Required both taus with reconstructed $\pi^{\pm}$ and π^{0}, and $100 < m_{\tau\tau} < 140$ GeV
    - yields scaled by 3000/36.1 = 83.1 and the x-sec 13 $\rightarrow$ 14 TeV

ATLAS Collaboration, ATL-PHYS-PUB-2019-008

CP in H $\rightarrow \tau\tau$ decay: results





- Mixing angle can be measured at 68% CL with statistical precision of:
  - 18° with nominal (expected) π^0 resolution
  - 33° with π^0 resolution twice worse than nominal one
- Pure CP-odd coupling can be excluded at 95% CL even with π^0 resolution 1.5 time worse than nominal one

ATLAS Collaboration, ATL-PHYS-PUB-2019-008