Overview of Higgs CPV searches

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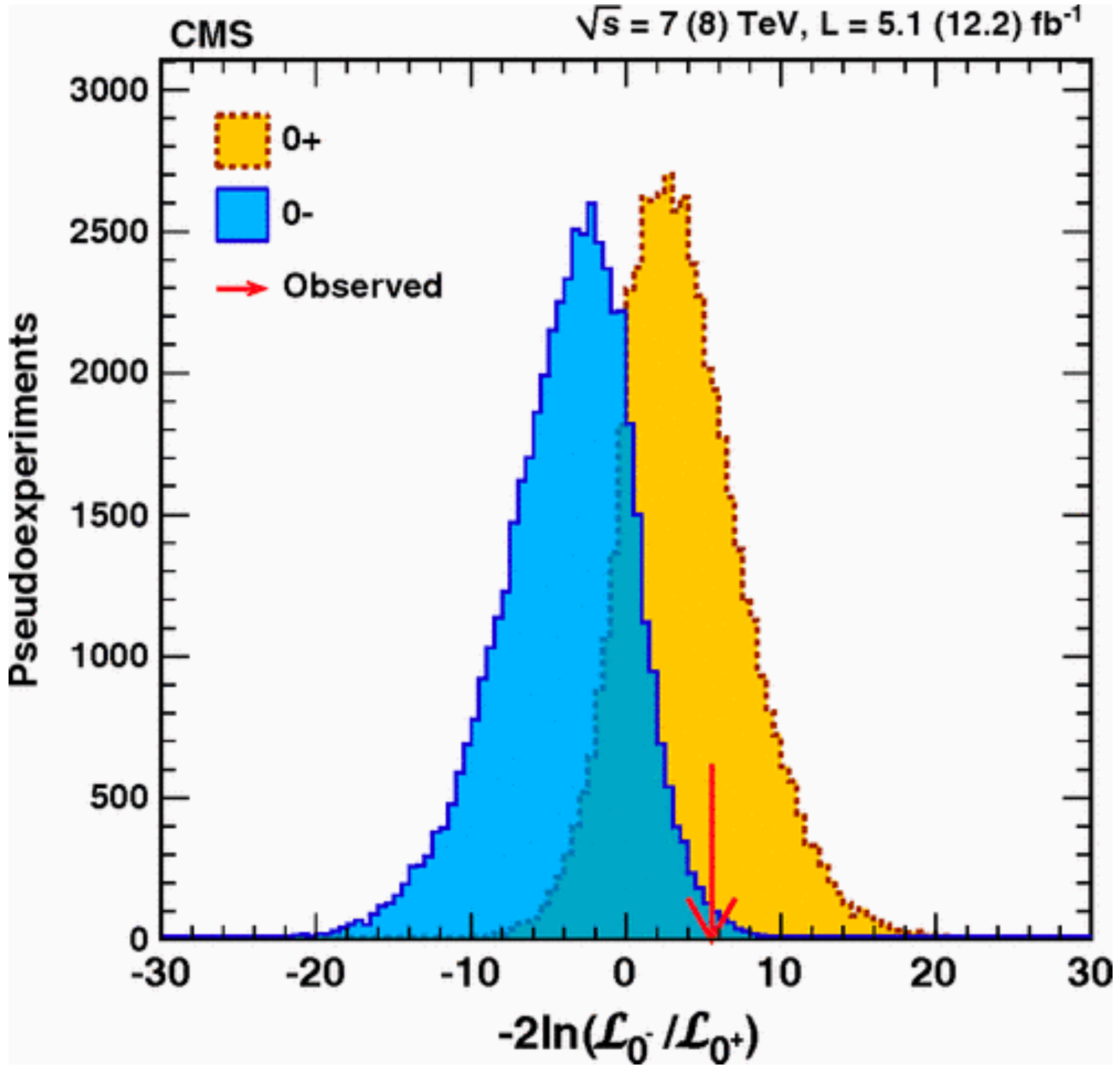
2026.1.31, 味物理前沿研讨会暨味物理讲座100期特别活动

CP violation in Higgs coupling

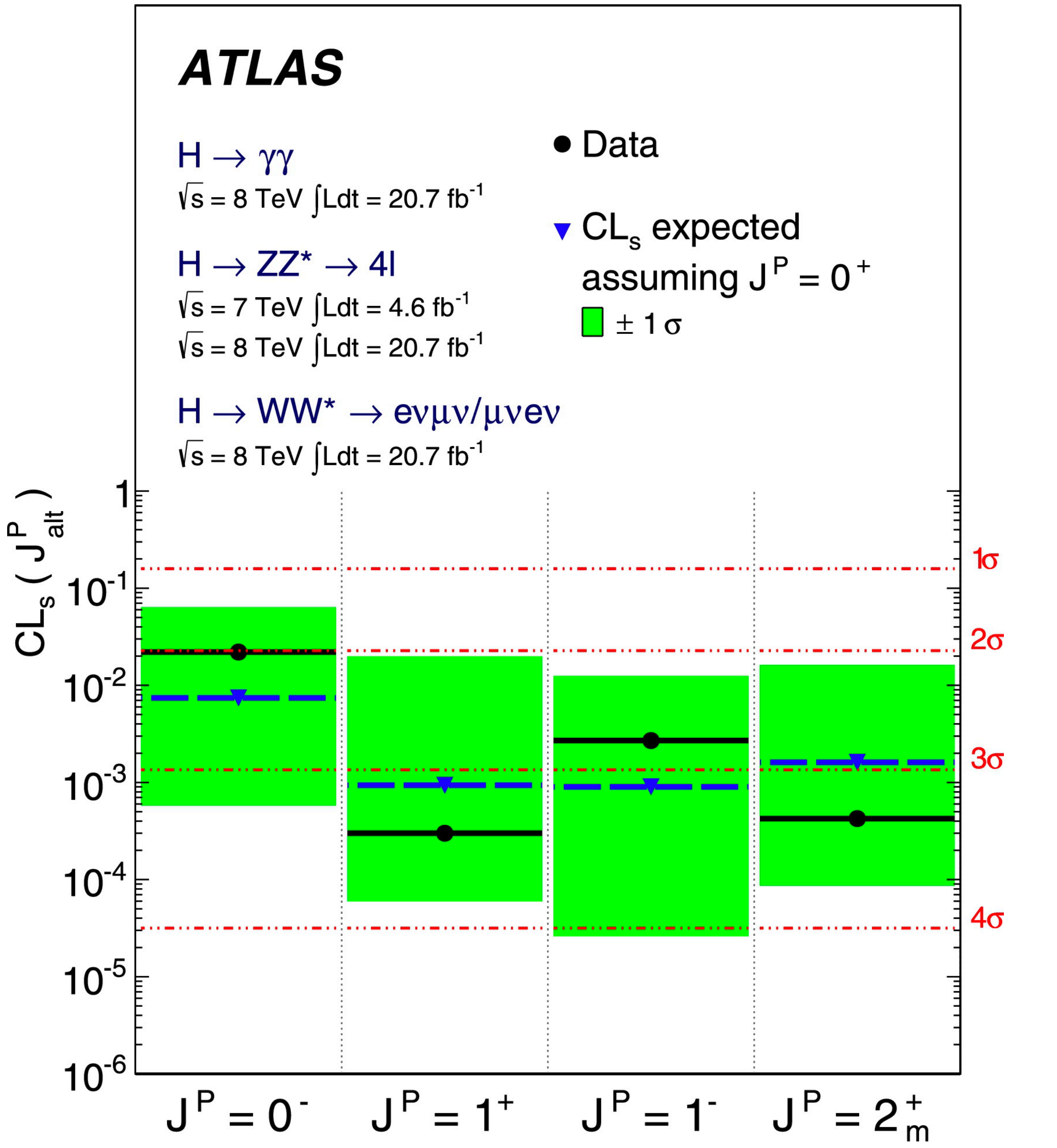
- CP violation is vital to matter anti-matter asymmetry
- Many fronts
  - Neutrino, hadron decays, EDM
- CPV in the Higgs sector
  - Theory: electroweak baryogensis

Higgs CP property

- CP is one of the first measured properties of the Higgs
- Higgs: the only scalar in the SM => CP even and conserving
- Pure CP odd state with HVV coupling was excluded with Run1 data
- What about CPV?



Phys. Rev. Lett. 110 (2013) 081803



Phys. Lett. B 726 (2013) 120

Where to look in Higgs sector

CPV: Non-zero CP-even and CP-odd eigenstate

Vector bosons

$$A(\mathrm{HVV}) = \underbrace{\frac{1}{v} a_1^{VV} m_V^2 \epsilon^*_{V_1} \epsilon^*_{V_2}}_{\text{CP-even}} + \underbrace{\frac{1}{v} a_3^{VV} f^{*(1)}_{\mu\nu} \tilde{f}^{*(2),\mu\nu}}_{\text{CP-odd}}$$

- Higer order, suppressed xsec
- 10% mixture, CP-odd xsec fraction 10^{-5}
- Seems like mission impossible, but
- More pronounced in high energy
  - VBF, VH, off-shell, high pT..

Fermions

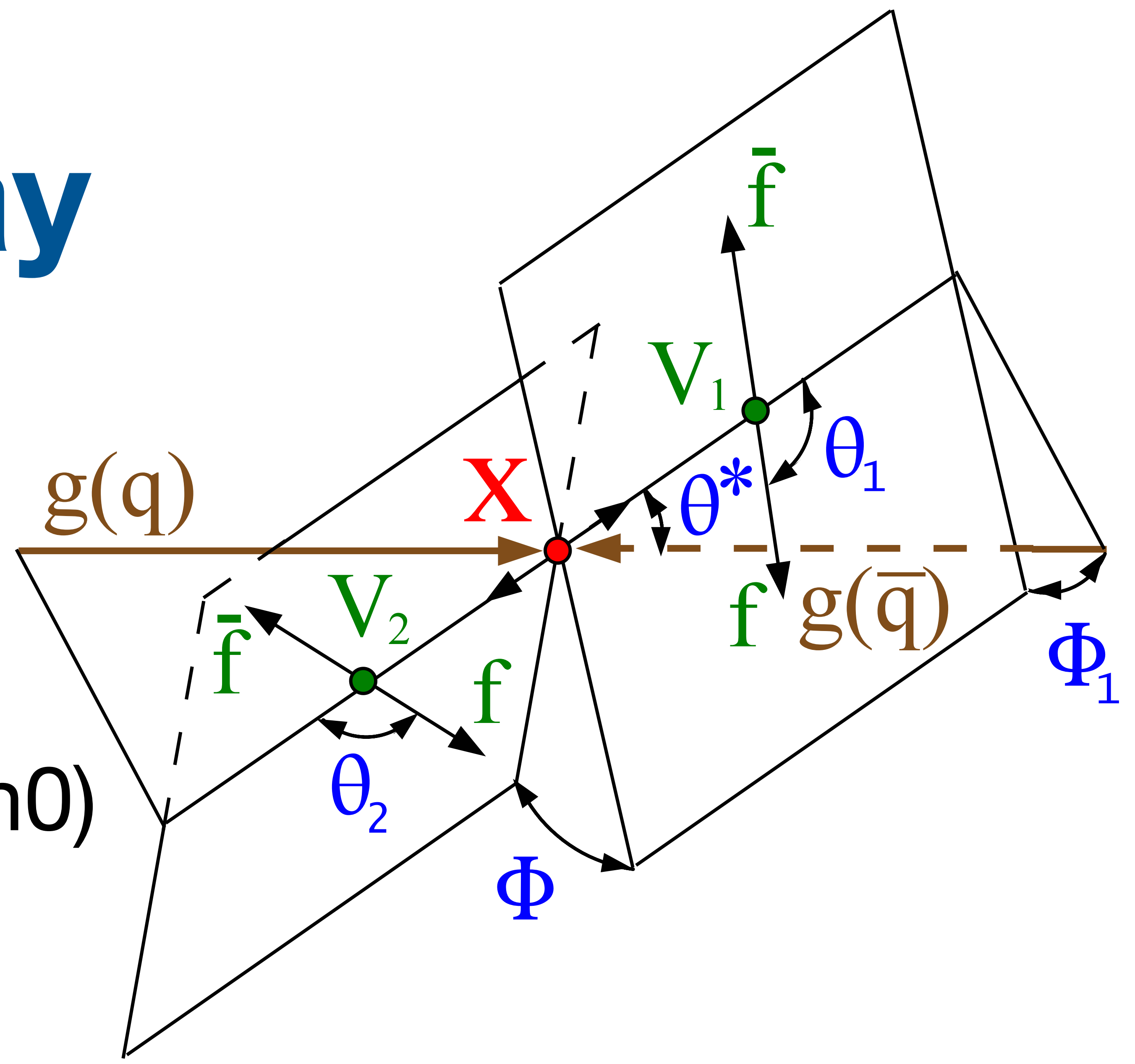
$$A(H \to f\bar{f}) = \frac{m_f}{v} \bar{u}_2 \left(\underbrace{b_1^{Hf\bar{f}}}_{\text{CP-even}} + \underbrace{i b_2^{Hf\bar{f}} \gamma_5}_{\text{CP-odd}} \right) u_1$$

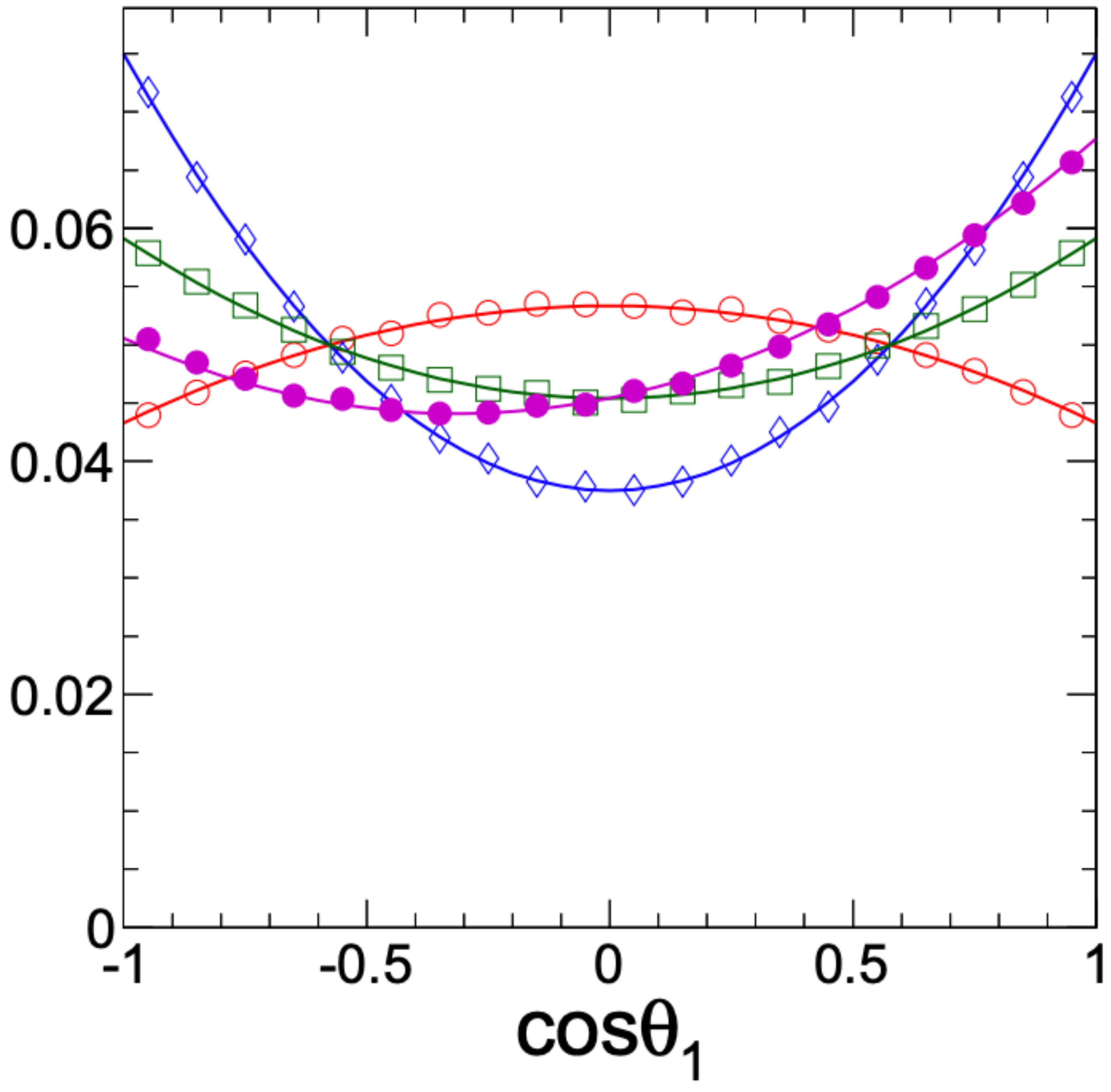
- Same order, similar xsec
- 10% mixture, CP-odd xsec fraction 10^{-2}

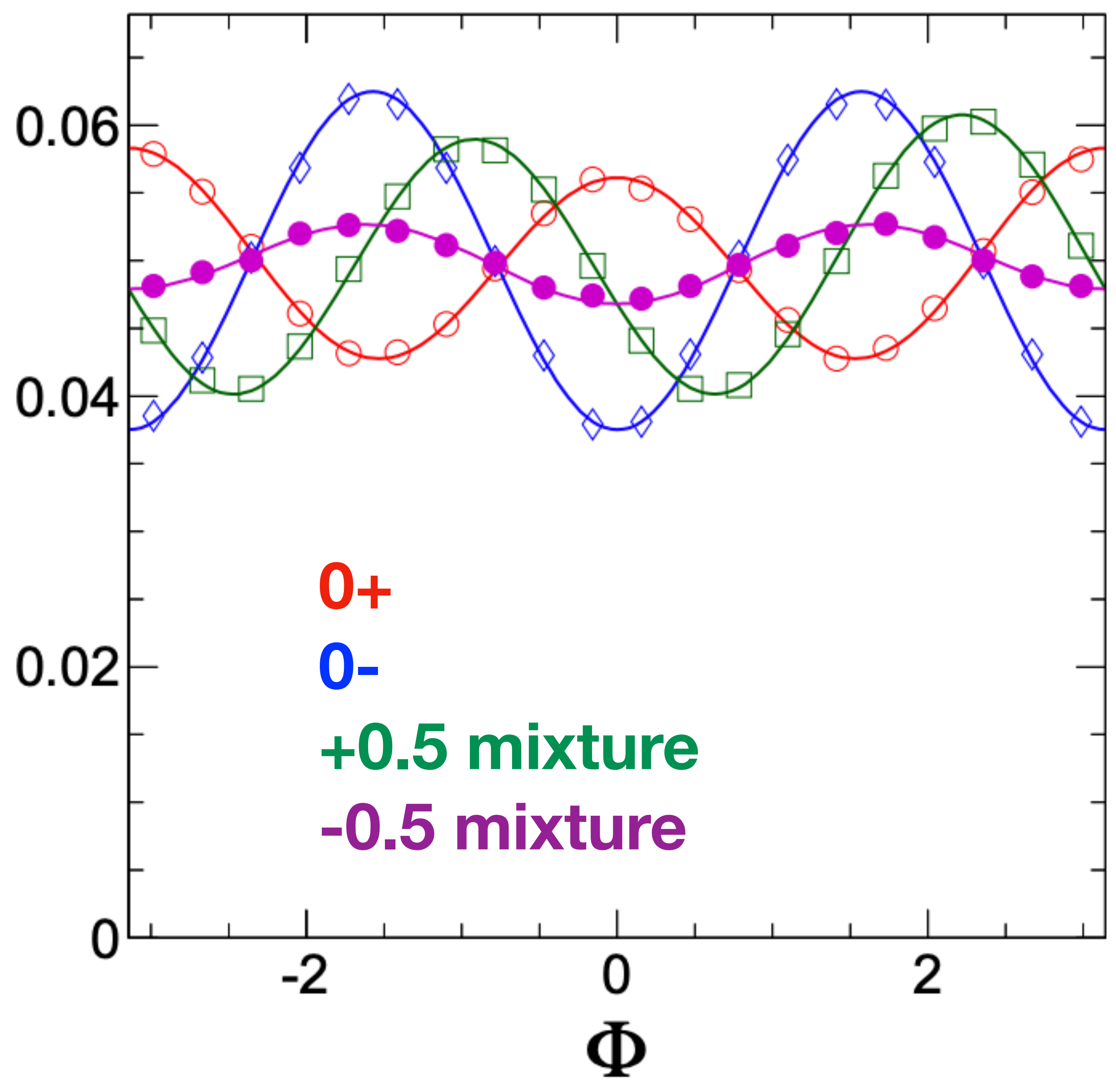
Measuring CP in HVV decay

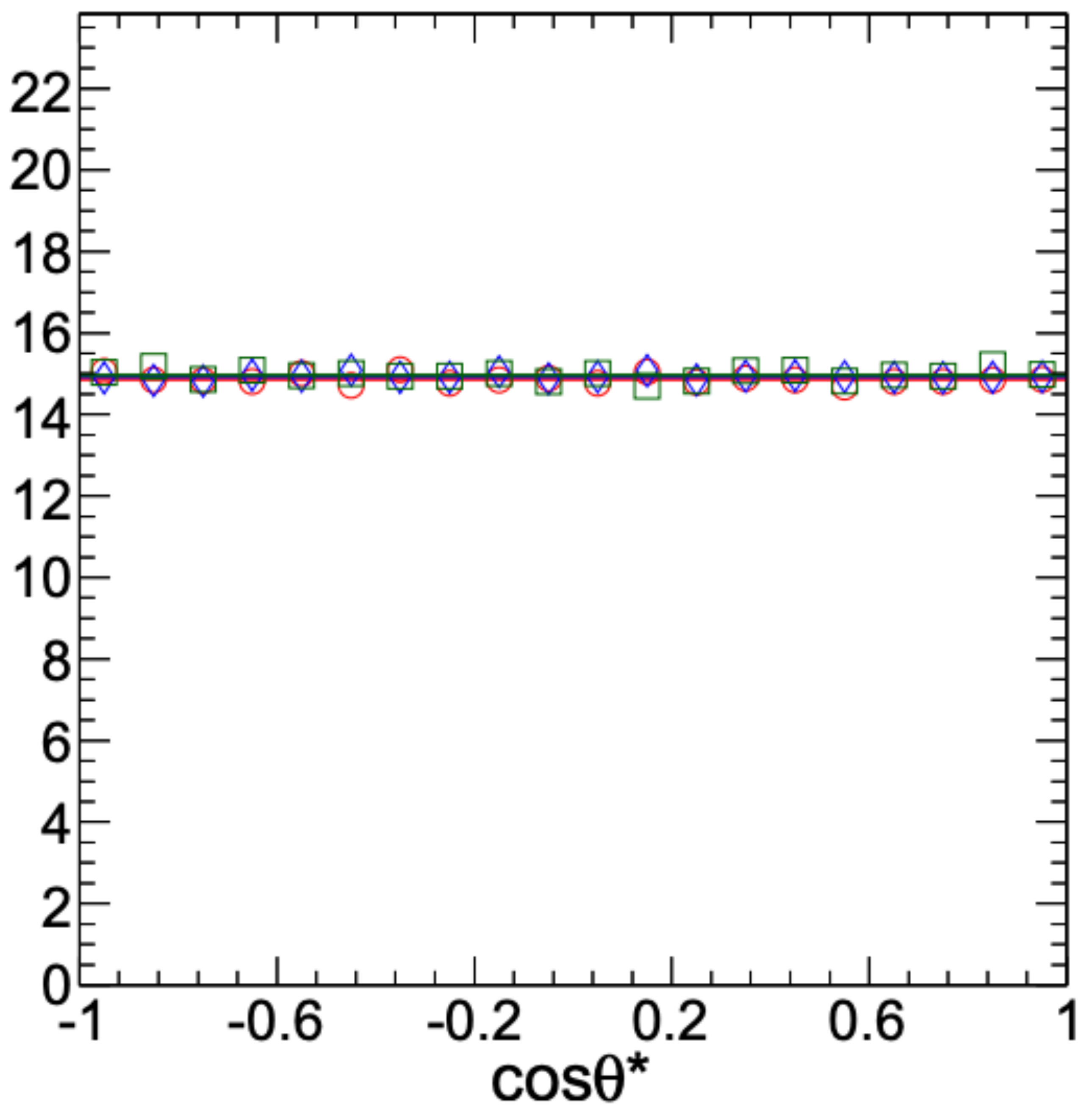
arXiv: 1208.4018
arXiv: 1309.4819

- H first observation in HVV channels
- General HVV decay, angles sensitive to CP
- If V doesn't further decay, no sensitive info (spin0)
- H→ ZZ→ 4l a natural choice



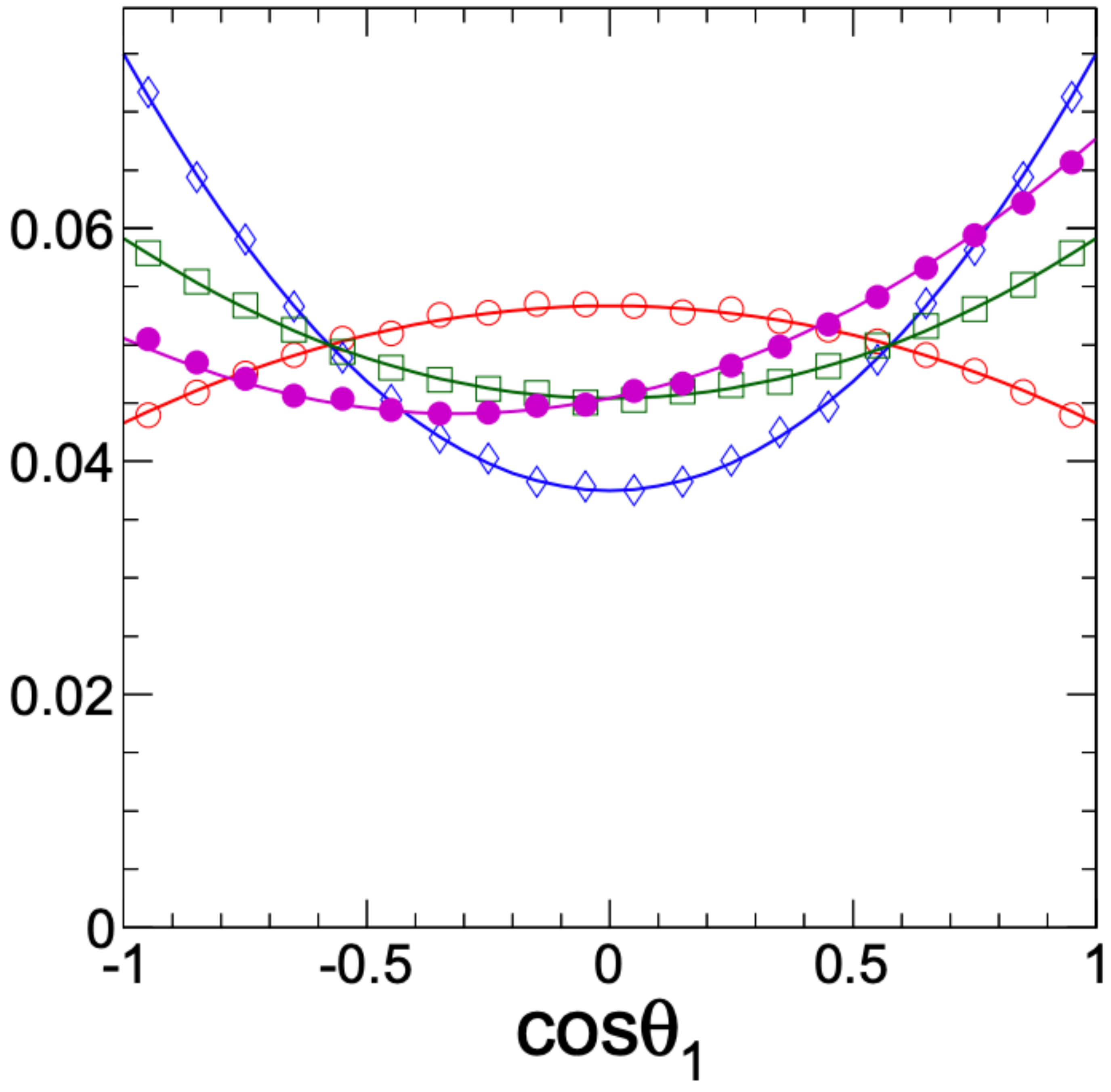






Measuring CP in HVV decay

- In principle, 5 angles + 3 invariant masses could be analytically written for 0+ and 0-
- In reality, a 8-dimensional fit requires efficiency, resolution convolution, CPU-consuming



$$
\frac{\mathcal{N}_J\, d\Gamma_J(m_1, m_2, \cos\theta^*, \Psi, \cos\theta_1, \cos\theta_2, \Phi)}{d\cos\theta^* d\Psi d\cos\theta_1 d\cos\theta_2 d\Phi} =
$$

$$
\begin{aligned}
F^J_{0,0}(\theta^*) \times \Big[& 4\,|A_{00}|^2 \, \sin^2\theta_1 \sin^2\theta_2 \\
& + |A_{++}|^2 \left(1 + 2A_{f_1}\cos\theta_1 + \cos^2\theta_1\right)\left(1 + 2A_{f_2}\cos\theta_2 + \cos^2\theta_2\right) \\
& + |A_{--}|^2 \left(1 - 2A_{f_1}\cos\theta_1 + \cos^2\theta_1\right)\left(1 - 2A_{f_2}\cos\theta_2 + \cos^2\theta_2\right) \\
& + 4|A_{00}||A_{++}|(A_{f_1} + \cos\theta_1)\sin\theta_1(A_{f_2} + \cos\theta_2)\sin\theta_2\cos(\Phi + \phi_{++}) \\
& + 4|A_{00}||A_{--}|(A_{f_1} - \cos\theta_1)\sin\theta_1(A_{f_2} - \cos\theta_2)\sin\theta_2\cos(\Phi - \phi_{--}) \\
& + 2|A_{++}||A_{--}|\sin^2\theta_1\sin^2\theta_2\cos(2\Phi - \phi_{--} + \phi_{++})\Big]
\end{aligned}
$$

CP sensitive observables

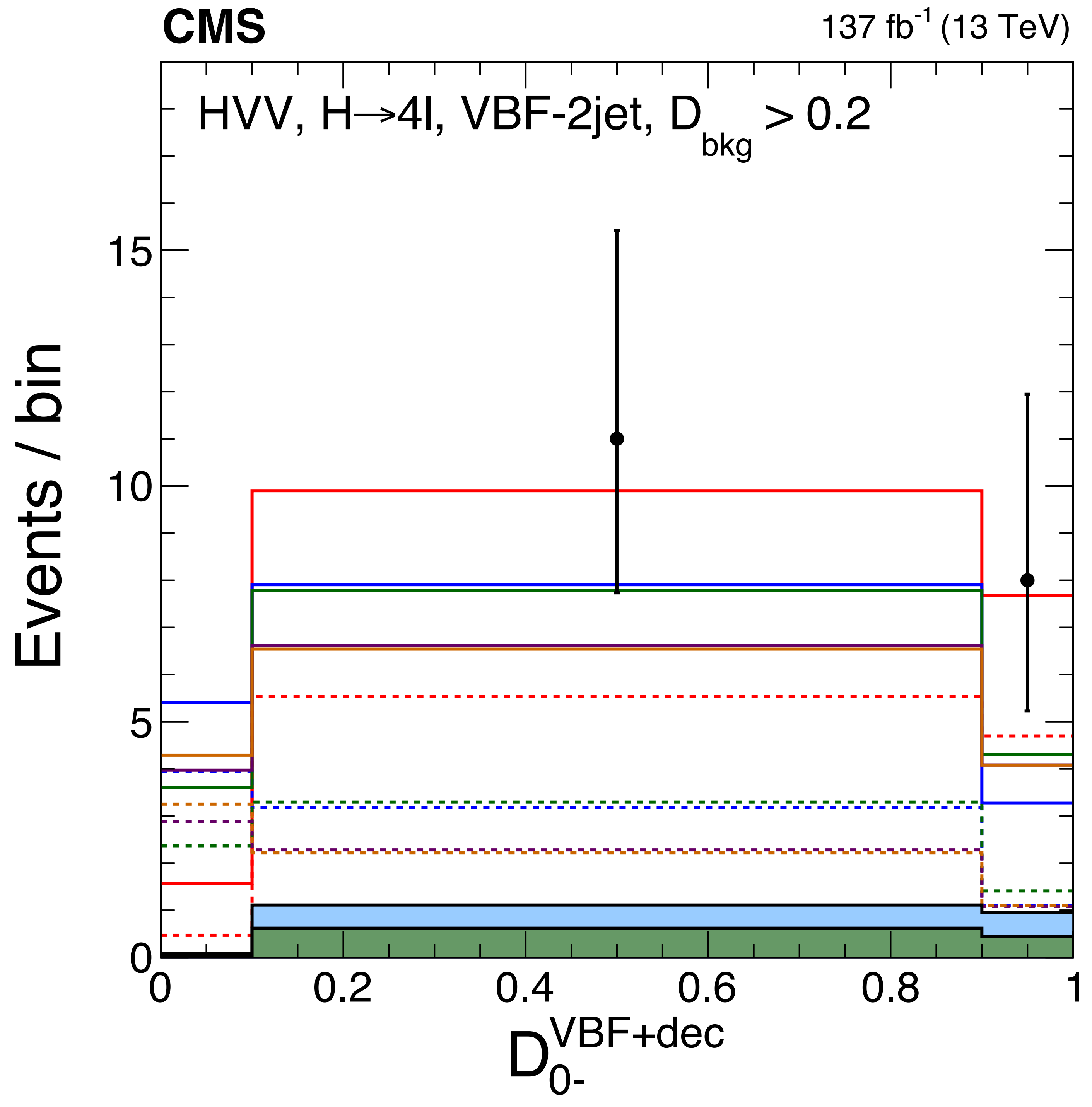
CP-even vs CP-odd

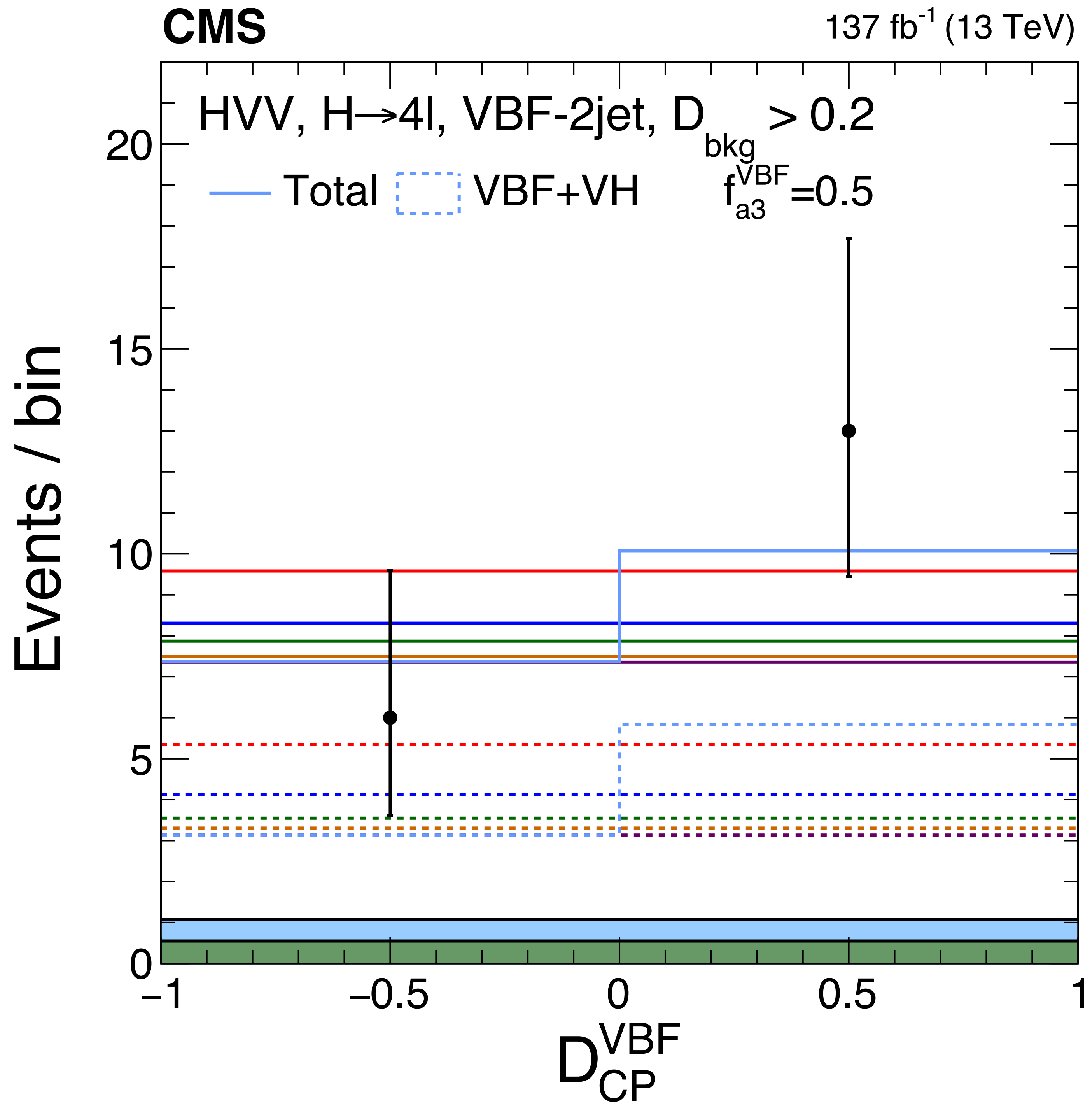
CPV

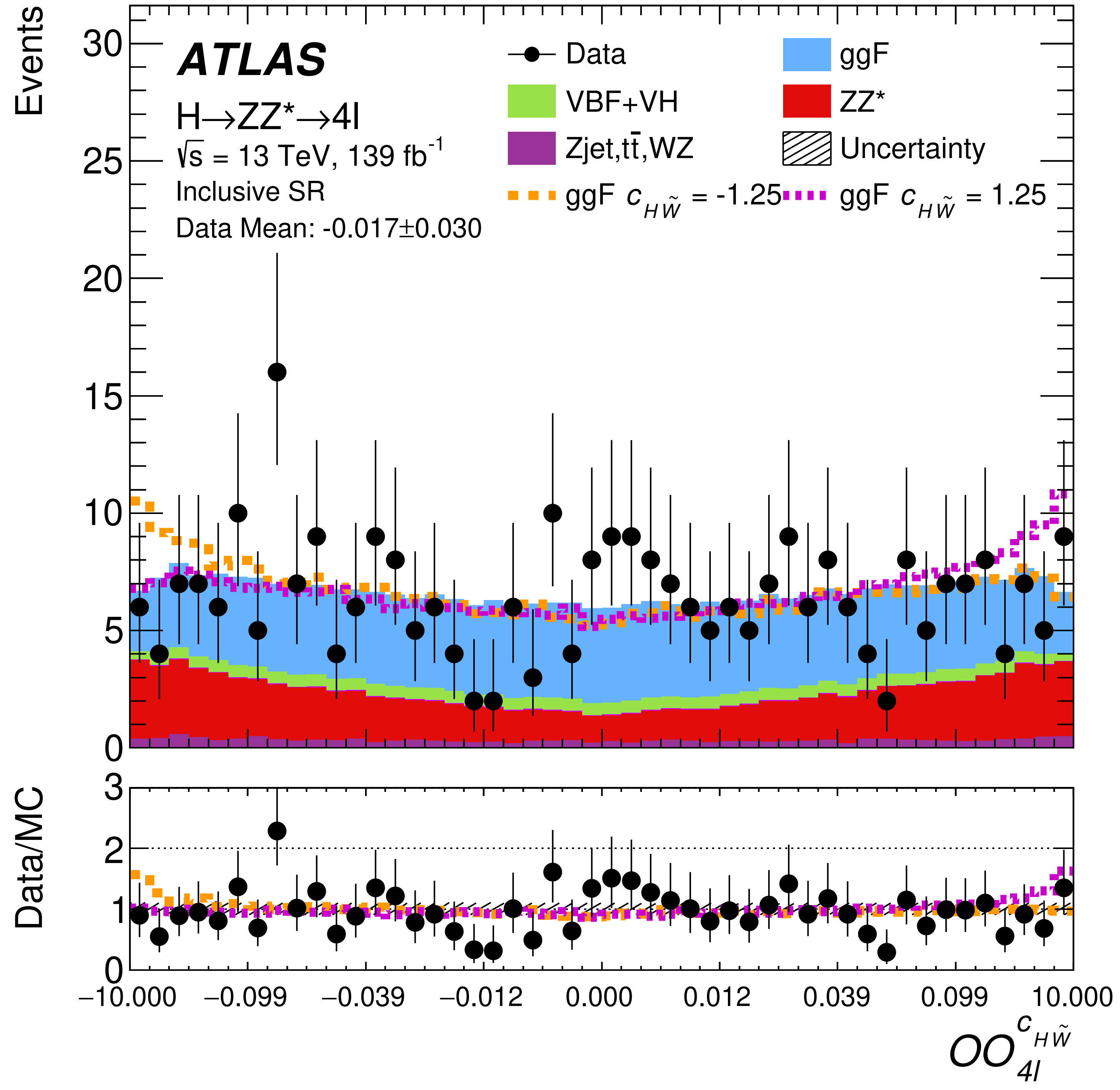
CPV

CMS, PRD 104 (2021) 052004

ATLAS, JHEP 05 (2024) 105







$$D_{0-} = \frac{|M_{0-}(\Omega)|^2}{|M_{0-}(\Omega)|^2 + |M_{0+}(\Omega)|^2}$$

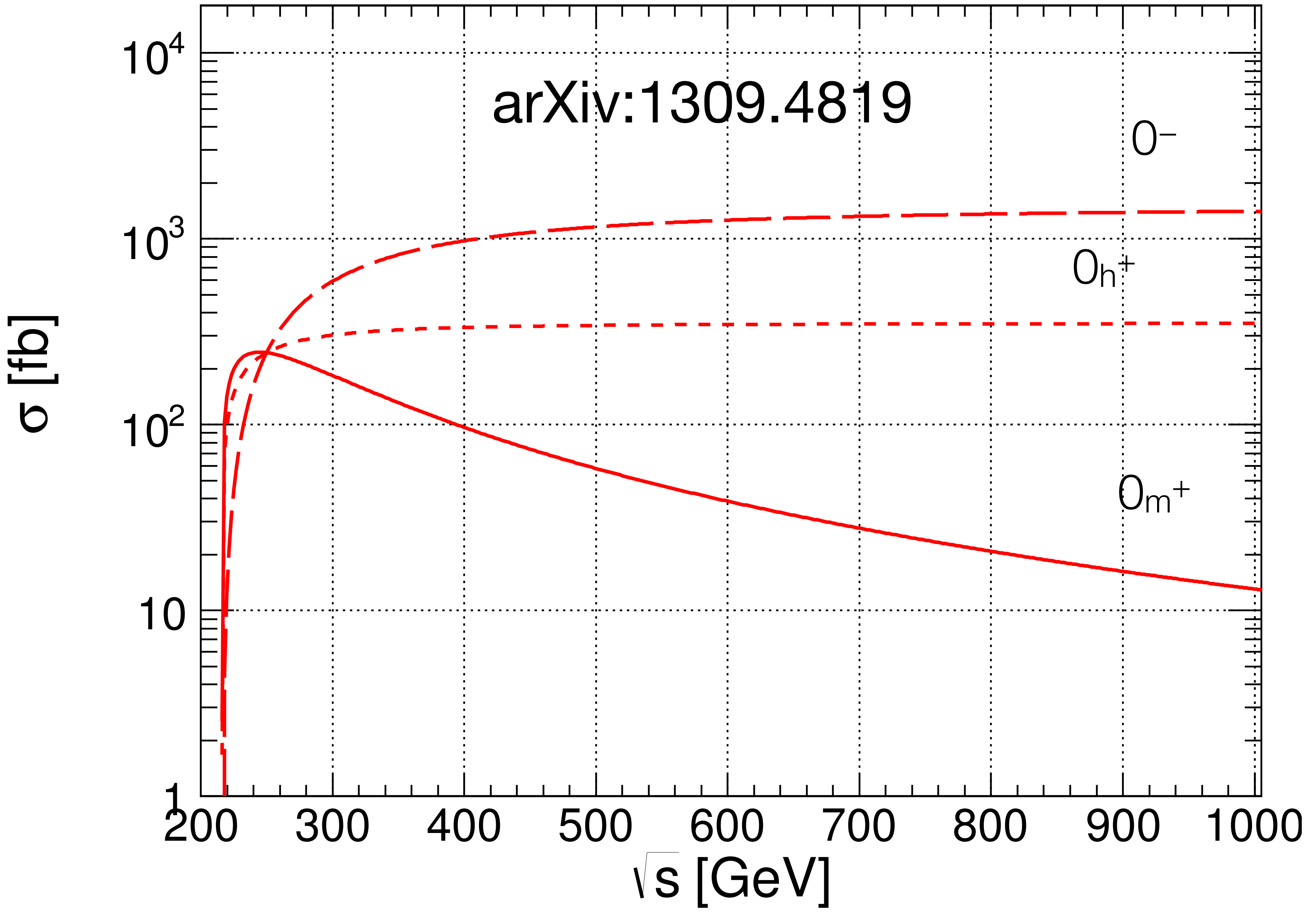
$$D_{CP} = \frac{2Re(M_{0-}(\Omega)M_{0+}(\Omega))}{\sqrt{|M_{0-}(\Omega)||M_{0+}(\Omega)|}}$$

$$OO = \frac{2Re(\mathcal{M}^*_{SM}\mathcal{M}_{BSM})}{|\mathcal{M}_{SM}|^2}$$

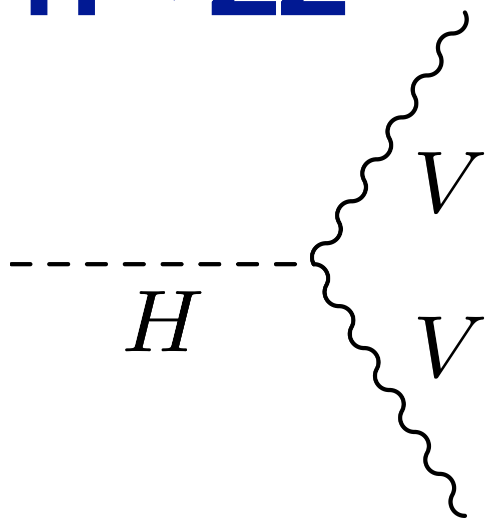
From HVV decay to production

CP-odd xsec increase with energy scale

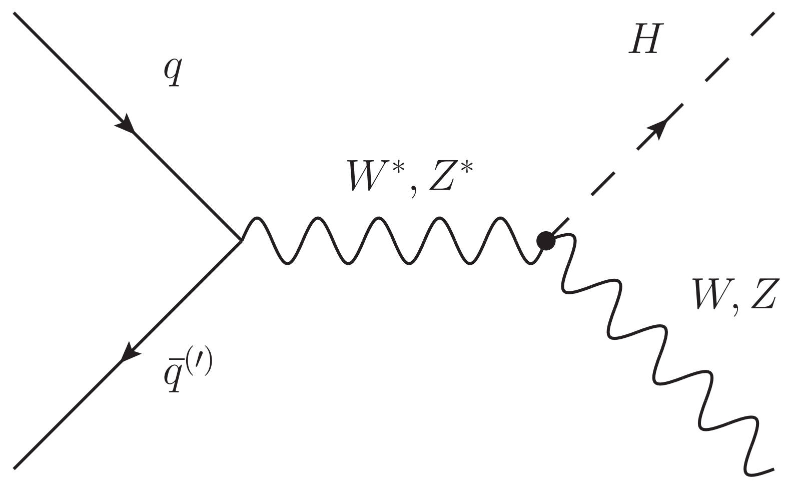
VH， VBF: higher energy scale



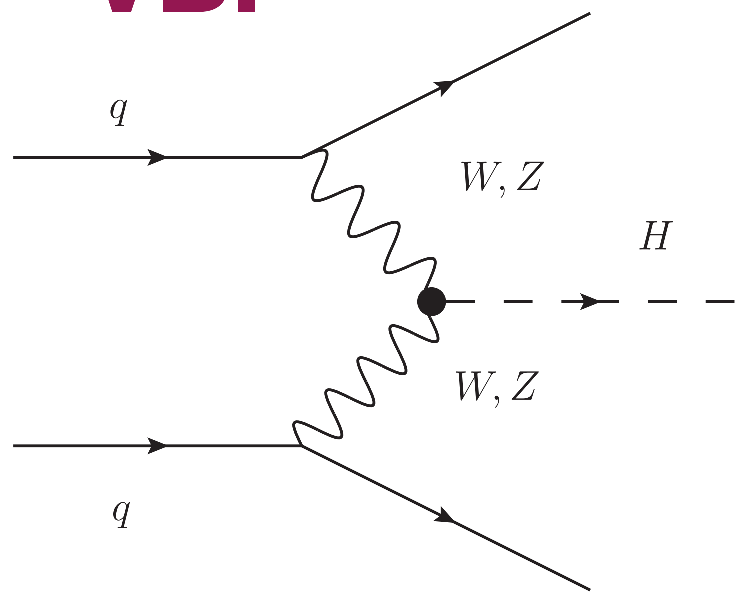
H→ZZ



VH



VBF



arXiv:1310.8361

Snowmass 2013 report

Collider	pp	pp	target
E (GeV)	14,000	14,000	(theory)
$\mathcal{L}$ (fb^{-1})	300	3,000	
spin-2_m^+	$\sim 10\sigma$	$\gg 10\sigma$	$>5\sigma$
$VVH^\dagger$	0.07	0.02	$< 10^{-5}$
$VVH^\ddagger$	$4{\cdot}10^{-4}$	$1.2{\cdot}10^{-4}$	$< 10^{-5}$
$VVH^\diamond$	$7{\cdot}10^{-4}$	$1.3{\cdot}10^{-4}$	$< 10^{-5}$

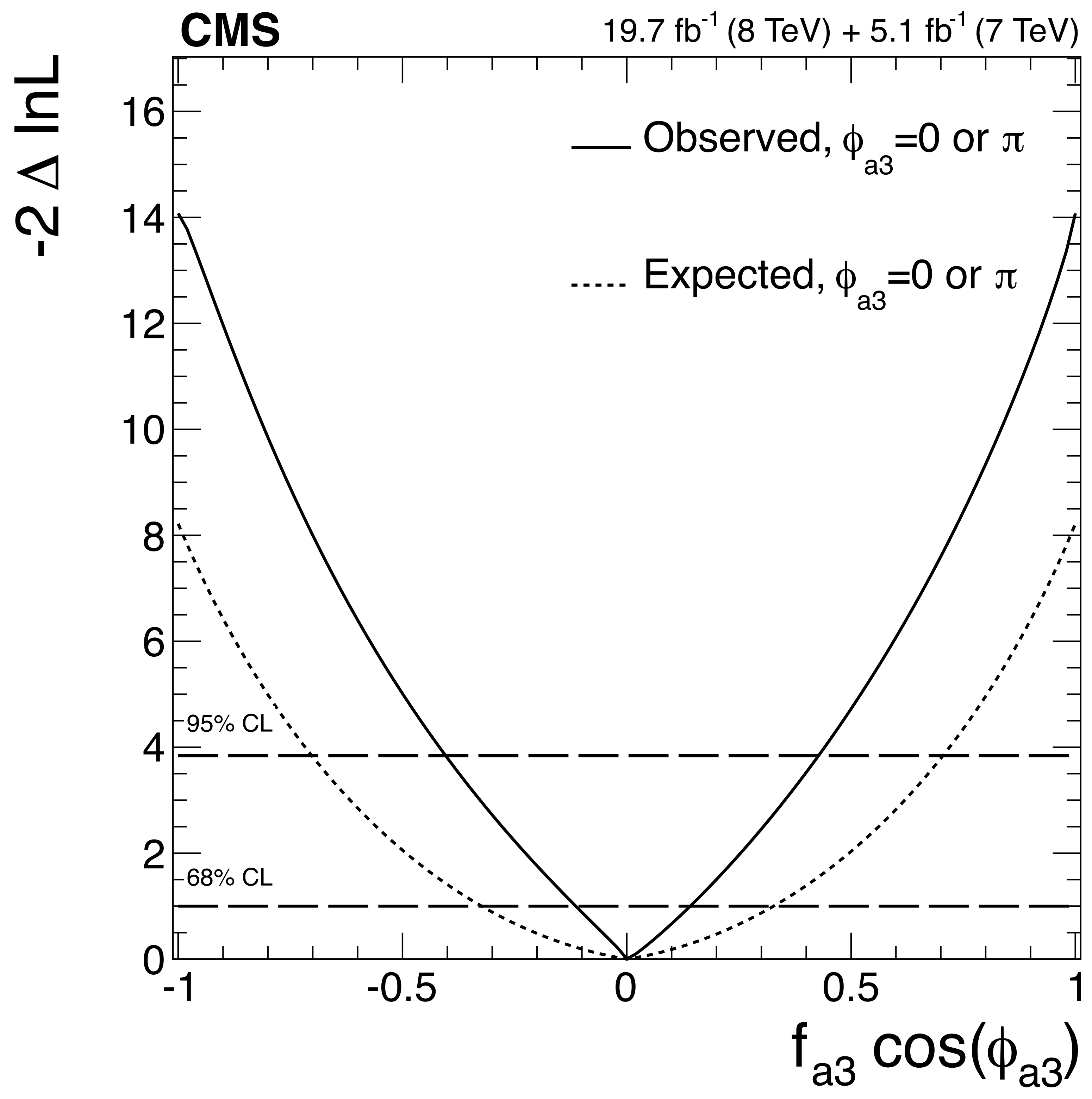
H→ZZ
VH
VBF

From HVV decay to production

Measured quantity, fa3: CP-odd xsec fraction

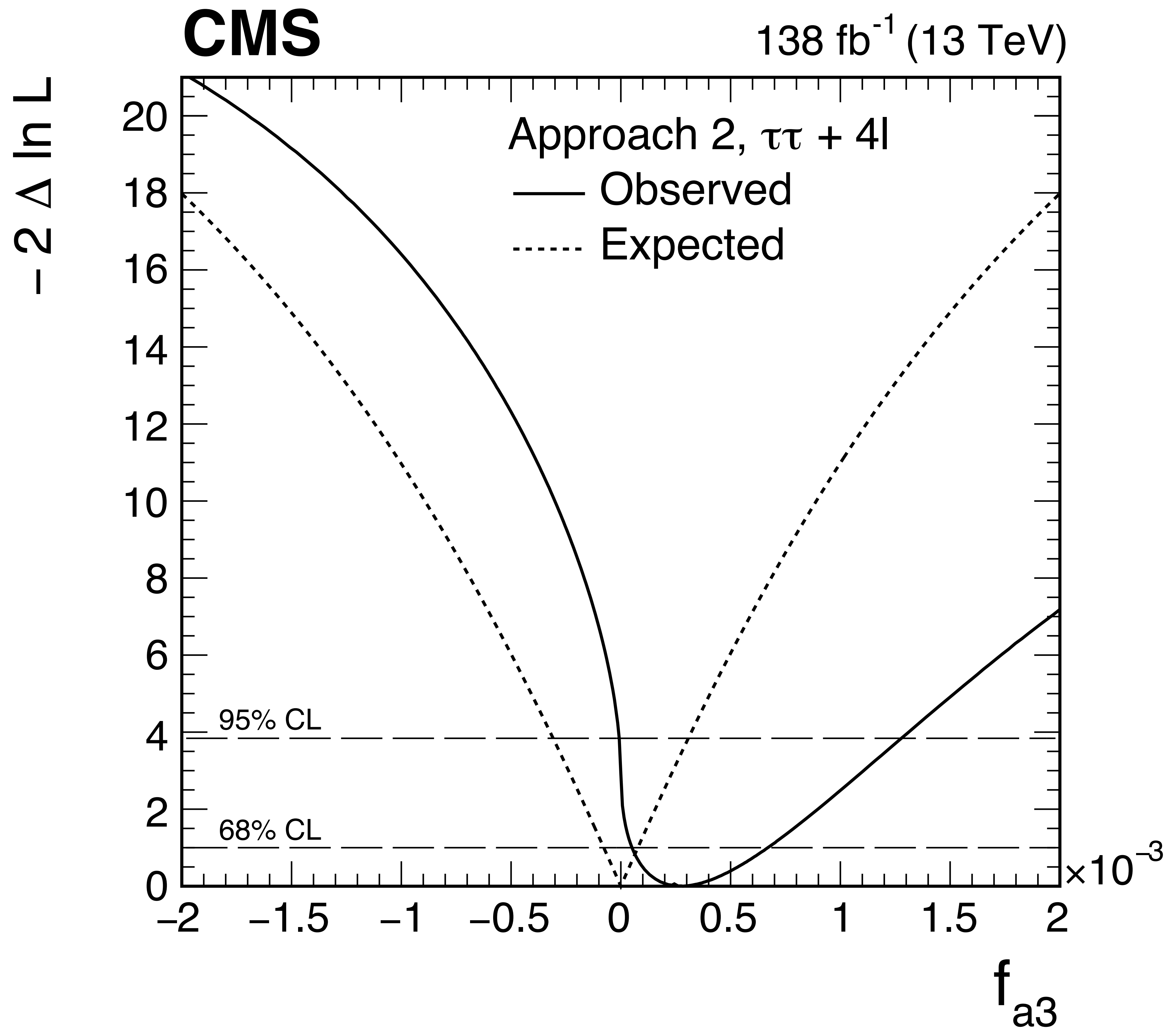
CMS, PRD 92 (2015) 012004

H→ 4l < 0.4



CMS, PRD 108 (2023) 032013

VBF, H→ ττ + 4l < 1.7 x 10^{-3}

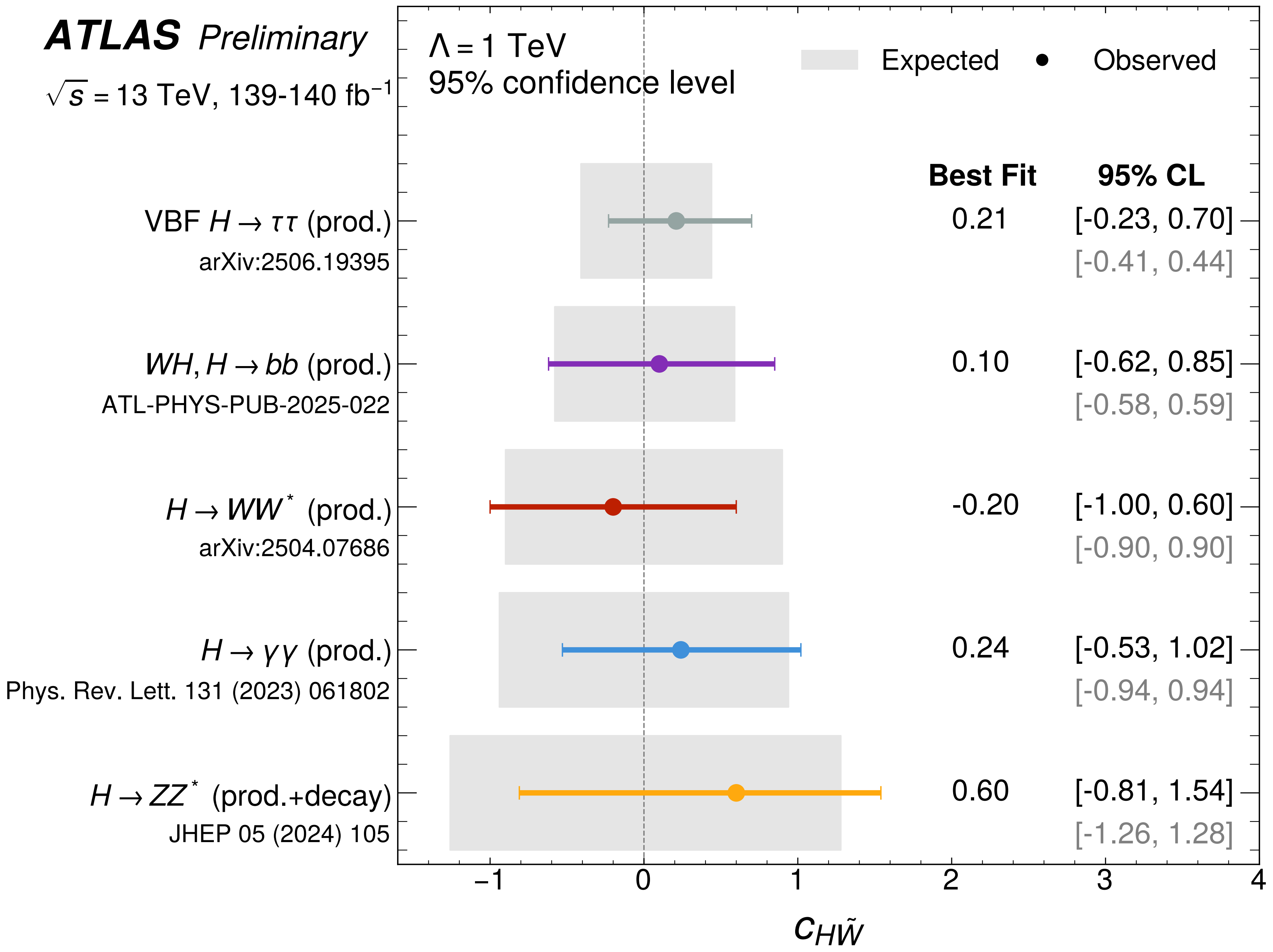


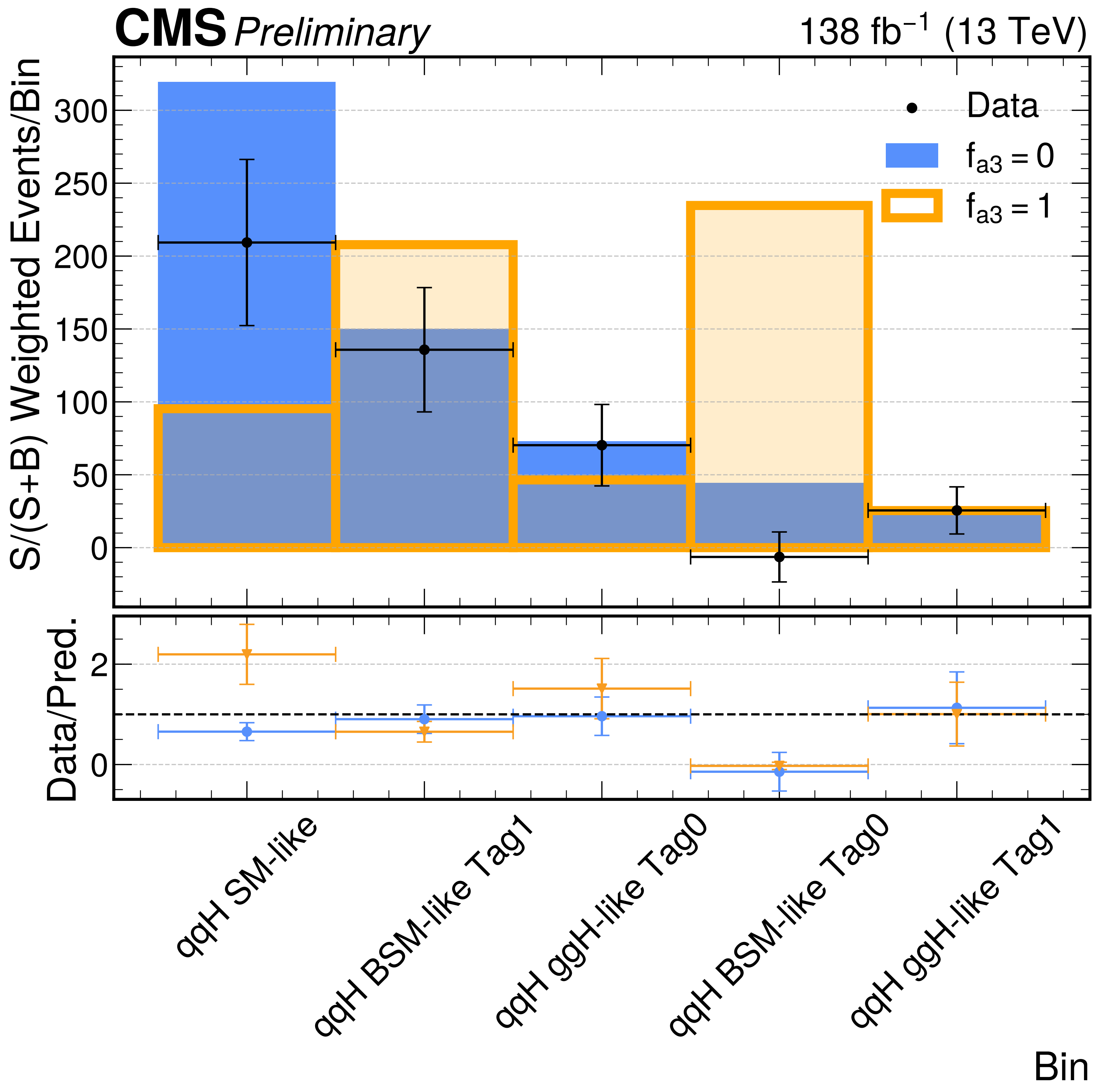
HVV production

- Can be measured in all different decay final states and combined

Parameter	Expected/(10^{-4}) $H \to \gamma\gamma$ (68% CL)	Observed/(10^{-4}) $H \to \gamma\gamma$ (68% CL)	Expected/(10^{-4}) $H \to 4\ell + H \to \tau^+\tau^-$ (68% CL)
f_{a3}	$0.0^{+2.1}_{-2.1}$	$0.00^{+0.39}_{-0.39}$	$[-0.5, 0.5]$

Already close to 10^{-5}





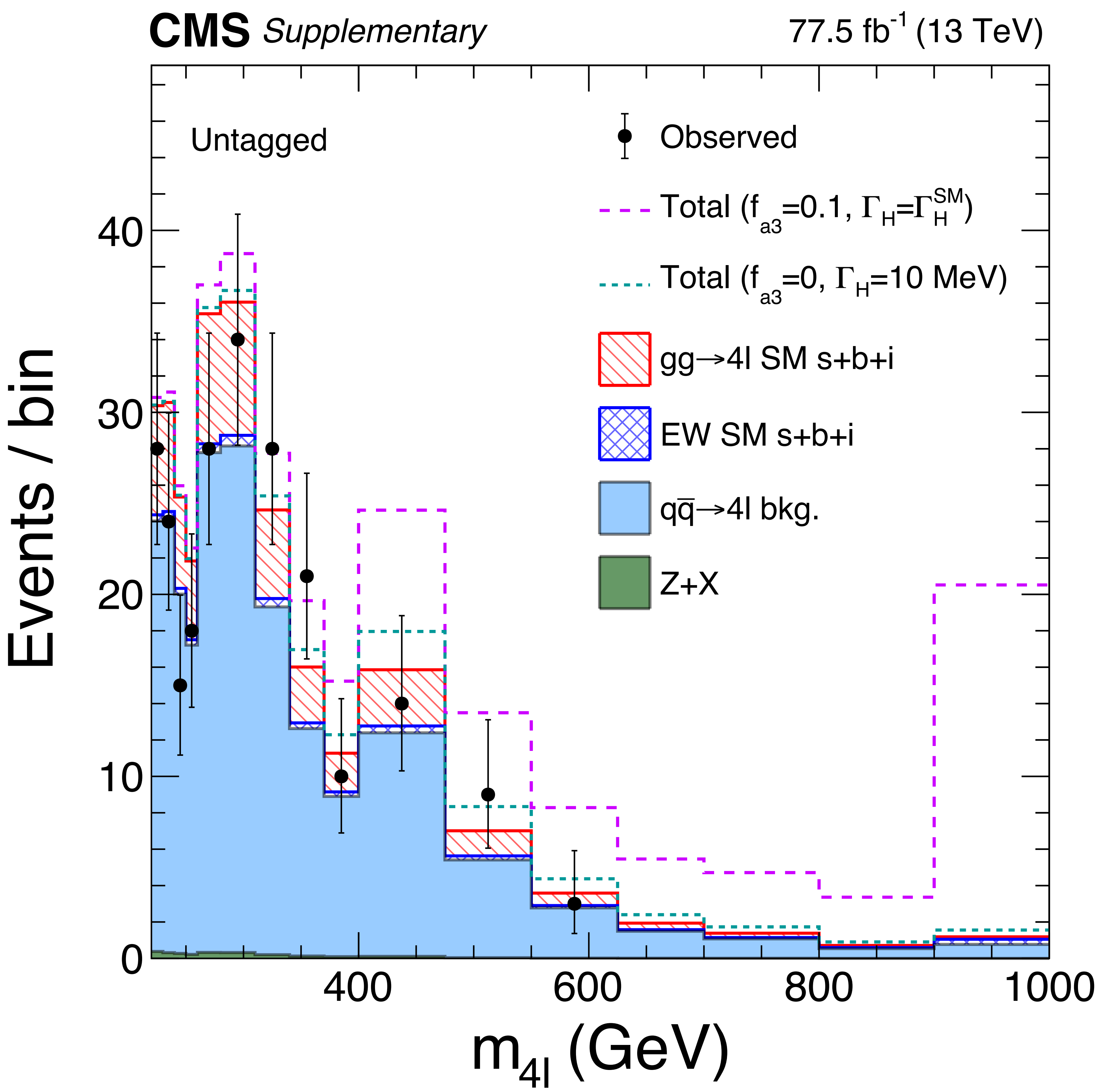
CMS-PAS-24-006
VBF, H→ γγ

ATL-PHYS-PUB-2025-031 Expressed in EFT WCs

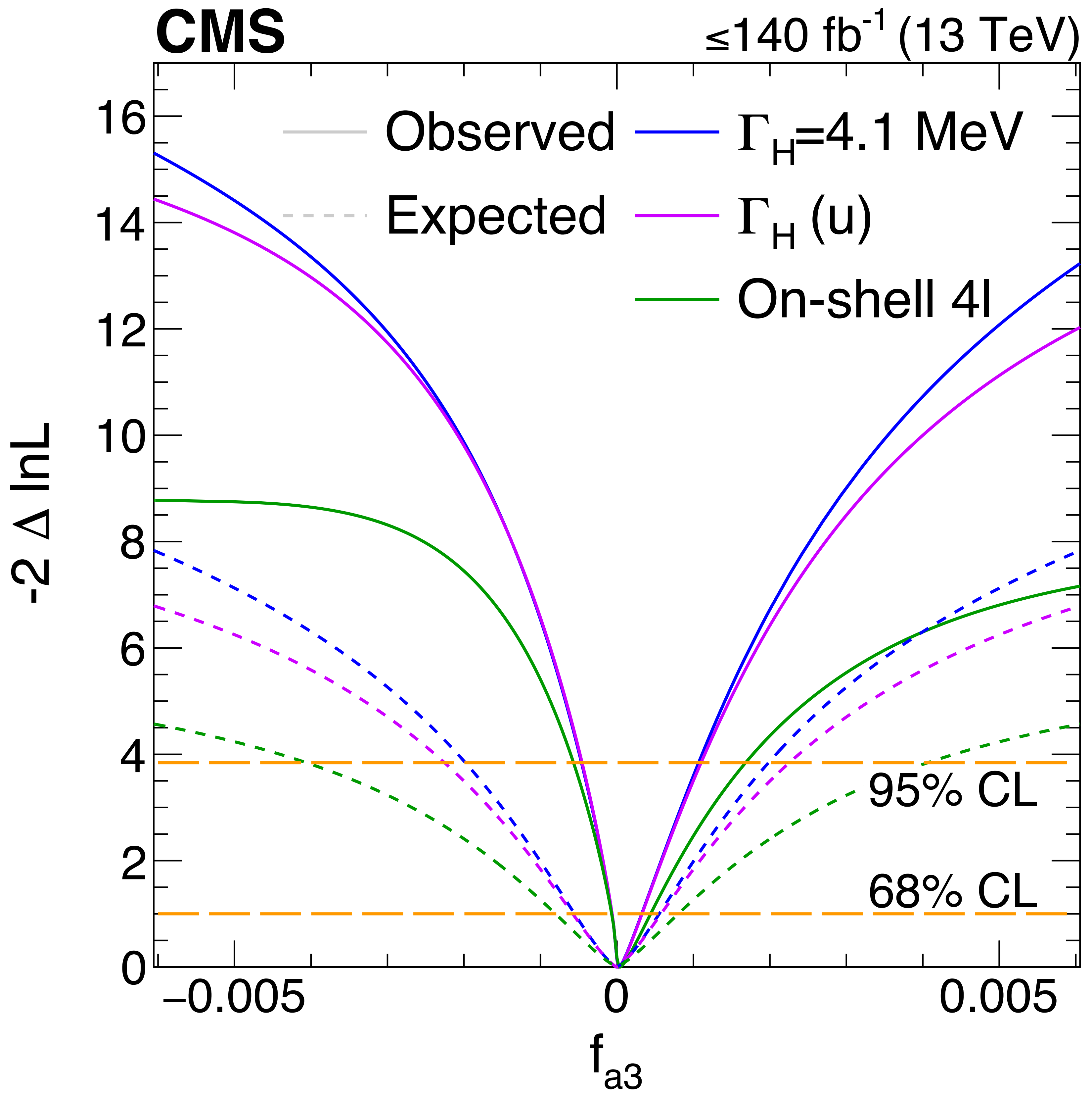
Off-shell HVV

- Similarly, off-shell H production, higher energy

PLB 775 (2017) 1



CMS Nat. Phys. 18 (2022) 1329



$\sim 10^{-4}$

Hff CP violation

Measure

$$A(H \to f\bar{f}) = \frac{m_f}{v}\bar{u}_2\left(b_1^{Hf\bar{f}} + i b_2^{Hf\bar{f}}\gamma_5\right)u_1$$

CP-even CP-odd

$$f_{CP}^{Hf\bar{f}} \equiv \frac{|b_2^{Hf\bar{f}}|^2}{|b_1^{Hf\bar{f}}|^2 + |b_2^{Hf\bar{f}}|^2} = \sin^2\left(\alpha^{Hf\bar{f}}\right)$$

- Need polarization information if u does not decay

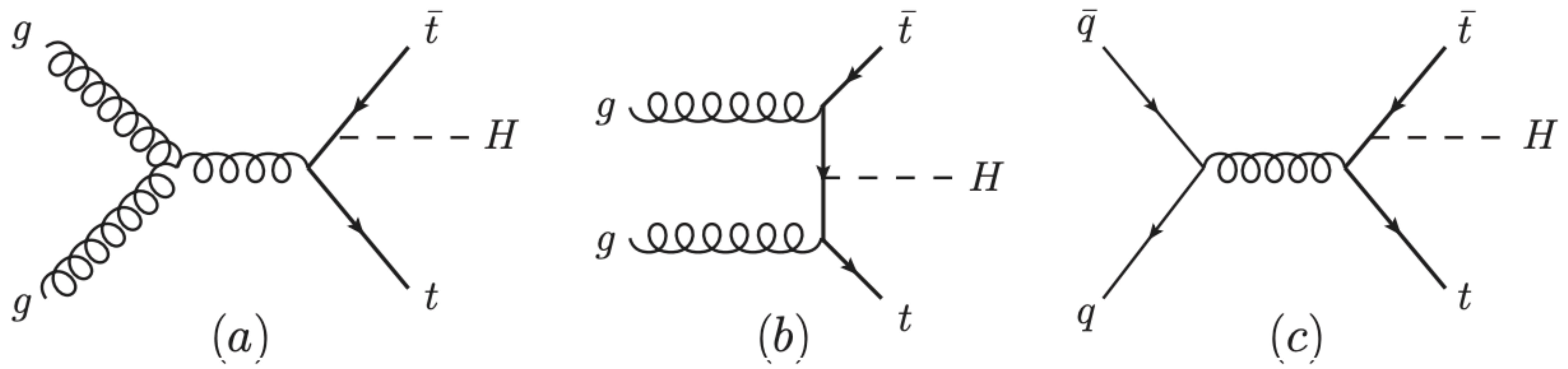
$$\sigma_{\text{pol}}(\zeta) = \sigma_{\text{unpol}}\left(1 + P_L^+ P_L^- + P_T^+ P_T^- \left[\frac{(b_1^{H\mu\mu})^2 - (b_2^{H\mu\mu})^2}{(b_1^{H\mu\mu})^2 + (b_2^{H\mu\mu})^2}\cos\zeta - \frac{2b_1^{H\mu\mu}b_2^{H\mu\mu}}{(b_1^{H\mu\mu})^2 + (b_2^{H\mu\mu})^2}\sin\zeta\right]\right),$$

arXiv: 2205.07715
Snowmass 2022 report

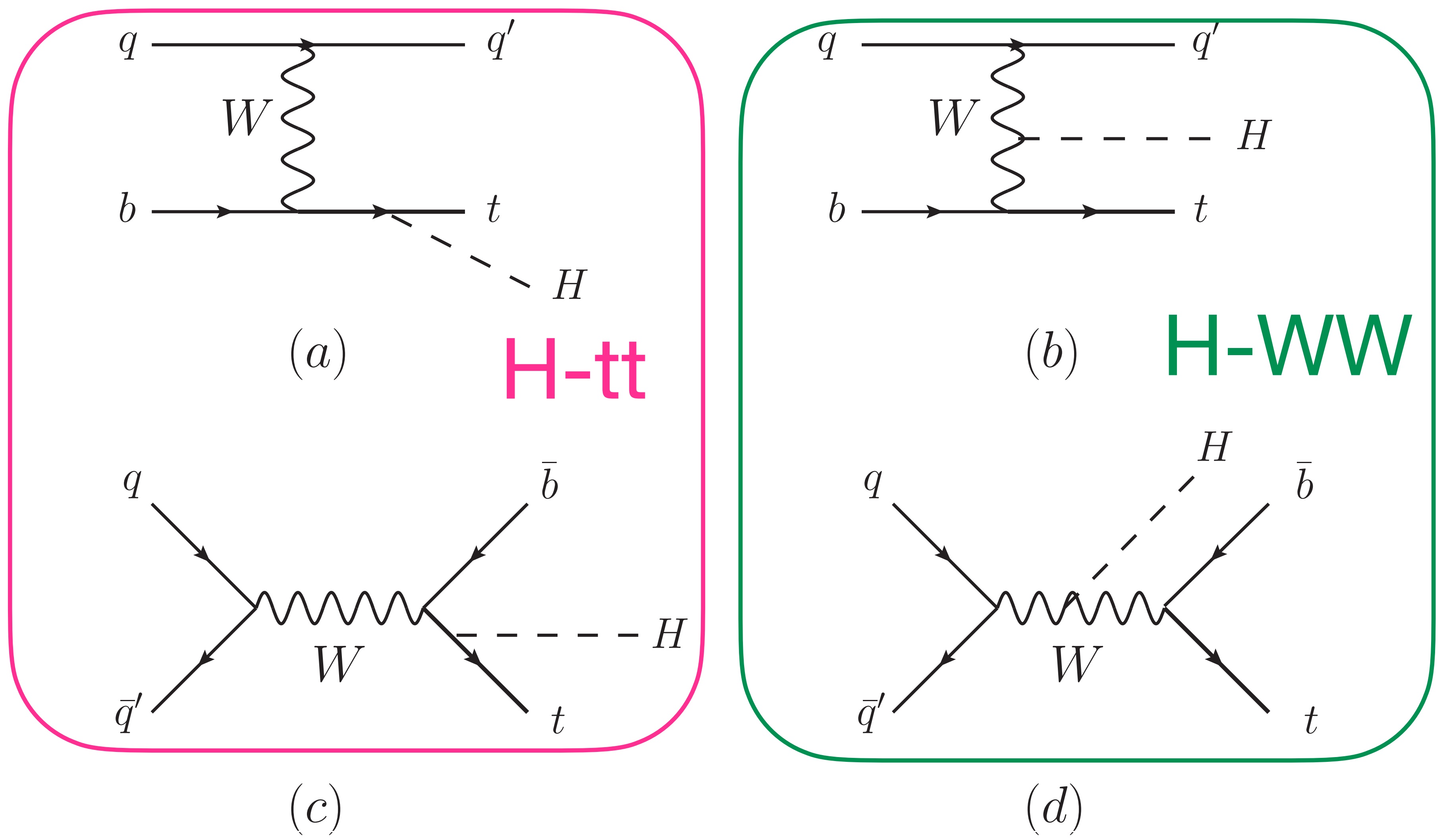
- Possible to measure at the LHC: tt, ττ
- Not possible: bb, μμ

Htt measurement with ttH and tH

ttH: fourth production xsec of the Higgs at the LHC

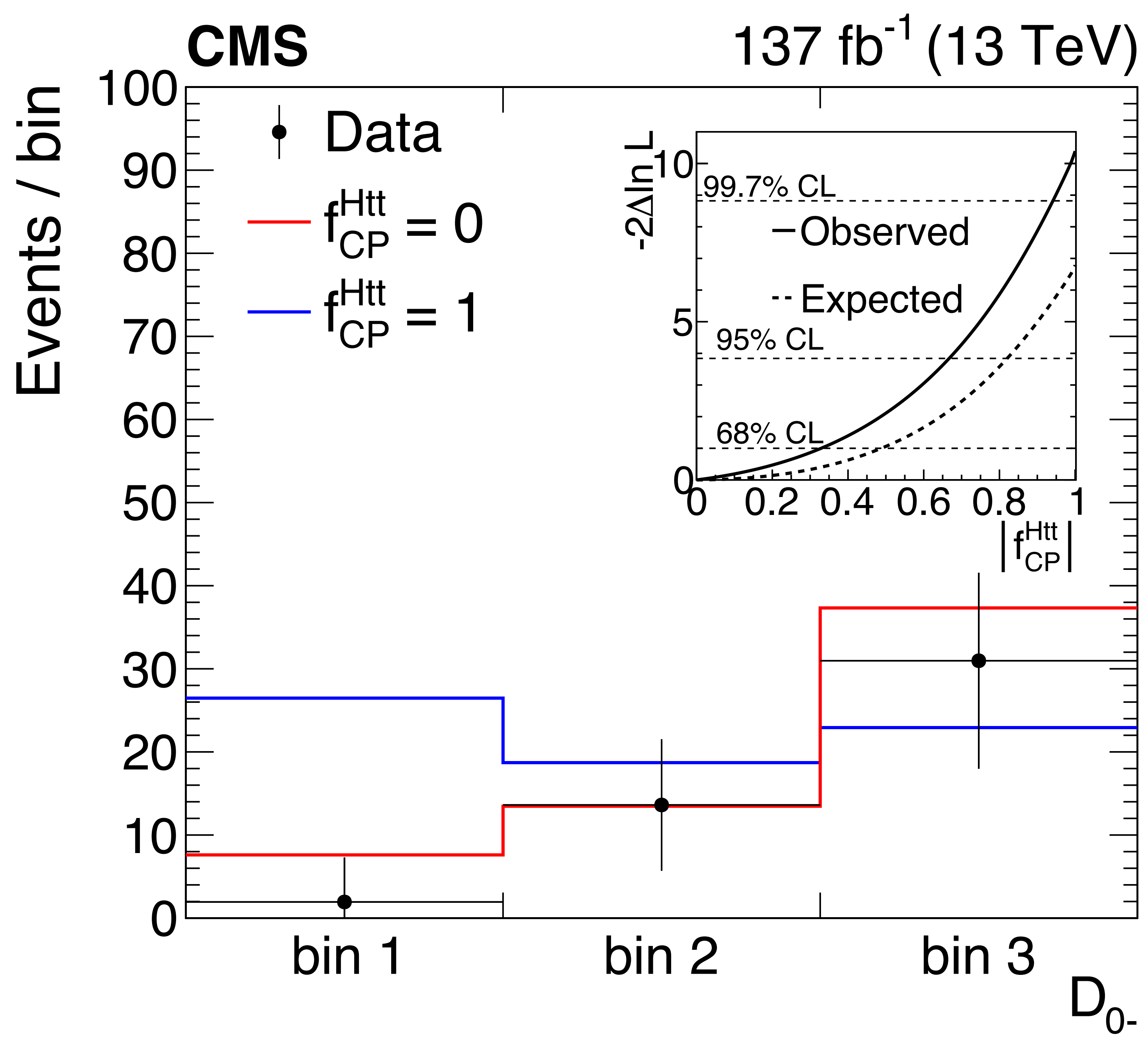


tH: small xsec due to negative interference, sensitve to Yukawa coupling sign



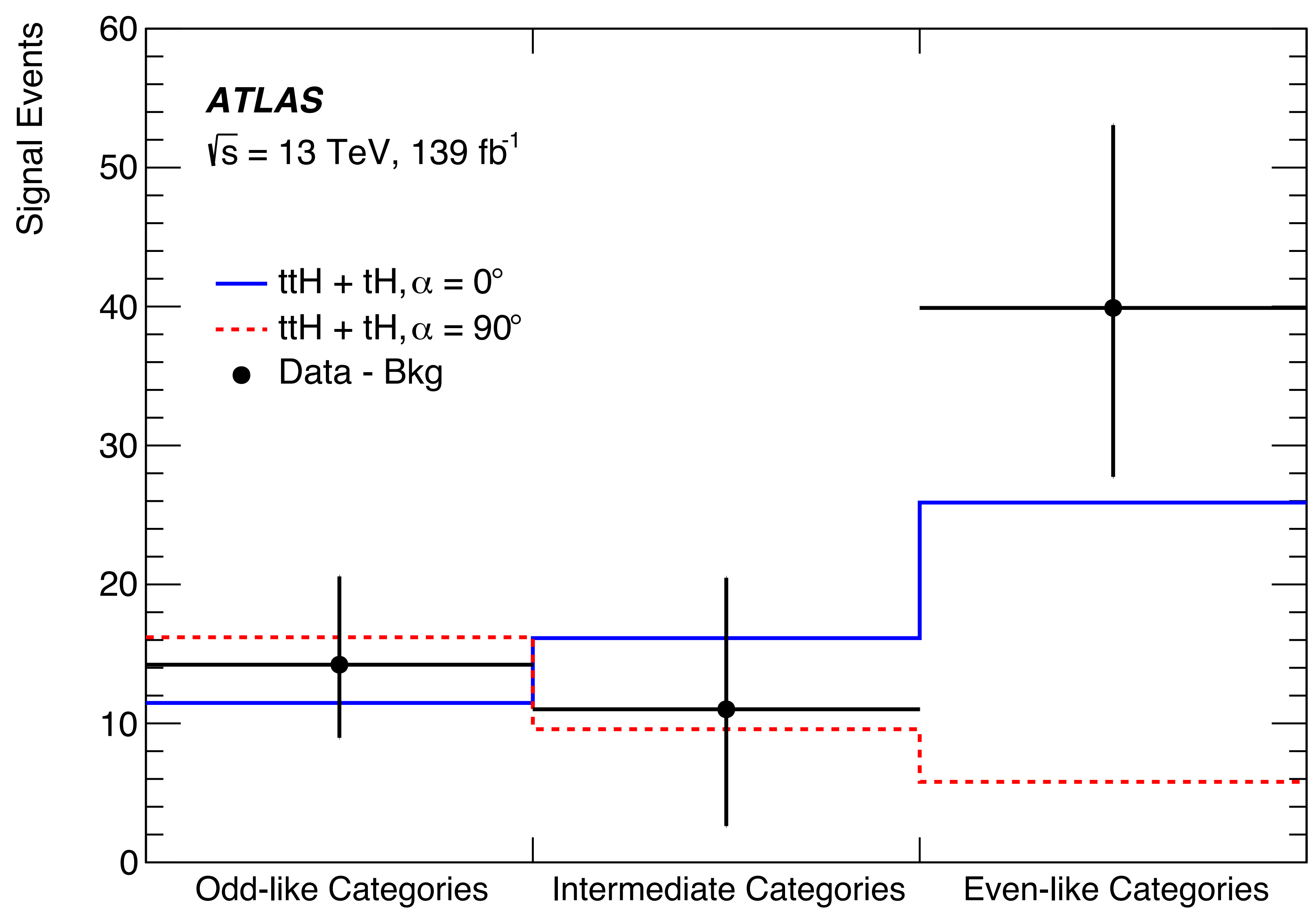
Htt measurement with ttH and tH

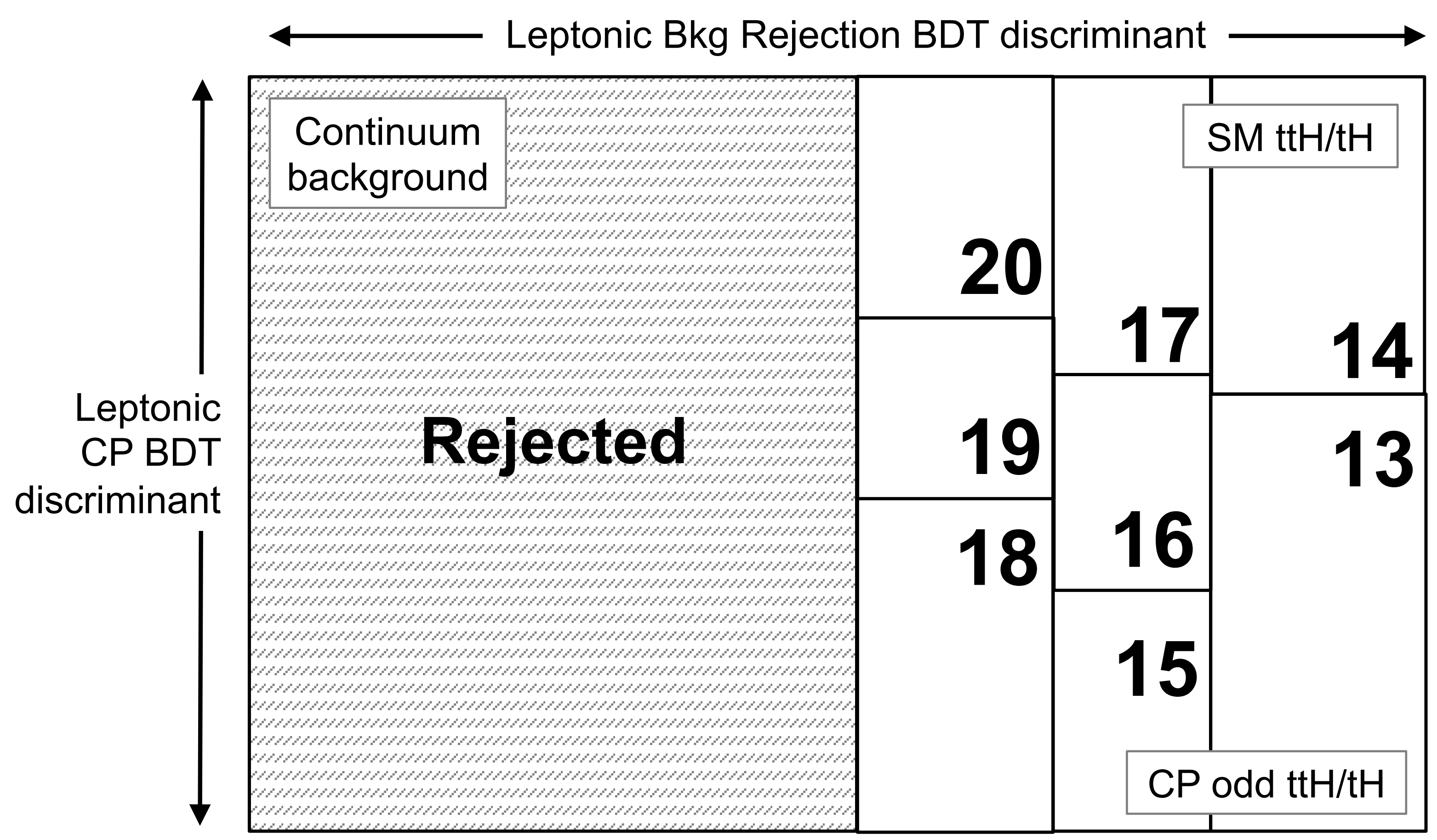
H→ γγ



CMS PRL 125 (2020) 061801

H→ γγ

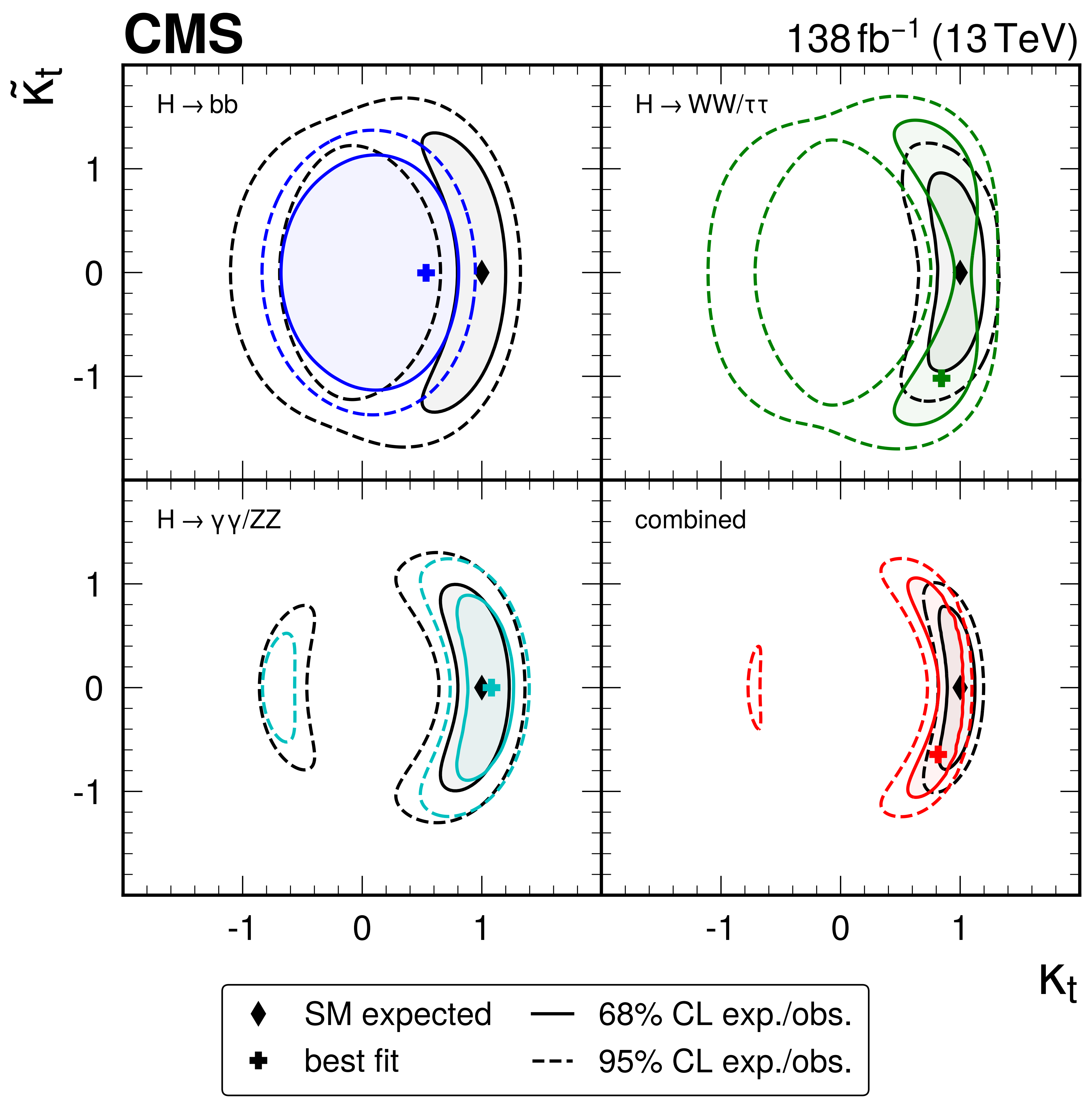




ATLAS PRL 125 (2020) 061802

Htt measurement with ttH and tH

CMS, JHEP 02 (2025) 097



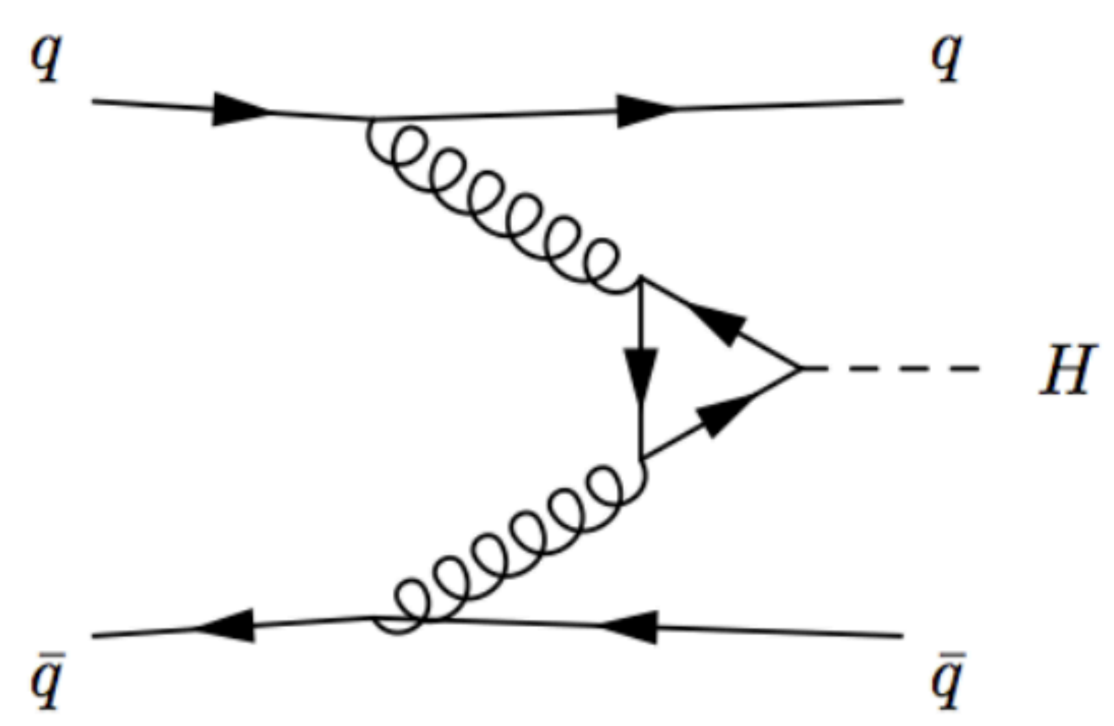
Multiple decay channels combined

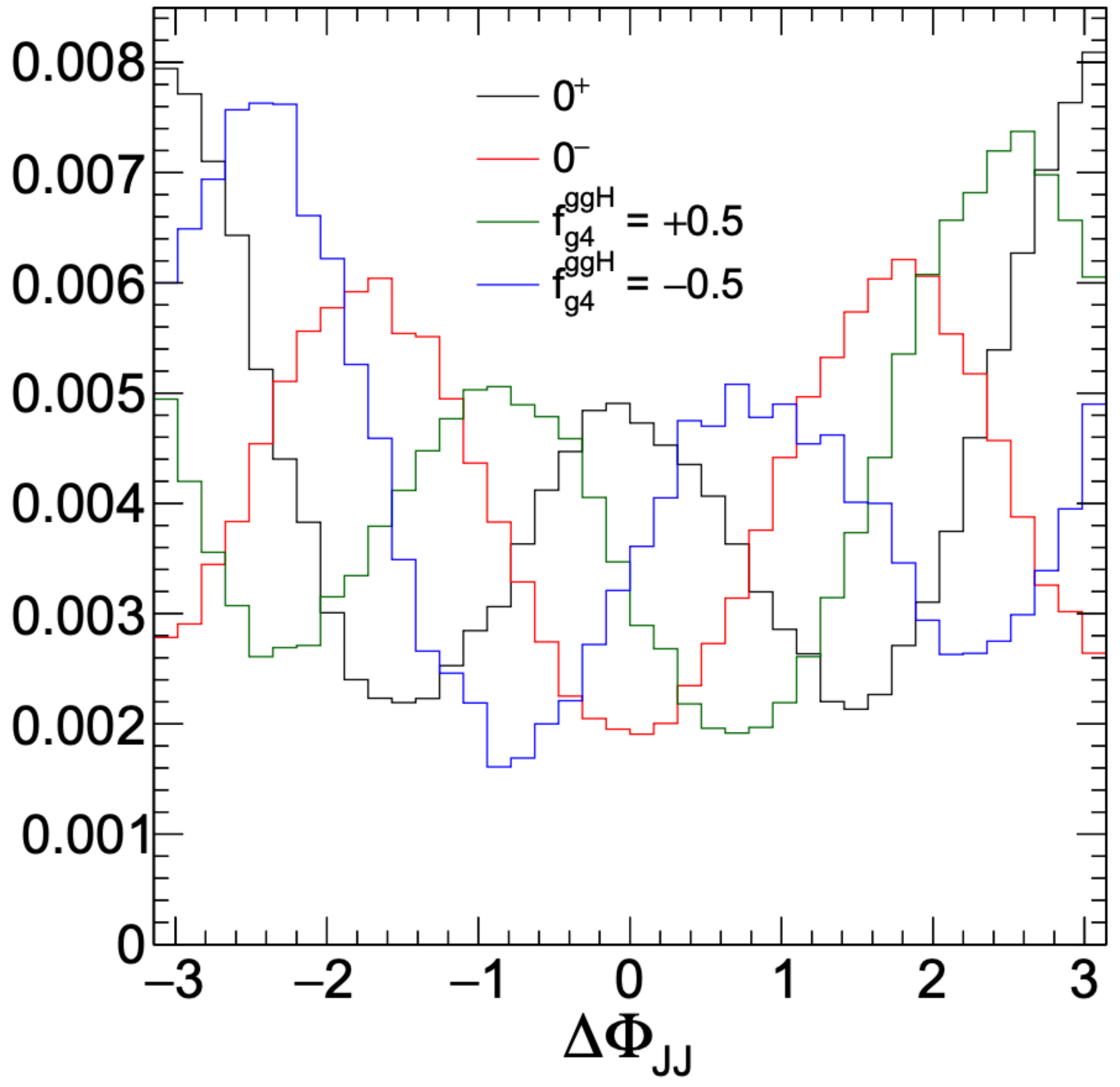
fcp<0.85, cos(α) >0.39

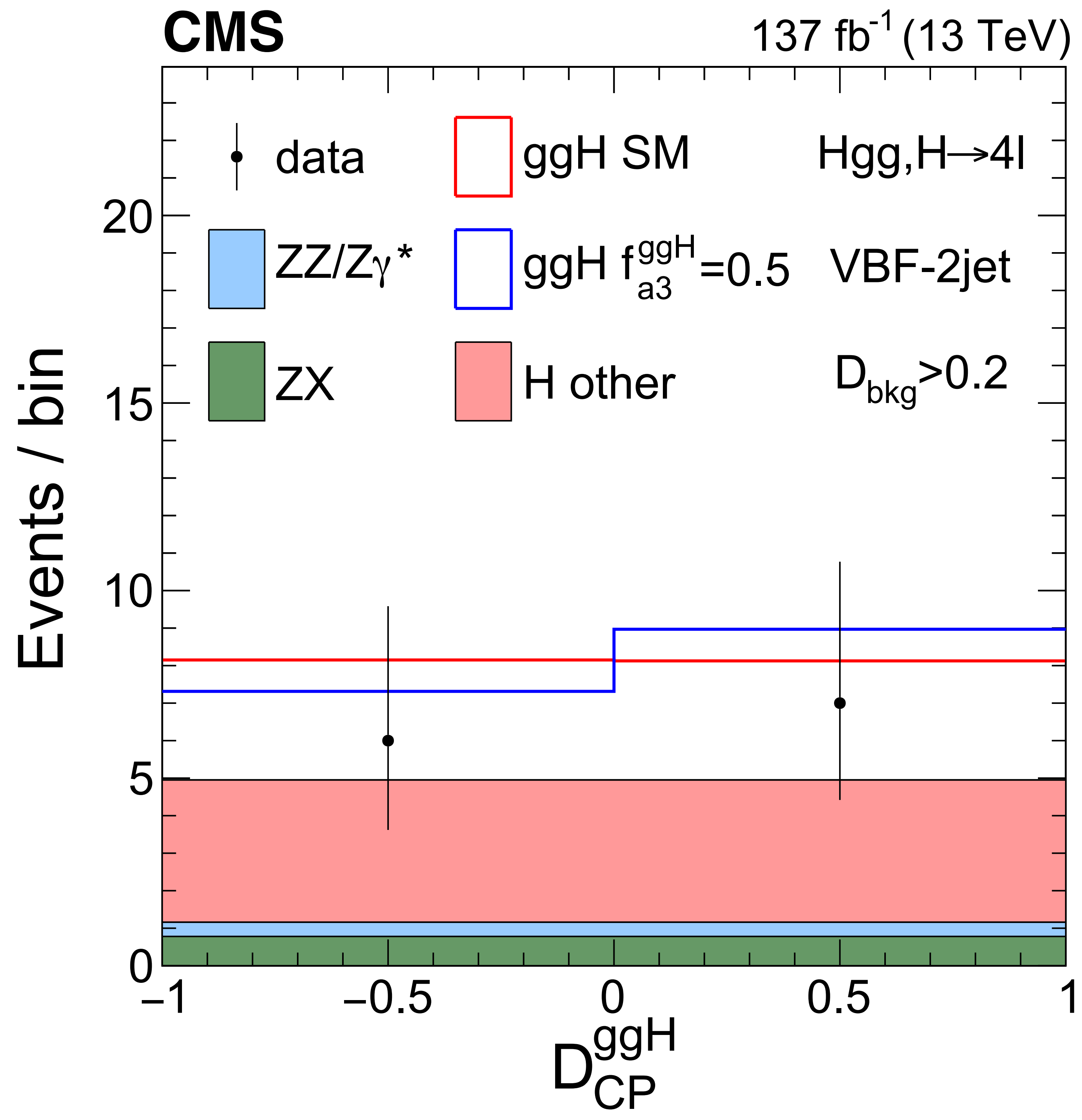
- Far from 0.01 precision
- Close to exclude negative kappa top

Htt measurement with ggH

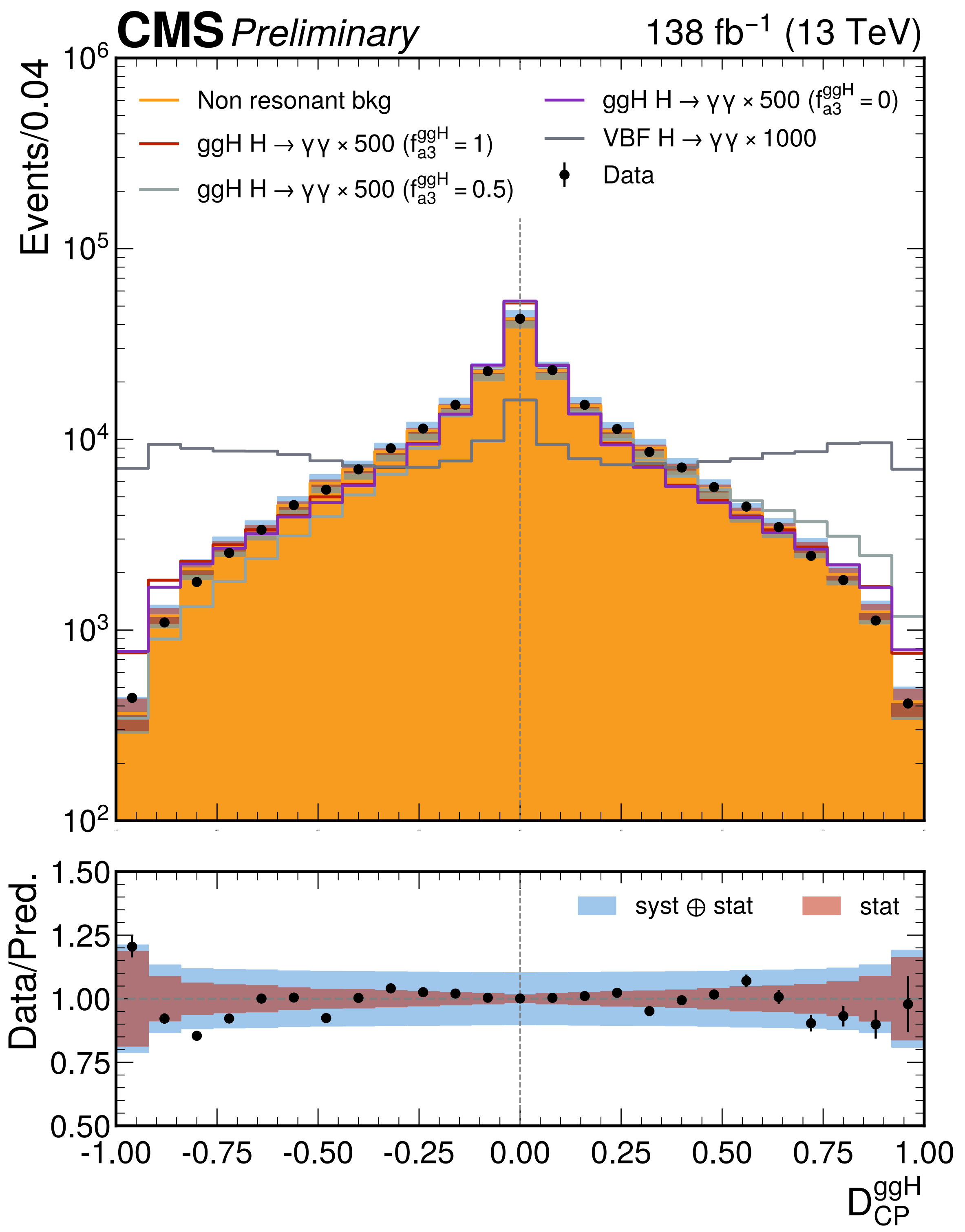
ggH large xsec, but need extra jets to obtain the CP information





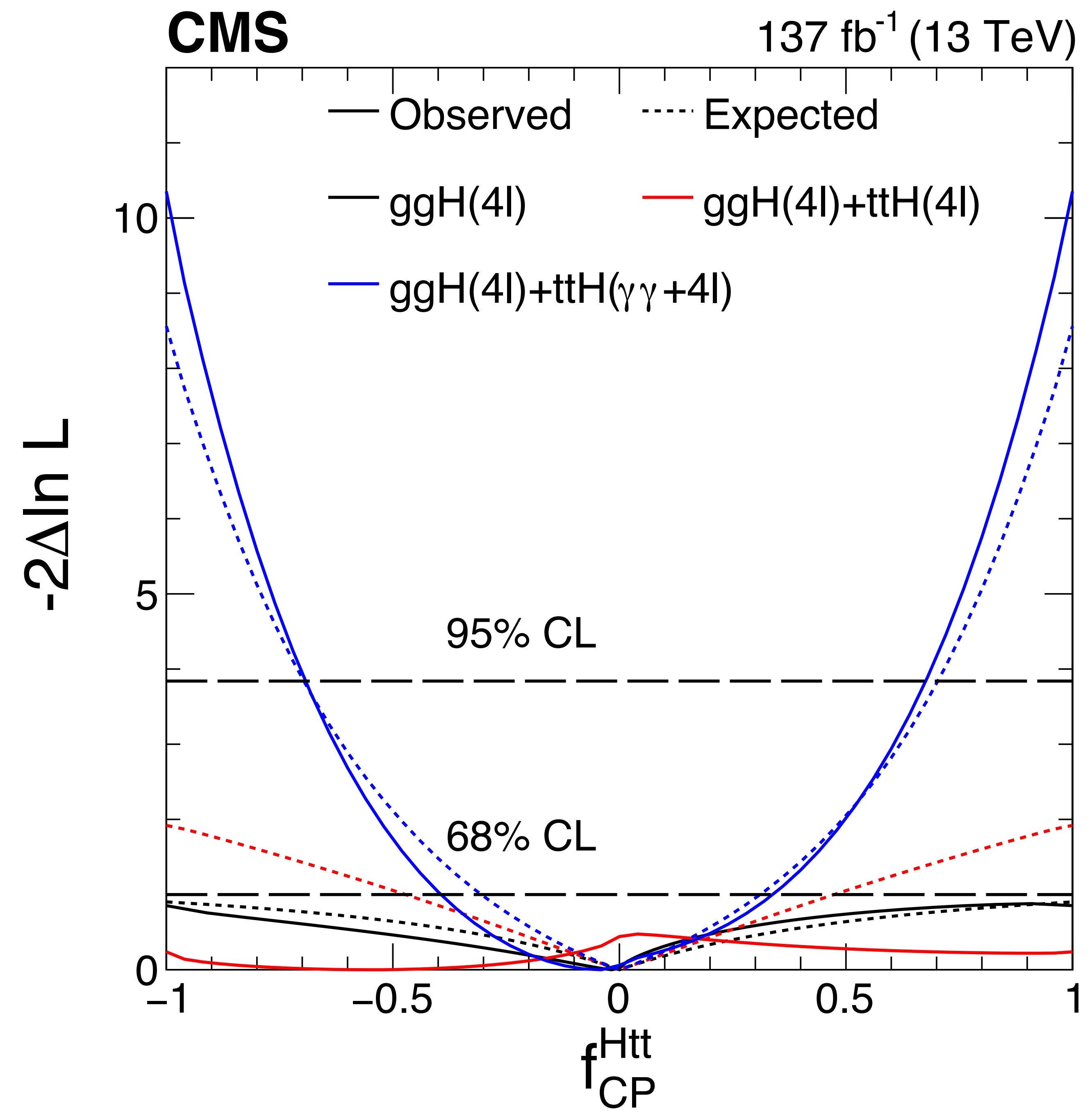


CMS, PRD 104 (2021) 052004

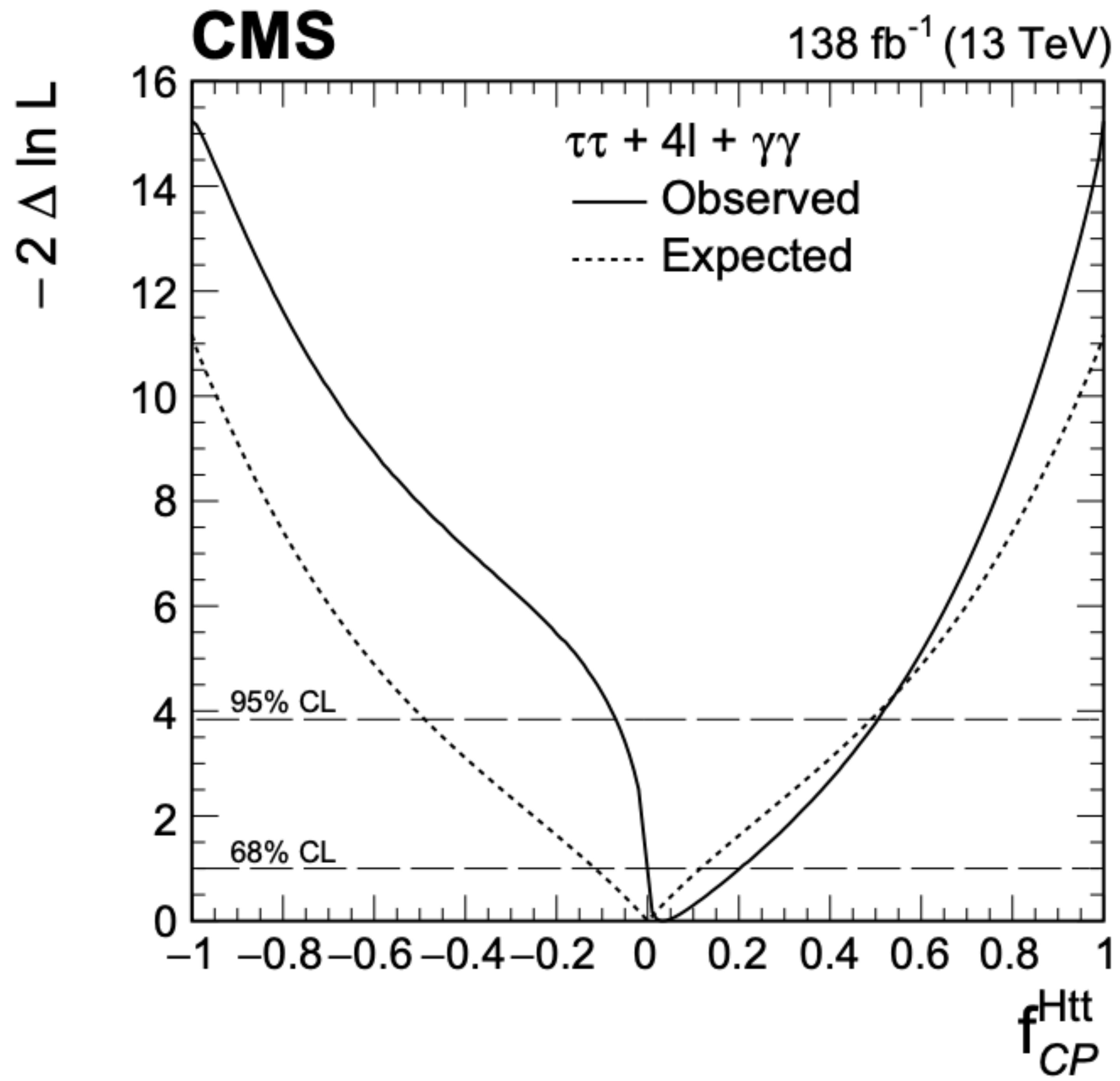


CMS, CMS-PAS-HIG-25-006

Htt measurement with ggH



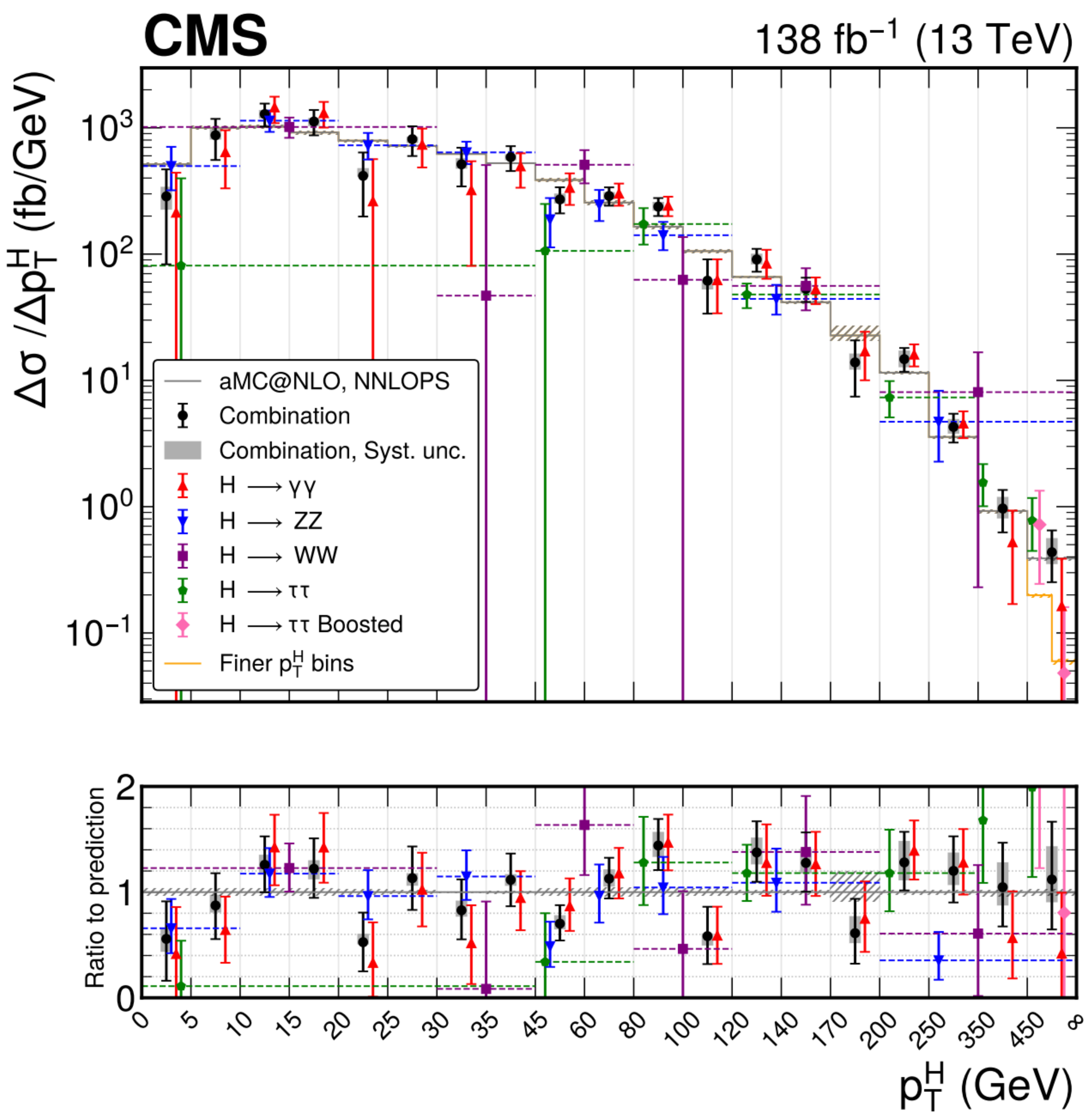
Adding ggH constraints
==>

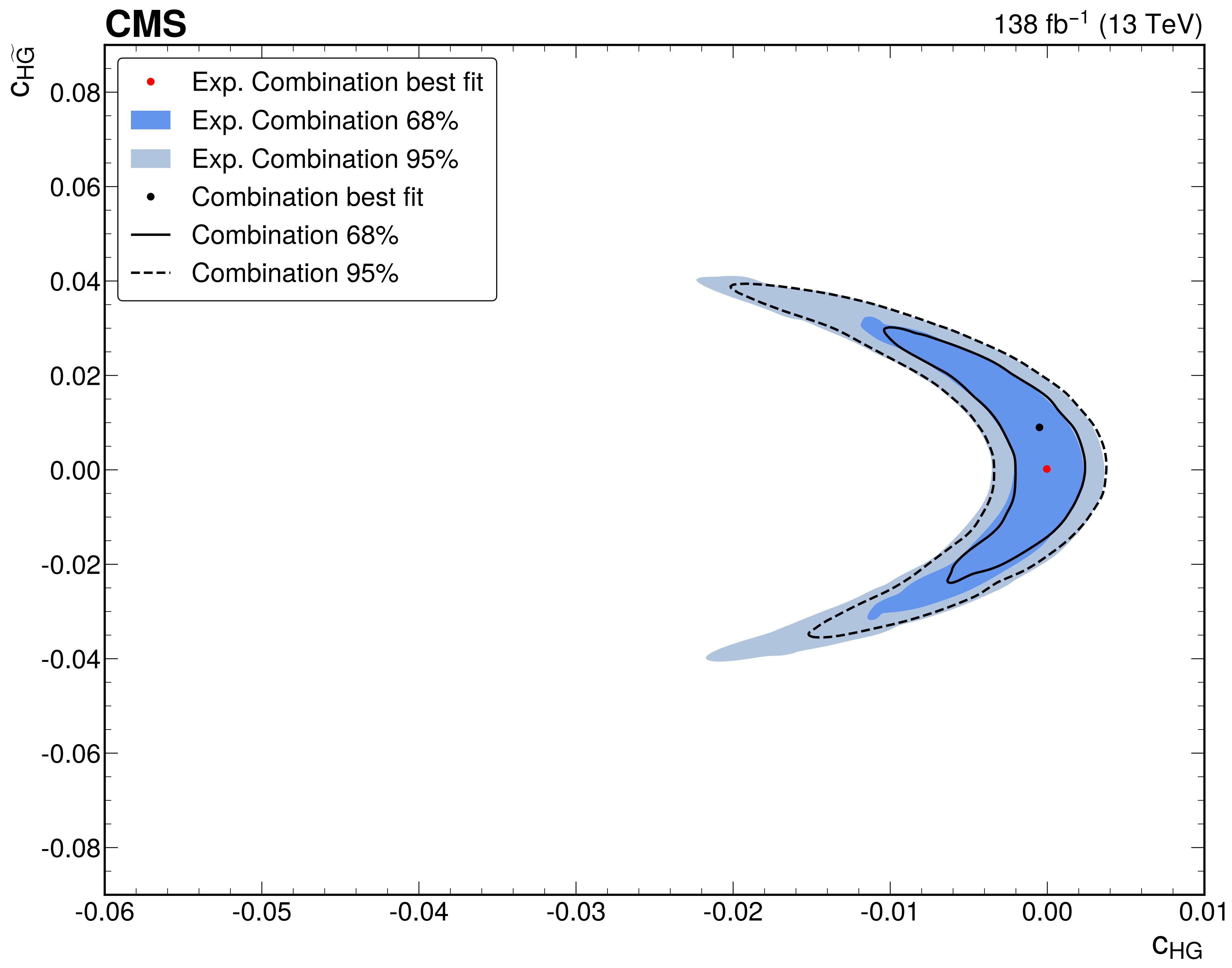


Htt measurement with ggH

Exploring Higgs differential pT distribution

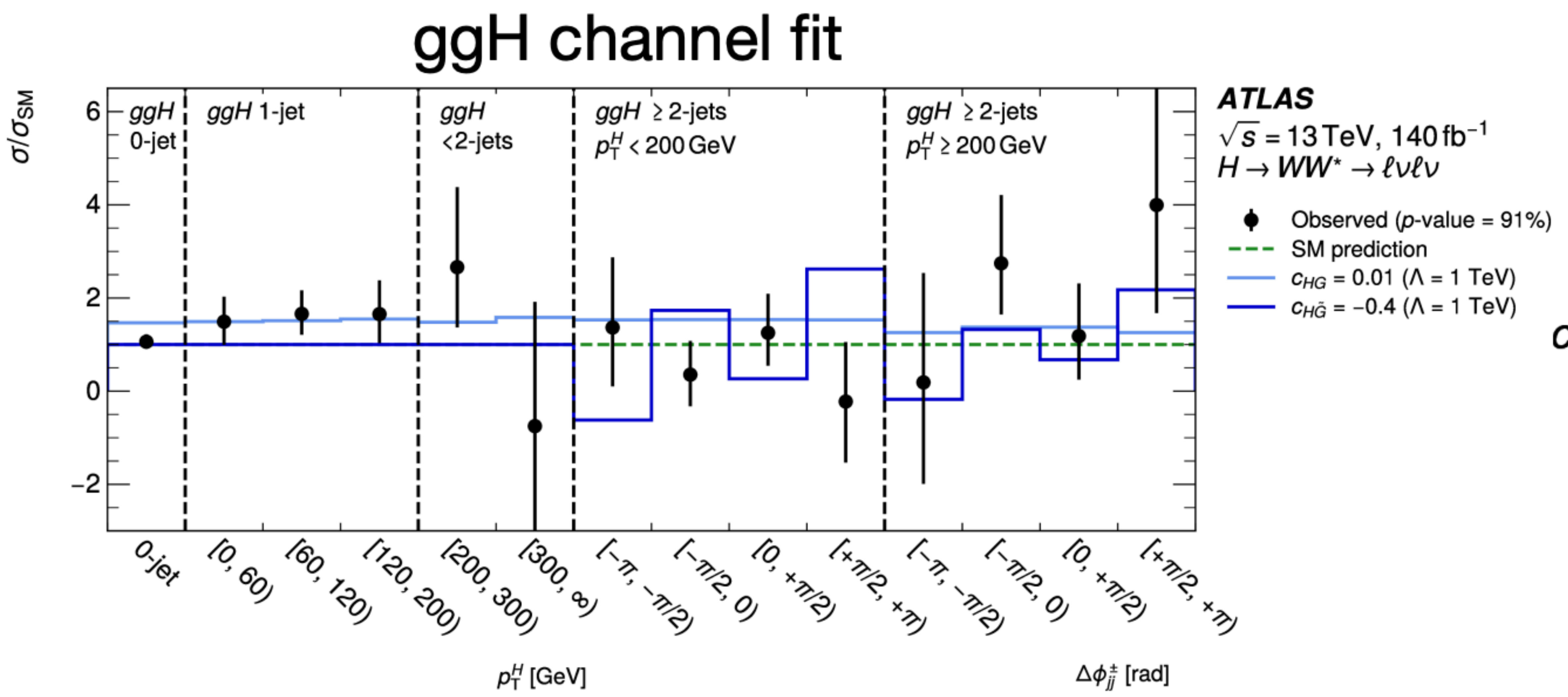
CMS, arXiv:2504.13081

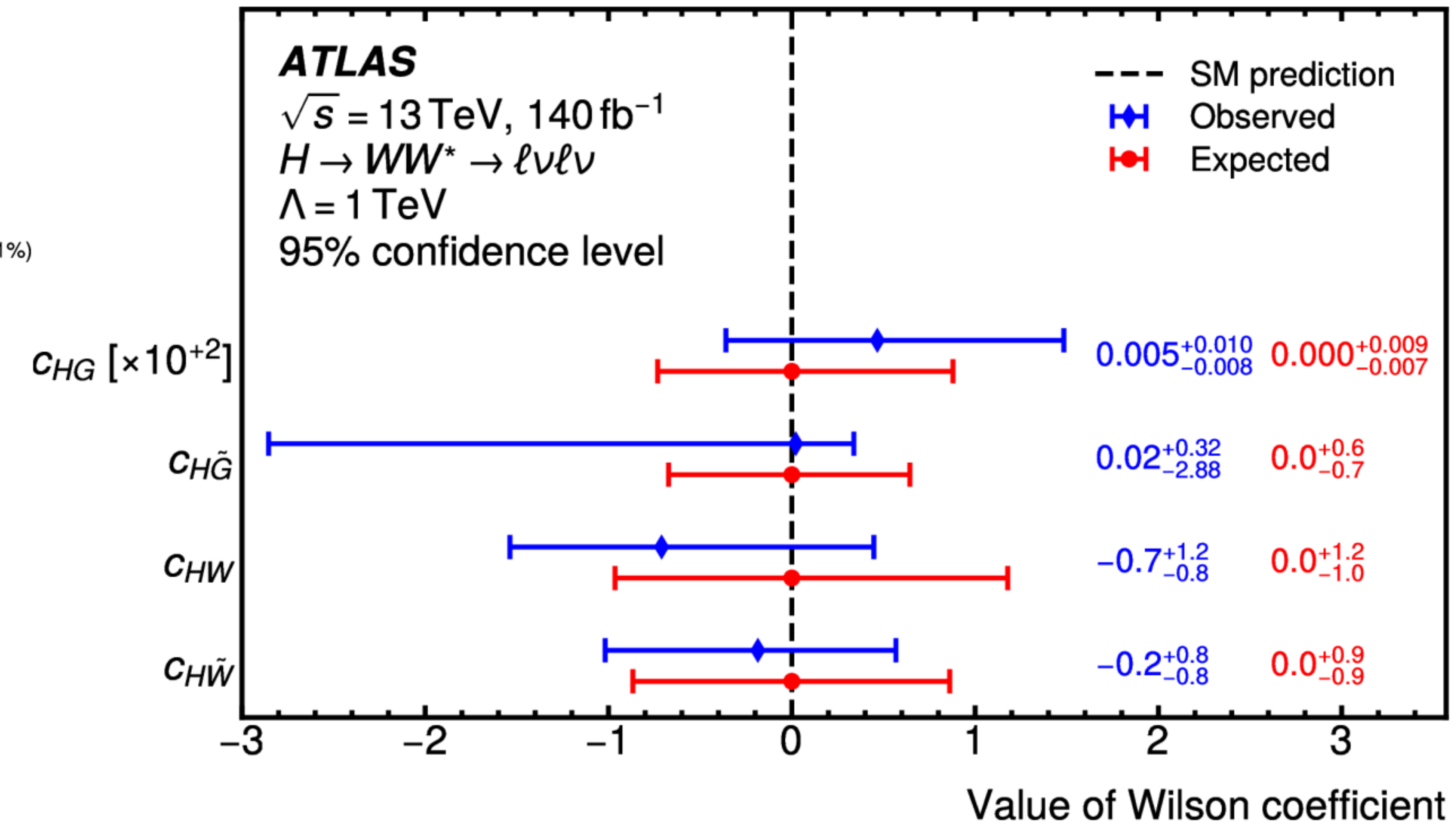




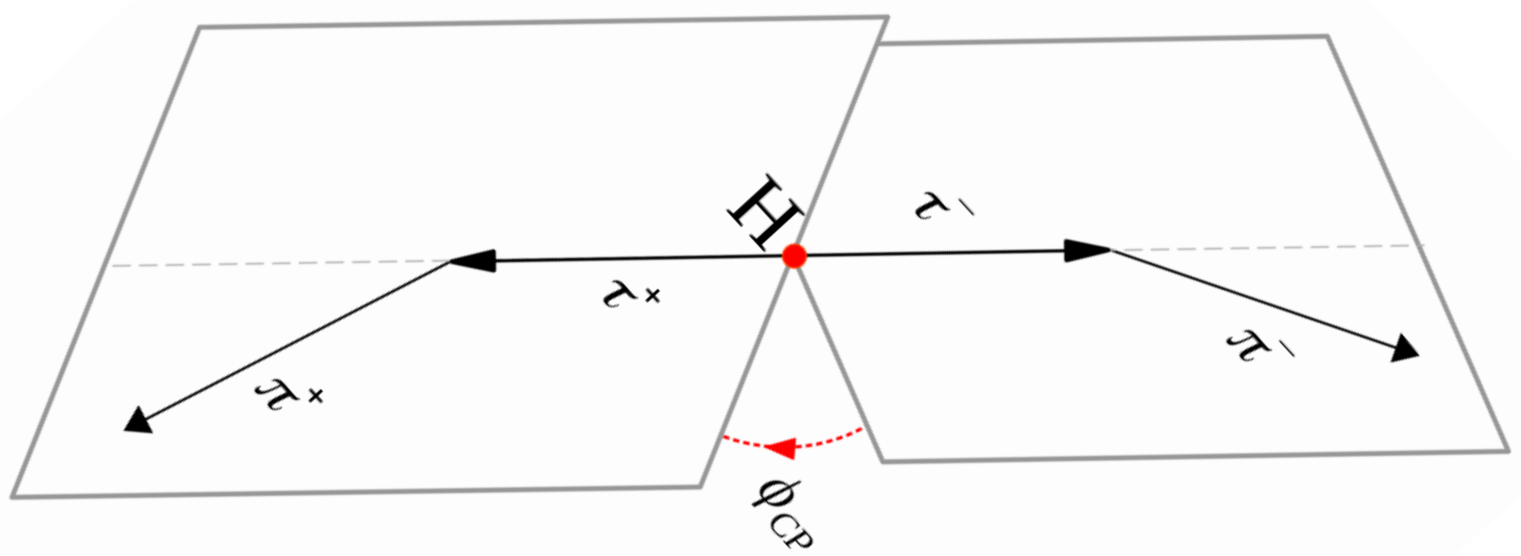
Combining Δφjj and H pT

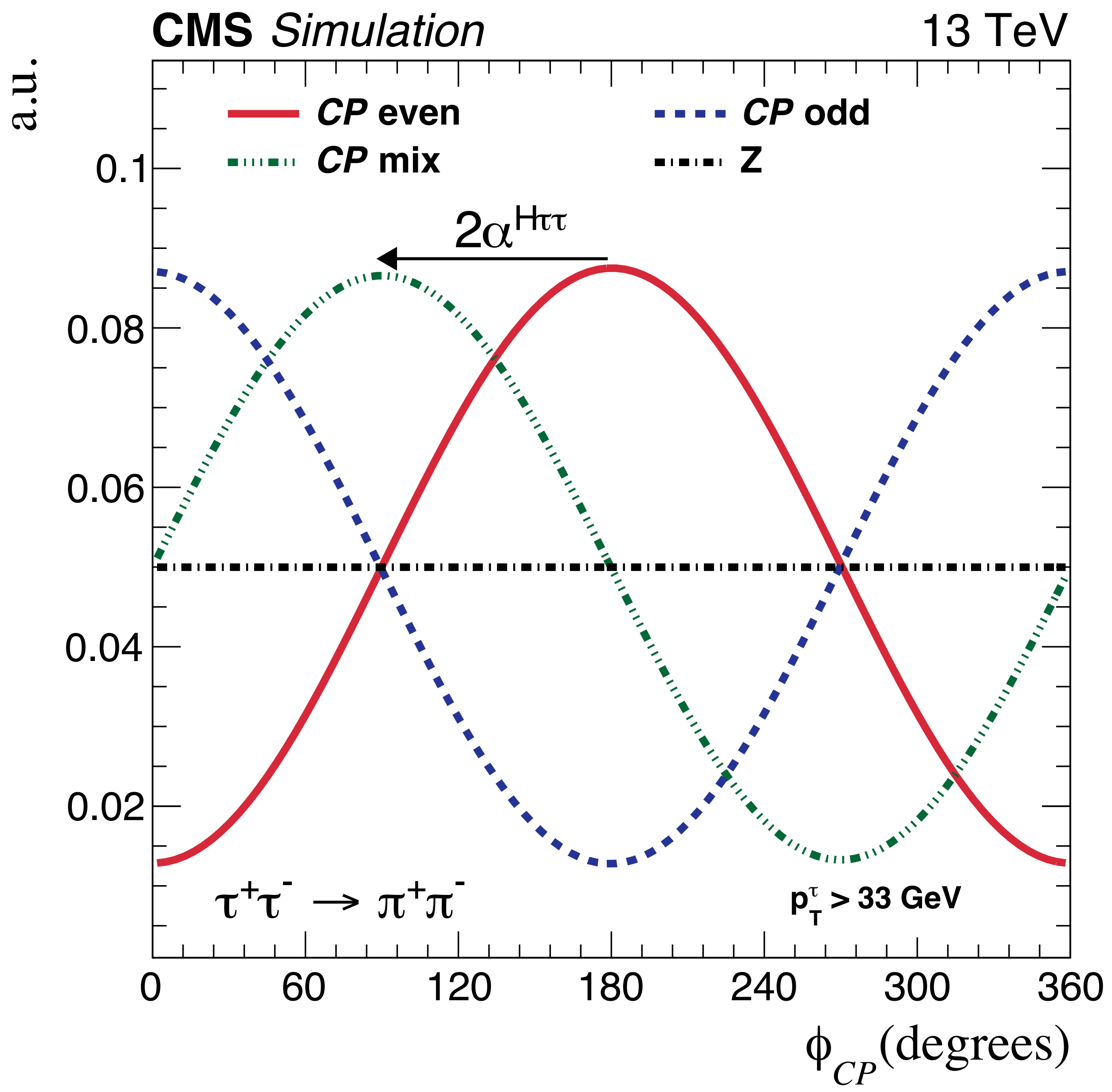
ATLAS, arXiv: 2504.07686



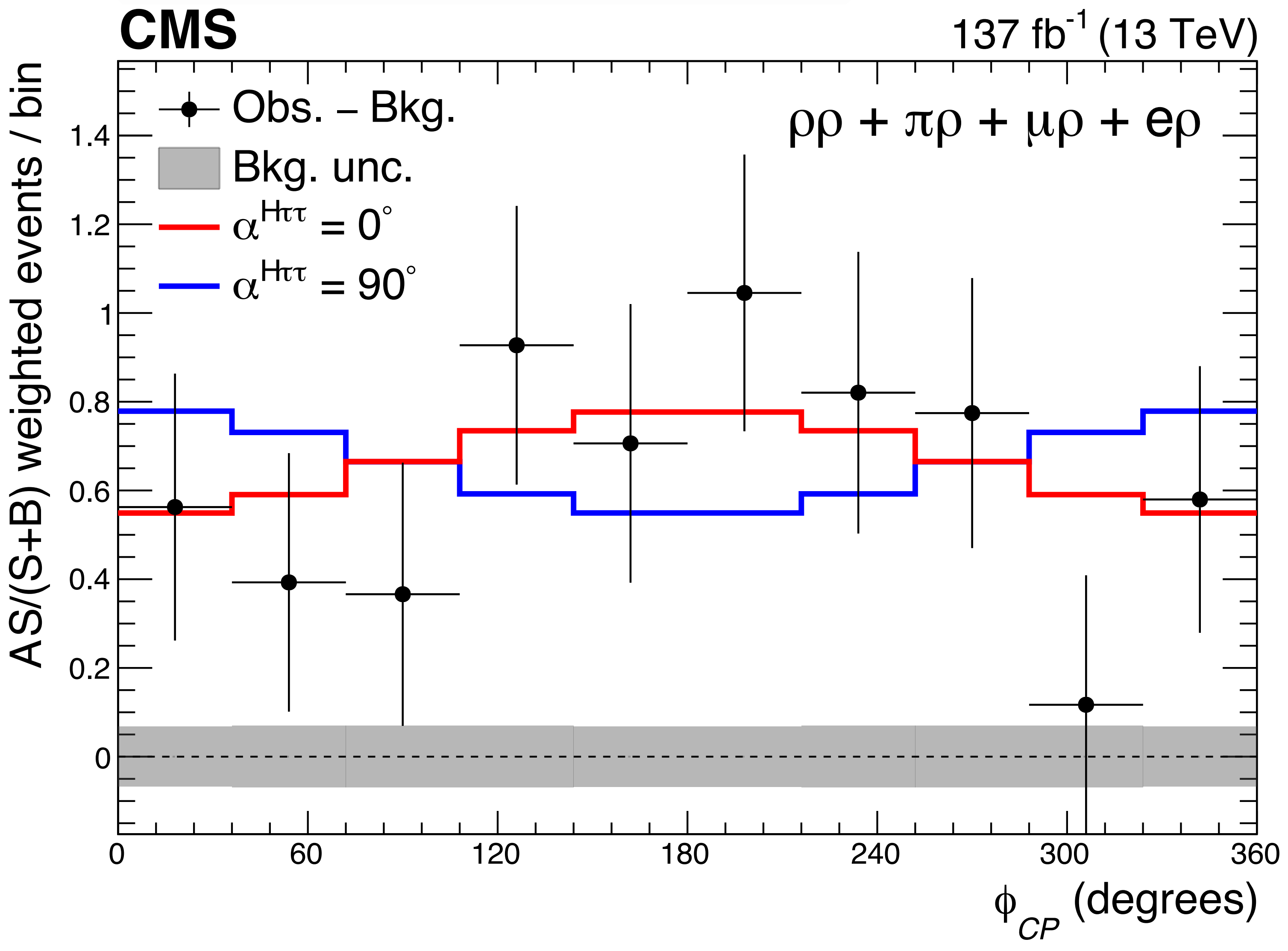


Hττ

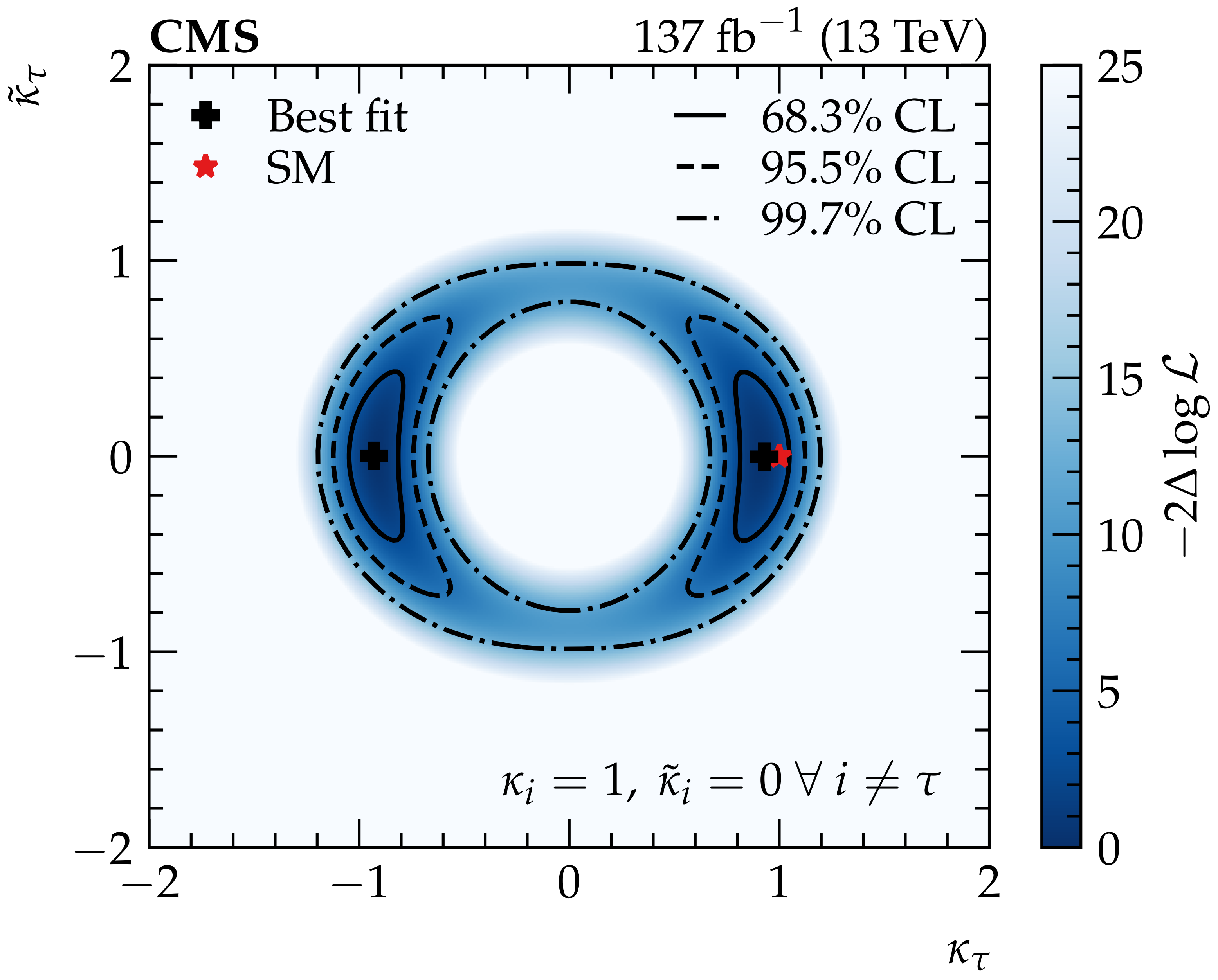




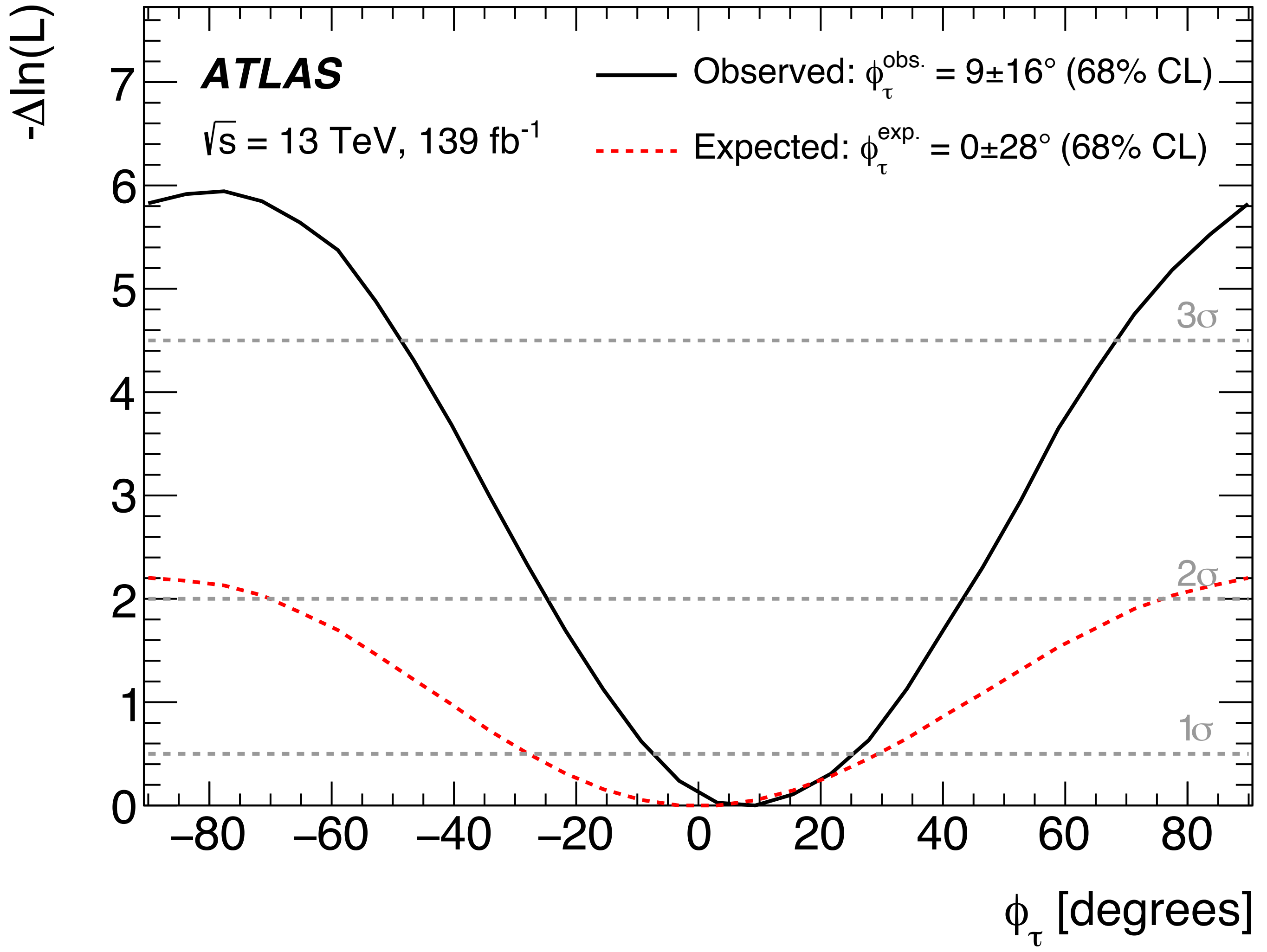
CMS, JHEP 06 (2022) 012
ATLAS, EPJC 83 (2023) 563



τ decay plane angle



$f_{CP} < 0.43$
CP odd excluded at 3σ



$f_{CP} < 0.31$
CP odd excluded at 3σ

Projected precision

arXiv: 2205.07715
Snowmass 2022 report

Collider	pp	pp	pp	e^+e^-	e^+e^-	e^+e^-	e^+e^-	e^-p	$\gamma\gamma$	$\mu^+\mu^-$	$\mu^+\mu^-$
E (GeV)	14,000	14,000	100,000	250	350	500	1,000	1,300	125	125	3,000
$\mathcal{L}$ (fb^{-1})	300	3,000	30,000	250	350	500	1,000	1,000	250	20	1,000
$Ht\bar{t}$	0.24	0.05	✓	–	–	0.29	0.08	✓	–	–	✓
$H\tau\tau$	0.07	0.008	✓	0.01	0.01	0.02	0.06	–	✓	✓	✓
$H\mu\mu$	–	–	–	–	–	–	–	–	–	✓	–

Conservative projection

Projected precision

arXiv: 2205.07715
Snowmass 2022 report

Collider	pp	pp	pp	e^+e^-	e^+e^-	e^+e^-	e^+e^-	e^-p	$\gamma\gamma$	$\mu^+\mu^-$	$\mu^+\mu^-$
E (GeV)	14,000	14,000	100,000	250	350	500	1,000	1,300	125	125	3,000
$\mathcal{L}$ (fb^{-1})	300	3,000	30,000	250	350	500	1,000	1,000	250	20	1,000
$Ht\bar{t}$	0.24	0.05	✓	–	–	0.29	0.08	✓	–	–	✓
$H\tau\tau$	0.07	0.008	✓	0.01	0.01	0.02	0.06	–	✓	✓	✓
$H\mu\mu$	–	–	–	–	–	–	–	–	–	✓	–

Conservative projection

Projected precision

arXiv:1310.8361
Snowmass 2013 report

	Collider	pp	pp	target
	E (GeV)	14,000	14,000	(theory)
	$\mathcal{L}$ (fb^{-1})	300	3,000	
	spin-2^+_m	$\sim 10\sigma$	$\gg 10\sigma$	$> 5\sigma$
H→ZZ	$VVH^\dagger$	0.07	0.02	$< 10^{-5}$
VH	$VVH^\ddagger$	$4 \cdot 10^{-4}$	$1.2 \cdot 10^{-4}$	$< 10^{-5}$
VBF	$VVH^\diamond$	$7 \cdot 10^{-4}$	$1.3 \cdot 10^{-4}$	$< 10^{-5}$

In a projection 10 years ago, the precision to be expected at 300 fb^{-1} has been reached at 138 fb^{-1}

Summary

- A rich program at the CMS probing CPV in the Higgs sector
- With various new developments, HVV has been close to 10% mixture precision
- For Hff, with more data and new improvements, 10% mixture should be reachable with Run3 data

Additional slides

AC and WC conversion

$$g_4^{ZZ} = -2\frac{v^2}{\Lambda^2}\left(s_w^2 w_{\phi\tilde{B}} + c_w^2 w_{\phi\tilde{W}} + s_w c_w w_{\phi B\tilde{W}}\right)$$