Search for CP violation in the Higgs sector at CMS

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FIND CP violation at electroweak scale and beyond, USTC, 2023.08.25

CPV in Higgs

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

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

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

SM: CP-even=1, CP-odd=0

BSM: EW Baryongenis, add CPV in Higgs sector

- 2HDM, EW singlets….

Experiment: model independent measurement of the coefficients

Current status

✓ Run1 (blue)
✓ Run2 (red)

HVV		Hff	
HZZ	✓ (Run1)	Htt	✓ (Run2)
HWW	✓ (Run1)	Hττ	✓ (Run2)
Hγγ	✓ (Run1)	Hbb	
Hgg	✓ (Run2)	Hμμ	
HZγ	✓ (Run1)		

Current status

✓ Run1
✓ Run2

HVV

HZZ ✓	H→ZZ	VBF, VH, H→anything	Off-shell H→ZZ
	PRD 92 (2015) 012004	bb: PLB 759 (2016) 672 4l: PLB 775 (2017) 1 ττ: PRD 100 (2019) 112002 4l: PRD 104 (2021) 052004 ττ: PRD 108 (2023) 032013	4l: PRD 99 (2019) 112003 4l+2l2v: Nat. Phys. 18 (2022) 1329
CP-odd xsec fraction: fa3	< 0.4	$< 1.7 \times 10^{-3}$	$< 1 \times 10^{-3}$

What's the needed precision

arXiv:1310.8361
Snowmass 2013 report

Collider	pp	pp	fa3: target (theory)
E (GeV)	14,000	14,000	
$\mathcal{L}$ (fb^{-1})	300	3,000	
spin-2^+_m	$\sim 10\sigma$	$\gg 10\sigma$	$>5\sigma$
$VVH^{\dagger}$	0.07	0.02	$< 10^{-5}$
$VVH^{\ddagger}$	$4 \cdot 10^{-4}$	$1.2 \cdot 10^{-4}$	$< 10^{-5}$
$VVH^{\diamond}$	$7 \cdot 10^{-4}$	$1.3 \cdot 10^{-4}$	$< 10^{-5}$

10% mixture of CP-odd state

Suppressed xsec of CP-odd

VBF and VH

CP-odd xsec increase with energy scale

VH，VBF: higher energy scale

arXiv:1310.8361

Snowmass 2013 report

Collider	pp	pp	target
E (GeV)	14,000	14,000	(theory)
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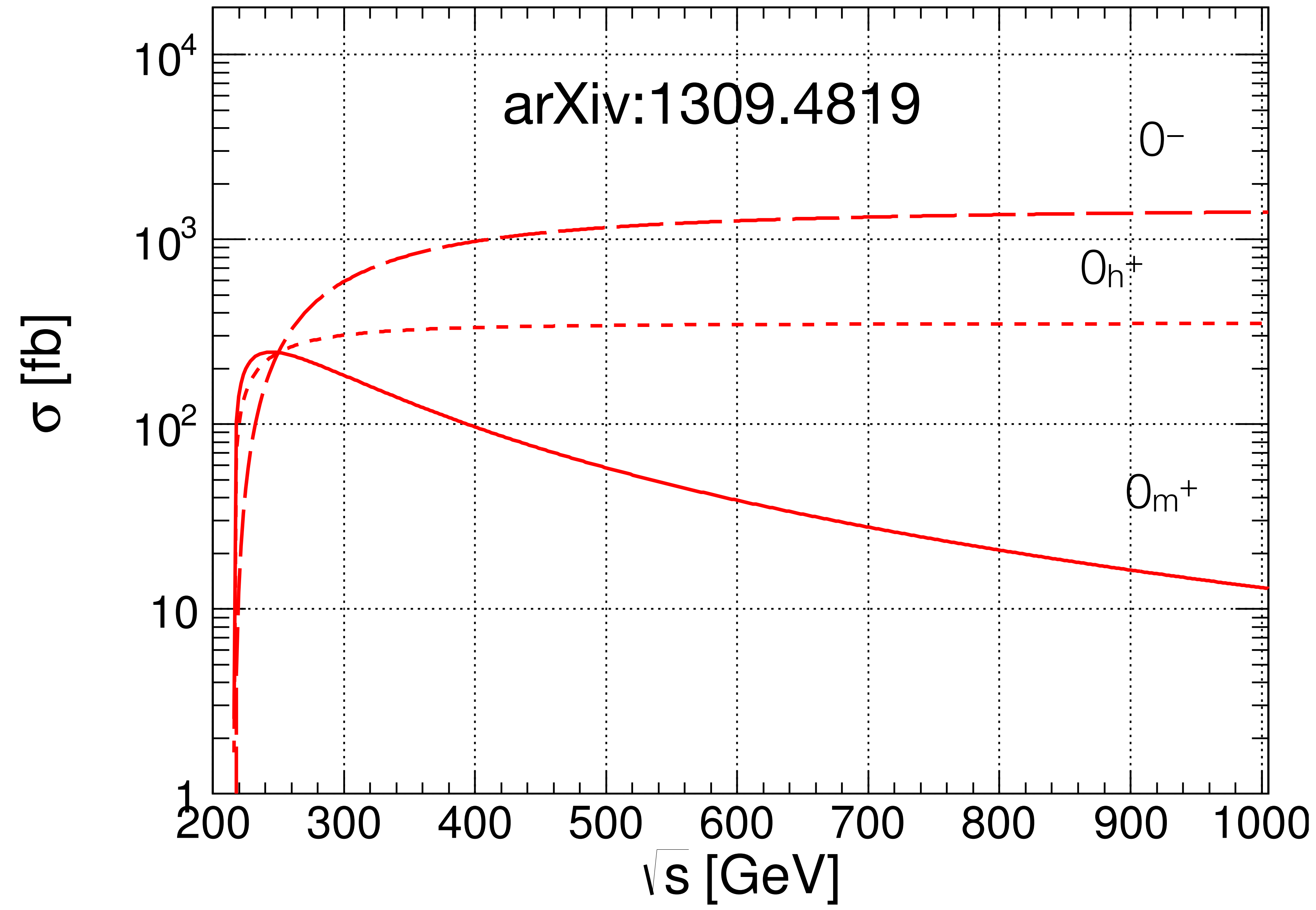
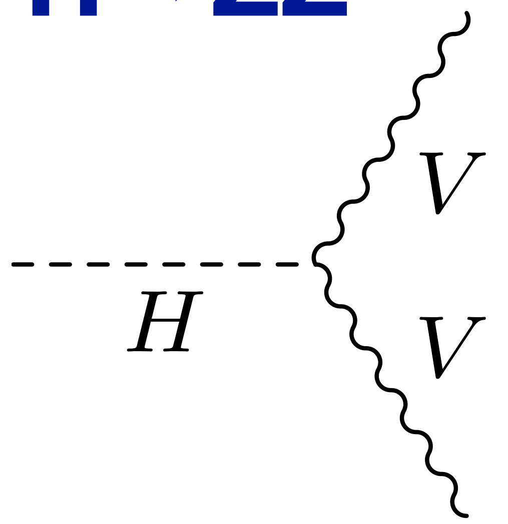
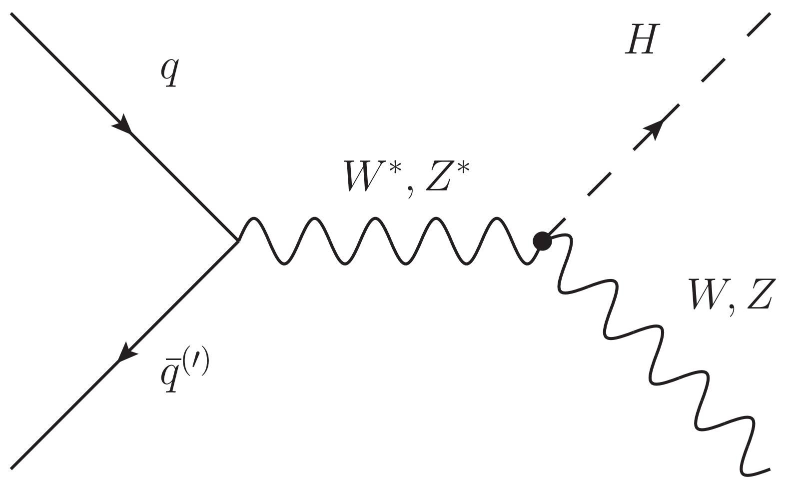
H→ZZ
VH
VBF



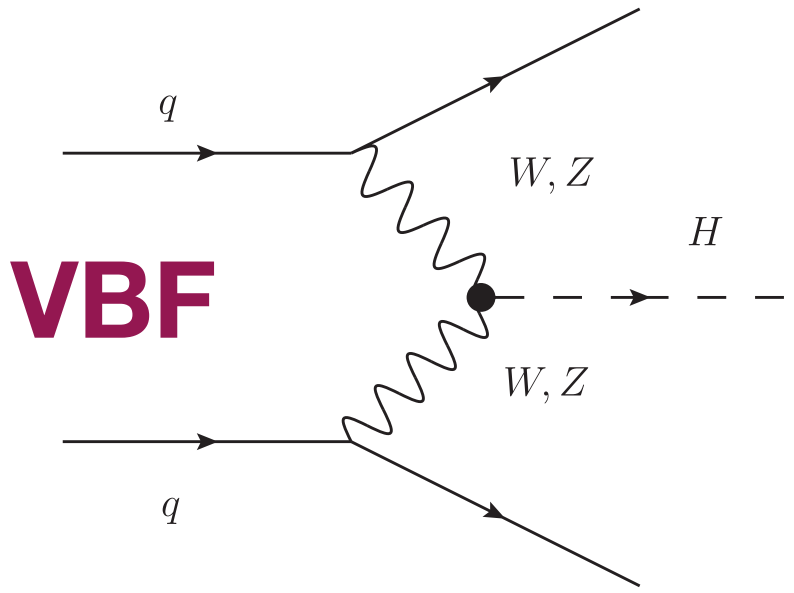
H→ZZ



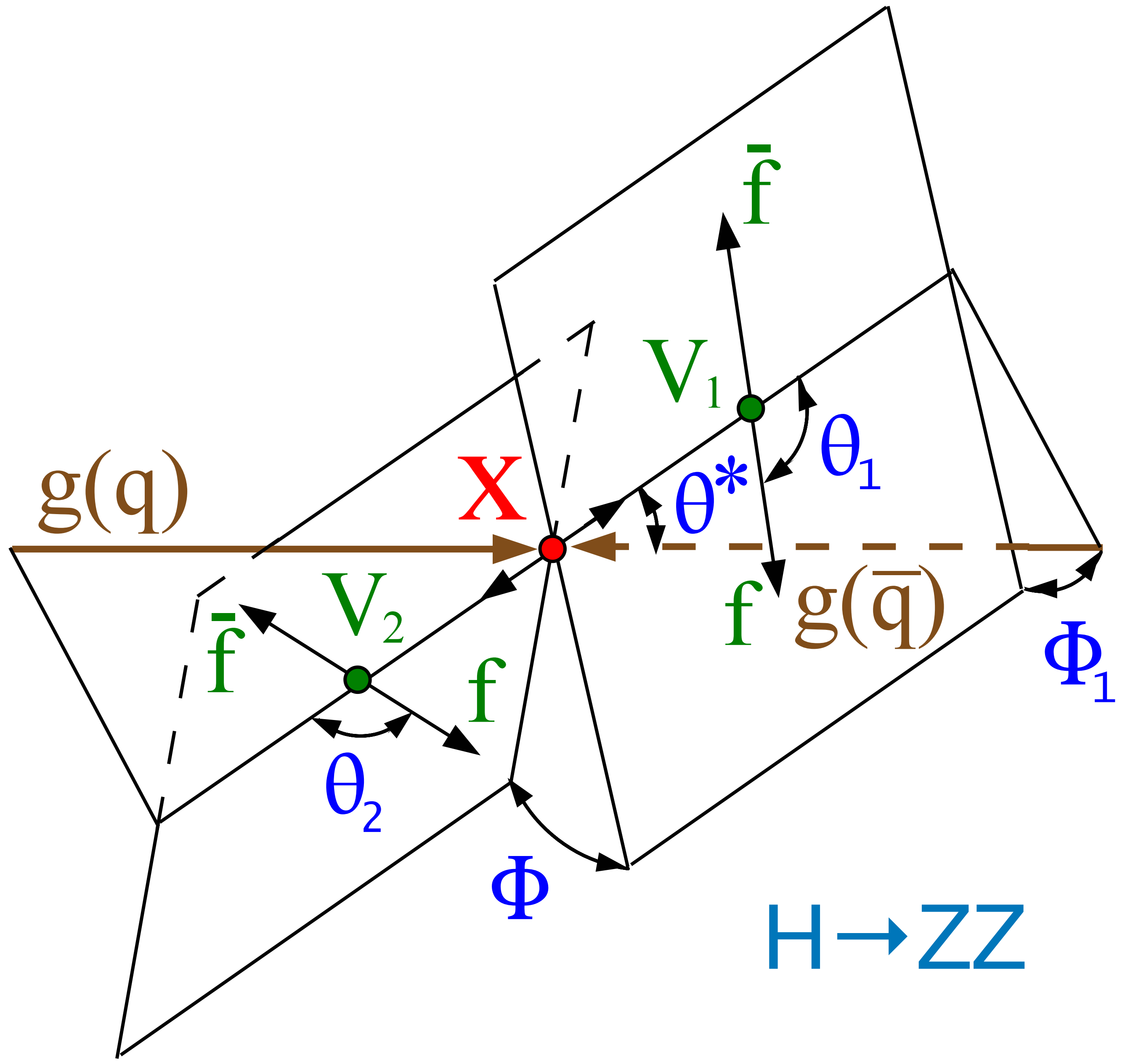
VH

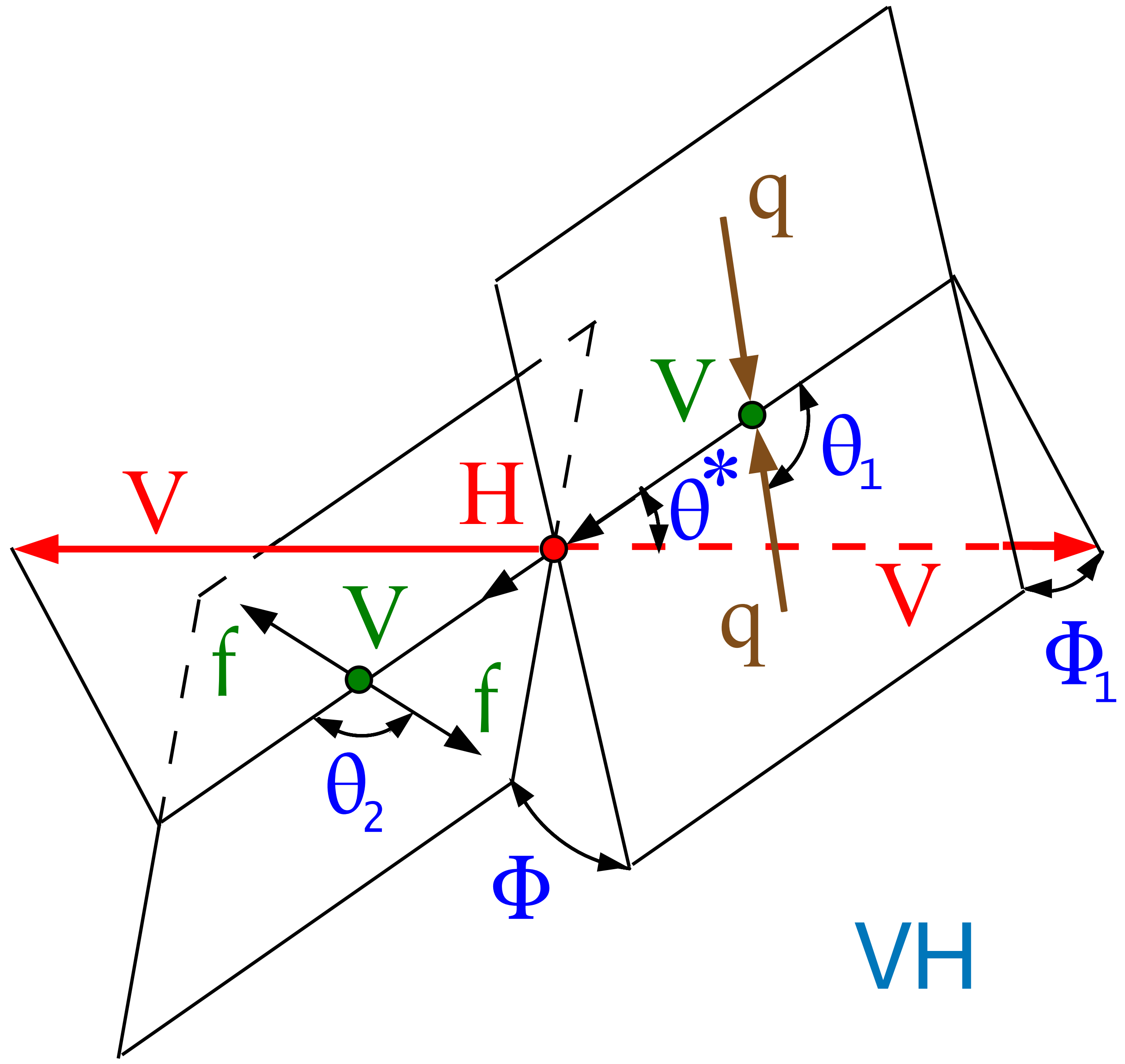


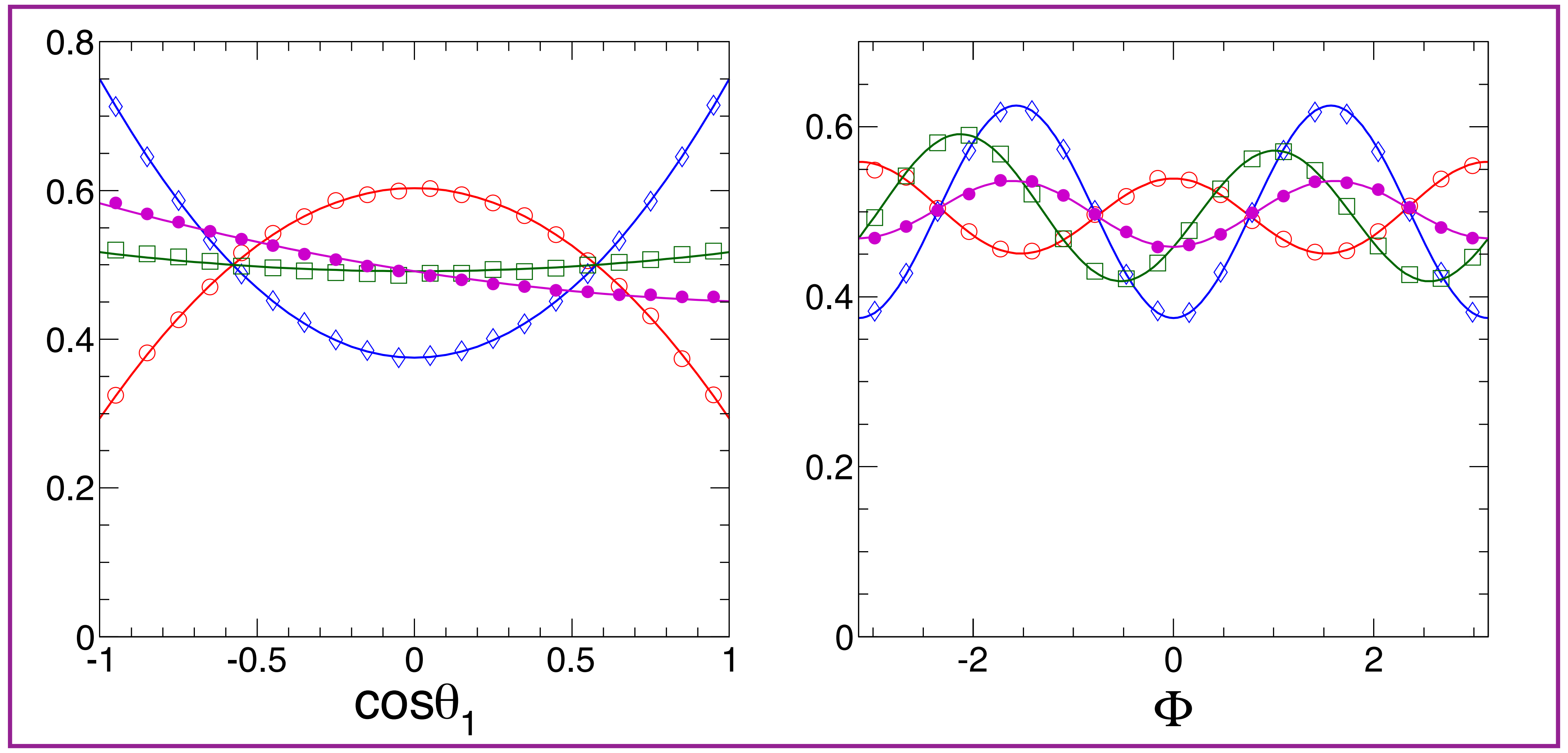
VBF

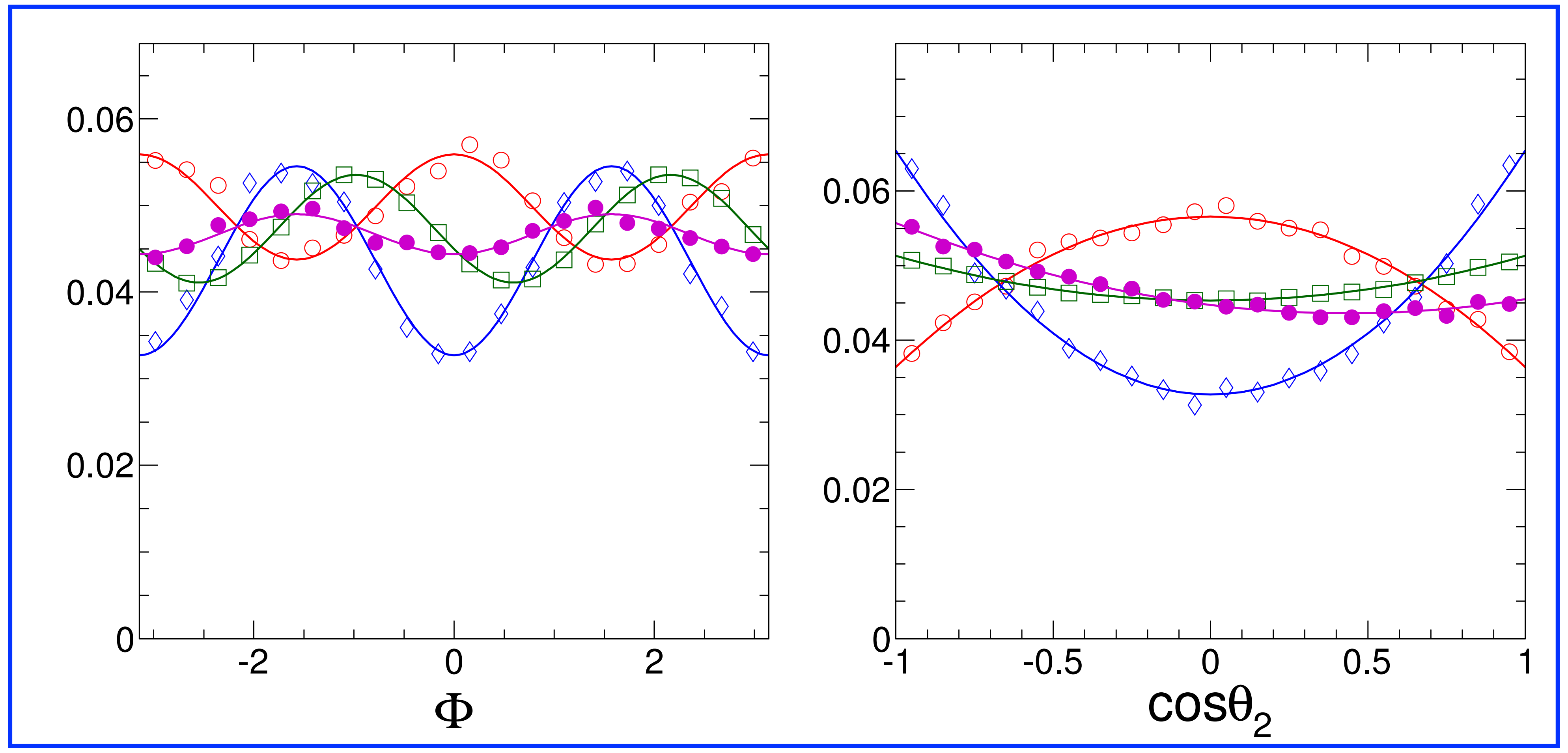


HVV, H→ 4l


g(q)
X
V1
f̄
θ1
θ*
f
g(q̄)
Φ1
V2
f̄
f
θ2
Φ
H→ZZ

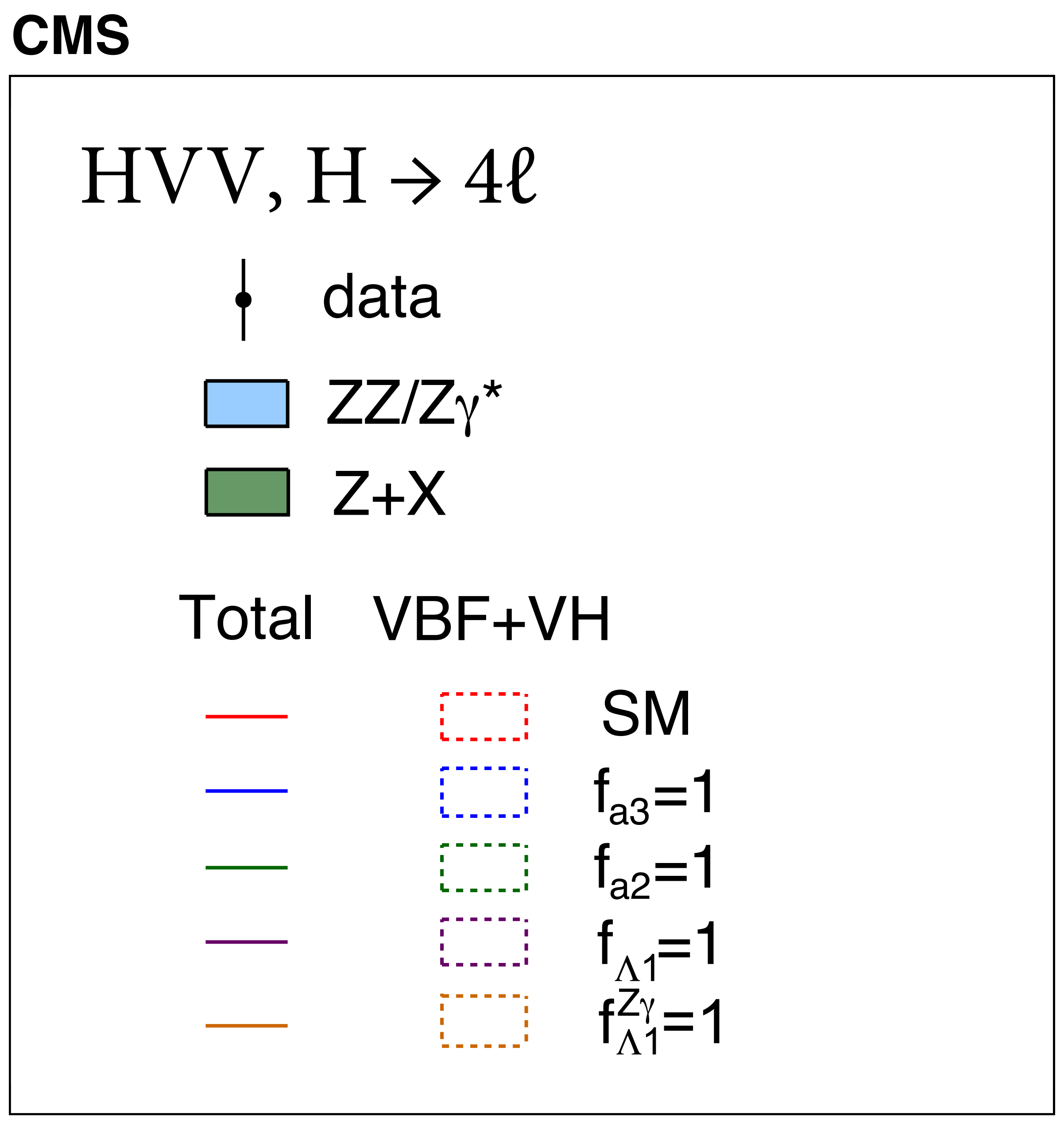

V
H
q
V
θ1
θ*
q
V
Φ1
V
f
f
θ2
Φ
VH


cosθ1
Φ

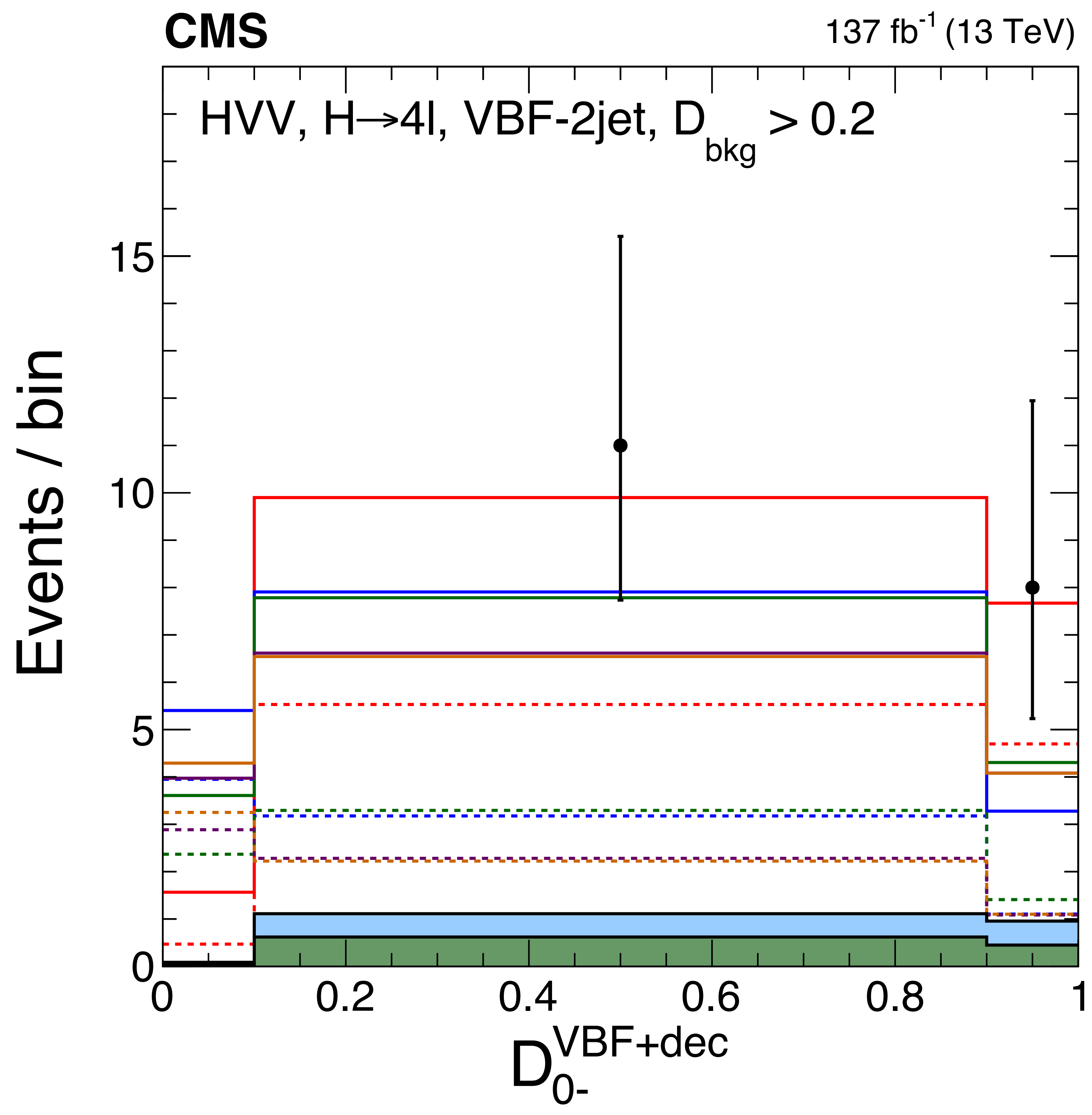

Φ
cosθ2

ME based observables

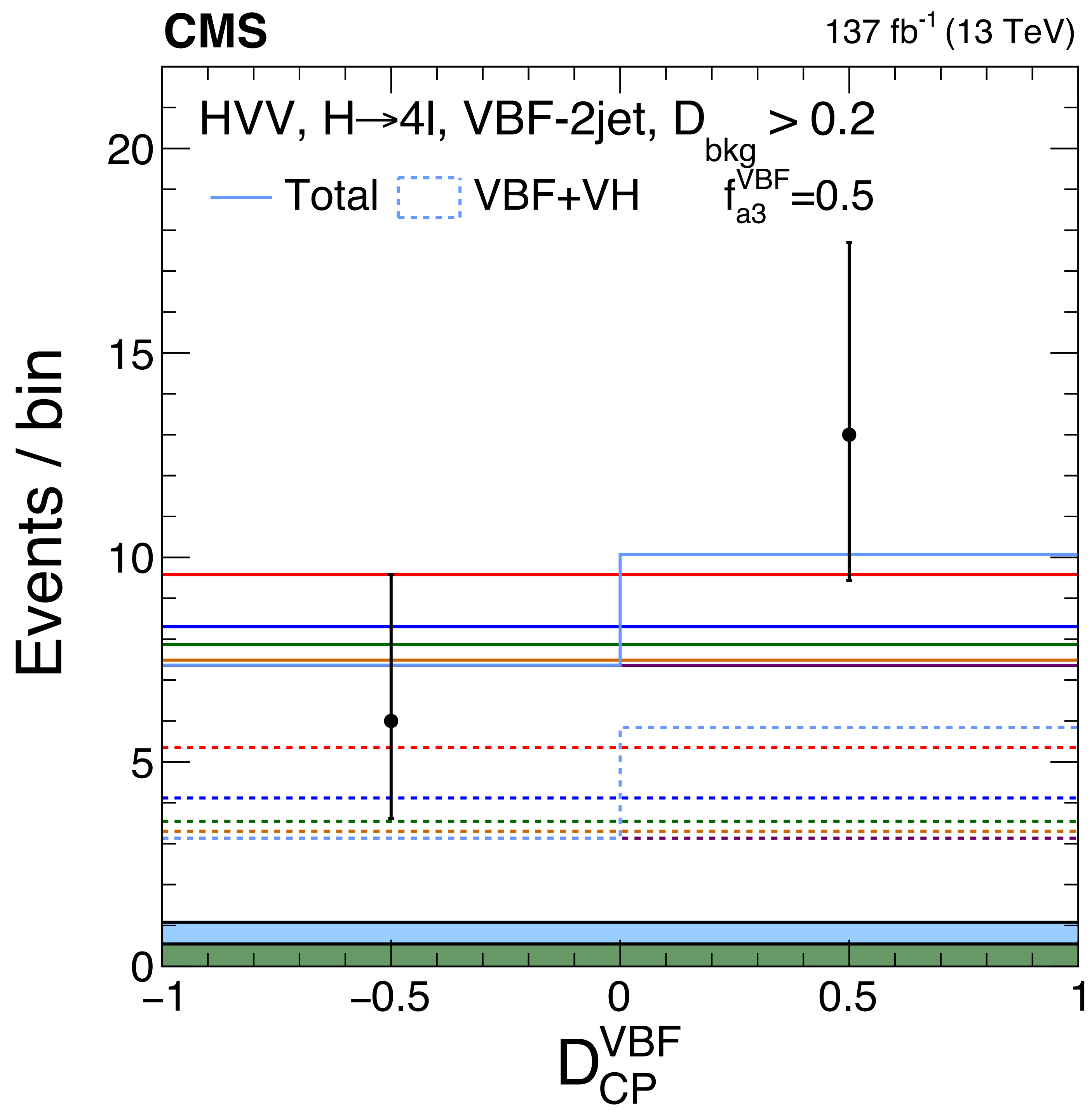
PRD 104 (2021) 052004



CP-even vs CP-odd

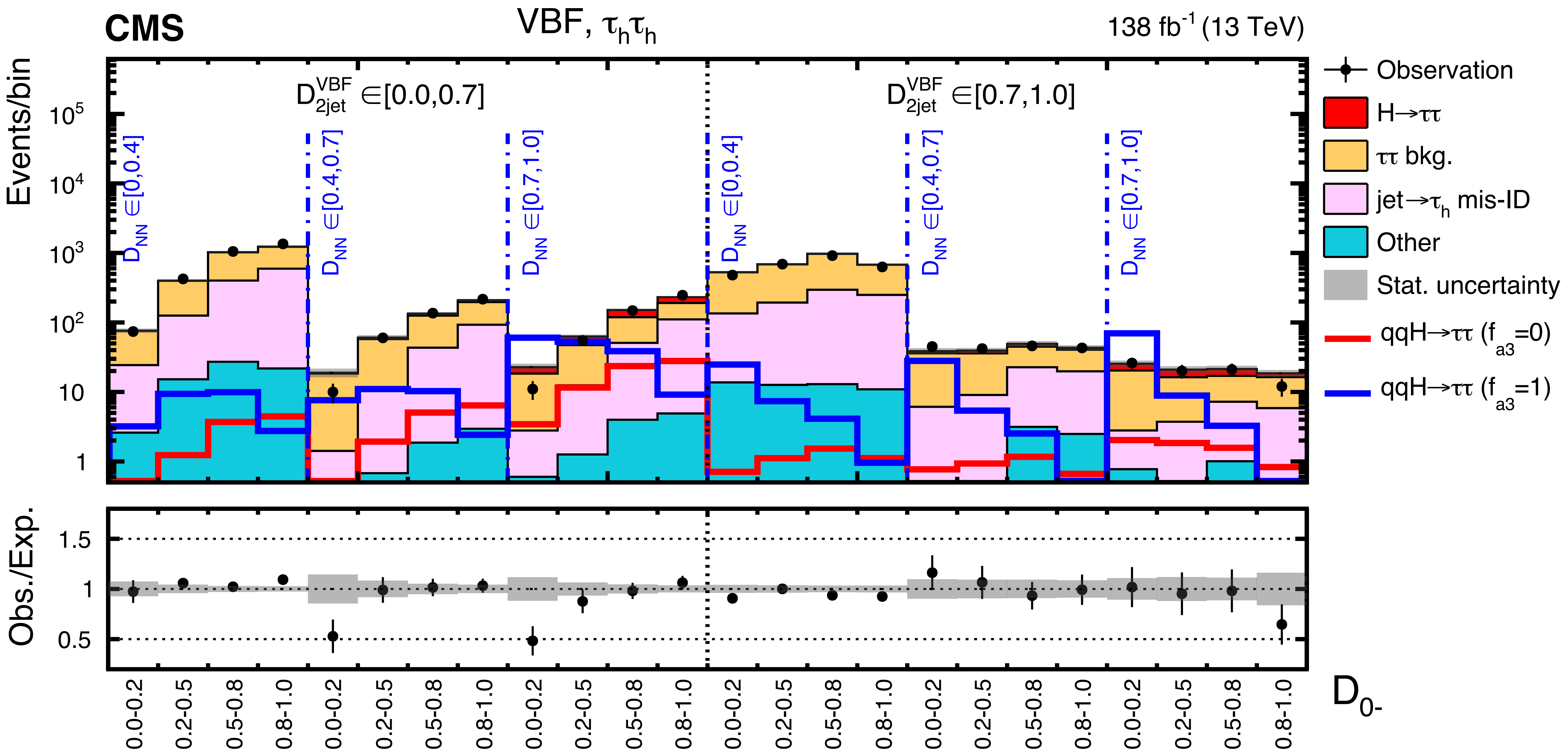


CPV



VVH, H→ττ

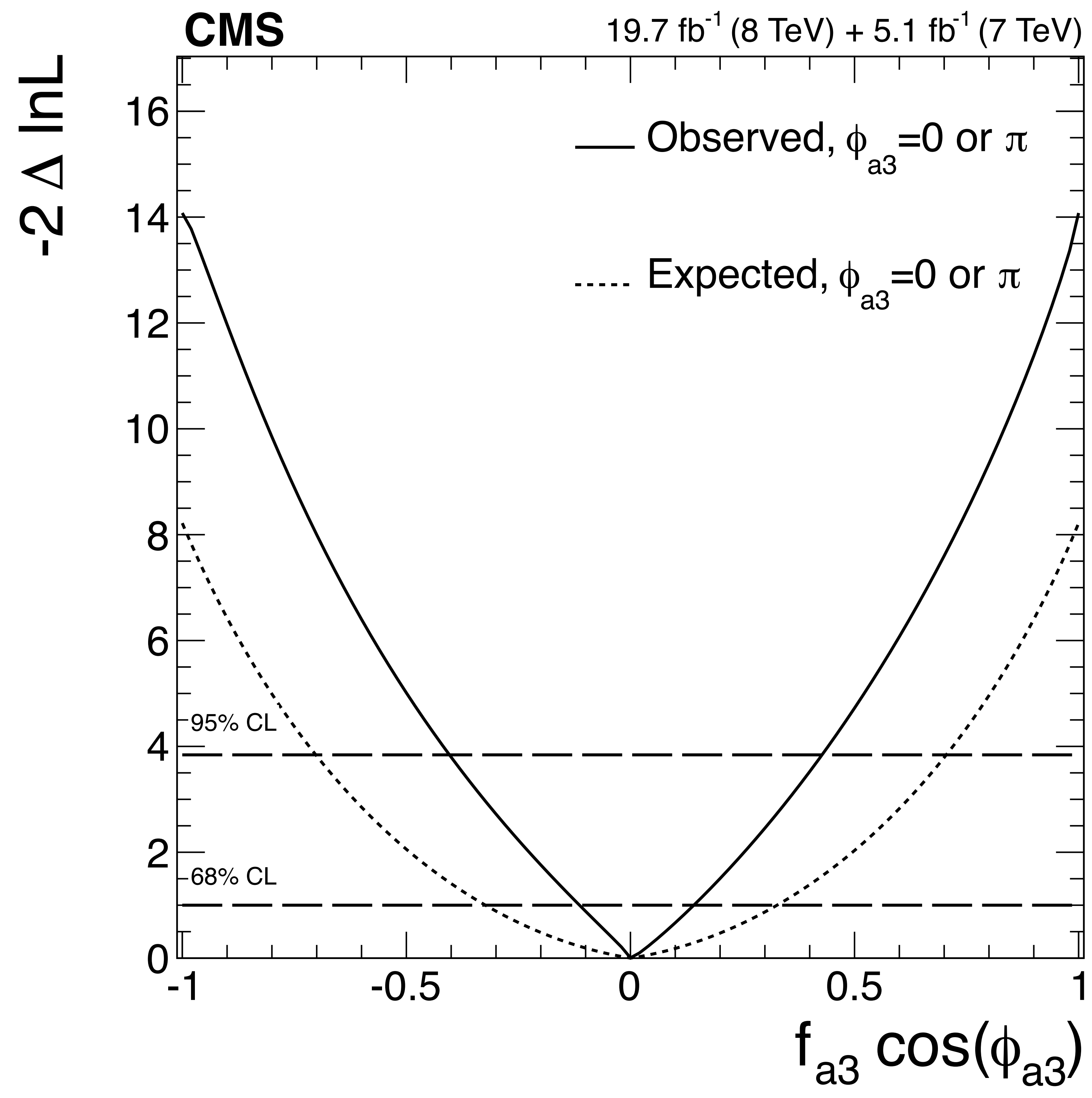
PRD 108 (2023) 032013



ME based observable, CP-even vs CP-odd

VVH

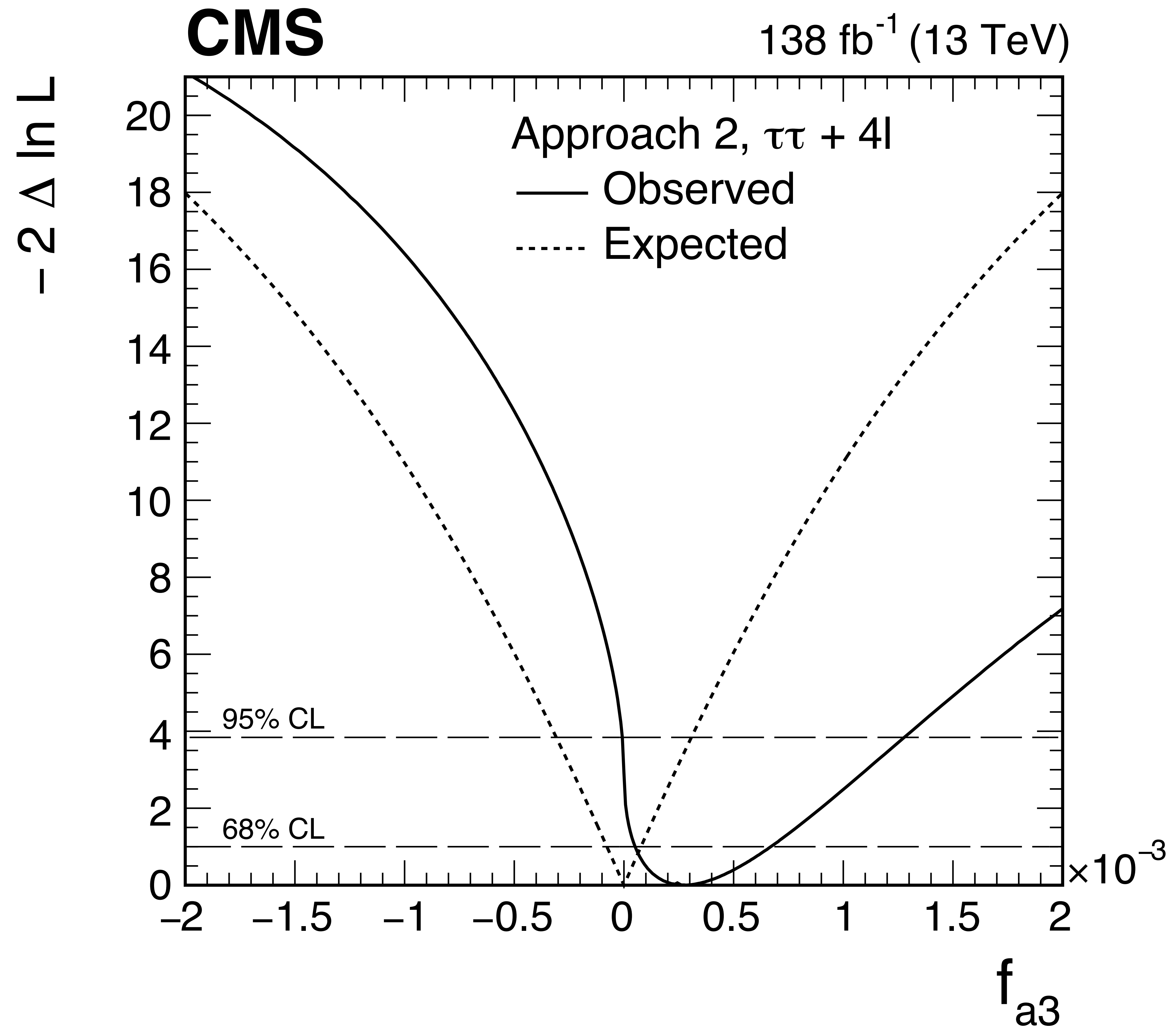
PRD 92 (2015) 012004



H→ 4l

< 0.4

PRD 108 (2023) 032013

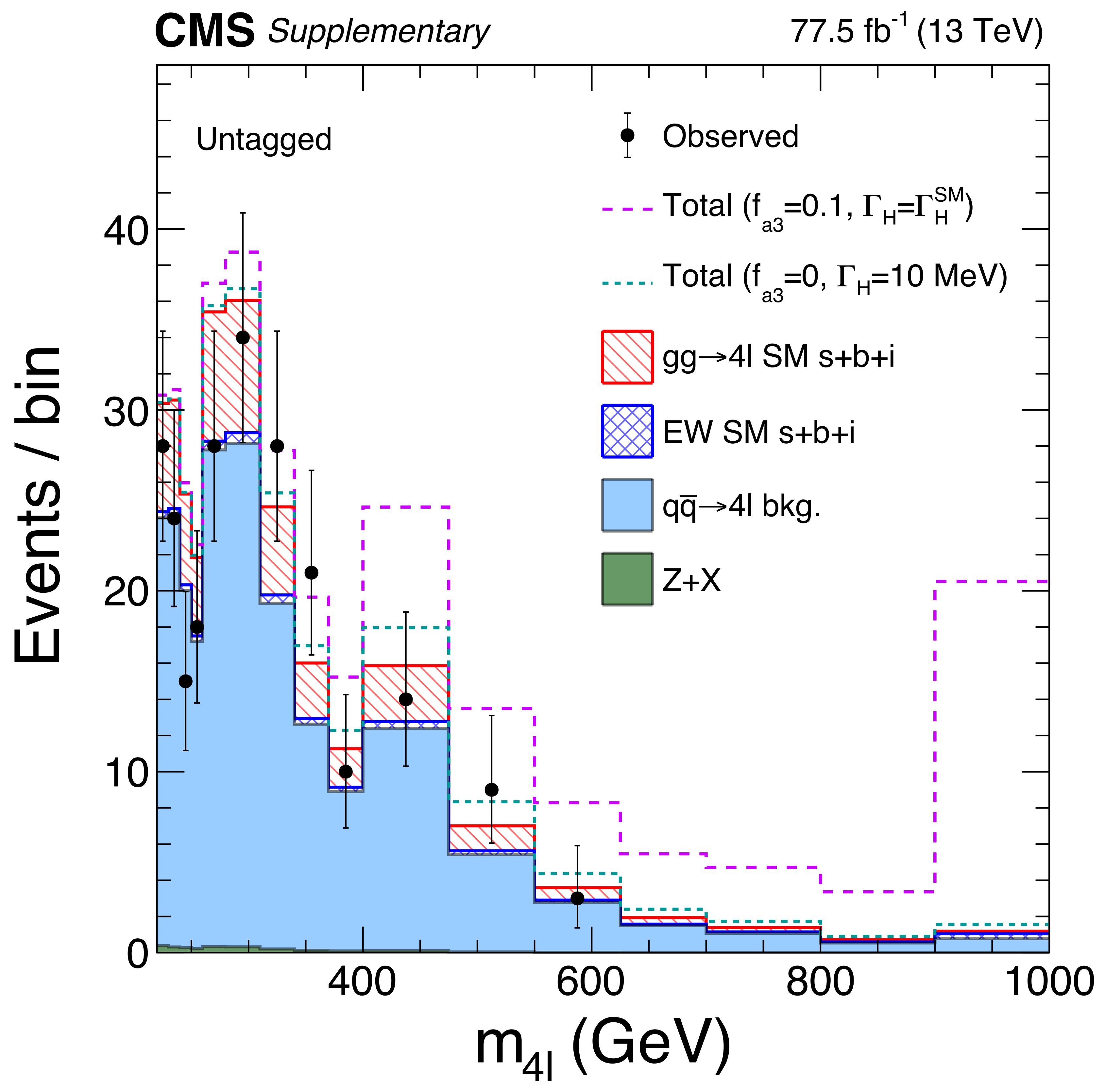


VBF, H→ ττ + 4l

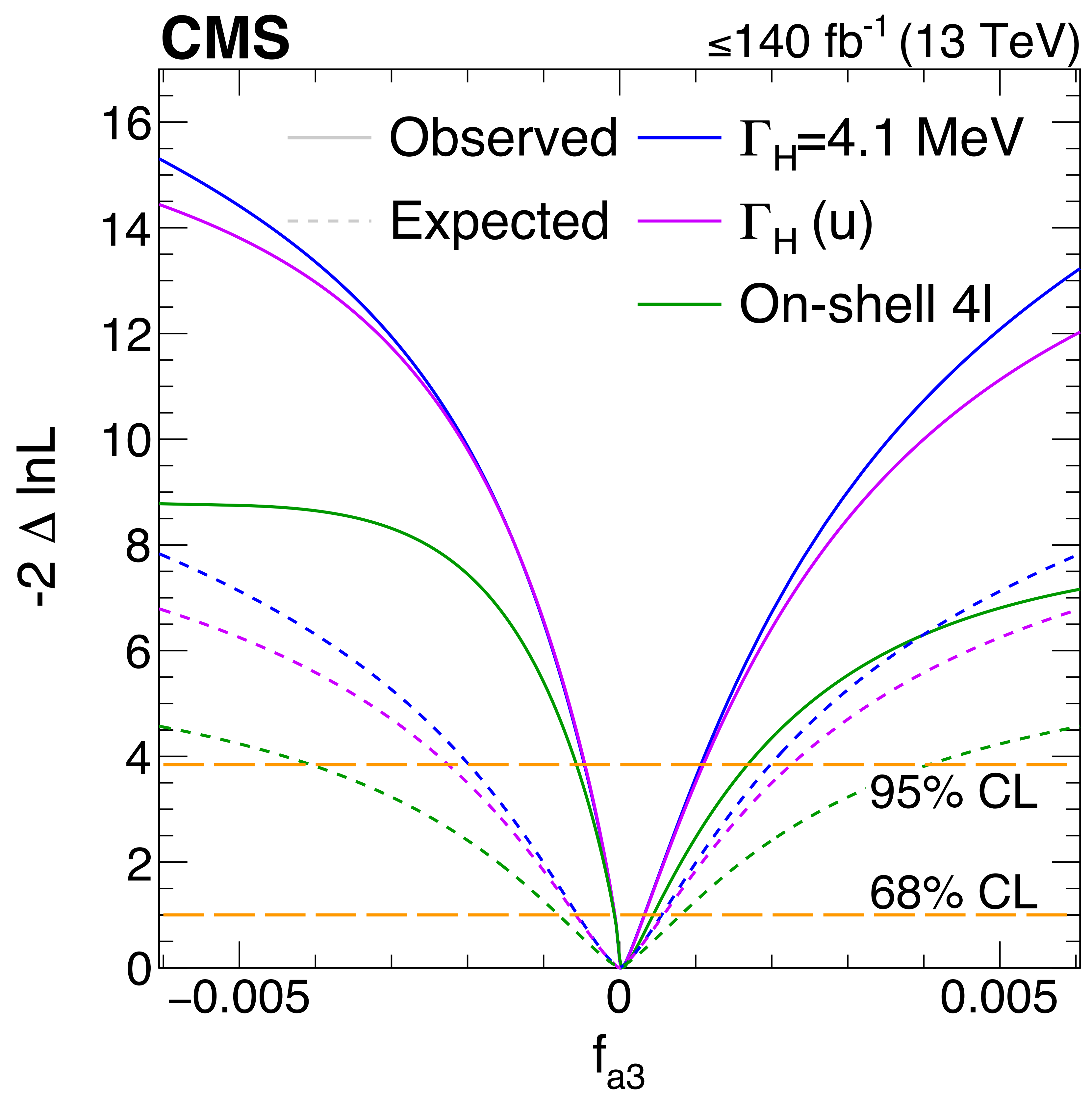
< 1.7 x 10^{-3}

Off-shell HVV

PLB 775 (2017) 1



Nat. Phys. 18 (2022) 1329



Hff CPV

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

ggH
4l: PRD 104 (2021) 052004
ττ: PRD 108 (2023) 032013

ττH
JHEP 06 (2022) 012

ttH
γγ: PRL 125 (2020) 061801
4l: PRD 104 (2021) 052004
multilepton: JHEP 07 (2023) 092
bb: CMS-PAS-HIG-19-011

arXiv:1310.8361
Snowmass 2013 report

Collider	pp	pp	target
E (GeV)	14,000	14,000	(theory)
$\mathcal{L}$ (fb^{-1})	300	3,000	
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$VVH^\diamond$	$7 \cdot 10^{-4}$	$1.3 \cdot 10^{-4}$	$< 10^{-5}$
ggH	0.50	0.16	$< 10^{-2}$
$\gamma\gamma H$	–	–	$< 10^{-2}$
$Z\gamma H$	–	✓	$< 10^{-2}$
$\tau\tau H$	✓	✓	$< 10^{-2}$
ttH	✓	✓	$< 10^{-2}$
$\mu\mu H$	–	–	$< 10^{-2}$

CP-odd and even same order

Which Yukawa couplings are possible

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

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

- Need polarization information if u does not decay

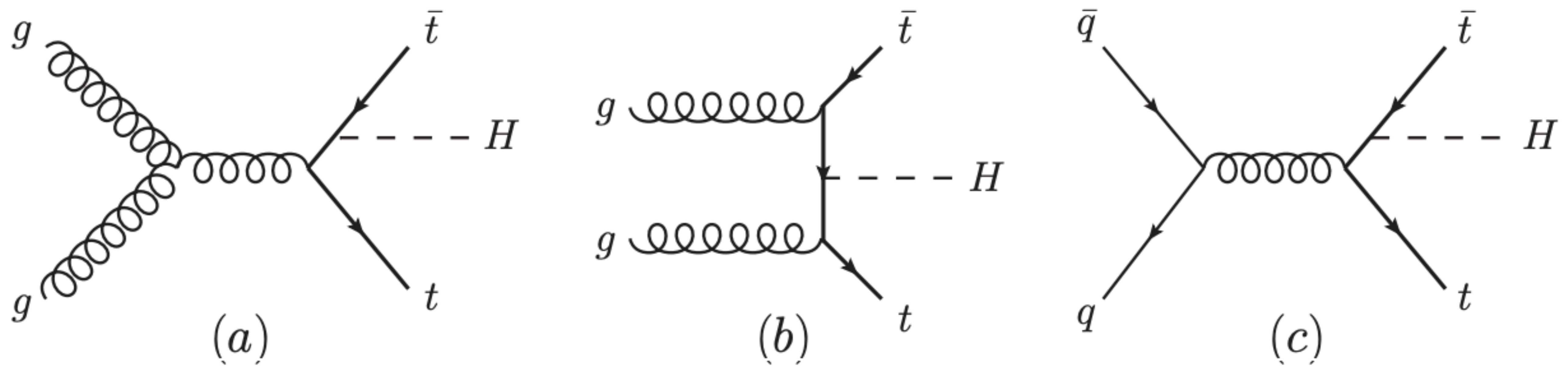
$$\sigma_{\text{pol}}(\zeta) = \sigma_{\text{unpol}}\left(1 + P_L^+ P_L^- + P_T^+ P_T^- \left[\frac{(b_1^{H\mu\mu})^2 - (b_2^{H\mu\mu})^2}{(b_1^{H\mu\mu})^2 + (b_2^{H\mu\mu})^2}\cos\zeta - \frac{2b_1^{H\mu\mu}b_2^{H\mu\mu}}{(b_1^{H\mu\mu})^2 + (b_2^{H\mu\mu})^2}\sin\zeta\right]\right),$$

- Possible to measure at the LHC: tt, ττ

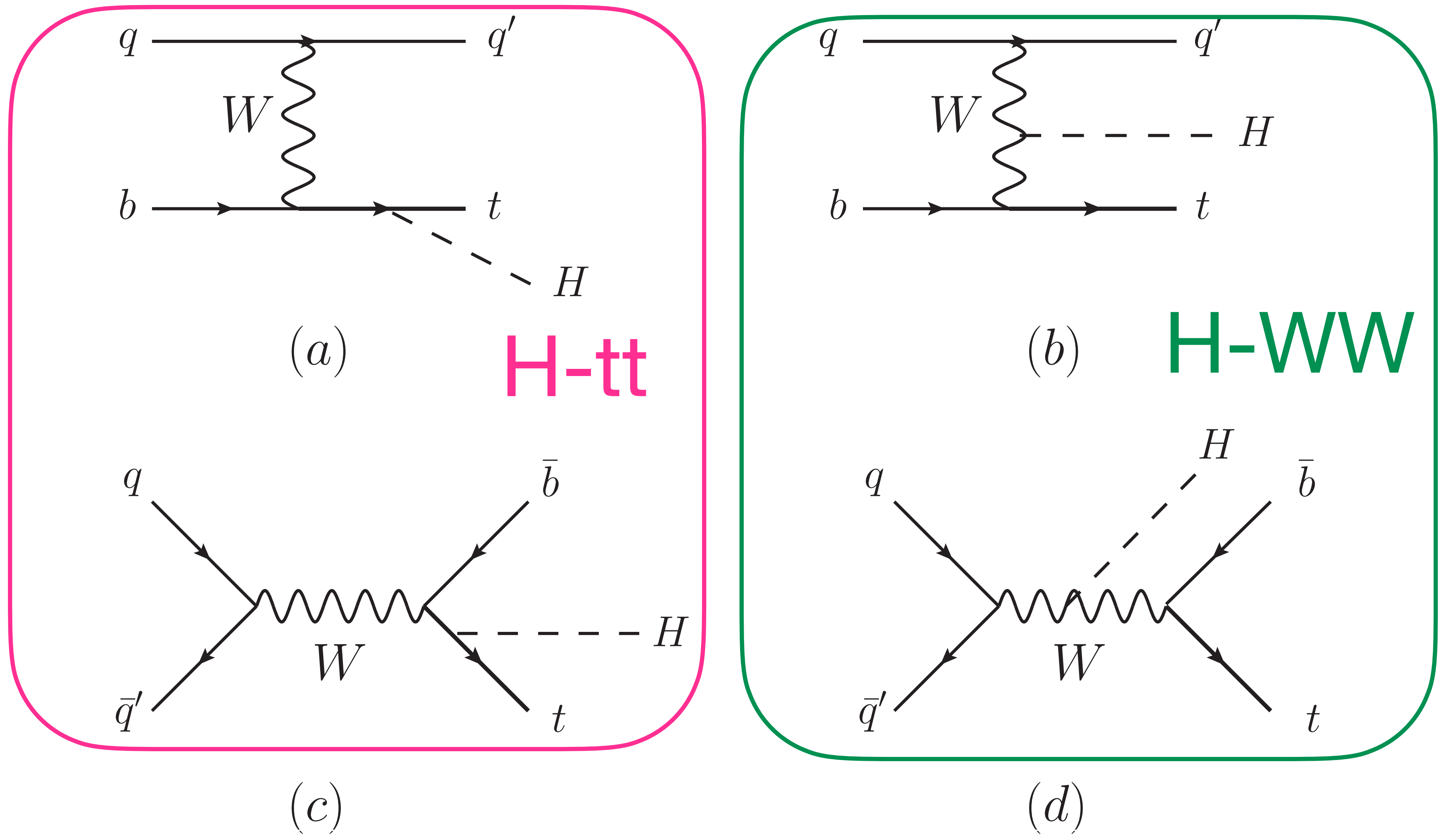
arXiv: 2205.07715
Snowmass 2022 report

Htt measurement with ttH

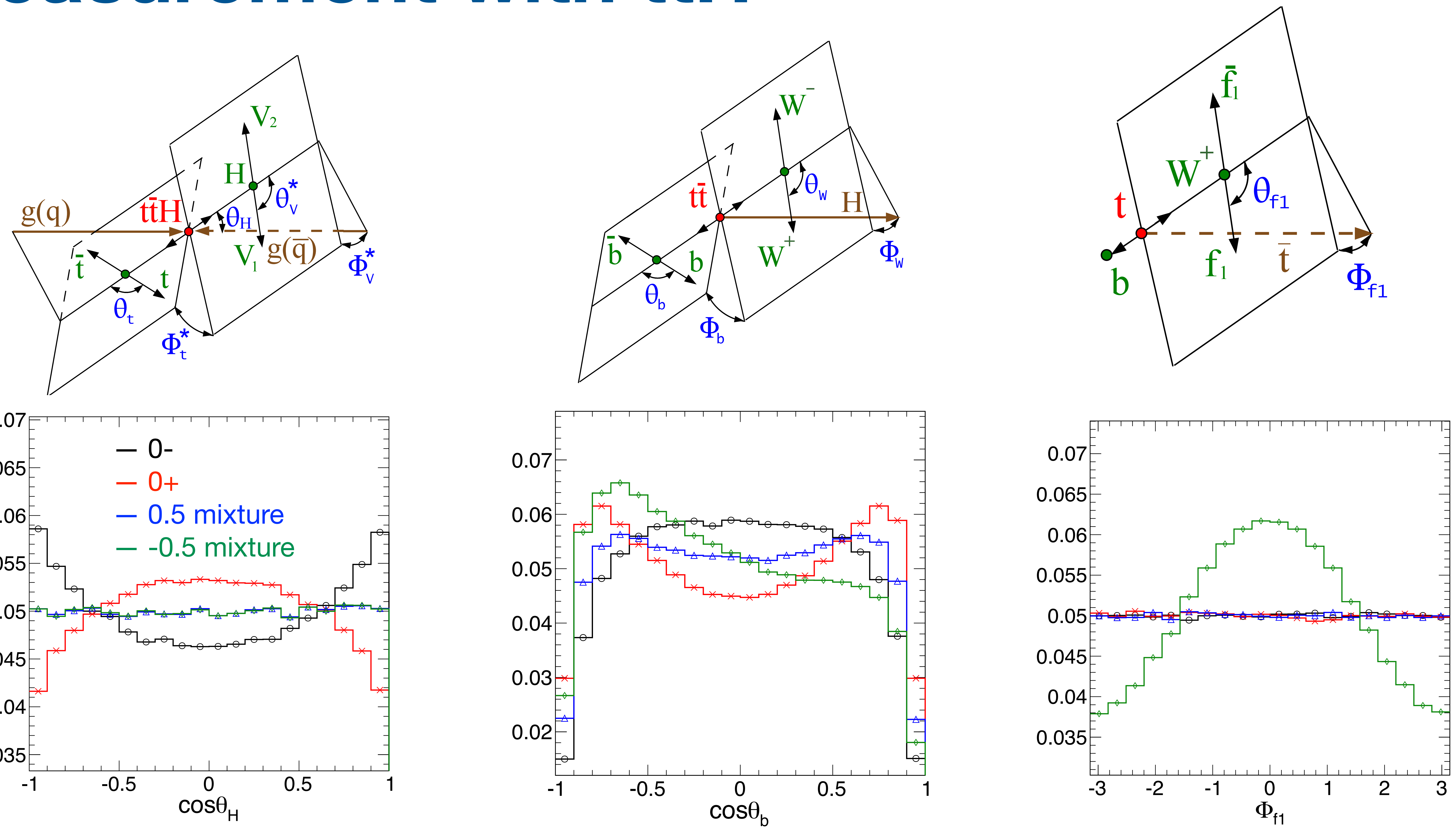
ttH: fourth production xsec of the Higgs at the LHC



tH: small xsec due to negative interference



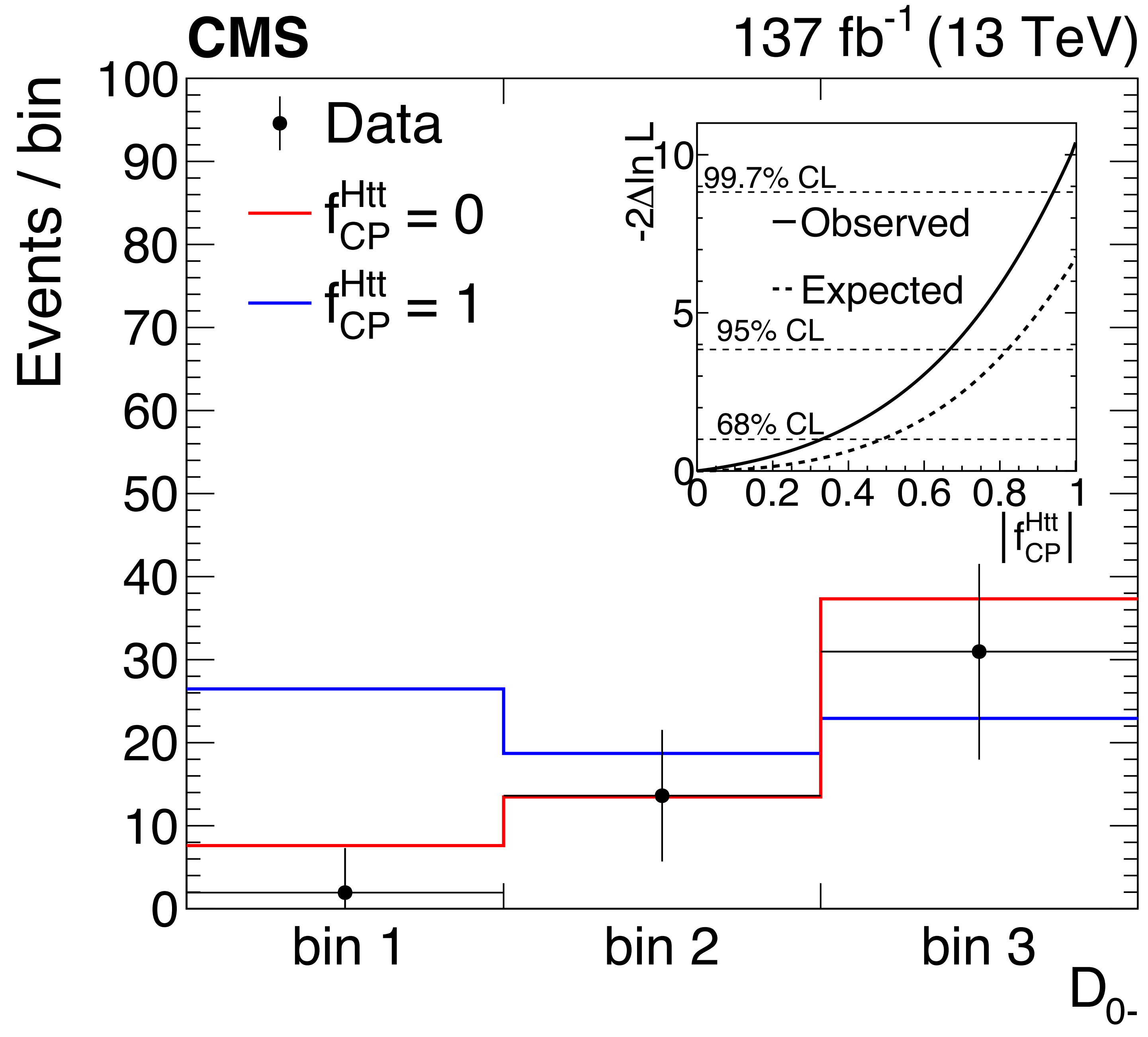
Htt measurement with ttH



- Multiple decay planes

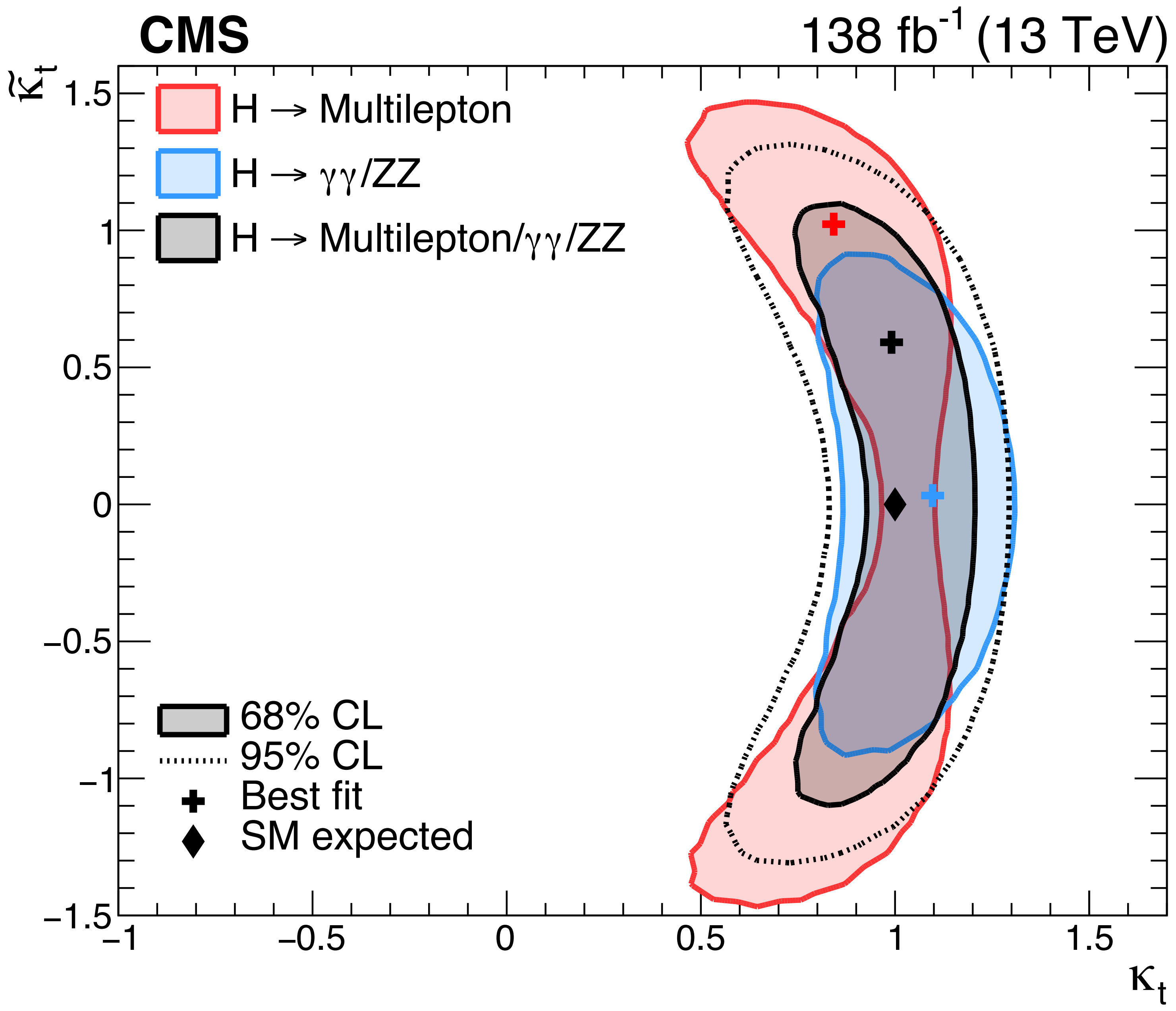
Htt measurement with ttH

H→ γγ



PRL 125 (2020) 061801

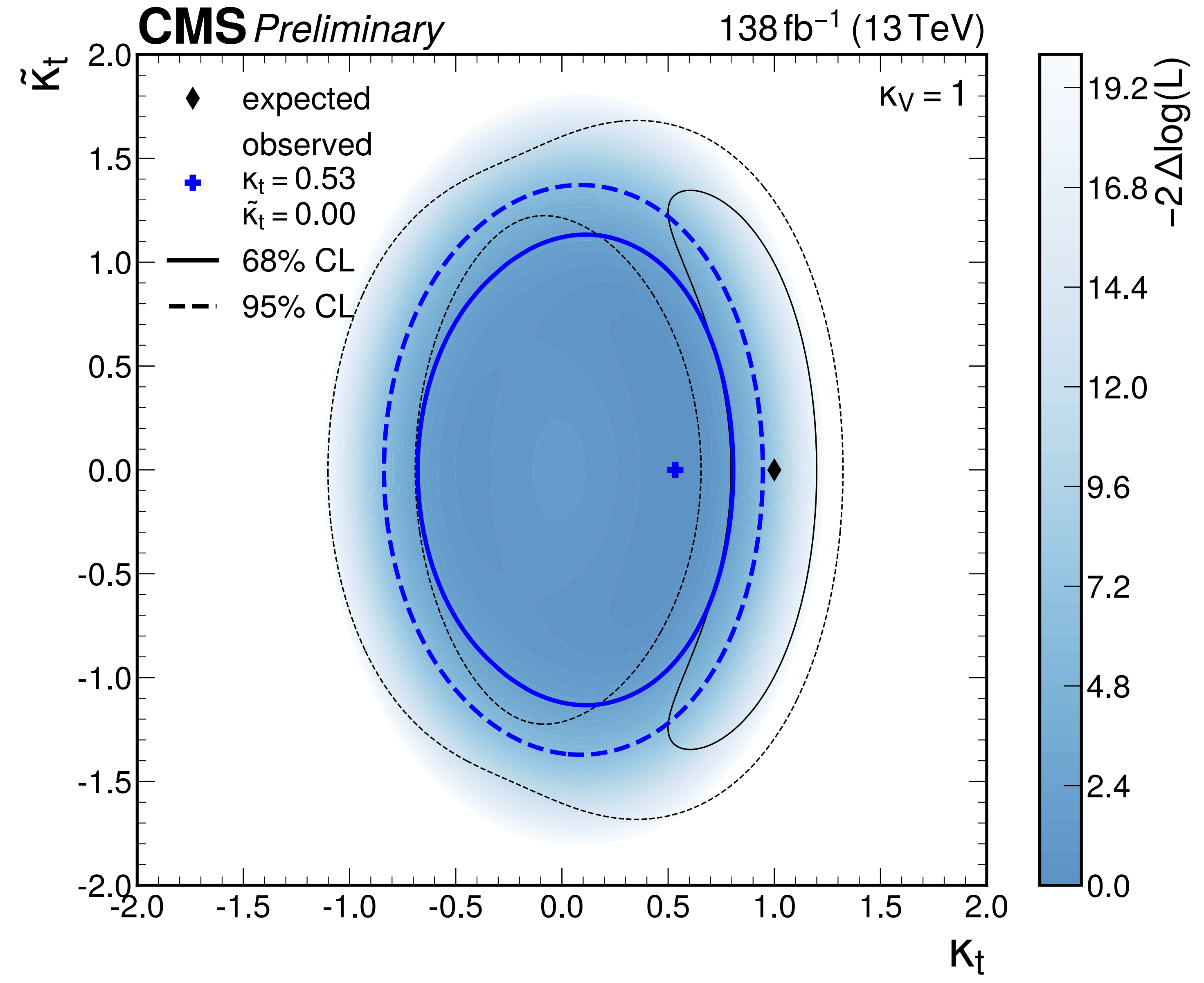
ttH→ multilepton



JHEP 07 (2023) 092

Machine learning techniques

H→ bb



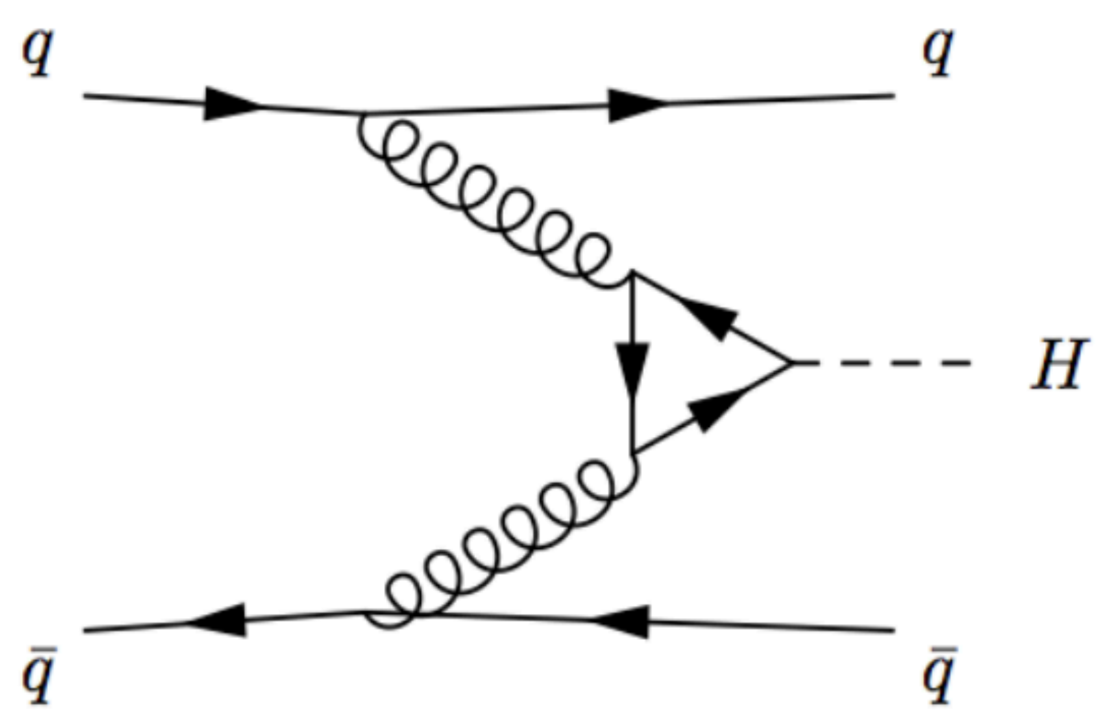
CMS-PAS-HIG-19-011

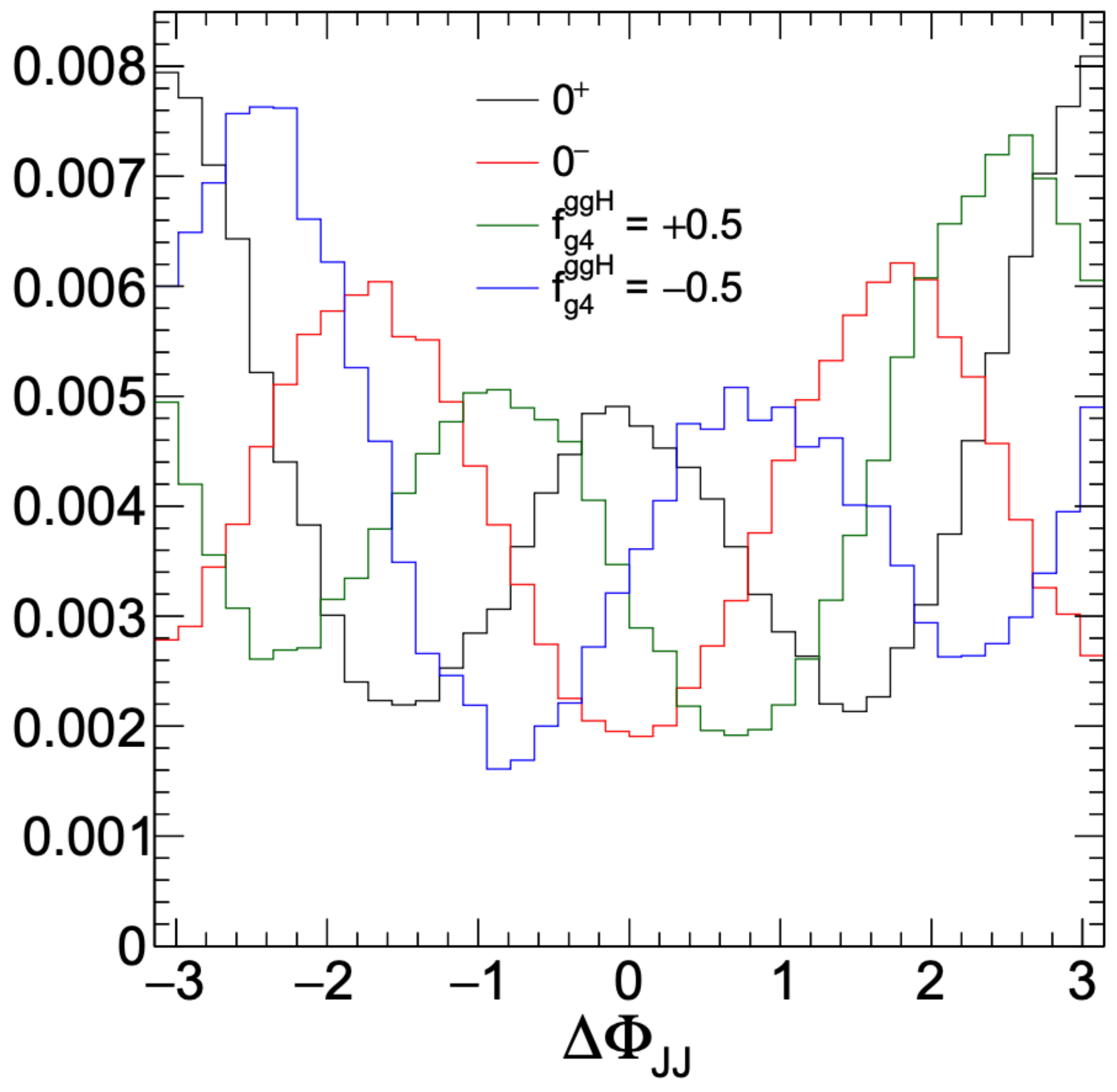
fCP < 0.28

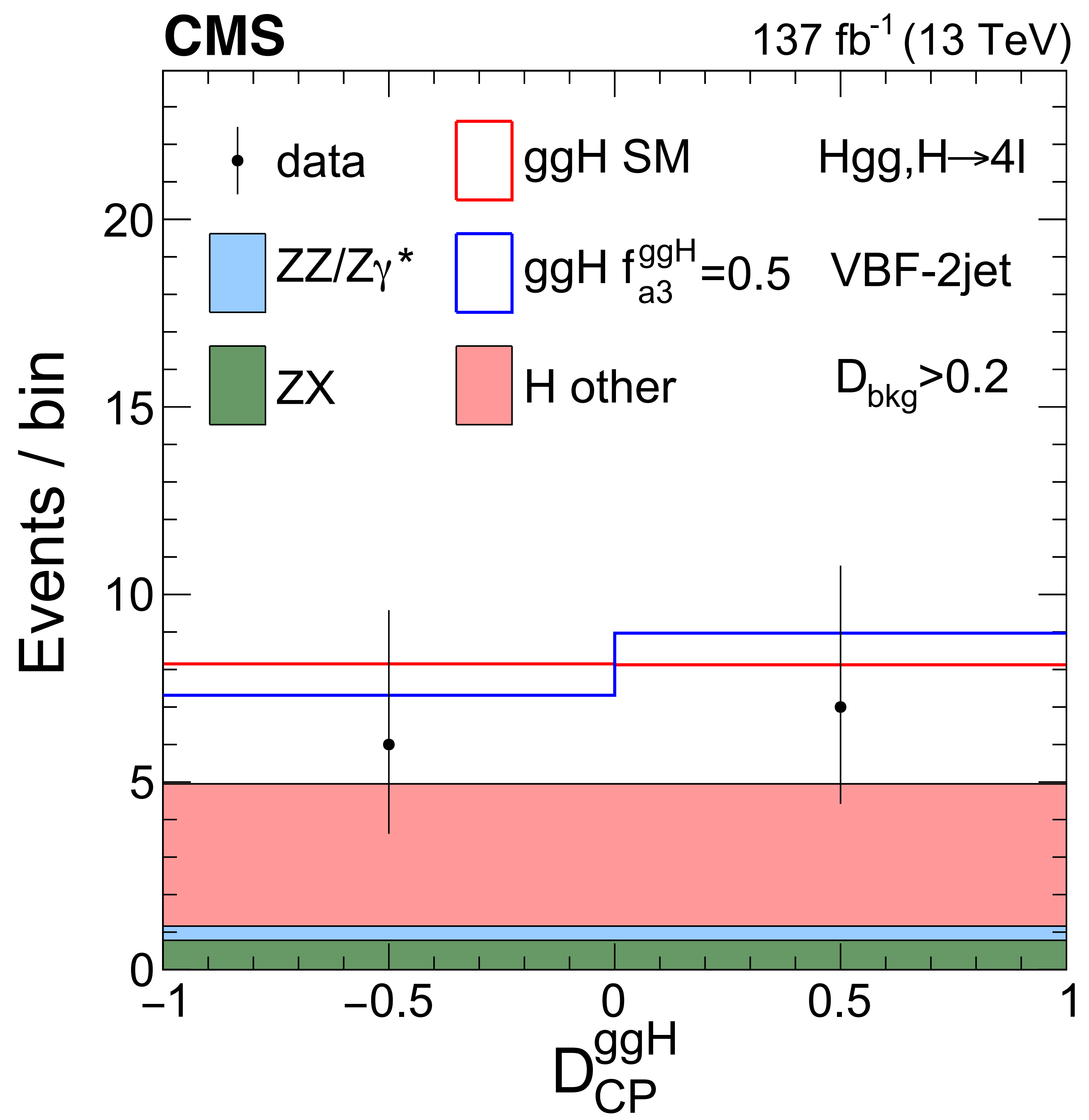
3.7 σ exclusion of pure CP-odd

Htt measurement, with ggH

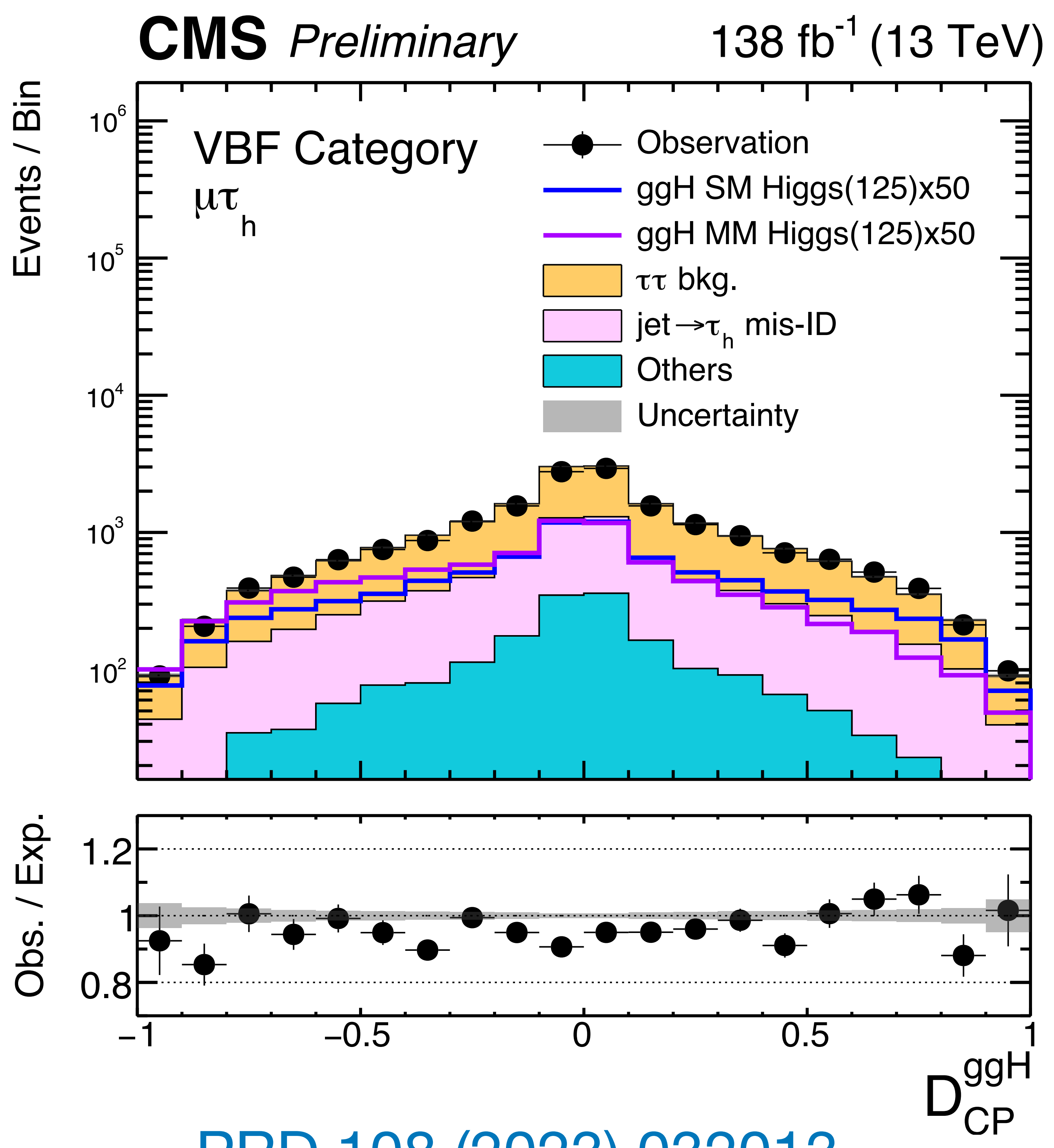
ggH large xsec, but need extra jets to obtain the CP information





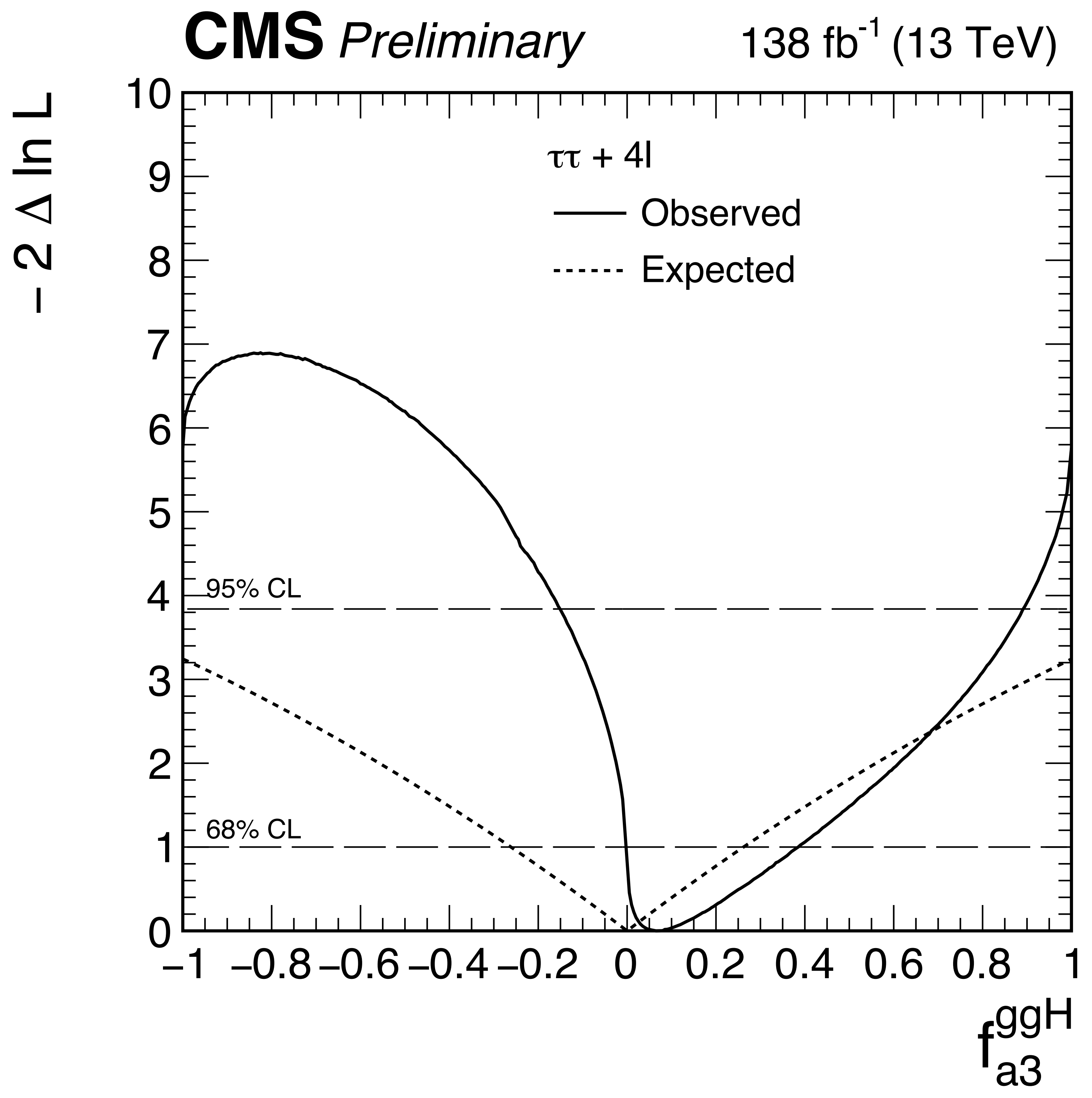


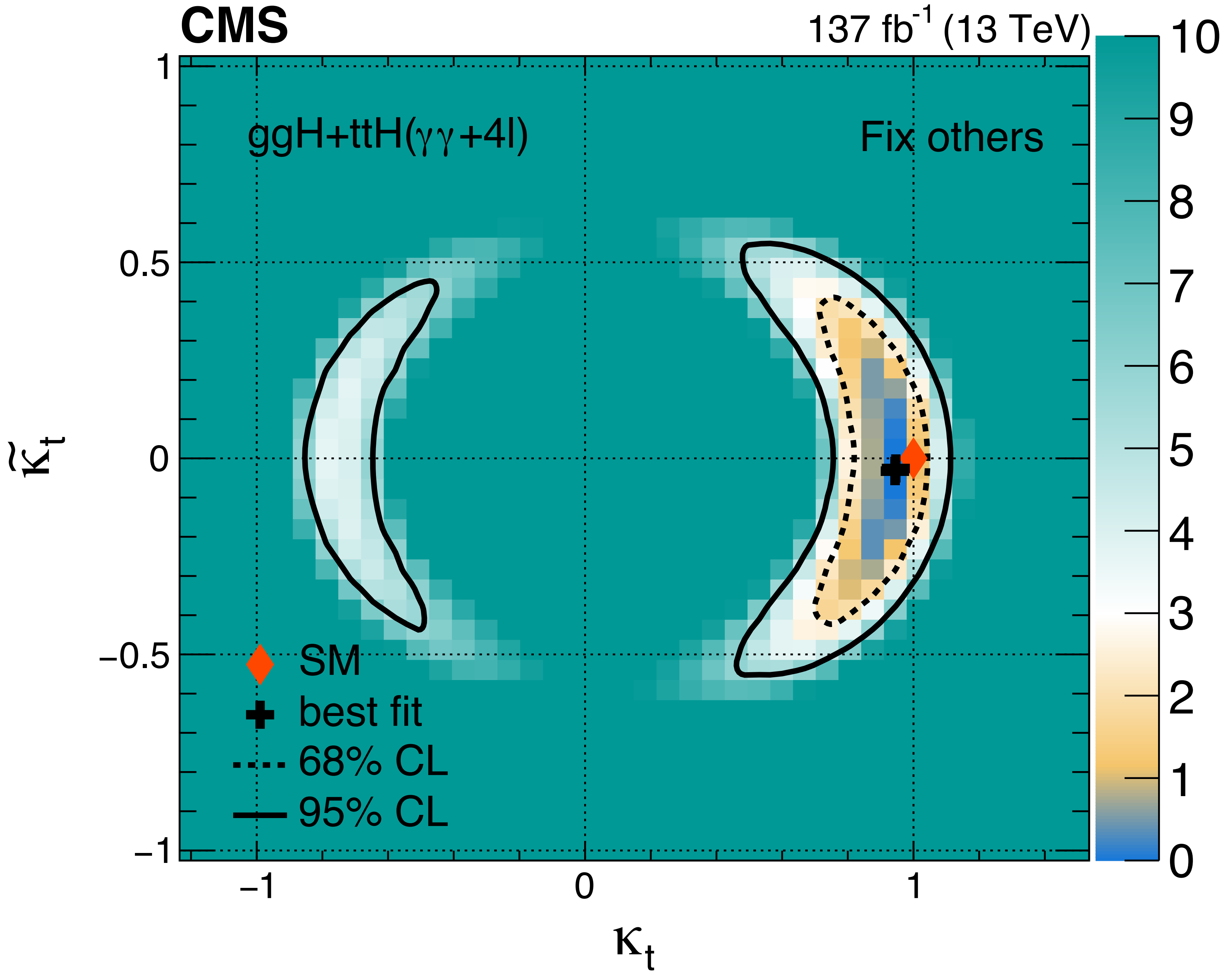
PRD 104 (2021) 052004

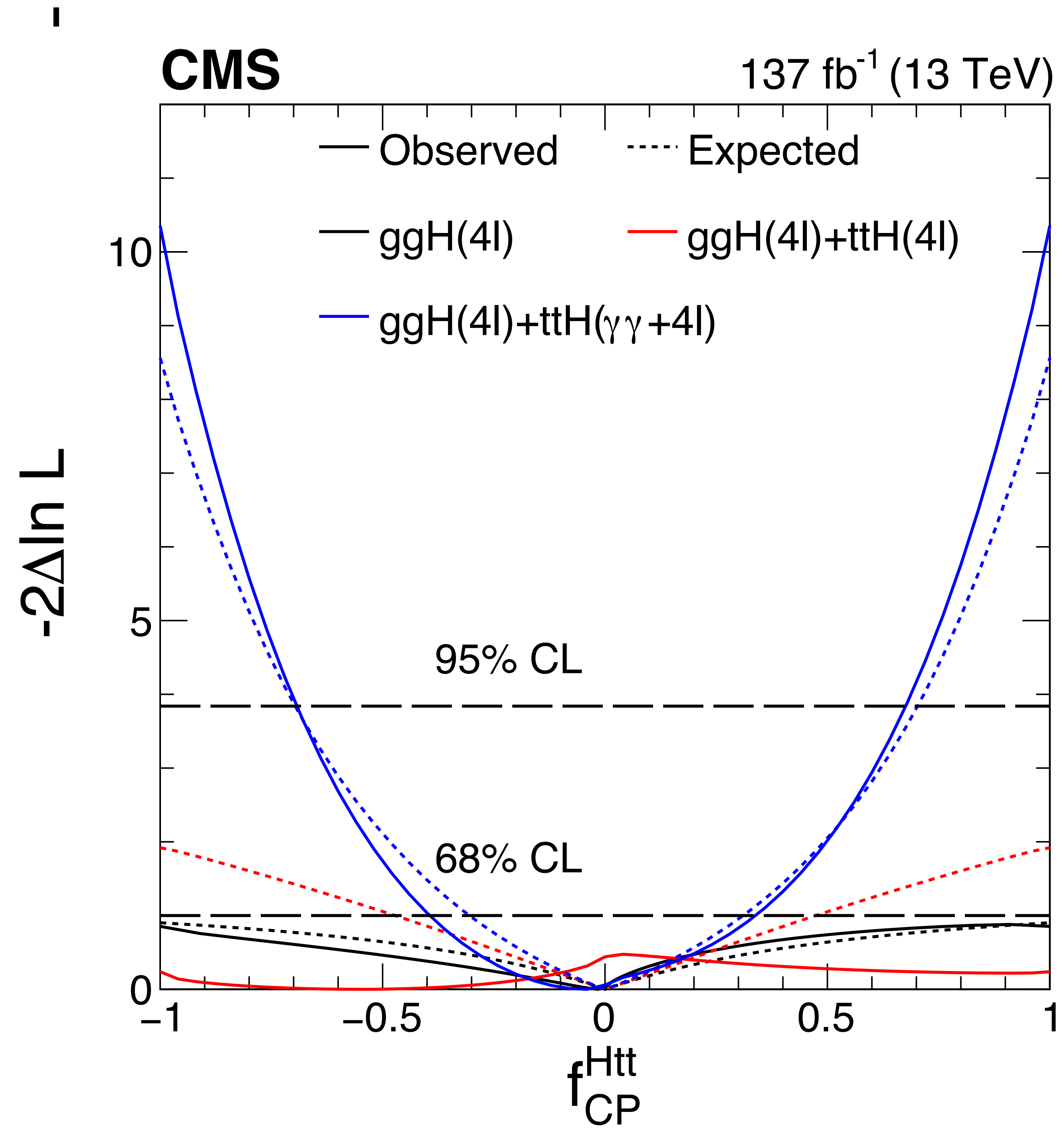


PRD 108 (2023) 032013

Htt measurement, with ggH



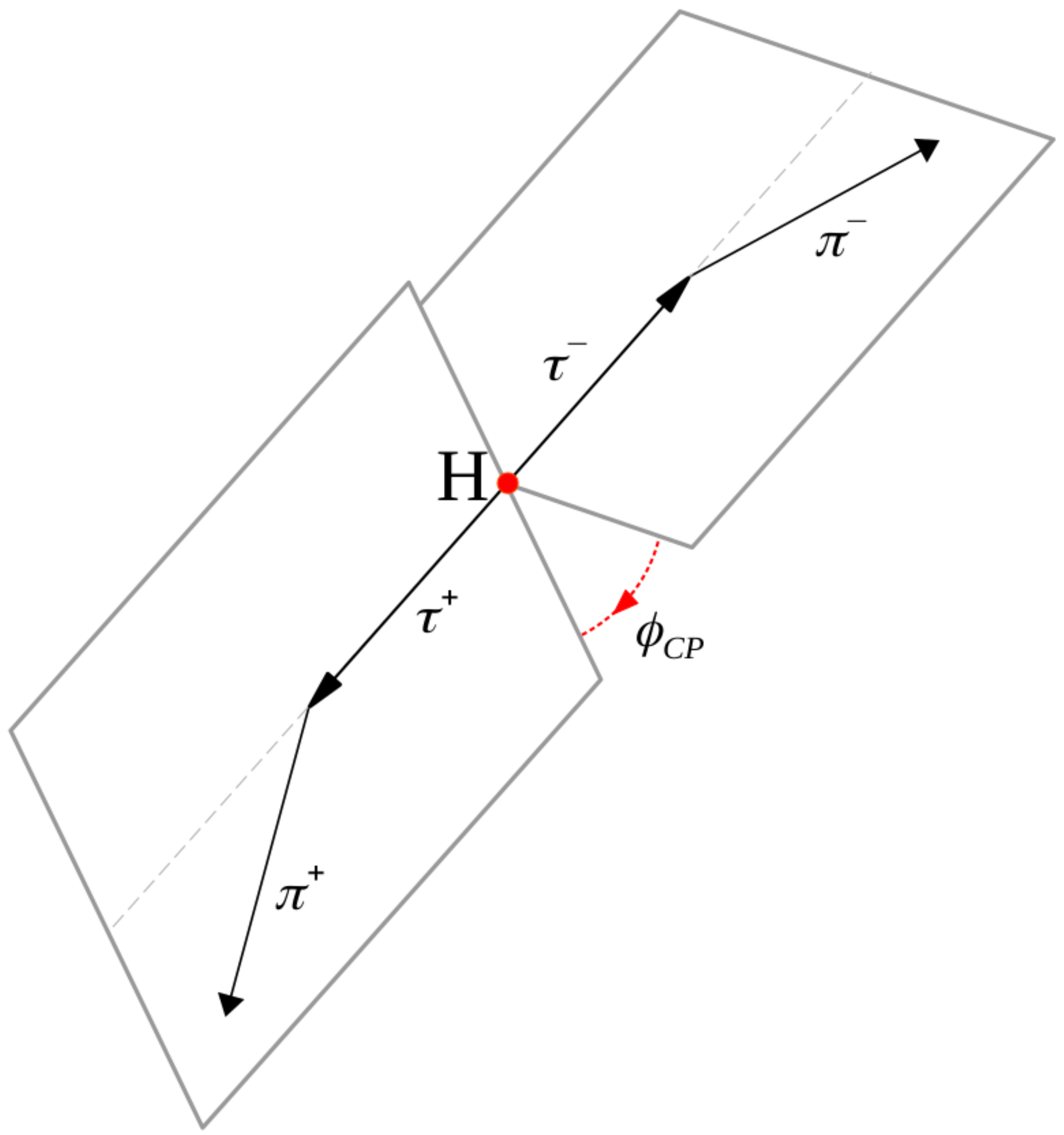


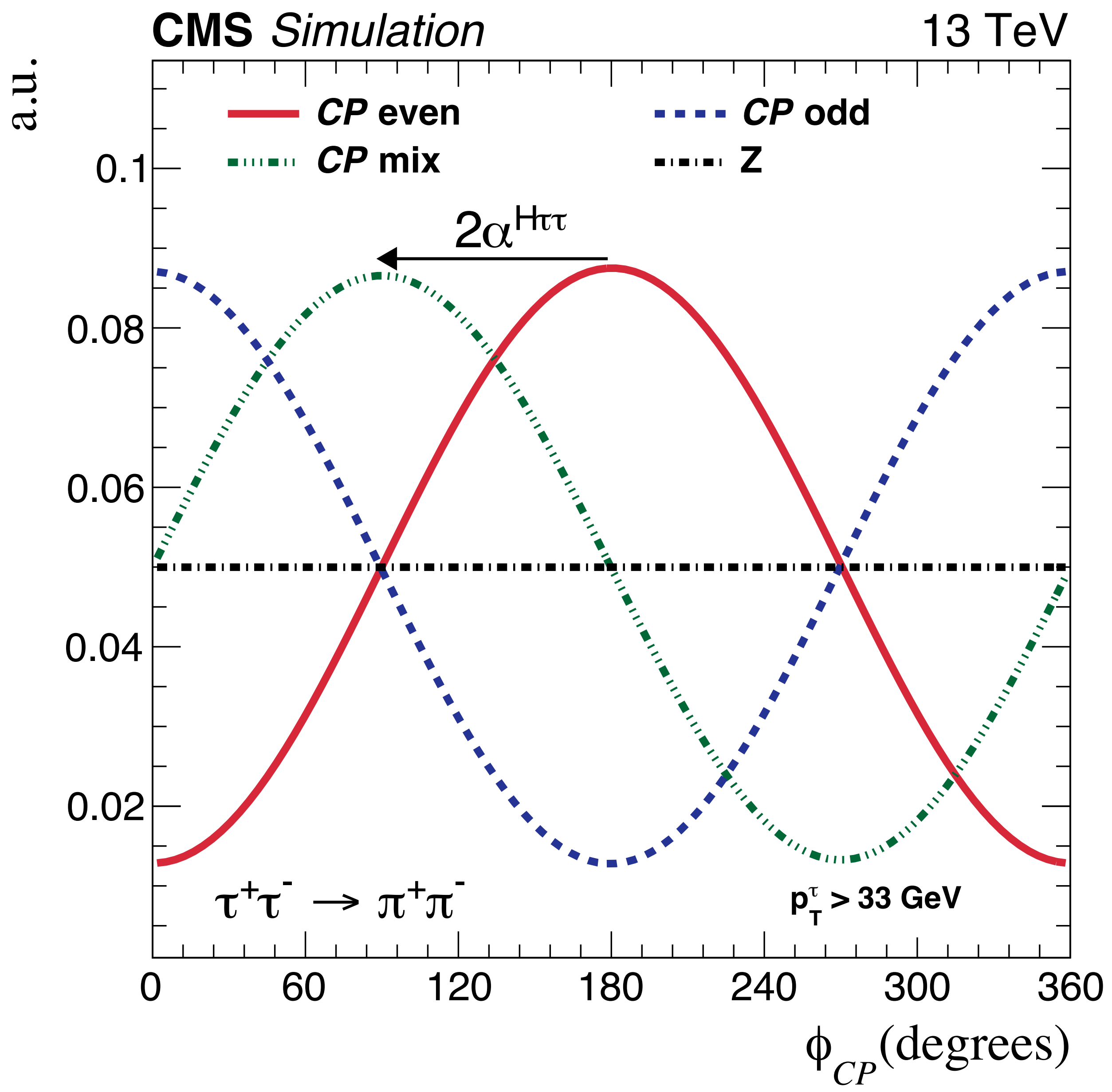


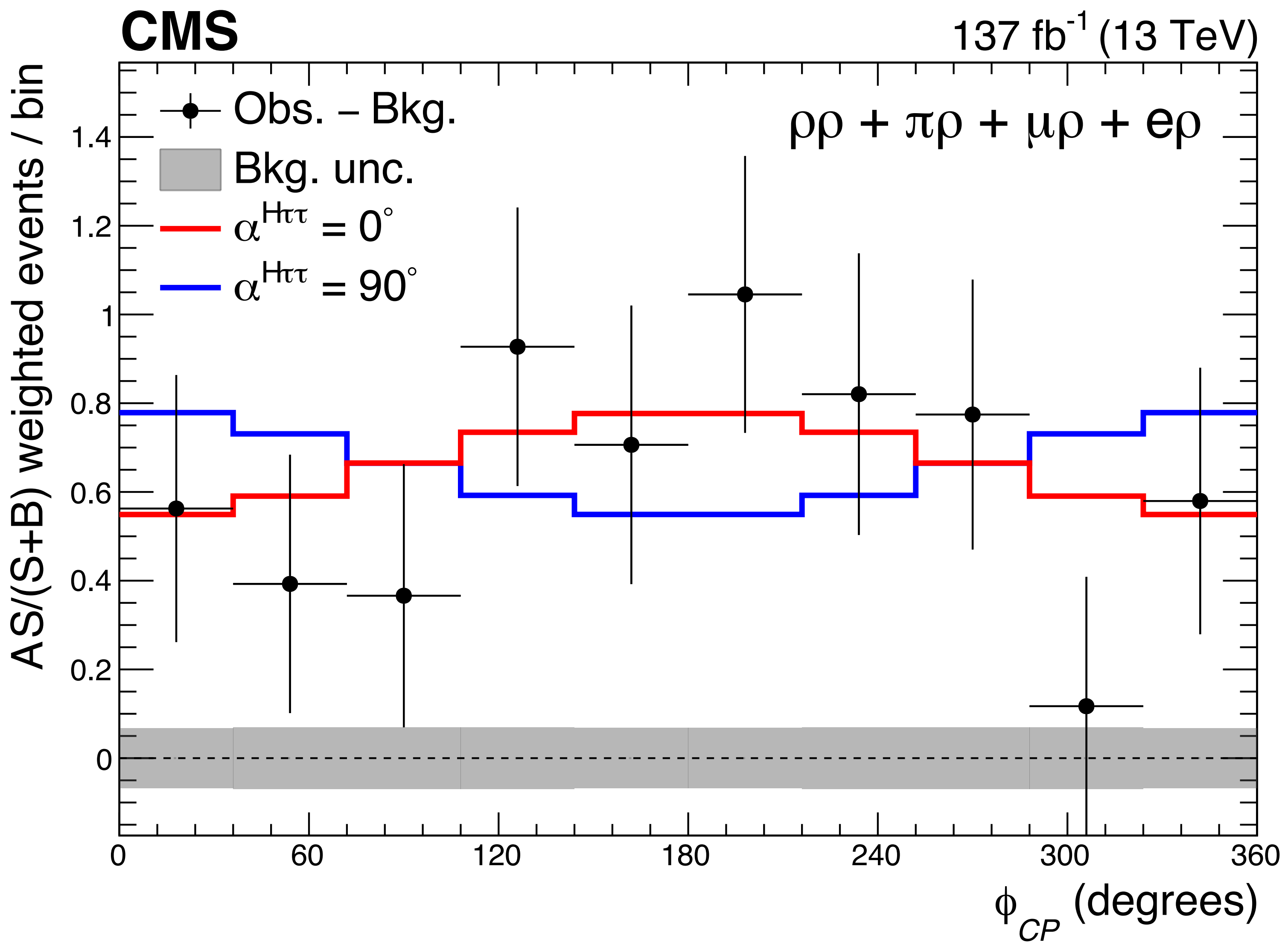
ggH fa3 < 0.09 (0.9)

ggH + ttH

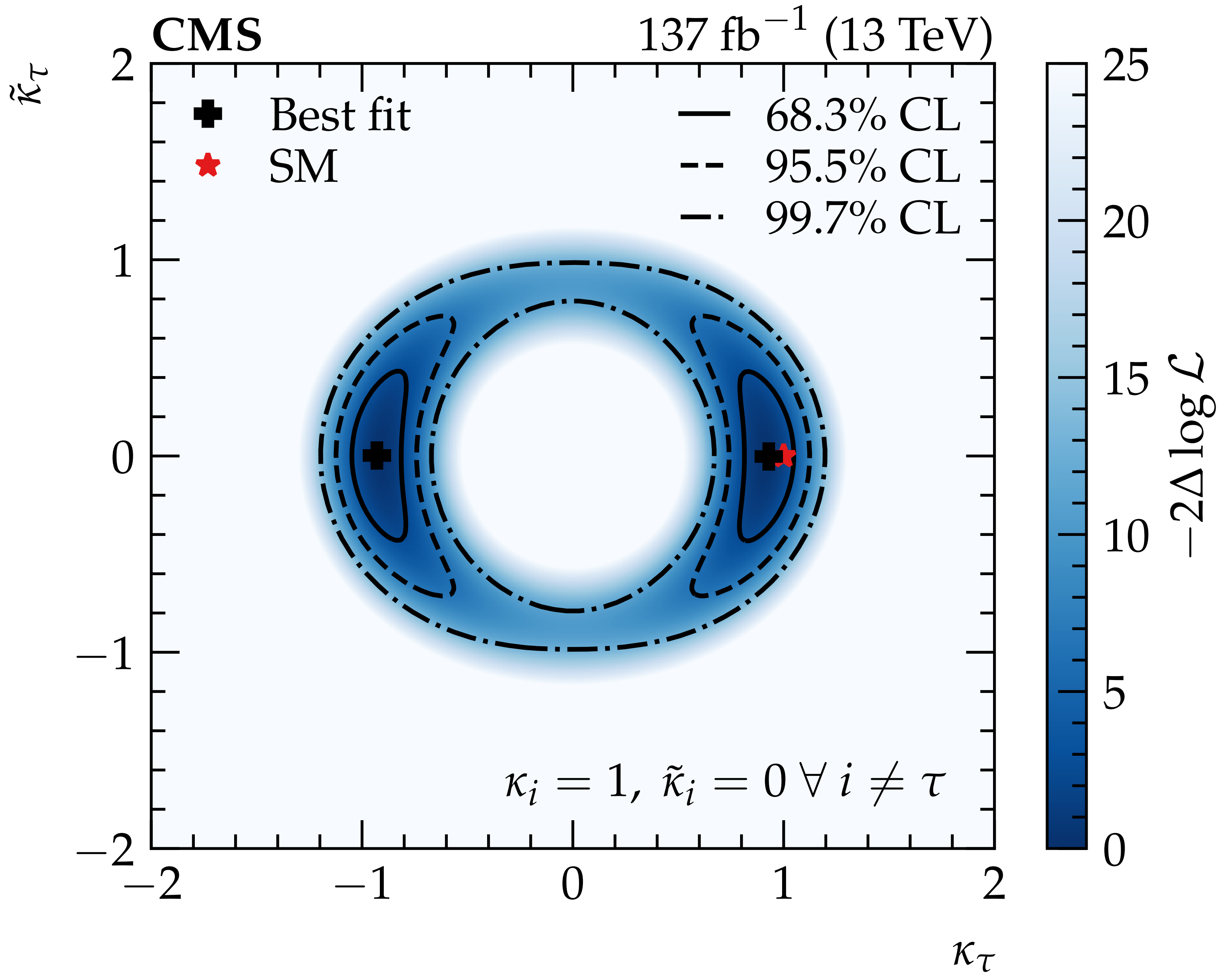
Hττ







JHEP 06 (2022) 012



$f_{CP} < 0.43$

CP odd excluded at 3σ

τ decay plane angle

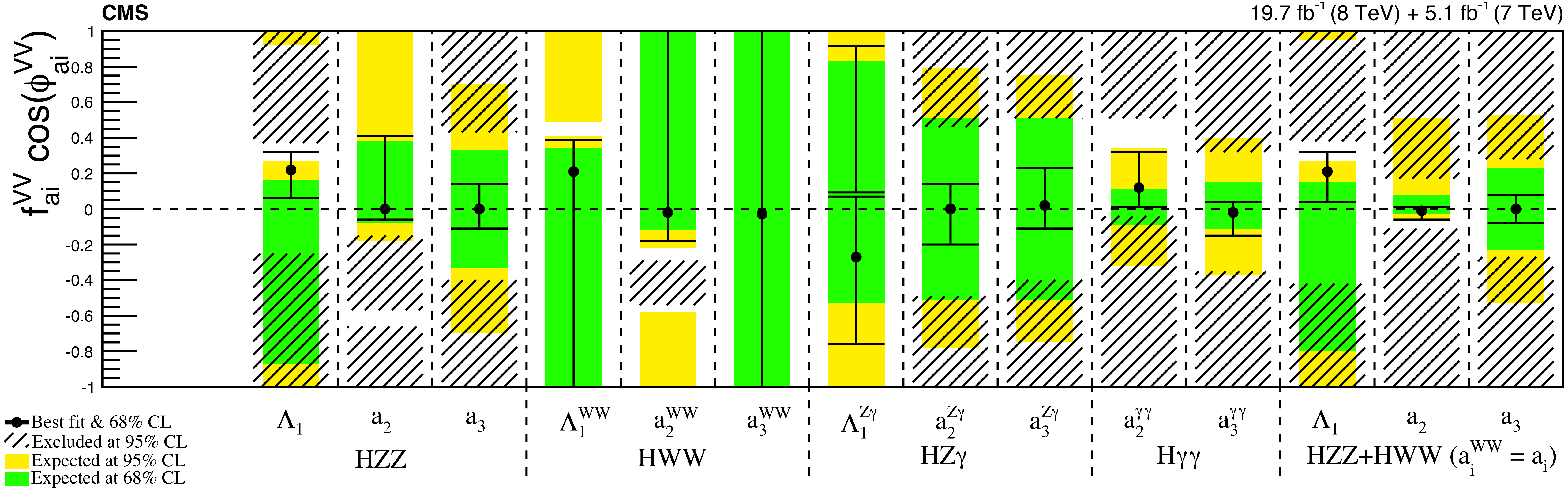
Projected precision

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	–	✓	✓	✓
$H\mu\mu$	–	–	–	–	–	–	–	–	–	✓	–

Summary

- A rich program at the CMS probing CPV in the Higgs sector
- Reaching 10% mixture requires more data and new techniques


CMS
19.7 fb⁻¹ (8 TeV) + 5.1 fb⁻¹ (7 TeV)
$f_{ai}^{VV} \cos(\phi_{ai}^{VV})$
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
Best fit & 68% CL
Excluded at 95% CL
Expected at 95% CL
Expected at 68% CL
Λ_1
a_2
a_3
HZZ
Λ_1^{WW}
a_2^{WW}
a_3^{WW}
HWW
$\Lambda_1^{Z\gamma}$
$a_2^{Z\gamma}$
$a_3^{Z\gamma}$
HZγ
$a_2^{\gamma\gamma}$
$a_3^{\gamma\gamma}$
Hγγ
Λ_1
a_2
a_3
HZZ+HWW ($a_i^{WW} = a_i$)