CP violation measurement of top Yukawa coupling at the LHC

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CP symmetry

- At first no rules about these symmetries
- Experiments important
  - Weak interactions violate C and P separately but preserve CP
  - Rare processes violate CP

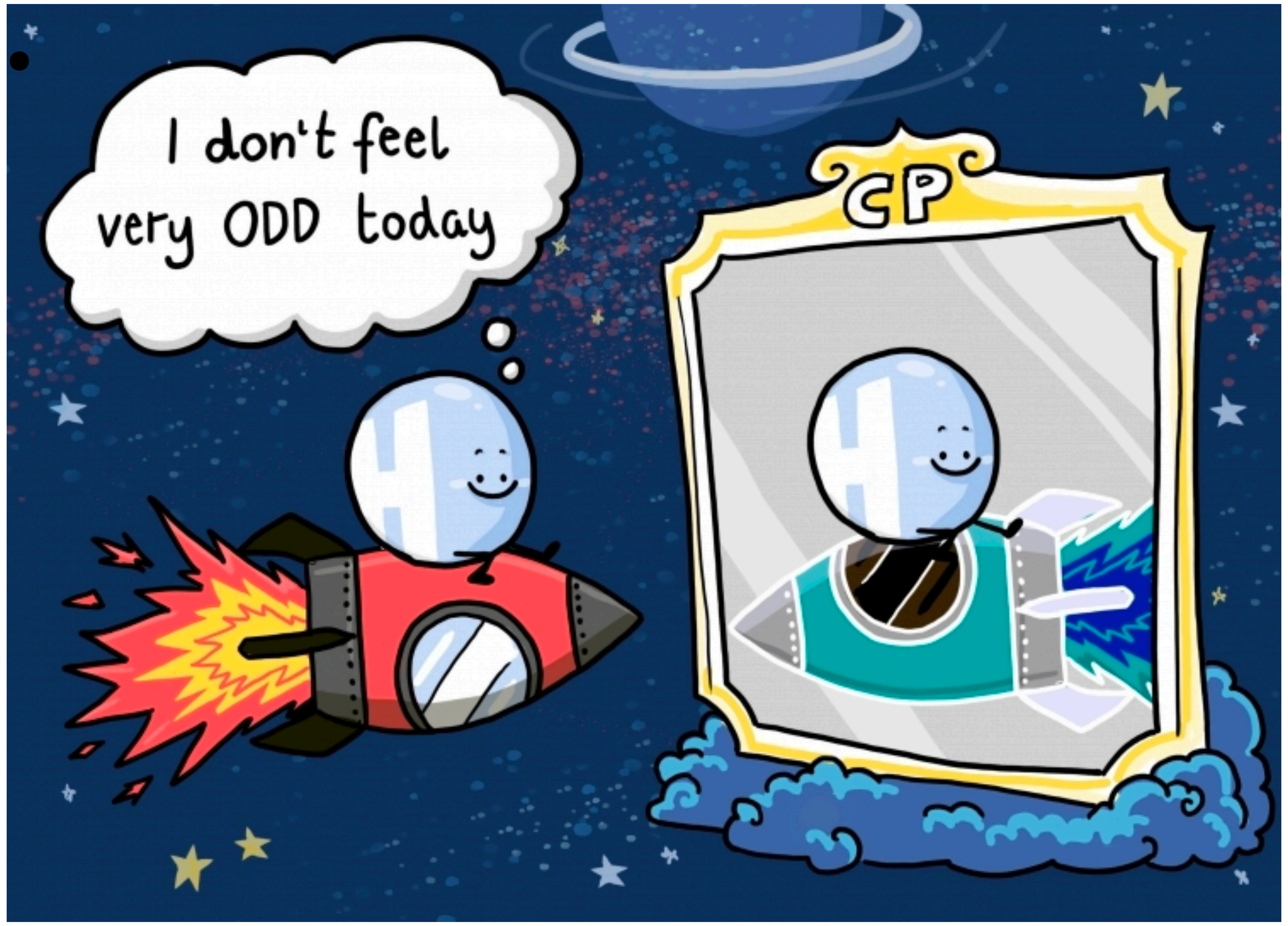


image: DESY/designdoppel

- In SM: CP violation only exists in quark mixing, small
- CP violation vital to the matter-antimatter imbalance, searched extensively
  - Hadron decays
  - EDM
  - Higgs
  - Neutrino oscillation

CP violation in Higgs sector

- Why search for CP violation in Higgs sector?
- Electroweak baryogensis:
  - 1st order phase transition by having 2 Higgs doublets, or 1 more singlet, or triplets..
  - CP violation in Higgs sector

CP violation in Higgs sector

- CP is one of the first measured properties of the Higgs
- Higgs: the only scalar in the SM => CP even and conserving
- Is this true?

From 2012.07.20 Higgs Hunting Workshop

M. Peskin

So, the fact that we see WW and ZZ at nearly Standard Model strength is prima facie evidence that the particle is a CP even spin 0 state from a field with a vacuum expectation value that breaks SU(2)xU(1).

From here on, I will call the new particle at 125 GeV "the Higgs boson" without further apology.

M. Strassler

What Is This Object?

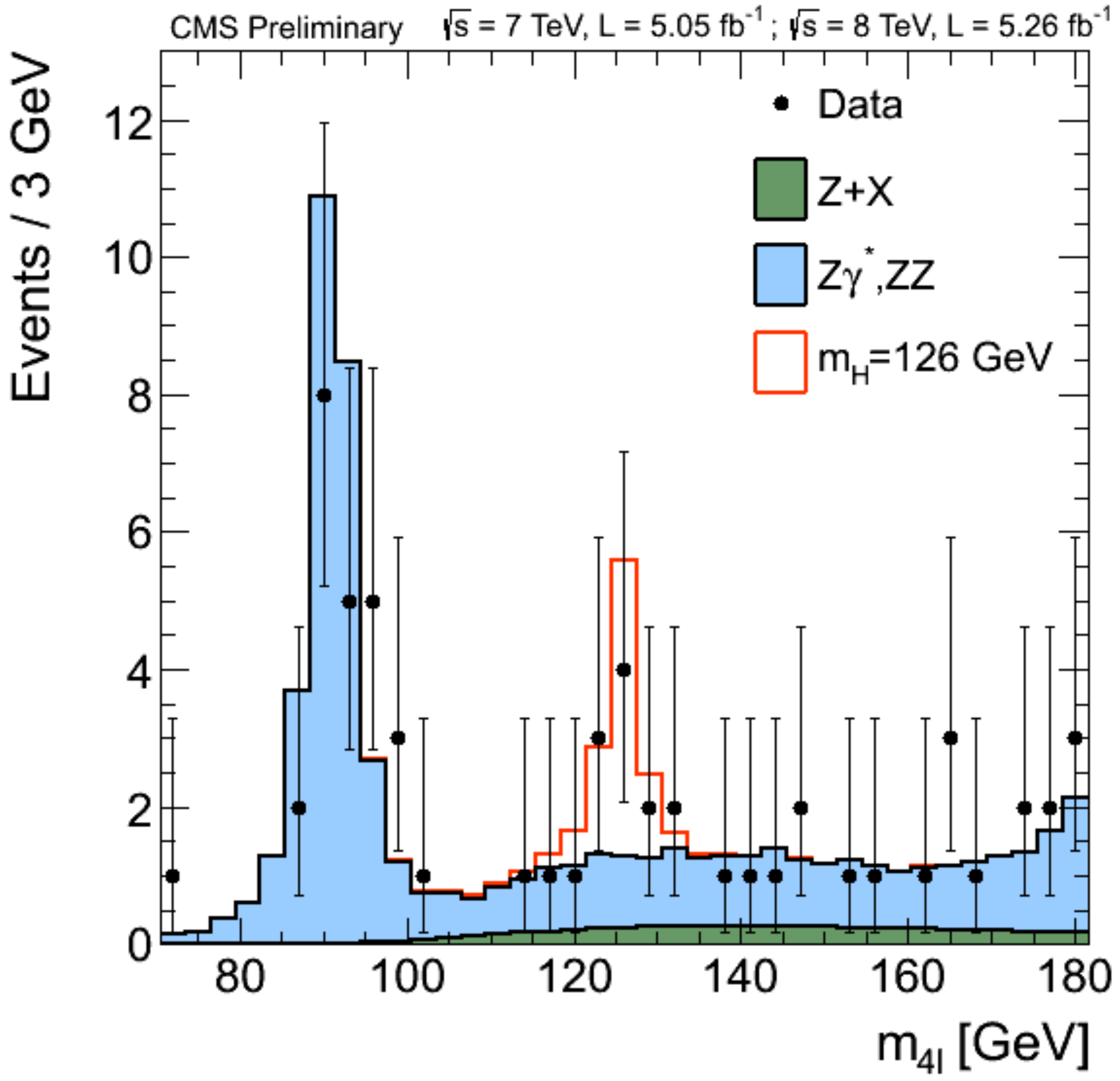
- **Possible but Implausible**
  - Spin 2
  - Pure CP odd Spin 0

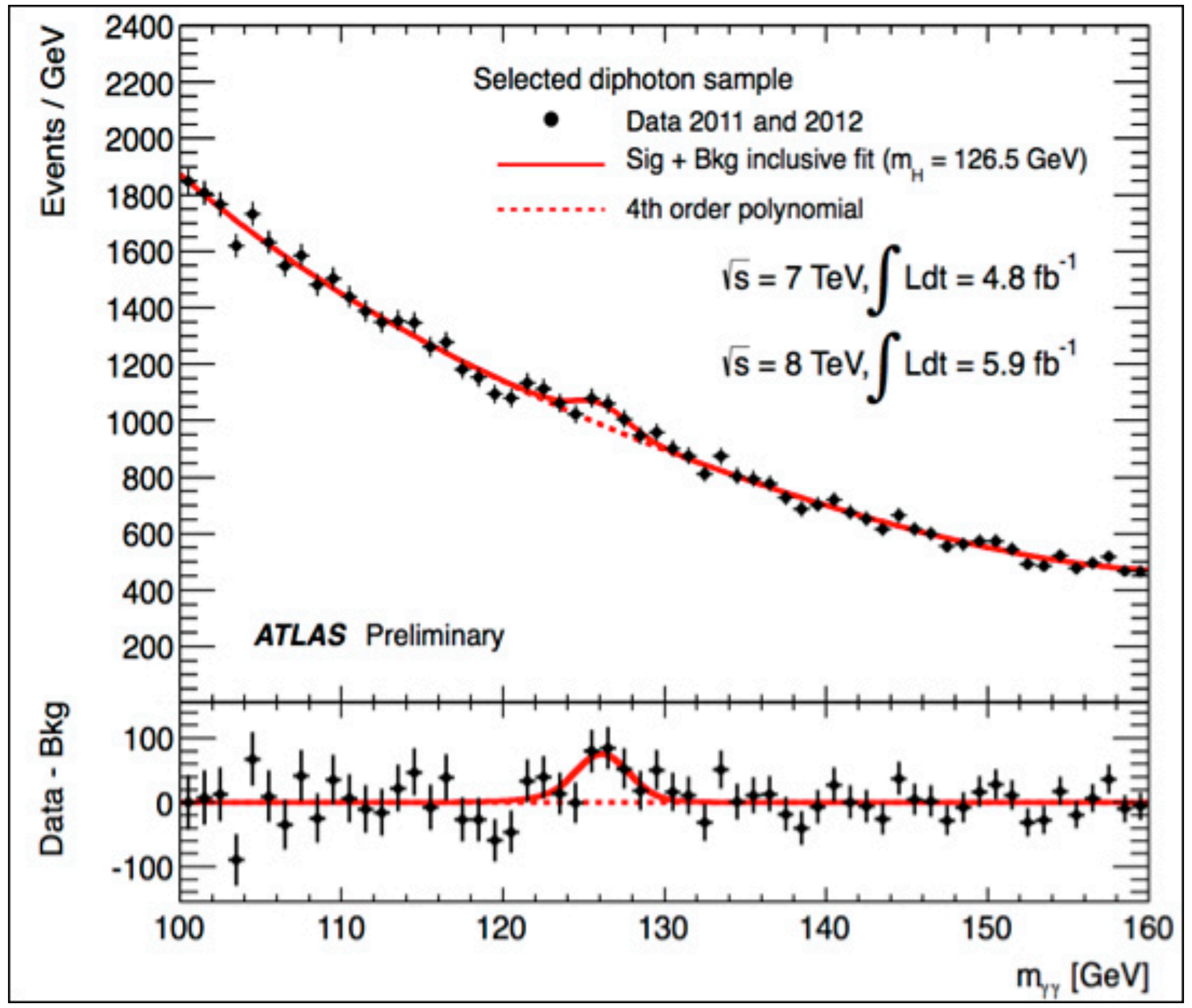
I'm glad someone thought of that!

Possible and Plausible
- Standard Model itself
- H mixed with the above CP even or odd scalars

I wish I'd thought of that!!

How to tell the Higgs CP



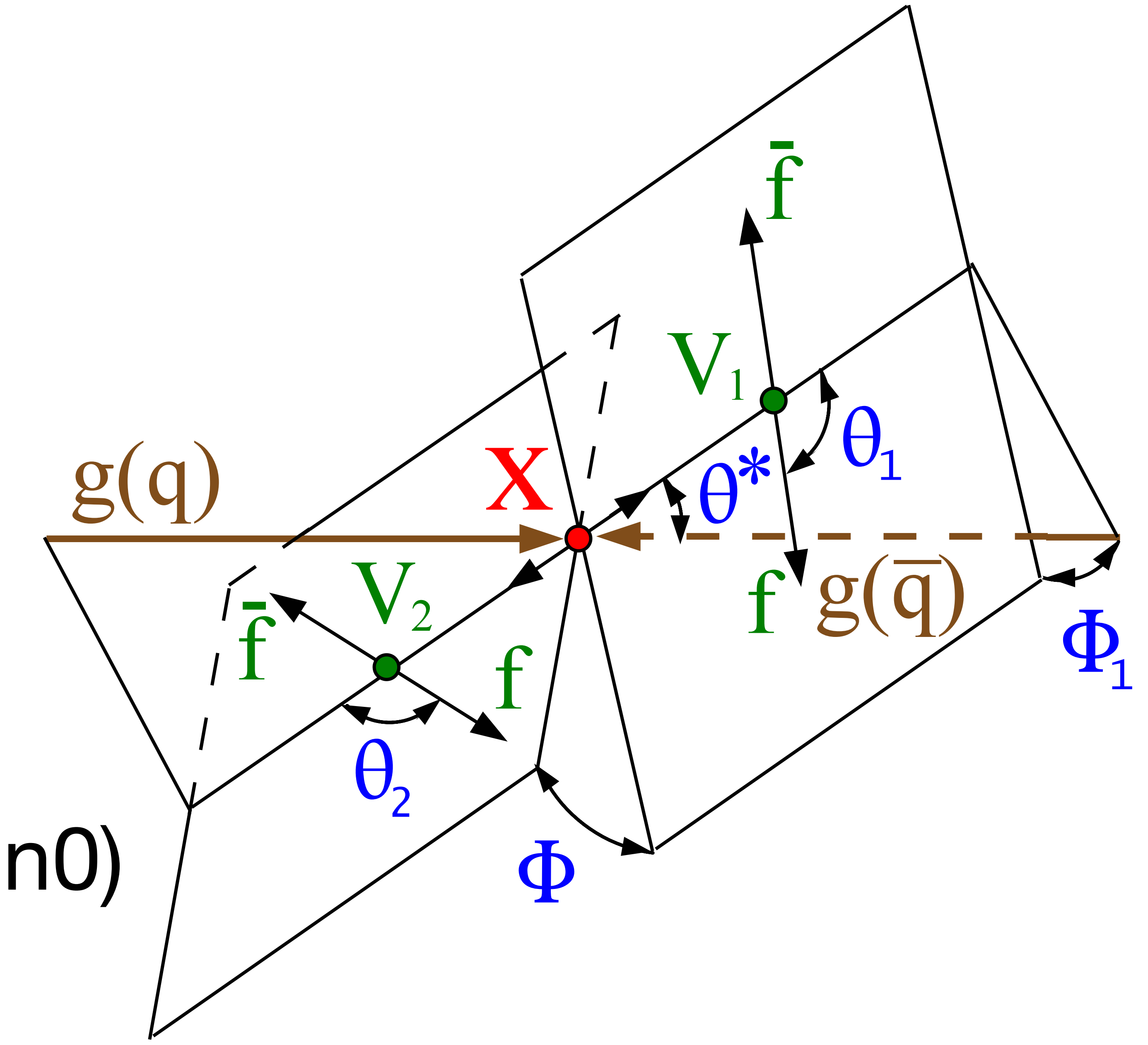


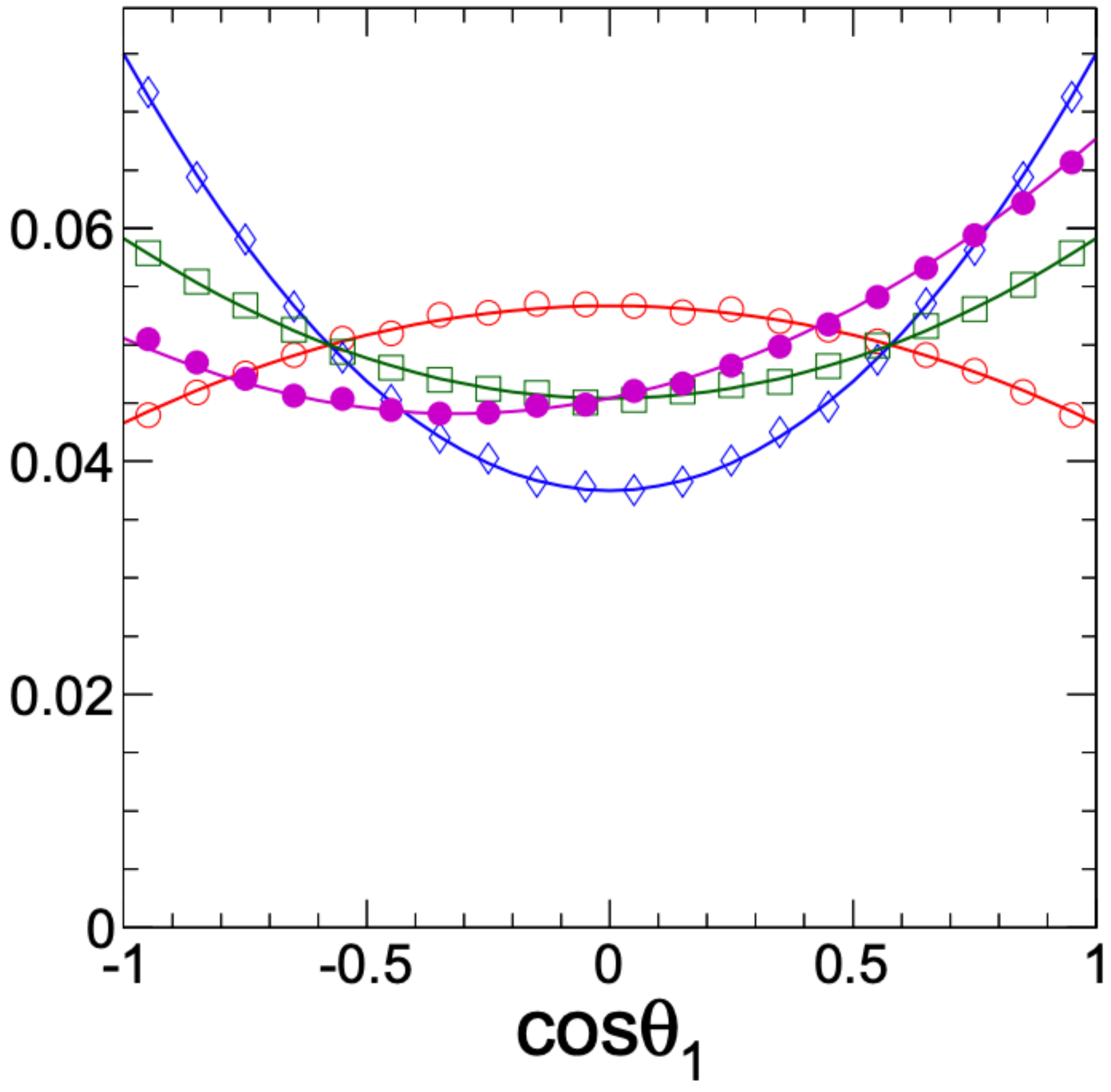
- The nice mass shapes help to identify the Higgs itself
- Carry CP information?

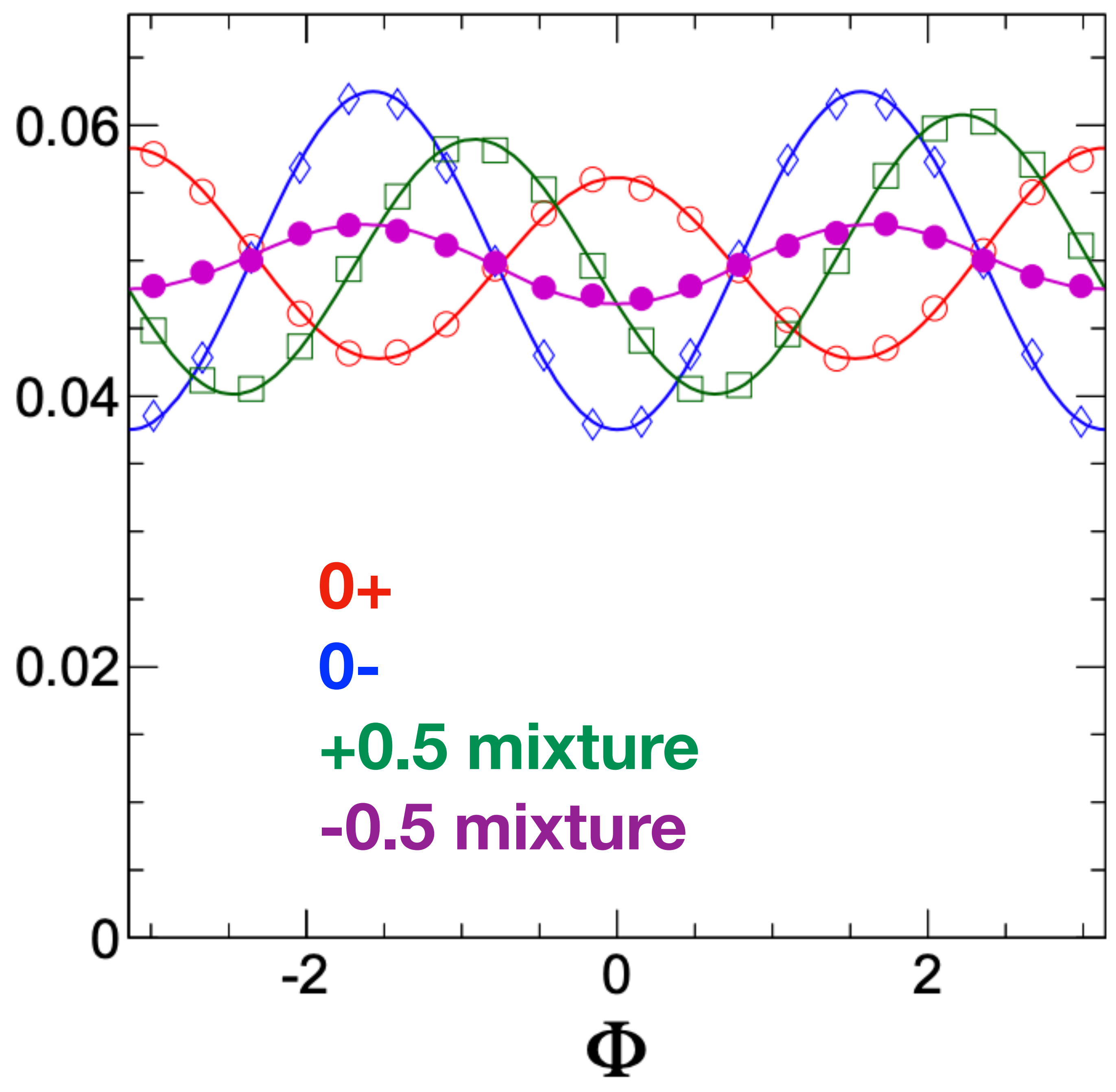
How to tell the Higgs CP

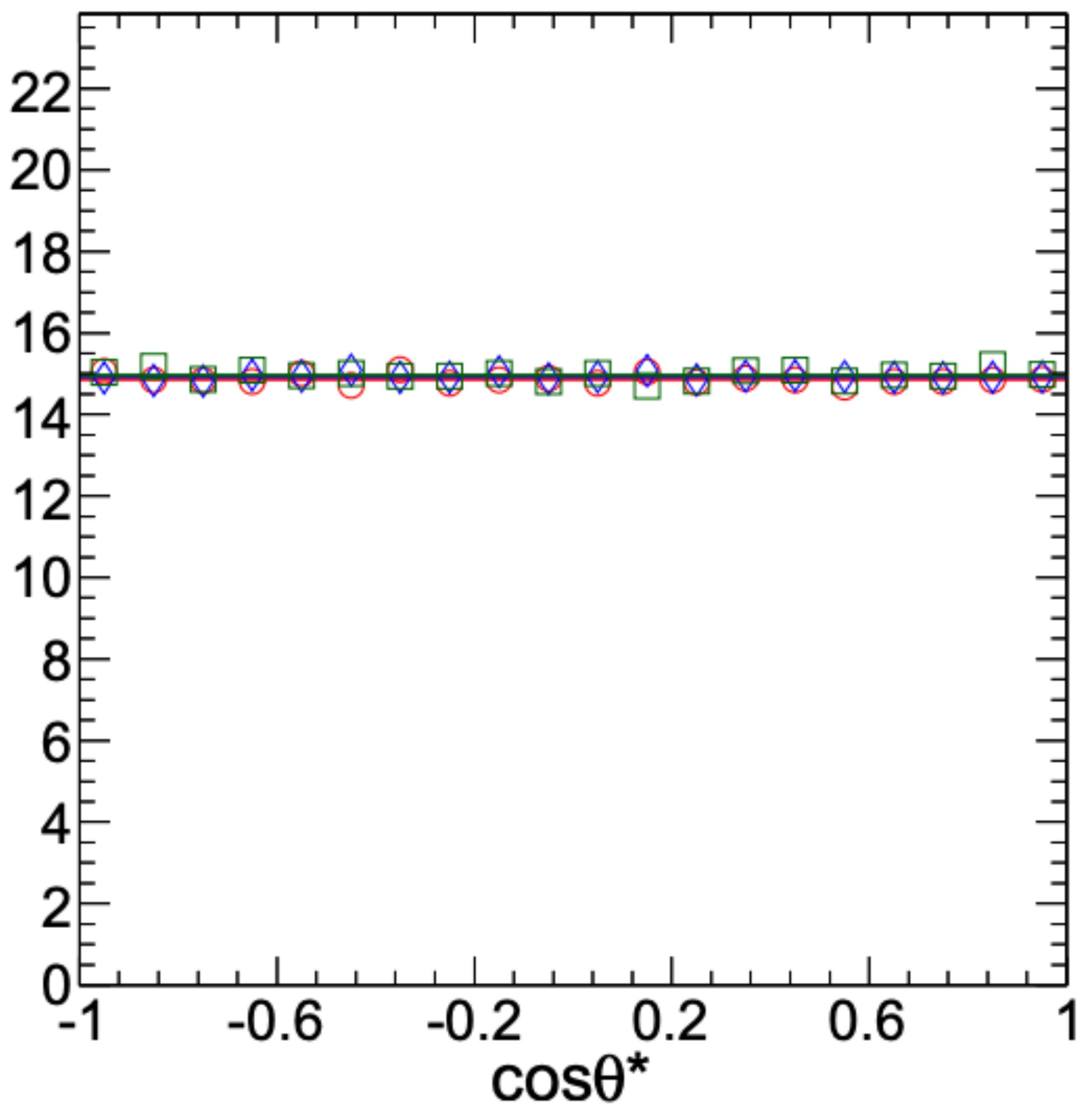
arXiv: 1208.4018
arXiv: 1309.4819

- H first observation in HVV channels
- General HVV decay, angles sensitive to CP
- If V doesn't further decay, no sensitive info (spin0)









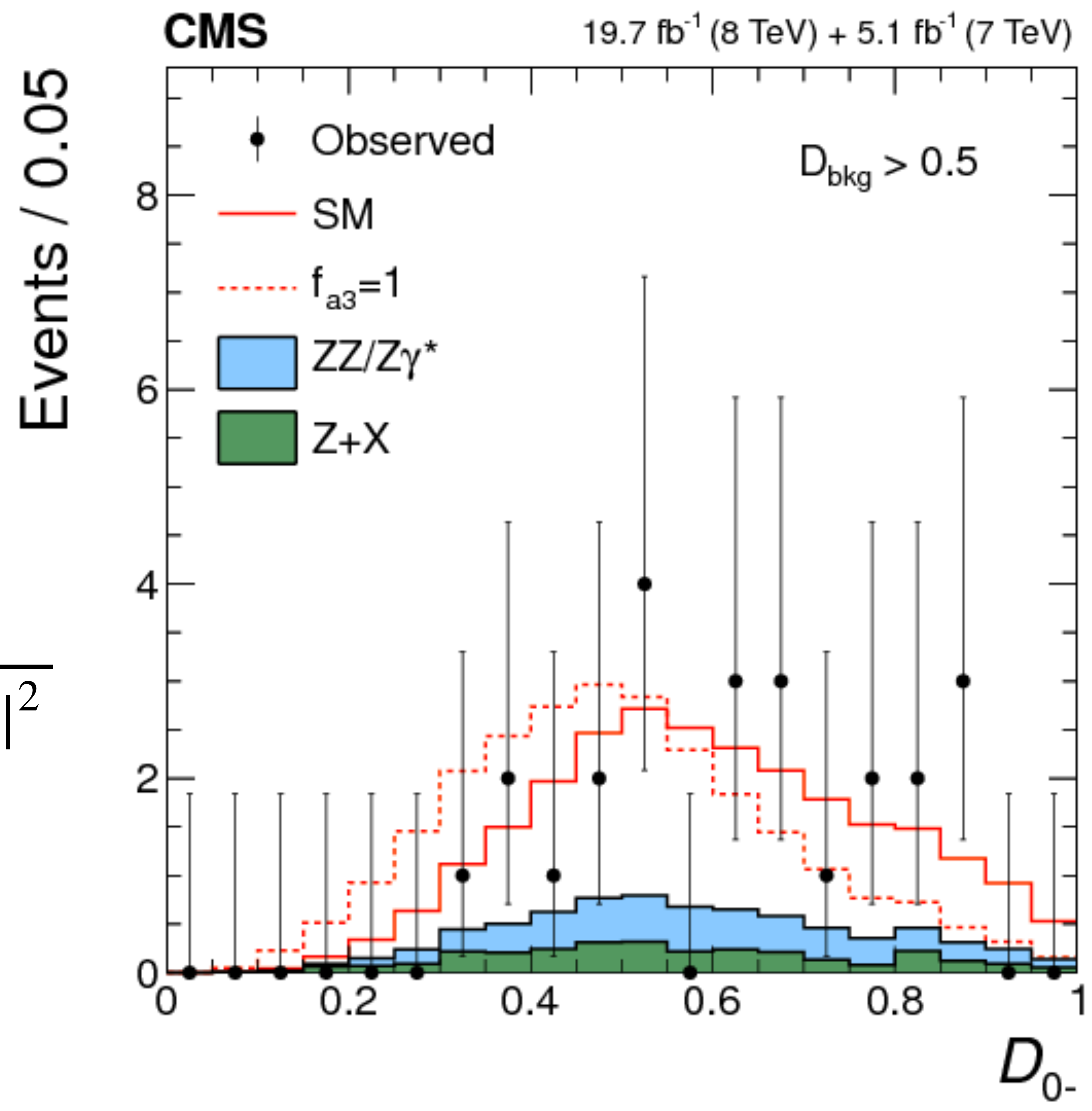
How to tell the Higgs CP

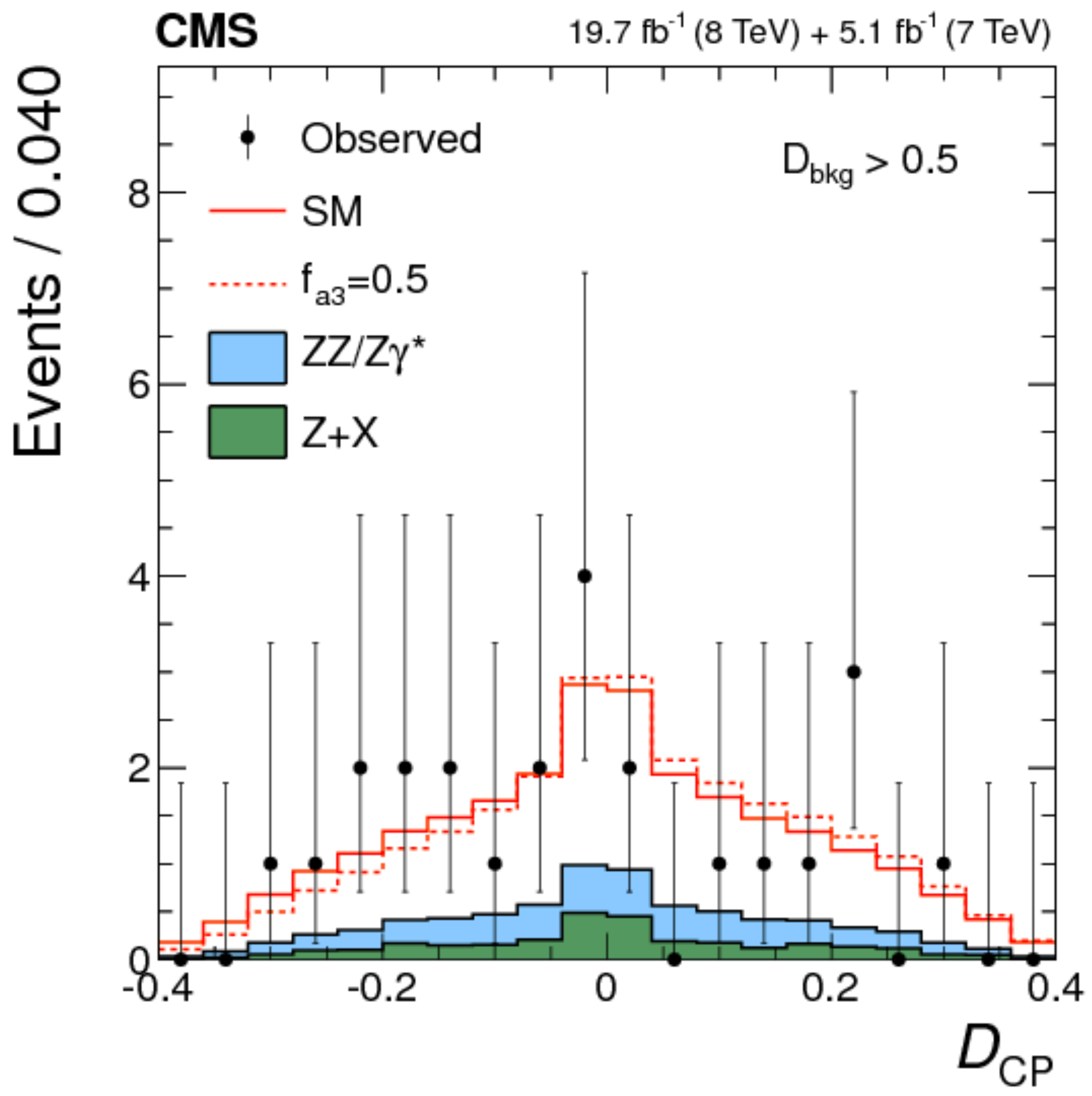
- These angles and invariant masses could be integrated into simple observables
- Matrix Element based methods
- Machine learning techniques

Run1

Phys. Rev. D 92 (2015) 012004

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



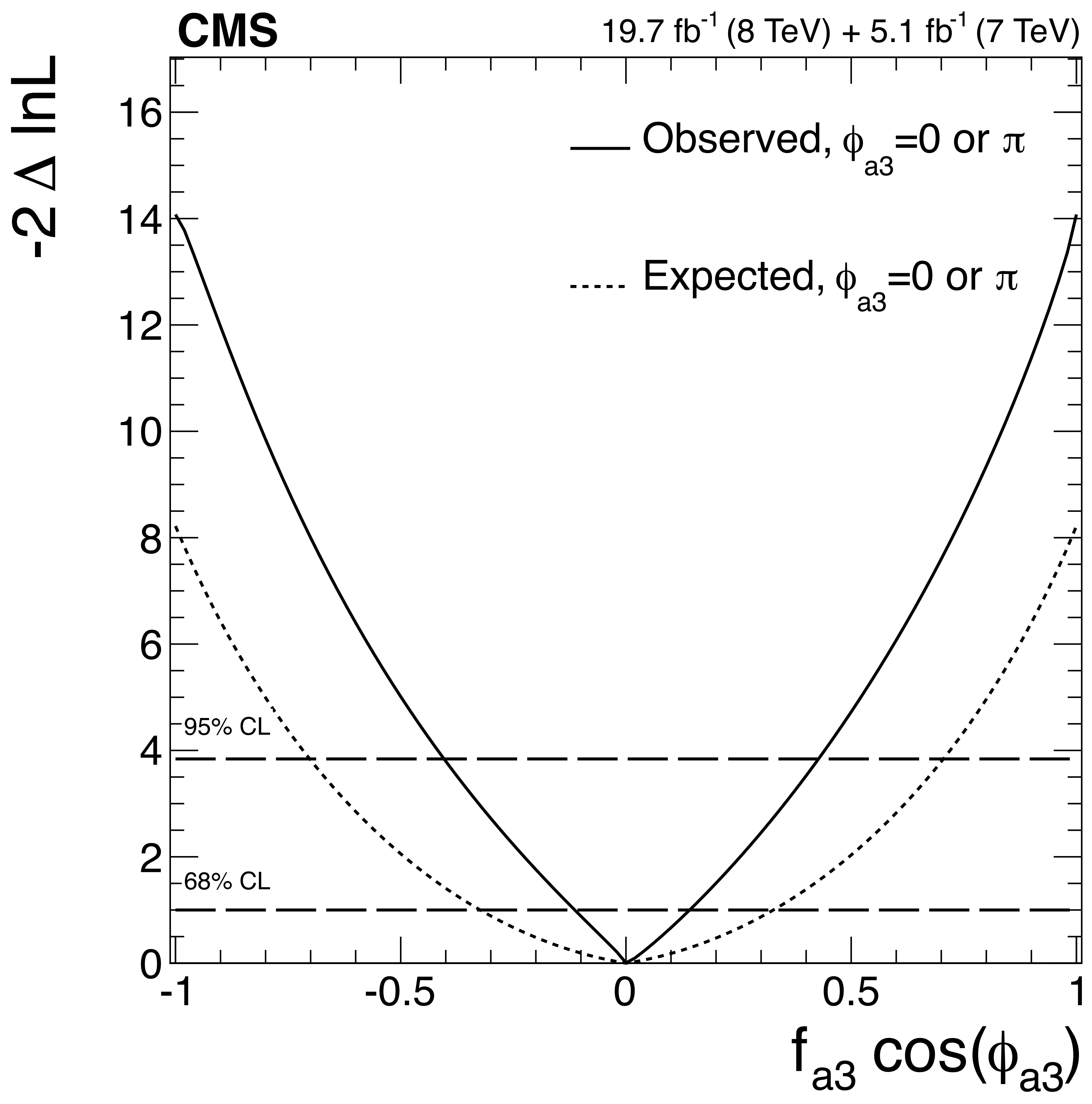


$$D_{CP} = \frac{2Re(M_{0-}(\Omega)M_{0+}(\Omega))}{\sqrt{|M_{0-}(\Omega)||M_{0+}(\Omega)|}}$$

Run1 measurements

CMS

Phys. Rev. D 92 (2015) 012004



CP-odd xsec fraction < 0.40 (0.43)

What's the target ?

arXiv:1310.8361
Snowmass 2013 report

fa3

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	$< 10^{-5}$
$VVH^\ddagger$	$4{\cdot}10^{-4}$	$1.2{\cdot}10^{-4}$	$< 10^{-5}$
$VVH^\diamond$	$7{\cdot}10^{-4}$	$1.3{\cdot}10^{-4}$	$< 10^{-5}$
ggH	0.50	0.16	$< 10^{-2}$
$\gamma\gamma H$	–	–	$< 10^{-2}$
$Z\gamma H$	–	✓	$< 10^{-2}$
$\tau\tau H$	✓	✓	$< 10^{-2}$
ttH	✓	✓	$< 10^{-2}$
$\mu\mu H$	–	–	$< 10^{-2}$

HVV coupling

10% mixture of CP-odd state

CP-odd contribution suppressed

$$A(\mathrm{HVV}) = \frac{1}{v}\left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_{\mathrm{V}1}^2 + \kappa_2^{\mathrm{VV}} q_{\mathrm{V}2}^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2} + \frac{\kappa_3^{\mathrm{VV}} (q_{\mathrm{V}1} + q_{\mathrm{V}2})^2}{\left(\Lambda_{\mathrm{Q}}^{\mathrm{VV}}\right)^2}\right] m_{\mathrm{V}1}^2 \epsilon_{\mathrm{V}1}^* \epsilon_{\mathrm{V}2}^* + \frac{1}{v} a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + \frac{1}{v} a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu},$$

Hff coupling

CP-odd and CP-even same order

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

Which Yukawa couplings?

$$A(H \to f\bar{f}) = \frac{m_f}{v} \bar{u}_2 \left(\underbrace{b_1^{Hf\bar{f}}}_{\text{CP-even}} + i \underbrace{b_2^{Hf\bar{f}}}_{\text{CP-odd}} \gamma_5 \right) u_1 \qquad f_{CP}^{Hf\bar{f}} \equiv \frac{|b_2^{Hf\bar{f}}|^2}{|b_1^{Hf\bar{f}}|^2 + |b_2^{Hf\bar{f}}|^2} = \sin^2\left(\alpha^{Hf\bar{f}}\right)$$

- LHC established Yukawa couplings: tt, bb, ττ, μμ
- Polarization info is needed

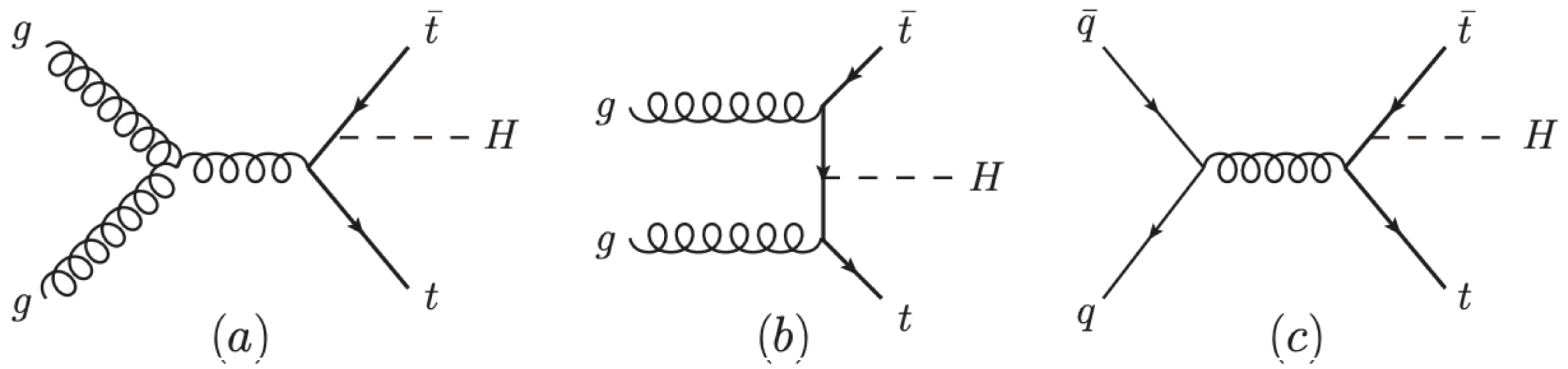
arXiv: 2205.07715
Snowmass 2022 report

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

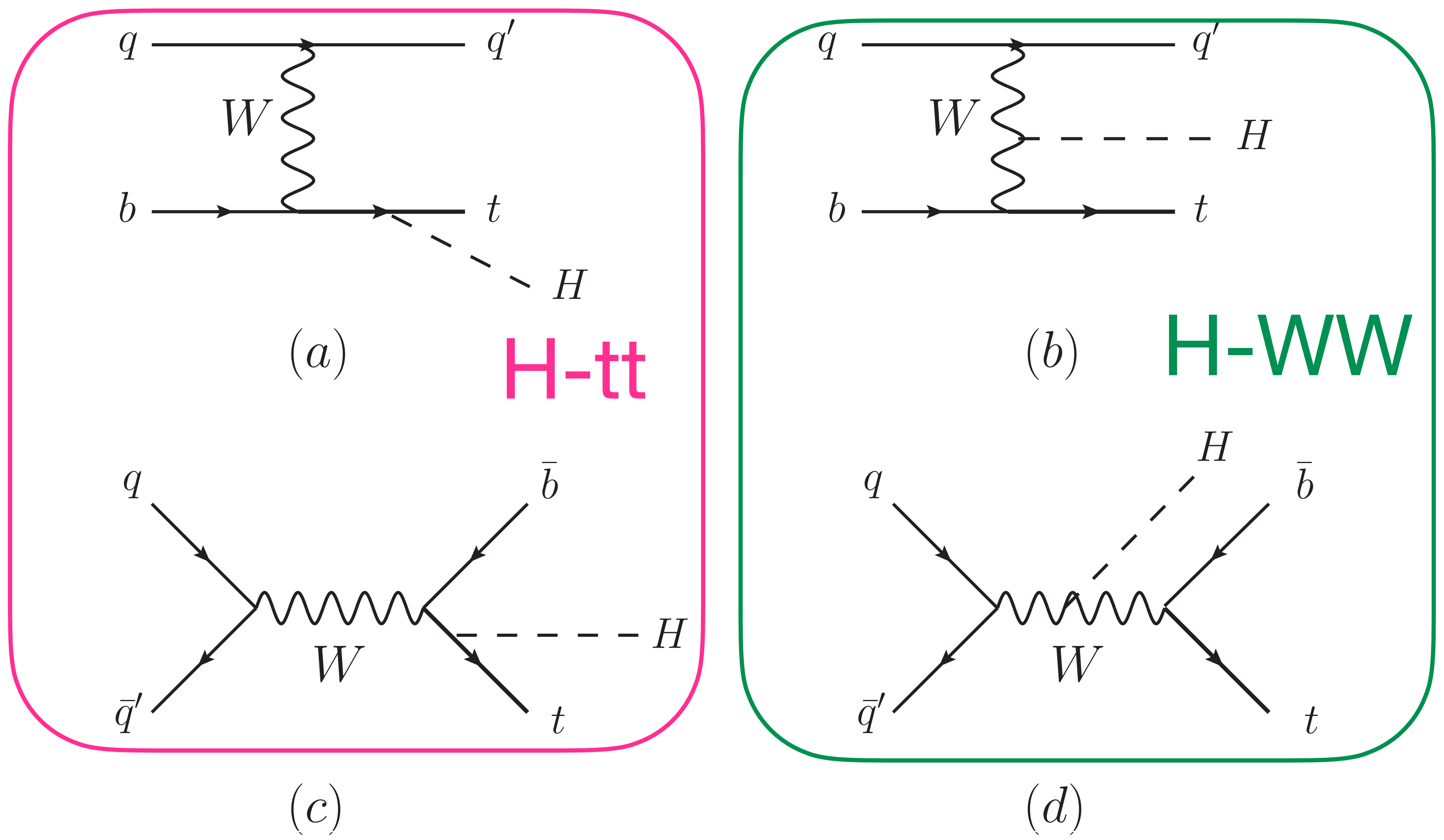
- Propagated to decay particles: tt, ττ

CP of H-tt Yukawa coupling: ttH production

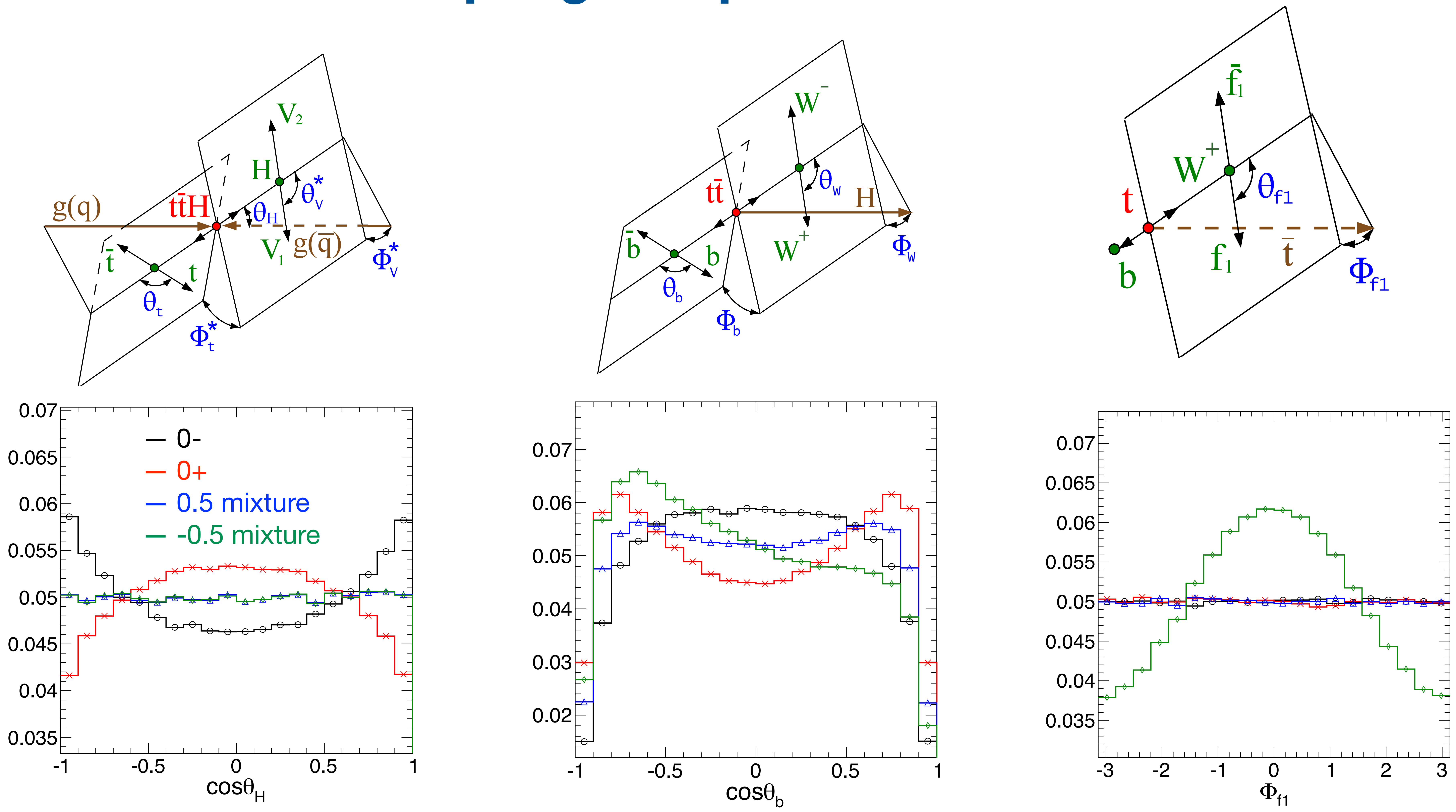
ttH: 4th major Higgs production at the LHC



tH: small xsec at the LHC

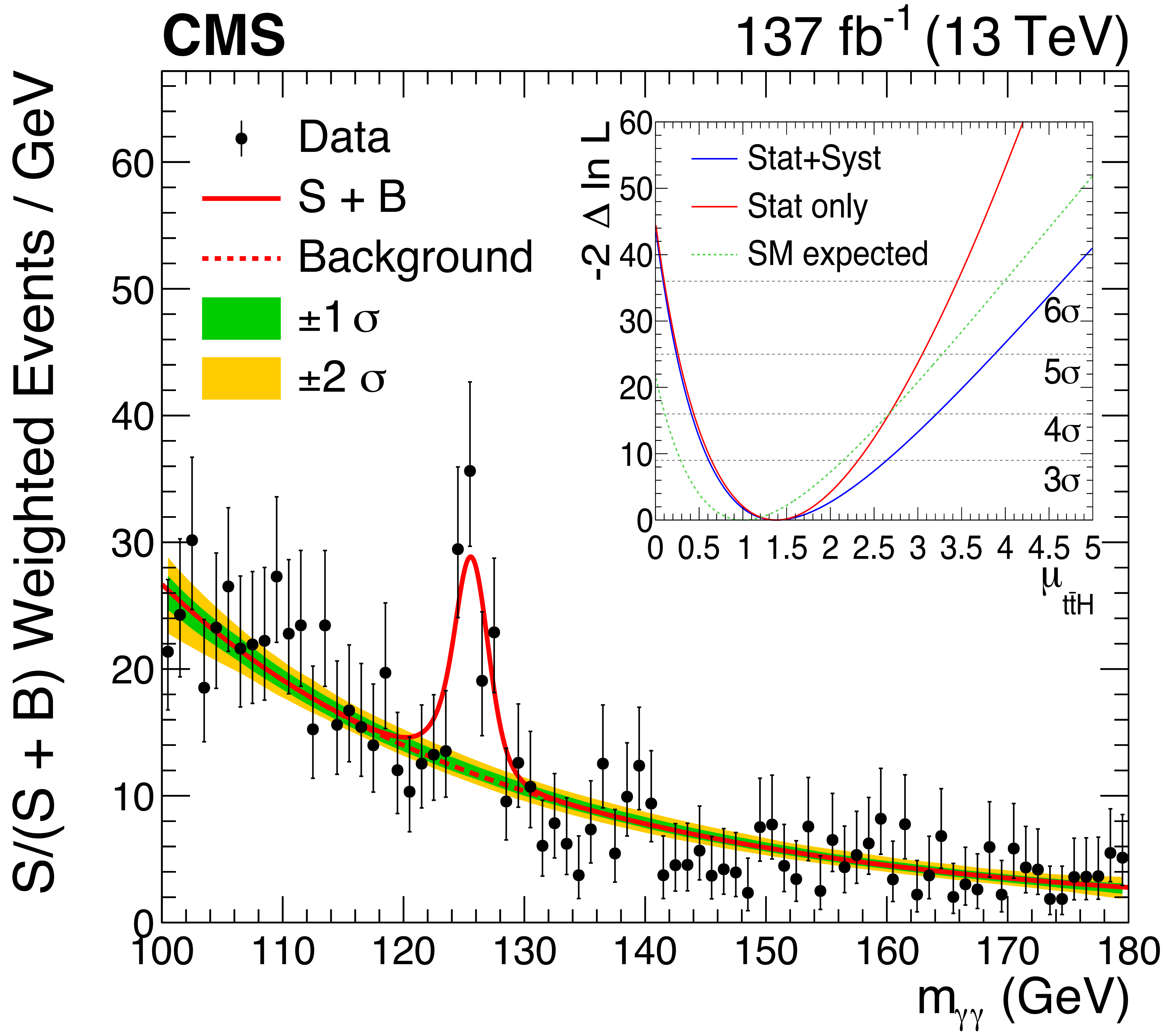


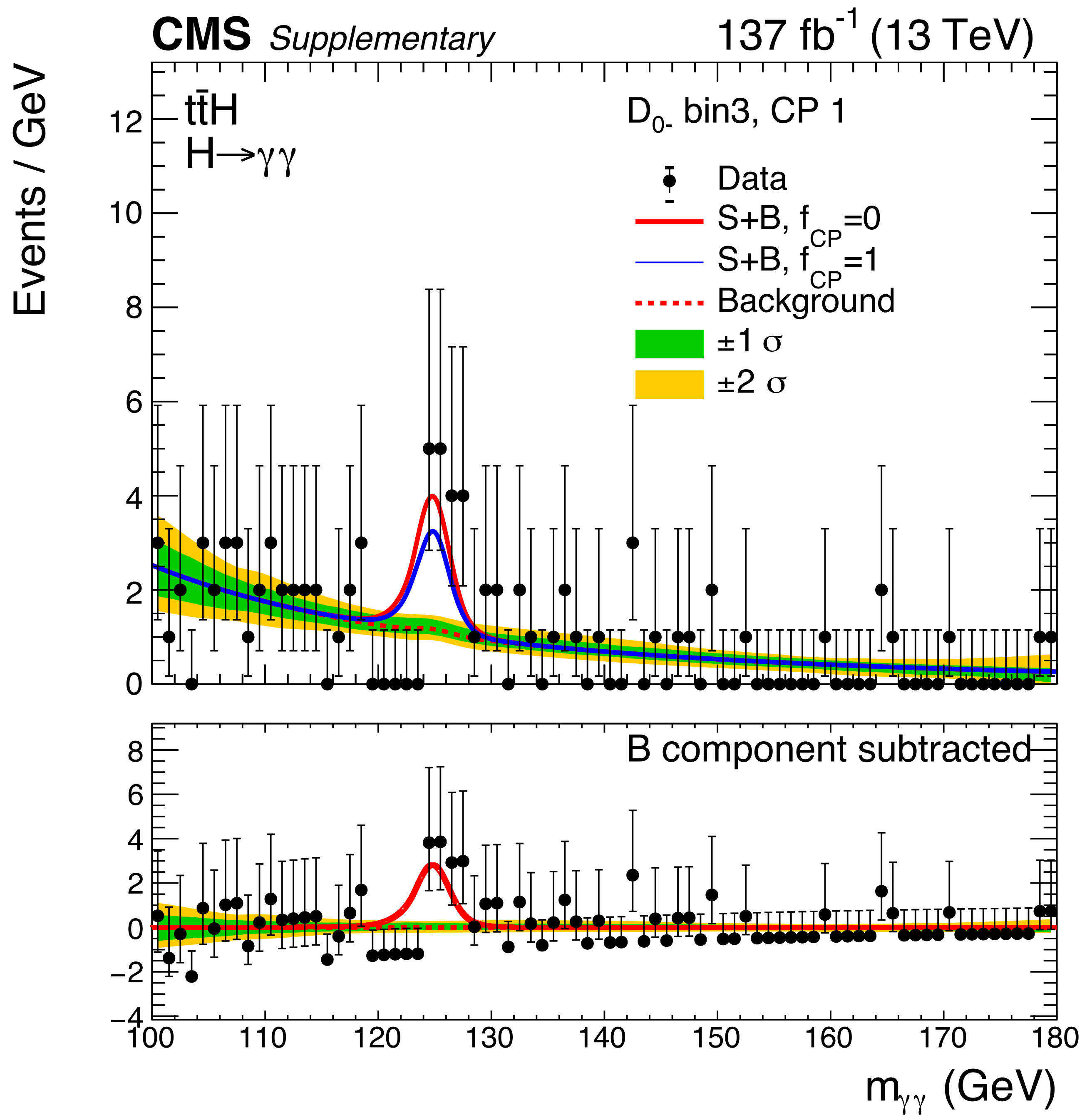
CP of H-tt Yukawa coupling: ttH production

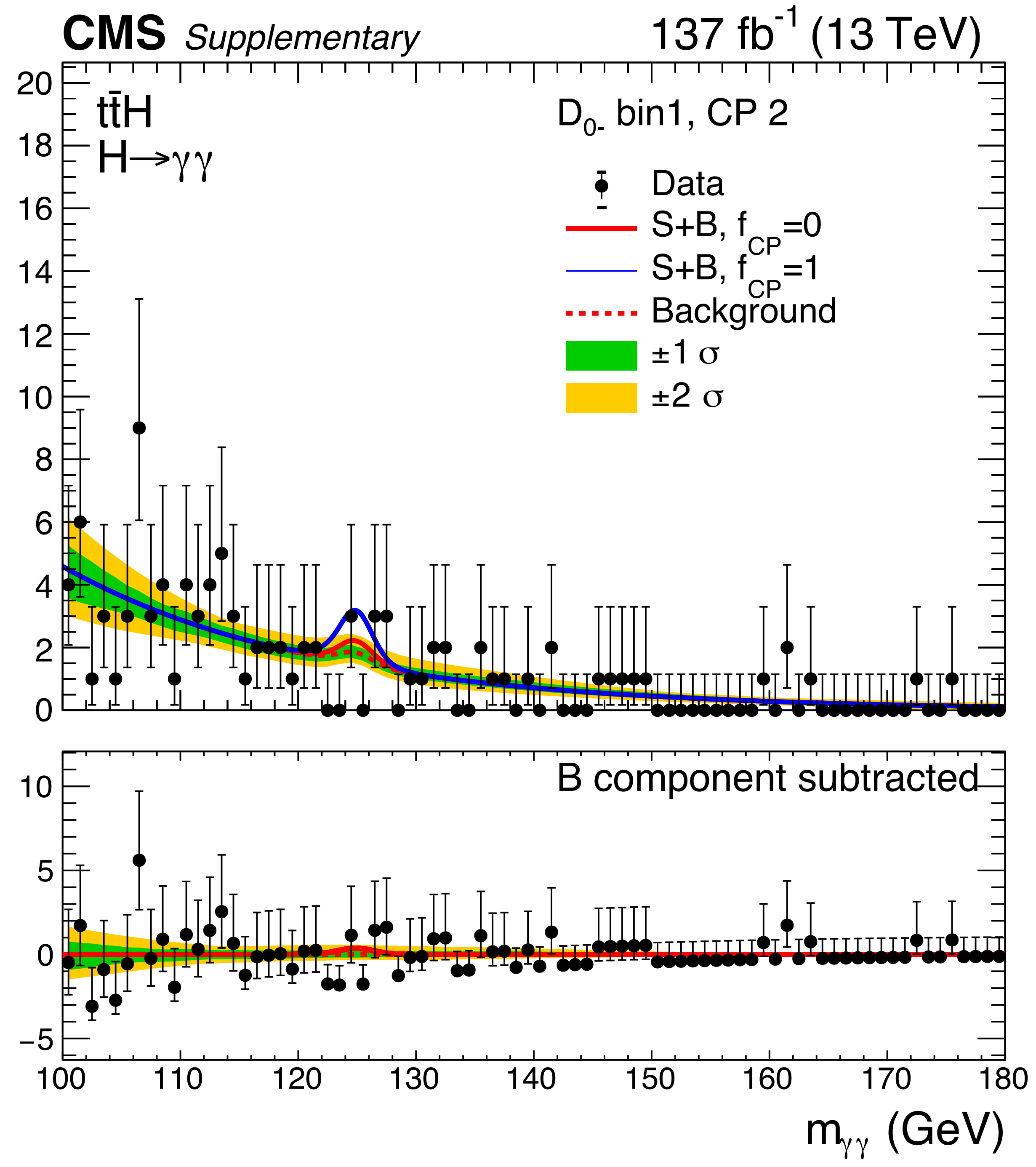


- Multiple decay plane, rich kinematic information to extract CP
- Complicated final states, difficult to completely reconstruct

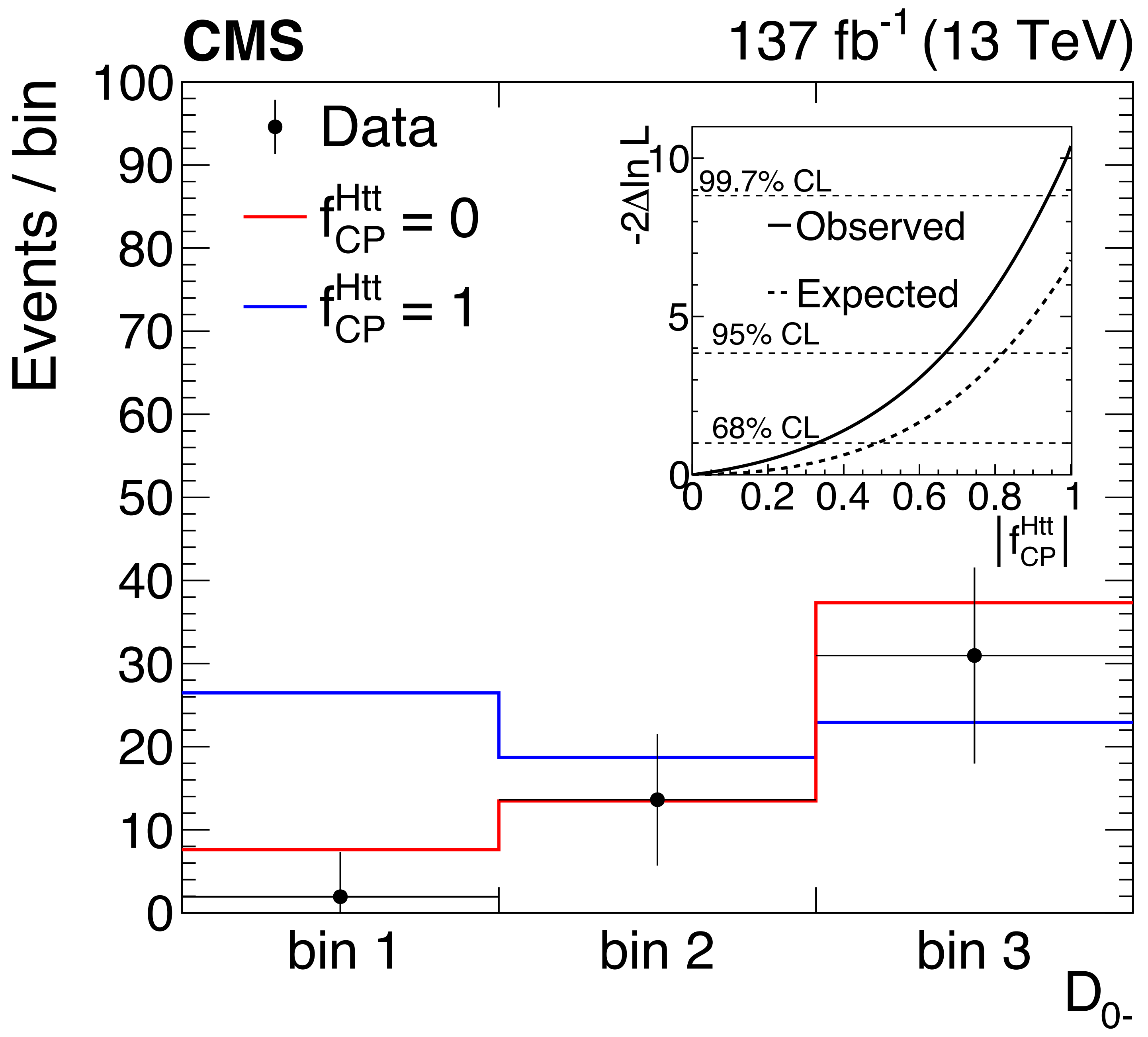
Measurement in ttH(γγ)







Phys, Rev. Lett. 125 (2020) 061801



- Machine learning methods to separate CP
- Categorize events, fit mass to extract signal in each category

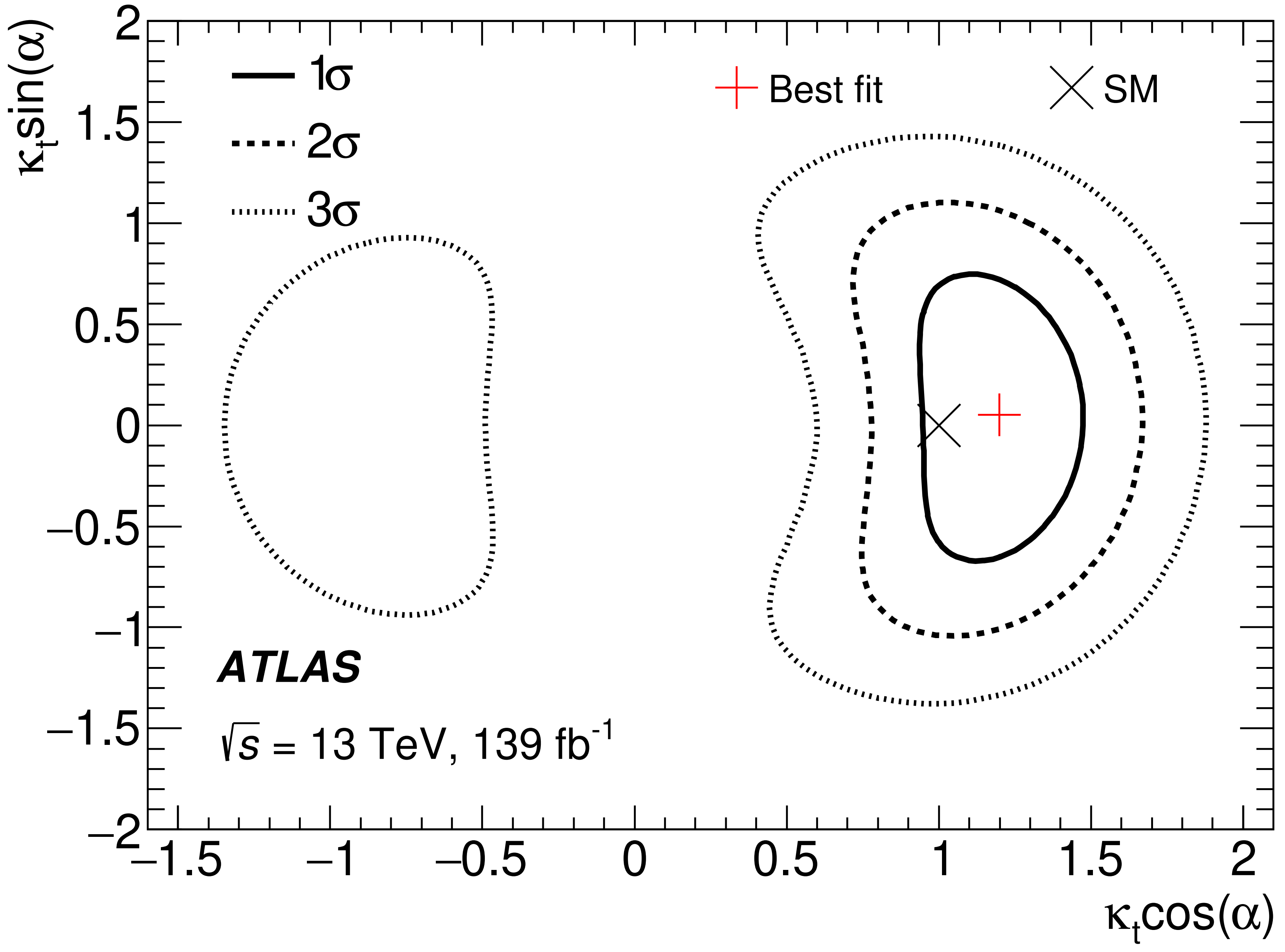
CP odd frac $f_{CP} = b_2^2/(b_1^2+b_2^2)$

3.2 σ exclusion on pure CP odd

$f_{CP} < 0.68$

Phys, Rev. Lett. 125 (2020) 061802

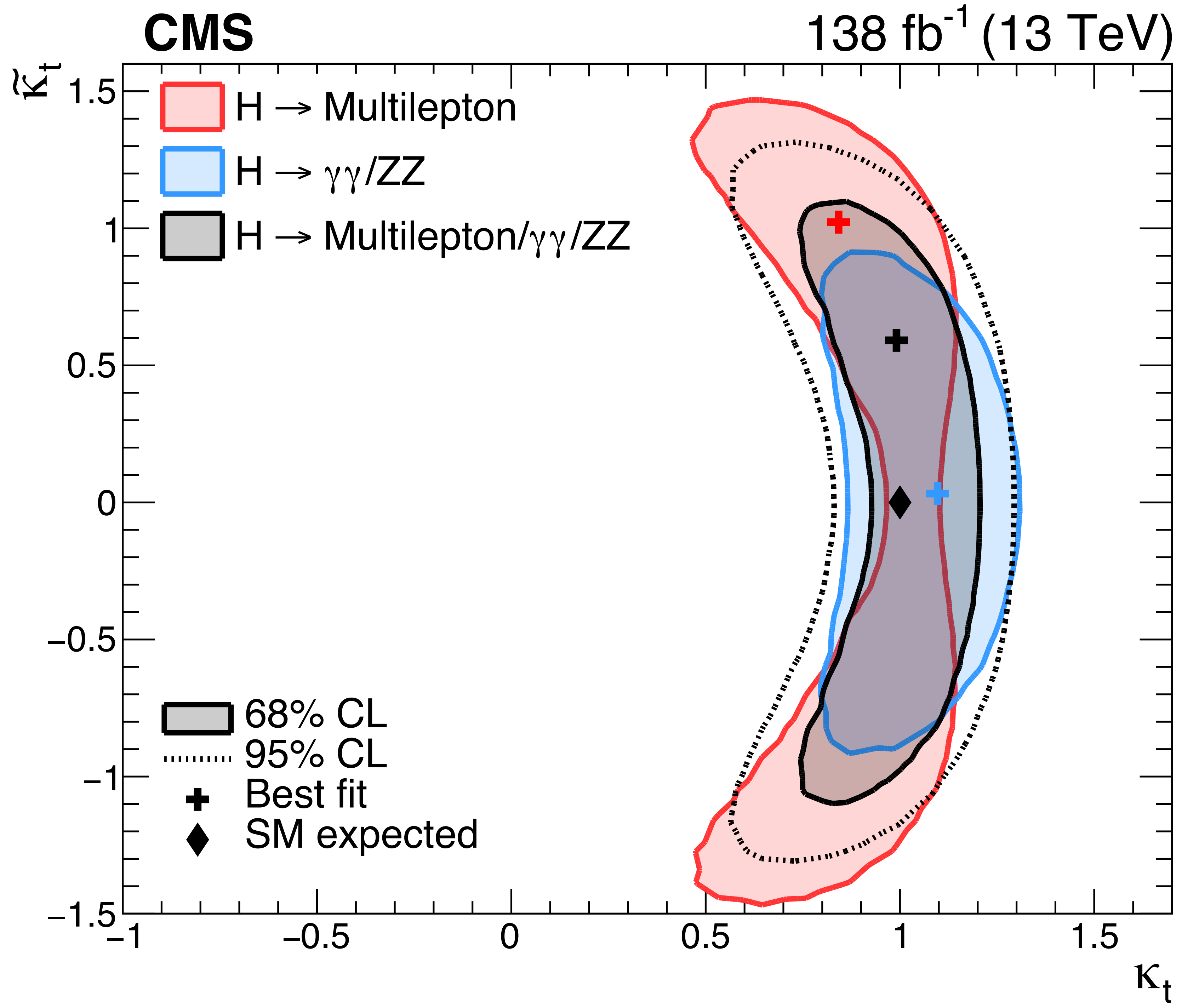
ATLAS ttH→ γγ



f_{CP}< 0.46

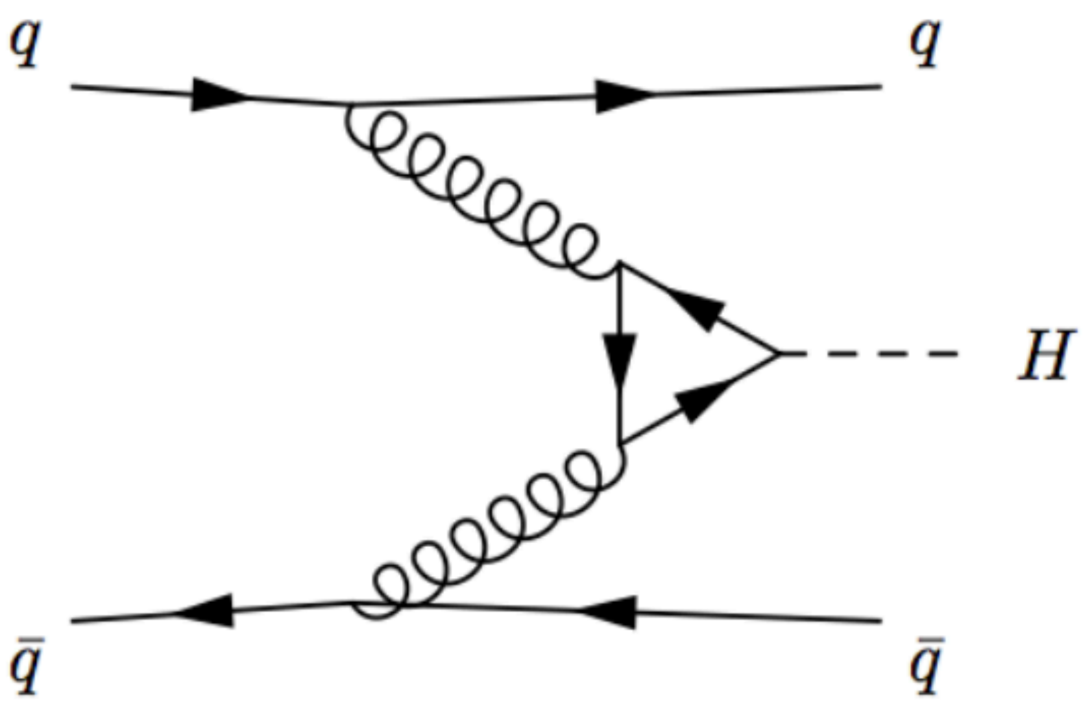
arXiv:2208.02686

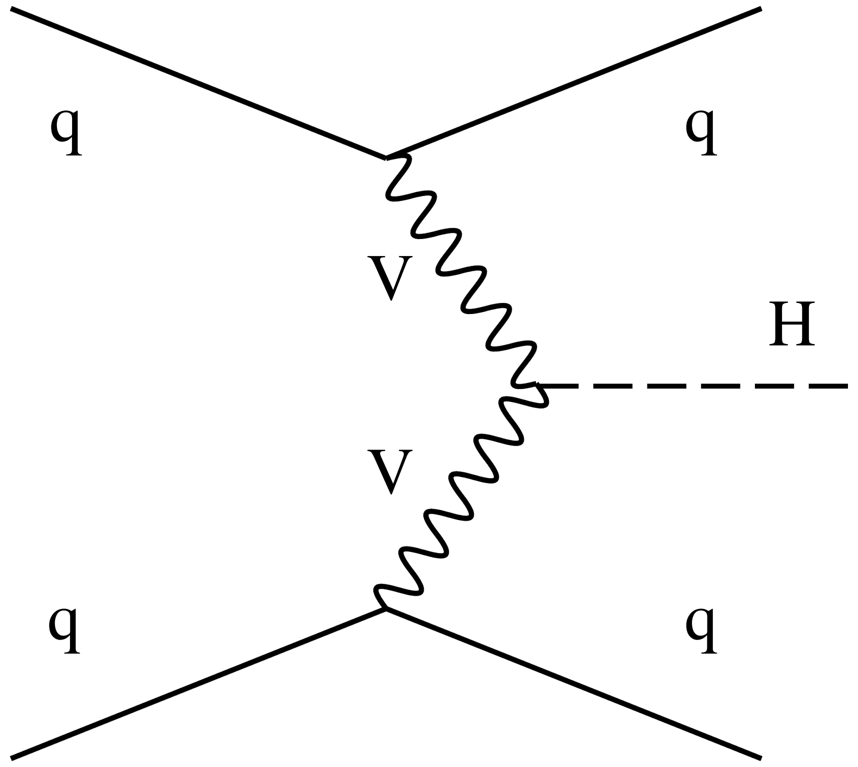
CMS ttH→ multilepton

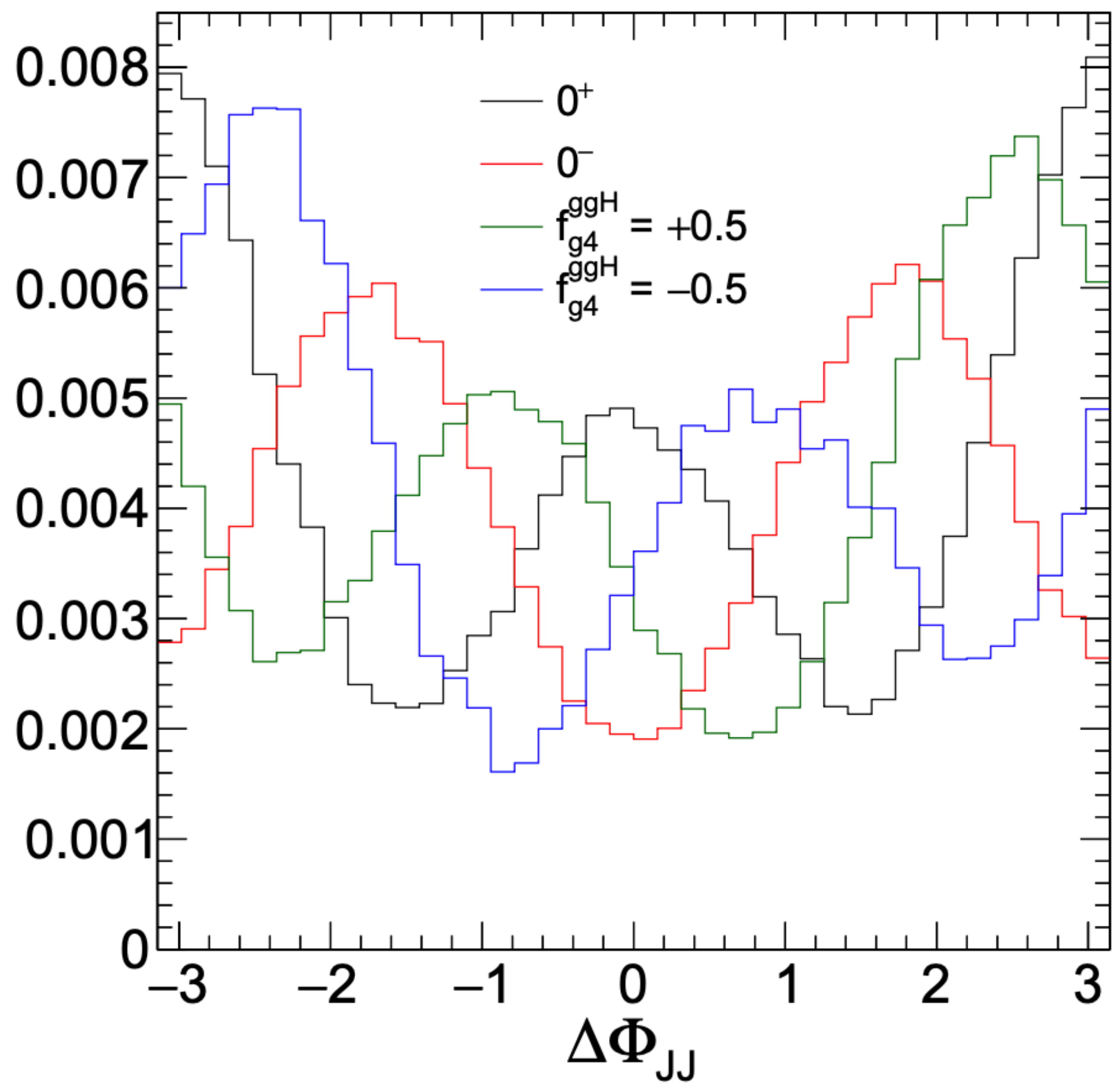


CP of H-tt Yukawa coupling: ggH production

ggH the largest xsec to probe Htt interaction
Additional jets needed to probe CP





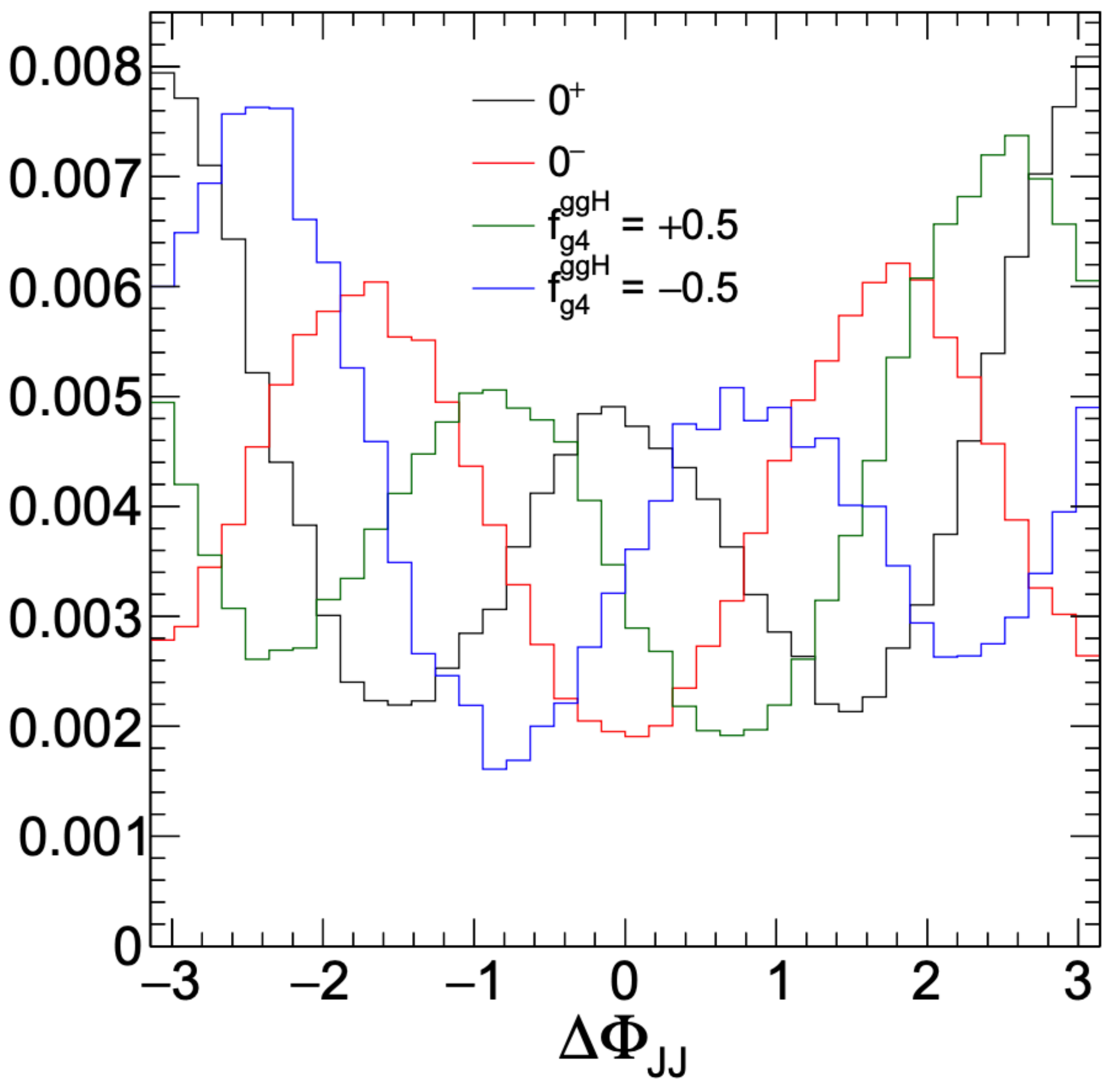


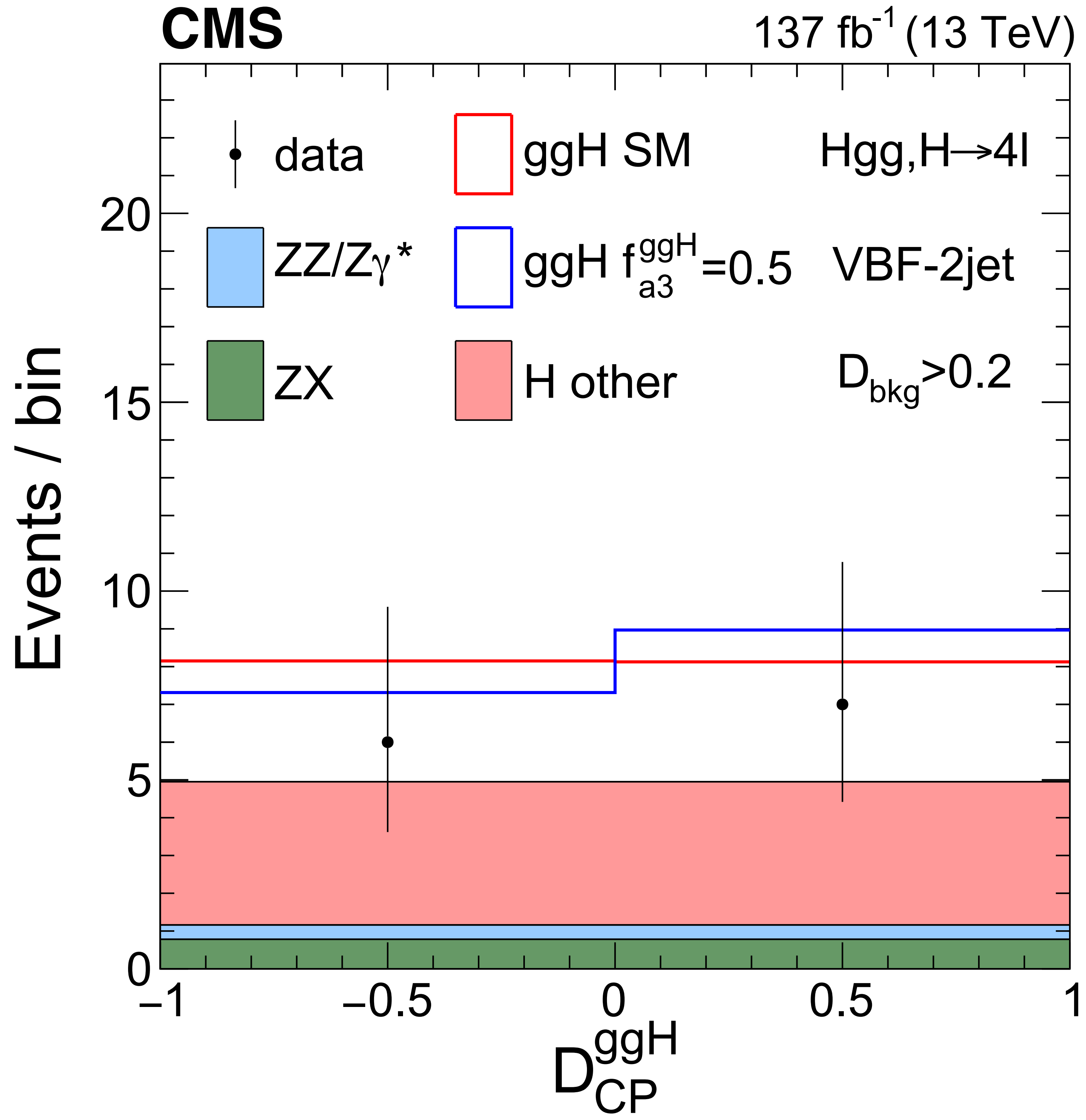
Similar signature as VBF, need to distinguish the two

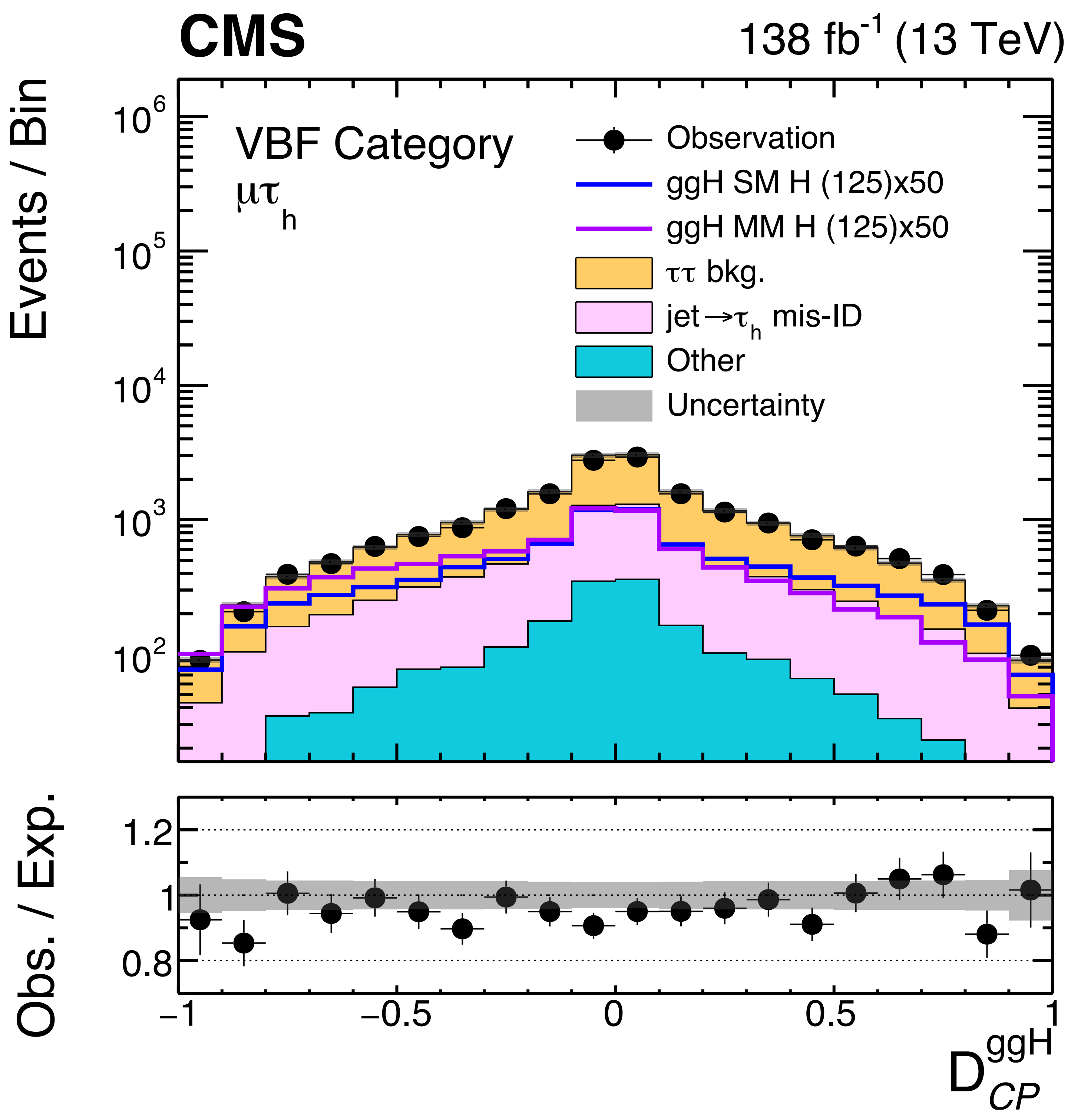
Measurements in ggH production

H+2jet： sensitive to the sign of κ/κ~

$$A(\mathrm{Hff}) = -\frac{m_\mathrm{f}}{v}\bar{\psi}_\mathrm{f}\left(\kappa_\mathrm{f} + \mathrm{i}\,\tilde{\kappa}_\mathrm{f}\gamma_5\right)\psi_\mathrm{f}\,.$$



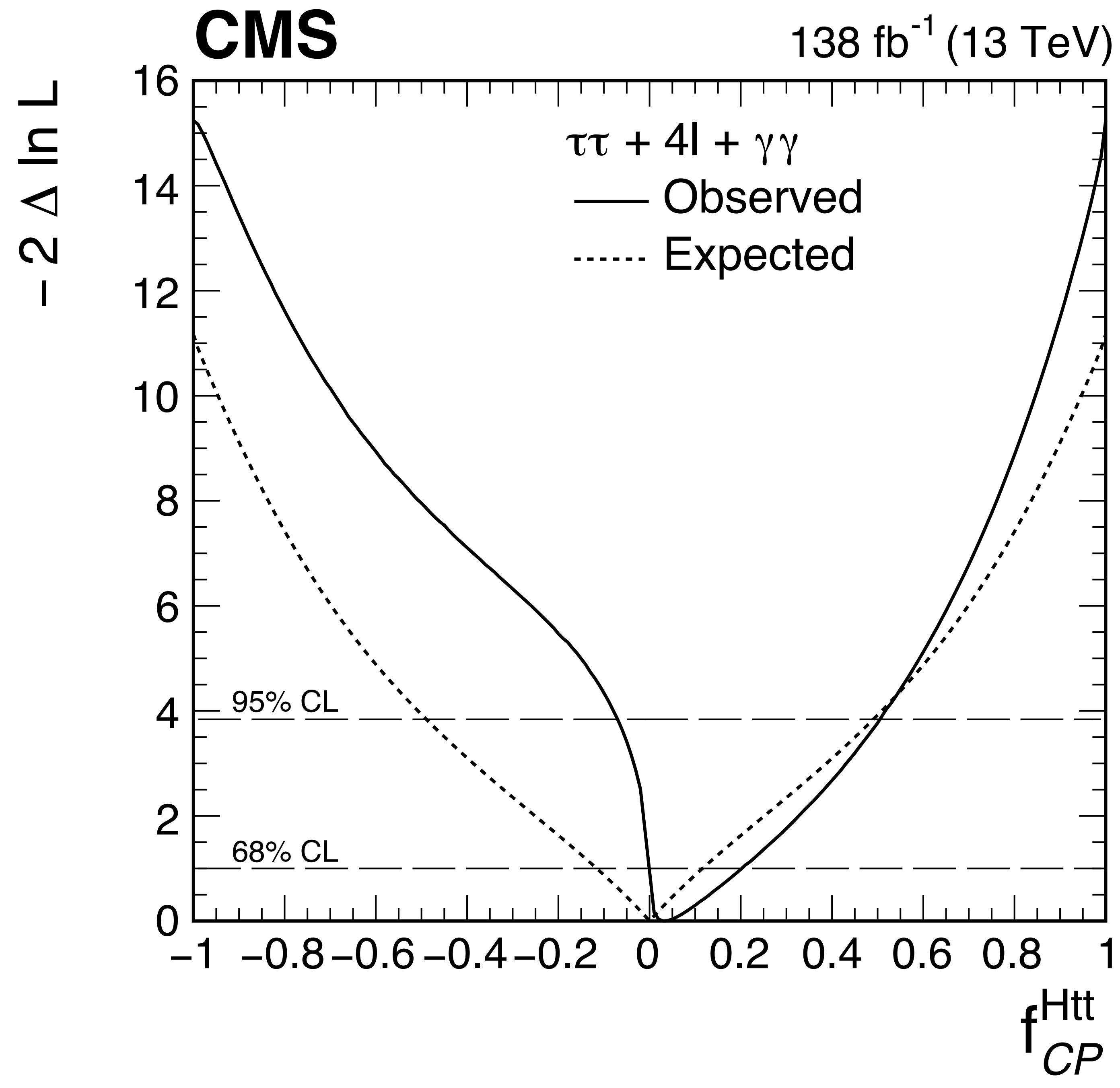




Phys. Rev. D 104 (2021) 052004

arXiv: 2205.05120

Measurements in ggH+ ttH

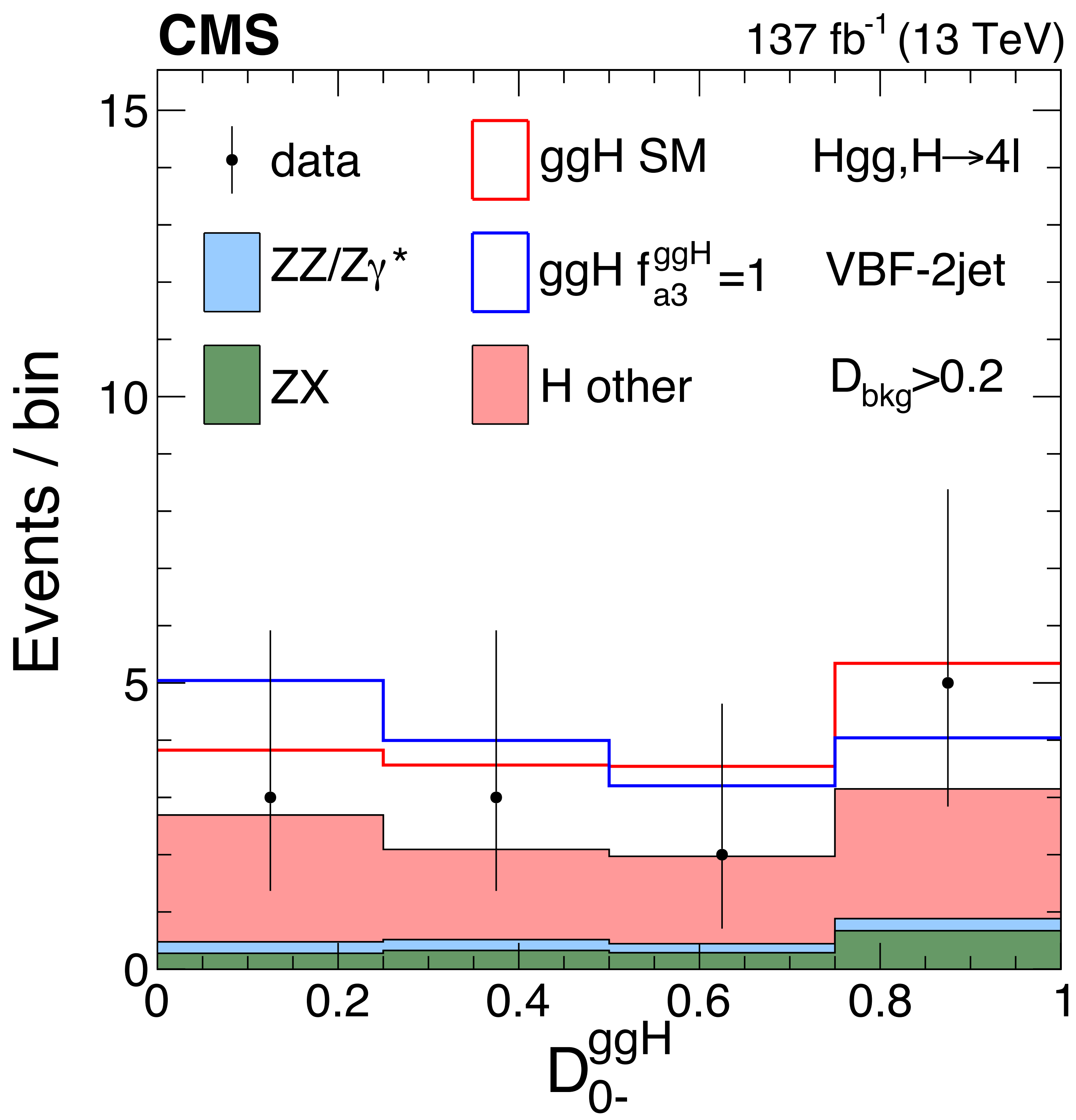


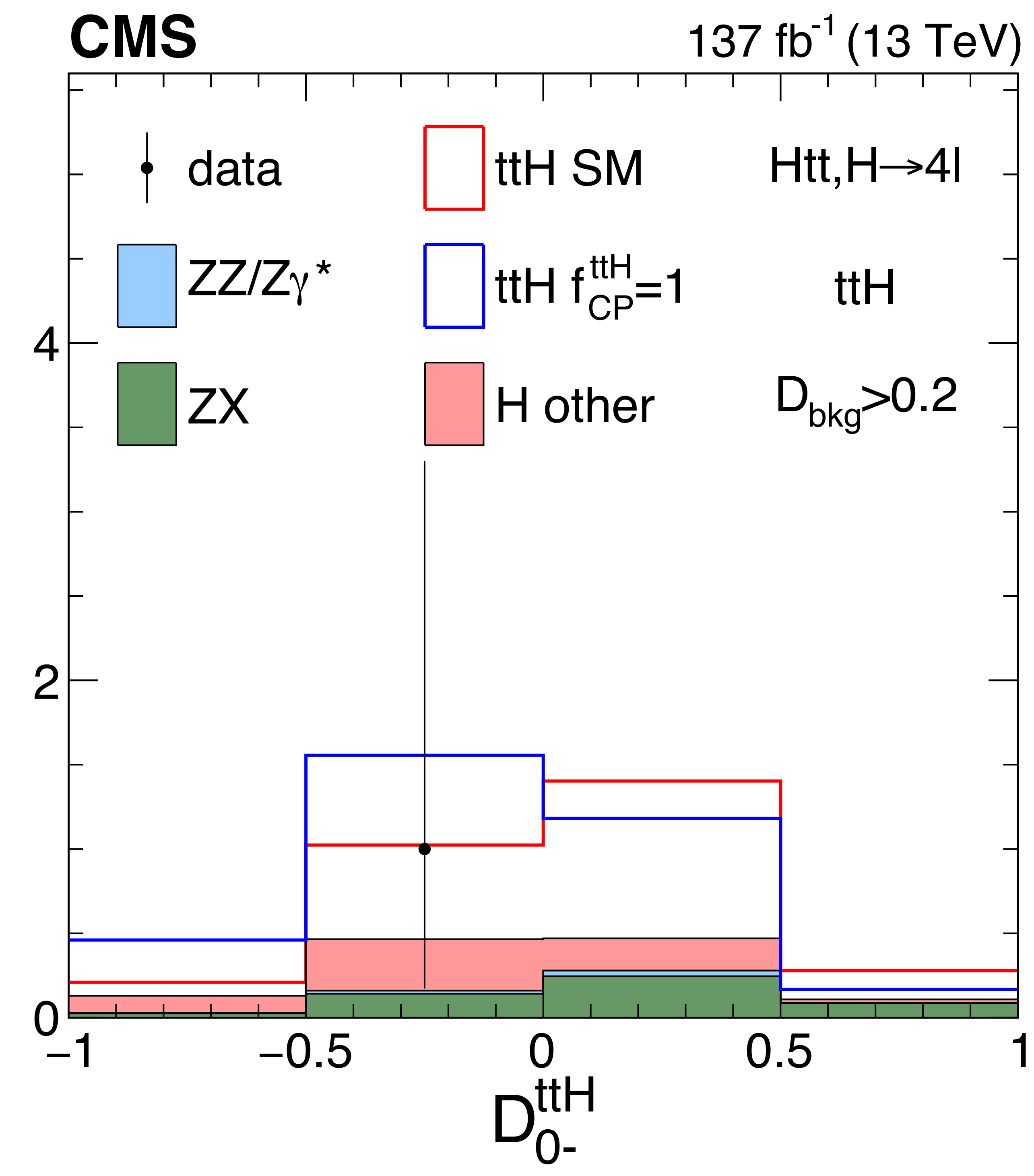
Extra power gained combining ggH + ttH

Xsec vary differently

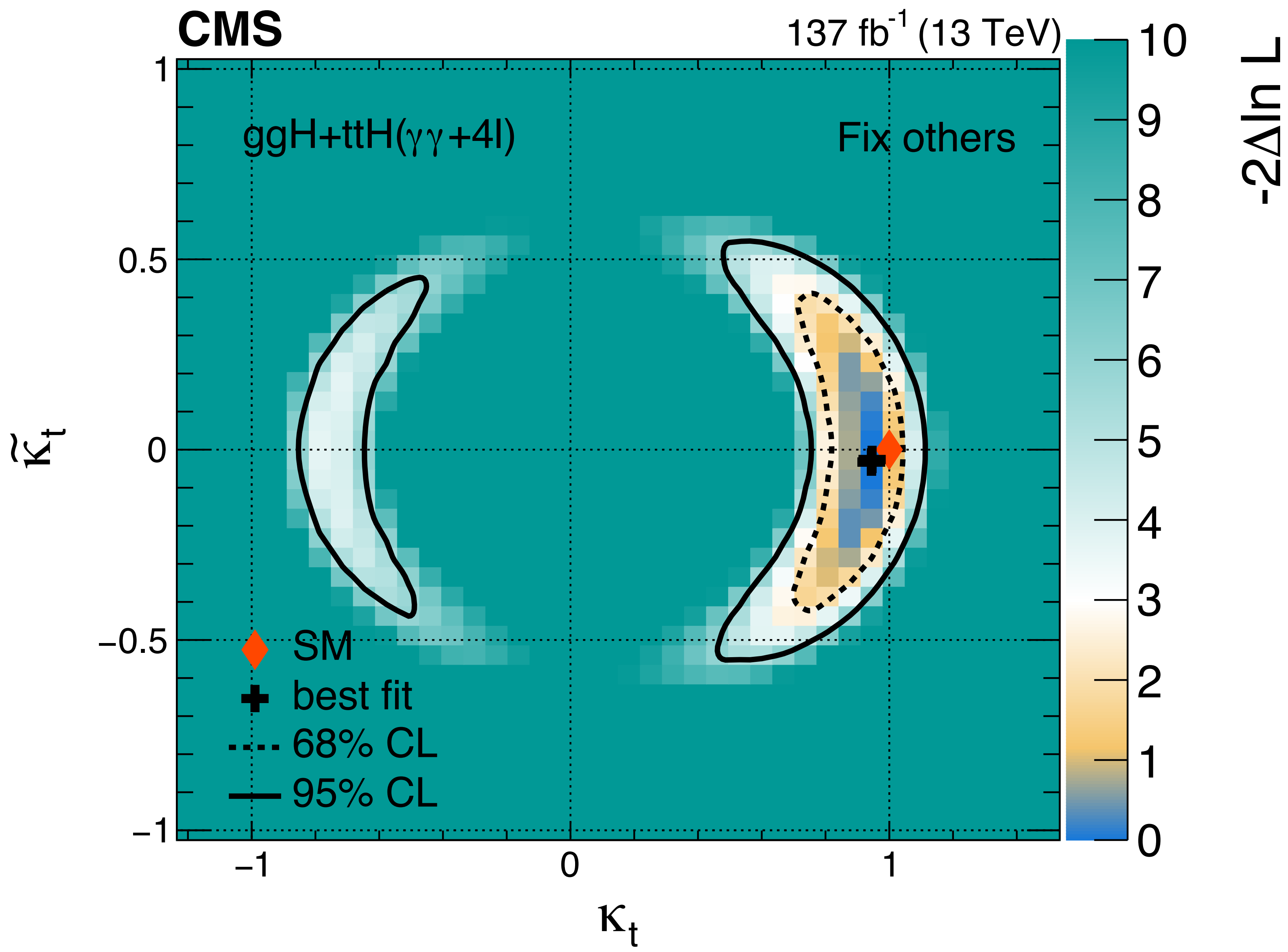
ggH: σ0-/ σ0+ = 2.38

ttH: σ0-/ σ0+ = 1/2.56

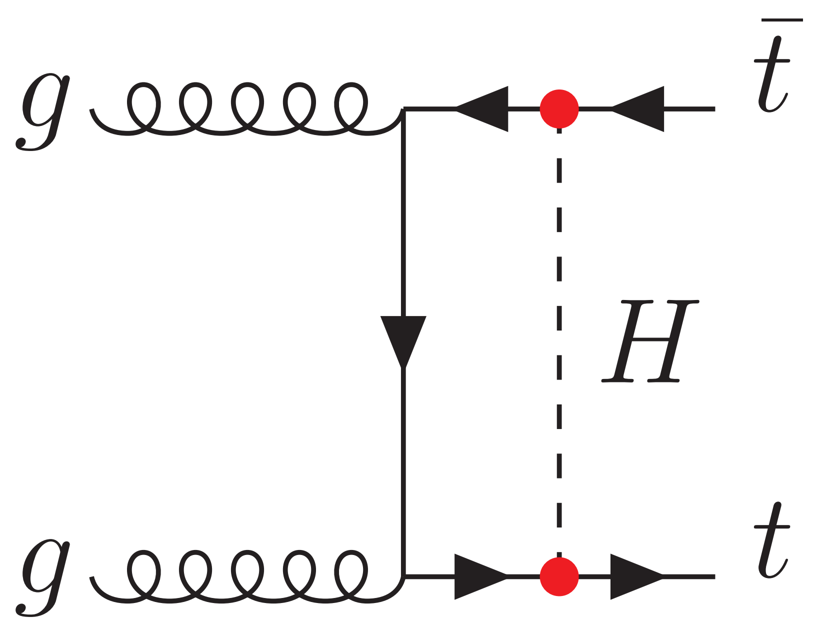


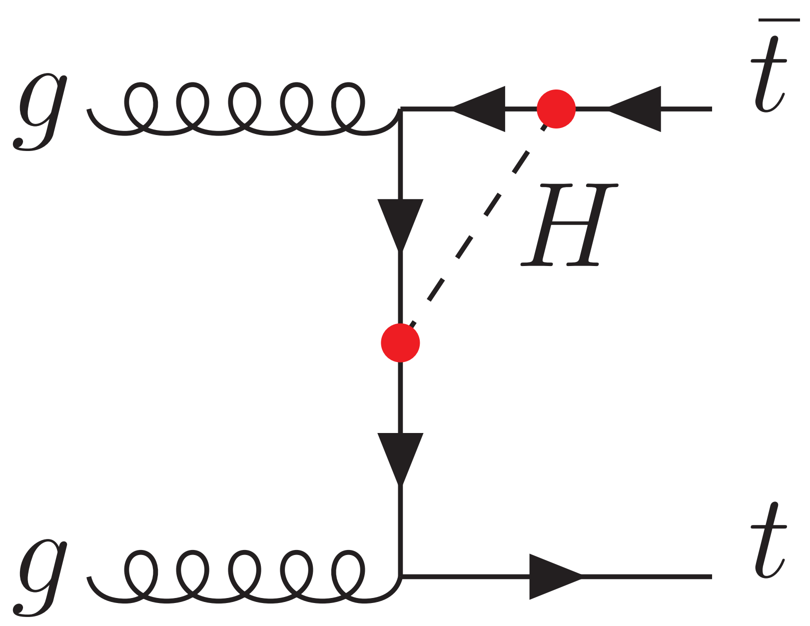


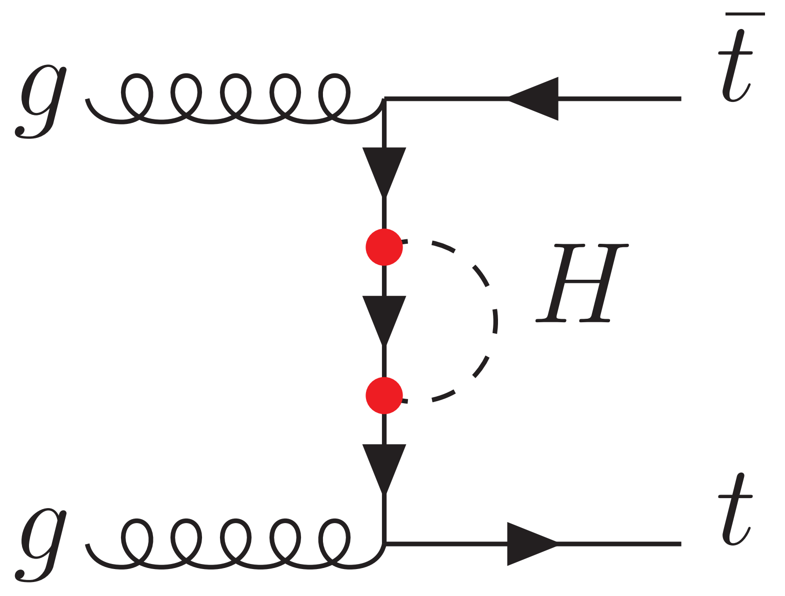
CP odd fraction $f_{CP} < 0.07$ (0.51)



$t\bar{t}$ production

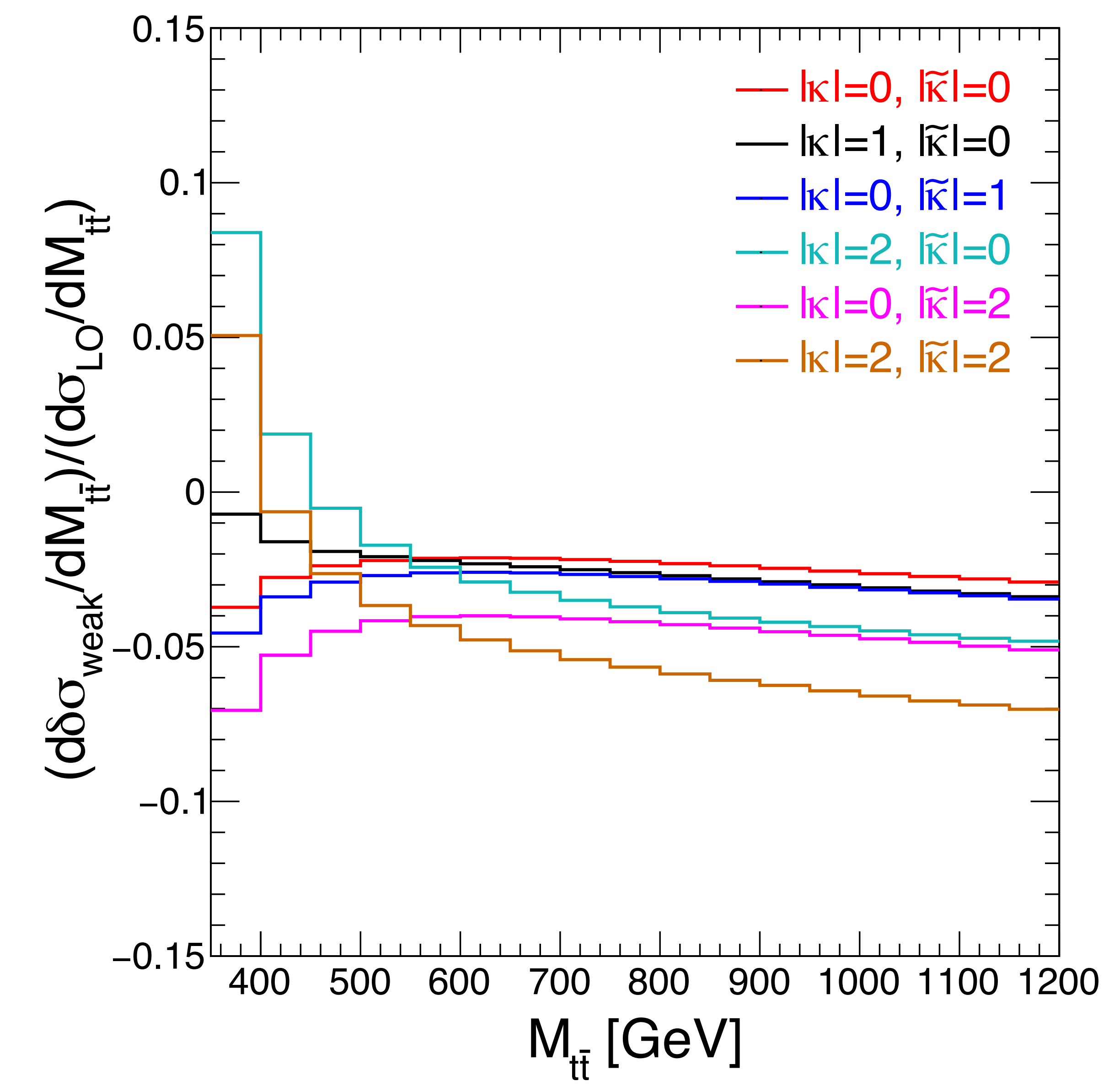


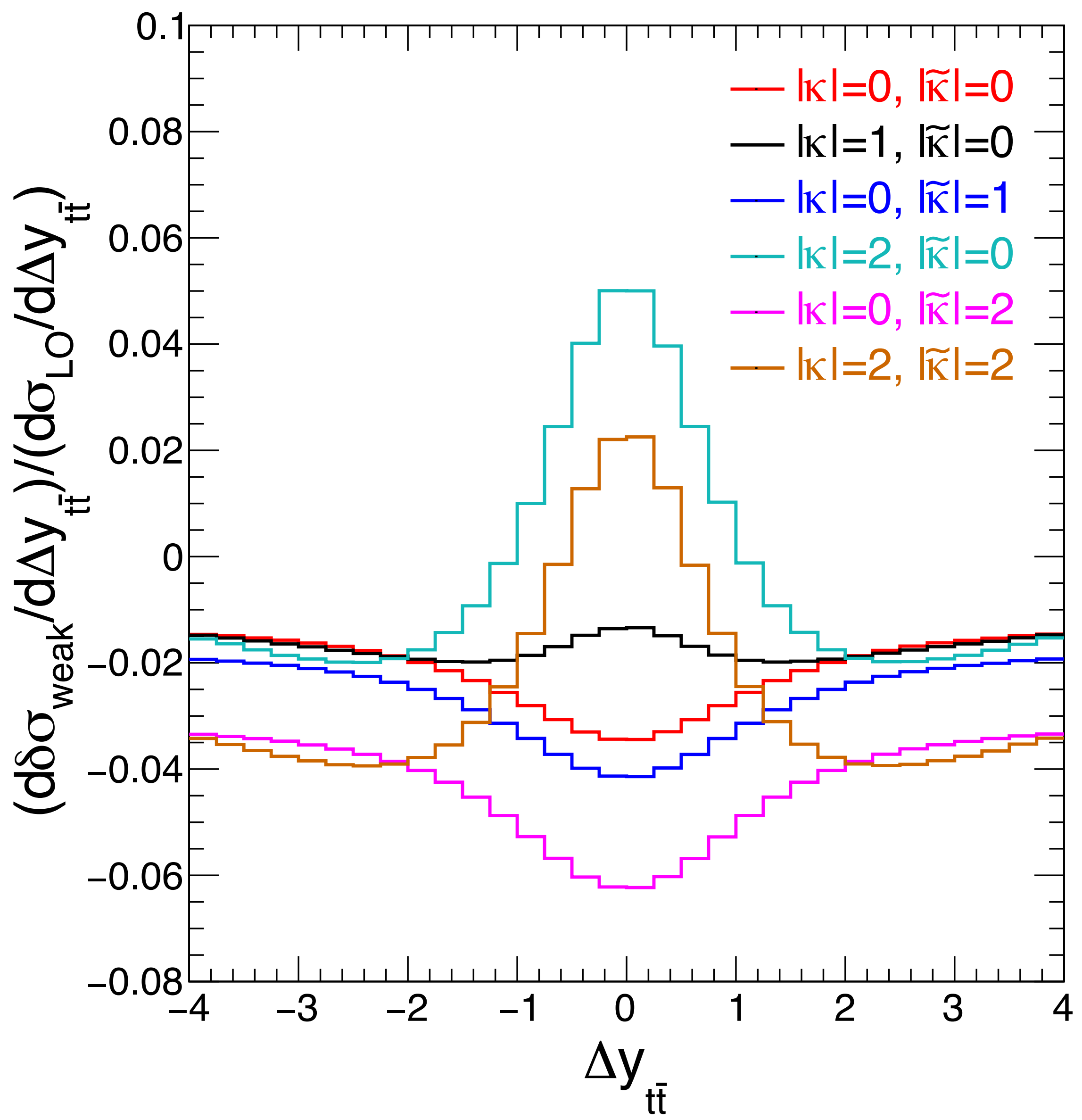




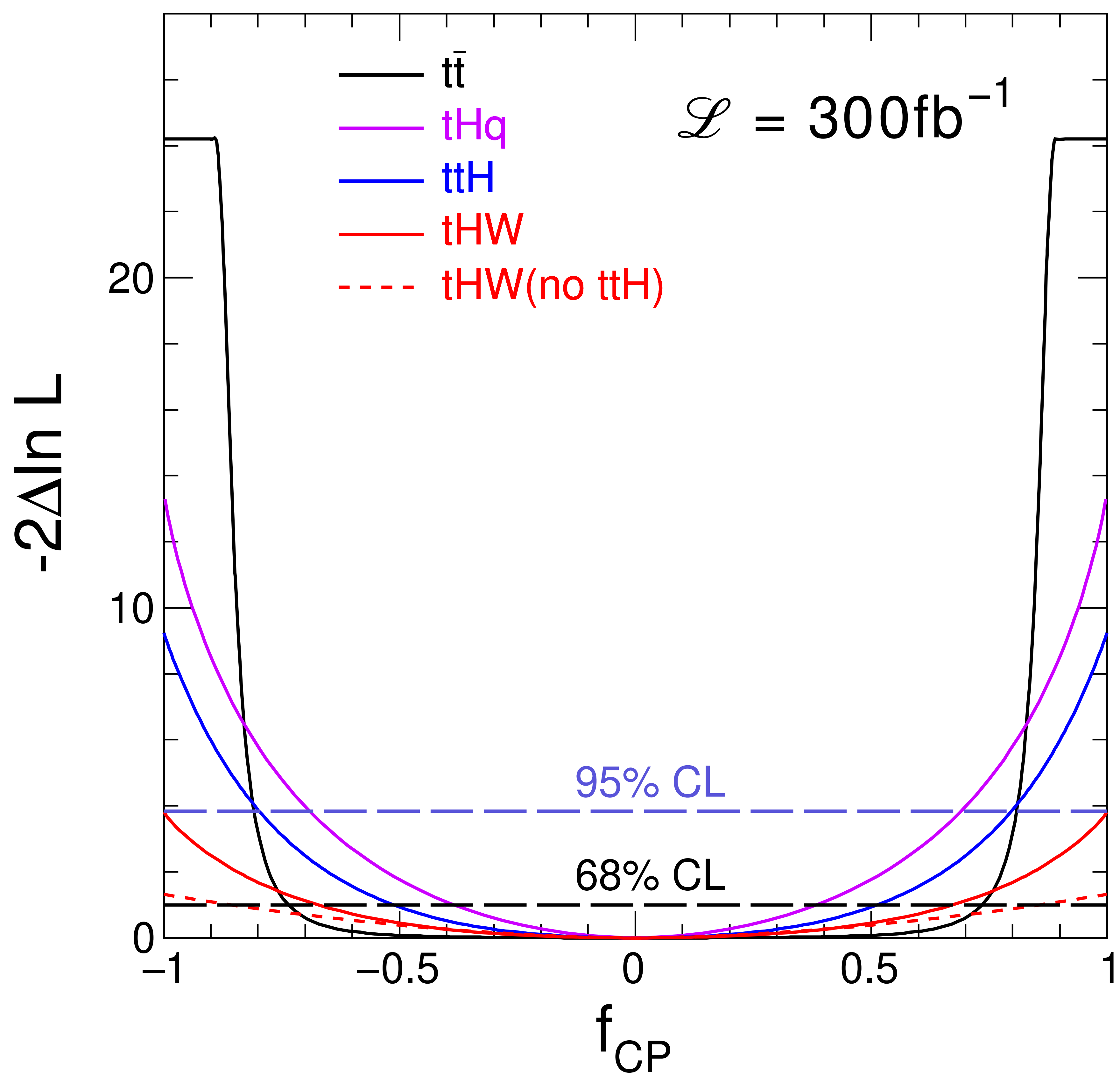
- Could the Htt coupling be accessed in other processes?
- EW correction in $t\bar{t}$ production
- Large xsec, ~ 800 pb (tt) w.r.t 0.5 pb (ttH)

EW corrections due to Htt





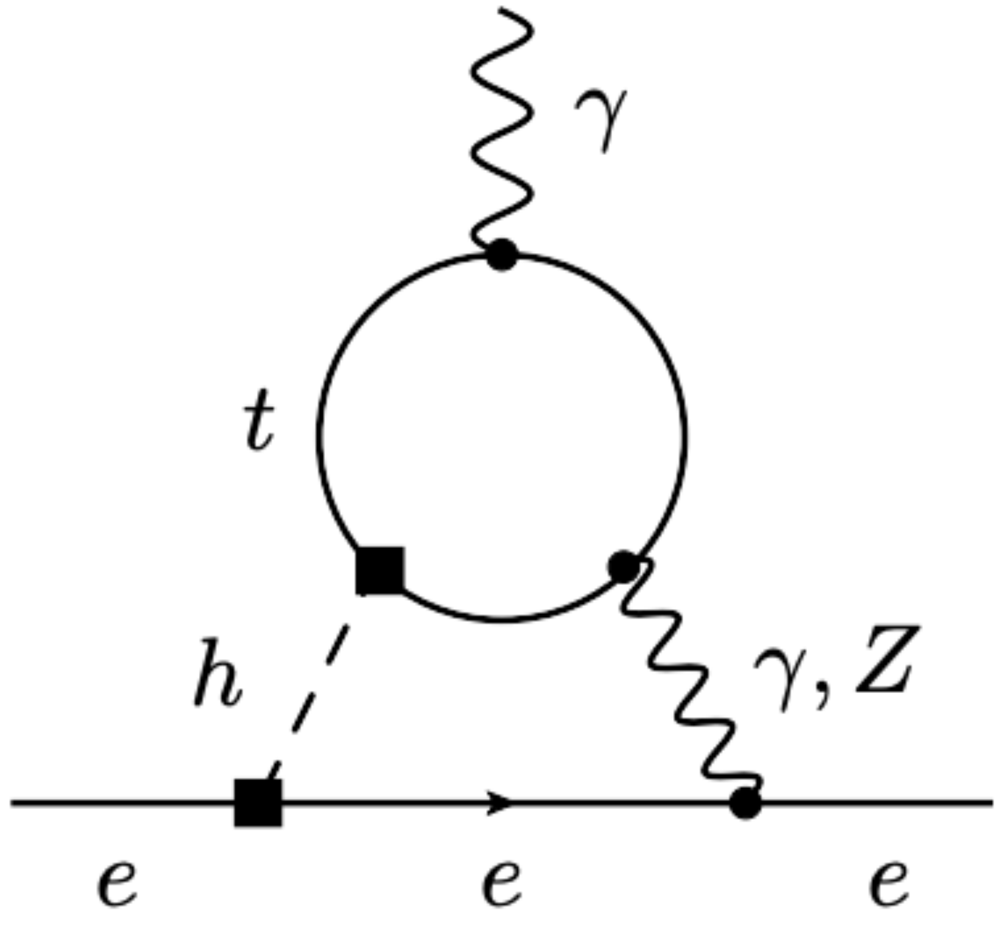
Phys. Rev. D **104**, 055045 (2021)
Pheno study



CMS analysis ongoing

Sensitivity in rather complementary phase space

EDM



- Electron EDM is known to put stringent constraint on Yukawa CP violation

- Strong assumptions on the electron-Yukawa coupling

arXiv: 2202.11753

$$\frac{d_e}{d_e^{\rm ACME}} = c_e\left(870.0\tilde{c}_t + 3.9\tilde{c}_b + 2.8\tilde{c}_c + 0.01\tilde{c}_s + 8\cdot 10^{-5}\tilde{c}_u + 7\cdot 10^{-5}\tilde{c}_d + 3.4\tilde{c}_\tau + 0.03\tilde{c}_\mu\right)$$
$$+\tilde{c}_e\left(610.1c_t + 3.1c_b + 2.3c_c + 0.01c_s + 7\cdot 10^{-5}c_u + 6\cdot 10^{-5}c_d + 2.8c_\tau + 0.02c_\mu - 1082.6c_V\right)$$
$$+ 2\cdot 10^{-6}c_e\tilde{c}_e. \quad (13)$$

If c_e and $\tilde{c}_e$ deviate tiny from SM coupling, could yield large cancellation in $\tilde{c}_t$

Direct measurement of $\tilde{c}_t$ is important

Baryon Asymmetry of the Universe

- Could the top Yukawa CP violation account for BAU under current constraint?

$$Y_B^{\rm VIA}/Y_B^{\rm obs} = 28\tilde{c}_t - 0.2\tilde{c}_b - 0.03\tilde{c}_c - 2\cdot 10^{-4}\tilde{c}_s - 9\cdot 10^{-8}\tilde{c}_u - 4\cdot 10^{-7}\tilde{c}_d$$
$$- 11\tilde{c}_\tau - 0.1\tilde{c}_\mu - 3\cdot 10^{-6}\tilde{c}_e,$$

arXiv: 2202.11753

If all the other couplings are 0, $\tilde{c}_t > 0.036$ to account for BAU

Current constraints: $\tilde{c}_t < \sim 1$

Projection on f_{CP}

arXiv: 2205.07715
Snowmass 2022 report

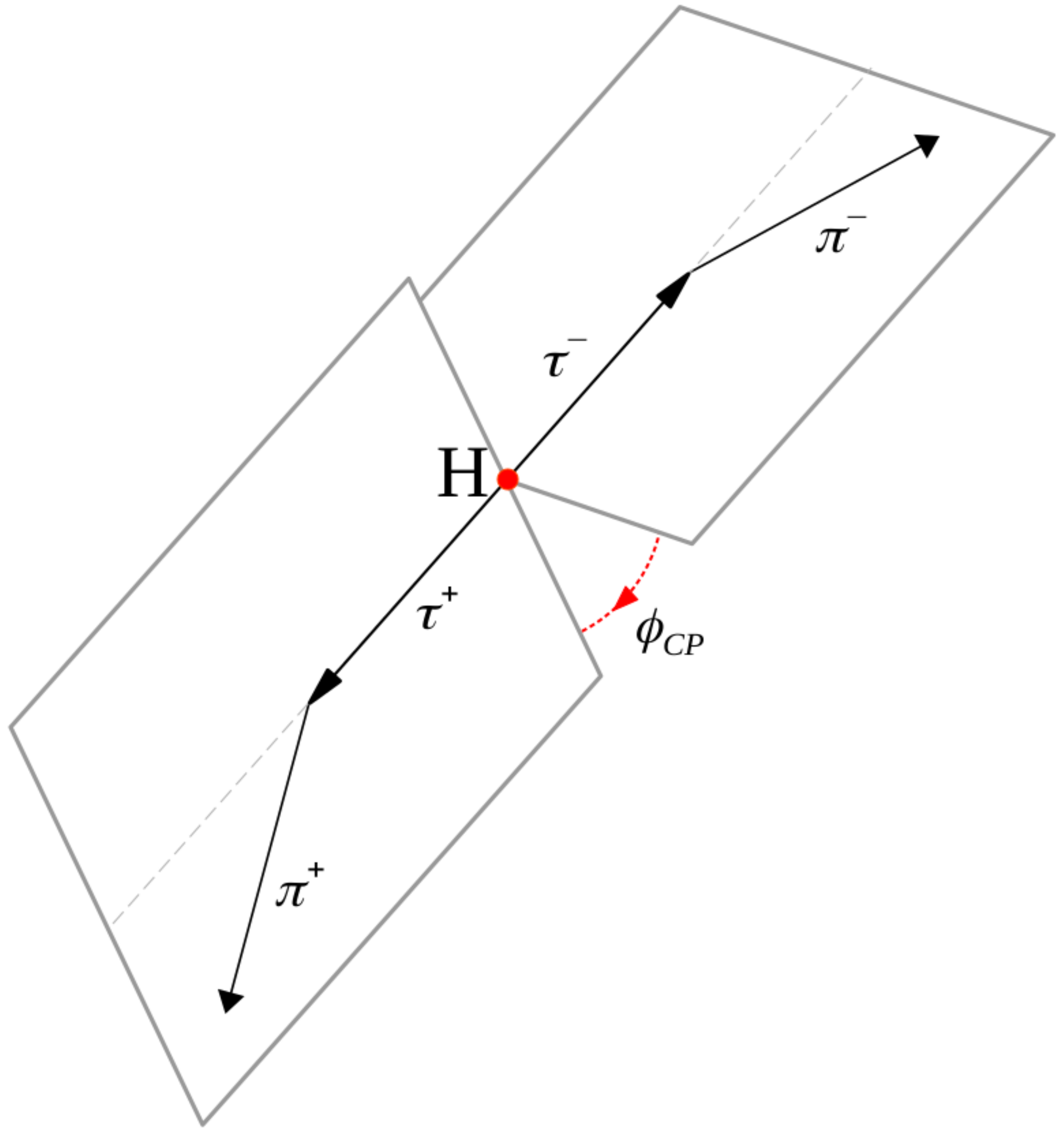
Collider	pp	pp	pp	e^+e^-	e^+e^-	e^+e^-	e^+e^-	e^-p	$\gamma\gamma$	$\mu^+\mu^-$	$\mu^+\mu^-$
E (GeV)	14,000	14,000	100,000	250	350	500	1,000	1,300	125	125	3,000
$\mathcal{L}$ (fb^{-1})	300	3,000	30,000	250	350	500	1,000	1,000	250	20	1,000
$Ht\bar{t}$	0.24	0.05	✓	–	–	0.29	0.08	✓	–	–	✓
$H\tau\tau$	0.07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

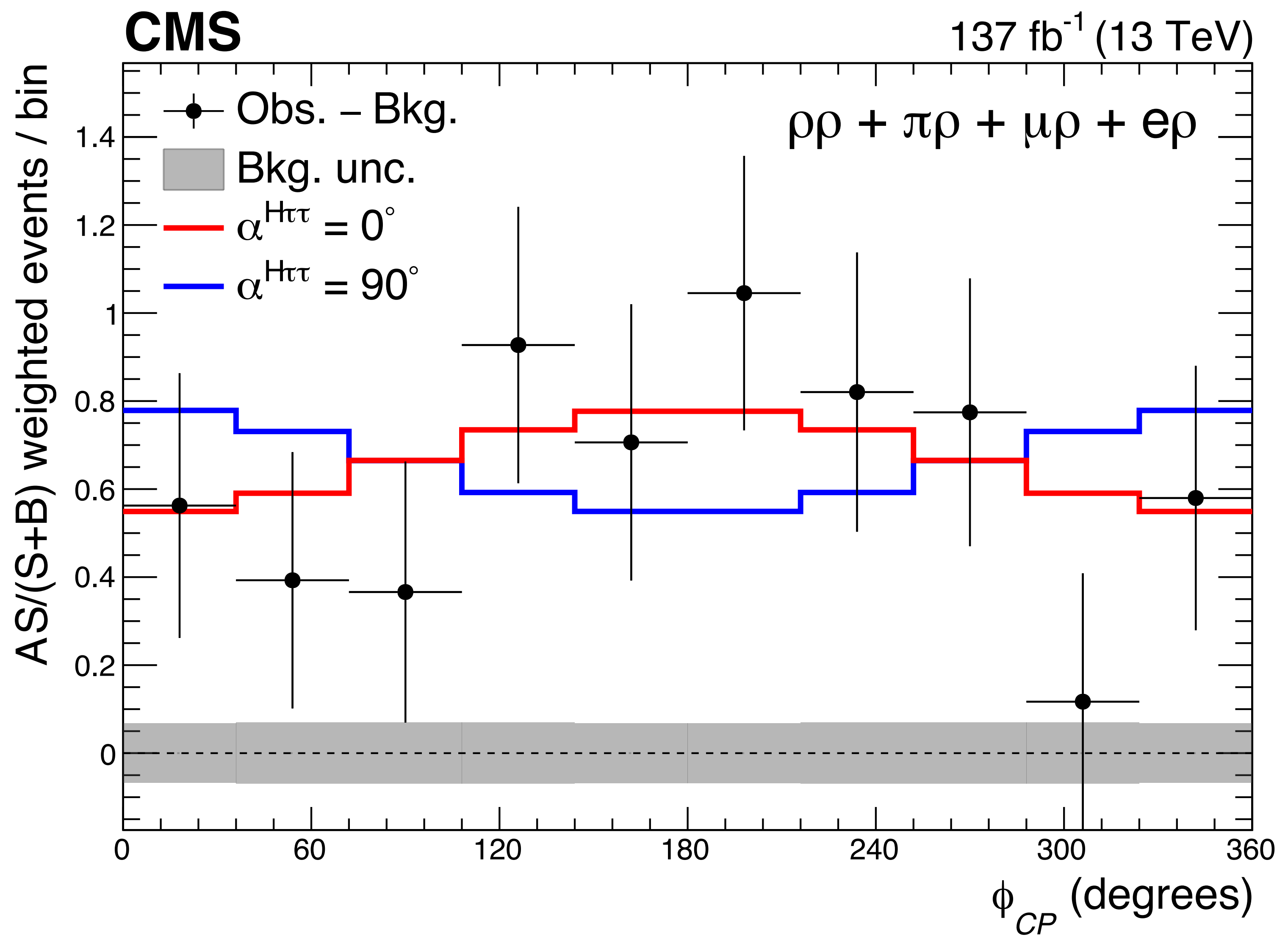
Summary

- Rich physics in top Yukawa CP violation at the LHC
- Direct and model independent measurements are important, complementary to EDM constraints
- No significant violation observed yet
- Still large room to explain the BAU

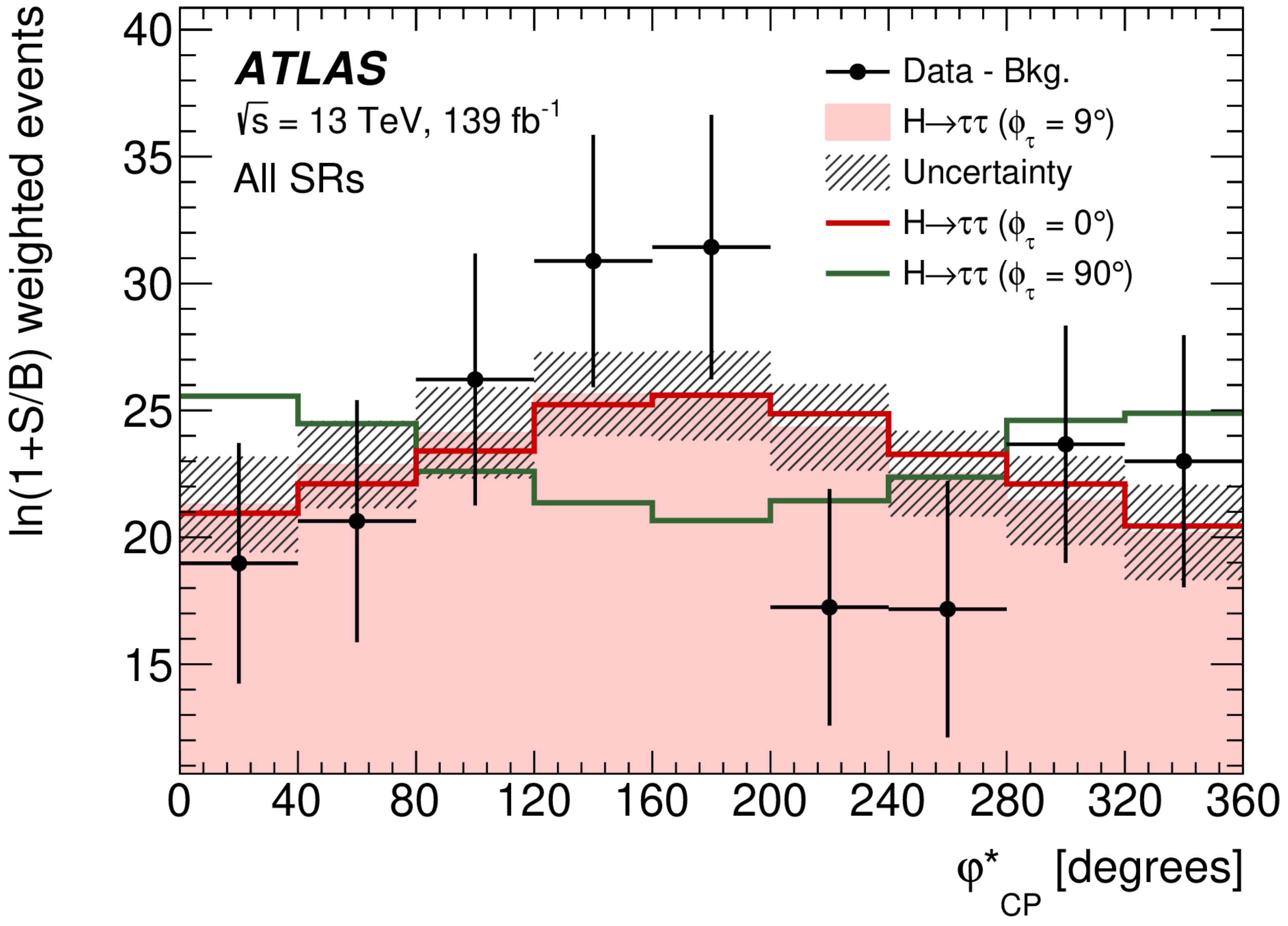
Backup

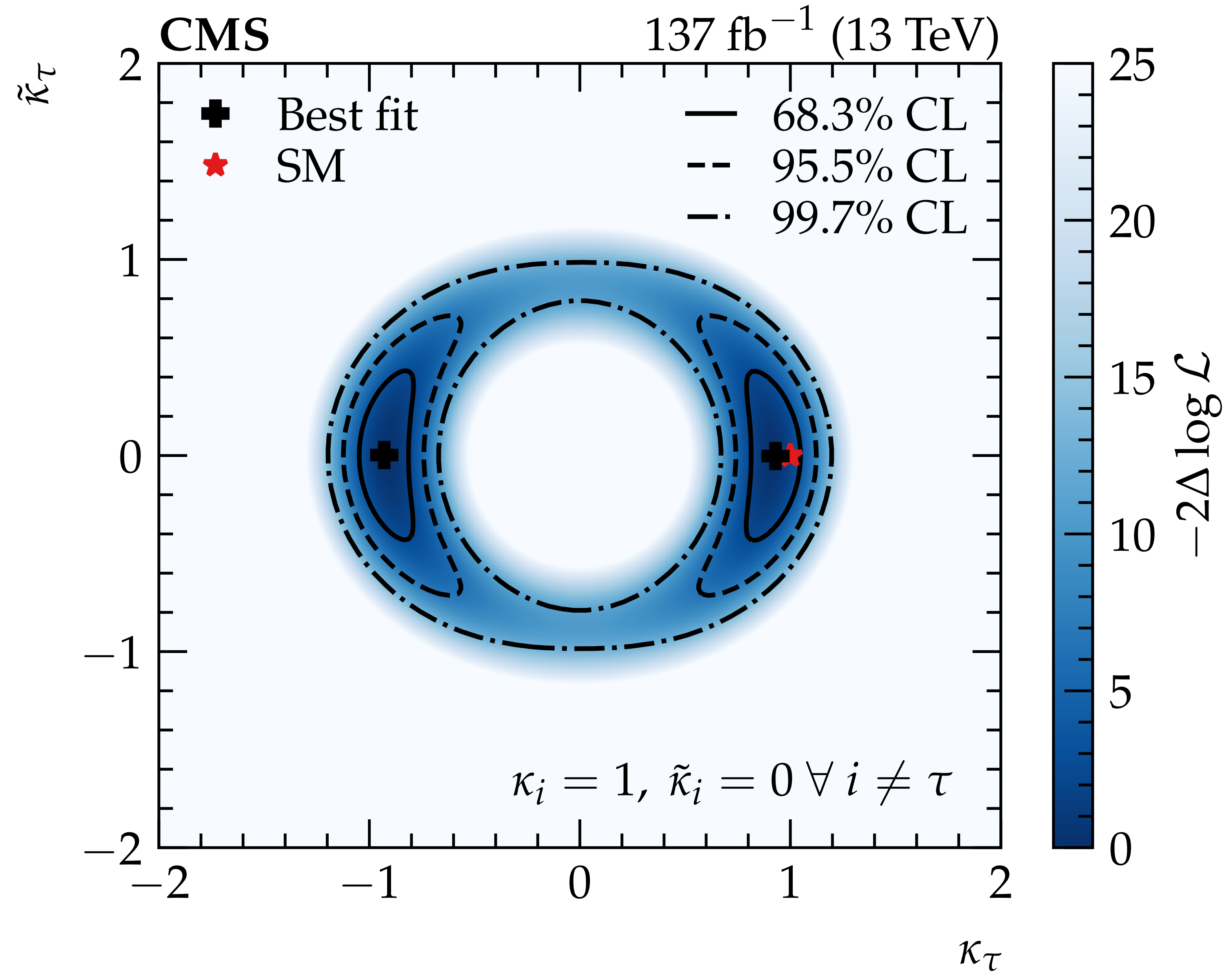
Hττ CP





CMS: JHEP 06 (2022) 012
ATLAS: arXiv: 2212.05833





f_{CP} < 0.43 (0.46) CMS (ATLAS)

Decay plane variable sensitive to Hττ CP
Using various τ decay final states