THE WIDE WORLD OF CP VIOLATION AT HL-LHC AND HE-LHC

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Based, in part, on Roni Harnik, Adam Martin, Takemichi Okui, Reinard Primulando, FY
Phys. Rev. D**88** (2013) 076009 [1308.1094 [hep-ph]]

Workshop on the physics of HL-LHC and perspectives at HE-LHC,
CERN – November 1, 2017

CP Violation – Motivated and Required

We think, ergo CP violation *R. Descartes (?)*

- Sakharov's three conditions for baryogenesis motivate searches for new sources of CP violation

  Sakharov, Pisma Zh. Eksp. Teor. Fiz. **5**, 32 (1967)
  - Need B violation
  - Need C and CP violation
  - Need interactions to happen out of thermal equilibrium
- Our picture of baryogenesis is embarrassingly incomplete
  - SM EW baryogenesis is insufficient
  - Strongly motivates new sources of CPV

CP Violation – Motivated and Required

- Many CP puzzles remain outstanding
  - Leading SM CPV comes from CKM phase
  - Θ-parameter of QCD constrained to be < 10^{-10}
  - Possible Dirac and Majorana phases of PMNS matrix are next targets of neutrino experiments
- SM predicts no tree-level CPV in Higgs couplings
  - Attractive possibility to use first-order electroweak phase transition + CP violation in Higgs couplings to generate the baryon asymmetry

See, e.g. Konstandin [1302.6713]

CP and the Higgs

- Higgs couplings can naturally have CP phases: distinct UV origins
  - scalar-pseudoscalar admixture
    - e.g. scalar potential has imaginary phase in 2HDM bilinear
    - readily (naïvely) tested via rate suppression

CP and the Higgs

- Higgs couplings can naturally have CP phases: distinct UV origins
  - scalar-pseudoscalar admixture
  - couplings to gauge bosons (*e.g.* bosonic CPV)

$$\mathcal{L} = \frac{m_Z^2}{v} h Z_\mu Z^\mu + c_{ZZ} \frac{h}{\Lambda} Z_{\mu\nu} Z^{\mu\nu} + c_{Z\tilde{Z}} \frac{h}{\Lambda} Z_{\mu\nu} \tilde{Z}^{\mu\nu}$$

    - Many results and constraints
    - For example, tested via acoplanarity measurement in h→ZZ^*→4l (see talk by Y. Chen next)

CP and the Higgs

- Higgs couplings can naturally have CP phases: distinct UV origins
  - scalar-pseudoscalar admixture
  - couplings to gauge bosons (*e.g.* bosonic CPV)
  - couplings to fermions (*e.g.* fermionic CPV)

$$\mathcal{L} = -m_f \bar{f} f - \frac{y_f}{\sqrt{2}} h \bar{f} (\cos\Delta + i\gamma_5 \sin\Delta) f$$

  - Δ = 0 is predicted in the SM (purely CP-even)
  - Δ = π/2 is pure CP-odd (and CP conserving)
  - Δ = ±π/4 is maximally CP-violating

Yukawa CP phases

$$\mathcal{L} = -\left(\alpha_{ij} + \beta_{ij}\frac{H^\dagger H}{\Lambda^2}\right) H \bar{f}^i f^j$$

- In dim-6 SMEFT, can readily generate BSM Yukawa couplings including
  - Enhanced/suppressed diagonal flavor couplings
  - New off-diagonal flavor-violating couplings
  - CP phases in diagonal or off-diagonal couplings
- α and β are generally complex matrices – must have flavor symmetry in UV physics to ensure they are aligned

- In EW broken phase, one combination gives known fermion masses, other generally leads to *complex* Yukawa matrices

Yukawa CP phases

- Curious fact: Suppressing Yukawa CP phases in SMEFT requires parametrically (chirally) large scale separation

$$\begin{aligned}\mathcal{L} \supset\ & y_u \bar{Q}_L \tilde{H} u_R + y'_u \frac{H^\dagger H}{\Lambda^2} \bar{Q} \tilde{H} u_R + y_\ell \bar{L} H \ell_R + y'_\ell \frac{H^\dagger H}{\Lambda^2} \bar{L} H \ell_R \\ + & \ y_d \bar{Q}_L H d_R + y'_d \frac{H^\dagger H}{\Lambda^2} \bar{Q} H d_R + \text{ h.c.}\end{aligned}$$

- Flavor symmetries diagonalize and remove phases in mass matrices

$$m_f = \frac{y_f v}{\sqrt{2}} + \frac{y'_f v^3}{2\sqrt{2}\Lambda^2}$$

- Yukawa phases can be chirally enhanced for light fermions

$$\frac{y_{f,\text{ eff}}}{\sqrt{2}} = \frac{y_f}{\sqrt{2}} + \frac{3 y'_f v^2}{2\sqrt{2}\Lambda^2} = \frac{m_f}{v} + \frac{2 y'_f v^2}{2\sqrt{2}\Lambda^2}$$

  - (Bluntly, fine-tune mass generation ↔ large BSM effects)

Complementarity with EDMs

- Top CPV phase naïvely constrained by electron EDM

Brod, Haisch, Zupan [1310.1385]

  - Indirect probe, still important to perform direct tests at LHC

See Buckley, Goncalves [1507.07926],
Mileo, Kies, Szynkman, Crane, Gegner [1603.03632],
cf. F. Maltoni slides from yesterday

- Light quark CPV phases confront neutron EDM

Chien, Cirigliano, Dekens, de Vries, Mereghetti [1510.00725]

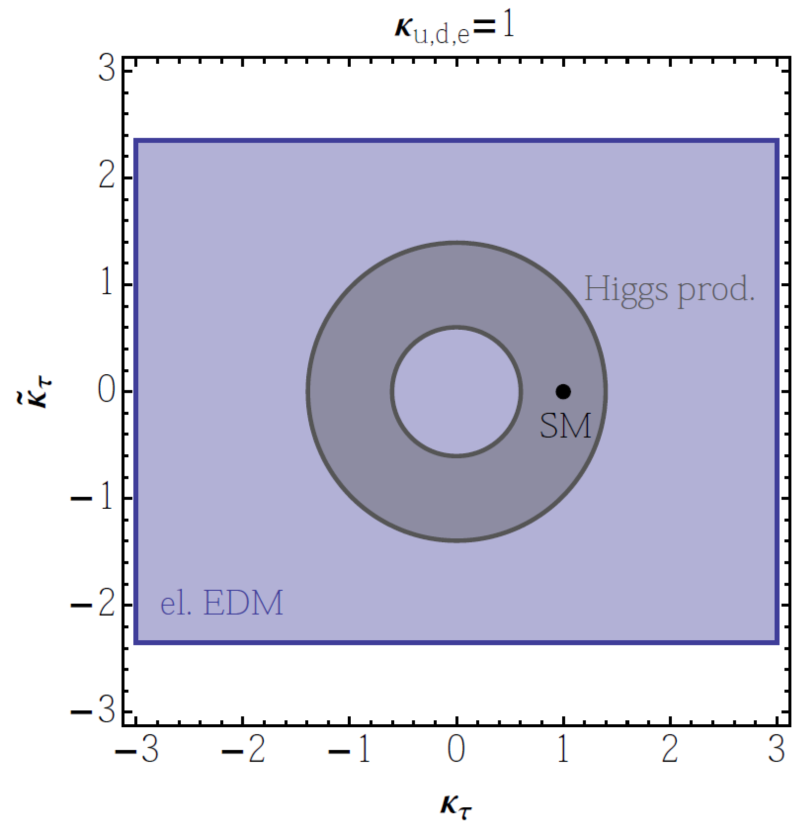
- Open room for τ Yukawa phase – HL-LHC and HE-LHC could provide leading sensitivity

Harnik, Martin, Okui, Primulando, FY [1308.1094]
Berge, Bernreuther, Kirchner [1510.03850]

CP phase in Tau Yukawa

$$\mathcal{L} = -m_\tau \bar{\tau}\tau - \frac{y_\tau}{\sqrt{2}} h \bar{\tau}(\cos\Delta + i\gamma_5 \sin\Delta)\tau$$

- eEDM probes currently leave Δ unconstrained



Brod, Haisch, Zupan [1310.1385]

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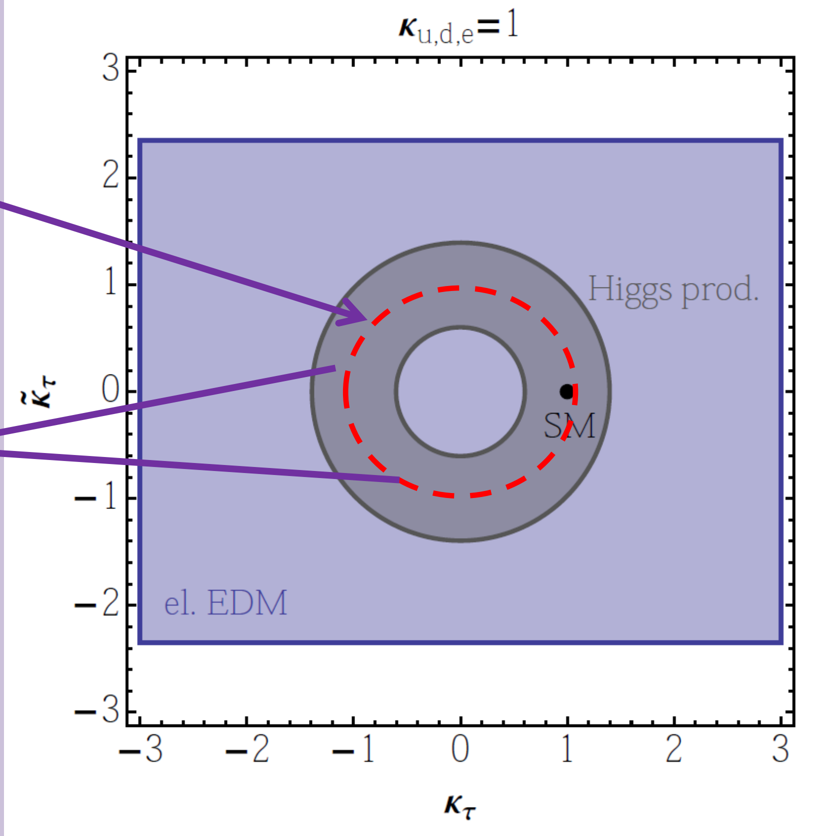


Signal strengths only constrain the quadrature sum

Must use differential distributions to test CP

Brod, Haisch, Zupan [1310.1385]

Basic CPV collider phenomenology

- NP CPV sources generally affect inclusive rates
  - Normalized differential distributions fold out rate information (by construction)
  - Need statistics (=inclusive distributions=integrated luminosity) before asymmetry variables or differential distributions are meaningful
- Canonical observables
  - triple product of 3-vectors – CP-odd, T-odd combination
    - $\mathbf{p}_1 \cdot (\mathbf{p}_2 \times \mathbf{p}_3)$
  - angular distributions – uses decays of polarized intermediate particles
    - acoplanarity in $h \to ZZ^* \to 4$ leptons

Review: Angular observables

- X decays to V_1 V_2, decays to 4 fermions
- Characterize by five angles, two masses (+X mass if unknown)

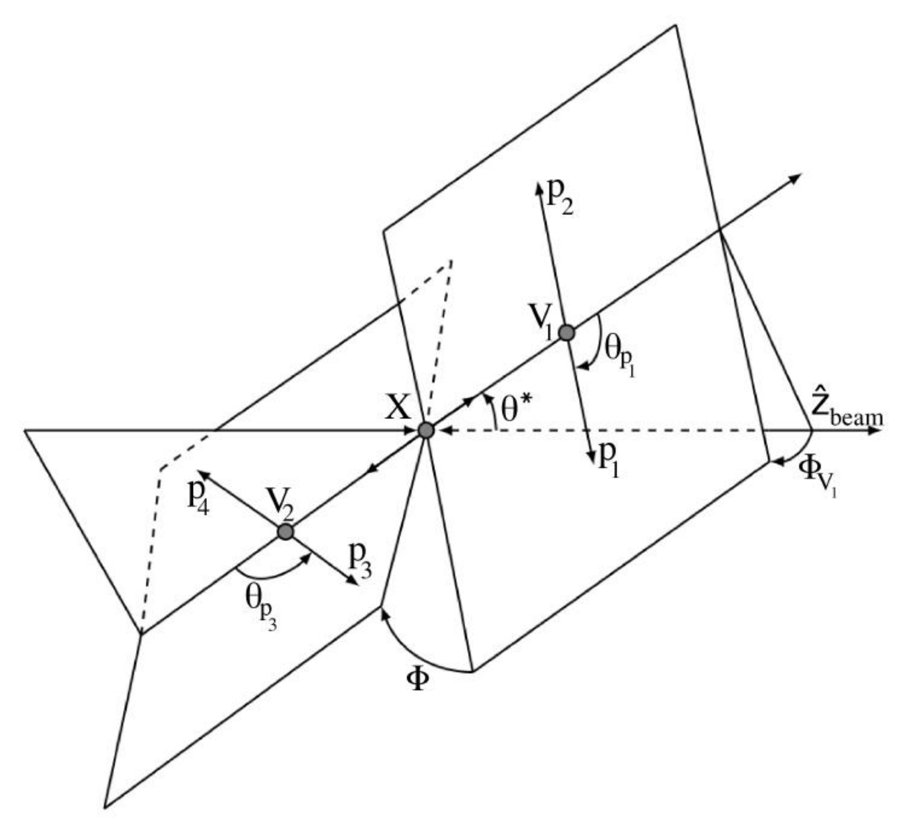
$$\cos\theta_{p_1} = -\hat{p}_{p_1}\cdot\hat{p}_{V_2}$$

$$\cos\theta_{p_3} = -\hat{p}_{p_3}\cdot\hat{p}_{V_1}$$

$$\cos\theta^* = \hat{p}_{V_1}\cdot\hat{z}_{\text{beam}}$$

$$\Phi_{V_1} = \frac{\vec{p}_{V_1}\cdot(\hat{n}_1\times\hat{n}_{sc})}{\vec{p}_{V_1}\cdot(\hat{n}_1\times\hat{n}_{sc})|}\arccos(\hat{n}_1\cdot\hat{n}_{sc})$$

$$\Phi = \frac{\vec{p}_{V_1}\cdot(\hat{n}_1\times\hat{n}_2)}{\vec{p}_{V_1}\cdot(\hat{n}_1\times\hat{n}_2)|}\arccos(-\hat{n}_1\cdot\hat{n}_2)$$



Buschmann, FY [1604.06096]

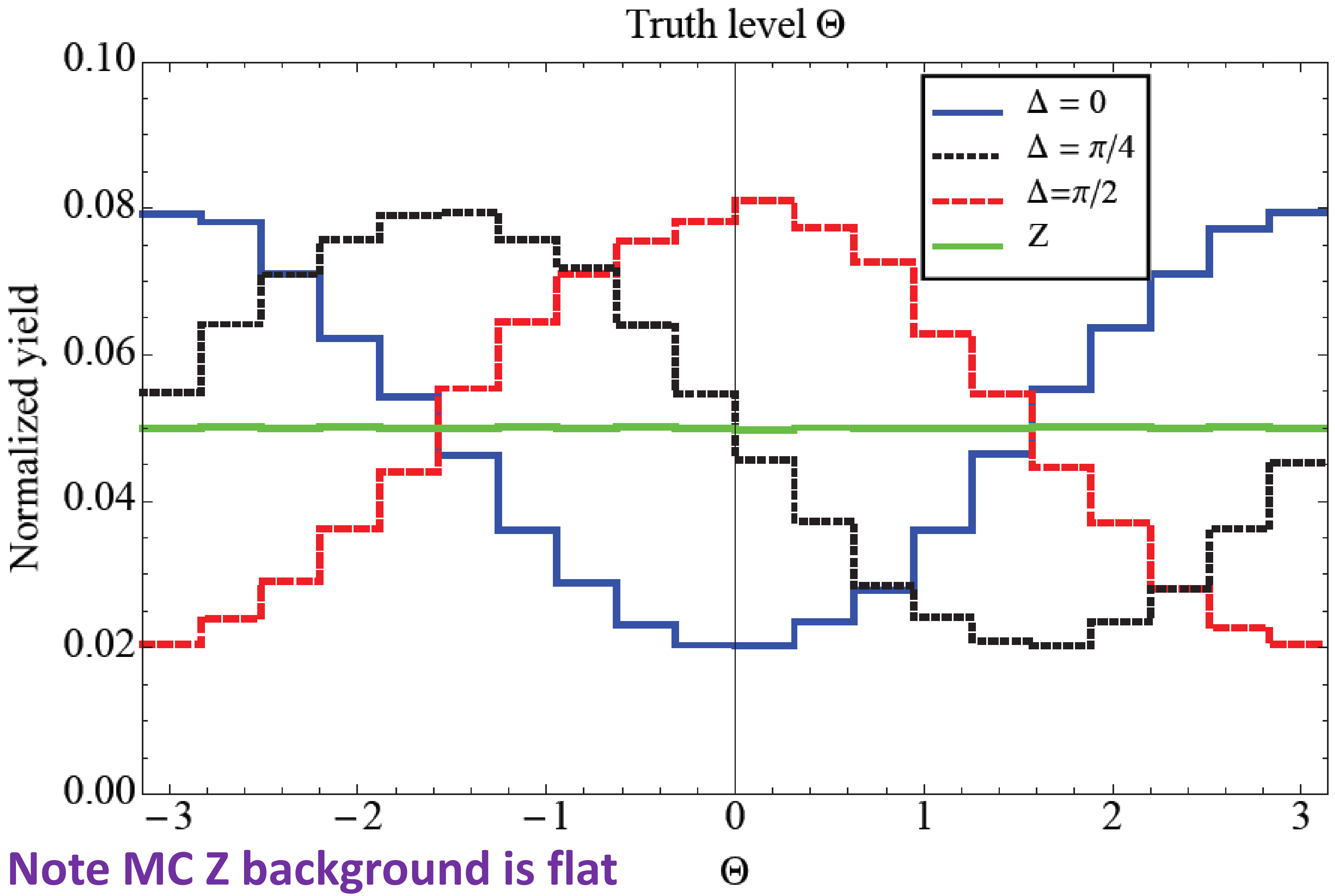
Extracting the phase in Higgs decays to taus

- Tau Yukawa CPV is imprinted on the tau polarizations relative to each other
  - Tau polarizations then get imprinted on the ν and ρ, ρ polarization is imparted to the πs
- Simplest observable (appropriate for LHC) is $\rho^+\rho^-$ acoplanarity angle
    - [New, better observable (appropriate for e^+e^- collider) is Θ]

$$\begin{aligned} h &\to \tau^-\tau^+ \\ &\to \rho^-\nu_\tau\rho^+\bar{\nu}_\tau \\ &\to \pi^-\pi^0\nu_\tau\pi^+\pi^0\bar{\nu}_\tau \end{aligned}$$

Ideal situation

Θ is an optimal reconstructable angular variable senstive to CPV in h→ττ



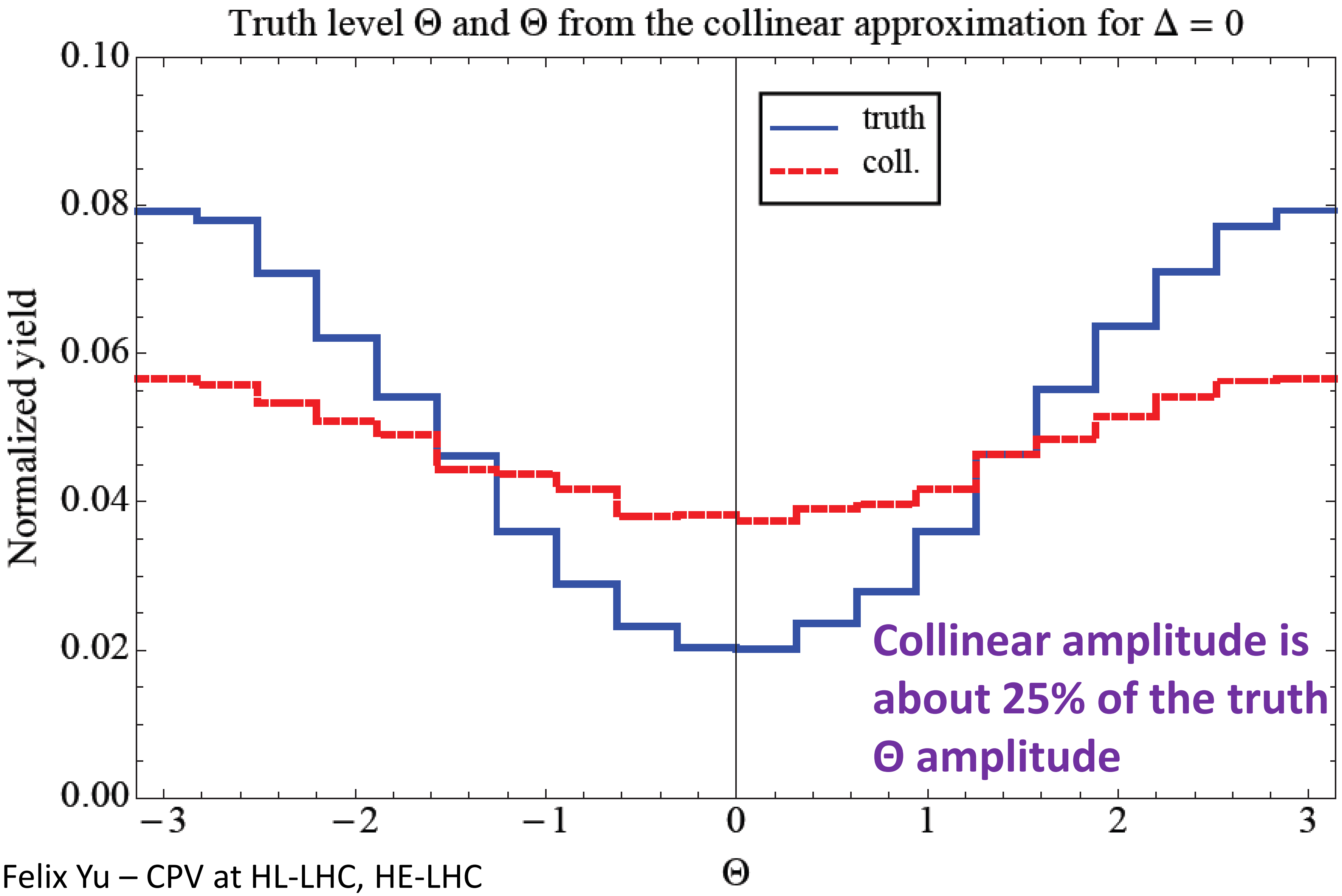
Note MC Z background is flat

Harnik, Martin, Okui, Primulando, FY [1308.1094]

LHC prospects

- Consider h+j events (“boosted” $\tau_{had}\tau_{had}$ sample)
- At the LHC, need to approximate neutrino momenta
  - Have (8-2-2-2=) 2 unknown four-momentum components
  - Will use collinear approximation for neutrino momenta
    - In this approximation, Θ is identical to ρρ acoplanarity angle
    - Other approximations considered tended to wash out or distort the sinuisoidal shape of the Θ distribution
  - First proposal to measure Δ at the LHC with prompt tau decays and kinematics

Ideal vs. Collinear approximation



Collinear amplitude is about 25% of the truth Θ amplitude

LHC14 simulation details

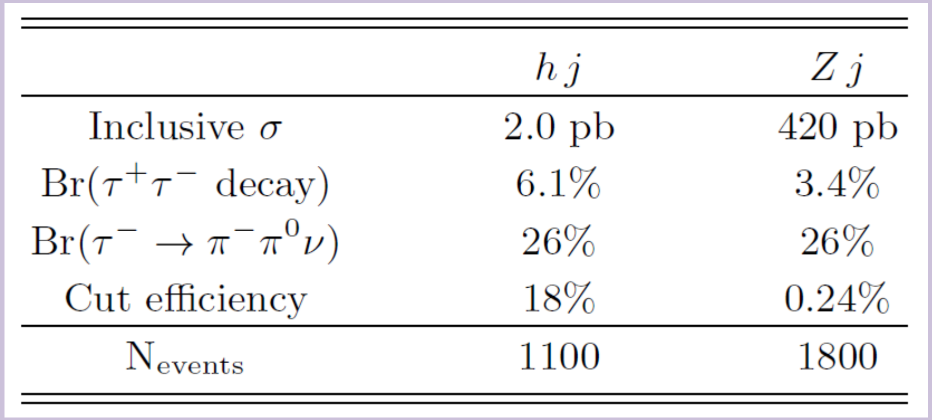
- Use MadGraph5 for h+j and Z+j events at LHC14
  - Mimic cuts for 1-jet, hadronic taus Higgs search category
  - Impose preselection of $p_T(j) > 140$ GeV, $|\eta(j)| < 2.5$
  - Normalize to MCFM NLO $\sigma(h+j)=2.0$ pb, $\sigma(Z+j)=420$ pb
  - No pileup or detector simulation, aside from tau-tagging efficiencies
    - Pileup degrades primary vertex determination for charged pion tracks and adds ECAL deposits that reduce neutral pion resolution
    - Tracking and detector resolution will clearly smear the Θ distribution

Yields for 3 ab^{-1} LHC

- Signal region:

  MET > 40 GeV, $p_T(\rho)$ > 45 GeV, $|\eta(\rho)| < 2.1$,
  m_{coll} > 120 GeV

  - Inject an additional 10% contribution to (flat) Zj background to account for QCD multijets

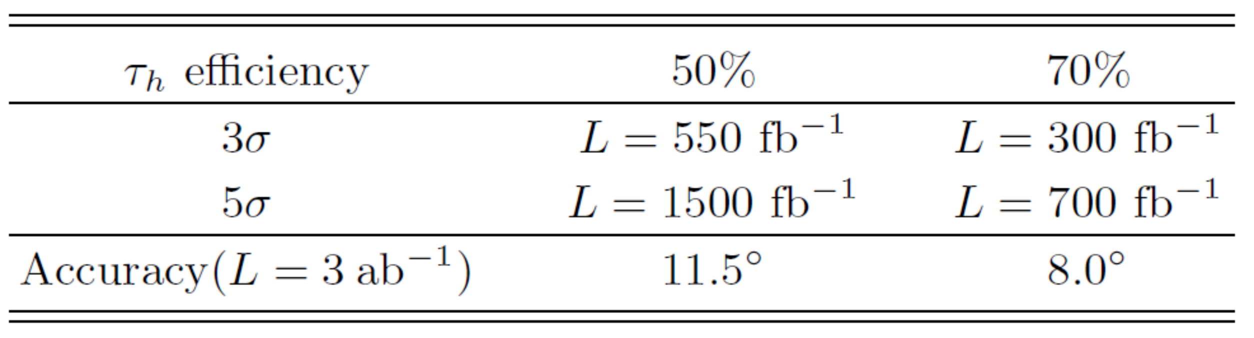


	$h\,j$	$Z\,j$
Inclusive σ	2.0 pb	420 pb
$\mathrm{Br}(\tau^+\tau^-$ decay$)$	6.1%	3.4%
$\mathrm{Br}(\tau^- \to \pi^-\pi^0\nu)$	26%	26%
Cut efficiency	18%	0.24%
$\mathrm{N}_{\mathrm{events}}$	1100	1800

N_{events} for 3 ab^{-1} with τ-tagging 50% efficiency

Yields for 3 ab^{-1} LHC

- Consider τ tagging efficiency benchmarks of 50% and 70%, use likelihood analysis testing different Δ



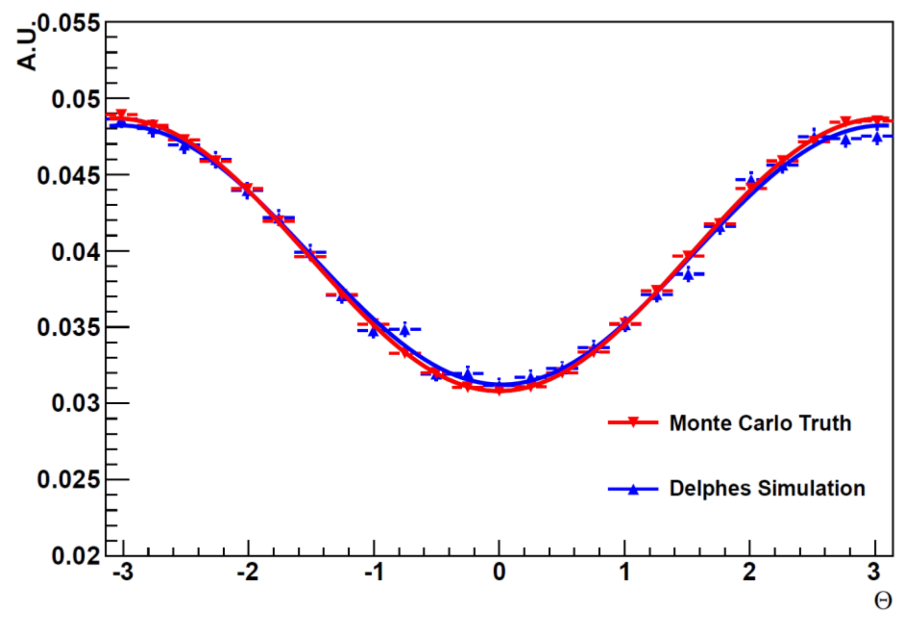
τ_h efficiency	50%	70%
3σ	$L = 550\ \text{fb}^{-1}$	$L = 300\ \text{fb}^{-1}$
5σ	$L = 1500\ \text{fb}^{-1}$	$L = 700\ \text{fb}^{-1}$
Accuracy$(L = 3\ \text{ab}^{-1})$	11.5°	8.0°

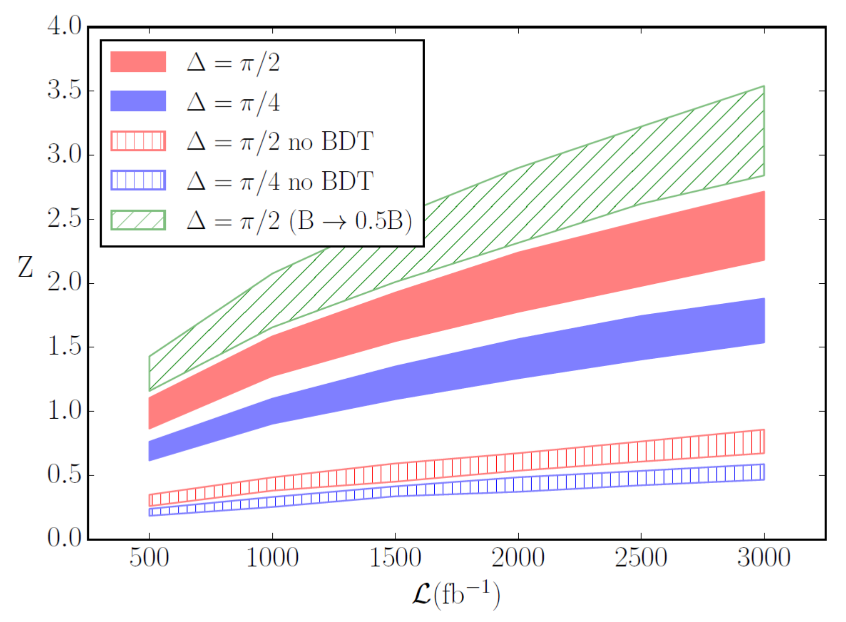
  - Discriminating pure scalar vs. pure pseudoscalar at **3σ** requires 550 (300) fb^{-1} with 50% (70%) τ tagging efficiency
    - For **5σ**, require 1500 (700) fb^{-1} with 50% (70%) τ tagging efficiency
    - Again, detector effects and pileup are neglected

Updated Delphes analysis

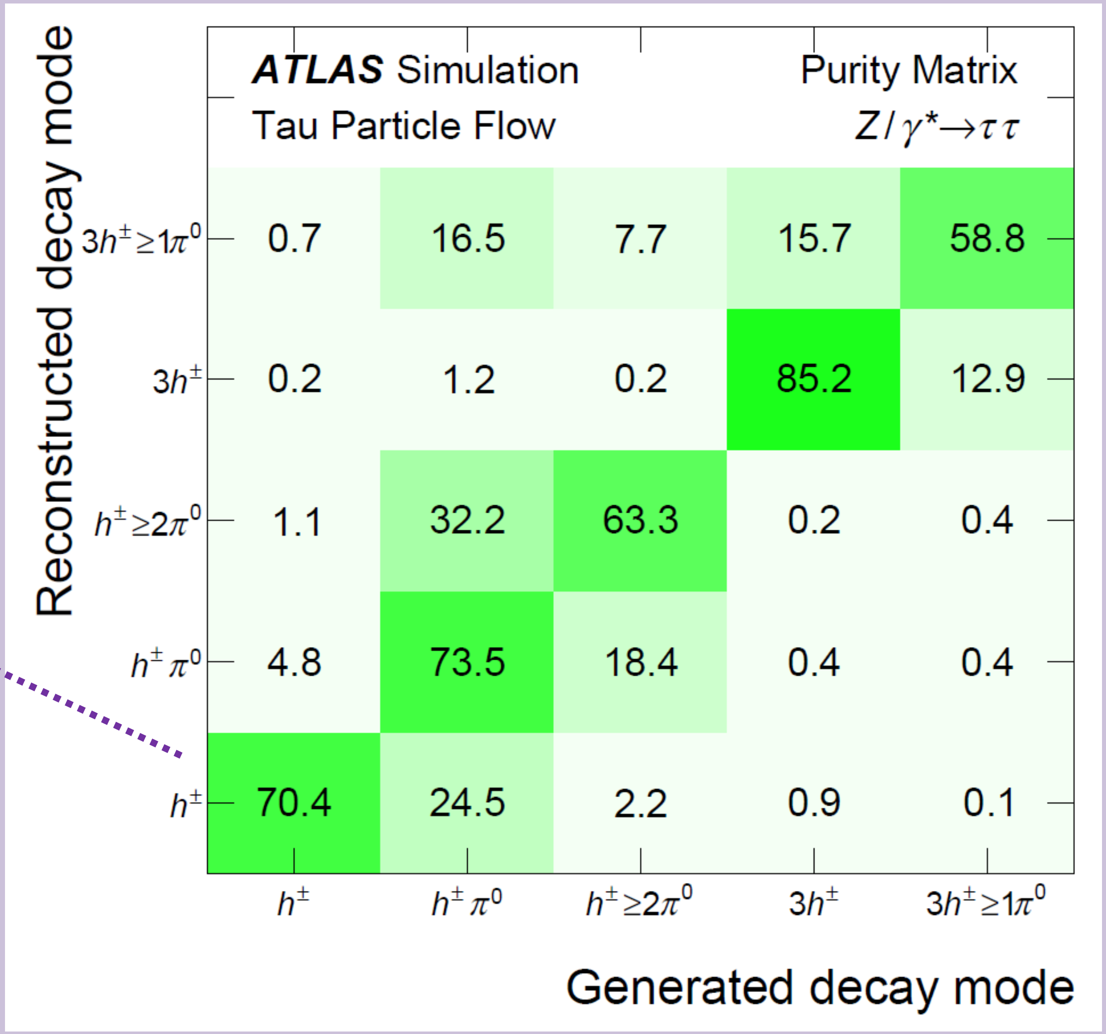
Askew, Jaiswal, Okui, Prosper, Sato [1501.03156]

- Collinear approx. at LHC is likely a hard limit
- Angular resolution negligibly (4%) degrades Θ distribution
- MET resolution most significantly affects contamination from irreducible Z background





Hadronic τ Reconstruction



Reconstructed \ Generated	$h^{\pm}$	$h^{\pm}\pi^{0}$	$h^{\pm}\geq 2\pi^{0}$	$3h^{\pm}$	$3h^{\pm}\geq 1\pi^{0}$
$3h^{\pm}\geq 1\pi^{0}$	0.7	16.5	7.7	15.7	58.8
$3h^{\pm}$	0.2	1.2	0.2	85.2	12.9
$h^{\pm}\geq 2\pi^{0}$	1.1	32.2	63.3	0.2	0.4
$h^{\pm}\pi^{0}$	4.8	73.5	18.4	0.4	0.4
$h^{\pm}$	70.4	24.5	2.2	0.9	0.1

Single prong decay also important if impact parameter information is used

Berge, Bernreuther, Niepelt, Spiesberger [1108.0670]

Zanzi for ATLAS and CMS [1703.10259]

See also poster by M. L. Ojeda with 1-prong and 3-prong p_T dependence

HE-LHC (first look)

- Higgs+jet rates will give 3.5× increase in signal statistics

p_T cut (GeV) on h+j for	NLO cross section for 27 TeV pp collider (MCFM 8.0)	Signal enhancement compared to 14 TeV, $p_T > 140$ GeV
100	12.1 pb	6.05×
140	6.96 pb	3.48× [Our original working point]
150	6.12 pb	3.06×
200	3.43 pb	1.72×
250	2.08 pb	1.04×

- Remark: Boosted Higgs studies will gain significantly by going to HE-LHC
  - Important for exotic Higgs decays with jet substructure

Many more Higgs modes to study

- EW dibosons — See, e.g. Anderson, *et. al.* [1309.4819]
  - Probe in both decays and production, especially VBF and VH (using crossing symmetry)
  - Part of general study of differential distributions to test momentum-dependent form factors
- ttH — See, e.g. Buckley, Goncalves [1507.07926]
  - Dileptonic tt final state with H→bb jet substructure
- Zγ — Farina, Grossman, Robinson [1503.06470]
  - Take advantage of interference between continuum background and signal from gluon initiated events
- gg — Dolan, Harris, Jankowiak, Spannowsky [1406.3322]
  - Use associated jets for angular analysis
- γγ — Bishara, Grossman, Harnik, Robinson, Shu, Zupan [1312.2955]
  - Require converted photons (detector material) and angular resolution on leptonic opening angles
- bb, cc, etc. — Galanti, Giammanco, Grossman, Kats, Stamou, Zupan [1505.02771]
  - Can possible overcome QCD wash-out of quark polarization

Open issues

- Post-discovery: what Lagrangian CPV source is responsible in the case of a positive measurement?
- Targets for CPV sensitivity
  - Tree-level operator (Yukawa) vs. loop-induced
  - How to include rate effects
- Straw man NP models for precision Higgs physics
  - Real coefficients induce unitarity violation in scattering
    - Imply a NP scale for UV completion
  - Imaginary coefficients – any guiding principle for size of effects?

Summary

- New CP phases are motivated from general baryogenesis arguments
- Each measured Higgs coupling can be a test bed for CPV
  - No tree-level CPV expected in any Higgs coupling
  - Yukawa phases should up at dimension-4 in EW broken phase
  - h→ττ is a promising first channel to study at HL-LHC and HE-LHC
  - Direct tests at colliders still strongly motivated even though EDM results are null
  - Post-(pre?-)discovery model building needed to connect directly CP phases to EW baryogenesis

CPV in HVV interactions

- Comparison for e^+e^- and pp

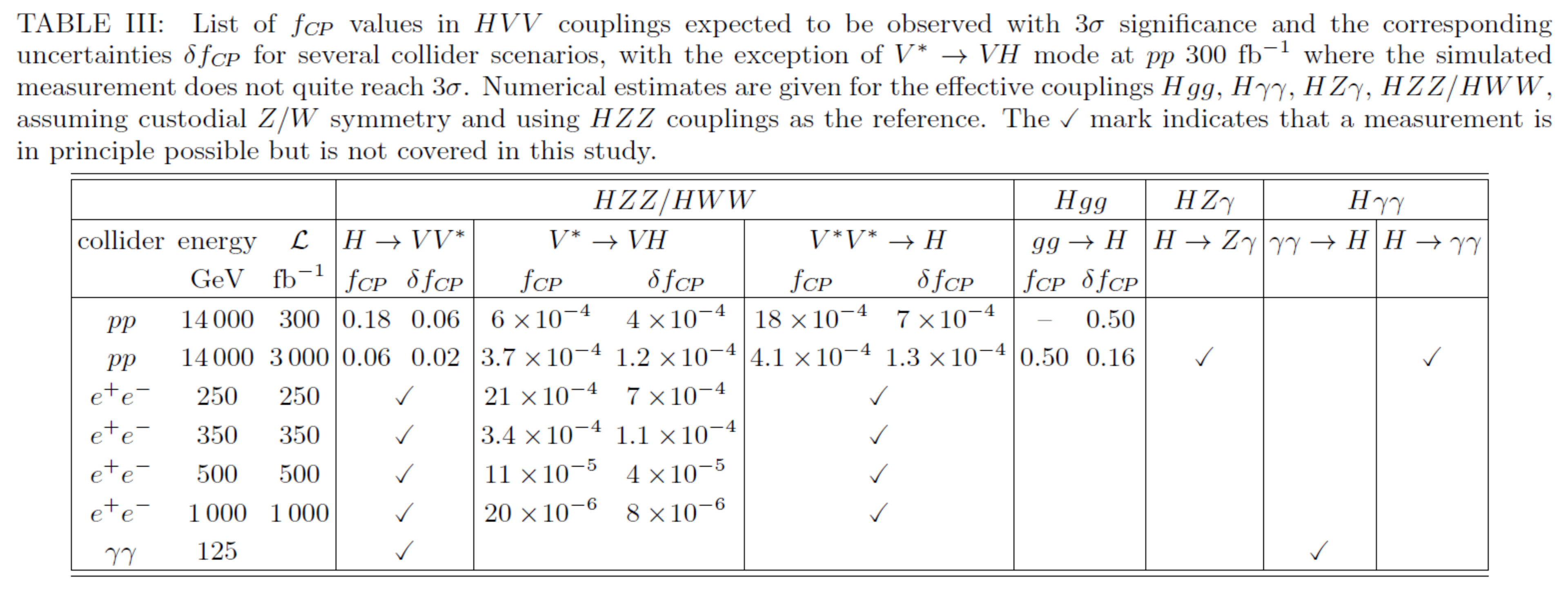


TABLE III: List of f_{CP} values in HVV couplings expected to be observed with 3σ significance and the corresponding uncertainties δf_{CP} for several collider scenarios, with the exception of $V^* \to VH$ mode at pp 300 fb^{-1} where the simulated measurement does not quite reach 3σ. Numerical estimates are given for the effective couplings Hgg, $H\gamma\gamma$, $HZ\gamma$, HZZ/HWW, assuming custodial Z/W symmetry and using HZZ couplings as the reference. The ✓ mark indicates that a measurement is in principle possible but is not covered in this study.

			HZZ/HWW						Hgg		$HZ\gamma$	$H\gamma\gamma$	
collider	energy	$\mathcal{L}$	$H \to VV^*$		$V^* \to VH$		$V^*V^* \to H$		$gg \to H$		$H \to Z\gamma$	$\gamma\gamma \to H$	$H \to \gamma\gamma$
	GeV	fb^{-1}	f_{CP}	δf_{CP}	f_{CP}	δf_{CP}	f_{CP}	δf_{CP}	f_{CP}	δf_{CP}			
pp	14 000	300	0.18	0.06	6×10^{-4}	4×10^{-4}	18×10^{-4}	7×10^{-4}	–	0.50			
pp	14 000	3 000	0.06	0.02	3.7×10^{-4}	1.2×10^{-4}	4.1×10^{-4}	1.3×10^{-4}	0.50	0.16	✓		✓
e^+e^-	250	250	✓		21×10^{-4}	7×10^{-4}	✓						
e^+e^-	350	350	✓		3.4×10^{-4}	1.1×10^{-4}	✓						
e^+e^-	500	500	✓		11×10^{-5}	4×10^{-5}	✓						
e^+e^-	1 000	1 000	✓		20×10^{-6}	8×10^{-6}	✓						
$\gamma\gamma$	125		✓									✓	

Anderson, *et. al.* [1309.4819]