CURRENT STATUS AND FUTURE COLLIDER TESTS FOR CP VIOLATION IN HIGGS PHYSICS

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Johannes Gutenberg University, Mainz

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

Testing CP Violation for Baryogenesis
UMass Amherst – March 30, 2018

CP Violation – Motivated and Required

- Our picture of baryogenesis is embarrassingly incomplete
  - SM EW baryogenesis is insufficient
  - Strongly motivates new mechanisms for strengthening EW phase transition

    c.f. talk by Ramsey-Musolf
  - Also strongly motivates new sources of CPV

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- Our picture of baryogenesis is embarrassingly incomplete
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    c.f. talk by Ramsey-Musolf
  - Also strongly motivates new sources of CPV
- Open question – establishing targets for CPV searches (in Higgs physics and elsewhere) for specific mechanisms of EW SFOPTs

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] and many others

Outline

- Bosonic CPV observables in Higgs physics
  - CPV counting in SMEFT
  - Current status on bosonic CPV
- Fermionic CPV observables in Higgs physics
  - Focus on $h \to \tau\tau$
- Future prospects
- Conclusions

CP and the Higgs

- SM Higgs physics in broken phase of EW symmetry is highly predictive: $J^{CP}(h) = 0^{++}$
- Mass-coupling degeneracy strong consequence of chiral EW symmetry
  - Generally expect any modification of Higgs couplings to cause deviation in rate and distribution

Basic CPV collider phenomenology

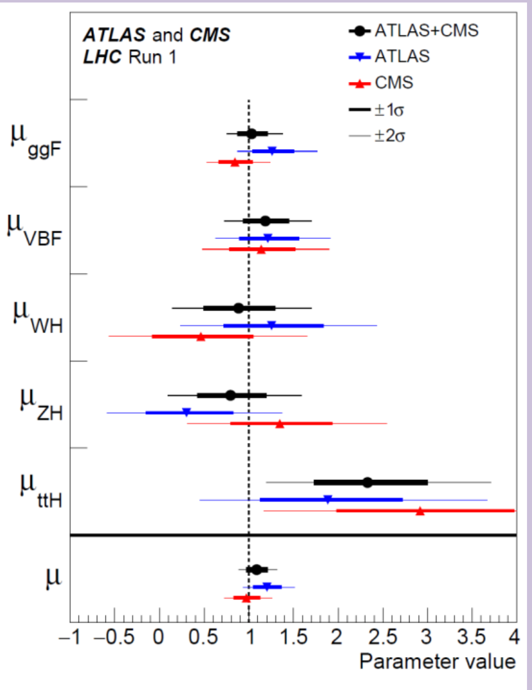
- CPV couplings generally affect inclusive rates
  - Normalized differential distributions fold out rate information (by construction)
  - Need statistics (=inclusive distributions=integrated luminosity) before asymmetry variables or differential distributions are meaningful
- Canonical observables
  - 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

CP and the Higgs

- Each Higgs coupling (except h^3) can readily have a CP phase: distinct UV origins
  - **scalar-pseudoscalar admixture**
    - e.g. scalar potential has imaginary phase in 2HDM bilinear
    - readily (naïvely) tested via rate suppression

$$\mu = 1.09^{+0.11}_{-0.10}$$
$$= 1.09^{+0.07}_{-0.07}(\text{stat})^{+0.04}_{-0.04}(\text{expt})^{+0.03}_{-0.03}(\text{thbgd})^{+0.07}_{-0.06}(\text{thsig})$$

ATLAS, CMS [1606.02266]



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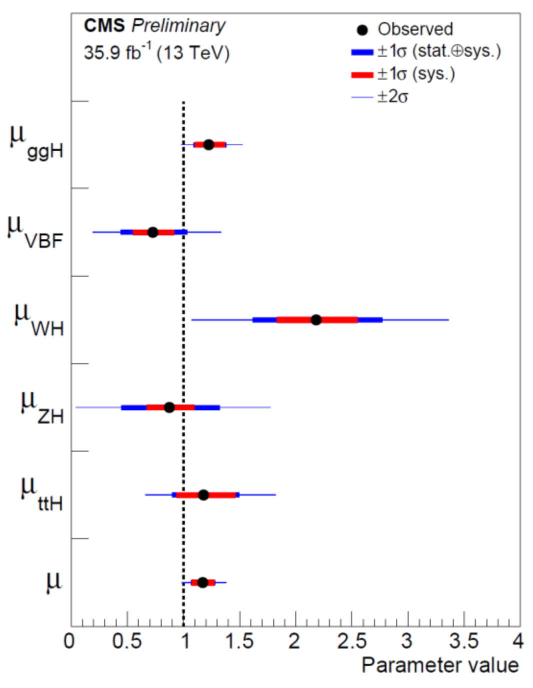
$$\mu = 1.17^{+0.10}_{-0.10}$$
$$= 1.17^{+0.06}_{-0.06}(\text{stat.})^{+0.06}_{-0.05}(\text{sig. th.})^{+0.06}_{-0.06}(\text{other sys.})$$

CMS-HIG-17-031



CP and the Higgs

- Each Higgs coupling (except h^3) can readily have a CP phase: 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 $h \to ZZ^* \to 4l$

Review: Angular observables

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

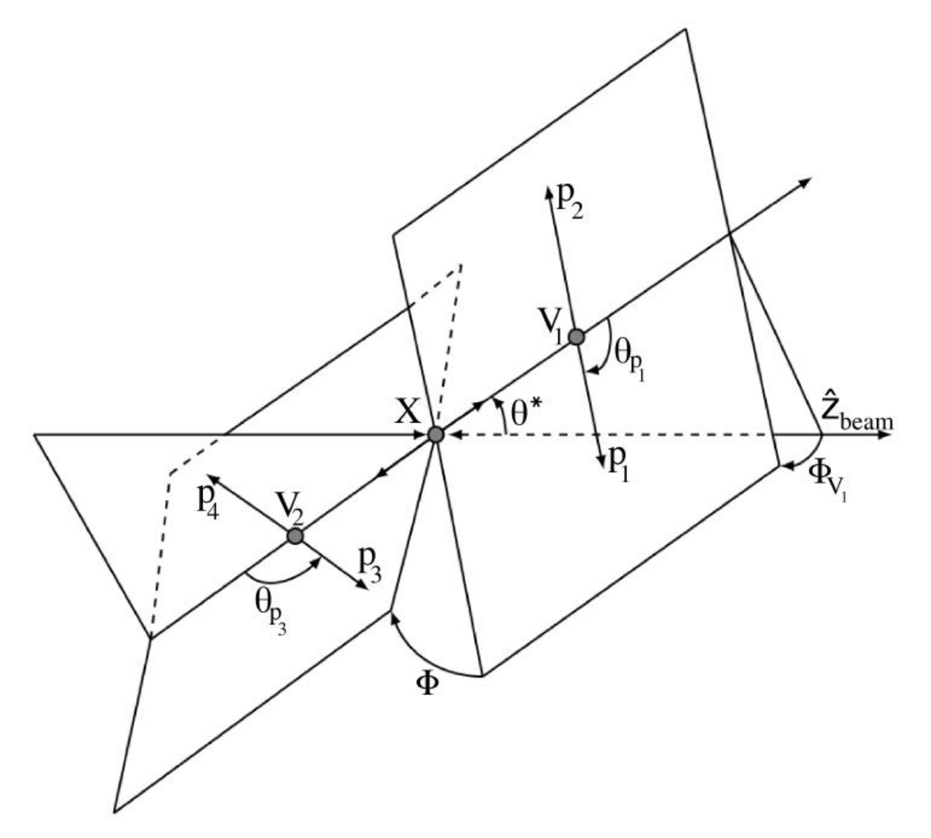
$$\cos\theta_{p_1} = -\hat{p}_{p_1} \cdot \hat{p}_{V_2}$$

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

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

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

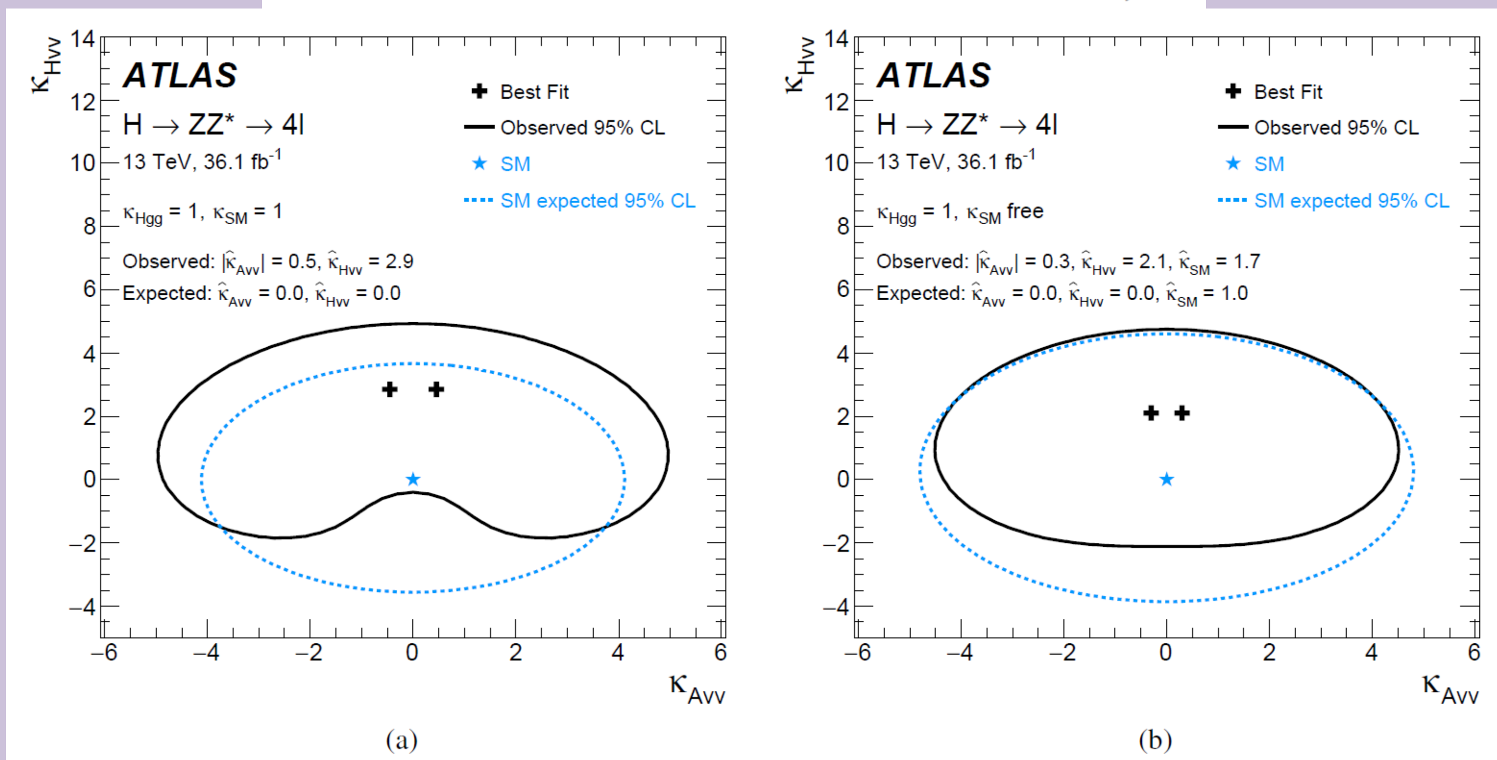
$$\Phi = \frac{\vec{p}_{V_1} \cdot (\hat{n}_1 \times \hat{n}_2)}{\vec{p}_{V_1} \cdot (\hat{n}_1 \times \hat{n}_2)|} \arccos(-\hat{n}_1 \cdot \hat{n}_2)$$



Buschmann, FY [1604.06096]

Current status – 4l tests

$$
\begin{aligned}
\mathcal{L}_0^V = \Big\{ & \kappa_{\rm SM}\left[\frac{1}{2} g_{HZZ} Z_\mu Z^\mu + g_{HWW} W^+_\mu W^{-\mu}\right] \\
& - \frac{1}{4}\left[\kappa_{Hgg} g_{Hgg} G^a_{\mu\nu} G^{a,\mu\nu} + \tan\alpha\, \kappa_{Agg} g_{Agg} G^a_{\mu\nu} \tilde{G}^{a,\mu\nu}\right] \\
& - \frac{1}{4}\frac{1}{\Lambda}\left[\kappa_{HZZ} Z_{\mu\nu} Z^{\mu\nu} + \tan\alpha\, \kappa_{AZZ} Z_{\mu\nu} \tilde{Z}^{\mu\nu}\right] \\
& - \frac{1}{2}\frac{1}{\Lambda}\left[\kappa_{HWW} W^+_{\mu\nu} W^{-\mu\nu} + \tan\alpha\, \kappa_{AWW} W^+_{\mu\nu} \tilde{W}^{-\mu\nu}\right] \Big\} X_0 .
\end{aligned}
$$



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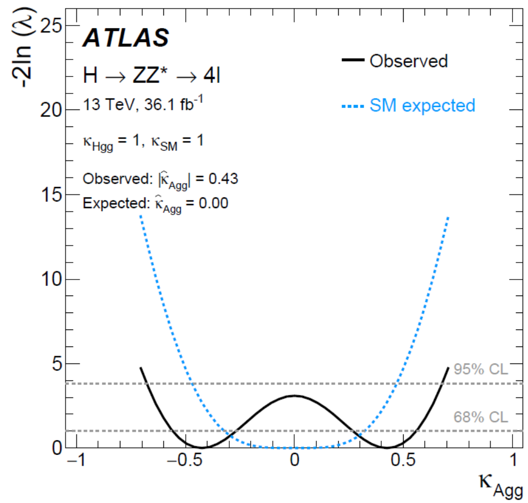
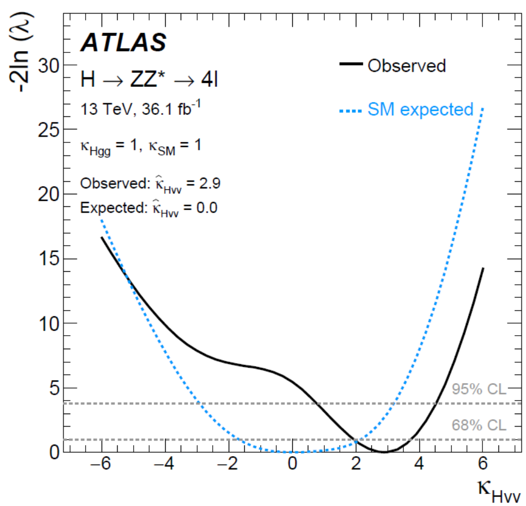
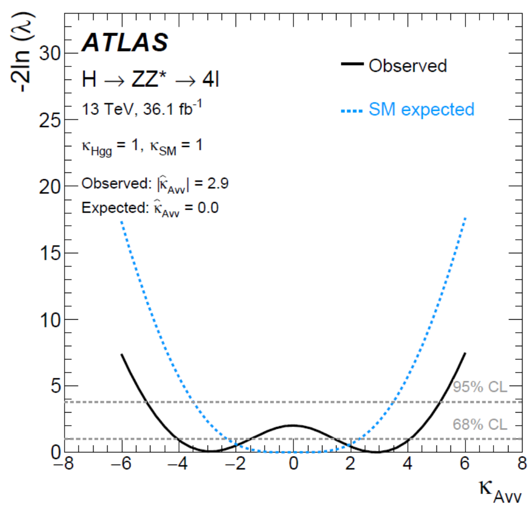


(a)



(b)



(c)

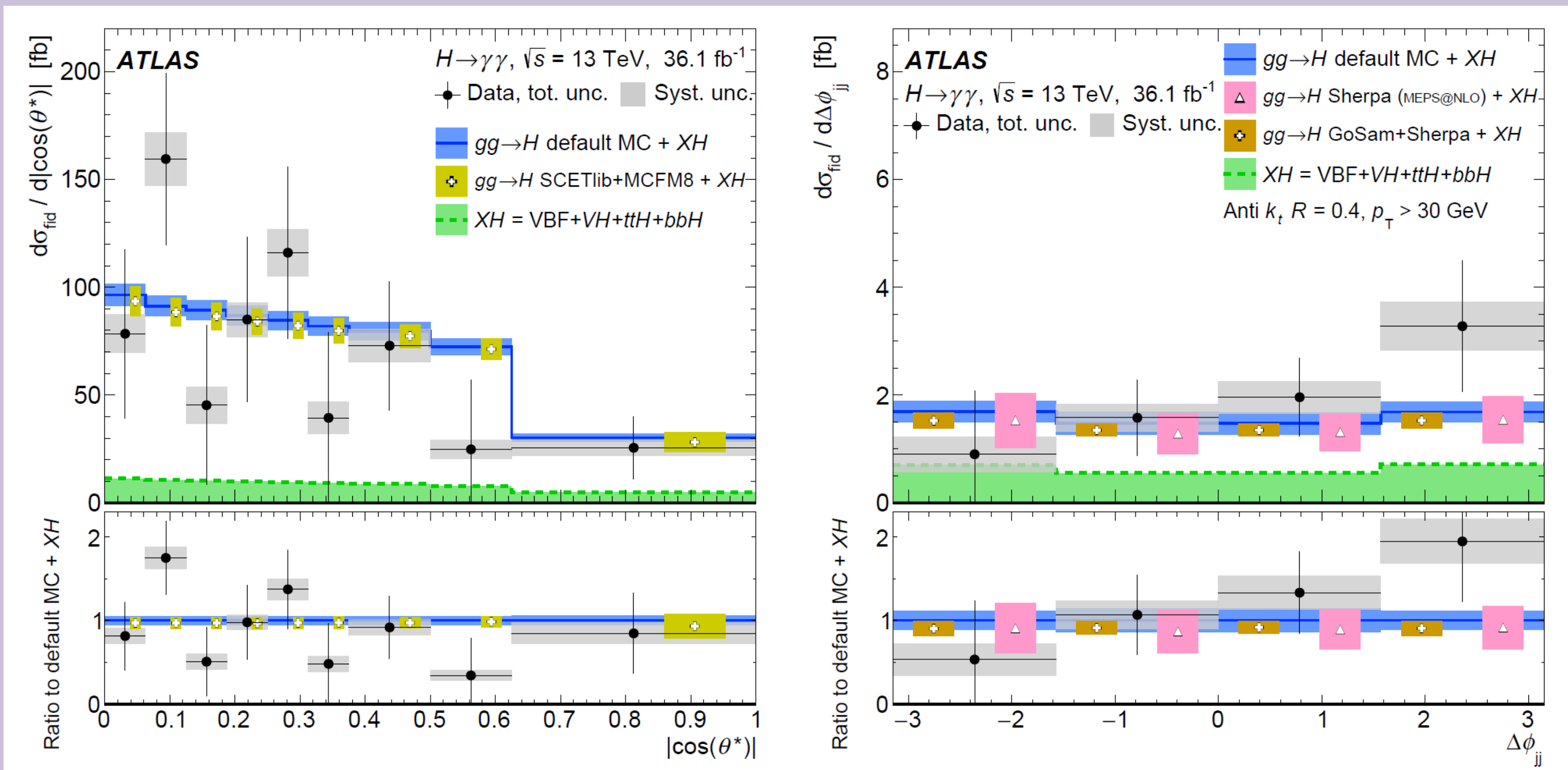
ATLAS [1712.02304]

Current status – diphotons

- Analyze in Collins-Soper frame

$$A^{\text{meas}}_{|\Delta\phi_{jj}|} = 0.45^{+0.18}_{-0.24}\,(\text{stat.})\,^{+0.10}_{-0.11}\,(\text{syst.})$$

$$A^{\text{SM}}_{|\Delta\phi_{jj}|} = 0.44 \pm 0.01$$



ATLAS [1802.04146]

CP and the Higgs

- Each Higgs coupling (except h^3) can readily have a CP phase: distinct UV origins
  - scalar-pseudoscalar admixture
  - couplings to gauge bosons (*e.g.* bosonic CPV)
  - couplings to **fermions** (*e.g.* fermionic CPV)

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

    - $\Delta = 0$ is predicted in the SM (purely CP-even)
    - $\Delta = \pi/2$ is pure CP-odd (and CP conserving)
    - $\Delta = \pm\pi/4$ 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

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

- Fine-tuning mass generation ↔ large BSM effects

Dimension 6 CPV

Alonso, Jenkins, Manohar, Trott [1312.2014]
Also see Grzadowski, Iskrzynski, Misiak, Rosiek [1008.4884]
Henning, Lu, Melia, Murayama [1512.03433]

1: X^3 2: H^6 3: H^4D^2 4: X^2H^2
5: ψ^2H^3+ h.c. 6: ψ^2XH+ h.c. 7: ψ^2H^2D
8: $(\bar{L}L)(\bar{L}L)$ 8: $(\bar{R}R)(\bar{R}R)$ 8: $(\bar{L}L)(\bar{R}R)$
8: $(\bar{L}R)(\bar{R}L)+$ h.c. 8: $(\bar{L}R)(\bar{L}R)+$ h.c.

1350 CP-even, 1149-CP odd operators (B-conserving)

Class	$N_{\rm op}$	CP-even n_g	1	3	CP-odd n_g	1	3
1	4	2	2	2	2	2	2
2	1	1	1	1	0	0	0
3	2	2	2	2	0	0	0
4	8	4	4	4	4	4	4
5	3	$3n_g^2$	3	27	$3n_g^2$	3	27
6	8	$8n_g^2$	8	72	$8n_g^2$	8	72
7	8	$\frac{1}{2}n_g(9n_g+7)$	8	51	$\frac{1}{2}n_g(9n_g-7)$	1	30
8 : $(\overline{L}L)(\overline{L}L)$	5	$\frac{1}{4}n_g^2(7n_g^2+13)$	5	171	$\frac{7}{4}n_g^2(n_g-1)(n_g+1)$	0	126
8 : $(\overline{R}R)(\overline{R}R)$	7	$\frac{1}{8}n_g(21n_g^3+2n_g^2+31n_g+2)$	7	255	$\frac{1}{8}n_g(21n_g+2)(n_g-1)(n_g+1)$	0	195
8 : $(\overline{L}L)(\overline{R}R)$	8	$4n_g^2(n_g^2+1)$	8	360	$4n_g^2(n_g-1)(n_g+1)$	0	288
8 : $(\overline{L}R)(\overline{R}L)$	1	n_g^4	1	81	n_g^4	1	81
8 : $(\overline{L}R)(\overline{L}R)$	4	$4n_g^4$	4	324	$4n_g^4$	4	324
8 : All	25	$\frac{1}{8}n_g(107n_g^3+2n_g^2+89n_g+2)$	25	1191	$\frac{1}{8}n_g(107n_g^3+2n_g^2-67n_g-2)$	5	1014
Total	59	$\frac{1}{8}(107n_g^4+2n_g^3+213n_g^2+30n_g+72)$	53	1350	$\frac{1}{8}(107n_g^4+2n_g^3+57n_g^2-30n_g+48)$	23	1149

Complementarity with EDMs

Talks by Fuyuto, Brod, Stamou

- Top CPV phase naïvely constrained by electron EDM

Brod, Haisch, Zupan [1310.1385]

  - Indirect probe, still complementary to direct tests at LHC

See Buckley, Goncalves [1507.07926],
Mileo, Kies, Szynkman, Crane, Gegner [1603.03632],
slides by Sakurai

- Light quark CPV phases confront neutron EDM

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

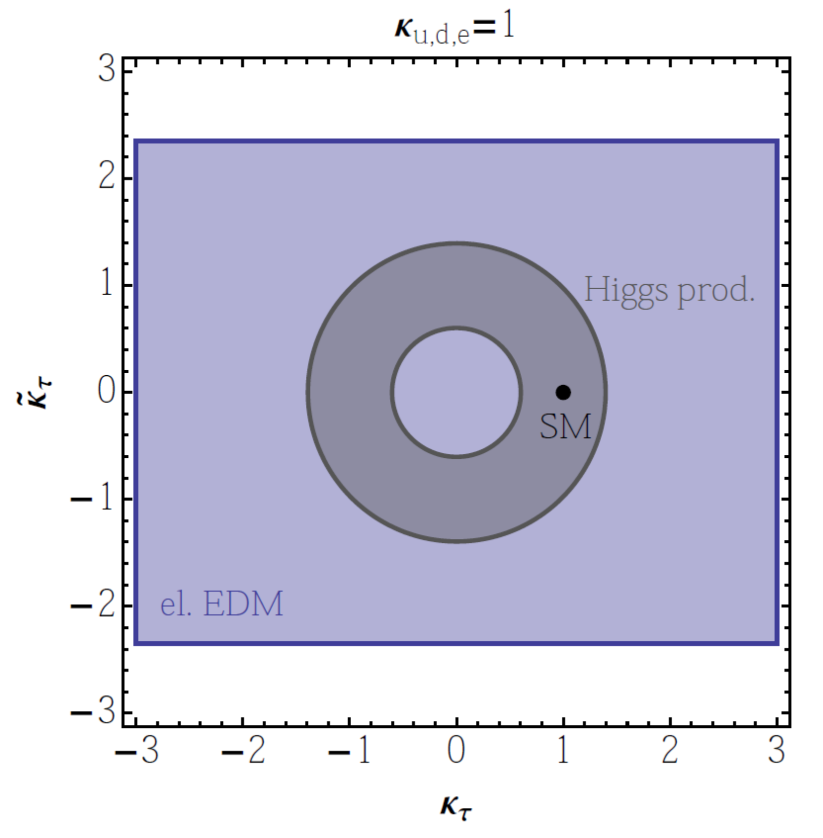
- Open room for τ Yukawa phase – HL-LHC and future colliders could provide leading sensitivity

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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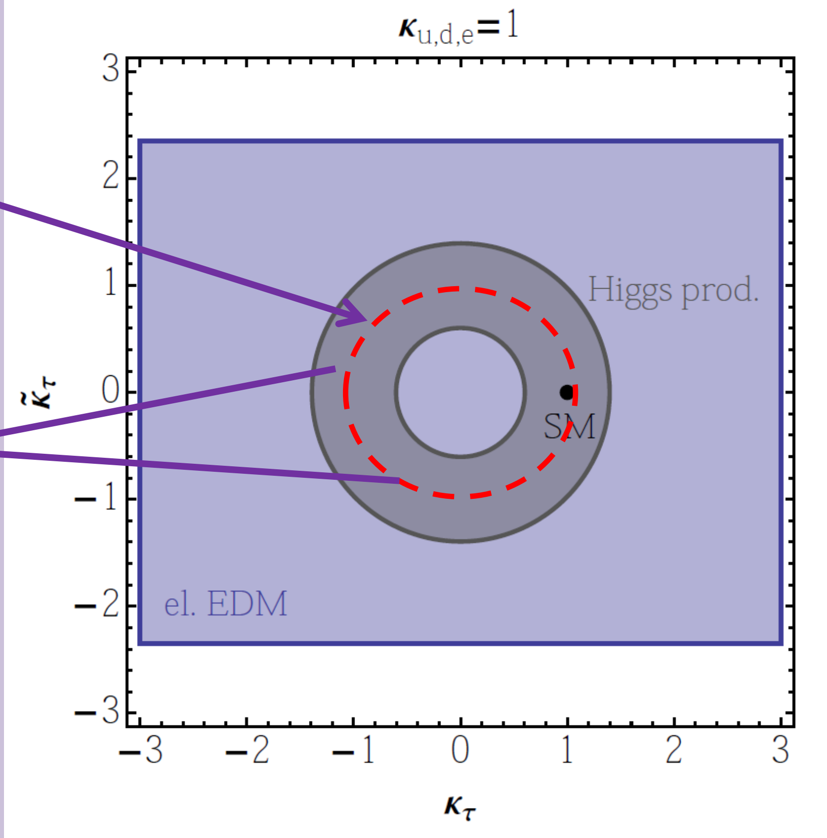
Signal strengths only constrain the quadrature sum



Must use differential distributions to test CP

Brod, Haisch, Zupan [1310.1385]

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
  - Better observable (appropriate for e^+e^- collider) is Θ

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

Matrix element calculation

- Treat the Higgs decay as a sequence of on-shell 2-body decays

$$\mathcal{M}_{h\to\tau\tau} \propto \sum_{s,s'} \chi_{s,s'} \bar{u}^s_{\tau^-} (\cos\Delta + i\gamma_5 \sin\Delta) v^{s'}_{\tau^+}$$

$$\mathcal{M}_{\tau\to\rho\nu} \propto (\epsilon^*_{\rho^-})_\mu \bar{u}_{\nu_\tau} \gamma^\mu P_L u_{\tau^-}$$

$$\mathcal{M}_{\rho\to\pi\pi} \propto \epsilon_{\rho^-} \cdot (p_{\pi^-} - p_{\pi^0})$$

- Together, gives

$$\begin{aligned}\mathcal{M}_{\text{full}} \propto\ & \bar{u}_{\nu^-} (\not{p}_{\pi^-} - \not{p}_{\pi^0 -}) P_L (\not{p}_{\tau^-} + m_\tau) \\ & \times (\cos\Delta + i\gamma_5 \sin\Delta) \\ & \times (-\not{p}_{\tau^+} + m_\tau)(\not{p}_{\pi^+} - \not{p}_{\pi^0 +}) P_L v_{\nu^+}\end{aligned}$$

Matrix element calculation assumptions

$$\mathcal{M}_{\text{full}} \propto \bar{u}_{\nu^-}(\not{p}_{\pi^-} - \not{p}_{\pi^0 -})P_L(\not{p}_{\tau^-} + m_\tau) \\ \times (\cos\Delta + i\gamma_5 \sin\Delta) \\ \times (-\not{p}_{\tau^+} + m_\tau)(\not{p}_{\pi^+} - \not{p}_{\pi^0 +})P_L v_{\nu^+}$$

- Neglect π^0 exchange (spatially separated; the τ's are boosted and back-to-back in the Higgs rest frame)
- All intermediate particles assumed on-shell
- Neglect $\pi^\pm$–π^0 mass difference
- Obtain $\mathcal{M}_{\text{full}} \propto \bar{u}_{\nu^-}\not{q}_-(e^{i\Delta}\not{p}_{\tau^-} - e^{-i\Delta}\not{p}_{\tau^+})\not{q}_+ P_L v_{\nu^+}$ with $q_\pm \equiv p_{\pi^\pm} - p_{\pi^0\pm}$
  - Recall $\rho_\pm$ polarization is generally aligned with $q_\pm$

Calculating the Theta Variable

- We then write the squared matrix element as

$$|\mathcal{M}|^2 \propto P_{\not{\Delta},S} + P_{\Delta,\not{S}} + P_{\Delta,S} + P^*_{\Delta,S}$$

where the most interesting piece is

$$P_{\Delta,S} = -2e^{i(2\Delta-\Theta)}|\vec{E}_+||\vec{E}_-|$$

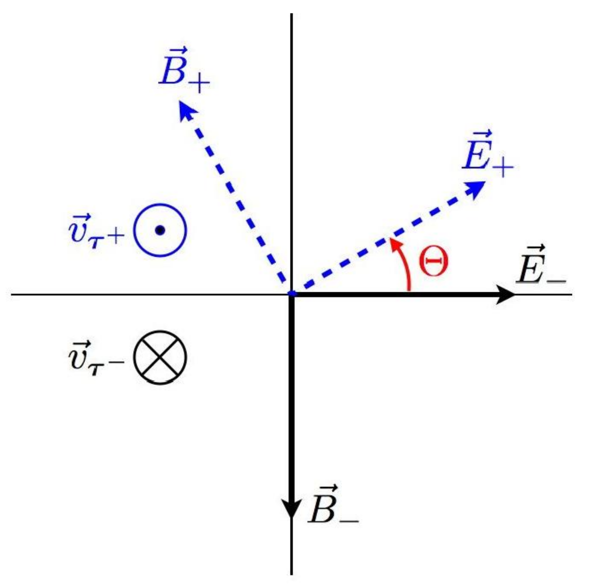
- In the Higgs rest frame, the "electric" components are

$$\vec{E}_\pm = \frac{m_h}{2}\left[(y_\pm - r)\vec{p}_{\pi^\pm}|_0 - (y_\pm + r)\vec{p}_{\pi^0\pm}|_0\right]^\perp$$

$$y_\pm \equiv \frac{2q_\pm \cdot p_{\tau^\pm}}{m_\tau^2 + m_\rho^2} = \frac{q_\pm \cdot p_{\tau^\pm}}{p_{\rho^\pm} \cdot p_{\tau^\pm}}$$

$$r \equiv \frac{m_\rho^2 - 4m_\pi^2}{m_\tau^2 + m_\rho^2} \approx 0.14$$

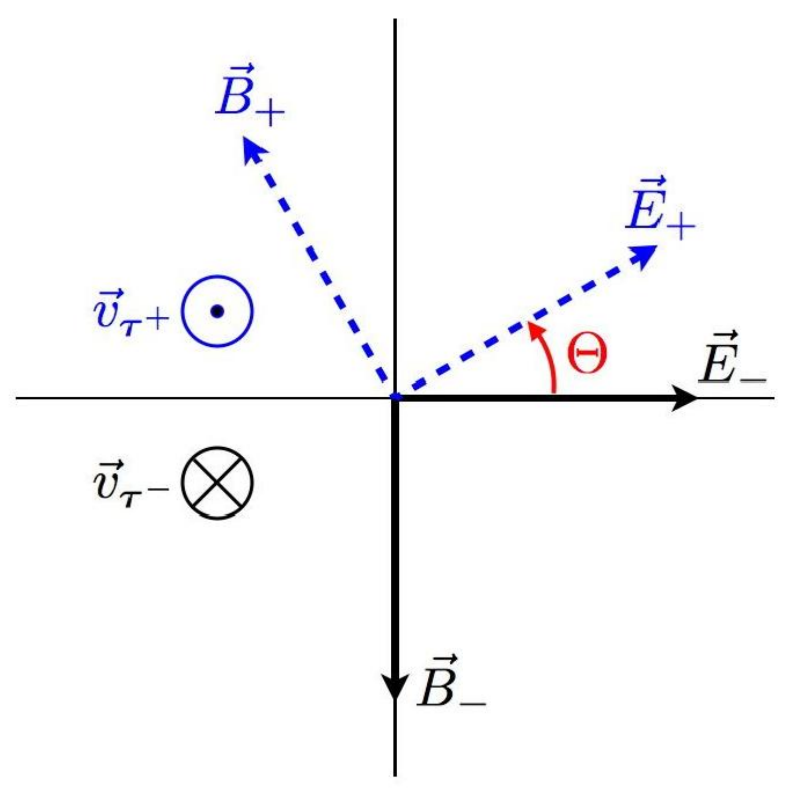
$|_0$ = tau rest frame, $y_\pm$ and r are kinematic constants



Calculating the Theta Variable

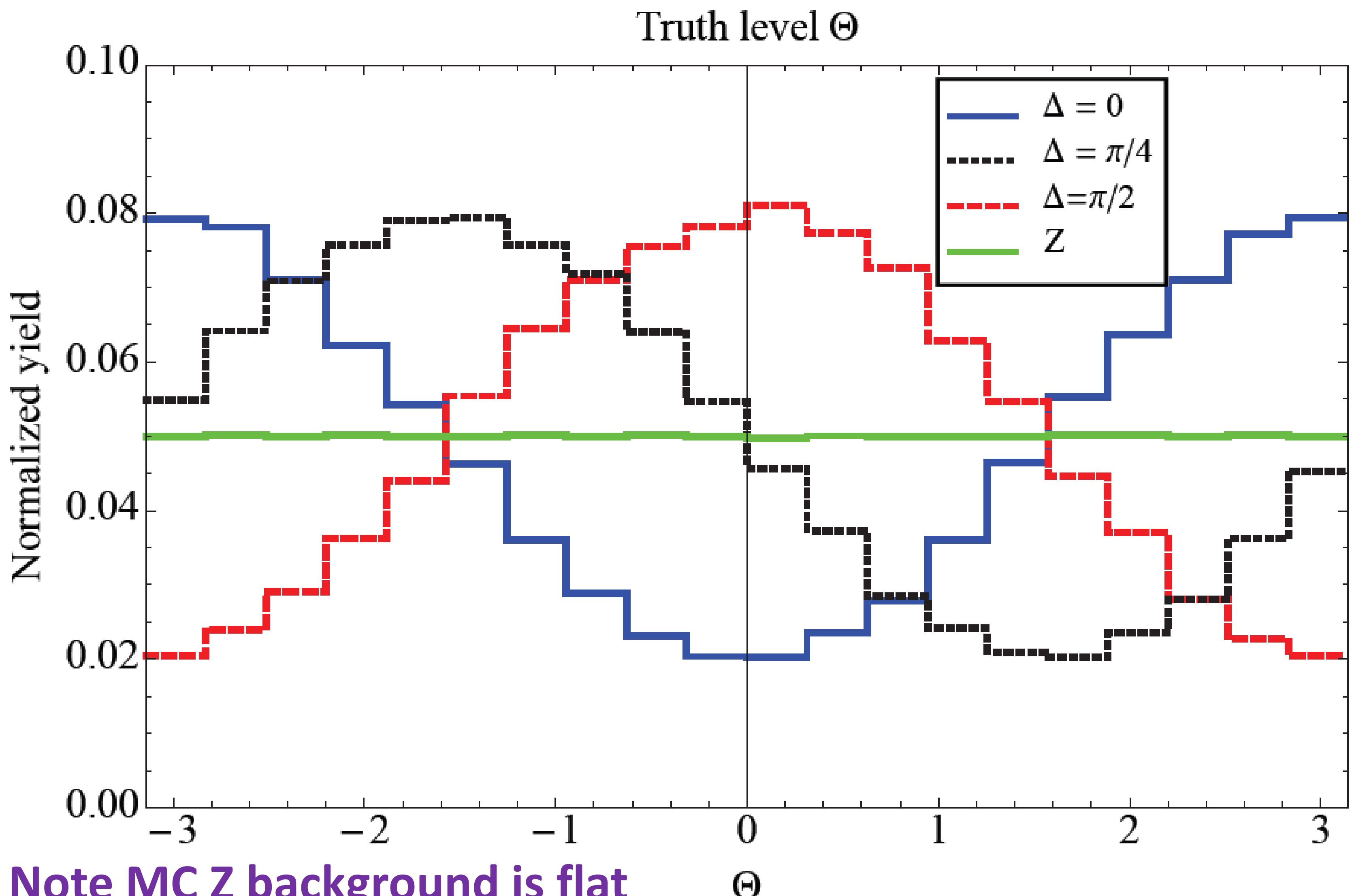
$$\Theta = \mathrm{sgn}\left[\vec{v}_{\tau^+} \cdot (\vec{E}_- \times \vec{E}_+)\right] \arccos\left[\frac{\vec{E}_+ \cdot \vec{E}_-}{|\vec{E}_+||\vec{E}_-|}\right]$$

- If neutrino 4-momenta were determined, could then reconstruct tau momentum as well as tau and Higgs rest frames
  - Not possible at LHC
    - Have 2 undetermined momenta
  - Possible at CEPC, FCCee, ILC



Ideal situation

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



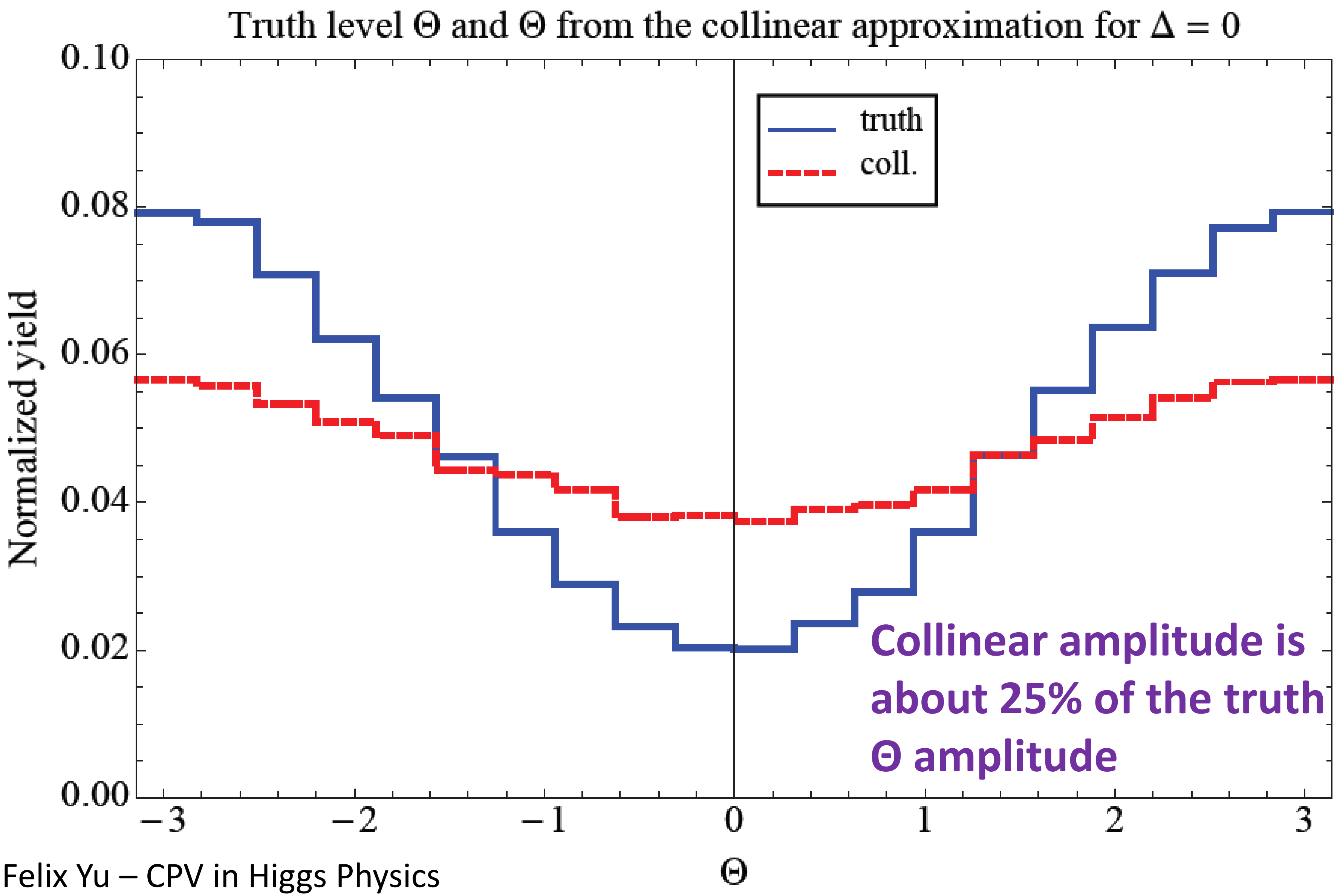
Note MC Z background is flat

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



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
$\mathrm{Br}(\tau^+\tau^-\ \mathrm{decay})$	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

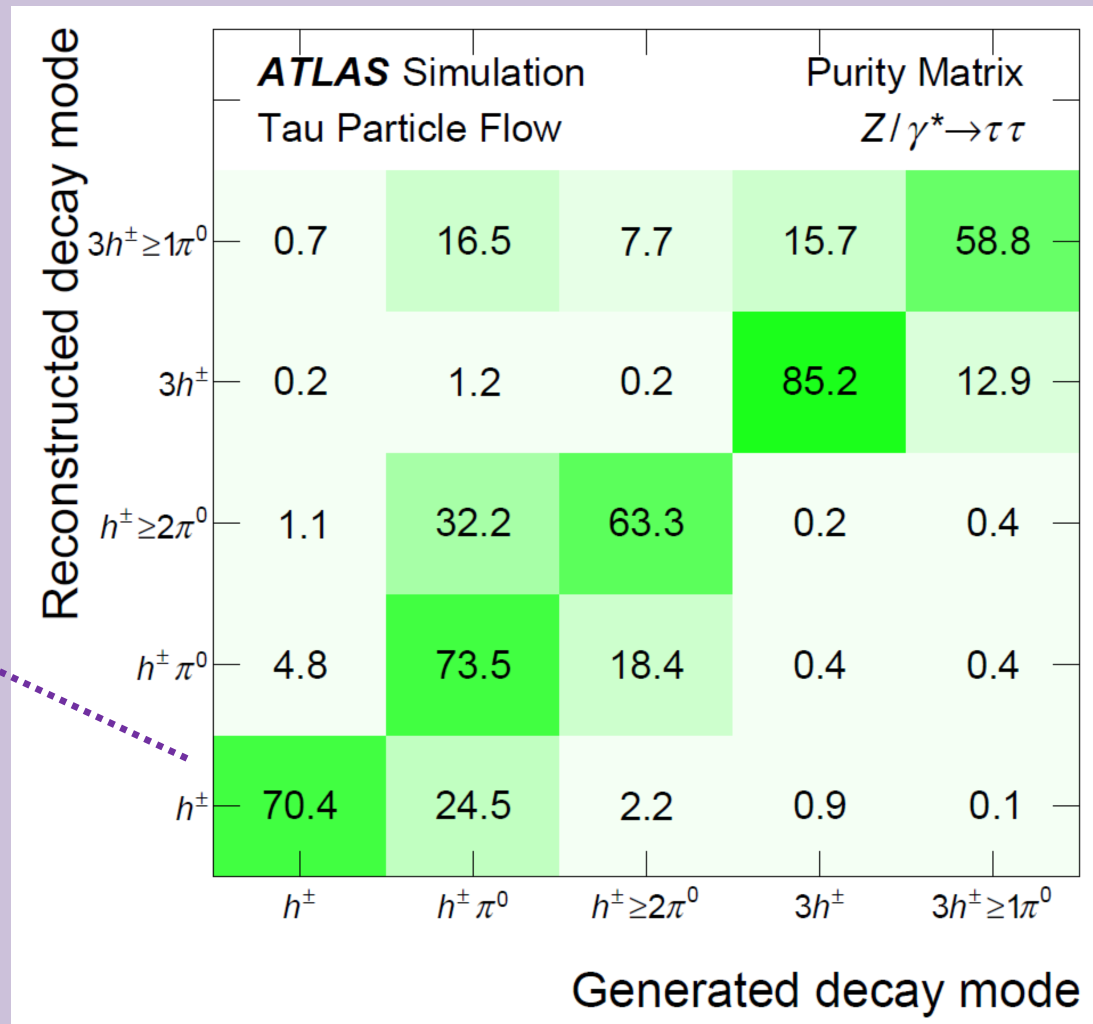
Yields for 3 ab^{-1} LHC

- 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

Hadronic τ Reconstruction



Single prong decay also important if impact parameter information is used

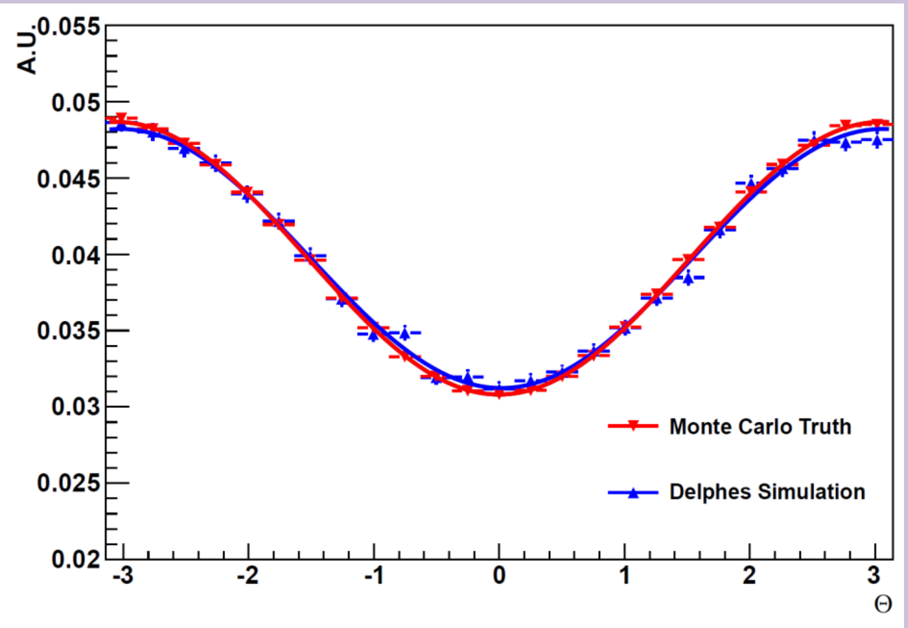
Berge, Bernreuther, Niepelt, Spiesberger [1108.0670]

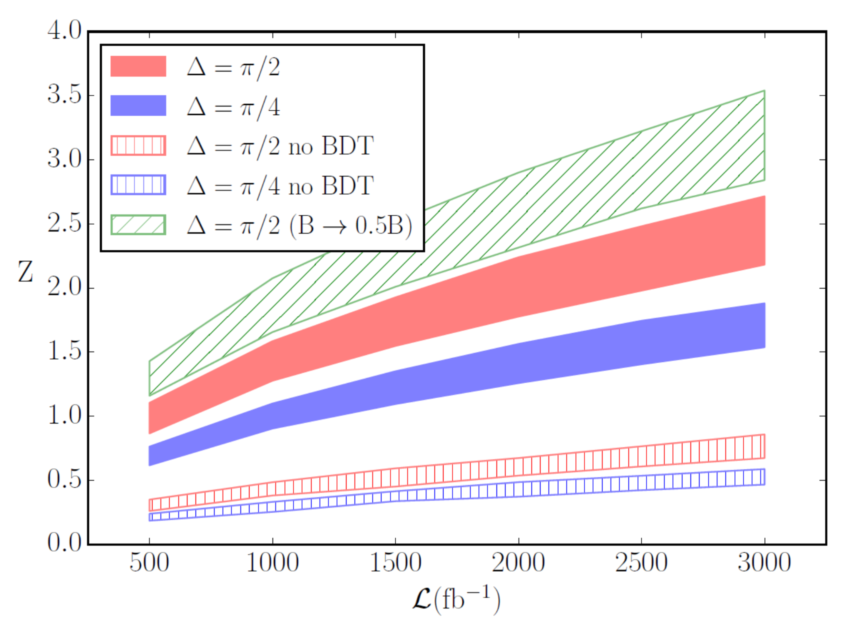
Zanzi for ATLAS and CMS [1703.10259]

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





HE-LHC (first look)

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

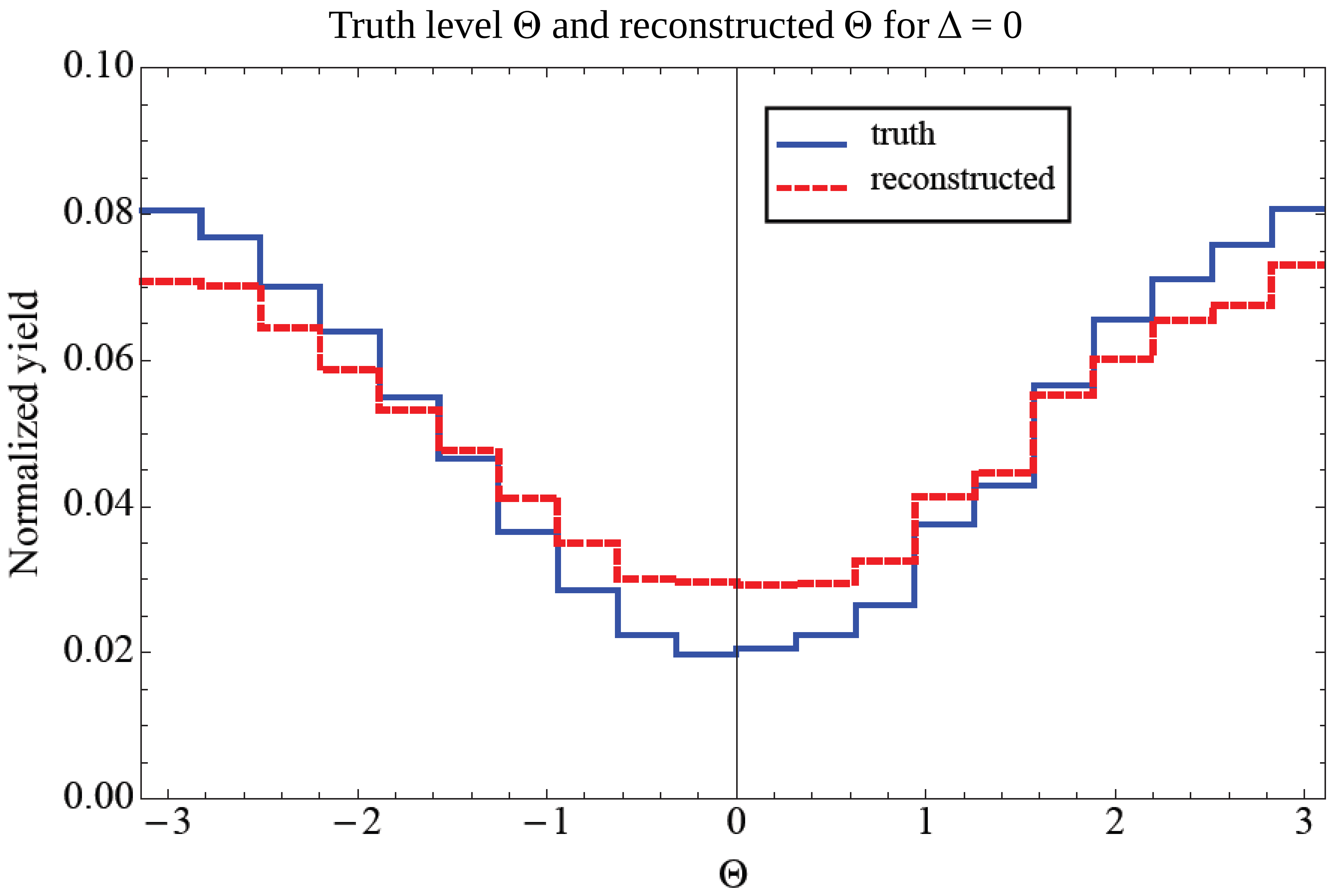
p_T cut (GeV) on h+j for	NLO cross section for 27 TeV pp collider (MCFM 8.0)	Signal enhancement compared to 14 TeV, p_T > 140 GeV
100	12.1 pb	6.05×
140	6.96 pb	3.48× [Our original working point]
150	6.12 pb	3.06×
200	3.43 pb	1.72×
250	2.08 pb	1.04×

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

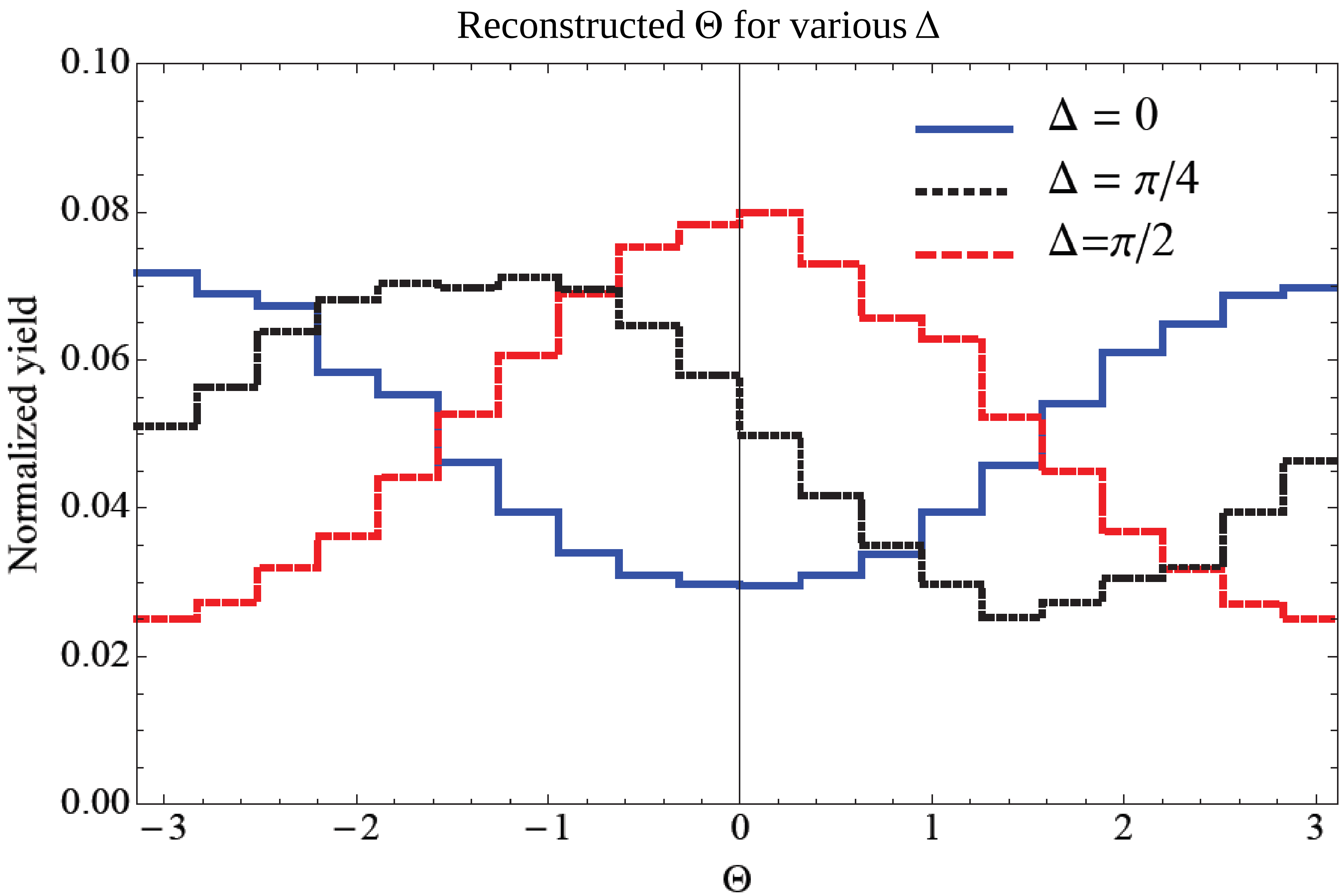
Lepton collider possibilities

- At a lepton collider, have enough constraints to solve algebraically for neutrino momenta
  - Have two neutrino momenta solution sets
    - Both solutions give correct Higgs mass
    - Weight each solution by half an event
    - Necessarily require visible Z decay
  - Finite resolution on different Z decay channels will moderate the Θ distribution (not included)

Lepton collider – reconstructed



Lepton collider – reconstructed

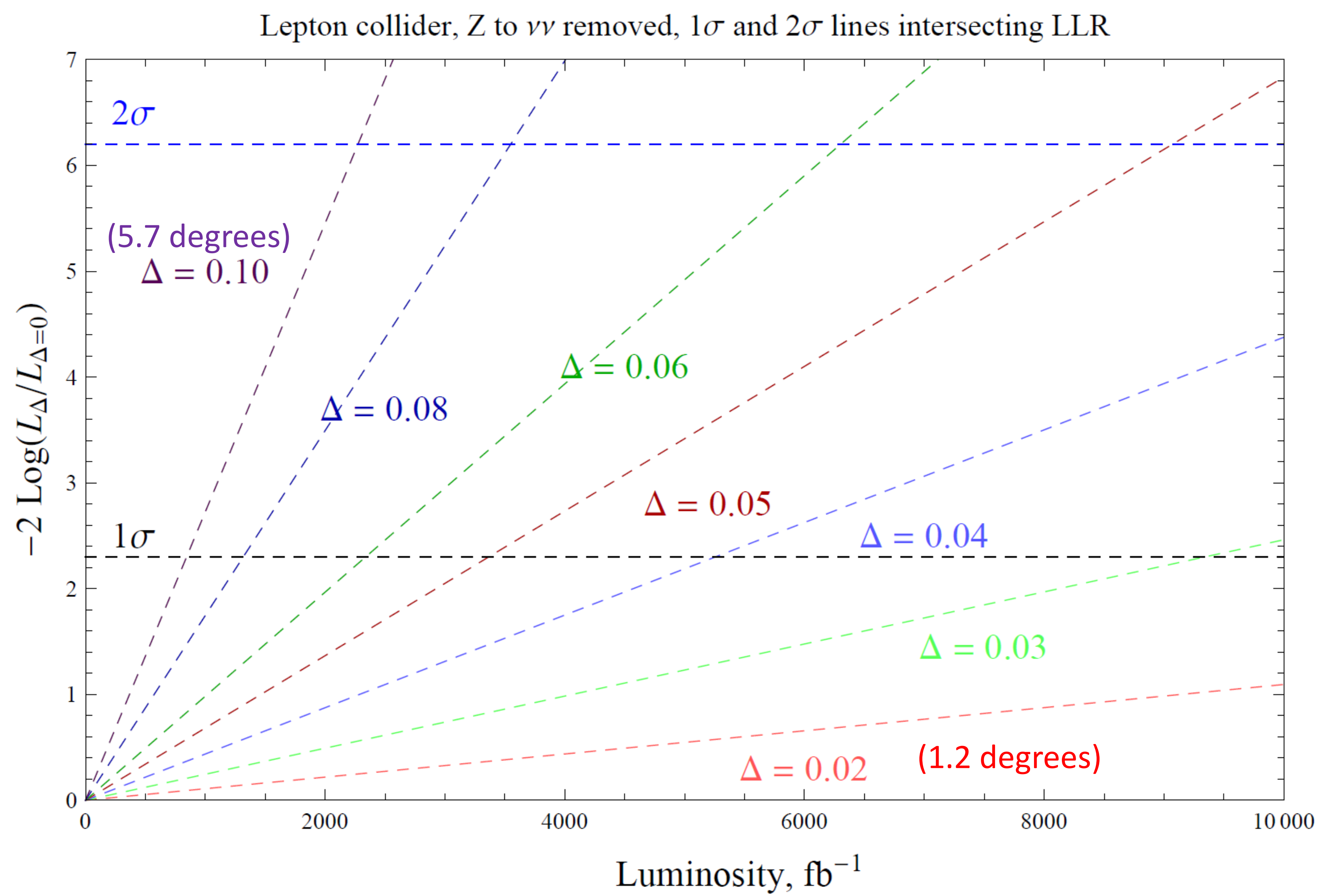


Lepton collider possibilities

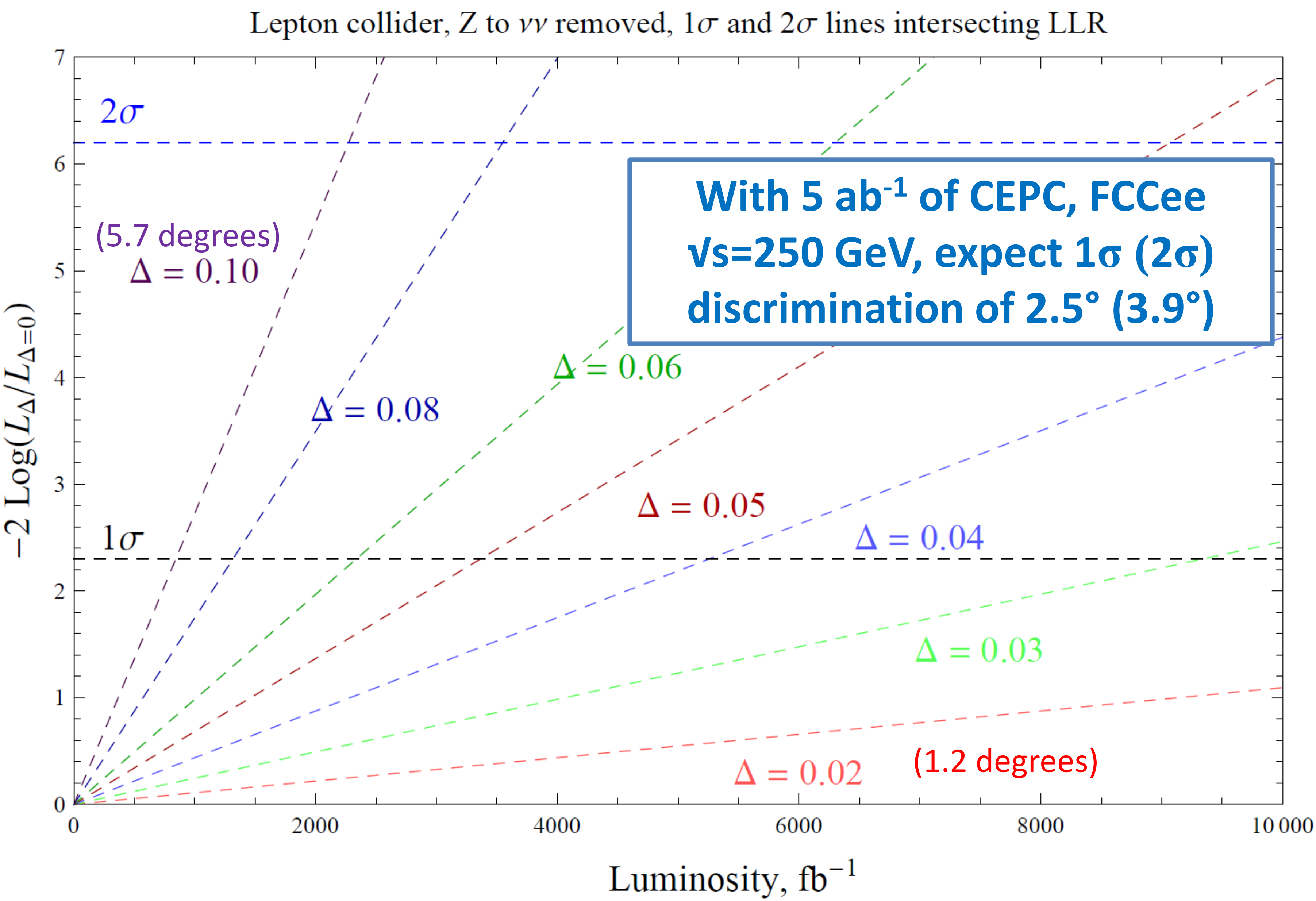
- For √s = 250 GeV, Zh production is about 0.23 pb
  - Signal yield (using SM Br(h →ττ) and restricting to visible Z decays) is about 770 events with 1 ab^{-1}
    - Restricting to Z → ee, μμ decays gives about 65 events
    - Hadronic Z decays will help CPV study statistics at price of worse resolution
  - Construct binned likelihood using a sinuisoidal fit to signal, determine sensitivity by variation of test Δ

$$L = \frac{\prod_{i=1}^{N} \mathrm{Pois}(B_i + S_i^{\Delta=0} | B_i + S_i^{\Delta=\delta})}{\prod_{i=1}^{N} \mathrm{Pois}(B_i + S_i^{\Delta=0} | B_i + S_i^{\Delta=0})}$$

Luminosity scaling (without systematics)



Luminosity scaling (without systematics)



With 5 ab^{-1} of CEPC, FCCee √s=250 GeV, expect 1σ (2σ) discrimination of 2.5° (3.9°)

Lepton Collider Prospects

- Systematics will affect high luminosity estimates
- Expect some sensitivity losses from detector resolution, charged and neutral pion efficiency
    - Will update numbers using preliminary CEPC Delphes card
  - Reconstructing neutrino momenta is equivalent to knowing the rest frames of the Higgs and tau daughters
- Also expect a NP model giving a nonzero CP phase could enhance Br($h \to \tau\tau$)

CPV in HVV interactions at future colliders

- 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]

Suite of 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], talk by Sakurai
  - 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

Schematic collider program for CPV in Higgs to bb, cc

- Study baryonic decays

$$\Lambda_b \to X_c \ell^- \nu$$

$$\Lambda_c^+ \to p K^- \pi^+$$

Galanti, Giammanco, Grossman, Kats, Stamou, Zupan [1505.02771]
Kats [1505.06731]

  - Baryonic decays preserve polarization to O(1)
  - About 10% of b-quarks create Λ_b
  - Measure polarization in tt, W+c SM processes
- Use data to control reconstruction techniques in Higgs decays

Open issues

- Post-discovery: what Lagrangian CPV source is responsible in the case of a positive measurement?
- Targets for CPV sensitivity – theory questions
  - Tree-level operator (Yukawa) vs. loop-induced
  - How to include rate effects
- Targets for CPV sensitivity – optimal experimental probes ("flavored" CPV)

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
  - $h \rightarrow \tau\tau$ is a promising first channel to study at HL-LHC and future colliders
  - Post-(pre?-)discovery model building needed to connect directly CP phases to EW baryogenesis

$h \rightarrow \tau\tau$ at Colliders	LHC	HL-LHC	ee unpolarized (5 ab^{-1})
Accuracy (1σ)	25°	8.0°	2.5°
Accuracy (2σ)	34°	11.5°	3.9°

CPV at dimension 6

$1: X^3$		$2: H^6$		$3: H^4D^2$		$5: \psi^2 H^3 + \text{h.c.}$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_H	$(H^\dagger H)^3$	$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$	Q_{eH}	$(H^\dagger H)(\bar l_p e_r H)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$			Q_{HD}	$\left(H^\dagger D_\mu H\right)^* \left(H^\dagger D_\mu H\right)$	Q_{uH}	$(H^\dagger H)(\bar q_p u_r \widetilde H)$
Q_W	$\epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$					Q_{dH}	$(H^\dagger H)(\bar q_p d_r H)$
$Q_{\widetilde W}$	$\epsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$						

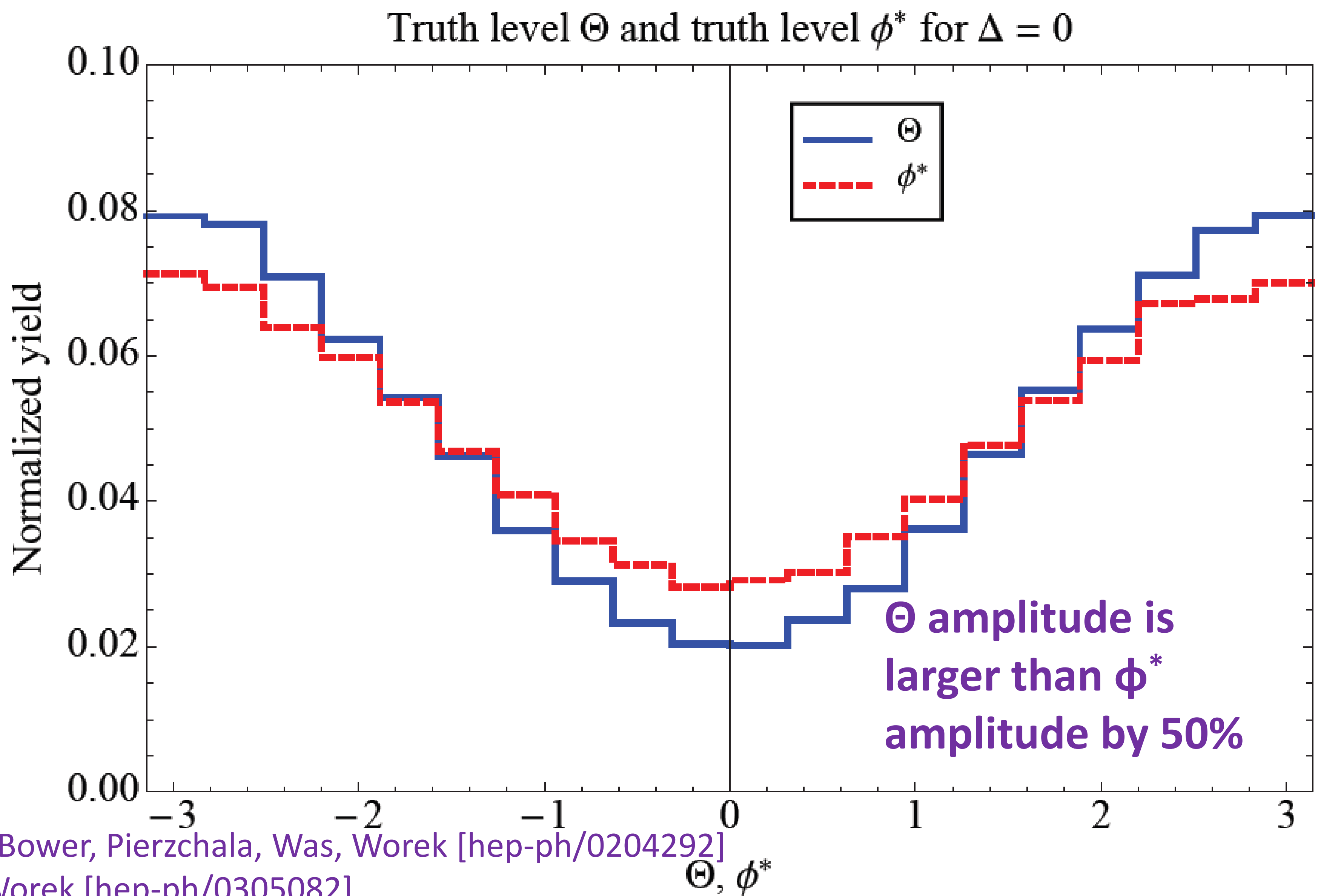
$4: X^2H^2$		$6: \psi^2 XH + \text{h.c.}$		$7: \psi^2 H^2 D$	
Q_{HG}	$H^\dagger H\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r) \tau^I H W^I_{\mu\nu}$	$Q_{Hl}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar l_p \gamma^\mu l_r)$
$Q_{H\widetilde G}$	$H^\dagger H\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$	$Q_{Hl}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar l_p \tau^I \gamma^\mu l_r)$
Q_{HW}	$H^\dagger H\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r) \widetilde H\, G^A_{\mu\nu}$	Q_{He}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar e_p \gamma^\mu e_r)$
$Q_{H\widetilde W}$	$H^\dagger H\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r) \tau^I \widetilde H\, W^I_{\mu\nu}$	$Q_{Hq}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar q_p \gamma^\mu q_r)$
Q_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r) \widetilde H\, B_{\mu\nu}$	$Q_{Hq}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{H\widetilde B}$	$H^\dagger H\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r) H\, G^A_{\mu\nu}$	Q_{Hu}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar u_p \gamma^\mu u_r)$
Q_{HWB}	$H^\dagger \tau^I H\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r) \tau^I H\, W^I_{\mu\nu}$	Q_{Hd}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar d_p \gamma^\mu d_r)$
$Q_{H\widetilde W B}$	$H^\dagger \tau^I H\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r) H\, B_{\mu\nu}$	Q_{Hud} + h.c.	$i(\widetilde H^\dagger D_\mu H)(\bar u_p \gamma^\mu d_r)$

$8: (\bar LL)(\bar LL)$		$8: (\bar RR)(\bar RR)$		$8: (\bar LL)(\bar RR)$	
Q_{ll}	$(\bar l_p \gamma_\mu l_r)(\bar l_s \gamma^\mu l_t)$	Q_{ee}	$(\bar e_p \gamma_\mu e_r)(\bar e_s \gamma^\mu e_t)$	Q_{le}	$(\bar l_p \gamma_\mu l_r)(\bar e_s \gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar q_s \gamma^\mu q_t)$	Q_{uu}	$(\bar u_p \gamma_\mu u_r)(\bar u_s \gamma^\mu u_t)$	Q_{lu}	$(\bar l_p \gamma_\mu l_r)(\bar u_s \gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar q_p \gamma_\mu \tau^I q_r)(\bar q_s \gamma^\mu \tau^I q_t)$	Q_{dd}	$(\bar d_p \gamma_\mu d_r)(\bar d_s \gamma^\mu d_t)$	Q_{ld}	$(\bar l_p \gamma_\mu l_r)(\bar d_s \gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar l_p \gamma_\mu l_r)(\bar q_s \gamma^\mu q_t)$	Q_{eu}	$(\bar e_p \gamma_\mu e_r)(\bar u_s \gamma^\mu u_t)$	Q_{qe}	$(\bar q_p \gamma_\mu q_r)(\bar e_s \gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar l_p \gamma_\mu \tau^I l_r)(\bar q_s \gamma^\mu \tau^I q_t)$	Q_{ed}	$(\bar e_p \gamma_\mu e_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar u_s \gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar u_p \gamma_\mu u_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar u_s \gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar u_p \gamma_\mu T^A u_r)(\bar d_s \gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar d_s \gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar d_s \gamma^\mu T^A d_t)$

$8: (\bar LR)(\bar RL) + \text{h.c.}$		$8: (\bar LR)(\bar LR) + \text{h.c.}$	
Q_{ledq}	$(\bar l_p^j e_r)(\bar d_s q_{tj})$	$Q_{quqd}^{(1)}$	$(\bar q_p^j u_r) \epsilon_{jk} (\bar q_s^k d_t)$
		$Q_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r) \epsilon_{jk} (\bar q_s^k T^A d_t)$
		$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r) \epsilon_{jk} (\bar q_s^k u_t)$
		$Q_{lequ}^{(3)}$	$(\bar l_p^j \sigma_{\mu\nu} e_r) \epsilon_{jk} (\bar q_s^k \sigma^{\mu\nu} u_t)$

Alonso, Jenkins, Manohar, Trott [1312.2014]

Ideal – compare to ρ⁺ρ⁻ acoplanarity*



Θ amplitude is larger than ϕ^* amplitude by 50%

*Bower, Pierzchala, Was, Worek [hep-ph/0204292]
Worek [hep-ph/0305082]