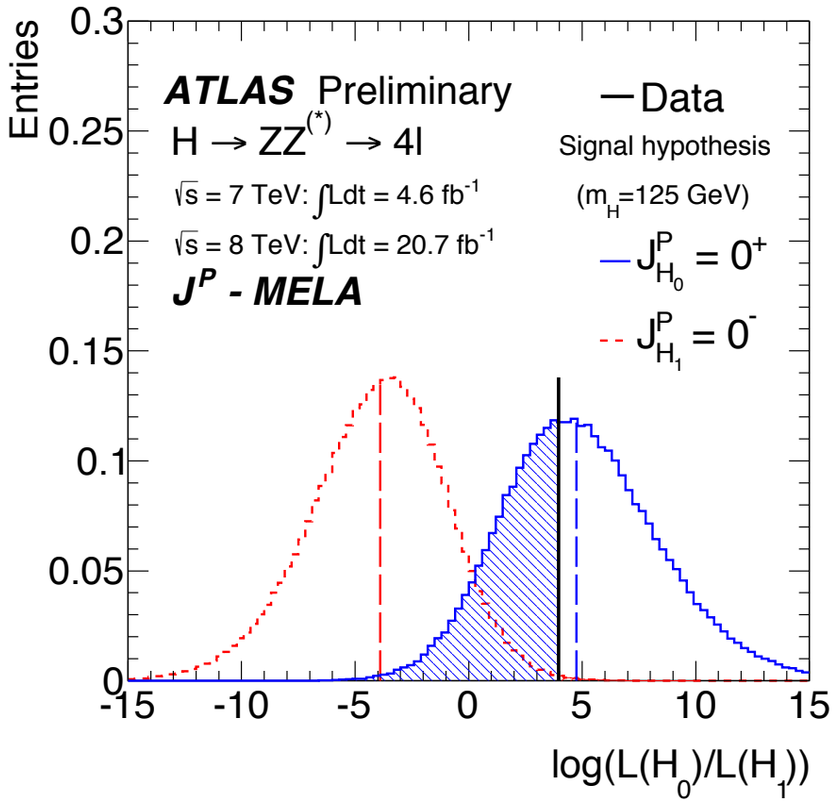
Measuring CP Violation in $h \to \tau^+ \tau^-$ at Colliders

Reinard Primulando
with R. Harnik, A. Martin, T. Okui and F. Yu
(arXiv:1308.1094)

CP Property of h → ZZ



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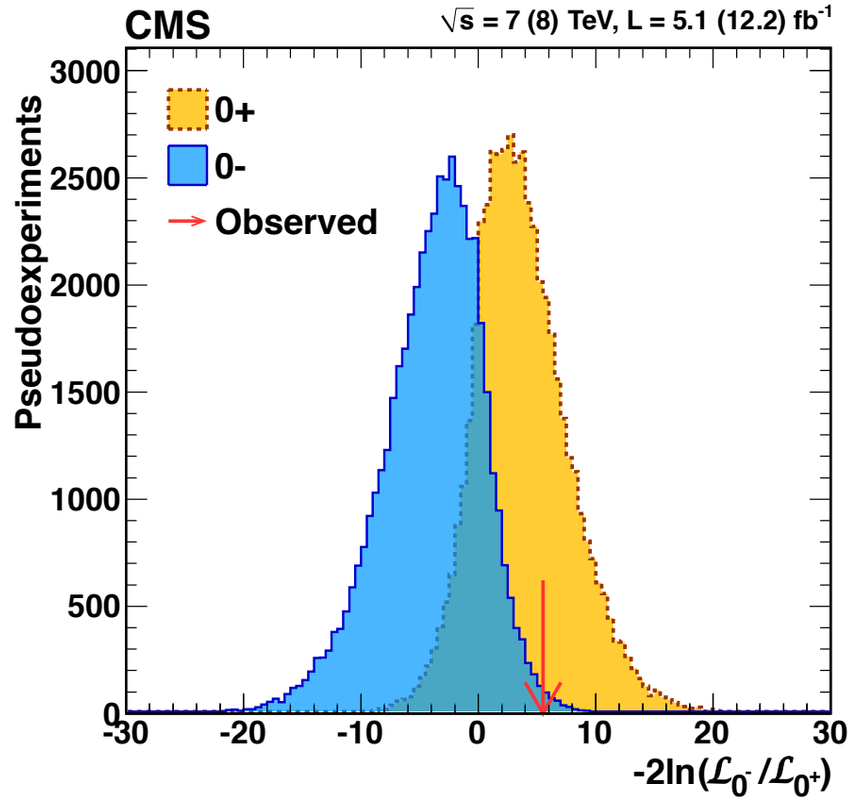


CMS collaboration, Phys. Rev. Lett. 110 (2013) 081803

CP Property of $h \to f \bar{f}$

- $h \to q\bar{q}$ (polarization washed out by hadronization)
- $h \to e^+ e^-, \mu^+ \mu^-$ (unable to measure lepton polarization)
- ttH (can be done, see e.g. Gunion & He: hep-ph/9602226, Godbole, et.al.: 1103.5404, Primulando, Stolarski, Zupan: in progress)
- $h \to \tau^+ \tau^-$ (this work)

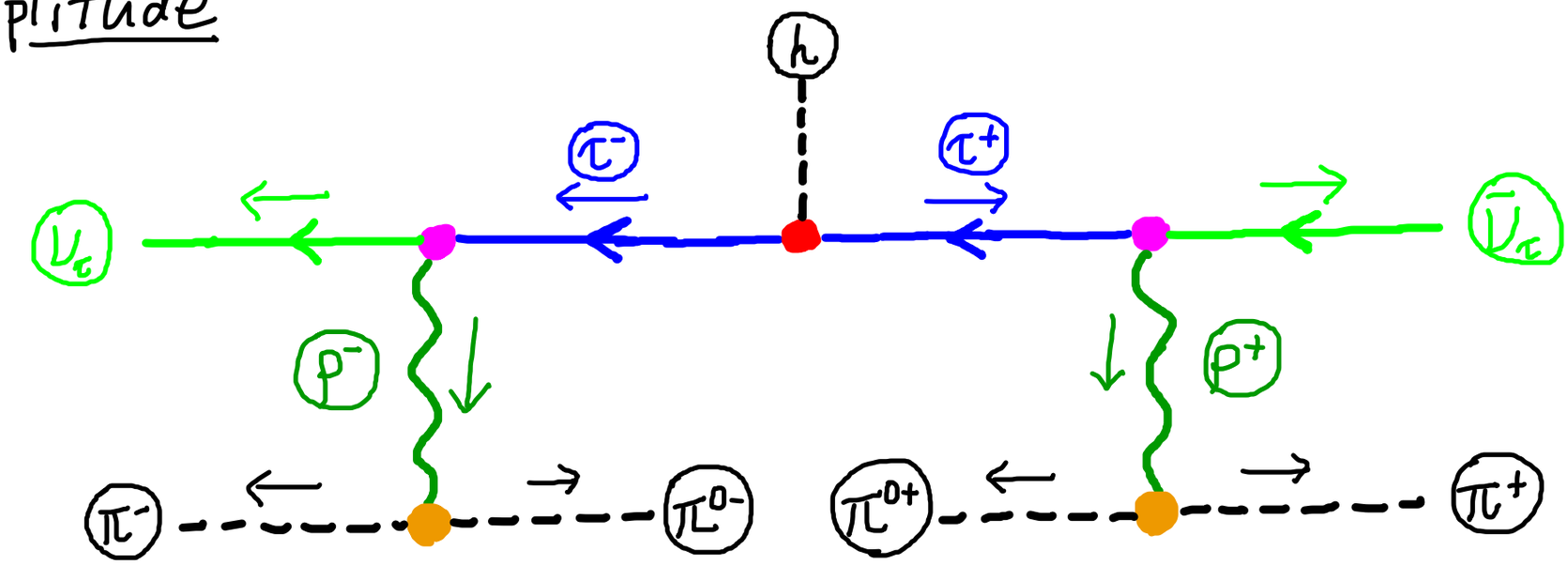
CP Violation in $h \to \tau^+ \tau^-$

$$\mathcal{L}_{\text{pheno}} \supset -m_\tau \, \bar{\tau}\tau - \frac{y_\tau}{\sqrt{2}} \, h\bar{\tau}(\cos\Delta + \mathrm{i}\gamma_5 \sin\Delta)\tau$$

- The tau spin correlation is sensitive to the CP phase, Δ.
- We consider the decay of $\tau \to \rho\nu$ with subsequent decay of $\rho^\pm \to \pi^\pm\pi^0$
- The tau spin information is encoded in the momentum distribution of its decay products.

The Amplitude

Amplitude



$$\mathcal{M} \propto \bar{u}_{\nu_\tau} \gamma^\mu P_L (\not{\pi}^- + m_\tau)(\cos\Delta + i\gamma_5 \sin\Delta)(-\not{\pi}^+ + m_\tau)\gamma^\nu P_L v_{\bar{\nu}_\tau}$$
$$\times \eta_{\mu\alpha} \times (\pi^- - \pi^{0-})^\alpha$$
$$\times \eta_{\nu\beta} \times (\pi^+ - \pi^{0+})^\beta$$

The Amplitude

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

The Amplitude

Independent of τ spin

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Independent of Δ

The Amplitude

Independent of τ spin

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

Independent of Δ

Δ and τ spin dependent

The Amplitude

Define

$$\vec{E}_{\pm} = p^0_{\tau\pm}\,\vec{k}_{\pm} - k^0_{\pm}\,\vec{p}_{\tau\pm}$$

where

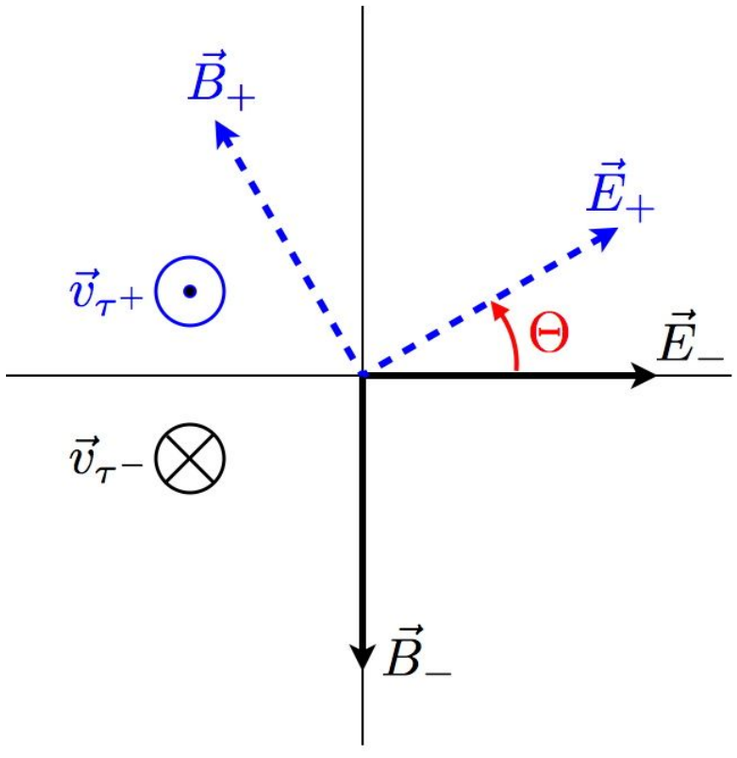
$$k^\mu = y_{\pm}(p^\mu_{\pi\pm} - p^\mu_{\pi^0}) + r\,p^\mu_{\nu\pm}$$

$$y_{\pm} = \left.\frac{E_{\pi\pm} - E_{\pi^0_\pm}}{E_{\pi\pm} + E_{\pi^0_\pm}}\right|_{\tau \text{ rest frame}} \qquad r \equiv \frac{m_\rho^2 - 4m_\pi^2}{m_\tau^2 + m_\rho^2}$$

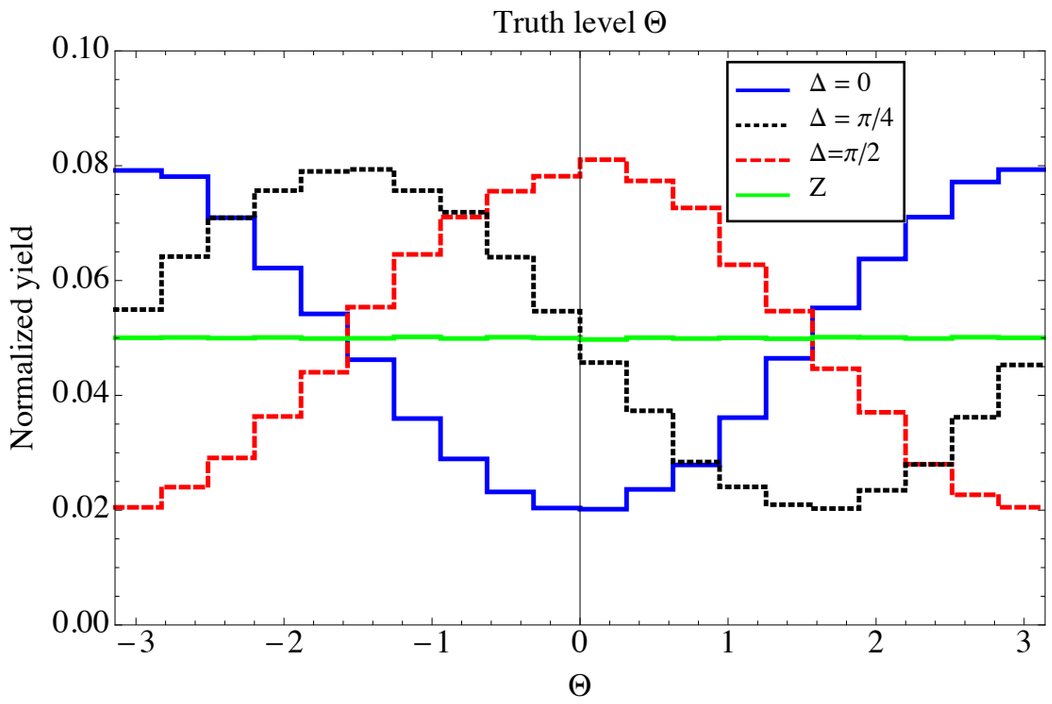
The Amplitude

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

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



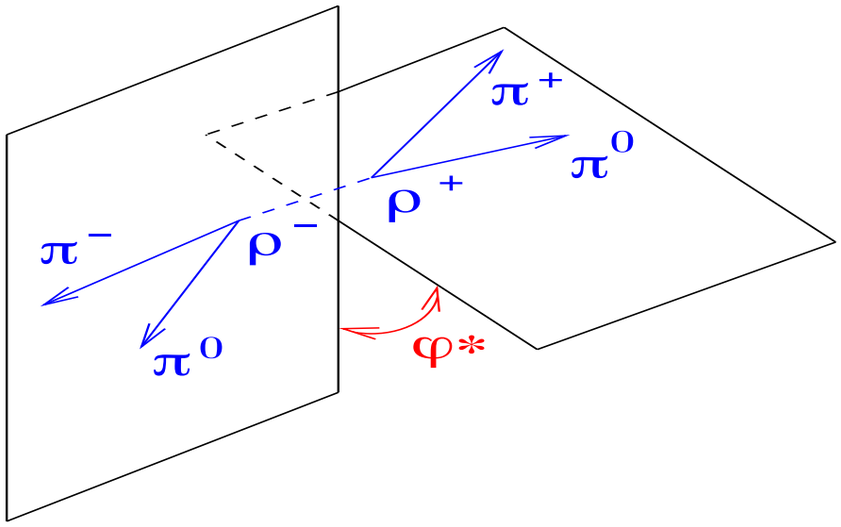
Θ Variable



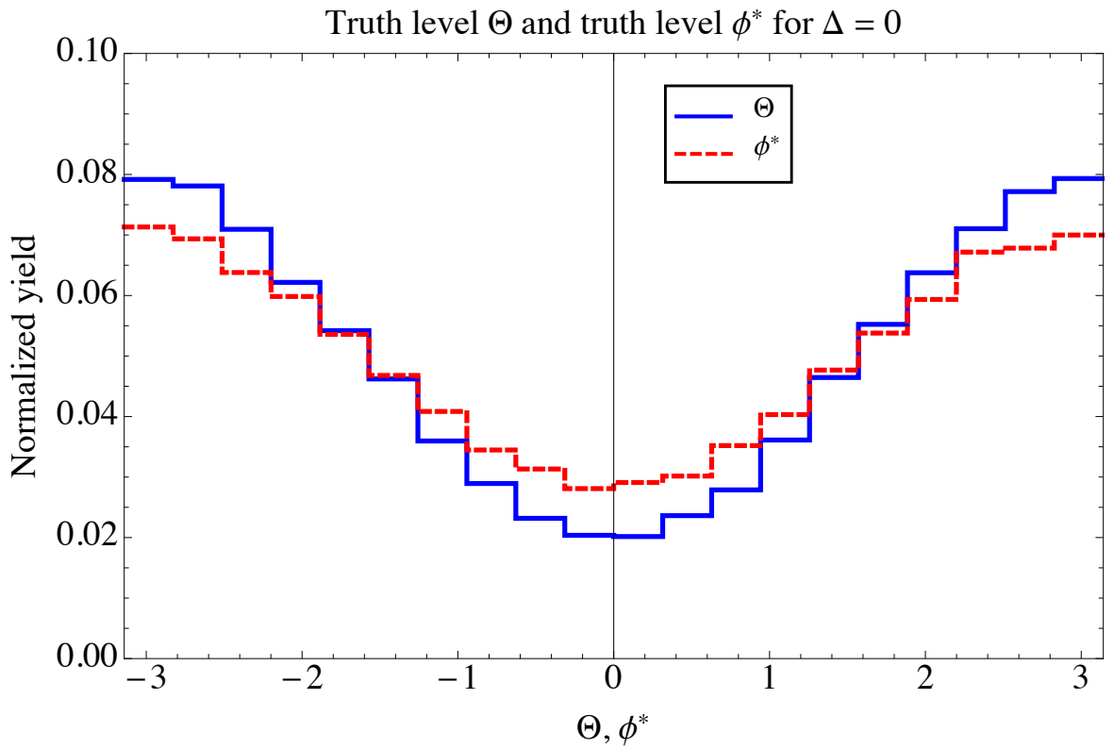
$$|\mathcal{M}|^2 \propto \; P_{\not\Delta,\mathrm{S}} + P_{\Delta,\not\mathrm{S}} \; -4|\vec{E}_+||\vec{E}_-|\cos(2\Delta - \Theta)$$

- The CP phase Δ can be determined by observing the minimum of the Θ distribution.
- The Θ distribution for $Z \rightarrow \tau^+ \tau^-$ is flat.

Comparison with φ*



Worek, hep-ph/0305082

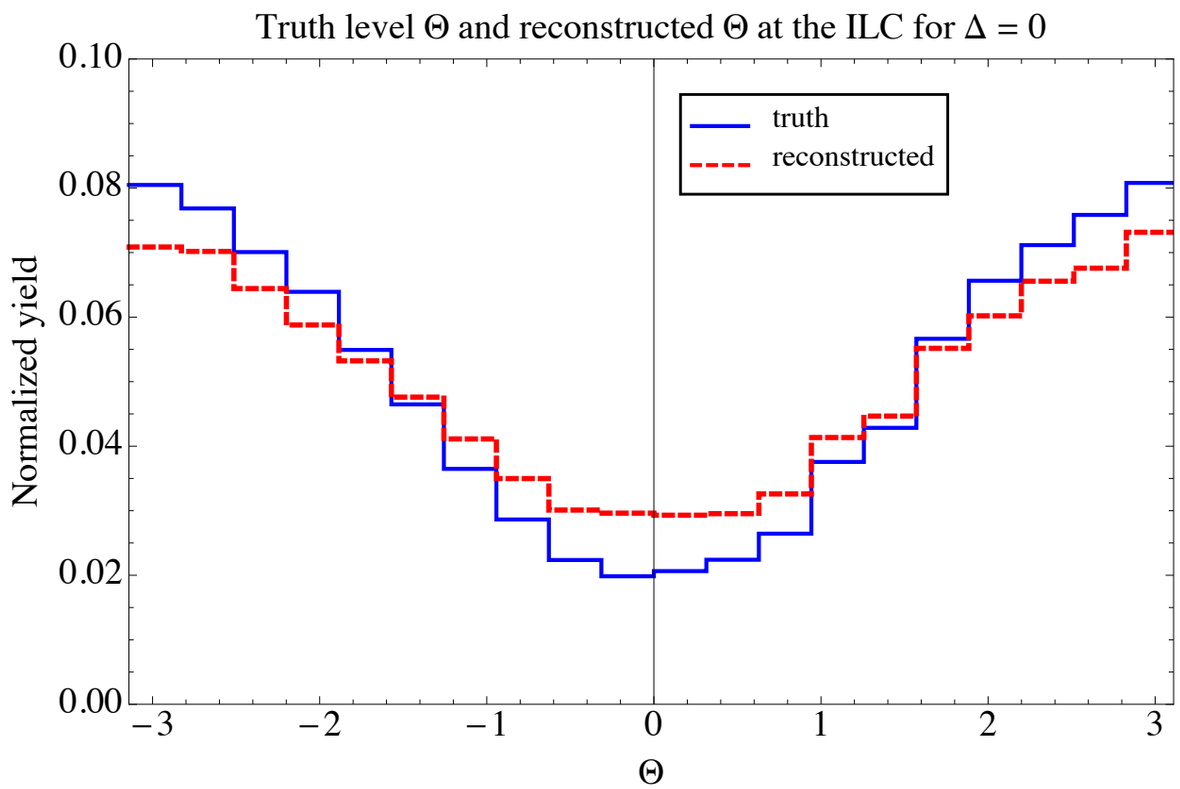


- The acoplanarity angle (φ*) between the decay plane of ρ^+ and ρ^- in the $\rho^+\rho^-$ rest frame can also be used to distinguish various CP phase; Bower, et.al. (hep-ph/0204292).

- Other studies e.g. Berge,et.al. (1308.2674) are based on reconstructing the impact parameter vectors of the visible τ decay products.

ILC

- We consider ILC 250 GeV with luminosity 1 ab^{-1}.
- We assume the SM production cross section of hZ and SM branching ratio of $h \to \tau^+ \tau^-$.
- The ZZ background is neglected because we can reconstruct the Higgs mass.
- The neutrino momenta can be reconstructed at the ILC with a twofold ambiguity.



ILC

- The accuracy is obtained by comparing the $\Delta = 0$ hypothesis with an alternative $\Delta = \delta$ hypothesis.

$\sigma_{e^+e^-\to hZ}$	0.30 pb
$\mathrm{Br}(h \to \tau^+\tau^-)$	6.1%
$\mathrm{Br}(\tau^- \to \pi^-\pi^0\nu)$	26%
$\mathrm{Br}(Z \to \text{visibles})$	80%
$\mathrm{N_{events}}$	990
Accuracy	4.4°

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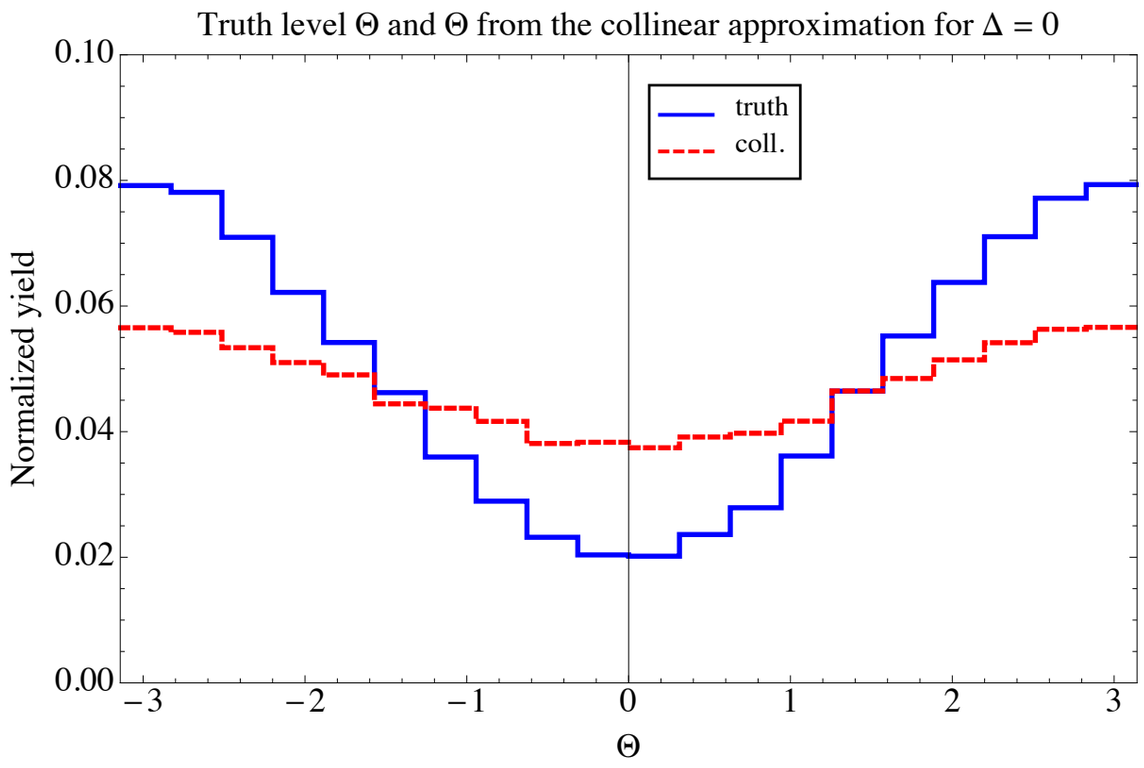
LHC

- We consider pp → h j process at 14 TeV LHC with the Higgs is produced by gluon fusion process.
- At the LHC, the neutrino momentum can not be reconstructed.
- We employ collinear approximation for neutrino momenta.



LHC

- The main backgrounds are Z+jets and QCD.
- We employ cuts:

$$\begin{aligned}
&\text{leading jet } p_{\mathrm{T}} > 140 \text{ GeV with } |\eta| < 2.5 \\
&\not{E}_{\mathrm{T}} > 40 \text{ GeV}, \\
&p_{\mathrm{T}}^{\rho^{\pm}} > 45 \text{ GeV}, \\
&|\eta^{\rho^{\pm}}| < 2.1, \\
&m_{\mathrm{coll}} > 120 \text{ GeV},
\end{aligned}$$

- We assume that the QCD background is 10% of Z+jets.
- We assume 50% and 70% tau tagging efficiencies.

LHC

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

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

Pseudoscalar and scalar hypotheses can be distinguished at 3 sigma with 550 fb^{-1} assuming 50% tau tagging efficiency.

Conclusion

- We constructed a new variable, Θ, that can be used to distinguish various CP mixing of $h \rightarrow \tau^+ \tau^-$.
- The accuracy of 250 GeV, 1 ab^{-1}ILC is 4.4^0.
- The accuracy of 14 TeV LHC, 3 ab^{-1}LHC is 11.5^0 assuming 50% tau tagging efficiency and 5.0^0 assuming 70% efficiency.
- Study on other production and decay channels might increase the sensitivity.