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

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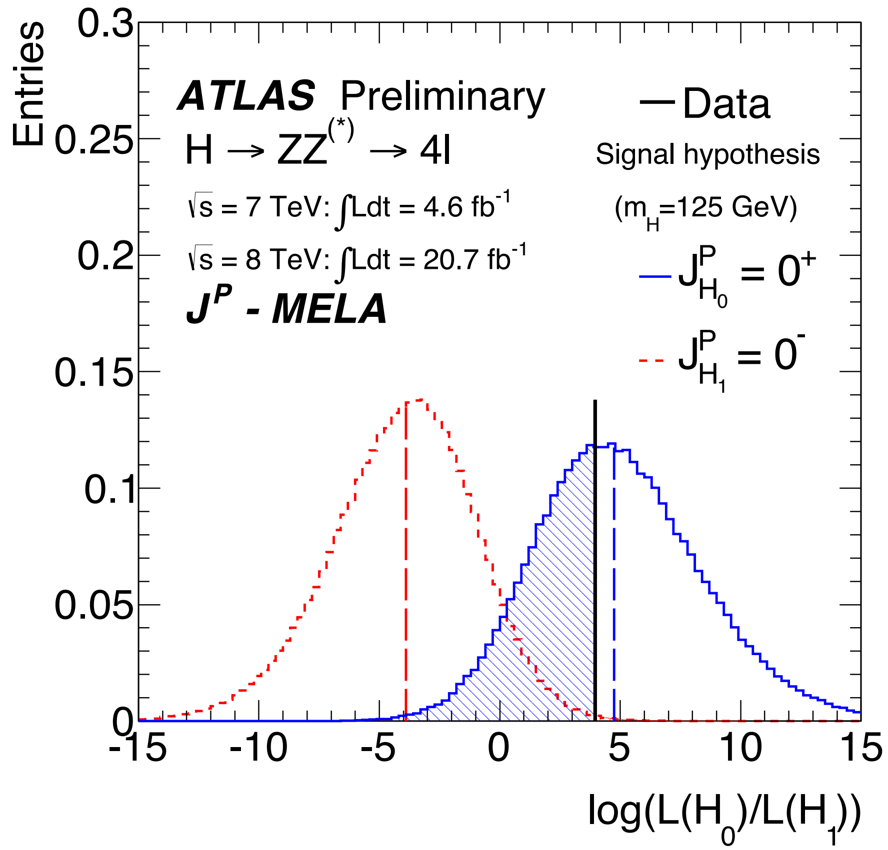
Motivation

- Shakarov conditions for baryogenesis suggest some additional sources of CP violation.
- One of the unexplored territory for CP violation to happen is at the sector of the newly found Higgs.

CP Property of h → ZZ



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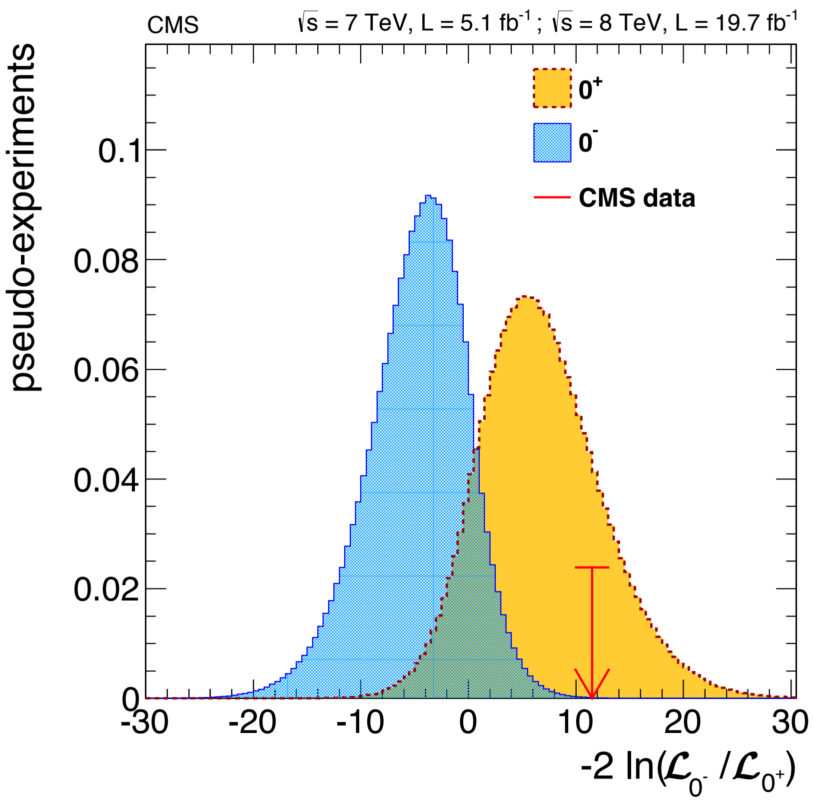


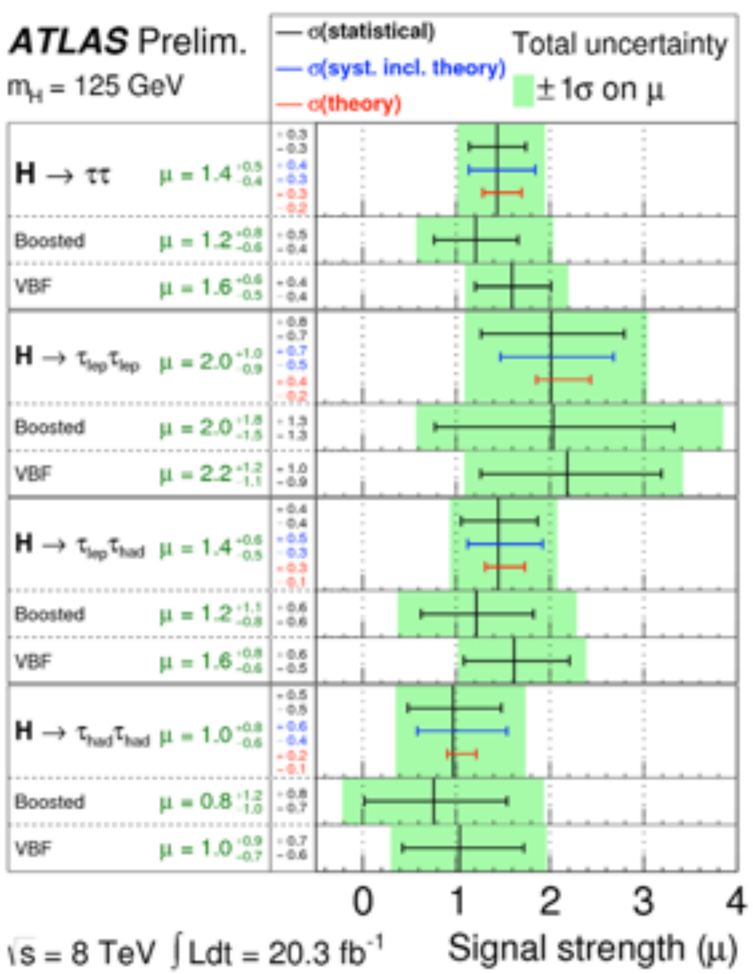
CMS collaboration, 1312.5353

- CMS constraints $|a_3/a_1| < 2.6$ at 95% CL.

$$A(\mathrm{H} \to \mathrm{ZZ}) = v^{-1}\left(a_1 m_Z^2 \epsilon_1^* \epsilon_2^* + a_2 f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3 f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}\right)$$

Higgs decay to fermions

- Both ATLAS and CMS start to see some evidence of Higgs decay to a pair of taus.



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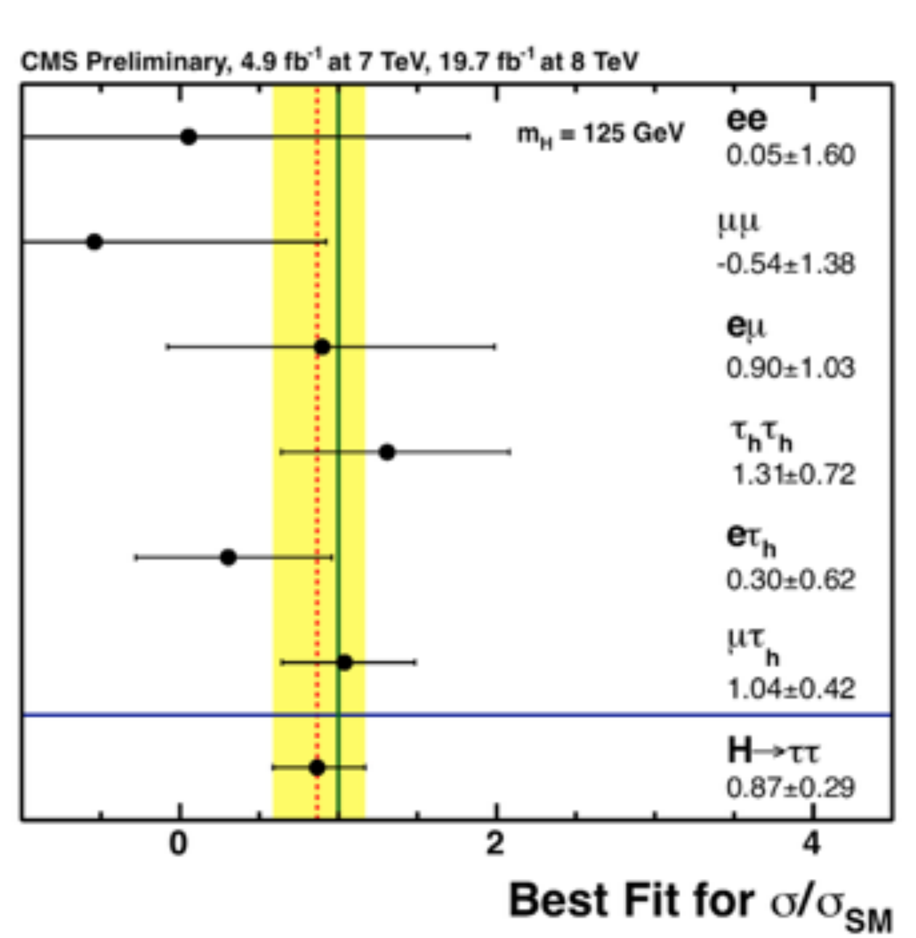


CMS-HIG-13-004

CP Property of $h \to \tau^+ \tau^-$

- Measuring the CP phase of $h \to \tau^+ \tau^-$ requires knowledge of the tau spins.
- Unlike in the quark cases, the tau polarization is not going to be washed out by hadronization.
- The tau decay is complex enough so its spin can be inferred from the decay kinematics.

EFT Perspective

$$\mathcal{L}_{\rm eff} \supset -\Big(\alpha + \beta\frac{H^\dagger H}{\Lambda^2}\Big) H \ell^\dagger_{3\rm L}\tau_{\rm R} + {\rm c.c.}\,,$$

- In general the coefficients can be complex.
- After inserting the Higgs vev, one can identify

$$\alpha + \beta\frac{v^2}{\Lambda^2} = y_\tau^{\rm SM} > 0\,.$$

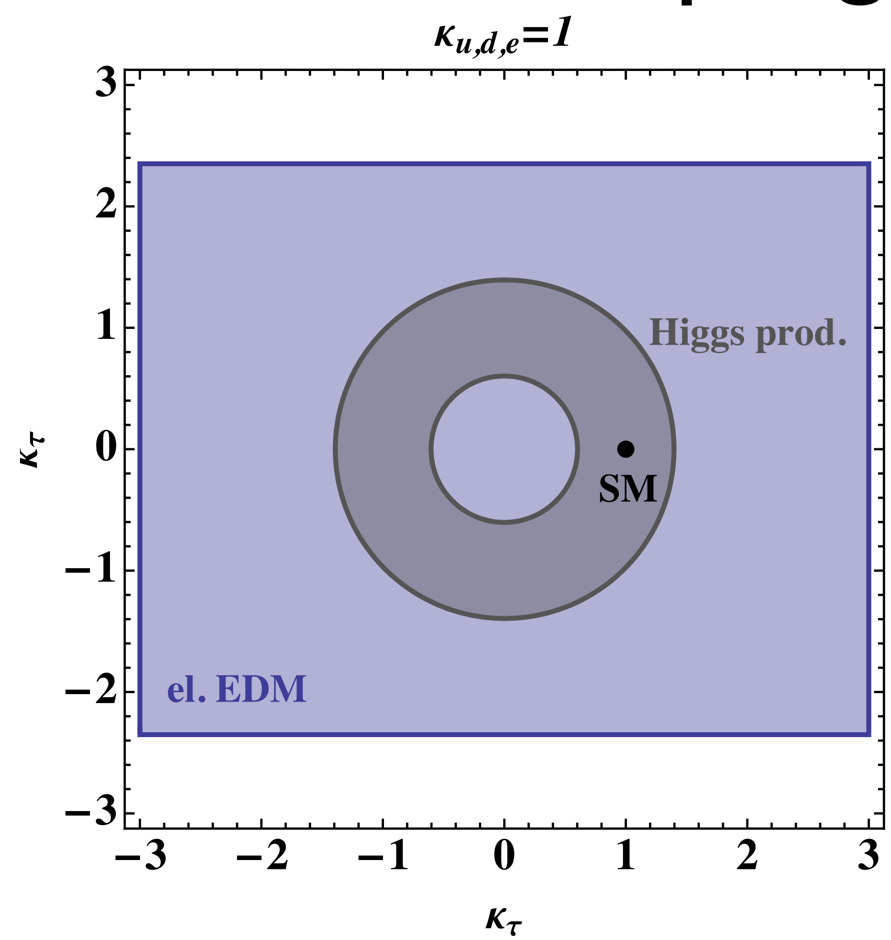
- And the Higgs coupling to tau

$$\begin{aligned} y_\tau(\cos\Delta + {\rm i}\sin\Delta) &= \alpha + 3\beta\frac{v^2}{\Lambda^2} \\ &= y_\tau^{\rm SM} + 2\beta\frac{v^2}{\Lambda^2}\,. \end{aligned}$$

CP Violation in h → $\tau^+ \tau^-$

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

- There are some indirect bounds on the phase and overall coupling.



$$\kappa_f = \frac{y_f}{y_f^{SM}} \cos\Delta$$

$$\tilde\kappa_f = \frac{y_f}{y_f^{SM}} \sin\Delta$$

Brod, Haisch, Zupan: 1310.1385

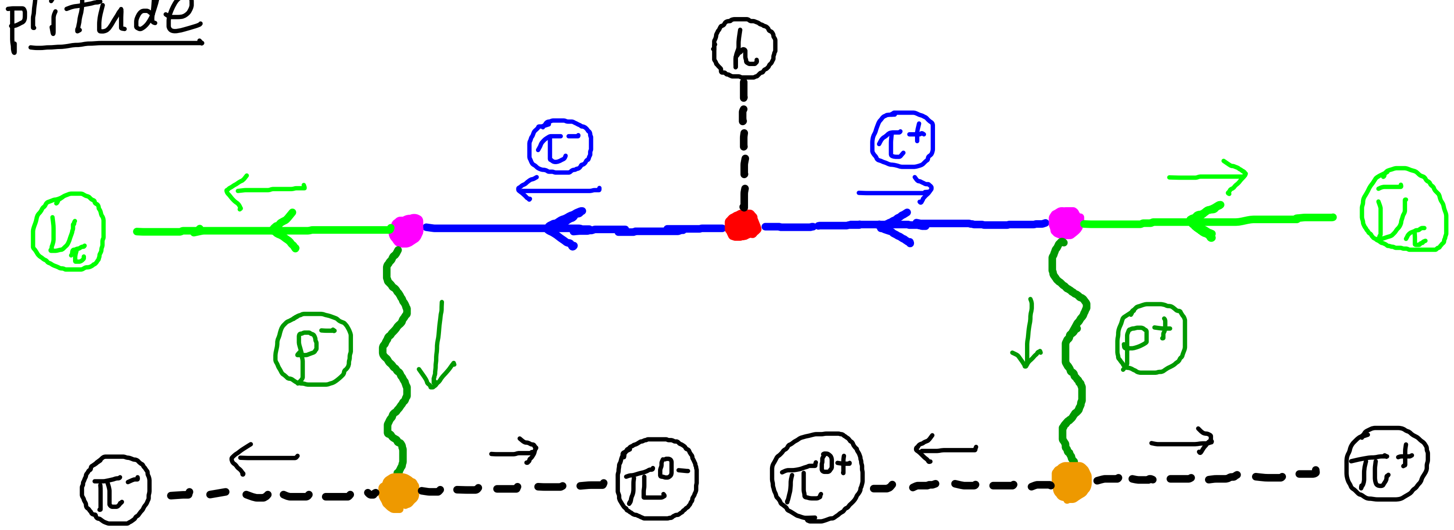
CP Violation in h → τ⁺ τ⁻

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

- The tau spin correlation is sensitive to the CP phase, Δ.
- The tau spin information is encoded in the momentum distribution of its decay products.
- We consider the decay of $\tau \to \rho\nu$ with subsequent decay of $\rho^\pm \to \pi^\pm\pi^0$ (26% of BF)

The Amplitude

Amplitude



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

$$\times\, \eta_{\mu\alpha} \qquad \times\, \eta_{\nu\beta}$$

$$\times\, (\pi^- - \pi^{0-})^\alpha \qquad \times\, (\pi^+ - \pi^{0+})^\beta$$

- Neglect diagram with the neutral pion exchanged.
- Assume all intermediate particles are onshell.
- Neglect the charged and neutral pion mass difference

The Amplitude

Define

$$q_{\pm} \equiv p_{\pi^{\pm}} - p_{\pi^{0\pm}}$$

we can simplify the amplitude to be

$$\mathcal{M}_{\text{full}} \propto \;\; \bar{u}_{\nu^-} \not{q}_- \left(\mathrm{e}^{\mathrm{i}\Delta} \not{p}_{\tau^-} - \mathrm{e}^{-\mathrm{i}\Delta} \not{p}_{\tau^+}\right) \not{q}_+ P_{\mathrm{L}} v_{\nu^+}$$

The Amplitude

Squaring 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 most interesting term is

$$P_{\Delta,\,\mathrm{S}} \equiv -\mathrm{e}^{2\mathrm{i}\Delta}\big[(k_-\cdot p_{\tau^+})(k_+\cdot p_{\tau^-}) - (p_{\tau^-}\cdot p_{\tau^+})(k_-\cdot k_+) \\ - \mathrm{i}\epsilon_{\mu\nu\rho\sigma}\, k_-^{\mu}\, p_{\tau^-}^{\nu} k_+^{\rho}\, p_{\tau^+}^{\sigma}\big].$$

where

$$k_\pm^\mu \equiv y_\pm\, q_\pm^\mu + r\, p_{\nu^\pm}^\mu$$

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

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

The Amplitude

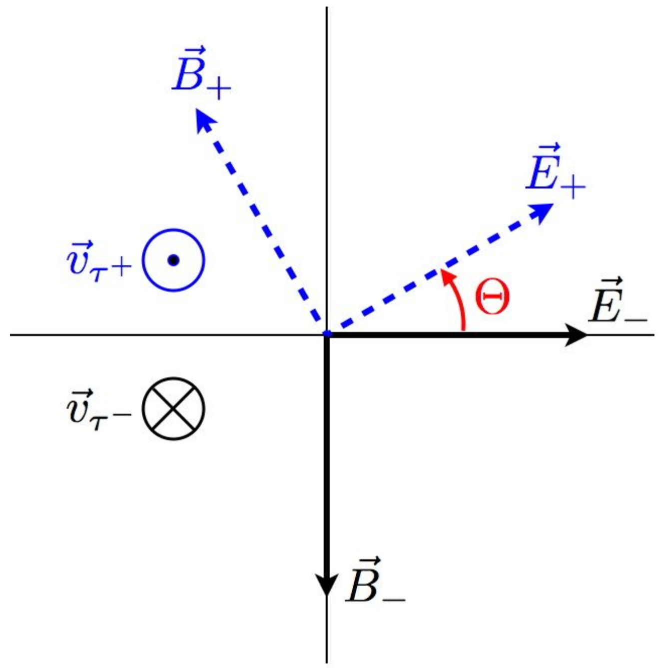
At the Higgs rest frame

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

where

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

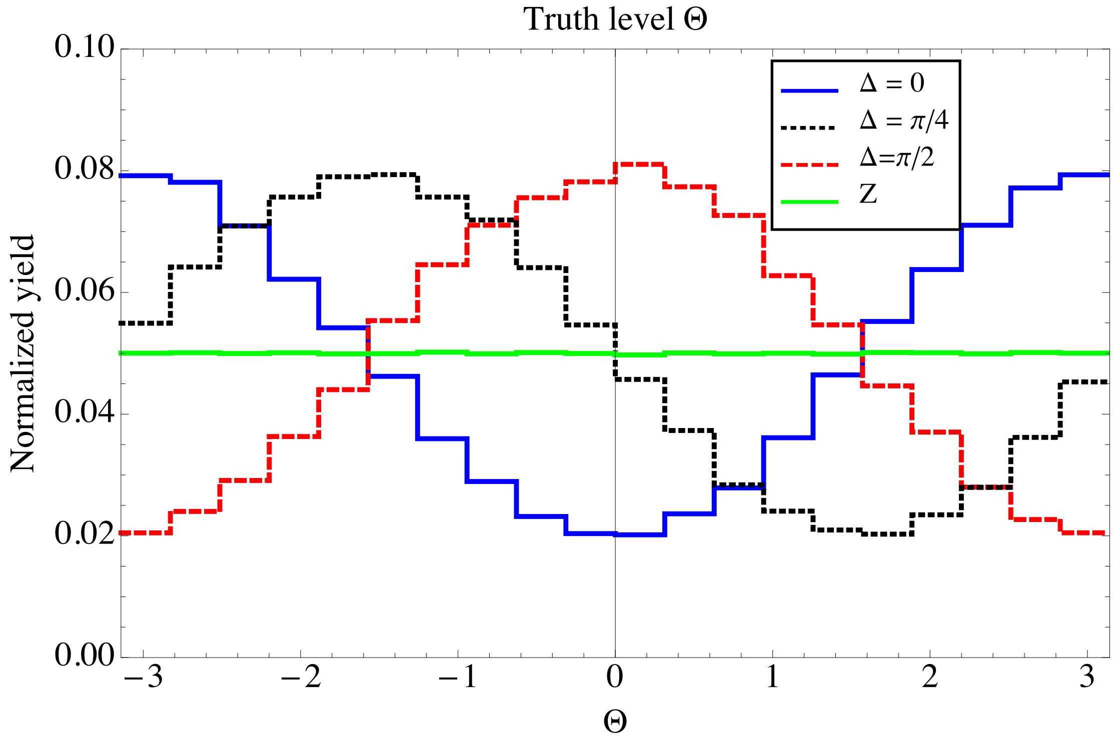
$$\Theta = \mathrm{sgn}\left[\vec{v}_{\tau^+}\cdot(\vec{E}_-\times\vec{E}_+)\right]\,\mathrm{Arccos}\left[\frac{\vec{E}_+\cdot\vec{E}_-}{\left|\vec{E}_+\right|\left|\vec{E}_-\right|}\right]$$



E_+E_- plane is perpendicular to the tau velocity

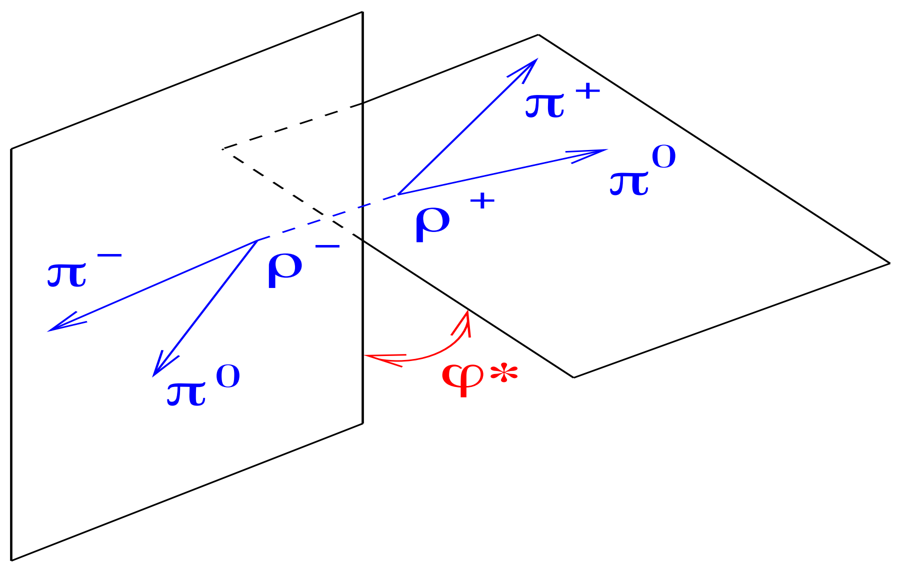
Θ Variable

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

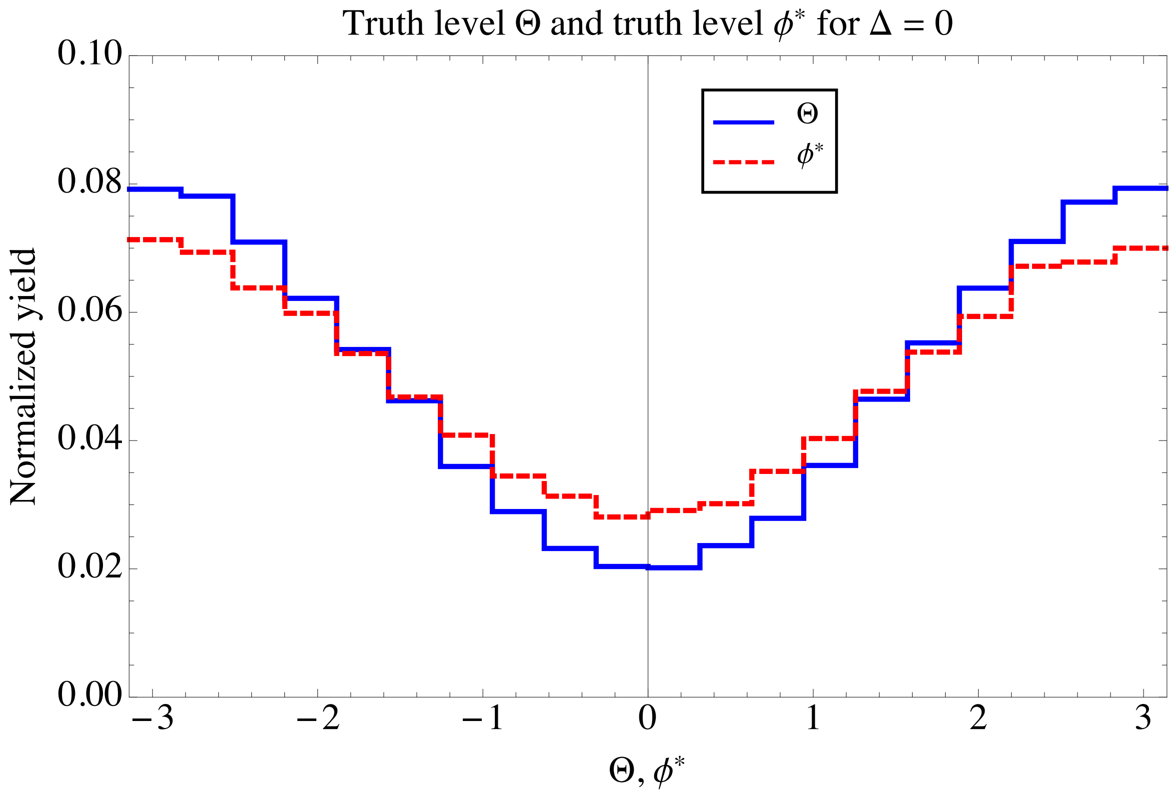


- The CP phase Δ can be determined by observing the minimum of the Θ distribution.
- The Θ distribution for $Z \to \tau^+ \tau^-$ is flat.

Comparison with previous works



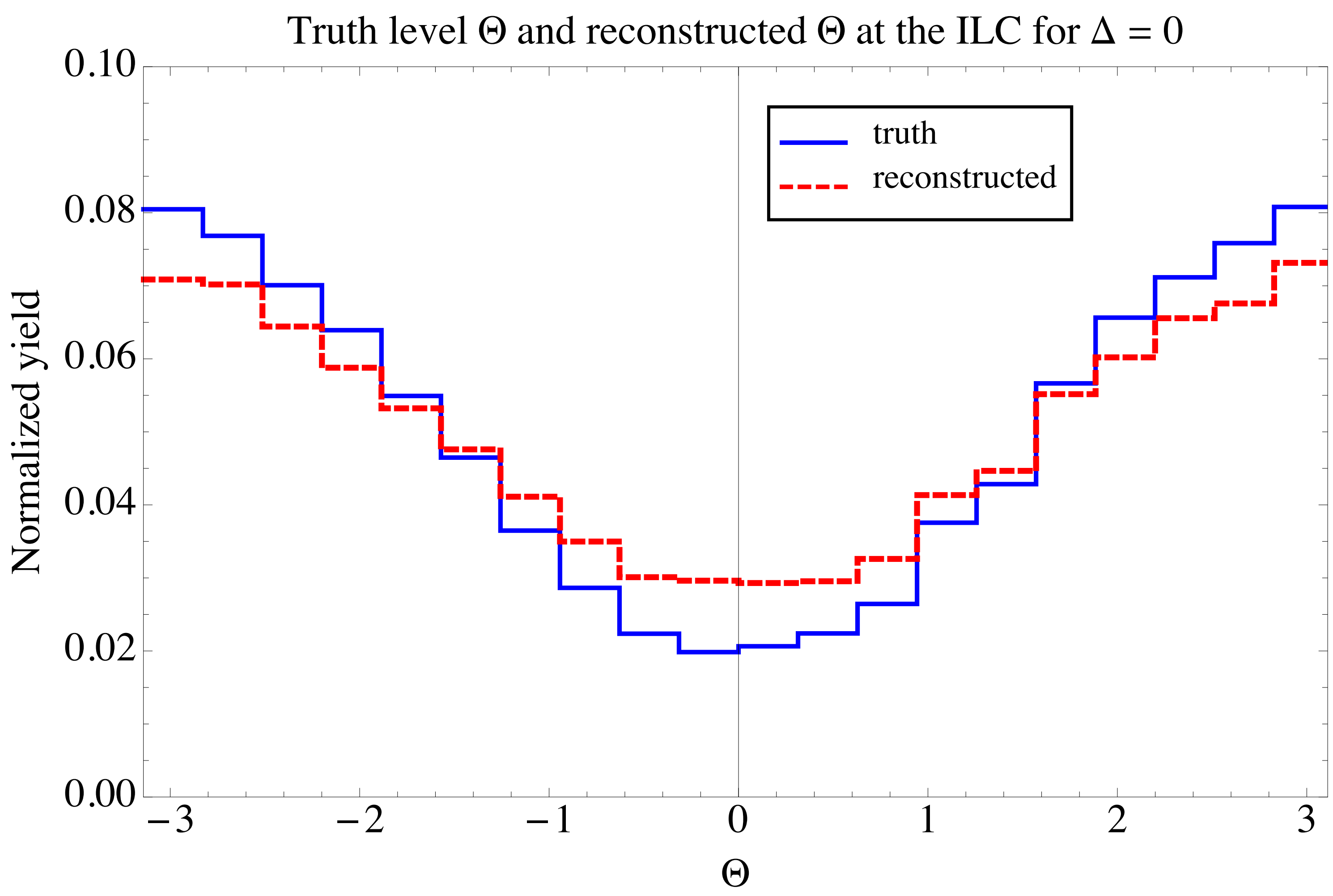
Worek, hep-ph/0305082



- 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

- Our Θ variable requires construction of the Higgs rest frame, hence knowledge of neutrino momenta is required.
- The neutrino momenta can be reconstructed at the ILC with a twofold ambiguity



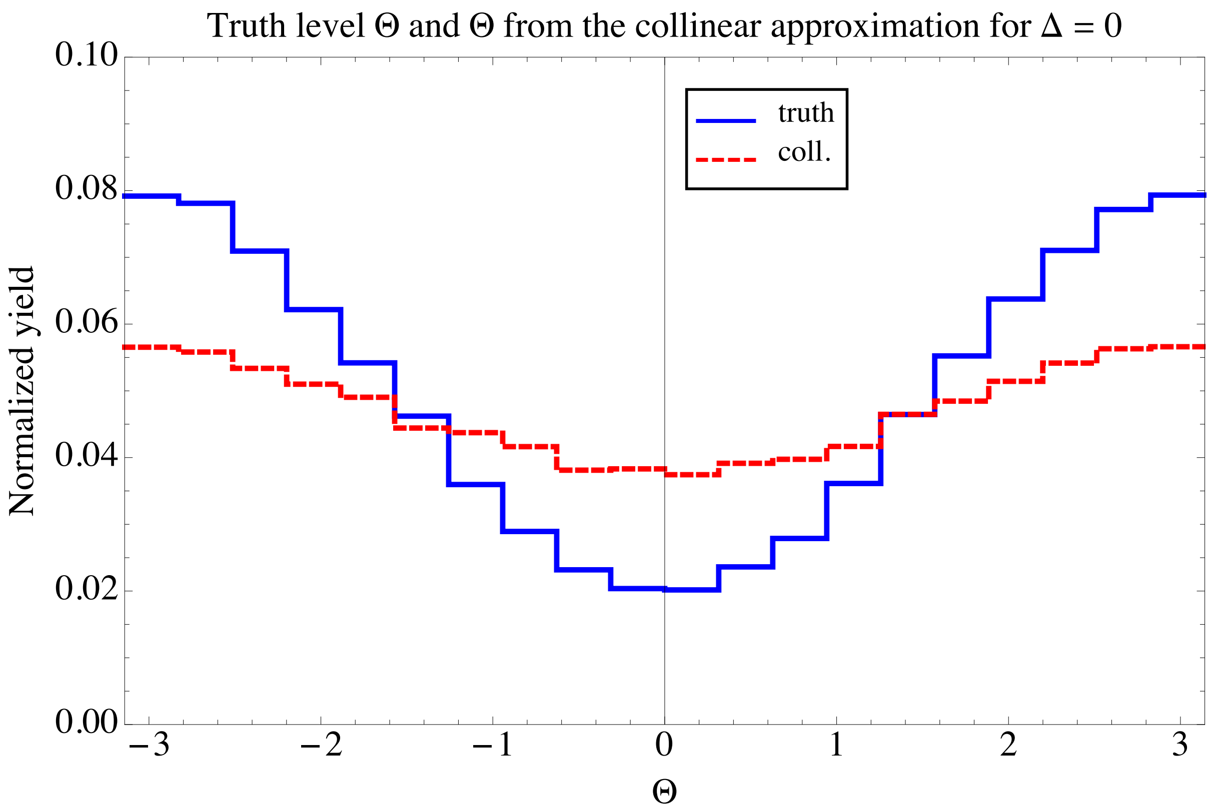
ILC

- We consider ILC 250 GeV with luminosity 1 ab^{-1}.
- We assume the SM production cross section of hZ and SM branching ratio of $h \to \tau^+ \tau^-$.
- Detector effect was not included in this estimate.
- 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%
$\mathrm{N}_{\text{events}}$	990
Accuracy	4.4°

LHC

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



LHC

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

$$\text{leading jet } p_T > 140 \text{ GeV with } |\eta| < 2.5$$
$$\not{E}_T > 40 \text{ GeV},$$
$$p_T^{\rho^\pm} > 45 \text{ GeV},$$
$$|\eta^{\rho^\pm}| < 2.1,$$
$$m_{\text{coll}} > 120 \text{ GeV},$$

- We assume that the QCD background is 10% of Z+jets.
- Again, pileups and detector effects are not considered.
- We assume 50% and 70% tau tagging efficiencies.

LHC

	$h\,j$	$Z\,j$
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%
$\mathrm{N_{events}}$	1100	1800

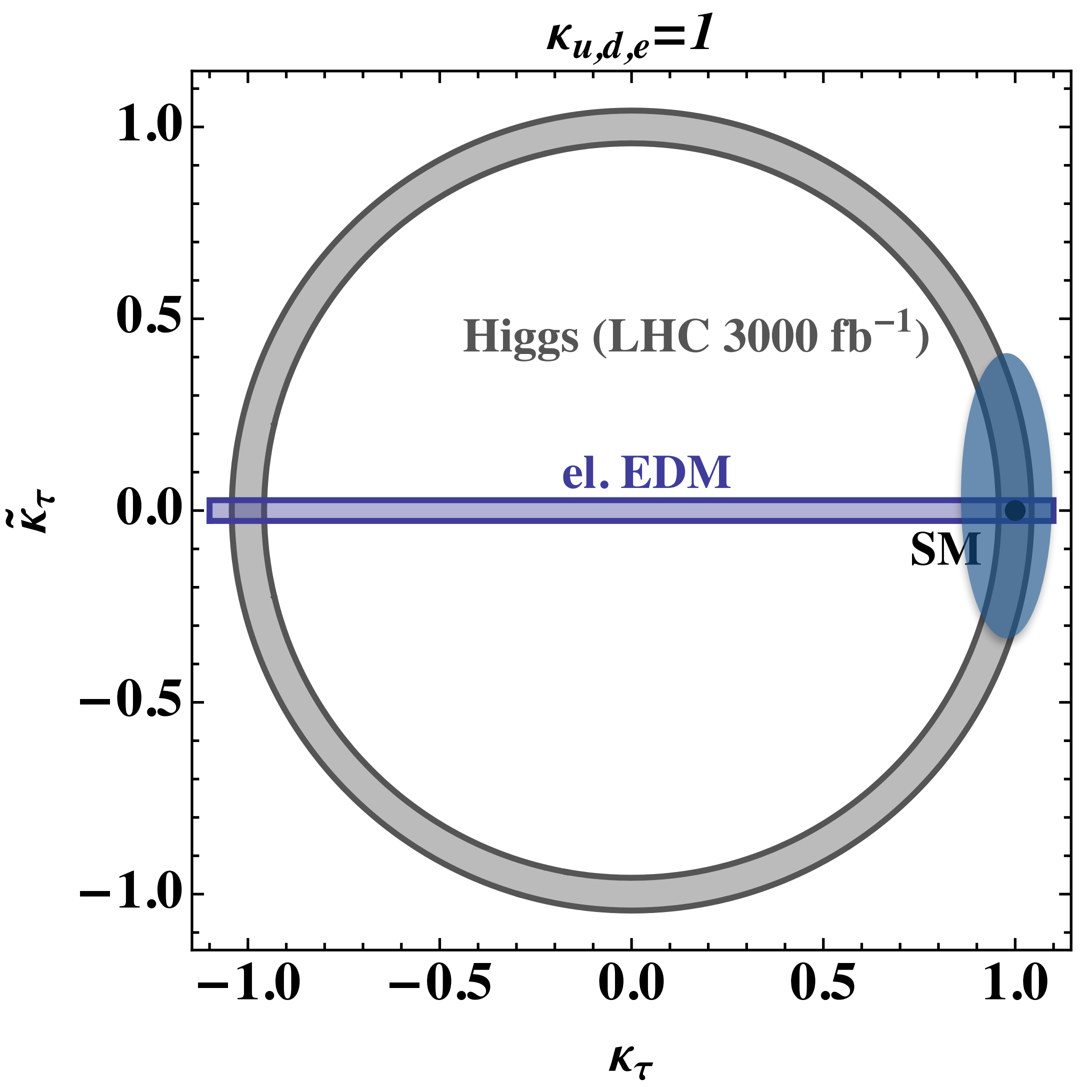
τ_h efficiency	50%	70%
3σ	$L = 550\ \mathrm{fb}^{-1}$	$L = 300\ \mathrm{fb}^{-1}$
5σ	$L = 1500\ \mathrm{fb}^{-1}$	$L = 700\ \mathrm{fb}^{-1}$
Accuracy($L = 3\,\mathrm{ab}^{-1}$)	11.5°	8.0°

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

Possible Improvements

- Better reconstruction of tau and Higgs frames.
- Consider other production and decay modes.

Indirect vs direct searches



Reach for direct searches

Brod, Haisch, Zupan: 1310.1385

May indirectly probe the Higgs coupling to the first generation fermions, if the signal is discovered.

Summary

- We constructed a new variable, Θ, that can be used to distinguish various CP mixing of $h \to \tau^+ \tau^-$ at colliders.

$\sigma_{e^+e^- \to hZ}$	0.30 pb
$\mathrm{Br}(h \to \tau^+\tau^-)$	6.1%
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ILC

τ_h efficiency	50%	70%
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LHC

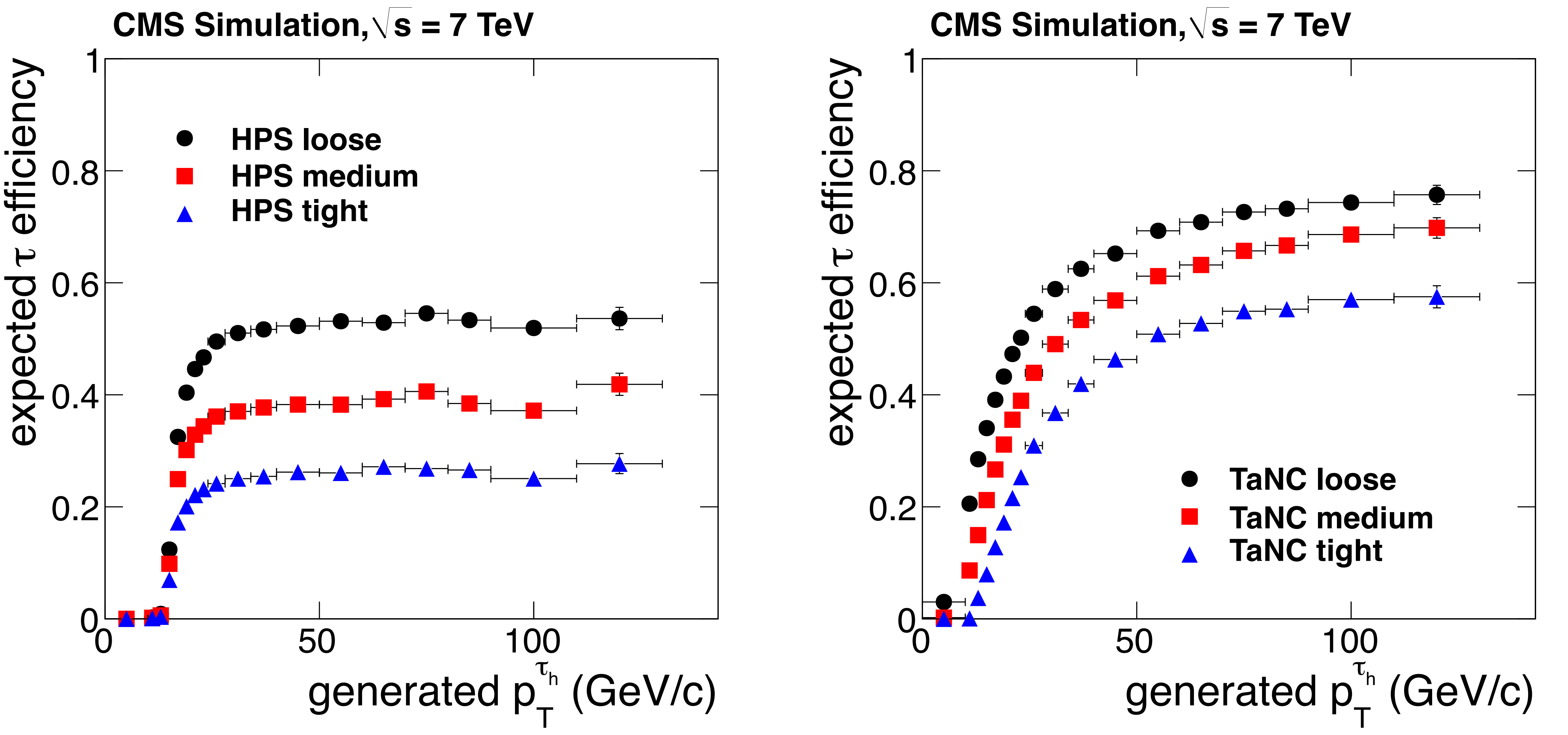
Backup

An UV Completion

$$\begin{aligned}\mathcal{L}_{\rm tree} = \mathcal{L}_{{\rm SM}-y_\tau} \\ + |{\rm D}\Phi|^2 - m_\Phi^2|\Phi|^2 - \lambda_\Phi|\Phi|^4 \\ - \left(yH\ell^\dagger_{3\rm L}\tau_{\rm R} + y'\Phi\ell^\dagger_{3\rm L}\tau_{\rm R} + \lambda'(\Phi^\dagger H)|H|^2 + {\rm c.c.}\right),\end{aligned} \tag{A1}$$

$$\mathcal{L}_{\text{dim-6}} = \frac{|\lambda'|^2}{m_\Phi^2}|H|^6 + \Big(\frac{\lambda' y'}{m_\Phi^2}|H|^2 H\ell^\dagger_{3\rm L}\tau_{\rm R} + {\rm c.c.}\Big).$$

CMS tau measurement



CMS, JINST 7 P01001