CPV Higgs Di-tau Decays: Baryogenesis and Higgs Factories

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arXiv:2012.13922 (PRD) in collaboration with

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Electroweak baryogenesis

BAU: more matter than anti-matter

$$Y_B \equiv \frac{n_b}{s} = (8.50 \pm 0.11) \times 10^{-11}$$

Three necessary conditions must satisfy to achieve successful baryogenesis:

- B violation
- C & CP violation
- Out-of-equilibrium

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	SM	
• B violation	✓	sphaleron
• C & CP violation	✘	CPV in CKM matrix is not enough
• Out-of-equilibrium	✘	crossover EWPT

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Three necessary conditions must satisfy to achieve successful baryogenesis:

	SM	BSM	
• B violation	✓	✓	sphaleron
• C & CP violation	✘	✓	new sources of CPV
• Out-of-equilibrium	✘	✓	strongly first-order EWPT

EW baryogenesis

Kuzmin, Rubakov, Shaposhnikov, Phys.Lett.B 155 (1985) 36
Morrissey, Ramsey-Musolf, New J.Phys. 14 (2012) 125003

Why CPV $h\overline{\tau}\tau$ interaction?

EW baryogenesis has been extensively studied with special attention to the quark sector, but less explored in the lepton sector

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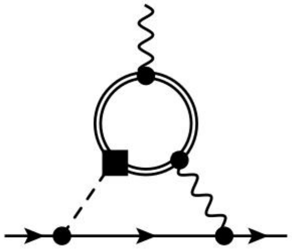
$$y_f \; \bar{f}(a + ib\gamma_5)f \; h$$

top quark

$y_t \approx 1, \; b < 0.0013$



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tau lepton

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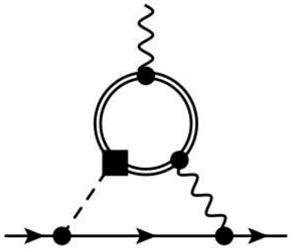

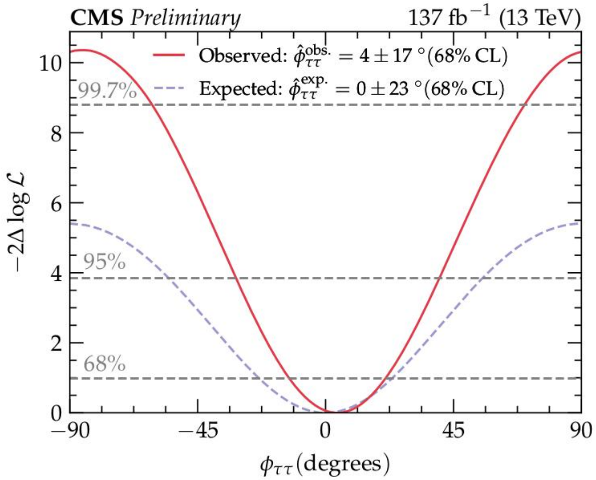

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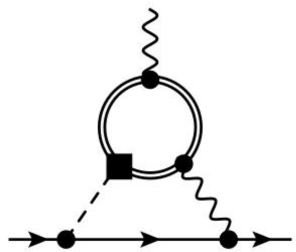

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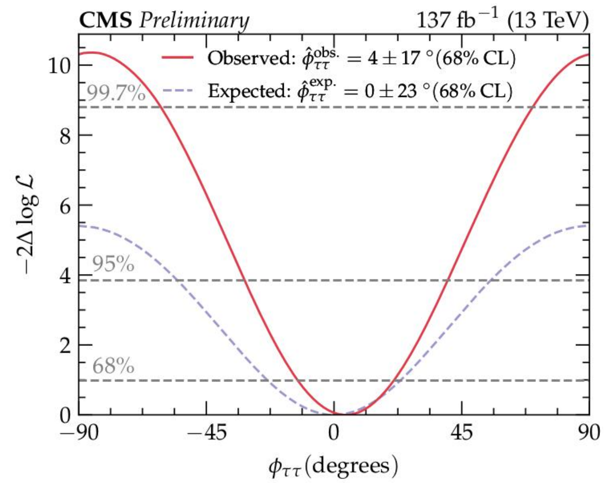


EW baryogenesis may be triggered by the CPV $h\bar{\tau}\tau$ interaction

Guo, Li, Liu, Ramsey-Musolf, Shu, 1609.09849 (PRD)
Chiang, Fuyuto, Senaha, 1607.07316 (PLB)

tau lepton-mediated EW baryogenesis

In the context of type-III 2HDM

$$\mathcal{L}_Y = -\overline{L} Y_1 \ell_R \Phi_1 - \overline{L} Y_2 \ell_R \Phi_2 + \text{h.c.}$$

Consider a texture:

$$Y_{1,33} = Y_{2,33} \qquad Y_{1,32} = r_{32} Y_{2,32}$$

The Jarlskog-like invariant

coupling modifier

CP phase

$$\text{Im}[J_A] = -\text{Im}[r_{32}]|Y_{2,32}|^2 = \frac{2m_\tau^2}{v^2 c_{\beta-\alpha}} \kappa_\tau \sin\Delta$$

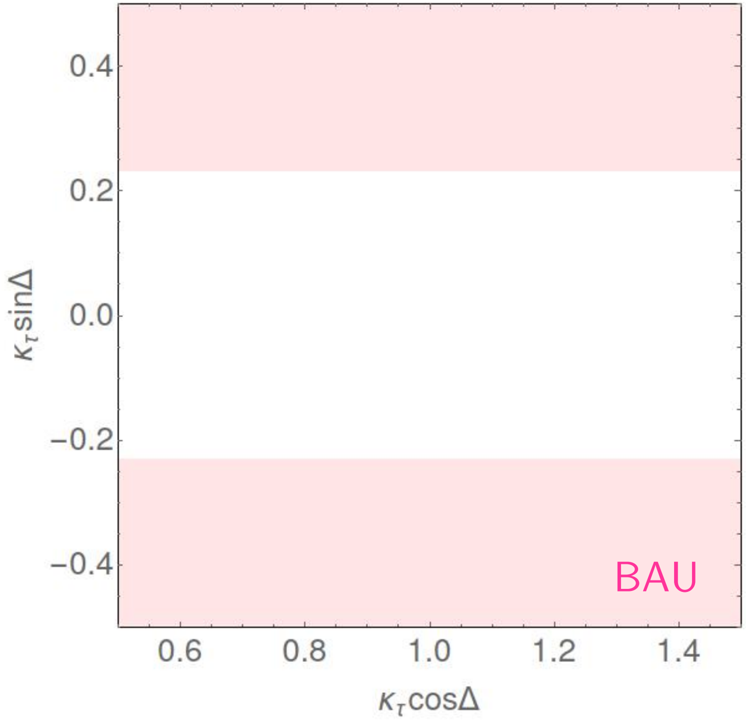
which is directly related to the CPV source term in EWPT

Guo, Li, Liu, Ramsey-Musolf, Shu, 1609.09849 (PRD)
Ge, GL, Pasquini, Ramsey-Musolf, 2012.13922 (PRD)

tau lepton-mediated EW baryogenesis

Viable region for BAU

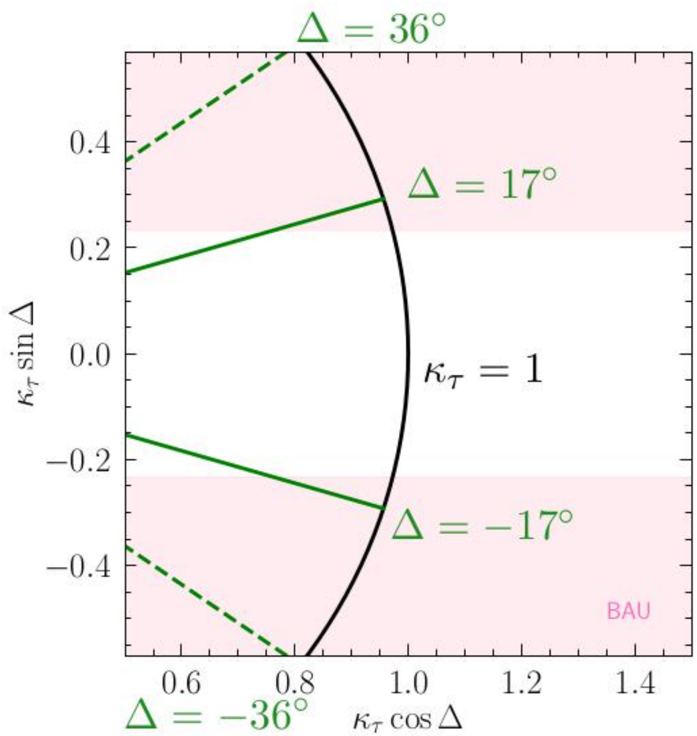
$$|\kappa_\tau \sin\Delta| > 0.23$$

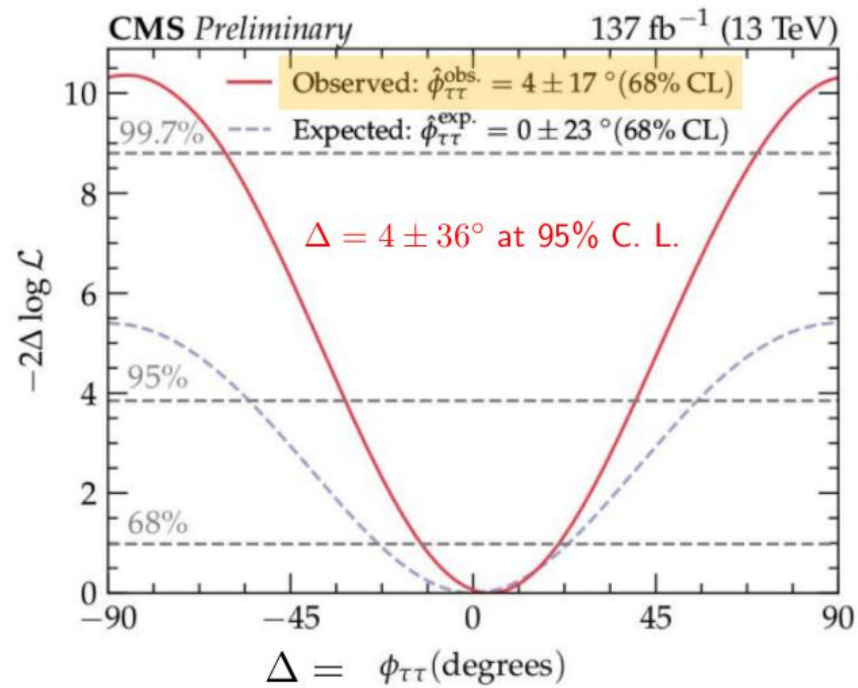


$$\mathcal{L}_{h\tau\tau} = -\kappa_\tau \frac{m_\tau}{v} \bar{\tau}(\cos\Delta + i\gamma_5 \sin\Delta)\tau h$$

tau lepton-mediated EW baryogenesis

Viable region for BAU → Collider probe of CPV $h\bar{\tau}\tau$





Test tau lepton-mediated EW baryogenesis at colliders!!

We need Higgs factories

- Better reconstruction of τ leptons results from
    - clearner environment at e^+e^- colliders
    - determined Higgs rest frame in $e^+e^- \to Zh,\ h \to \tau^+\tau^-$
- Improved sensitivity to CP phase also benefits from
    - significant abundance of signal events produced at Higgs factories

τ decay products	Number of Higgs decay events					
	CEPC		FCC-ee		ILC	
	before	after	before	after	before	after
(π, π)	684	99	622	90	398	58
(π, ρ)	3223	465	2930	423	1875	271
(ρ, ρ)	3797	541	3451	491	2209	314

Ge, GL, Pasquini, Ramsey-Musolf, 2012.13922 (PRD)

CP observables

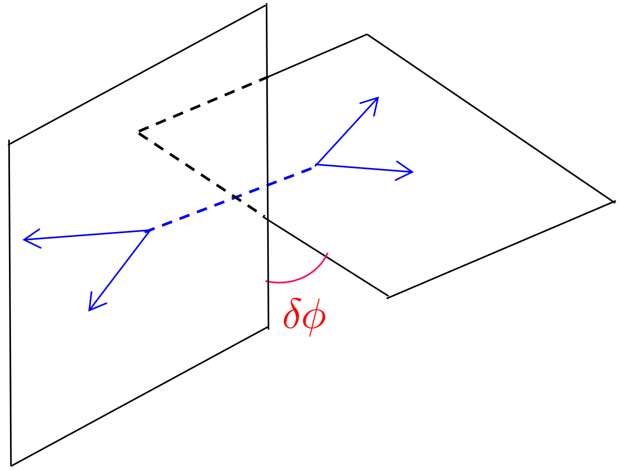
Consider the Higgs di-tau decays

$$h \to \tau^+\tau^- \to X^+\overline{\nu}_\tau X^-\nu_\tau \qquad X = \pi, \rho$$

Different observables $\delta\phi$ are proposed in consideration of

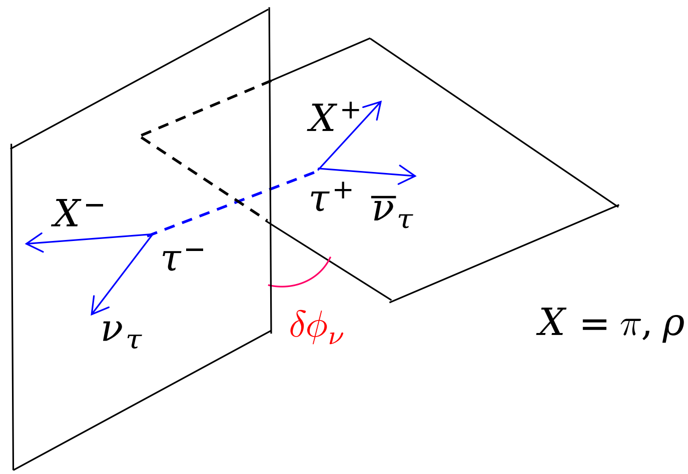
- apmplitude of the CP-odd term
- ambiguities of neutrino momenta (impact parameter)

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\delta\phi} = \frac{1}{2\pi}\left[1 + A\cos(2\Delta - \delta\phi)\right]$$



CP observables

In the simplest case, $\delta\phi = \delta\phi_\nu$ is the difference of neutrino azimuthal angles



$$\frac{1}{\Gamma}\frac{d\Gamma(h\to\pi^+\pi^-\nu_\tau\overline{\nu}_\tau)}{d\delta\phi_\nu} = \frac{1}{2\pi}\left[1 - \frac{\pi^2}{16}\cos(2\Delta - \delta\phi_\nu)\right]$$

$$\frac{1}{\Gamma}\frac{d\Gamma(h\to\rho^+\rho^-\nu_\tau\overline{\nu}_\tau)}{d\delta\phi_\nu} = \frac{1}{2\pi}\left[1 - \frac{\pi^2}{16}\left(\frac{m_\tau^2 - 2m_\rho^2}{m_\tau^2 + 2m_\rho^2}\right)^2\cos(2\Delta - \delta\phi_\nu)\right]$$

$$\approx 0.2$$

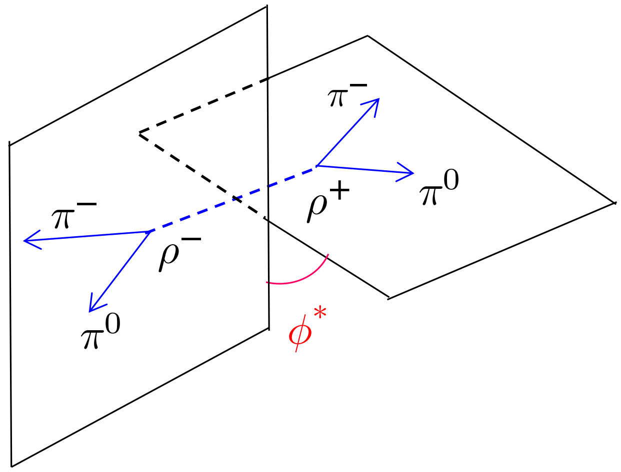
CP observables

Better observales in ρρ mode take advantage of the subsequent decay

$\rho^\pm \to \pi^\pm \pi^0$ the branching ratio is almost 100%

several observables have been proposed

- acoplanarity angle



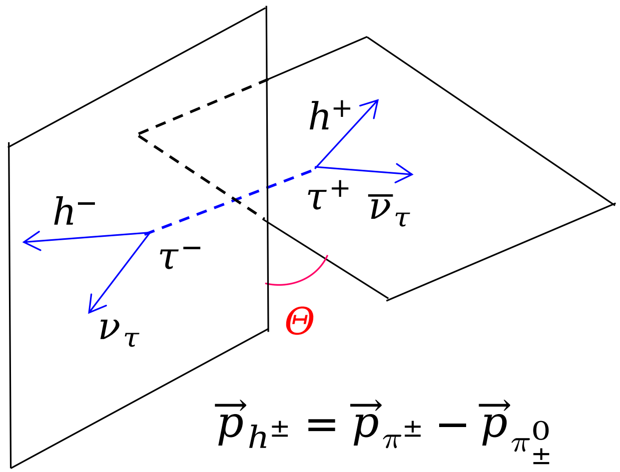
M. Worek, Acta Phys. Polon. B34 (2003) 4549

$$\tan\phi^* \equiv \frac{\hat{\mathbf{p}}_{\rho^-} \cdot [(\mathbf{p}_{\pi^+} \times \mathbf{p}_{\pi^0_+}) \times (\mathbf{p}_{\pi^-} \times \mathbf{p}_{\pi^0_-})]}{(\mathbf{p}_{\pi^+} \times \mathbf{p}_{\pi^0_+}) \cdot (\mathbf{p}_{\pi^-} \times \mathbf{p}_{\pi^0_-})}$$

CP observables

- the Θ variable

Harnik, Martin, Okui, Primulando, Yu, 1308.1094 (PRD)



$$\vec{p}_{h^\pm} = \vec{p}_{\pi^\pm} - \vec{p}_{\pi^0_\pm}$$

$$\tan\Theta \equiv \frac{\hat{\mathbf{p}}_{\tau^+} \cdot (\mathbf{E}_+ \times \mathbf{E}_-)}{\mathbf{E}_- \cdot \mathbf{E}_+ - (\mathbf{E}_+ \cdot \hat{\mathbf{p}}_{\tau^+})(\mathbf{E}_- \cdot \hat{\mathbf{p}}_{\tau^+})}$$

in $\tau^\pm$ rest frames

$$\mathbf{E}_\pm \equiv \frac{m_\rho^2 - 4m_\pi^2}{2m_\tau}\left[\frac{m_\tau^2 - m_\rho^2}{m_\tau^2 + m_\rho^2}\hat{\mathbf{p}}_{\nu_{\tau^\pm}} + \frac{2m_\tau}{m_\rho^2 - 4m_\pi^2}\frac{(E_{\pi^\pm} - E_{\pi^0})}{(E_{\pi^\pm} + E_{\pi^0})}\left(\mathbf{p}_{\pi^\pm} - \mathbf{p}_{\pi^0_\pm}\right)\right]$$

CP observables

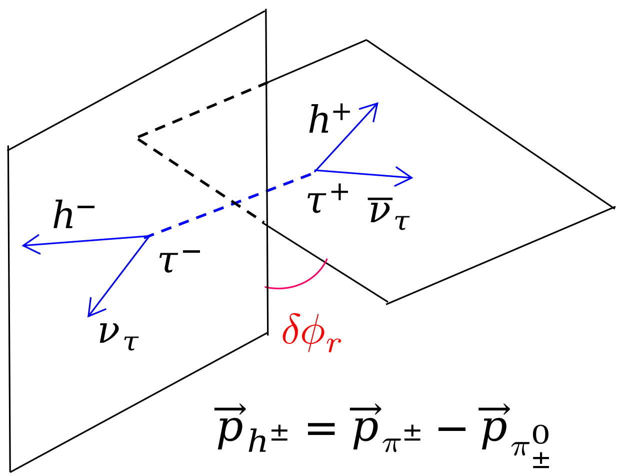
- polarimeter azimuthal angle difference in $\tau^{\pm}$ rest frames

Grzadkowski and Gunion, Phys. Lett. B 350, 218-224 (1995)

$$\tau^{\pm} \to \pi^{\pm}\nu_{\tau^{\pm}} \quad : \quad \mathbf{r}_{\pm} \equiv -\hat{\mathbf{p}}_{\nu_{\tau^{\pm}}},$$

$$\tau^{\pm} \to \rho^{\pm}(\to \pi^{\pm}\pi^{0})\nu_{\tau^{\pm}} \quad : \quad \mathbf{r}_{\pm} \equiv -\frac{1}{N_{\pm}}\left[\hat{\mathbf{p}}_{\nu_{\tau^{\pm}}} + \frac{2m_{\tau}}{m_{\rho}^{2} - 4m_{\pi}^{2}}\frac{E_{\pi^{\pm}} - E_{\pi^{0}_{\pm}}}{E_{\pi^{\pm}} + E_{\pi^{0}_{\pm}}}\left(\mathbf{p}_{\pi^{\pm}} - \mathbf{p}_{\pi^{0}_{\pm}}\right)\right]$$

$$\tan\delta\phi_{r} = \frac{\hat{\mathbf{p}}_{\tau^{-}}\cdot(\mathbf{r}_{+}\times\mathbf{r}_{-})}{\mathbf{r}_{-}\cdot\mathbf{r}_{+} - (\mathbf{r}_{+}\cdot\hat{\mathbf{p}}_{\tau^{-}})(\mathbf{r}_{-}\cdot\hat{\mathbf{p}}_{\tau^{-}})} \qquad \delta\phi_{r} \equiv \phi_{\mathbf{r}_{+}} - \phi_{\mathbf{r}_{-}}$$



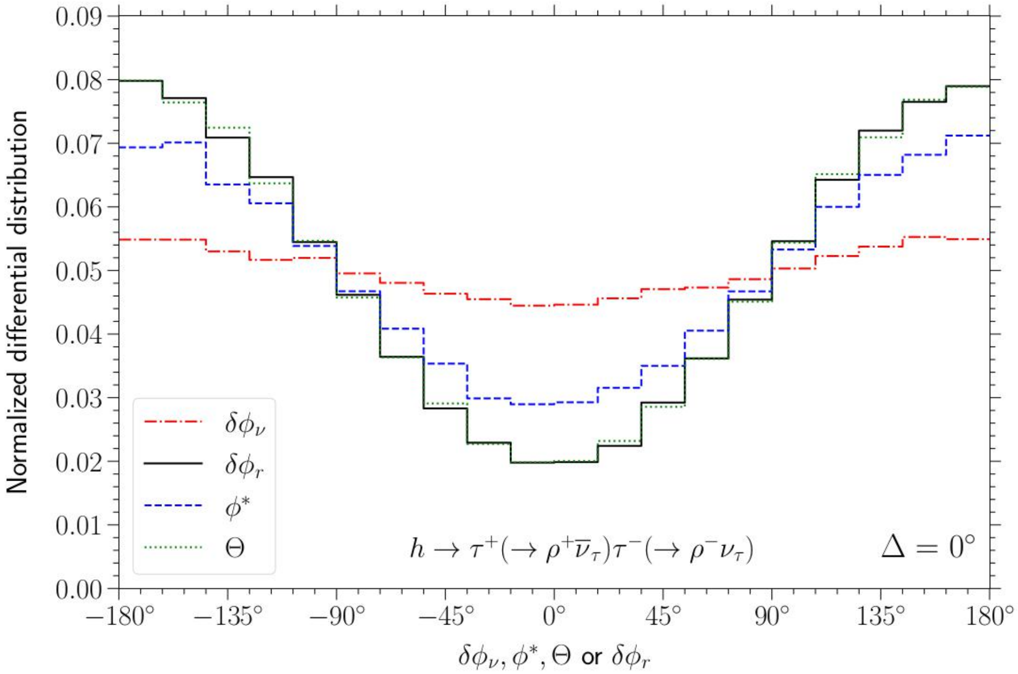
$$\vec{p}_{h^{\pm}} = \vec{p}_{\pi^{\pm}} - \vec{p}_{\pi^{0}_{\pm}}$$

CP observables

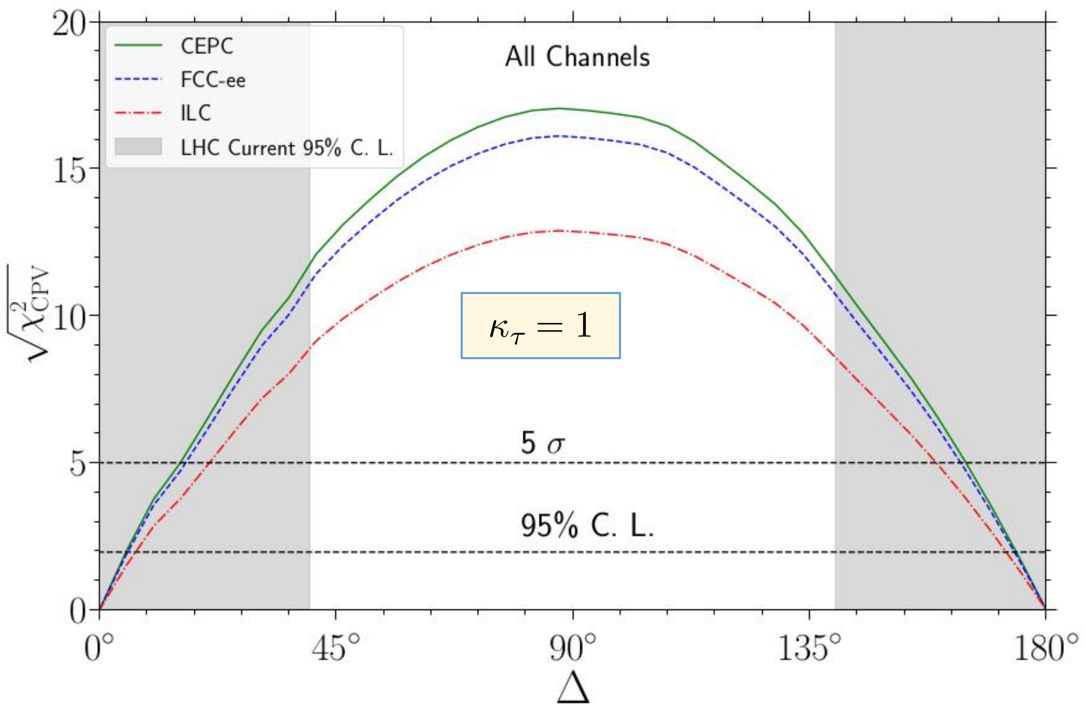
Polarimeter azimuthal angle difference $\delta\phi_r$ is chosen!

- best sensitivity in $\rho\rho$ mode
- also applies in $\pi\pi$ and even $\pi\rho$ modes

$\rho^{\pm} \to \pi^{\pm}\pi^{0}$



Discovery potential of a non-zero CP phase



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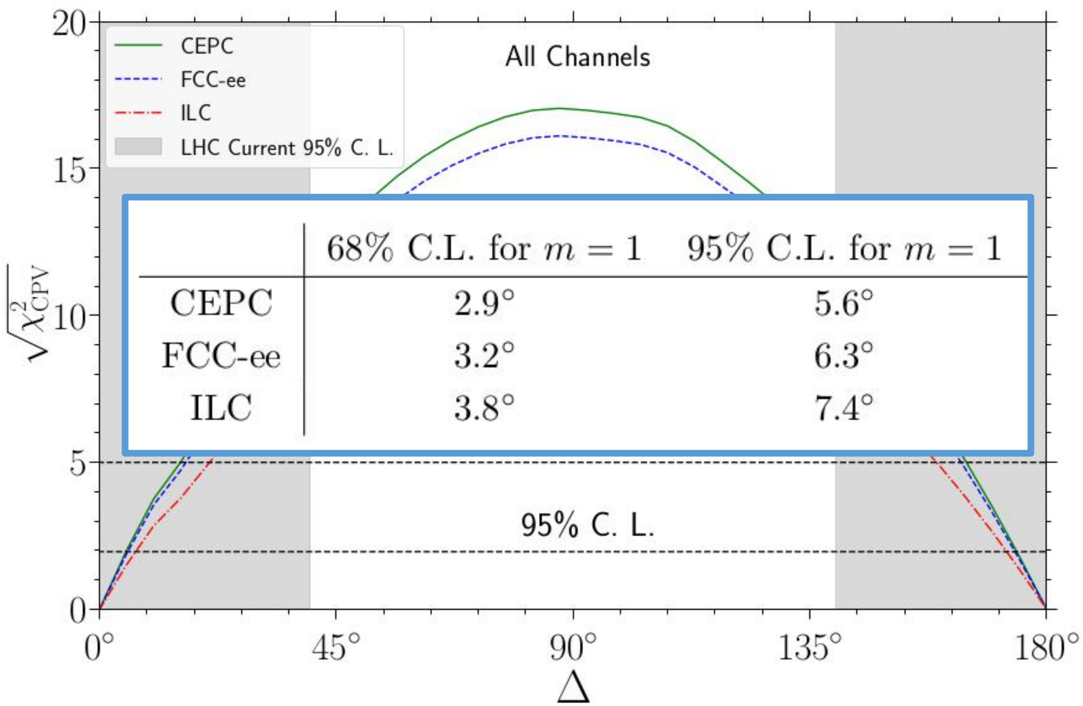
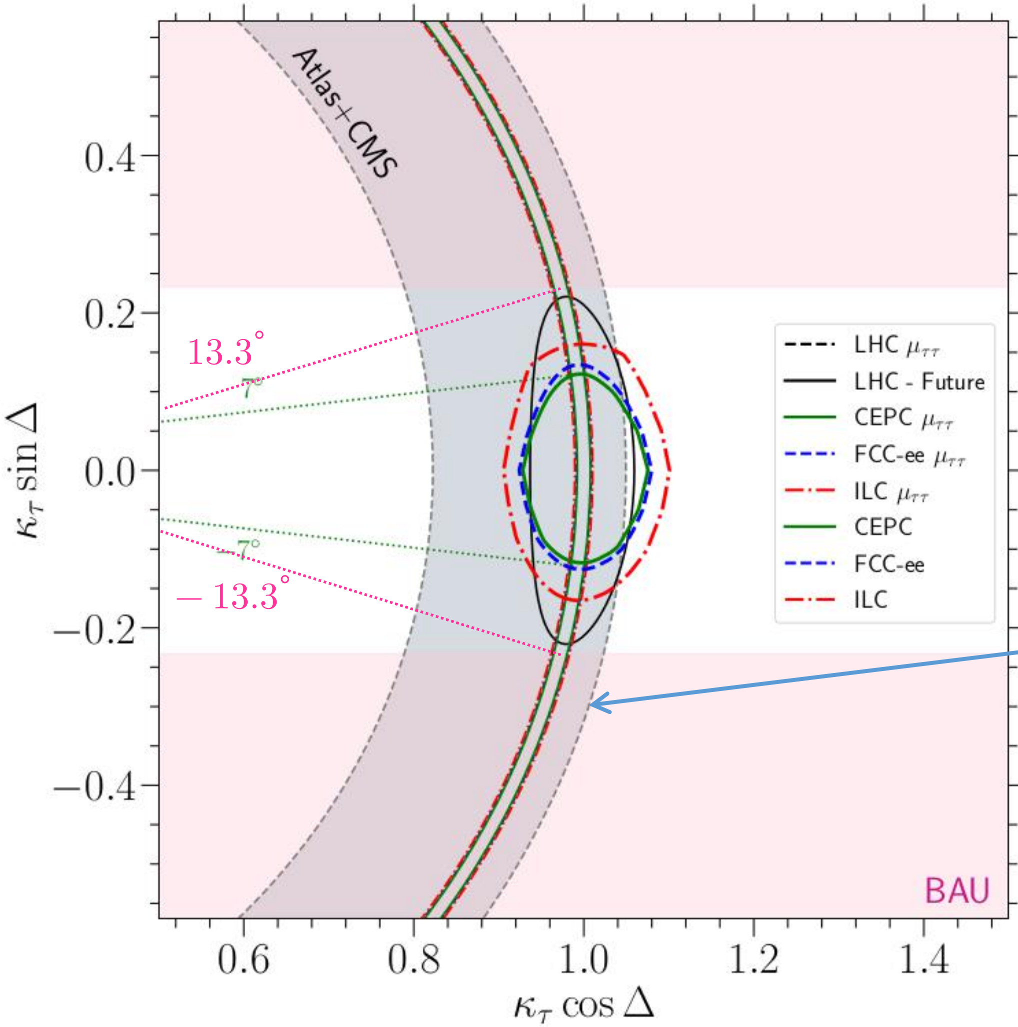


	68% C.L. for $m = 1$	95% C.L. for $m = 1$
CEPC	2.9°	5.6°
FCC-ee	3.2°	6.3°
ILC	3.8°	7.4°

Interplay with EW baryogenesis



κ_τ is free

signal strength measurements

$$\mu_{\tau\tau} = \kappa_\tau^2$$

current:

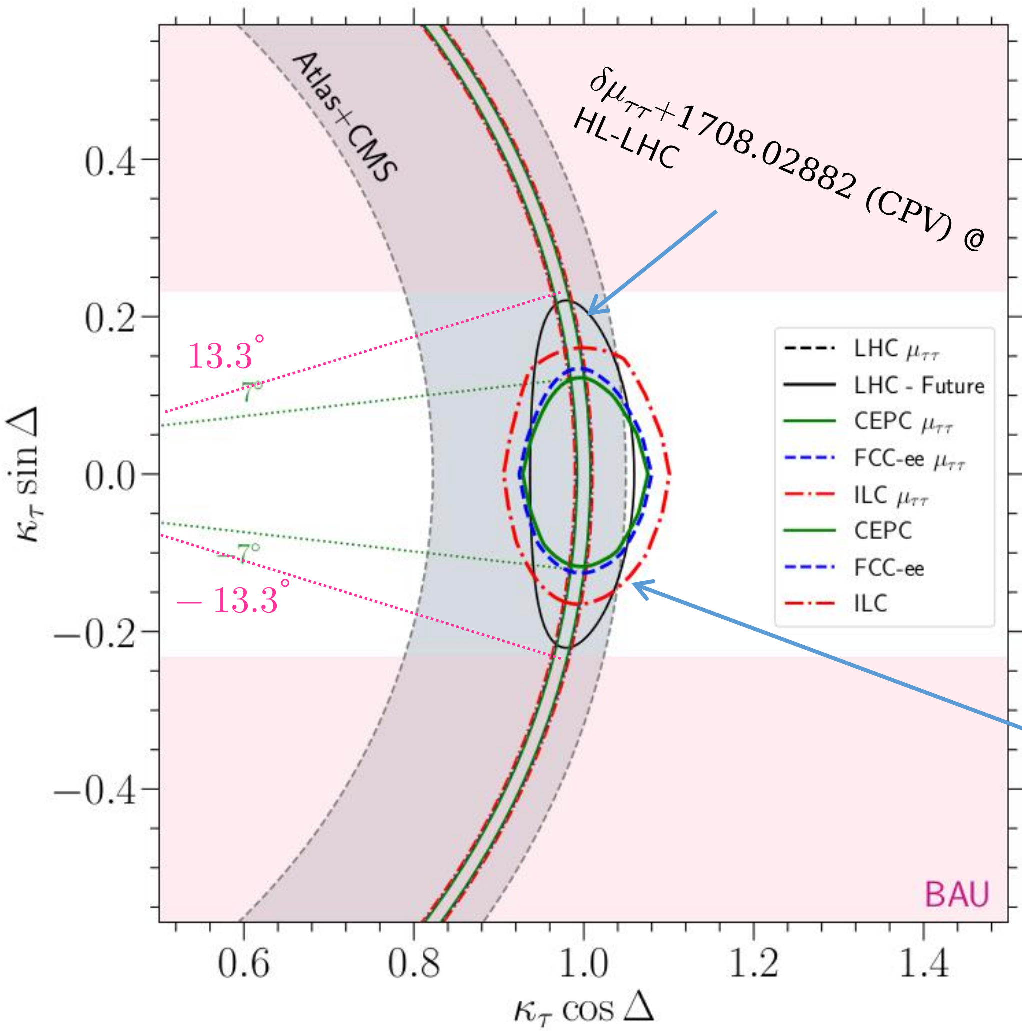
$$\mu_{\tau\tau} = 1.09^{+0.35}_{-0.30} \quad \text{ATLAS}$$

$$\mu_{\tau\tau} = 0.85^{+0.12}_{-0.11} \quad \text{CMS}$$

future:

$$\delta\mu_{\tau\tau} = \begin{cases} 5\% & \text{HL-LHC} \\ 0.8\% & \text{CEPC} \\ 0.9\% & \text{FCC-ee} \\ 1.09\% & \text{ILC} \end{cases}$$

Interplay with EW baryogenesis



pink regions give observed BAU

with $\kappa_\tau = 1$, $|\Delta| \geq 13.3^\circ$ is required

95% C.L. constraints at Higgs factories from CP measurement

$|\Delta| \geq 7^\circ$ can be determined

κ_τ is free

Summary

- Tau lepton-mediated EW baryogenesis is well-motivated to explain BAU
- Millions of Higgs bosons can be produced at Higgs factories, which enables the precise determination of CPV $h\bar{\tau}\tau$ interaction in Higgs ditau decays
- Higgs factories may have a conclusive test of tau lepton-mediated EW baryogenesis