CP violation in $H \to \tau^+ \tau^- \gamma$

(With a phenomenological overview)

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(Based on an ongoing work in collaboration with

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Workshop on the Standard Model and Beyond

Corfu, Greece

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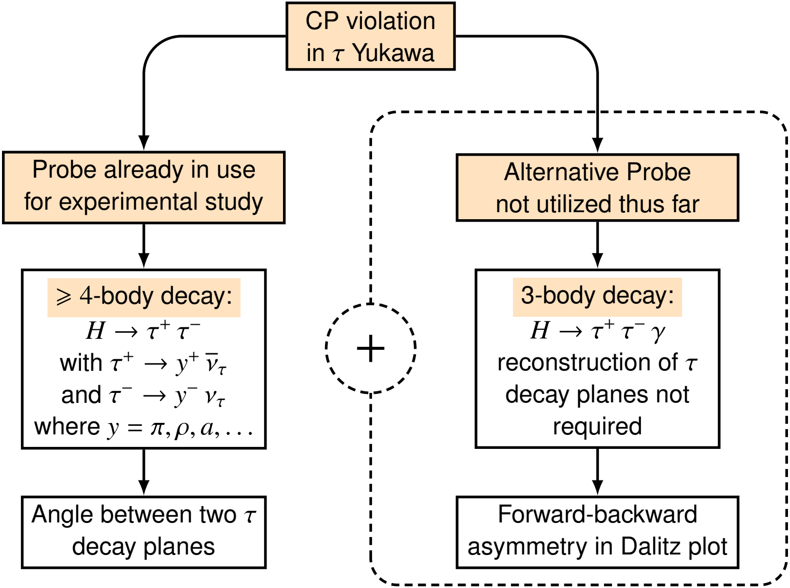
Overview


CP violation
in τ Yukawa
Probe already in use
for experimental study
Alternative Probe
not utilized thus far
$\geqslant$ 4-body decay:
$H \to \tau^+ \tau^-$
with $\tau^+ \to y^+ \bar{\nu}_\tau$
and $\tau^- \to y^- \nu_\tau$
where $y = \pi, \rho, a, \ldots$
+
3-body decay:
$H \to \tau^+ \tau^- \gamma$
reconstruction of τ
decay planes not
required
Angle between two τ
decay planes
Forward-backward
asymmetry in Dalitz plot

CP violating Lagrangian

- CP violating $H\tau\tau$ Yukawa interaction is written using various notations in the literature. For simplicity we shall use the following,

$$\mathscr{L}_{H\tau\tau} = -\frac{m_\tau}{v}\,\bar{\tau}\left(a_\tau + i\,\gamma^5\, b_\tau\right)\tau\, H\,,$$

  where $v = \left(\sqrt{2}\,G_F\right)^{-1/2} \simeq 246\ \text{GeV}$, and $a_\tau^{\text{SM}} = 1$, $b_\tau^{\text{SM}} = 0$ in the SM.

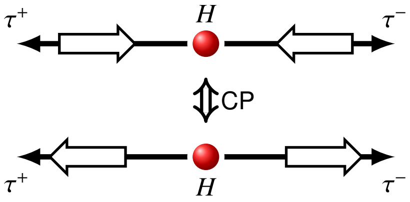
- $b_\tau \neq 0 \implies$ CP violation (NP). Both a_τ and b_τ are real.

- Measurement of e^- EDM suggest[1]: $|b_\tau| \lesssim 0.29$ at 90% C.L.

[1] J. Alonso-Gonzalez, A. de Giorgi, L. Merlo and S. Pokorski, JHEP **05**, 041 (2022).

The 2-body decay $H \to \tau^+ \tau^-$

- Branching ratio in SM: $\sim 6.15\%$
- Energies and momenta of $\tau^\pm$ fixed in H rest frame.
- Very highly boosted τs:
  $\beta_\tau = 0.99960\, c.$



- Only 2 helicity configurations allowed: $\tau_L^+ \tau_L^- \xleftrightarrow{\text{CP}} \tau_R^+ \tau_R^-$.
- Partial decay rate: $\Gamma_{\tau\tau} = \frac{m_H}{8\pi} \frac{m_\tau^2}{v^2} \left(a_\tau^2 \left(1 - \frac{4\, m_\tau^2}{m_H^2} \right) + b_\tau^2 \right) \sqrt{1 - \frac{4\, m_\tau^2}{m_H^2}}$.
  Experimental constraint[2]: $a_\tau^2 + b_\tau^2 \approx 0.93^{+0.14}_{-0.12}$.
- Both helicity configurations equally likely:

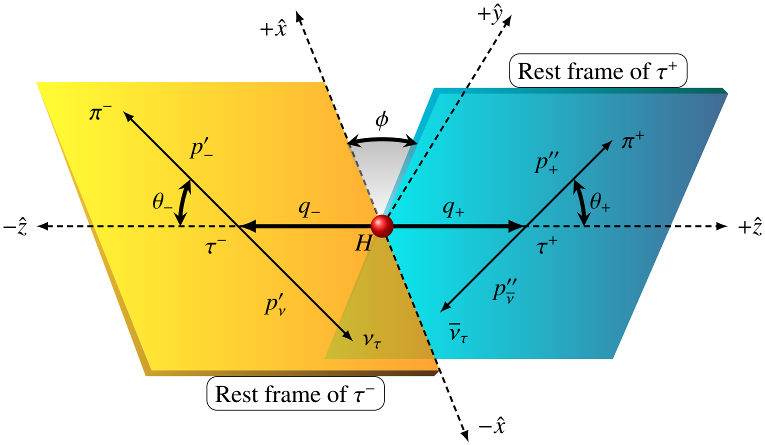
$$|\mathscr{M}_{++}|^2 = |\mathscr{M}_{--}|^2 = \left(\frac{m_\tau}{v} \right)^2 \left[\left(a_\tau^2 + b_\tau^2 \right) m_H^2 - 4\, a_\tau^2 m_\tau^2 \right].$$

$\therefore$ No way to measure CP violation, if we study this 2-body decay only.

[2] inferred from G. Aad *et al.* [ATLAS], JHEP **08**, 175 (2022), neglecting m_τ.

The 4-body decay $H \to \tau^+ \tau^- \to \pi^+ \pi^- \nu_\tau \bar{\nu}_\tau$

- Final state has two missing particles: τ reconstruction issues
- Much richer kinematics: 3 uni-angular distributions possible



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$$\frac{\mathrm{d}^3\Gamma_{\pi\pi\nu\bar{\nu}}}{\mathrm{d}\cos\theta_+\,\mathrm{d}\cos\theta_-\,\mathrm{d}\varphi} = \frac{\left\langle \left|\mathscr{M}_{\pi\pi\nu\bar{\nu}}\right|^2 \right\rangle}{2^{15}\,\pi^6\,m_H} \left(1 - \frac{4\,m_\tau^2}{m_H^2}\right)^{\frac{1}{2}} \left(1 - \frac{m_\pi^2}{m_\tau^2}\right)^2,$$

with

$$\left\langle \left|\mathscr{M}_{\pi\pi\nu\bar{\nu}}\right|^2 \right\rangle = \left(\frac{G_F}{\sqrt{2}} f_\pi\, V_{ud}\right)^4 \left(\frac{m_\tau}{v}\right)^2 \left(\frac{\pi}{m_\tau\,\Gamma_\tau}\right)^2$$
$$\times \Big(8\, a_\tau^2\, m_\tau^4 \left(m_H^2 - 4\,m_\tau^2\right) \left(m_\tau^2 - m_\pi^2\right)^2 \left(1 - \cos\theta_+\,\cos\theta_- - \sin\theta_+\,\sin\theta_-\,\cos\varphi\right)$$
$$+\, 8\, b_\tau^2\, m_H^2\, m_\tau^4 \left(m_\tau^2 - m_\pi^2\right)^2 \left(1 - \cos\theta_+\,\cos\theta_- + \sin\theta_+\,\sin\theta_-\,\cos\varphi\right)$$
$$-\, 16\, a_\tau\, b_\tau\, m_H\, m_\tau^4 \sqrt{m_H^2 - 4\,m_\tau^2} \left(m_\tau^2 - m_\pi^2\right)^2 \sin\theta_+\,\sin\theta_-\,\sin\varphi\Big).$$

The 4-body decay $H \to \tau^+ \tau^- \to \pi^+ \pi^- \nu_\tau \bar{\nu}_\tau$

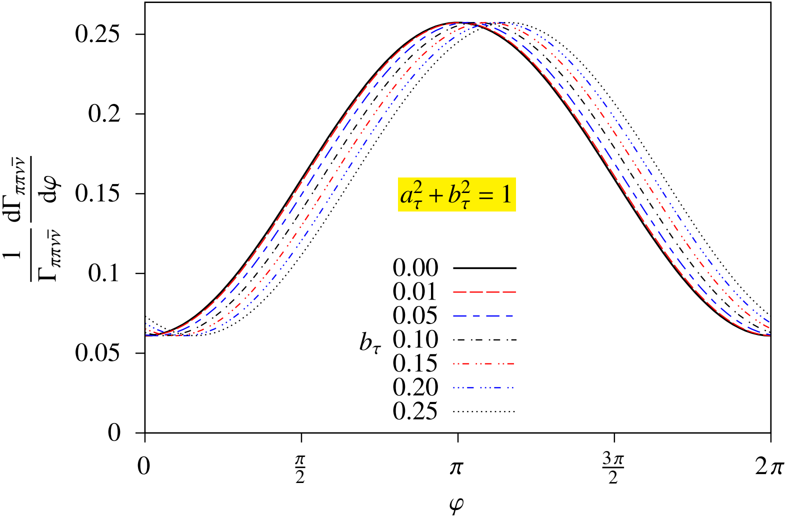
- Final state has two missing particles: τ reconstruction issues
- Much richer kinematics: 3 uni-angular distributions possible

- Only the uni-angular distribution $\frac{\mathrm{d}\Gamma_{\pi\pi\nu\bar{\nu}}}{\mathrm{d}\varphi}$ gets contribution from $a_\tau \, b_\tau$.

$$\frac{1}{\Gamma_{\pi\pi\nu\bar{\nu}}} \frac{\mathrm{d}\Gamma_{\pi\pi\nu\bar{\nu}}}{\mathrm{d}\varphi} = \frac{\begin{pmatrix} a_\tau^2 \left(m_H^2 - 4m_\tau^2\right)\left(16 - \pi^2 \cos\varphi\right) \\ + \, b_\tau^2 \, m_H^2 \left(16 + \pi^2 \cos\varphi\right) \\ - \, 2\,\pi^2 \, a_\tau \, b_\tau \, m_H \sqrt{m_H^2 - 4m_\tau^2} \, \sin\varphi \end{pmatrix}}{32\,\pi \left(a_\tau^2 \left(m_H^2 - 4m_\tau^2\right) + b_\tau^2 m_H^2\right)}.$$

$\therefore$ It is sensitive to **CP violation**.

The 4-body decay $H \to \tau^+ \tau^- \to \pi^+ \pi^- \nu_\tau \bar{\nu}_\tau$



The 4-body decay $H \to \tau^+ \tau^- \to \pi^+ \pi^- \nu_\tau \bar{\nu}_\tau$

- This distribution is well explored in the literature.

- The final π's and $\nu/\bar{\nu}$: almost collinear to the parent τs due to the large boosts.
  $\Longrightarrow$ constructing τ decay planes and finding the angle φ between them is not an easy task.

- Experimentalists prefer $\rho^\pm$ instead of $\pi^\pm$ as $\rho^\pm \to \pi^\pm \pi^0$ make the plane reconstruction easier.
  $\therefore$ Only $H \to \tau^+ \tau^- \to \underbrace{\pi^+ \pi^- \pi^0 \pi^0 \nu_\tau \bar{\nu}_\tau}_{\text{6-body final state}}$ events useful.

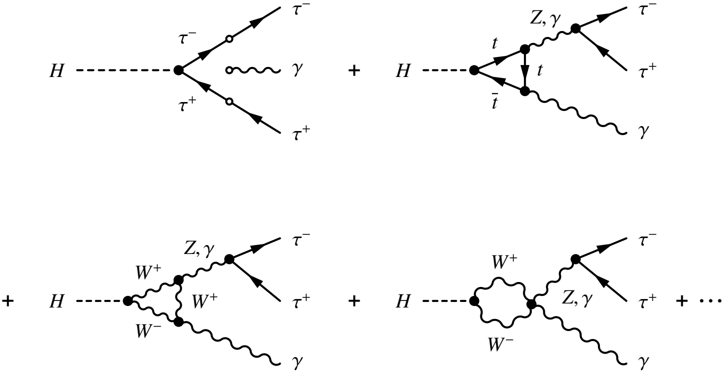
- Constraint on b_τ from such studies[a]: $|b_\tau| \lesssim 0.34$.

- Only experimental studies with more statistics, better reconstruction of decay planes and better angular resolutions, seem to be the way forward.

[a] A. Tumasyan *et al.* [CMS], JHEP **06**, 012 (2022).

The 3-body decay $H \to \tau^+ \tau^- \gamma$

Decay proceeds via both tree and loop diagrams



Br$(H \to \tau^+ \tau^- \gamma)_{\text{SM}} \sim 3.24 \times 10^{-3}$ with $E_\gamma > 5$ GeV and angular separation $> 5^\circ$

See for example Phys. Rev. D **55**, 5647-5656 (1997); Phys. Rev. D **90**, no.11, 113006 (2014); Eur. Phys. J. C **74**, no.11, 3141 (2014); JHEP **12**, 111 (2016).

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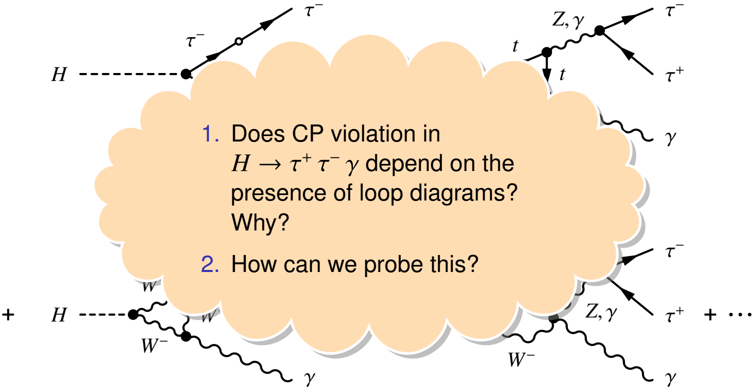

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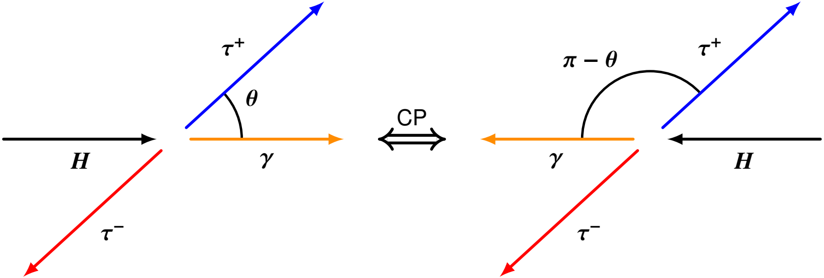
The 3-body decay $H \to \tau^+ \tau^- \gamma$

A first-principle analysis

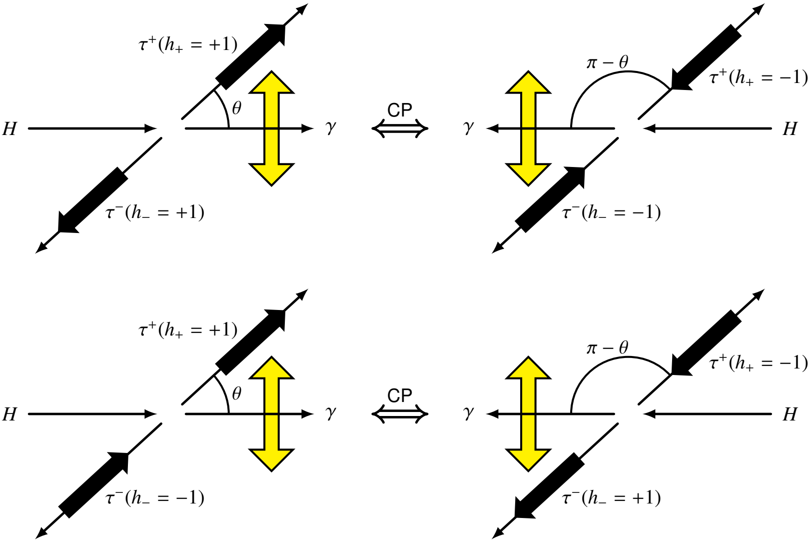


CP violation $\Leftrightarrow$ **asymmetry** under $\theta \leftrightarrow \pi - \theta \equiv \cos\theta \leftrightarrow -\cos\theta$

$\equiv$ Forward-Backward asymmetry

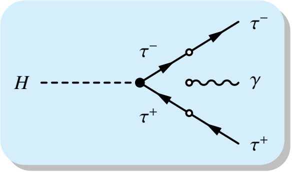
The 3-body decay $H \to \tau^+ \tau^- \gamma$

All τ helicity configurations possible here unlike the case in $H \to \tau^+ \tau^-$

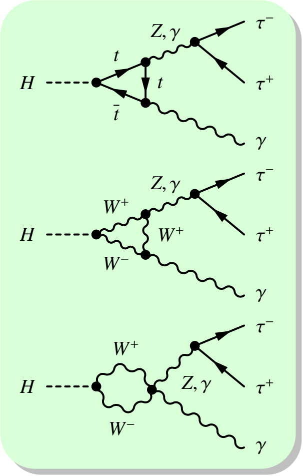


The 3-body decay $H \to \tau^+ \tau^- \gamma$

Phenomenological Lagrangians and Amplitudes



$$\mathscr{M} = \mathscr{M}^{(\mathrm{Yuk})} + \mathscr{M}^{(Z\gamma)} + \mathscr{M}^{(\gamma\gamma)}$$

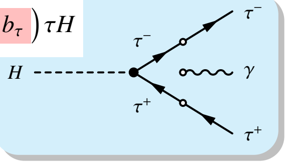


1-loop SM box diagrams negligible

The 3-body decay $H \to \tau^+ \tau^- \gamma$

Phenomenological Lagrangians and Amplitudes

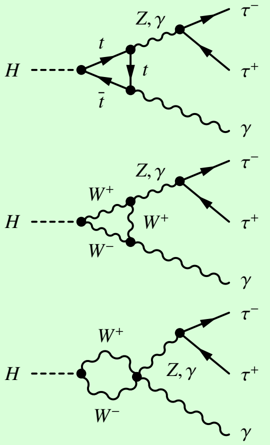
$$\mathscr{L}_{H\tau\tau} = -\frac{m_\tau}{v}\,\bar{\tau}\left(a_\tau + i\gamma^5\, b_\tau\right)\tau H$$



$$a_\tau^{\text{SM}} = 1,\ b_\tau^{\text{SM}} = 0$$

$$a_\tau^{\text{NP}} \neq 1,\ b_\tau^{\text{NP}} \neq 0$$

$$\mathscr{M} = \mathscr{M}^{(\text{Yuk})} + \mathscr{M}^{(Z\gamma)} + \mathscr{M}^{(\gamma\gamma)}$$



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$$\mathscr{L}_{H\mathcal{V}\gamma} = \frac{H}{4v}\Big(2\,A_2^{Z\gamma}\,F^{\mu\nu}Z_{\mu\nu} + 2\,A_3^{Z\gamma}\,F^{\mu\nu}\widetilde{Z}_{\mu\nu} + A_2^{\gamma\gamma}\,F^{\mu\nu}F_{\mu\nu} + A_3^{\gamma\gamma}\,F^{\mu\nu}\widetilde{F}_{\mu\nu}\Big),$$

where $\mathcal{V}_{\mu\nu} = \partial_\mu \mathcal{V}_\nu - \partial_\nu \mathcal{V}_\mu, \quad \widetilde{\mathcal{V}}_{\mu\nu} = \frac{1}{2}\epsilon_{\mu\nu\rho\sigma}\mathcal{V}^{\rho\sigma},$

for $\mathcal{V} = Z, \gamma$.

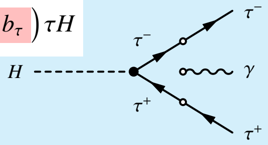
The 3-body decay $H \to \tau^+ \tau^- \gamma$

Phenomenological Lagrangians and Amplitudes

$$\mathscr{L}_{H\tau\tau} = -\frac{m_\tau}{v}\,\bar{\tau}\left(a_\tau + i\gamma^5 b_\tau\right)\tau H$$

$a_\tau^{\mathrm{SM}} = 1,\ b_\tau^{\mathrm{SM}} = 0$

$a_\tau^{\mathrm{NP}} \neq 1,\ b_\tau^{\mathrm{NP}} \neq 0$



$$\mathscr{M} = \mathscr{M}^{(\mathrm{Yuk})} + \mathscr{M}^{(Z\gamma)} + \mathscr{M}^{(\gamma\gamma)}$$

SM loop effects only

$A_3^{\gamma\gamma} = 0 = A_3^{Z\gamma}$

$$\mathscr{L}_{H\mathcal{V}\gamma} = \frac{H}{4v}\Big(2\,A_2^{Z\gamma}\,F^{\mu\nu}Z_{\mu\nu} + 2\,A_3^{Z\gamma}\,F^{\mu\nu}\widetilde{Z}_{\mu\nu} + A_2^{\gamma\gamma}\,F^{\mu\nu}F_{\mu\nu} + A_3^{\gamma\gamma}\,F^{\mu\nu}\widetilde{F}_{\mu\nu}\Big),$$

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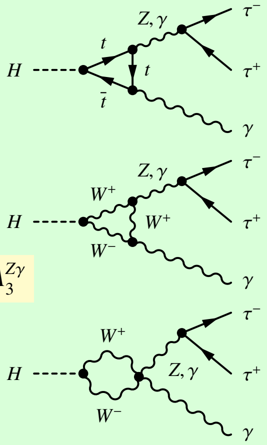


1-loop SM box diagrams negligible

The 3-body decay $H \to \tau^+ \tau^- \gamma$

Source of CP asymmetry in the amplitude square

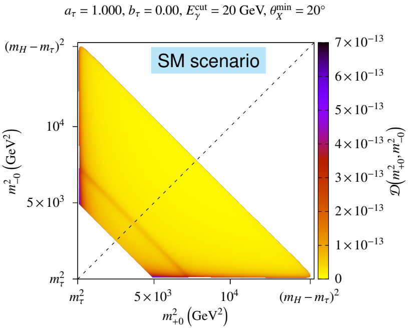
$$|\mathcal{M}|^2 = \underbrace{\left|\mathcal{M}^{(\mathrm{Yuk})}\right|^2 + \left|\mathcal{M}^{(Z\gamma)}\right|^2 + \left|\mathcal{M}^{(\gamma\gamma)}\right|^2 + 2\,\mathrm{Re}\left(\mathcal{M}^{(\mathrm{Yuk})}\,\mathcal{M}^{(\gamma\gamma)*}\right)}_{\textbf{even under } \cos\theta \leftrightarrow -\cos\theta}$$

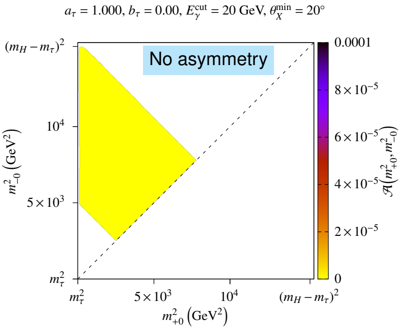
$$+ \underbrace{2\,\mathrm{Re}\left(\mathcal{M}^{(\gamma\gamma)}\,\mathcal{M}^{(Z\gamma)*}\right)}_{\text{has a term linear in } \cos\theta \text{ which vanishes when } A_3^{\gamma\gamma} = 0 = A_3^{Z\gamma}} + \underbrace{2\,\mathrm{Re}\left(\mathcal{M}^{(\mathrm{Yuk})}\,\mathcal{M}^{(Z\gamma)*}\right)}_{\text{has a term } \propto b_\tau \text{ \& linear in } \cos\theta \text{, which survives even when } A_3^{\gamma\gamma} = 0 = A_3^{Z\gamma}},$$

- non-zero CP-odd phase difference comes from $b_\tau \neq 0$,
- non-zero CP-even phase difference comes from Z-propagator.

The 3-body decay $H \to \tau^+ \tau^- \gamma$

Analytical Dalitz plot distributions and asymmetry





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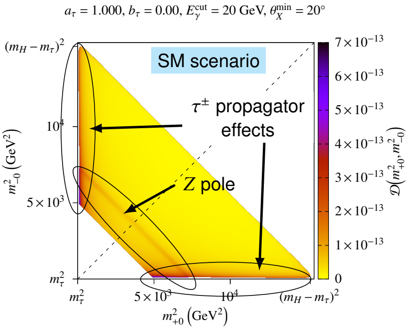

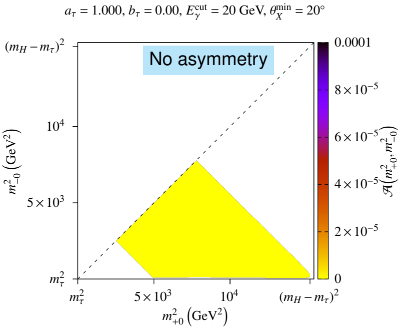

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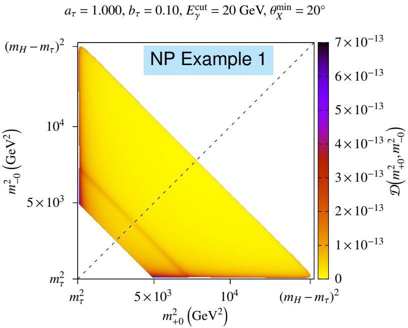

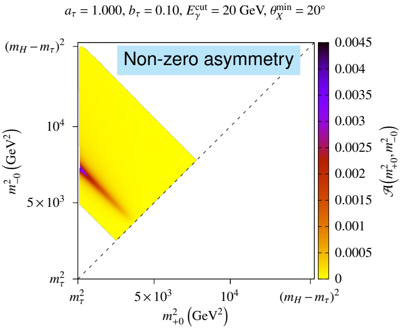

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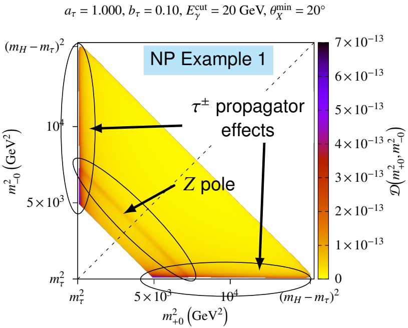

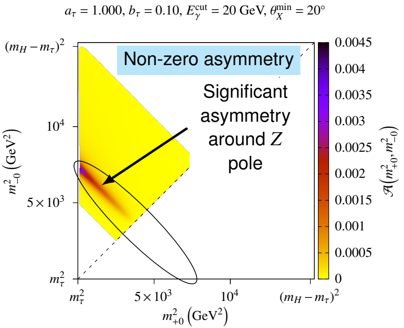

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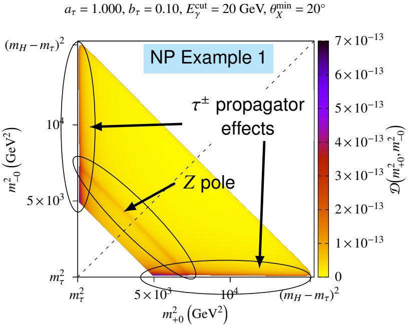

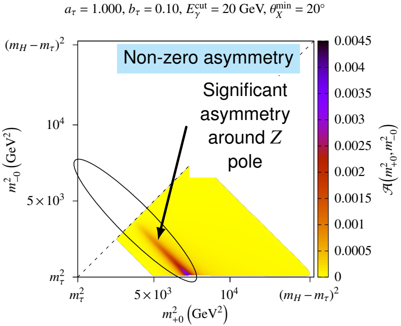

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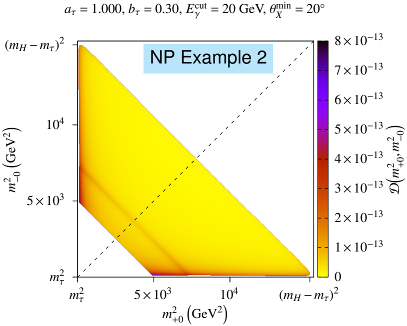

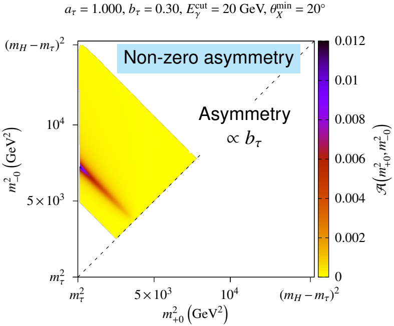

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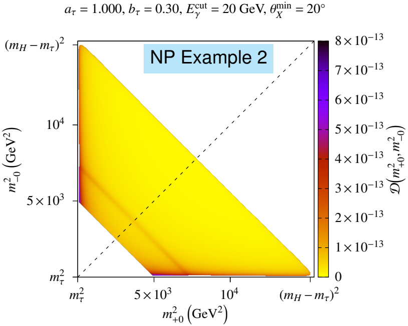
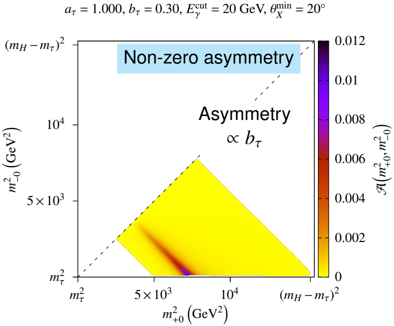




The 3-body decay $H \to \tau^+ \tau^- \gamma$

Feasibility study for experimental prospect...

- **In summary**
  (1) CP violation $(b_\tau \neq 0) \implies$ Forward-Backward asymmetry in Gottfried-Jackson frame

  (2) Forward-Backward asymmetry ≡ Asymmetry in m^2_{+0} vs. m^2_{-0} Dalitz plot under $m^2_{+0} \leftrightarrow m^2_{-0}$:

$$\underbrace{\mathcal{A}\left(m^2_{+0}, m^2_{-0}\right) \neq 0,}_{\text{full distribution asymmetry}} \quad \left[\text{asymmetry } \sim \mathcal{O}\left(10^{-3}\right)\right]$$

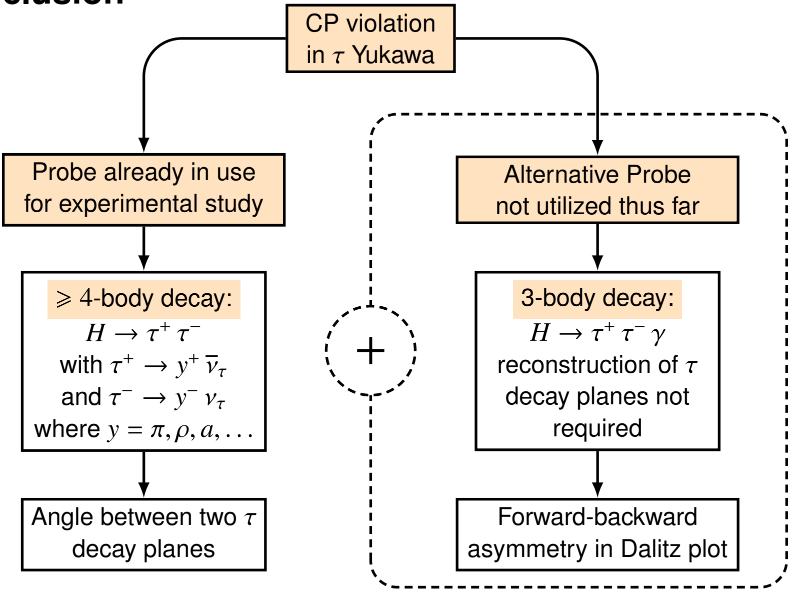
  (3) m^2_{+0} vs. m^2_{-0} Dalitz plot: can be obtained in *any frame of reference*

  (4) Asymmetry is prominent surrounding the Z pole

On going studies related to ...

- **Feasibility: Can these asymmetries be probed in ongoing or future experiments?**
- **Prospect: What range of b_τ would get constrained from such experimental studies?**

Conclusion



Thank You

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Understanding the Early Universe:
interplay of theory and collider experiments

Joint research project between the University of Warsaw & University of Bergen