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

(A phenomenological overview)

Norway grants

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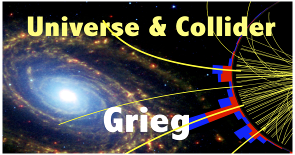
Dibyakrupa Sahoo
University of Warsaw, Warsaw, Poland



Understanding the Early Universe:
interplay of theory and collider experiments

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

UNIVERSITAS VARSOVIENSIS

Based on an *ongoing work*
in collaboration with

Janusz Rosiek, Stefan Pokorski,
(University of Warsaw, Poland)
Anna Lipniacka and Nikolai Fomin
(University of Bergen, Norway)

WG2 WG3 joint meeting on CP violation in extended Higgs sector
26 September 2023

CP violating $H\tau\tau$ Lagrangian

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

where $v = \left(\sqrt{2}\,G_F\right)^{-1/2} \simeq 246\ \mathrm{GeV}$.

- Only 2 real parameters: a_τ, b_τ

	CP-even	CP-odd
SM:	$a_\tau = 1$	$b_\tau = 0$
NP:	$a_\tau \neq 1$	$b_\tau \neq 0$

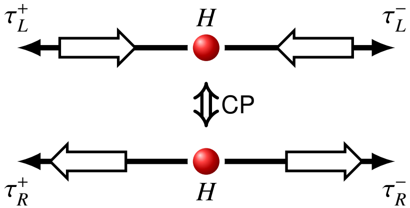
- Constraint from e^- EDM measurement:

$|b_\tau| \lesssim 0.29$ at 90% C.L.

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

The 2-body decay $H \to \tau^+ \tau^-$ is *not* suitable to probe $b_\tau \neq 0$.

- $\mathrm{Br}\,(H \to \tau^+ \tau^-) = \left(6.0^{+0.8}_{-0.7}\right)\%$
  [PDG 2023]



- Only 2 allowed helicity configurations

- Partial decay rate

$$\Gamma_{\tau\tau} = \frac{m_H}{8\,\pi} \left(\frac{m_\tau}{v}\right)^2 \left(a_\tau^2 \left(1 - \frac{4\,m_\tau^2}{m_H^2}\right) + b_\tau^2\right) \times \sqrt{1 - \frac{4\,m_\tau^2}{m_H^2}}\,.$$

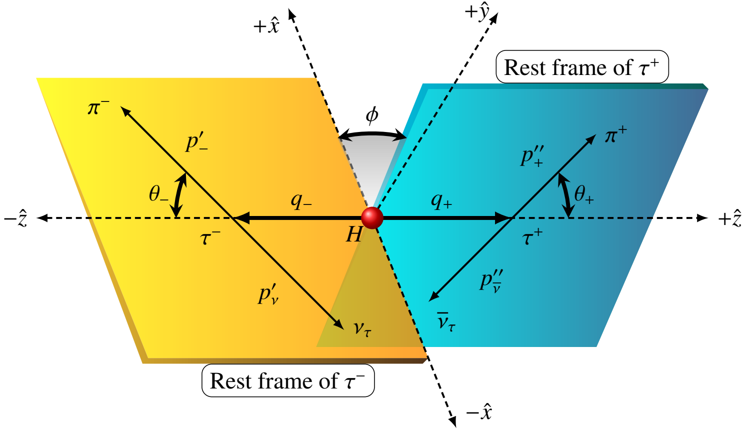
- Experimental constraint:

$$a_\tau^2 + b_\tau^2 \approx 0.93^{+0.14}_{-0.12}$$

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

The 4-body decay $H \to \tau^+ \tau^- \to \pi^+ \pi^- \nu_\tau \bar{\nu}_\tau$ can probe $b_\tau \neq 0$.

- Much richer kinematics: 3 uni-angular distributions possible.



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- Much richer kinematics: 3 uni-angular distributions possible.

- Full angular distribution:

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

$$\left\langle \left| \mathcal{M}_{\pi\pi\nu\bar{\nu}} \right|^2 \right\rangle = \left(\frac{G_F}{\sqrt{2}} f_\pi \, V_{ud}\right)^4 \left(\frac{m_\tau}{v}\right)^2 \left(\frac{\pi}{m_\tau\, \Gamma_\tau}\right)^2$$

$$\times \Big(8\, a_\tau^2 \, m_\tau^4 \left(m_H^2 - 4\, m_\tau^2\right) \left(m_\tau^2 - m_\pi^2\right)^2 \left(1 - \cos\theta_+ \, \cos\theta_- - \sin\theta_+ \, \sin\theta_- \, \cos\varphi\right)$$

$$+ 8\, b_\tau^2 \, m_H^2 \, m_\tau^4 \left(m_\tau^2 - m_\pi^2\right)^2 \left(1 - \cos\theta_+ \, \cos\theta_- + \sin\theta_+ \, \sin\theta_- \, \cos\varphi\right)$$

$$- 16\, a_\tau \, b_\tau \, m_H \, m_\tau^4 \sqrt{m_H^2 - 4\, m_\tau^2} \left(m_\tau^2 - m_\pi^2\right)^2 \sin\theta_+ \, \sin\theta_- \, \sin\varphi \Big).$$

The 4-body decay $H \to \tau^+ \tau^- \to \pi^+ \pi^- \nu_\tau \bar{\nu}_\tau$ can probe $b_\tau \neq 0$.

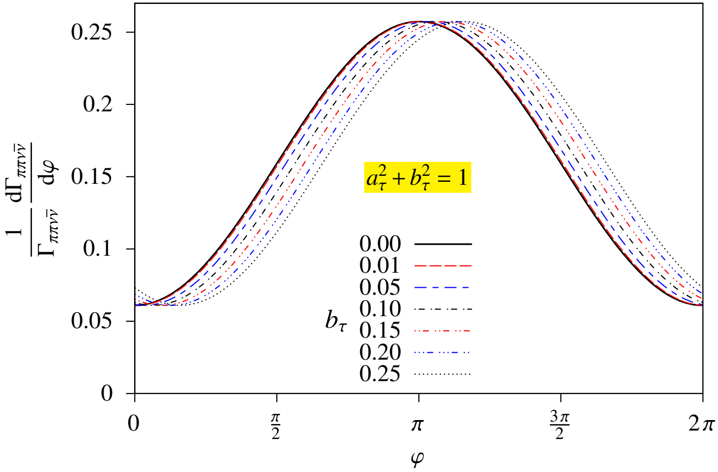
- Much richer kinematics: 3 uni-angular distributions possible.

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

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

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

The 4-body decay $H \to \tau^+ \tau^- \to \pi^+ \pi^- \nu_\tau \bar{\nu}_\tau$ can probe $b_\tau \neq 0$.



The 4-body decay $H \to \tau^+\tau^- \to \pi^+\pi^-\nu_\tau\bar{\nu}_\tau$ can probe $b_\tau \neq 0$.

- In H rest frame, τ's are highly boosted
  $\implies$ final π's and $\nu/\bar{\nu}$ are almost collinear to the parent τs
  $\implies$ constructing τ decay planes and measuring φ not straightforward.

- 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:

$$|b_\tau| \lesssim 0.34$$

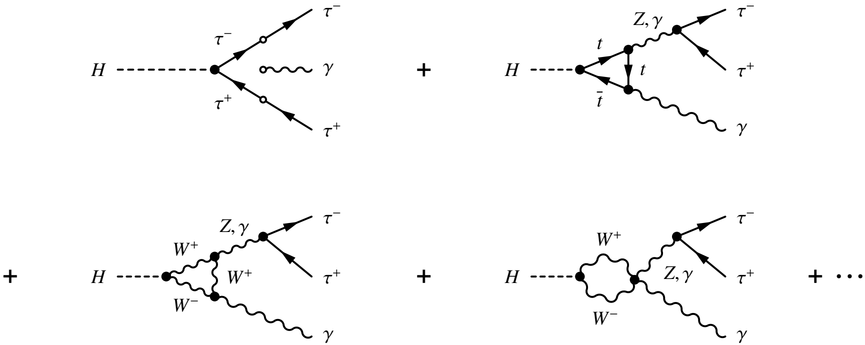
[A. Tumasyan *et al.* [CMS], JHEP **06**, 012 (2022)]

- Way forward: More data + improved decay plane reconstruction + better angular resolutions.

- **Is there an alternative method, of probing CP violation in $H\tau\tau$ Yukawa interaction, which does not require reconstruction of τ decay planes?**

The 3-body decay $H \to \tau^+ \tau^- \gamma$ offers an alternative methodology.

Decay proceeds via both tree and loop diagrams



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

[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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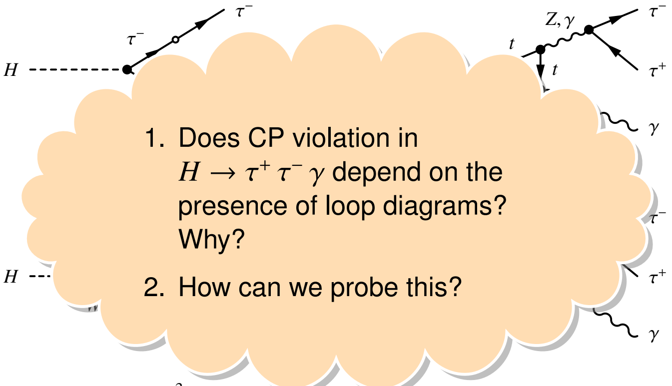

1. Does CP violation in $H \to \tau^+ \tau^- \gamma$ depend on the presence of loop diagrams? Why?
2. How can we probe this?

$+ \cdots$

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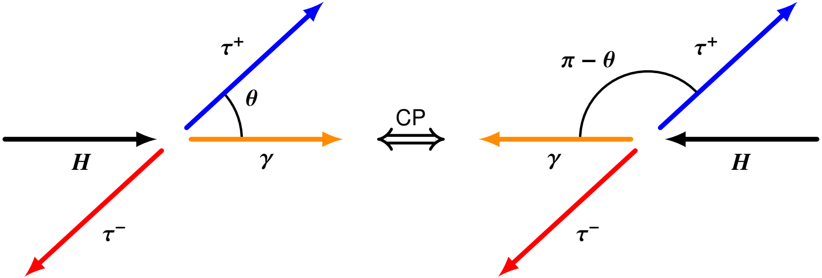
The 3-body decay $H \to \tau^+ \tau^- \gamma$ must exhibit forward-backward asymmetry if CP is violated.

A first-principle analysis

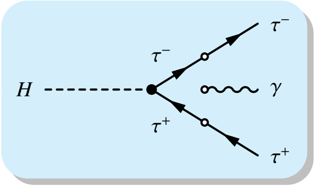
Gottfried-Jackson (GJ) frame
Center-of-momentum frame of $\tau^+ \tau^-$



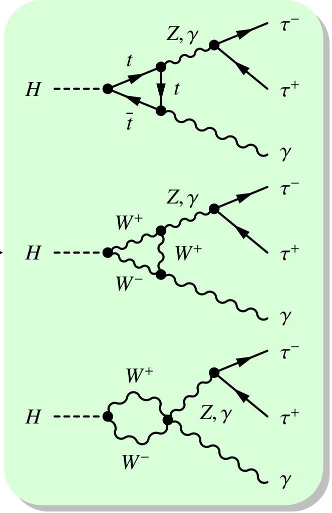
CP violation $\Leftrightarrow$ **asymmetry** under $\theta \leftrightarrow \pi - \theta \equiv \cos\theta \leftrightarrow -\cos\theta$

$\equiv$ Forward-Backward asymmetry

The amplitude for $H \to \tau^+ \tau^- \gamma$ can be split into one tree-level amplitude and two loop-level amplitudes.



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



1-loop SM box diagrams negligible

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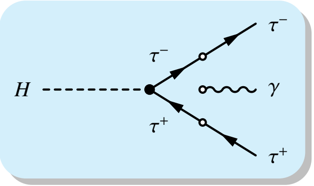
$$a_\tau^{\mathrm{SM}} = 1,\ b_\tau^{\mathrm{SM}} = 0$$

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

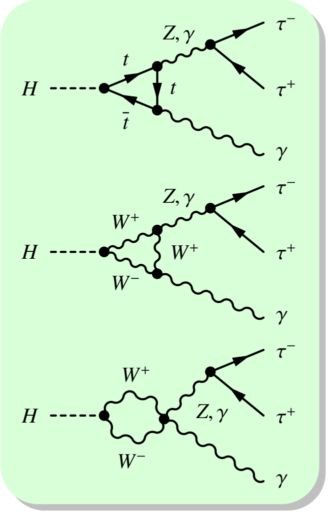


$$\mathscr{M} = \mathscr{M}^{(\mathrm{Yuk})} + \mathscr{M}^{(Z\gamma)} + \mathscr{M}^{(\gamma\gamma)}$$

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

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



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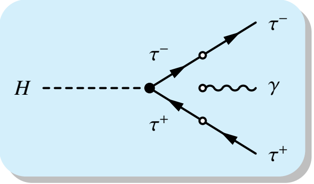
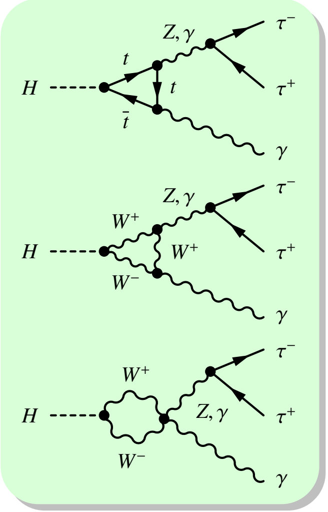


$$\mathcal{M} = \mathcal{M}^{(\mathrm{Yuk})} + \mathcal{M}^{(Z\gamma)} + \mathcal{M}^{(\gamma\gamma)}$$

SM loop effects only

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



1-loop SM box diagrams negligible

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

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

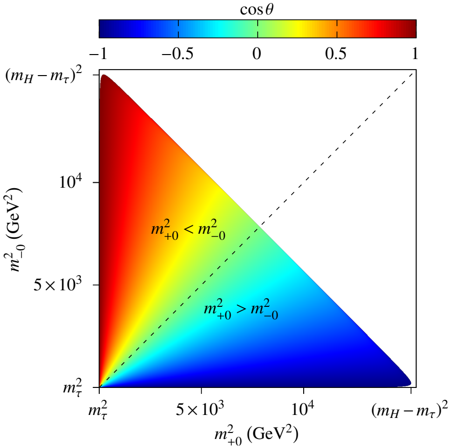
The interference of tree-level and loop-level amplitudes of $H \to \tau^+\tau^-\gamma$ is sensitive to $b_\tau \neq 0$.

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

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

- non-zero CP-odd (“weak”) phase difference $\Longleftarrow$ $b_\tau \neq 0,\ A_3^{\gamma\gamma} \neq 0,\ A_3^{Z\gamma} \neq 0,$
- non-zero CP-even (“strong”) phase difference $\Longleftarrow$ $\mathrm{Im}\left[\left((p_+ + p_-)^2 - m_Z^2 + i\,m_Z\,\Gamma_Z\right)^{-1}\right].$

The amplitude square can be expressed using Lorentz invariant mass-squares.



- Only 3 Lorentz invariant mass-squares:

$$m_{+-}^2 \equiv (p_H - p_0)^2 = (p_+ + p_-)^2\,,$$
$$m_{+0}^2 \equiv (p_H - p_-)^2 = (p_+ + p_0)^2\,,$$
$$m_{-0}^2 \equiv (p_H - p_+)^2 = (p_- + p_0)^2\,,$$
$$m_{+-}^2 + m_{+0}^2 + m_{-0}^2 = m_H^2 + 2\,m_\tau^2\,.$$

$\therefore$ Only 2 *independent* mass-squares.

- In the GJ frame,

$$m_{+0}^2 = M^2 - M'^2\cos\theta,$$
$$m_{-0}^2 = M^2 + M'^2\cos\theta,$$

where $M^2 = \frac{1}{2}\left(m_H^2 + 2\,m_\tau^2 - m_{+-}^2\right)$,

$$M'^2 = \frac{1}{2}\left(m_H^2 - m_{+-}^2\right)\left(1 - \frac{4\,m_\tau^2}{m_{+-}^2}\right)^{\frac{1}{2}}.$$

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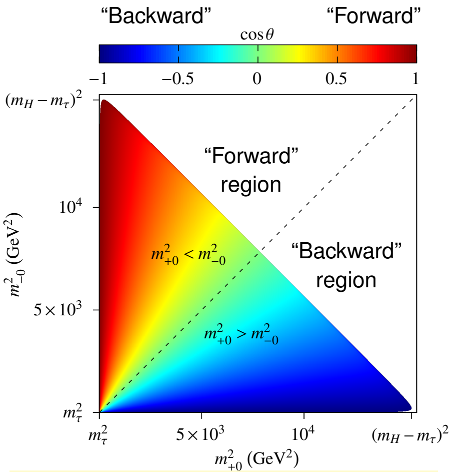


$$\theta \leftrightarrow \pi - \theta \equiv \cos\theta \leftrightarrow -\cos\theta \equiv m^2_{+0} \leftrightarrow m^2_{-0}$$

- Only 3 Lorentz invariant mass-squares:

$$m^2_{+-} \equiv (p_H - p_0)^2 = (p_+ + p_-)^2\,,$$
$$m^2_{+0} \equiv (p_H - p_-)^2 = (p_+ + p_0)^2\,,$$
$$m^2_{-0} \equiv (p_H - p_+)^2 = (p_- + p_0)^2\,,$$
$$m^2_{+-} + m^2_{+0} + m^2_{-0} = m^2_H + 2\,m^2_\tau\,.$$

∴ Only 2 *independent* mass-squares.

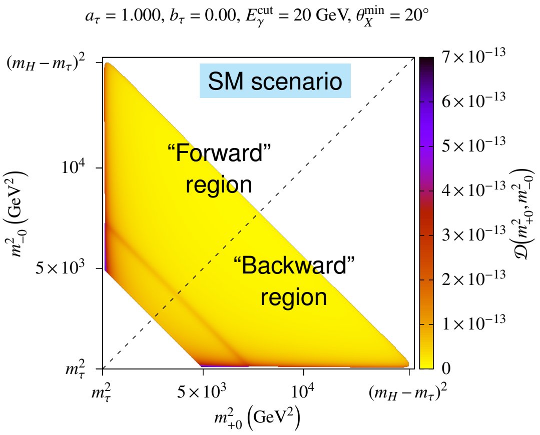
- In the GJ frame,

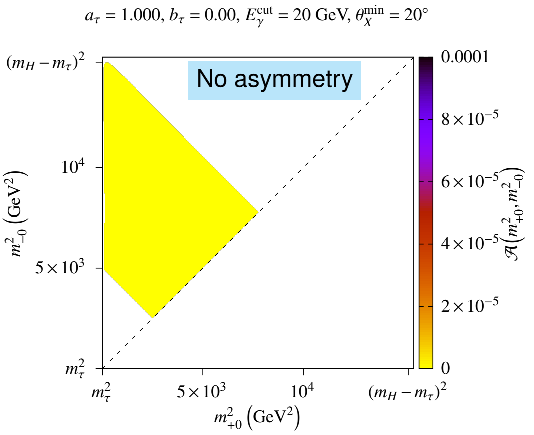
$$m^2_{+0} = M^2 - M'^2\cos\theta,$$
$$m^2_{-0} = M^2 + M'^2\cos\theta,$$

where $M^2 = \frac{1}{2}\left(m_H^2 + 2\,m_\tau^2 - m^2_{+-}\right),$

$$M'^2 = \frac{1}{2}\left(m_H^2 - m^2_{+-}\right)\left(1 - \frac{4\,m_\tau^2}{m^2_{+-}}\right)^{\frac{1}{2}}.$$

The forward-backward asymmetry can be easily observed in Lorentz invariant Dalitz plot distribution.





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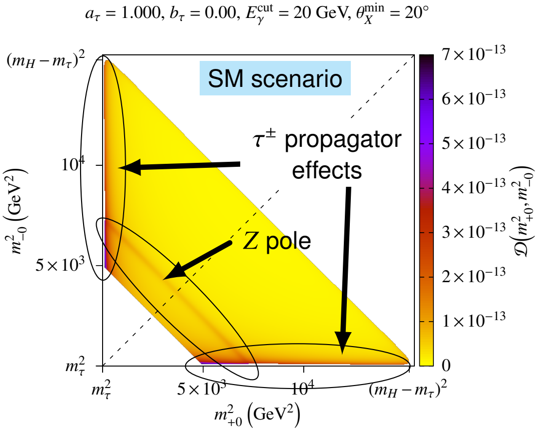

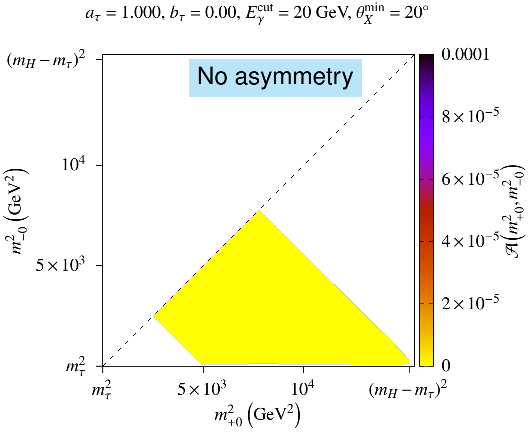

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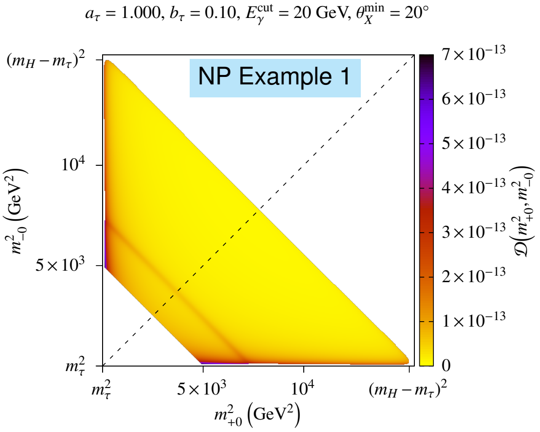

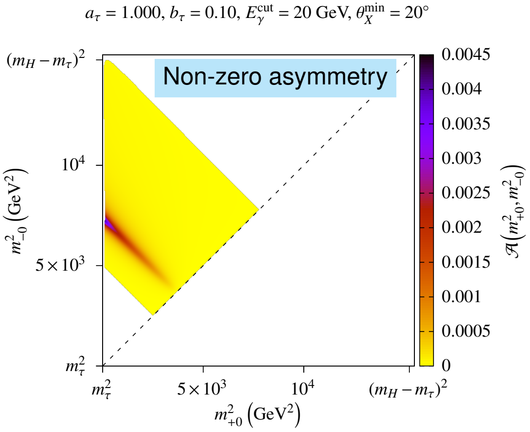

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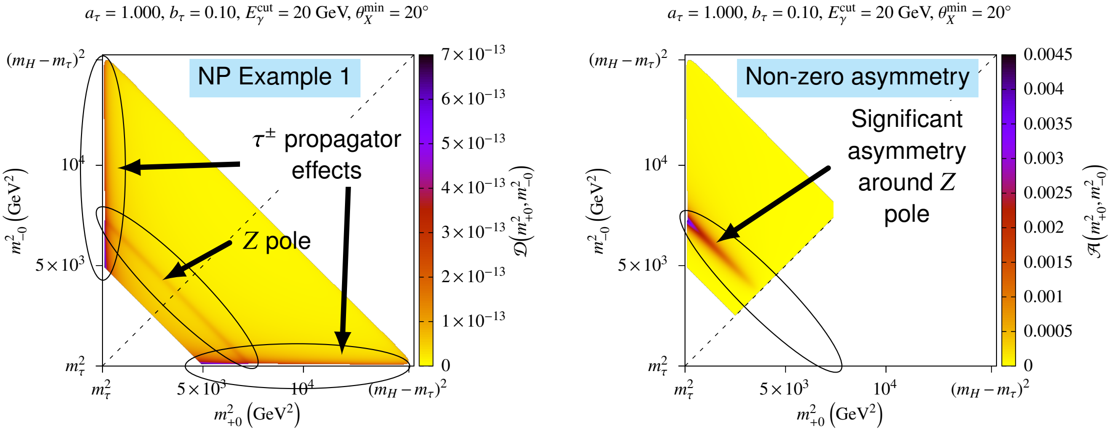

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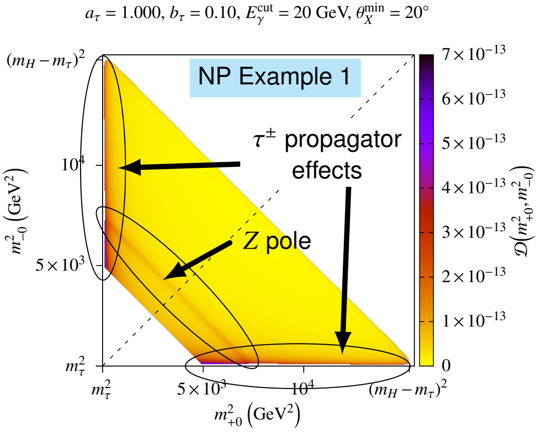

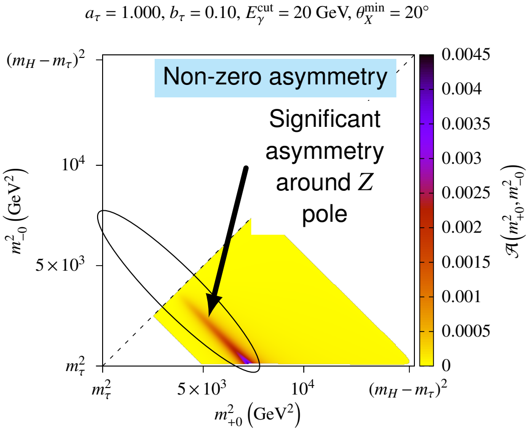

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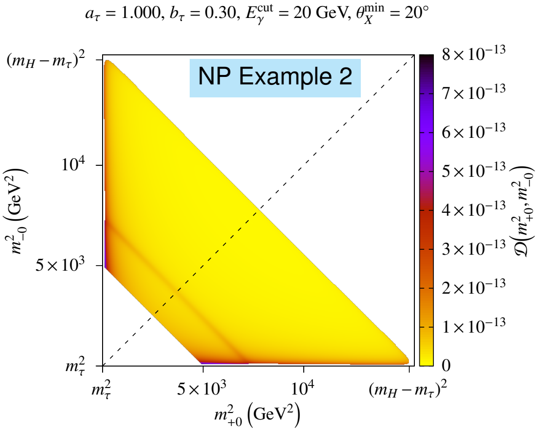

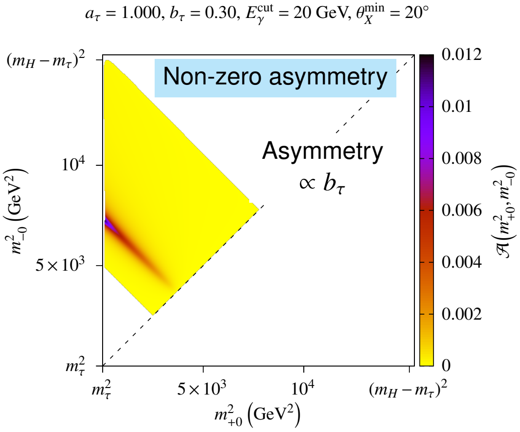

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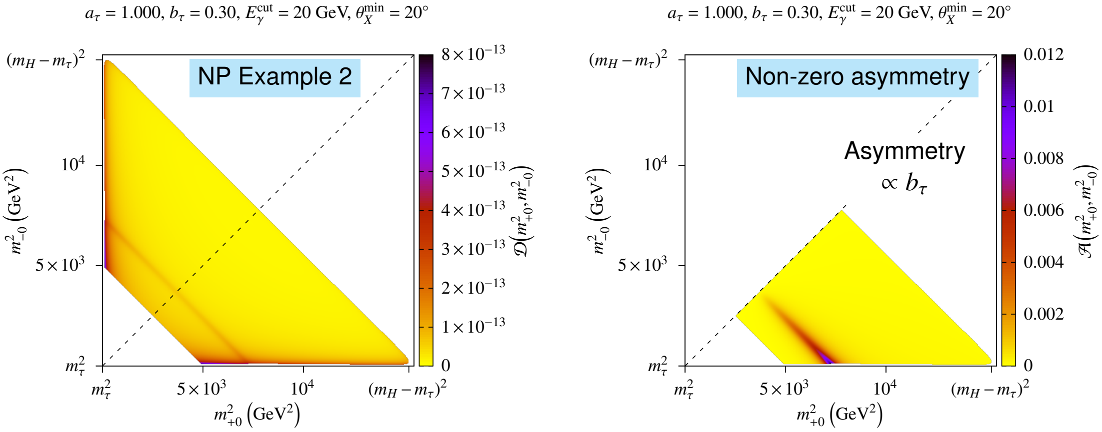


We are investigating how well can this Dalitz plot asymmetry be probed experimentally.

- **We have noticed that**
  (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*

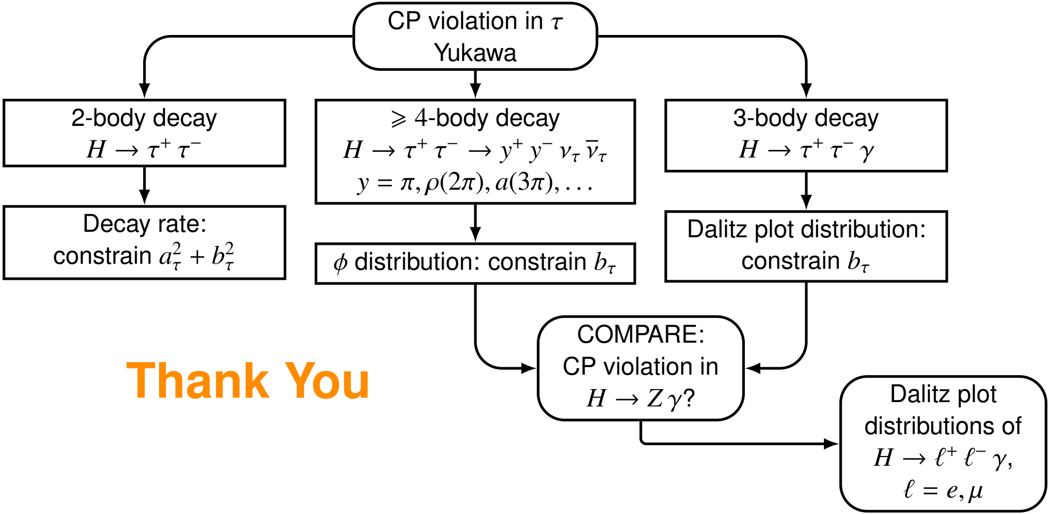
  (4) Asymmetry is prominent surrounding the Z pole

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?**

A publication looking at HL-LHC capabilities with use of detector response and reconstruction simulation is in progress.

The 3-body decay $H \to \tau^+ \tau^- \gamma$ is an interesting and complementary avenue to probe CP violation.



Thank You