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

(A phenomenological overview)

Norway grants

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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

Based on an ongoing work in collaboration with Janusz Rosiek, Stefan Pokorski, Anna Lipniacka and Nikolai Fomin

Scalars 2023, Warsaw

15 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:	$a_\tau \neq 1$	$b_\tau \neq 0$

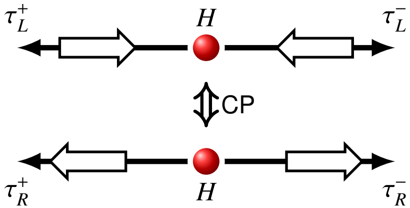
- Constraint from e^- EDM measurement:

$|b_\tau| \lesssim 0.29$ 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

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

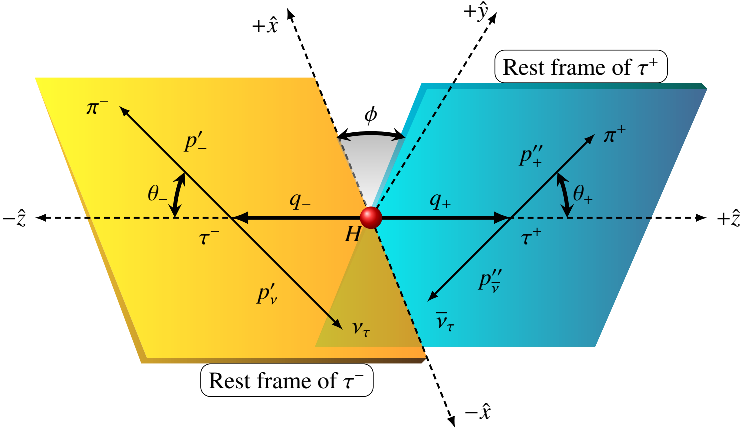
- Experimental constraint:

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

[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.



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.

- 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 $b_\tau \neq 0$.

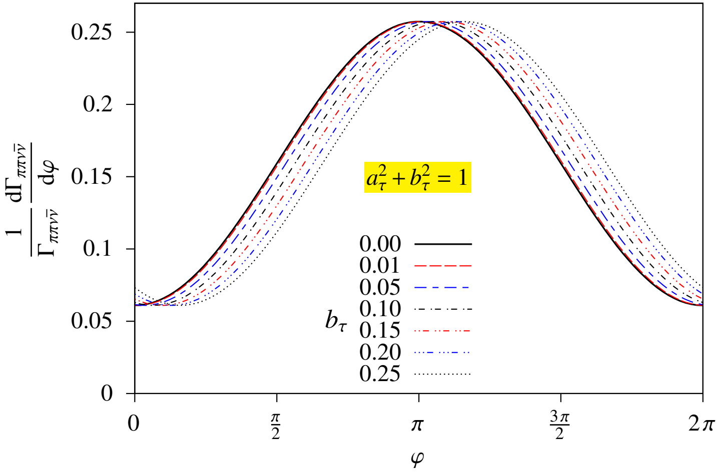
- Much richer kinematics: 3 uni-angular distributions possible.

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

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

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

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

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

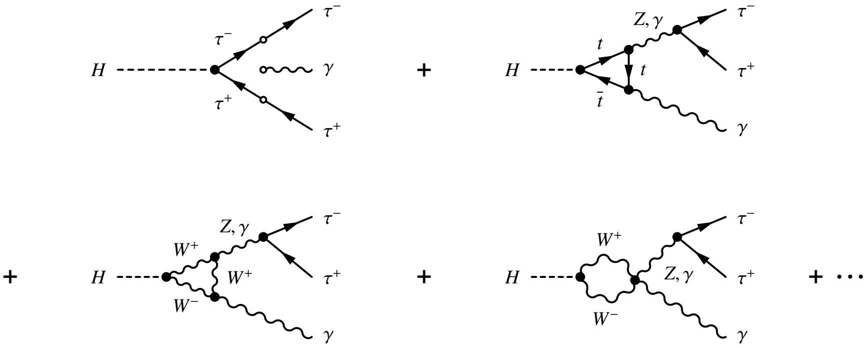
  [A. Tumasyan *et al.* [CMS], JHEP **06**, 012 (2022)]

- 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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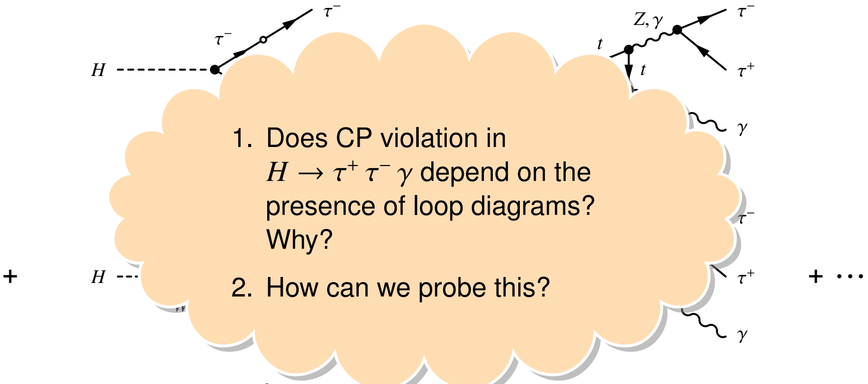

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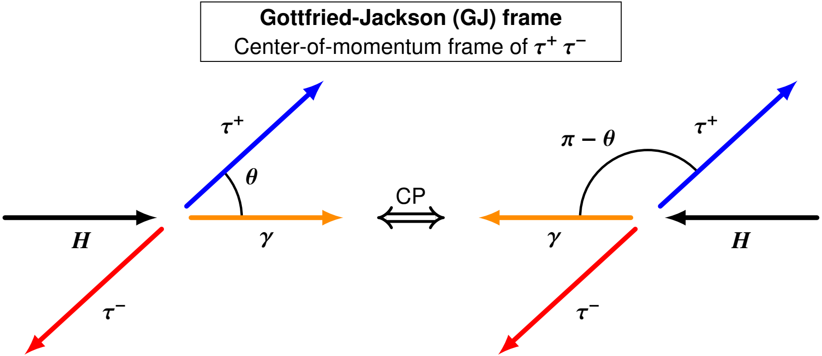
The 3-body decay $H \to \tau^+ \tau^- \gamma$ must exhibit forward-backward asymmetry if CP is violated.

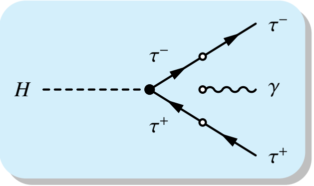
A first-principle analysis



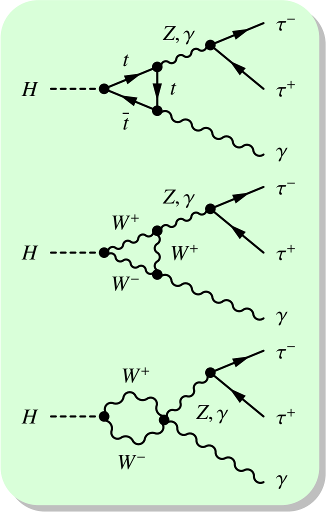
CP violation $\Leftrightarrow$ **asymmetry** under $\theta \leftrightarrow \pi - \theta \equiv \cos\theta \leftrightarrow -\cos\theta$

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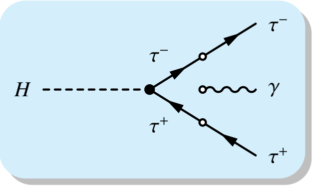
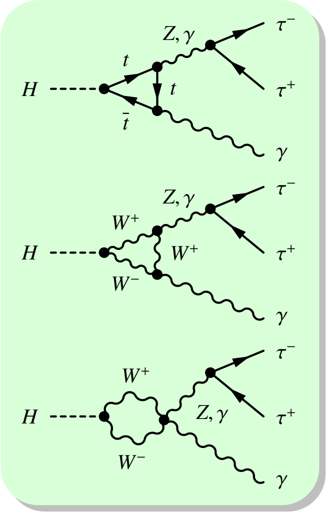
$$\mathscr{L}_{H\tau\tau} = -\frac{m_\tau}{v}\,\bar{\tau}\left(a_\tau + i\,\gamma^5\, b_\tau \right)\tau H$$

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

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



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



1-loop SM box diagrams negligible

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

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

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

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

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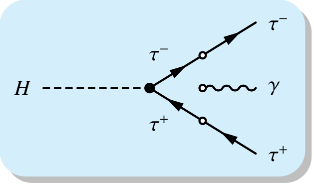

$$\boxed{\mathscr{M} = \mathscr{M}^{(\text{Yuk})} + \mathscr{M}^{(Z\gamma)} + \mathscr{M}^{(\gamma\gamma)}}$$

SM loop effects only

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

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

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

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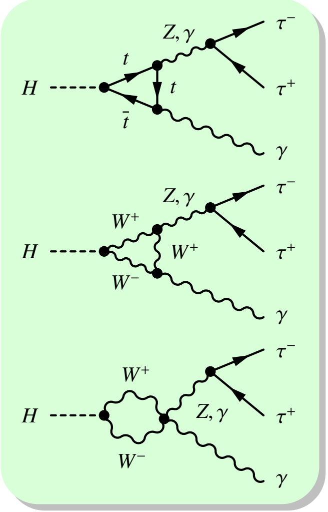


1-loop SM box diagrams negligible

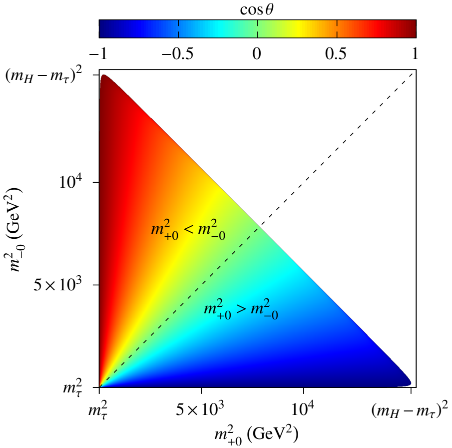
The interference of tree-level and loop-level amplitudes of $H \to \tau^+ \tau^- \gamma$ is sensitive to $b_\tau \neq 0$.

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

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

- non-zero CP-odd ("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:

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

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

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

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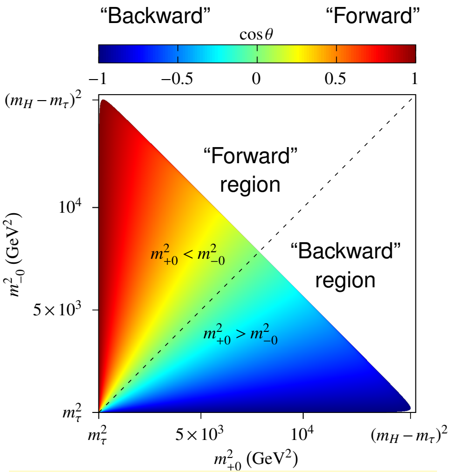


$$\theta \leftrightarrow \pi - \theta \equiv \cos\theta \leftrightarrow -\cos\theta \equiv m_{+0}^2 \leftrightarrow m_{-0}^2$$

- Only 3 Lorentz invariant mass-squares:

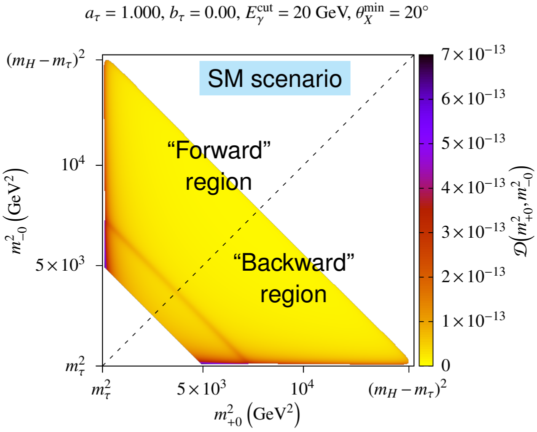
$$m_{+-}^2 \equiv (p_H - p_0)^2 = (p_+ + p_-)^2\,,$$
$$m_{+0}^2 \equiv (p_H - p_-)^2 = (p_+ + p_0)^2\,,$$
$$m_{-0}^2 \equiv (p_H - p_+)^2 = (p_- + p_0)^2\,,$$
$$m_{+-}^2 + m_{+0}^2 + m_{-0}^2 = m_H^2 + 2\,m_\tau^2\,.$$

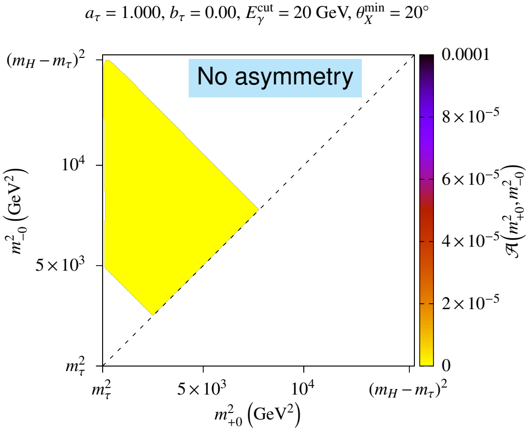
∴ Only 2 *independent* mass-squares.

- In the GJ frame,

$$m_{+0}^2 = M^2 - M'^2\cos\theta,$$
$$m_{-0}^2 = M^2 + M'^2\cos\theta,$$
$$\text{where } M^2 = \frac{1}{2}\left(m_H^2 + 2\,m_\tau^2 - m_{+-}^2\right),$$
$$M'^2 = \frac{1}{2}\left(m_H^2 - m_{+-}^2\right)\left(1 - \frac{4\,m_\tau^2}{m_{+-}^2}\right)^{\frac{1}{2}}.$$

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





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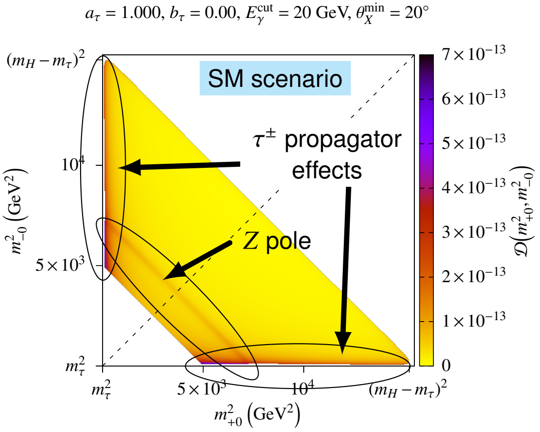

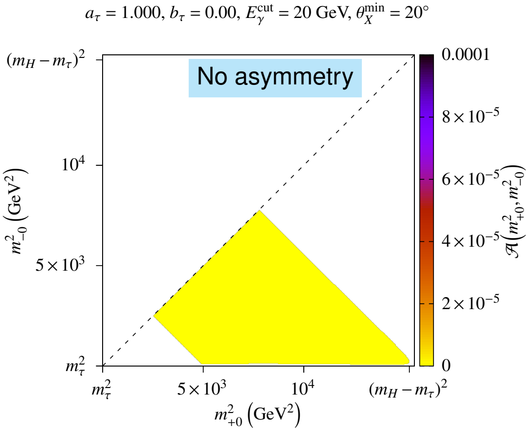

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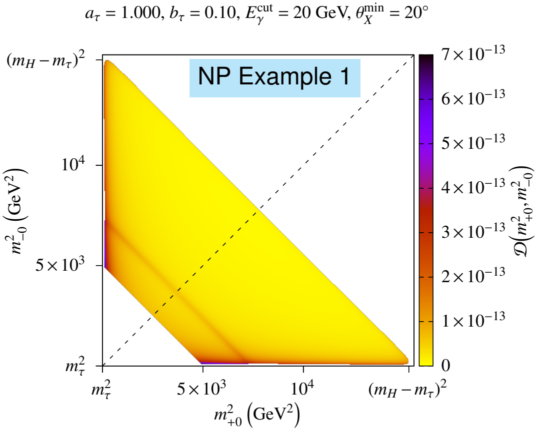

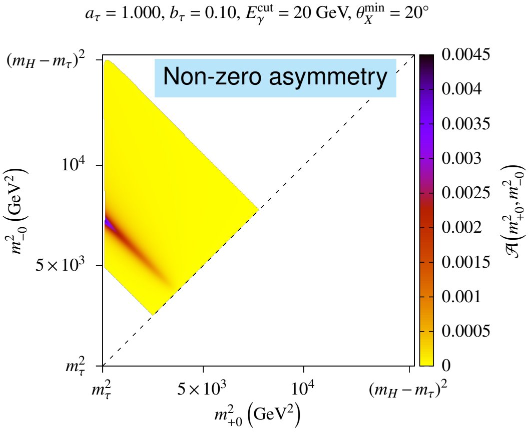

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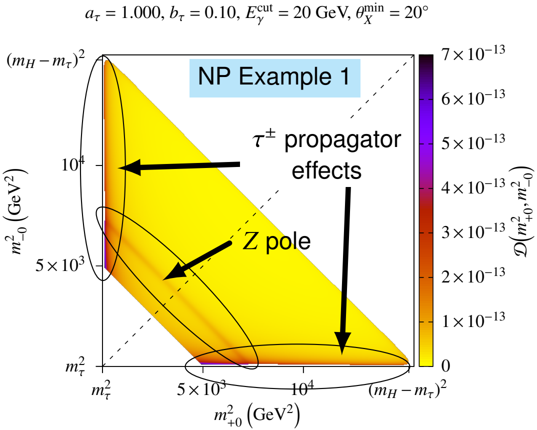
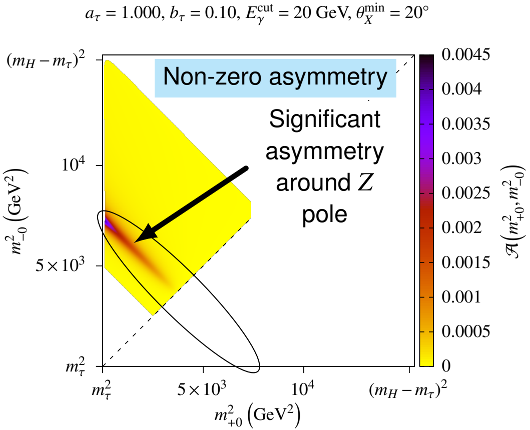
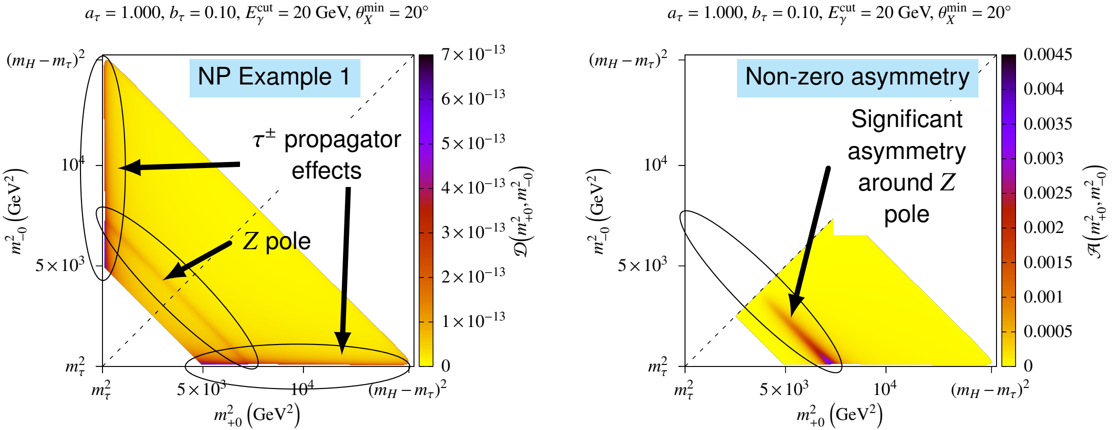




The forward-backward asymmetry can be easily observed in Lorentz invariant Dalitz plot distribution.



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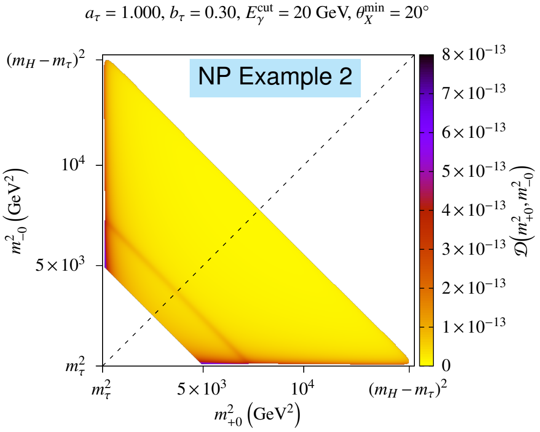

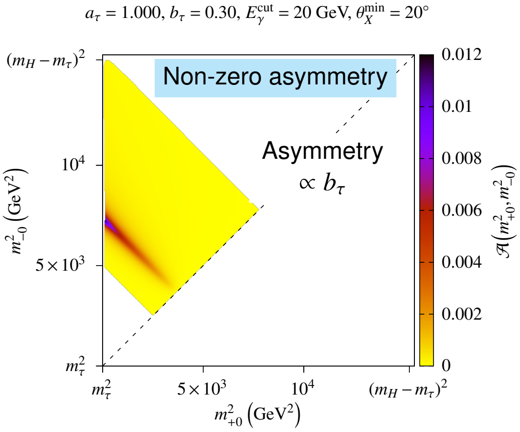

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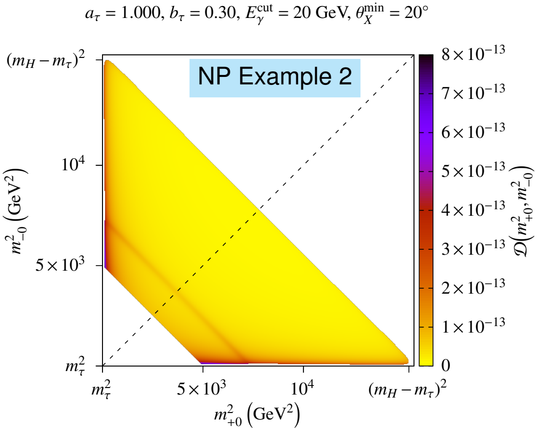

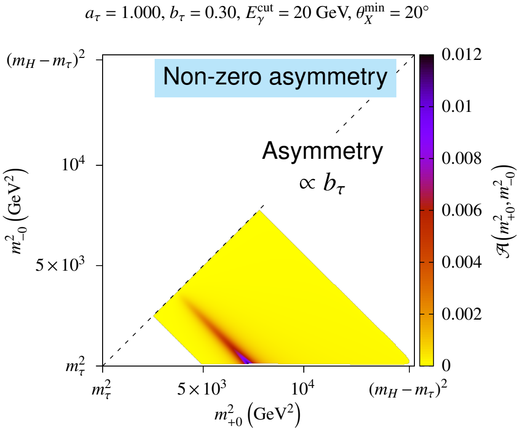

We are investigating how well can this Dalitz plot asymmetry be probed experimentally.

- **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 $m^2_{+0} \leftrightarrow m^2_{-0}$:

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

  (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?**

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

CP violation in τ Yukawa

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

Decay rate:
constrain $a_\tau^2 + b_\tau^2$

$\geqslant$ 4-body decay
$H \to \tau^+ \tau^- \to y^+ y^- \nu_\tau \bar{\nu}_\tau$
$y = \pi, \rho(2\pi), a(3\pi), \ldots$

ϕ distribution: constrain b_τ

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

Dalitz plot distribution:
constrain b_τ

COMPARE:
CP violation in
$H \to Z \gamma$?

Dalitz plot
distributions of
$H \to \ell^+ \ell^- \gamma$,
$\ell = e, \mu$

Thank You