Testing CP violating Higgs sectors at the International Linear Collider

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S. Kanemura, MK, K. Yagyu, arXiv:2101.03702

to appear in JHEP

Introduction

[Sakharov (1967)]
[Kuzmin, Rubakov, Shaposhnikov (1985)]
[Huet and Sather (1995)]
[Kajantie, Laine, Rummukainen, Shaposhnikov (1996)]

- Baryon asymmetry of the Universe requires the Sakharov's conditions:

  1. B violation 2. C and CP violation 3. departure from equilibrium.

- Standard model cannot satisfy them:
  - Kobayashi-Maskawa phase is numerically not sufficient.
  - Phase transition is not first-order getting out of equilibrium.

- Extended Higgs model with extra CP-phases and modifications to Higgs potential can realize electroweak baryogenesis.

- However, such a CP-phase is normally strongly constrained by the current data for the electric dipole moment (EDM).

- We have investigated a scenario with O(1) CP-phase but avoiding the EDM constraint.

[S. Kanemura, MK, K. Yagyu, JHEP 08 (2020) 026]

Can such a CP phase be tested in future accelerator experiments?

Higgs potential

[T. D. Lee (1973)]

$$\Phi_1 = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + h_1 + iG^0) \end{pmatrix}$$

$$\Phi_2 = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(h_2 + ih_3) \end{pmatrix}$$

(Higgs basis)

[Davidson, Haber, PRD72, 035004 (2005)]

$$V = -\mu_1^2|\Phi_1|^2 - \mu_2^2|\Phi_2|^2 - \left\{\boxed{\mu_3^2}(\Phi_1{}^\dagger\Phi_2) + h.c.\right\}$$
$$+ \frac{1}{2}\lambda_1|\Phi_1|^4 + \frac{1}{2}\lambda_2|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_2{}^\dagger\Phi_1|^2$$
$$+ \left\{\left[\frac{1}{2}\boxed{\lambda_5}(\Phi_1{}^\dagger\Phi_2) + \boxed{\lambda_6}|\Phi_1|^2 + \boxed{\lambda_7}|\Phi_2|^2\right](\Phi_1{}^\dagger\Phi_2) + h.c.\right\}$$

Stationary condition:

$$0 = \left.\frac{\partial V}{\partial h_j}\right|_{\Phi_{1,2}=\langle\Phi_{1,2}\rangle} \rightarrow \begin{cases} \mu_1^2 = \frac{1}{2}v^2\lambda_1 \\ \boxed{\mu_3^2} = \frac{1}{2}v^2\boxed{\lambda_6} \end{cases}$$

Phase redefinition: $\arg(\lambda_5) = 0$

Two complexes: $\boxed{\lambda_{6,7} = |\lambda_{6,7}|e^{i\theta_{6,7}}}$

Higgs potential

$$\Phi_1 = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + h_1 + iG^0) \end{pmatrix}$$
$$\Phi_2 = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(h_2 + ih_3) \end{pmatrix}$$

We assume $\lambda_6 = 0$.

Mass eigenstate

- Mass matrix: $\mathcal{M}^2 = v^2 \begin{pmatrix} \lambda_1 & \cancel{|\lambda_6|\cos\theta_6} & \cancel{-|\lambda_6|\sin\theta_6} \\ & \mathcal{M}_{22} & -\frac{1}{2}|\lambda_5|\sin\theta_5 \\ & & \mathcal{M}_{33} \end{pmatrix}$ $\begin{matrix} h_1 = H_1^0 \\ h_2 = H_2^0 \\ h_3 = H_3^0 \end{matrix}$

The one scalar h_1 does not mix with the others.

$\rightarrow$ At tree level, $\boxed{\dfrac{g^{\rm 2HDM}_{H_1^0 XX}}{g^{\rm SM}_{hXX}} = 1}$

$\begin{cases} X & \text{: SM particle} \\ H_1^0 & \text{: 125 GeV Higgs} \end{cases}$

$\rightarrow$ In the potential, one CP-violating phase, $\boldsymbol{\theta_7}$ of λ_7 remains.

Yukawa interaction

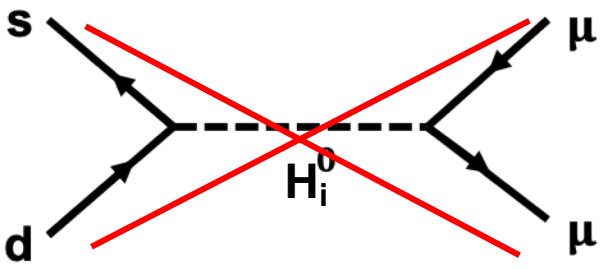
$$\Phi_1 = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + h_1 + iG^0) \end{pmatrix}$$

$$\Phi_2 = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(h_2 + ih_3) \end{pmatrix}$$

$$\mathcal{L}_Y \supset -\frac{\sqrt{2}}{v}\bar{Q}_L^i \left(M_d^{ij}\Phi_1 + \boxed{Y_d^{ij}}\Phi_2 \right) d_R^j + h.c.$$

FCNC should be suppressed.

FCNC: Flavor changing neutral current



We assume $Y_f^{ij} = \zeta_f M_f^{ij}$. → No FCNC

[A. Pich, P. Tuzon, PRD80, 091702 (2009)]

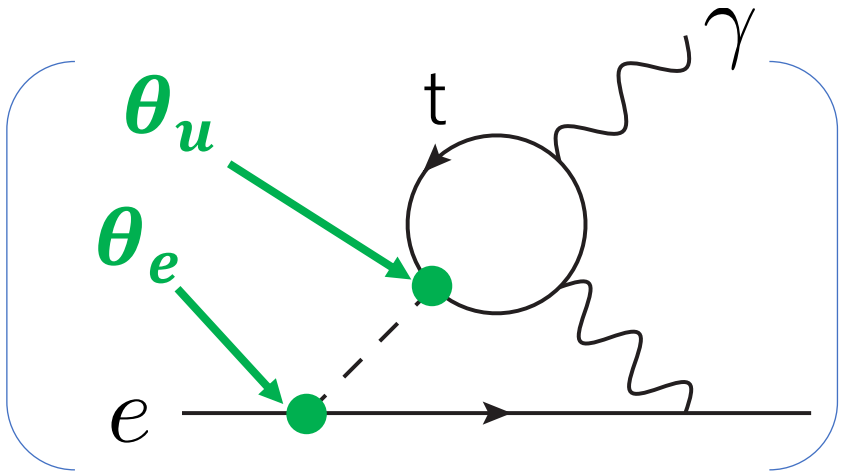
$$\boxed{\zeta_f = |\zeta_f| e^{i\theta_f}} \quad f = u, d, e$$

→ Three CP-violating phases, θ_f (f = u,d,e) arise from Yukawa term.

Contribution to the EDM $\mathcal{L}_{EDM} = -i\frac{d}{2}\,\bar{\psi}\sigma^{\mu\nu}\gamma^5\psi\,F_{\mu\nu}$

- Barr-Zee diagram is the leading contribution to electron EDM.

$d_e =$



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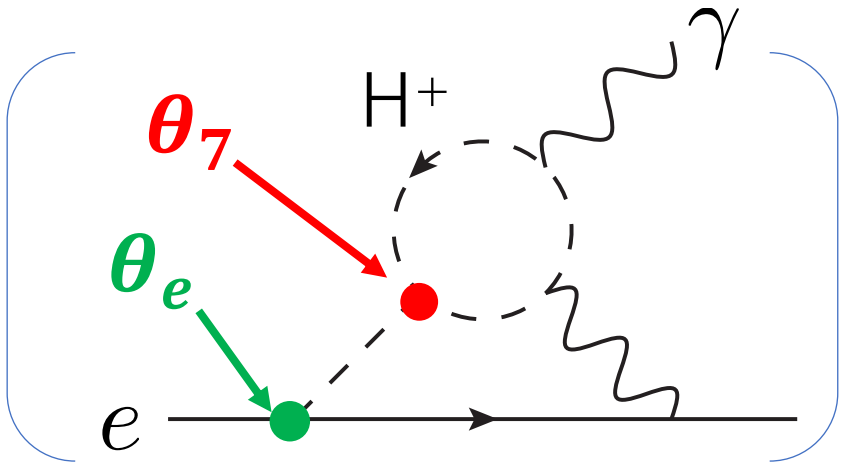


$< d_e^{(\mathrm{exp.})}$

$\zeta_f = |\zeta_f| e^{i\theta_f}$

$f = u, d, e$

$\lambda_7 = |\lambda_7| e^{i\theta_7}$

Destructive interference

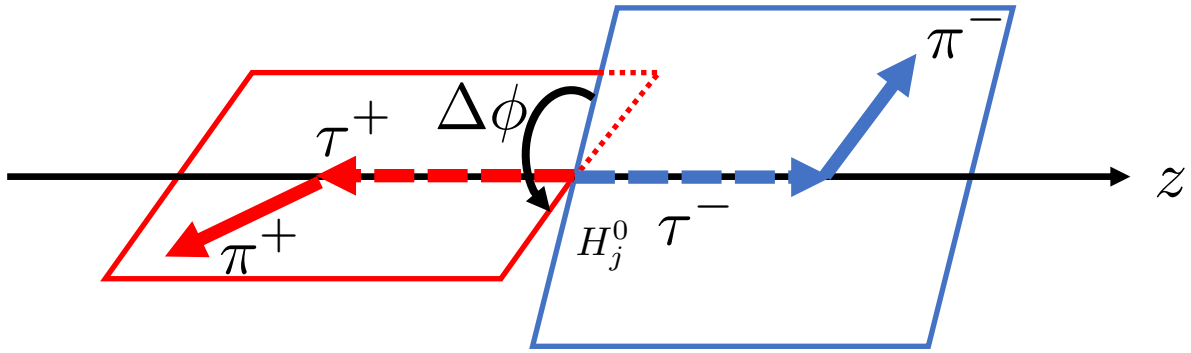
While the CP phase is O (1), the EDM constraint can be satisfied.

[S. Kanemura, MK, K. Yagyu, JHEP 08 (2020) 026]

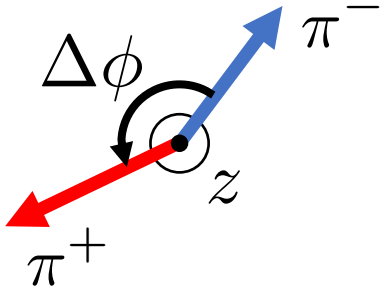
Angular distribution

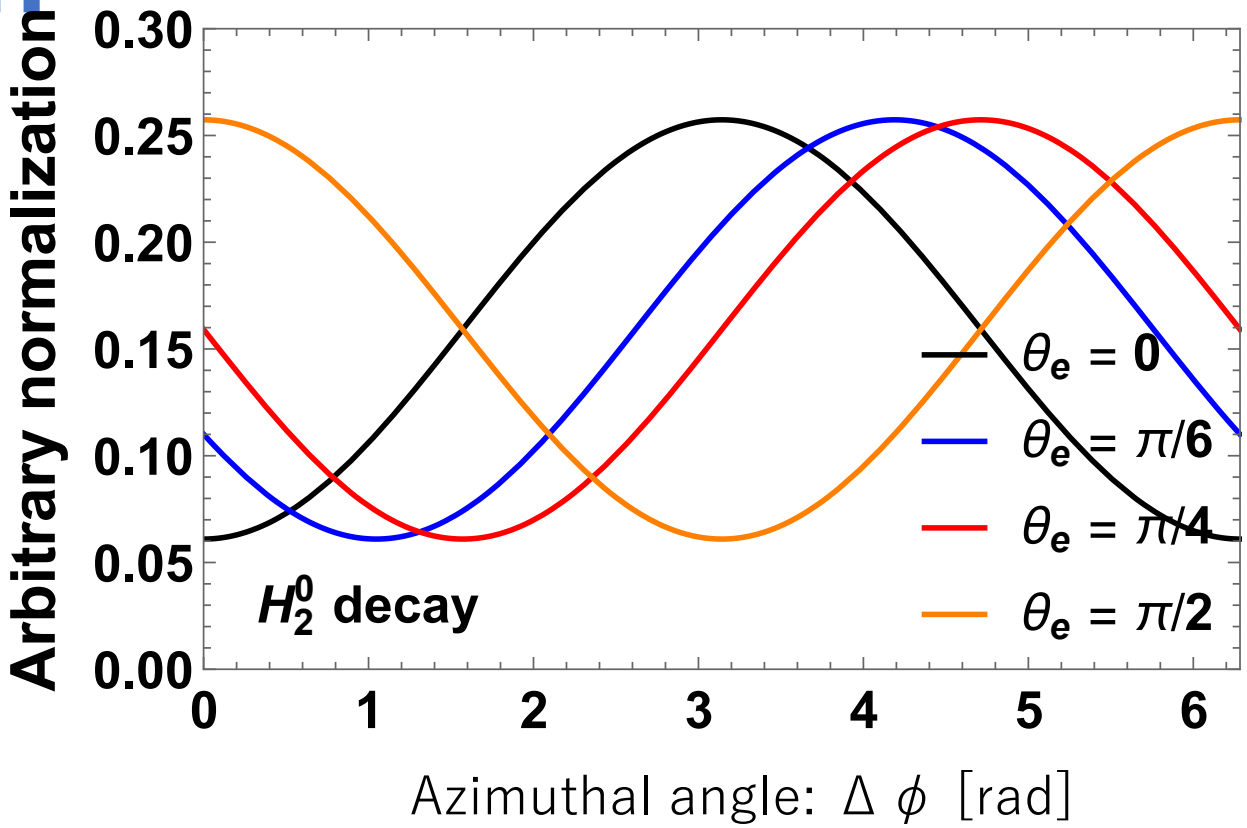
[S. Kanemura, MK, K. Yagyu, arXiv:2101.03702]

Decay of the extra Higgs boson



View looking along the z axis:





Can such a CP phase be tested in future accelerator experiments?

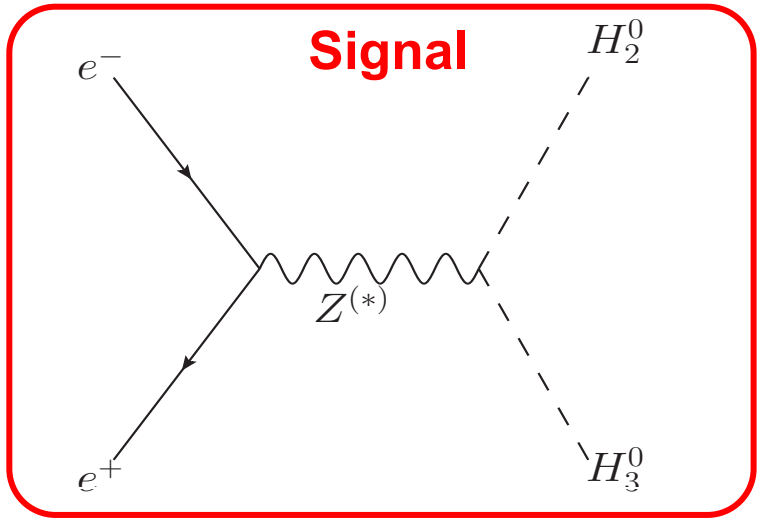
Difficult in the LHC in terms of additional Higgs boson production and background.

We focus on testing the angular distribution on the ILC.

Signal & background

$e^+ e^- \to b \bar{b} \tau^+ \tau^- \ (\nu \nu)$

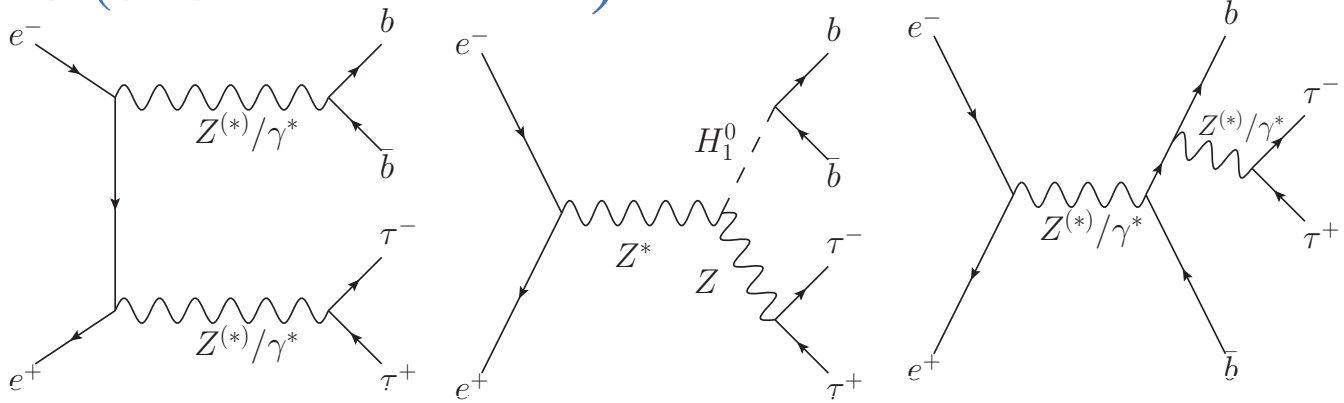
[S. Kanemura, MK, K. Yagyu, arXiv:2101.03702]



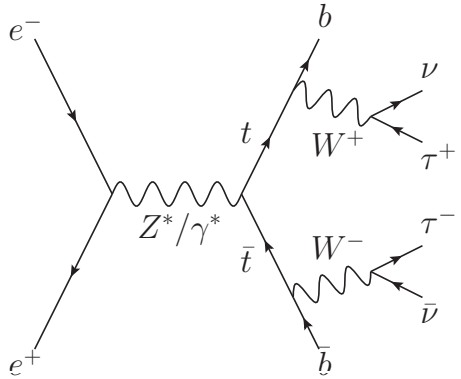
- "MadGraph5" and "TauDecay" were used.
- Decay mode: $\tau^\pm \to \pi^\pm \nu$, $\varrho^\pm \nu$ and $a_1^\pm \nu$
- Bottom tagging efficiency: 70%
- Beam polarization of $e^- e^+$: (-0.8,0.3)

MadGraph5: [Alwall, Herquet, Maltoni, Mattelaer, Stelzer (2011)]
TauDecay: [Hagiwara, Li, Mawatari, Nakamura (2013)]

BG $(e^+ e^- \to b \bar{b} \tau^+ \tau^-)$

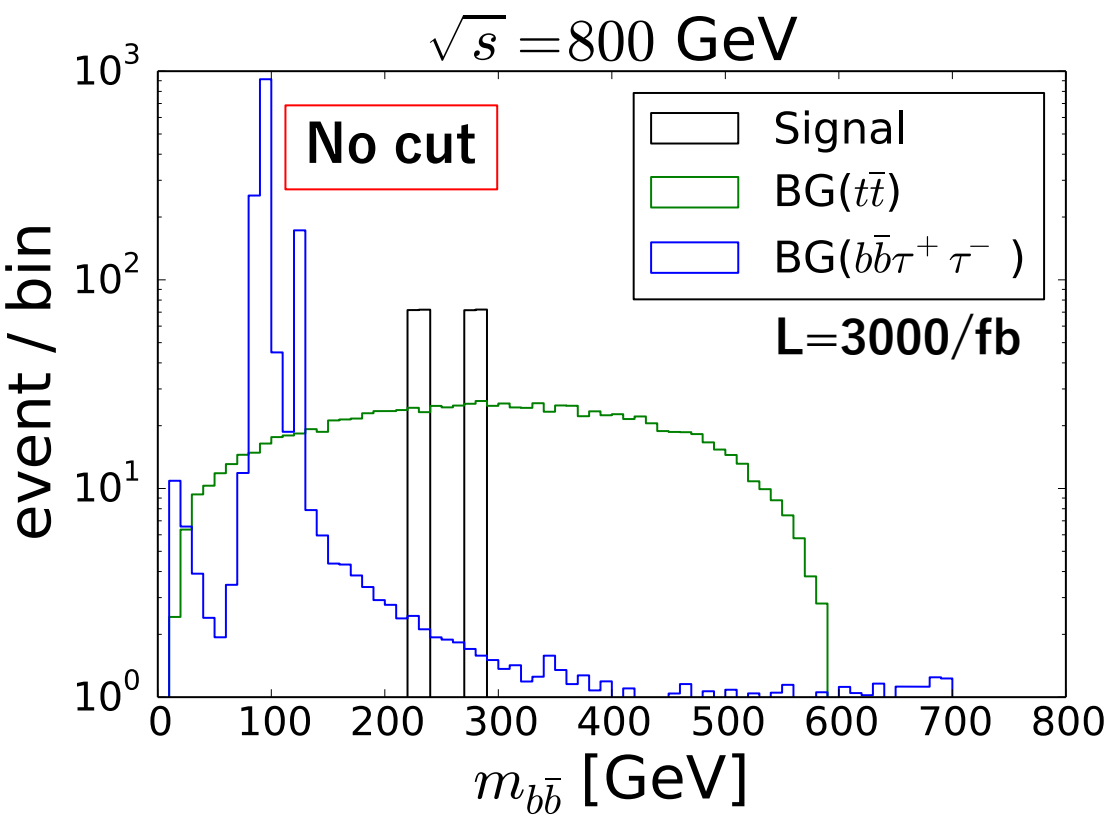


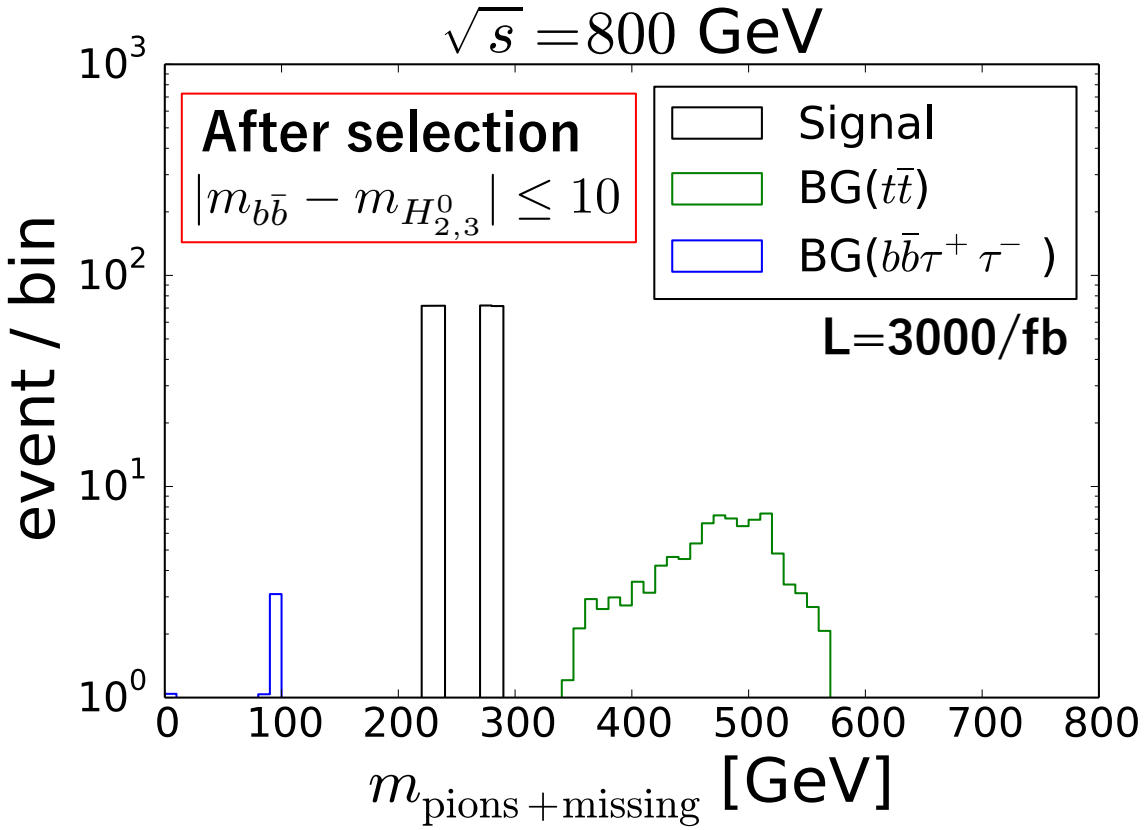
BG $(e^+ e^- \to b \bar{b} \tau^+ \tau^- \nu \nu)$



Signal & background

[S. Kanemura, MK, K. Yagyu, arXiv:2101.03702]





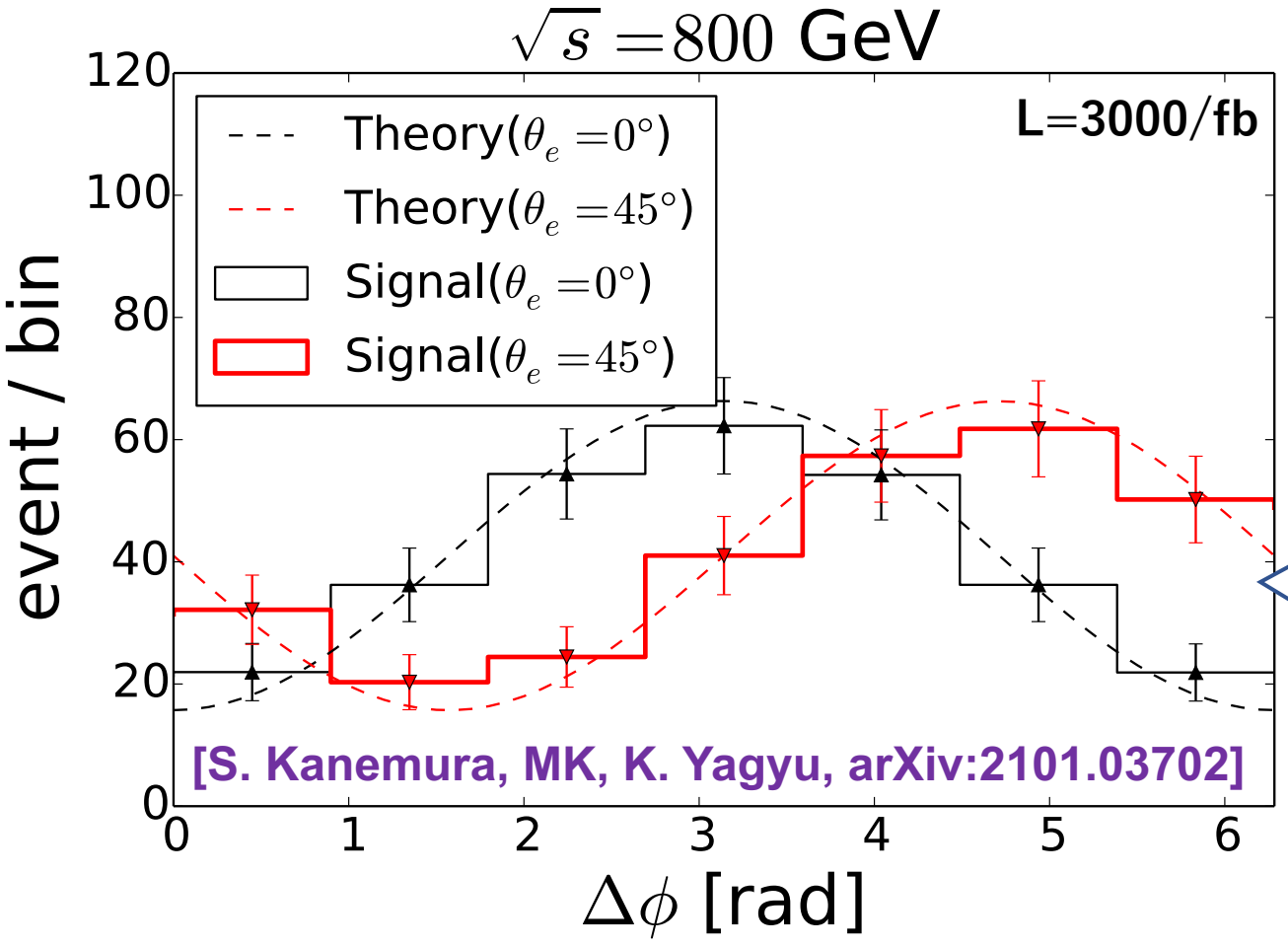
Cut:

$$|m_{b\bar{b}} - m_{H^0_{2,3}}| \leq 10$$
$$|m_{\text{pions+missing}} - m_{H^0_{2,3}}| \leq 10$$

Most of the background events can be removed by two kinematic cuts.

Result

Process : $e^+ e^- \to H_2 H_3, \begin{cases} H_2 \to \tau^+ \tau^-, H_3 \to b\,\bar{b} \\ H_2 \to b\,\bar{b}, H_3 \to \tau^+ \tau^- \end{cases}$



Input:

$|\zeta_u| = 0.01, |\zeta_d| = 0.1,$ $m_{H^+} = 230[\mathrm{GeV}]$

$|\zeta_e| = 0.5, |\lambda_7| = 0.3$ $m_{H_2^0} = 280[\mathrm{GeV}]$

$m_{H_3^0} = 230[\mathrm{GeV}]$

The deviation from the CP conserving case:

$$\frac{N_{\theta_e=\frac{\pi}{4}} - N_{\mathrm{CPC}}}{\sqrt{N_{\mathrm{CPC}}}} > 5$$

CP violation can be detected at the ILC!

[S. Kanemura, MK, K. Yagyu, arXiv:2101.03702]

Other scenario

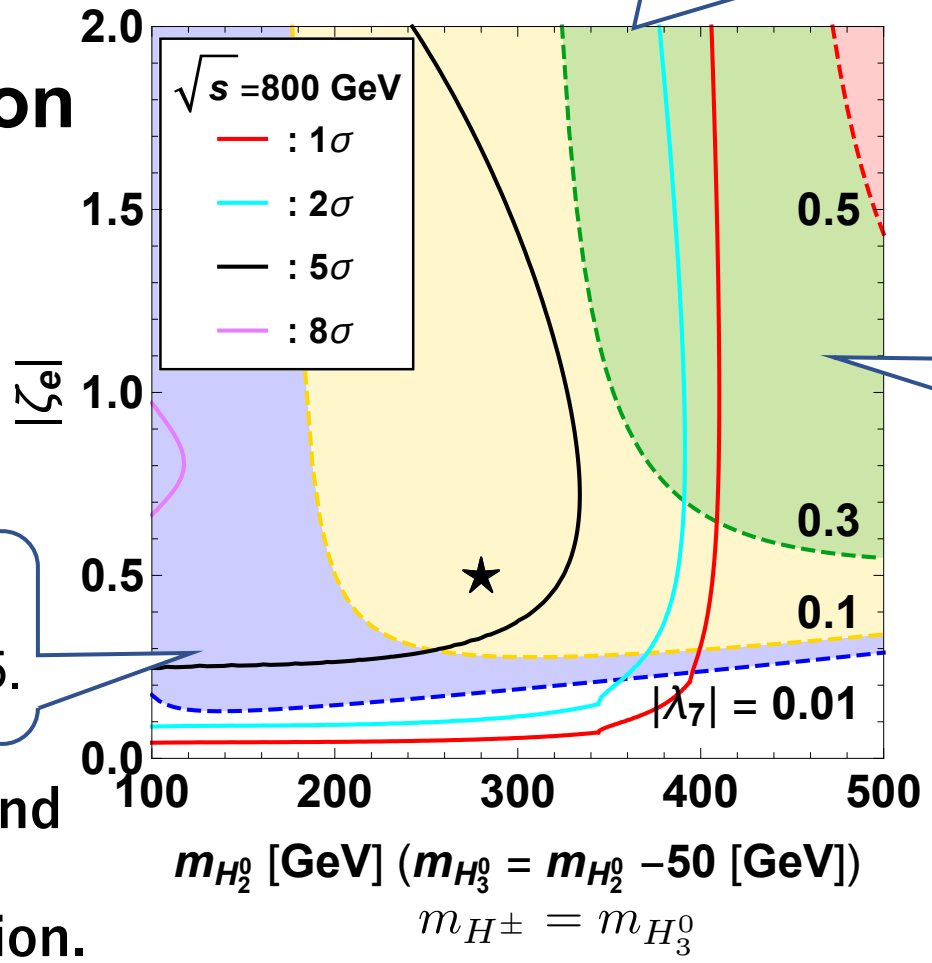
★: Benchmark point when $|\lambda_7|$ = 0.3 and θ_7= -1.8.

Angular distribution (Solid lines)

$$\Delta_{\rm CP} \equiv \frac{N_{\theta_e=\frac{\pi}{4}} - N_{\rm CPC}}{\sqrt{N_{\rm CPC}}}$$

L=3000/fb

Black solid line: $\Delta_{CP} = 5$.
Left side of the line: $\Delta_{CP} > 5$.



EDM experiment (Colored region)

Green area: when $|\lambda_7|$ = 0.3, the EDM constraint cannot be satisfied for any value of θ_7.

In the area with heavier $H^\pm$, the EDM cancellation cannot work due to the unbalance of the two contributions between the fermion-loops and the Higgs boson-loops on the BZ diagrams.

In the area with lighter H_2 and H_3, the Δ_{CP} becomes grater due to the larger cross section.

The ILC can play a complement role to the future EDM experiments!

Summary

1. We have considered the two Higgs doublet model with CP violation in the Yukawa interaction and the Higgs potential.
2. EDM constraint can be satisfied by the destructive interference between multiple O(1) CP-violating phases.
3. The analysis of the angular distribution of the additional Higgs boson decay showed that the CP phase of this scenario can be detected by the ILC.
4. In the future work, we will further develop this scenario and propose a new scenario that can be tested in future experiments while satisfying existing experiments and solving BAU.

Back up

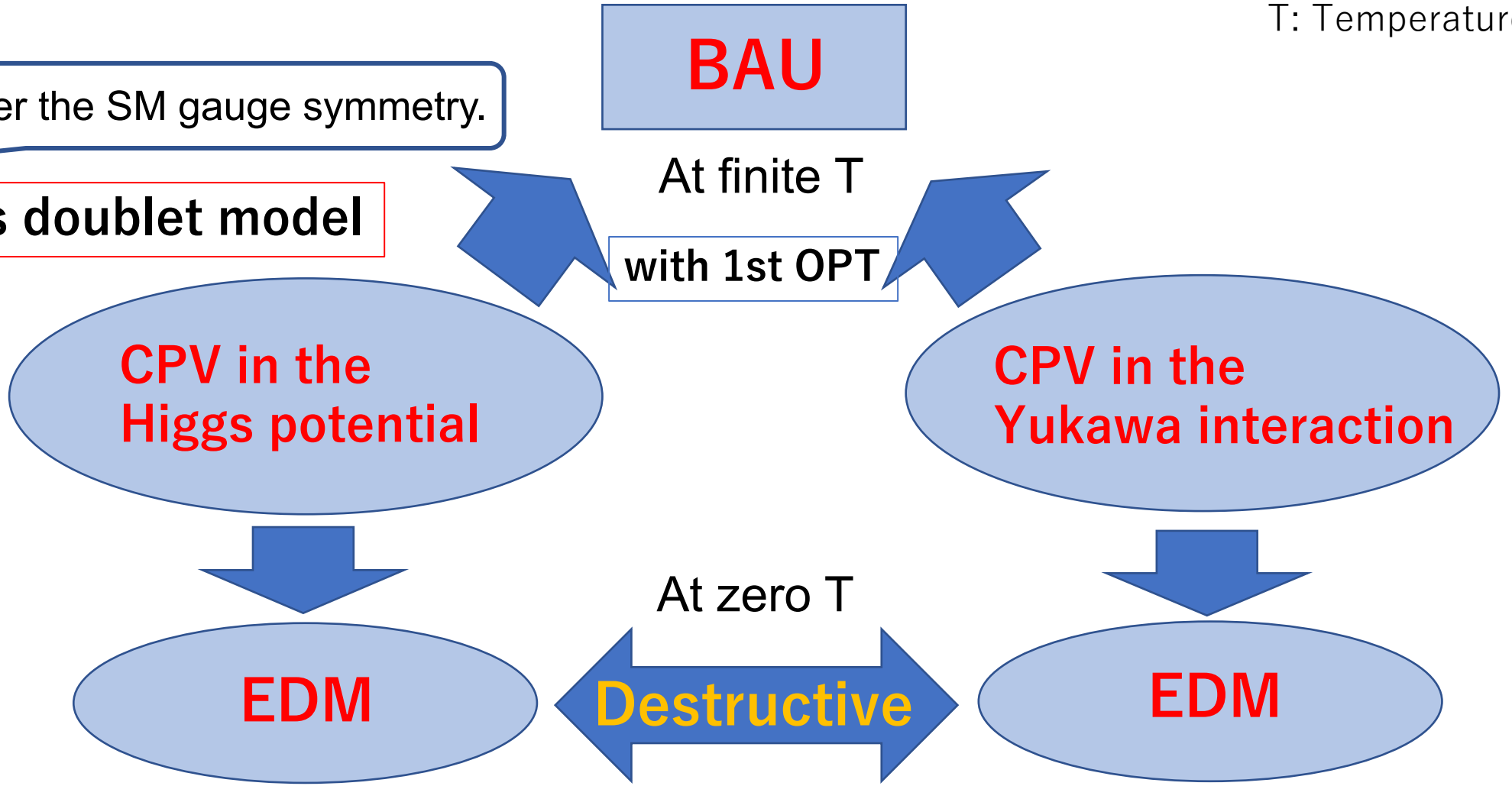
Our model

BAU: Baryon number asymmetry of the Universe

T: Temperature

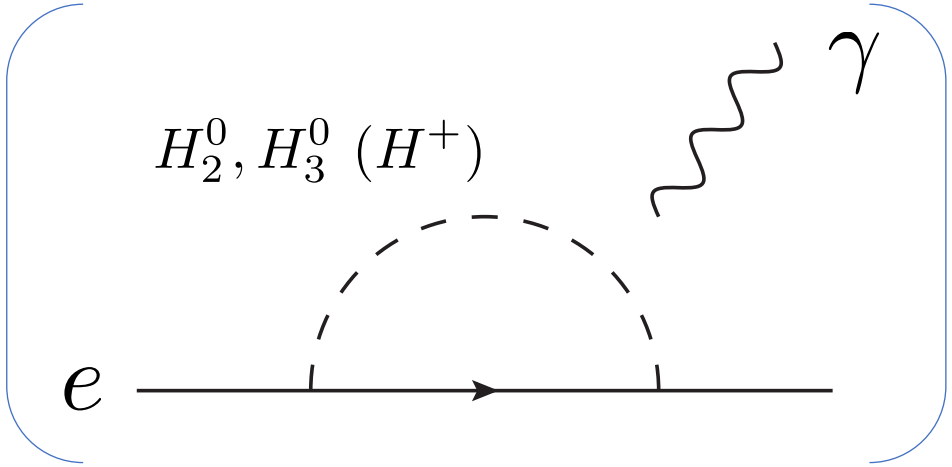
It is general under the SM gauge symmetry.

Two Higgs doublet model



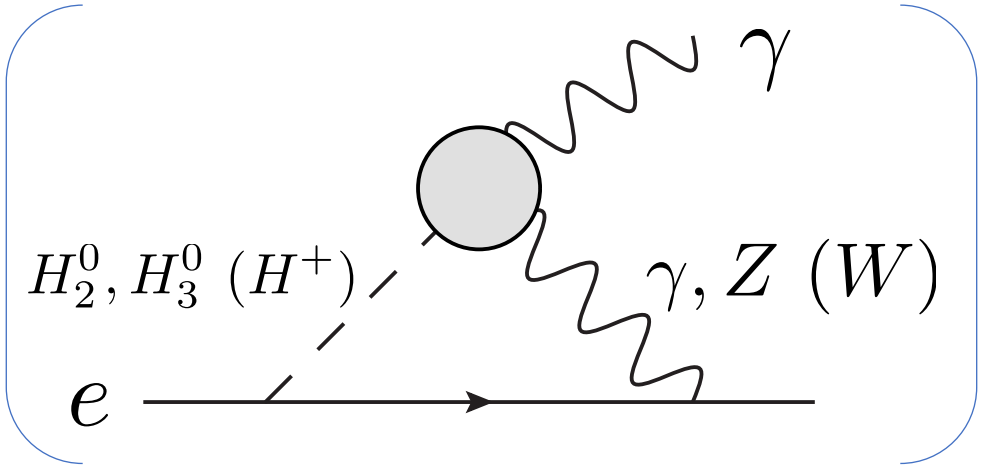
Contribution to the EDM $\mathcal{L}_{EDM} = -i\frac{d}{2}\,\bar{\psi}\sigma^{\mu\nu}\gamma^5\psi\,F_{\mu\nu}$

- Barr-Zee diagrams (2-loop) give a larger contribution.
  [Barr, Zee, PRL (1990)]



$$\propto \frac{1}{(4\pi)^2} y_e^3$$

$<$



$$\propto \frac{1}{(4\pi)^4} y_e$$

[S. Kanemura, MK, K. Yagyu, JHEP 08 (2020) 026]

Numerical result: Electron EDM

- Input: $(\theta_u, \theta_d, \theta_e, \theta_7) = (2, 0, \pi/2, 1)$

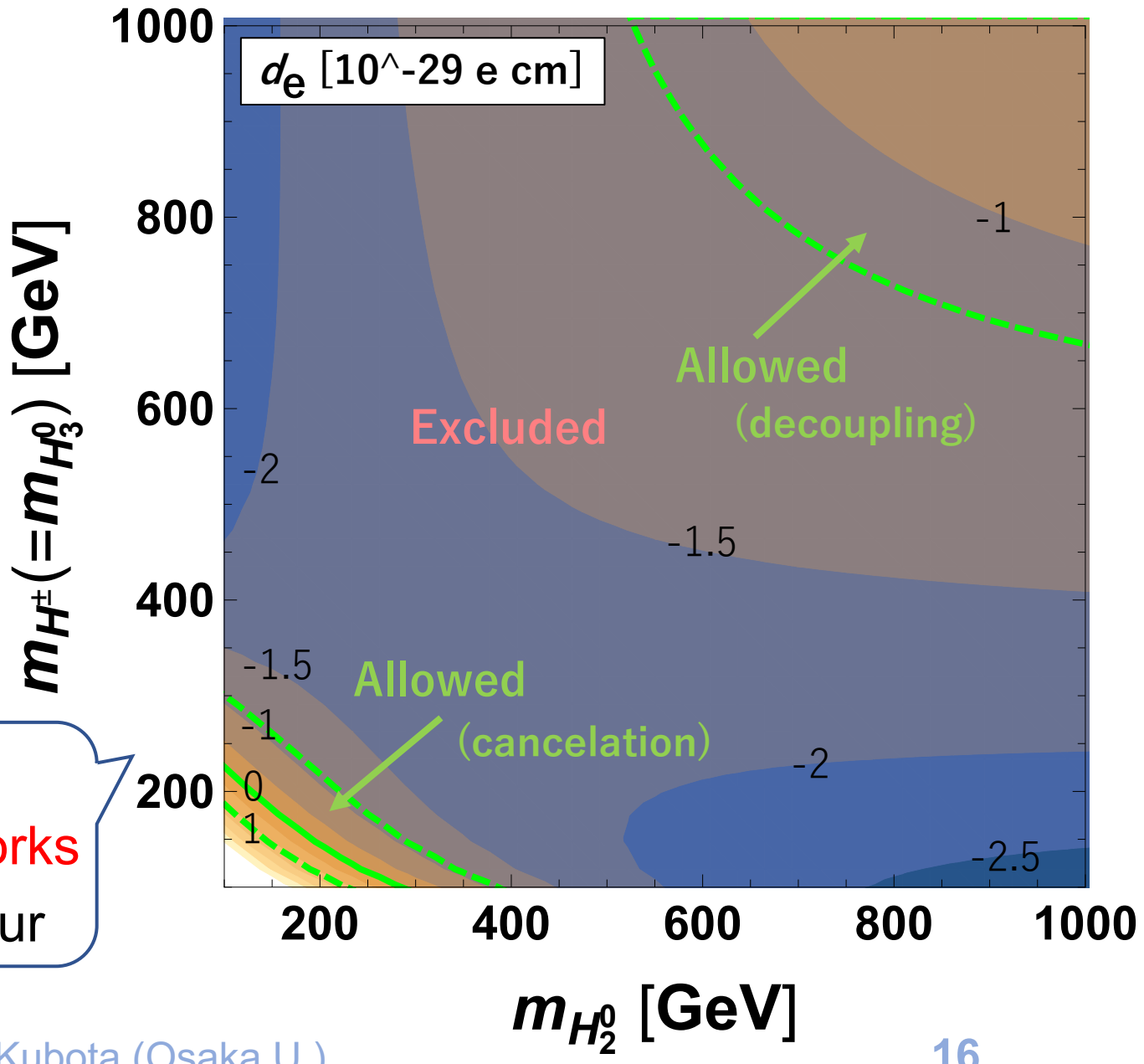
  $|\zeta_u| = 0.01, |\zeta_d| = 0.1,$

  $|\zeta_e| = 0.5, |\lambda_7| = 0.3$

- Output:

  — : $d_e = 0$

  - - -: Latest EDM bound



EDM is getting the small value:

Masses ~ 200 GeV -> Cancellation works

Masses ~1000 GeV -> Decoupling occur

[S. Kanemura, MK, K. Yagyu, JHEP 08 (2020) 026]

Numerical result: Electron EDM

- Input:

$$m_{H^+} = 230[\mathrm{GeV}]$$

$$|\zeta_u| = 0.01, |\zeta_d| = 0.1, \quad m_{H_2^0} = 280[\mathrm{GeV}]$$

$$|\zeta_e| = 0.5, |\lambda_7| = 0.3 \quad m_{H_3^0} = 230[\mathrm{GeV}]$$

- Output:

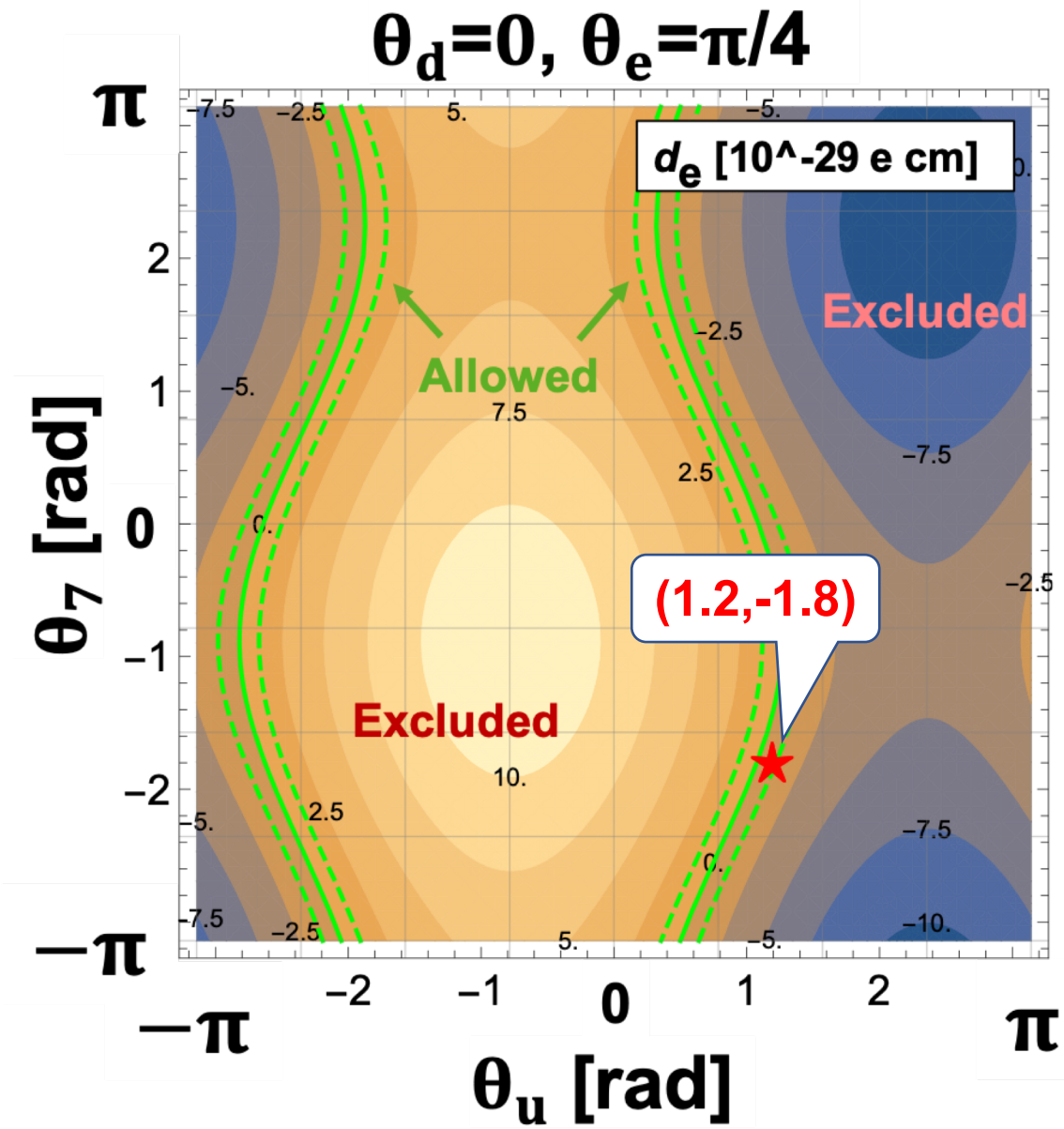
— : $d_e = 0$
- - -: Latest EDM bound

At the benchmark point (1.2, -1.8):

$$d_e = -0.95\,[10^{-29}\ \mathrm{e\ cm}]$$

$$|d_e^{\mathrm{exp.}}| < 1.1 \quad [10^{-29}\ \mathrm{e\ cm}]$$

[ACME collaboration, Nature (2018)]



→ **While the CP phase is O (1), the EDM constraint can be satisfied.**

Angular distribution

$$\theta_e = n\pi \quad (n = 0, 1, 2, ...) \ : \text{CP even}$$
$$\theta_e = n\pi + \pi/2 \ : \text{CP odd}$$

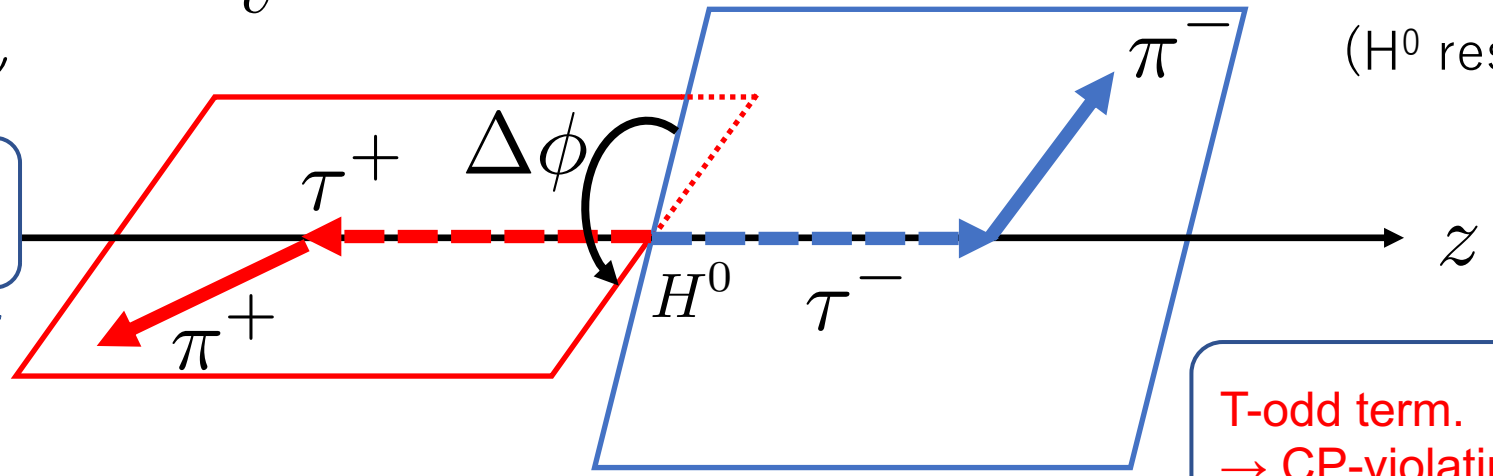
Decay of the extra Higgs boson

$$\mathcal{L}_{H^0\tau\tau} = -\frac{m_\tau}{v}|\kappa|\bar{\tau}(\cos\theta_e + i\sin\theta_e\gamma_5)\tau H^0$$

Ex.)$H_j^0 \to \tau^+\tau^- \to \pi^+\bar{\nu}\pi^-\nu$

(H⁰ rest frame)

The plane is defined by the tau and pi momenta.



$$\vec{\chi}^\pm \equiv \frac{\vec{p}_{\chi^\pm}}{|\vec{p}_{\chi^\pm}|}, \ \chi = \tau, \ \pi$$

T-odd term. $p \xrightarrow{T} -p$
→ CP-violating term.

$$\overline{|\mathcal{M}|^2} \propto 1 + (\vec{\pi}^- \cdot \vec{\tau}^-)(\vec{\pi}^+ \cdot \vec{\tau}^-)$$
$$- \cos 2\theta_e (\vec{\pi}^- \times \vec{\tau}^-) \cdot (\vec{\pi}^+ \times \vec{\tau}^-) - \sin 2\theta_e (\vec{\pi}^- \times \vec{\pi}^+) \cdot \vec{\tau}^-$$

When CP even and CP odd mix, sinθ appears.

Angular distribution

$$\theta_e = n\pi \quad (n = 0, 1, 2, ...) \ : \text{CP even}$$
$$\theta_e = n\pi + \pi/2 \ : \text{CP odd}$$

Decay of the extra Higgs boson

$$\mathcal{L}_{H^0\tau\tau} = -\frac{m_\tau}{v}|\kappa|\bar{\tau}(\cos\theta_e + i\sin\theta_e\gamma_5)\tau H^0$$

Ex.)$H_j^0 \to \tau^+\tau^- \to \pi^+\bar{\nu}\pi^-\nu$

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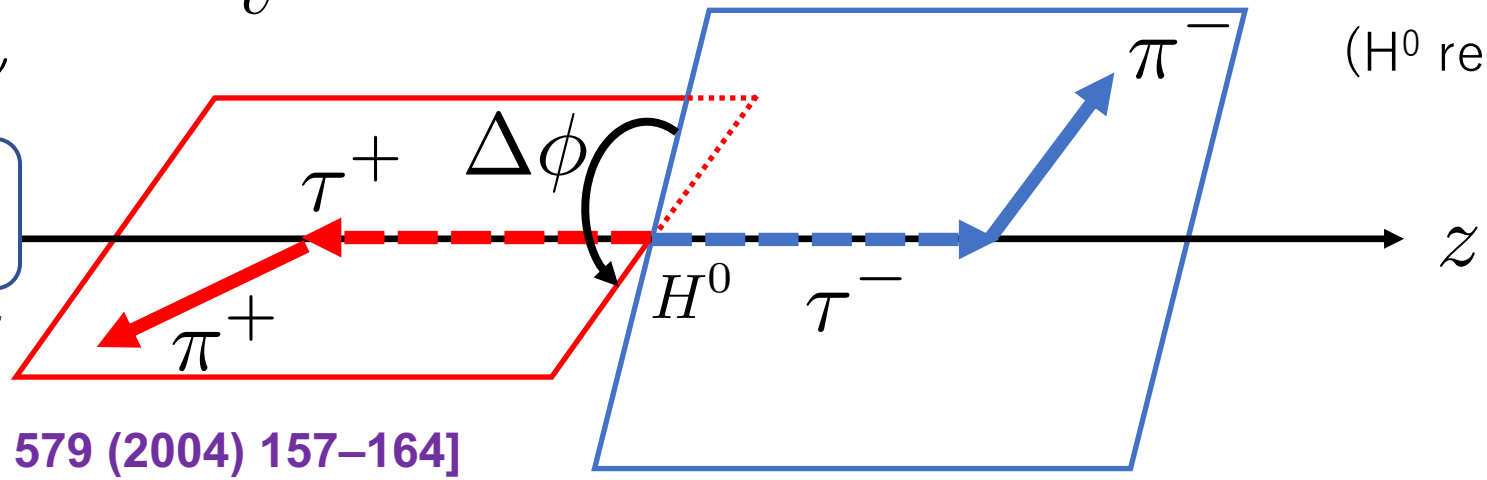


[Desch, Imhof, Was, Worek, PLB 579 (2004) 157–164]

$$\overline{|\mathcal{M}|^2} \propto 1 + \vec{\pi}^-_{||} \cdot \vec{\pi}^+_{||} - \cos 2\theta_e \underbrace{\vec{\pi}^-_{\perp} \cdot \vec{\pi}^+_{\perp}}_{\cos\Delta\phi} - \sin 2\theta_e \underbrace{(\vec{\pi}^-_{\perp} \times \vec{\pi}^+_{\perp})_{||}}_{\sin\Delta\phi}$$

$\vec{\chi}^\pm \equiv \frac{\vec{p}_{\chi^\pm}}{|\vec{p}_{\chi^\pm}|}$

$||$: parallel to z axis

$\perp$: vertical to z axis

Signal & background

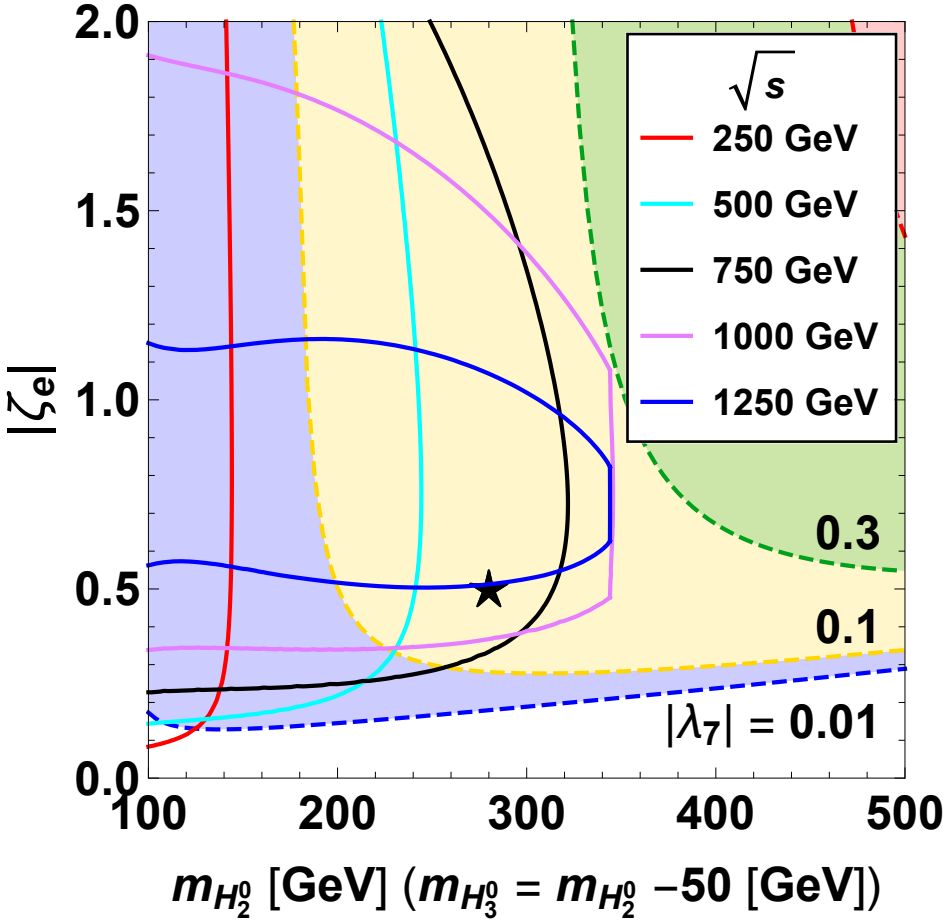
- $e^+ e^- \rightarrow b \bar{b} \tau^+ \tau^- (\nu \nu)$

[S. Kanemura, MK, K. Yagyu, arXiv:2101.03702]

	$t\bar{t}$	$b\bar{b}\tau^+\tau^-$	$H_2^0 H_3^0$	$S/\sqrt{S+B}$
No cut	6093	10080	1867	13.90
$\lvert m_{b\bar{b}} - m_{H^0_{3/2}} \rvert \leq 10$ GeV	272/308	23/24	934/933	26.64/26.23
$\lvert m_{\text{pions+missing}} - m_{H^0_{2/3}} \rvert \leq 10$ GeV	0/0	0/0	934/933	30.56/30.55
Combined values after $m_{b\bar{b}}$ cut	580	47	1867	37.28
Combined values after two cuts	0	0	1867	43.21

[S. Kanemura, MK, K. Yagyu, arXiv:2101.03702]

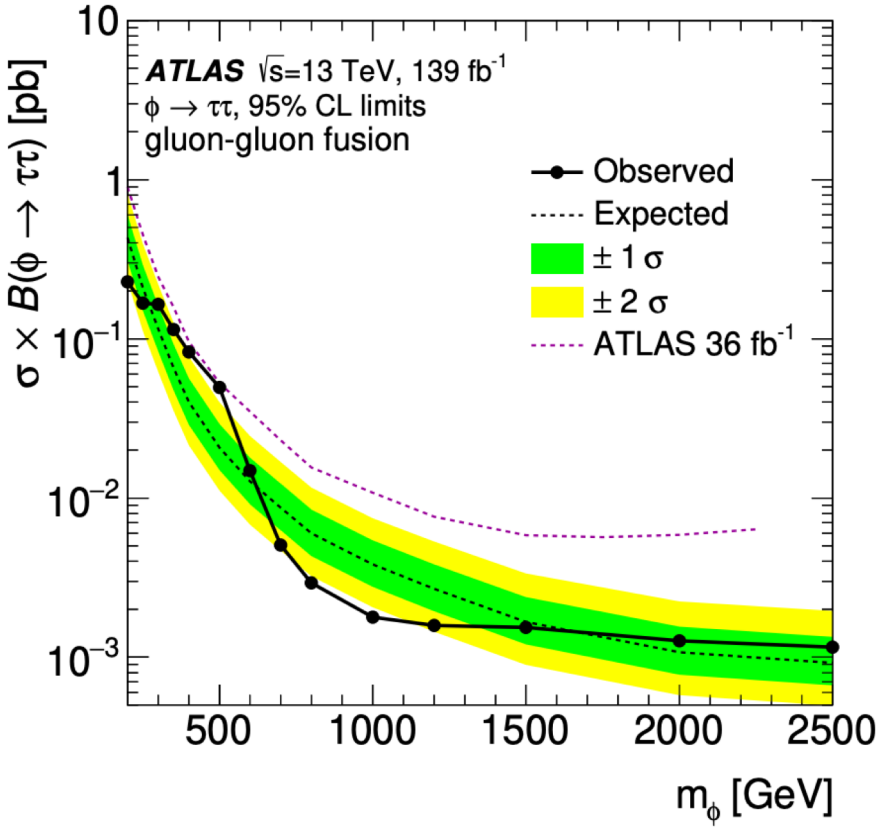
Other scenario

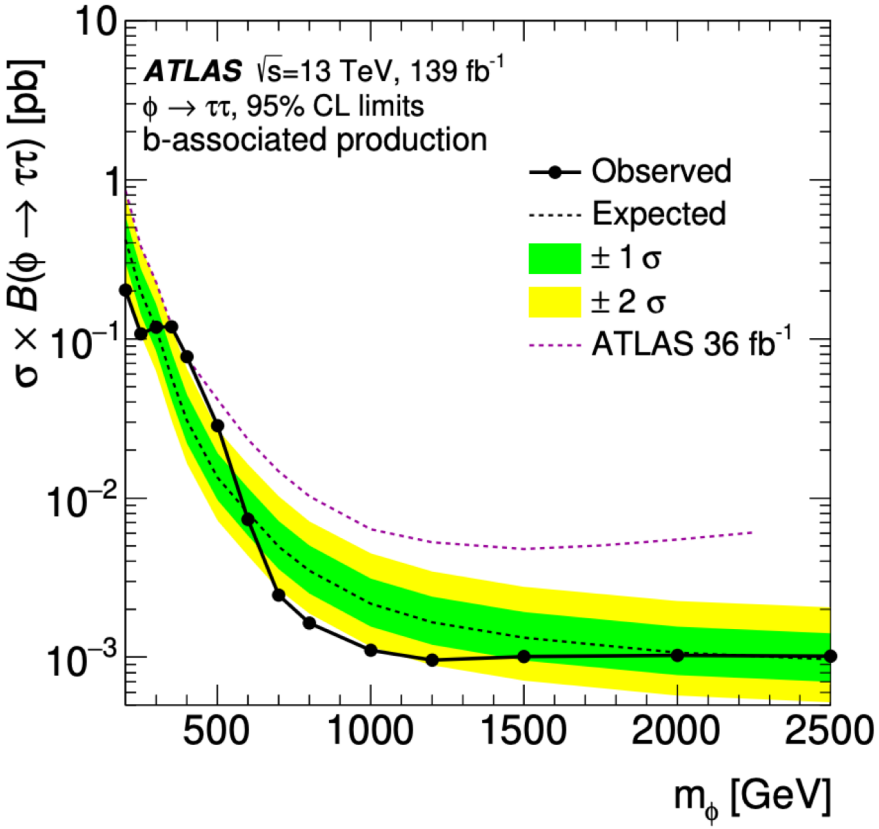


$m_{H^\pm} = m_{H_3^0}$

Productions

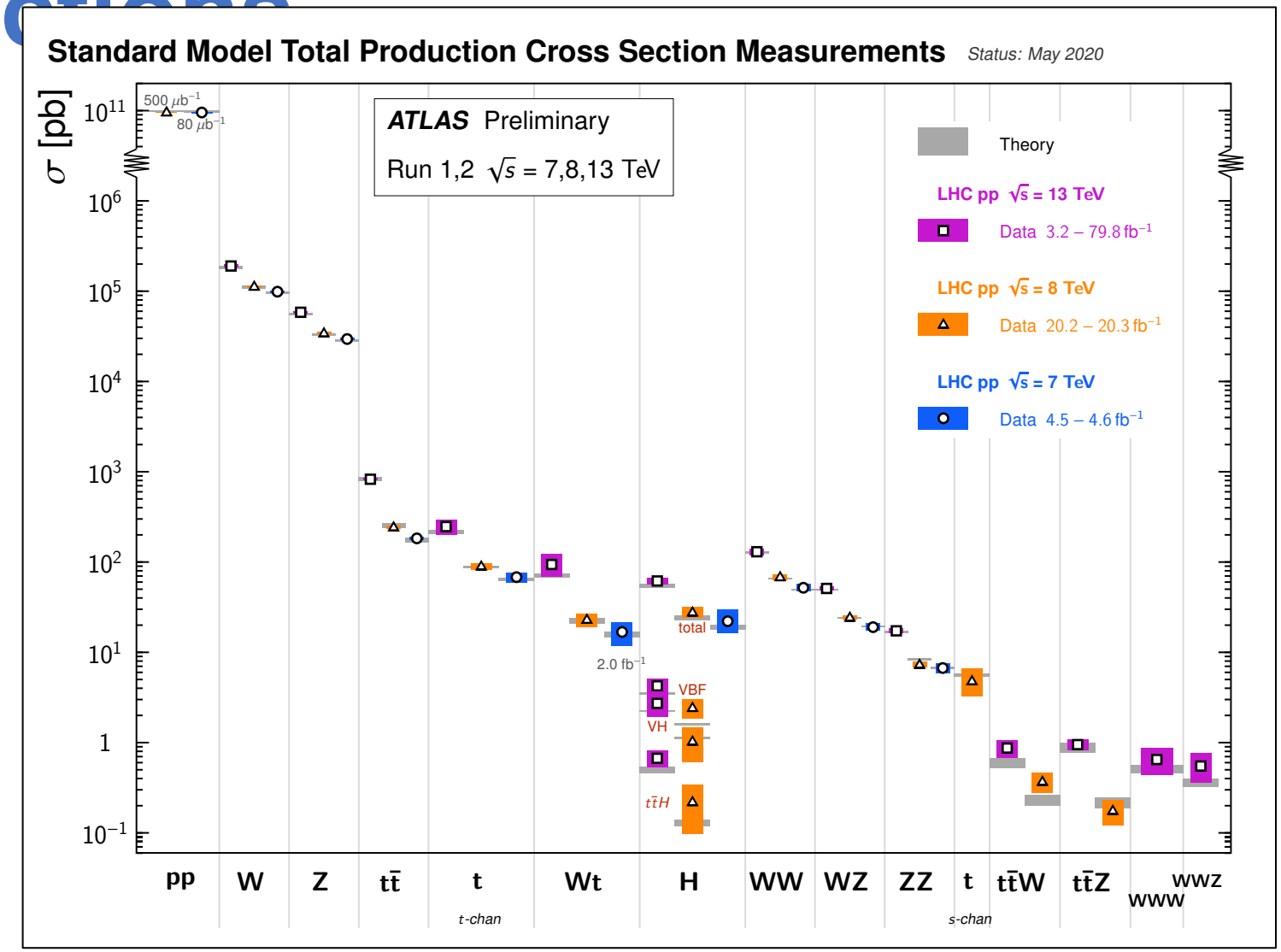
[arXiv:2002.12223]





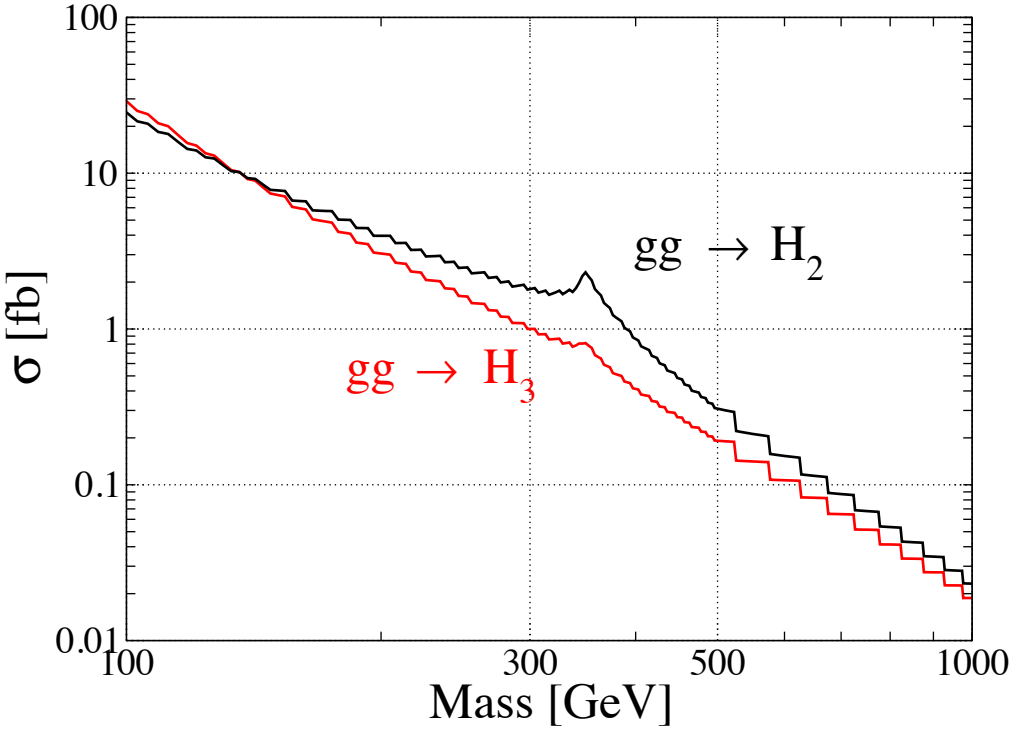
The observed and expected 95% CL upper limits on the production cross section times branching fraction for a scalar boson (φ) produced via (left) ggF and (right) b-associated production.

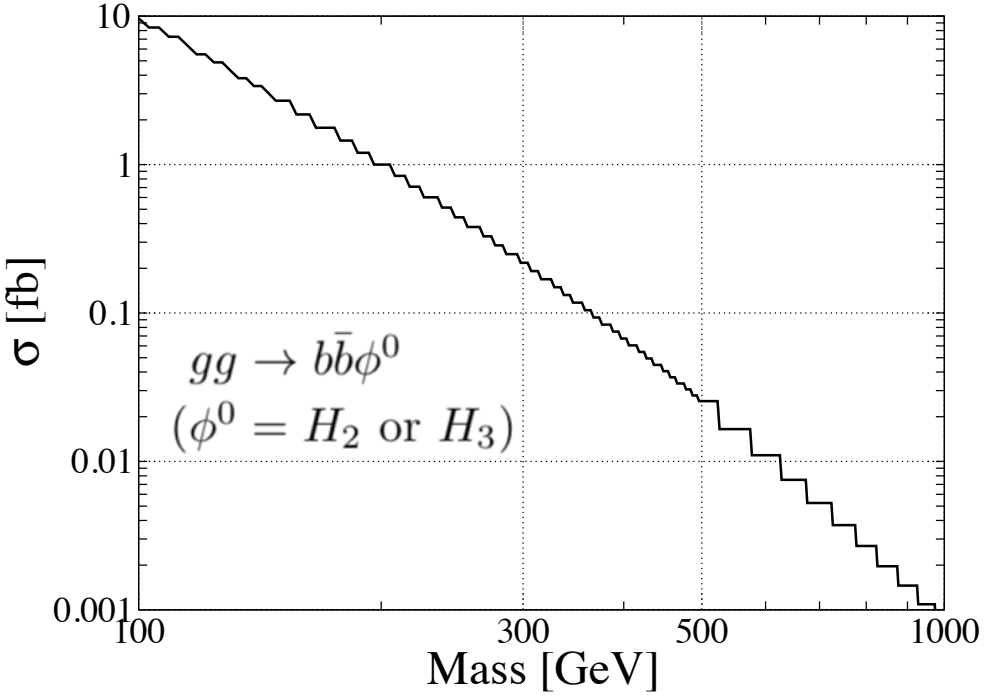
Productions



Productions

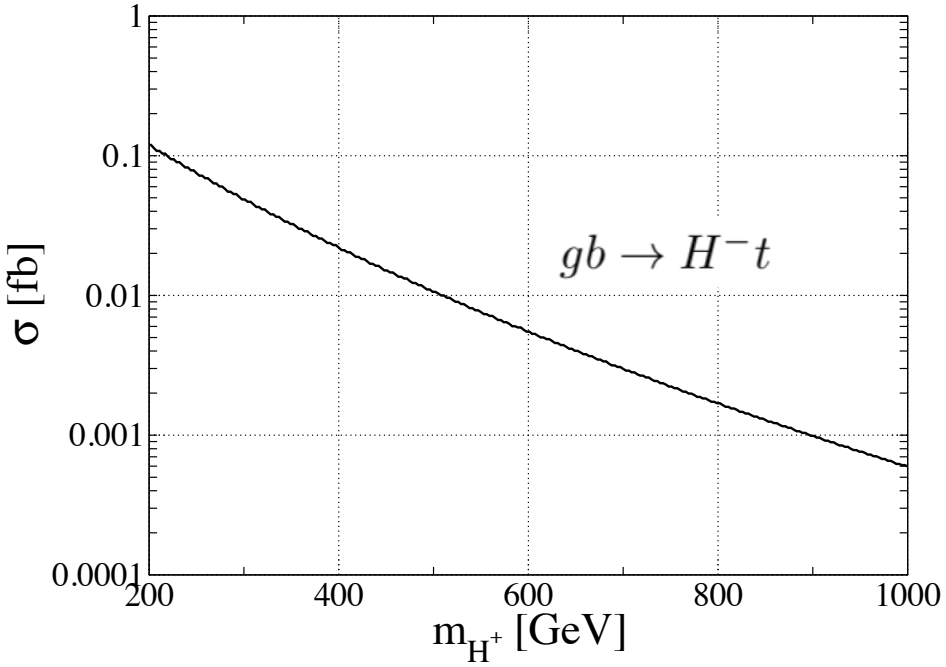
at $\sqrt{s} = 13$ TeV

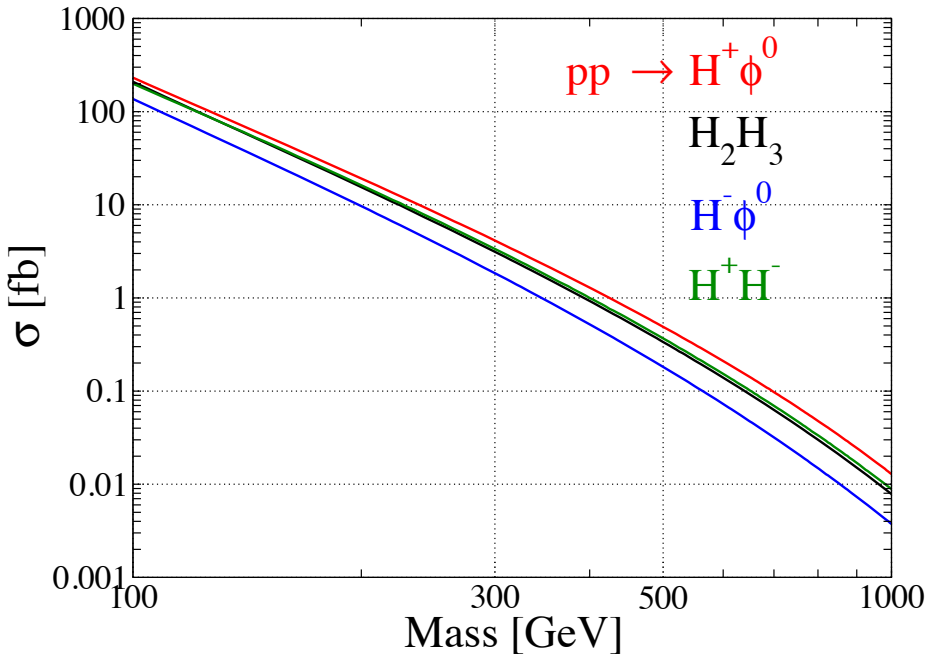




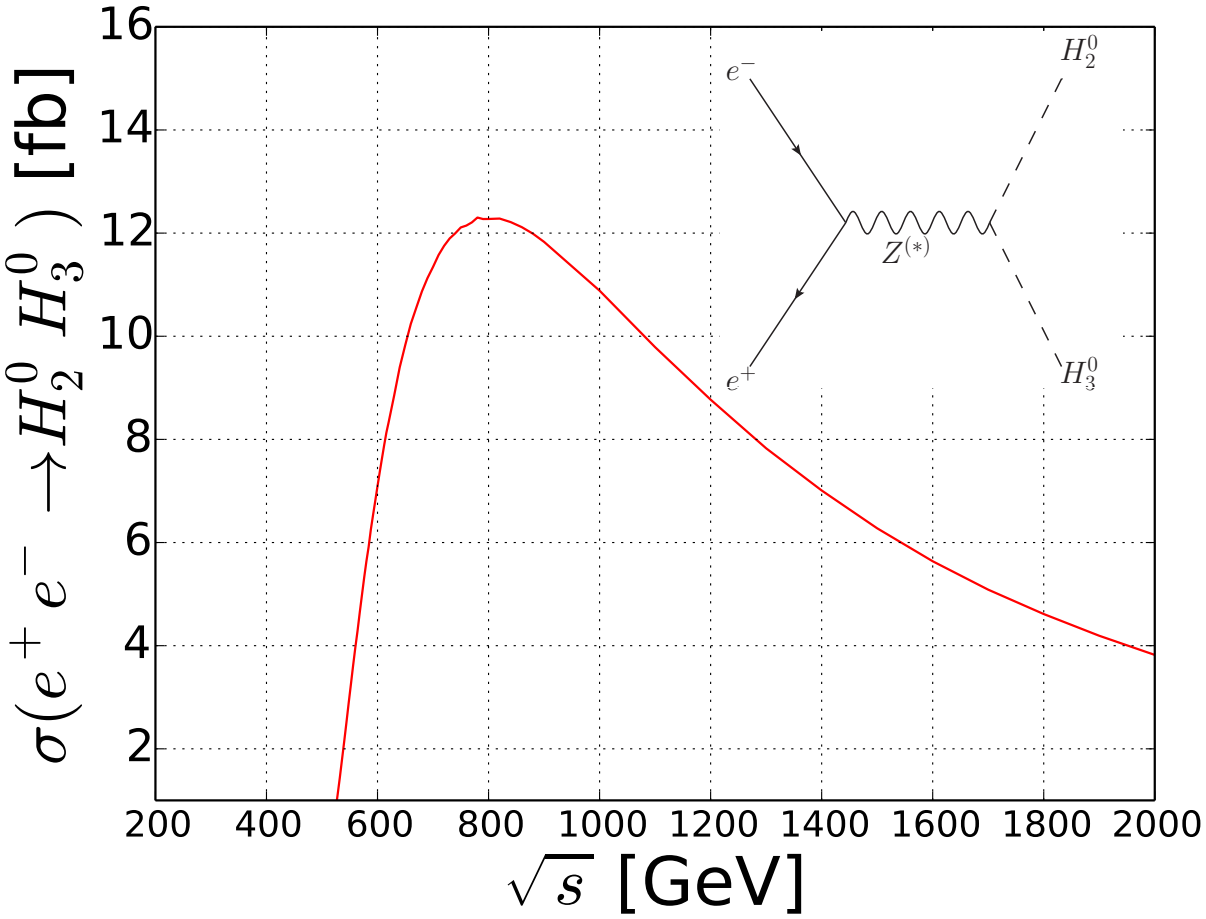
Productions

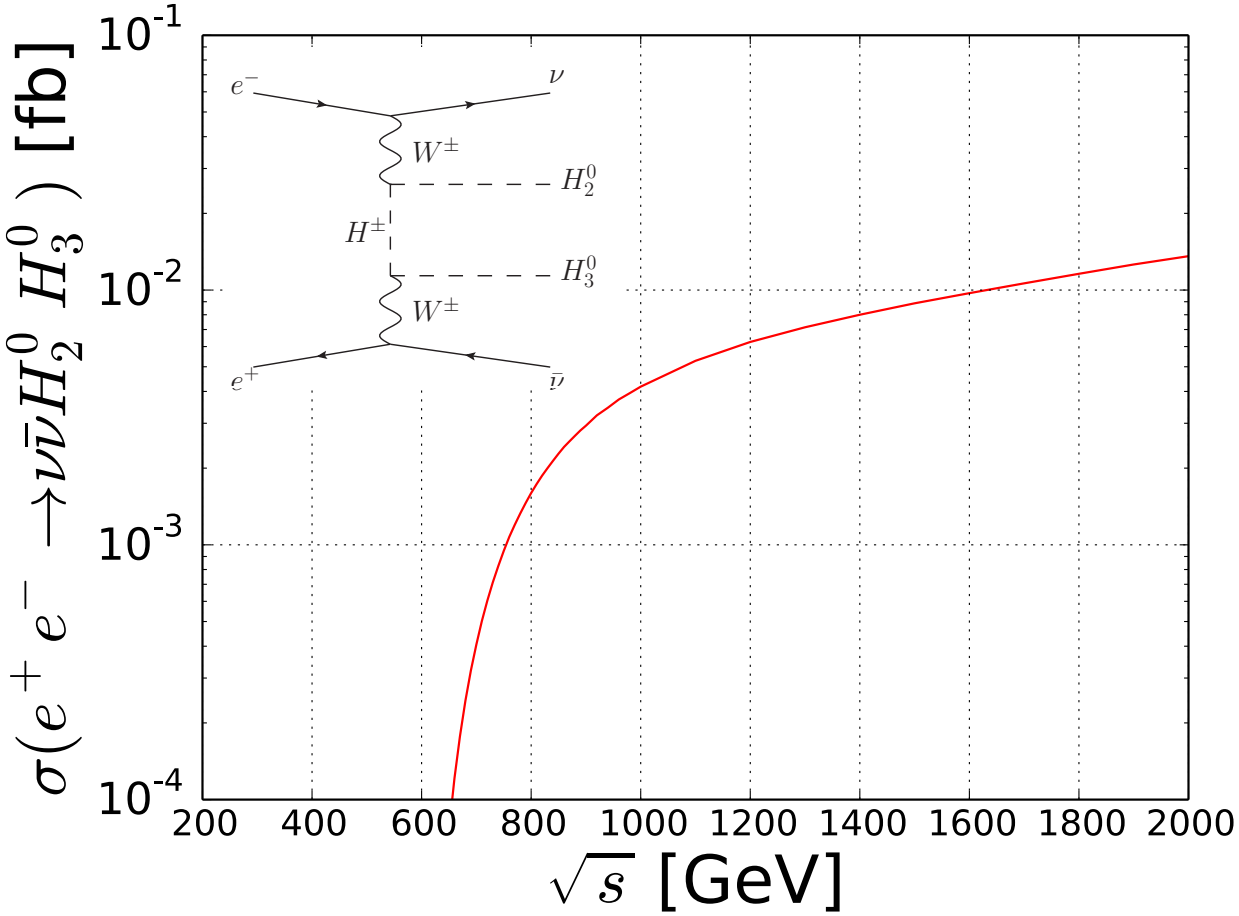
at $\sqrt{s} = 13$ TeV



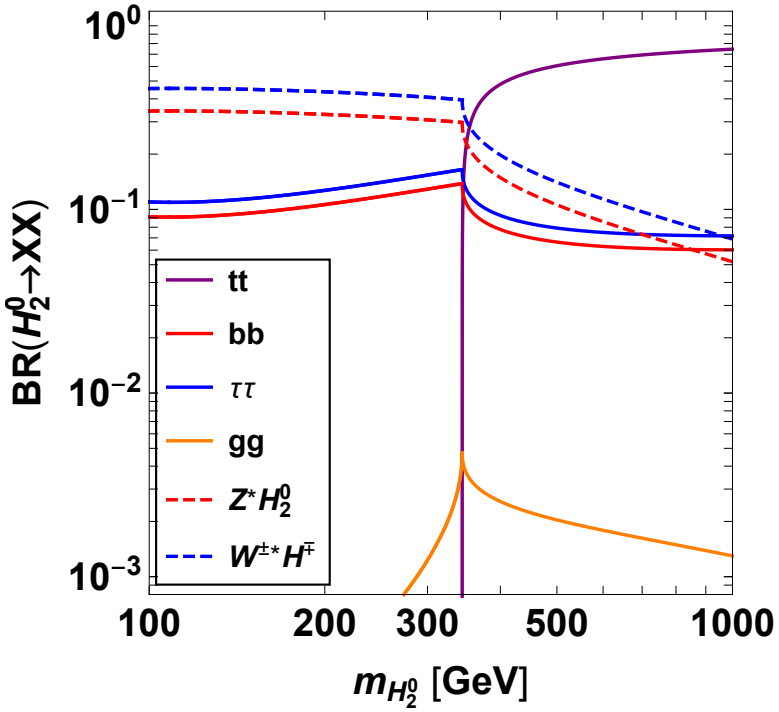


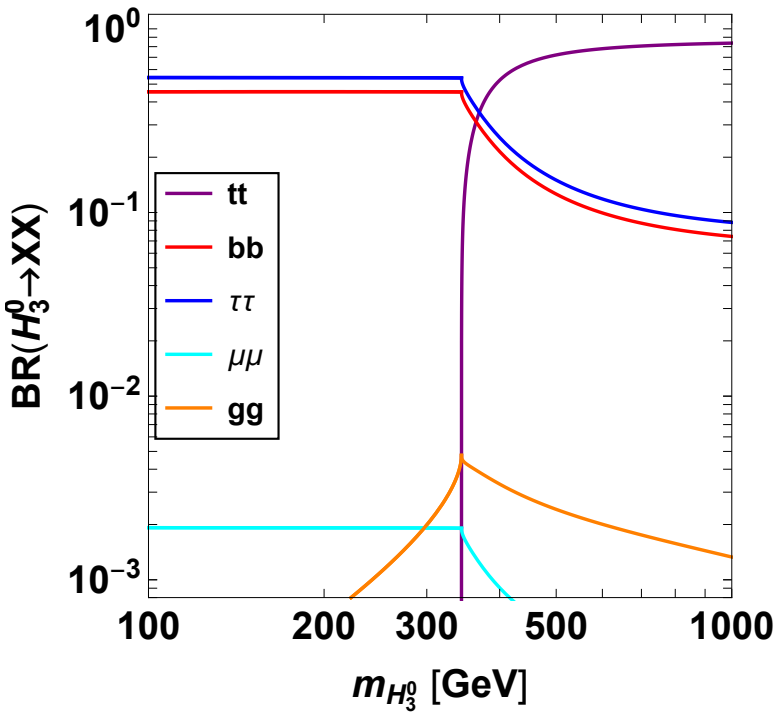
Productions

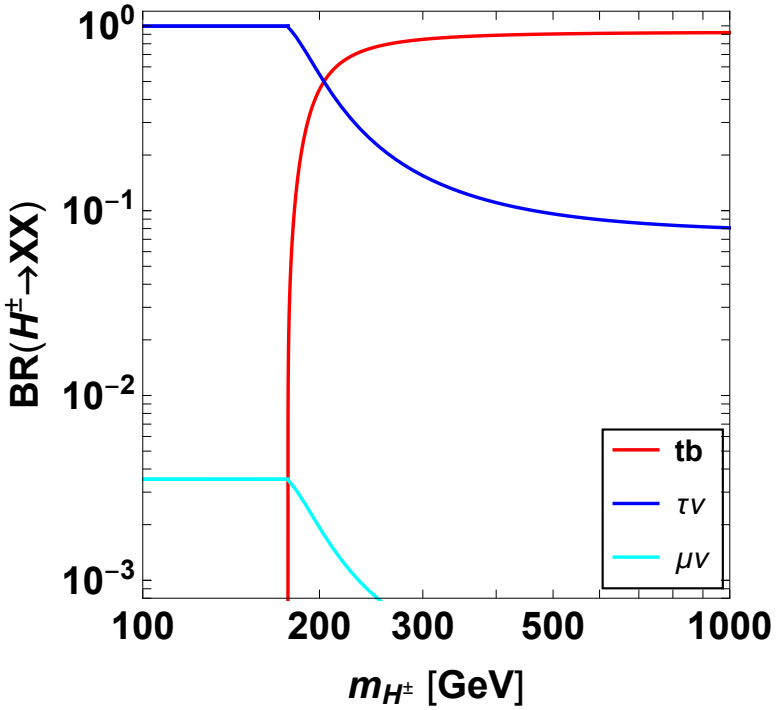




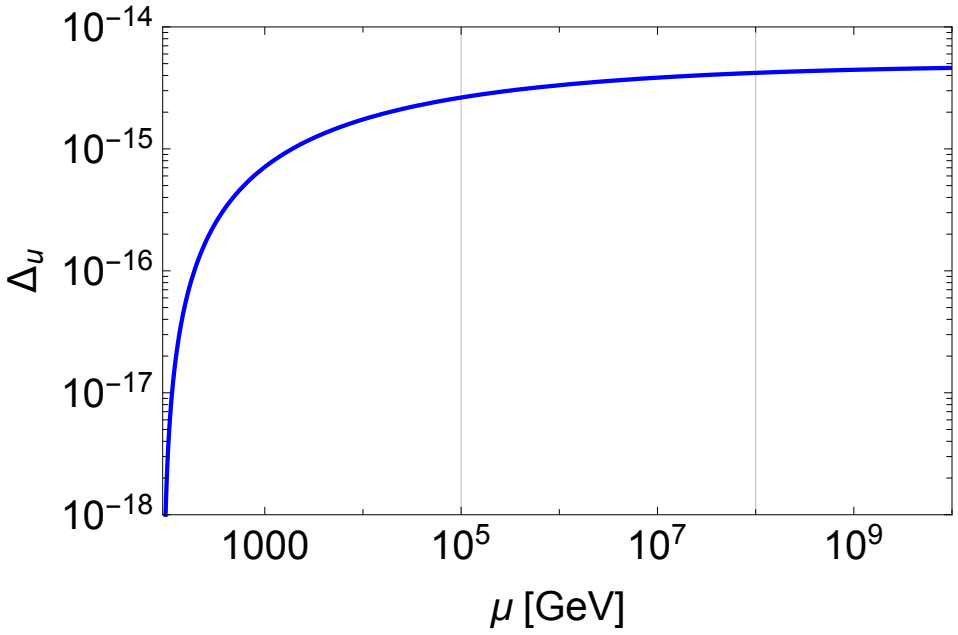
Branching ratios

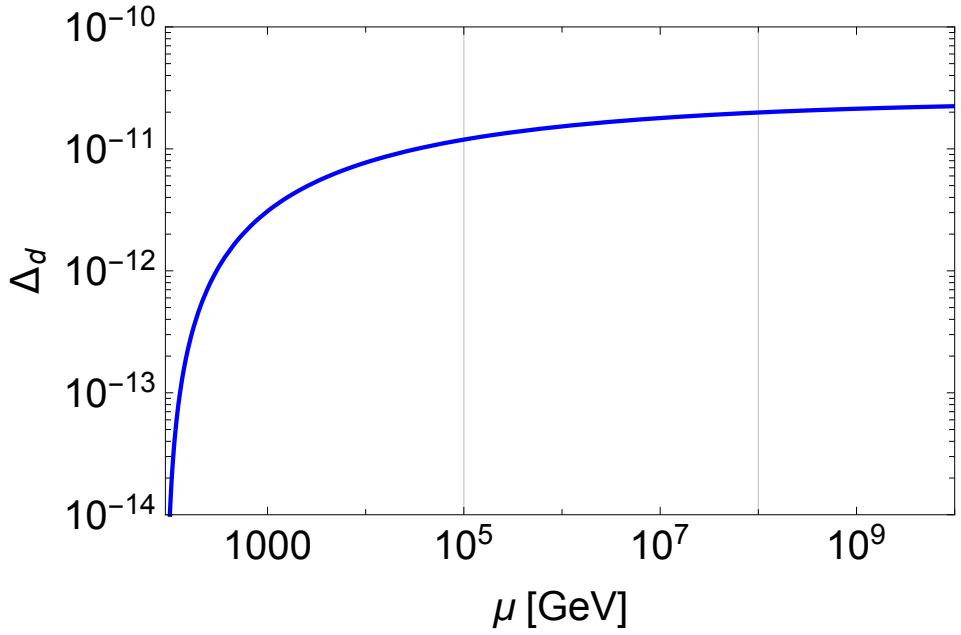






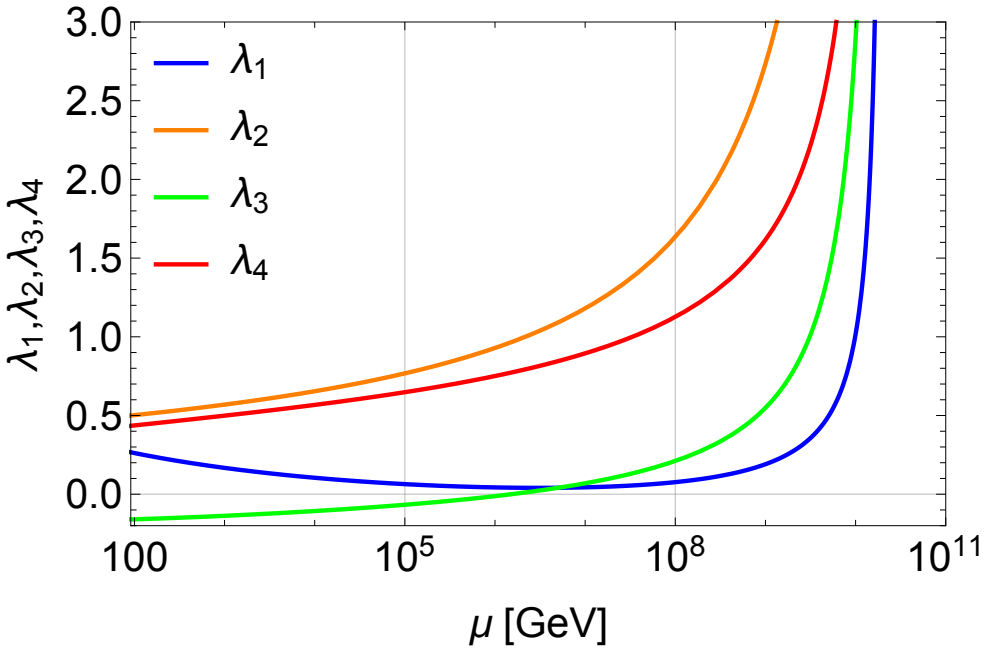
RGE -Yukawa couplings-

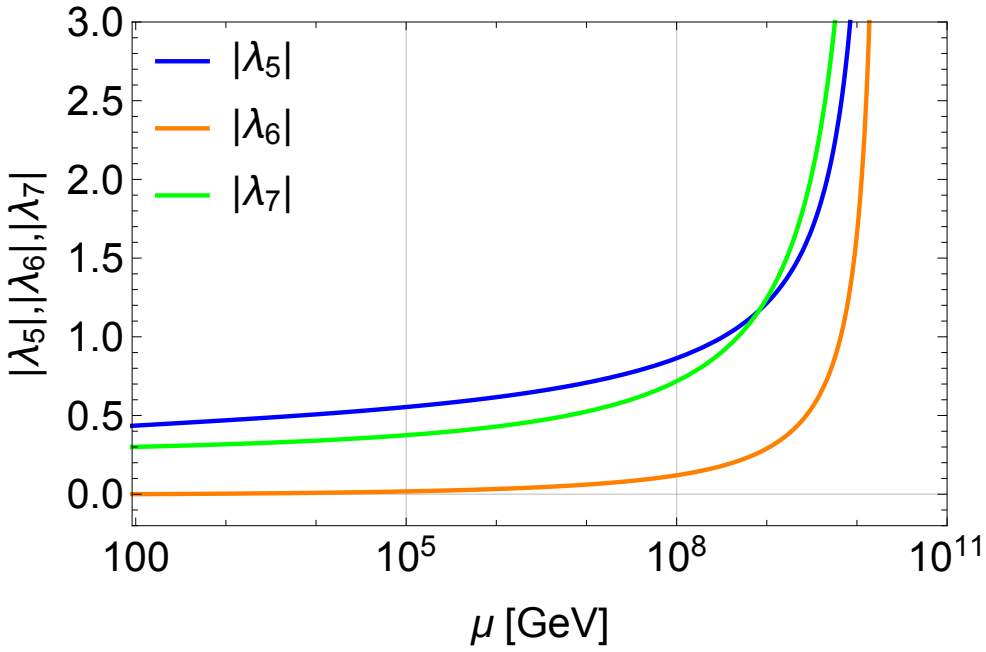




$$\Delta_q \equiv \mathrm{Tr}\left[\delta y_q^\dagger \delta y_q\right], \quad \text{where} \quad \delta y_q \equiv \hat{\rho}_q - \left\{ \frac{\hat{\rho}_q^{33}}{\hat{M}_q^{33}} \right\} \hat{M}_q, \quad (q = u, d)$$

RGE -Higgs couplings-

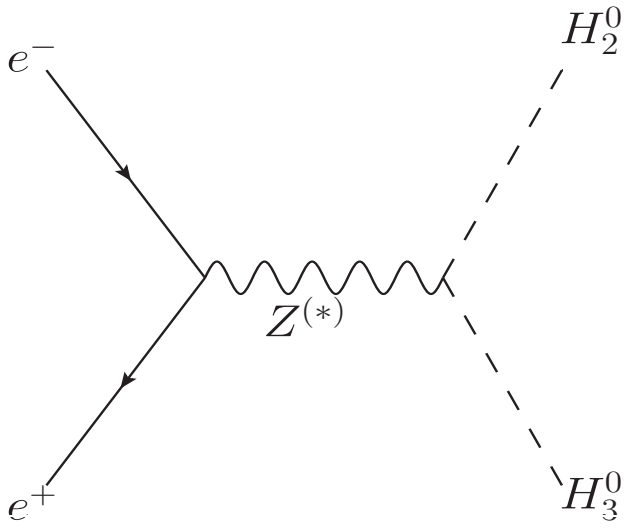




Other scenario

Process : $e^+ e^- \to H_2 H_3$, $H_2 \to b\bar{b}$, $H_3 \to \tau^+ \tau^-$

or $H_2 \to \tau^+ \tau^-$, $H_3 \to b\bar{b}$



- Input:

$|\zeta_u| = 0.01, |\zeta_d| = 0.1,$

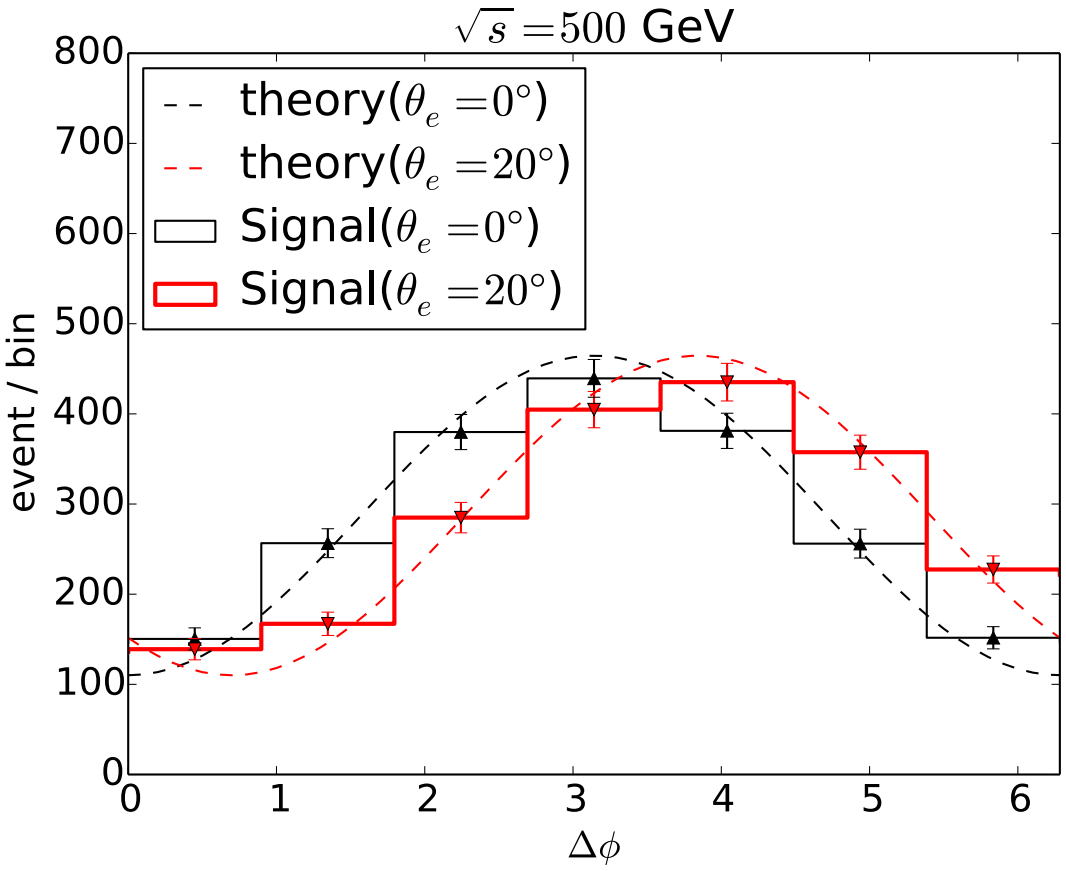
$|\zeta_e| = 1 \quad , |\lambda_7| = 0.3$

BM1 : $m_{H_2} = 150, \; m_{H_3} = m_{H^+} = 170$ (GeV)

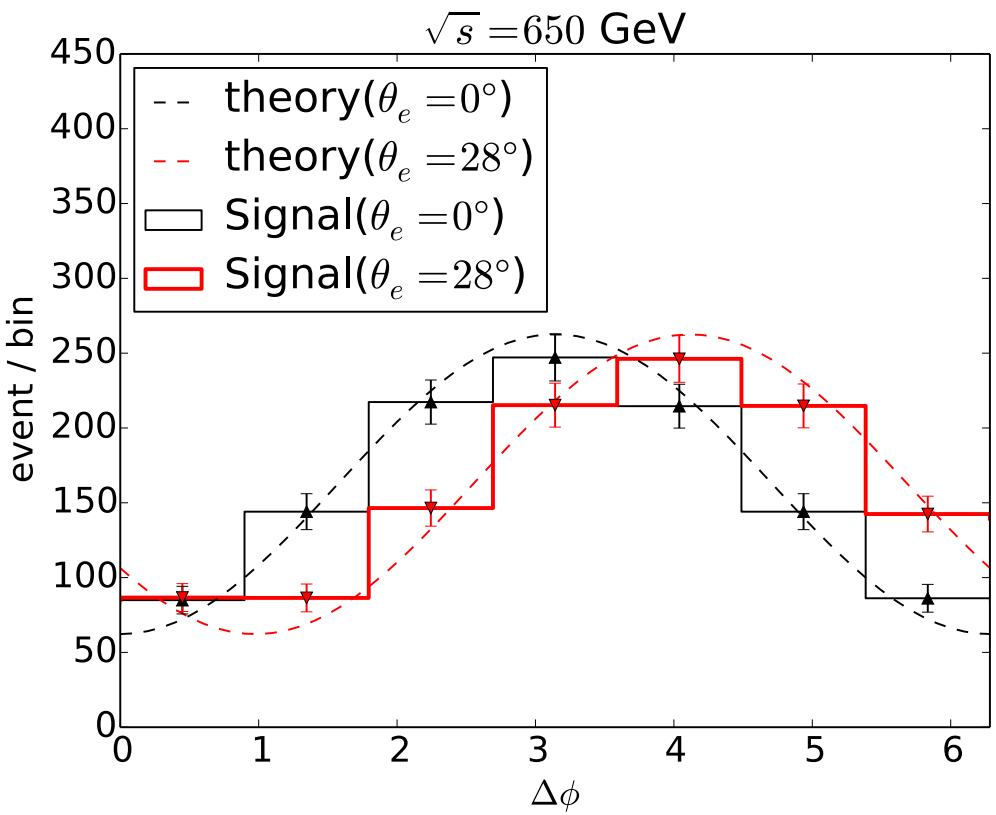
BM2 : $m_{H_2} = 200, \; m_{H_3} = m_{H^+} = 220$

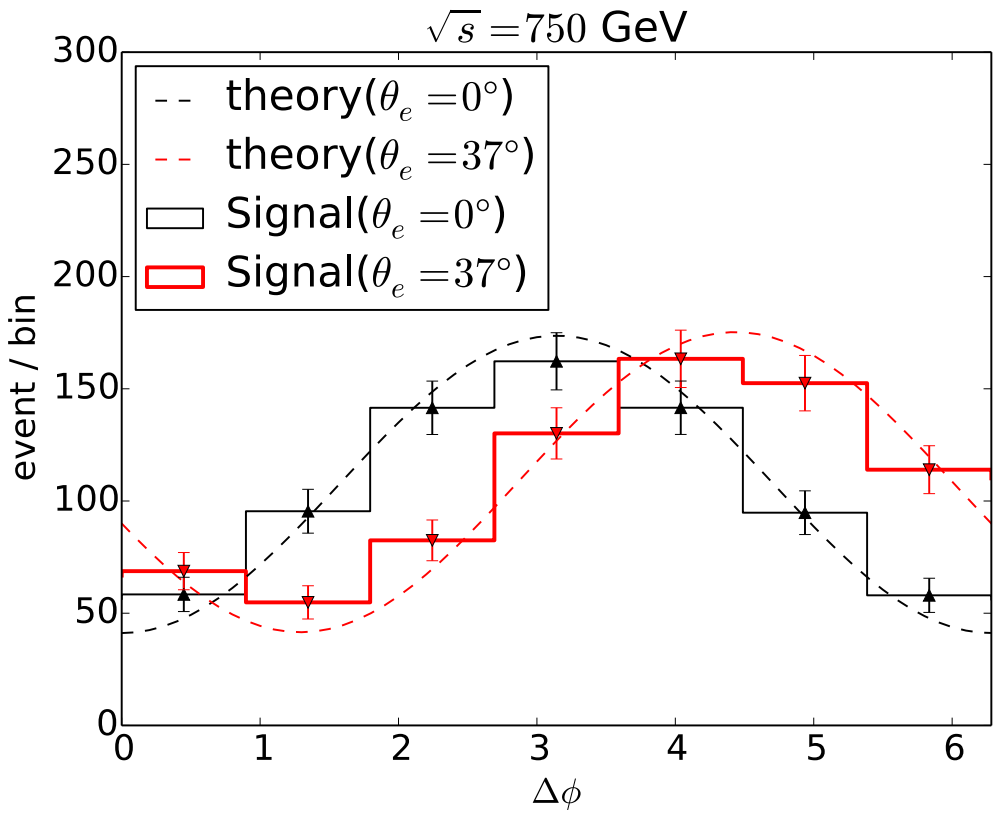
BM3 : $m_{H_2} = 230, \; m_{H_3} = m_{H^+} = 250$

Other scenario (BM1)

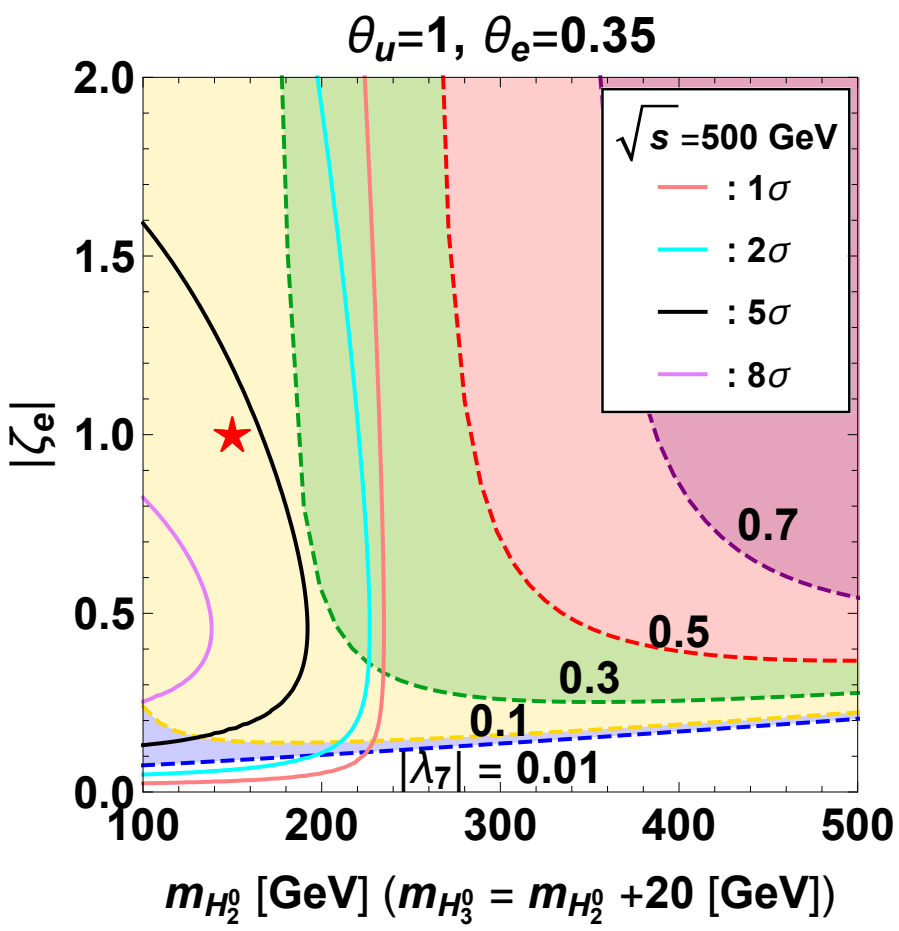


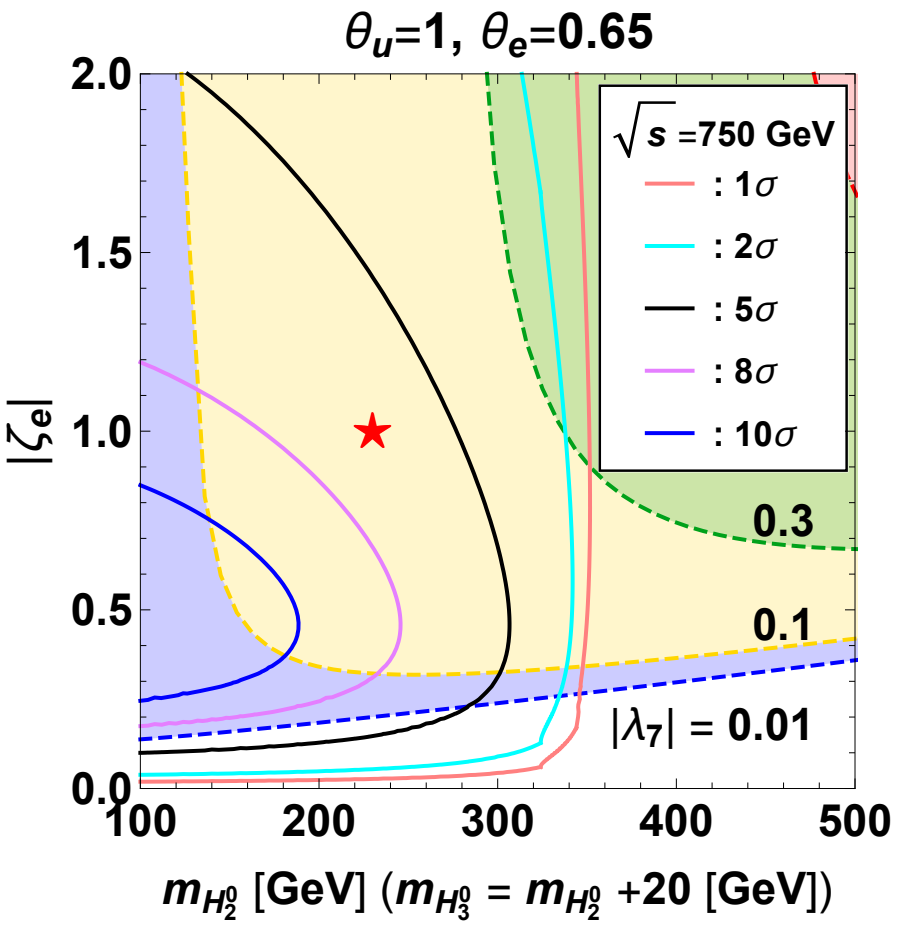
Other scenario (BM2,3)



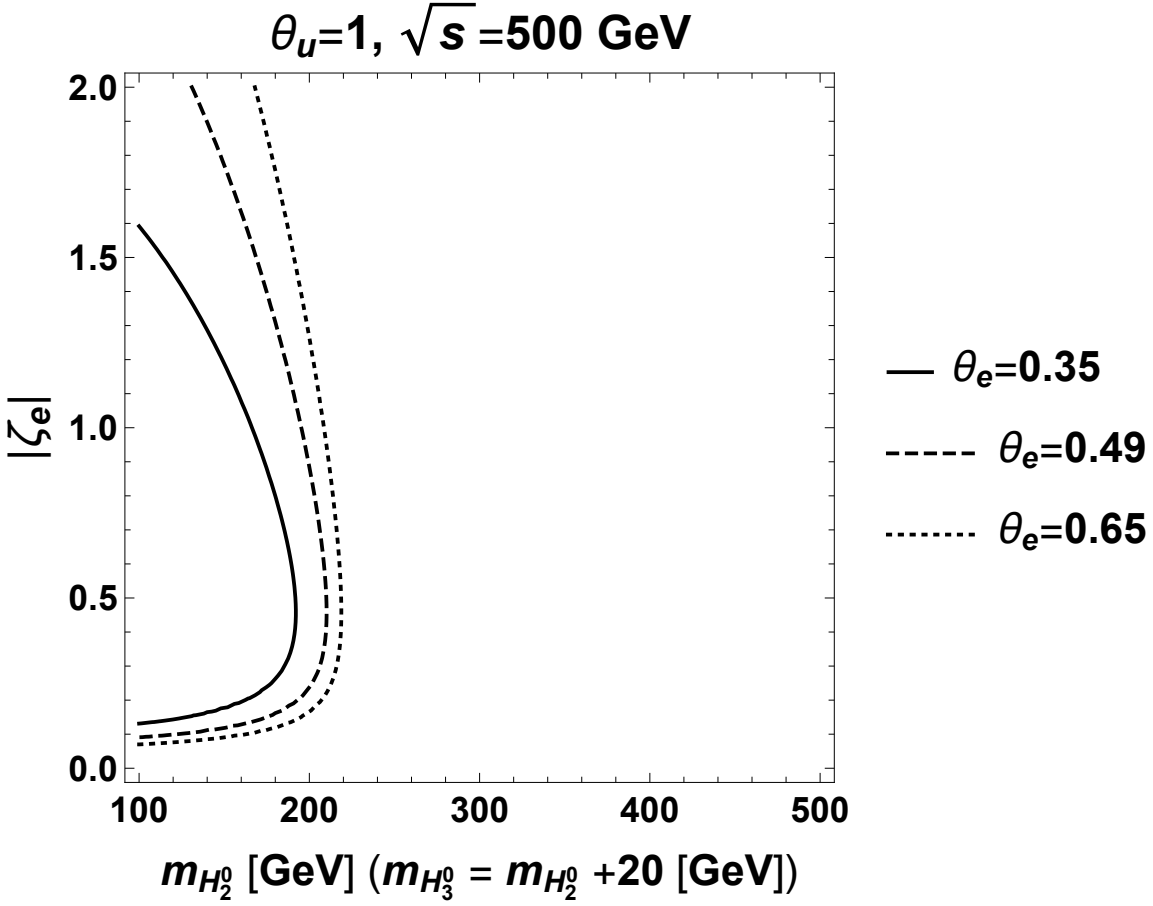


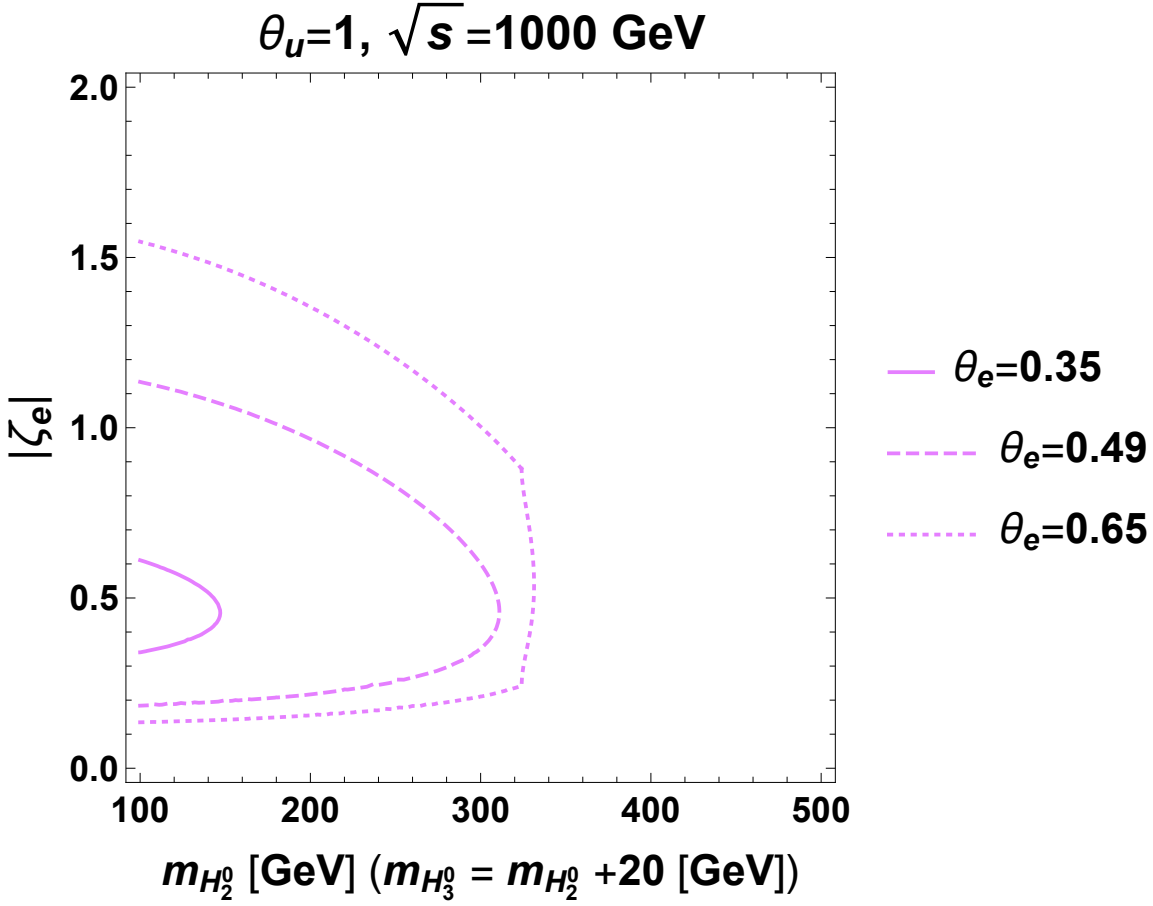
Other scenario (1,3)



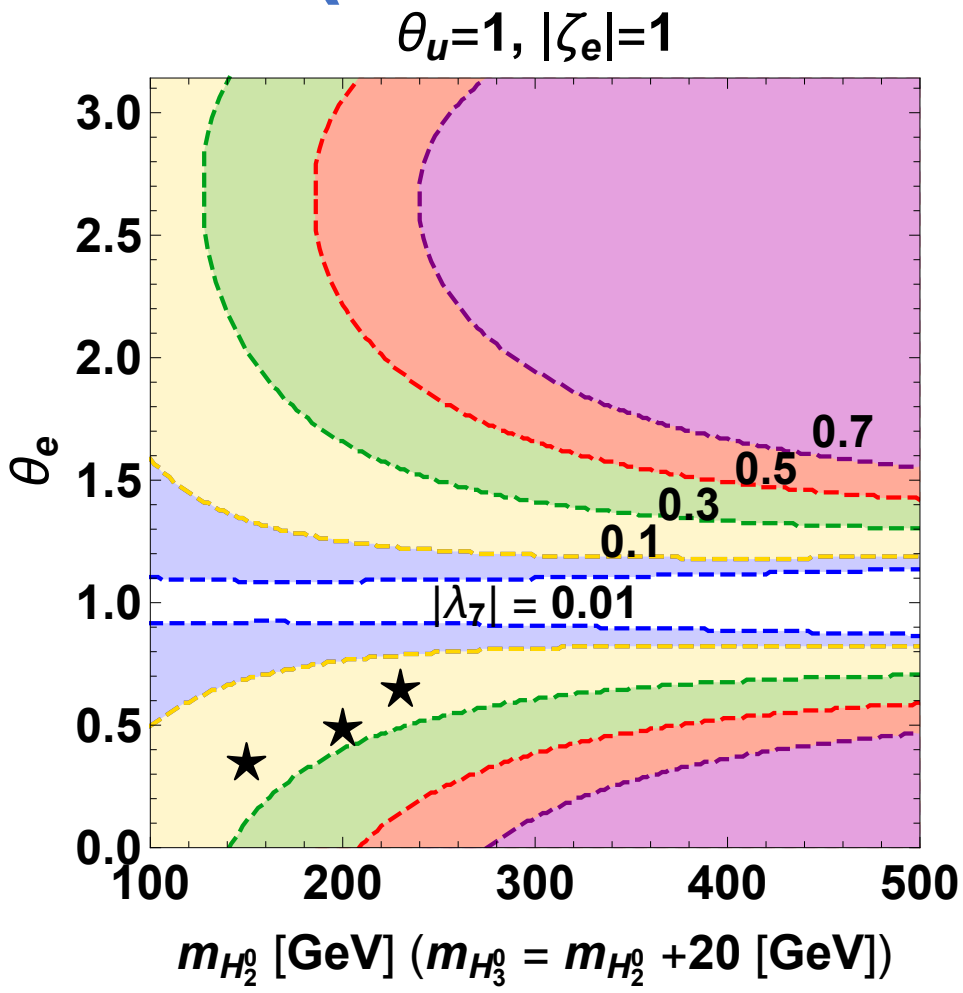


Other scenario





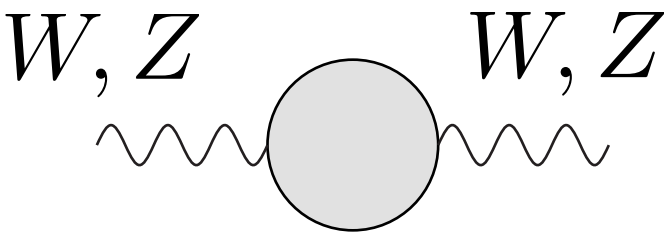
Other scenario (BM1, 2 and 3)



rho parameter

$$\rho = \frac{m_W^2}{m_Z^2 \cos^2\theta_W} = 1$$ (at tree level)

- When CP symmetry is broken, the custodial symmetry is not respected and the rho parameter deviates from the SM value.



Corrections to the rho parameter do not contain the Higgs self couplings at 1-loop level.

$$V \supset \lambda_7 (\Phi_2^\dagger \Phi_2)(\Phi_1^\dagger \Phi_2)$$

-> λ_7 does not change the rho parameter at 1-loop level.