Testing CP violating Higgs sectors at the International Linear Collider

Mitsunori Kubota (Osaka U.) [Shinya Kanemura, MK, Kei Yagyu, arXiv:2101.03702] (to appear in JHEP)

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1. Introduction

- Extended Higgs model with extra CP-phases can realize electroweak baryogenesis.
- New CP-phase is normally strongly constrained by the current data for the electric dipole moment (EDM).

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

2. Two Higgs Doublet Model

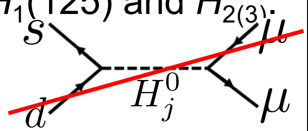
[Lee (1973)] [Davidson, Haber (2005)]

$$\Phi_1 = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + H_1^0 + iG^0) \end{pmatrix} \quad \Phi_2 = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(H_2^0 + iH_3^0) \end{pmatrix}$$

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

- Stationary condition : $\mu_1^2 = v^2\lambda_1/2,\ \mu_3^2 = v^2\lambda_6/2$
- Phase redefinition : $\arg(\lambda_5) = 0$
- Assume $\lambda_6 = 0$: No mixing between $H_1(125)$ and $H_{2(3)}$.

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

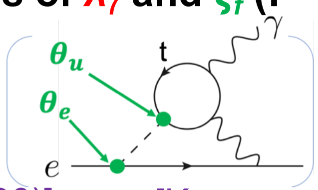


- Assume $Y_f^{ij} = \zeta_f M_f^{ij}$: No flavor-changing-neutral current.

[Pich, Tuzon (2009)]

→ CP-phases of λ_7 and ζ_f (f = u,d,e) remain.

EDM: $d_e =$



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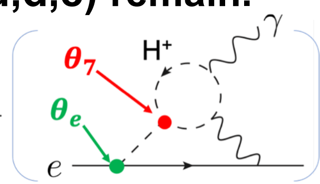
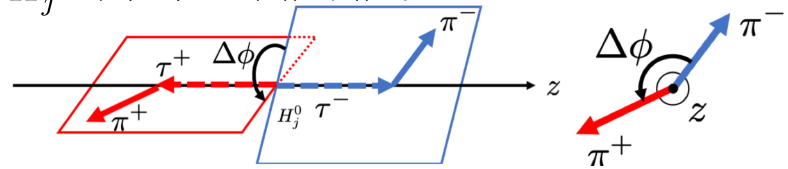


$< d_e^{(\mathrm{exp.})}$

[Barr, Zee (1990)] [Kanemura, MK, Yagyu (2020)]

3. Angular distribution ($H_j \to \tau^+\tau^-$)

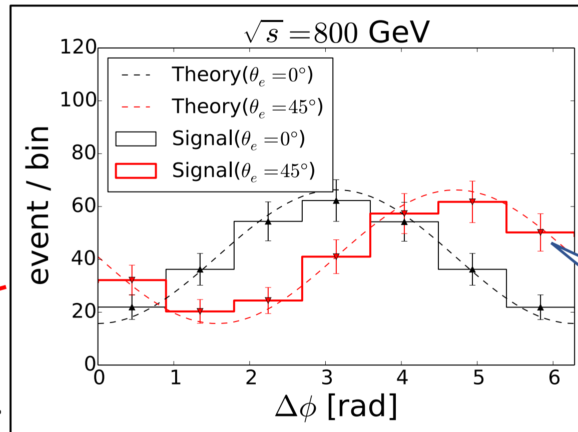
Ex.) $H_j^0 \to \tau^+\tau^- \to \pi^+\bar{\nu}\pi^-\nu$



4. Simulation Result ("MadGraph5", "TauDecay")

- Process : $e^+ e^- \to H_2 H_3$, $\begin{cases} H_2 \to \tau^+\tau^-,\ H_3 \to b\bar{b} \\ H_2 \to b\bar{b},\ H_3 \to \tau^+\tau^- \end{cases}$
- One of H_2 and H_3 decays to $\tau^+\tau^-$ and the other to $b\bar{b}$ for the reconstruction of the momentum of the decay products.

[Jeans, Wilson (2018)]



Input : $m_{H^+} = 230$[GeV]
$m_{H_2^0} = 280$[GeV]
$m_{H_3^0} = 230$[GeV]
$(\theta_u, \theta_d, \theta_e, \theta_7) = (1.2, 0, \pi/4, -1.8)$
$|\zeta_u| = 0.01, |\zeta_d| = 0.1,$
$|\zeta_e| = 0.5, |\lambda_7| = 0.3$

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

5. Conclusion

By looking at the angular distribution of the additional Higgs boson decay, the CP phase of this scenario can be detected by the ILC.

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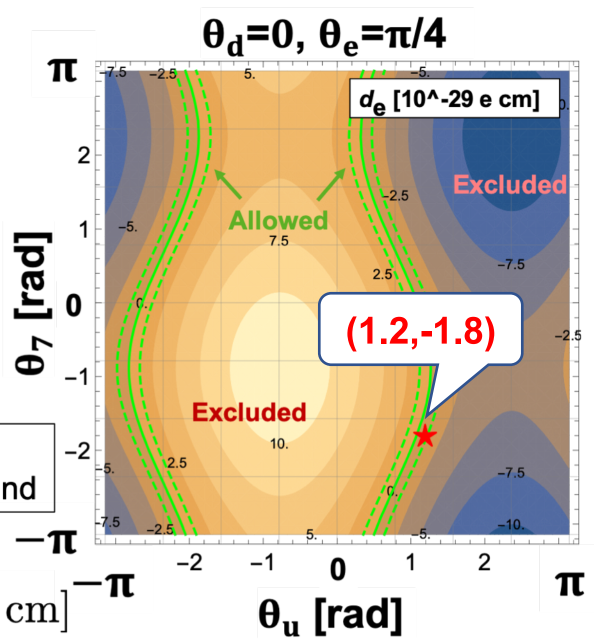
Backup (1/2)

Numerical calculation

- Input $m_{H^+} = 230\,[\mathrm{GeV}]$
  $m_{H_2^0} = 280\,[\mathrm{GeV}]$
  $m_{H_3^0} = 230\,[\mathrm{GeV}]$
  $|\zeta_u| = 0.01, |\zeta_d| = 0.1,$
  $|\zeta_e| = 0.5, |\lambda_7| = 0.3$

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



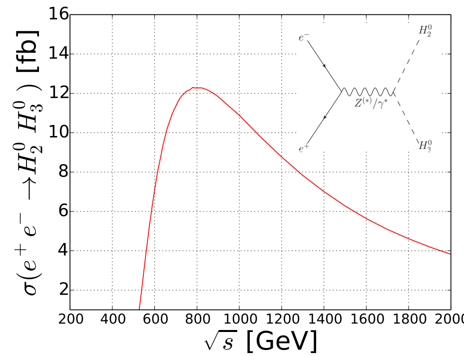
At the benchmark point (1.2, -1.8):

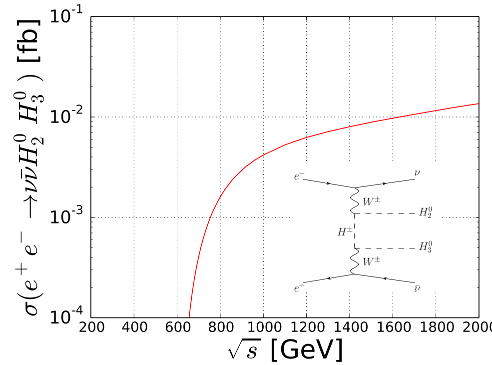
$$d_e = -0.95\,[10^{-29}\ \mathrm{e\ cm}]$$

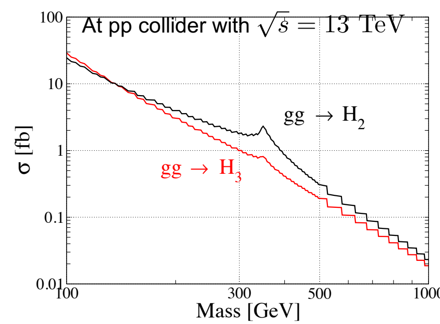
$$|d_e^{\mathrm{exp.}}| < 1.1\ \ [10^{-29}\ \mathrm{e\ cm}]$$

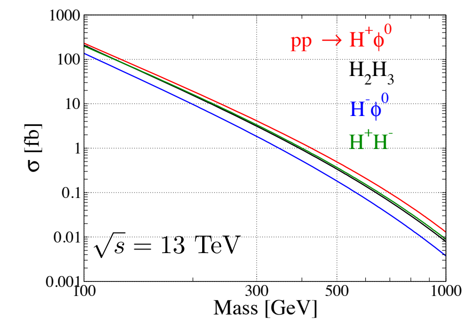
[ACME collaboration, Nature (2018)]

Production



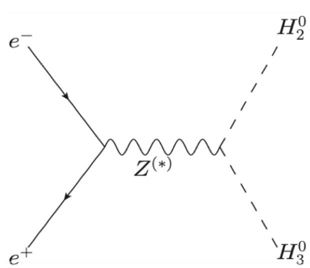




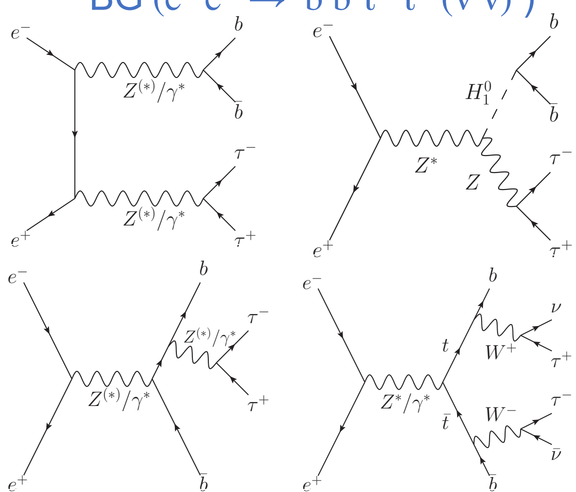


Signal and background ($e^+ e^- \to b\, b\, \tau^+ \tau^-$ ($\nu\, \nu$))

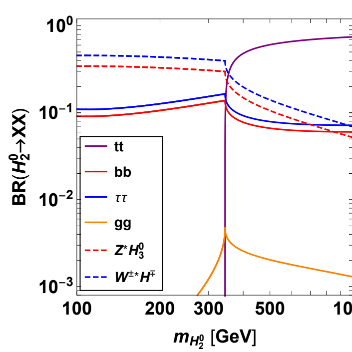
Signal

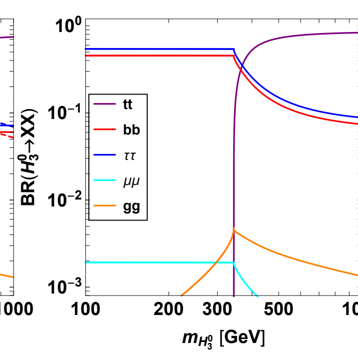


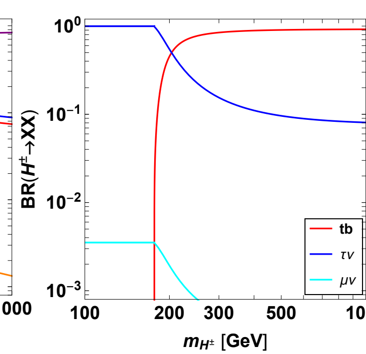
BG ($e^+ e^- \to b\, b\, \tau^+ \tau^-$ ($\nu\, \nu$))



Branching ratio

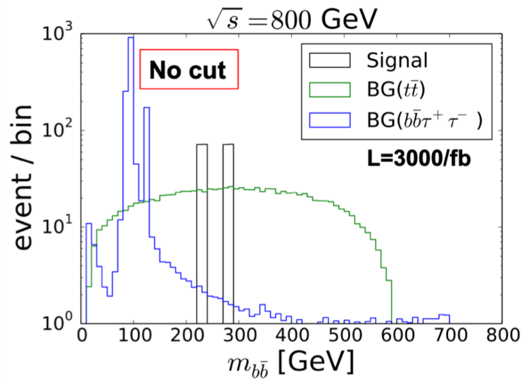


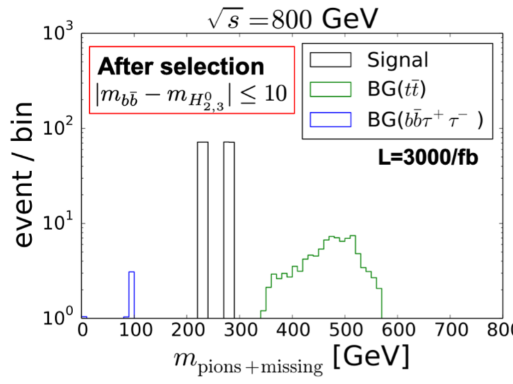




Backup (2/2)

Kinematic cut

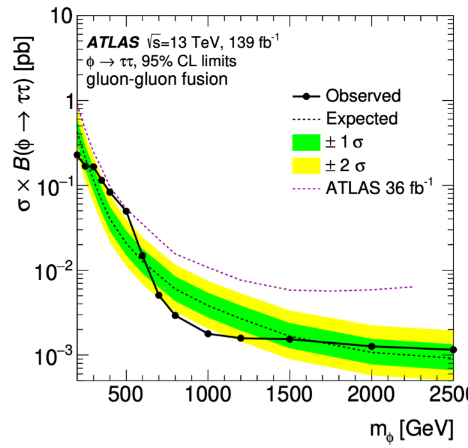


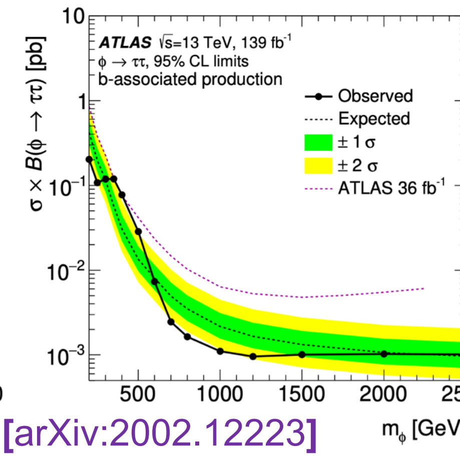


Cut:
$$|m_{b\bar{b}} - m_{H^0_{2,3}}| \leq 10$$
$$|m_{\text{pions+missing}} - m_{H^0_{2,3}}| \leq 10$$

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

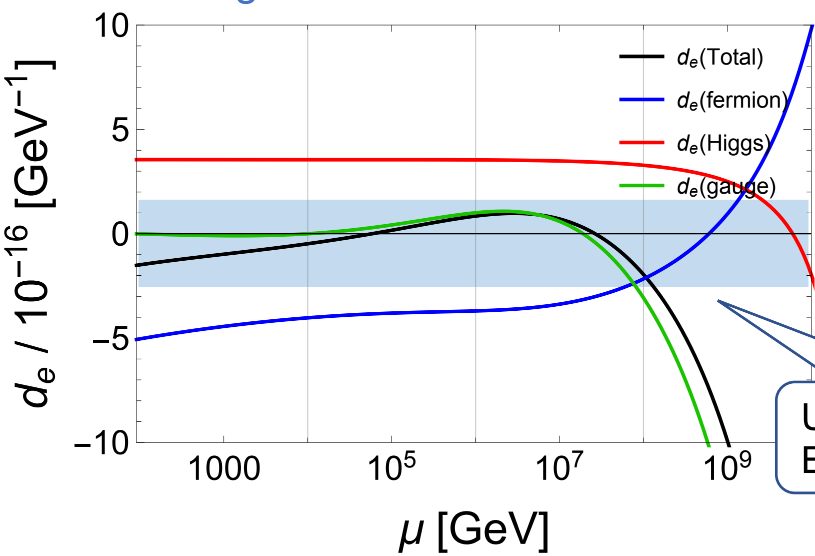
Current bound for the production of the neutral scalar





[arXiv:2002.12223]

Fine tuning?



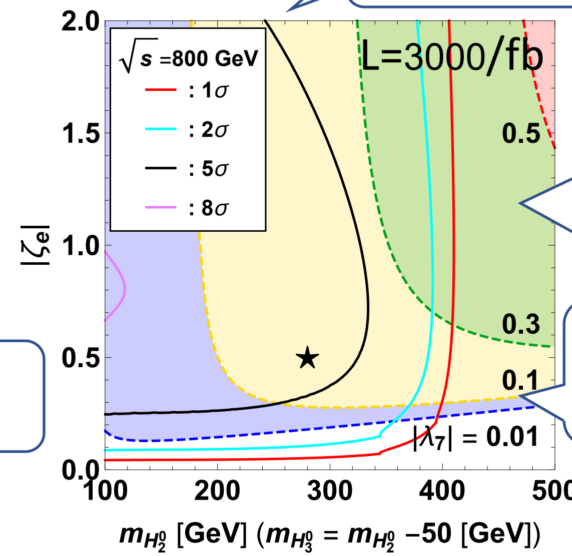
Until 10^8 GeV, the EDM is stable.

Beta functions: the general 2HDM at 1-loop level

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

Other scenario

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



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

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