CP violating mode of the stoponium decay into Zh

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Introduction

- In the MSSM (Minimal Supersymmetry SM), the lighter **Stop**, $\widetilde{t}_1$ superpartner of top, can be lighter than other squarks.

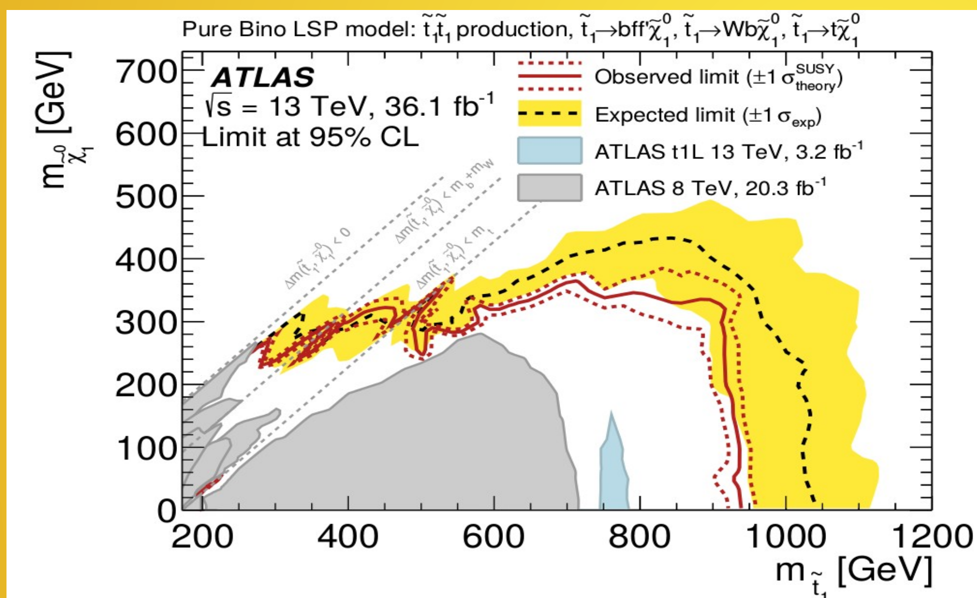
- Because, i) top is heavy, large mixing angle between, $\widetilde{t}_{L,R}$. ii) if squarks have equal mass at high scale, the radiative correction will reduce the mass of $\widetilde{t}_{L,R}$.

M. Drees, Mihoko M. Nojiri, PRL 72, 2324(1994)

- **Stop** cancel with the top quadratic divergence in the radiative correction to the Higgs mass. Hierarchy problem.

Introduction

- The LHC has put the **Stop** mass above 1 TeV:



ATLAS, 1711.11520, CMS,1711.00752.

- $\tilde{t}_1$ is compress just above the lightest neutralino mass, there is not much missing momentum for tagging events at LHC.

Introduction

- Lighter **Stop** is long-lived in comparison to the time scale QCD hadronization.

- **Stoponium**, $\tilde{\eta} \equiv {}^1S_0(\tilde{t}_1 \tilde{t}^*{}_1)$ **stop-anti-stop** bound state, can be formed.

  V.D. Bager, W.Y. Keung, PRL 211, 355(1988)

- It produced through gluon-gluon fusion and be identified by its distinctive decays: $hh, WW, ZZ, \gamma\gamma \ldots$

  M. Drees, Mihoko M. Nojiri, PRL 72, 2324(1994)

- Studies the QCD corrections, lattice calculation, and dark matter co-annihilation.

  S.P. Martin, J.E. Younkin, PRD 80, 035026(2009),
  S. Kim, PRD 92, no.9 094505,
  F.Luo, J.Ellis et al, EPJ C78 (2018) no.5, 425.

Introduction

- The **stoponium** decay into channel **hZ** is forbidden by the assumption of ***CP conservation***.
- There is no strong argument against ***CP violation*** in the stop sector.
- We will show $\widetilde{\eta} \to hZ$ can have significant branching ratio withing the constraint from **eEDM** (electron electric dipole moment).

CP-violation in the **Stop** sector

- The Z-boson couplings to the **Stops** $\widetilde{t}_{1,2}$, through the convection Feynman vertex amplitude:

$$\langle\widetilde{t}_i(p_i)|J^{\mu}_{ij}|\widetilde{t}_j(p_j)\rangle = (p_j + p_i)^{\mu}$$

- Where the convection current is

$$J^{\mu}_{ij} = i\widetilde{t}^*_i \overleftrightarrow{\partial} \widetilde{t}_j \quad \text{where} \quad \overleftrightarrow{\partial} \equiv \overrightarrow{\partial} - \overleftarrow{\partial}$$

for incoming p_j and outgoing p_i .

CP-violation in the **Stop** sector

- The Z-boson couplings to the **Stops** $\widetilde{t}_{1,2}$, through the convection Feynman vertex amplitude:

$$\langle \widetilde{t}_i(p_i) | J^{\mu}_{ij} | \widetilde{t}_j(p_j) \rangle = (p_j + p_i)^{\mu}$$

- Under the charge conjugation

$$C, \ \widetilde{t}_i \xleftrightarrow{C} \widetilde{t}_i^*$$

$$J^{\mu}_{ij} \xleftrightarrow{C} -J^{\mu}_{ji}$$

- We need to make C-odd transformation for Z:

$$Z^{\mu} \xleftrightarrow{C} -Z^{\mu}$$

CP-violation in the **Stop** sector

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$$\langle \widetilde{t}_i(p_i) | J^\mu_{ij} | \widetilde{t}_j(p_j) \rangle = (p_j + p_i)^\mu$$

- The hermiticity of the unitary interaction $\mathcal{L} \supset \sum_{ij} g^Z_{ij} J^\mu_{ij} Z_\mu$ requires $g^Z_{ij} = g^{Z*}_{ji}$.

- If Charge conjugation is good symmetry, $g^Z_{ij} = g^Z_{ji}$.

CP-violation in the **Stop** sector

- Summarizing above discussion: **Complex** $g_{ij}^{Z}\ (\text{for } i \neq j)$ if its phase is **NOT** removable implies ***C-parity violation***.

- We can make g_{12}^{Z} real by redefining the relative phase between $\widetilde{t}_{1,2}$.

- To have ***C-parity violation***, additional complex coupling coefficient y from Higgs vertex $yh(\widetilde{t}_2^*\widetilde{t}_1)$ is needed.

CP-violation in the **Stop** sector

- The **P-parity** is conserved in the **Z-vertex**.

- Because for the renormalizable interaction of the pure bosonic sector, operators of dim 4 or less do not involve the **P-odd** Levi-Civita $\epsilon-$symbol.

- **C-parity** violation is ***CP-violation***.

CP-violation in the **Stop** sector

- Our example is the decay of the ground state **stoponium** in $^1S_0(\widetilde{t}_1\widetilde{t}_1^*) \to Zh$.

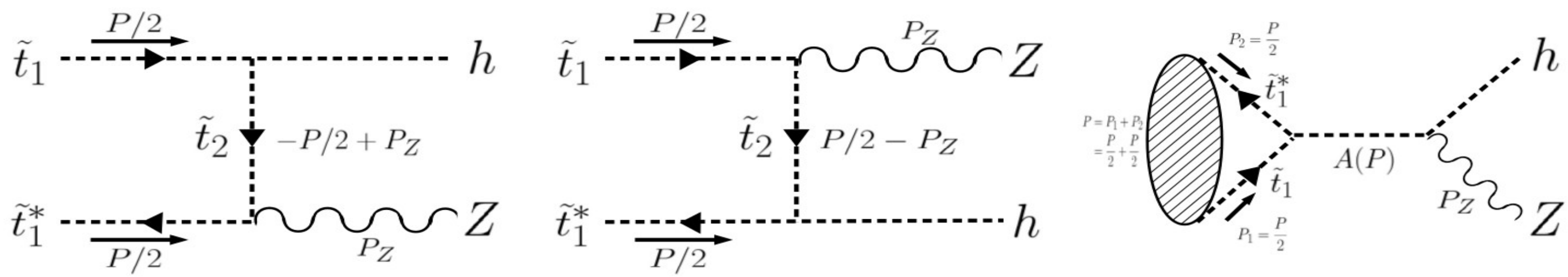

FIG. 1. Feynman diagrams for the stoponium decaying into Zh via the t,u,s channels from the left to the right.

- The exchange $\widetilde{t}_2$ appear in t-channel and u-channel.

CP-violation in the **Stop** sector

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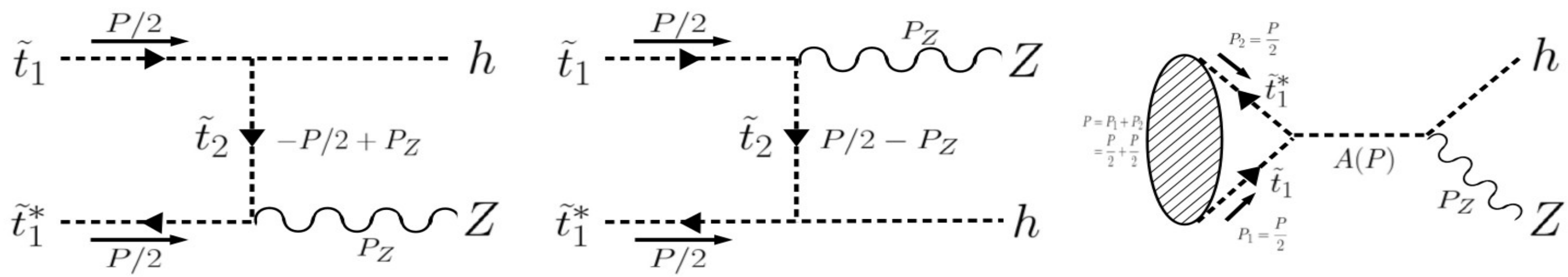

FIG. 1. Feynman diagrams for the stoponium decaying into Zh via the t,u,s channels from the left to the right.

- The phase of g_{ij}^Z is tied with vertex $yh(\widetilde{t}_2^*\widetilde{t}_1)$, and thus overall unremovable.

CP-violation in the **Stop** sector

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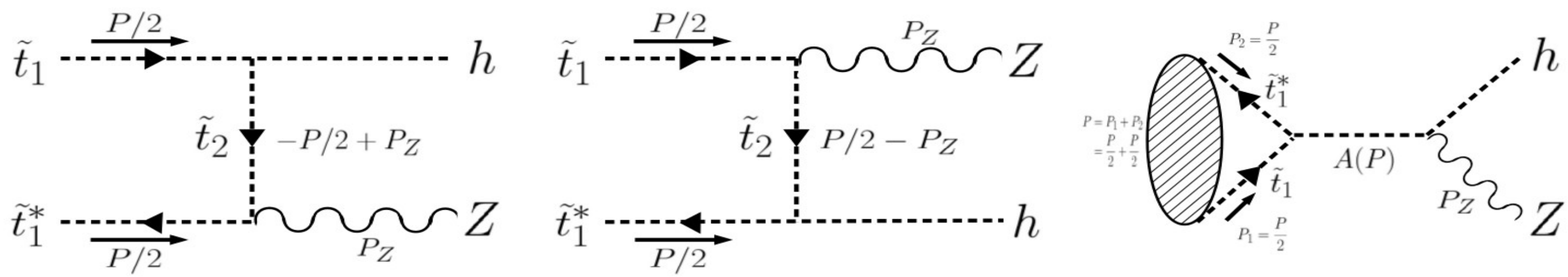

FIG. 1. Feynman diagrams for the stoponium decaying into Zh via the t,u,s channels from the left to the right.

- The two amplitudes of t- and u-channels cancel if the coupling factor is real, but add up if imaginary.

CP-violation in the **Stop** sector

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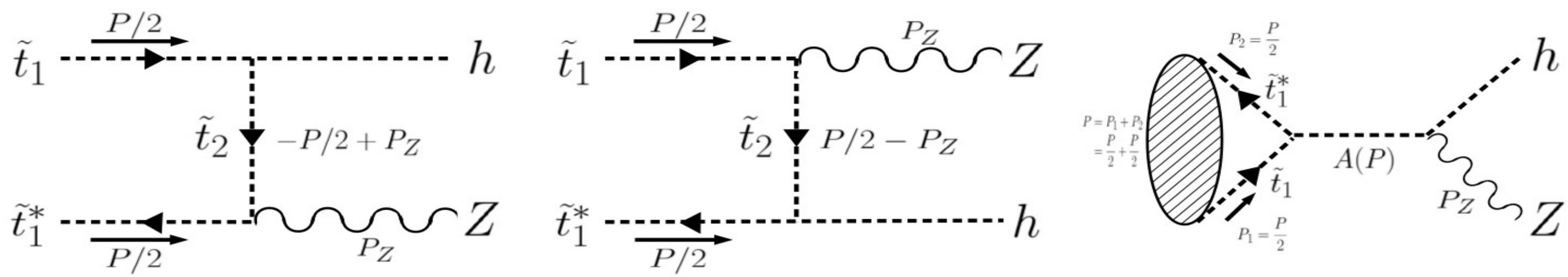

FIG. 1. Feynman diagrams for the stoponium decaying into Zh via the t,u,s channels from the left to the right.

- The production of **Zh** from **stoponium** decay is a sign of ***CP-violation***.

CP-violation in the **Stop** sector

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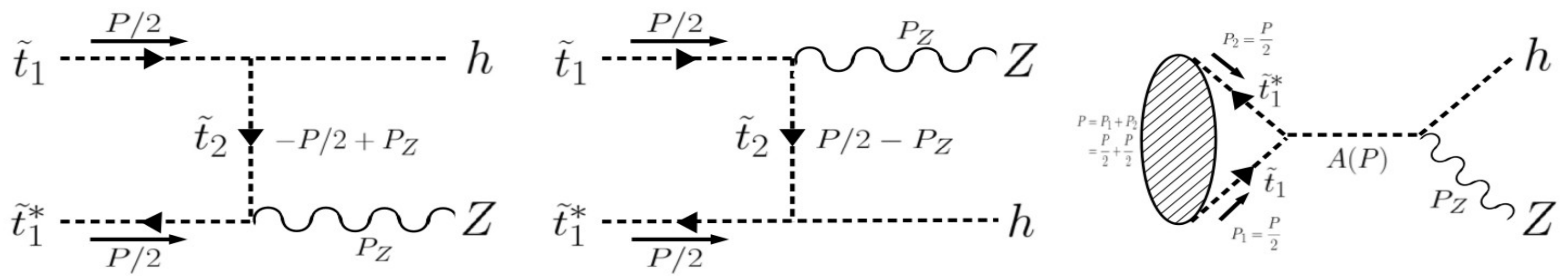

FIG. 1. Feynman diagrams for the stoponium decaying into Zh via the t,u,s channels from the left to the right.

- Direct coupling of pseudoscalar **A** to the **Stops** $A^0(\widetilde{t}_1^*\widetilde{t}_1 - \widetilde{t}_2^*\widetilde{t}_2)$, which is CP-violating.

CP-violation in the **Stop** sector

- Our example is the decay of the ground state **stoponium** in $^1S_0(\widetilde{t}_1\widetilde{t}_1^*) \to Zh$.

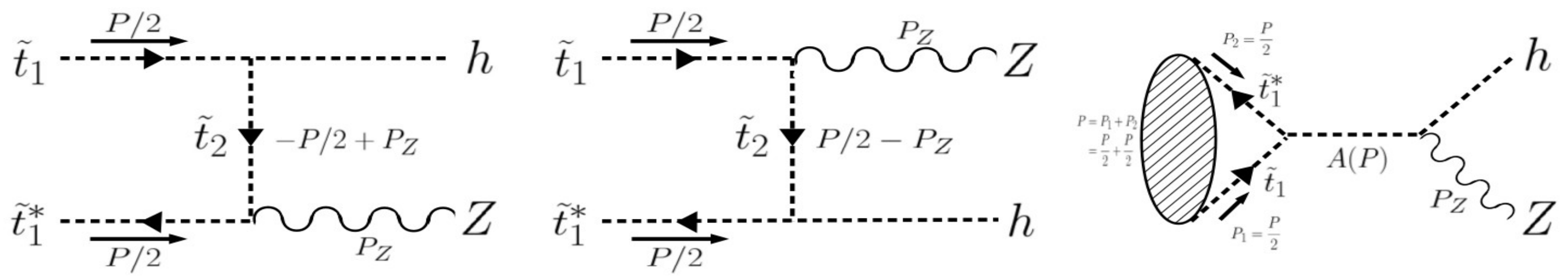

FIG. 1. Feynman diagrams for the stoponium decaying into Zh via the t,u,s channels from the left to the right.

- $m_{A^0} \simeq m_{\tilde{\eta}}$ will enhance the **Zh** decay mode, but restricted by the **eEDM**.

Decay width of Stoponium

- The process $\widetilde{t}_1\widetilde{t}_1^* \to hZ$.

- In the non-relativistic approximation, the amplitude is

$$\mathcal{M}(\widetilde{t}_1\widetilde{t}_1^* \to hZ) = -\left[\frac{4i\mathrm{Im}(g^{Z*}_{\widetilde{t}_1\widetilde{t}_2} y^h_{\widetilde{t}_1\widetilde{t}_2})}{\underline{m_h^2 + m_Z^2 - 2(m^2_{\widetilde{t}_1} + m^2_{\widetilde{t}_2})}} + \frac{2y^A_{\widetilde{t}_1\widetilde{t}_1} g^Z_{Ah}}{4m^2_{\widetilde{t}_1} - m_A^2}\right](P\cdot\varepsilon_Z)$$

$u-$ and $t-$channel, exchange $\widetilde{t}_2$

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polarization sum

$$\sum_{\varepsilon_Z}(P\cdot\varepsilon_Z)^2 = P^\mu\left(-g_{\mu\nu} + \frac{p_{Z\mu}p_{Z\nu}}{m_Z^2}\right)P^\nu = \frac{\lambda(s, m_h^2, m_Z^2)}{4m_Z^2}$$

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The amplitude is suppressed by
non-alignment factor $\cos(\beta-\alpha)$

Decay width of Stoponium

- The process $\widetilde{t}_1\widetilde{t}_1^* \to hZ$.

- In the non-relativistic approximation, the amplitude is

$$\mathcal{M}(\widetilde{t}_1\widetilde{t}_1^* \to hZ) = -\left[\frac{4i\mathrm{Im}(g^{Z*}_{\widetilde{t}_1\widetilde{t}_2} y^{h}_{\widetilde{t}_1\widetilde{t}_2})}{m_h^2 + m_Z^2 - 2(m^2_{\widetilde{t}_1} + m^2_{\widetilde{t}_2})} + \frac{2y^{A}_{\widetilde{t}_1\widetilde{t}_1} g^{Z}_{Ah}}{4m^2_{\widetilde{t}_1} - m_A^2}\right](P\cdot\varepsilon_Z)$$

- The partial decay width:

$$\Gamma(\widetilde{t}_1\widetilde{t}_1^* \to hZ) = \frac{1}{(2m_{\widetilde{t}_1})^2}\sum_{\varepsilon_Z}|\mathcal{M}(\widetilde{t}_1\widetilde{t}_1^* \to hZ)|^2 \underline{|\psi(0)|^2} \frac{3}{8\pi}\lambda^{\frac{1}{2}}(1, m_h^2/s, m_Z^2/s)$$

bound state wave function at the origin

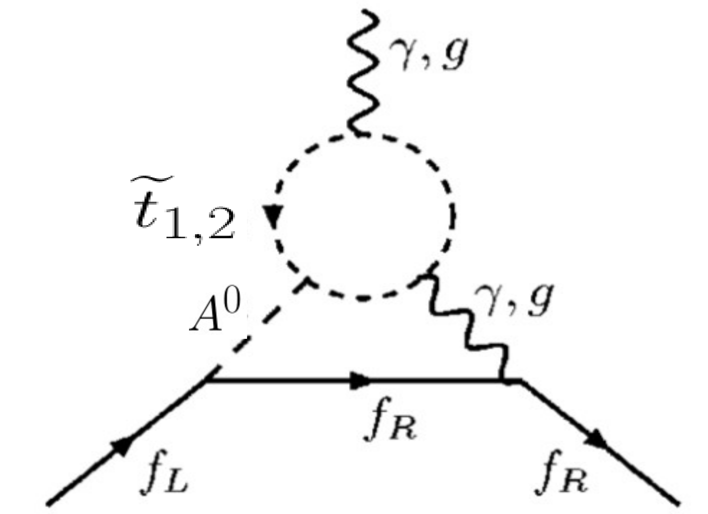
$$|\psi(0)|^2 = \frac{1}{27\pi}(\alpha_s 2m_{\widetilde{t}_1})^3$$

Contribution to the Electron EDM

- The eEDM constraint: $|d_e| < 8.7 \times 10^{-29}\ e \cdot [\mathrm{cm}]\ ,\ \text{at } 90\%\ \text{C.L.}$

  ACME Collaboration, Science 343, 269(2014)

- In MSSM, ***CP-violating*** contribution in **Stop** sector via two-loop Barr-Zee diagram. D.Chang, W.Y.Keung, A.Pilaftsis,, PRL 82, 900 (1999)



$$\mathcal{L}_{CP} = -\xi_f v a(\tilde{f}_1^* \tilde{f}_1 - \tilde{f}_2^* \tilde{f}_2) + \frac{i g_w m_f}{2M_W} R_f a \bar{f} \gamma_5 f$$

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$$\left(\frac{d_e}{e}\right)^{\tilde{t}}_{2-\text{loop}} = 2Q_eQ_t^2\frac{3\alpha_{\text{em}}}{64\pi^3}\frac{m_e}{m_A^2}\left(\frac{\sin 2\theta_{\tilde{t}}\ m_t\text{Im}[\mu^* e^{-i\delta_u}]}{v^2\sin\beta\cos\beta}\right)\left[F\left(\frac{m^2_{\tilde{t}_1}}{m_A^2}\right) - F\left(\frac{m^2_{\tilde{t}_2}}{m_A^2}\right)\right]$$

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$\tilde{t}_{L,R}$ mixing angle

two-loop function

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Vanishing if

i) A^0 becomes very heavy

ii) when $m_{\tilde{t}_1} \simeq m_{\tilde{t}_2}$

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- We ignore one-loop contribution from neutralino-selectron, and chargino-sneutrino diagrams, involve different CP-violating parameters.

Analysis

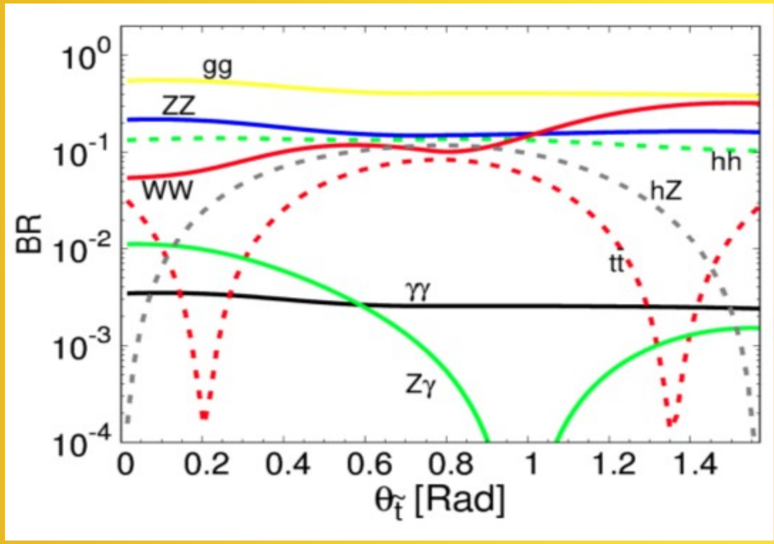
- Interplay between **Zh** channel and **eEDM**:

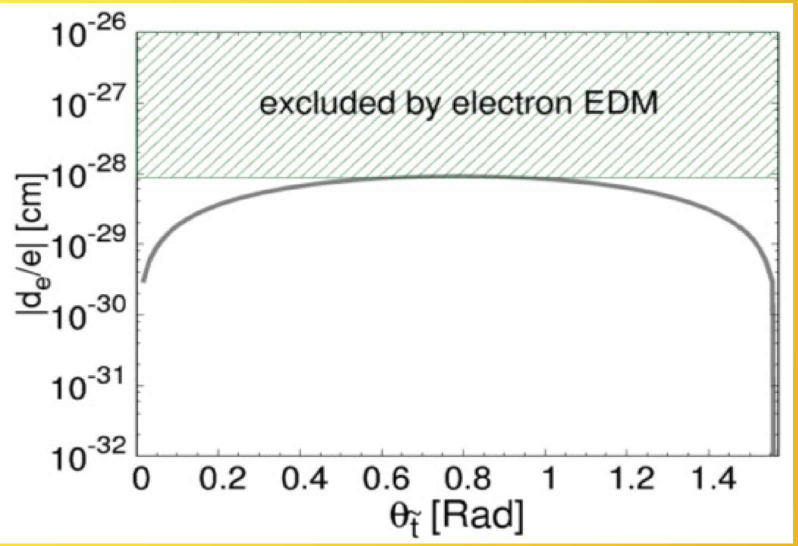
1. Near and below the pole, $m_{\tilde{\eta}} < m_A$ by setting $2m_{\tilde{t}_1} = 1200$ GeV and $m_A = 1.5$ TeV.
2. Well below the pole, $m_{\tilde{\eta}} \ll m_A$ by setting $2m_{\tilde{t}_1} = 1200$ GeV and $m_A = 2.5$ TeV.
3. Far from the pole for an extremely heavy m_A. We set $2m_{\tilde{t}_1} = 1200$ GeV $\ll m_A$.

Analysis

- Interplay between **Zh** channel and **eEDM**:

$$m_{\tilde{t}_1} \simeq m_{\tilde{t}_2}$$
$$\mathrm{BR}(\tilde{\eta} \to Zh) \simeq 10^{-1}$$





$$m_{H,A} = 2.5 \text{ TeV},\ m_{\tilde{t}_2} = 650 \text{ GeV, and } \mathrm{Im}[\mu^* e^{-i\delta_u}] = \quad (2000) \text{ GeV}$$

$$m_{\tilde{t}_1} = 600 \text{ GeV}$$

Observability at LHC

- The **Stoponium** LO production cross section at LHC through the gluon-gluon fusion:

$$\sigma(pp \to \widetilde{\eta}) = \frac{\pi^2}{8m_{\widetilde{\eta}}^3}\Gamma(\widetilde{t}_1\widetilde{t}_1^* \to gg)\int_\tau^1 dx \frac{\tau}{x} g(x,Q)g(\tau/x,Q)$$

- Including NLO, at 13 TeV LHC, the cross section is

$$\sigma(pp \to \widetilde{\eta}) \simeq 1\ [\text{fb}]\ \text{for}\ m_{\widetilde{\eta}} \simeq 1.2\ \text{TeV}$$

- At LHC, the signal would be

$$pp \to \widetilde{\eta} \to hZ\,,$$

$$\text{then } h \to b\bar{b} \text{ and } Z \to \ell\ell \text{ (or } jj)$$

Observability at LHC

- At LHC, the signal would be

$$pp \to \widetilde{\eta} \to hZ\,,$$
$$\text{then } h \to b\bar{b} \text{ and } Z \to \ell\ell \text{ (or } jj)$$

- The **Z** and **Higgs** bosons are very **boosted** in contrast to the conventional QCD background.

- The current limit from ATLAS and CMS:

$$\sigma(pp \to X \to Zh) \times B(h \to b\bar{b} + c\bar{c}) < 10 \text{ fb.}$$

- 300 fb^-1 luminosity at Run-II, 15 events for $\mathrm{BR}(\widetilde{\eta} \to Zh) = 10\%$

Conclusions

- The **Zh** channel decay mode from the ground state of **stoponium** is clean signal of ***CP-violation***.

- Under the **eEDM** constraint, $\widetilde{\eta} \to Zh$ can have a significant branching ratio.

- If **stoponium** is around 1.2 TeV, highly boosted **Z** and **Higgs** bosons are distinguishable from the QCD background.

Thank You!

Back Up

Conclusions

- The Stop mixing:

The stop mass matrix can be expressed as

$$(\widetilde{t}_L^*, \widetilde{t}_R^*) \begin{pmatrix} m_t^2 + M_{\widetilde{Q}}^2 + m_Z^2(\frac{1}{2} - \frac{2}{3}x_W)\cos(2\beta) & m_t(A_t^* - \mu\cot\beta) \\ m_t(A_t - \mu^*\cot\beta) & m_t^2 + M_{\widetilde{U}}^2 + m_Z^2(\frac{2}{3}x_W)\cos(2\beta) \end{pmatrix} \begin{pmatrix} \widetilde{t}_L \\ \widetilde{t}_R \end{pmatrix}$$

We can define a phase δ_u by

$$A_t - \mu^*\cot\beta = |A_t - \mu^*\cot\beta| e^{i\delta_u} \, ,$$

$$\begin{pmatrix} \widetilde{t}_L \\ \widetilde{t}_R \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 0 & e^{i\delta_u} \end{pmatrix} \begin{pmatrix} \cos\theta_{\widetilde{t}} & -\sin\theta_{\widetilde{t}} \\ \sin\theta_{\widetilde{t}} & \cos\theta_{\widetilde{t}} \end{pmatrix} \begin{pmatrix} \widetilde{t}_1 \\ \widetilde{t}_2 \end{pmatrix}$$

Conclusions

- The Higgs-Stop-Stop couplings:

The interaction between h and $\widetilde{t}_{L,R}$ is

$$\begin{aligned}\mathcal{L} \subset\, & h(\widetilde{t}_L^*, \widetilde{t}_R^*) \begin{pmatrix} V_{LL} & V_{LR}^* \\ V_{LR} & V_{RR} \end{pmatrix} \begin{pmatrix} \widetilde{t}_L \\ \widetilde{t}_R \end{pmatrix} \\ =\, & h(\widetilde{t}_L^*, \widetilde{t}_R^*) \begin{pmatrix} -\frac{g m_t^2 c_\alpha}{m_W s_\beta} + \frac{g m_Z}{\sqrt{1-x_W}}(\frac{1}{2} - \frac{2}{3}x_W) s_{\alpha+\beta} & -\frac{1}{2}\frac{g m_t}{m_W s_\beta}(A_t^* c_\alpha + \mu s_\alpha) \\ -\frac{1}{2}\frac{g m_t}{m_W s_\beta}(A_t c_\alpha + \mu^* s_\alpha) & -\frac{g m_t^2 c_\alpha}{m_W s_\beta} + \frac{g m_Z}{\sqrt{1-x_W}}(\frac{2}{3}x_W) s_{\alpha+\beta} \end{pmatrix} \begin{pmatrix} \widetilde{t}_L \\ \widetilde{t}_R \end{pmatrix} \\ \equiv\, & h(\widetilde{t}_1^*, \widetilde{t}_2^*) \begin{pmatrix} y^h_{\widetilde{t}_1\widetilde{t}_1} & {y^h_{\widetilde{t}_1\widetilde{t}_2}}^* \\ y^h_{\widetilde{t}_1\widetilde{t}_2} & y^h_{\widetilde{t}_2\widetilde{t}_2} \end{pmatrix} \begin{pmatrix} \widetilde{t}_1 \\ \widetilde{t}_2 \end{pmatrix}, \end{aligned} \tag{5}$$

Conclusions

- The Z-Stop-Stop couplings:

The interaction between Z boson and $\widetilde{t}_{L,R}$ is

$$
\begin{aligned}
\mathcal{L} \supset & \frac{g}{\sqrt{1-x_W}} Z^\mu (\widetilde{t}_L^*, \widetilde{t}_R^*) i \overleftrightarrow{\partial}_\mu \begin{pmatrix} -\frac{1}{2} + Q_t x_W & 0 \\ 0 & Q_t x_W \end{pmatrix} \begin{pmatrix} \widetilde{t}_L \\ \widetilde{t}_R \end{pmatrix} \\
= & \frac{g}{\sqrt{1-x_W}} Z^\mu \ (\widetilde{t}_1^*, \widetilde{t}_2^*) i \overleftrightarrow{\partial}_\mu \begin{pmatrix} -\frac{1}{2} c_{\theta_{\widetilde{t}}} + Q_t x_W & \frac{1}{2} s_{\theta_{\widetilde{t}}} c_{\theta_{\widetilde{t}}} \\ \frac{1}{2} s_{\theta_{\widetilde{t}}} c_{\theta_{\widetilde{t}}} & -\frac{1}{2} s^2_{\theta_{\widetilde{t}}} + Q_t x_W \end{pmatrix} \begin{pmatrix} \widetilde{t}_1 \\ \widetilde{t}_2 \end{pmatrix} \\
\equiv & Z^\mu (\widetilde{t}_1^*, \widetilde{t}_2^*) i \overleftrightarrow{\partial}_\mu \begin{pmatrix} g^Z_{\widetilde{t}_1 \widetilde{t}_1} & g^Z_{\widetilde{t}_1 \widetilde{t}_2} \\ g^Z_{\widetilde{t}_1 \widetilde{t}_2} & g^Z_{\widetilde{t}_2 \widetilde{t}_2} \end{pmatrix} \begin{pmatrix} \widetilde{t}_1 \\ \widetilde{t}_2 \end{pmatrix} ,
\end{aligned}
$$

Conclusions

- The A-Stop-Stop couplings:

$$\mathcal{L} \supset -\frac{i m_t}{v \sin\beta} A^0 (\widetilde{t}_L^*, \widetilde{t}_R^*) \begin{pmatrix} 0 & -(A_t^* c_\beta + \mu s_\beta) \\ A_t c_\beta + \mu^* s_\beta & 0 \end{pmatrix} \begin{pmatrix} \widetilde{t}_L \\ \widetilde{t}_R \end{pmatrix}$$

$$= \frac{m_t}{v \sin\beta} A^0 (\widetilde{t}_1^*, \widetilde{t}_2^*) \begin{pmatrix} 2 s_{\theta_{\tilde{t}}} c_{\theta_{\tilde{t}}} \mathrm{Im}[\hat{A}_t] & i(c^2_{\theta_{\tilde{t}}} \hat{A}_t^{\,*} + s^2_{\theta_{\tilde{t}}} \hat{A}_t) \\ -i(c^2_{\theta_{\tilde{t}}} \hat{A}_t + s^2_{\theta_{\tilde{t}}} \hat{A}_t^{\,*}) & -2 s_{\theta_{\tilde{t}}} c_{\theta_{\tilde{t}}} \mathrm{Im}[\hat{A}_t] \end{pmatrix} \begin{pmatrix} \widetilde{t}_1 \\ \widetilde{t}_2 \end{pmatrix}$$

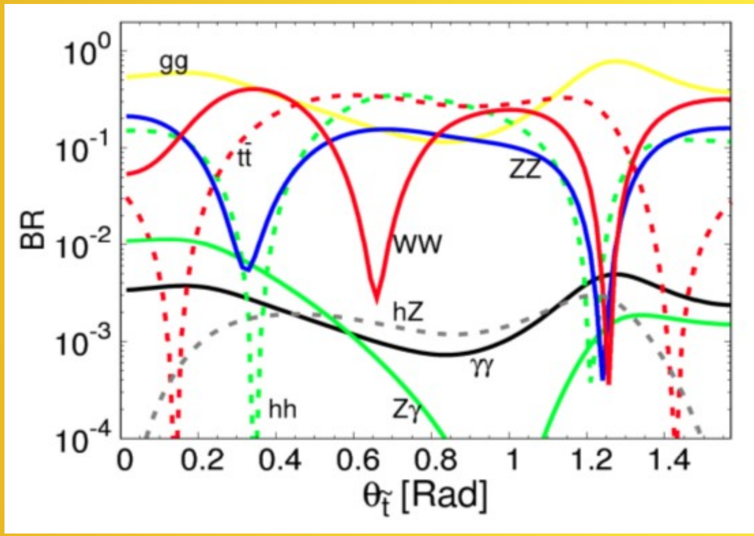
$$\equiv A^0 (\widetilde{t}_1^*, \widetilde{t}_2^*) \begin{pmatrix} y^A_{\widetilde{t}_1 \widetilde{t}_1} & {y^A_{\widetilde{t}_1 \widetilde{t}_2}}^* \\ y^A_{\widetilde{t}_1 \widetilde{t}_2} & y^A_{\widetilde{t}_2 \widetilde{t}_2} \end{pmatrix} \begin{pmatrix} \widetilde{t}_1 \\ \widetilde{t}_2 \end{pmatrix}$$

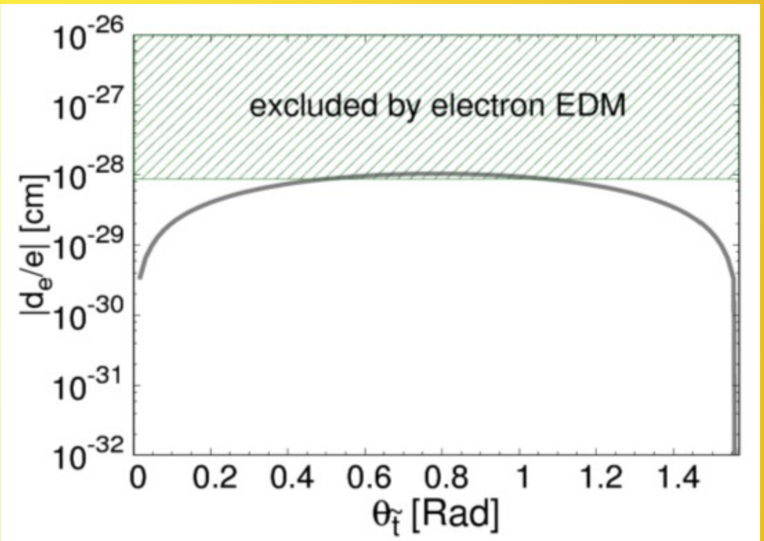
Analysis

- Interplay between **Zh** channel and **eEDM**:

$m_{A^0} \simeq m_{\tilde{\eta}}$

$\mathrm{BR}(\tilde{\eta} \to Zh) \simeq 10^{-3}$





$\mathrm{Im}[\mu^* e^{-i\delta_u}] =$ (200) GeV. For all panels we fix $m_{\tilde{t}_1} = 600$ GeV, $m_{\tilde{t}_2} = 1$ TeV, $m_{\tilde{g}} = 2$ TeV,

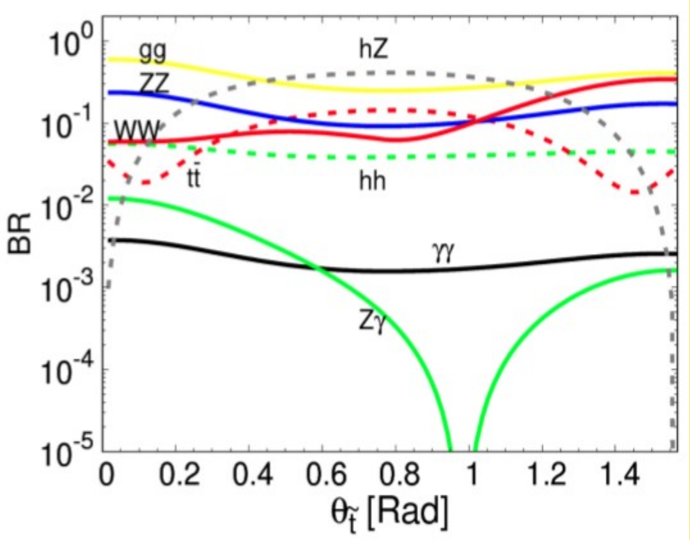
$\tan\beta = 10$, $\cos(\beta - \alpha) = 0.1$, $m_h = 125$ GeV, $m_{H,A} = 1.5$ TeV, and vary $\theta_{\tilde{t}} \subseteq [0, \frac{\pi}{2}]$.

Analysis

- Interplay between **Zh** channel and **eEDM**:

$m_{A^0} \to \infty$ and $m_{\tilde{t}_1} \simeq m_{\tilde{t}_2}$

$\mathrm{BR}(\tilde{\eta} \to Zh)$ can be dominating



$m_{A^0} \to \infty,\ m_{\tilde{t}_1} = 600$ GeV, $m_{\tilde{t}_2} = 650$ GeV.