LHC Signatures of MSSM Higgs-sector CP Violation

JAE SIK LEE

Center for Theoretical Physics, School of Physics and Astronomy,
Seoul National University, Seoul 151-747, Korea
jslee@muon.kaist.ac.kr

Received 15 June 2007

We discuss a few new characteristic features of the loop-induced MSSM Higgs-sector CP violation at the LHC based on two scenarios: (i) CPX and (ii) Trimixing.

Keywords: Higgs; CP violation; LHC.

PACS numbers: 14.80.Cp, 12.60.Jv, 11.30.Er

1. Introduction

Supersymmetric models contain many possible sources of CP violation beyond the SM CKM phase. In the Minimal Supersymmetric extension of the Standard Model (MSSM), for example, we have 8 CP phases when we even consider only the third generation, that is, stops, sbottoms, and staus:

- $\Phi_\mu [1]$: $W \supset \mu \tilde{H}_2 \cdot \tilde{H}_1$
- $\Phi_t [3]$: $-L_{\text{soft}} \supset \frac{1}{2}(M_3 \bar{g} \bar{g} + M_2 \bar{W} \bar{W} + M_1 \bar{B} \bar{B} + \text{h.c.})$
- $\Phi_A [3]$ with $f = t, b, \tau$: $-L_{\text{soft}} \supset A_t \bar{\tilde{t}} Q_3 \cdot H_2 - A_b \bar{\tilde{b}} R_3 \cdot H_1 - A_\tau \bar{\tilde{\tau}} L_3 \cdot H_1 + \text{h.c.}$
- $\Phi_{m_{12}^2} [1]$: $-L_{\text{soft}} \supset - (m_{12}^2 H_1 \cdot H_2 + \text{h.c.})$

The numbers of relevant CP phases are given in the brackets. These 8 CP phases are not all independent and physical observables depend on the combinations of $\text{Arg}(M_1 \mu (m_{12}^2)^*)$ and $\text{Arg}(A_f \mu (m_{12}^2)^*)$. In the convention of $\text{Arg}(m_{12}^2) = 0$, we have 6 rephasing invariant CP phases:

$$\text{Arg}(M_1 \mu), \text{Arg}(M_2 \mu), \text{Arg}(M_3 \mu); \text{Arg}(A_t \mu) \text{Arg}(A_b \mu) \text{Arg}(A_\tau \mu).$$

These non-vanishing CP phases can induce a significant CP-violating mixing between CP-even and CP-odd Higgs states via radiative corrections. There are two approaches to calculate this CP-violating mixing. Here we use the calculation based on the renormalization-group-improved effective potential method.
including the Higgs-boson pole mass shift. For the Feynman-diagrammatic approach, we refer to Ref. [12] and references therein.

In this contribution, we discuss a few characteristic features of the Higgs-sector CP violation at the LHC which have been recently observed after the appearance of CPNSH Report. And we put emphasis on importance of the \( \tau \) lepton polarization measurement to construct genuine CP-odd signal at the LHC. For numerical analysis, two scenarios are considered: (i) CPX (Sec. 2) and (ii) Trimixing (Sec. 3). See, for example, Ref. [17] for detailed description and comparison of two scenarios with some numerical results. The code CPsuperH is used to generate numerical outputs.

2. CPX Scenario

First we consider the constraint on the CPX scenario coming from the non-observation of an EDM in the Thallium atom. The contributions of the first and second generation phases, e.g. \( \Phi_{A_\mu,\tau} \), etc., to EDMs can be drastically reduced either by making these phases sufficiently small, or if the first- and second-generation squarks and sleptons are sufficiently heavy. In this case, the dominant contribution to EDMs occurs at two-loop level. We refer to Ref. [22] for the explicit expression of the two-loop Higgs-mediated Thallium EDM in the CPsuperH conventions and notations.

In the left frame of Fig. 1, the rescaled Thallium EDM \( \hat{d}_{Tl} \equiv d_{Tl} \times 10^{24} \) in units of \( e \) cm for the CPX scenario with \( \Phi_{A_\mu,\tau} = \Phi_3 = 90^\circ \) on the \( \tan \beta - M_{H_1} \) plane. We take \( \Phi_\mu = 0 \) convention. In the right frame the CUSB bound from the decay \( \Upsilon(1S) \rightarrow \gamma H_1 \) is also shown as a thick solid line. See Ref. [27] for details.

In the right frame of Fig. 1, the rescaled Thallium EDM \( \hat{d}_{Tl} \equiv d_{Tl} \times 10^{24} \) is shown on the \( \tan \beta - M_{H_1} \) plane in units of \( e \) cm. The current upper limit is \( |\hat{d}_{Tl}| \lesssim 1.3 \).
We divide the plane into 4 regions depending on the size of $|\hat{d}_{T1}|$. The unshaded region is not allowed theoretically. We have $|\hat{d}_{T1}| < 1$ only in the narrow region filled with black squares when $\tan \beta \lesssim 5$ and $M_{H_1} \lesssim 8$ GeV. However, if we allow 10 %-level cancellation between the two-loop contributions and possible one-loop contributions not considered here, the (green) region with $1 \leq |\hat{d}_{T1}| < 10$ is allowed. Furthermore, if very strong 1 %-level cancellation is possible, most of the region can be made consistent with the Thallium EDM constraint if the lightest Higgs boson is not so light. In the right frame of Fig. 1, we magnify the region with $3 \lesssim \tan \beta \lesssim 10$ and $M_{H_1} \lesssim 15$ GeV. This region is of particular interest since $H_1$ lighter than about 10 GeV has not been excluded by the LEP experiments for the given range of $\tan \beta$. The bound on this light Higgs boson comes from low-energy experiment. We find that the region $M_{H_1} \lesssim 8$ GeV (the region below the thick solid CUSB line) is excluded by data on $\Upsilon(1S)$ decay. For details, see Ref. 27.

Fig. 2. The differential cross sections in units of fb/GeV at $\Phi_{A\mu} = 100^\circ$ (left frames) and $\Phi_{A\mu} = 105^\circ$ (right frames), versus the invariant mass $\sqrt{s}$ of two muons (uppers frames) or two photons (lower frames). The charged Higgs-boson pole mass is solved to give $M_{H_1} = 115$ GeV for $\tan \beta = 10$ and $\text{Arg}(M_3 \mu) = 180^\circ$ in the CPX scenario. See Ref. 30 for details.
For the scenario with large $|\mu|$ and $|M_3|$ such as CPX, the threshold corrections to the bottom-quark Yukawa coupling should not be neglected especially for intermediate and large values of $\tan \beta$. In this case, the production cross sections of the three neutral Higgs bosons through $b\bar{b}$ fusion can deviate substantially from those obtained in CP conserving scenarios, thanks to the nontrivial role played by the threshold corrections combined with the CP-violating mixing in the neutral-Higgs-boson sector.\textsuperscript{28} The largest deviations in the case of $H_1$ and $H_2$ are for values of $\Phi_{A_{\mu}} \equiv \text{Arg}(A_{t,b} \mu)$ around $100^\circ$, with a large enhancement for the production cross section of $H_1$ and a large suppression for that of $H_2$. To detect this large enhancement and/or suppression, we need to know whether it is possible to disentangle the two corresponding peaks in the invariant mass distributions of the $H_1$- and $H_2$-decay products at the LHC. To address this issue, we consider the Higgs-boson decays into muon and photon pairs. For these two decay modes, the invariant-mass resolutions are, respectively, $\delta M_{\gamma\gamma} \sim 1$ GeV and $\delta M_{\mu\mu} \sim 3$ GeV for a Higgs mass of $\sim 100$ GeV.\textsuperscript{29} In Fig. 2, we show the differential cross sections in units of fb/GeV taking two values of $\Phi_{A_{\mu}}$. The upper two frames are for $H_{1,2} \rightarrow \mu^+\mu^-$ and the lower frames for $H_{1,2} \rightarrow \gamma\gamma$. For $\Phi_{A_{\mu}} = 100^\circ$ (left frames), by combining the muon-decay mode with the photon-decay mode, $H_2$ can be located more precisely and disentangled from $H_1$. For $\Phi_{A_{\mu}} = 105^\circ$ (right frames), actually, two well separated peaks may be observed. For details, we refer to Ref.\textsuperscript{30}

3. Trimixing Scenario

![Fig. 3](image-url)  

Fig. 3. The CP asymmetry $A_{WW}^{\text{CP}}$ as functions of $\Phi_A \equiv \Phi_{A_t} = \Phi_{A_b} = \Phi_{A_\tau}$ for $\Phi_3 = -10^\circ$ (left frame) and $\Phi_3 = -90^\circ$ (right frame) in the Trimixing scenario. We take $\Phi_\mu = 0$. See Ref.\textsuperscript{14} for details.

To construct CP asymmetry at the LHC, we consider the production of CP-violating
MSSM $H_{1,2,3}$ bosons via $W^+W^-$ collisions and their subsequent decays into $\tau^+\tau^-$ pairs assuming the longitudinal polarization of $\tau$ leptons can be measured. In this case, one can define integrated CP asymmetry:

$$A_{WW}^{\text{CP}} \equiv \frac{\sigma_{RR}^{WW} - \sigma_{LL}^{WW}}{\sigma_{RR}^{WW} + \sigma_{LL}^{WW}},$$

(2)

where

$$\sigma_{RR} = \sigma(pp(WW) \rightarrow H \rightarrow \tau^+_R\tau^-_R X),$$
$$\sigma_{LL} = \sigma(pp(WW) \rightarrow H \rightarrow \tau^+_L\tau^-_L X).$$

(3)

In Fig. 3, we show the CP asymmetry $A_{WW}^{\text{CP}}$ as functions of $\Phi_A \equiv \Phi_{A_+} = \Phi_{A_3}$ for $\Phi_3 = -10^\circ$ (left frame) and $\Phi_3 = -90^\circ$ (right frame) taking $\Phi_{\mu} = 0^\circ$. We observe the CP asymmetry is large over the whole region of $\Phi_A$ independently of $\Phi_3$. For more detailed discussion, see Ref. 14.

4. Conclusions

We obtain the constraint $M_{H_1} \gtrsim 8$ GeV from the decay $\Upsilon(1S) \rightarrow \gamma H_1$. By combining the Higgs-boson decay mode into two muons with that into two photons, it is possible to disentangle two adjacent peaks with the mass difference larger than $\sim 3$ GeV at the LHC. The process $W^+W^- \rightarrow H_{1,2,3} \rightarrow \tau^+\tau^-$ is promising to probe CP violation through the CP asymmetry based on longitudinal $\tau$-lepton polarization.

Acknowledgments

I wish to thank F. Borzumati, J. Ellis, S. Scopel, and A. Pilaftsis for valuable collaborations. This work was supported in part by Korea Research Foundation and the Korean Federation of Science and Technology Societies Grant funded by the Korea Government (MOEHRD, Basic Research Promotion Fund).

5. References

References

1. M. Dugan, B. Grinstein and L. J. Hall, Nucl. Phys. B 255 (1985) 413.
2. S. Dimopoulos and S. D. Thomas, Nucl. Phys. B 465 (1996) 23 [arXiv:hep-ph/9510220].
3. A. Pilaftsis, Phys. Rev. D 58 (1998) 096010 [arXiv:hep-ph/9803297].
4. A. Pilaftsis, Phys. Lett. B 435 (1998) 88 [arXiv:hep-ph/9805373].
5. A. Pilaftsis and C. E. M. Wagner, Nucl. Phys. B 553 (1999) 3 [arXiv:hep-ph/9902371].
6. D. A. Demir, Phys. Rev. D 60 (1999) 055006 [arXiv:hep-ph/9901389].
7. S. Y. Choi, M. Drees and J. S. Lee, Phys. Lett. B 481 (2000) 57 [arXiv:hep-ph/0002287].
8. T. Ibrahim and P. Nath, Phys. Rev. D 63 (2001) 035009 [arXiv:hep-ph/0008237].
9. T. Ibrahim and P. Nath, Phys. Rev. D 66 (2002) 015005 [arXiv:hep-ph/0204092].
10. M. Carena, J. R. Ellis, A. Pilaftsis and C. E. M. Wagner, Nucl. Phys. B 586 (2000) 92 [arXiv:hep-ph/0003180].
11. M. Carena, J. R. Ellis, A. Pilaftsis and C. E. M. Wagner, Nucl. Phys. B 625 (2002) 345 [arXiv:hep-ph/0111245].
12. S. Heinemeyer, W. Hollik, R. Rzehak and G. Weiglein, AIP Conf. Proc. 903 (2007) 149 [arXiv:0705.0746 [hep-ph]].
13. E. Accomando et al., arXiv:hep-ph/0608079.
14. J. R. Ellis, J. S. Lee and A. Pilaftsis, Phys. Rev. D 70 (2004) 075010 [arXiv:hep-ph/0404167].
15. J. R. Ellis, J. S. Lee and A. Pilaftsis, Mod. Phys. Lett. A 21 (2006) 1405 [arXiv:hep-ph/0605288].
16. M. Carena, J. R. Ellis, A. Pilaftsis and C. E. M. Wagner, Phys. Lett. B 495 (2000) 155 [arXiv:hep-ph/0009212].
17. J. S. Lee, arXiv:0705.1089 [hep-ph].
18. J. S. Lee, A. Pilaftsis, M. Carena, S. Y. Choi, M. Drees, J. R. Ellis and C. E. M. Wagner, Comput. Phys. Commun. 156 (2004) 283 [arXiv:hep-ph/0307377].
19. D. Chang, W. Y. Keung and A. Pilaftsis, Phys. Rev. Lett. 82 (1999) 900 [Erratum-ibid. 83 (1999) 3972] [arXiv:hep-ph/9811202].
20. A. Pilaftsis, Phys. Lett. B 471 (1999) 174 [arXiv:hep-ph/9909485].
21. D. Chang, W. F. Chang and W. Y. Keung, Phys. Lett. B 478 (2000) 239 [arXiv:hep-ph/9910465].
22. J. R. Ellis, J. S. Lee and A. Pilaftsis, Phys. Rev. D 72 (2005) 095006 [arXiv:hep-ph/0507046].
23. B. C. Regan, E. D. Commins, C. J. Schmidt and D. DeMille, Phys. Rev. Lett. 88 (2002) 071805.
24. S. Schael et al. [ALEPH Collaboration], Eur. Phys. J. C 47 (2006) 547 [arXiv:hep-ex/0602042].
25. See P. Bechtle in Ref. 13.
26. P. Franzini et al., Phys. Rev. D 35 (1987) 2883.
27. J. S. Lee and S. Scopel, Phys. Rev. D 75 (2007) 075001 [arXiv:hep-ph/0701221].
28. F. Borzumati, J. S. Lee and W. Y. Song, Phys. Lett. B 595 (2004) 347 [arXiv:hep-ph/0401024].
29. The Atlas Collaboration, Atlas: detector and physics performance technical design report, vol 2, CERN-LHCC-99-15, ATLAS-TDR-15 (1999).
30. F. Borzumati and J. S. Lee, Phys. Lett. B 641 (2006) 486 [arXiv:hep-ph/0605273].