Two Higgs bosons around 125 GeV in the CPV-NMSSM at the LHC

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Outline

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Introduction: Beyond the MSSM

- The LHC (ATLAS and CMS) data indicate that the properties of the observed Higgs boson are mostly compatible with the Standard Model (SM), although details from different production and decay modes are needed to understand.
- Calls for detailed phenomenological studies on the extended Higgs sector of different beyond Standard Model (BSM) scenarios.
- Supersymmetric (SUSY) extensions are most popular BSM candidates, resulting a comparatively richer Higgs sector with various features distinct from the SM.
- The Minimal Supersymmetric Standard Model (MSSM) is the simplest SUSY extention of the SM.
- MSSM super potential is not conformal invariant.

$$W_{\rm MSSM} = y_u \hat{Q}\hat{H}_u\hat{U}^c - y_d\hat{Q}\hat{H}_d\hat{D}^c - y_e\hat{L}\hat{H}_d\hat{E}^c + \mu\hat{H}_u\hat{H}_d. \quad (1)$$

Introduction: Beyond the MSSM

- μ-problem of MSSM: Difficulty to generate μ parameter which is naturally of order the EW scale.

$$\mu^2 = -\frac{m_Z^2}{2} + \frac{M_{H_d}^2 - M_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1} \quad (2)$$

- For 125 GeV Higgs boson at the LHC, MSSM requires large values of A_t.

$$\Delta m_h^2 = \frac{3m_t^4}{4\pi^2 v^2}\left[\ln\left(\frac{M_{\rm SUSY}^2}{m_t^2}\right) + \frac{X_t^2}{M_{\rm SUSY}^2}\left(1 - \frac{X_t^2}{12M_{\rm SUSY}^2}\right)\right] \quad (3)$$

- The LHC Run 2 data severely constrain the parameter space of the MSSM, by excluding $\tan\beta$ above 7.6 for $m_A = 200$ GeV in $\tau\tau$ final state. (ATLAS Col., arXiv:1608.00890)
- Some unique phenomenological possibilities in the NMSSM, precluded or excluded in the MSSM: Any one of the two lightest Higgs bosons could be the observed one, or both may lie around 125 GeV.

CPV-NMSSM Higgs sector

- NMSSM contains an extra Higgs singlet $\hat{S}$ in addition to the two MSSM Higgs doublets.
- NMSSM superpotential:

$$W_{\rm NMSSM} = W_{\rm MSSM}^{\rm Yukawa} + \lambda \hat{S} \hat{H}_u \hat{H}_d + \frac{\kappa}{3} \hat{S}^3 \tag{4}$$

Solve μ-problem: $\mu_{\rm eff} = \lambda v_s$ (At EWSB scale)

- 5 new parameters: λ, κ, A_λ, A_κ, v_s
- 5 neutral Higgs bosons and 5 neutralinos.
- Enhanced tree-level mass of the SM-like Higgs with reduced fine tuning

$$m^2_{H_{\rm SM}} \simeq m_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta - \frac{\lambda^2 v^2}{\kappa^2}\left[\lambda - \sin 2\beta\left(\kappa + \frac{A_\lambda}{2s}\right)\right]^2. \tag{5}$$

CPV-NMSSM Higgs sector

- CP violation could be a necessary condition for EW baryogenesis.
- CP violation can be invoked at the tree-level of the NMSSM Higgs sector, unlike the NMSSM.

$$\lambda =\mid \lambda \mid e^{i\phi_\lambda} \; , \; \kappa =\mid \kappa \mid e^{i\phi_\kappa}.$$

- Two Higgs doublets

$$H_d = \begin{pmatrix} \frac{1}{\sqrt{2}}(v_d + H_{dR} + iH_{dI}) \\ H_d^- \end{pmatrix}, H_u = e^{i\phi_u} \begin{pmatrix} H_d^+ \\ \frac{1}{\sqrt{2}}(v_u + H_{uR} + iH_{uI}) \end{pmatrix}$$

and a singlet

$$S = \frac{e^{i\phi_s}}{\sqrt{2}}(v_s + S_R + iS_I) \tag{6}$$

CPV-NMSSM Higgs sector

- The tree-level Higgs mass matrix can be given as

$$\mathcal{M}_0^2 = \left(\begin{array}{c|c} \mathcal{M}_S^2 & \mathcal{M}_{SP}^2 \\ \hline \left(\mathcal{M}_{SP}^2\right)^T & \mathcal{M}_P^2 \end{array} \right), \tag{7}$$

in the basis $\mathrm{H}^T \equiv (H_{dR}, H_{uR}, S_R, H_{dI}, H_{uI}, S_I)$.

- $\mathcal{M}_S^2/\mathcal{M}_P^2$: Represents mixing between the CP-even/CP-odd states and of the Higgs fields.

  $\mathcal{M}_{SP}^2$: Represents mixing between CP-even and CP-odd states.

CPV-NMSSM Higgs sector

- **Physical Higgs mass eigenstates from the interaction states:**

  The massless Goldstone boson field G is separated out through a rotation by $\mathcal{R}^G$

  $$(H_{dR}, H_{uR}, S_R, H_I, S_I, G)^T = \mathcal{R}^G (H_{dR}, H_{uR}, S_R, H_{dI}, H_{uI}, S_I)^T , \quad (8)$$

  and then using another rotation by $\mathcal{R}^H$

  $$(H_1, H_2, H_3, H_4, H_5, G)^T = \mathcal{R}^H (H_{dR}, H_{uR}, S_R, H_I, S_I, G)^T , \quad (9)$$

  where the diagonalised squared mass matrix

  $$\mathrm{diag}\left(m^2_{H_1}, m^2_{H_2}, m^2_{H_3}, m^2_{H_4}, m^2_{H_5}, 0\right) = \mathcal{R}^H \left[\mathcal{R}^G \mathcal{M}^2_0 \left(\mathcal{R}^G\right)^T\right] \left(\mathcal{R}^H\right)^T . \quad (10)$$

- H_1, H_2, H_3, H_4, H_5: Five physical neutral Higgs bosons in the CPV-NMSSM.
- In ascending order of their masses: $m_{H_1} \leq m_{H_2} \leq m_{H_3} \leq m_{H_4} \leq m_{H_5}$.

Two Higgs bosons around 125 GeV

- CPV phases can modify the Higgs mass and decay widths. Thus non-zero CPV phases are strongly constrained by the LHC measurements. Mass-degenerate scenarios were not considered. [S. Moretti, et al., Phys. Rev. D 89, 015022 (2014)]

- CPV scenarios where the observed Higgs resonance, can actually be explained by two mass-degenerate neutral Higgs states, give improved fit to the LHC data, compared to (a) the CPC-NMSSM. (b) Scenarios with a single Higgs boson $\sim$ 125 GeV. [S. Moretti, S. Munir., Adv. High Energy Phys. 2015, 509847 (2015)].

- Objective: To study the effect of CPV phases on the cross-section of the process $gg \to H_i \to H_j \to \gamma\gamma$, $i, j = 1, .., 5$, for scenarios with two mass-degenerate Higgs bosons $\sim$ 125 GeV in the CPV-NMSSM, with possibilities of mixing in the Higgs propagator.

Diphoton production through gluon fusion: NWA and beyond

- The squared amplitude for $gg \to H_i \to \gamma\gamma$, $i = 1, 2, .., 5$

$$| \mathcal{M} |^2 = \sum_{\lambda,\sigma=\pm} \mathcal{M}_{P\lambda} \mathcal{M}^*_{P\lambda} \left| D_H(\hat{s}) \right|^2 \mathcal{M}_{D\sigma} \mathcal{M}^*_{D\sigma} \,, \qquad (11)$$

$\lambda, \sigma = \pm 1$: the gluon and photon helicities, $D_H(\hat{s})$: Higgs propagator.

- The amplitudes for the production and decay [J. Lee et al., Comput.Phys.Commun. 156 (2004) 283317]

$$\mathcal{M}_{P\lambda} = \sum_{i=1-5} \mathcal{M}_{P_i\lambda} = \sum_{i=1-5} \frac{\alpha_s m^2_{H_i}}{4\pi v} \left\{ S^g_i(m_{H_i}) + i\lambda P^g_i(m_{H_i}) \right\}, \qquad (12)$$

$$\mathcal{M}_{D\sigma} = \sum_{i=1-5} \mathcal{M}_{D_i\sigma} = \sum_{i=1-5} \frac{\alpha_{em} m^2_H}{4\pi v} \left\{ S^\gamma_H(m_H) + i\sigma P^\gamma_H(m_H) \right\}. \qquad (13)$$

Diphoton production through gluon fusion: NWA and beyond

- For the scalar and pseudoscalar form factors we refer [J. Baglio et al., arXiv:1312.4788 [hep-ph]].
- The full propagator matrix [J. Ellis et al., Phys.Rev. D70 (2004) 075010]

$$D_H(\hat{s}) = \hat{s}\begin{pmatrix} \mathrm{m}_{11} + i\Im\mathrm{m}\hat{\Pi}_{11}(\hat{s}) & i\Im\mathrm{m}\hat{\Pi}_{12}(\hat{s}) & i\Im\mathrm{m}\hat{\Pi}_{13}(\hat{s}) & i\Im\mathrm{m}\hat{\Pi}_{14}(\hat{s}) & i\Im\mathrm{m}\hat{\Pi}_{15}(\hat{s}) \\ i\Im\mathrm{m}\hat{\Pi}_{21}(\hat{s}) & \mathrm{m}_{22} + i\Im\mathrm{m}\hat{\Pi}_{22}(\hat{s}) & i\Im\mathrm{m}\hat{\Pi}_{23}(\hat{s}) & i\Im\mathrm{m}\hat{\Pi}_{24}(\hat{s}) & i\Im\mathrm{m}\hat{\Pi}_{25}(\hat{s}) \\ i\Im\mathrm{m}\hat{\Pi}_{31}(\hat{s}) & i\Im\mathrm{m}\hat{\Pi}_{32}(\hat{s}) & \mathrm{m}_{33} + i\Im\mathrm{m}\hat{\Pi}_{33}(\hat{s}) & i\Im\mathrm{m}\hat{\Pi}_{34}(\hat{s}) & i\Im\mathrm{m}\hat{\Pi}_{35}(\hat{s}) \\ i\Im\mathrm{m}\hat{\Pi}_{41}(\hat{s}) & i\Im\mathrm{m}\hat{\Pi}_{42}(\hat{s}) & i\Im\mathrm{m}\hat{\Pi}_{43}(\hat{s}) & \mathrm{m}_{44} + i\Im\mathrm{m}\hat{\Pi}_{44}(\hat{s}) & i\Im\mathrm{m}\hat{\Pi}_{45}(\hat{s}) \\ i\Im\mathrm{m}\hat{\Pi}_{51}(\hat{s}) & i\Im\mathrm{m}\hat{\Pi}_{52}(\hat{s}) & i\Im\mathrm{m}\hat{\Pi}_{53}(\hat{s}) & i\Im\mathrm{m}\hat{\Pi}_{54}(\hat{s}) & \mathrm{m}_{55} + i\Im\mathrm{m}\hat{\Pi}_{55}(\hat{s}) \end{pmatrix}^{-1}, \tag{14}$$

with $\mathrm{m}_{ii} \equiv \hat{s} - m_{H_i}^2$, and $\Im\mathrm{m}\hat{\Pi}_{ij}(\hat{s})$: the absorptive parts of the Higgs self-energies, for $i, j = 1 - 5$.

- CPV phases turned on $\Longrightarrow$ Non-zero off-diagonal terms

Diphoton production through gluon fusion: NWA and beyond

- Larger splitting between the Higgs boson masses than the sizes of $\Im\mathrm{m}\hat{\Pi}_{ij}(\hat{s})$, $\implies$ NWA in the *i*th Higgs boson propagator

$$|D_{ii}(\hat{s})|^2 = \left| \frac{1}{\hat{s} - m_{H_i}^2 + i m_{H_i}\Gamma_{H_i}} \right|^2 \to \frac{\pi}{m_{H_i}\Gamma_{H_i}} \delta(\hat{s} - m_{H_i}^2). \qquad (15)$$

[E. Fuchs et al., Eur. Phys. J. C75 (2015) 254]

- The partonic cross section [J. Ellis et al., Phys.Rev. D70 (2004) 075010]

$$\hat{\sigma}(gg \to H_i \to \gamma\gamma) = \frac{1}{1024\pi\hat{s}} \sum_{i=1-5} \left(\sum_{\lambda=\pm} \left| \mathcal{M}_{P_i\lambda} \right|^2 \times \frac{\pi}{m_{H_i}\Gamma_{H_i}} \delta(\hat{s} - m_{H_i}^2) \times \sum_{\sigma=\pm} \left| \mathcal{M}_{D_i\sigma} \right|^2 \right). \qquad (16)$$

- The total cross-section for the process $pp \to H_i \to \gamma\gamma$ in the NWA

$$\sigma(pp \to H_i \to \gamma\gamma) = \int_{\frac{m_{H_i}^2}{s}}^{1} dx_1 \, \frac{1}{1024 s m_{H_i}^3 \Gamma_{H_i}} \sum_{i=1-5} \left(\sum_{\lambda=\pm} \left| \mathcal{M}_{P_i\lambda} \right|^2 \sum_{\sigma=\pm} \left| \mathcal{M}_{D_i\sigma} \right|^2 \right) \frac{g(x_1) g(\frac{m_{H_i}^2}{s}/x_1)}{x_1}. \qquad (17)$$

Diphoton production through gluon fusion: NWA and beyond

- Beyond the NWA: $\Im\mathrm{m}\hat{\Pi}_{ij}(\hat{s})$ become comparable to the Higgs mass difference. $i-$th Higgs state can undergo resonant transition to the $j-$th state, invalidating the NWA

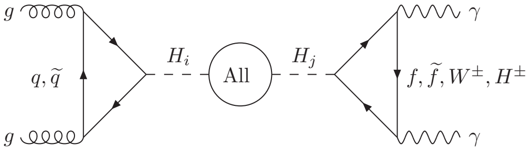


Figure : Leading order (LO) Feynman diagram for $gg \to H_i \to H_i \to \gamma\gamma$.

- The total cross section

$$\sigma(pp \to H \to \gamma\gamma) = \int_0^1 d\tau \int_\tau^1 \frac{dx_1}{x_1} \frac{g(x_1)g(\tau/x_1)}{1024\pi\hat{s}^3} \sum_{i,j=1-5} \left\{ \sum_{\lambda=\pm} \left|\mathcal{M}_{P_i\lambda}\right|^2 |D_{ij}(\hat{s})|^2 \sum_{\sigma=\pm} \left|\mathcal{M}_{D_j\sigma}\right|^2 \right\}. \quad (18)$$

$g(x_1)$ and $g(\tau/x_1)$ are the pdfs of the two gluons.

Diphoton production through gluon fusion: NWA and beyond

- The differential cross section wrt τ

$$\frac{d\sigma}{d\tau} = \int_{\tau}^{1} \frac{dx_1}{x_1} \frac{g(x_1)g(\tau/x_1)}{1024\pi\hat{s}^3} \sum_{i,j=1-5} \left\{ \sum_{\lambda=\pm} \left|\mathcal{M}_{P_i\lambda}\right|^2 \left|D_{ij}(\hat{s})\right|^2 \sum_{\sigma=\pm} \left|\mathcal{M}_{D_j\sigma}\right|^2 \right\}, \tag{19}$$

and then substituting $\tau = \frac{\hat{s}}{s}$ gives

$$\frac{d\sigma}{d\sqrt{\hat{s}}} = \int_{\tau}^{1} \frac{2\sqrt{\hat{s}}}{s} \frac{dx_1}{x_1} \frac{g(x_1)g(\hat{s}/sx_1)}{1024\pi\hat{s}^3} \sum_{i,j=1-5} \left\{ \sum_{\lambda=\pm} \left|\mathcal{M}_{P_i\lambda}\right|^2 \left|D_{ij}(\hat{s})\right|^2 \sum_{\sigma=\pm} \left|\mathcal{M}_{D_j\sigma}\right|^2 \right\}. \tag{20}$$

- Packages used: (a)The above cross sections are calculated by a locally developed fortran program, (b)NMSSMCALC to compute Higgs mass spectrum, decay widths and branching ratios (BRs), (c)LAPACK for propagator matrix inversion, (d)VEGAS for two dimensional numerical integration.

Diphoton production through gluon fusion: NWA and beyond

- **Model parameters:** Following supergravity-inspired universality conditions are used on the model parameters

$$M_0 \equiv M_{Q_{1,2,3}} = M_{U_{1,2,3}} = M_{D_{1,2,3}} = M_{L_{1,2,3}} = M_{E_{1,2,3}},$$
$$M_{\frac{1}{2}} \equiv 2M_1 = M_2 = \frac{1}{3}M_3, \qquad A_f \equiv A_t = A_b = A_\tau. \tag{21}$$

- Thus the set of CPV-NMSSM model parameters in our analysis:

$$M_0,\ |M_{\frac{1}{2}}|,\ |A_f|,\ \tan\beta,\ |\lambda|,\ |\kappa|,\ \mu_{\rm eff},\ |A_\lambda|,\ |A_\kappa|,\ \phi_{\frac{1}{2}},\ \phi_f,\ \phi'_\lambda, \phi'_\kappa.$$

- **Mass-degeneracy condition:** $m_{H_2} - m_{H_1} < 2$ GeV (LHC mass resolution). [G. Aad et al. Phys. Rev. Lett. 114, 191803 (2015)]

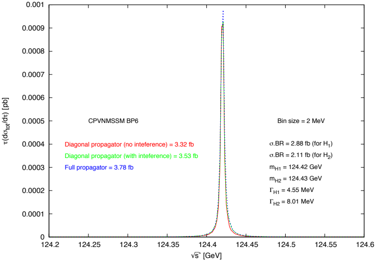
Diphoton production through gluon fusion: NWA and beyond

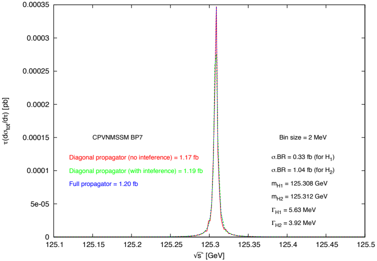
- **CPV-NMSSM Parameter set:** $\phi_\kappa = 3^o$, 10^o, 30^o. All other phases are set to zero. [J. F. Gunion, et al., Phys. Rev. D 86, 071702 (2012), S. Moretti, S. Munir., Adv. High Energy Phys. 2015, 509847 (2015)]

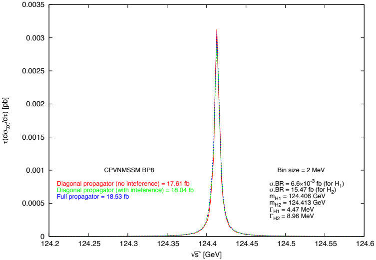
NMSSM parameter	Scanned range
M_0(GeV)	200-2000
$M_{\frac{1}{2}}$(GeV)	100-1000
A_f(GeV)	-3000-0
tanβ	1-8
λ	0.4-0.7
κ	0.3-0.6
μ_{eff}(GeV)	100-300
A_λ(GeV)	-1000-1000
A_κ(GeV)	-1000-1000

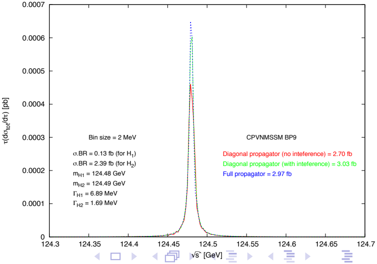
Table : Ranges of the scanned CPV-NMSSM parameters, with fixed ϕ_κ.

Diphoton production through gluon fusion: NWA and beyond: Differential cross sections wrt $\sqrt{\hat{s}}$ vs. $\sqrt{\hat{s}}$

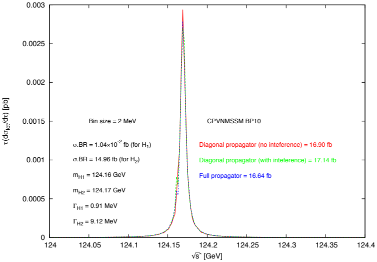








Diphoton production through gluon fusion: NWA and beyond: Differential cross sections wrt $\sqrt{\hat{s}}$ vs. $\sqrt{\hat{s}}$



BP	M_0	$M_{1/2}$	A_0	$\tan\beta$	λ	A_λ	A_κ	μ_{eff}
6	1121.3	462.13	-1849.5	3.10	0.6624	196.51	-73.12	101.25
7	1224.8	209.70	-2624.0	4.35	0.6869	480.86	-286.99	145.43
8	1329.5	206.00	-2854.8	5.43	0.6743	640.54	-288.23	144.02
9	1166.5	158.97	-2940.7	2.48	0.6761	306.89	-456.92	193.89
10	1044.7	124.67	-1835.1	2.46	0.6602	441.92	-633.05	265.67

Table : All dimensionful parameters are in GeV.

Summary

- The NMSSM Higgs sector contains interesting scenarios which are precluded or excluded in the MSSM.
- Particularly, we focus on the scenarios where the experimentally visible peak can actually be explained by two nearly mass-degenerate neutral Higgs boson states.
- Its important to consider the full propagator when the mass difference between the two Higgs bosons is comparable to their widths.
- The combined CMS result in the WW and ZZ decay modes, for the Higgs boson off-shell production in ggF and VBF processes, at 7 and 8 TeV, puts the observed and expected upper limits of 13 and 26 MeV, respectively on the total Higgs decay widths at 95% CL [CMS Col., arXiv:1605.02329].
- This combined result on the Higgs total decay widths serves as a stringent constraint on the choices of our benchmark points.

Summary

- Some points corresponding to these scenarios give an overall slightly improved fit to the data, more so for non-zero values of the CPV phase, compared to the scenarios containing a single Higgs boson near 125 GeV, invalidating the NWA.

Thank You