

Di-photon Signal in NMSSM at the LHC

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Table of Contents

- 1 NMSSM Higgs sector
- 2 Non SM-like Higgs in NMSSM
- 3 NMSSM Higgs phenomenology.
- 4 Two photon decay mode of Pseudoscalar Higgs
- 5 Two photon Signal in NMSSM
- 6 Signal and Background
- 7 Conclusion

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The NMSSM

- The NMSSM model was proposed to generate μ term dynamically.

The Superpotential:

$$W_{\text{NMSSM}} = W_{\text{MSSM}} + \lambda \hat{S} \hat{h}_u \hat{h}_d + \frac{1}{3} \kappa \hat{S}^3$$

The MSSM superpotential:

$$W_{\text{Yukawa}} = h_u \hat{Q} \cdot \hat{H}_u \hat{U}_R^c + h_d \hat{Q} \cdot \hat{H}_d \hat{D}_R^c + h_e \hat{L} \cdot \hat{H}_d \hat{E}_R^c$$

The corresponding soft-breaking potential for NMSSM Higgs sector

$$V_{\text{soft}} = m_{h_u}^2 |h_u|^2 + m_{h_d}^2 |h_d|^2 + m_S^2 |S|^2 + \left[\lambda A_\lambda S h_u h_d + \frac{1}{3} \kappa A_\kappa S^3 + \text{h.c.} \right].$$

The VEV of $S \equiv v_s$ generates the

$$\mu_{\text{eff}} = \lambda v_s$$

The NMSSM Higgs sector contains free parameters:

$$\lambda, \kappa, A_\lambda, A_\kappa, \mu_{\text{eff}}, \tan \beta$$

Higgs Masses

- Real and Imaginary parts of Higgs field mixes via 3×3 mass matrix and yield CP even and CP odd physical Higgs bosons.
- 3×3 mass matrices describe Higgs bosons in NMSSM.
- 3 CP even Higgs bosons: H_1, H_2, H_3
- 2 CP odd Higgs bosons: A_1, A_2
- Two Charged Higgs Bosons: H^+, H^-

In NMSSM the upper bound,

$$m_{H_1}^2 < M_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta,$$

The tree level mass of lightest Higgs boson is already higher than the MSSM case.

- **Discovery of SM-like Higgs bosons with mass $m_H \sim 125$ GeV**
 \Rightarrow **NMSSM has received special attention.**

U.Ellanwanger et. al, Phys, Rept. 2010,
D. Miller et. al. NPB. 2004.

Non SM like Higgs in NMSSM

Parameter space scan: NMSSMTool

$$0.1 < \lambda < 0.7; \quad 0.1 < \kappa < 0.7; \quad 0 < A_\lambda < 2 \text{ TeV} \\ -2 \text{ TeV} < A_\kappa < 200 \text{ GeV};$$

The soft mass parameters:

$$M_{Q_{1/2}} = M_{U_{1/2}} = M_{D_{1/2/3}} = 1 \text{ TeV}, \quad M_{Q_3} = M_{U_3} = 300 - 3000 \text{ GeV}. \\ A_t = -4 \text{ TeV to } +4 \text{ TeV}; \quad A_b = 2 \text{ TeV}; \quad A_{E_3} = 1 \text{ TeV}.$$

- Constraints from LEP, Flavour Physics are used.

- g_μ -2 and DM constraints are tested:

$$\delta a_\mu = (28.7 \pm 8.0) \times 10^{-10}. \quad \Omega^2 h = 0.1187 \pm 0.0017.$$

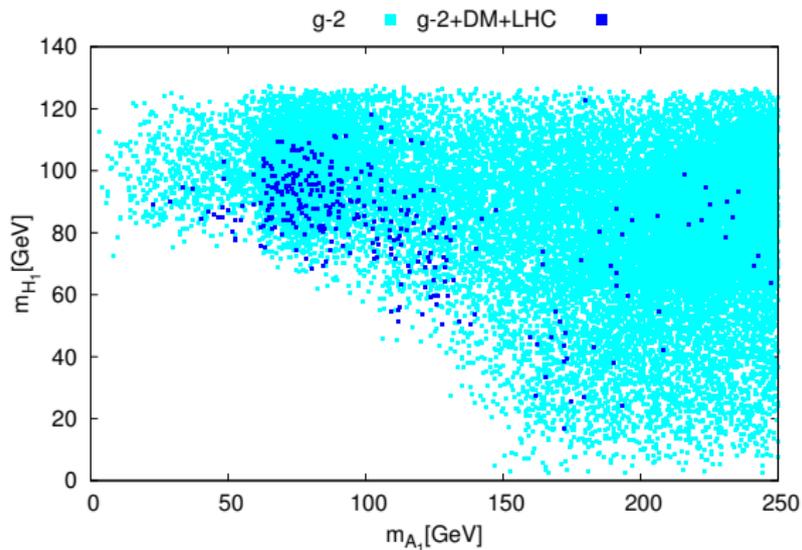
$$M_{L_{1,2}} = 100 \text{ GeV}; \quad M_{E_{1,2}} = 100 \text{ GeV};$$

$$50 \text{ GeV} < M_1 < 1 \text{ TeV}; \quad 50 \text{ GeV} < M_2 < 1 \text{ TeV}; \quad M_3 = 1.2 \text{ TeV}.$$

- LHC Higgs data on mass and reduced couplings are also checked.

Non SM-like Higgs Mass

- **Case A:** $H_2 \sim H_{SM} = 125.02 \pm 3 \text{ GeV}$.



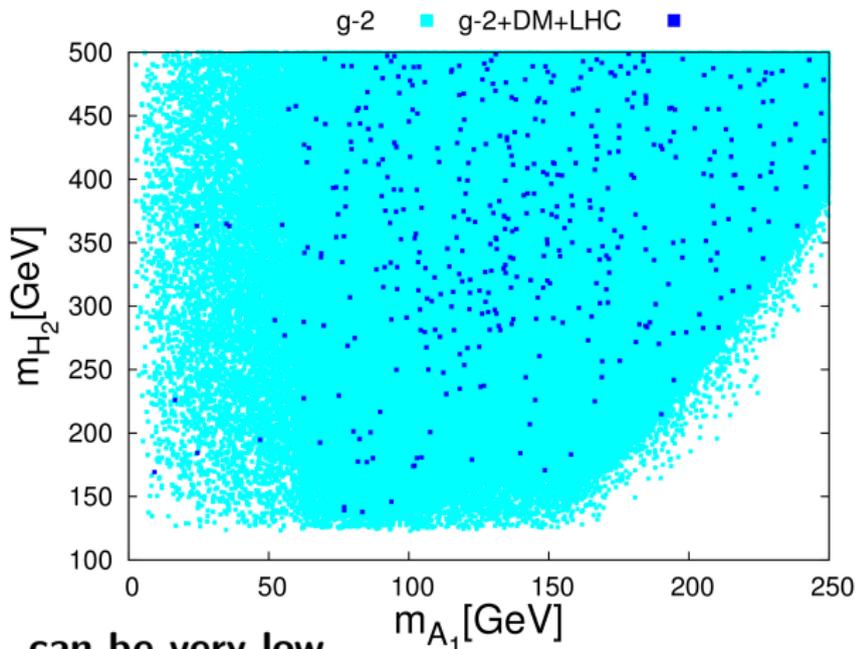
U. Ellwanger, EPJC, 2011,
S.king et.al, NPB,2012,2013,
T.Han, JHEP, 2011,
T.Cao, JHEP, 2013,
Z. Zhang, 2012
MG, JAcKy Kumar, 2015

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- m_{H_1}, m_{A_1} can be very low.
- States are singlet like, reduced couplings($\frac{g}{g_{SM}}$), are very small,

Non SM-like Higgs Mass

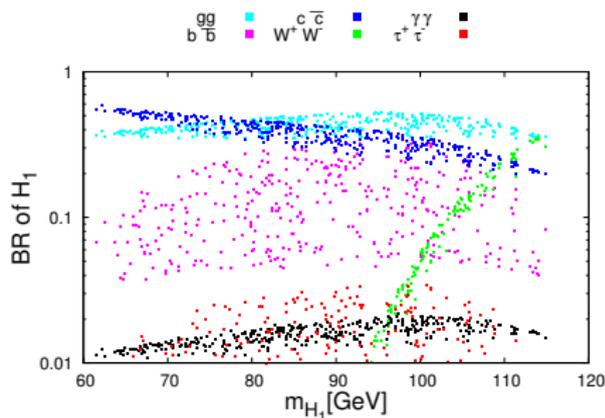
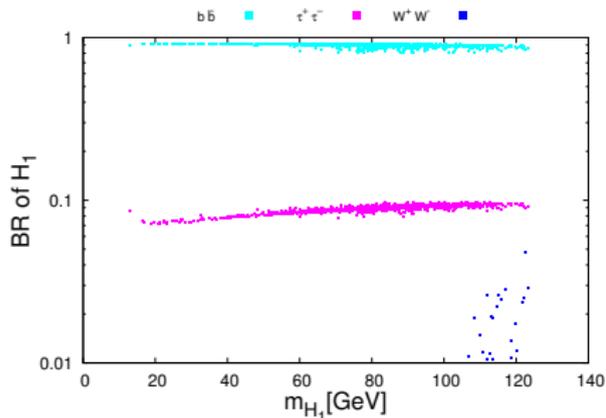
- **Case B: $H_1 \sim H_{SM} = 125.02 \pm 3$ GeV**



- m_{H_2}, m_{A_1} can be very low.
- States are singlet like, reduced coupling($\frac{g}{g_{SM}}$) are very small.

Higgs Decays

- $H_2 \sim H_{\text{SM}}$ H_1 decays



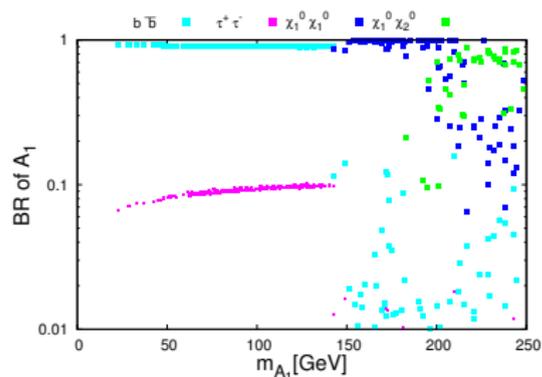
- $H_1 \rightarrow A_1 A_1$ allowed, BR \sim 90%.

- $H_1 \sim H_{\text{SM}}$, H_1 decays same as SM Higgs.

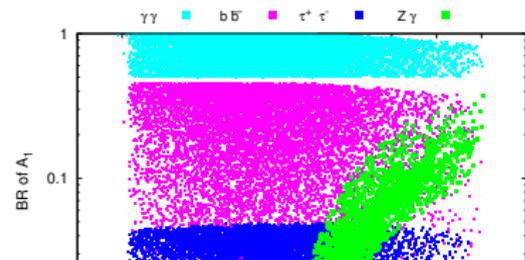
$H_1 \rightarrow A_1 A_1, \tilde{\chi}_1^0 \tilde{\chi}_1^0$ viable, restricted by data.

Higgs Decays

- $H_2 \sim H_{\text{SM}}$ A_1 decays



$H_2 \sim H_{\text{SM}}$
 $gg, c\bar{c}, \gamma\gamma$ sub-dominant channels.



$H_1 \sim H_{\text{SM}}$
 $\gamma\gamma$ mode dominant
 also $\tilde{\chi}_1^0\tilde{\chi}_1^0, b\bar{b}$ dominant for certain region.

Rates in Different channels: H_1

The H_1 production at 13 TeV, $H_2 \sim H_{SM}$

$$R_{XX} = \sigma_\phi(\phi) \times \text{BR}(\phi \rightarrow XX); \quad \sigma_\phi = \sigma_{ggF}, \sigma_{b\bar{b}\phi}$$
$$XX = b\bar{b}, \tau\tau, \gamma\gamma, gg, c\bar{c}, \mu\mu$$

σ_{ggF} : SusHi+NMSSM calculations(NLO);

$\sigma_{b\bar{b}\phi}$: SusHi(NNLO)

Rates (fb)	m_{H_1} (GeV)			
	13	48	89	120
$R_{b\bar{b}}(gg)$	144927	1164 – 9835	4.5 – 4345	45 – 1126
$R_{b\bar{b}}(bb)$	1733	170-2133	868	6 – 249
$R_{\gamma\gamma}(gg)$	1.4	2.6E-3 – 1	79	2.5E-4 – 0.88
$R_{\gamma\gamma}(bb)$	1.7E-2	7E-4 – 0.09	0.22	1.2E-4 – 0.1
$R_{gg}(gg)$	1028	3 – 38	5.6E-3 – 2077	0.11 – 15
$R_{gg}(bb)$	12.6	0.8 – 6	1E-4 – 4.5	4.3E-2 – 1.6

MG, Jacky Kumar, IJMPA, 2015.(1509.02452).

Rates in Different channels: A_1

The A_1 production at 13 TeV, $H_2 \sim H_{SM}$

$$R_{XX} = \sigma_\phi(\phi) \times \text{BR}(\phi \rightarrow XX); \quad \sigma_\phi = \sigma_{ggF}, \sigma_{b\bar{b}\phi}$$

$$XX = b\bar{b}, \tau\tau, \gamma\gamma, gg, c\bar{c}, \mu\mu$$

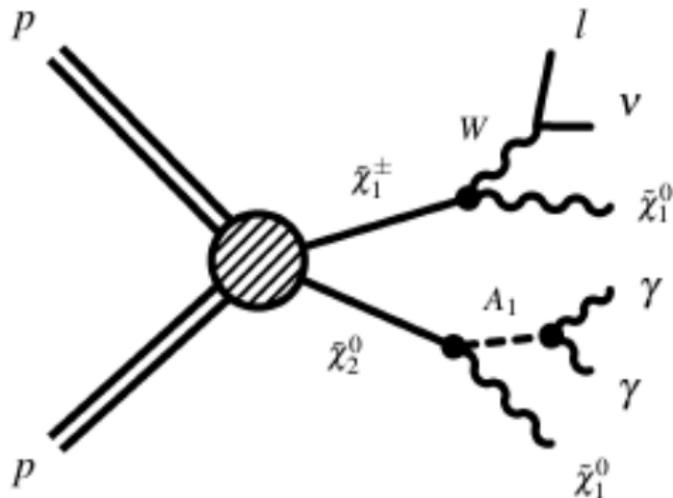
σ_{ggF} : SusHi+NMSSM calculations(NLO);

$\sigma_{b\bar{b}\phi}$: SusHi(NNLO)

Rates (fb)	m_{H_1} (GeV)				
	22	60	100	140	250
$R_{b\bar{b}}(gg)$	72336	818 – 1685	143 – 226	1.53 – 29	9E-3 – 0.6
$R_{b\bar{b}}(bb)$	1392	385 – 869	115 – 262	4 – 65	0.04 – 0.06
$R_{\tau\tau}(gg)$	5939	76 – 156	14 – 23	0.17 – 3.2	1E-3 – 7E-2
$R_{\tau\tau}(bb)$	99	36 – 82	12 – 27	0.007 – 0.02	5E-3 – 7E-3
$R_{\gamma\gamma}(gg)$	0.9	0.08 – 0.15	0.04 – 0.07	1E-3 – 1.7E-2	3.5E-3
$R_{\gamma\gamma}(bb)$	0.02	0.04 – 0.1	0.03 – 0.09	0.003 – 0.04	(E-4 – 2E-4)
$R_{gg}(gg)$	465 2	1.8 – 4.1	0.14 – 0.3	1E-3 – 2.2E-2	1.2E-2
$R_{gg}(bb)$	9	0.9 – 1.8	0.14 – 0.31	0.003 – 0.05	8E-4

Pseudoscalar Higgs Production in SUSY channel

A_1 production and decay: $PP \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_{2,3}^0; \tilde{\chi}_{2,3}^0 \rightarrow \tilde{\chi}_1^0 A_1; A_1 \rightarrow \gamma\gamma$



Signal: $l + \gamma\gamma + \cancel{E}_T$

$$\sigma_{l\gamma\cancel{E}_T} = \sigma(PP \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_{2,3}^0) \cdot \text{Br}(\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 A_1) \cdot \text{Br}(A_1 \rightarrow \gamma\gamma) \cdot \epsilon_{ac}$$

Sensitive to the parameter space because of the couplings.

The Neutralino mass matrix: in the basis $\tilde{\psi}^0 = (-i\tilde{B}, -i\tilde{W}, \tilde{H}_d^0, \tilde{H}_u^0, \tilde{S})$:

$$\begin{pmatrix} M_1 & 0 & \frac{-g_2 v_d}{\sqrt{2}} & \frac{g_1 v_u}{\sqrt{2}} & 0 \\ & M_2 & \frac{g_2 v_d}{\sqrt{2}} & \frac{-g_2 v_u}{\sqrt{2}} & 0 \\ & & 0 & -\mu_{\text{eff}} & -\lambda v_u \\ & & & 0 & -\lambda v_d \\ & & & & 0 & 2\kappa S \end{pmatrix}$$

Mass of neutralinos:

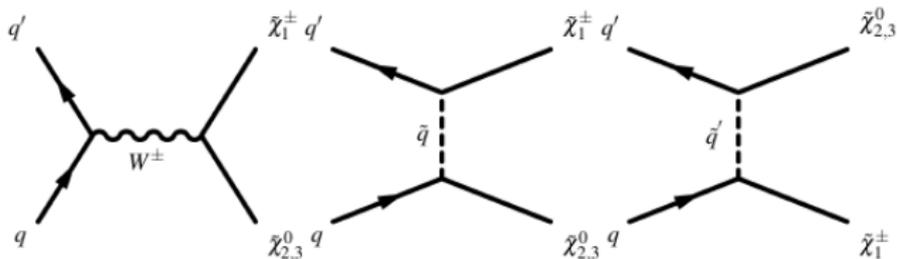
$$M_N^D = N M_N N^T$$

Physical neutralino state:

$$\tilde{\chi}_i^0 = \sum_{j=1}^4 N_{ij} \tilde{\psi}_j^0 + N_{i5} \tilde{S}$$

Parameters: $M_1, M_2, \tan \beta, \mu_{\text{eff}}, \lambda, \kappa$

Chargino-Neutralino Production in NMSSM



$$\frac{d\hat{\sigma}}{d\hat{t}} = \frac{\pi\alpha^2}{3\hat{s}^2} [|Q_{LL}|^2 (\hat{u} - m_{\tilde{\chi}_l^0}^2)(\hat{u} - m_{\tilde{\chi}_k^-}^2) + |Q_{LR}|^2 (\hat{t} - m_{\tilde{\chi}_l^0}^2)(\hat{t} - m_{\tilde{\chi}_k^-}^2) + 2\text{Re}(Q_{LL}^* Q_{LR}) m_{\tilde{\chi}_l^0} m_{\tilde{\chi}_k^-} \hat{s}]$$

$$Q_{LL} = \frac{1}{\sqrt{2}s_w^2} \left[\frac{N_{l2}^* V_{k1} - 1/\sqrt{2} N_{l4}^* V_{k2}}{\hat{s} - M_W^2} + V_{k1} \frac{I_{3\tilde{q}} N_{l2}^* + (e_{\tilde{q}} - I_{3\tilde{q}}) N_{l1}^* \tan\theta_w}{\hat{u} - m_{\tilde{q}}^2} \right]$$

$$Q_{LR} = \frac{1}{\sqrt{2}s_w^2} \left[\frac{N_{l2} U_{k1}^* + 1/\sqrt{2} N_{l3} U_{k2}^*}{\hat{s} - M_W^2} - (U_{k1})^* \frac{I_{3\tilde{q}'} N_{l2} + (e_{\tilde{q}'} - I_{3\tilde{q}'}) N_{l1} \tan\theta_w}{\hat{t} - m_{\tilde{q}'}^2} \right]$$

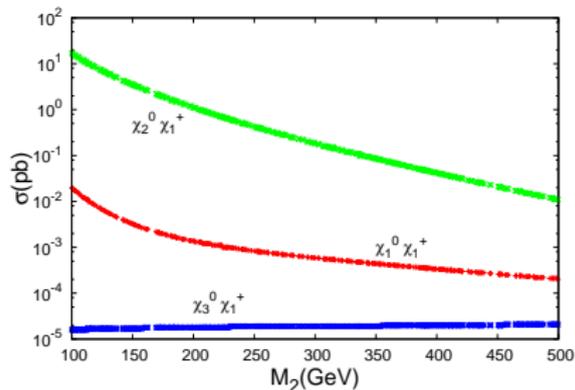
$$Q_{RR} = Q_{RL} = 0$$

NMSSM parameters affect indirectly.

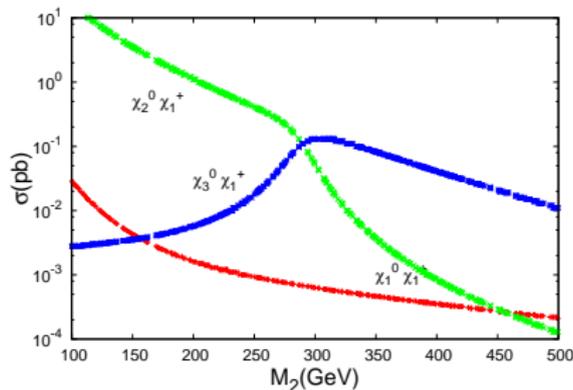
Chargino-Neutralino cross section(1)

Gauginolike scenario. $M_2 \ll \mu_{eff}$; $\sqrt{S}=13$ TeV

$\mu_{eff} = 1$ TeV; $M_1 = 0.5 M_2$, $\tan \beta = 10$



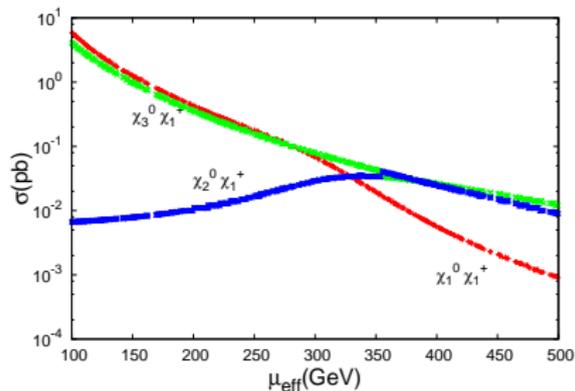
$\lambda = 0.1, \kappa = 0.7$



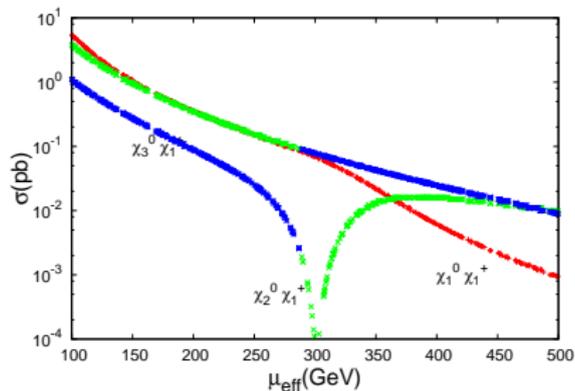
$\lambda = 0.7, \kappa = 0.1$

Chargino-Neutralino cross section(2)

Higgsino like scenario: $M_2 \gg \mu_{eff}$
 $M_2 = 1 \text{ TeV}, M_1 = 0.5 M_2, \tan \beta = 10$

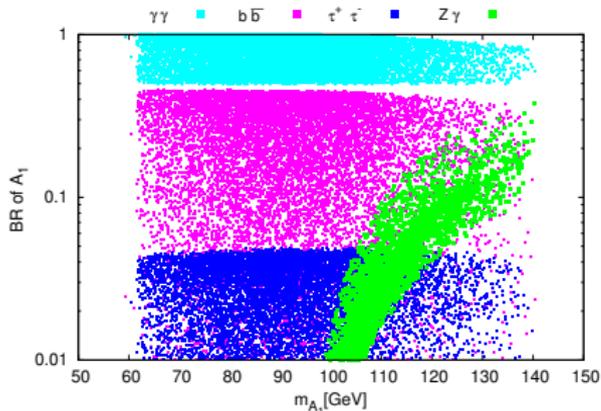
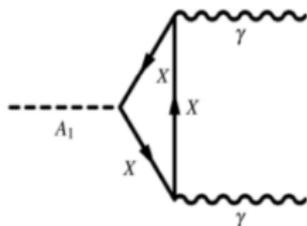


$\lambda = 0.1, \kappa = 0.7$



$\lambda = 0.2, \kappa = 0.1$

Decay: $A_1 \rightarrow \gamma\gamma$



$\mathbf{X} = \mathbf{t}, \mathbf{b} \tilde{\chi}_i^\pm$;

J.F. Gunion, PRD, 2007, U.Ellwanger, 2011,
J.Cao 2011, T. Han(2013), MG, Jacky Kumar, IJMPA 2015

$$\Gamma(A_1 \rightarrow \gamma\gamma) = \frac{G_F \alpha_{em}^2 M_{A_1}^3}{32\sqrt{2}\pi^3} \left| \sum_f N_c e_f^2 g_f^{A_1} A_f^{A_1} (\tau_f) + \sum_{\tilde{\chi}^\pm} g_{\tilde{\chi}^\pm}^{A_1} A_{\tilde{\chi}^\pm} (\tau_{\tilde{\chi}^\pm}) \right|^2$$

Contribution by SM fermions are suppressed, since A_1 is very much singlet like.

$$g_{\tilde{\chi}^\pm}^{A_1} = g_{\tilde{\chi}^\pm} = i \left(\frac{\lambda}{\sqrt{2}} P_{13} U_{i2} V_{i2} - \frac{g_2}{\sqrt{2}} (P_{12} U_{i1} V_{i2} + P_{11} U_{i2} V_{i1}) \right)$$

Decay: $A_1 \rightarrow \gamma\gamma$

Pseudoscalar Higgs mass matrix:

$$M_P = \begin{bmatrix} M_A^2 & \lambda(A_\lambda - 2\kappa s)v \\ \lambda(A_\lambda - 2\kappa s)v & M_S^2 \end{bmatrix}$$

where,

$$M_A^2 = \frac{2\mu_{\text{eff}}(A_\lambda + \kappa s)}{\sin(2\beta)}; \quad M_S^2 = \lambda(A_\lambda + 4\kappa s)\frac{v_u v_d}{s} - 2\kappa A_k s$$

The mixing angle

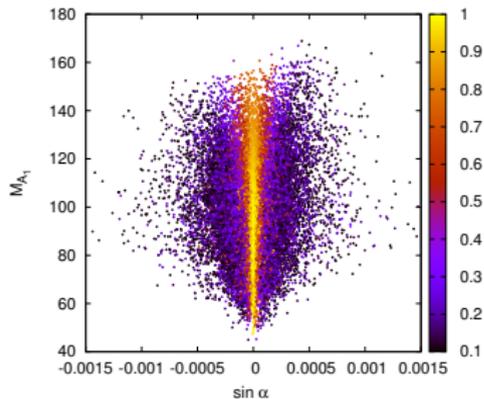
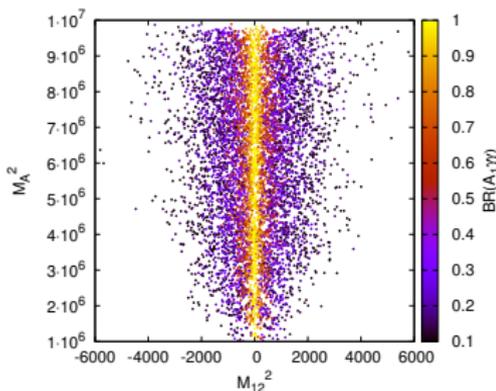
$$\tan 2\alpha = \frac{2\lambda(A_\lambda - 2\kappa s)v}{(M_A^2 - M_S^2)}$$

Decay: $A_1 \rightarrow \gamma\gamma$

- **Very tiny mixing angle leads A_1 dominantly singlet like state,**

(a) $M_A^2 \gg M_{12}^2, M_S^2$

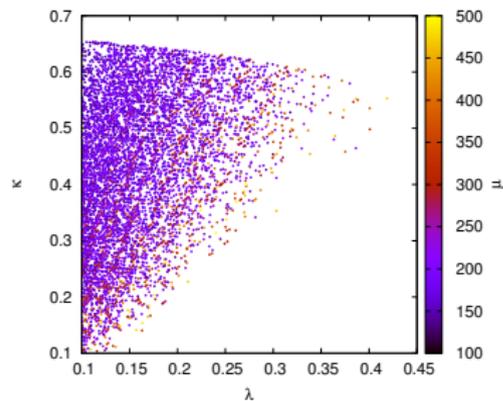
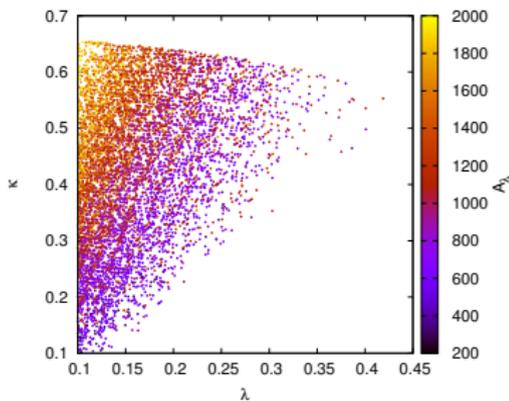
(b) $M_{12}^2 \sim 0$



$$M_{12}^2 = \lambda(A_\lambda - 2\kappa s)v \sim 0 \Rightarrow Br(A_1 \rightarrow \gamma\gamma) > 90\%$$

Decay: $A_1 \rightarrow \gamma\gamma$

$\text{Br}(A_1 \rightarrow \gamma\gamma) > 10\%$



- $\kappa \sim 0.1 - 0.65$; $\lambda \sim 0.1 - 0.35$,
- Large values of $A_\lambda \sim 1000$ GeV and lower values of μ_{eff} are favoured.

Signal and Background simulation(1)

- **Signal:** $l + \gamma\gamma + \cancel{E}_T, \sqrt{S}=13 \text{ TeV}$
- **Backgrounds:** $W\gamma, W\gamma\gamma, Z\gamma, Z\gamma\gamma, W\gamma j$

Tools:

- **Signal,** : NMSSMtool + PYTHIA6 + STDHEP + Delphes

- **Background:**

$(V\gamma, V=W,Z):$ PYTHIA6 + STDHEP+ Delphes

$V\gamma(\gamma/j) (V=W,Z) :$ MadGraph5 + PYTHIA6 + STDHEP+ Delphes

Delphes is used for Detector effects

- **Lepton Selection:**

$p_T^\ell \geq 20 \text{ GeV}; |\eta|^\ell \leq 2.5$. Isolation is ensured $E_T^{ac} \leq 0.2P_T^\ell$,
 $E_T^{ac} = \sum_j P_T^j(\Delta R(l, j) \leq 0.5)$

- **Photon Selection:**

$p_T^\gamma > 20\text{GeV}; (|\eta|_\gamma) < 2.4$, Photon is isolated, if $E_{AC}^T(\gamma) < 0.2p_T^\gamma$

- **Missing Energy:**

$\vec{E}_T = -\sum \vec{p}_T(i), \cancel{E}_T > 50\text{GeV}$

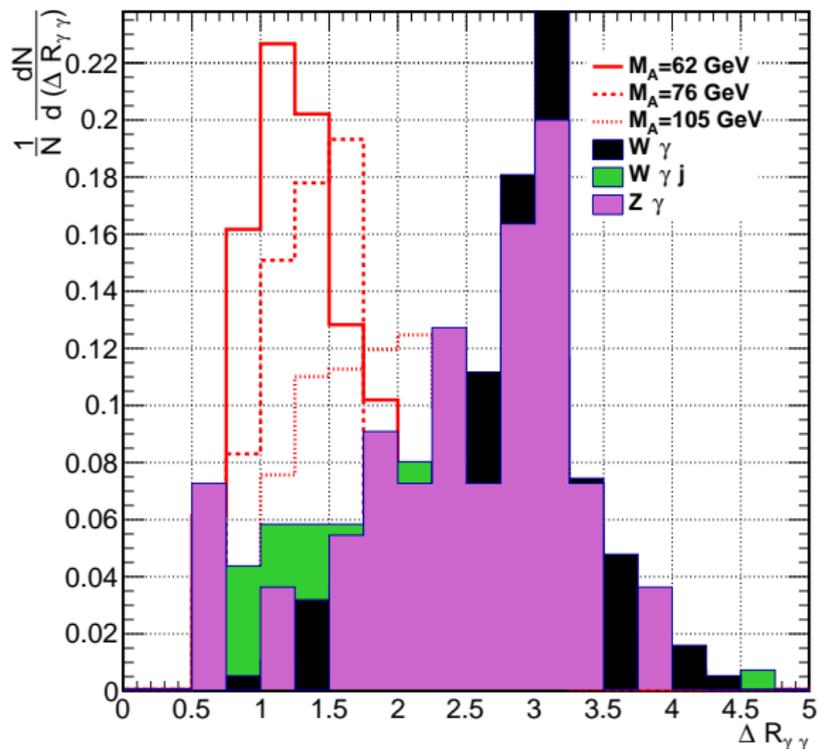
- $\Delta R_{\gamma_1\gamma_2} = \sqrt{(\eta_{\gamma_2} - \eta_{\gamma_1})^2 + (\phi_{\gamma_1} - \phi_{\gamma_2})^2}$

Signal: Benchmark scenario(2)

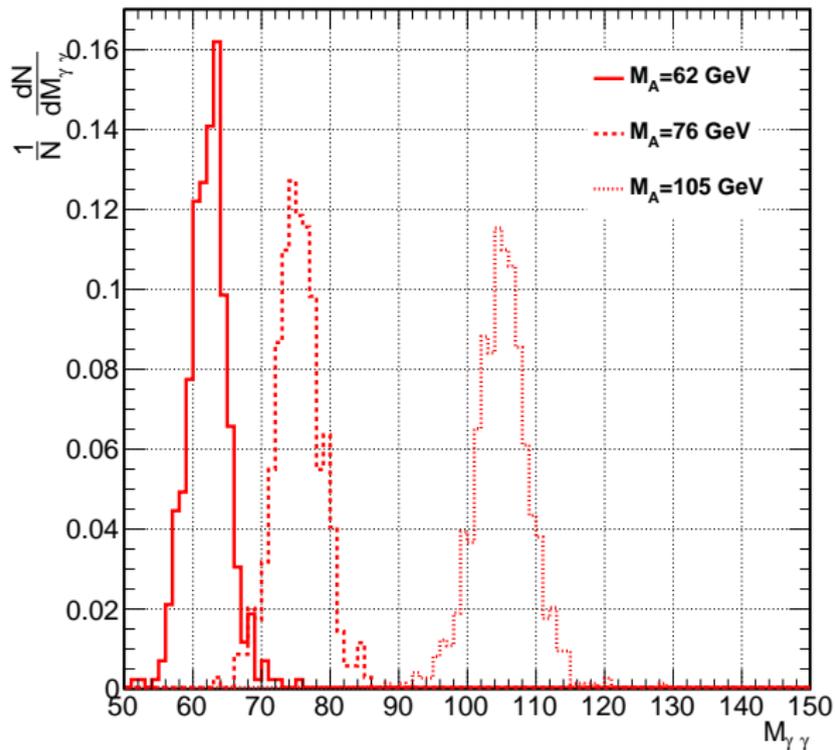
	BP1	BP2	BP3	BP4
$M_{\tilde{\chi}_1^0}$	280.6	131.4	113.4	261.8
$M_{\tilde{\chi}_2^0}$	356.4	210.0	169.0	379.1
$M_{\tilde{\chi}_3^0}$	356.7	215.6	182.3	385.5
$M_{\tilde{\chi}_1^+}$	340.0	199.3	161.7	377.5
M_{A_1}	62	76	63.1	105.2
M_{H_1}	124	124	124	124
$BR(\chi_2^0 \rightarrow \tilde{\chi}_1^0 A_1)$	0.92	0.83	0.0	0.44
$BR(\chi_3^0 \rightarrow \tilde{\chi}_1^0 A_1)$	0.27	0.31	0.52	0.002
$BR(A_1 \rightarrow \gamma\gamma)$	0.79	0.91	0.98	0.87
λ	0.29	0.40	0.10,	0.53
κ	0,373	0.45	0.20	0,39
$\tan \beta$	6.5	6.5	11.0	4.0,
μ_{eff}	342.4	200.0	158.5	365.4
M_A	1722	340.7	1311.5	1262.4
A_{κ}	-4.97	-4.97	-3.9	-5.8
M_1	300	150.0	135.4	275.9
M_2	606.6	606.6	1000.0	9000

Signal and Background Simulation(3)

Discriminating variable: $\Delta R(\gamma, \gamma)$



Signal and Background Simulation(3)



Signal and Background Simulation: Event summary

$C1 :: N_\gamma \geq 2, p_{T_{\gamma_{1,2}}} > 40(20)$
 $C2 :: N_l = 1$
 $C3 :: \cancel{E}_T \geq 50$
 $C4 :: \Delta R_{\gamma_1 \gamma_2} \leq 2.0$
 $C5 :: M_{\gamma\gamma} \pm 3\text{GeV}$

Process	$\sigma(\text{LO})$	N_{ev}	C1	C2	C3	C4	$\sigma \cdot \epsilon(\text{fb})$
BP2							
$(\tilde{\chi}_2^0 \tilde{\chi}_1^\pm)$	258 fb	0.3L	9303	1140	590	415	2.7
$(\tilde{\chi}_3^0 \tilde{\chi}_1^\pm)$	340 fb	0.3L	9593	1213	682	499	1.6
BP4							
$(\tilde{\chi}_2^0 \tilde{\chi}_1^\pm)$	47 fb	0.3L	14750	2555	1916	910	0.54
$(\tilde{\chi}_3^0 \tilde{\chi}_1^\pm)$	34 fb	0.3L	14827	2447	1873	935	0.002
$W\gamma$	340 pb	200M	11169	865	188	22	0.04
$W\gamma j$	180 pb	2.1M	2987	282	137	49	4.2
$Z\gamma$	212 pb	200M	16749	1613	55	14	0.015
$W\gamma\gamma$	110 fb	0.5L	6011	760	260	66	0.145
$Z\gamma\gamma$	142 fb	0.5L	5312	233	12	7	0.034

Total background cross section : 4.4 fb

Process	BP1	BP2	BP3	BP4
$\sigma \cdot \epsilon$ (fb)	0.46	4.3	1.9	0.542
S/\sqrt{B}				
100 fb ⁻¹	2.2	20.5	9.0	2.6
300 fb ⁻¹	3.8	35.5	15.7,	4.5
1000 fb ⁻¹	7.0	64.5	28.6	8.17

Table: Significance.

- Invariant mass selection can improve the significance substantially
- An unique and robust signal of NMSSM model, also a characteristic signal

MG, Jacky Kumar work in progress..

- **NMSSM model is one of the potential model which can accommodate SM like Higgs very easily.**
- **Higgs phenomenology is very reach.**
- **Potential of finding the Di-photon signal of light Higgs is very high.**
- **Di-photon phenomena can distinguish the NMSSM and MSSM.**