130 GeV gamma ray line and enhanced Higgs di-photon rate from Triplet-Singlet extended MSSM

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Plan of the talk

Motivation

- SM works beautifully, explaining all experimental phenomena to date with great precision.
- But many questions remain unanswered :
  - Higgs mass is not protected by any symmetry $\Rightarrow$ Hierarchy Problem.
  - No cold dark matter candidate.
  - Neutrinos are massless in SM.

  and many more.....
- SUPERSYMMETRY : a good BSM
  - Helps stabilize the weak-scale Planck scale hierarchy
  - Provides good Dark Matter candidate
  - Allows for Gauge coupling Unification
- An intriguing possibility of a signal beyond SM in the $h \to \gamma\gamma$ channel (if confirmed by future data).
- Recent analysis of Fermi-LAT data reveals a gamma ray peak around 130 GeV $\Rightarrow$ Smoking gun signature for DM

Framework of the Model

Triplet-Singlet extended MSSM (TSMSSM) :

- In addition to the MSSM, a SU(2) singlet and a complex Higgs triplet with zero hypercharge is introduced:

$$\hat{T}_0 = \begin{pmatrix} \frac{\hat{T}^0}{\sqrt{2}} & -\hat{T}_0^+ \\ \hat{T}_0^- & \frac{-\hat{T}^0}{\sqrt{2}} \end{pmatrix}$$

Superpotential

$$\mathcal{W} = (\mu + \lambda \hat{S})\hat{H}_d.\hat{H}_u + \frac{\lambda_1}{3}\hat{S}^3 + \lambda_2 \hat{H}_d.\hat{T}_0 \hat{H}_u + \lambda_3 \hat{S}^2 Tr(\hat{T}_0)$$
$$+\lambda_4 \hat{S}\, Tr(\hat{T}_0 \hat{T}_0) + W_{Yuk.}$$

where, $W_{Yuk.}$ is the Yukawa Superpotential as in MSSM.

- No interaction term between triplet and fermion superfields.

TB and S. Mohanty, Phys. Rev. D **86**, (2012)

Solution to μ-problem

- To solve the μ-problem : a scale invariant superpotential is introduced

$$W_{sc.inv.} = \lambda \hat{S}\hat{H}_d.\hat{H}_u + \frac{\lambda_1}{3}\hat{S}^3 + \lambda_2 \hat{H}_d.\hat{T}_0\hat{H}_u + \lambda_4 \hat{S}\,Tr(\hat{T}_0\hat{T}_0) + W_{Yuk.}$$

- Effective μ-term : $\mu_{eff} = \lambda v_s - \frac{\lambda_2}{\sqrt{2}} v_t$.
- After Electroweak symmetry breaking, only the neutral components of the scalars fields acquire vev's, i.e,

$$\langle H_u^0 \rangle = v_u \;,\; \langle H_d^0 \rangle = v_d \;,\; \langle S \rangle = v_s \text{ and } \langle T^0 \rangle = v_t$$

Scalar Potential

- Scalar potential (involving only Higgs field) :

$$V = V_{SB} + V_F + V_D$$

where, V_{SB}, V_F, V_D are the contributions from the soft-supersymmetry breaking terms, F-terms and D-terms respectively.

Soft-breaking terms

$$\begin{aligned} V_{SB} &= m_{H_u}^2[|H_u^0|^2 + |H_u^+|^2] + m_{H_d}^2[|H_d^0|^2 + |H_d^-|^2] + m_S^2|S|^2 + \\ & m_T^2 Tr(T_0^\dagger T_0) + (-\lambda A_\lambda S H_u.H_d + \frac{\lambda_1}{3} A_{\lambda_1} S^3 + \lambda_2 A_{\lambda_2} H_d.T_0 H_u + \\ & \lambda_4 B_\lambda S Tr(T_0^2) + h.c) \end{aligned}$$

contd..

F-term & D-term Potential

$$
\begin{aligned}
V_F &= |-\lambda S H_d^0 + \frac{\lambda_2}{\sqrt{2}} H_d^0 T^0 - \lambda_2 H_d^- T_0^+|^2 + |-\lambda S H_u^0 + \frac{\lambda_2}{\sqrt{2}} H_u^0 T^0 - \lambda_2 H_u^+ T_0^-|^2 + \\
&\quad |\lambda(H_d^- H_u^+ H_u^0 H_d^0) + \lambda_1 S^2 + \lambda_4 (T^{0^2} - 2 T_0^+ T_0^-)|^2 + |\frac{\lambda_2}{\sqrt{2}}(H_u^0 H_d^0 + H_d^- H_u^+) + 2\lambda_4 S T^0|^2 + \\
&\quad |\lambda S H_d^- + \frac{\lambda_2}{\sqrt{2}} T^0 H_d^- - \lambda_2 H_d^0 T_0^-|^2 + |-\lambda_2 H_d^- H_u^0 - 2\lambda_4 S T_0^-|^2 + \\
&\quad |\lambda S H_u^+ + \frac{\lambda_2}{\sqrt{2}} T^0 H_u^+ - \lambda_2 H_u^0 T_0^+|^2 + |-\lambda_2 H_u^+ H_d^0 - 2\lambda_4 S T_0^+|^2 \\
V_D &= \frac{g_1^2}{8}[|H_d^-|^2 + |H_d^0|^2 - |H_u^+|^2 - |H_u^0|^2]^2 + \\
&\quad \frac{g_2^2}{8}[|H_d^-|^2 + |H_d^0|^2 - |H_u^+|^2 - |H_u^0|^2 + 2|T_0^+|^2 - 2|T_0^-|^2]^2 + \\
&\quad \frac{g_2^2}{8}[H_d^{0*} H_d^- + H_u^{+*} H_u^0 + \sqrt{2}(T_0^+ + T_0^-) T_0^* + h.c]^2 - \\
&\quad \frac{g_2^2}{8}[H_d^{-*} H_d^0 + H_u^{0*} H_u^+ + \sqrt{2}(T_0^+ - T_0^-) T_0^* + h.c]^2
\end{aligned}
$$

ρ-parameter

- Due to the addition of the triplet, the gauge bosons receive additional contribution in their masses,

$$M_Z^2 = \frac{1}{2}(g_1^2 + g_2^2)v^2$$
$$M_W^2 = \frac{1}{2}g_2^2(v^2 + 4v_t^2)$$

- The ρ-parameter at the tree-level becomes,

$$\rho = \frac{M_W^2}{M_Z^2 \cos^2\theta_W} = 1 + 4\frac{v_t^2}{v^2}$$

- Current experimental measured value of which is,

$$\rho = 1.0004^{+0.0003}_{-0.0004}$$

- The triplet Higgs vev v_t is thus constrained to be less than 3 GeV at 95% C.L.

Higgs Sector

- Higgs spectrum :
  - Four CP-even Higgs (h, H_1, H_2, H_3)
  - Three pseudo-scalar Higgs (A_1, A_2, A_3)
  - Three charged Higgs ($H_1^{\pm}$, $H_2^{\pm}$, $H_3^{\pm}$).

Tree-level bound on the Lightest physical Higgs mass

$$m_h^2 \leqslant M_Z^2 \left[\cos^2 2\beta + \frac{2\lambda^2}{g_1^2 + g_2^2} \sin^2 2\beta + \frac{\lambda_2^2}{g_1^2 + g_2^2} \sin^2 2\beta\right]$$

$\Rightarrow$ Considerable improvement over MSSM and NMSSM.

J. R. Espinosa and M. Quiros, Phys. Lett. B **279**, 92 (1992)

Neutralino Mass Matrix

The neutralino mass matrix extended by the singlet and triplet sector, in the basis $(\tilde{B}, \tilde{W}^0, \tilde{H}_d^0, \tilde{H}_u^0, \tilde{S}, \tilde{T}^0)$ is given by,

$$\mathcal{M}_{\bar{G}} = \begin{pmatrix} M_1 & 0 & -c_\beta s_w M_Z & s_\beta s_w M_Z & 0 & 0 \\ 0 & M_2 & c_\beta c_w M_Z & -s_\beta c_w M_Z & 0 & 0 \\ -c_\beta s_w M_Z & c_\beta c_w M_Z & 0 & -\mu_{eff} & -\lambda v_u & \frac{\lambda_2}{\sqrt{2}} v_u \\ s_\beta s_w M_Z & -s_\beta c_w M_Z & -\mu_{eff} & 0 & -\lambda v_d & \frac{\lambda_2}{\sqrt{2}} v_d \\ 0 & 0 & -\lambda v_u & -\lambda v_d & 2\lambda_1 v_s & 2\lambda_4 v_t \\ 0 & 0 & \frac{\lambda_2}{\sqrt{2}} v_u & \frac{\lambda_2}{\sqrt{2}} v_d & 2\lambda_4 v_t & 2\lambda_4 v_s \end{pmatrix}$$

where, M_1, M_2 are the soft breaking mass parameters for Bino and Wino respectively.

Chargino

The chargino mass terms in the Lagrangian can be written as,

$$-\frac{1}{2}[\tilde{G}^{+T} M_c^T . \tilde{G}^{-} + \tilde{G}^{-T} M_c . \tilde{G}^{+}]$$

where, the basis $\tilde{G}^+$ and $\tilde{G}^-$ are specified as,

$$\tilde{G}^+ = \begin{pmatrix} \tilde{W}^+ \\ \tilde{H_u}^+ \\ \tilde{T}^+ \end{pmatrix} , \; \tilde{G}^- = \begin{pmatrix} \tilde{W}^- \\ \tilde{H_d}^- \\ \tilde{T}^- \end{pmatrix}$$

and the chargino matrix in the gauge basis is given by,

$$M_c = \begin{pmatrix} M_2 & \frac{1}{\sqrt{2}} g_2 v_d & g_2 v_t \\ \frac{1}{\sqrt{2}} g_2 v_u & \lambda v_s + \frac{\lambda_2}{\sqrt{2}} v_t & \lambda_2 v_d \\ g_2 v_t & \lambda_2 v_u & 2\lambda_4 v_s \end{pmatrix}$$

Constraints on Parameter space

Our Wishlist :

- A lightest physical Higgs boson of mass around 125 GeV, with little radiative correction.
- Neutralino LSP $\rightarrow M_{DM}$, with mass $\sim$ 130 GeV.
- A pseudoscalar Higgs of mass $\sim 2M_{DM}$, in order to obtain a resonant enhancement in the cross-section of $\sigma v_{\gamma\gamma}$.
- DM relic abundance should be consistent with present WMAP-9/PLANCK results.
- Spin-independent cross-section of DM off nucleons, $\sigma_{p,n}$, must comply with the latest XENON 100 exclusion limit.
- Light Charginos and light Charged Higgses - in order to get enhancement in $R_{\gamma\gamma}$.

- all these phenomenological and experimental constraints restrict the choice of parameter space.

Choice of Parameter Space

Benchmark Points @ EW scale

Parameters at EW scale	
$\tan\beta$	1.8
λ	0.55
λ_1	0.20
λ_2	0.80
λ_4	0.25
μ_{eff} [GeV]	246
A_λ [GeV]	400
A_{λ_1} [GeV]	-50
A_{λ_2} [GeV]	297.6
B_λ [GeV]	270
v_t [GeV]	2
M_1 [GeV]	154.5
M_2 [GeV]	375

Mass Spectrum

Masses at Tree-level

Higgs Spectrum [GeV]	
m_h	122.93
m_{H_1}	175.29
m_{H_2}	457.27
m_{H_3}	538.86
m_A	534.56
m_{A_1}	142.12
m_{A_2}	260.54
$m^{\pm}_{H_1}$	133.13
$m^{\pm}_{H_2}$	365.61
$m^{\pm}_{H_3}$	545.59

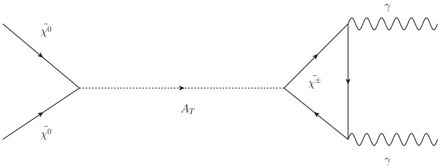
Neutralino Masses [GeV]	
$m_{\tilde{\chi}^0_1}$	130.02
$m_{\tilde{\chi}^0_2}$	189.0
$m_{\tilde{\chi}^0_3}$	215.47
$m_{\tilde{\chi}^0_4}$	269.30
$m_{\tilde{\chi}^0_5}$	283.49
$m_{\tilde{\chi}^0_6}$	414.20

Chargino Masses [GeV]	
$m_{\tilde{\chi}^\pm_1}$	131.92
$m_{\tilde{\chi}^\pm_2}$	299.38
$m_{\tilde{\chi}^\pm_3}$	422.24

TB and S. Mohanty, JHEP08(2013)020

- The LSP $\tilde{\chi}_1^0$ is dominantly bino-like $(N_{11} \sim 0.84)$ but contains substantial higgsino-fraction $(N_{13} \sim -0.31$ and $N_{14} \sim 0.36)$.
- A dominantly triplet-like pseudoscalar Higgs $A_T(or\ A_2)$ with mass ~ 260.54 GeV is obtained, which has no tree-level coupling with the SM fermions or Z-boson.
- A_T interacts with the neutralinos and charginos via the Yukawa term in the lagrangian like $\lambda_2 A_T \tilde{H}_u^0.\tilde{H}_d^0$.
- The width of A_T is small, $\Gamma_T \simeq 6.84$ MeV- which boosts the Breit-Weigner propagator and cross-section $\langle \sigma v \rangle_{\gamma\gamma}$.

Cross-section of the Fermi line



Resonant pair annihilation into two photon via pseudoscalar triplet Higgs

Analytical expression of $\langle \sigma v \rangle_{\gamma\gamma}$

$$\langle \sigma v \rangle_{\gamma\gamma} = \frac{\alpha^2 g_f^2 g_\chi^2}{256\pi^3} \frac{m^2_{\chi_1^+}}{[(4m^2_{DM} - m^2_{A_T})^2 + \Gamma_T^2 m^2_{A_T}]} \times [arctan[(m^2_{\chi_1^+} - m^2_{DM})/m^2_{DM}]^{-1/2}]^2$$

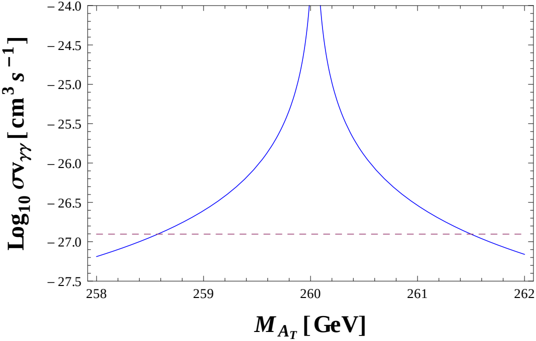
L. Bergstrom *et al.*, Nucl. Phys. B **504**, 27 (1997)
M. R. Buckley *et al.*, Phys. Rev. D **86**, 043524 (2012)

- g_χ : coupling of pseudoscalar Higgs A_T with DM
- g_f : coupling of pseudoscalar Higgs with charged fermion in the loop
- Upto an approximation, $g_\chi \sim \lambda_2 N_{13} N_{14}$ and $g_f \sim \lambda_2 U_{12} V_{12}$
- For the specific set of benchmark points, we obtain

$$m_{DM} = 130.02 \text{ GeV}, \ m_{A_T} = 260.54 \text{ GeV}, \ m_{\tilde{\chi}_1^\pm} = 131.92 \text{ GeV},$$
$$m_h^{Tree} = 122.93 \text{ GeV}$$

- In the resonance limit of $m_{A_T} \sim 2m_{DM}$ and $m_{\chi^+} \to m_{DM}$,
$\Rightarrow \langle \sigma v \rangle_{\gamma\gamma} \sim 1.249 \times 10^{-27} cm^3 s^{-1}$, consistent with FERMI-LAT data.

Behaviour of $\sigma v_{\gamma\gamma}$ near resonance



Plot of $\sigma v_{\gamma\gamma}$ as a function of pseudoscalar mass M_{A_T}. The dashed line shows the maximum value of $\langle\sigma v\rangle_{\gamma\gamma} \simeq 1.249 \times 10^{-27} cm^3 s^{-1}$

A second γ-ray line at 114 GeV

- Hint for a second line at $\sim$111 GeV : best fit to the relative cross-section is $\langle\sigma v\rangle_{\gamma Z}/\langle\sigma v\rangle_{\gamma\gamma} = 0.66^{+0.71}_{-0.48}$
- Kinematically if there is a $Z\gamma$ final state in the annhilation of $\tilde{\chi}_1^0$,

$$E_\gamma = m_{\tilde{\chi}_1^0}\left(1 - \frac{m_Z^2}{4m_{\tilde{\chi}_1^0}^2}\right)$$

where, $E_\gamma = 114$ GeV for $m_{\tilde{\chi}_1^0} = 130$ GeV.

- Cross-section for $\langle\sigma v\rangle_{\gamma Z}$ is calculated for the set of benchmark points presented in Table.I, and we find

$$\langle\sigma v\rangle_{\gamma Z} \simeq 0.943 \times 10^{-27} cm^3 s^{-1}$$

T. Bringmann *et al.*, JCAP **1207**, 054 (2012)

A. Rajaraman *et al.*, JCAP **1209**, 003 (2012)

Relic Abundance

- The dark matter pair annihilations into final state W^+W^-, ZZ, $b\bar{b}$, $\tau^+\tau^-$.
- We obtain the following cross-sections for various final states,

Observables	
$\langle\sigma v\rangle(\chi_1^0\chi_1^0 \to WW)$ $[10^{-27}\text{cm}^3\ \text{s}^{-1}]$	3.57
$\langle\sigma v\rangle(\chi_1^0\chi_1^0 \to ZZ)$ $[10^{-27}\text{cm}^3\ \text{s}^{-1}]$	0.62
$\langle\sigma v\rangle(\chi_1^0\chi_1^0 \to b\bar{b})$ $[10^{-27}\text{cm}^3\ \text{s}^{-1}]$	0.045
$\langle\sigma v\rangle(\chi_1^0\chi_1^0 \to \tau\bar{\tau})$ $[10^{-27}\text{cm}^3\ \text{s}^{-1}]$	0.082
Ωh^2	0.109

$\Rightarrow$ Therefore, a bino dominated but with a substantial higgsino component dark matter is preferable in order to satisfy the latest PLANCK and 9-year WMAP data.

G. Belanger *et al.*, Comput. Phys. Commun. **182**, 842 (2011)

Lagrangian for Spin-independent interaction

- Effective lagrangian for spin-independent interaction between neutralino and quark is,

$$L_{eff} = a_q \bar{\tilde{\chi}}_1^0 \tilde{\chi}_1^0 \bar{q} q$$

where, a_q is the neutralino-quark coupling.

- Scattering cross section (spin-independent) off of a nucleon,

$$\sigma_{scalar} = \frac{4 m_r^2}{\pi} f_{p,n}^2$$

where, m_r is the reduced mass of the nucleon and $f_{p,n}$ is the neutralino coupling to nucleons.

Approximate form of a_q

- Analytical form (approx.) of a_q :

$$\frac{a_q}{m_q} \simeq \frac{S_{\chi\chi h_i}}{m_{h_i}^2} S_{h_i qq}$$

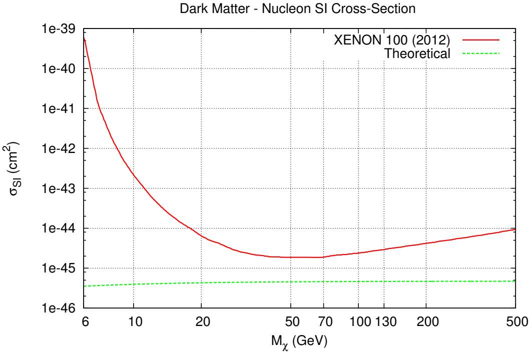
where, $S_{h_i qq}$ is the coupling between the CP-even Higgs bosons and the quarks

  - $S_{h_i uu} = \frac{g_2}{2M_w \sin\beta} S_{i1}$, for up-type quarks
  - $S_{h_i dd} = \frac{g_2}{2M_w \cos\beta} S_{i2}$, for down-type quarks

- $S_{\chi\chi h_i}$ is the coupling between the neutralino and the CP-even Higgs bosons

$$\begin{aligned} S_{\chi\chi h_1} \simeq\ & g_2(N_{12} - \tan\theta_W N_{11})(S_{11}N_{13} - S_{12}N_{14}) \\ & -\sqrt{2}\lambda(S_{11}N_{14}N_{15} + S_{12}N_{13}N_{15} + S_{14}N_{14}N_{13}) + \sqrt{2}\lambda_1 S_{14}N_{15}^2 \\ & +\lambda_2(S_{11}N_{16}N_{13} + S_{12}N_{16}N_{14} + S_{13}N_{13}N_{14}) \\ & +\sqrt{2}\lambda_4(S_{14}N_{16}^2 + 2S_{13}N_{15}N_{16}) \end{aligned}$$

Spin-independent Cross-Section and XENON 100 Limits



σ_p , well below the latest XENON 100 exclusion limits, plotted as a function of M_χ

E. Aprile *et al.* [XENON100 Collaboration], Phys. Rev. Lett. **109**, 181301 (2012)

Formulation of Di-photon Decay Rate

Branching width of Higgs decay to di-photon

$$\Gamma(h \to \gamma\gamma) = \frac{\alpha^2 m_h^3}{1024\pi^3}\left|\frac{g_{hVV}}{m_V^2} Q_V^2 A_1(\tau_V) + \frac{2g_{hf\bar{f}}}{m_f} N_{c,f} Q_f^2 A_{1/2}(\tau_f) + N_{c,S} Q_S^2 \frac{g_{hSS}}{m_S^2} A_0(\tau_S)\right|^2$$

- V, f, and S refer $\to$ generic spin-1, spin-1/2, and spin-0 particles
- $A_1(\tau_V)$, $A_{1/2}(\tau_f)$ and $A_0(\tau_S)$ are the loop functions

In Standard Model :

$$\Gamma(h \to \gamma\gamma) = \frac{G_F \alpha^2 m_h^3}{128\sqrt{2}\pi^3}\left|A_1(\tau_W) + N_c Q_t^2 A_{1/2}(\tau_t)\right|^2$$

Numerical values : $A_1(\tau_W) \simeq -8.3$, $A_{1/2}(\tau_t) \simeq 1.4$ for $m_h = 125$ GeV

A. Djouadi, Phys. Rept. **459** (2008)

Enhancement in the Di-photon Decay Rate

- Additional contribution : from light chargino and charged Higgs.
- Considering main contributions due to charginos, charged triplet, W-boson and top-quark

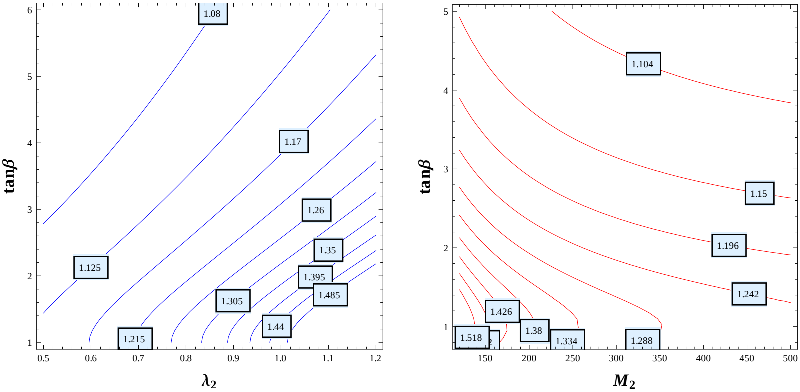
$$R_{\gamma\gamma} = \left| 1 + \frac{\frac{4}{3}\frac{\partial}{\partial \log v}\log\det \mathcal{M}_{ch}(v) + \frac{g_{hH^\pm H^\pm}}{m^2_{H_1^\pm}} A_0(\tau_s)}{A_1(\tau_W) + \frac{4}{3}A_{1/2}(\tau_t)} \right|^2$$

where, coupling $g_{hH^\pm H^\pm} \sim \lambda_2^2 v \sin\beta S_{11} C_{13} C_{14}$ (considering only lightest charged Higgs).

- We find numerically, the factor $g_{hH^\pm H^\pm}/m^2_{H_1^\pm} \sim 0.0024 \Rightarrow$ contribution due to the extra charged triplet is treated to be negligible.
- For the specific Benchmark set, $R_{\gamma\gamma} \simeq 1.224$.

A. Delgado *et al.*, Phys. Rev. D **86**, 115010 (2012)

Contours of $R_{\gamma\gamma}$



Left Panel : Contours of $R_{\gamma\gamma}$ as a function of $\tan\beta$ and the triplet coupling λ_2 with $M_2 = 375$ GeV. Right Panel : Contours of $R_{\gamma\gamma}$ as a function of $\tan\beta$ and M_2 with $\lambda_2 = 0.8$

Summary and Outlook

- We propose an economic extension of minimal supersymmetric standard model with a SU(2) singlet and $Y = 0$ triplet.
- TSMSSM alleviates the fine tuning problem compared to MSSM, NMSSM.
- 130 GeV gamma-ray line can be explained through the resonant annihilation of neutralino LSP into two photons.
- Our model predicts an enhancement in the diphoton decay rate as, $R\gamma\gamma \sim 1.224$.
- Collider phenomenology of the Higgs sector is still unexplored,
- One can restrict the choice of parameter space based on the low energy constraints such as $B_s \to \mu\mu$ and other.

Thank you!