Supersymmetry with R-symmetry: neutrinos, Higgs boson and dark matter

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Discovery of Higgs Boson

Discovery of Higgs boson with a mass of $\sim$ 125 GeV

- ATLAS collaboration reported

$$\mu_{\gamma\gamma} = 1.17 \pm 0.27$$

$$\mu_{\gamma\gamma} = \frac{\sigma(pp \to h \to \gamma\gamma)}{\sigma(pp \to h \to \gamma\gamma)^{SM}}$$

- CMS collaboration presented their results

$$\mu_{\gamma\gamma} = 1.14^{+0.26}_{-0.23}$$

G. Aad *et al.* [ATLAS Collaboration], ArXiv:1408.7084

V. Khachatryan *et al.* [CMS Collaboration], ArXiv:1407.0558

Neutrinos

- There is strong evidence in favour of neutrino masses and mixing

- An indication of physics beyond the SM

- Naturally, the neutrino sector is a testing ground for various models going beyond the SM

- Question: since the BSM physics has a strong candidate in SUSY, could SUSY also be responsible for neutrino masses ?

- It might also end up predicting specific experimental signals at LHC

Dark matter

- Compelling evidence in favor of DM

- Cosmological observations measured the relic density of DM with a very high degree of precision

- The identity of DM remains unknow to date

Potential candidates are – Neutralino, gravitino, axino, axion, keV sterile neutrino

3.5 keV X-ray line

- ⋆ Very recent observation of an X-ray line signal at around 3.5 keV

- ⋆ Detected in the X-ray spectra of Andromeda galaxy and various galaxy clusters including the perseus galaxy cluster

- ⋆ Can be explained in terms of a keV sterile neutrino dark matter decaying into ν + γ

- ⋆ Question: Can one accommodate such a sterile neutrino dark matter in a SUSY theory ?

Goals

- Tempting to see whether there exist SUSY models
  - Can explain the observed mass of the Higgs boson at 125 GeV and its decays BRs
  - Provide a suitable DM candidate
  - Produce neutrino masses and mixing consistent with current data
  - Relax the strong constraints on SUSY particle masses from the LHC

Supersymmetry

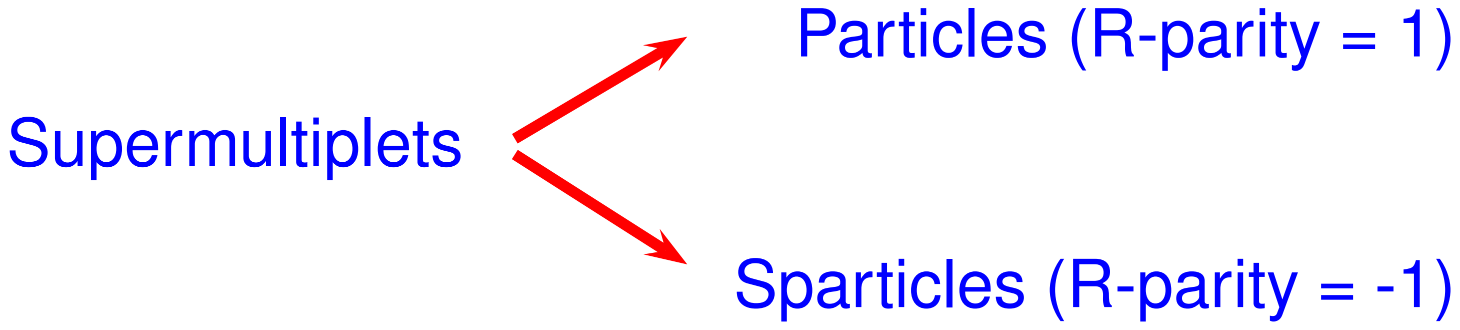
- Supersymmetry one of the most attractive extensions of the Standard Model
- Discovery of SUSY particles, their properties – among the main topics at LHC
- MSSM with R-parity violation (RPV) is an intrinsically SUSY way of generating neutrino mass and mixing
- SUSY can provide a suitable dark matter candidate

Supersymmetry

- What is supersymmetry ?

SUSY is a global symmetry that transforms fermions and bosons into each other by spin $\frac{1}{2}$ carrying supercharges

- SUSY algebra – commutation and anticommutation



Supermultiplets

Particles (R-parity = 1)

Sparticles (R-parity = -1)

- Supersymmetry – a broken symmetry

$$M_{sparticle} - M_{particle} \sim M_s$$

MSSM

What is MSSM ?

MSSM – a SUSY extension of the SM fields

(two Higgs fields)

+ a Higgs μ-term + SUSY breaking soft terms

+ R-parity conservation

$$\mathcal{L}_{\rm MSSM} = \mathcal{L}_{\rm SUPER-SM} + \mathcal{L}_{(\mu)} + \mathcal{L}_{\rm SOFT}$$

MSSM

Why does one need SUSY and MSSM ?

Radiative corrections – Higgs mass and VEV run away to the

next higher scale, M_{GUT}

EW scale (M_W) – radiatively unstable

SUSY stabilizes it – fermion boson cancellation

- MSSM – natural, radiatively stable theory $(M_s <$ a few TeV)

SUSY breaking – Theorists' approach

- Explicitely add soft $\cancel{SUSY}$ terms

↓

- Arbitrary, lacks any theoretical explanation

- Understand their origin in terms of some kind of spontaneous $\cancel{SUSY}$

- In terms of some high scale VEV $\sim \Lambda_{ss}$

$$M_s \sim \frac{\Lambda_{ss}^2}{M_{HS}}$$

Sum Rule

If spontaneous SUSY breaking arose from MSSM fields themselves –

Dimopoulos–Georgi sum rule

$$\begin{array}{ccc} \text{Str } M_u^2 & + & \text{Str } M_d^2 = 0 \\ \uparrow & & \uparrow \\ m^2_{\tilde{u}_1} + m^2_{\tilde{u}_2} - 2m_u^2 & & m^2_{\tilde{d}_1} + m^2_{\tilde{d}_2} - 2m_d^2 \end{array}$$

Disagrees with experiment!!

True for tree level renormalizable coupligs

MSSM soft terms arise indirectly or radiatively

Need a hidden sector

SUSY breaking gets transmitted to observable sector by some mediation mechanism (loops or non-renormalizable operators)

MSSM Superpotential

R-parity conserving

$$W = h_u Q U^c H_u + h_d Q D^c H_d + h_e L E^c H_d + \mu H_u H_d$$

R-parity violating

$$W = \lambda'' D^c U^c U^c + \lambda' Q D^c L + \lambda L L E^c + \mu_l H_u L$$

MSSM Soft SUSY breaking terms

- Scalar masses: $\tilde{m}^2\tilde{q}^*\tilde{q}$
- B-terms: $B_\mu H_u H_d$
- Trilinear scalar couplings (A-terms): $A_{ij}H_{u/d}\tilde{q}^i_L\tilde{q}^j_R$
- Majorana gaugino masses: $M_m\lambda\lambda$

No evidence of SUSY

Squark and gluino masses going

above 1.8 TeV in simplified models

(arXiv:1405.7875)

Look for some alternatives to MSSM

Dirac Gauginos in Supersymmetry

Given a D-term SUSY breaking spurion

$$W'_\alpha = \theta_\alpha D'$$

Dirac gaugino masses arise from:

$$\int d^2\theta \frac{W'_\alpha}{\Lambda} \sqrt{2} \kappa_j W_j^\alpha A_j$$

giving

$$\mathcal{L} = M_j^D \lambda_j \psi_j \text{ + scalar terms}$$

fermion in adjoint rep.

gaugino for jth gauge group

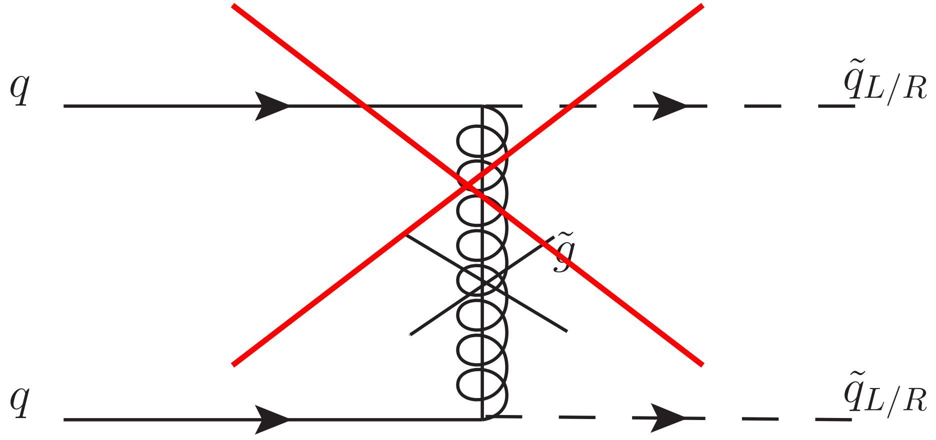
$$M_j^D = \kappa_j \frac{D'}{\Lambda}$$

Gluino and Squark

- ⋆ No Majorana mass for the gauginos

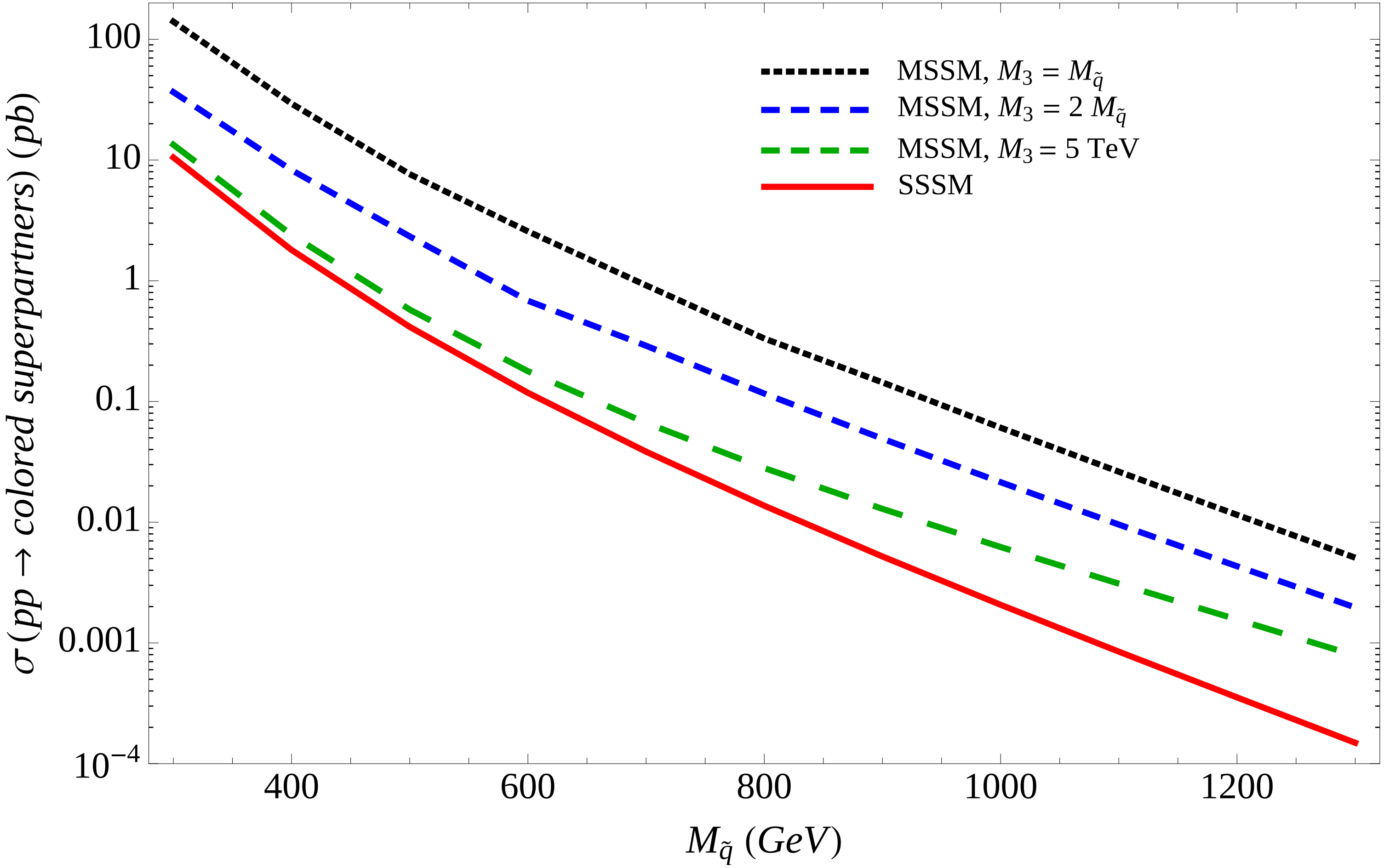
$$\mathcal{L} = \int d^4\theta \, [\cancel{M_1 W^\alpha W_\alpha + M_2 W^{i\alpha} W^i_\alpha + M_3 W^{a\alpha} W^a_\alpha}]\delta^4(\theta, \bar{\theta})$$

- ⋆ Gluinos are naturally heavier than squarks
- ⋆ Relaxed bounds on squark masses (Kribs, PRD 78, 055010, 2008)



Squark production cross sections

(Kribs and Martin, PRD, 2012)



Suppressed by factor of ≈ 100

Vanishing D-term (quartic coupling)

- With just D-term spurions

$$\int d^2\theta \frac{W'_\alpha}{\Lambda}\sqrt{2}\kappa_j W_j^\alpha A_j$$

in components:

$$\mathcal{L} \supset -M_D\lambda_j\psi_j - \sqrt{2}M_D(\phi_j+\phi_j^*)D_j - D_j(\textstyle\sum_i g_k q_i^* t_j q_i) - \frac{1}{2}D_j^2$$

- Integrating out massive Re[ϕ_j], forces D_j = 0, hence

tree level quartic vanishes.

- A DISASTER ! Only stop loop contributions to Higgs mass (Requires $\gg$ 10 TeV mass stops)

Higgs Mass

- Dirac gauginos with only D-term SUSY breaking (and no F-term) is strongly disfavored

- Need either Majorana winos and binos, or other additional contributions to Higgs mass

- R-symmetric contributions from triplet (T) and singlet(S) couplings

- With soft SUSY breaking mass terms for T (m_T) and S (m_S)

  (With F type SUSY breaking vev $\langle F_X \rangle$)

C. Frugiuele, T. Gregoire, P. Kumar, E. Ponton, JHEP 03 (2013) 156

Models with $U(1)_R$ symmetry

- A class of very interesting models are those with a global continuous $U(1)_R$ symmetry
- R-symmetric models have Dirac gauginos instead of Majorana gauginos
- Bounds on first two generation squarks are somewhat relaxed because of the presence of a Dirac gluino
- Flavor and CP violating constraints are also suppressed in this class of models

$U(1)_R$ symmetry

Transformation rules of fields under $U(1)_R$ symmetry

- $\mathbf{R}\hat{V}(x,\theta,\bar{\theta}) = \hat{V}(x, e^{-i\alpha}\theta, e^{i\alpha}\bar{\theta})$

- $\mathrm{R}\hat{\Phi}(x,\theta) = e^{i\alpha n}\hat{\Phi}(x, e^{-i\alpha}\theta)$ n: R-charge of the chiral superfield

- $\mathbf{R}W(x,\theta) = e^{i\alpha \sum_i n_i} W(x, e^{-i\alpha}\theta)$

- Hence, $\mathcal{L} = \int d^2\theta W(x,\theta)$ is invariant if the superpotential W has R-charge 2, i.e. $\sum n_i$ = 2

Transformation rules of the component fields

- Components of chiral superfield

$$\phi \to e^{i\alpha n}\phi$$

$$\psi \to e^{i\alpha(n-1)}\psi$$

$$F \to e^{i\alpha(n-2)}F$$

- Components of vector superfield

$$V_\mu \to V_\mu$$

$$\lambda \to e^{i\alpha}\lambda$$

$$D \to D$$

R-charges of the superfields

	$\hat{Q}_i$	$\hat{U}_i^c$	$\hat{D}_i^c$	$\hat{L}_i$	$\hat{E}_i^c$	$\hat{H}_u$	$\hat{H}_d$	$\hat{R}_u$	$\hat{R}_d$	$\hat{S}$	$\hat{T}$	$\hat{O}$	$\hat{N}^c$
$U(1)_R$	1	1	1	0	2	0	0	2	2	0	0	0	2

S. Chakraborty, SR, JHEP 1401 (2014) 101

R-charges of the scalars

- $\tilde{\nu}_L,\ \tilde{e}_L,\ S,\ T,\ H_u,\ H_d \to 0, \quad \tilde{e}_R^c,\ \tilde{N}^c \to 2,$
  $\tilde{u}_L,\ \tilde{d}_L,\ \tilde{u}_R^c,\ \tilde{d}_R^c \to 1,$

R-charges of the fermions

- $\nu,\ e_L,\ \tilde{H}_u,\ \tilde{H}_d \to -1, \quad e_R^c, N^c,\ \tilde{B},\ \tilde{W},\ \tilde{R}_u,\ \tilde{R}_d \to 1,$
  $u_L,\ d_L,\ u_R^c,\ d_R^c \to 0$

$U(1)_R$-lepton number model

- Identify lepton number with the negative of the R-charges
- Lepton numbers of SM fermions = -R charges
- Squarks, charged sleptons, sneutrinos carry *non-standard* lepton number

C. Frugiuele, T. Gregoire, P. Kumar, E. Ponton, JHEP 03 (2013) 156
S. Chakraborty, S.Roy, JHEP 01 (2014) 101

$U(1)_R$-lepton number model

Interesting features

- $\mu \hat{H}_u \hat{H}_d$ and trilinear scalar ‘A’ terms are not present in the R-symmetric theory
- Sneutrinos can have nonzero VEV – not constrained from small neutrino Majorana mass (down type Higgs)
- A subset of trilnear R-parity violating operators ($\lambda,\ \lambda'$) are consistent with such an R-symmetry

Frugiuele and Gregoire, PRD 85, 015016 (2012)
Bertuzzo and Frugiuele, JHEP 05, (2012) 100

$U(1)_R$-lepton number model

Interesting features

- ⋆ Dirac gauginos with *supersoft* mass term

P. Fox, A.E. Nelson, N. Weiner, JHEP 08 (2002) 035

$$W'_\alpha = \lambda'_\alpha + \theta_\alpha D'$$

$$\mathcal{L}^{\rm Dirac}_{\rm gaugino} = \int d^2\theta \frac{W'_\alpha}{\Lambda}[\kappa_1 W_{1\alpha}\hat{S} + \kappa_2(W^i_{2\alpha}\hat{T}^i) + \kappa_3(W^a_{3\alpha}\hat{O}^a)] + h.c.$$

$$\mathcal{L}^{\rm Dirac}_{\rm gaugino} = M^D_1 \lambda_1 \tilde{S} + M^D_2 \lambda_{2i}\tilde{T}_i + M^D_3 \lambda_{3a}\tilde{O}_a$$

where $M^D_j = \kappa_j D'/\Lambda$

Superpotential

	$\hat{Q}_i$	$\hat{U}_i^c$	$\hat{D}_i^c$	$\hat{L}_i$	$\hat{E}_i^c$	$\hat{H}_u$	$\hat{H}_d$	$\hat{R}_u$	$\hat{R}_d$	$\hat{S}$	$\hat{T}$	$\hat{N}^c$
$U(1)_R$	1	1	1	0	2	0	0	2	2	0	0	2

⋆ Superpotential

$$W = y_{ij}^u \hat{H}_u \hat{Q}_i \hat{U}_j^c + \mu_u \hat{H}_u \hat{R}_d + f \hat{L}_a \hat{H}_u \hat{N}^c + \lambda_S \hat{S} \hat{H}_u \hat{R}_d$$
$$+ 2\lambda_T \hat{H}_u \hat{T} \hat{R}_d + M_R \hat{N}^c \hat{S} + W_{\text{Yukawa}} + W_{\text{Trilinear}}$$

⋆ RPV couplings

$$W_{\text{Yukawa}} = \sum\nolimits_{b=2,3} f_b^l \hat{L}_a \hat{L}_b' \hat{E}_b'^c + \sum\nolimits_{k=1,2,3} f_k^d \hat{L}_a \hat{Q}_k' \hat{D}_k'^c$$

$$W_{\text{Trilinear}} = \sum\nolimits_{k=1,2,3} \frac{1}{2} \tilde{\lambda}_{23k} \hat{L}_2' \hat{L}_3' \hat{E}_k'^c + \sum\nolimits_{j,k=1,2,3;b=2,3} \tilde{\lambda}_{bjk}' \hat{L}_b' \hat{Q}_j' \hat{D}_k'^c$$

Scalar potential and soft terms

F and D terms

$$V_F = \left|\frac{\partial W}{\partial \phi}\right|^2$$

$$V_D = \tfrac{1}{2}\textstyle\sum_a D^a D^a + \tfrac{1}{2} D_Y D_Y$$

$$D^a = g(H_u^\dagger \tau^a H_u + \tilde{L}_i^\dagger \tau^a \tilde{L}_i + T^\dagger \lambda^a T) + \sqrt{2}(M_2^D T^a + M_2^D T^{a\dagger})$$

$$D_Y = \tfrac{g'}{2}(H_u^+ H_u - \tilde{L}_i^+ \tilde{L}_i) + \sqrt{2} M_1^D (S + S^\dagger)$$

Soft terms

$$\begin{aligned} V_{soft} = \; & m_{H_u}^2 H_u^\dagger H_u + m_{R_d}^2 R_d^\dagger R_d + m_{\tilde{L}_a}^2 \tilde{L}_a^\dagger \tilde{L}_a + \textstyle\sum_{b=2,3} m_{\tilde{L}_b}^2 \tilde{L}_b^\dagger \tilde{L}_b \\ & + m_{\tilde{R}_i}^2 \tilde{l}_{Ri}^\dagger \tilde{l}_{Ri} + M_N^2 \tilde{N}^{c\dagger} \tilde{N}^c + m_S^2 S^\dagger S + 2 m_T^2 \mathrm{tr}(T^\dagger T) \\ & - (b\mu_L H_u \tilde{L}_a + \mathrm{h.c.}) + (t_S S + \mathrm{h.c.}) + \tfrac{1}{2} b_S (S^2 + \mathrm{h.c.}) \\ & + b_T(\mathrm{tr}(TT) + \mathrm{h.c.}) \end{aligned}$$

Tree level Higgs mass

- Large sneutrino VEV ($\langle\tilde{\nu}\rangle$) is possible

  Not constrained by neutrino Majorana mass

- Sneutrino can play the role of the down-type Higgs

CP-even scalar mass matrix in the limit when S and T are decoupled

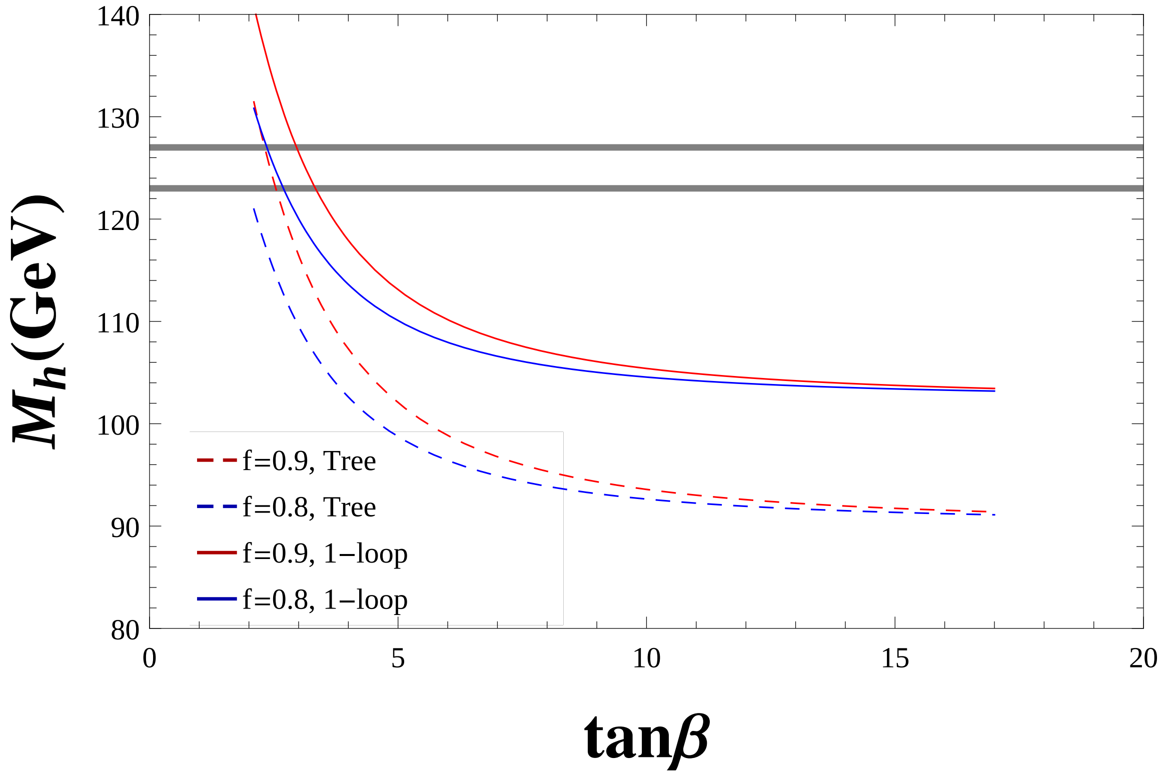
gives at the Tree level

S. Chakraborty, S.Roy, JHEP 01 (2014) 101

$$m_h^2 = \left[M_Z^2 \cos^2 2\beta + f^2 v^2 \sin^2 2\beta\right]$$

Can be important for an order one f and low $\tan\beta$

Large neutrino Yukawa coupling and Higgs boson mass



Dashed lines represent Higgs boson mass at the tree level, $f = 0.9$ (red), $f = 0.8$ (blue) whereas the continuous lines take into account the radiative corrections with $m_{\tilde{t}_1}$ = $m_{\tilde{t}_2}$ = 500 GeV

Neutrino Mass in $U(1)_R$ model

Neutrino sector in the R-conserving limit

⋆ Neutralino mass matrix in the basis $\psi^{0+} = (\tilde{b}^0, \tilde{w}^0, \tilde{R}_d^0, N^c)$ and $\psi^{0-} = (\tilde{S}, \tilde{T}^0, \tilde{H}_u^0, \nu_e)$

$$M_\chi^D = \begin{pmatrix} M_1^D & 0 & \frac{g' v_u}{\sqrt{2}} & -\frac{g' v_a}{\sqrt{2}} \\ 0 & M_2^D & -\frac{g v_u}{\sqrt{2}} & \frac{g v_a}{\sqrt{2}} \\ \lambda_S v_u & \lambda_T v_u & \mu_u + \lambda_S v_S + \lambda_T v_T & 0 \\ M_R & 0 & -f v_a & -f v_u \end{pmatrix}$$

⋆ With $M_R = \frac{\sqrt{2} f M_1^D \tan\beta}{g \tan\theta_W}$ and $\lambda_T = \tan\theta_W \lambda_S$

$$m_{\nu_e}^D = \frac{v^3 \sin\beta f g \lambda_T}{\sqrt{2}(\mu_u + \lambda_s v_S + \lambda_T v_T)} \frac{(M_2^D - M_1^D)}{M_1^D M_2^D}$$

R-breaking

- Gravitino mass $m_{3/2}$ is the order parameter of R-breaking

- R-breaking communicated to the visible sector via anomaly mediation.

G.D. Kribs, T. Okui, T.S. Roy, PRD (2010)

- Imagine a setup in which $m_{3/2}$ is much smaller than the TeV scale

- Important implications in neutrino physics

Neutralino mass matrix in the R-breaking scenario

⋆ In the basis $(\tilde{b}^0, \tilde{S}, \tilde{w}^0, \tilde{T}, \tilde{R}_d^0, \tilde{H}_u^0, N^c, \nu_e)$

$$M_\chi^M = \begin{pmatrix} M_1 & M_1^D & 0 & 0 & 0 & \frac{g' v_u}{\sqrt{2}} & 0 & -\frac{g' v_a}{\sqrt{2}} \\ M_1^D & 0 & 0 & 0 & \lambda_S v_u & 0 & M_R & 0 \\ 0 & 0 & M_2 & M_2^D & 0 & -\frac{g v_u}{\sqrt{2}} & 0 & \frac{g v_a}{\sqrt{2}} \\ 0 & 0 & M_2^D & 0 & \lambda_T v_u & 0 & 0 & 0 \\ 0 & \lambda_S v_u & 0 & \lambda_T v_u & 0 & \gamma & 0 & 0 \\ \frac{g' v_u}{\sqrt{2}} & 0 & -\frac{g v_u}{\sqrt{2}} & 0 & \gamma & 0 & -f v_a & 0 \\ 0 & M_R & 0 & 0 & 0 & -f v_a & 0 & -f v_u \\ -\frac{g' v_a}{\sqrt{2}} & 0 & \frac{g v_a}{\sqrt{2}} & 0 & 0 & 0 & -f v_u & 0 \end{pmatrix}$$

where

$$M_i = b_i \frac{g_i^2}{16\pi^2} m_{3/2}, \qquad A_{u/d} = \frac{\hat{\beta}_{h_{u/d}}}{16\pi^2} \frac{v_{u/d}}{m_{u/d}} m_{3/2}$$

Anomaly mediated R-breaking

Neutrino mass in the R-breaking scenario

- Tree level Majorana neutrino mass

$$(m_\nu)_{\rm Tree} \simeq -v^2 \frac{\left[g\lambda_T v^2 (M_2^D - M_1^D)\sin\beta\right]^2}{[M_1\alpha^2 + M_2\delta^2]}$$

- Sterile neutrino mass

$$M_N^R \simeq \left(\frac{M_1}{M_1^D}\right)\left(\frac{M_R}{M_1^D}\right) \simeq M_1 \frac{2f^2\tan^2\beta}{g'^2}$$

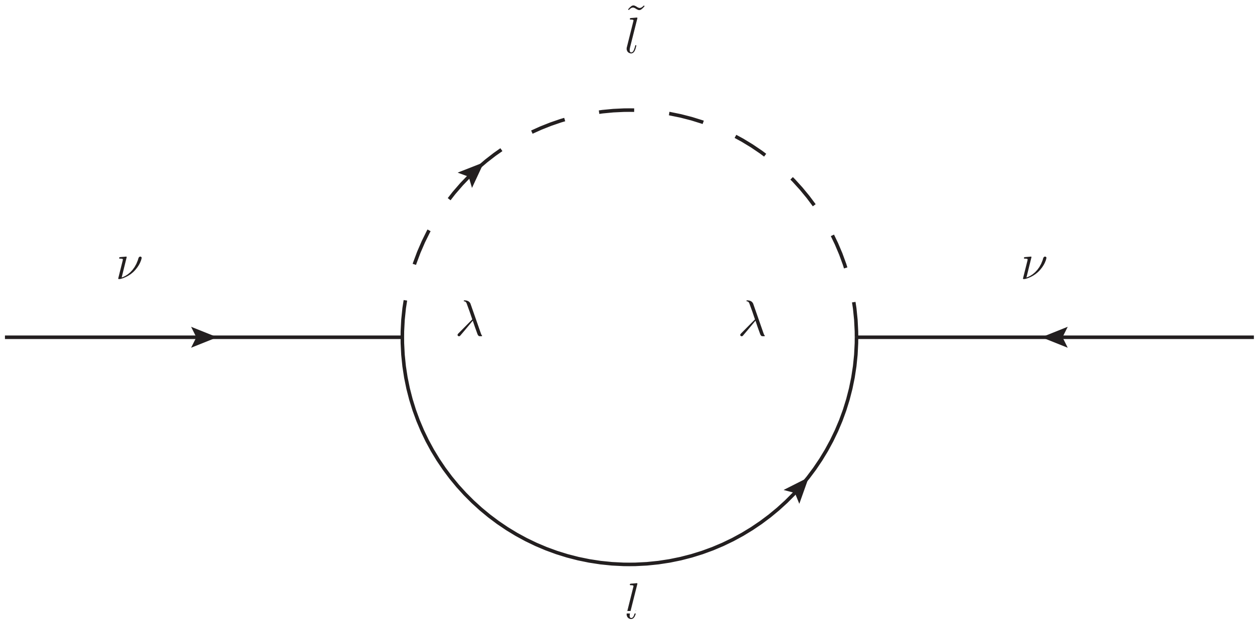
- Active-sterile mixing

$$\theta_{14}^2 \approx \frac{(m_\nu)_{Tree}}{M_N^R}$$

S. Chakraborty and SR, JHEP 1401, 2014, 101

Neutrino mass generation via loop corrections

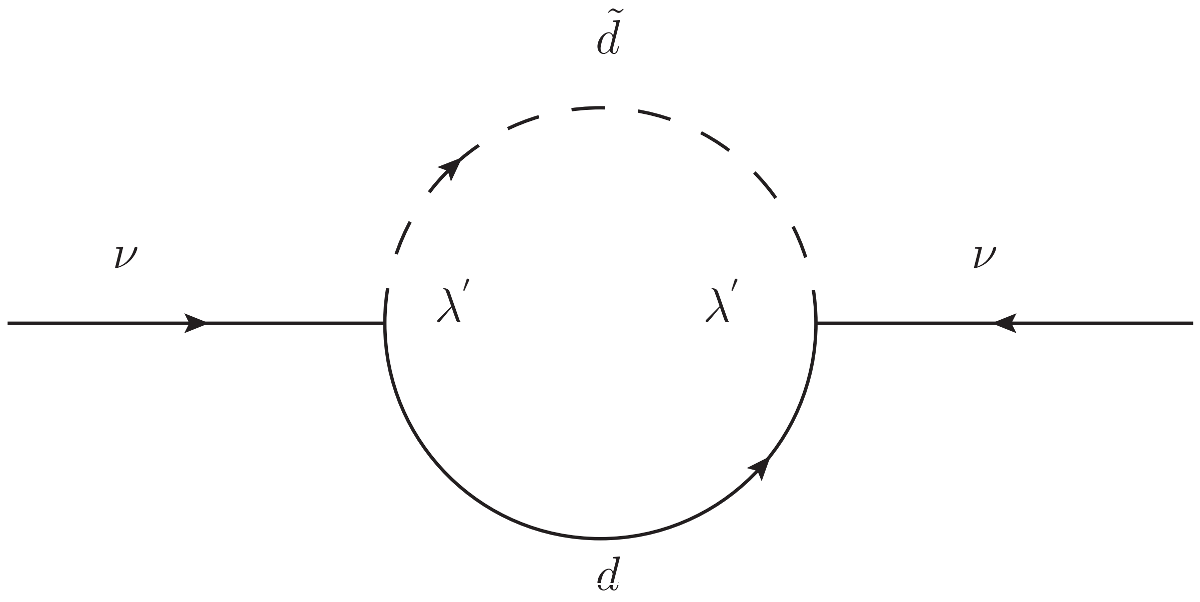
- Lepton-Slepton loop



$$(\mathbf{m}_\nu)_{\mathbf{ij}} = \frac{\mathbf{1}}{(\mathbf{16}\pi^{\mathbf{2}})^{\mathbf{2}}} \left[\frac{\mathbf{m}_\tau \mathbf{m}_{\mathbf{3/2}} \mathbf{v}_{\mathbf{a}}}{\mathbf{m}^{\mathbf{2}}_{\tilde{\tau}}} \right] \hat{\beta}_\tau \lambda_{\mathbf{i33}} \lambda_{\mathbf{j33}} \ln \left(\frac{\mathbf{m}^{\mathbf{2}}_{\tilde{\tau}_{\mathbf{1}}}}{\mathbf{m}^{\mathbf{2}}_{\tilde{\tau}_{\mathbf{2}}}} \right)$$

Neutrino mass generation via loop corrections

- ⋆ Quark-Squark loop

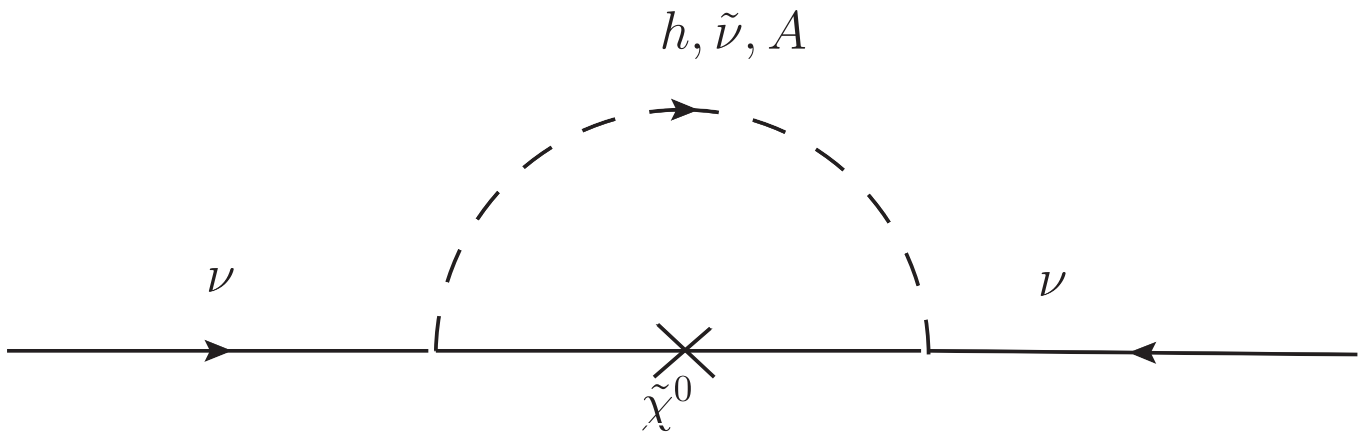


$$(\mathbf{m}_\nu)_{\mathbf{ij}} = \frac{\mathbf{3}}{(\mathbf{16}\pi^{\mathbf{2}})^{\mathbf{2}}}\left[\frac{\mathbf{m_{3/2}v_a}}{\mathbf{m}^{\mathbf{2}}_{\tilde{\mathbf{b}}}}\right]\hat{\beta}_{\mathbf{b}}\left[\mathbf{m_b}\lambda'_{\mathbf{i33}}\lambda'_{\mathbf{j33}} + \mathbf{m_s}\lambda'_{\mathbf{i23}}\lambda'_{\mathbf{j32}}\right]\ln\left(\frac{\mathbf{m}^{\mathbf{2}}_{\tilde{\mathbf{b}}_{\mathbf{1}}}}{\mathbf{m}^{\mathbf{2}}_{\tilde{\mathbf{b}}_{\mathbf{2}}}}\right)$$

$$+\frac{\mathbf{3}}{(\mathbf{16}\pi^{\mathbf{2}})^{\mathbf{2}}}\left[\frac{\mathbf{m_{3/2}v_a}}{\mathbf{m}^{\mathbf{2}}_{\tilde{\mathbf{s}}}}\right]\hat{\beta}_{\mathbf{b}}\left[\mathbf{m_b}\lambda'_{\mathbf{i32}}\lambda'_{\mathbf{j23}} + \mathbf{m_s}\lambda'_{\mathbf{i22}}\lambda'_{\mathbf{j22}}\right]\ln\left(\frac{\mathbf{m}^{\mathbf{2}}_{\tilde{\mathbf{s}}_{\mathbf{1}}}}{\mathbf{m}^{\mathbf{2}}_{\tilde{\mathbf{s}}}}\right)$$

Neutrino mass generation via loop corrections

- ⋆ Neutralino-Sneutrino/Higgs loop



$$(\mathbf{m}_\nu)_{\mathbf{11}} = \frac{\mathbf{g}^{\mathbf{2}}}{\mathbf{64}\pi^{\mathbf{2}}} \sum_{\gamma=\mathbf{1,2}} [\mathbf{Z}_{\gamma\mathbf{2}} - \tan\theta_{\mathbf{W}} \mathbf{Z}_{\gamma\mathbf{1}}]^{\mathbf{2}} \frac{\mathbf{M_1}}{\mathbf{2}}$$

$$\left[\cos^{\mathbf{2}}\alpha \mathbf{B_0}(\mathbf{0}, \mathbf{m}^{\mathbf{2}}_{\mathbf{H}}, \mathbf{m}^{\mathbf{2}}_{\tilde{\chi}^{\mathbf{0}}}) + \sin^{\mathbf{2}}\alpha \mathbf{B_0}(\mathbf{0}, \mathbf{m}^{\mathbf{2}}_{\mathbf{h}}, \mathbf{m}^{\mathbf{2}}_{\tilde{\chi}^{\mathbf{0}}}) - \sin^{\mathbf{2}}\beta \mathbf{B_0}(\mathbf{0}, \mathbf{m}^{\mathbf{2}}_{\mathbf{A}}, \mathbf{m}^{\mathbf{2}}_{\tilde{\chi}^{\mathbf{0}}})\right]$$

$$+\frac{\mathbf{g}^{\mathbf{2}}}{\mathbf{64}\pi^{\mathbf{2}}} \sum_{\gamma=\mathbf{3,4}} [\mathbf{Z}_{\gamma\mathbf{2}} - \tan\theta_{\mathbf{W}} \mathbf{Z}_{\gamma\mathbf{1}}]^{\mathbf{2}} \frac{\mathbf{M_2}}{\mathbf{2}}$$

$$\left[\cos^{\mathbf{2}}\alpha \mathbf{B_0}(\mathbf{0}, \mathbf{m}^{\mathbf{2}}_{\mathbf{H}}, \mathbf{m}^{\mathbf{2}}_{\tilde{\chi}^{\mathbf{0}}}) + \sin^{\mathbf{2}}\alpha \mathbf{B_0}(\mathbf{0}, \mathbf{m}^{\mathbf{2}}_{\mathbf{h}}, \mathbf{m}^{\mathbf{2}}_{\tilde{\chi}^{\mathbf{0}}}) - \sin^{\mathbf{2}}\beta \mathbf{B_0}(\mathbf{0}, \mathbf{m}^{\mathbf{2}}_{\mathbf{A}}, \mathbf{m}^{\mathbf{2}}_{\tilde{\chi}^{\mathbf{0}}})\right]$$

Sterile Neutrino Dark Matter

Sterile neutrino dark matter

- Dark matter can be keV sterile neutrinos

- keV sterile neutrinos with mixing of 10^{-5} with active neutrinos can decay: $\nu_s \to Z \to \nu\nu\nu$ at tree level.

- Its life time is fairly larger than the age of the Universe, and hence ν_s form warm dark matter particle.

- The phenomenologically interesting channel is $\nu_s \to \nu\gamma$, which is a one loop diagram induced by W boson

$$\Gamma_\gamma(m_s,\theta) = 1.38 \times 10^{-29}\ \mathrm{s}^{-1}\ \left(\frac{\sin^2 2\theta}{10^{-7}}\right)\left(\frac{m_s}{1\ \mathrm{keV}}\right)^5,$$

P.B. Pal and L. Wolfenstein, Phys. Rev. D25, 766 (1982)

X-rays from galaxy clusters

- If the dark matter is keV sterile neutrinos, we should detect X-rays from the center of a galaxy

- The signal due to sterile neutrino decay will have background due to inter-cluster medium of a galaxy cluster

- If the signal is stronger than the background, we should see a sharp peak in the X-ray spectrum on top of the background

- *Chandra*, *XMM-Newton* and *Suzaku* satellite based telescopes have been launched to detect X-ray flux from various clusters of galaxies

R.S. Hundi, SR, PLB (2011)

P. Dey, B. Mukhopadhyaya, SR, S.K. Vempati, JCAP (2012)
S. Chakraborty, D.K. Ghosh, SR, JHEP (2014)

Flux of X-ray from dark matter halos

- An object such as a galaxy or cluster of galaxies possessing a dark matter halo of mass M_{DM} is composed of

$$N = M_{DM}/m_X$$

dark matter particles of mass m_X.

- If Γ_γ is the dark matter particle decay rate into photons of energy E_γ, then the X-ray luminosity is

$$\mathcal{L} = \frac{E_\gamma}{m_X} M_{\rm DM} \Gamma_\gamma \qquad E_\gamma = m_X/2.$$

- The X-ray flux from a cluster of galaxy is

$$F = \frac{\mathcal{L}}{4\pi D_L^2}$$

D_L is the luminosity distance to the object

7 keV sterile neutrino

- Recent detection of a 3.5 keV line in the X-ray spectra of Andromeda galaxy and various other glaxy clusters by XMM-Newton Space observatory

- Observed flux and best fit energy peak are at

$$\Phi_\gamma = 4 \pm 0.8 \times 10^{-6}\ \mathrm{photons\ cm^{-2}\ sec^{-1}}$$

$$E_\gamma = 3.57 \pm 0.02\ \mathrm{keV}$$

- This translates to an active-sterile mixing in the range $2.2 \times 10^{-11} < \sin^2 2\theta_{14} < 2 \times 10^{-10}$ and mass of the sterile neutrino dark matter $M_N^R = 7.06 \pm 0.05$ keV

Bulbul *et al.* arXiv:1402.2301; Boyarsky *et al.* arXiv:1402.4119

Sterile neutrino production

The Dodelson-Widrow mechanism

- In the absence of any primordial lepton asymmetry, sterile neutrinos can be produced through mixing with the active neutrinos

- The production of sterile neutrinos depend only on the mass of the sterile neutrinos and its mixing with the active neutrinos

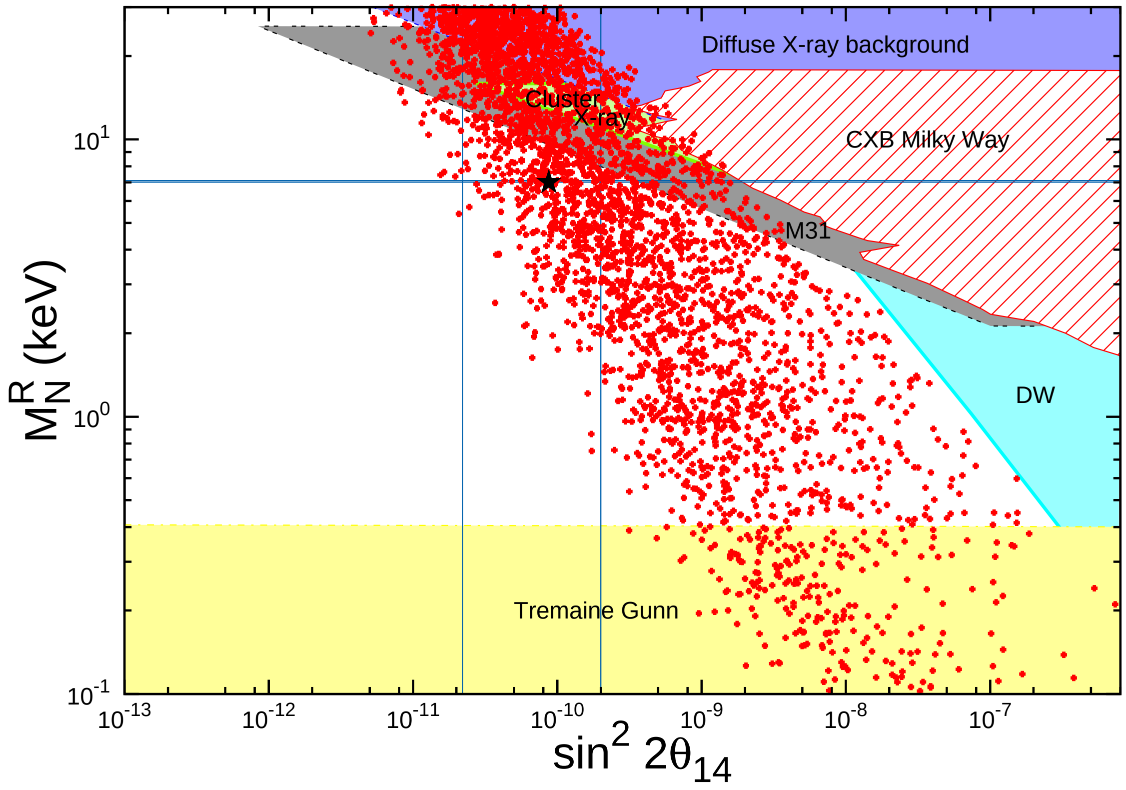
$$\Omega_s h^2 \approx 0.3 \left(\frac{\sin^2 2\theta}{10^{-10}}\right) \left(\frac{m_s}{100\ \mathrm{keV}}\right)^2$$

The Shi-Fuller mechanism

- Production mechanism proposed by DW is altered in the presence of a primordial lepton asymmetry
- The production of sterile neutrinos can be enhanced by MSW effect
- Shi-Fuller deduced that the MSW resonance makes the production more efficient for small active-sterile mixing angles
- Smaller mixing angles opens up, which are less constrained by X-ray data
- Momentum distribution cooler compared to sterile neutrinos produced via DW mechanism

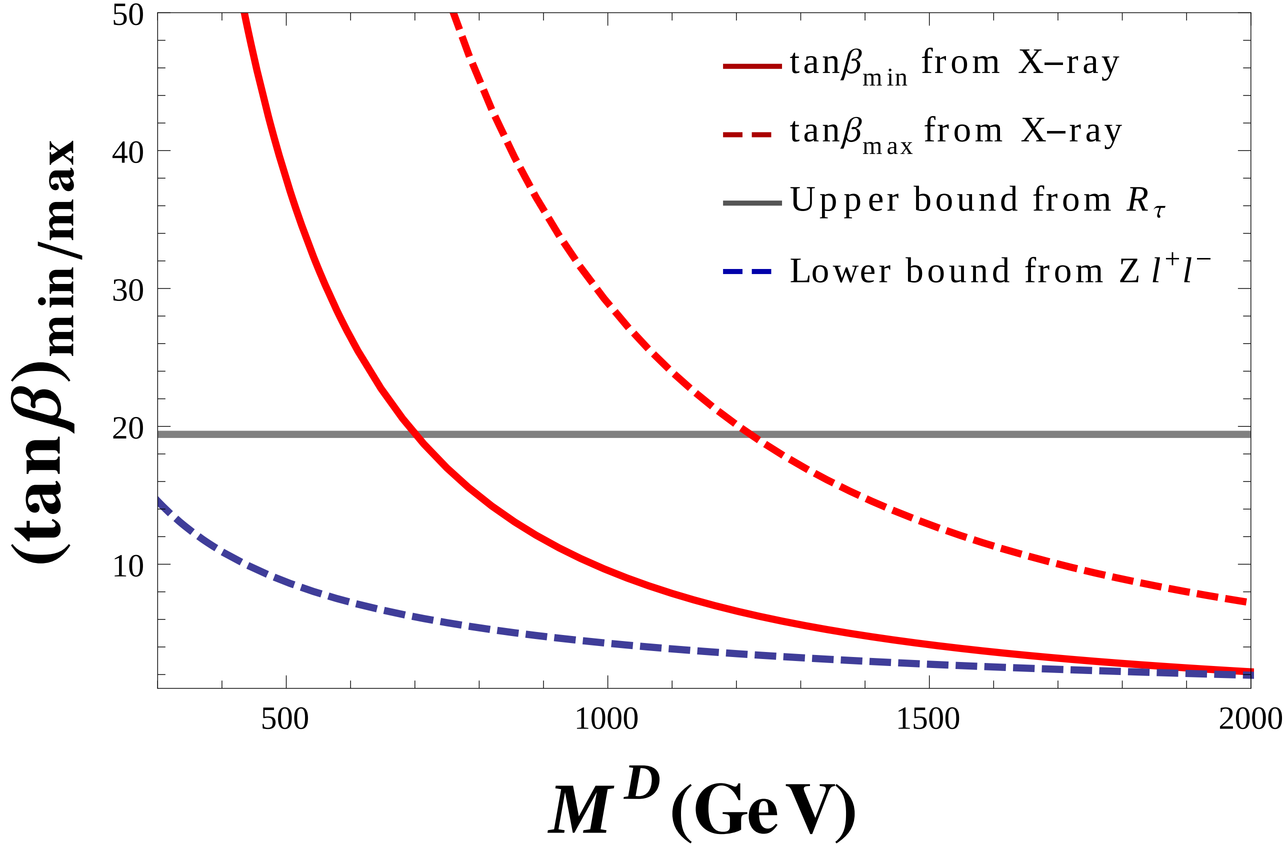
7 keV sterile neutrino

(S. Chakraborty, D.K. Ghosh, SR, arXiv:1405.6967)



Red points are obtained by scanning the parameter space. The black star represents the central value of the mass and active-sterile mixing from the 3.5 keV line observation

7 keV sterile neutrino constrains parameter space



$$R_\tau \equiv \frac{\Gamma(\tau\to e\bar{\nu}_e\nu_\tau)}{\Gamma(\tau\to\mu\bar{\nu}_\mu\nu_\tau)}$$

Showing the lower and upper limits of $\tan\beta$ from X-ray analysis as a function of M_2^D for μ_u = 700 GeV, $m_{3/2}$ = 10 GeV

(S. Chakraborty, D.K. Ghosh, SR, arXiv:1405.6967)

Gravitino cosmology

⋆ The most dominant decay of the gravitino

$$\Gamma_{\tilde{G}\to N\gamma} \sim \frac{|U_{\tilde{b}N}|^2 m_{3/2}^3}{32\pi M_P^2}$$

⋆ Upper bound on the gravitino relic density

$$\Omega_{3/2}h^2 < 4.34 \times 10^{-13} \left(\frac{10^{-2}}{U_{\tilde{b}N}}\right)^2$$

⋆ Upper bound on the reheating temperature

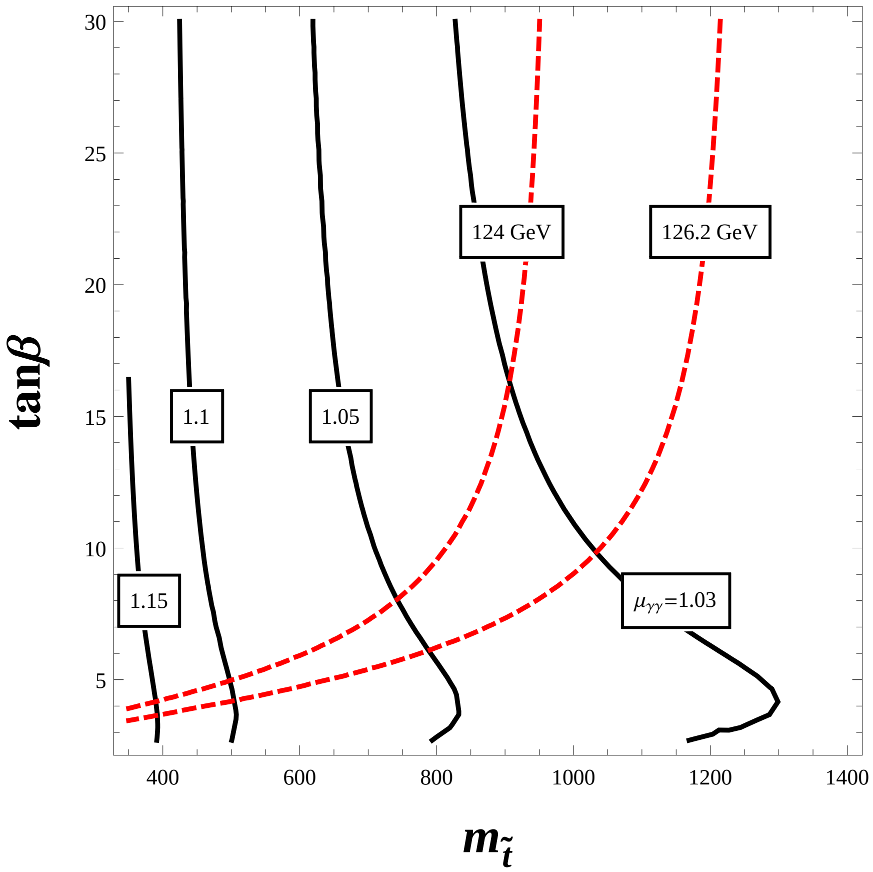
$$\boxed{T_R < 127 \left(\frac{v_a}{30\text{GeV}}\right)^{2/7} \left(\frac{m_{\tilde{b}}}{500\text{GeV}}\right)^{4/7} \left(\frac{10^{-2}}{U_{\tilde{b}N}}\right)^{2/7} \text{GeV}}$$

Higgs signal strength $\mu_{\gamma\gamma}$

Contours of $\mu_{\gamma\gamma}$

Large f ($f \sim 1$) case, characterised by a light (MeV) bino like neutralino

S. Chakraborty, A. Datta and SR (2015)

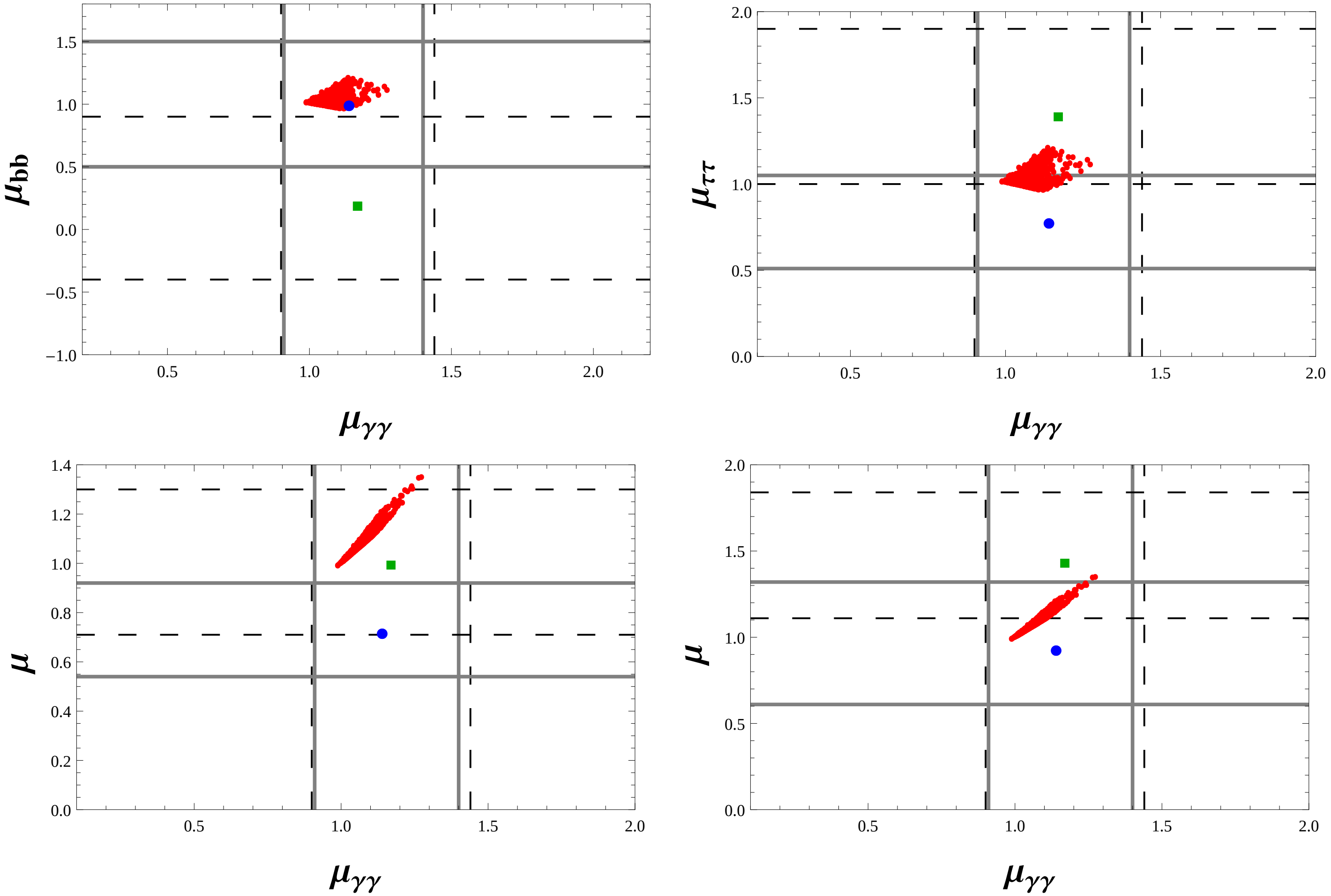


$$\mu_{\gamma\gamma} = \frac{\sigma(pp \to h \to \gamma\gamma)}{\sigma(pp \to h \to \gamma\gamma)^{SM}}$$

Contours of $\mu_{\gamma\gamma}$ and M_h are shown in the $\tan\beta$-$m_{\tilde{t}}$ plane for λ_T = 0.45 and f = 0.8

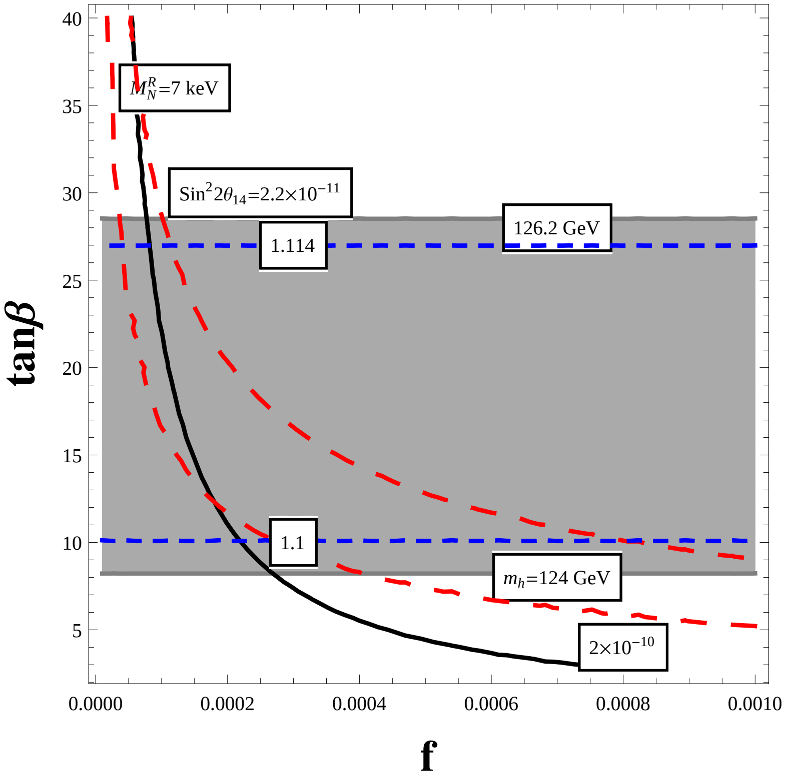
Relative signal strengths

- Large f ($f \sim 1$) case



Contours of $\mu_{\gamma\gamma}$

- Small f case, $f \sim \mathcal{O}(10^{-4})$. 7 keV sterile neutrino as a warm dark matter

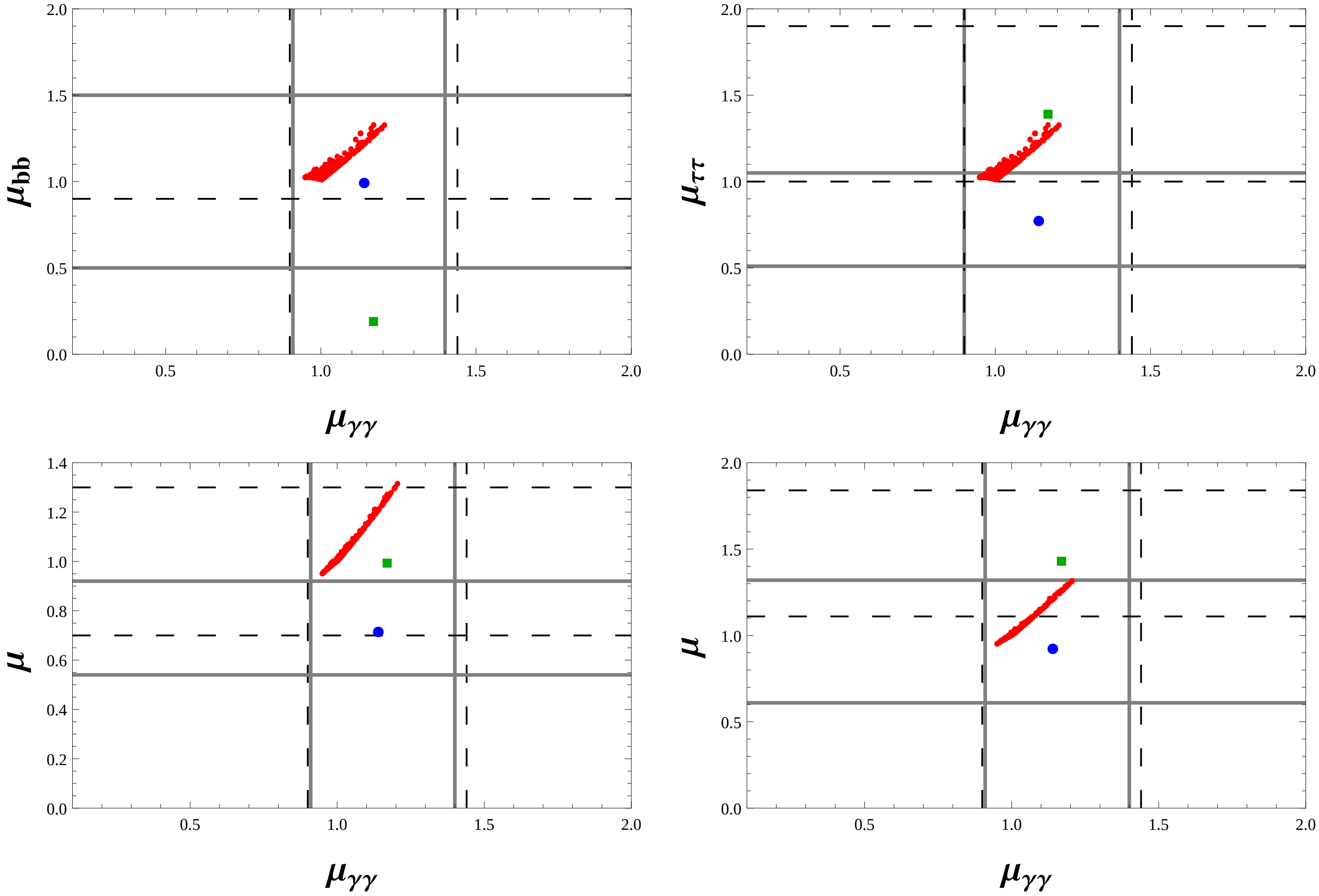


Contours of M_N^R = 7.06 keV, $\sin^2 2\theta_{14} = 2.2 \times 10^{-11}$ and 2×10^{-10} are shown along with contours of M_h and $\mu_{\gamma\gamma}$

Relative signal strengths

S. Chakraborty, A. Datta and SR (2015)

- Small f ($f \sim 10^{-4}$) case



Conclusions

- $U(1)_R$ symmetric SUSY models are viable alternatives
- Appearance of Dirac gauginos: relaxed bounds on squark masses
- An interesting possibility – R-symmetry identified with lepton number
- R-symmetry identified with lepton number
- Generation of neutrino Majorana mass with mild R-symmetry breaking
- Light neutrino masses and mixing can be explained (Tree + one-loop)

Conclusions

- Sterile neutrino warm dark matter with mass 7.06 keV
- Higgs boson mass receives an extra contribution at tree level for large Yukawa coupling f
- $f \sim 1$, bino like lightest neutralino with mass around a few hundred MeV
- Upper bound on the reheating temperature $T_R \leq 130$ GeV