Supersymmetric minimal $U(1)_X$ model at the TeV scale with right-handed Majorana neutrino dark matter

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Work with Nobuchika Okada, manuscript in progress

Outline

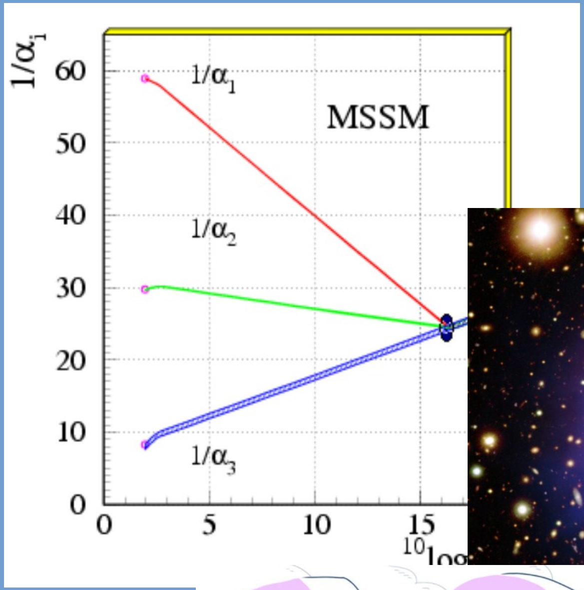
- Motivation
- Model Basics
- RH Neutrino DM
- LHC Constraints & Complementarity
- Conclusions

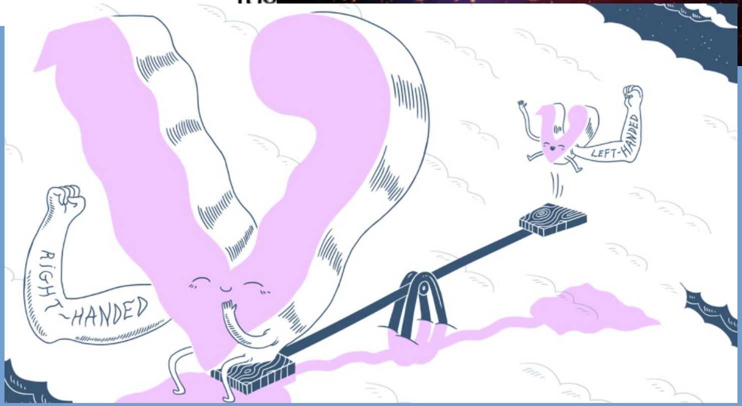
$U(1)_X$ Non-SUSY: **A. Das, N. Okada and D. Raut, Phys. Rev. D 97, no. 11, 115023 (2018)**

$U(1)_{BL}$ MSSM: **Z. M. Burell and N. Okada, Phys. Rev. D 85, 055011 (2012)**

Why MSSM?

- Gauge unification
- Hierarchy problem
- DM candidates
- Easily extended to explain neutrino masses





MSSM $U(1)_X$ Model

chiral superfield	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)_X$	R-parity	Z_2
Q^i	$\mathbf{3}$	$\mathbf{2}$	$+1/6$	$(1/6)x_H + 1/3$	$-$	$+$
U_i^c	$\mathbf{3}^*$	$\mathbf{1}$	$-2/3$	$(-2/3)x_H - 1/3$	$-$	$+$
D_i^c	$\mathbf{3}^*$	$\mathbf{1}$	$+1/3$	$(1/3)x_H - 1/3$	$-$	$+$
L_i	$\mathbf{1}$	$\mathbf{2}$	$-1/2$	$(-1/2)x_H - 1$	$-$	$+$
N_1^c	$\mathbf{1}$	$\mathbf{1}$	0	$+1$	$-$	$-$
$N_{2,3}^c$	$\mathbf{1}$	$\mathbf{1}$	0	$+1$	$-$	$+$
E_i^c	$\mathbf{1}$	$\mathbf{1}$	$+1$	$x_H + 1$	$-$	$+$
H_u	$\mathbf{1}$	$\mathbf{2}$	$+1/2$	$(1/2)x_H$	$+$	$+$
H_d	$\mathbf{1}$	$\mathbf{2}$	$-1/2$	$(-1/2)x_H$	$+$	$+$
Φ	$\mathbf{1}$	$\mathbf{1}$	0	-2	$+$	$+$
$\bar{\Phi}$	$\mathbf{1}$	$\mathbf{1}$	0	$+2$	$+$	$+$

added symmetries

added particles

- $U(1)_X$ charge: $Q_x = Yx_H + Q_{B-L}$
- RH Neutrinos: needed to cancel gauge/gravity anomalies!
- Z_2 parity $\rightarrow$ prevents N_1 decay
- Scalars $\rightarrow$ seesaw and $\cancel{U(1)_X}$

MSSM U(1)$_X$ Model

- Superpotential: $$W_X = \underbrace{\sum_{i=2}^{3}\sum_{j=1}^{3} y_D^{ij} N_i^C L_j H_u}_{\substack{\textbf{Dirac} \\ \textbf{(no } y_D^{1j} \textbf{ terms)}}} + \underbrace{\sum_{k=1}^{3} y_M^k \Phi N_k^C N_k^C}_{\textbf{Majorana}} - \underbrace{\mu_\Phi \bar{\Phi}\Phi}_{\textbf{mu}}$$

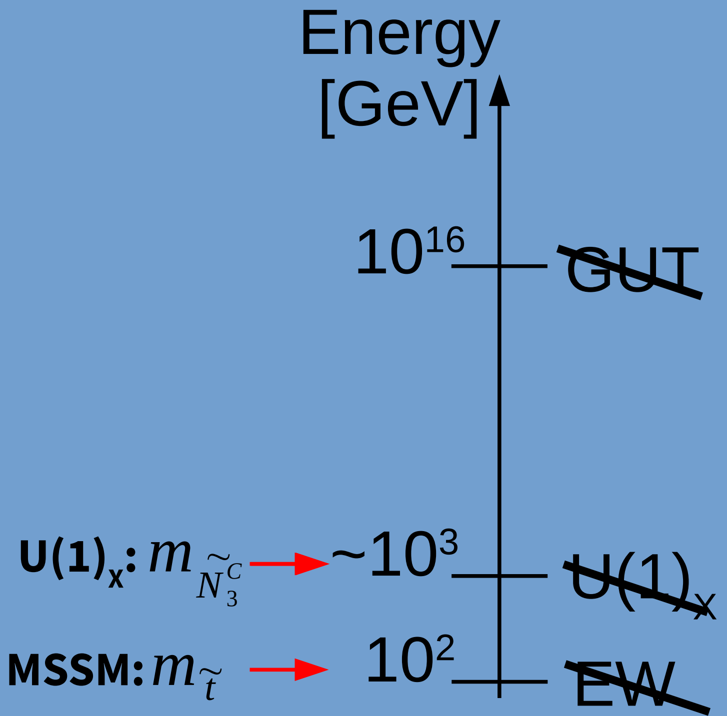
- Soft ~~SUSY~~: $$L_{soft} \supset -\left(\frac{1}{2}\underbrace{M_X \lambda_X \lambda_X}_{\substack{\textbf{U(1)}_X \\ \textbf{gaugino}}} + h.c.\right) - \left(\sum_{k=1}^{3} m_{\tilde{N}_k^C}^2 |\tilde{N}_k^C|^2 + m_\Phi^2 |\Phi|^2 + m_{\bar{\Phi}}^2 |\bar{\Phi}|^2\right)$$ $$+\left(B_\Phi \bar{\Phi}\Phi + \sum_{k=1}^{3} A_k \Phi \tilde{N}_k^C \tilde{N}_k^C + h.c.\right)$$

MSSM $U(1)_X$ Symmetry Breaking

- In MSSM, the top quark radiative contributions break EW symmetry

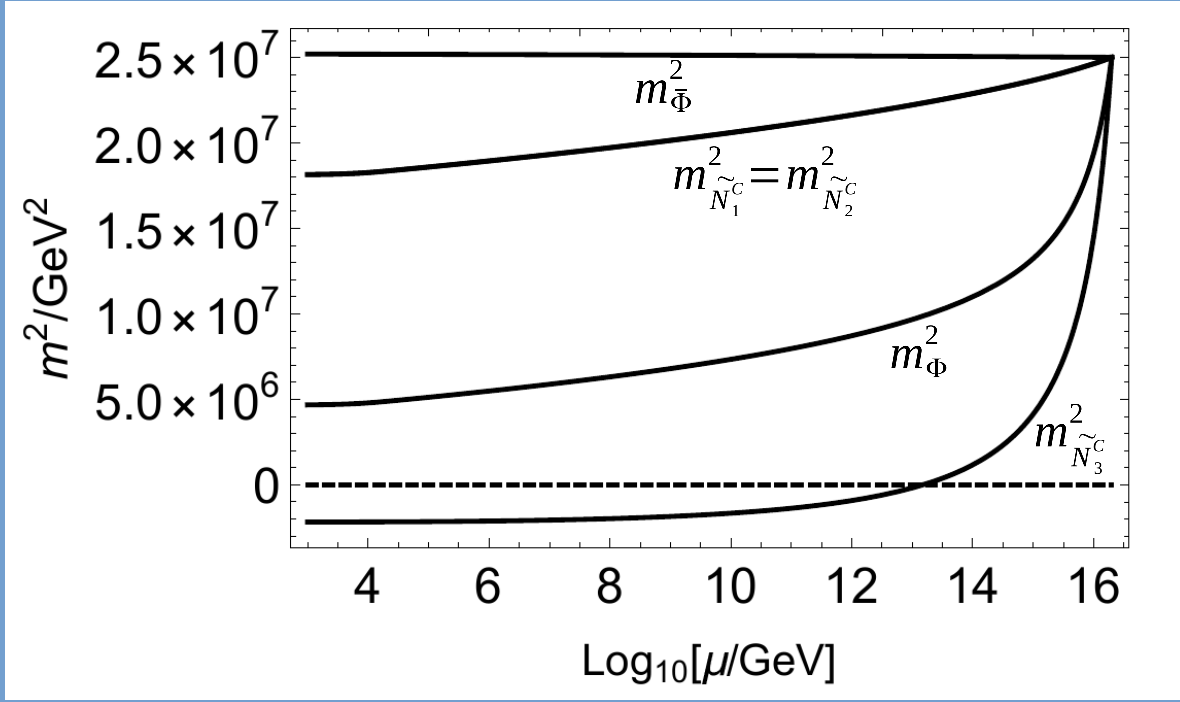
- In $U(1)_X$ model this analogous behavior occurs due to radiative contributions from a RH sneutrino

- As shown in $\boxed{\text{S. Khali, et al, Phys.Lett.B 665 (2008) 374-377}}$ this radiative mechanism can ensure $\cancel{U(1)_X}$ at O(TeV) scale



MSSM $U(1)_X$ Symmetry Breaking

- This example shows solution to relevant RGE's and running of the ~~SUSY~~ terms
- From top to bottom is the running of $m^2_{\bar{\Phi}}, m^2_{\tilde{N}^C_1} = m^2_{\tilde{N}^C_2}$, m^2_{Φ}, and $m^2_{\tilde{N}^C_3}$
- The negative $m^2_{\tilde{N}^C_3}$ results in the breaking of $U(1)_X$



I.C.'s at GUT scale:

$x_H = -0.8, g_x = 0.532, y_1 = y_2 = 0.4, y_3 = 2.5,$
$M_x = 1\,TeV, m_{\tilde{N}^C_i} = m_{\Phi} = m_{\bar{\Phi}} = 5\,TeV, A_i = 0$

Potential stability analysis

- Scalar potential consists of SUSY and Soft terms

$$V(\bar{\Phi}, \Phi, \tilde{N}_3^C) = V_{SUSY} + V_{Soft}$$

- The ~~U(1)x~~ scale is set at 26 TeV and the ~~SUSY~~ parameters are found using the solved RGE’s

- Values for μ_Φ and B_Φ are found from numerically satisfying the potential stationary conditions

- From this we find that

$$m_{Z'} = g_x v_x = 5\,TeV \qquad v_x = \sqrt{2\langle \tilde{N}_3^C \rangle^2 + 8\langle \bar{\Phi} \rangle^2 + 8\langle \Phi \rangle^2} = \underline{26\,TeV}$$

from RGEs At 26 TeV

$$g_x = 0.192$$
$$y_1 = y_2 = 0.264$$
$$y_3 = 0.533$$
$$M_x = 766\,GeV$$
$$m^2_{\tilde{N}_1^C} = m^2_{\tilde{N}_1^C} = 1.83 \times 10^7\,GeV^2$$
$$m^2_{\tilde{N}_3^C} = -2.18 \times 10^6\,GeV^2$$
$$m^2_{\Phi} = 4.91 \times 10^6\,GeV^2$$
$$m^2_{\bar{\Phi}} = 2.52 \times 10^7\,GeV^2$$
$$A_1 = A_2 = 30.4\,GeV$$
$$A_3 = 36.5\,GeV$$

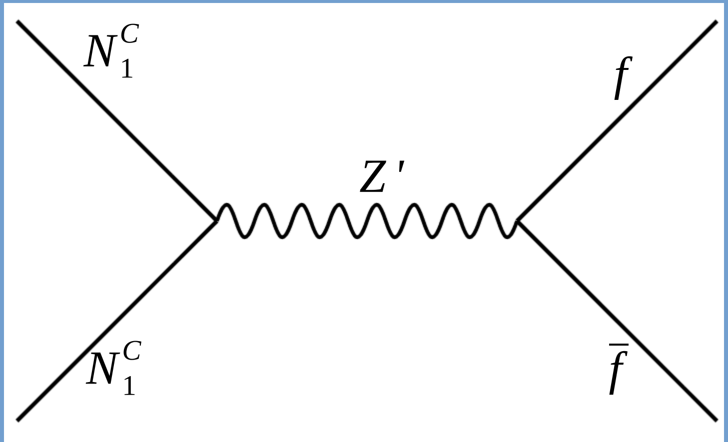
RH Neutrino DM

- Since ~~R-parity~~ by $\langle \widetilde{N}_3^C \rangle$, a RH neutrino DM candidate seems in jeopardy

- Z_2-parity remains exact, meaning it's still possible

- Since N_1^C is the lightest Z_2 odd particle, it remains stable

- Dominant process is given by s-channel Z´ exchange: $N_1^C N_1^C \rightarrow Z' \rightarrow f \bar{f}$



RH Neutrino DM

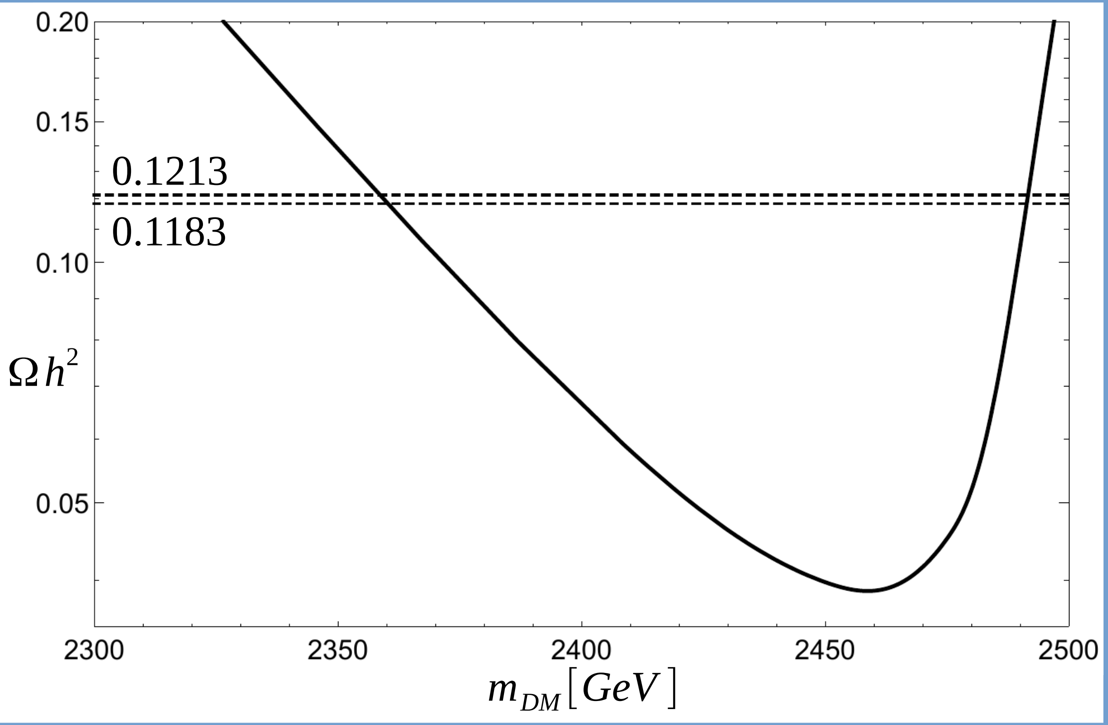
- $m_{DM} = m_{N_1^C}$ can be constrained by solving the Boltzmann eq and comparing to the relic abundance $\Omega h^2 = 0.1198 \pm 0.0015$

- For this parameter choice, all other BSM particles are $> \frac{m_{Z'}}{2}$

- The decay width of the Z´ is

$$\Gamma_{Z'} = \frac{g_x^2}{24\pi}\left[\underbrace{F(x_H)}_{\textbf{SM}} + 2\underbrace{\left(1 - 4\frac{m_{DM}^2}{m_{Z'}^2}\right)^{3/2}\theta\left(\frac{m_{Z'}^2}{m_{DM}^2} - 1\right)}_{\textbf{DM}}\right]$$

where, $F(x_H) = 13 + 16x_H + 10x_H^2$



Boltzmann parameter values:
$x_H = -0.8, g_x = 0.192, m_{Z'} = 5\,TeV$

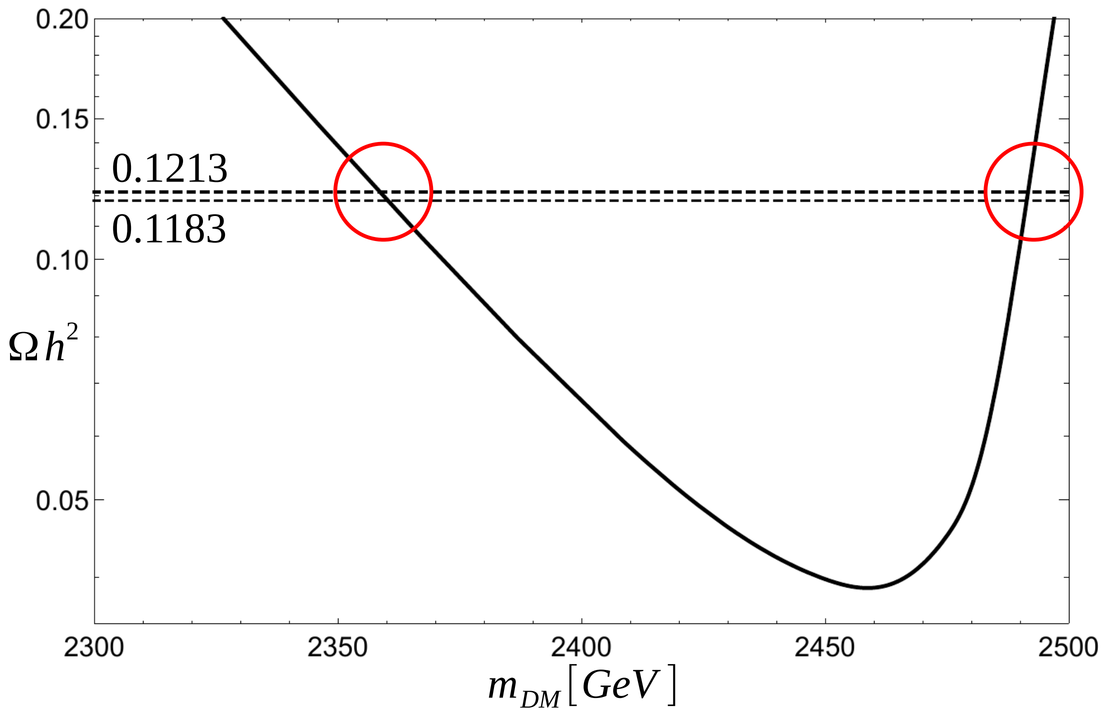
RH Neutrino DM

- Resonance enhancement is essential for obtaining the proper relic abundance

- The lower and upper DM mass bounds are found to be

$$m_{DM} = 2359\,,\underline{2492\, GeV}$$

- This upper bound is very close to the $\frac{m_{Z'}}{2}$ resonance point



Boltzmann parameter values:
$x_H = -0.8\,, g_x = 0.192\,, m_{Z'} = 5\,TeV$

LHC Constraints

- The differential cross section for the process $p\,p \to Z' + X \to l^+ l^- + X,\ l^+ l^- = e^+ e^- / \mu^+ \mu^-$ w.r.t. the dilepton mass M_{ll} is given by

$$\frac{d\sigma}{dM_{ll}} = \sum_{q,\bar{q}} \int_{M_{ll}^2/E_{LHC}^2}^{1} dx \frac{2M_{ll}}{xE_{LHC}^2} \underbrace{f_q(x, Q^2)\, f_{\bar{q}}\left(\frac{2M_{ll}^2}{xE_{LHC}^2}, Q^2\right)}_{\textbf{PDFs}} \hat{\sigma}(q\bar{q} \to Z' \to l^+ l^-)$$

$$\boxed{\alpha_X = \frac{g_X^2}{4\pi}}$$

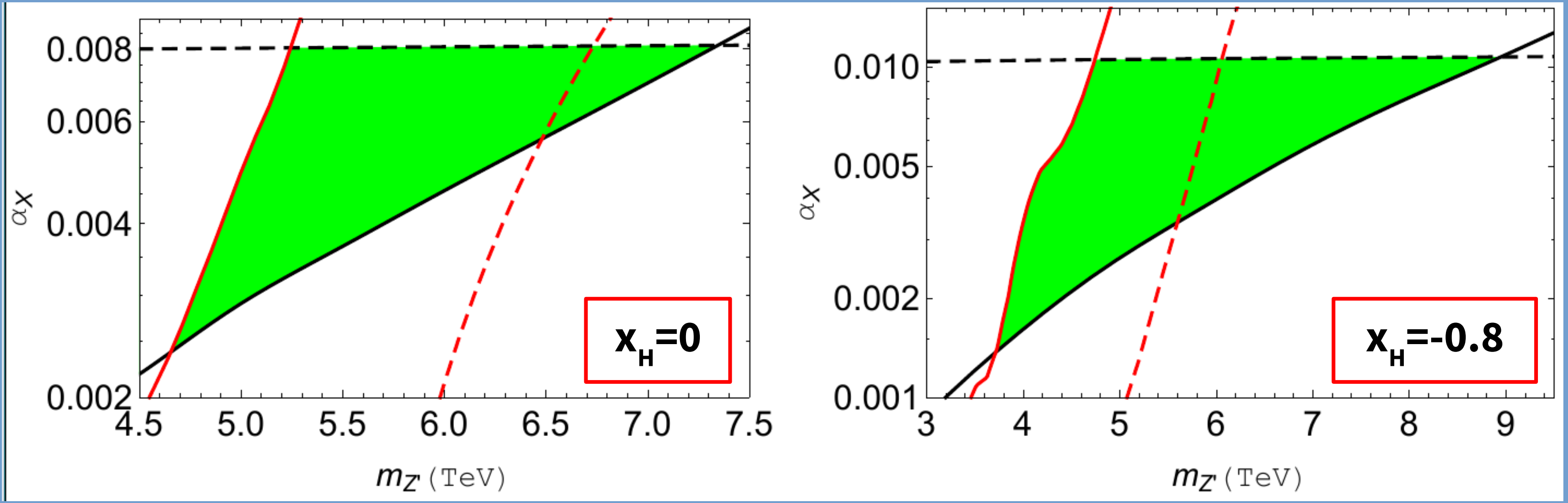
- The parton cross section is $\hat{\sigma}(q\bar{q} \to Z' \to l^+ l^-) = \frac{\pi}{1296} \alpha_x^2 \frac{M_{ll}^2}{(M_{ll}^2 - m_{Z'}^2)^2 + m_{Z'}^2 \Gamma_{Z'}^2} F_{ql}(x_H)$

where $F_{ql}(x_H)$ is dependent on the quark and lepton $U(1)_X$ charges

LHC Constraints

- The differential cross section is numerically evaluated through the s-channel Z´ boson exchange
- To satisfy the DM constraints, the DM has a mass of $\sim m_{Z'}/2$, meaning that the cross section dominantly depends on α_X, $m_{Z'}$, and x_H
- The $U(1)_X$ Z´ boson mass can be constrained by comparing to recent ATLAS constraints on the Z'_{SSM}
- Past LEP experiments also put limits on 4-Fermi interactions mediated by Z´ boson

Bringing it all together



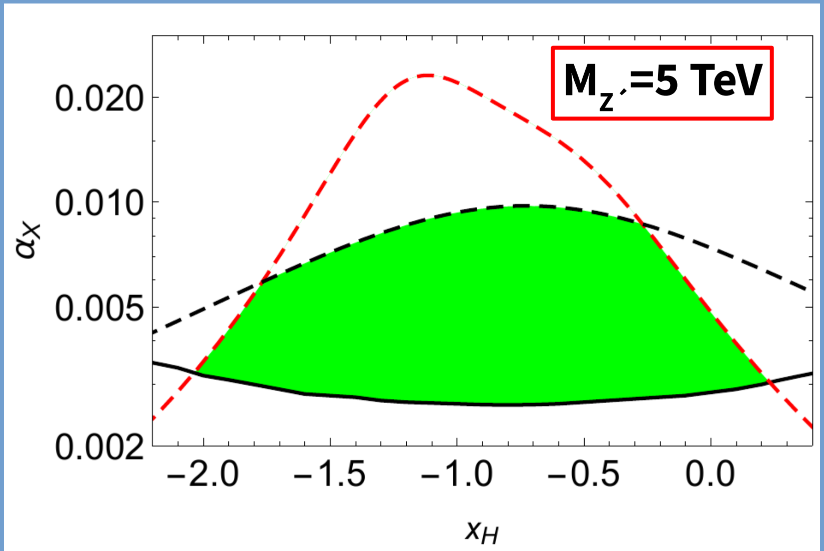
$$\alpha_X = \frac{g_X^2}{4\pi}$$

- Green bounded region in each x_H scenario shows allowed parameter space based on

LEP
LHC
DM
RGE

- x_H=0: B-L scenario
- x_H=-0.8: $U(1)_X$ SU(5) scenario

Another perspective



$$\alpha_X = \frac{g_X^2}{4\pi}$$

- Green bounded region formed by scanning over x_H values shows allowed parameter space based on

LHC

DM

RGE

- x_H=-0.8 (SU(5)) case is well within allowed region

Conclusions

- Minimal $U(1)_X$ model extends MSSM gauge symmetry and contains the following attractive features
  - Neutrino masses (**must include to avoid anomalies**)
  - Dark matter candidate (**Z_2-parity maintains N_1 stability**)
  - $U(1)_X$ symmetry radiatively broken at TeV scale
  - Combination of collider, theory, and DM constraints illustrates narrow phenomenologically viable regions (**complementarity**)

    → **$U(1)_X$ SUSY SU(5) still allowed!**