R-parity conserving U(1)x extended MSSM and its phenomenological aspects

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The model: R-parity conserving Minimal SUSY $SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_X$

	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_X$	R-parity
Q_i	3	2	$+1/6$	$x_Q = +\frac{1}{3}x_H + \frac{1}{3}x_\Psi$	−
U_i^c	3^*	1	$-2/3$	$x_U^c = -\frac{4}{3}x_H - \frac{1}{3}x_\Psi$	−
D_i^c	3^*	1	$+1/3$	$x_D^c = +\frac{2}{3}x_H - \frac{1}{3}x_\Psi$	−
L_i	3	2	$-1/2$	$x_L = -x_H - x_\Psi$	−
$N_{1,2}^c$	1	1	0	$x_N^c = +x_\Psi$	−
Ψ	1	1	0	$x_\Psi = x_\Psi$	+
E_i^c	1	1	+1	$x_E^c = +2x_H + x_\Psi$	−
H_u	1	2	$+1/2$	$x_{H_u} = +x_H$	+
H_d	1	2	$-1/2$	$x_{H_d} = -x_H$	+

□ : MSSM ■ : Additional parts of R-parity conserving Minimal SUSY $U(1)_X$ Model

$(x_H, x_\Psi) = (0,1) \Rightarrow U(1)_{B-L}$

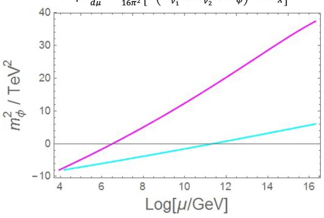
$(x_H, x_\Psi) = \left(\frac{1}{2}, 0\right) \Rightarrow U(1)_Y$

$(x_H, x_\Psi) = (-1,1) \Rightarrow U(1)_R$

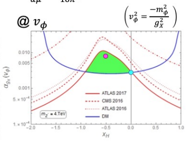
- Suppose only ϕ (scalar component of Ψ) develops a VEV.
  → $U(1)_X$ symmetry is broken, while R-parity is conserved.

Radiative $U(1)_X$ symmetry breaking

- Suppose $m_{\tilde{\nu}_i^c}^2 \gg m_\phi^2$ and MSSM sparticle mass²
  - $\mu \frac{dm_\phi^2}{d\mu} = \frac{g_X^2}{16\pi^2}\left[2\left(m_{\tilde{\nu}_1^c}^2 + m_{\tilde{\nu}_2^c}^2 + m_\phi^2\right) - 8M_X^2\right]$, $\mu \frac{dM_X}{d\mu} = \frac{g_X^2}{16\pi^2} \cdot 32 M_X$,
  - $\mu \frac{dm_{\tilde{\nu}_i^c}^2}{d\mu} = \frac{g_X^2}{16\pi^2}\left[2\left(m_{\tilde{\nu}_1^c}^2 + m_{\tilde{\nu}_2^c}^2 + m_\phi^2\right) - 8M_X^2\right]$



@ v_ϕ $\left(v_\phi^2 = \frac{-m_\phi^2}{g_X^2}\right)$

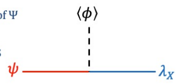


@ GUT scale
α_{g_X} = 0.019, 0.0033
M_X = 14 TeV, 7.4 TeV
m_ϕ = 6.1 TeV, 2.5 TeV
$m_{\tilde{\nu}_i^c}$ = 25 TeV, 25 TeV

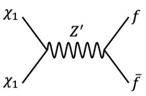
$m_{Z'} = \sqrt{2} g_X v_\phi = 4$ TeV

Dark Matter candidates

- LSP (Lightest Super Particle) neutralino is a candidate for DM as usual in the MSSM.
- New DM candidate:
  $\begin{pmatrix}\chi_1 \\ \chi_2\end{pmatrix} = \begin{pmatrix}\cos\theta & -\sin\theta \\ \sin\theta & \cos\theta\end{pmatrix}\begin{pmatrix}\psi \\ \lambda_X\end{pmatrix}$ ← fermion component of Ψ; ← $U(1)_X$ gaugino
  - Assuming that the lighter mass eigenstate χ_1 is the lightest neutralino.
    → χ_1 is DM candidate.



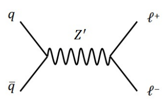
- If $m_{\chi_1} = m_{DM} \sim \frac{1}{2} m_{Z'}$, the annihilation process is efficient and the DM relic abundance is reproduced.
  - $\Omega_{DM} h^2 = 0.120 \pm 0.01$ [Planck 2018 (68% CL)]



LHC Run-2 bounds on Z' boson mass

- The dilepton production cross section:

$$\frac{d\sigma(pp \to \ell^+\ell^- X)}{dM_{\ell\ell}} = \sum_{a,b} \int_{\frac{M_{\ell\ell}^2}{E_{CM}^2}}^{1} dx_1 \frac{2M_{\ell\ell}}{x_1 E_{CM}^2} f_a(x_1, M_{\ell\ell}^2) f_b\left(\frac{M_{\ell\ell}^2}{x_1 E_{CM}^2}, M_{\ell\ell}^2\right) \hat{\sigma}(\bar{q}q \to \ell^+\ell^-)$$



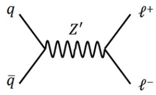
Superfields

- Chiral Superfields
  - $Q_i = \tilde{q}_i + \sqrt{2}\theta q_i + \theta^2 F_{q_i}$, $L_i = \tilde{\ell}_i + \sqrt{2}\theta \ell_i + \theta^2 F_{\ell_i}$,
  - $U_i^c = \tilde{u}_i^c + \sqrt{2}\theta u_i^c + \theta^2 F_{u_i^c}$, $N_{1,2}^c = \tilde{\nu}_{1,2}^c + \sqrt{2}\theta \nu_{1,2}^c + \theta^2 F_{\nu_{1,2}^c}$,
    $\Psi = \phi + \sqrt{2}\theta\psi + \theta^2 F_\psi$,
  - $D_i^c = \tilde{d}_i^c + \sqrt{2}\theta d_i^c + \theta^2 F_{d_i^c}$, $E_i^c = \tilde{e}_i^c + \sqrt{2}\theta e_i^c + \theta^2 F_{e_i^c}$,
  - $H_u = h_u + \sqrt{2}\theta \tilde{h}_u + \theta^2 F_{h_u}$, $H_d = h_d + \sqrt{2}\theta \tilde{h}_d + \theta^2 F_{h_d}$.
- Vector Superfields (Wess-Zumino gauge)
  - $V_3^a = \theta\sigma^\mu\bar{\theta}G_\mu^a + \bar{\theta}^2\theta\widetilde{G^a} + \theta^2\bar{\theta}\overline{\widetilde{G^a}} + \frac{1}{2}\theta^2\bar{\theta}^2 D_3^a$, $V_3 = V_3^a T^a$,
  - $V_2^i = \theta\sigma^\mu\bar{\theta}W_\mu^i + \bar{\theta}^2\theta\widetilde{W^i} + \theta^2\bar{\theta}\overline{\widetilde{W^i}} + \frac{1}{2}\theta^2\bar{\theta}^2 D_2^i$, $V_2 = V_2^i T^i$,
  - $V_1 = \theta\sigma^\mu\bar{\theta}B_\mu + \bar{\theta}^2\theta\tilde{B} + \theta^2\bar{\theta}\bar{\tilde{B}} + \frac{1}{2}\theta^2\bar{\theta}^2 D_1$,
  - $V_X = \theta\sigma^\mu\bar{\theta}B'_\mu + \bar{\theta}^2\theta\widetilde{B}' + \theta^2\bar{\theta}\overline{\widetilde{B}}' + \frac{1}{2}\theta^2\bar{\theta}^2 D_X$.

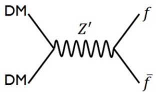
LHC physics and DM physics

For fixed X_H and $m_{Z'}$

- LCH
  - g_X Upper Bound
    - LHC Run-2



- Z' portal DM
  - g_X Lower Bound
    - DM Relic Abundance



⇒ Complementarity between
DM physics and **LHC physics**

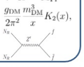
DM relic abundance [Non-equilibrium system]

Boltzmann Equation: 【 yield : $Y = \frac{n}{s}$ 】

$$\frac{dY}{dx} = -\frac{xs\langle\sigma v\rangle}{H(m_{DM})}(Y^2 - Y_{EQ}^2)$$

$$x = \frac{m_{DM}}{T}, \quad s = \frac{2\pi^2}{45} g_* \frac{m_{DM}^3}{x^3}, \quad H(m_{DM}) = \sqrt{\frac{4\pi^3}{45} g_*} \frac{m_{DM}^2}{M_{Pl}}, \quad sY_{EQ} = \frac{g_{DM}}{2\pi^2} \frac{m_{DM}^3}{x} K_2(x),$$

$\langle\sigma v\rangle$ =



DM relic abundance:

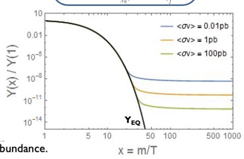
$$\Omega_{DM} h^2 = \frac{m_{DM} s_0 Y(\infty)}{\rho_c / h^2}$$

||

Observed DM relic abundance:

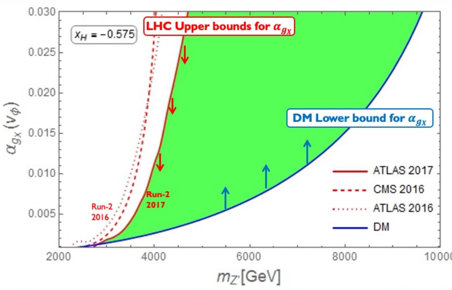
$$\Omega_{DM} h^2 = 0.120 \pm 0.01$$

Planck 2018 (68% CL)



- ⟨σv⟩∼1pb leads to the right DM relic abundance.

Z' boson search ($x_H = -0.575$, g_X, v_ϕ)



- Remark: $m_{Z'} = \sqrt{2} g_X v_\phi$

Properties of R-parity conserving Minimal SUSY $U(1)_X$ Model

- $U(1)_X$ symmetry is broken by VEV of R-parity even scalar ϕ (scalar component of Ψ).
- R-parity is still conserved.
- Two light neutrinos are Dirac particles.

$$W_{Yukawa} \supset \sum_{i=1}^{2}\sum_{j=1}^{3} Y_\nu^{ij} N_i^c H_u L_j$$

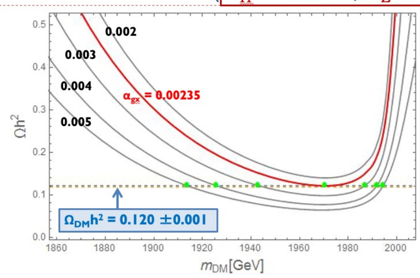
- 3 left-handed neutrinos + 2 right-handed neutrinos
  → 1 massless Wyle + 2 massive Dirac neutrinos

Previous research:
"Minimal Gauged $U(1)_{B-L}$ Model with Spontaneous R Parity Violation," V.Barger, P.Perez, and S.Spinner, Phys. Rev. Lett. 102, 181802 (2009), in which $U(1)_{B-L}$ and R-parity are both broken.

Dark Matter and LHC Run-2 (Apr. 2017)

- R-parity Conserving Minimal SUSY $U(1)_X$ Model,
  - 3 free parameters (x_H, g_X, v_ϕ)
    - x_H : Charge of MSSM Higgs ($x_H = 0$ for Minimal SUSY B-L model)
    - g_X : new $U(1)_X$ gauge coupling
    - v_ϕ : VEV of R-parity even scalar ϕ (scalar component of Ψ)
    - □ $m_{Z'}$ (Z' boson mass) ∼ 2 m_{DM} (Dark matter mass)
- Phenomenological constraints
  - Dark Matter Relic Abundance constraint
  - LHC Run-2 (Apr. 2017) bounds (Z' boson search)

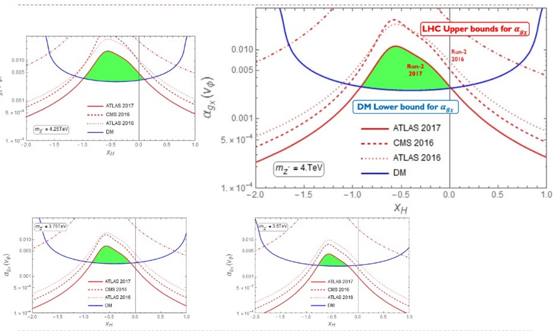
The DM relic abundance for various α_{g_X} ($x_H = -0.575$, $m_{Z'}$=4TeV)



α_{g_X} = 0.00235 is a lower bound from the DM relic abundance constraint.

- I.) Fixed X_H and $m_{Z'}$

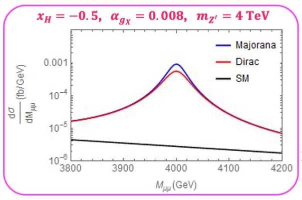
Z' boson search (x_H, g_X, $m_{Z'}$=4.25, 4, 3.75, 3.5TeV)



- I.) For fixed X_H and $m_{Z'}$, α_{g_X} has upper **(red)** and lower **(blue)** bounds.

Dirac neutrinos at HL-LHC

- 1 massless Wyle + 2 massive Dirac neutrinos
  - 3 light Majorana neutrinos + 3 heavy Majorana nuetrinos



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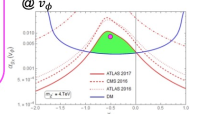
@ v_ϕ



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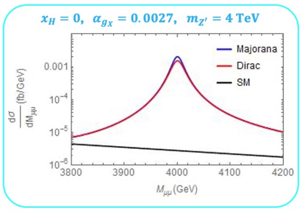
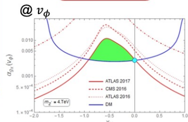


@ GUT scale
α_{g_X} = 0.0033
M_X = 7.4 TeV
m_ϕ = 2.5 TeV
$m_{\tilde{\nu}_i^c}$ = 25 TeV

@ v_ϕ



Summary

- We have considered R-parity conserving Minimal SUSY $U(1)_X$ Model.
- 3 right-handed neutrinos are introduced to make the model free from all gauge & gravitational anomalies.
- We assign an even R-parity to one right-handed chiral superfield (Ψ).
- R-parity conserved and LSP neutralino is a candidate of DM.
- A mixture of the R-parity odd right-handed neutrino (ψ) and $U(1)_X$ gaugino (λ_X) is a new candidate of DM.
- Neutrinos are Dirac particles because of R-parity conservation.
- We have investigated Phenomenological constraints.
  - Dark Matter Relic Abundance constraint
  - LHC Run-2 (Apr. 2017) bounds (Z' boson search)
  - Dirac neutrinos at HL-LHC