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Minimal SUSY $\mathrm{U(1)}_X$ model with an *R*-parity conservation

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    (heterotic strings [hep-th/0512177; arXiv:0911.1569])
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- DM physics and LHC physics
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The model: $\boldsymbol{R}$-parity conserving Minimal SUSY $SU(3)_C \times SU(2)_L \times U(1)_Y \times \mathbf{U(1)}_X$

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

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

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

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

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

- Suppose only $\boldsymbol{\phi}$ (scalar component of $\boldsymbol{\Psi}$) develops a VEV.
  - $\rightarrow$ $\mathbf{U(1)}_X$ symmetry is broken, while $\boldsymbol{R}$-parity is conserved.

Superfields

- Chiral Superfields
  - $Q_i = \tilde{q}_i + \sqrt{2}\theta q_i + \theta^2 F_{q_i}$,
  - $U_i^c = \tilde{u}_i^c + \sqrt{2}\theta u_i^c + \theta^2 F_{u_i^c}$,
  - $D_i^c = \tilde{d}_i^c + \sqrt{2}\theta d_i^c + \theta^2 F_{d_i^c}$,
  - $H_u = h_u + \sqrt{2}\theta \tilde{h}_u + \theta^2 F_{h_u}$,

  $L_i = \tilde{\ell}_i + \sqrt{2}\theta \ell_i + \theta^2 F_{\ell_i}$,

  $N_{1,2}^c = \tilde{n}_{1,2}^c + \sqrt{2}\theta n_{1,2}^c + \theta^2 F_{\nu_{1,2}^c}$,

  $\Psi = \phi + \sqrt{2}\theta \psi + \theta^2 F_\psi$,

  $E_i^c = \tilde{e}_i^c + \sqrt{2}\theta e_i^c + \theta^2 F_{e_i^c}$,

  $H_d = h_d + \sqrt{2}\theta \tilde{h}_d + \theta^2 F_{h_d}$.

- Vector Superfields (Wess-Zumino gauge)
  - $V_3^a = \theta\sigma^\mu\bar{\theta} G_\mu^a + \bar{\theta}^2\theta\widetilde{G^a} + \theta^2\bar{\theta}\overline{\widetilde{G^a}} + \frac{1}{2}\theta^2\bar{\theta}^2 D_3^a$, $\quad V_3 = V_3^a T^a$,
  - $V_2^i = \theta\sigma^\mu\bar{\theta} W_\mu^i + \bar{\theta}^2\theta\widetilde{W^i} + \theta^2\bar{\theta}\overline{\widetilde{W^i}} + \frac{1}{2}\theta^2\bar{\theta}^2 D_2^i$, $\quad V_2 = V_2^i T^i$,
  - $V_1 = \theta\sigma^\mu\bar{\theta} B_\mu + \bar{\theta}^2\theta\tilde{B} + \theta^2\bar{\theta}\bar{\tilde{B}} + \frac{1}{2}\theta^2\bar{\theta}^2 D_1$,
  - $V_X = \theta\sigma^\mu\bar{\theta} B'_\mu + \bar{\theta}^2\theta\widetilde{B}' + \theta^2\bar{\theta}\bar{\widetilde{B}}' + \frac{1}{2}\theta^2\bar{\theta}^2 D_X$.

Properties of $\boldsymbol{R}$-parity conserving Minimal SUSY $\mathbf{U(1)}_X$ Model

- $\mathbf{U(1)}_X$ symmetry is broken by VEV of $\boldsymbol{R}$-parity even scalar $\boldsymbol{\phi}$ (scalar component of $\boldsymbol{\Psi}$).

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

- $\boldsymbol{R}$-parity is still conserved.

- Yukawa coupling with $\boldsymbol{\Psi}$ is forbidden by its R-parity even.

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

  - 3 left-handed neutrinos + 2 right-handed neutrinos
    $\longrightarrow$ 1 massless Wyle + 2 massive Dirac neutrinos
  - No mixing of fermion component of $\boldsymbol{\Psi}$ with Higginos and MSSM gauginos.

Radiative $\mathbf{U(1)}_X$ symmetry breaking

- Suppose $m^2_{\tilde{n}^c_i} \gg m^2_\phi$, and MSSM sparticle mass^2
  - $\mu \frac{dm^2_\phi}{d\mu} = \frac{g^2_X}{16\pi^2}\left[2\left(m^2_{\tilde{n}^c_1} + m^2_{\tilde{n}^c_2} + m^2_\phi\right) - 8M^2_X\right]$,
  - $\mu \frac{dm^2_{\tilde{n}^c_i}}{d\mu} = \frac{g^2_X}{16\pi^2}\left[2\left(m^2_{\tilde{n}^c_1} + m^2_{\tilde{n}^c_2} + m^2_\phi\right) - 8M^2_X\right]$

$$\mu \frac{dM_X}{d\mu} = \frac{g^2_X}{16\pi^2} \cdot 32M_X ,$$

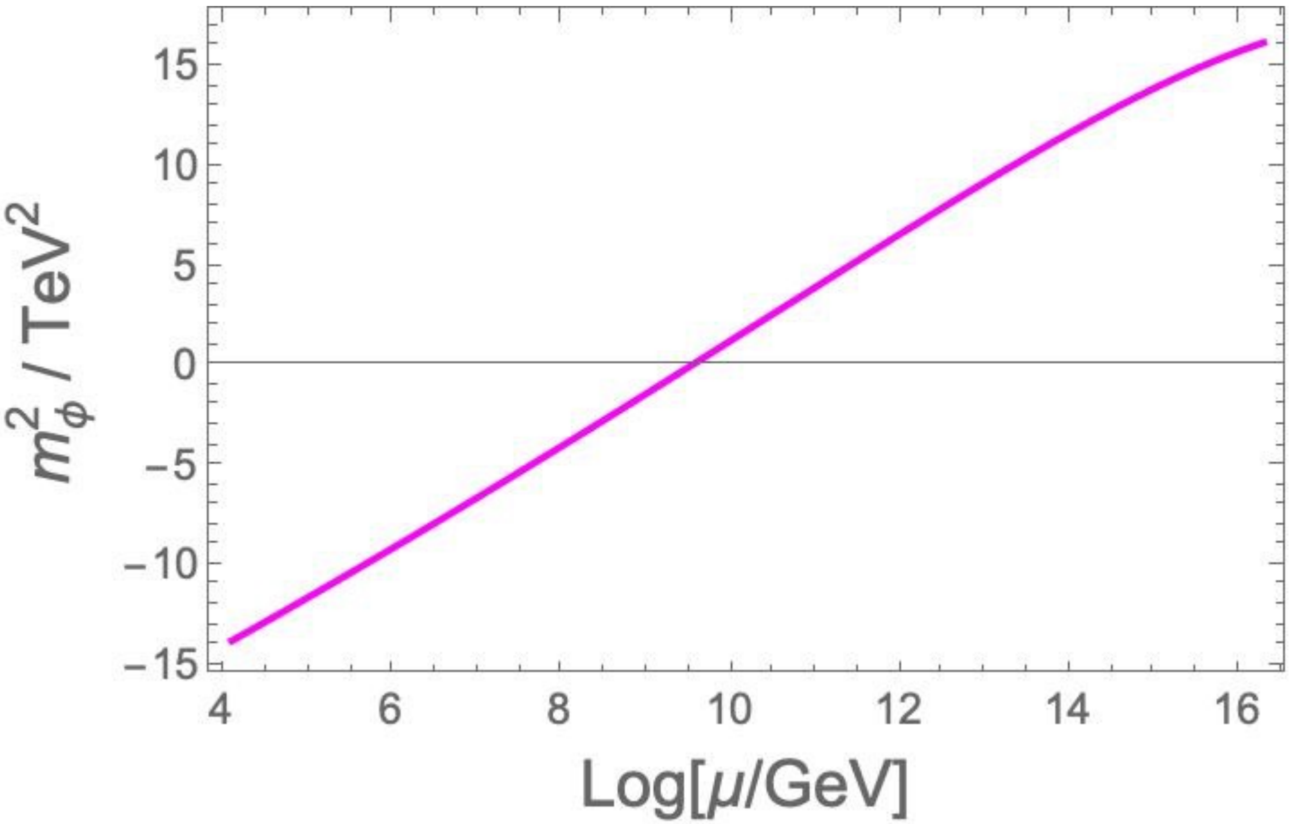
@ GUT scale

$\alpha_{g_X} = 0.014$

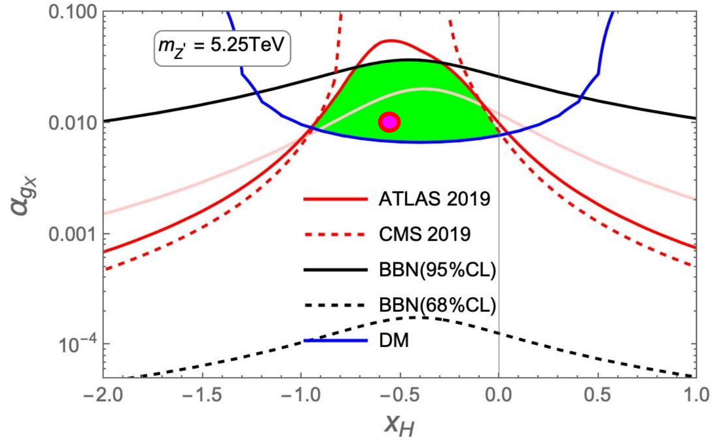
$M_X = 16$ TeV

$m_\phi = 4.0$ TeV

$m_{\tilde{n}^c_i} = 25$ TeV



@ v_ϕ $\left(v^2_\phi = \frac{-m^2_\phi}{g^2_X}\right)$

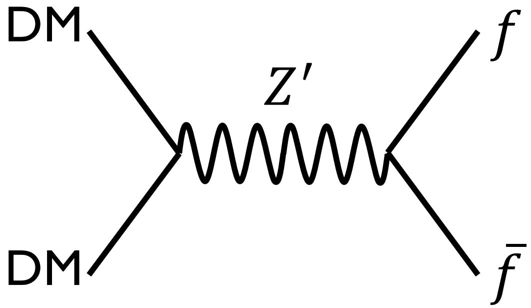


$$m_{Z'} = \sqrt{2}g_X v_\phi = 4.25 \text{ TeV}$$

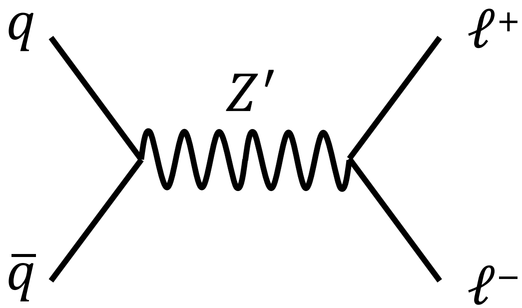
DM physics and **LHC physics**

- 3 free parameters $(x_H, g_X, m_{Z'})$

For fixed x_H and $m_{Z'}$



- Z' portal DM
  - g_x Lower Bound
    - DM Relic Abundance
    - $\Omega_{\rm DM}h^2 = 0.120 \pm 0.01$ [Planck 2018 (68% CL)]



- LCH
  - g_x Upper Bound
    - LHC Run-2

$\Rightarrow$ Complementarity between

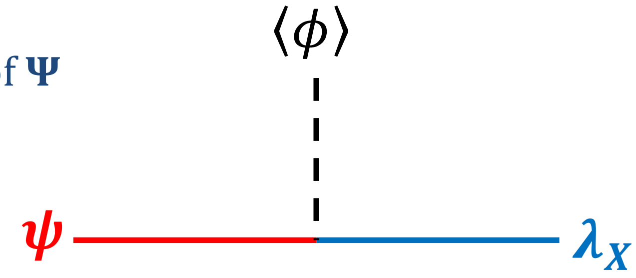
DM physics and **LHC physics**

Dark Matter candidates

- LSP (Lightest Super Particle) neutralino is a candidate for DM as usual in the MSSM.
- New DM candidate:

$$\begin{pmatrix}\chi_1\\ \chi_2\end{pmatrix} = \begin{pmatrix}\cos\theta & -\sin\theta\\ \sin\theta & \cos\theta\end{pmatrix}\begin{pmatrix}\psi\\ \lambda_X\end{pmatrix}$$

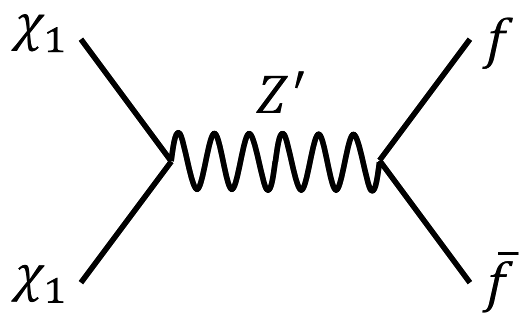
← fermion conponent of Ψ
← $U(1)_X$ gaugino



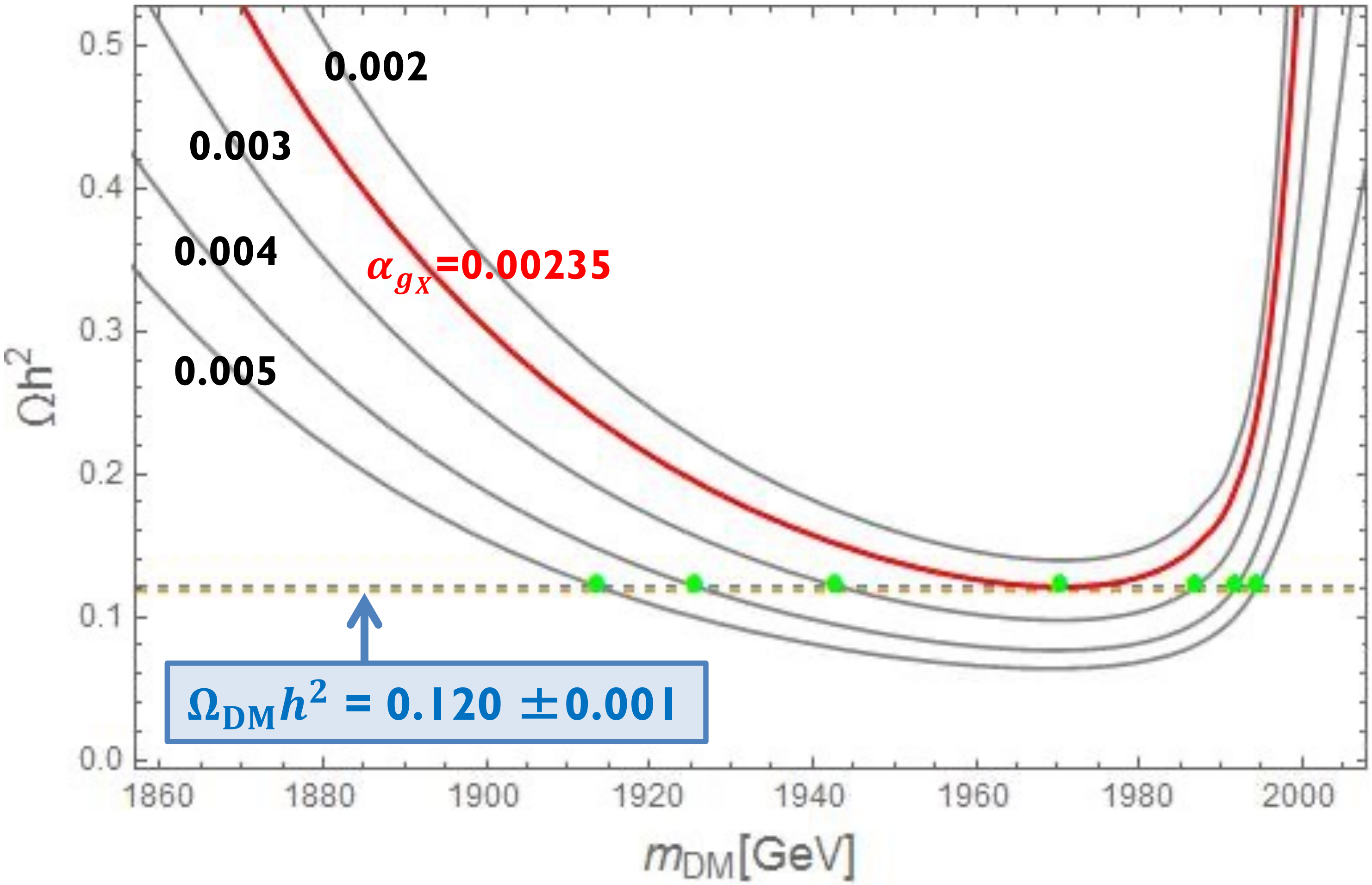
  - Assuming that the lighter mass eigenstate χ_1 is the lightest neutralino.

    → χ_1 is DM candidate.

- If $m_{\chi_1} = m_{\rm DM} \sim \frac{1}{2} m_{Z'}$, the annihilation process is efficient and the DM relic abundance is reproduced.



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

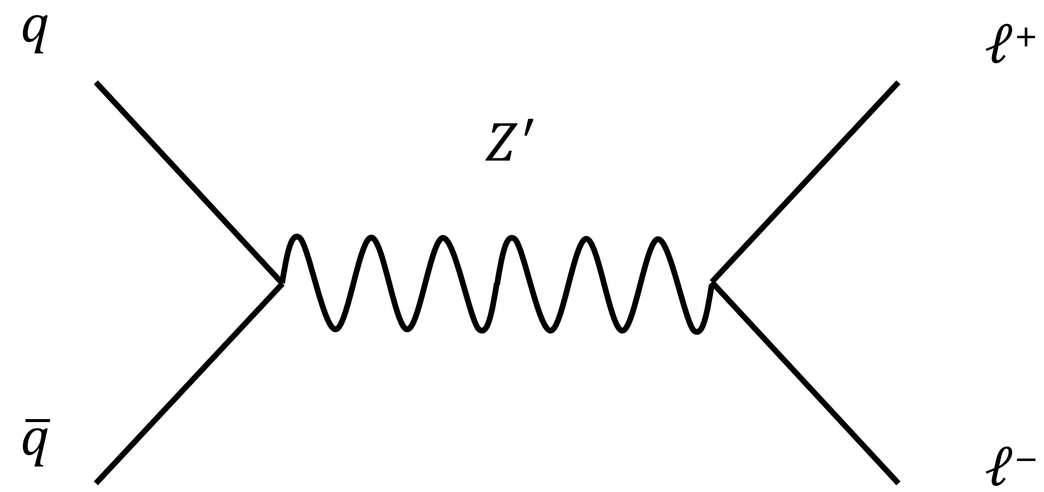


α_{g_X}= 0.00235 is a lower bound from the DM relic abundance constraint.

- 1.) Fixed x_H and $m_{Z'}$

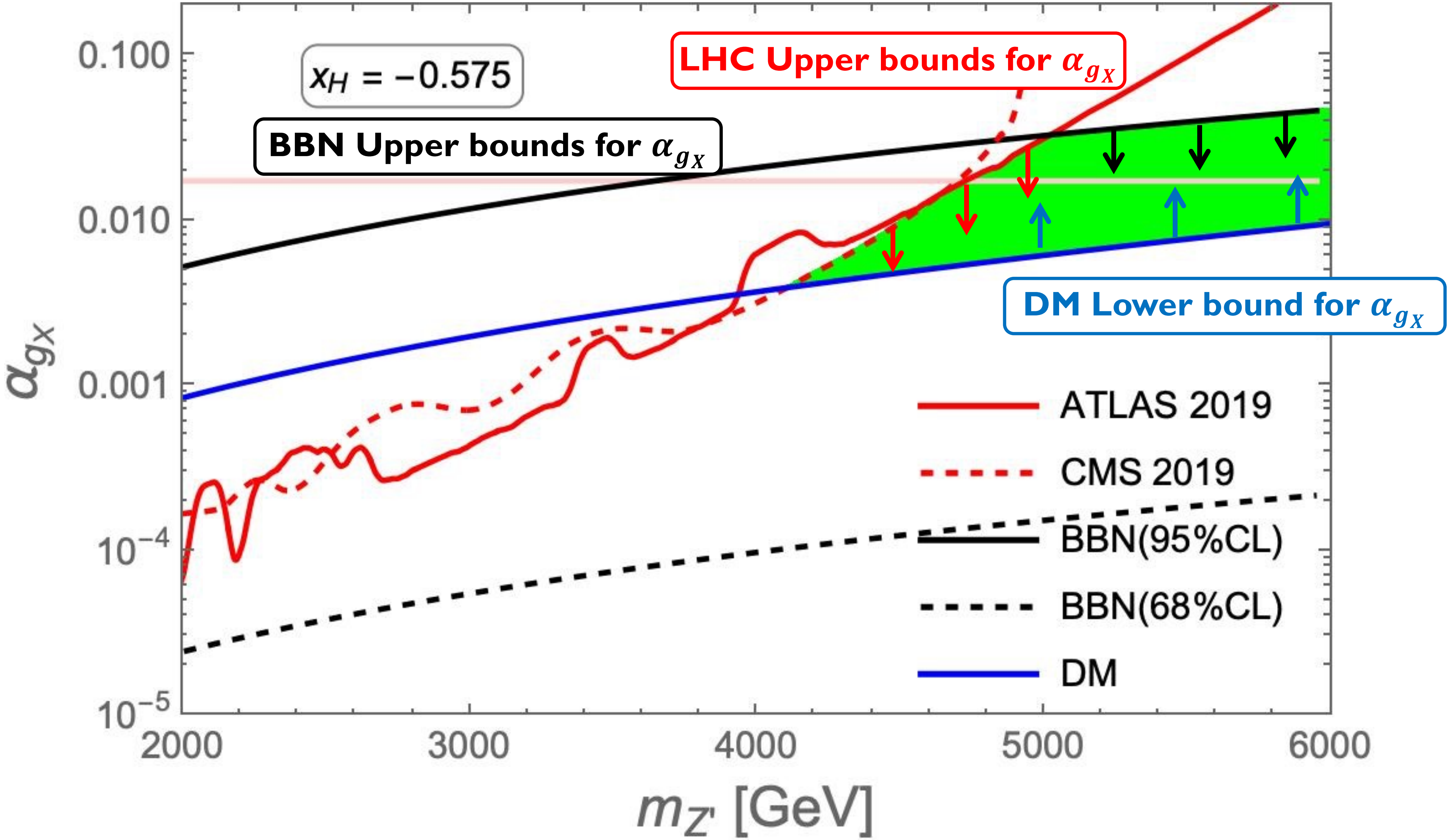
LHC Run-2 bounds on Z' boson mass

- The dilepton production cross section:



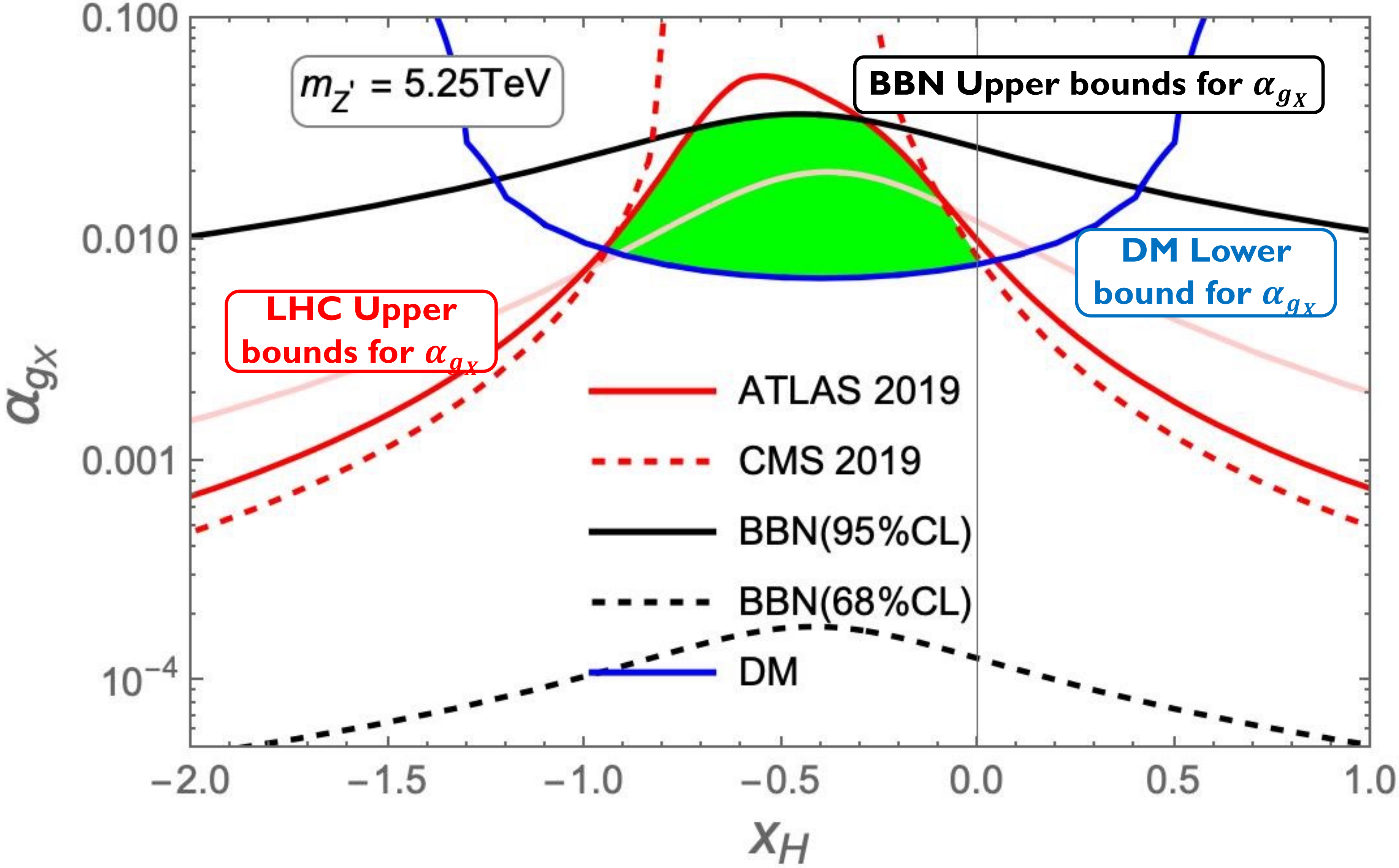
$$\frac{d\sigma(pp \to \ell^+\ell^- X)}{dM_{\ell\ell}} = \sum_{a,b} \int_{\frac{M_{\ell\ell}^2}{E_{\text{CM}}^2}}^{1} dx_1 \frac{2M_{\ell\ell}}{x_1 E_{\text{CM}}^2} f_a\left(x_1, M_{\ell\ell}^2\right) f_b\left(\frac{M_{\ell\ell}^2}{x_1 E_{\text{CM}}^2}, M_{\ell\ell}^2\right) \hat{\sigma}(\bar{q}q \to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

Z' boson search ($x_H = -0.575$, g_X, $m_{Z'}$)



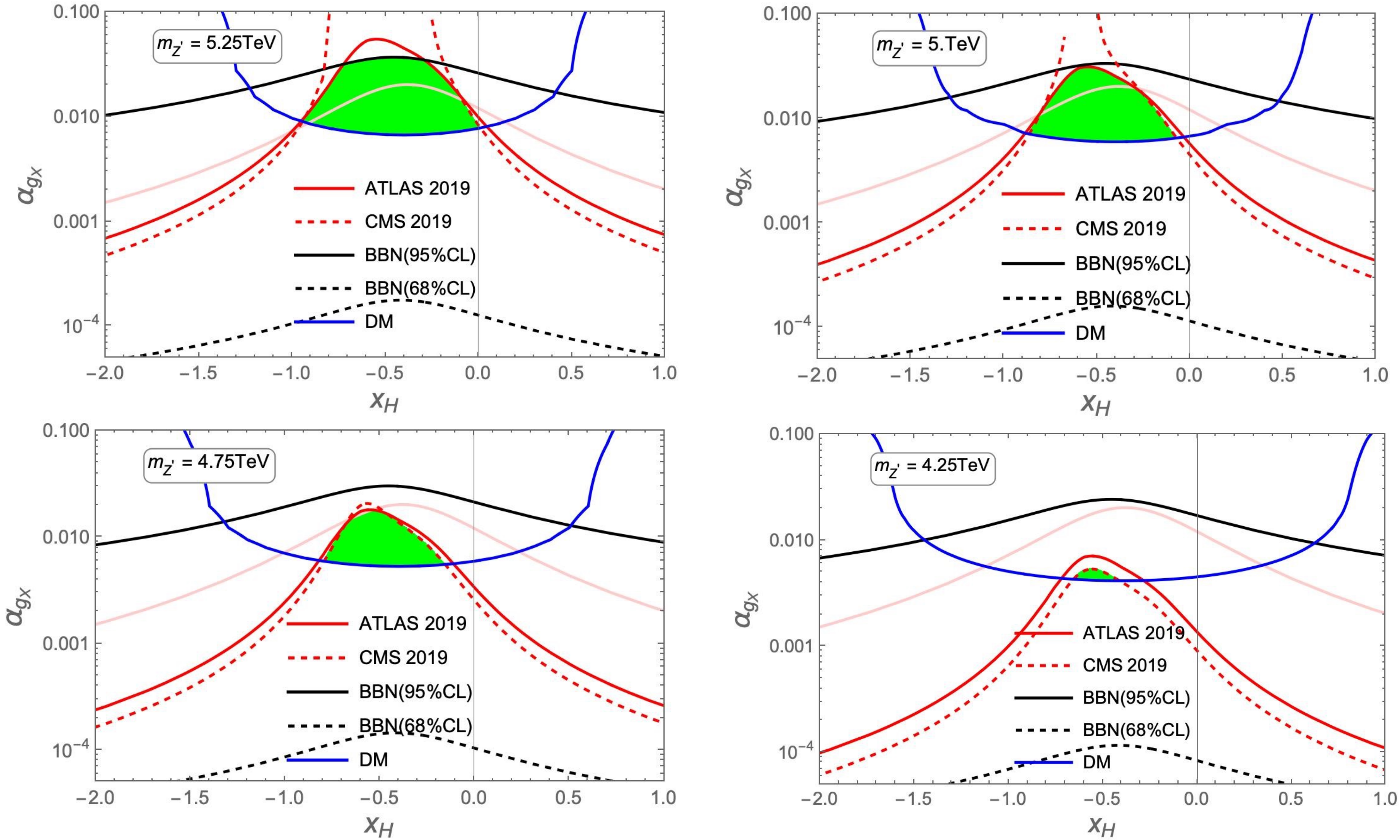
Remark: $m_{Z'} = \sqrt{2} g_X v_\phi$

Z' boson search (x_H, g_X, $m_{Z'} = 5.25$ TeV)



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

Z' boson search $(x_H, g_X, m_{Z'} = 5.25, 5, 4.75, 4.25\ \text{TeV})$

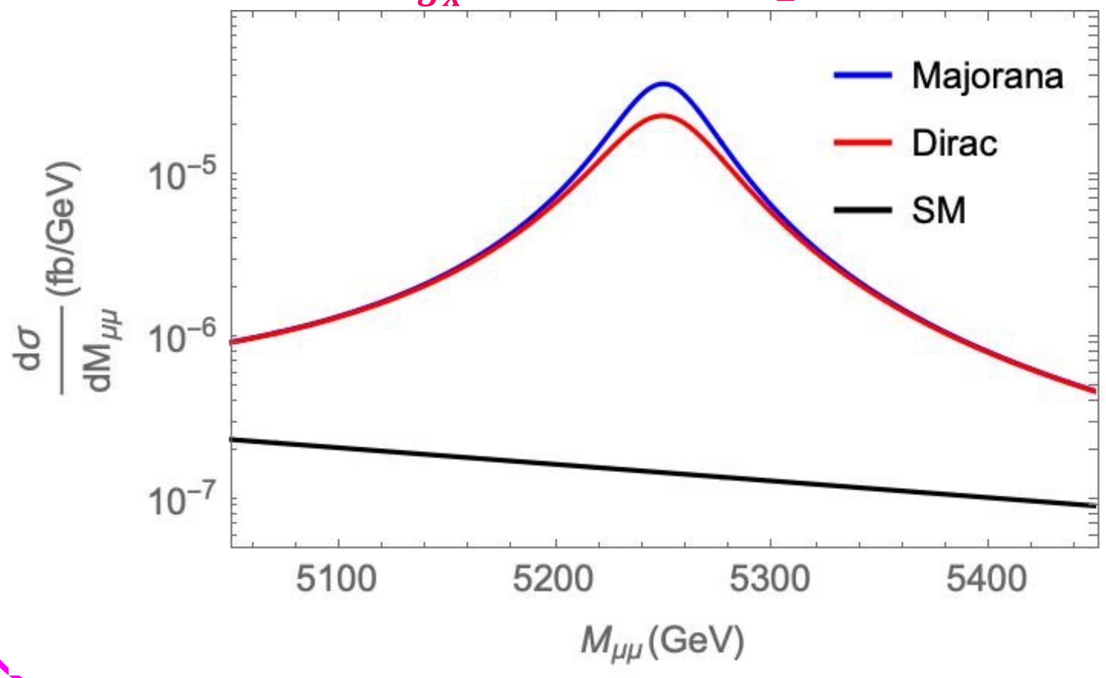


- 1.) For fixed x_H and $m_{Z'}$, α_{g_X} has upper **(red)** **(black)** and lower **(blue)** bounds.

Dirac neutrinos at LHC

- Our model: 1 massless Wyle + 2 massive Dirac neutrinos
- ex.) 3 light Majorana neutrinos + 3 heavy Majorana neutrinos

$x_H = -0.575, \ \alpha_{g_X} = 0.007, \ m_{Z'} = 5.25\ \mathrm{TeV}$



@ GUT scale

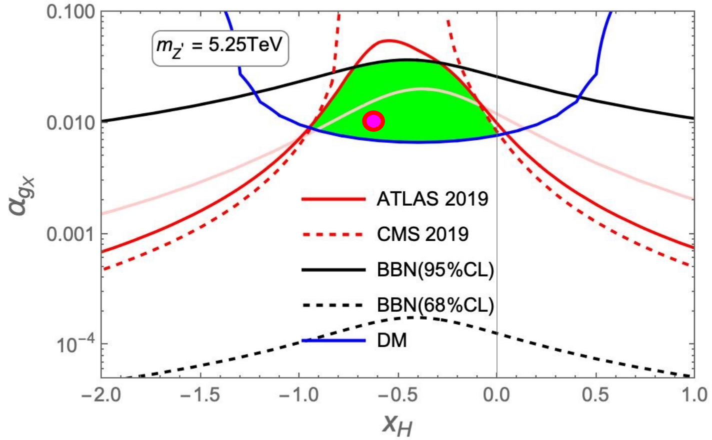
$\alpha_{g_X} = 0.014$

$M_X = 16\ \mathrm{TeV}$

$m_\phi = 4.0\ \mathrm{TeV}$

$m_{\tilde{n}_i^c} = 25\ \mathrm{TeV}$

@ v_ϕ



Summary

- We have considered $\boldsymbol{R}$-parity conserving Minimal SUSY $\mathbf{U(1)}_X$ Model.

- 3 right-handed neutrinos are introduced to make the model free from all gauge & gravitational anomalies.
- We assign an even $\boldsymbol{R}$-parity to one right-handed chiral superfield ($\boldsymbol{\Psi}$).

- $\boldsymbol{R}$-parity conserved and LSP neutralino is a candidate of DM.
- A mixture of the $\boldsymbol{R}$-parity odd right-handed neutrino ($\boldsymbol{\psi}$) and $\mathbf{U(1)}_X$ gaugino ($\boldsymbol{\lambda_X}$) is a new candidate of DM.
- Neutrinos are Dirac particles because of $\boldsymbol{R}$-parity conservation.

- We have investigated Phenomenological constraints.
  - Dark Matter Relic Abundance constraint
  - LHC Run-2 (ATLAS 2019, CMS 2019) bounds (Z' boson search)
  - BBN bounds
  - Dirac neutrinos at HL-LHC

THE END

Thank you very much

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