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

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The model: $\boldsymbol{R}$-parity conserving Minimal SUSY $\mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \times \mathbf{U(1)}_X$

	$\mathbf{SU(3)}_C$	$\mathbf{SU(2)}_L$	$\mathbf{U(1)}_Y$	$\mathbf{U(1)}_X$	$\boldsymbol{R}$-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

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

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

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

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

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

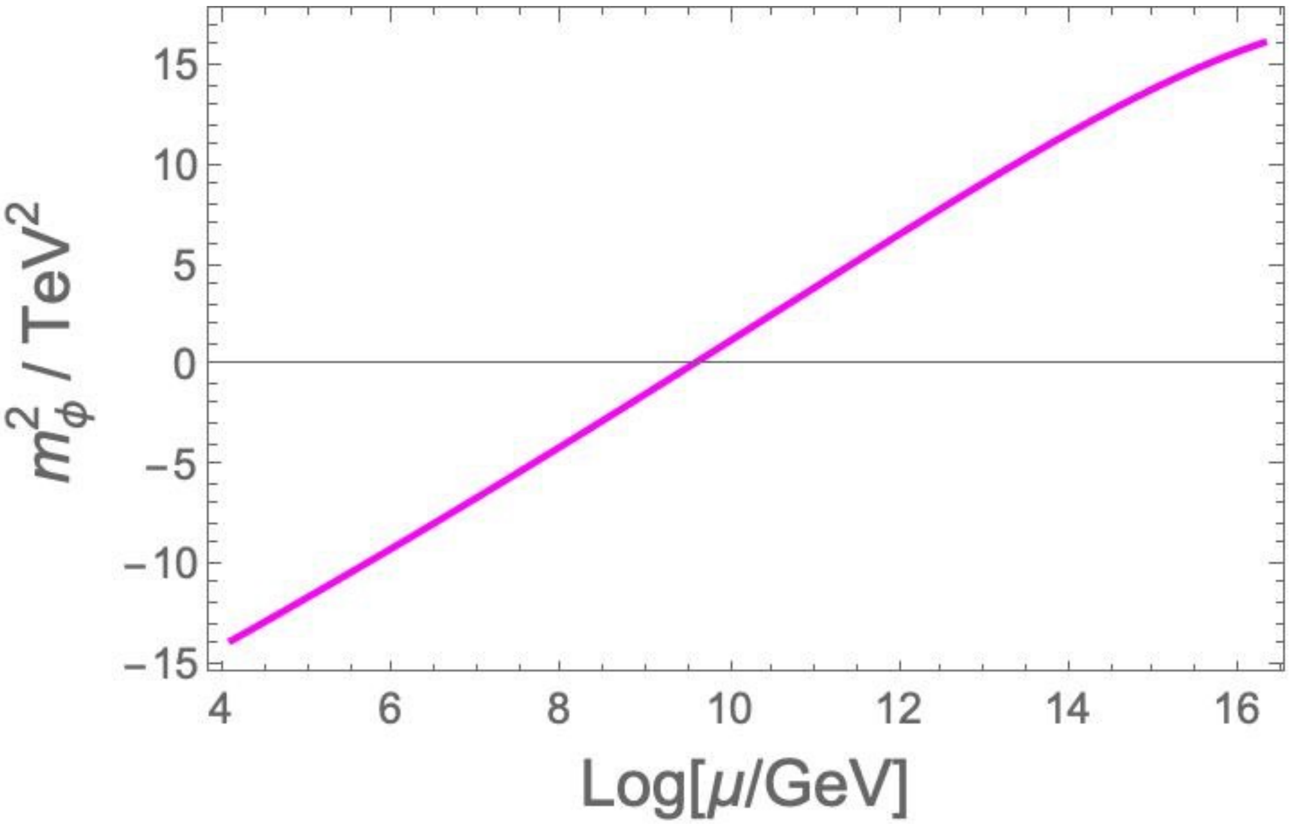
$\rightarrow$ 1 massless Wyle + 2 massive Dirac neutrinos

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.

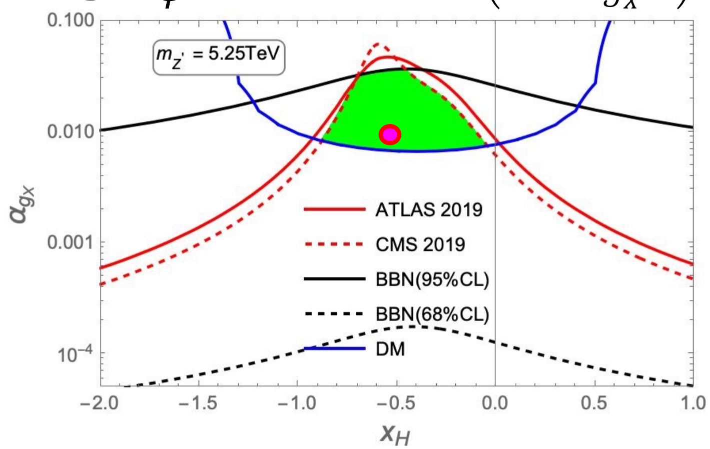
Radiative $\mathbf{U(1)}_X$ symmetry breaking

- Suppose $m^2_{\tilde{N}^c_i} \gg m^2_\phi$ and MSSM sparticle mass^2
  - $\mu \frac{dm^2_\phi}{d\mu} = \frac{g_X^2}{16\pi^2}\left[2\left(m^2_{\tilde{N}^c_1} + m^2_{\tilde{N}^c_2} + m^2_\phi\right) - 8M_X^2\right],$ $\mu \frac{dM_X}{d\mu} = \frac{g_X^2}{16\pi^2} \cdot 32 M_X$,
  - $\mu \frac{dm^2_{\tilde{N}^c_i}}{d\mu} = \frac{g_X^2}{16\pi^2}\left[2\left(m^2_{\tilde{N}^c_1} + m^2_{\tilde{N}^c_2} + m^2_\phi\right) - 8M_X^2\right]$



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



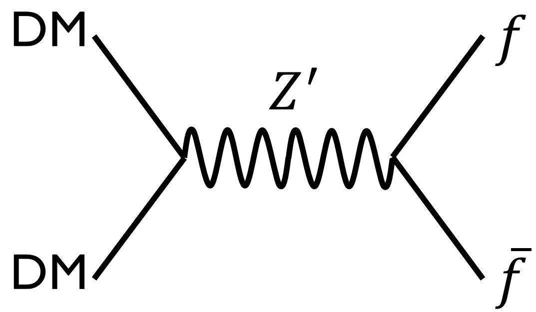
$m_{Z'} = \sqrt{2} g_X v_\phi = 4.25$ TeV

DM physics and **LHC physics**

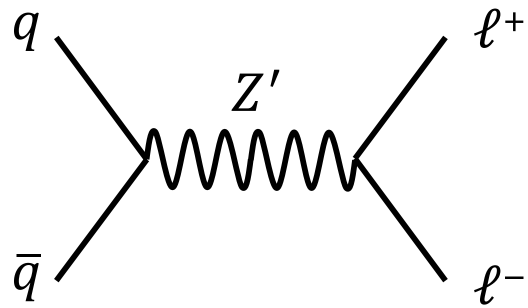
- 3 free parameters $(x_H, g_X, m_{Z'})$

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



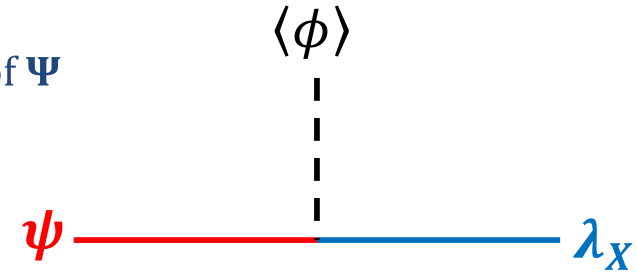
$\Rightarrow$ Complementarity between

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:

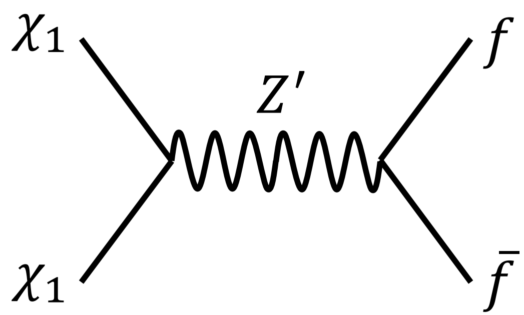
$$\begin{pmatrix}\chi_1\\ \chi_2\end{pmatrix} = \begin{pmatrix}\cos\theta & -\sin\theta\\ \sin\theta & \cos\theta\end{pmatrix}\begin{pmatrix}\boldsymbol{\psi}\\ \boldsymbol{\lambda_X}\end{pmatrix} \begin{matrix}\leftarrow \text{ fermion conponent of } \boldsymbol{\Psi}\\ \leftarrow \ \mathbf{U(1)}_X \text{ gaugino}\end{matrix}$$



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

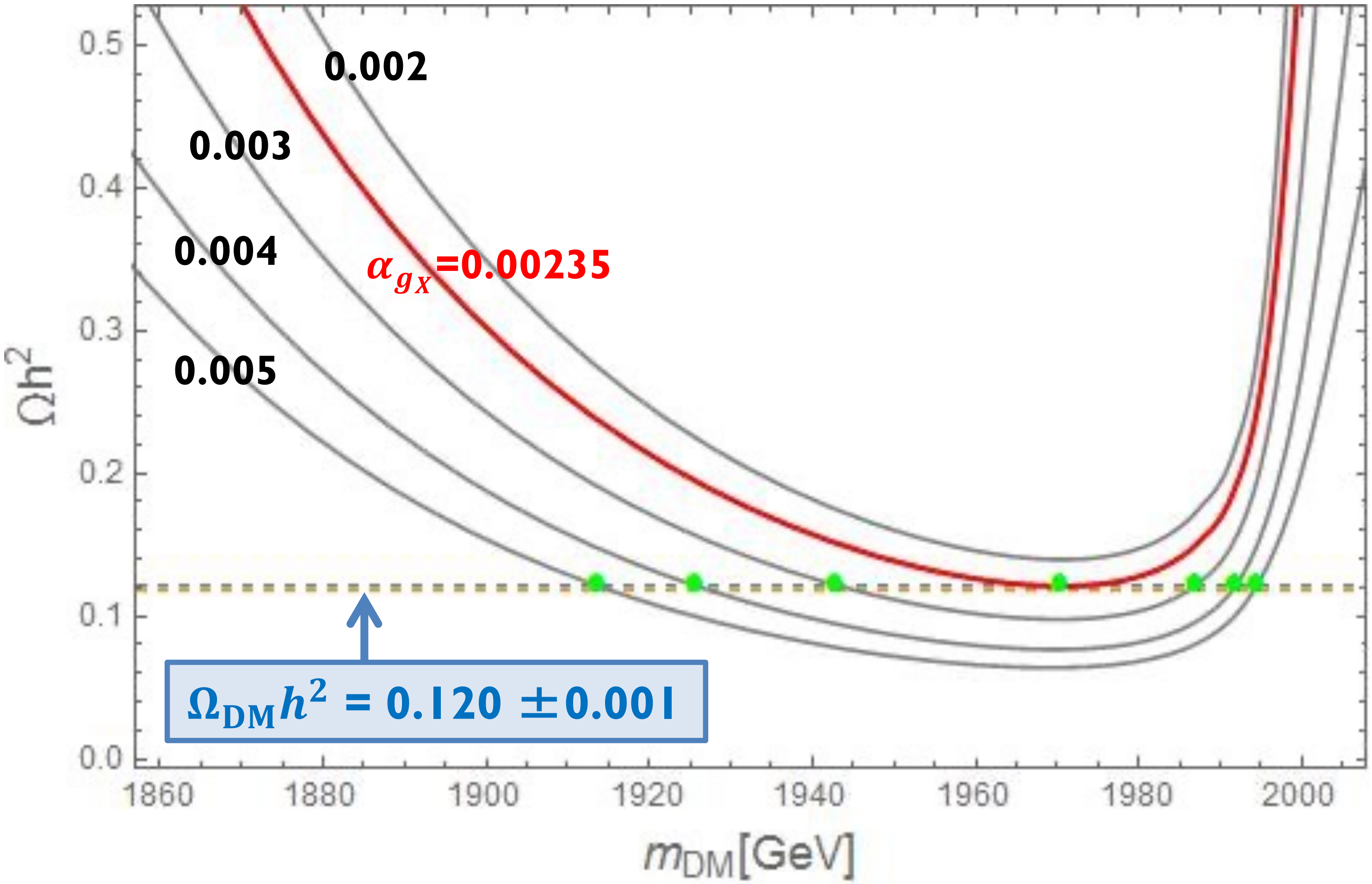
    $\rightarrow$ χ_1 is DM candidate.

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



The DM relic abundance for various α_{g_X}

$(\boxed{x_H = -0.575,\ m_{Z'} = 4\ \mathrm{TeV}})$



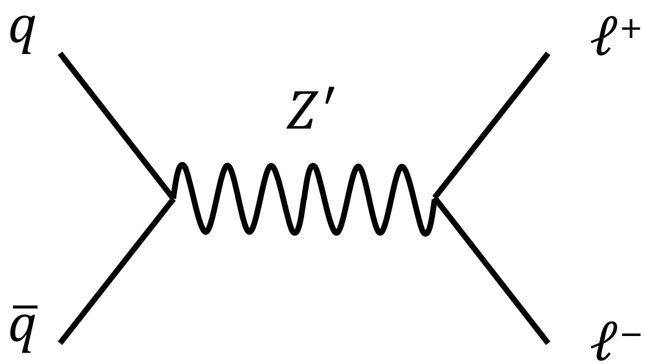
α_{g_X}= 0.00235 is a lower bound from the DM relic abundance constraint.

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

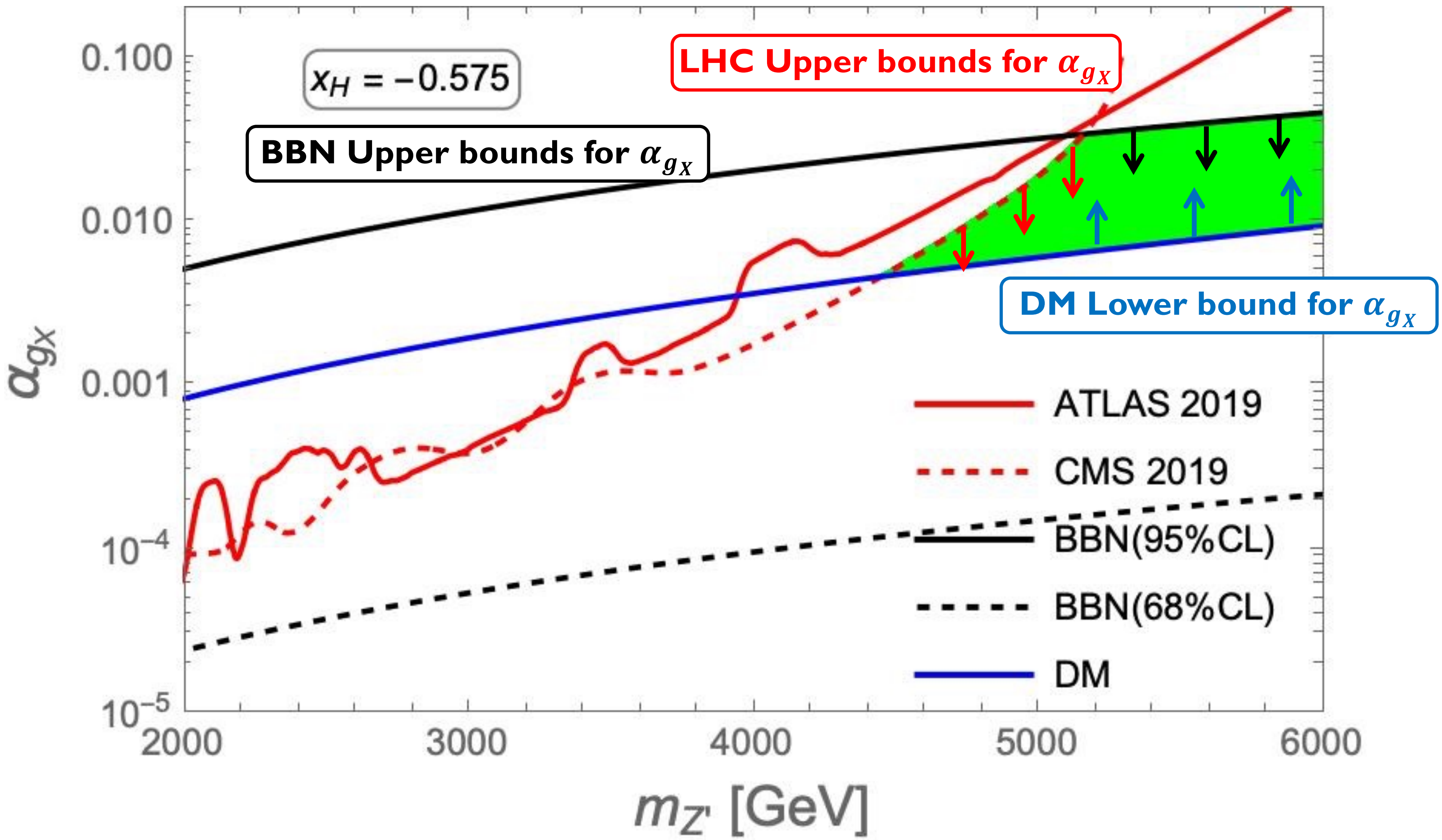
LHC Run-2 bounds on Z' boson mass

- The dilepton production cross section:

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

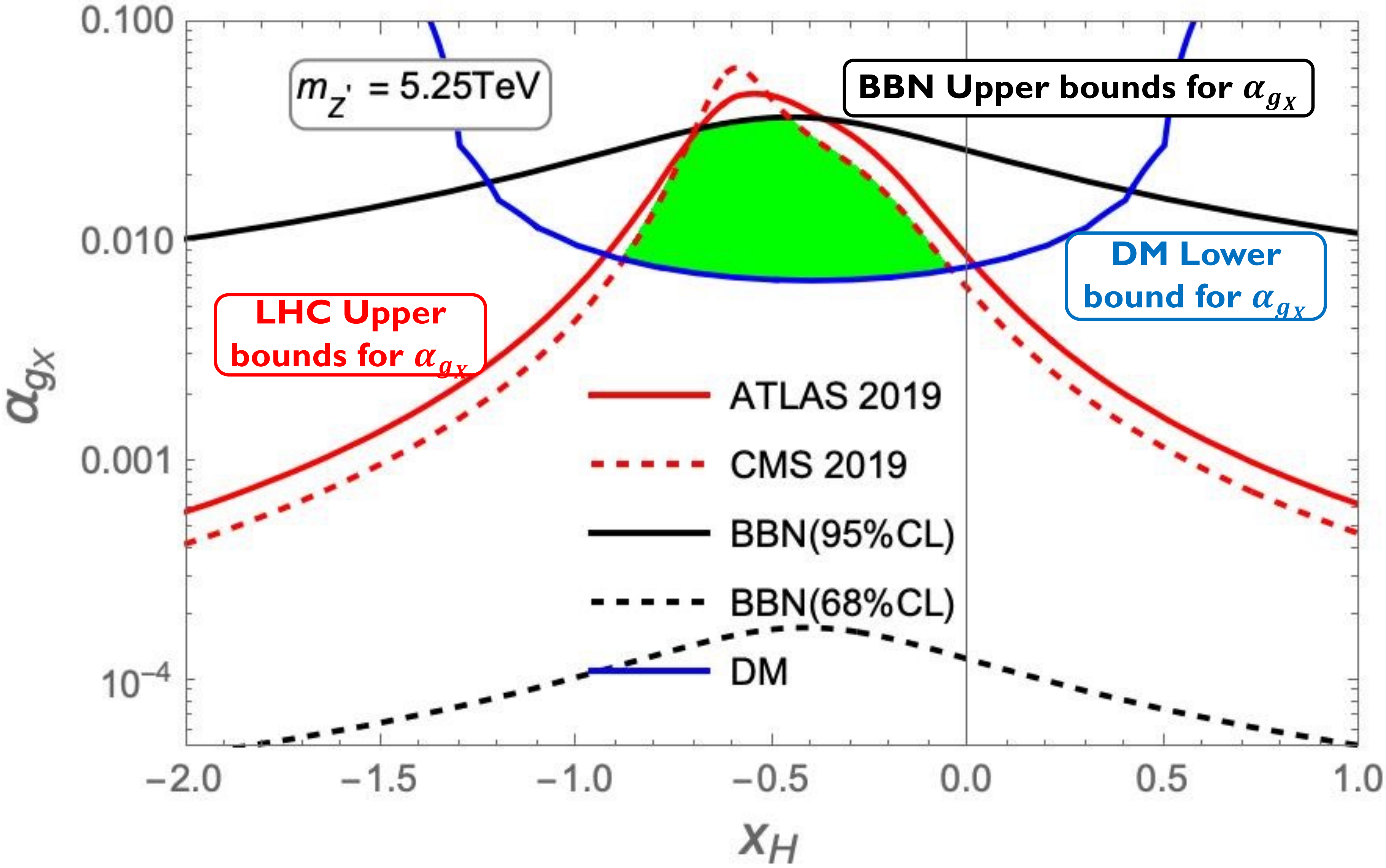


Z' boson search ($\boxed{x_H = -0.575}$, g_X, $m_{Z'}$)



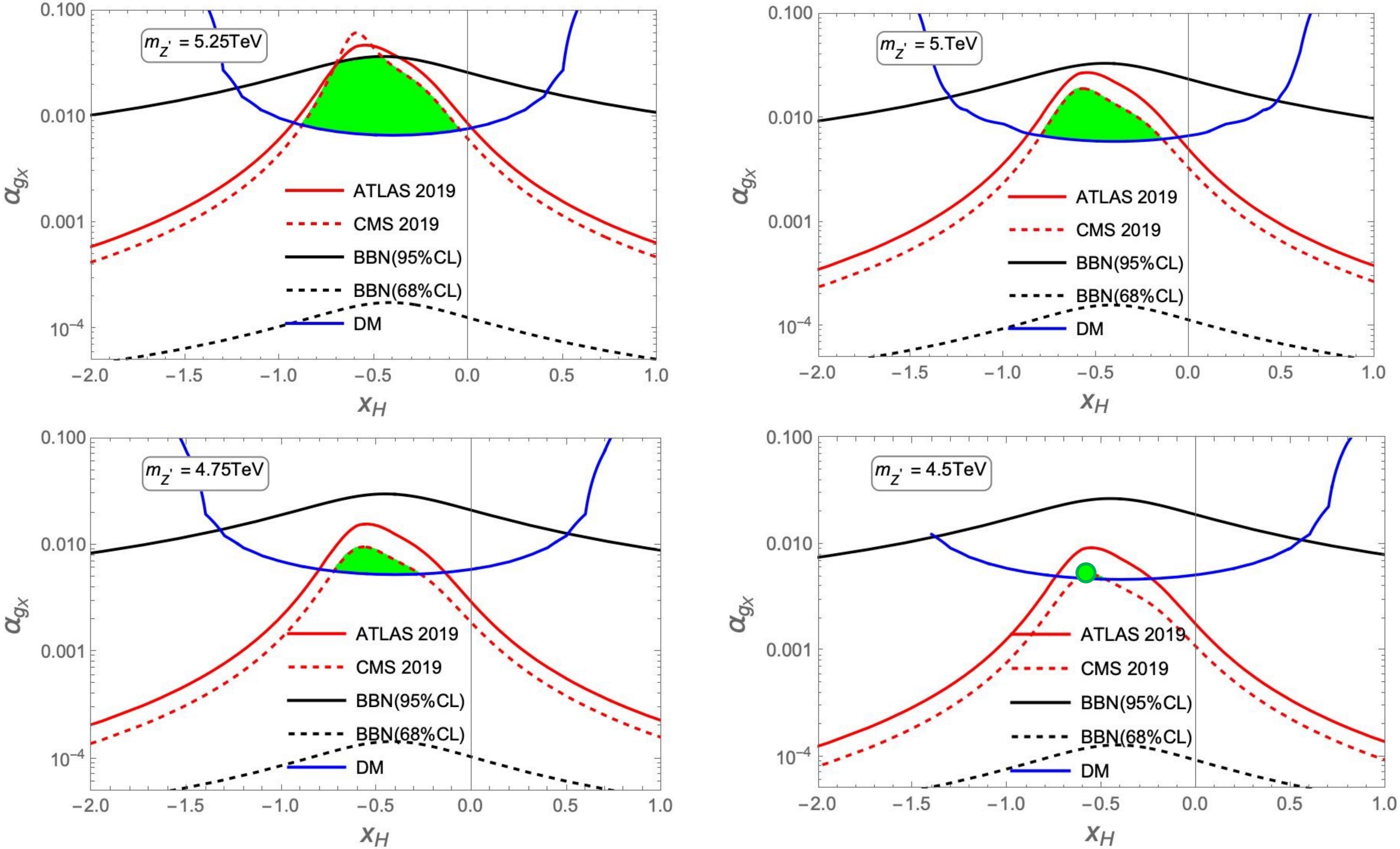
Remark: $m_{Z'} = \sqrt{2} g_X v_\phi$

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 $(x_H,\ g_X,\ m_{Z'} = 5.25, 5, 4.75, 4.5\ \mathrm{TeV})$

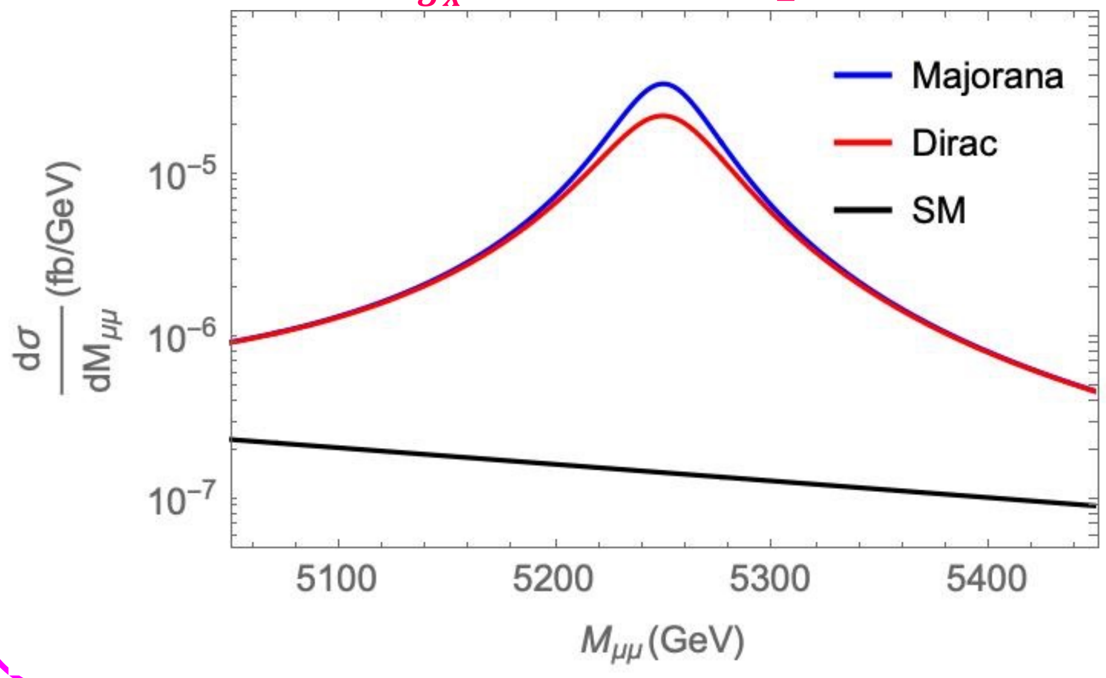


- 1.) For fixed x_H and $m_{Z'}$, α_{g_X} has upper **(red)** **(black)** and lower **(blue)** bounds.

Dirac neutrinos at LHC

- Our model: I massless Wyle + 2 massive Dirac neutrinos
  - 3 light Majorana neutrinos + 3 heavy Majorana neutrinos

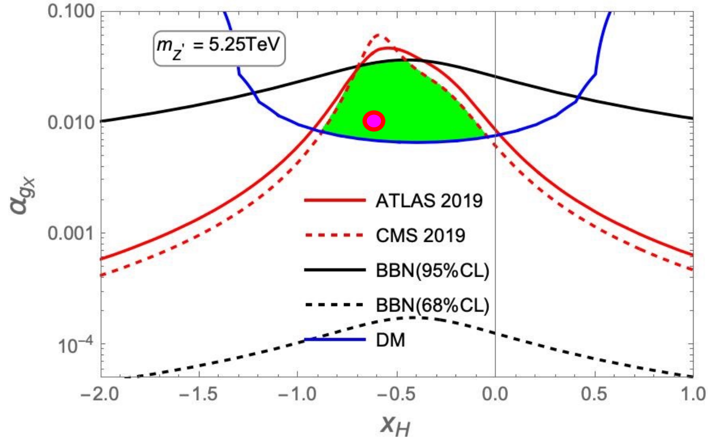
$$x_H = -0.575,\quad \alpha_{g_X} = 0.007,\quad m_{Z'} = 5.25\ \mathrm{TeV}$$



@ 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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