Triplet-quadruplet fermionic dark matter

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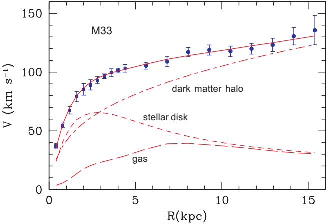
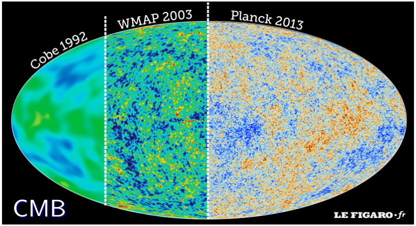
CoEPP lunch meeting

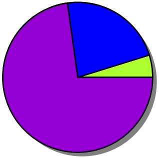
22 Oct 2015

Dark matter in the Universe

Dark matter (DM) makes up most of the matter component in the Universe, as suggested by astrophysical and cosmological observations.







Planck 2015
[1502.01589]

Cold DM (25.8%)
$\Omega_c h^2 = 0.1186 \pm 0.0020$

Baryons (4.8%)
$\Omega_b h^2 = 0.02226 \pm 0.00023$

Dark energy (69.3%)
$\Omega_\Lambda = 0.692 \pm 0.012$

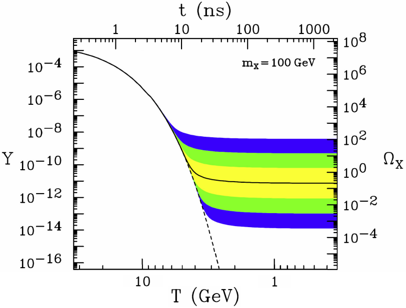
DM relic abundance

If DM particles (χ) were thermally produced in the early Universe, their **relic abundance** would be determined by the annihilation cross section $\langle\sigma_{\mathrm{ann}}v\rangle$:

$$\Omega_\chi h^2 \simeq \frac{3\times10^{-27}\ \mathrm{cm}^3\ \mathrm{s}^{-1}}{\langle\sigma_{\mathrm{ann}}v\rangle}$$

Observation value $\Omega_\chi h^2 \simeq 0.1$

$$\Rightarrow \quad \langle\sigma_{\mathrm{ann}}v\rangle \simeq 3\times10^{-26}\ \mathrm{cm}^3\ \mathrm{s}^{-1}$$



[Feng, arXiv:1003.0904]

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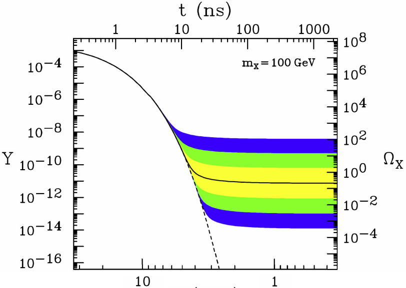

[Feng, arXiv:1003.0904]

Assuming the annihilation process consists of two weak interaction vertices with the $SU(2)_L$ gauge coupling $g \simeq 0.64$, for $m_\chi \sim \mathcal{O}(\text{TeV})$ we have

$$\langle\sigma_{\text{ann}} v\rangle \sim \frac{g^4}{16\pi^2 m_\chi^2} \sim \mathcal{O}(10^{-26})\ \text{cm}^3\ \text{s}^{-1}$$

$\Rightarrow$ A very attractive class of DM candidates:

Weakly interacting massive particles (WIMPs)

WIMP models

WIMPs are typically introduced in the extensions of the Standard Model (SM) aiming at solving the **gauge hierarchy problem**

- **Supersymmetry:** the lightest neutralino ($\tilde{\chi}_1^0$)
- **Universal extra dimensions:** the lightest KK particle ($B^{(1)}$, $W^{3(1)}$, or $\nu^{(1)}$)

WIMP models

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For DM phenomenology, it is quite natural to construct WIMP models by extending the SM with a dark sector consisting of **$SU(2)_L$ multiplets**, whose neutral components could provide a viable DM candidate

- 1 multiplet in a high dim rep.: **minimal DM model** [Cirelli *et al.*, hep-ph/0512090]
  (DM stability is explained by an accidental symmetry)
- 2 types of multiplets: an artificial Z_2 symmetry is usually needed
  - **Singlet-doublet DM model** [Mahbubani & Senatore, hep-ph/0510064; D'Eramo, 0705.4493; Cohen *et al.*, 1109.2604]
  - **Doublet-triplet DM model** [Dedes & Karamitros, 1403.7744]
  - ... ...

Triplet-quadruplet DM model

Dark sector Weyl fermions:

$$T = \begin{pmatrix} T^+ \\ T^0 \\ T^- \end{pmatrix} : (\mathbf{3}, 0), \quad Q_1 = \begin{pmatrix} Q_1^+ \\ Q_1^0 \\ Q_1^- \\ Q_1^{--} \end{pmatrix} : \left(\mathbf{4}, -\frac{1}{2}\right), \quad Q_2 = \begin{pmatrix} Q_2^{++} \\ Q_2^+ \\ Q_2^0 \\ Q_2^- \end{pmatrix} : \left(\mathbf{4}, +\frac{1}{2}\right)$$

Covariant kinetic and mass terms:

$$\mathcal{L}_{\mathrm{T}} = iT^\dagger \bar{\sigma}^\mu D_\mu T - \frac{1}{2}(m_T TT + \mathrm{h.c.})$$

$$\mathcal{L}_{\mathrm{Q}} = iQ_1^\dagger \bar{\sigma}^\mu D_\mu Q_1 + iQ_2^\dagger \bar{\sigma}^\mu D_\mu Q_2 - (m_Q Q_1 Q_2 + \mathrm{h.c.})$$

Yukawa couplings: $\mathcal{L}_{\mathrm{HTQ}} = y_1 \varepsilon_{jl} (Q_1)_i^{jk} T_k^i H^l - y_2 (Q_2)_i^{jk} T_k^i H_j^\dagger + \mathrm{h.c.}$

Z_2 symmetry: odd for dark sector fermions, even for SM particles

$\Rightarrow$ forbids operators like TLH, $Te^c H^\dagger H^\dagger$, $Q_1 L^\dagger H H^\dagger$, $Q_2 LHH^\dagger$, ...

State mixing

$$\mathcal{L}_{\text{mass}} = -m_Q Q_1^{--} Q_2^{++} - \frac{1}{2}(T^0, Q_1^0, Q_2^0)\mathcal{M}_N \begin{pmatrix} T^0 \\ Q_1^0 \\ Q_2^0 \end{pmatrix} - (T^-, Q_1^-, Q_2^-)\mathcal{M}_C \begin{pmatrix} T^+ \\ Q_1^+ \\ Q_2^+ \end{pmatrix} + \text{h.c.}$$

$$= -m_Q \chi^{--}\chi^{++} - \frac{1}{2}\sum_{i=1}^{3} m_{\chi_i^0}\chi_i^0\chi_i^0 - \sum_{i=1}^{3} m_{\chi_i^\pm}\chi_i^-\chi_i^+ + \text{h.c.}$$

$$\mathcal{M}_N = \begin{pmatrix} m_T & \frac{1}{\sqrt{3}}y_1 v & -\frac{1}{\sqrt{3}}y_2 v \\ \frac{1}{\sqrt{3}}y_1 v & 0 & m_Q \\ -\frac{1}{\sqrt{3}}y_2 v & m_Q & 0 \end{pmatrix}, \quad \mathcal{M}_C = \begin{pmatrix} m_T & \frac{1}{\sqrt{2}}y_1 v & -\frac{1}{\sqrt{6}}y_2 v \\ -\frac{1}{\sqrt{6}}y_1 v & 0 & -m_Q \\ \frac{1}{\sqrt{2}}y_2 v & -m_Q & 0 \end{pmatrix}$$

$$\begin{pmatrix} T^0 \\ Q_1^0 \\ Q_2^0 \end{pmatrix} = \mathcal{N}\begin{pmatrix} \chi_1^0 \\ \chi_2^0 \\ \chi_3^0 \end{pmatrix}, \quad \begin{pmatrix} T^+ \\ Q_1^+ \\ Q_2^+ \end{pmatrix} = \mathcal{C}_L\begin{pmatrix} \chi_1^+ \\ \chi_2^+ \\ \chi_3^+ \end{pmatrix}, \quad \begin{pmatrix} T^- \\ Q_1^- \\ Q_2^- \end{pmatrix} = \mathcal{C}_R\begin{pmatrix} \chi_1^- \\ \chi_2^- \\ \chi_3^- \end{pmatrix}$$

$$\chi^{--} \equiv Q_1^{--}, \quad \chi^{++} \equiv Q_2^{++}$$

3 Majorana fermions, 3 singly charged fermions, 1 doubly charged fermion

χ_1^0 can be an excellent DM candidate if it is the lightest dark sector fermion

$y_1 = y_2$: A custodial $SU(2)_R$ global symmetry

When the two Yukawa couplings are equal ($y = y_1 = y_2$), the Lagrangians have **an $SU(2)_L \times SU(2)_R$ invariant form:**

$$\mathcal{L}_\mathrm{Q} + \mathcal{L}_\mathrm{HTQ} = i(\mathbf{Q}^{\dagger A})^k_{ij}\bar{\sigma}^\mu D_\mu (\mathbf{Q}_A)^{ij}_k - \frac{1}{2}[m_Q \varepsilon^{AB}\varepsilon_{il}(\mathbf{Q}_A)^{ij}_k(\mathbf{Q}_B)^{lk}_j + \mathrm{h.c.}]$$
$$+[y\varepsilon^{AB}(\mathbf{Q}_A)^{jk}_i T^i_k (\mathbf{H}_B)_j + \mathrm{h.c.}]$$

$$SU(2)_R \text{ doublets: } (\mathbf{Q}_A)^{ij}_k = \begin{pmatrix} (Q_1)^{ij}_k \\ (Q_2)^{ij}_k \end{pmatrix}, \quad (\mathbf{H}_A)_i = \begin{pmatrix} H^\dagger_i \\ H_i \end{pmatrix}$$

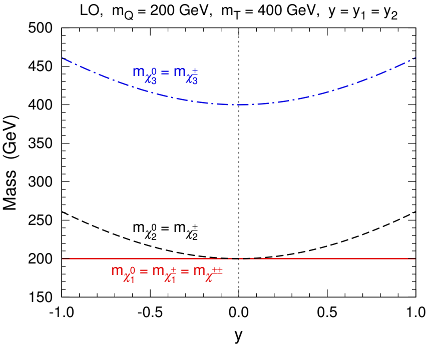
This symmetry is explicitly broken by the $U(1)_Y$ gauge symmetry

There are still some important properties under this approximate symmetry

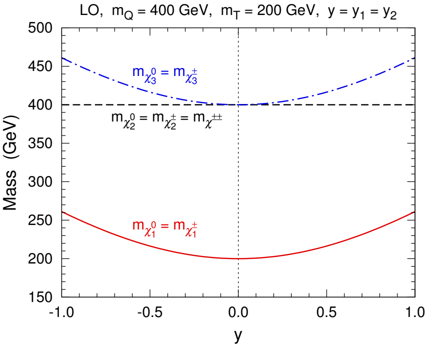
$y_1 = y_2$: A custodial $SU(2)_R$ global symmetry

In the custodial symmetry limit, each of the dark sector neutral fermions is **exactly degenerate in mass** with a singly charged fermion at the LO.

Mass corrections at the NLO are required to check if $m_{\chi_1^0} < m_{\chi_1^\pm}, m_{\chi^{\pm\pm}}$.



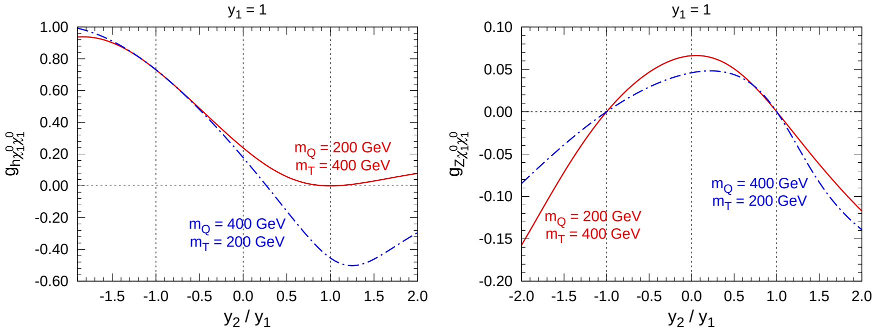
$m_Q < m_T$ case



$m_T < m_Q$ case

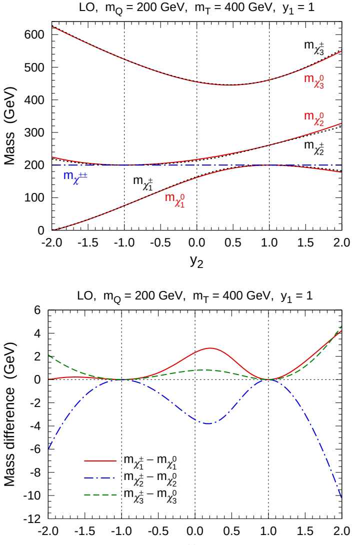
$y_1 = y_2$: A custodial $SU(2)_R$ global symmetry

In the custodial symmetry limit, when $m_Q < m_T$, we have $\chi_1^0 = (Q_1^0 + Q_2^0)/\sqrt{2}$, which leads to vanishing χ_1^0 couplings to h and Z at the tree level. As a result, χ_1^0 cannot interacts with nuclei at the LO and could easily escape from current DM direct detection bounds.

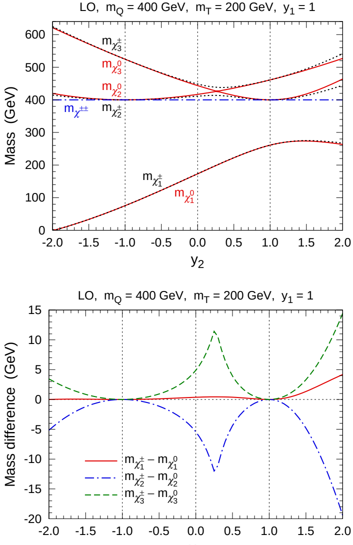


$h\chi_1^0\chi_1^0$ coupling $\quad$ $Z\chi_1^0\chi_1^0$ coupling

LO mass spectrum: $m_{\chi_i^0} \simeq m_{\chi_i^\pm}$ in any cases



$(m_Q < m_T$ case$)$

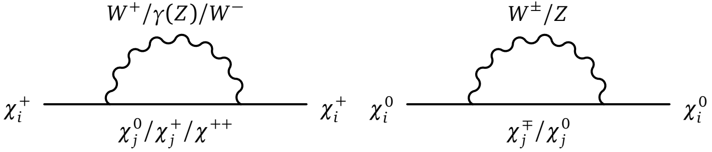


$(m_T < m_Q$ case$)$

Mass corrections at the NLO

One-loop corrections to an $SU(2)_L$ multiplet from **electroweak gauge boson loops** usually drive a charged component **heavier** than the neutral component (by $\sim Q^2 \cdot 170$ MeV for a multiplet much heavier than Z with $Y = 0$).

[Feng *et al.*, hep-ph/9904250; Cirelli *et al.*, hep-ph/0512090; Hill & Solon, 1111.0016]



$\Rightarrow \; m_{\chi_1^0} < m_{\chi_1^\pm}$

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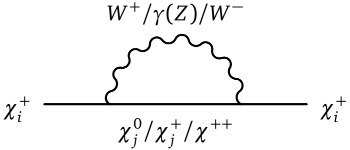
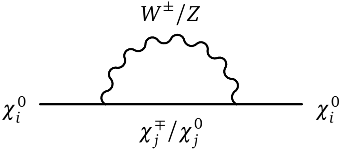
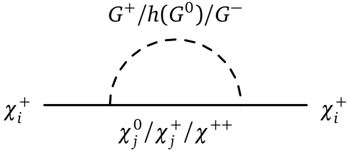
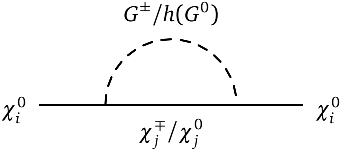




$\Rightarrow\ m_{\chi_1^0} < m_{\chi_1^\pm}$

There are **mixings** among T, Q_1, and Q_2, and corrections from the Higgs sector due to the HTQ **Yukawa couplings**. The situation is more complicated.

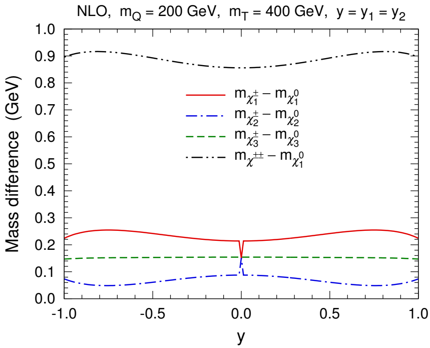




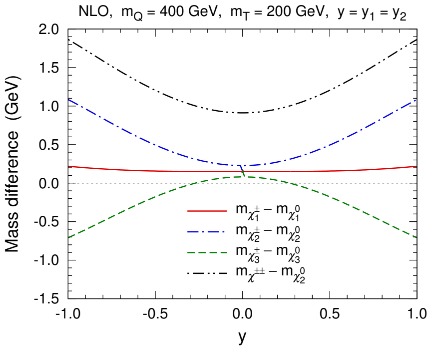
?

Mass corrections at the NLO

In the **custodial symmetry limit**, we always have $m_{\chi_1^0} < m_{\chi_1^\pm}$ at the NLO and hence χ_1^0 is stable as required for a DM candidate.



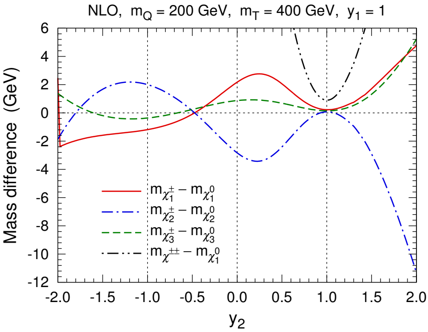
$m_Q < m_T$ case



$m_T < m_Q$ case

Mass corrections at the NLO

Beyond the custodial symmetry limit:



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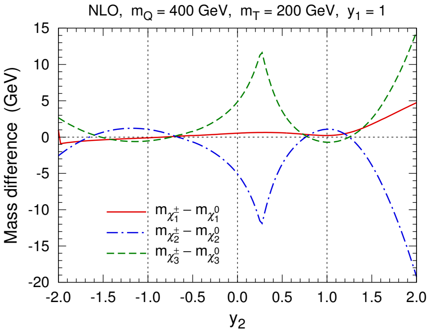

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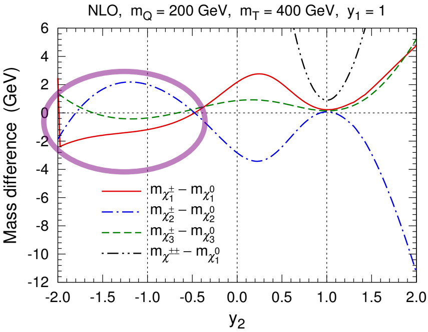

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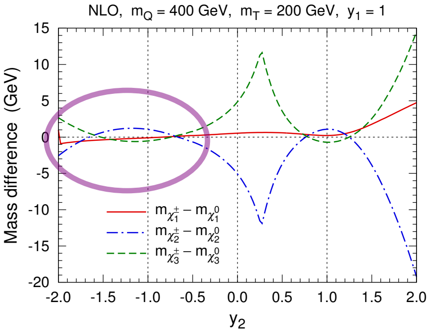


$m_T < m_Q$ case

When y_1 and y_2 have opposite signs, we may have $m_{\chi_1^\pm} < m_{\chi_1^0}$ at the NLO and χ_1^0 is no longer a viable DM candidate because it can decay.

Relic abundance

In this model, we always have the mass degeneracy $m_{\chi_1^\pm} \simeq m_{\chi_1^0}$. Besides,

$$m_Q < m_T \quad \Rightarrow \quad \text{maybe } m_{\chi^{\pm\pm}} \simeq m_{\chi_1^0}$$

$$|y_{1,2}v| \ll m_Q < m_T \quad \Rightarrow \quad m_{\chi_2^0} \simeq m_{\chi_2^\pm} \simeq m_{\chi_1^0}$$

These dark sector fermions, with close masses and comparable interaction strengths, basically decoupled at the same time in the early Universe.

Coannihilation processes among them significantly affected their abundances.

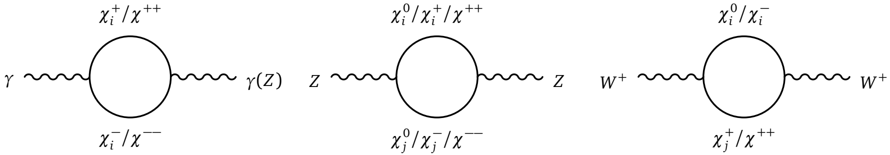
After freeze-out, $\chi_1^\pm$, $\chi^{\pm\pm}$, χ_2^0, and $\chi_2^\pm$ decayed into χ_1^0 and contributed to the DM relic abundance.

`FeynRules` $\rightarrow$ `MadGraph` $\rightarrow$ `MadDM`:

includes all annihilation and coannihilation channels

Observed DM abundance $\Omega h^2 = 0.1186 \quad \Longleftrightarrow \quad m_{\chi_1^0} \sim 2.4$ TeV

Electroweak oblique parameters



Gauge interactions of the triplet and quadruplets would affect the **electroweak oblique parameters** [Peskin & Takeuchi, '90, '92]

$$S = \frac{16\pi c_W^2 s_W^2}{e^2}\left[\Pi'_{ZZ}(0) - \frac{c_W^2 - s_W^2}{c_W s_W}\Pi'_{ZA}(0) - \Pi'_{AA}(0)\right]$$

$$T = \frac{4\pi}{e^2}\left[\frac{\Pi_{WW}(0)}{m_W^2} - \frac{\Pi_{ZZ}(0)}{m_Z^2}\right]$$

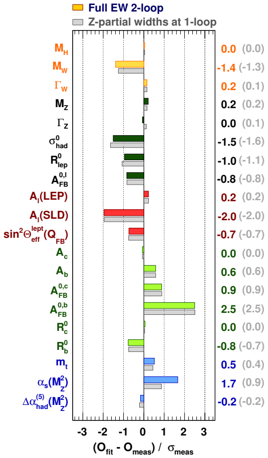
$$U = \frac{16\pi s_W^2}{e^2}\left[\Pi'_{WW}(0) - c_W^2\Pi'_{ZZ}(0) - 2c_W s_W\Pi'_{ZA}(0) - s_W^2\Pi'_{AA}(0)\right]$$

The Standard Model predicts $S = T = U = 0$.

Electroweak oblique parameters

A global fit based on the measurements of **electroweak precision observables**:

[Gfitter Group, 1407.3792]



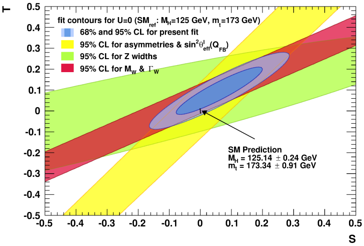
Fixed $U = 0$ $\to$

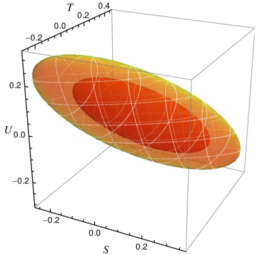
$$S = 0.06 \pm 0.09,\ T = 0.10 \pm 0.07,\ \rho_{ST} = +0.91$$

Free U $\to$

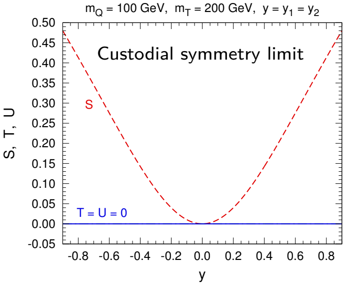
$$S = 0.05 \pm 0.11,\ T = 0.09 \pm 0.13,\ U = 0.01 \pm 0.11$$

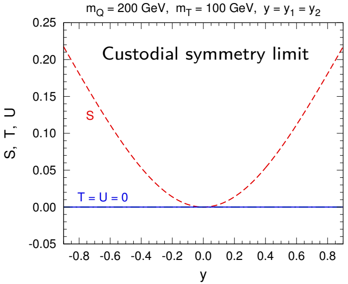
$$\rho_{ST} = +0.90,\ \rho_{SU} = -0.59,\ \rho_{TU} = -0.83$$

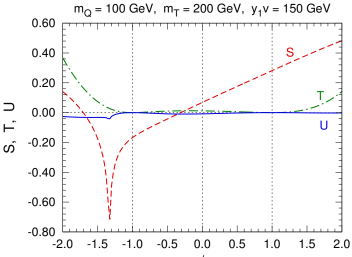




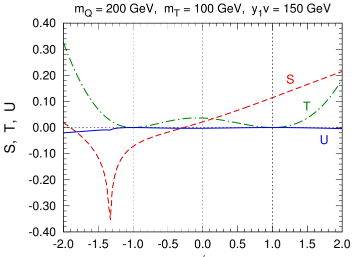
Electroweak oblique parameters







($m_Q < m_T$ case)



($m_T < m_Q$ case)

Direct detection

$$\mathcal{L} \supset \frac{1}{2} g_{h\chi_1^0\chi_1^0} h \bar{\chi}_1^0 \chi_1^0 + \frac{1}{2} g_{Z\chi_1^0\chi_1^0} Z_\mu \bar{\chi}_1^0 \gamma^\mu \gamma_5 \chi_1^0$$

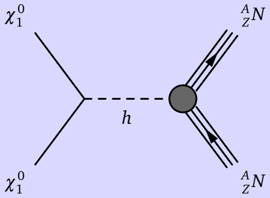
$$g_{h\chi_1^0\chi_1^0} = -\frac{2}{\sqrt{3}}(y_1\mathcal{N}_{21} - y_2\mathcal{N}_{31})\mathcal{N}_{11}$$

$$g_{Z\chi_1^0\chi_1^0} = \frac{g}{2c_W}(|\mathcal{N}_{31}|^2 - |\mathcal{N}_{21}|^2)$$

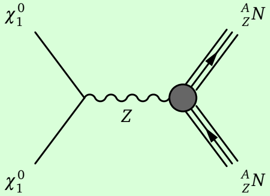
For $m_Q < m_T$ in the custodial symmetry limit, we have $\mathcal{N}_{11} = 0$ and $|\mathcal{N}_{31}| = |\mathcal{N}_{21}|$, and both $g_{h\chi_1^0\chi_1^0}$ and $g_{Z\chi_1^0\chi_1^0}$ vanish

Current direct detection experiments are much more sensitive to the SI DM-nucleus scatterings than the SD scatterings

The exclusion limit on the SI cross section from the **LUX experiment** [1310.8214] is used to constrain the model



Spin independent (SI)



Spin dependent (SD)

Indirect detection

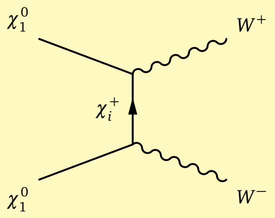
Indirect detection searches for products from **nonrelativistic DM annihilations**

Suppressions on $\chi_1^0\chi_1^0$ annihilations into SM particles

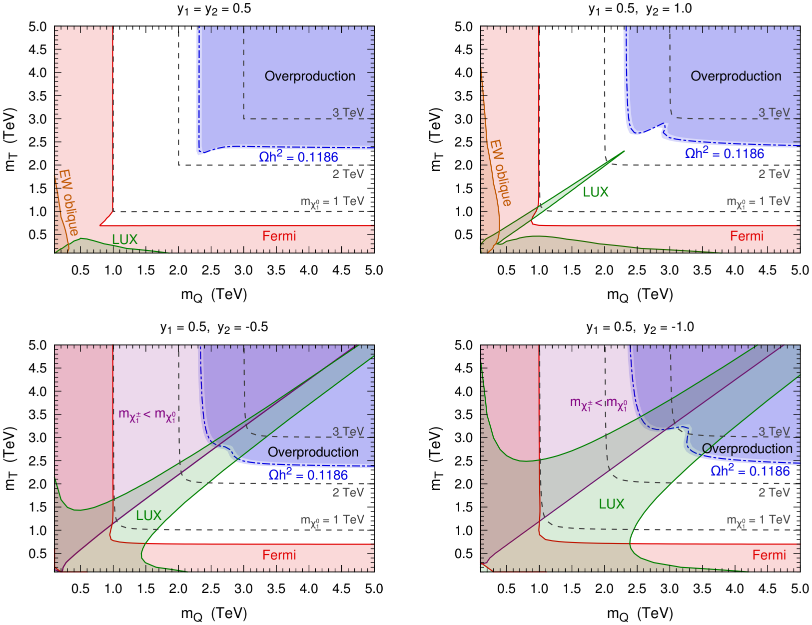
- $\chi_1^0\chi_1^0 \to Z^* \to f\bar{f}$: helicity suppression in s wave ($\langle\sigma v\rangle \propto m_f^2/m_{\chi_1^0}^2$)
- $\chi_1^0\chi_1^0 \to h^* \to f\bar{f}$: p-wave suppression ($\langle\sigma v\rangle \propto v^2$)
- $\chi_1^0\chi_1^0 \to hh$: p-wave suppression ($\langle\sigma v\rangle \propto v^2$)

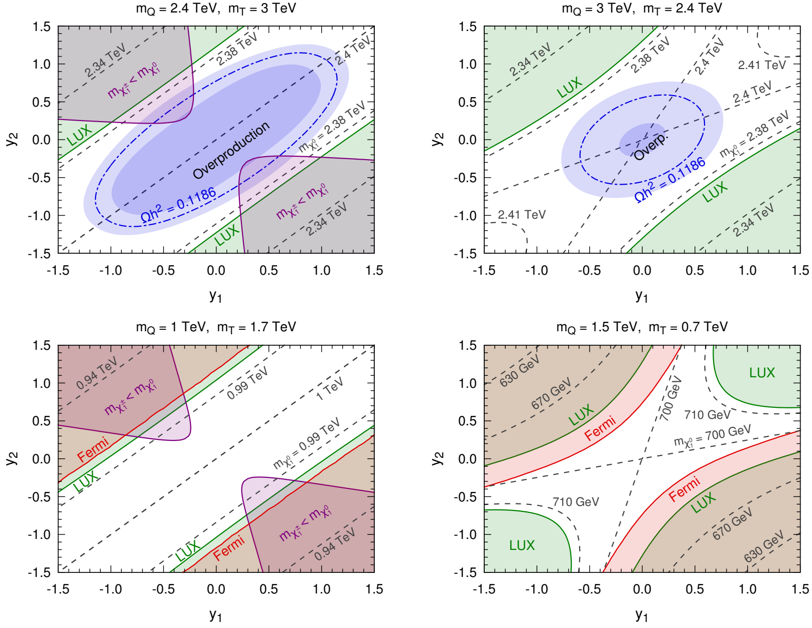
The cross section of $\chi_1^0\chi_1^0 \to W^+W^-$ usually larger than those of $\chi_1^0\chi_1^0 \to ZZ$, Zh, $t\bar{t}$ by at least 1 to 2 orders of magnitude

The upper limit on the annihilation cross section into W^+W^- given by **Fermi-LAT** 6-year γ-ray observations of dwarf galaxies [1503.02641] is used to constrain the model



Dominant channel


$y_1 = y_2 = 0.5$
$y_1 = 0.5,\ y_2 = 1.0$
$y_1 = 0.5,\ y_2 = -0.5$
$y_1 = 0.5,\ y_2 = -1.0$
m_T (TeV)
m_Q (TeV)
Overproduction
$\Omega h^2 = 0.1186$
3 TeV
2 TeV
$m_{\chi_1^0} = 1$ TeV
EW oblique
LUX
Fermi
$m_{\chi_1^\pm} < m_{\chi_1^0}$
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0



m_Q = 2.4 TeV, m_T = 3 TeV
2.34 TeV
2.38 TeV
2.4 TeV
$m_{\chi_1^\pm} < m_{\chi_1^0}$
LUX
Overproduction
$\Omega h^2 = 0.1186$
$m_{\chi_1^0}$ = 2.38 TeV
m_Q = 3 TeV, m_T = 2.4 TeV
2.41 TeV
Overp.
m_Q = 1 TeV, m_T = 1.7 TeV
0.94 TeV
0.99 TeV
1 TeV
$m_{\chi_1^0}$ = 0.99 TeV
Fermi
m_Q = 1.5 TeV, m_T = 0.7 TeV
630 GeV
670 GeV
700 GeV
710 GeV
$m_{\chi_1^0}$ = 700 GeV
y_1
y_2

Conclusions and discussions

1. We investigate a **triplet-quadruplet WIMP model**, whose dark sector involves 3 Majorana fermions, 3 singly charged fermions, and 1 doubly charged fermion.
2. The triplet and quadruplets can interact with the SM Higgs doublet through two Yukawa couplings, whose equality leads to **an approximate custodial symmetry** that would make the DM candidate χ_1^0 easily escaping from direct searches.
3. There are mass degeneracies among dark sector fermions. **One-loop mass corrections** are calculated to check if χ_1^0 can be stable.
4. The observed relic abundance suggests $m_{\chi_1^0} \sim 2.4\ \text{TeV}$. Phenomenological constraints from EW oblique parameters and direct and indirect detection experiments are also considered.

Conclusions and discussions

5. There may be extra constraints from 8 TeV LHC results, such as **$h \to \gamma\gamma$ measurements, monojet searches, and direct searches for exotic charged particles**. But it is unlikely that they could give more stringent constraints than the Fermi-LAT bound.

Conclusions and discussions

5. There may be extra constraints from 8 TeV LHC results, such as $h \to \gamma\gamma$ **measurements, monojet searches, and direct searches for exotic charged particles**. But it is unlikely that they could give more stringent constraints than the Fermi-LAT bound.

Thanks for your attention!