Exploring Triplet-Quadruplet Fermionic Dark Matter at the LHC and Future Colliders

JW Wang, XJ Bi, QF Xiang, PF Yin, ZH Yu, arXiv:1711.05622, PRD
Tait, ZH Yu, arXiv:1601.01354, JHEP

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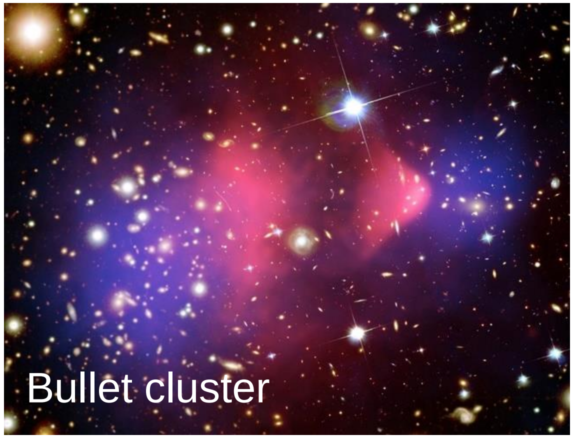
Shanghai, June 22, 2018

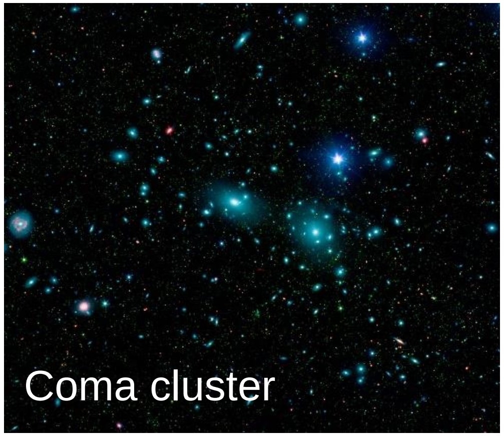
Outline

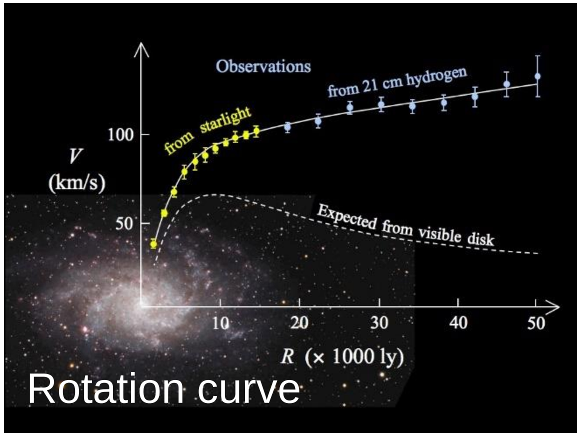
- Introduction and motivation
- Model details
- Constrains at proton-proton colliders
- Constrains at electron-positron colliders
- Summary

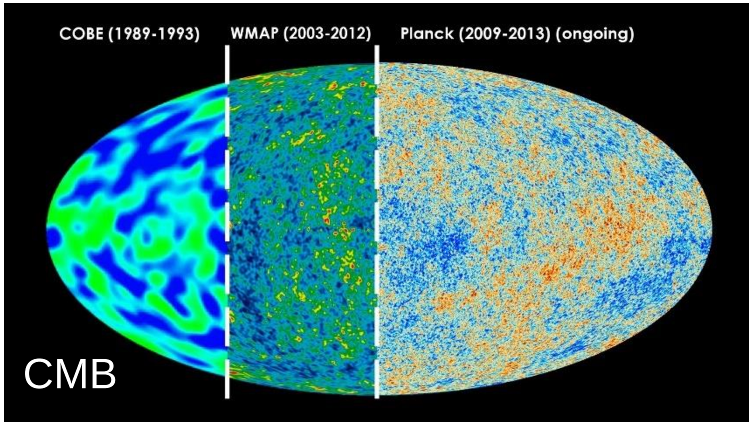
Dark matter in the Universe

- The astrophysical and cosmological observations have provided compelling evidences of the existence of **dark matter (DM)**.









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%)

$$\Omega_\Lambda = 0.692 \pm 0.012$$

Triplet-quadruplet DM model

Dark sector Weyl fermions ($SU(2)_L \times U(1)_Y$):

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

Gauge invariant kinetic terms, mass terms and Yukawa couplings:

$$\mathcal{L}_T = iT^\dagger \bar{\sigma}^\mu D_\mu T - \left(m_T a_{ij} T^i T^j + \text{h.c.}\right)$$

$$\mathcal{L}_Q = iQ_1^\dagger \bar{\sigma}^\mu D_\mu Q_1 + iQ_2^\dagger \bar{\sigma}^\mu D_\mu Q_2 - \left(m_Q b_{ij} Q_1^i Q_2^j + \text{h.c.}\right)$$

$$\mathcal{L}_{HTQ} = y_1 c_{ijk} Q_1^i T^j H^k + y_2 d_{ijk} Q_2^i T^j \widetilde{H}^k + \text{h.c.}$$

There are four independent parameters: m_T, m_Q, y_1, y_2

State mixing

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

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

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

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

3 Majorana fermions, 3 singly charged fermions, 1 doubly charged fermion.
If Z_2 symmetry is conserved, χ_1^0 will be the excellent DM candidate.

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

When the two Yukawa couplings are equal ($y = y_1 = y_2$), the Lagrangian have an $SU(2)_\mathrm{L} \times SU(2)_\mathrm{R}$ invariant form:

$$\mathcal{L}_Q + \mathcal{L}_{HTQ} = i\left(Q^{\dagger A}\right)_{ij}^{k} \bar{\sigma}^\mu D_\mu (Q_A)_{ij}^{k} - \frac{1}{2}\left[m_Q \varepsilon^{AB} \varepsilon_{il} (Q_A)_k^{ij} (Q_B)_j^{lk} + \text{h.c.}\right] + \left[y \varepsilon^{AB} (Q_A)_i^{jk} T_k^i (H_B)_j + \text{h.c.}\right]$$

$SU(2)_\mathrm{R}$ doublets: $(Q_A)_k^{ij} = \begin{pmatrix} (Q_1)_k^{ij} \\ (Q_2)_k^{ij} \end{pmatrix}, (H_B)_j = \begin{pmatrix} H_i^\dagger \\ H_i \end{pmatrix}$

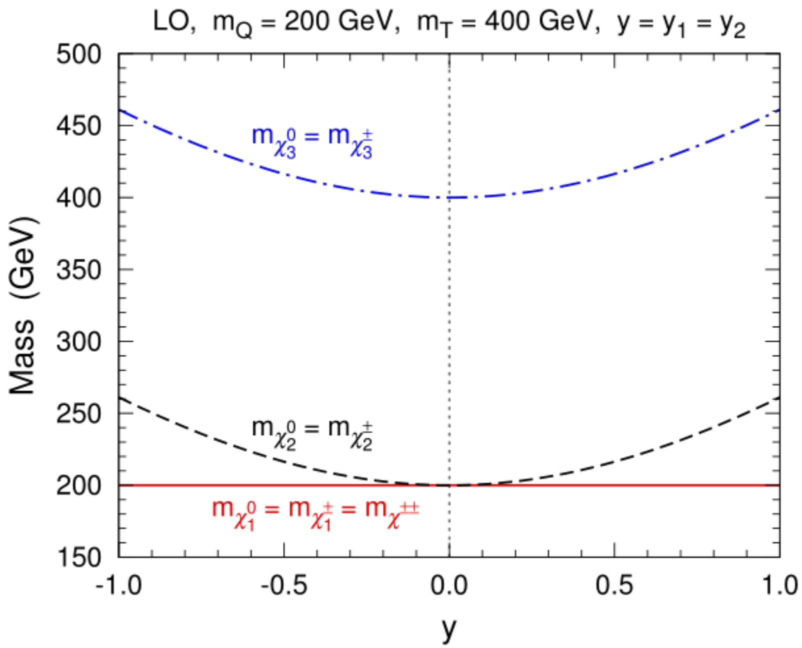
This symmetry is explicitly broken by the hypercharge.

There are still some important properties under this approximate symmetry.

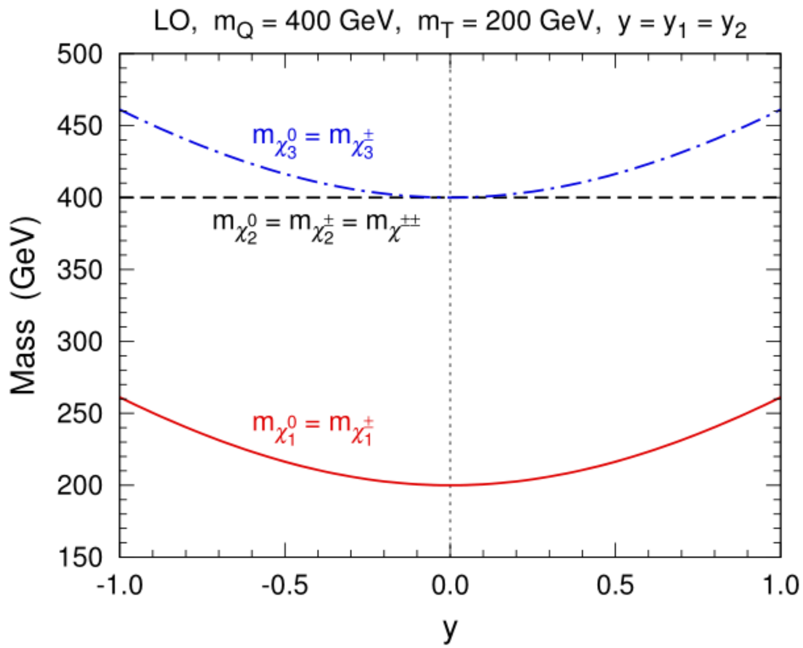
$y_1 = y_2$: A custodial $SU(2)_R$ global symmetry limit

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

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



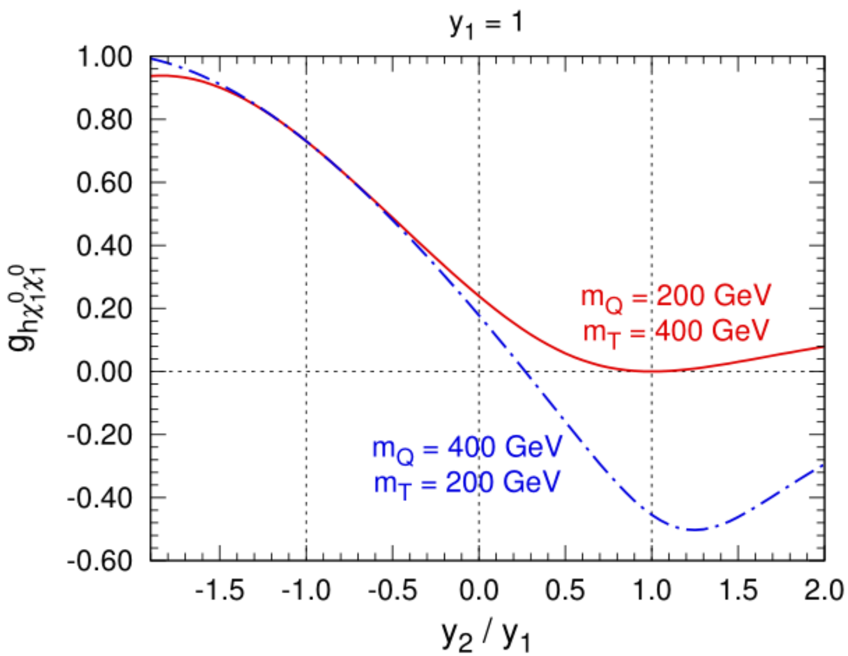
$m_Q < m_T$ case



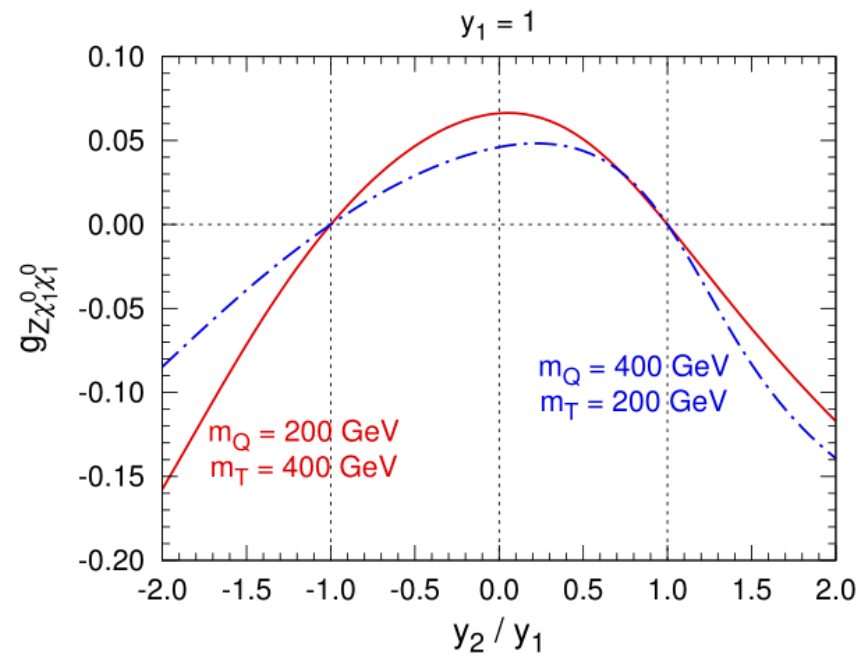
$m_T < m_Q$ case

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

In the custodial symmetry limit, when $m_Q < m_T$, χ_1^0 will not interact with h or 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



$Z\chi_1^0\chi_1^0$ coupling

Mass spectrums

When $m_Q, m_T \gtrsim 1\text{TeV}$

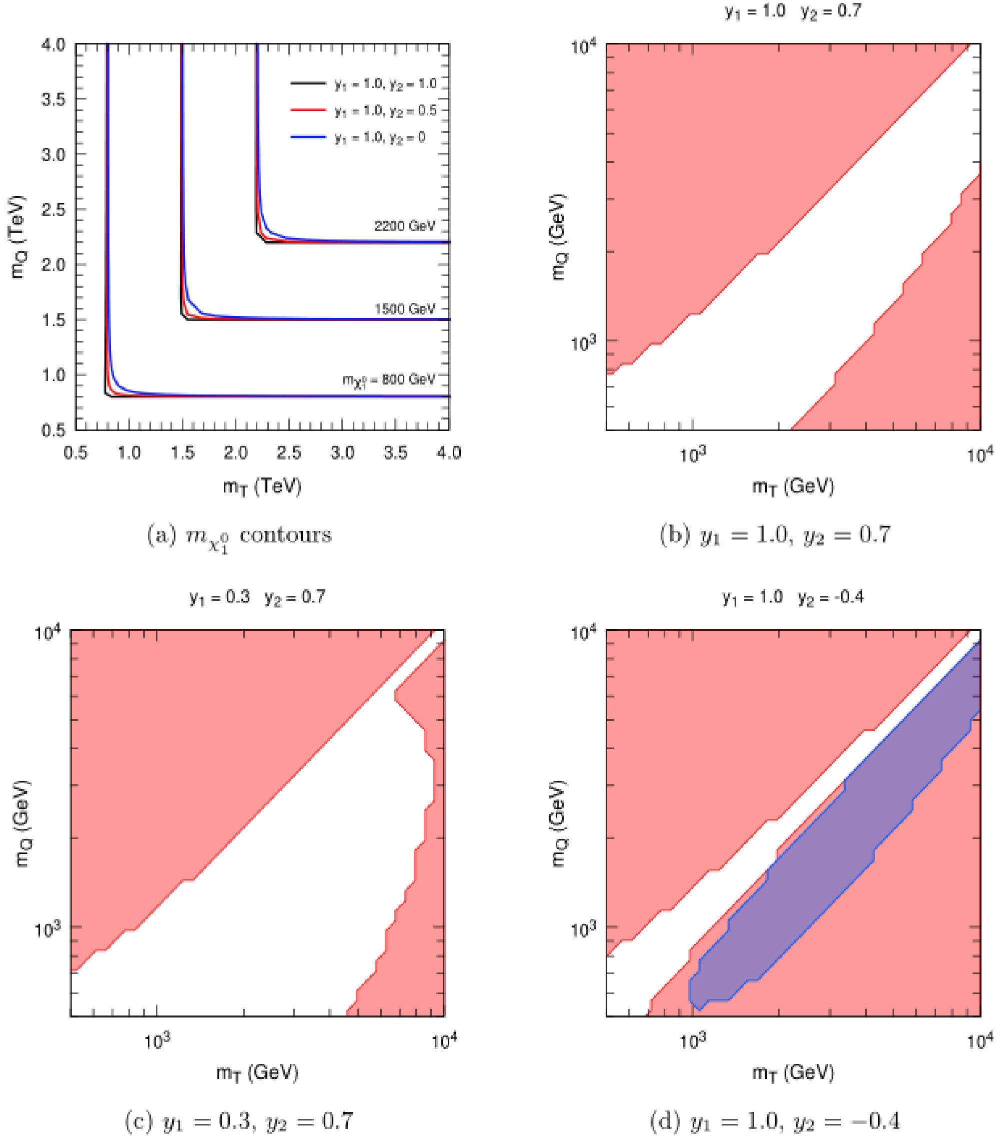
y_1 and y_2 will not significant affect $m_{\chi_1^0}$.

Because the Yukawa couplings affect the mixing between triplet and quadruples at $\sim \mathcal{O}(100\ \text{GeV})$.

Even $y_1 \neq y_2$, the mass degenerate is ubiquitous.

Blue regions: $m_{\chi_1^0}$ is not the lightest.

Red regions: $m_{\chi_1^0} - m_{\chi_1^\pm} \leq 250$ Mev and disappearing track channel can be used.



(a) $m_{\chi_1^0}$ contours

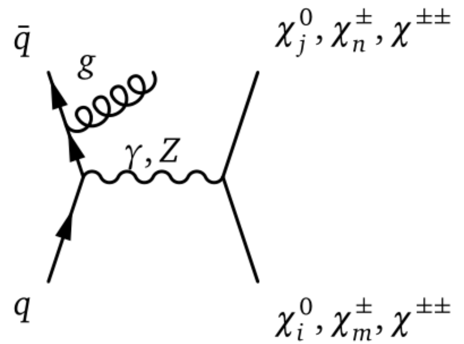
(b) $y_1 = 1.0,\ y_2 = 0.7$

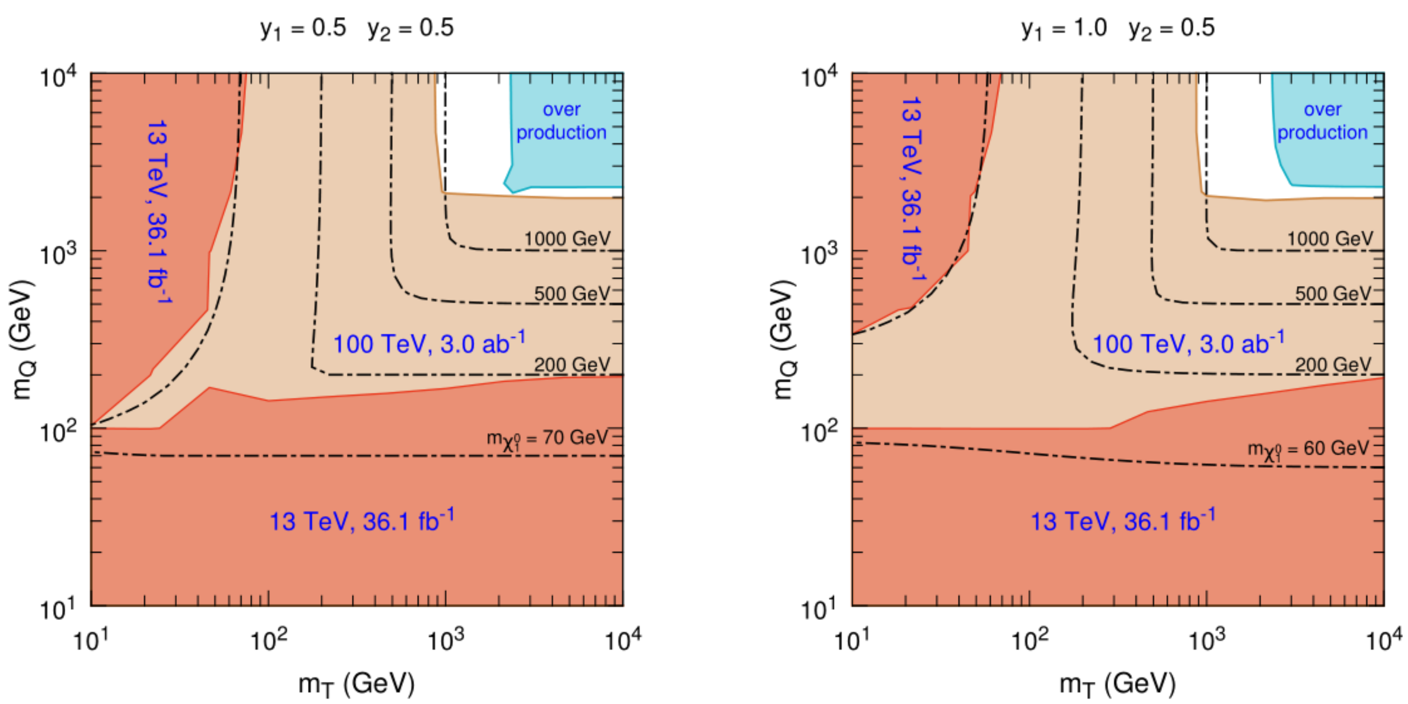
(c) $y_1 = 0.3,\ y_2 = 0.7$

(d) $y_1 = 1.0,\ y_2 = -0.4$

Constrains from mono-jet like channel

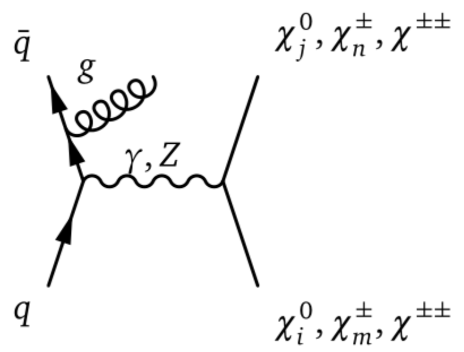
- New light particle may directly produced at high energy colliders.
- The DM candidate χ_1^0 will be the missing energy, additional jets are used to tag the events.
- The relic density has been calculated including coannihilation effects.

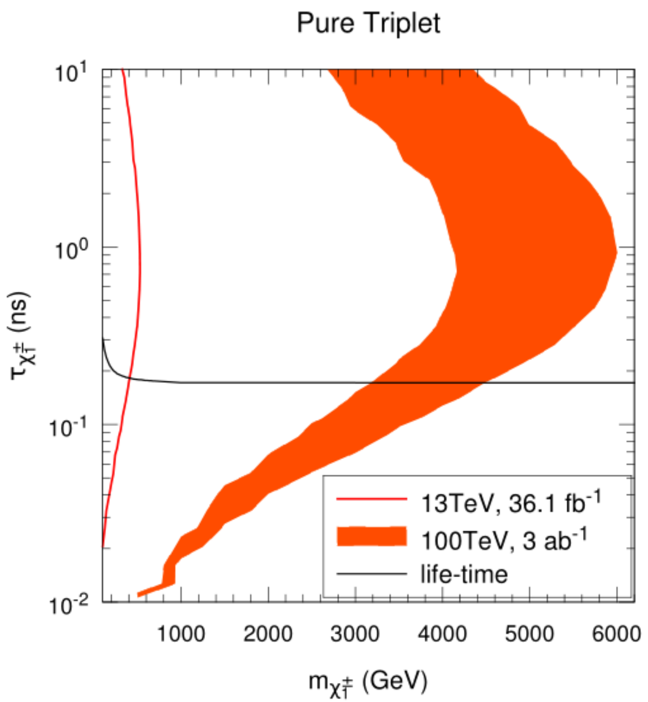


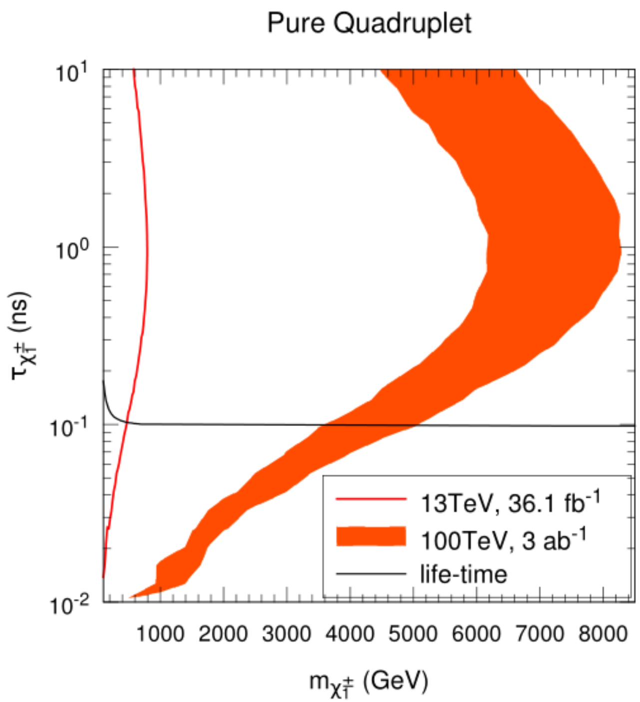


Constrains from disappearing track channel

- In the custodial limit, the mass split only comes from loop correction at order of 167 MeV.
- Even $y_1 \neq y_2$, the mass degenerate is ubiquitous.
- Two different cases are considered: pure triplet and pure quadruplets.

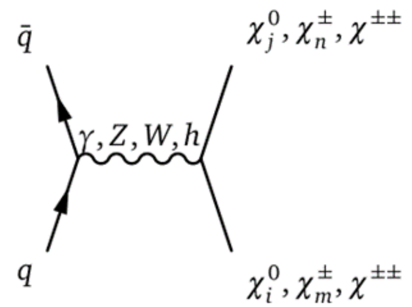


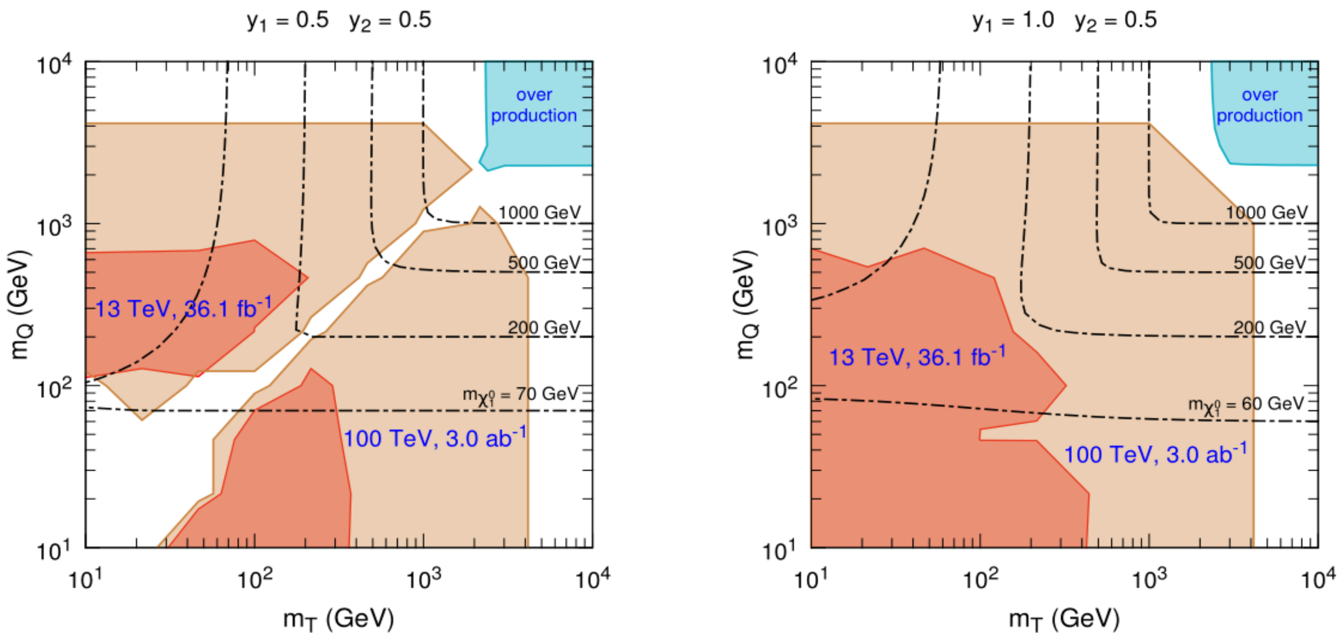




Constrains from multilepton channel

- The heavier charged and neutral dark sector particles can decay into lighter ones plus leptons ;
- We focus on the cased which contain two or three leptons in the final state.
- The relic density has been calculated for completeness.

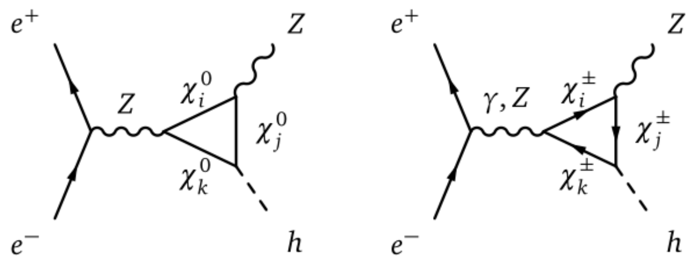




(a) $y_1 = y_2 = 0.5$ (b) $y_1 = 1.0,\ y_2 = 0.5$

Constrains from $e^+e^- \longrightarrow hZ$ channel

We use **FeynArts** and **FormCalc** to calculate the one-loop correction to $e^+e^- \longrightarrow hZ$ channel.



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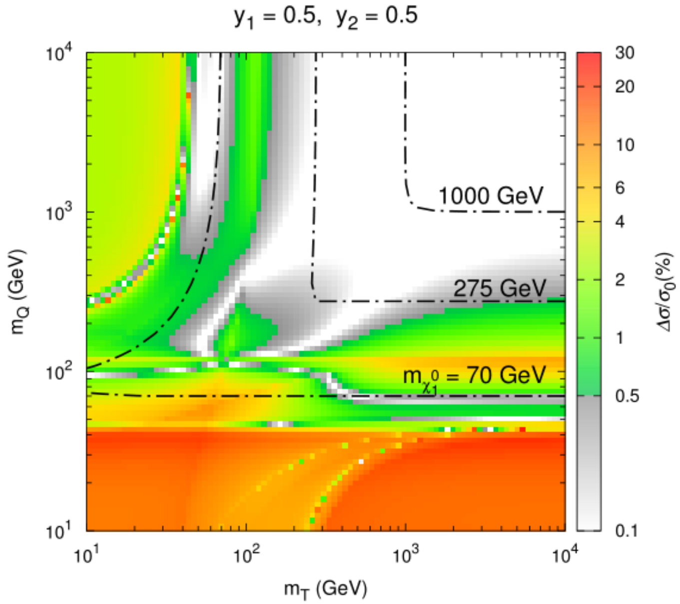
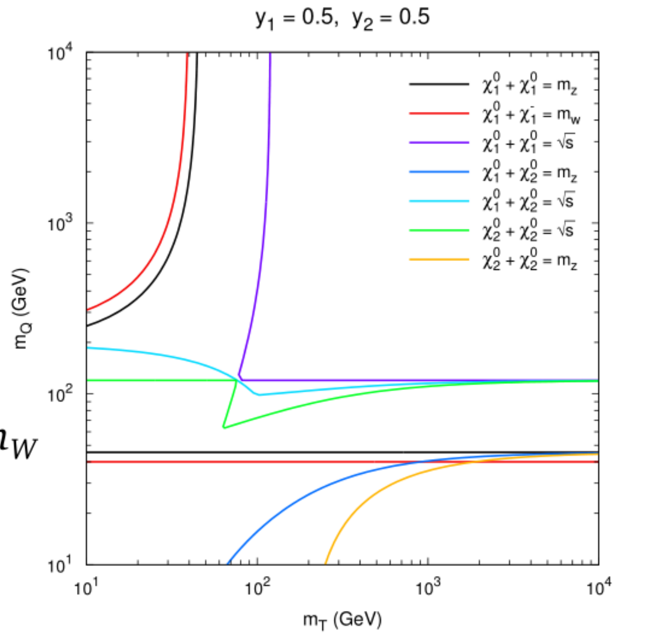
Color regions: $\Delta\sigma_{ZH}/\sigma_{ZH} \geq 0.5\%$ with $\sqrt{s} = 240$ GeV, $5\ ab^{-1}$

The **threshold effects** have been used to explain the results.

- $m_{\chi_i^0} + m_{\chi_j^0} = m_Z(m_H)$, $m_{\chi_i^\pm} + m_{\chi_j^\pm} = m_Z(m_H)$, $m_{\chi_i^0} + m_{\chi_j^\pm} = m_W$
- $m_{\chi_i^0} + m_{\chi_j^0} = \sqrt{s}$, $m_{\chi_i^\pm} + m_{\chi_j^\pm} = \sqrt{s}$



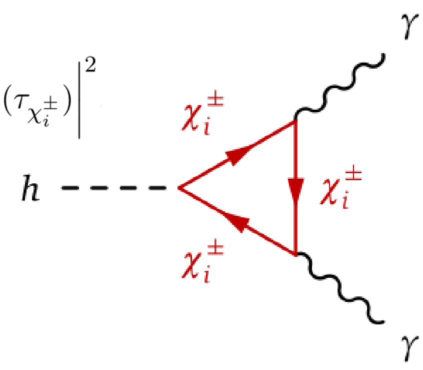


Constrains from h $\longrightarrow \gamma\gamma$ channel

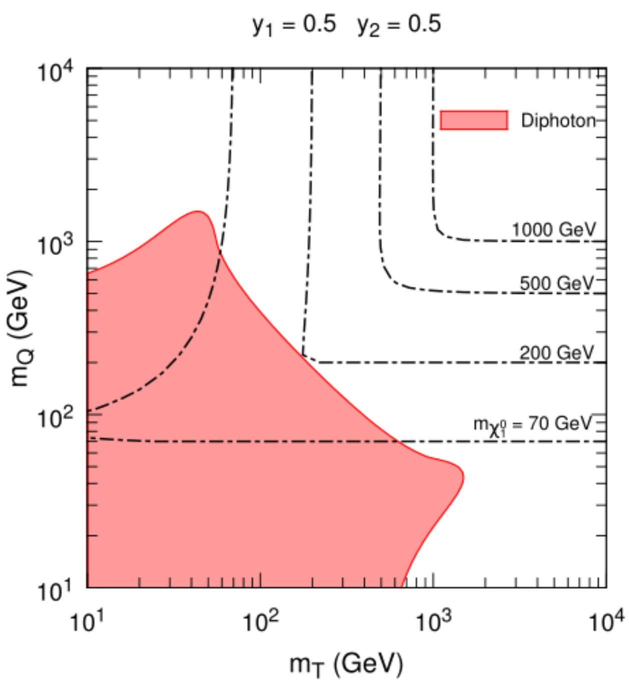
In this model, the dark sector can come into the loop and modified the partial decay width of higgs.

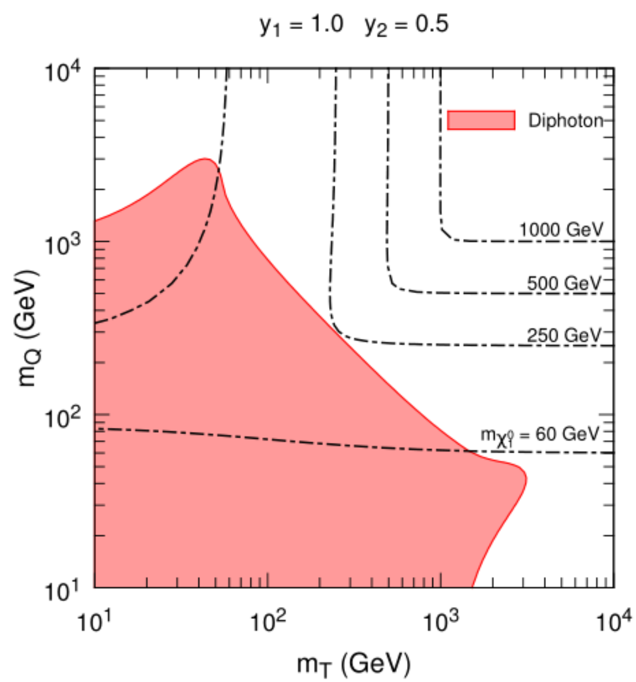
$$\Gamma_{\gamma\gamma} = \frac{G_F \alpha^2 m_h^3}{128\sqrt{2}\pi^3}\left|\sum_f N_c Q_f^2 A_{1/2}(\tau_f) + A_1(\tau_W) + \sum_i \frac{G_{h,ii} v}{m_{\chi_i^\pm}} A_{1/2}(\tau_{\chi_i^\pm})\right|^2$$

$$G_{h,ii} = \mathrm{Re}\left(-\frac{y_1}{\sqrt{2}}\mathcal{C}_{L,2i}\mathcal{C}_{R,1i} + \frac{y_1}{\sqrt{6}}\mathcal{C}_{L,1i}\mathcal{C}_{R,2i} + \frac{y_2}{\sqrt{6}}\mathcal{C}_{L,3i}\mathcal{C}_{R,1i} - \frac{y_2}{\sqrt{2}}\mathcal{C}_{L,1i}\mathcal{C}_{R,3i}\right)$$



$\Gamma_{\gamma\gamma} \propto \kappa_\gamma^2$ so the constrains to κ_γ can be used to constrains $\Gamma_{\gamma\gamma}$





Summary

- I introduce the motivations of the DM research, and investigate the triplet-quadruplet dark matter model;
- The approximate custodial symmetry is studied and the one-loop mass corrections are calculated at order of 167 MeV;
- For the hadron colliders, the mono-jet like channel, disappearing track channel and multilepton channel are considered;
- For the electron colliders, the $e^+e^- \longrightarrow hZ$ channel and $\mathrm{h} \longrightarrow \gamma\gamma$ channel are considered;
- The relic density also have been calculated with considering the effects of co-annihilation.

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Thank you