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

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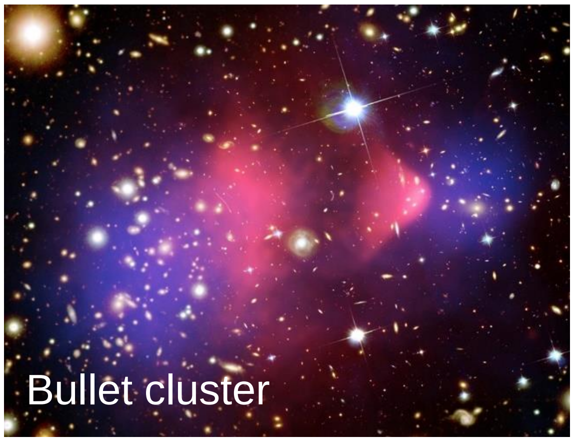
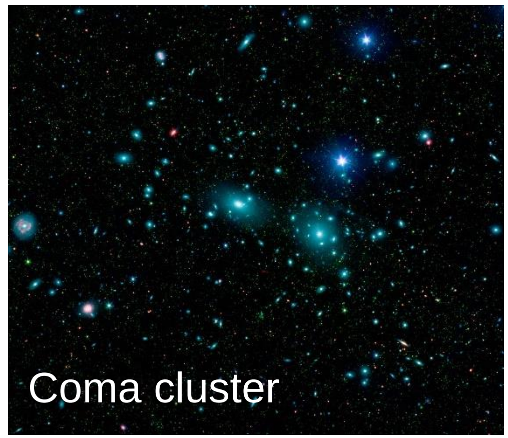
Outline

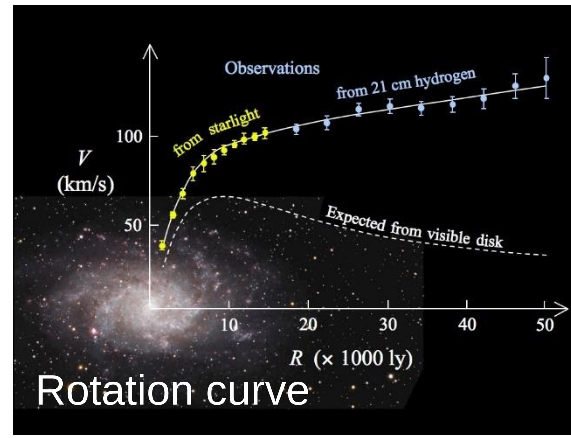
- Introduction and motivation
- Model details
- Constrains at proton-proton colliders
- Constrains at electron-positron colliders
- Summary

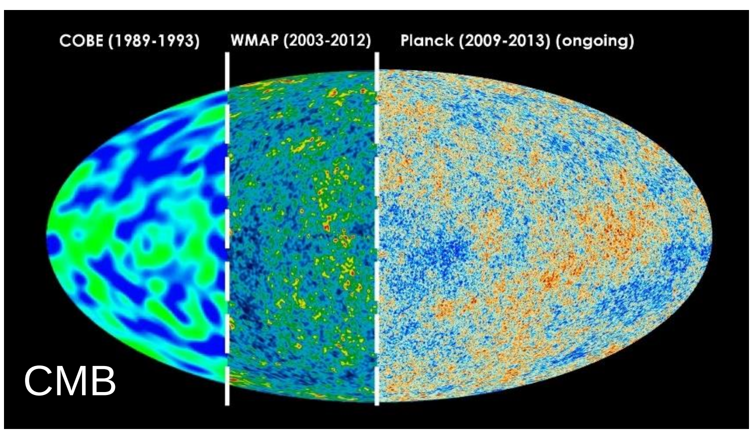
Dark matter in the Universe

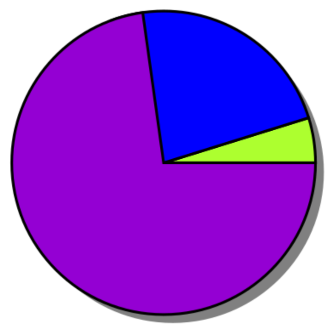
- The astrophysical and cosmological observations have provided compelling evidences of the existence of **dark matter (DM)**.











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%)

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

WIMP models

Weakly interacting massive particles (WIMPs) are very compelling DM candidates. WIMPs are typically introduced in the extensions of the SM.

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

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

- 1 multiplet in a high dim rep. : **minimal DM model** [Cirelli et al., 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** [0510064, 0705.4493, 1109,2604]
  - **Doublet-triplet DM model** [1403.7744, 1707.03094]
  - **Triplet-quadruplet DM model** [1601.01354, 1711.05622]

  … …

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: $\quad (Q_A)_k^{ij} = \begin{pmatrix} (Q_1)_k^{ij} \\ (Q_2)_k^{ij} \end{pmatrix}, (H_B)_j = \begin{pmatrix} H_i^\dagger \\ H_i \end{pmatrix}$

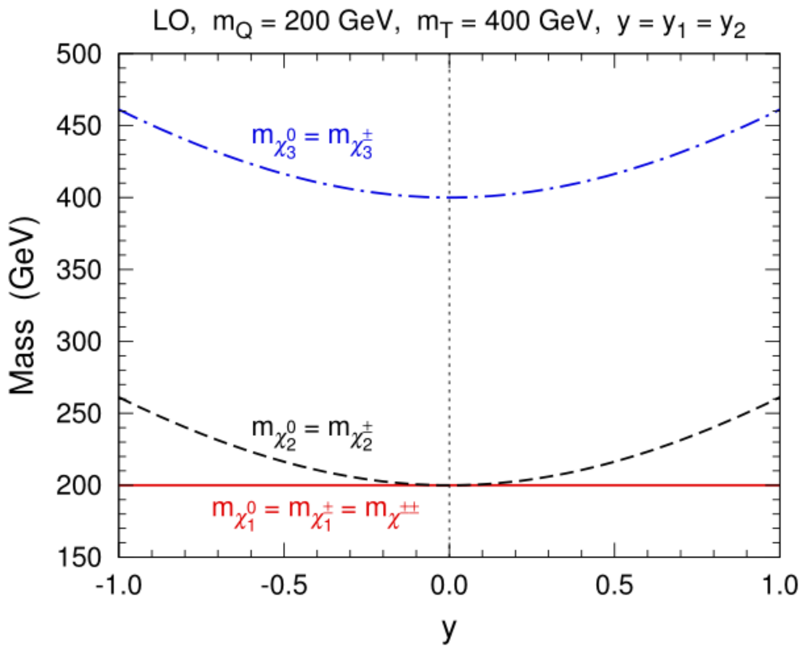
This symmetry is explicitly broken by the $U(1)_Y$ gauge symmetry.

There are still some important properties under this approximate symmetry.

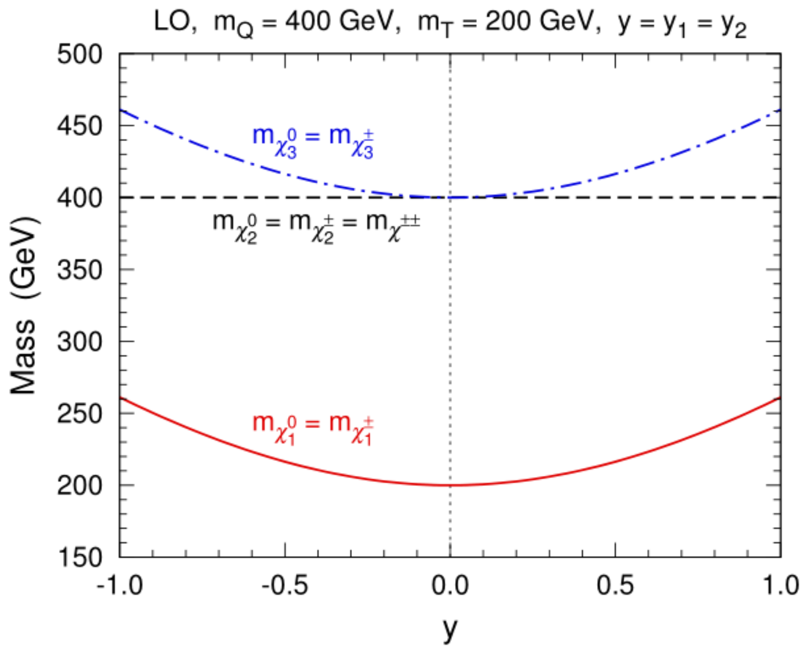
$y_1 = y_2$: A custodial $SU(2)_R$ global symmetry limit

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 $m_{\chi_1^0} < m_{\chi_i^\pm}, m_{\chi^{++}}$.



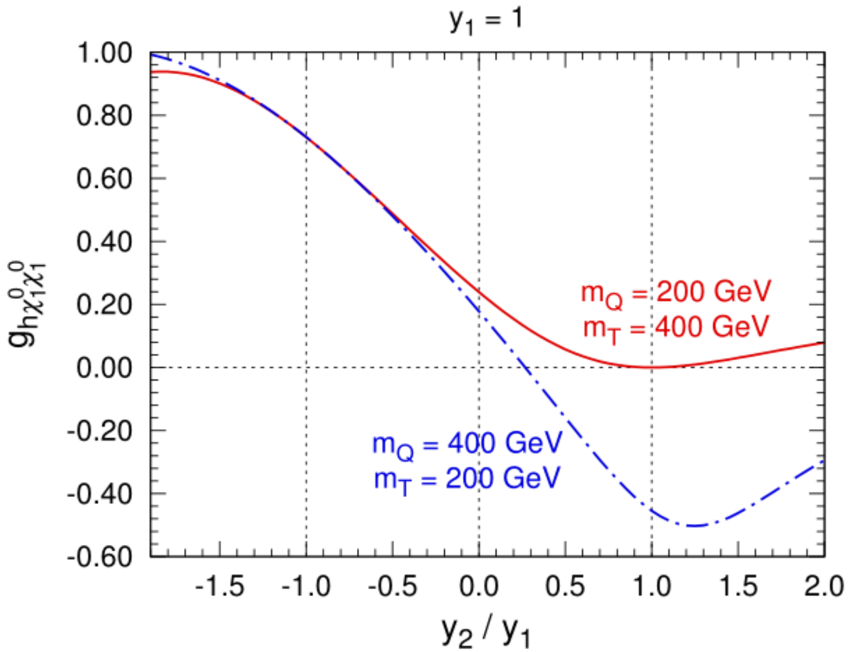
$m_Q < m_T$ case



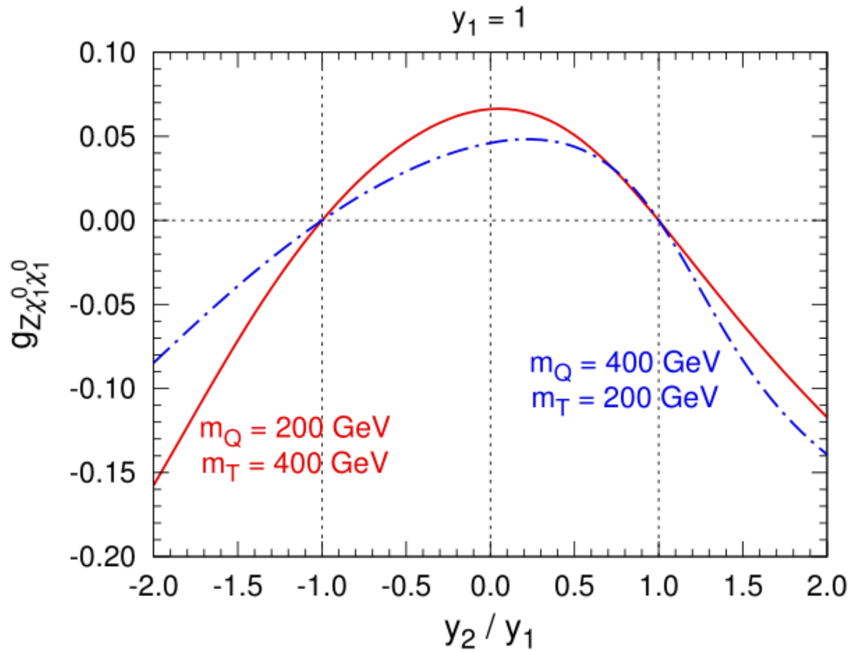
$m_T < m_Q$ case

$y_1 = y_2$: 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 $m_Q, m_T \gtrsim 1\text{TeV}$

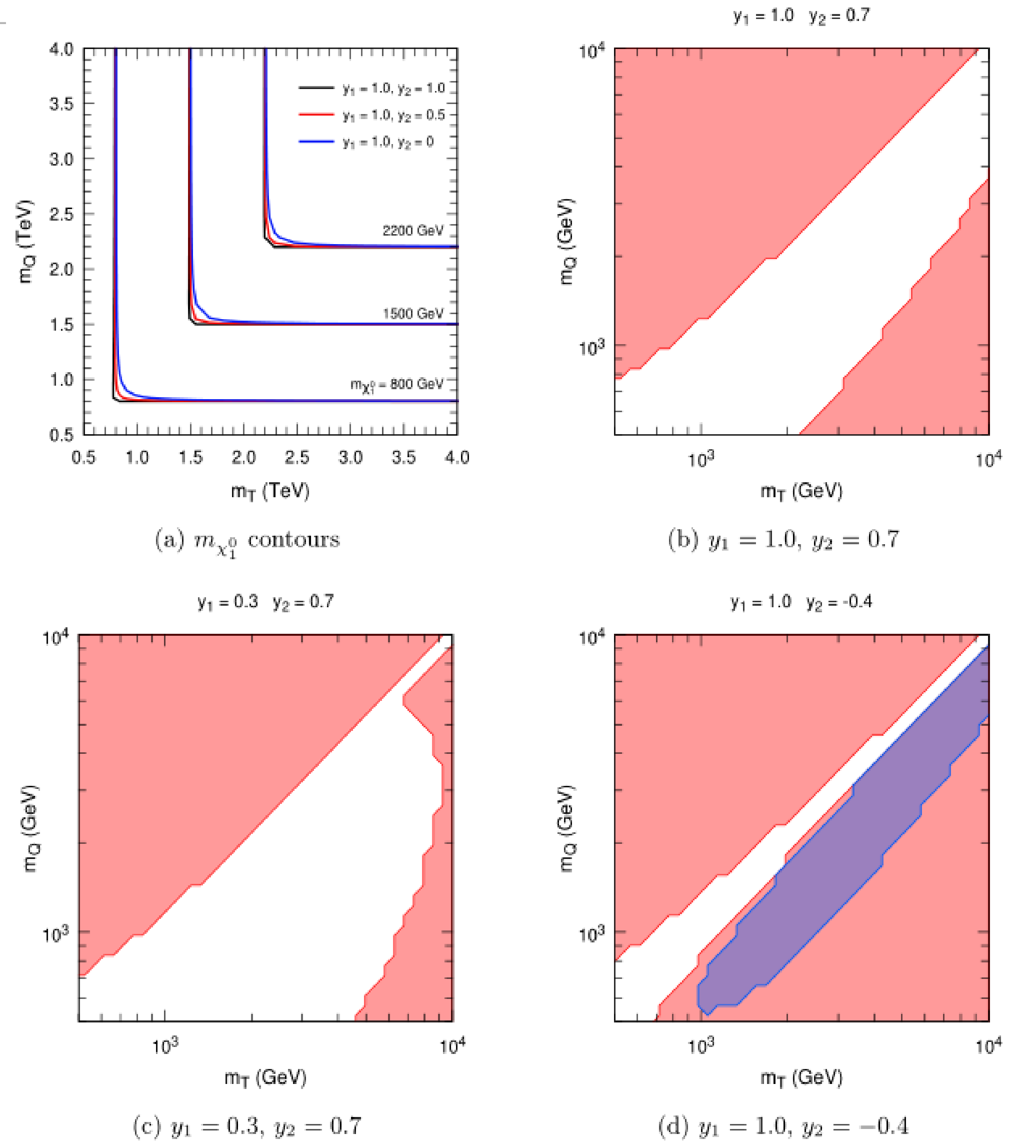
y_1 and y_2 will not significant affect $m_{\chi_1^0}$.

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



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

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

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

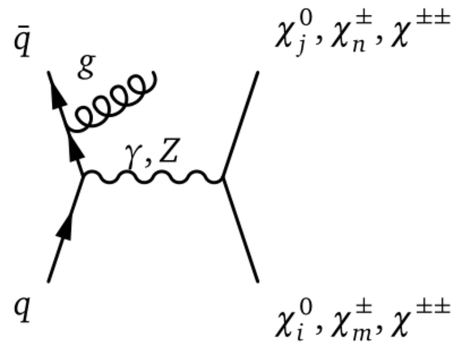
(d) $y_1 = 1.0,\ y_2 = -0.4$

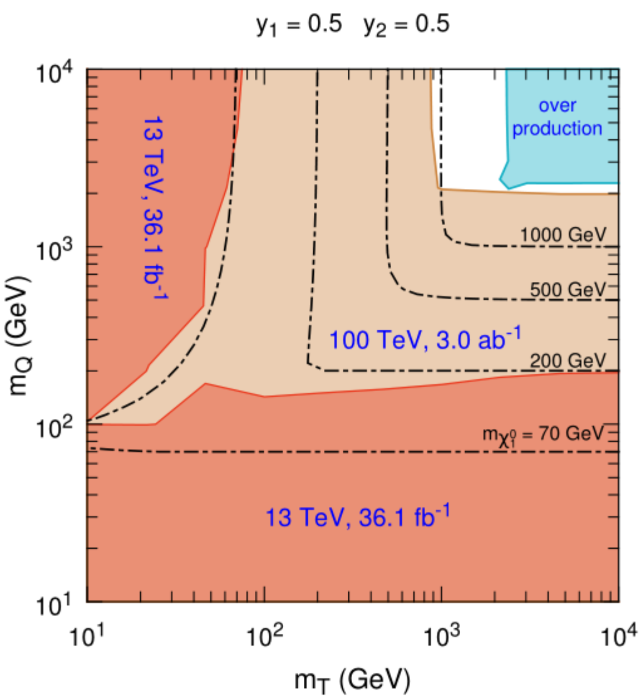
Constrains from mono-jet like channel

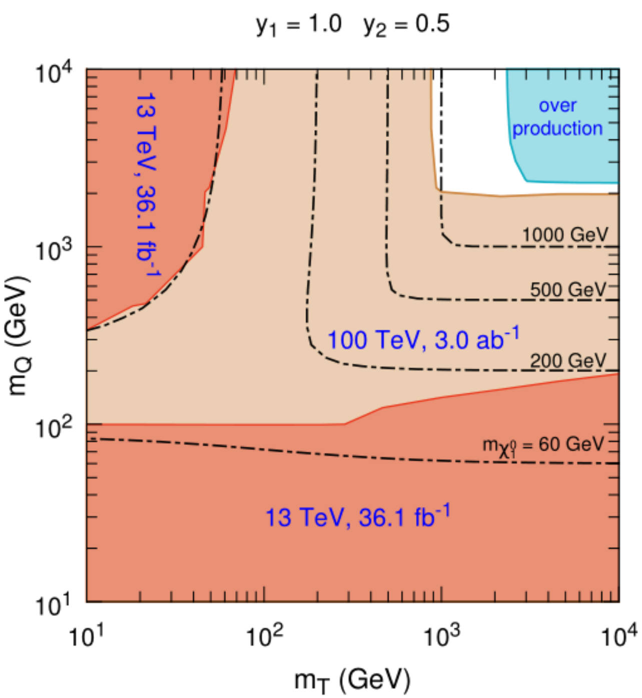
New light particle may directly produced at high energy colliders.

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.





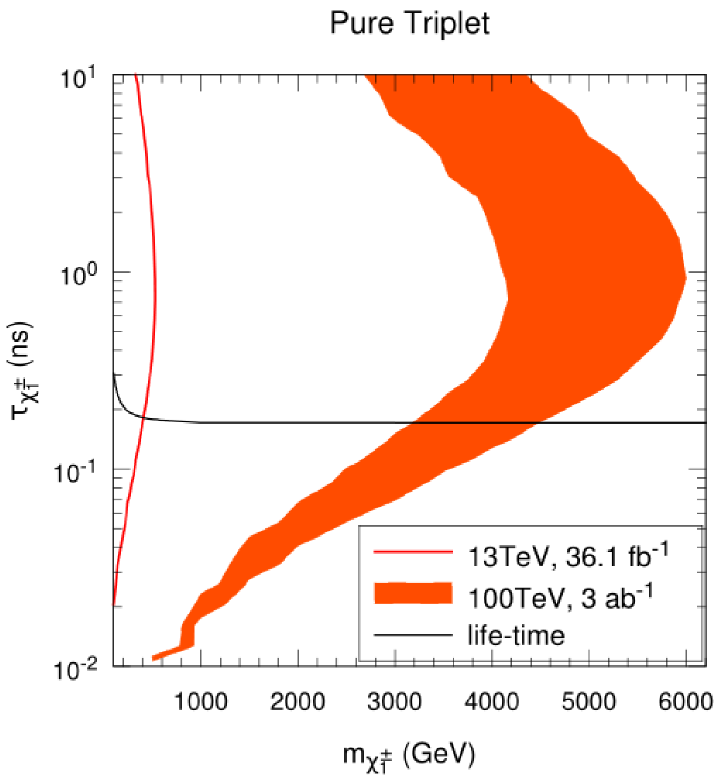


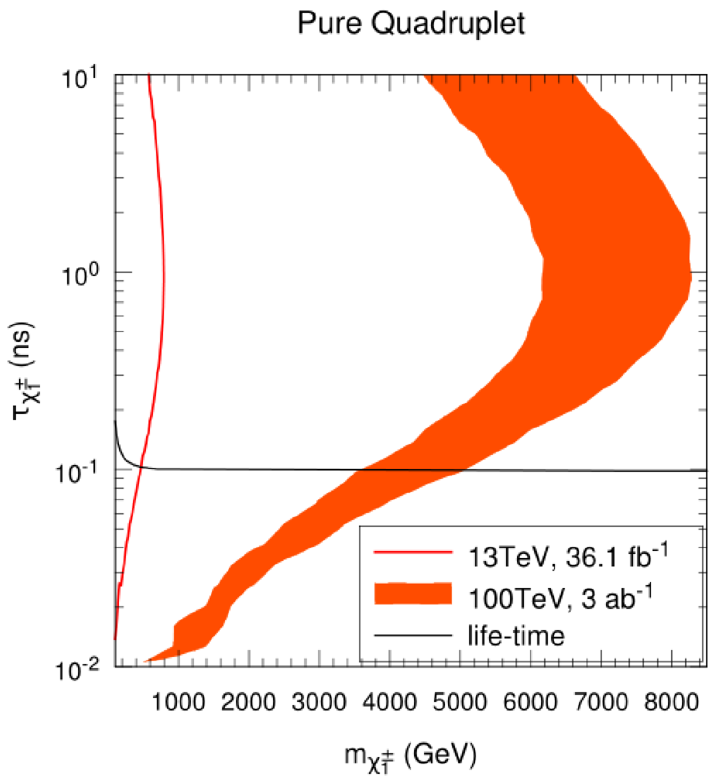
Constrains from disappearing track channel

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.

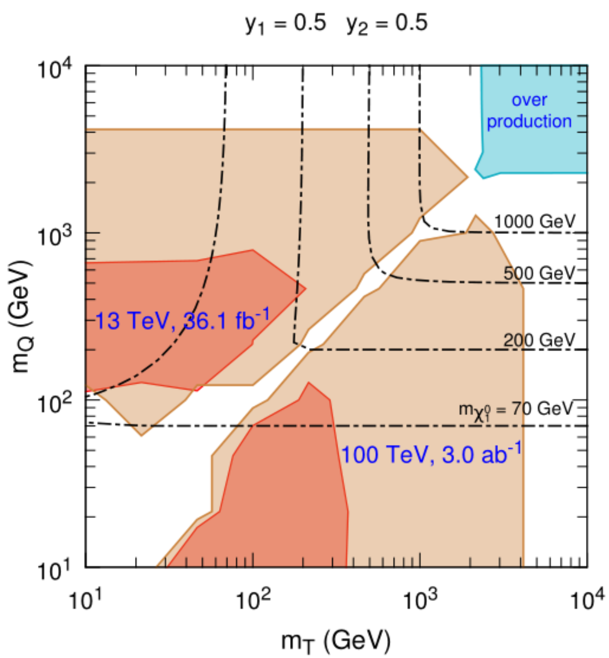




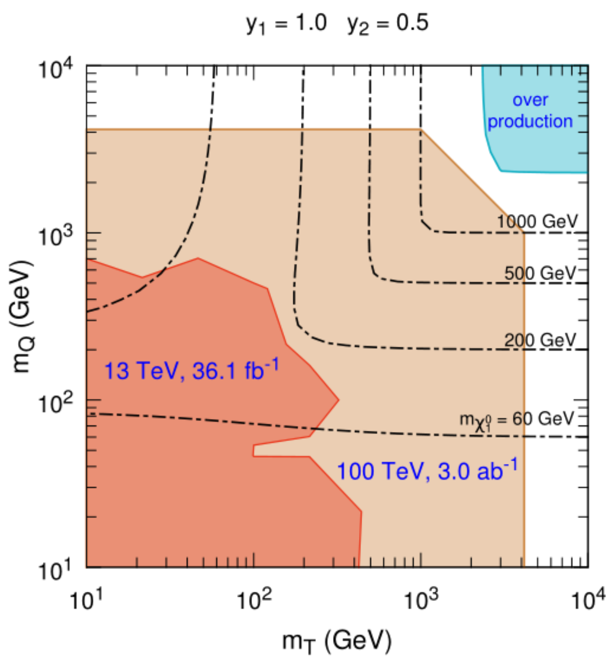
Constrains from multilepton channel

The heavier charged and neutral dark sector particles can decay into lighter ones plus leptons, and here we focus on the cased which contain two or three leptons in the final state.

The relic density has been calculated for completeness.



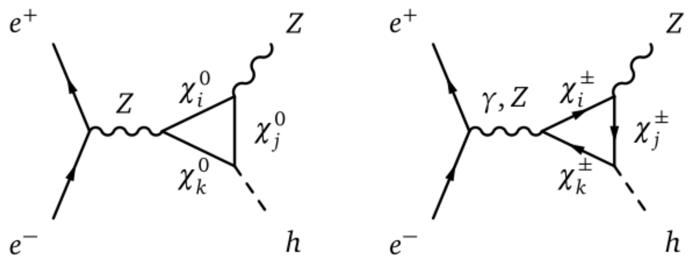
(a) $y_1 = y_2 = 0.5$



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

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

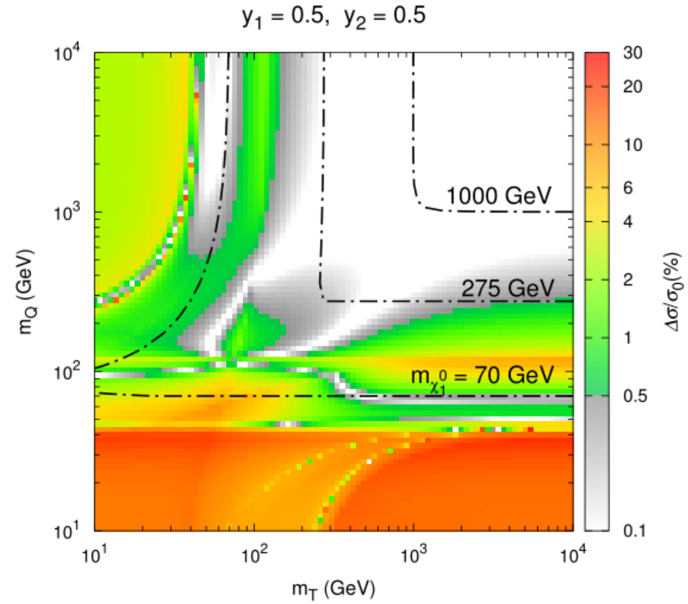
We use **FeynArts** and **FormCalc** to calculate the one-loop correction to $e^+e^- \longrightarrow hZ$ channel.

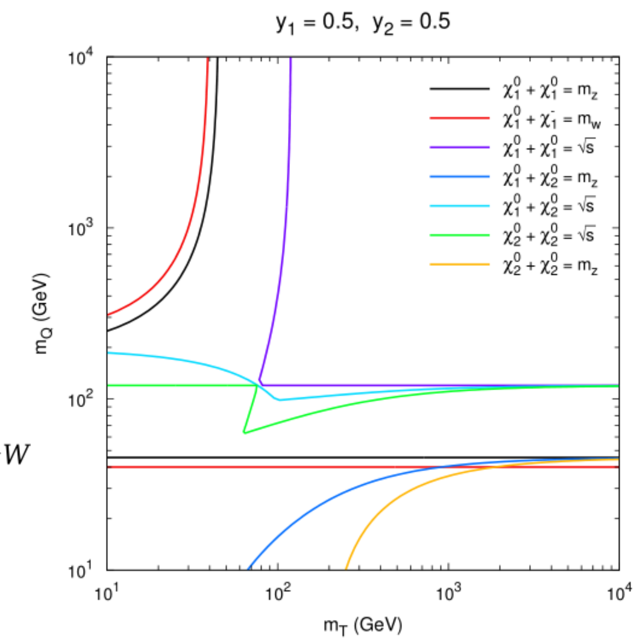


Color regions: $\Delta\sigma_{ZH}/\sigma_{ZH} \geq 0.5\%$ with $\sqrt{s} = 240$ GeV, $5\ ab^{-1}$

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

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



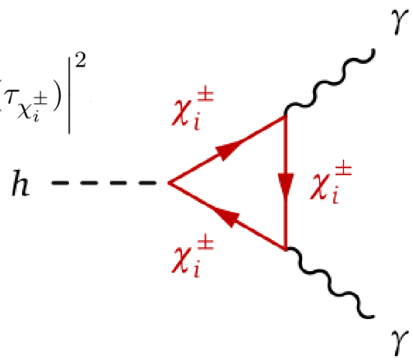


Constrains from h $\longrightarrow \gamma\gamma$ channel

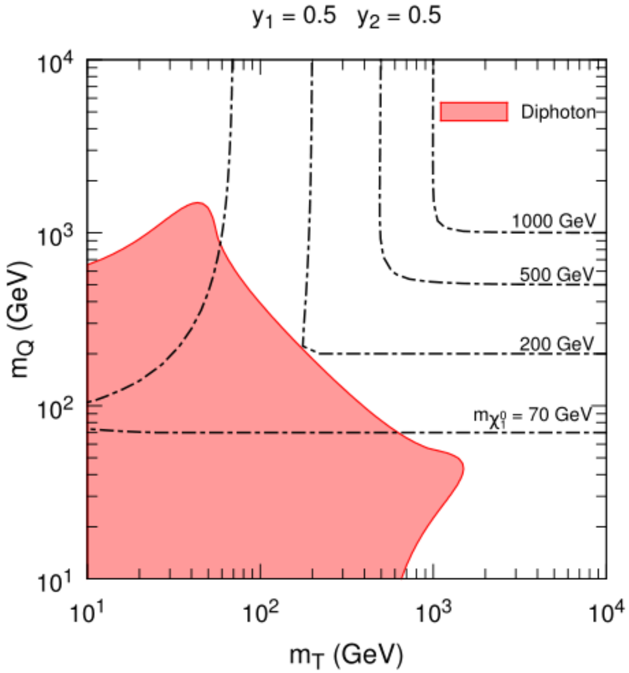
In this model, the dark sector can come into the loop and modified the partial decay width of higgs.

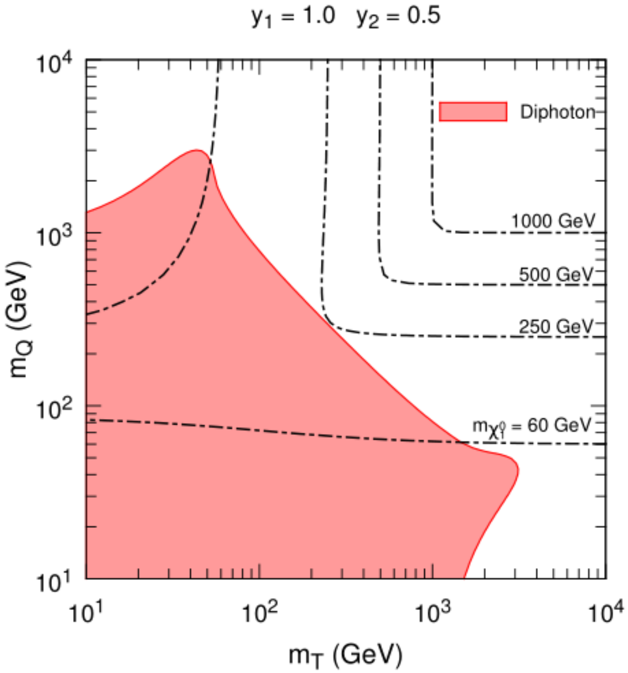
$$\Gamma_{\gamma\gamma} = \frac{G_F \alpha^2 m_h^3}{128\sqrt{2}\pi^3}\left|\sum_f N_c Q_f^2 A_{1/2}(\tau_f) + A_1(\tau_W) + \sum_i \frac{G_{h,ii} v}{m_{\chi_i^\pm}} A_{1/2}(\tau_{\chi_i^\pm})\right|^2$$

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



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





Summary

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- 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;
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Thank you