Exploring Dark Matter at the CEPC via Loop Effects

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Based on QFX, XJ Bi, PF Yin, ZH Yu, arXiv:1707.03094, PRD

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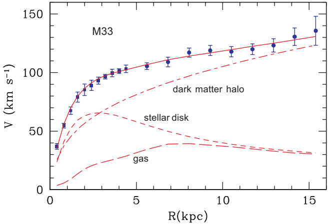
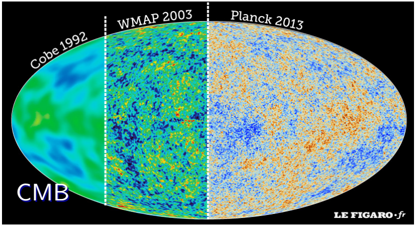
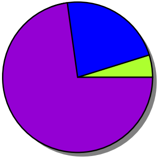
Evidence of dark matter

Dark matter evidences: Dwarf galaxies, glaxies, cluster, large scale structure and even the whole observation universe (**via gravitational effects**)







Planck 2015

Cold dark matter (25.8%)

$\Omega_c h^2 = 0.1186 \pm 0.0020$

Baryonic matter (4.8%)

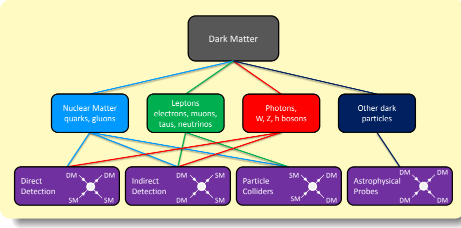
$\Omega_b h^2 = 0.02226 \pm 0.00023$

Dark energy (69.3%)

$\Omega_\Lambda = 0.692 \pm 0.012$

Dark matter detections

- **Direct detection:**
  Searching for nuclear recoil signatures induced by DM-nucleus scatterings
  DAMA, CoGeNT, XENON, CDMS, LUX, CDEX, PANDAX, ...



Dark Matter

Nuclear Matter quarks, gluons

Leptons electrons, muons, taus, neutrinos

Photons, W, Z, h bosons

Other dark particles

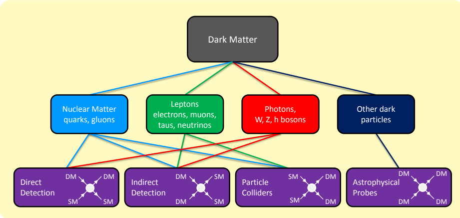
Direct Detection

Indirect Detection

Particle Colliders

Astrophysical Probes

Dark matter detections



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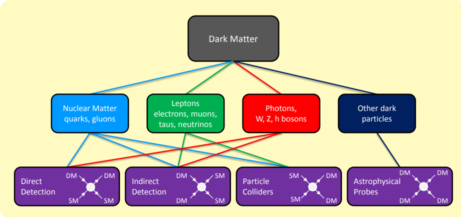
  Searching for SM particle from DM annihilation or decay
  PAMELA, ATIC, Fermi, IceCube, AMS-02, DAMPE, HERD ...

Dark matter detections



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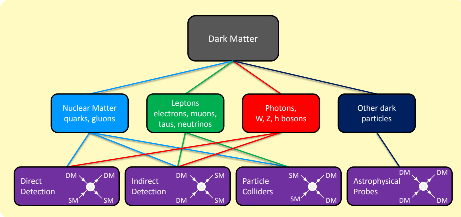
- **Collider searches**:

  Searching for DM signals at colliders

  LHC, ILC, CLIC, CEPC/SppC, ...

Dark matter detections



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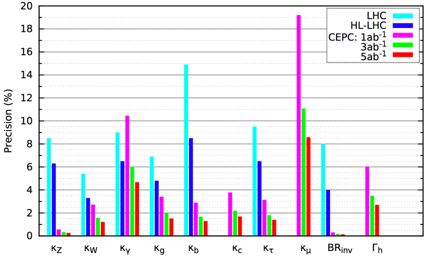
- **Collider searches**:
  Searching for DM signals at colliders
  LHC, ILC, CLIC, CEPC/SppC, ...
- **Pure gravitational effects**:
  Influencing galaxy rotation curves, large scale structure

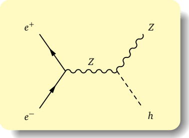
CEPC measuremets

- future electron positron collider， such as CEPC and ILC, can measure SM parameters with very high precision.
- $\sqrt{s} = 250$ GeV, 5 ab^{-1} ， precision of $\sigma(Zh)$ can be 0.51%



If new particle couples with SM particles, it will influence the SM measurements

We study the effects of $SU(2)_L$ multiplets on the $\sigma(e^+e^- \to Zh)$



Singlet-Doublet Fermionic Dark Matter (SDFDM)

Introduce left-handed Weyl fermions in the dark sector:

$$S \in (\mathbf{1}, 0), \quad D_1 = \begin{pmatrix} D_1^0 \\ D_1^- \end{pmatrix} \in (\mathbf{2}, -1/2), \quad D_2 = \begin{pmatrix} D_2^+ \\ D_2^0 \end{pmatrix} \in (\mathbf{2}, +1/2)$$

$$\mathcal{L}_{\mathrm{S}} = iS^\dagger \bar{\sigma}^\mu \partial_\mu S - \frac{1}{2}(m_S SS + \mathrm{h.c.})$$

$$\mathcal{L}_{\mathrm{D}} = iD_1^\dagger \bar{\sigma}^\mu D_\mu D_1 + iD_2^\dagger \bar{\sigma}^\mu D_\mu D_2 - (m_D \epsilon_{ij} D_1^i D_2^j + \mathrm{h.c.})$$

Yukawa couplings: $\mathcal{L}_{\mathrm{HSD}} = y_1 H_i S D_1^i - y_2 H_i^\dagger S D_2^i + \mathrm{h.c.}$

Custodial symmetry limit $y = y_1 = y_2$ $\Rightarrow$ $\mathrm{SU}(2)_{\mathrm{L}} \times \mathrm{SU}(2)_{\mathrm{R}}$ invariant form:

$$\mathcal{L}_{\mathrm{D}} + \mathcal{L}_{\mathrm{HSD}} = i\mathcal{D}_A^\dagger \bar{\sigma}^\mu D_\mu \mathcal{D}^A - \frac{1}{2}[m_D \epsilon_{AB} \epsilon_{ij} (\mathcal{D}^A)^i (\mathcal{D}^B)^j + \mathrm{h.c.}] + [y \epsilon_{AB} (\mathcal{H}^A)_i S (\mathcal{D}^B)^j + \mathrm{h.c.}]$$

$\mathrm{SU}(2)_{\mathrm{R}}$ doublets: $(\mathcal{D}^A)^i = \begin{pmatrix} D_1^i \\ D_2^i \end{pmatrix}, \quad (\mathcal{H}^A)_i = \begin{pmatrix} H_i^\dagger \\ H_i \end{pmatrix}$

SDFDM: State Mixing

The dark sector involves 3 Majorana fermions and 1 singly charged fermion

$$\mathcal{L}_{\text{mass}} = -\frac{1}{2}(S \quad D_1^0 \quad D_2^0)\mathcal{M}_{\text{N}}\begin{pmatrix} S \\ D_1^0 \\ D_2^0 \end{pmatrix} - m_D D_1^- D_2^+ + \text{h.c.} = -\frac{1}{2}\sum_{i=1}^{3} m_{\chi_i^0}\chi_i^0\chi_i^0 - m_{\chi^\pm}\chi^-\chi^+ + \text{h.c.}$$

$$\mathcal{M}_{\text{N}} = \begin{pmatrix} m_S & \frac{1}{\sqrt{2}}y_1 v & \frac{1}{\sqrt{2}}y_2 v \\ \frac{1}{\sqrt{2}}y_1 v & 0 & -m_D \\ \frac{1}{\sqrt{2}}y_2 v & -m_D & 0 \end{pmatrix}, \quad \begin{pmatrix} S \\ D_1^0 \\ D_2^0 \end{pmatrix} = \mathcal{N}\begin{pmatrix} \chi_1^0 \\ \chi_2^0 \\ \chi_3^0 \end{pmatrix}$$

$$\mathcal{N}^{\text{T}}\mathcal{M}_{\text{N}}\mathcal{N} = \text{diag}(m_{\chi_1^0}, m_{\chi_2^0}, m_{\chi_3^0}), \quad \chi^+ = D_2^+, \quad \chi^- = D_1^-$$

Couplings of the **DM candidate** χ_1^0 to the Higgs and Z bosons:

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

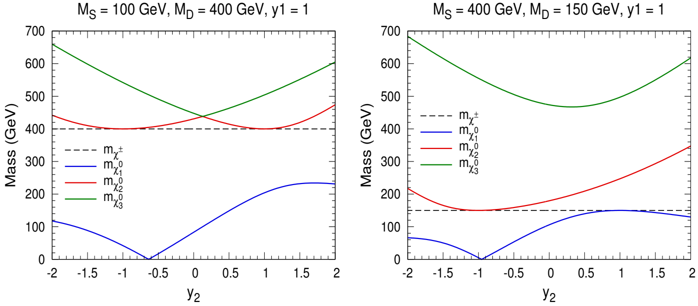
$$g_{h\chi_1^0\chi_1^0} = -\sqrt{2}(y_1\mathcal{N}_{21} + y_2\mathcal{N}_{31})\mathcal{N}_{11}, \quad g_{Z\chi_1^0\chi_1^0} = -\frac{g}{2c_{\text{W}}}(|\mathcal{N}_{21}|^2 - |\mathcal{N}_{31}|^2)$$

Custodial symmetry limit $y_1 = y_2 \;\Rightarrow\; g_{Z\chi_1^0\chi_1^0} = 0$

$y_1 = y_2$ and $m_D < m_T \;\Rightarrow\; g_{h\chi_1^0\chi_1^0} = 0$

SDFDM spectrums

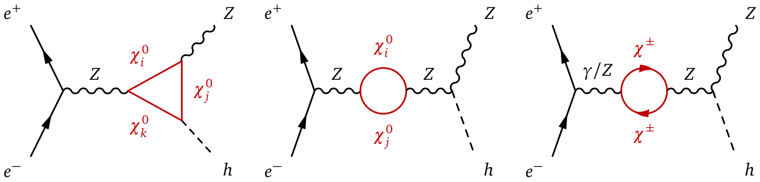
Particle mass as functions of y_1.



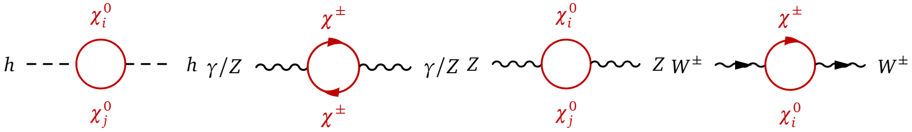
- $m_{\chi^\pm} = m_D$.
- $y_1 = y_2$, or $y_1 = -y_2$, the mass of one neutral particle equals to the mass of $\chi^\pm$. $\chi^\pm$ could be long live particle if this neutral particls is the lightest one.

The corrections of electroweak multiplets to $\sigma(Zh)$

New physics will influence hZZ **vertex** and **propagators**



New physics will also influence the self-energy of W, Z bosons

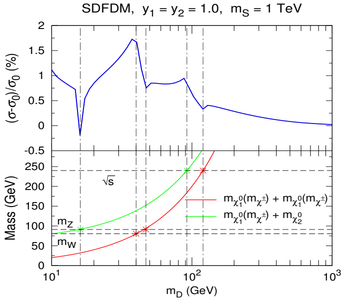


The corrections of electroweak multiplets to $\sigma(Zh)$

Defining relative corrections

$$\delta\sigma/\sigma_0 \equiv \frac{|\sigma_{ZH} - \sigma_{ZH,SM}|}{\sigma_{ZH}}$$

We use **FeynArts**, **FormCalc** to calculate $\delta\sigma/\sigma_0$



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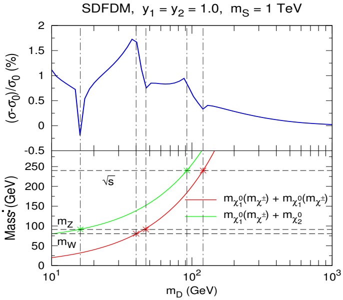

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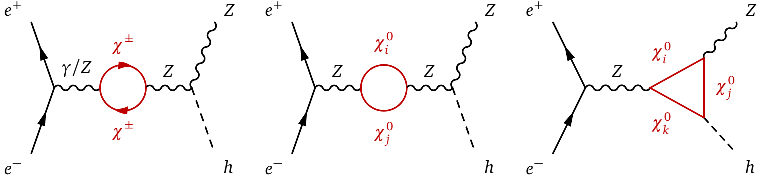
Corrections in two cases could be enhanced

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



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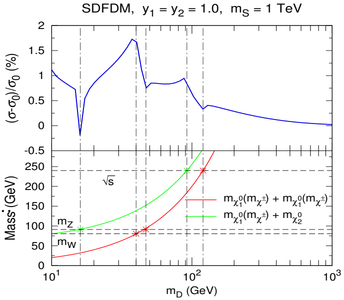
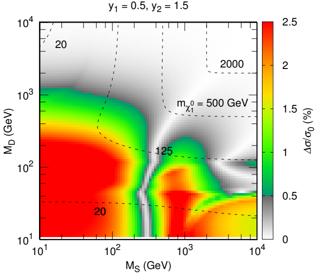
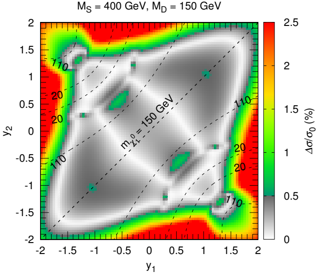




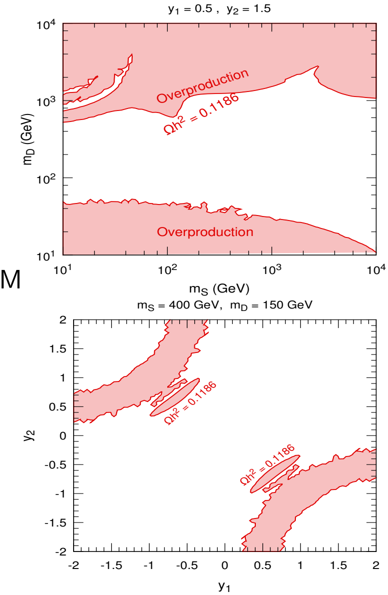


Direct detection

The couplings of the DM candidate χ_1^0 to the Higgs and Z bosons

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

induce **spin-independent (SI)** and **spin-dependent (SD)** scatterings between DM and nuclei, respectively



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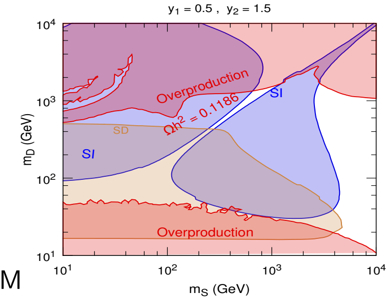
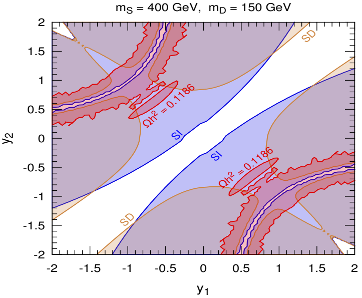
Most stringent constraints from current direct detection experiments:

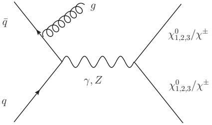
- **SI:** PandaX-II [1607.07400], LUX [1608.07648]
- **SD:** PandaX-II (proton)[1611.06553], LUX (neutron) [1602.03489], PICO (proton) [1503.00008, 1510.07754]





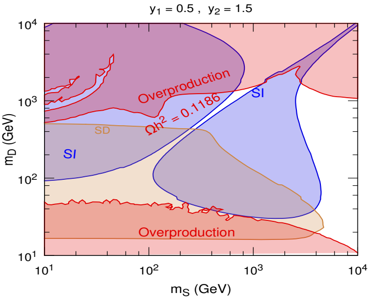
Colliders constrains

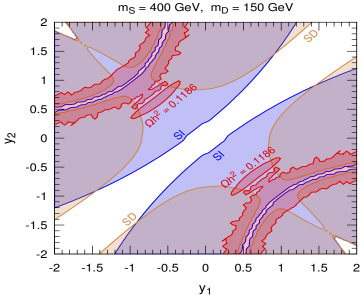
New light particles could be produced directly at high energy colliders:



We consider all possible processes:

$$\boxed{pp \to \chi_i^0\chi_j^0, \chi_i^0\chi^\pm, \chi^\pm\chi^\pm}$$


y₁ = 0.5 , y₂ = 1.5


m_S = 400 GeV, m_D = 150 GeV

Colliders constrains

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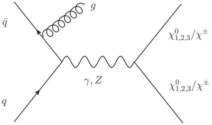

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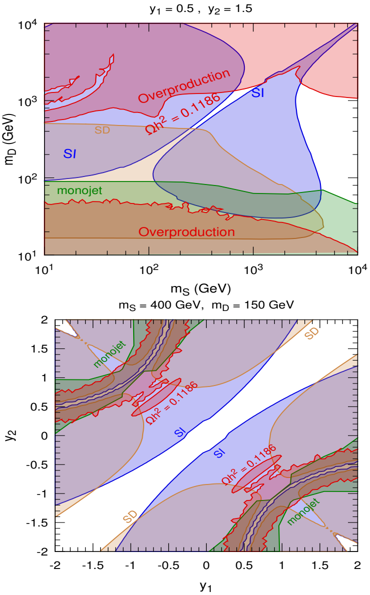
$$pp \to \chi_i^0\chi_j^0, \chi_i^0\chi^\pm, \chi^\pm\chi^\pm$$

LHC monojet search at 8 TeV with 20.3 ifb data. [1502.01518]



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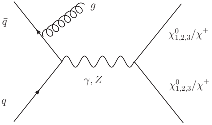

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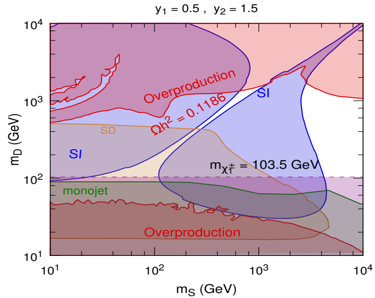
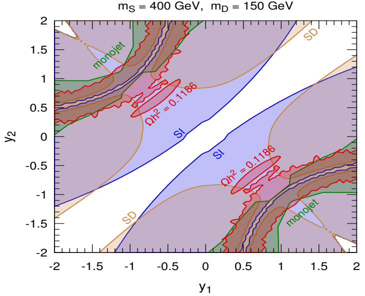
LHC monojet search at 8 TeV with 20.3 ifb data. [1502.01518]

In addition, LEP charged particles searches require $m_{\chi^\pm} \leq 103.5$ GeV [0509008].
In our model SDFDM, $m_{\chi^\pm} = m_D$.





Higgs and Z decays

- If the kinematics is allowed, the Higgs and Z could decay into DM particles. Such **invisible decays** are constrained by the relevant searches at colliders.
- If new charged particles couple to the Higgs, they could modify the Higgs decay width to di-photon via triangle loops. $\Delta\Gamma/\Gamma$ could be tested at a level of 9%.

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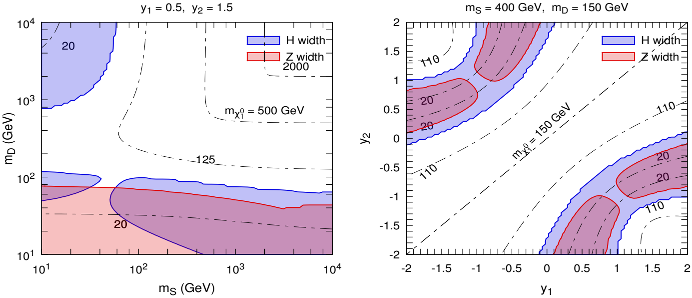
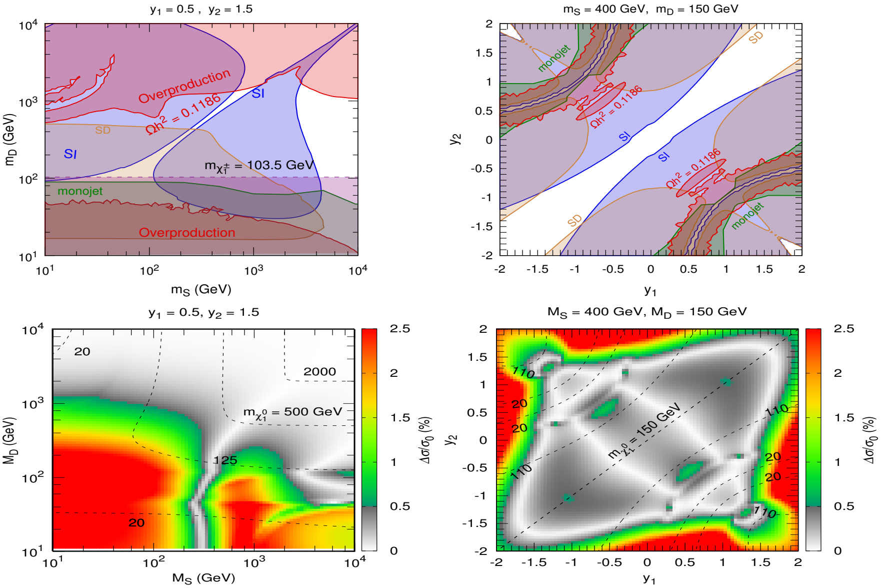


We require $\Gamma(Z \to \text{inv}) < 2$ MeV, LEP [0509008].
and $\Gamma(h \to \text{inv})/\Gamma_h < 0.28\%$, [CEPC-pre-CDR].

Comparison


$y_1 = 0.5\ ,\ \ y_2 = 1.5$
m_D (GeV)
m_S (GeV)
10^1
10^2
10^3
10^4
Overproduction
$\Omega h^2 = 0.1186$
SI
SD
SI
$m_{\chi_1^\pm} = 103.5$ GeV
monojet
Overproduction
$m_S = 400$ GeV, $\ m_D = 150$ GeV
y_2
y_1
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
monojet
SD
$\Omega h^2 = 0.1186$
SI
SI
$\Omega h^2 = 0.1186$
SD
monojet
$y_1 = 0.5$, $y_2 = 1.5$
M_D (GeV)
M_S (GeV)
20
2000
$m_{\chi_1^0} = 500$ GeV
125
20
$\Delta\sigma/\sigma_0$ (%)
0
0.5
1
1.5
2
2.5
$M_S = 400$ GeV, $M_D = 150$ GeV
y_2
y_1
110
20
20
110
$m_{\chi_1^0} = 150$ GeV
110
20
20
110
$\Delta\sigma/\sigma_0$ (%)

Doublet-Triplet Fermionic Dark Matter (DTFDM)

Introduce left-handed Weyl fermions in the dark sector:

$$D_1 = \begin{pmatrix} D_1^0 \\ D_1^- \end{pmatrix} \in (2,-1/2), \quad D_2 = \begin{pmatrix} D_2^+ \\ D_2^0 \end{pmatrix} \in (2,+1/2), \quad T = \begin{pmatrix} T^+ \\ T^0 \\ T^- \end{pmatrix} \in (3,0)$$

$$\mathcal{L}_\mathrm{D} = iD_1^\dagger \bar{\sigma}^\mu D_\mu D_1 + iD_2^\dagger \bar{\sigma}^\mu D_\mu D_2 + (m_D \epsilon_{ij} D_1^i D_2^j + \text{h.c.})$$

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

Yukawa couplings: $\mathcal{L}_\mathrm{HDT} = y_1 H_i T^a (\sigma^a)^i_j D_1^j - y_2 H_i^\dagger T^a (\sigma^a)^i_j D_2^j + \text{h.c.}$

Custodial symmetry limit $y = y_1 = y_2$ ⇒ $\mathrm{SU}(2)_\mathrm{L} \times \mathrm{SU}(2)_\mathrm{R}$ invariant form:

$$\mathcal{L}_\mathrm{D} + \mathcal{L}_\mathrm{HDT} = i\mathcal{D}_A^\dagger \bar{\sigma}^\mu D_\mu \mathcal{D}^A + \frac{1}{2}[m_D \epsilon_{AB} \epsilon_{ij} (\mathcal{D}^A)^i (\mathcal{D}^B)^j + \text{h.c.}] + [y \epsilon_{AB} (\mathcal{H}^A)_i T^a (\sigma^a)^i_j (\mathcal{D}^B)^j + \text{h.c.}]$$

$$\mathrm{SU}(2)_\mathrm{R} \text{ doublets: } (\mathcal{D}^A)^i = \begin{pmatrix} D_1^i \\ D_2^i \end{pmatrix}, \quad (\mathcal{H}^A)_i = \begin{pmatrix} H_i^\dagger \\ H_i \end{pmatrix}$$

DTFDM: State Mixing

The dark sector involves 3 Majorana fermions and 2 singly charged fermions

$$\mathcal{L}_{\text{mass}} = -\frac{1}{2}(T^0 \quad D_1^0 \quad D_2^0)\mathcal{M}_{\text{N}}\begin{pmatrix} T^0 \\ D_1^0 \\ D_2^0 \end{pmatrix} - (T^- \quad D_1^-)\mathcal{M}_{\text{C}}\begin{pmatrix} T^+ \\ D_2^+ \end{pmatrix} + \text{h.c.}$$

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

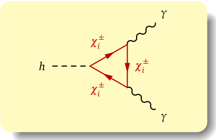
$$\mathcal{M}_{\text{N}} = \begin{pmatrix} m_T & \frac{1}{\sqrt{2}}y_1 v & -\frac{1}{\sqrt{2}}y_2 v \\ \frac{1}{\sqrt{2}}y_1 v & 0 & m_D \\ -\frac{1}{\sqrt{2}}y_2 v & m_D & 0 \end{pmatrix}, \quad \mathcal{M}_{\text{C}} = \begin{pmatrix} m_T & -y_2 v \\ -y_1 v & -m_D \end{pmatrix}$$

$$\begin{pmatrix} T^0 \\ D_1^0 \\ D_2^0 \end{pmatrix} = \mathcal{N}\begin{pmatrix} \chi_1^0 \\ \chi_2^0 \\ \chi_3^0 \end{pmatrix}, \quad \begin{pmatrix} T^+ \\ D_2^+ \end{pmatrix} = \mathcal{C}_{\text{L}}\begin{pmatrix} \chi_1^+ \\ \chi_2^+ \end{pmatrix}, \quad \begin{pmatrix} T^- \\ D_1^- \end{pmatrix} = \mathcal{C}_{\text{R}}\begin{pmatrix} \chi_1^- \\ \chi_2^- \end{pmatrix}$$

Custodial symmetry limit $y_1 = y_2 \;\Rightarrow\; g_{Z\chi_1^0\chi_1^0} = 0$

$y_1 = y_2$ and $m_D < m_T \;\Rightarrow\; g_{h\chi_1^0\chi_1^0} = 0$

Higgs decays to $\gamma\gamma$



Higgs couples to new charged particles:

$$\mathcal{L} \supset \sum_{ij} G^{S}_{h,ij} h \bar{\Psi}^+_i \Psi^+_j - \sum_{ij} G^{P}_{h,ij} h \bar{\Psi}^+_i i\gamma^5 \Psi^+_j$$

$C^{S}_{h,ij} = \sqrt{2}\ \mathrm{Re}(y_1 \mathcal{N}_{1i}\mathcal{N}_{2j} + y_2 \mathcal{N}_{1i}\mathcal{N}_{3j}), C^{P}_{h,ij} = \sqrt{2}\ \mathrm{Im}(y_1 \mathcal{N}_{1i}\mathcal{N}_{2j} + y_2 \mathcal{N}_{1i}\mathcal{N}_{3j})$

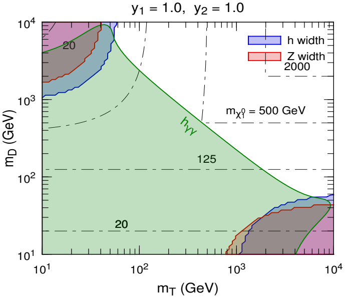
Higgs decays to $\gamma\gamma$

$$\Gamma(h \to \gamma\gamma) = \frac{G_F \alpha^2 m_h^3}{128\sqrt{2}\pi^3} \left| A_1(\tau_W) + \sum_f c_f Q_f^2 A_{1/2}(\tau_f) + \sum_i \frac{G^S_{h,ii} v}{m_{\chi^\pm}} A_{1/2}(\tau_{\chi^\pm}) \right|^2 ,$$

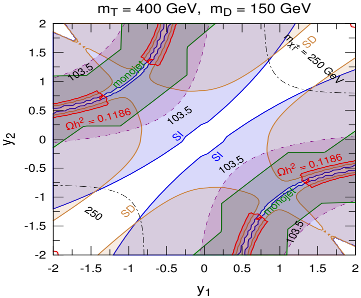
CEPC with 5 ab^{-1} data

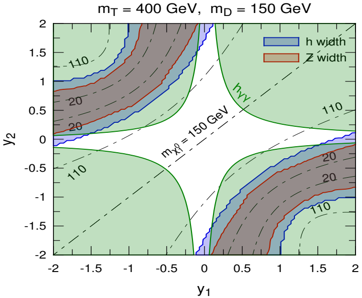
$$\frac{\delta\Gamma(h\to\gamma\gamma)}{\Gamma(h\to\gamma\gamma)} < 9.4\%$$

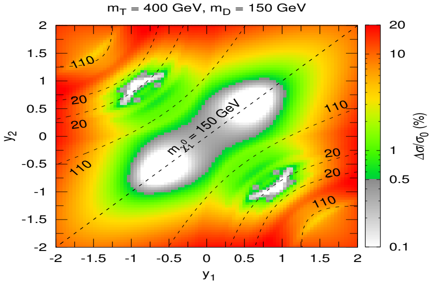
the effect on $\Gamma(h \to \gamma\gamma)$ via loops would not be bounded by mass thresholds.



Comparisons







CEPC can probe large part of parameter space where all other experiments lose sensitivities.

Conclusions

- We proposed **two UV-completed models** with **two electroweak multiplets.** After EW vacuum breaking, three neutral particles are obtained with the lightest one could service as the **DM candidate.**
- We considerd the constrains from **relic density, direct detections,** and **colliders**.
- We calculated the **corrections to the cross section of Zh associated production**. The ability of CEPC with 5 ifb data is comparable to or greater than other detections, especially when $y_1 = \pm y_2$, where other detections may lose significance.