Current and Future Collider Searches for Electroweak Dark Matter Models

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Based on Tait, ZHY, arXiv:1601.01354, JHEP
CF Cai, ZHY, HH Zhang, arXiv:1611.02186, NPB
CF Cai, ZHY, HH Zhang, arXiv:1705.07921, NPB
QF Xiang, XJ Bi, PF Yin, ZHY, arXiv:1707.03094, PRD
JW Wang, XJ Bi, QF Xiang, PF Yin, ZHY, arXiv:1711.05622, PRD

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An attractive class of dark matter (DM) candidates is weakly interacting massive particles (WIMPs), as they can explain the observed DM relic abundance via thermal production mechanism.

It is natural to construct WIMP models by extending the Standard Model (SM) with a dark sector consisting of electroweak (EW) SU(2)$_L$ multiplets, whose neutral components could provide a viable DM candidate.
**Direct Detection of Dark Matter**

For a **Majorana DM candidate** $\chi$, the couplings to the Higgs and $Z$ bosons

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

would induce **spin-independent (SI)** and **spin-dependent (SD)** DM-nucleus scatterings.

For scalar multiplets, interactions with the Higgs doublet could split the real and imaginary parts of neutral components, leading to a **CP-even or CP-odd real scalar DM candidate**. Its coupling to the Higgs boson would induce **SI scatterings**.

**Stringent constraints from current direct detection experiments**

- **SI**: PandaX-II, XENON1T, LUX
- **SD**: PICO (proton), PandaX-II (neutron)
Fermionic Models

1. **SDFDM: Singlet + 2 Doublets** [Mahbubani, Senatore, hep-ph/0510064, PRD; D’Eramo, 0705.4493, PRD; Cohen et al., 1109.2604, PRD]

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

   \[ \mathcal{L} \supset -\frac{1}{2} m_S S S - m_D \epsilon_{ij} D_1^i D_2^j + y_1 H_i S D_1^i - y_2 H_i^+ S D_2^i + \text{h.c.} \]

2. **DTFDM: 2 Doublets + Triplet** [Dedes, Karamitros, 1403.7744, PRD]

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

   \[ \mathcal{L} \supset m_D \epsilon_{ij} D_1^i D_2^j - \frac{1}{2} m_T T^a T^a + y_1 H_i T^a (\sigma^a)^j_i D_1^j - y_2 H_i^+ T^a (\sigma^a)^j_i D_2^j + \text{h.c.} \]

3. **TQFDM: Triplet + 2 Quadruplets** [Tait, ZHY, 1601.01354, JHEP]

   \[ T = \begin{pmatrix} T^+ \\ T^0 \\ T^- \end{pmatrix} \in (3, 0), \quad Q_1 = \begin{pmatrix} Q_1^+ \\ Q_1^0 \\ Q_1^- \end{pmatrix} \in (4, -1/2), \quad Q_2 = \begin{pmatrix} Q_2^{++} \\ Q_2^+ \\ Q_2^0 \\ Q_2^- \end{pmatrix} \in (4, +1/2) \]

   \[ \mathcal{L} \supset -\frac{1}{2} m_T T T - m_Q Q_1 Q_2 + y_1 \epsilon_{jk} (Q_1)_i^{jk} T_k^i H^l - y_2 (Q_2)_i^{jk} T_k^i H_j^+ + \text{h.c.} \]

Impact on vacuum stability will be discussed in Prof. Xiao-Jun Bi’s talk on Jan 25
Mass Eigenstates

Take the TQFDM model as an example [Tait, ZHY, 1601.01354, JHEP]

\[
\mathcal{L}_{\text{mass}} = -\frac{1}{2} (T^0, Q^0_1, Q^0_2) \mathcal{M}_N \begin{pmatrix} T^0 \\ Q^0_1 \\ Q^0_2 \end{pmatrix} - (T^-, Q^-_1, Q^-_2) \mathcal{M}_C \begin{pmatrix} T^- \\ Q^+_1 \\ Q^+_2 \end{pmatrix} - m_Q Q^- Q'^+= \text{h.c.}
\]

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

\[
\begin{pmatrix} T^0 \\ Q^0_1 \\ Q^0_2 \end{pmatrix} = \mathcal{N} \begin{pmatrix} \chi^0_1 \\ \chi^0_2 \\ \chi^0_3 \end{pmatrix}, \quad \begin{pmatrix} T^+ \\ Q^+_1 \\ Q^+_2 \end{pmatrix} = \mathcal{C}_L \begin{pmatrix} \chi^+_1 \\ \chi^+_2 \\ \chi^+_3 \end{pmatrix}, \quad \begin{pmatrix} T^- \\ Q^-_1 \\ Q^-_2 \end{pmatrix} = \mathcal{C}_R \begin{pmatrix} \chi^-_1 \\ \chi^-_2 \\ \chi^-_3 \end{pmatrix}, \quad \chi^- \equiv Q^-_1, \quad \chi'^+ \equiv Q'^+_2
\]

3 Majorana fermions \(\chi^0_i\), 3 singly charged fermions \(\chi^\pm_i\), 1 doubly charged fermion \(\chi^{\pm\pm}\)

\(\chi^0_1\) would be an excellent DM candidate if it is the lightest among them
Constraints on the TQFDM model

For $y_1 = y_2 = 0.5$:

- $m_T$ vs $m_Q$: Overproduction
- $\Omega h^2 = 0.1186$
- $m_{\chi^0_1} = 1$ TeV
- LUX
- Fermi

For $y_1 = 0.5$, $y_2 = 1.0$:

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- $\Omega h^2 = 0.1186$
- $m_{\chi^0_1} = 1$ TeV
- LUX
- Fermi

References:
[Tait, ZHY, 1601.01354, JHEP]
**Monojet + $\not{E}_T$ Channel at $pp$ Colliders (TQFDM)**

- **Pair production of dark sector fermions:**
  
  $$pp \rightarrow \chi \chi +\text{jets}, \quad \chi = \chi_i^0, \chi_i^\pm, \chi^{\pm\pm}$$

  Associated with $\geq 1$ hard jet from initial state radiation $\Rightarrow$ **monojet + $\not{E}_T$** final state

- **Main SM backgrounds:**
  
  $$Z(\rightarrow \nu \bar{\nu}) +\text{jets}, \quad W(\rightarrow \ell \nu) +\text{jets}$$

- **Current constraints:** ATLAS searches at the 13 TeV **LHC** with 36.1 fb$^{-1}$ data [ATLAS-CONF-2017-060] excluded parameter regions up to $m_{\chi_1^0} \sim 70 - 200$ GeV

- **Future prospect:** **SPPC** at 100 TeV collecting with 3 ab$^{-1}$ data would be able to explore up to $m_{\chi_1^0} \sim 1 - 2$ TeV

[JW Wang, XJ Bi, QF Xiang, PF Yin, ZHY, 1711.05622, PRD]
Multilepton + $\not{E}_T$ Channel at $pp$ Colliders (TQFDM)

**Signals in the 2$\ell + \not{E}_T$ channel:**
\[ \chi_i^+ \chi_j^- \rightarrow W^+ (\rightarrow \ell^+ \nu) \ W^- (\rightarrow \ell^- \bar{\nu}) \ \chi_1^0 \chi_1^0 \]

**Signals in the 2$\ell + \text{jets} + \not{E}_T$ channel:**
\[ \chi_i^0 \chi_j^\pm \rightarrow Z (\rightarrow \ell^+ \ell^-) \ W^\pm (\rightarrow j j) \ \chi_1^0 \chi_1^0 \]

**Signals in the 3$\ell + \not{E}_T$ channel:**
\[ \chi_i^0 \chi_j^\pm \rightarrow Z (\rightarrow \ell^+ \ell^-) \ W^\pm (\rightarrow \ell' \nu) \ \chi_1^0 \chi_1^0 \]

**Main SM backgrounds:**
$ZZ + \text{jets}, \ WW + \text{jets}, \ WZ + \text{jets}, \ tt + \text{jets}$

**Current constraints:** ATLAS searches at the 13 TeV LHC with 36.1 fb$^{-1}$ data [ATLAS-CONF-2017-039]

**Future prospect:** SPPC experiments at $\sqrt{s} = 100$ TeV with 3 ab$^{-1}$ data

[JW Wang, XJ Bi, QF Xiang, PF Yin, ZHY, 1711.05622, PRD]
**Correction to** $e^+e^- \to Zh$ (DTFDM)

![Diagrams showing interactions between fermions and dark sectors](diagrams)

**EURECOM**

$e^+e^- \to Zh$ cross section could be modified by dark sector fermions via loop effects

**CEPC** experiments with 5 ab$^{-1}$ data can measure the relative deviation from SM down to $\Delta \sigma/\sigma_0 \approx 0.51\%$ [CEPC-SPPC pre-CDR, Vol. II]

[QF Xiang, XJ Bi, PF Yin, ZHY, 1707.03094, PRD]
The **LEP** bound on the *Z invisible width* is

$$\Gamma_{Z,\text{inv}}^{\text{BSM}} < 2 \text{ MeV} \text{ at 95\% CL}$$

For **CEPC** experiments collecting 5 ab$^{-1}$ data, the 95\% CL expected constraint on the *h invisible width* would be $\Gamma_{h,\text{inv}} < 11.4 \text{ keV}$, while the relative precision of the $h \rightarrow \gamma \gamma$ decay width could be measured to 9.4\% [CEPC-SPPC pre-CDR, Vol. II]

$$y_1 = 0.5, \quad y_2 = 1.5$$

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**[QF Xiang, XJ Bi, PF Yin, ZHY, 1707.03094, PRD]**
Two classes of EW radiative corrections

- **Direct Corrections**: vertex, box, and bremsstrahlung corrections

- **Oblique Corrections**: gauge boson propagator corrections

Oblique corrections can be treated in a self-consistent, model-independent way through an effective lagrangian to incorporate a large class of Feynman diagrams into a few **running couplings** [Kennedy & Lynn, NPB 322, 1 (1989)]
EW oblique parameters $S$, $T$, and $U$ are introduced to describe new physics corrections to gauge boson propagators [Peskin, Takeuchi, PRL, '90; PRD '92]

\[
S = 16\pi [\Pi'_{33}(0) - \Pi'_{3Q}(0)]
\]

\[
T = \frac{4\pi}{s_W^2 c_W^2 m_Z^2} [\Pi_{11}(0) - \Pi_{33}(0)], \quad U = 16\pi [\Pi'_{11}(0) - \Pi'_{33}(0)]
\]

Here $\Pi'_{IJ}(0) \equiv \partial \Pi_{IJ}(p^2)/\partial p^2|_{p^2=0}$, $s_W \equiv \sin \theta_W$, $c_W \equiv \cos \theta_W$

$\gamma \sim \gamma = ie^2 \Pi_{QQ}(p^2)g^{\mu\nu} + (p^\mu p^\nu$ terms)$

$Z \sim Z = \frac{ie^2}{s_W c_W} [\Pi_{3Q}(p^2) - s_W^2 \Pi_{QQ}(p^2)]g^{\mu\nu} + (p^\mu p^\nu$ terms)$

$Z \sim Z = \frac{ie^2}{s_W^2 c_W^2} [\Pi_{33}(p^2) - 2s_W^2 \Pi_{3Q}(p^2) + s_W^4 \Pi_{QQ}(p^2)]g^{\mu\nu} + (p^\mu p^\nu$ terms)$

$W \sim W = \frac{ie^2}{s_W^2} \Pi_{11}(p^2)g^{\mu\nu} + (p^\mu p^\nu$ terms)$
For evaluating CEPC precision of oblique parameters, we use a simplified set of EW precision observables in the global fit:

\[ \alpha_s(m_Z^2), \Delta \alpha^{(5)}_{\text{had}}(m_Z^2), m_Z, m_t, m_h, m_W, \sin^2 \theta_{\text{eff}}^\ell, \Gamma_Z \]

**Free parameters:** the former 5 observables, \( S, T, \) and \( U \)

The remaining 3 observables are determined by the free parameters:

\[
m_W = m_W^{\text{SM}} \left[ 1 - \frac{\alpha}{4(c_W^2 - s_W^2)}(S - 1.55T - 1.24U) \right]
\]

\[
\sin^2 \theta_{\text{eff}}^\ell = (\sin^2 \theta_{\text{eff}}^\ell)^{\text{SM}} + \frac{\alpha}{4(c_W^2 - s_W^2)}(S - 0.69T)
\]

\[
\Gamma_Z = \Gamma_Z^{\text{SM}} - \frac{\alpha^2 m_Z}{72s_W^2 c_W(c_W^2 - s_W^2)}(12.2S - 32.9T)
\]

The calculation of **SM predictions** is based on 2-loop radiative corrections.
CEPC Precision of Electroweak Observables

<table>
<thead>
<tr>
<th></th>
<th>Current data</th>
<th>CEPC-B precision</th>
<th>CEPC-I precision</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha_s(m_Z^2)$</td>
<td>$0.1185 \pm 0.0006$</td>
<td>$\pm 1 \times 10^{-4}$</td>
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</tr>
<tr>
<td>$\Delta \alpha^{(5)}_{\text{had}}(m_Z^2)$</td>
<td>$0.02765 \pm 0.00008$</td>
<td>$\pm 4.7 \times 10^{-5}$</td>
<td></td>
</tr>
<tr>
<td>$m_Z$ [GeV]</td>
<td>$91.1875 \pm 0.0021$</td>
<td>$\pm 5 \times 10^{-4}$</td>
<td>$\pm 1 \times 10^{-4}$</td>
</tr>
<tr>
<td>$m_t$ [GeV]</td>
<td>$173.34 \pm 0.76_{\text{ex}} \pm 0.5_{\text{th}}$</td>
<td>$\pm 0.2_{\text{ex}} \pm 0.5_{\text{th}}$</td>
<td>$\pm 0.03_{\text{ex}} \pm 0.1_{\text{th}}$</td>
</tr>
<tr>
<td>$m_h$ [GeV]</td>
<td>$125.09 \pm 0.24$</td>
<td>$\pm 5.9 \times 10^{-3}$</td>
<td></td>
</tr>
<tr>
<td>$m_W$ [GeV]</td>
<td>$80.385 \pm 0.015_{\text{ex}} \pm 0.004_{\text{th}}$</td>
<td>$(\pm 3_{\text{ex}} \pm 1_{\text{th}}) \times 10^{-3}$</td>
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<tr>
<td>$\sin^2 \theta^\ell_{\text{eff}}$</td>
<td>$0.23153 \pm 0.00016$</td>
<td>$(\pm 2.3_{\text{ex}} \pm 1.5_{\text{th}}) \times 10^{-5}$</td>
<td></td>
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<tr>
<td>$\Gamma_Z$ [GeV]</td>
<td>$2.4952 \pm 0.0023$</td>
<td>$(\pm 5_{\text{ex}} \pm 0.8_{\text{th}}) \times 10^{-4}$</td>
<td>$(\pm 1_{\text{ex}} \pm 0.8_{\text{th}}) \times 10^{-4}$</td>
</tr>
</tbody>
</table>

For **CEPC baseline (CEPC-B) precisions**, experimental uncertainties will be mostly reduced by CEPC measurements; theoretical uncertainties of $m_W$, $\sin^2 \theta^\ell_{\text{eff}}$, and $\Gamma_Z$ can be reduced by fully calculating 3-loop corrections in the future.

**CEPC improved (CEPC-I) precisions** need:
- A high-precision beam energy calibration for improving $m_Z$ and $\Gamma_Z$ measurements
- A $t\bar{t}$ threshold scan for the $m_t$ measurement at other $e^+e^-$ colliders, like ILC
**Global Fit**

**Modified $\chi^2$ function** [JJ Fan, Reece, LT Wang, 1411.1054, JHEP]:

$$\sum_i \left( \frac{O_{i \text{meas}} - O_{i \text{pred}}}{\sigma_i} \right)^2 + \sum_j \left\{ -2 \ln \left[ \text{erf} \left( \frac{O_{j \text{meas}} - O_{j \text{pred}}}{\sqrt{2}\sigma_j} + \delta_j \right) - \text{erf} \left( \frac{O_{j \text{meas}} - O_{j \text{pred}} - \delta_j}{\sqrt{2}\sigma_j} \right) \right] \right\}$$

The **experimental uncertainty** $\sigma_j$ and the **theoretical uncertainty** $\delta_j$ of an observable $O_j$ are treated as **Gaussian** and **flat** errors.

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<th>CEPC-I</th>
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</thead>
<tbody>
<tr>
<td>$\sigma_S$</td>
<td>0.10</td>
<td>0.021</td>
<td>0.011</td>
</tr>
<tr>
<td>$\sigma_T$</td>
<td>0.12</td>
<td>0.026</td>
<td>0.0071</td>
</tr>
<tr>
<td>$\sigma_U$</td>
<td>0.094</td>
<td>0.020</td>
<td>0.010</td>
</tr>
<tr>
<td>$\rho_{ST}$</td>
<td>+0.89</td>
<td>+0.90</td>
<td>+0.74</td>
</tr>
<tr>
<td>$\rho_{SU}$</td>
<td>−0.55</td>
<td>−0.68</td>
<td>+0.15</td>
</tr>
<tr>
<td>$\rho_{TU}$</td>
<td>−0.80</td>
<td>−0.84</td>
<td>−0.21</td>
</tr>
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[CF Cai, ZHY, HH Zhang, 1611.02186, NPB]
Fit Results for Some Parameters Fixed to 0

95% CL contours for $U = 0$

$T = U = 0$ fixed

$S = U = 0$ fixed

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</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_S$</td>
<td>0.037</td>
<td>0.0085</td>
<td>0.0068</td>
</tr>
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</tr>
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<tbody>
<tr>
<td>$\sigma_T$</td>
<td>0.032</td>
<td>0.0079</td>
<td>0.0042</td>
</tr>
</tbody>
</table>

[CF Cai, ZHY, HH Zhang, 1611.02186, NPB]
CEPC Sensitivity to Fermionic Models

- **Dotted lines:** expected 95% CL constraints from current, CEPC-B, and CEPC-I precisions of EW oblique parameters assuming $T = U = 0$

- **DD-SI:** excluded by spin-independent direct detection experiments at 90% CL

- **Dashed lines:** DM particle mass

[CF Cai, ZHY, HH Zhang, 1611.02186, NPB]
Singlet-Doublet Scalar Dark Matter (SDSDM)

A real singlet scalar $S \in (1, 0)$ and a complex doublet scalar $\Phi \in (2, 1/2)$:

$$\mathcal{L} \supset \frac{1}{2} (\partial_\mu S)^2 - \frac{1}{2} m_S^2 S^2 + (D_\mu \Phi)^\dagger D^\mu \Phi - m_D^2 |\Phi|^2 - (\kappa S \Phi^\dagger H + \text{h.c.}) - \frac{1}{2} \lambda_{Sh} S^2 |H|^2 - \lambda_1 |H|^2 |\Phi|^2 - [\lambda_2 (\Phi^\dagger H)^2 + \text{h.c.}] - \lambda_3 |\Phi^\dagger H|^2$$

The DM candidate can be either a CP-even or CP-odd scalar.

Dot-dashed lines: free $S$, $T$, and $U$

Solid lines: assuming $U = 0$

[CF Cai, ZHY, HH Zhang, 1705.07921, NPB]
In the limit $\kappa = 0$ and $m_S \rightarrow \infty$, the singlet decouples the SDSDM model reduces to the **inert Higgs doublet model** [Deshpande, Ma, PRD 18, 2574 (1978)]

- $\lambda_2 < 0$: **CP-even** DM candidate, coupling to the Higgs $\propto \lambda_1 + 2\lambda_2 + \lambda_3$
- $\lambda_2 > 0$: **CP-odd** DM candidate, coupling to the Higgs $\propto \lambda_1 - 2\lambda_2 + \lambda_3$

Dot-dashed lines: free $S$, $T$, and $U$

**Solid lines:** assuming $U = 0$

[CF Cai, ZHY, HH Zhang, 1705.07921, NPB]
Singlet-Triplet Scalar Dark Matter (STSDM)

A real singlet scalar \( S \in (1,0) \) and a complex triplet scalar \( \Delta \in (3,0) \):

\[
\mathcal{L} \supset \frac{1}{2} m_S^2 S^2 + m_\Delta^2 |\Delta|^2 + \frac{1}{2} \lambda_{Sh} S^2 |H|^2 + \lambda_0 |H|^2 |\Delta|^2 + \lambda_1 H_i^\dagger \Delta^j (\Delta^\dagger)_k^i H^k \\
+ \lambda_2 H_i^\dagger (\Delta^\dagger)_j^i \Delta^j_k H^k - (\lambda_3 H_i^\dagger \Delta^j \Delta^j_k H^k + \lambda_3' |H|^2 \Delta^i_j \Delta^i_j + \lambda_4 S H_i^\dagger \Delta^j_i H^j + \text{h.c.})
\]

Define \( \lambda_\pm \equiv \lambda_1 \pm \lambda_2 \), and \( \lambda_3' \) and \( \lambda_0 \) can be absorbed into \( \lambda_3 \) and \( \lambda_+ \)

Dot-dashed lines: assuming \( S = 0 \)  
Solid lines: assuming \( S = U = 0 \)

[CF Cai, ZHY, HH Zhang, 1705.07921, NPB]
A complex quadruplet scalar $X \in (4, 1/2)$:

$$-\mathcal{L} \supset m_X^2 |X|^2 + \lambda_0 |H|^2 |X|^2 + \lambda_1 H_i^+ X_k^i (X^\dagger)^k_j H^j_k + \lambda_2 H_i^+ (X^\dagger)_j^k X^i_l H^l + \lambda_3 H_i^+ H_j^+ X^k_l X^i_j + \text{h.c.}$$

Define $\lambda_\pm \equiv \lambda_1 \pm \lambda_2$, and $\lambda_0$ can be absorbed into $\lambda_+$

Dot-dashed lines: free $S$, $T$, and $U$

Solid lines: assuming $U = 0$

[CF Cai, ZHY, HH Zhang, 1705.07921, NPB]
Conclusions

1. WIMP models can be naturally constructed by extending the Standard Model with a dark sector consisting of **electroweak multiplets**, whose electrically neutral components provide a DM candidate.

2. Such models typically introduce several **new electroweak particles** that could lead to remarkable signatures at \( pp \) and \( e^+e^- \) colliders.

3. We have studied the corresponding **direct production signals** at the LHC and at the future **SPPC**, as well as the indirect searches via **Higgs and electroweak precision measurements** at the future **CEPC**.
WIMP models can be naturally constructed by extending the Standard Model with a dark sector consisting of **electroweak multiplets**, whose electrically neutral components provide a DM candidate.

Such models typically introduce several **new electroweak particles** that could lead to remarkable signatures at $pp$ and $e^+e^-$ colliders.

We have studied the corresponding **direct production signals** at the LHC and at the future SPPC, as well as the indirect searches via Higgs and **electroweak precision measurements** at the future CEPC.

**Thanks for your attention!**
WIMP Models

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

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

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

- 1 multiplet in a high-dimensional representation:
  - **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]
  - \ldots
Connection to SUSY models

The above models with SU(2)_L multiplets can be understood as simplifications of more complete models, but the model parameters are much more free.

**Singlet-doublet** fermionic DM model:

- **Bino-Higgsino** sector in the MSSM

\[ \mathcal{L}_{\text{mass}} \supset -\frac{1}{2} M_1 \tilde{B}\tilde{B} - \mu (\tilde{H}_u^+ \tilde{H}_d^- - \tilde{H}_u^0 \tilde{H}_d^0) + \frac{g' v_d}{\sqrt{2}} \tilde{B}\tilde{H}_d^0 - \frac{g' v_u}{\sqrt{2}} \tilde{B}\tilde{H}_u^0 + \text{h.c.} \]

- **Singlino-Higgsino** sector in the NMSSM

\[ \mathcal{L}_{\text{mass}} \supset -\kappa v_s \tilde{S}\tilde{S} - \lambda v_s (\tilde{H}_u^+ \tilde{H}_d^- - \tilde{H}_u^0 \tilde{H}_d^0) + \lambda v_u \tilde{S}\tilde{H}_d^0 + \lambda v_d \tilde{S}\tilde{H}_u^0 + \text{h.c.} \]

**Doublet-triplet** fermionic DM model: **Higgsino-wino** sector in the MSSM

\[ \mathcal{L}_{\text{mass}} \supset -\frac{1}{2} M_2 \tilde{W}^0 \tilde{W}^0 - M_2 \tilde{W}^+ \tilde{W}^- - \mu (\tilde{H}_u^+ \tilde{H}_d^- - \tilde{H}_u^0 \tilde{H}_d^0) - \frac{g v_d}{\sqrt{2}} \tilde{W}^0 \tilde{H}_d^0 \\
+ \frac{g v_u}{\sqrt{2}} \tilde{W}^0 \tilde{H}_u^0 - g v_u \tilde{H}_u^0 \tilde{W}^- - g v_d \tilde{W}^+ \tilde{H}_d^- + \text{h.c.} \]

**Triplet-quadruplet** fermionic DM model: **no analogue** in usual SUSY models
Custodial Symmetry

Standard model (SM) scalar potential \( V = -\mu^2 H^\dagger H + \lambda (H^\dagger H)^2 \) is a function of \( H^\dagger H \), which respects an \( SU(2)_L \times SU(2)_R \) global symmetry:

\[ H^\dagger H = -\frac{1}{2} \epsilon_{AB} \epsilon^{ij} (\mathcal{H}^A)_i (\mathcal{H}^B)_j, \quad (\mathcal{H}^A)_i \equiv \begin{pmatrix} H^\dagger_i \\ H_i \end{pmatrix} \text{ is an } SU(2)_R \text{ doublet} \]

The custodial symmetry protects the tree-level relation

\[ m_{W}^2 = (m_{Z}^2 c_{W}^2) = 1 \]

up to EW radiative corrections [Sikivie et al., NPB 173, 189 (1980)], and leads to \( T = U = 0 \) (note that \( \rho - 1 = \alpha T \))

The custodial symmetry is approximate in the SM, explicitly broken by the Yukawa couplings of fermions and the \( U(1)_Y \) gauge interaction.
Oblique Parameters and Electroweak Multiplets

We study the CEPC sensitivity to WIMP models with a dark sector consisting of **EW multiplets**. By imposing a $Z_2$ symmetry, the DM candidate would be the lightest mass eigenstate of the neutral components.

1. **EW oblique parameters** $S$, $T$, and $U$ respond to **EW symmetry breaking**
   - Mass splittings among the multiplet components induced by the nonzero Higgs VEV would break the EW symmetry
     - Nonzero oblique parameters
   - If the Higgs VEV just gives a common mass shift to every component in a multiplet, the effect can be absorbed into the gauge-invariant mass term
     - No EW symmetry breaking effect manifests
     - Vanishing $S$, $T$, and $U$

2. $S$ relates to the $U(1)_Y$ gauge field
   - A multiplet with zero hypercharge cannot contribute to $S$

3. Multiplet couplings to the Higgs respect a **custodial symmetry**
   - Vanishing $T$ and $U$
Fermionic and Scalar Multiplets

In order to have nonzero contributions to EW oblique parameters, dark sector multiplets should couple to the SM Higgs doublet.

1. **Fermionic multiplets**
   - 1 vector-like fermionic $SU(2)_L$ multiplet: the $Z_2$ symmetry for stabilizing DM forbids the multiplet coupling to the Higgs $\Rightarrow S = T = U = 0$
   - 2 types of vector-like $SU(2)_L$ multiplets whose dimensions differ by one: Yukawa couplings split the components $\Rightarrow$ Nonzero oblique parameters

2. **Scalar multiplets**
   - 1 real scalar multiplet $\Phi$: the quartic coupling $\lambda'\Phi^\dagger\Phi H^\dagger H$ can only induce a common mass shift $\Rightarrow S = T = U = 0$
   - 1 complex scalar multiplet $\Phi$: the quartic coupling $\lambda''\Phi^\dagger\tau^a\Phi H^\dagger\sigma^a H$ can induce mass splittings $\Rightarrow$ Nonzero oblique parameters
   - $\geq 2$ scalar multiplets: various trilinear and quartic couplings could break the mass degeneracy $\Rightarrow$ Nonzero oblique parameters
**Fermionic Models with** $y_1 = 1$ and $y_2 = 1.5$

Expected 95% CL constraints from current, CEPC-B, and CEPC-I precisions of EW oblique parameters

**Dot-dashed lines:** free $S$, $T$, and $U$

**Solid lines:** assuming $U = 0$

**DD-SI:** excluded by SI direct detection

**DD-SD:** excluded by SD direct detection