Current and Future Collider Searches for Electroweak Dark Matter Models

Zhao-Huan Yu（余钊焕）

School of Physics, Sun Yat-Sen University

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

Workshop on High Energy Physics Frontiers

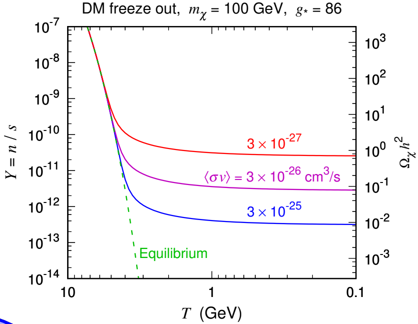
Sun Yat-Sen University, Guangzhou

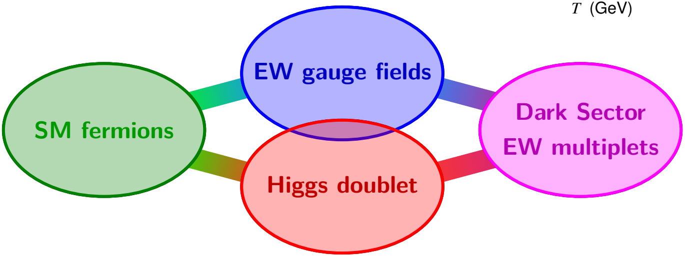
January 22, 2019

Electroweak Dark Matter Models

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) $\mathrm{SU(2)_L}$ **multiplets**, whose **neutral** components could provide a viable DM candidate





Direct Detection of Dark Matter

For a **Majorana DM candidate** χ, the couplings to the Higgs and Z bosons

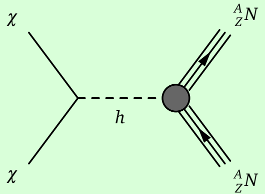
$$\mathcal{L} \supset \frac{1}{2} g_{h\chi\chi} h \bar{\chi}\chi + \frac{1}{2} g_{Z\chi\chi} Z_\mu \bar{\chi}\gamma^\mu\gamma_5\chi$$

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

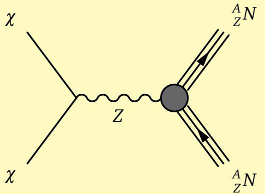
For scalar multiplets, interactions with the Higgs doublet could split the real and imaginary parts of neutral components, leading to a **CP-even or CP-odd real scalar DM candidate**. Its coupling to the Higgs boson would induce **SI scatterings**.

Stringent constraints from current direct detection experiments

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



SI for both fermionic and scalar χ



SD for Majorana χ
SI for complex scalar χ

Fermionic Models

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

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

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

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

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

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

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

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

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

☞ 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]

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

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

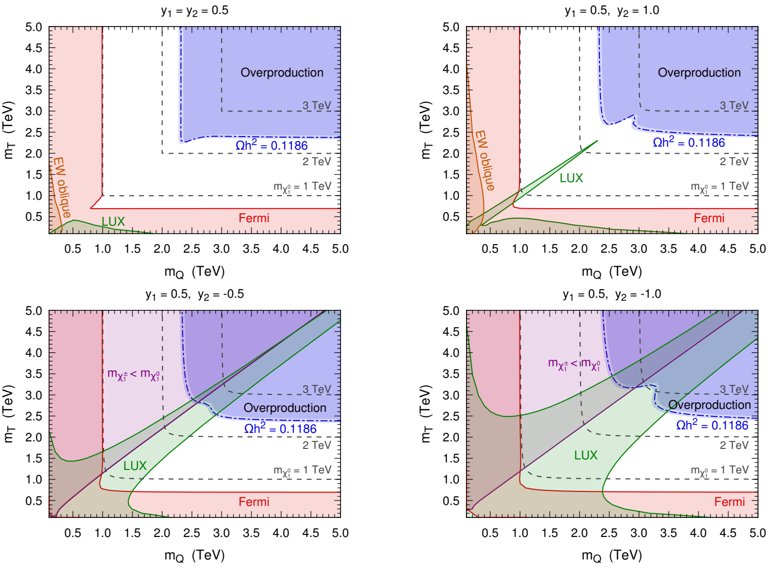
$$\mathcal{M}_{\text{N}} = \begin{pmatrix} m_T & \frac{1}{\sqrt{3}} y_1 v & -\frac{1}{\sqrt{3}} y_2 v \\ \frac{1}{\sqrt{3}} y_1 v & 0 & m_Q \\ -\frac{1}{\sqrt{3}} y_2 v & m_Q & 0 \end{pmatrix}, \quad \mathcal{M}_{\text{C}} = \begin{pmatrix} m_T & \frac{1}{\sqrt{2}} y_1 v & -\frac{1}{\sqrt{6}} y_2 v \\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

$$\begin{pmatrix} T^0 \\ Q_1^0 \\ Q_2^0 \end{pmatrix} = \mathcal{N} \begin{pmatrix} \chi_1^0 \\ \chi_2^0 \\ \chi_3^0 \end{pmatrix}, \quad \begin{pmatrix} T^+ \\ Q_1^+ \\ Q_2^+ \end{pmatrix} = \mathcal{C}_{\text{L}} \begin{pmatrix} \chi_1^+ \\ \chi_2^+ \\ \chi_3^+ \end{pmatrix}, \quad \begin{pmatrix} T^- \\ Q_1^- \\ Q_2^- \end{pmatrix} = \mathcal{C}_{\text{R}} \begin{pmatrix} \chi_1^- \\ \chi_2^- \\ \chi_3^- \end{pmatrix}, \quad \begin{matrix} \chi^{--} \equiv Q_1^{--} \\ \chi^{++} \equiv Q_2^{++} \end{matrix}$$

3 Majorana fermions χ_i^0, 3 singly charged fermions $\chi_i^\pm$, 1 doubly charged fermion $\chi^{\pm\pm}$

✨ χ_1^0 would be an excellent **DM candidate** if it is the lightest among them

Constraints on the TQFDM model



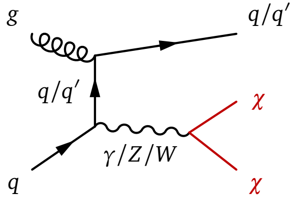
[Tait, **ZHY**, 1601.01354, JHEP]

Monojet + $\not{E}_T$ Channel at pp Colliders (TQFDM)

Pair production of dark sector fermions:

$$pp \to \chi\chi + \text{jets}, \quad \chi = \chi_i^0, \chi_i^\pm, \chi^{\pm\pm}$$

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

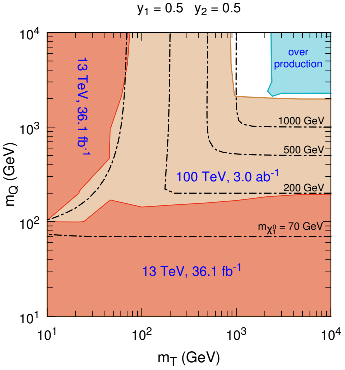


Main SM backgrounds:

$$Z(\to \nu\bar{\nu}) + \text{jets}, \quad W(\to \ell\nu) + \text{jets}$$

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

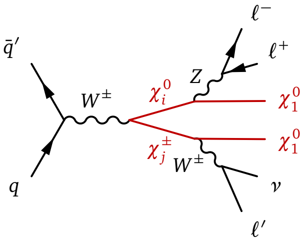
Future prospect: **SPPC** at 100 TeV collecting with 3 ab^{-1} data would be able to explore up to $m_{\chi_1^0} \sim 1-2$ TeV



[JW Wang, XJ Bi, QF Xiang, PF Yin, **ZHY**, 1711.05622, PRD]

Multilepton + $\not{E}_\mathrm{T}$ Channel at pp Colliders (TQFDM)

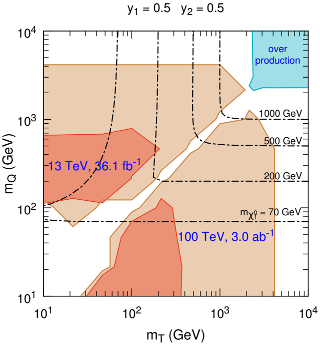
- Signals in the $2\ell + \not{E}_\mathrm{T}$ **channel**:
  $\chi_i^+ \chi_j^- \to W^+(\to \ell^+ \nu)\ W^-(\to \ell'^- \bar{\nu})\ \chi_1^0 \chi_1^0$
- Signals in the $2\ell +$ **jets** $+ \not{E}_\mathrm{T}$ **channel**:
  $\chi_i^0 \chi_j^\pm \to Z(\to \ell^+\ell^-)\ W^\pm(\to jj)\ \chi_1^0 \chi_1^0$
- Signals in the $3\ell + \not{E}_\mathrm{T}$ **channel**:
  $\chi_i^0 \chi_j^\pm \to Z(\to \ell^+\ell^-)\ W^\pm(\to \ell' \nu)\ \chi_1^0 \chi_1^0$



Main SM backgrounds:
ZZ + jets, WW + jets, WZ + jets, $t\bar{t}$ + jets

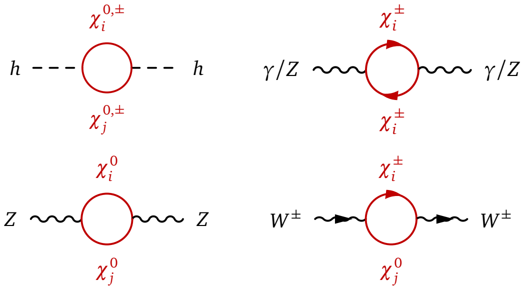
Current constraints: ATLAS searches at the 13 TeV **LHC** with 36.1 fb^{-1} data [ATLAS-CONF-2017-039]

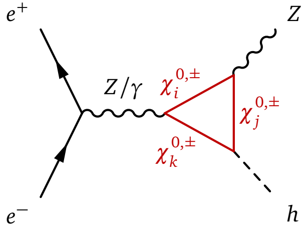
Future prospect: **SPPC** experiments at $\sqrt{s} = 100$ TeV with 3 ab^{-1} data



[JW Wang, XJ Bi, QF Xiang, PF Yin, **ZHY**, 1711.05622, PRD]

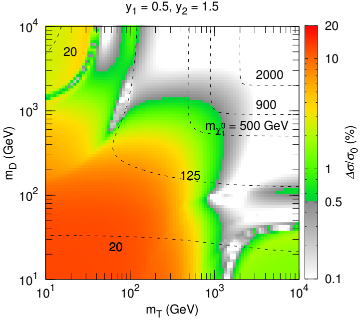
Correction to $e^+e^- \to Zh$ (DTFDM)





💥 $e^+e^- \to Zh$ **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 $\Delta\sigma/\sigma_0 \simeq 0.51\%$ [CEPC-SPPC pre-CDR, Vol. II]



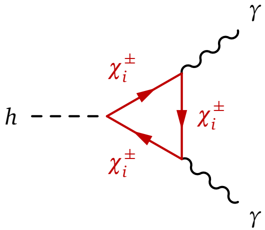
[QF Xiang, XJ Bi, PF Yin, **ZHY**, 1707.03094, PRD]

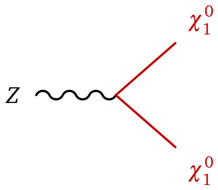
Higgs Boson Invisible and Diphoton Decays (DTFDM)

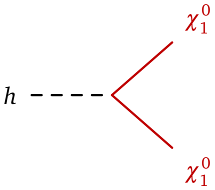
The **LEP** bound on the Z **invisible width** is

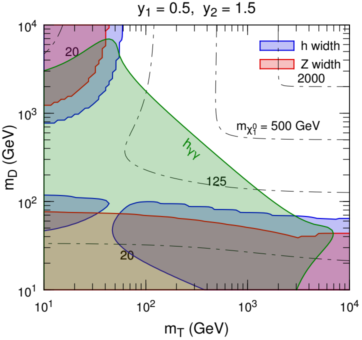
$$\Gamma_{Z,\text{inv}}^{\text{BSM}} < 2\ \text{MeV at } 95\%\ \text{CL}$$

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







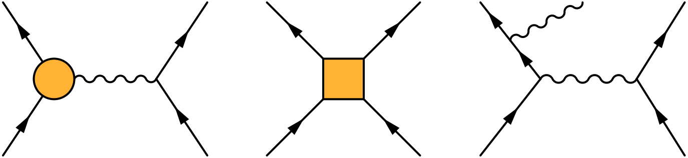


[QF Xiang, XJ Bi, PF Yin, **ZHY**, 1707.03094, PRD]

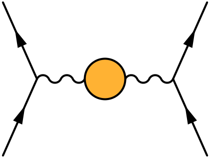
Electroweak Radiative Corrections

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)]

Electroweak Oblique Parameters

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

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

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

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

W  W $= \dfrac{ie^2}{s_W^2} \Pi_{11}(p^2) g^{\mu\nu} + (p^\mu p^\nu \text{ terms})$

Electroweak Precision Observables

📌 For evaluating CEPC precision of oblique parameters, we use a simplified set of EW precision observables in the **global fit**:

$$\alpha_s(m_Z^2),\ \Delta\alpha_{\text{had}}^{(5)}(m_Z^2),\ m_Z,\ m_t,\ m_h,\ m_W,\ \sin^2\theta_{\text{eff}}^{\ell},\ \Gamma_Z$$

✨ **Free parameters:** the former 5 observables, S, T, and U

👉 The remaining 3 observables are determined by the free parameters:

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

$$\sin^2\theta_{\text{eff}}^{\ell} = (\sin^2\theta_{\text{eff}}^{\ell})^{\text{SM}} + \frac{\alpha}{4(c_{\text{W}}^2 - s_{\text{W}}^2)}(S - 0.69T)$$

$$\Gamma_Z = \Gamma_Z^{\text{SM}} - \frac{\alpha^2 m_Z}{72 s_{\text{W}}^2 c_{\text{W}}^2 (c_{\text{W}}^2 - s_{\text{W}}^2)}(12.2S - 32.9T)$$

The calculation of **SM predictions** is based on 2-loop radiative corrections

CEPC Precision of Electroweak Observables

	Current data	CEPC-B precision	CEPC-I precision
$\alpha_s(m_Z^2)$	0.1185 ± 0.0006	$\pm 1 \times 10^{-4}$	
$\Delta\alpha_{\rm had}^{(5)}(m_Z^2)$	0.02765 ± 0.00008	$\pm 4.7 \times 10^{-5}$	
m_Z [GeV]	91.1875 ± 0.0021	$\pm 5 \times 10^{-4}$	$\pm 1 \times 10^{-4}$
m_t [GeV]	$173.34 \pm 0.76_{\rm ex} \pm 0.5_{\rm th}$	$\pm 0.2_{\rm ex} \pm 0.5_{\rm th}$	$\pm 0.03_{\rm ex} \pm 0.1_{\rm th}$
m_h [GeV]	125.09 ± 0.24	$\pm 5.9 \times 10^{-3}$	
m_W [GeV]	$80.385 \pm 0.015_{\rm ex} \pm 0.004_{\rm th}$	$(\pm 3_{\rm ex} \pm 1_{\rm th}) \times 10^{-3}$	
$\sin^2\theta_{\rm eff}^\ell$	0.23153 ± 0.00016	$(\pm 2.3_{\rm ex} \pm 1.5_{\rm th}) \times 10^{-5}$	
Γ_Z [GeV]	2.4952 ± 0.0023	$(\pm 5_{\rm ex} \pm 0.8_{\rm th}) \times 10^{-4}$	$(\pm 1_{\rm ex} \pm 0.8_{\rm th}) \times 10^{-4}$

For **CEPC baseline (CEPC-B) precisions**, experimental uncertainties will be mostly reduced by CEPC measurements; theoretical uncertainties of m_W, $\sin^2\theta_{\rm eff}^\ell$, and Γ_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 Γ_Z measurements
- A $t\bar{t}$ threshold scan for the m_t measurement at other e^+e^- colliders, like ILC

Global Fit

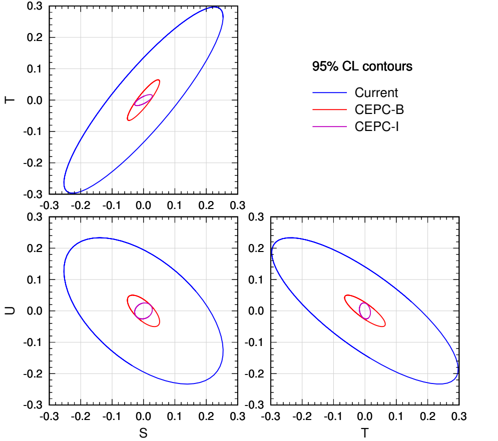
Modified χ^2 function [JJ Fan, Reece, LT Wang, 1411.1054, JHEP]:

$$\sum_i \left(\frac{O_i^{\rm meas} - O_i^{\rm pred}}{\sigma_i} \right)^2 + \sum_j \left\{ -2\ln \left[\mathrm{erf}\left(\frac{O_j^{\rm meas} - O_j^{\rm pred} + \delta_j}{\sqrt{2}\sigma_j} \right) - \mathrm{erf}\left(\frac{O_j^{\rm meas} - O_j^{\rm pred} - \delta_j}{\sqrt{2}\sigma_j} \right) \right] \right\}$$

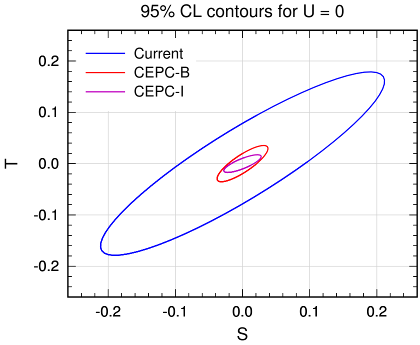
The **experimental uncertainty** σ_j and the **theoretical uncertainty** δ_j of an observable O_j are treated as **Gaussian** and **flat** errors

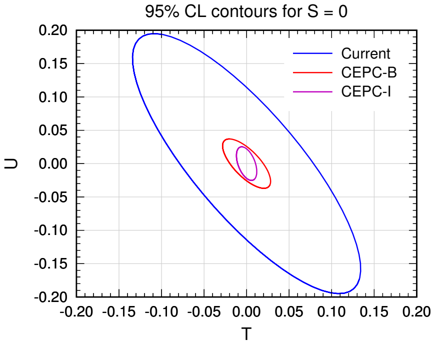
	Current	CEPC-B	CEPC-I
σ_S	0.10	0.021	0.011
σ_T	0.12	0.026	0.0071
σ_U	0.094	0.020	0.010
ρ_{ST}	+0.89	+0.90	+0.74
ρ_{SU}	−0.55	−0.68	+0.15
ρ_{TU}	−0.80	−0.84	−0.21

[CF Cai, **ZHY**, HH Zhang, 1611.02186, NPB]



Fit Results for Some Parameters Fixed to 0





$T = U = 0$ fixed

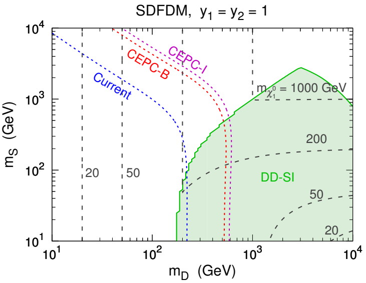
	Current	CEPC-B	CEPC-I
σ_S	0.037	0.0085	0.0068

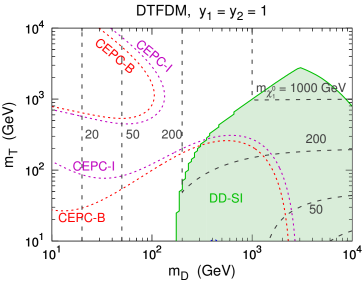
$S = U = 0$ fixed

	Current	CEPC-B	CEPC-I
σ_T	0.032	0.0079	0.0042

[CF Cai, **ZHY**, HH Zhang, 1611.02186, NPB]

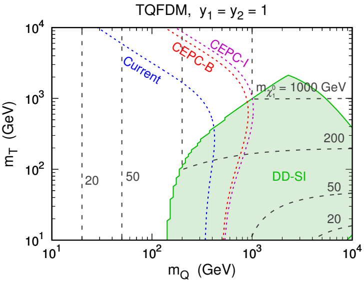
CEPC Sensitivity to Fermionic Models





- **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]

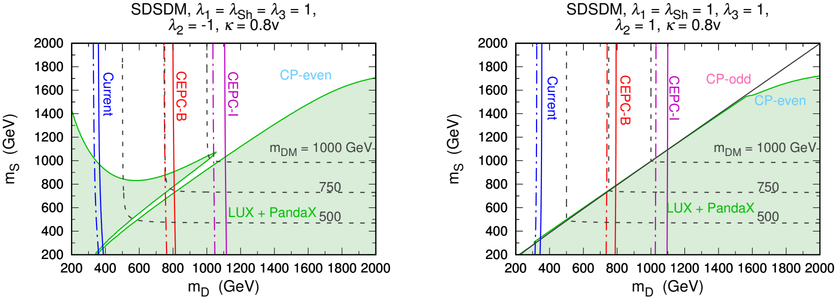


Singlet-Doublet Scalar Dark Matter (SDSDM)

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

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

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



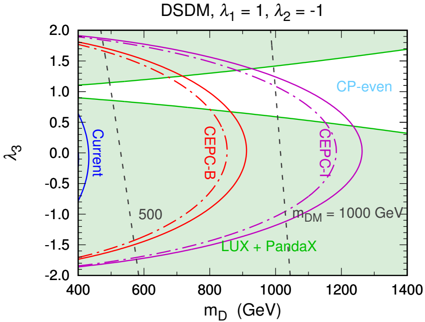
Dot-dashed lines: free S, T, and U **Solid lines:** assuming $U = 0$

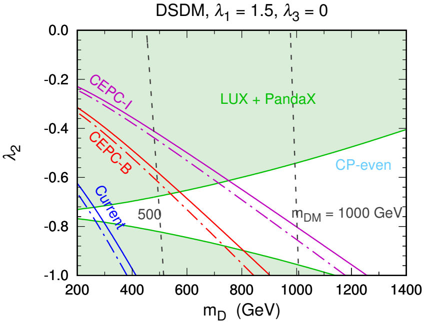
[CF Cai, **ZHY**, HH Zhang, 1705.07921, NPB]

Reduction to the Inert Higgs Doublet Model

In the limit $\kappa = 0$ and $m_S \to \infty$, 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 $U = 0$

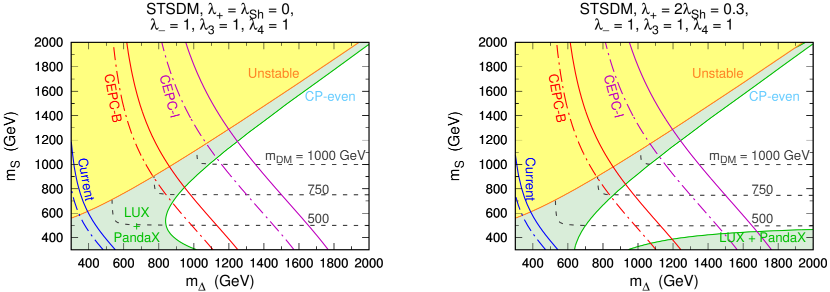
[CF Cai, **ZHY**, HH Zhang, 1705.07921, NPB]

Singlet-Triplet Scalar Dark Matter (STSDM)

A **real singlet scalar** $S \in (\mathbf{1}, 0)$ and a **complex triplet scalar** $\Delta \in (\mathbf{3}, 0)$:

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

Define $\lambda_\pm \equiv \lambda_1 \pm \lambda_2$, and λ_3' and λ_0 can be absorbed into λ_3 and λ_+



Dot-dashed lines: assuming $S = 0$ **Solid lines:** assuming $S = U = 0$

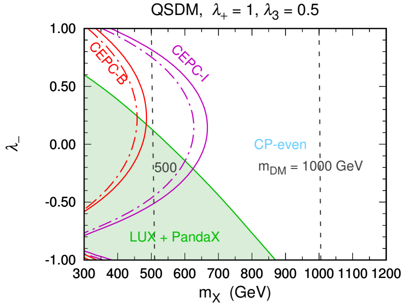
[CF Cai, **ZHY**, HH Zhang, 1705.07921, NPB]

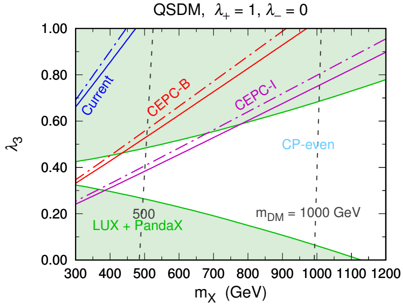
Quadruplet Scalar Dark Matter (QSDM)

A **complex quadruplet scalar** $X \in (\mathbf{4}, 1/2)$:

$$-\mathcal{L} \supset m_X^2 |X|^2 + \lambda_0 |H|^2 |X|^2 + \lambda_1 H_i^\dagger X_k^{ij} (X^\dagger)_{jl}^k H^l + \lambda_2 H_i^\dagger (X^\dagger)_{jk}^i X_l^{jk} H^l$$
$$-(\lambda_3 H_i^\dagger H_j^\dagger X_l^{ik} X_k^{jl} + \text{h.c.})$$

Define $\lambda_\pm \equiv \lambda_1 \pm \lambda_2$, and λ_0 can be absorbed into λ_+





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**.

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**.

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 $\mathrm{SU}(2)_\mathrm{L}$ **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]
  - $\cdots\ \cdots$

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

$$\mathcal{L}_{\text{mass}} \supset -\frac{1}{2}M_2\tilde{W}^0\tilde{W}^0 - M_2\tilde{W}^+\tilde{W}^- - \mu(\tilde{H}_u^+\tilde{H}_d^- - \tilde{H}_u^0\tilde{H}_d^0) - \frac{gv_d}{\sqrt{2}}\tilde{W}^0\tilde{H}_d^0$$
$$+\frac{gv_u}{\sqrt{2}}\tilde{W}^0\tilde{H}_u^0 - gv_u\tilde{H}_u^+\tilde{W}^- - gv_d\tilde{W}^+\tilde{H}_d^- + \text{h.c.}$$

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 $\mathrm{SU(2)_L} \times \mathrm{SU(2)_R}$ **global symmetry**:

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

$$H \to \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v \end{pmatrix} \quad \Rightarrow \quad \mathrm{SU(2)_L} \times \mathrm{SU(2)_R} \to \mathrm{SU(2)_{L+R}} \text{ **custodial symmetry**}$$

$$\Downarrow$$

$\mathrm{SU(2)_L}$ gauge bosons W_μ^a transform as an $\mathrm{SU(2)_{L+R}}$ triplet and acquire the same mass from EW symmetry breaking

$$\Downarrow$$

The custodial symmetry protects the tree-level relation $\rho \equiv m_W^2/(m_Z^2 c_\mathrm{W}^2) = 1$ 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 $\mathrm{U(1)_Y}$ 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.

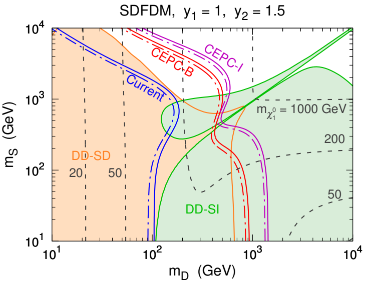
1. EW oblique parameters S, T, and U respond to **EW symmetry breaking**
   - **Mass splittings** among the multiplet components induced by the nonzero Higgs VEV would break the EW symmetry
     $\Rightarrow$ **Nonzero oblique parameters**
   - If the Higgs VEV just gives a **common mass shift** to every components in a multiplet, the effect can be absorbed into the gauge-invariant mass term
     $\Rightarrow$ No EW symmetry breaking effect manifests
     $\Rightarrow$ **Vanishing S, T, and U**
2. S relates to the $\mathrm{U}(1)_\mathrm{Y}$ gauge field
   $\Rightarrow$ A multiplet with **zero hypercharge cannot contribute to S**
3. Multiplet couplings to the Higgs respect a **custodial symmetry**
   $\Rightarrow$ **Vanishing T and U**

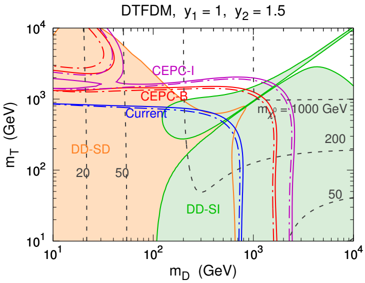
Fermionic and Scalar Multiplets

In other 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 $\mathrm{SU}(2)_\mathrm{L}$ 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 $\mathrm{SU}(2)_\mathrm{L}$ multiplets whose dimensions differ by one:** Yukawa couplings split the components $\Rightarrow$ Nonzero oblique parameters
2. **Scalar multiplets**
   - **1 real scalar multiplet Φ:** 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 Φ:** the quartic coupling $\lambda''\Phi^\dagger\tau^a\Phi H^\dagger\sigma^a H$ can induce mass splittings $\Rightarrow$ Nonzero oblique parameters
   - **≥ 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