

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



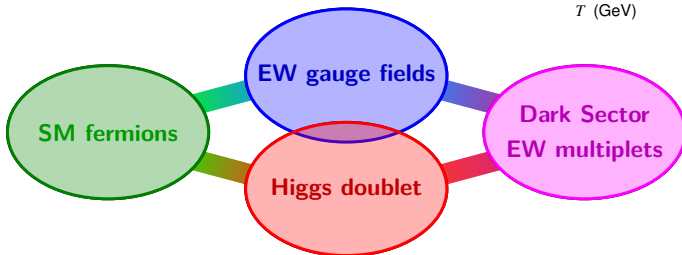
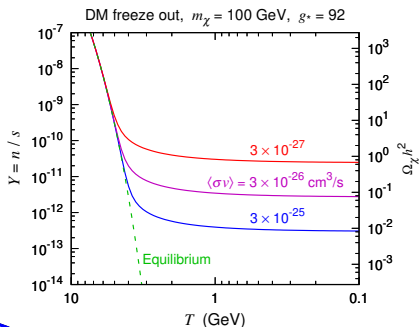
Workshop on High Energy Physics Frontiers
Sun Yat-Sen University, Guangzhou
January 22, 2019



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) **$SU(2)_L$ 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

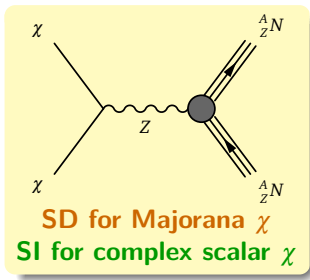
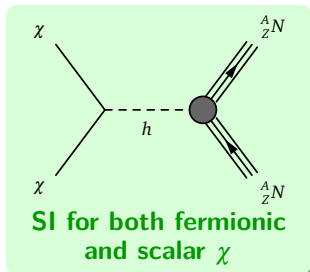
$$\mathcal{L} \supset \frac{1}{2} g_{h\chi\chi} h \bar{\chi} \chi + \frac{1}{2} g_{Z\chi\chi} Z_\mu \bar{\chi} \gamma^\mu \gamma_5 \chi$$

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)



Fermionic Models

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

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

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

- 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]

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

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

👉 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]

$$\begin{aligned}\mathcal{L}_{\text{mass}} &= -\frac{1}{2}(T^0, Q_1^0, Q_2^0)\mathcal{M}_N \begin{pmatrix} T^0 \\ Q_1^0 \\ Q_2^0 \end{pmatrix} - (T^-, Q_1^-, Q_2^-)\mathcal{M}_C \begin{pmatrix} T^+ \\ Q_1^+ \\ Q_2^+ \end{pmatrix} - m_Q Q_1^- Q_2^{++} + \text{h.c.} \\ &= -\frac{1}{2} \sum_{i=1}^3 m_{\chi_i^0} \chi_i^0 \chi_i^0 - \sum_{i=1}^3 m_{\chi_i^\pm} \chi_i^- \chi_i^+ + \text{h.c.} - m_Q \chi^- \chi^{++}\end{aligned}$$

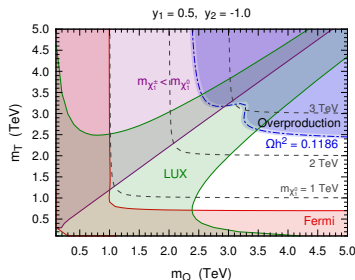
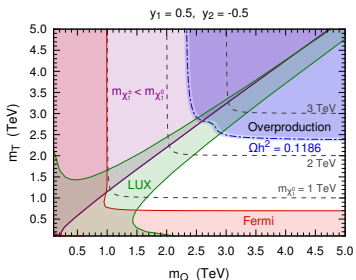
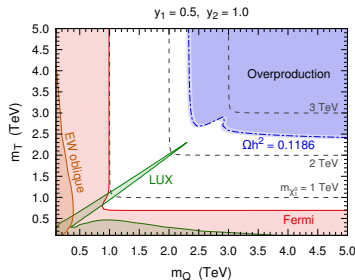
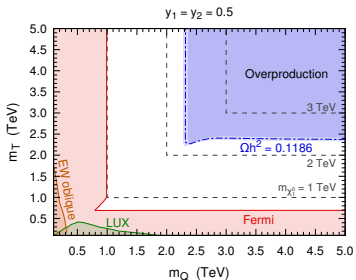
$$\mathcal{M}_N = \begin{pmatrix} m_T & \frac{1}{\sqrt{3}}y_1 v & -\frac{1}{\sqrt{3}}y_2 v \\ \frac{1}{\sqrt{3}}y_1 v & 0 & m_Q \\ -\frac{1}{\sqrt{3}}y_2 v & m_Q & 0 \end{pmatrix}, \quad \mathcal{M}_C = \begin{pmatrix} m_T & \frac{1}{\sqrt{2}}y_1 v & -\frac{1}{\sqrt{6}}y_2 v \\ -\frac{1}{\sqrt{6}}y_1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

$$\begin{pmatrix} T^0 \\ Q_1^0 \\ Q_2^0 \end{pmatrix} = \mathcal{N} \begin{pmatrix} \chi_1^0 \\ \chi_2^0 \\ \chi_3^0 \end{pmatrix}, \quad \begin{pmatrix} T^+ \\ Q_1^+ \\ Q_2^+ \end{pmatrix} = \mathcal{C}_L \begin{pmatrix} \chi_1^+ \\ \chi_2^+ \\ \chi_3^+ \end{pmatrix}, \quad \begin{pmatrix} T^- \\ Q_1^- \\ Q_2^- \end{pmatrix} = \mathcal{C}_R \begin{pmatrix} \chi_1^- \\ \chi_2^- \\ \chi_3^- \end{pmatrix}, \quad \begin{aligned} \chi^- &\equiv Q_1^- \\ \chi^{++} &\equiv Q_2^{++} \end{aligned}$$

3 Majorana fermions χ_i^0 , 3 singly charged fermions χ_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 + \cancel{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 ≥ 1 hard jet from initial state radiation \Rightarrow **monojet + \cancel{E}_T** final state

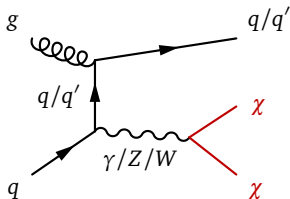
☁️ Main SM backgrounds:

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

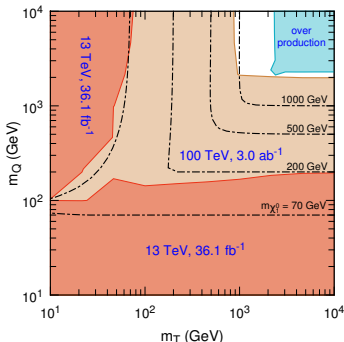
🔍 **Current constraints:** ATLAS searches at the 13 TeV **LHC** with 36.1 fb^{-1} data [ATLAS-CONF-2017-060] excluded parameter regions up to $m_{\chi_1^0} \sim 70 - 200 \text{ GeV}$

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

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



$$y_1 = 0.5 \quad y_2 = 0.5$$



Multilepton + \cancel{E}_T Channel at pp Colliders (TQFDM)

☀ Signals in the $2l + \cancel{E}_T$ channel:

$$\chi_i^+ \chi_j^- \rightarrow W^+(\rightarrow l^+ \nu) W^-(\rightarrow l'^- \bar{\nu}) \chi_1^0 \chi_1^0$$

☀ Signals in the $2l + \text{jets} + \cancel{E}_T$ channel:

$$\chi_i^0 \chi_j^\pm \rightarrow Z(\rightarrow l^+ l^-) W^\pm(\rightarrow jj) \chi_1^0 \chi_1^0$$

☀ Signals in the $3l + \cancel{E}_T$ channel:

$$\chi_i^0 \chi_j^\pm \rightarrow Z(\rightarrow l^+ l^-) W^\pm(\rightarrow l' \nu) \chi_1^0 \chi_1^0$$

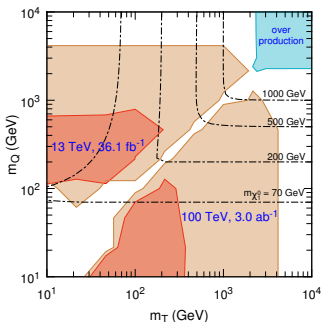
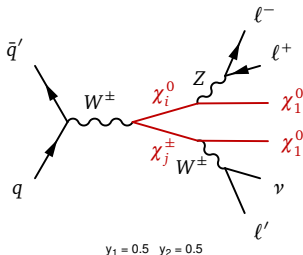
☁ Main SM backgrounds:

$ZZ + \text{jets}$, $WW + \text{jets}$, $WZ + \text{jets}$, $t\bar{t} + \text{jets}$

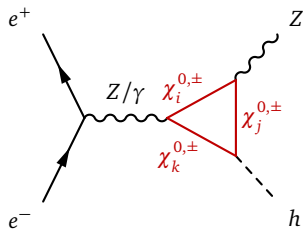
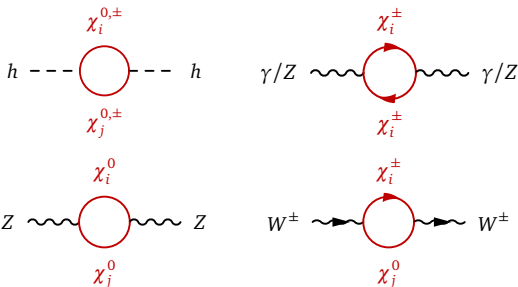
🔍 **Current constraints:** ATLAS searches at the 13 TeV **LHC** with 36.1 fb^{-1} data [ATLAS-CONF-2017-039]

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

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



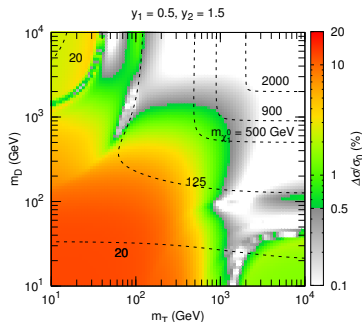
Correction to $e^+e^- \rightarrow Zh$ (DTFDM)



✨ $e^+e^- \rightarrow Zh$ 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]

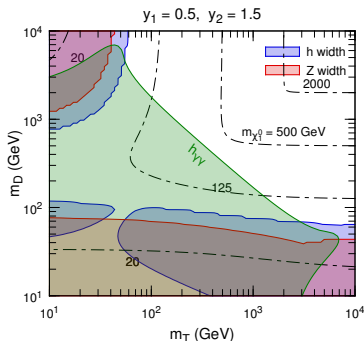
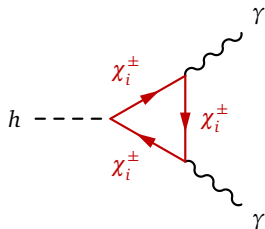
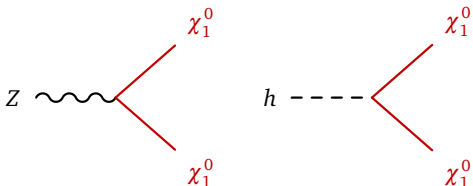


Higgs Boson Invisible and Diphoton Decays (DTFDM)

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

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

🎯 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]



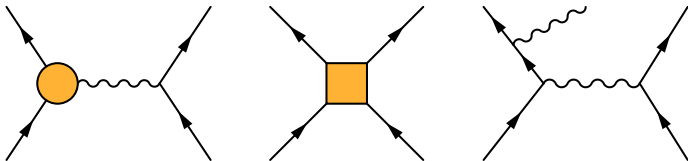
[QF Xiang, XJ Bi, PF Yin, **ZHY**, 1707.03094, PRD]

Electroweak Radiative Corrections

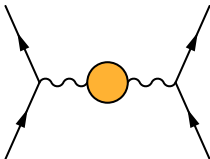


Two classes of EW radiative corrections

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

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

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

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

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

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:

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

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

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

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

CEPC Precision of Electroweak Observables


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

🌀 For **CEPC baseline (CEPC-B) precisions**, experimental uncertainties will be mostly reduced by CEPC measurements; theoretical uncertainties of m_W , $\sin^2\theta_{\text{eff}}^\ell$, 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

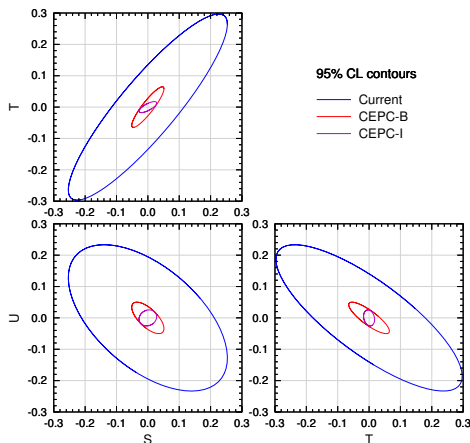
Global Fit

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

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

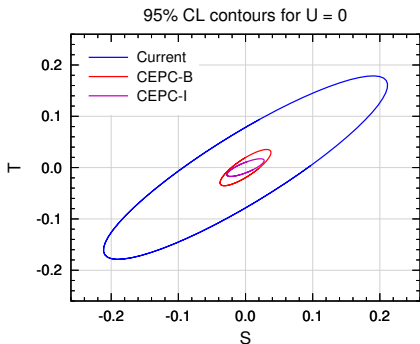
The **experimental uncertainty** σ_j and the **theoretical uncertainty** δ_j of an observable O_j are treated as **Gaussian** and **flat** errors

	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



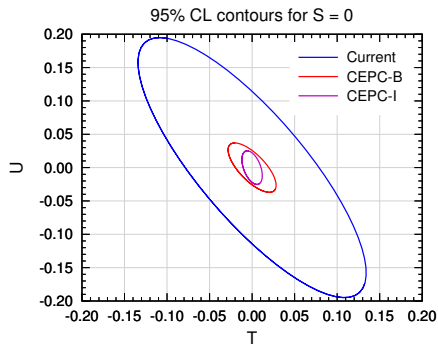
[CF Cai, **ZHY**, HH Zhang, 1611.02186, NPB]

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

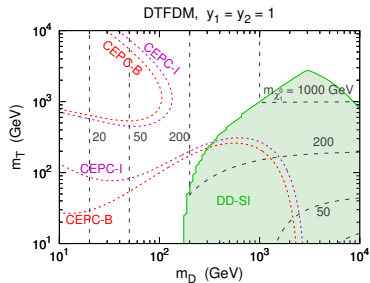
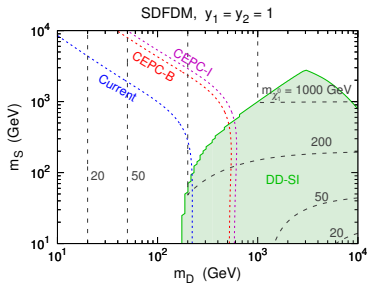



$S = U = 0$ fixed


	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

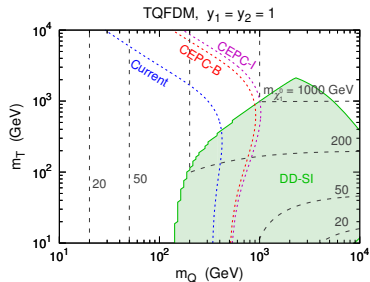


 **Dotted lines:** expected 95% CL constraints from **current**, **CEPC-B**, and **CEPC-I** precisions of EW oblique parameters assuming $T = U = 0$

 **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]

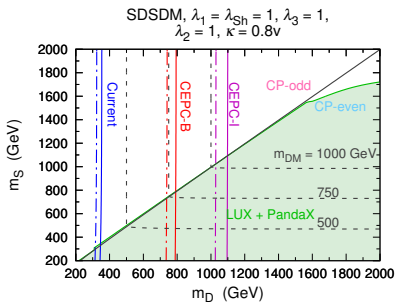
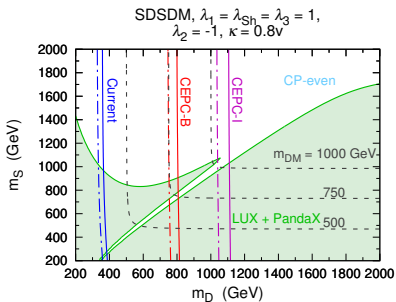


Singlet-Doublet Scalar Dark Matter (SDSDM)

💡 A **real singlet scalar** $S \in (1, 0)$ 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

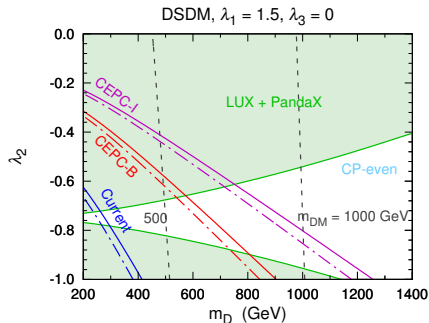
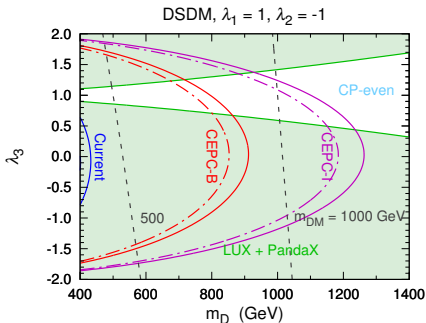
Solid lines: assuming $U = 0$

[CF Cai, ZHY, HH Zhang, 1705.07921, NPJ]

Reduction to the Inert Higgs Doublet Model

💡 In the limit $\kappa = 0$ and $m_S \rightarrow \infty$, the singlet decouples the SDSM 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]

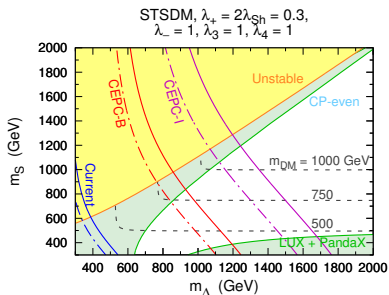
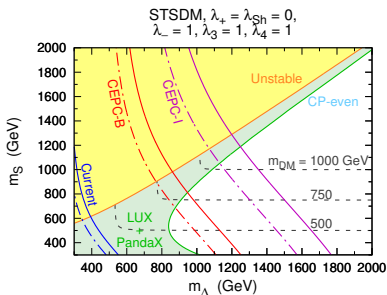
Singlet-Triplet Scalar Dark Matter (STSDM)

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

$$-\mathcal{L} \supset \frac{1}{2} m_S^2 S^2 + m_\Delta^2 |\Delta|^2 + \frac{1}{2} \lambda_{Sh} S^2 |H|^2 + \lambda_0 |H|^2 |\Delta|^2 + \lambda_1 H_i^\dagger \Delta_j^i (\Delta^\dagger)_k^j H^k$$

$$+ \lambda_2 H_i^\dagger (\Delta^\dagger)_j^i \Delta_k^j H^k - (\lambda_3 H_i^\dagger \Delta_j^i \Delta_k^j H^k + \lambda'_3 |H|^2 \Delta_j^i \Delta_i^j + \lambda_4 S H_i^\dagger \Delta_j^i H^j + \text{h.c.})$$

✍ 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 $S = U = 0$

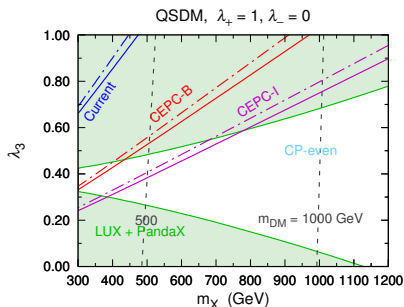
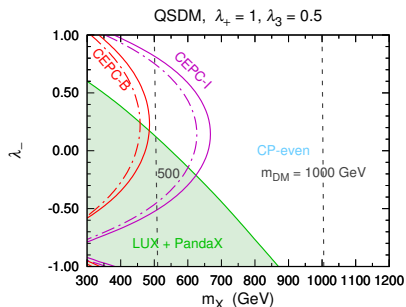
[CF Cai, ZHY, HH Zhang, 1705.07921, NPJ]

Quadruplet Scalar Dark Matter (QSDM)

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

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

✍ 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 **$SU(2)_L$ 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]
 -

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

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

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**:

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

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

↓

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

↓

The custodial symmetry protects the tree-level relation $\rho \equiv m_W^2 / (m_Z^2 c_W^2) = 1$ 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.

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

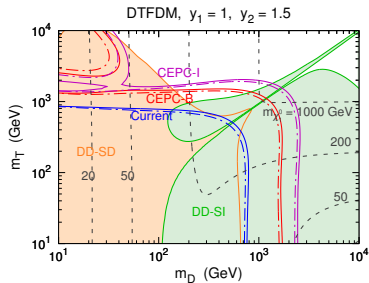
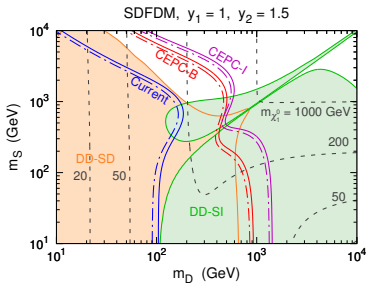
1 Fermionic multiplets

- **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 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

