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Exploring Fermionic Multiplet Dark Matter through Precision Measurements at the CEPC

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Based on

arXiv:2112.02519

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Online

CONTENTS

1 Introduction

Dark matter (DM) makes up most of the matter component in the Universe, as suggested by astrophysical and cosmological observations

WIMPs is a very attractive class of DM candidates, as it can satisfy DM relic density naturally and it is easy to detect.

Two fermionic multiplets Dark Matter **Models** are considered:
SDFDM: 1 singlet + 2 doublet Weyl spinors
DTFDM: 2 doublet + 1 triplet Weyl spinors

LHC: large backgrounds and the large theoretical/systematical uncertainties
CEPC: free of the QCD background
CEPC is suitable for precision measurements

CEPC -> precision measurements -> SDFDM and DTFDM

the Circular Electron Positron Collider (CEPC)

The goal of CEPC is precision measurements of Higgs coupling and EW observable.
The CEPC also offers excellent opportunities for searching new physics

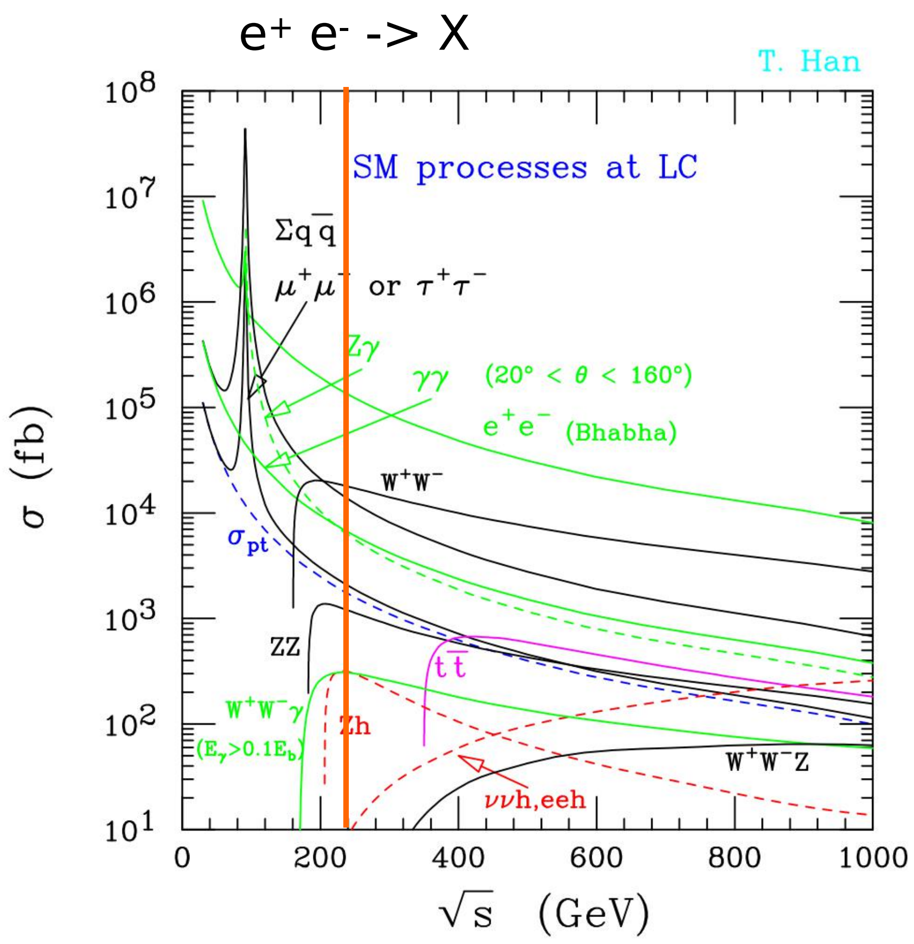
Operation mode	$\sqrt{s}$ (GeV)	L per IP (10^{34} cm^{-2} s^{-1})	Years	Total $\int L$ (ab^{-1}, 2 IPs)	Event yields
H	240	3	7	5.6	1×10^6
Z	91.2	32	2	16	7×10^{11}
W^+W^-	158-172	10	1	2.6	2×10^7

arXiv: 1811.10545

CEPC can be upgraded to $\sqrt{s}$ =360 GeV, enabling the $t\bar{t}$ pair production

Focus Higgs factory mode in this work

Precision estimation of cross section



Process	Cross section (pb)	Events in 5.6 ab^{-1}	precision
$e^+e^- \to \mu^+\mu^-$	1.8	10^7	0.1%
$e^+e^- \to Zh$	0.196	1.1×10^6	0.5% Dong 等 (2018)
$e^+e^- \to W^+W^-$	16.7	9.4×10^7	0.1%
$e^+e^- \to ZZ$	1.1	6.2×10^6	0.12%
$e^+e^- \to Z\gamma$	9.03	5.1×10^7	0.1%

arXiv: 1811.10545

Total = Sqrt (statistical^2 + systematic^2)

systematic error :

total luminosity: 0.1%

W^+W^-, ZZ process: ignore hadron decay

arXiv: 1811.10545

Conservative estimation :

all process: 0.5%

singlet-doublet fermionic DM model (SDFDM model)

The dark sector contains Weyl spinors S and D_i (i = 1, 2) obeying $SU(2)_L \times U(1)_Y$

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

The gauge invariant Lagrangians

$$\mathcal{L}_S = iS^+ \bar{\sigma}^\mu D_\mu S - \frac{1}{2}(\boxed{m_s} S^T(-\epsilon)S + h.c.),$$

$$\mathcal{L}_D = iD_1^+ \bar{\sigma}^\mu D_\mu D_1 + iD_2^+ \bar{\sigma}^\mu D_\mu D_2 + (\boxed{m_D} D_1^{iT}(-\epsilon)D_2^j + h.c.),$$

$$\mathcal{L}_Y = \boxed{y_1} S D_1^i H_i - \boxed{y_2} S D_2^i \tilde{H}_i + h.c.,$$

Four free parameters : m_S, m_Q, y_1, y_2

singlet-doublet fermionic DM model (SDFDM model)

After EWSB, S and D_i (i = 1, 2) will mix, mass term can be written

$$\mathcal{L}_m = -\frac{1}{2}(S, D_1^0, D_2^0) M_n(-\epsilon) \begin{pmatrix} S \\ D_1^0 \\ D_2^0 \end{pmatrix} - M_D D_1^-(-\epsilon) D_2^+ + h.c.$$

$$= -\frac{1}{2} m_{\chi_i^0} \sum \chi_i^0(-\epsilon)\chi_i^0 - m_{\chi^\pm}\chi^-(-\epsilon)\chi^+ + h.c.,$$

$$M_n = \begin{pmatrix} M_S & \frac{1}{\sqrt{2}}y_1 v & \frac{1}{\sqrt{2}}y_2 v \\ \frac{1}{\sqrt{2}}y_1 v & 0 & -M_D \\ \frac{1}{\sqrt{2}}y_2 v & -M_D & 0 \end{pmatrix} \qquad \begin{pmatrix} S \\ D_1^0 \\ D_2^0 \end{pmatrix} = \mathcal{N} \begin{pmatrix} \chi_1^0 \\ \chi_2^0 \\ \chi_3^0 \end{pmatrix}$$

mass order : $\chi_1^0 < \chi_2^0 < \chi_3^0$

mass composition

$m_S > m_D$: χ_1^0 , χ_2^0 doublet , χ_3^0 singlet

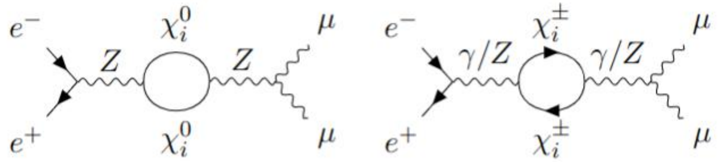
$m_S < m_D$: χ_1^0 singlet , χ_2^0 和 χ_3^0 doublet

In mass eigenstates , there is one charged particle $\chi^\pm$ and three neutral particles χ_i^0 $(i = 1,2,3)$

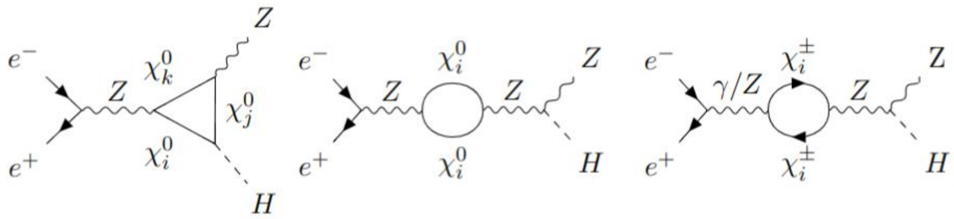
If consider Z_2 symmetry , χ_1^0 can be DM candidate

feynman diagrams of new sector

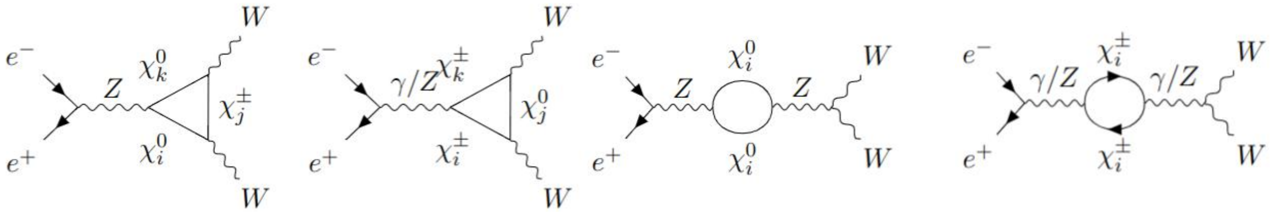
$e^+ e^- \to \mu^+ \mu^-$



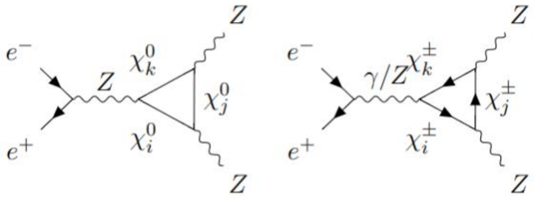
$e^+ e^- \to Z\,H$



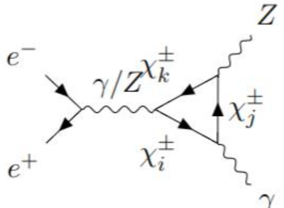
$e^+ e^- \to W^+ W^-$



$e^+ e^- \to Z\,Z$



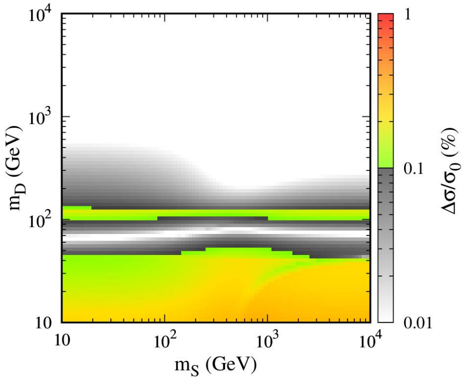
$e^+ e^- \to Z\,\gamma$



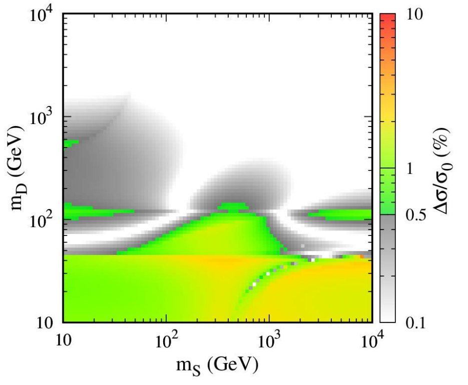
Contribution of new sector to the Cross Section

Fix Yukawa coupling : y_1=1.0, y_2=0.5。 In mass plane

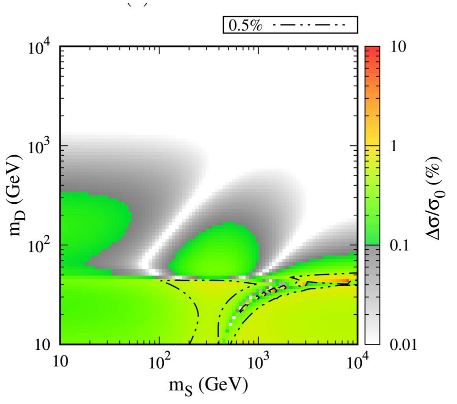
$$\frac{\Delta\sigma}{\sigma_0} = \frac{|\,\sigma_{\mathrm{SDFDM}} - \sigma_{\mathrm{SM}}\,|}{\sigma_{\mathrm{SM}}}$$



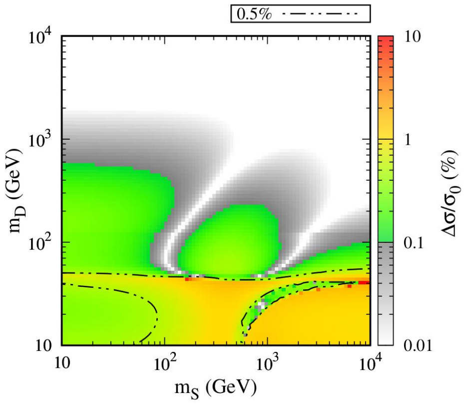
(a) $e^+e^- \to \mu^+\mu^-$



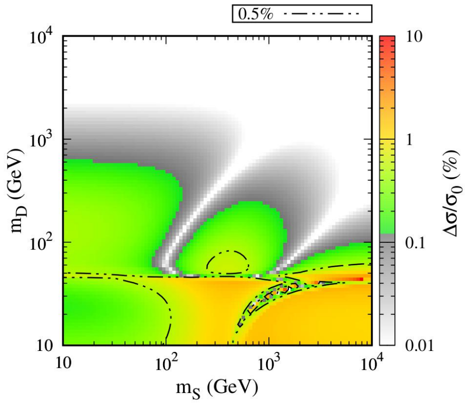
(b) $e^+e^- \to Zh$



(e) $e^+e^- \to Z\gamma$



(c) $e^+e^- \to W^+W^-$



(d) $e^+e^- \to ZZ$

Color region :
excluded by CEPC

Dot dashed line :
precision~0.5% excluded

characteristic :

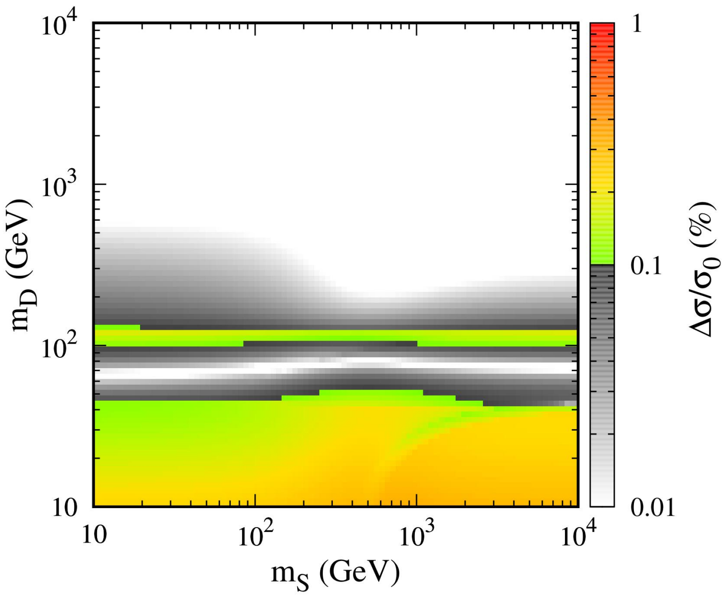
1. structure of diagrams is complex
   -> mass and coupling of particles and mass threshold
   $e^+ e^- \to \mu^+ \mu^-$ as an example

2. Constraints of five processes complementary
   -> combined results

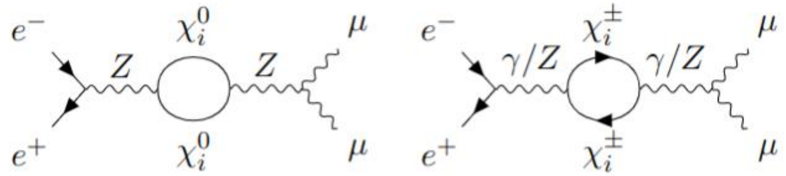
8 Constraints

$e^+ e^- \to \mu^+ \mu^-$ analysis

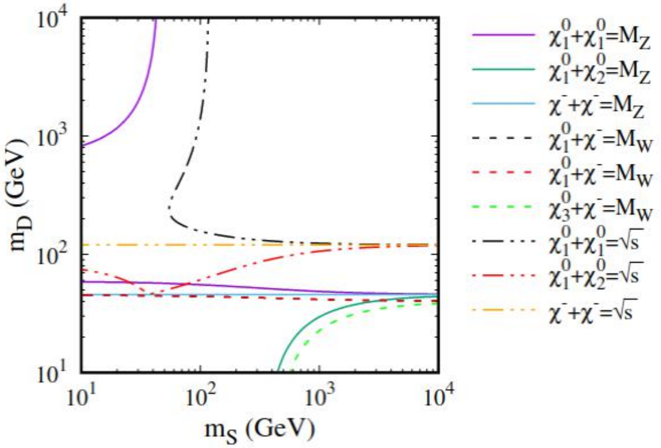
$$\frac{\Delta\sigma}{\sigma_0} = \frac{|\,\sigma_{\rm SDFDM} - \sigma_{\rm SM}\,|}{\sigma_{\rm SM}}$$



feynman diagrams of new sector



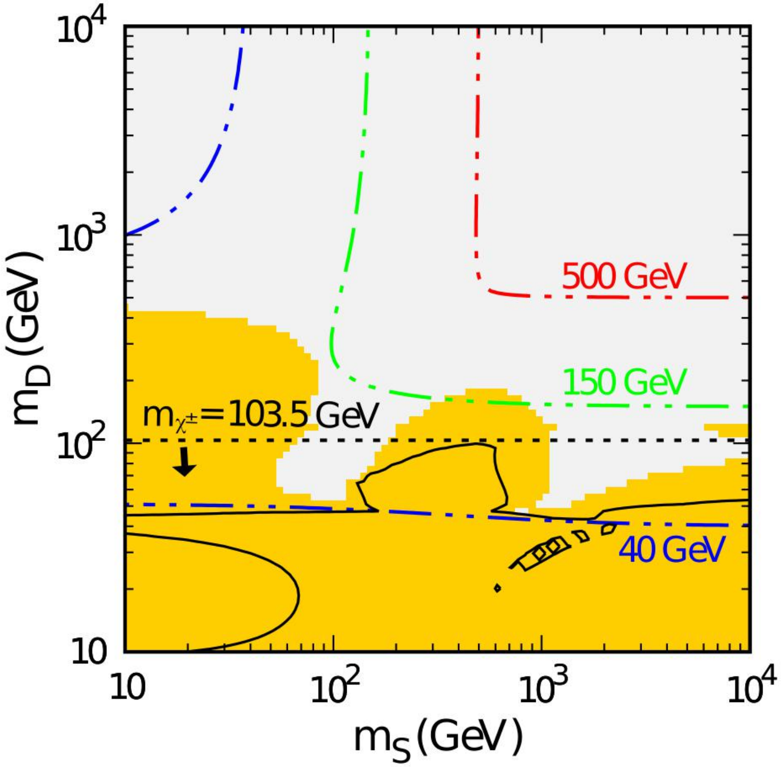
mass threshold



1. between 50~80 GeV , grey band
2. mainly dependent on m_D

combined constraints

In mass plane, Yukawa coupling : y_1=1.0, y_2=0.5



$$\chi^2 = \sum_i \frac{(\mu_i^{\rm NP} - \mu_i^{\rm obs})^2}{\sigma_{\mu_i}^2} \simeq \sum_i \frac{(\Delta\sigma/\sigma_0)^2}{\sigma_{\mu_i}^2}$$

2 degree 95% : χ^2=5.99

Yellow region : exlusion region at 95% C. L.
solid black lines: exlusion region (precision ~0.5%)
color lines : mass of χ_1^0

Detection capability of LEP、LHC and CEPC

LEP : constraints on charged particle **->** dashed black line
LHC : monojet+missE **->**mass of χ_1^0 is less than ~100 GeV

LEP: arXiv:hep-ex/0311019
LHC: arXiv: 1707.03094

combined constraints in Yukawa plane

In Yukawa coupling plane

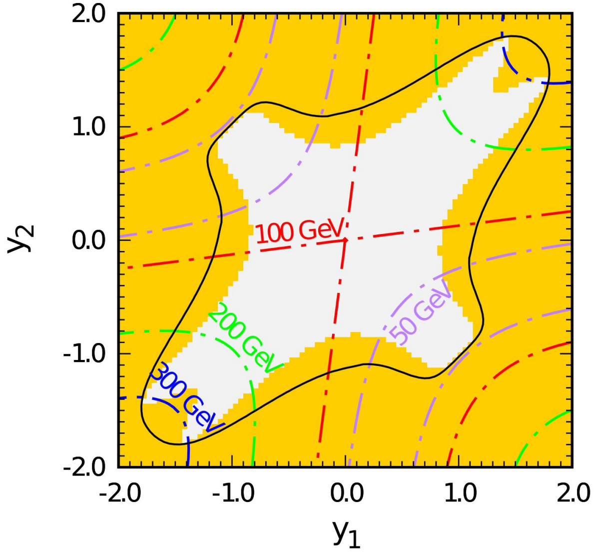
$$\frac{\Delta\sigma}{\sigma_0} = \frac{|\sigma_{SDFDM} - \sigma_{SM}|}{\sigma_{SM}}$$

mass composition

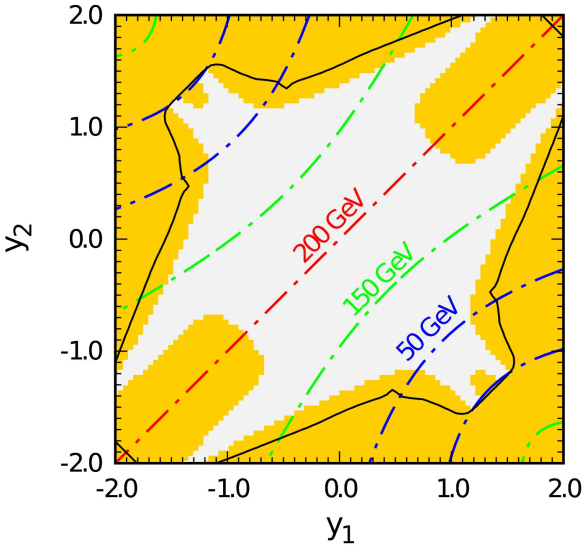
$m_S>m_D$: χ^0_1 , χ^0_2 doublet , χ^0_3 singlet

$m_S<m_D$: χ^0_1 singlet , χ^0_2 和 χ^0_3 doublet

M_S =100 GeV, M_D = 400 GeV



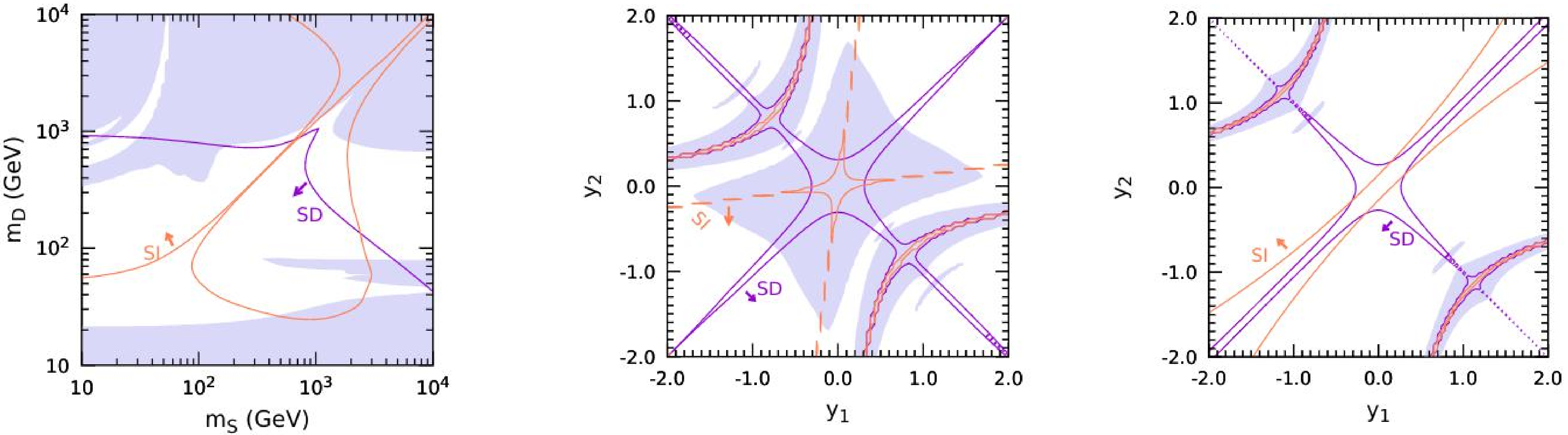
M_S = 400 GeV, M_D = 200 GeV



Yellow region : exlusion region
solid black lines : exlusion region(~0.5%)
color lines : mass of χ^0_1

LEP : no constraints, ($\chi^\pm$=M_D<103 GeV)
LHC : monojet+missE **->**
mass of χ^0_1 is less than ~100 GeV

DM relic density and direct detection （DM candidate χ_1^0 ）



(a) $y_1 = 1.0,\ y_2 = 0.5$　(b) $M_S = 100$ GeV, $M_D = 400$ GeV　(c) $M_S = 400$ GeV, $M_D = 200$ GeV

blue region：DM relic density， $\Omega h^2 > 0.12$ Planck2018

yellow liens： spin-independent，$h\chi_1^0\chi_1^0$ PandaX-4T

purple lines： spin-dependent，$Z\chi_1^0\chi_1^0$ PICO-60

doublet-triplet fermionic DM model (DTFDM model)

The dark sector contains Weyl spinors S and D_i (i = 1, 2) obeying $SU(2)_L \times U(1)_Y$

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

The gauge invariant Lagrangians

$$\mathcal{L}_T = iT^+ \bar{\sigma}^\mu D_\mu T - \frac{1}{2}(\boxed{m_T} T^T(-\epsilon)T + h.c.),$$

$$\mathcal{L}_D = iD_1^+ \bar{\sigma}^\mu D_\mu D_1 + iD_2^+ \bar{\sigma}^\mu D_\mu D_2 + (\boxed{m_D} D_1^{iT}(-\epsilon)D_2^j + h.c.),$$

$$\mathcal{L}_Y = \boxed{y_1} T D_1^i H_i - \boxed{y_2} T D_2^i \tilde{H}_i + h.c.,$$

Four free parameters : m_S, m_Q, y_1, y_2

In mass eigenstates , there are two charged particle $\chi_i^\pm$ $(i = 1,2)$

and three neutral particles χ_i^0 $(i = 1,2,3)$

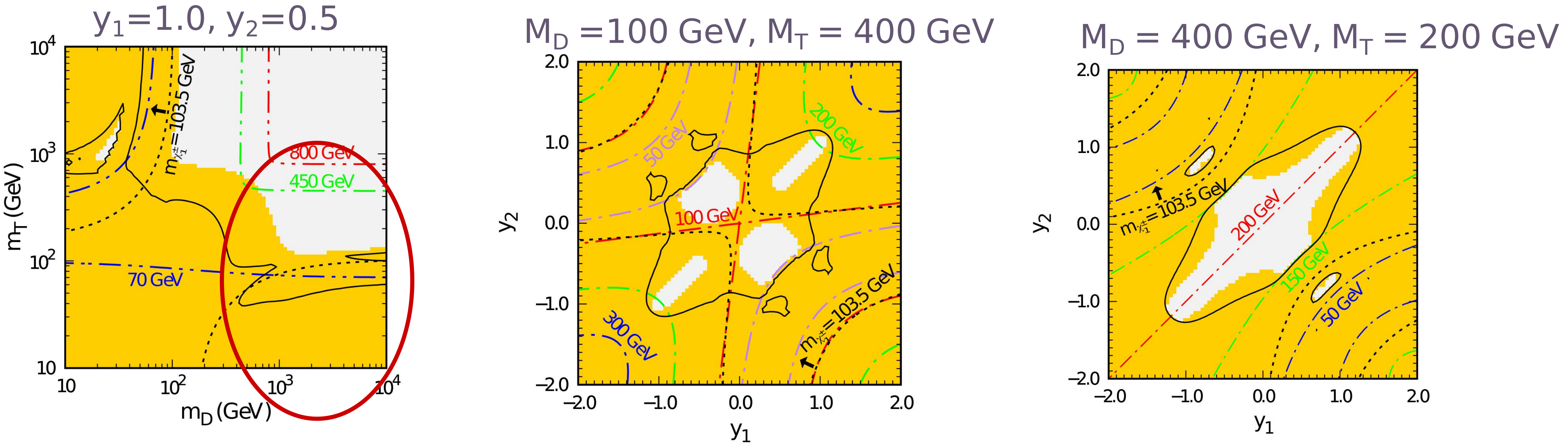
If consider Z_2 symmetry , χ_1^0 can be DM candidate

combined constraints

In mass plane and Yukawa coupling plane

$$\frac{\Delta\sigma}{\sigma_0} = \frac{|\,\sigma_{\rm SDFDM} - \sigma_{\rm SM}\,|}{\sigma_{\rm SM}}$$

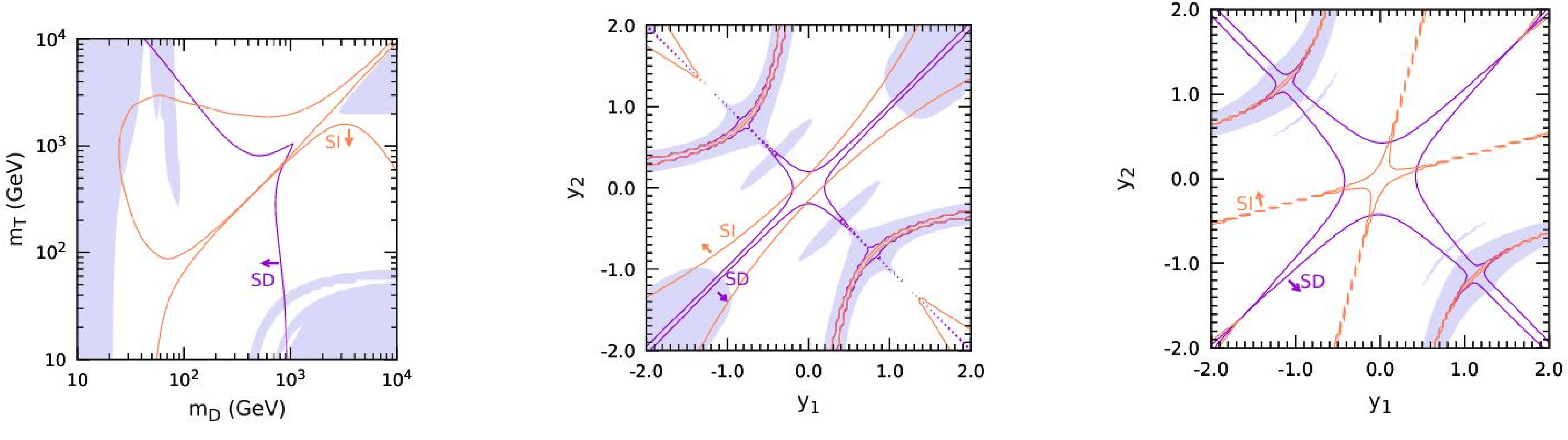
Yellow region : exlusion region
solid black lines : exlusion region(~0.5%)
color lines : mass of χ_1^0



LEP : dashed black line
LHC : mass of χ_1^0 is less than ~100 GeV

some differences with SDFDM model :
1. constraints is more strigent
2. red loop region

DM relic density and direct detection （DM candidate χ_1^0 ）



(a) $y_1 = 1.0,\ y_2 = 0.5$ (b) $M_D = 100$ GeV, $M_T = 400$ GeV (c) $M_D = 400$ GeV, $M_T = 200$ GeV

blue region：DM relic density， $\Omega h^2 > 0.12$
yellow region： spin-independent，$h\chi_1^0\chi_1^0$
purple region： spin-dependent， $Z\chi_1^0\chi_1^0$

difference with SDFDM model：
1. constraints of direct detection is same
2. constraints of relic density is weak

15 conclusion

1. We study two EW multiplet fermionic dark matter models through precision measurements at CEPC.

2. We focus on five processes: $e^+ e^- \to \mu^+ \mu^-$, Zh, W^+W^-, ZZ, $Z\gamma$. Precision of these processes are estimated as 0.1%, 0.5%, 0.1%, 0.12%, 0.1%, respectively. Moreover, we give a conservative precison 0.5%

We find the detectablity of CEPC would be complementary to LEP, LHC, DM relic density and direct detection in some parameter regions.

Thank You !