Dark matter searches at the CEPC

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Zheng Zhou， 2024.08.31

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Outline

- *Introduction*
- *Direct production of DM at the CEPC*
- *Indirect searches through precision measurements at the CEPC*
- *Summary*

DM searches at the e^+e^- colliders

- *Search for light DM directly produced, e.g. m<120GeV, at the CEPC*
  Search for interactions between the DM and electrons/EW gauge bosons/Higgs
  limited by the low CM energies of e^+e^- colliders

- *Probe DM and other relevant particles in new physics models (t-channel annihilation mediator, charged particles in multiplets…)*
  Indirect searches through loop effects, e.g. in the Higgs production and decay

- *Precise measurement rather than discovery*
  Full missing energy can be reconstructed
  possible to precisely measure the mass, spin, and other quantum numbers of DM

DM searches at the e^+e^- colliders

- *Advantage: No large QCD background; precise beam energy; larger luminosity polarized beams….*
  Precisely measurements of DM properties are possible
  Investigate the production mechanism of DM by using these results

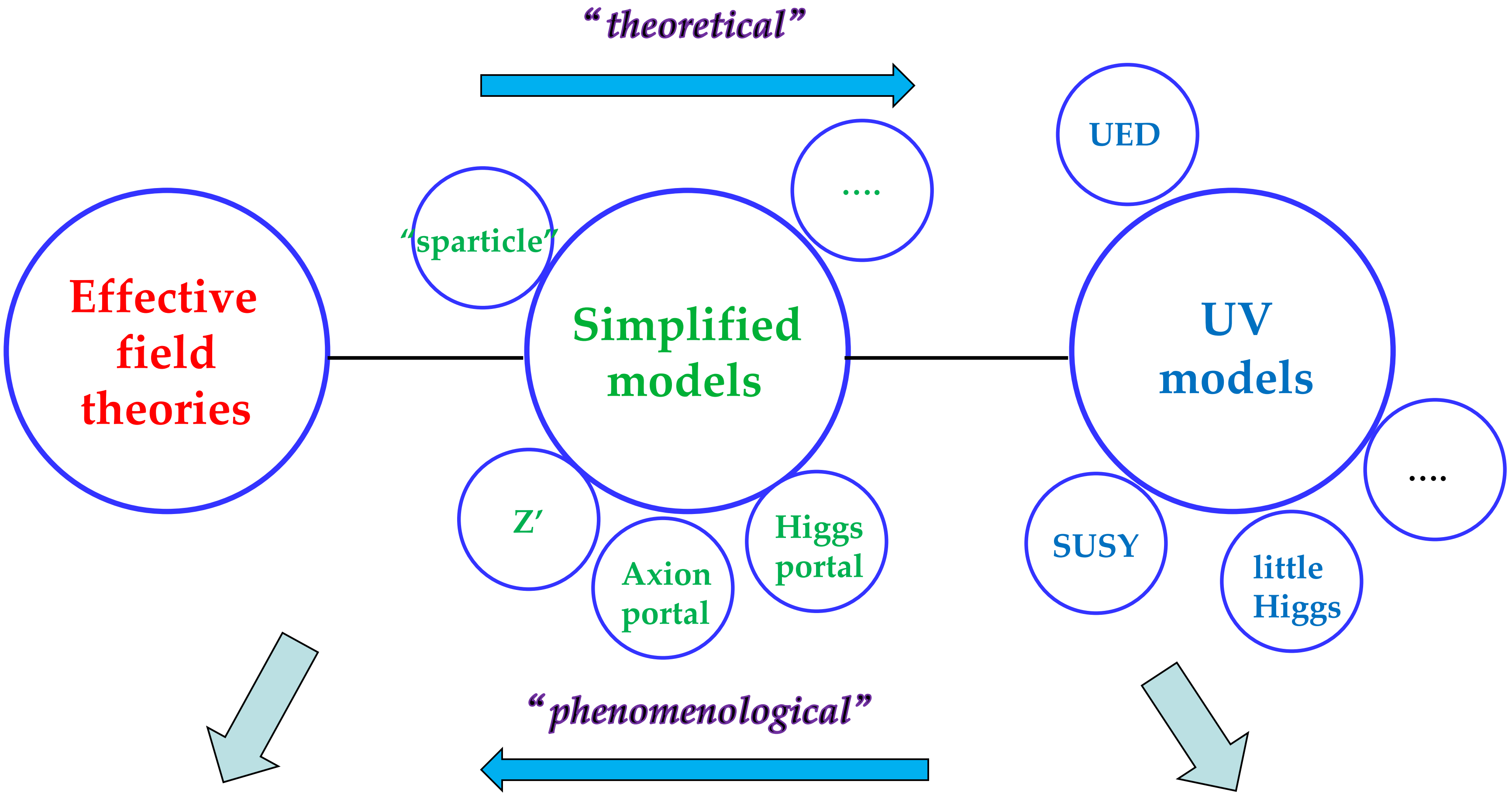
- ***Disadvantage**: Low CM energy….*
  difficult to directly detect heavy particles in the BSM

- *Complementary to searches at hadron colliders*

- *Complementary to direct and indirect DM detection experiments*

- *Even if a new neutral, stable, and weakly interacting particle is discovered at colliders, we should ascertain its potential as a constituent of dark matter within the Universe*

Direct signatures: theoretical approach



"theoretical"

Effective field theories

Simplified models

"sparticle"

….

Z′

Axion portal

Higgs portal

UV models

UED

SUSY

little Higgs

….

"phenomenological"

Mono-X signatures

Direct production, "model-independent"

Multi final states +Missing energy

Cascade decay, "model-dependent"

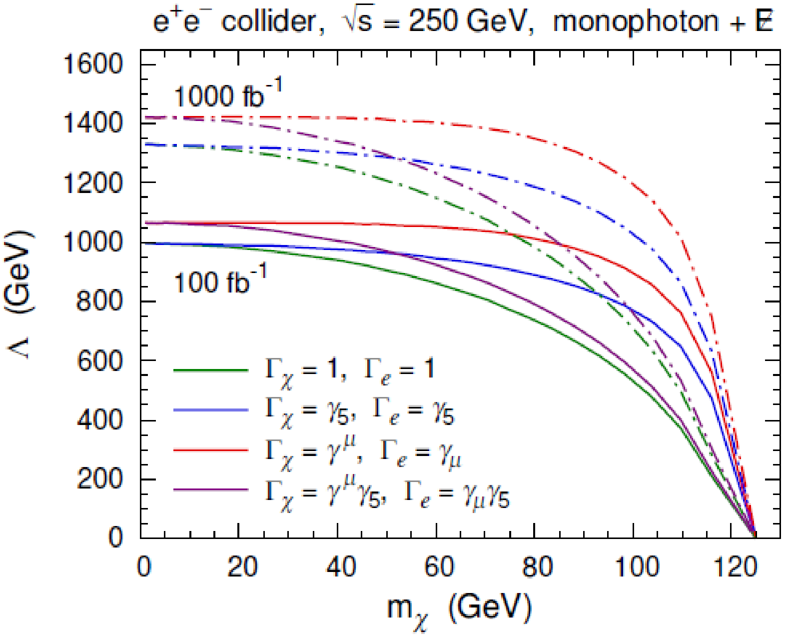
Other collider signatures and constraints

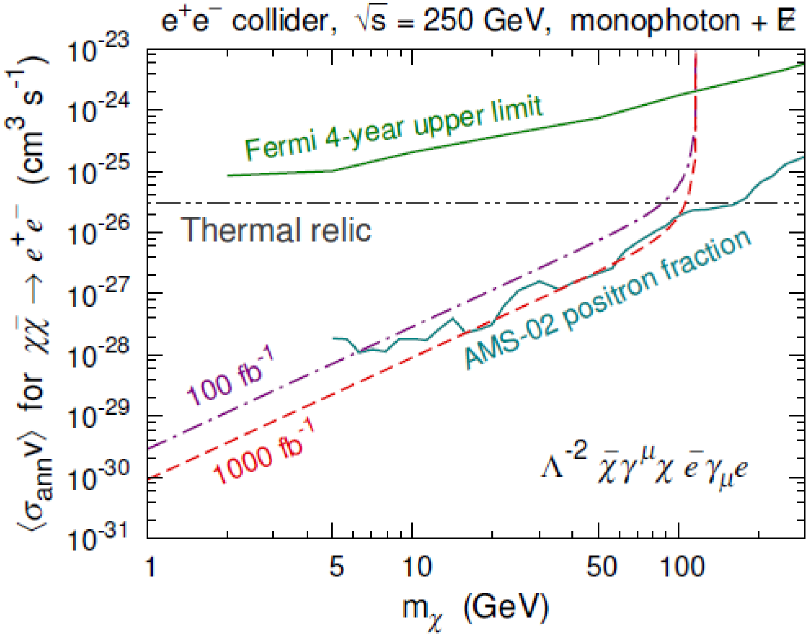
Mono-photon searches for EFTs

- *Consider the simplest EFTs*

$$\mathcal{O}_e = \frac{1}{\Lambda^2}\bar{\chi}\Gamma_\chi\chi\bar{e}\Gamma_e e \qquad\qquad \Gamma_\chi, \Gamma_e \in \{1, \gamma_5, \gamma^\mu, \gamma^\mu\gamma_5, \sigma^{\mu\nu}\}$$

- *Photon is emitted from the initial state radiation*

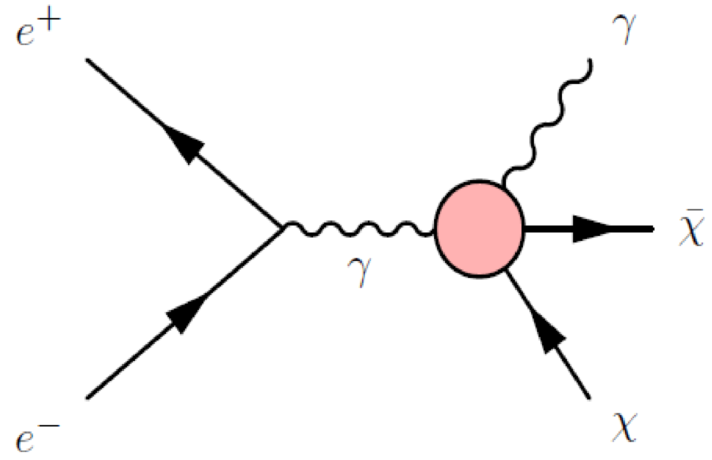




Gamma-ray line and mono-photon

- *Gamma-ray line signature is a critical evidence of DM annihilation/decay*

- *Search for corresponding mono-photon signals at future e^+e^- colliders*



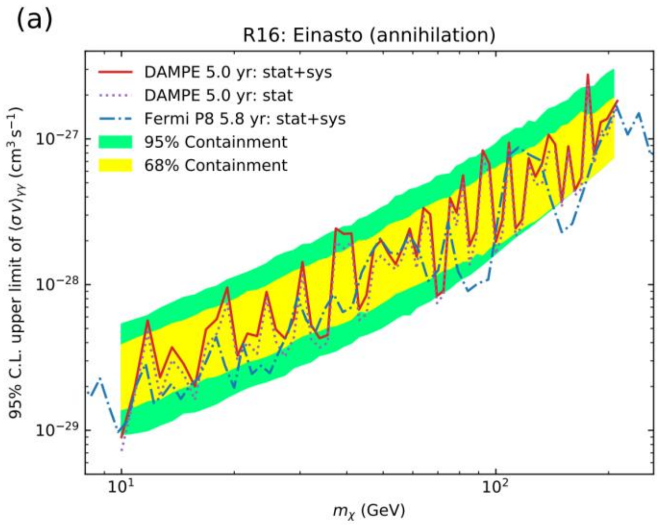
Yu, Yan, Yin, 1307.5740

- *Effective operator*

$$\mathcal{O}_F = \frac{1}{\Lambda^3}\bar{\chi}\, i\gamma_5\chi\, F_{\mu\nu}\tilde{F}^{\mu\nu}$$

Cut scale for a ~100 GeV DM and a detectable annihilation cross section is ~TeV

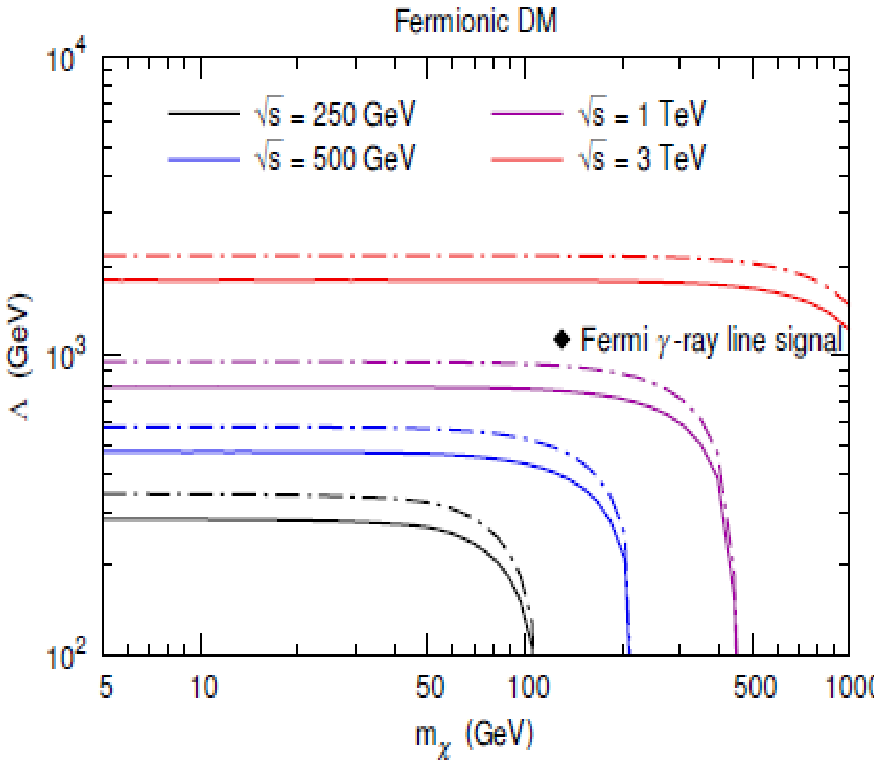
$$\langle\sigma_{\rm ann} v\rangle_{\chi\bar{\chi}\to 2\gamma} \simeq \frac{4m_\chi^4}{\pi\Lambda^6} = 10^{-27}\ {\rm cm}^3\ {\rm s}^{-1}\left(\frac{m_\chi}{130\ {\rm GeV}}\right)^4\left(\frac{1272\ {\rm GeV}}{\Lambda}\right)^6$$

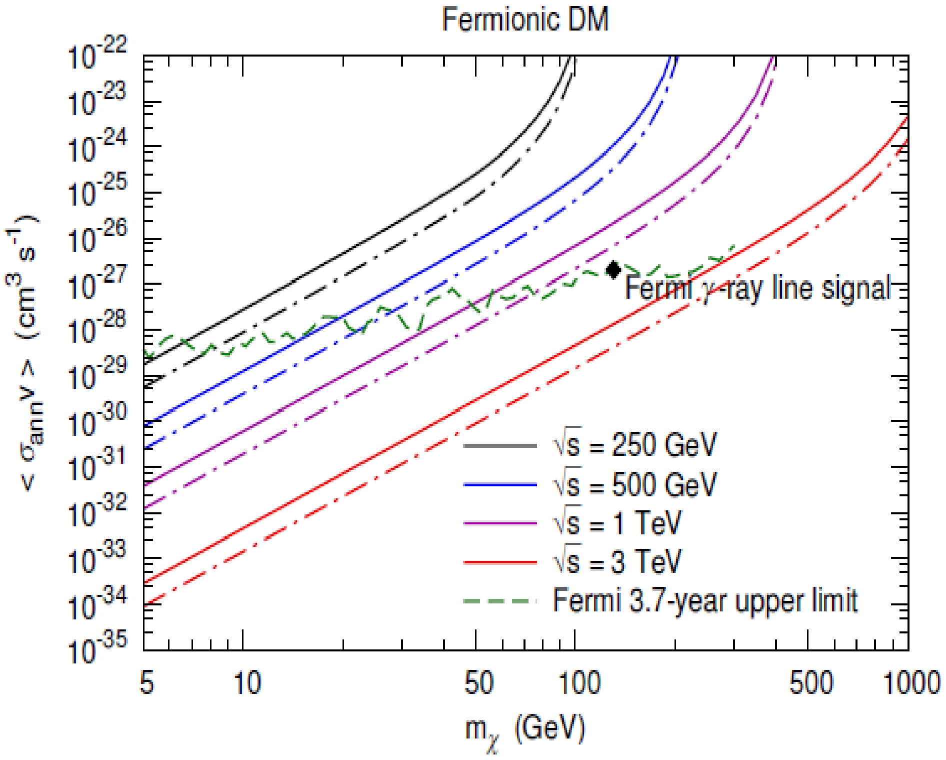


DAMPE, 2112.08860

Gamma-ray line and mono-photon

- *Consider possible e^+e^- colliders with several CM energies*
- *3σ reaches for mass scale and annihilation cross section*
- *Require large luminosities (>100 fb^{-1})*





Mono-Z signatures for EFTs

- *DM can interact with both the photon and Z boson*
- *Consider effective operators*

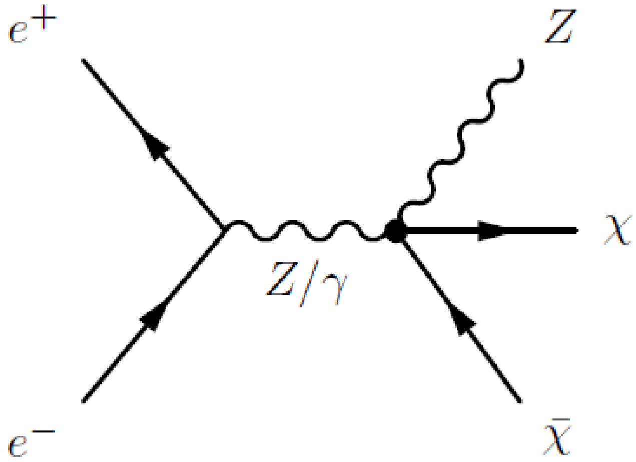
$$\mathcal{O}_{\mathrm{F1}} = \frac{1}{\Lambda_1^3}\bar{\chi}\chi B_{\mu\nu}B^{\mu\nu} + \frac{1}{\Lambda_2^3}\bar{\chi}\chi W^a_{\mu\nu}W^{a\mu\nu}$$

$$\supset \bar{\chi}\chi(G_{\mathrm{ZZ}}Z_{\mu\nu}Z^{\mu\nu} + G_{\mathrm{AZ}}A_{\mu\nu}Z^{\mu\nu})$$

$$\mathcal{O}_{\mathrm{F2}} = \frac{1}{\Lambda_1^3}\bar{\chi}i\gamma_5\chi B_{\mu\nu}\tilde{B}^{\mu\nu} + \frac{1}{\Lambda_2^3}\bar{\chi}i\gamma_5\chi W^a_{\mu\nu}\tilde{W}^{a\mu\nu}$$

$$\supset \bar{\chi}i\gamma_5\chi(G_{\mathrm{ZZ}}Z_{\mu\nu}\tilde{Z}^{\mu\nu} + G_{\mathrm{AZ}}A_{\mu\nu}\tilde{Z}^{\mu\nu})$$

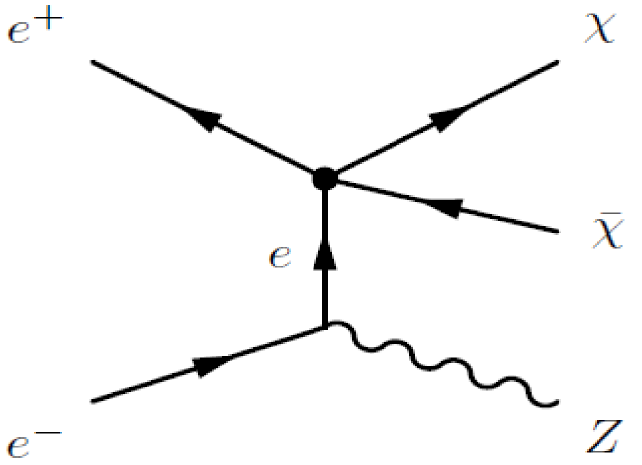
$$\mathcal{O}_{\mathrm{FH}} = \frac{1}{\Lambda^3}\bar{\chi}\chi(D_\mu H)^\dagger D_\mu H \to \frac{m_Z^2}{2\Lambda^3}\bar{\chi}\chi Z_\mu Z^\mu$$



- *Z boson can also come from initial state radiation*

$$\mathcal{O}_{\mathrm{FP}} = \frac{1}{\Lambda^2}\bar{\chi}\gamma_5\chi\bar{e}\gamma_5 e,$$

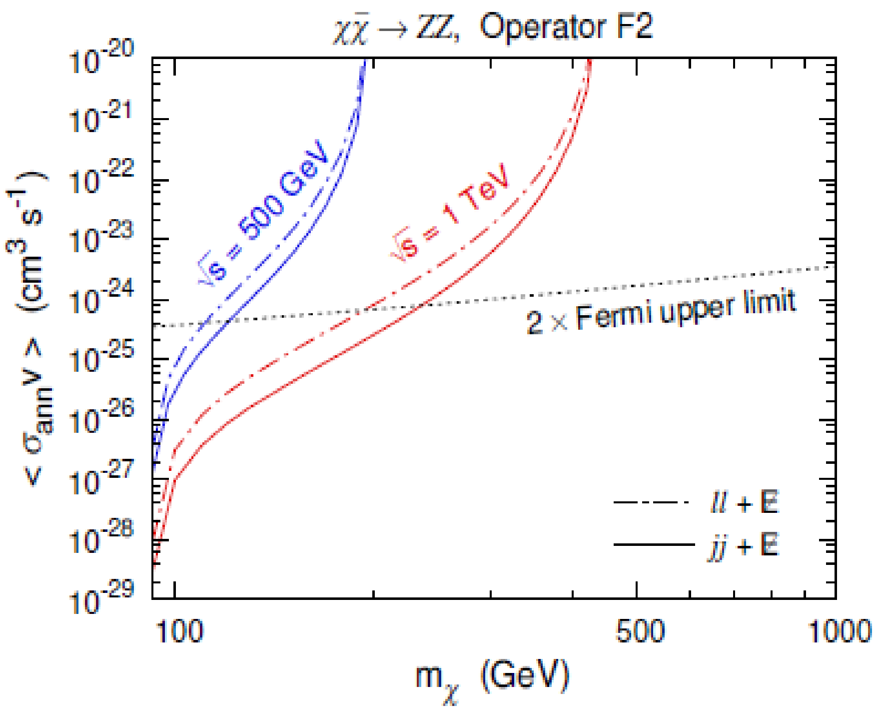
$$\mathcal{O}_{\mathrm{FA}} = \frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\gamma_5\chi\bar{e}\gamma_\mu\gamma_5 e$$

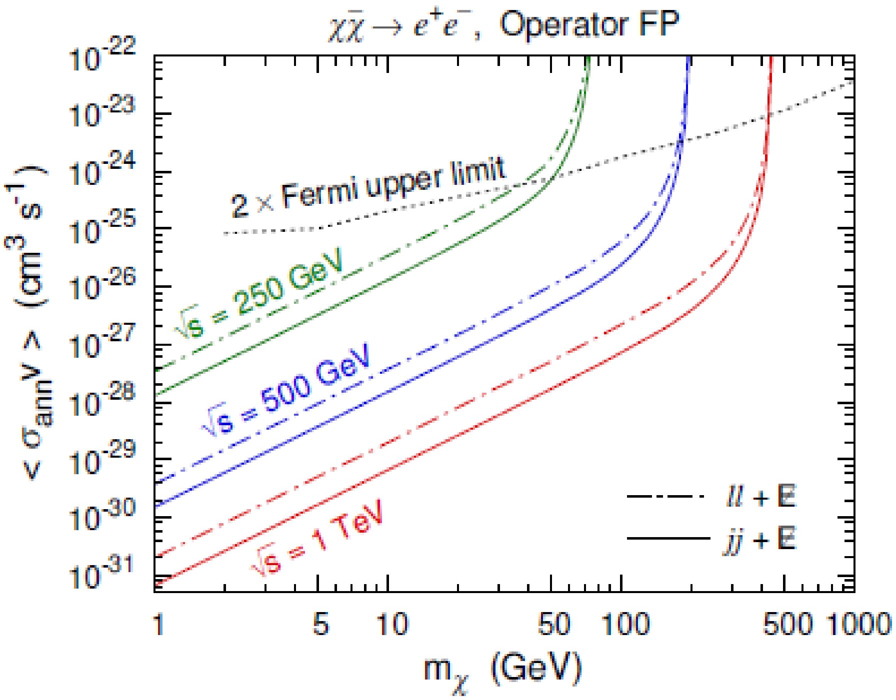


Yu, Bi, Yan, Yin, 1404.6990

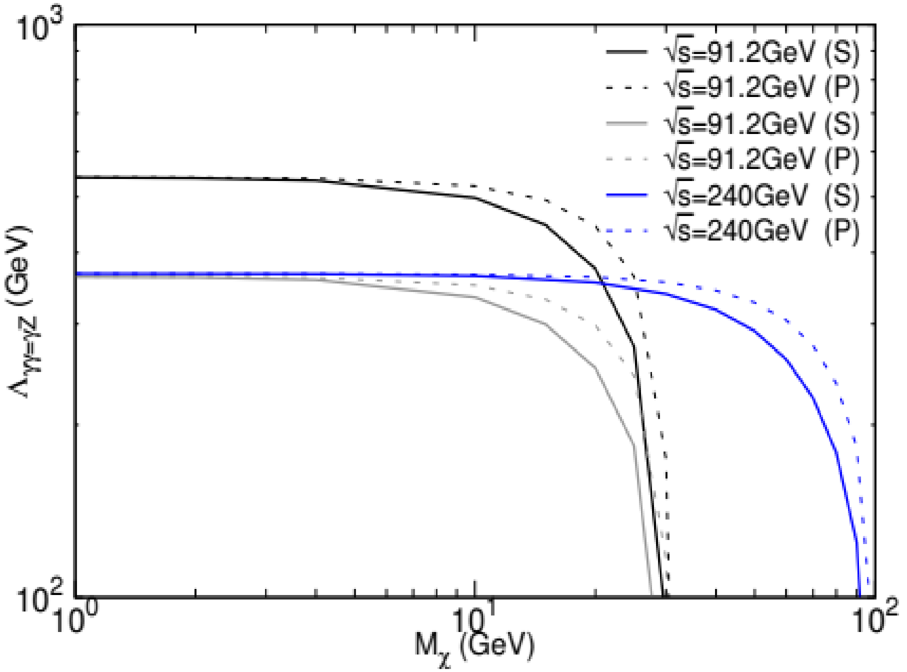
Mono-Z signatures for EFTs

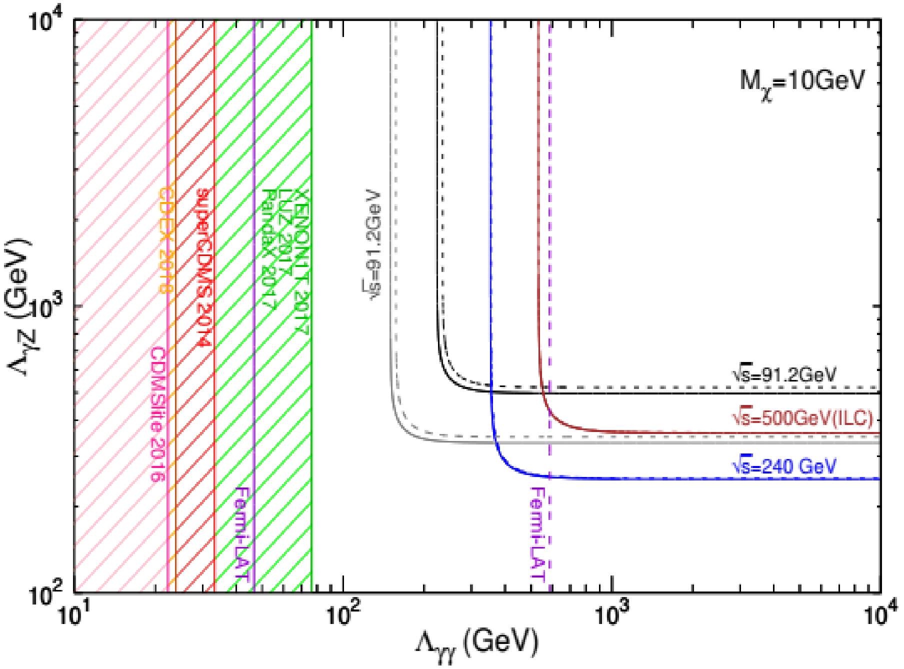
- *3s reaches for interactions between the DM and gauge bosons/electrons*
- *Assume: 1000 fb^{-1} of data; L=L$_1$=L$_2$*
- *Compare with the limits from Fermi-LAT dwarf galaxy observations*





Signatures at the Z-pole





Jin, Gao, 1712.02140

$$\mathcal{L}_{\rm S} \supset \frac{1}{\Lambda^3_{\gamma\gamma}}\bar{\chi}\chi A^{\mu\nu}A_{\mu\nu} + \frac{1}{\Lambda^3_{\gamma Z}}\bar{\chi}\chi A^{\mu\nu}Z_{\mu\nu},$$

$$\mathcal{L}_{\rm P} \supset \frac{1}{\Lambda^3_{\gamma\gamma}}\bar{\chi}i\gamma_5\chi A^{\mu\nu}\widetilde{A}_{\mu\nu} + \frac{1}{\Lambda^3_{\gamma Z}}\bar{\chi}i\gamma_5\chi A^{\mu\nu}\widetilde{Z}_{\mu\nu}$$

- *The high luminosity Z-pole run offers a unique opportunity to search for DM particles*

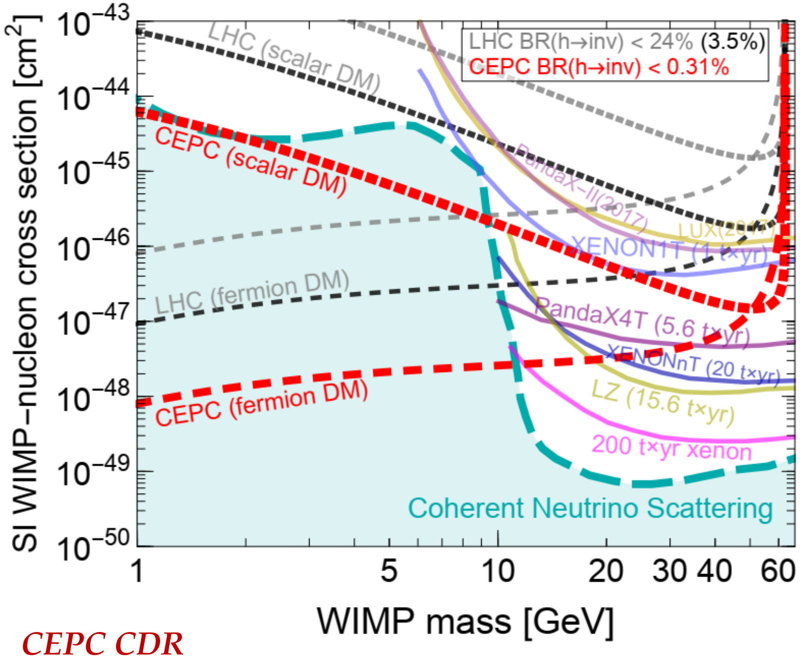
Simplified models: DM couples to mediators

- *Assume that DM couples to the SM particles through some SM mediators*

$$\mathcal{L} = -h J_h\,, \qquad J_h = \frac{1}{\sqrt{2}}\left[\sum_f y_f \bar{f} f + \bar{\psi}_{\rm DM}(y_{\rm DM} + i y^P_{\rm DM}\gamma_5)\psi_{\rm DM} + \frac{\lambda_{\rm DM} v}{2} s^2_{\rm DM}\right]$$

$$\mathcal{L} = -Z_\mu J^\mu_Z\,, \qquad J^Z_\mu = \frac{g_2}{\cos\theta_{\rm W}}\left[\sum_f [\bar{f}\gamma_\mu(g^f_V + \gamma_5 g^f_A) f] + \sum_s g_s[s^*(i\partial_\mu s) - (i\partial_\mu s^*)s]\right]$$

- *Searches for invisible Higgs/Z decays are useful to probe DM*

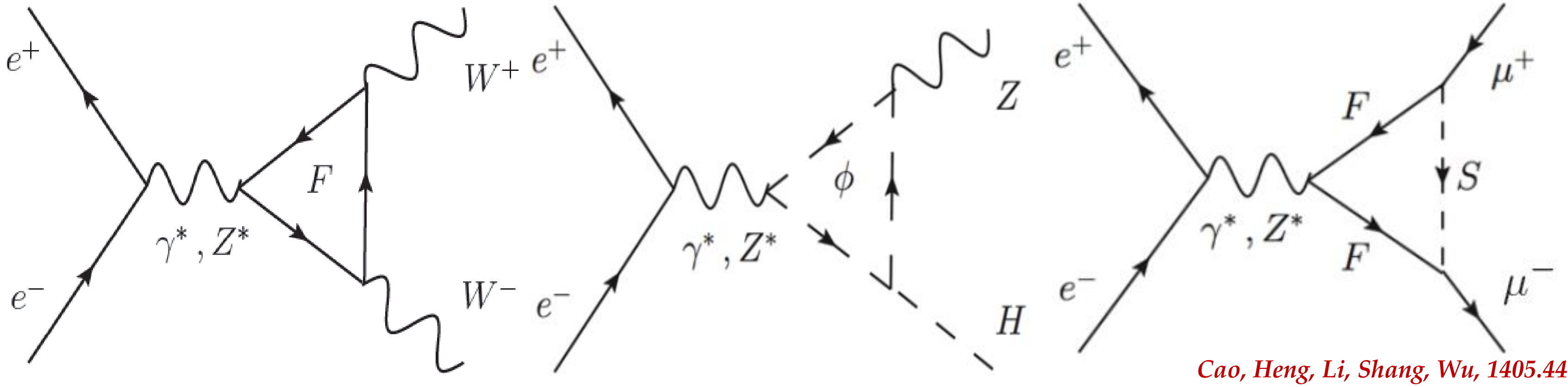


CEPC CDR

- *For discussions on more portals and UV models, referred to talks in other sessions, such as dark sector and SUSY.*

Probing DM at CEPC via loop effects

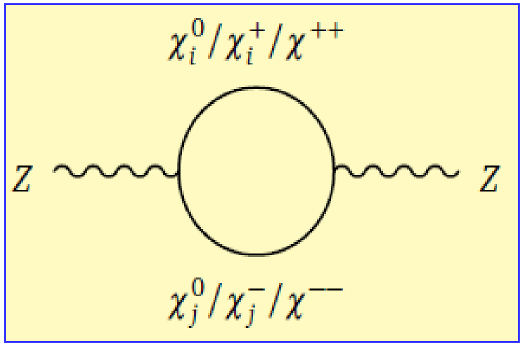
- *New particles give corrections to SM processes, which can be measured at a level of ~O(0.1%) at lepton colliders*

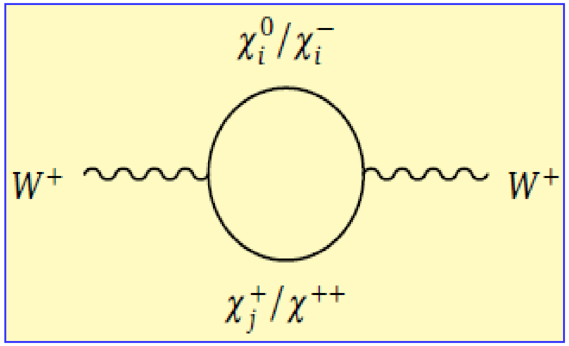


Cao, Heng, Li, Shang, Wu, 1405.4489
Cao, Li, Yan, Zhang, Zhang, 1604.07536
Liu, Wu, 1705.02534
Xiang, Bi, Yin, Yu, 1707.03094

- *Also give oblique corrections to gauge boson propagators*

Search for new particles via the precision measurements and global fitting





Fedderke, Lin, Wang, 1506.05465
Cai, Yu, Zhang, 1611.02186, 1705.07921

DM models with additional EW multiplets

- *Consider some simple Fermionic DM models containing new electro-weak multiplets: few new particles and no new mediator*

- *Add one high-dimensional representation: minimal DM model*

Cirelli et al, hep-ph/0512090

- *The model can also contain a vector-like fermion and a Z_2 symmetry stabilizing DM. But no coupling to the SM Higgs : no mass contribution from EWSB, degenerate mass spectrum…*

DM models with additional EW multiplets

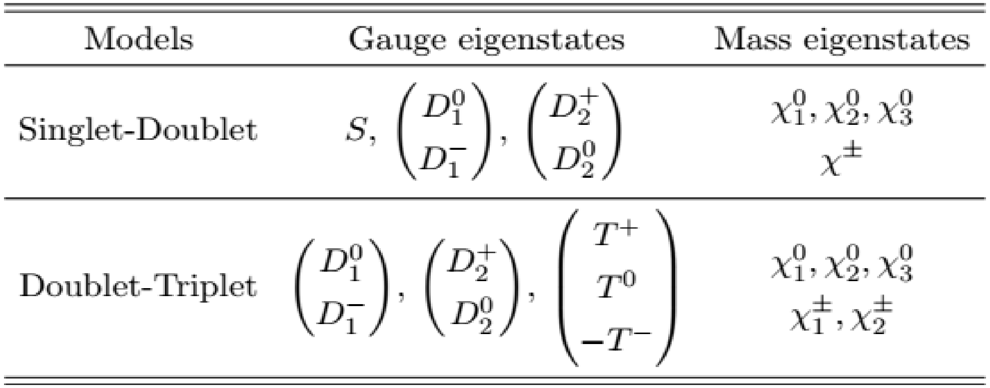
- *Add two types of vector EW Fermionic multiplets may be an economical option with a rich phenomenology. We consider the models:*

SDFDM: one singlet + two doublet Weyl spinors

DTFDM: two doublet + one triplet Weyl spinors

TQFDM: two quadruplet + one triplet Weyl spinors

Xiang, Bi, Yin, Yu, 1707.03094
Wang, et. al., 1711.05622



Models	Gauge eigenstates	Mass eigenstates
Singlet-Doublet	$S, \begin{pmatrix} D_1^0 \\ D_1^- \end{pmatrix}, \begin{pmatrix} D_2^+ \\ D_2^0 \end{pmatrix}$	$\chi_1^0, \chi_2^0, \chi_3^0$ $\chi^\pm$
Doublet-Triplet	$\begin{pmatrix} D_1^0 \\ D_1^- \end{pmatrix}, \begin{pmatrix} D_2^+ \\ D_2^0 \end{pmatrix}, \begin{pmatrix} T^+ \\ T^0 \\ -T^- \end{pmatrix}$	$\chi_1^0, \chi_2^0, \chi_3^0$ $\chi_1^\pm, \chi_2^\pm$

- *Analogous to some well-studied DM models, such as SUSY DM*

SDFDM-> Bino-Higssino in MSSM; Singlino-Higgsino in NMSSM

DTFDM-> Higgsino-Wino in MSSM

$$\Delta L = M_1 \tilde{B}\tilde{B} + M_2 \tilde{W}\tilde{W} + \mu \tilde{H}_u \tilde{H}_d$$
$$+ \sqrt{2}\kappa_1 h^\dagger \tilde{W} \tilde{H}_u + \sqrt{2}\kappa_2 h \tilde{W} \tilde{H}_d + \frac{\kappa_1'}{\sqrt{2}} h^\dagger \tilde{B} \tilde{H}_u + \frac{\kappa_2'}{\sqrt{2}} h \tilde{B} \tilde{H}_d$$

Arkani et. al, 1511.06495

Singlet-Doublet Fermionic Model

- *Introduce one weyl singlet and two doublets*
  Gauge invariant Lagrangian

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

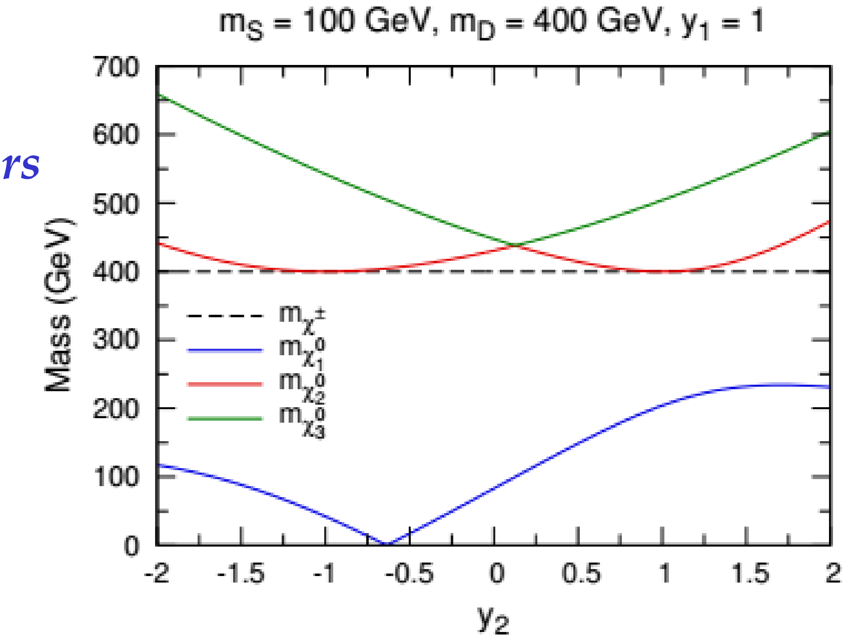
$$\mathcal{L}_{\text{D}} = iD_1^\dagger \bar{\sigma}^\mu D_\mu D_1 + iD_2^\dagger \bar{\sigma}^\mu D_\mu D_2 - (m_D \epsilon_{ij} D_1^i D_2^j + \text{h.c.})$$

Yukawa coupling

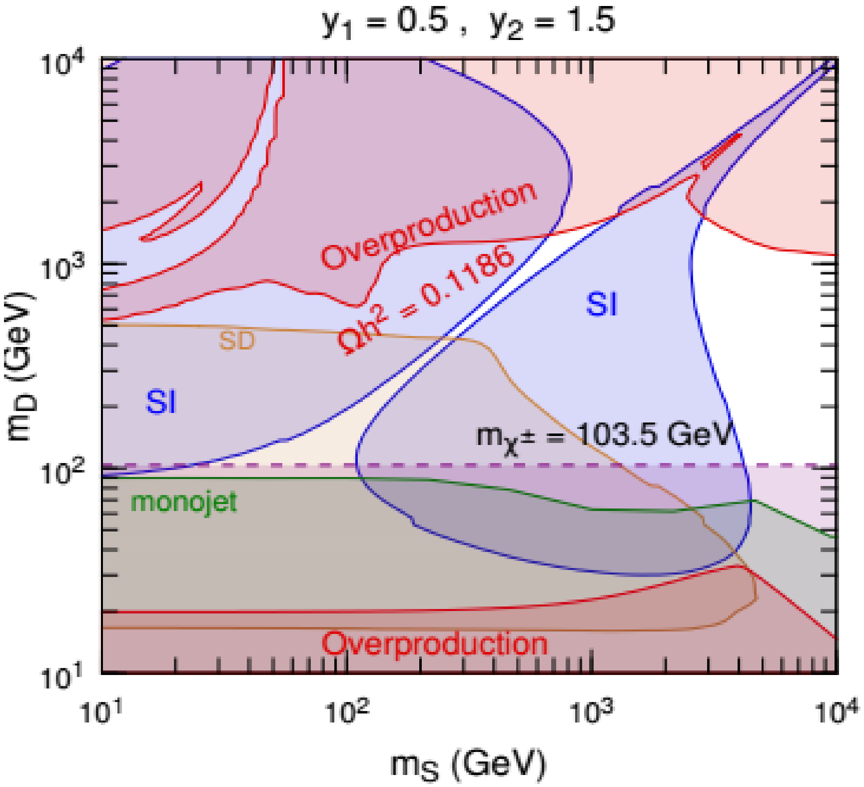
$$\mathcal{L}_{\text{yuk}} = y_1 S D_1^i H_i - y_2 S D_2^i H_i^\dagger + \text{h.c.}$$

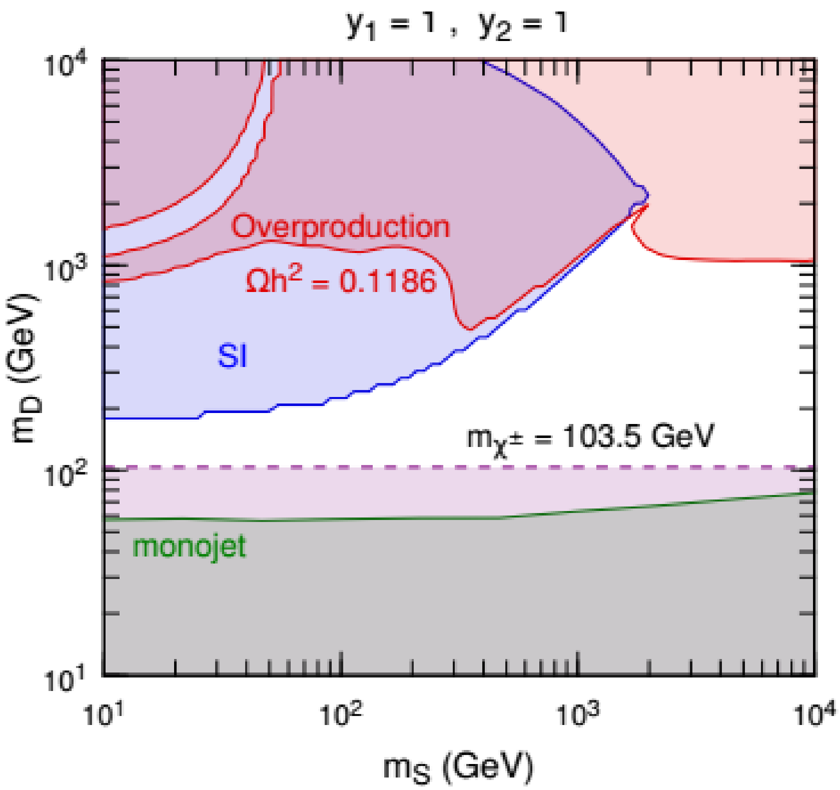
- *Four new parameters: two mass parameters m_S, m_D and two Yukawa couplings y_1, y_2*

- *DM is the lightest mass eigenstate in the neutral sector after EWSB*



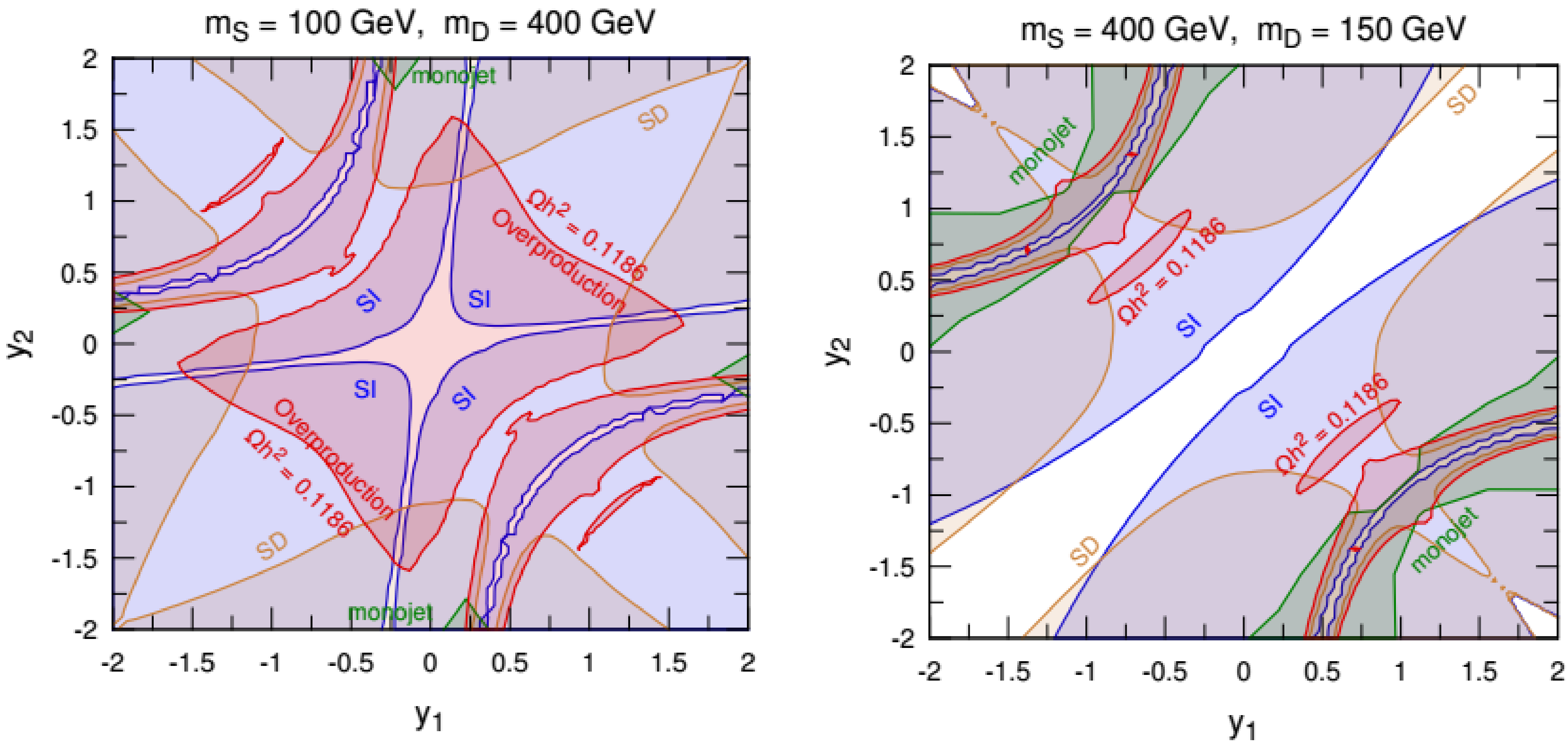
Constraints from DM searches





- *DM relic density: take into account the coanihilation effects*
- *Direct detection: Spin-independent (SI) and Spin-dependent (SD) constraints (PANDAX)*
- *LHC: mono-jet limits (ATLAS) on the production of dark sector particles*
- *LEP: require the mass of new charge particle is smaller than 103.5 GeV*

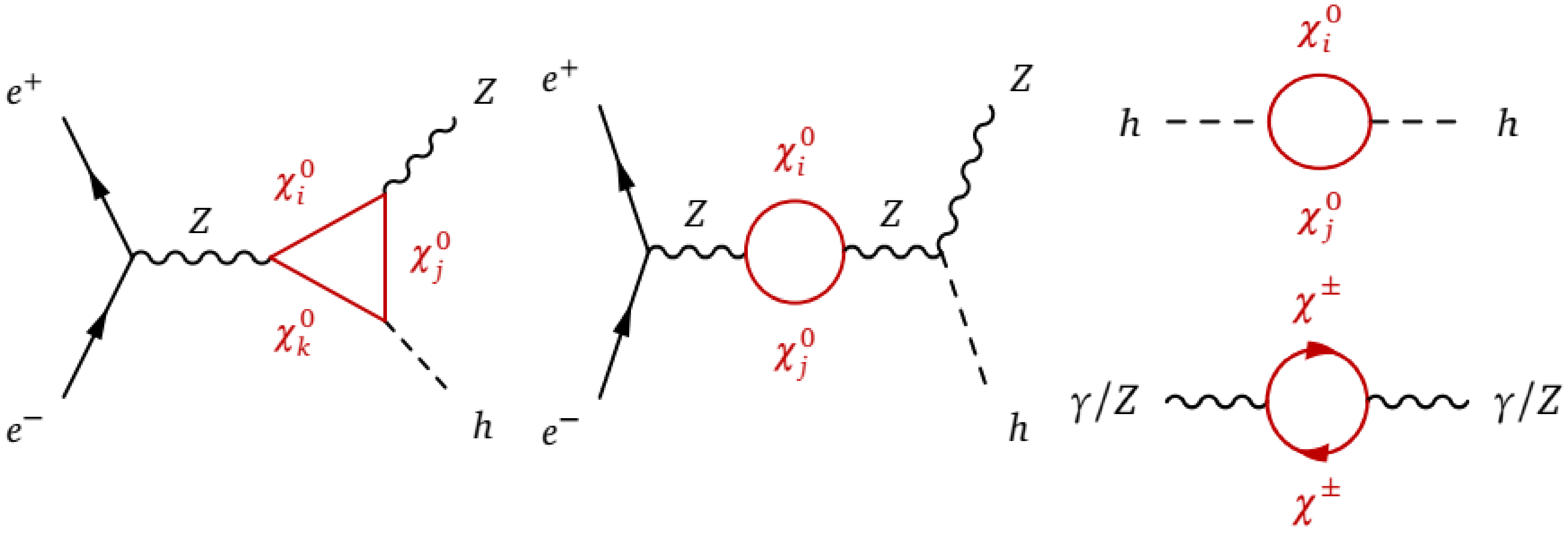
Constraints from DM searches



- *Parameter space is stringently constrained by direct detection, except for some regions where the DM couplings to Z and Higgs are suppressed*

Probing DM via measurements of Zh production

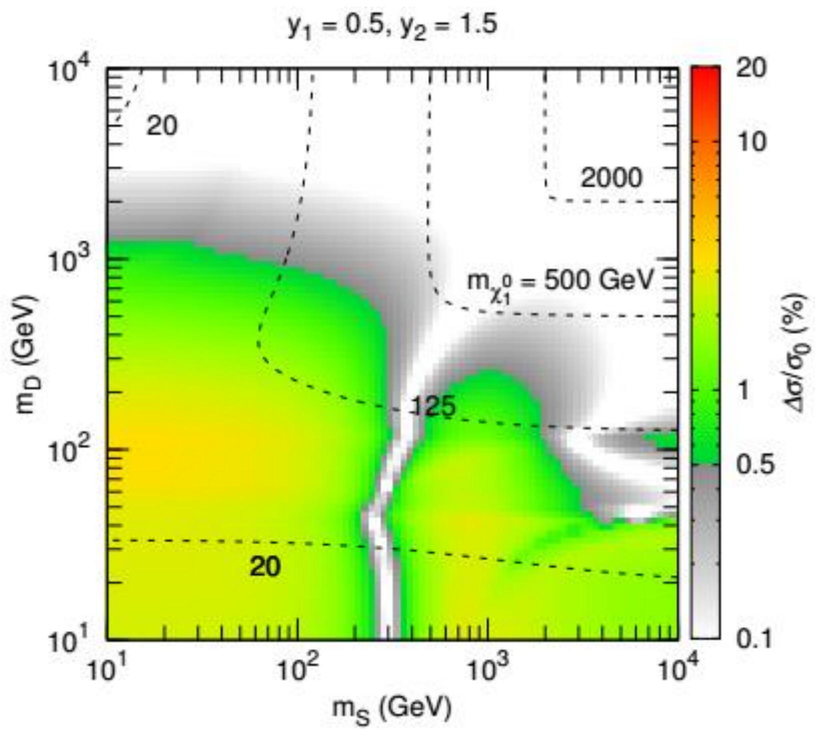
- *We consider the corrections of new particles to the associated* **Z-Higss production**
  This process is affected by both the gauge and Yukawa interactions

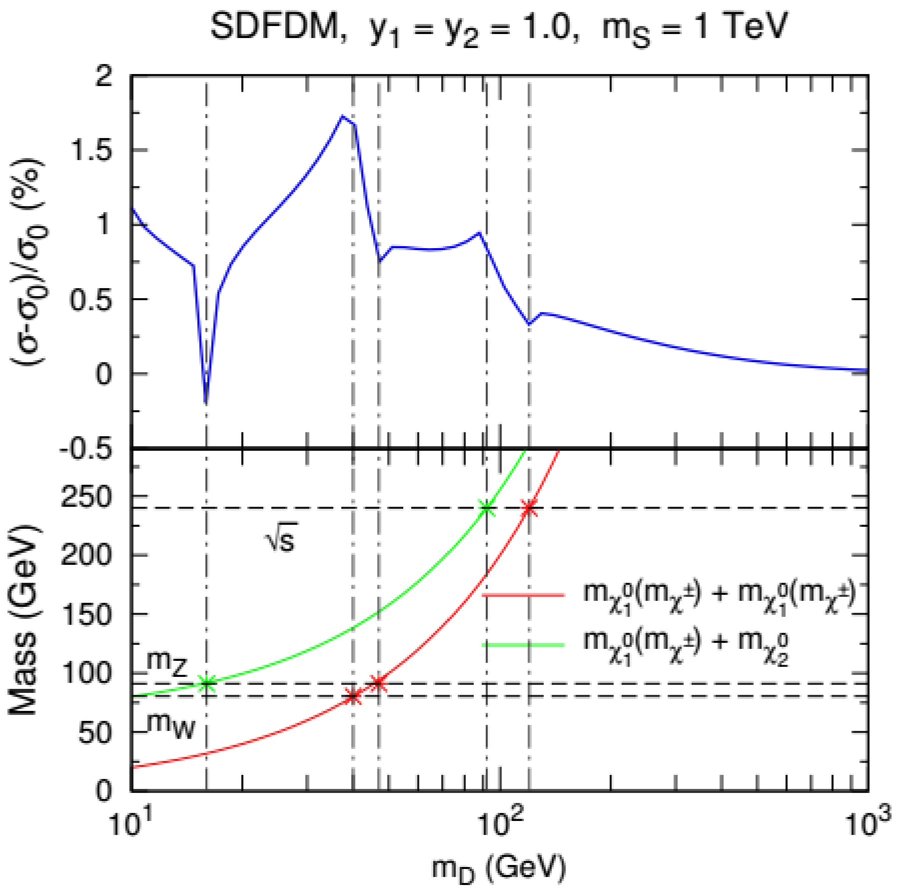


calculate corrections to the Zh production cross section ($\Delta\sigma/\sigma=(\sigma_{NP}-\sigma_{SM})/\sigma_{SM}$)

- *It is possible to measure* $\Delta\sigma/\sigma|_{Zh}$ *at a level of* ~**0.5%** *at CEPC (with* $5ab^{-1}$ *of data)*

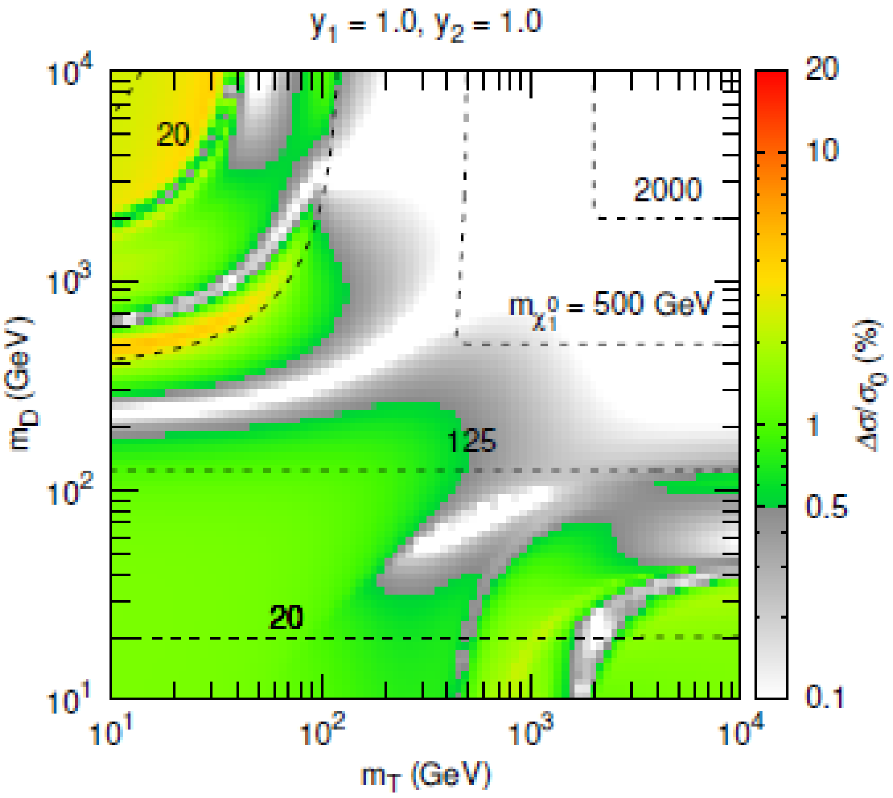
Probing DM via measurements of Zh production

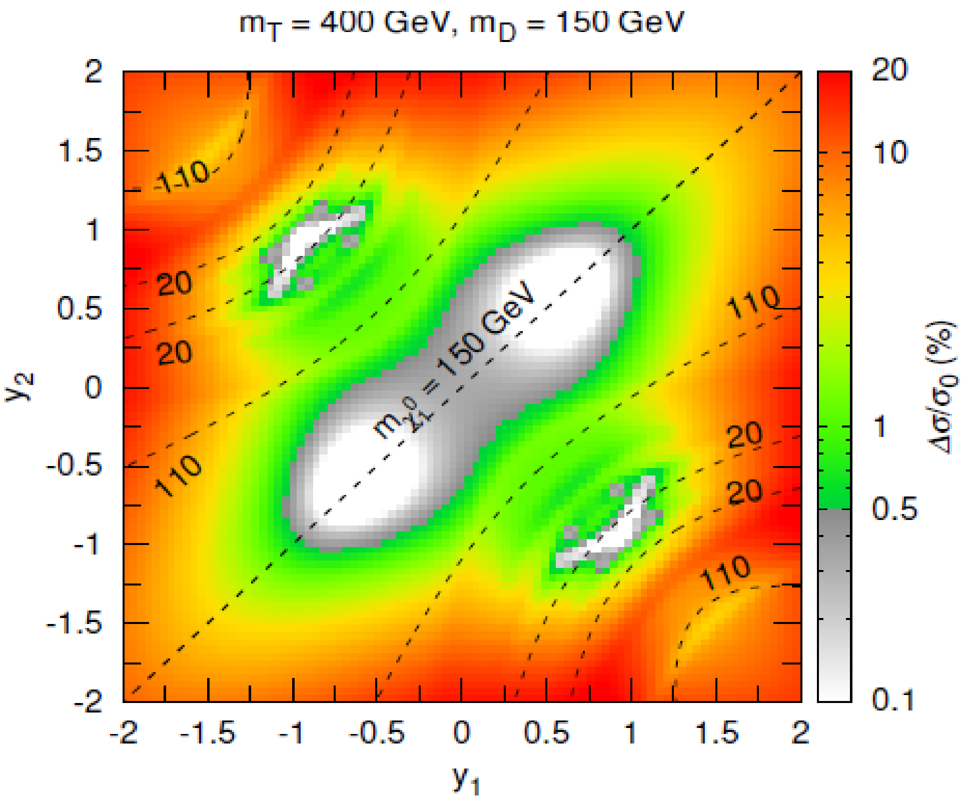




- *For* y_1*=0.5 and* y_2*=1.5, CEPC can probe up to* m_χ*~200 GeV*
- *When the dark sector particles in loops are close to their mass shells, their contributions vary dramatically*

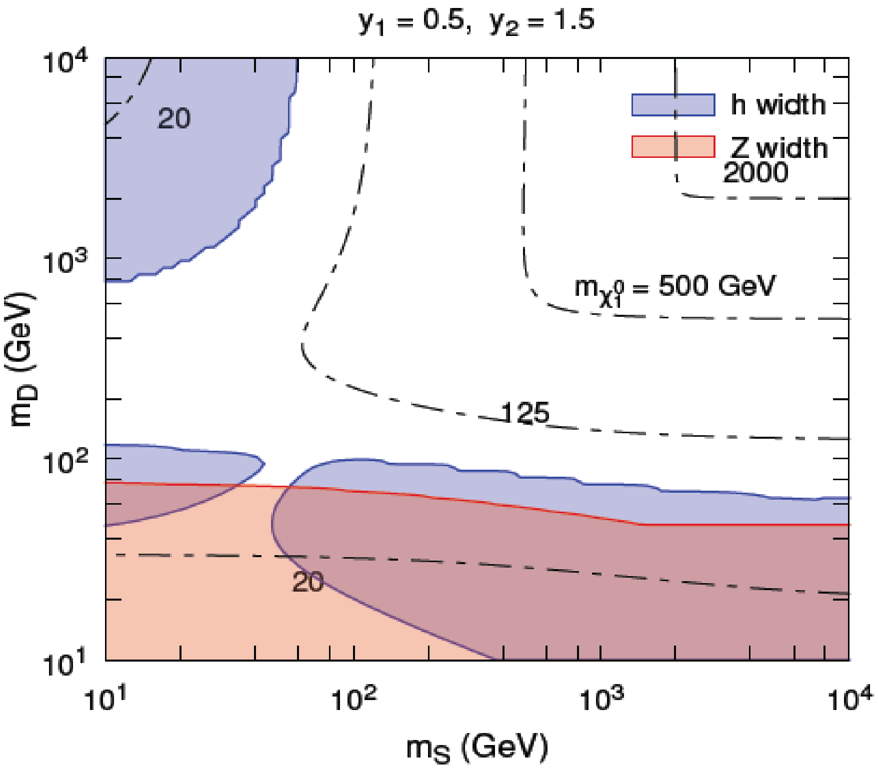
Probing DM via measurements of Zh production

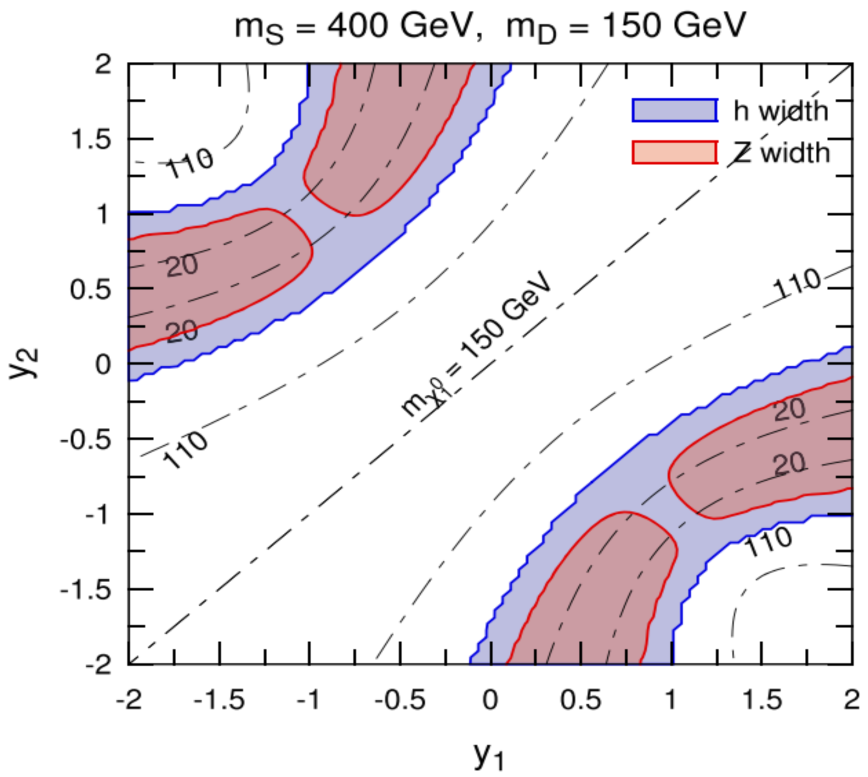




Searches of Higgs and Z decays

- *If new charged particles couple to the Higgs, they could modified the Higgs decay width to di-photons via triangle loops. ΔΓ/Γ can be test to be a level of ~9%*
- *If the kinematics is allowed, the Higgs and Z could decay into DM particles. Such invisible decays are constrained by the relevant searches at colliders*

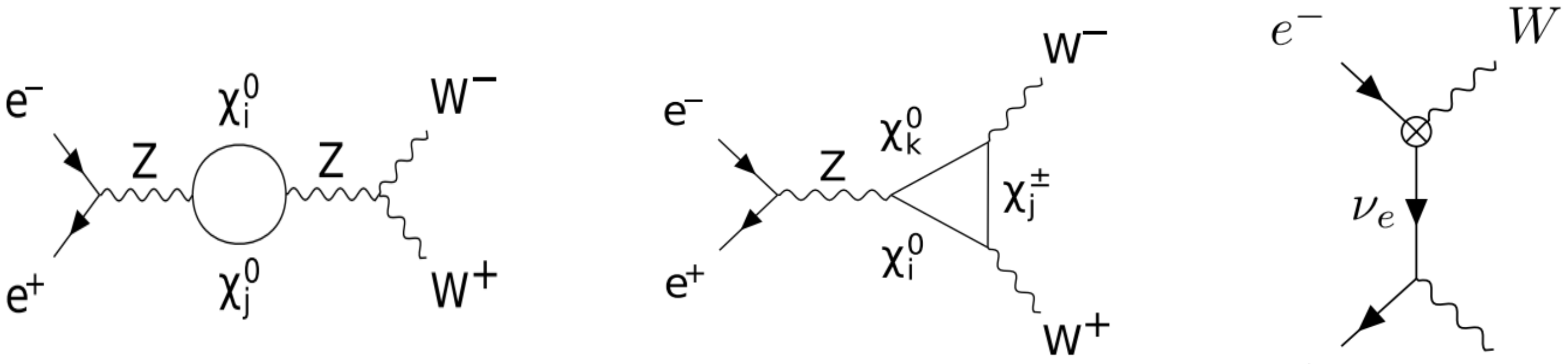




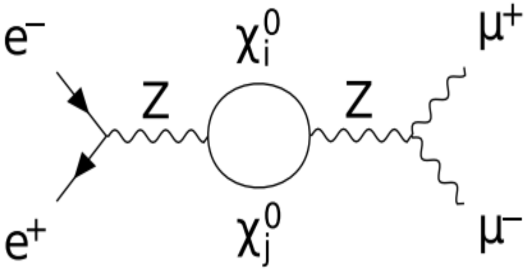
Take $G(Z\to inv) < 2$ MeV (LEP) and $G(h\to inv)/G_h < 2.8\%$ (for CEPC 5 ab^{-1})

Searches via precision measurements

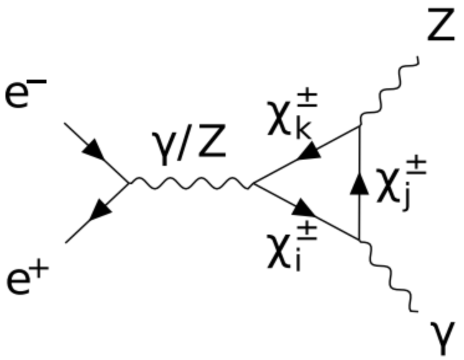
- *It is possible to explore these particles through loop effects using the precision measurements for other EW processes at the CEPC*



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



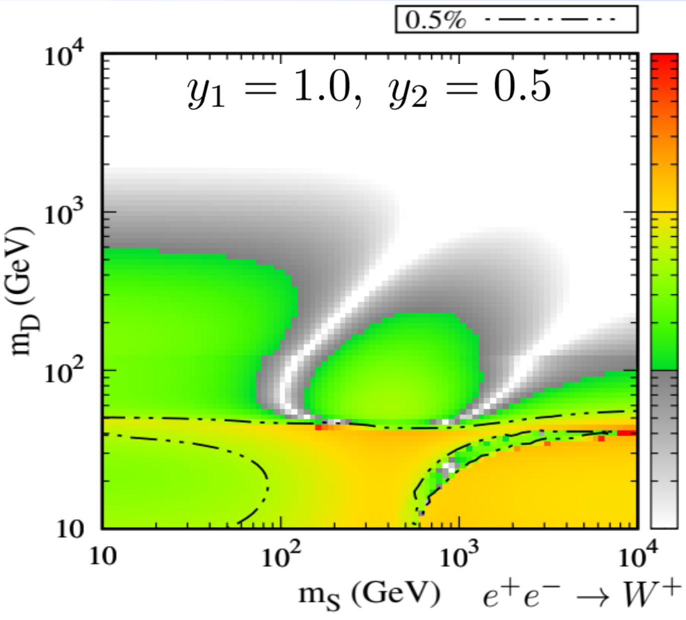
$e^+e^- \to \mu^+\mu^-$



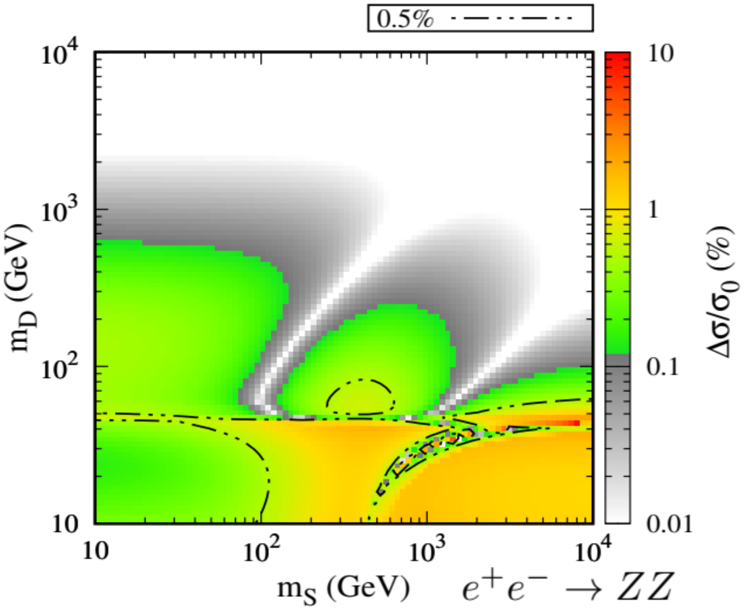
$e^+e^- \to ZZ$

Gao, Bi, Wang, Xiang, Yin, 2112.02519

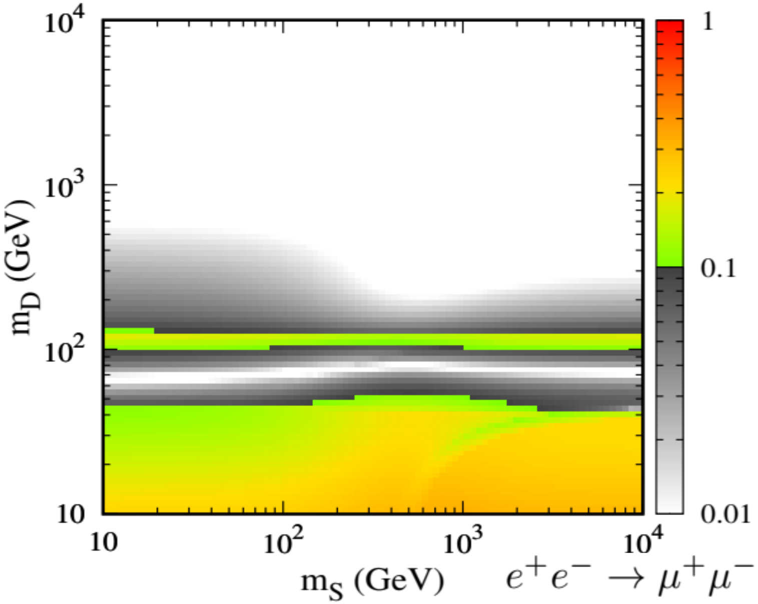
Searches via precision measurements



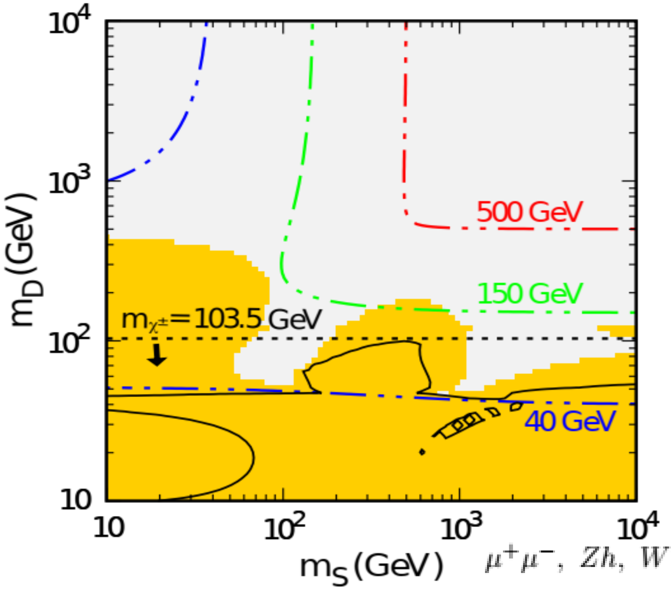
$e^+e^- \to W^+W^-$



$e^+e^- \to ZZ$

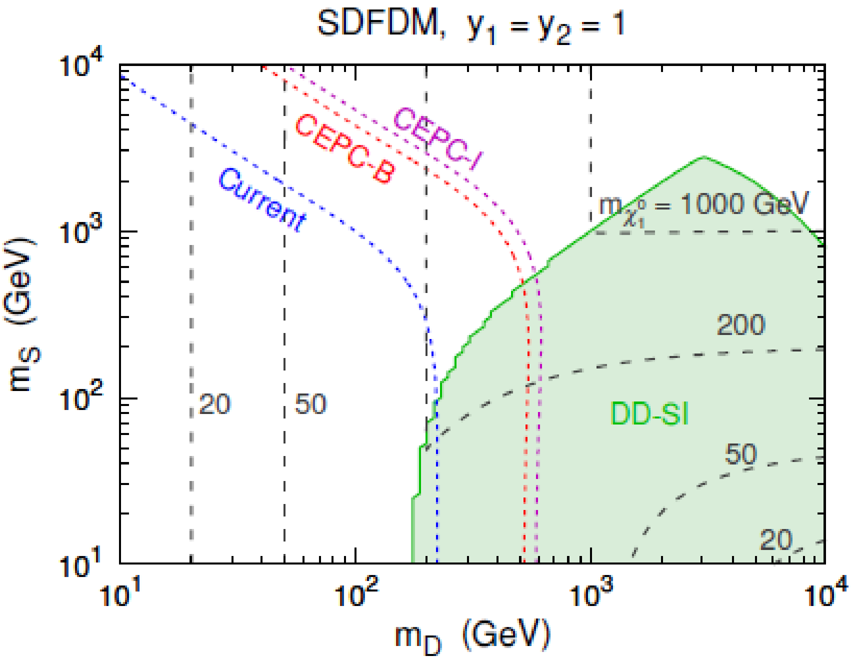


$e^+e^- \to \mu^+\mu^-$

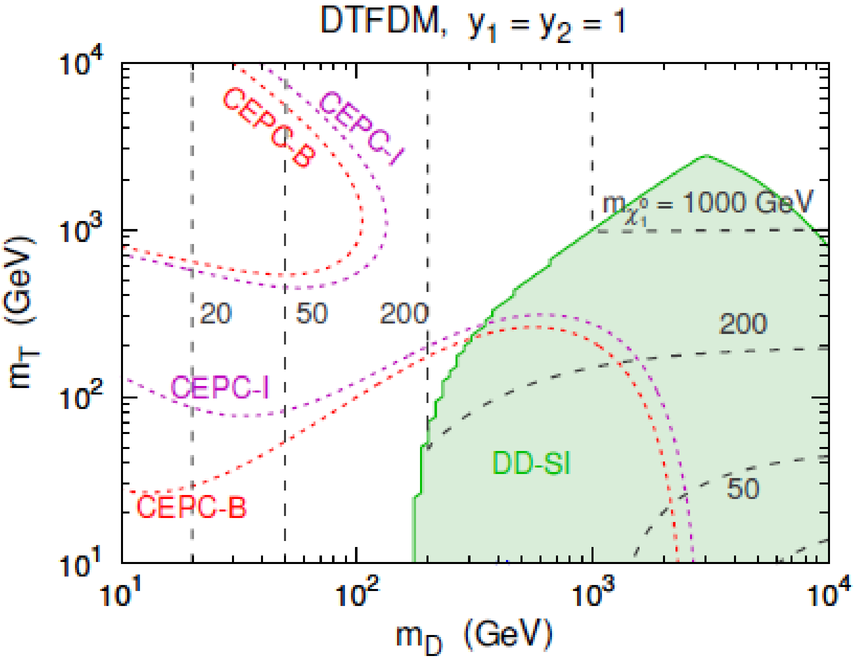


$\mu^+\mu^-,\ Zh,\ W^+W^-,\ ZZ$, and $Z\gamma$

Oblique parameters: fermionic DM



Singlet and Doublet Fermions



Doublet and Triplet Fermions

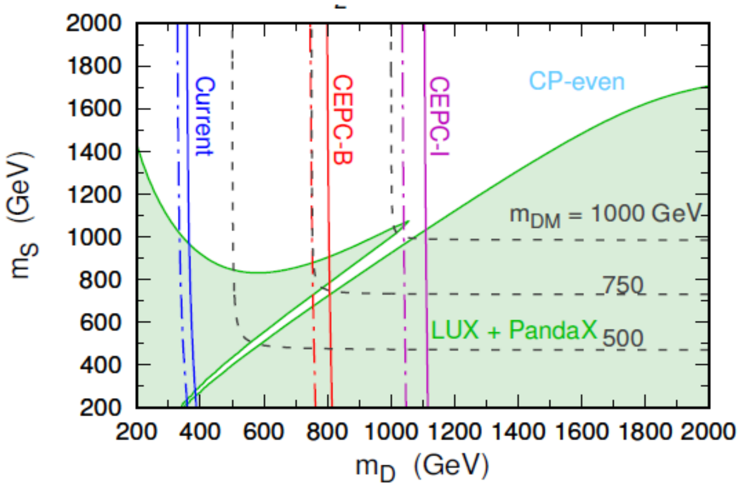
Cai, Yu, Zhang, 1611.02186

- *After EWSB, dark sector fermions contribute to the electroweak oblique parameters S, T, and U*

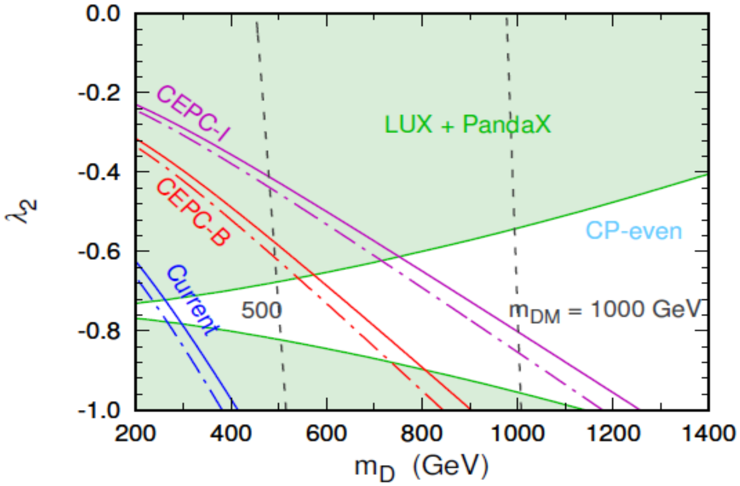
Fedderke, Lin, Wang, 1506.05465

- *Current: current precision for EW oblique parameters*
  CEPC-B: CEPC baseline precision
  CEPC-I : CEPC precision with improvements of m_Z, G_Z, and m_t measurement

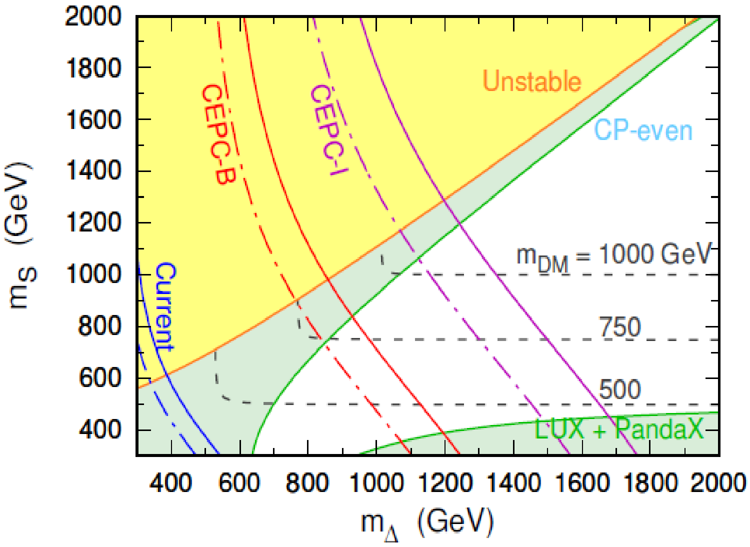
Oblique parameters: scalar DM



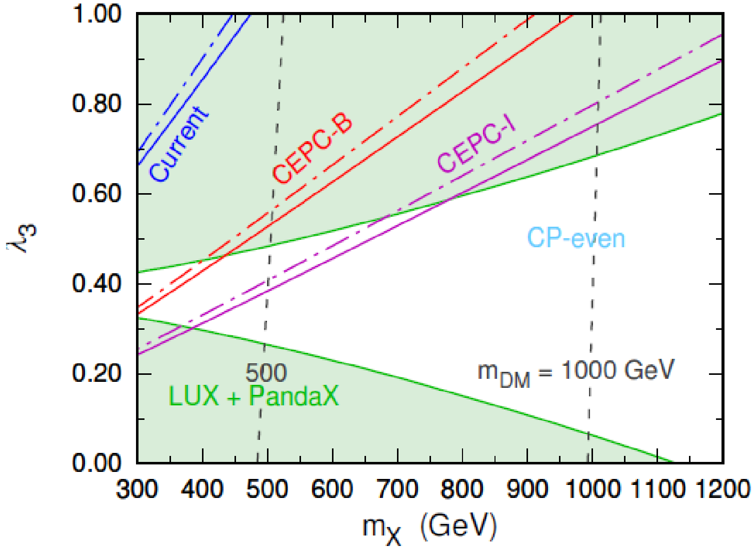
Singlet and Doublet Scalars



Doublet Scalar



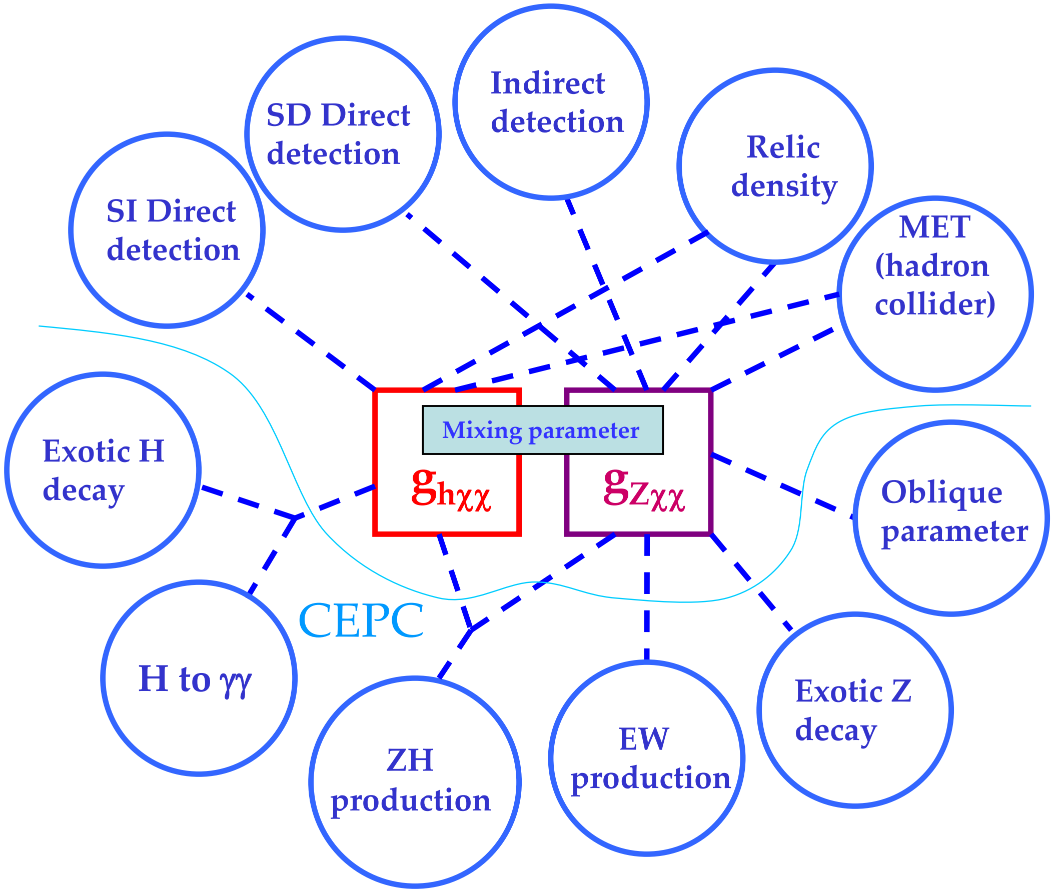
Singlet and Triplet Scalars



Quadruplet Scalar

Cai, Yu, Zhang, 1705.07921

Summary



- *It is possible to probe new particles directly produced or via loop effects at CEPC*
- *We consider a kind of DM models containing additional EW multiplets, and focus on their corrections to the EW processes at the CEPC*
- *The significant signatures at the CEPC require moderate interactions connecting new particles to Higgs and Z bosons. These interactions can be constrained by collider and DM detection experiments*

Thank you