Dark matter searches at the CEPC

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Hang Zhou， 2024.10.23

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Outline

- *Introduction*
- *Direct production of DM at the CEPC*
- *Indirect searches through precise 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

DM searches at the e^+e^- colliders

- ***Disadvantage**: Low CM energy….*
  Can not directly detect heavy particles in the BSM

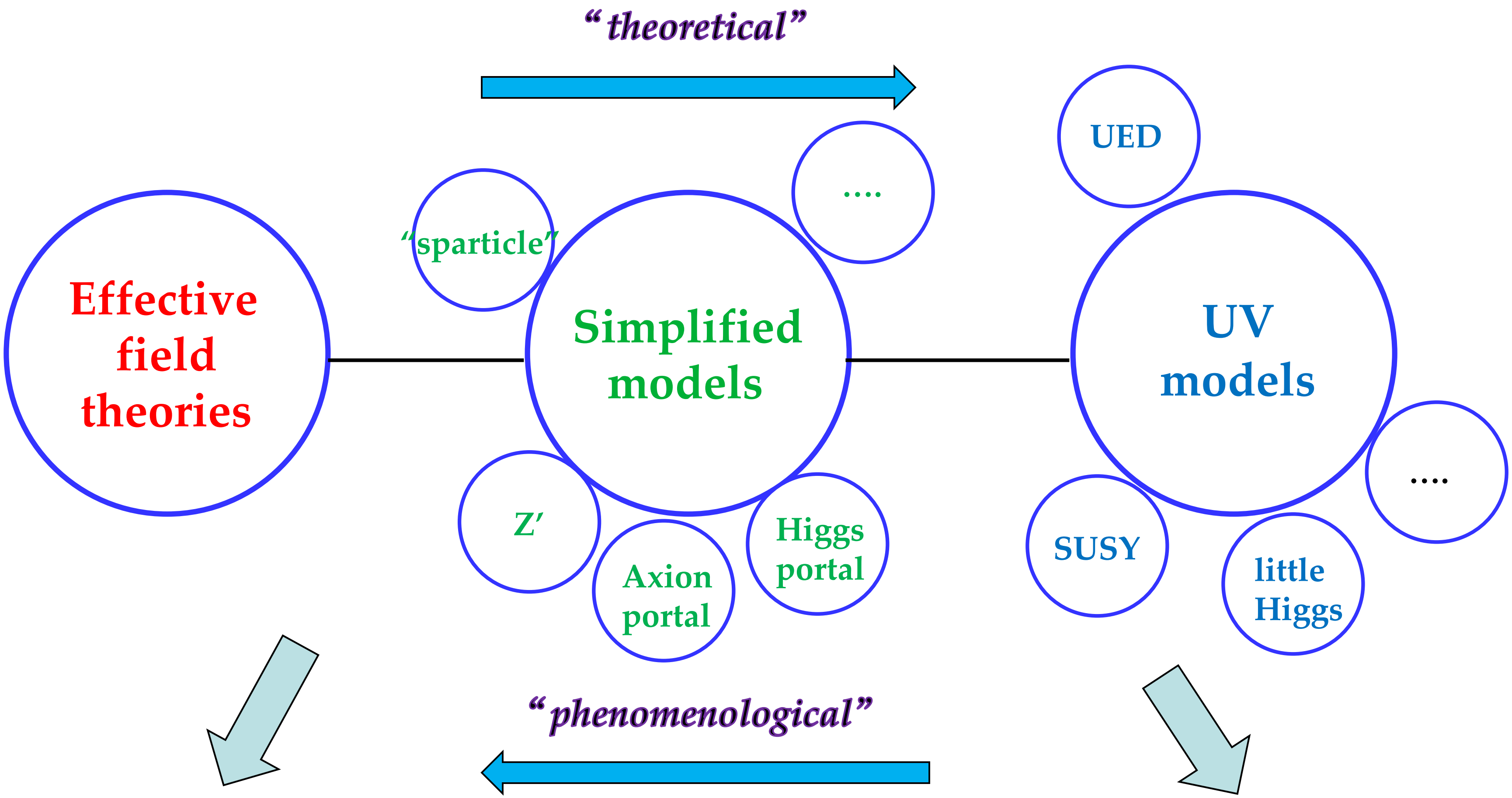
- ***Advantage**: No large QCD background; larger luminosity; precise beam energy; polarized beams…. The full missing energy can be reconstructed.*
  Precise measurements of DM properties are possible
  It is possible to measure the mass, spin, and other quantum numbers of DM.

- *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 determine its potential as a constituent of dark matter within the Universe. It is necessary to combined results from different DM detections.*

Direct signatures: theoretical approach



"theoretical"

Effective field theories

Simplified models

"sparticle"

....

Z'

Axion portal

Higgs portal

UED

UV models

SUSY

little Higgs

....

"phenomenological"

Mono-X signatures

Direct production, "model-independent"

Multi final states +Missing energy

Cascade decay, "model-dependent"

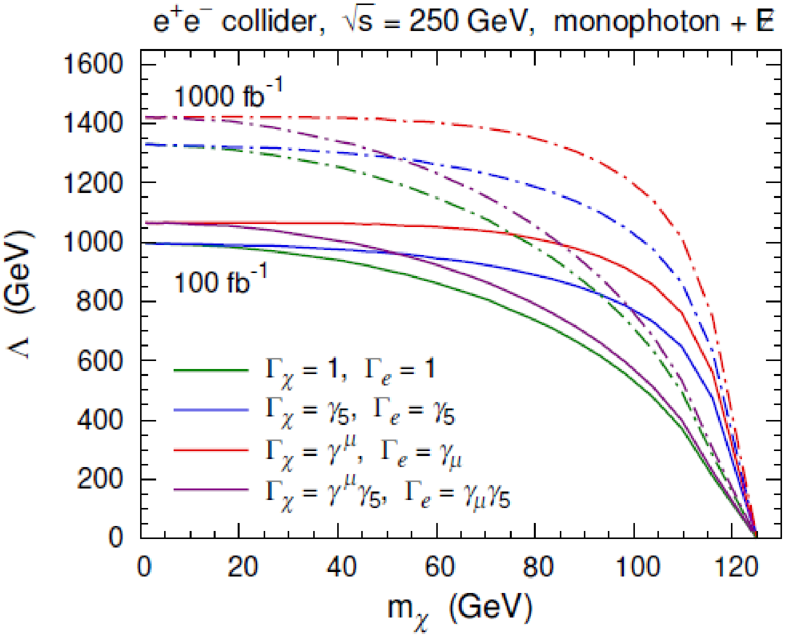
Many other collider signatures and constraints

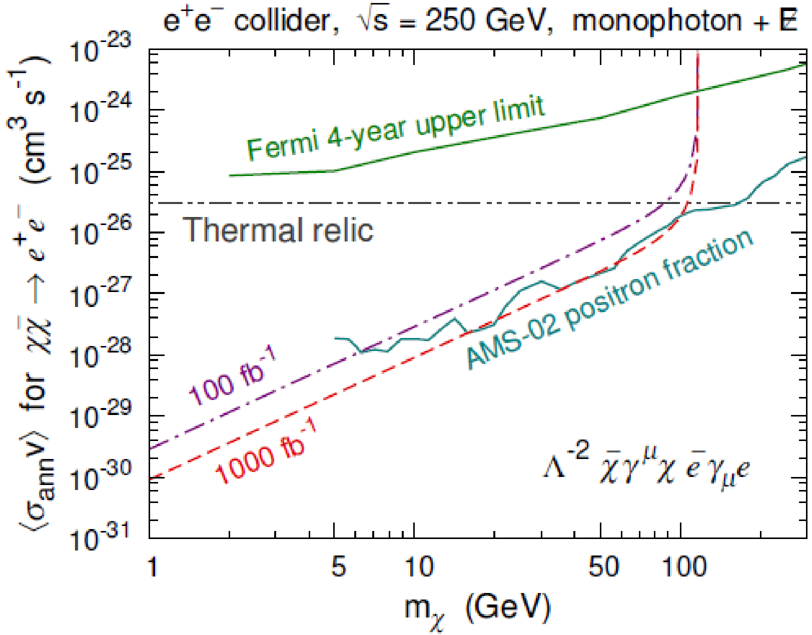
Mono-photon searches for EFTs

- *Consider the simplest EFTs*

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

- *Photon is emitted from the initial state radiation*



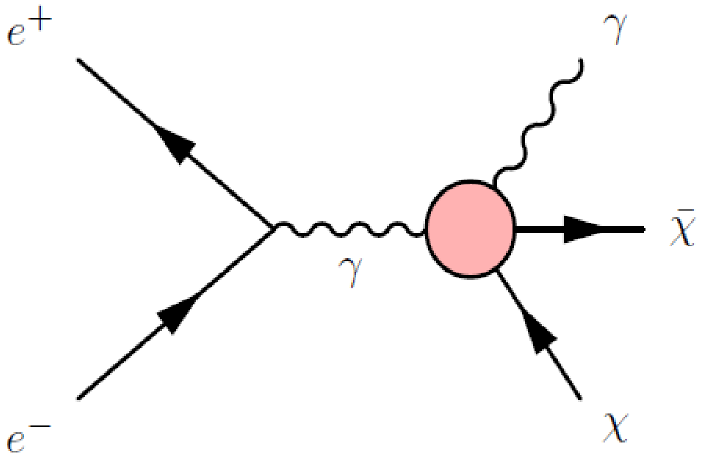


Gamma-ray line and mono-photon

- *Effective operator*

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

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

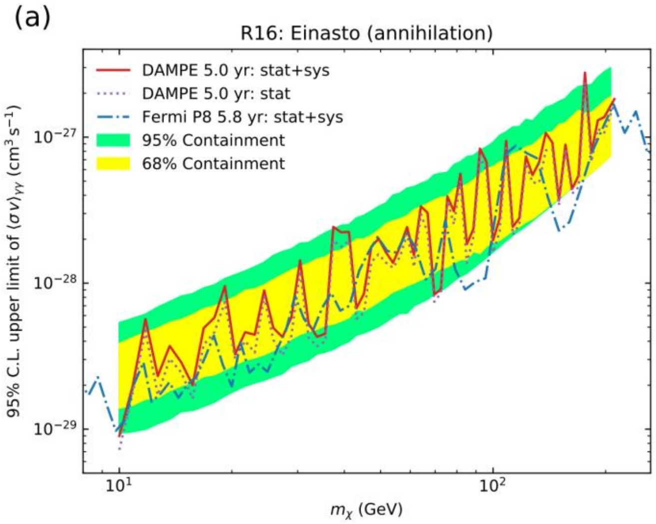


Yu, Yan, Yin, 1307.5740

- *The operator induces gamma-ray line signature, which is a critical evidence of DM annihilation/decay*

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

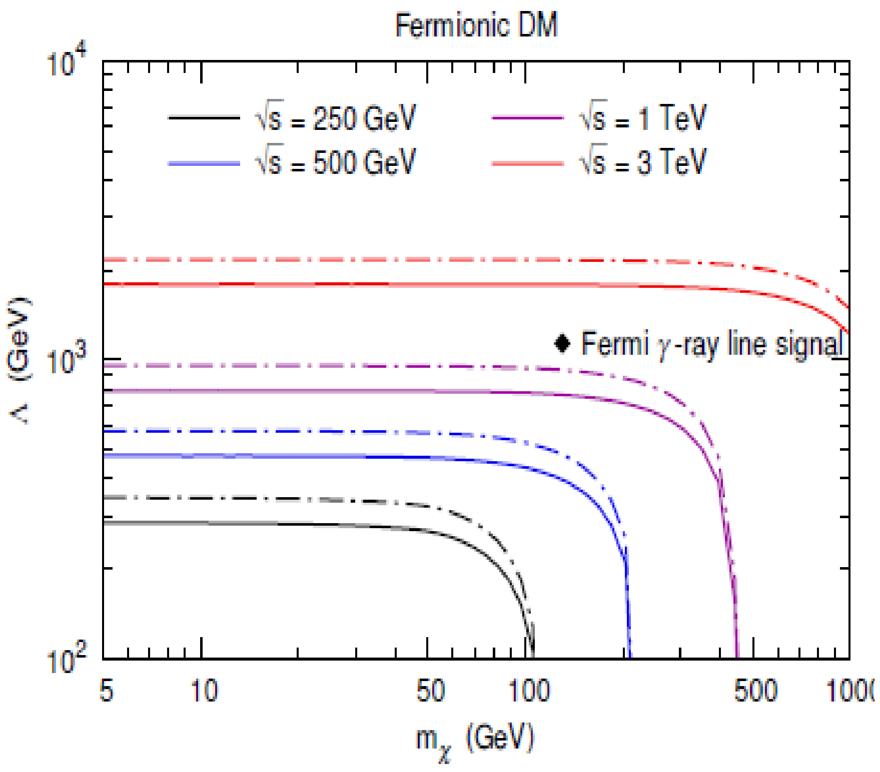
$$\langle\sigma_{\rm ann} v\rangle_{\chi\bar{\chi}\to 2\gamma} \simeq \frac{4m_\chi^4}{\pi\Lambda^6} = 10^{-27}\ {\rm cm}^3\ {\rm s}^{-1}\left(\frac{m_\chi}{130\ {\rm GeV}}\right)^4\left(\frac{1272\ {\rm GeV}}{\Lambda}\right)^6$$

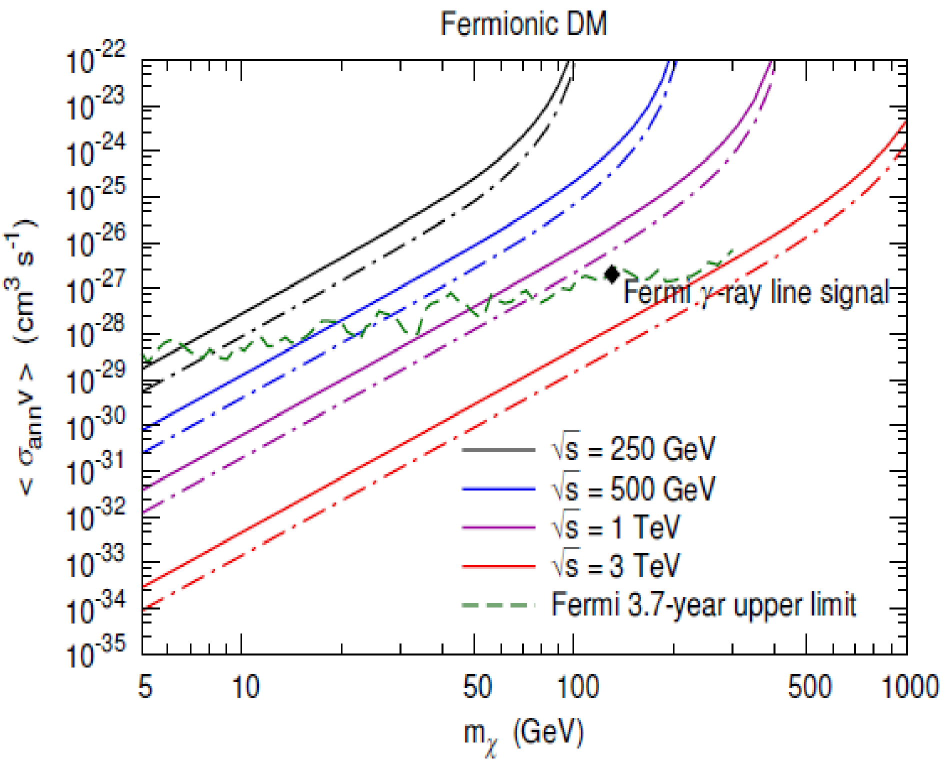


DAMPE, 2112.08860

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*

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

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

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

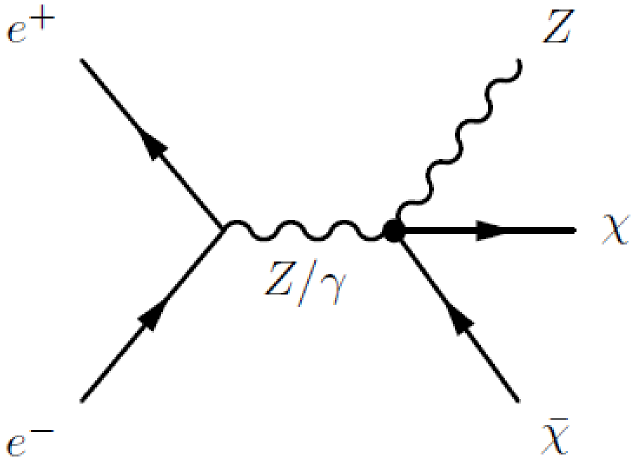
$$\supset \bar{\chi}i\gamma_5\chi(G_{\mathrm{ZZ}}Z_{\mu\nu}\tilde{Z}^{\mu\nu} + G_{\mathrm{AZ}}A_{\mu\nu}\tilde{Z}^{\mu\nu})$$

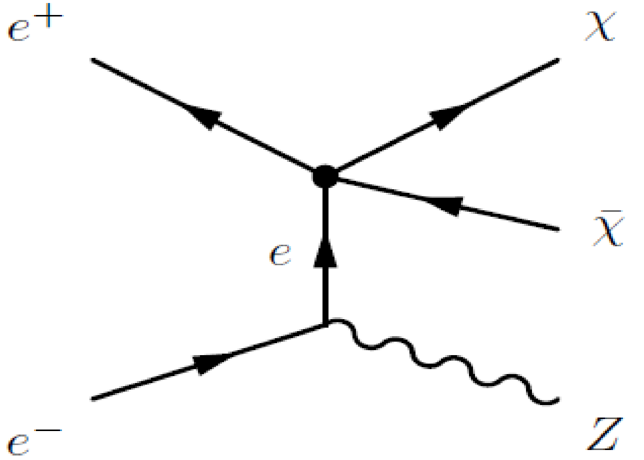
$$\mathcal{O}_{\mathrm{FH}} = \frac{1}{\Lambda^3}\bar{\chi}\chi(D_\mu H)^\dagger D_\mu H \to \frac{m_Z^2}{2\Lambda^3}\bar{\chi}\chi Z_\mu Z^\mu$$

- *Z boson can also originate 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

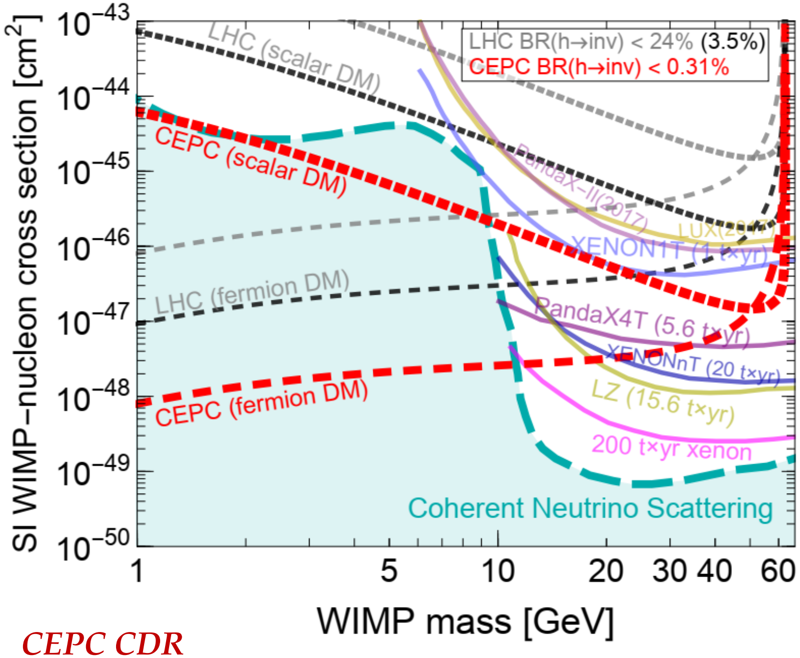
Simplified models: DM couples to mediators

- *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*

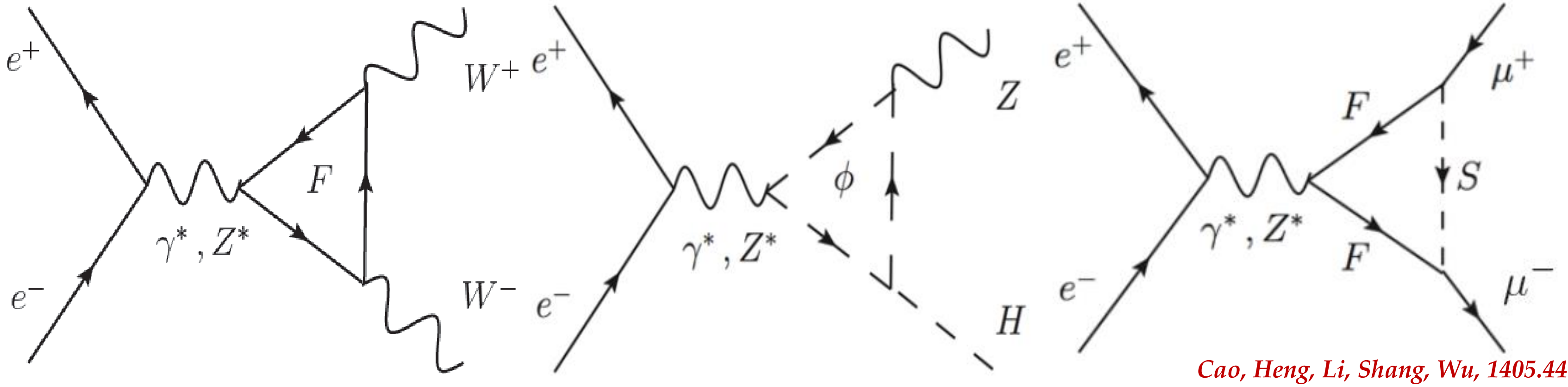


CEPC CDR

- *For discussions on more portals and UV models, referred to other talks in this session*

Probing DM at CEPC via loop effects

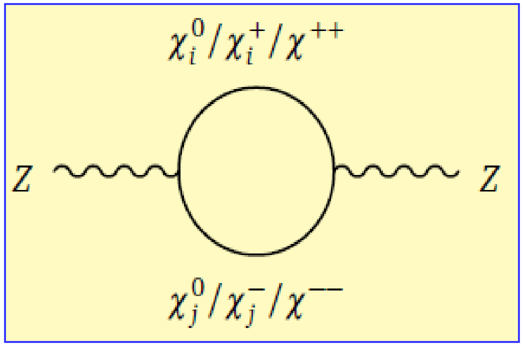
- *New particles give corrections to SM processes, which can be measured at a level of ~O(0.1%) at lepton colliders*

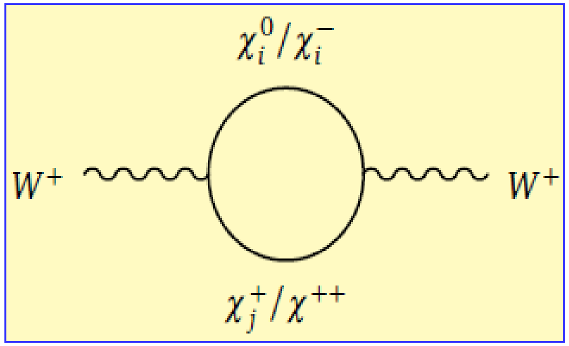


Cao, Heng, Li, Shang, Wu, 1405.4489
Cao, Li, Yan, Zhang, Zhang, 1604.07536
Liu, Wu, 1705.02534
Xiang, Bi, Yin, Yu, 1707.03094

- *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

- *e^+e^- colliders offer a conducive environment for exploring the electroweak sector. Consider some simple Fermionic DM models containing new electroweak multiplets: a few new particles but no new mediator*

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

Cirelli et al, hep-ph/0512090

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

DM models with additional EW multiplets

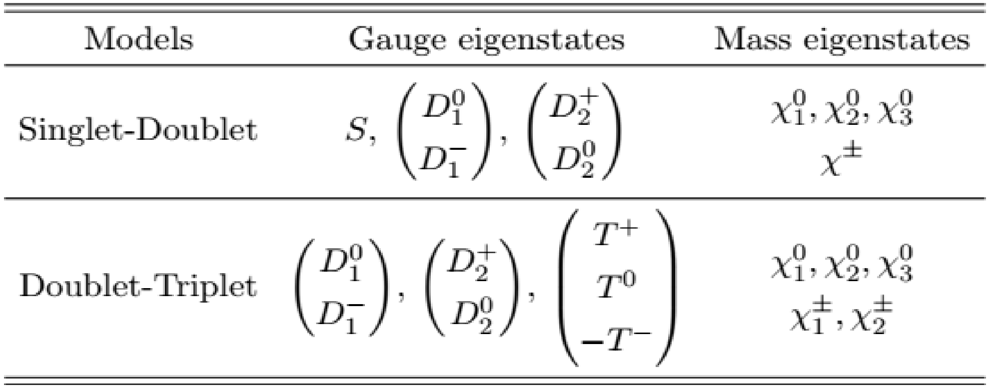
- *Adding two different EW Fermionic multiplets is an economical option with a rich phenomenology. We consider the models:*

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

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

"Mixed states"

Arkani et. al, 1511.06495

Doublet-Triplet Fermionic Model

- *Introduce one Weyl triplet and two doublets*

  Gauge invariant Lagrangian

$$\mathcal{L}_\mathrm{T} = iT^\dagger\bar{\sigma}^\mu D_\mu T + (m_T c_{ij} T^i T^j + \mathrm{H.c.})$$

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

  Yukawa coupling

$$\mathcal{L}_\mathrm{Y} = y_1 c_{ijk} T^i D_1^j H^k - y_2 c_{ijk} T^i D_2^j H^k + \mathrm{H.c.}$$

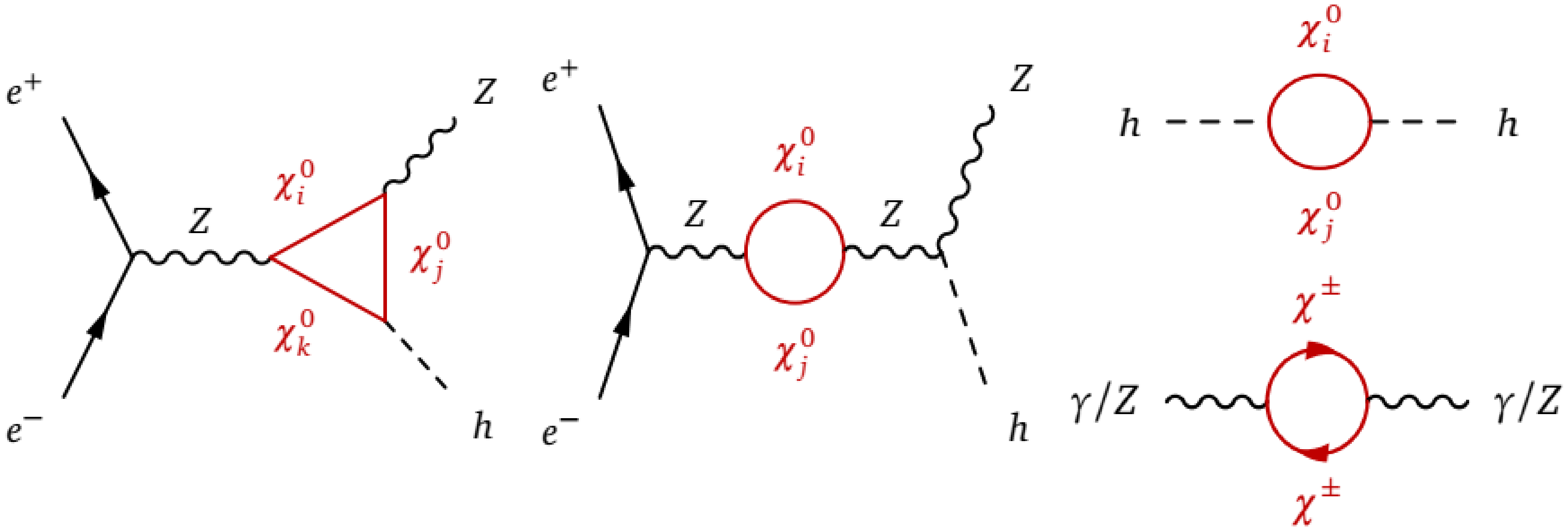
- *Four new parameters: two mass parameters* m_T, m_D
  and two Yukawa couplings y_1, y_2

- *DM is the lightest mass eigenstate in the neutral sector after EWSB*
  There are three neutral and two charged particles in the dark sector

$$\begin{pmatrix} T^0 \\ D_1^0 \\ D_2^0 \end{pmatrix} = \mathcal{N} \begin{pmatrix} \chi_1^0 \\ \chi_2^0 \\ \chi_3^0 \end{pmatrix}, \qquad \begin{pmatrix} T^+ \\ D_2^+ \end{pmatrix} = \mathcal{C}_\mathrm{L} \begin{pmatrix} \chi_1^+ \\ \chi_2^+ \end{pmatrix}$$

Probing DM via measurements of Zh production

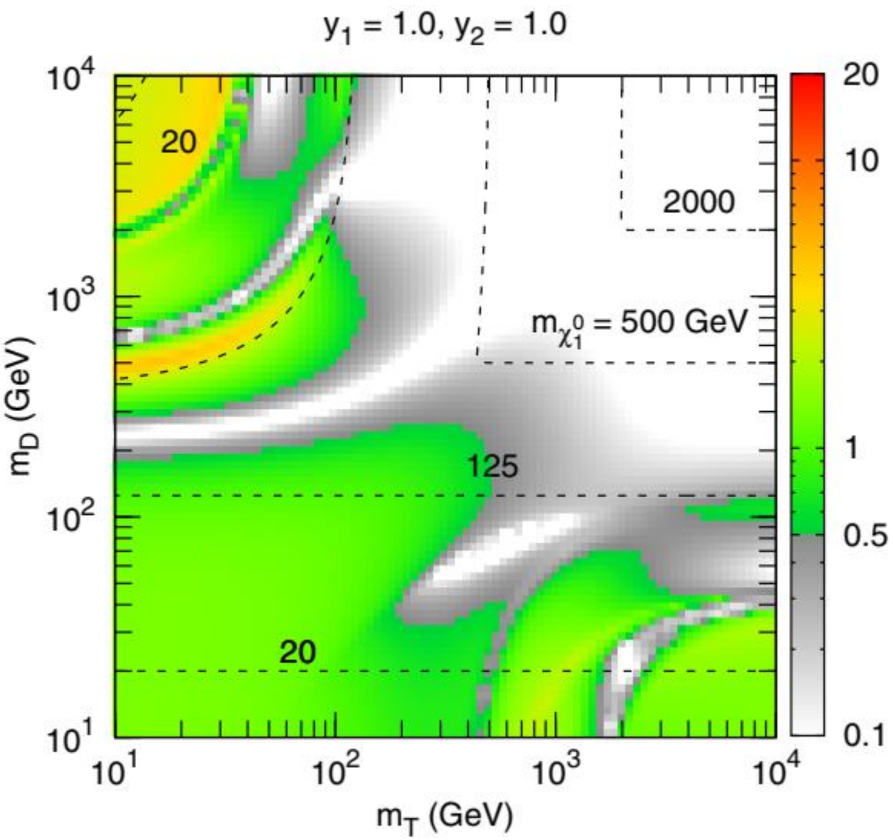
- *We consider the corrections of new particles to the associated* ***Z-Higss production***
  This process is affected by both the gauge and Yukawa interactions

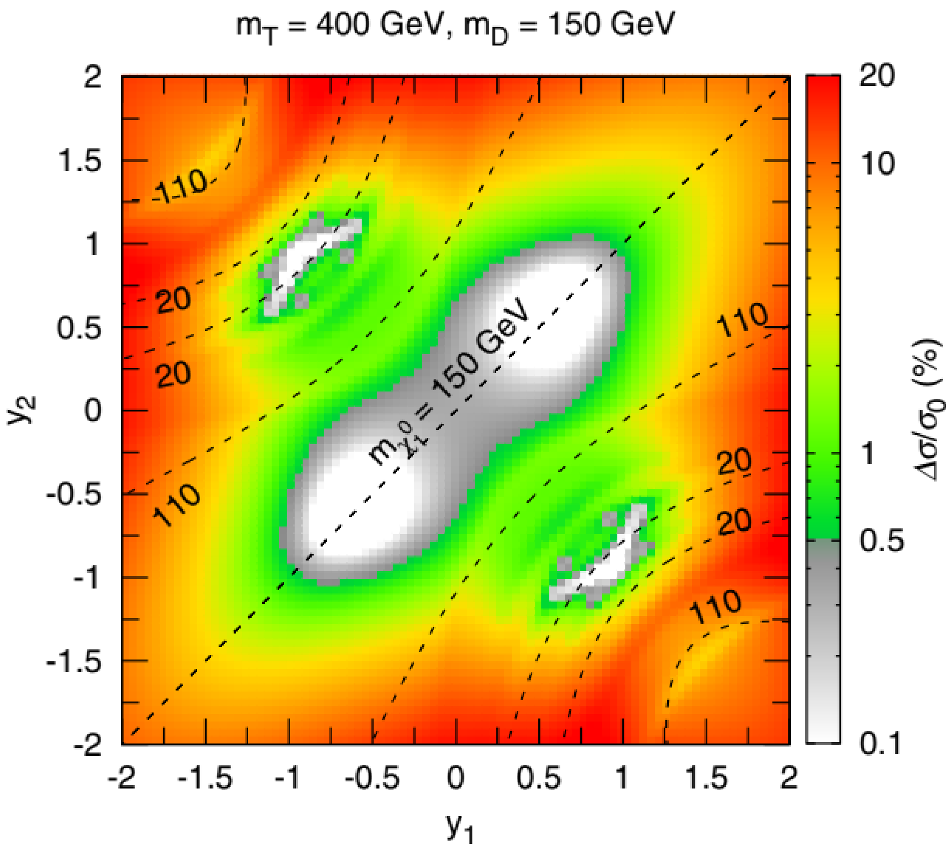


calculate corrections to the Zh production cross section ($\Delta\sigma/\sigma=(\sigma_{NP}-\sigma_{SM})/\sigma_{SM}$)

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

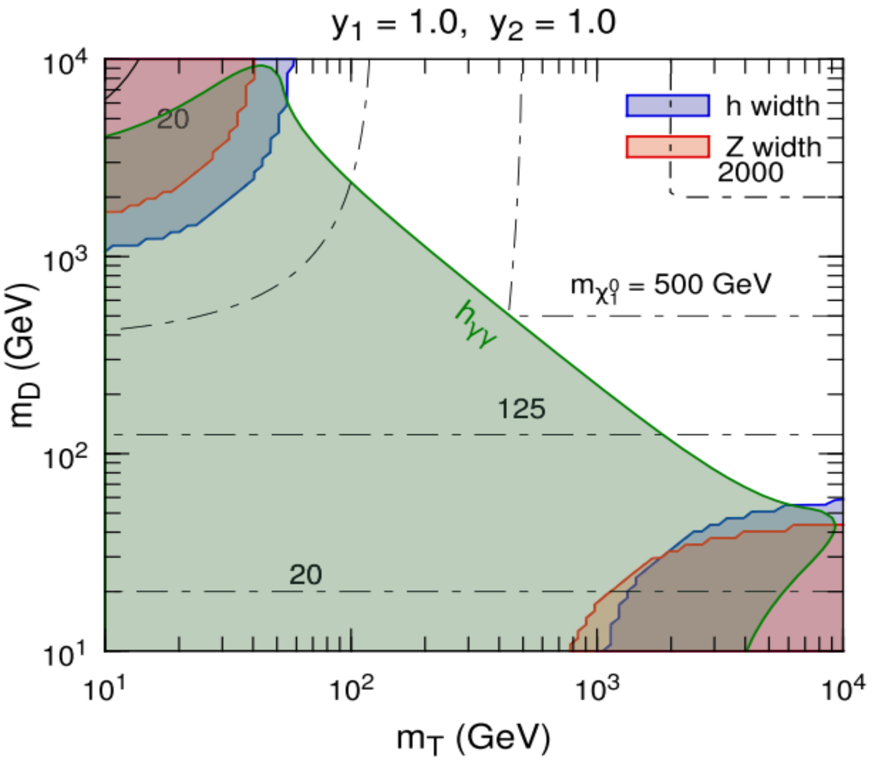
Probing DM via measurements of Zh production

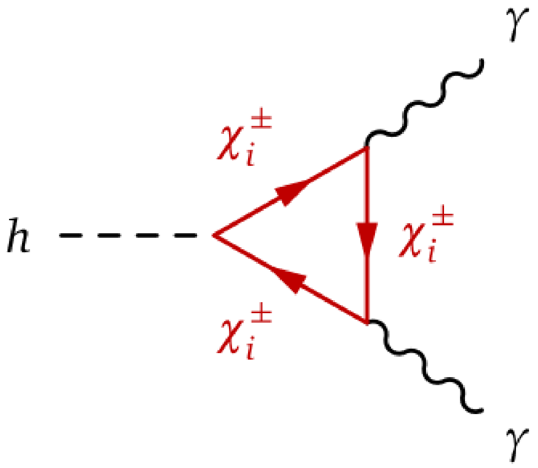




Searches of Higgs and Z decays

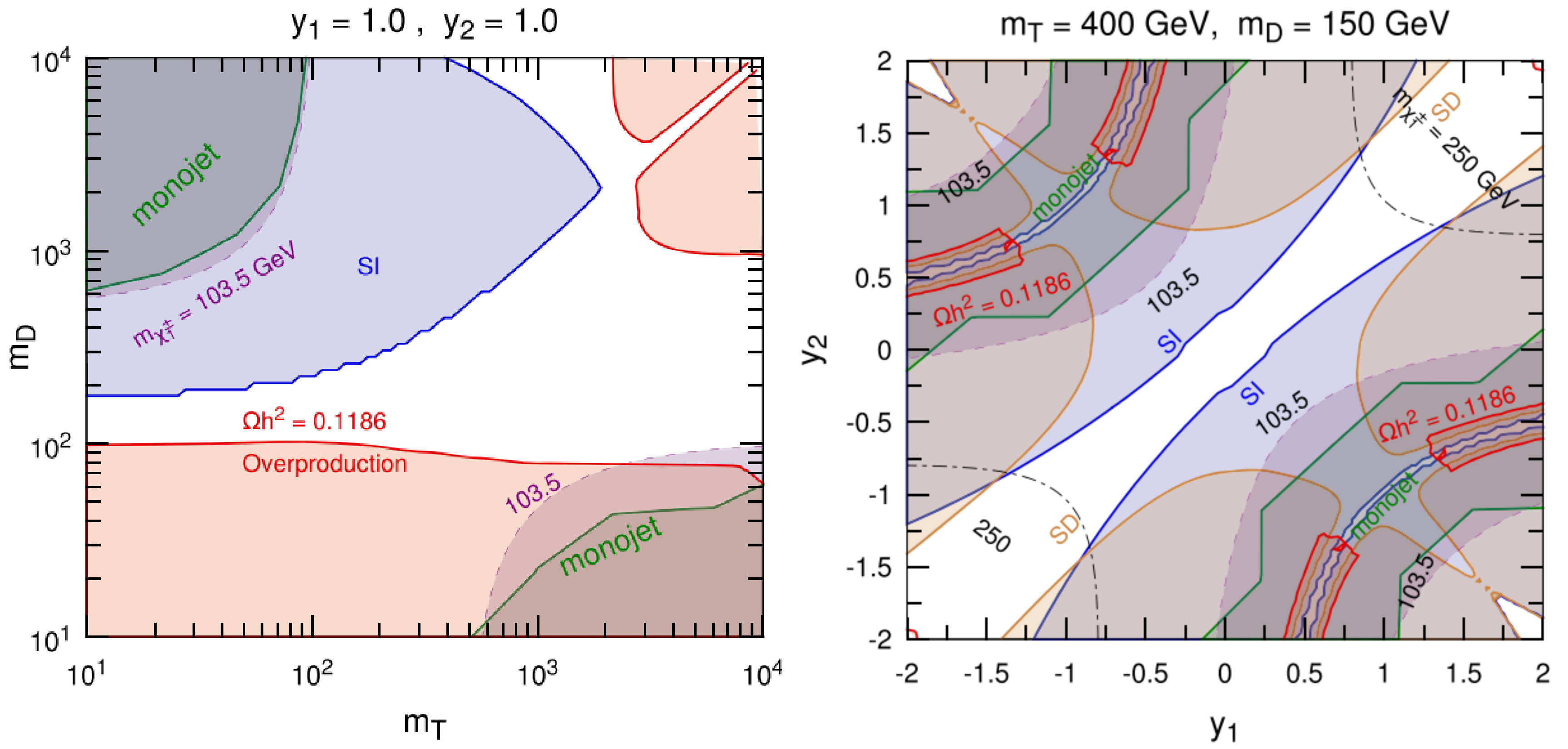
- *As new charged particles couple to the Higgs, they can modify the **Higgs decay width to di-photons** via triangle loops. $\Delta\Gamma/\Gamma$ can be tested to be a level of ~9%*
- *If the kinematics is allowed, the Higgs and Z can decay into DM particles. Such **invisible decays** are constrained by the relevant searches at colliders*





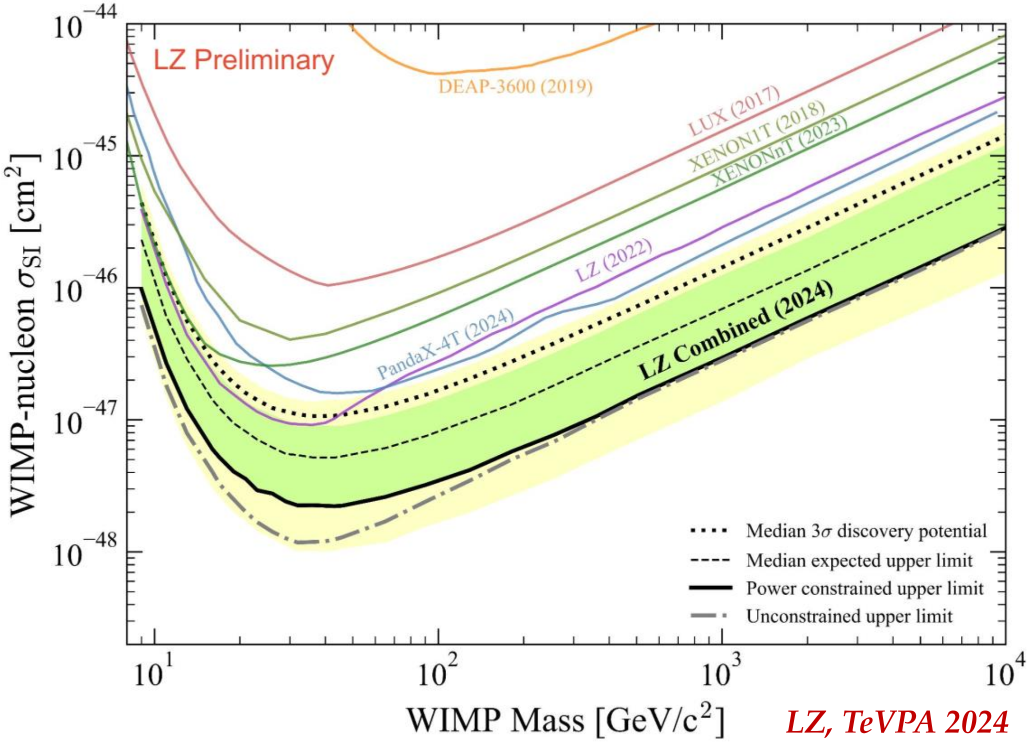
Take $\Gamma(Z\text{->}inv) < 2$ MeV (LEP) and $\Gamma(h\text{->}inv)/\Gamma_h < 2.8\%$ (for CEPC 5 ab^{-1})

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 charged particle is smaller than 103.5 GeV*

More about direct detection: blind spots



LZ, TeVPA 2024

- *Direct detection experiments have set stringent constraints on the DM-nucleon scattering cross section for both SI and SD interactions*
- *These results set strict limits on the DM-Higgs and DM-Z couplings*
- *Nevertheless, some parameter configurations have the capability to diminish these couplings, giving rise to what is known as the "blind-spot" scenario.*

Cheung et. al, 1211.4873

Symmetry argument

- *When $y_1=y_2$, there is a custodial symmetry*

Dedes, Karamitros, 1403.7744
Cai, Yu, Zhang, 1611.02186

Define

$$(\mathcal{D}^A)^i = \begin{pmatrix} D_1^i \\ D_2^i \end{pmatrix}, \quad (\mathcal{H}^A)_i = \begin{pmatrix} H_i^\dagger \\ H_i \end{pmatrix}$$

The singlet-doublet Largrangian can be rewritten as

$$y(H_i S D_1^i - H_i^\dagger S D_2^i) + \text{h.c.} = y\epsilon_{AB}(\mathcal{H}^A)_i S(\mathcal{D}^B)^j + \text{h.c.}$$

The components of D provide identical Dirac mass contributions. Thus, DM has equal D components and the DM-Z coupling tends to be 0.

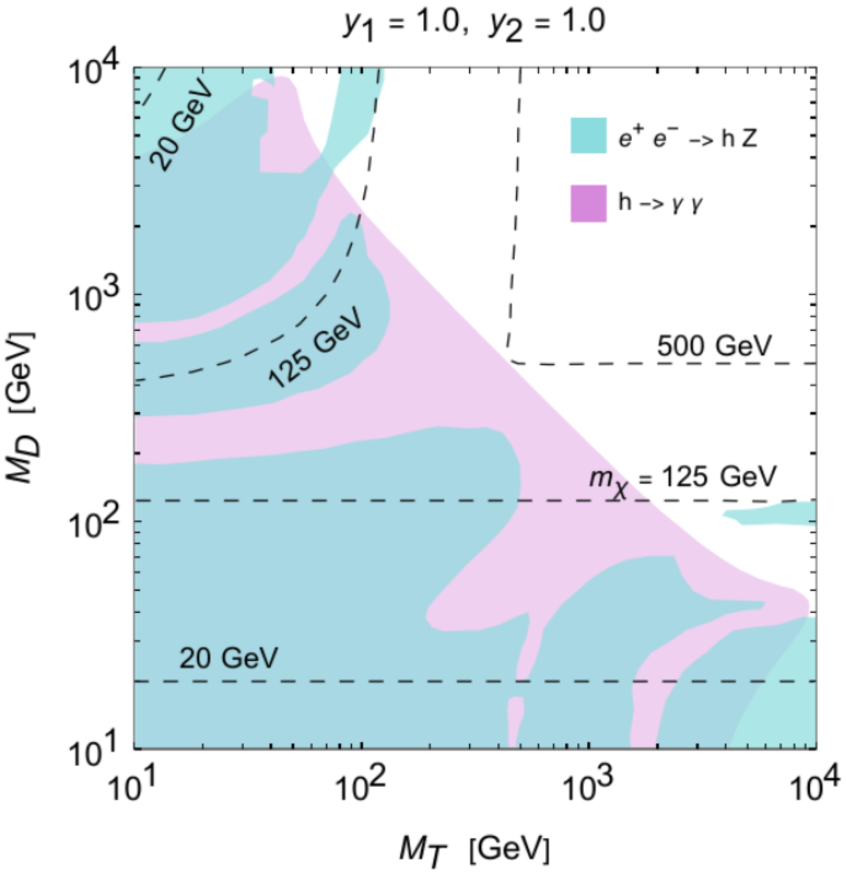
$$g_{Z\chi_1^0\chi_1^0} = -\frac{g}{2c_W}(|\mathcal{N}_{21}|^2 - |\mathcal{N}_{31}|^2)$$

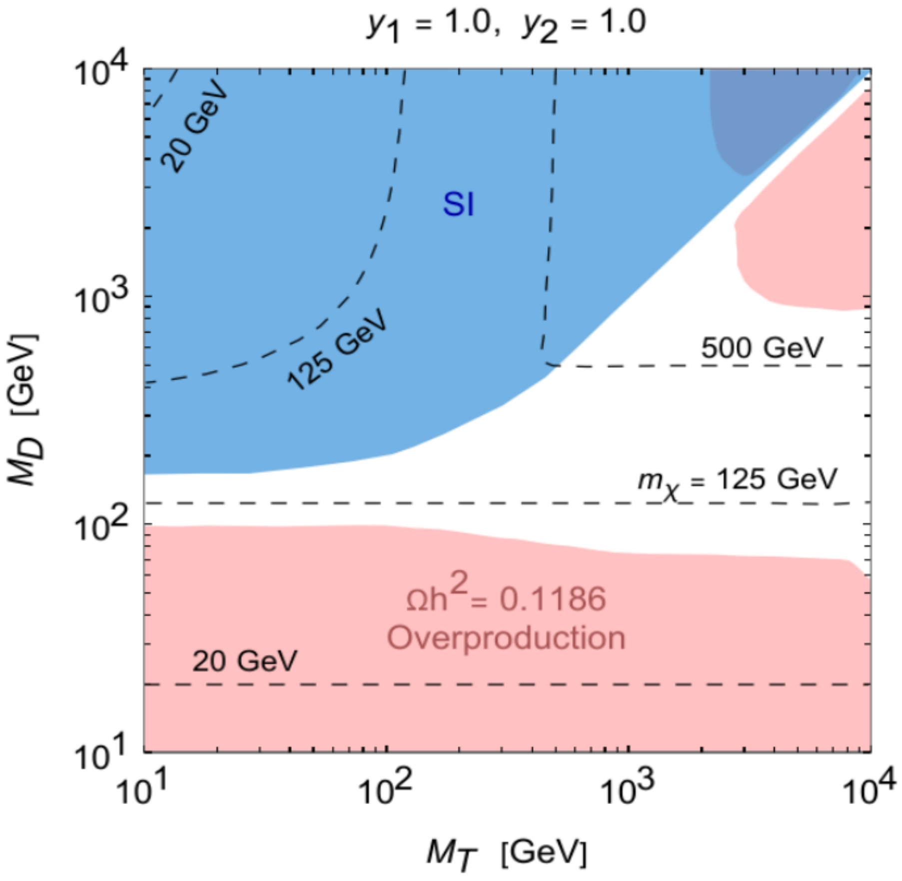
The Yukawa coupling of DM may also approach 0 in the limit $y_1=y_2$ with $m_D < m_T$

$$g_{h\chi_1^0\chi_1^0} = -\sqrt{2}(y_1\mathcal{N}_{21} + y_2\mathcal{N}_{31})\mathcal{N}_{11}$$

*This is a realization of "**blind-spot**", avoiding the stringent direct detection constraints.*

Complementary of DM detections

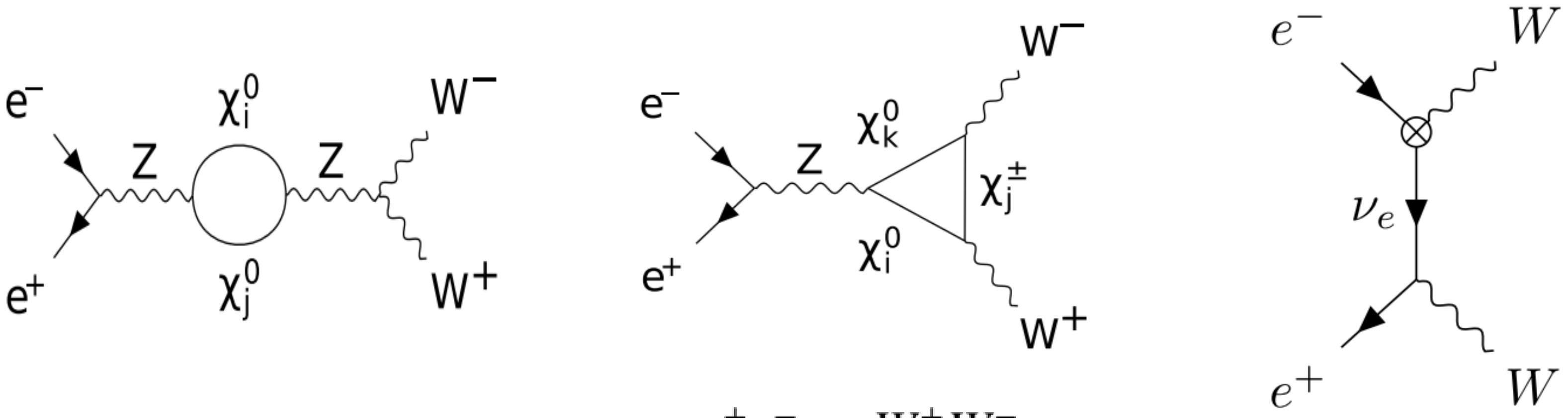




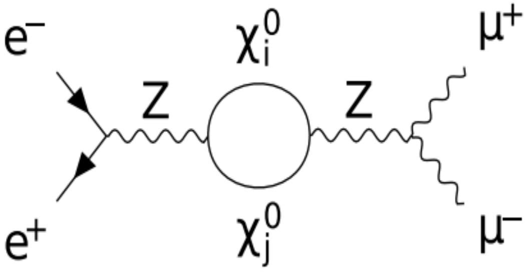
- *The exploration of the parameter space at the CEPC can serve as a complement to other DM detection experiments.*

Searches via other precision measurements

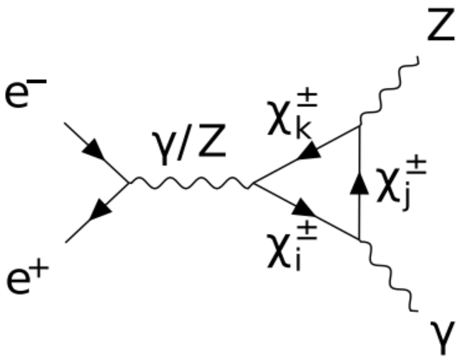
- *It is possible to explore these new particles through loop effects using the precise measurements for other EW processes at the CEPC.*



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



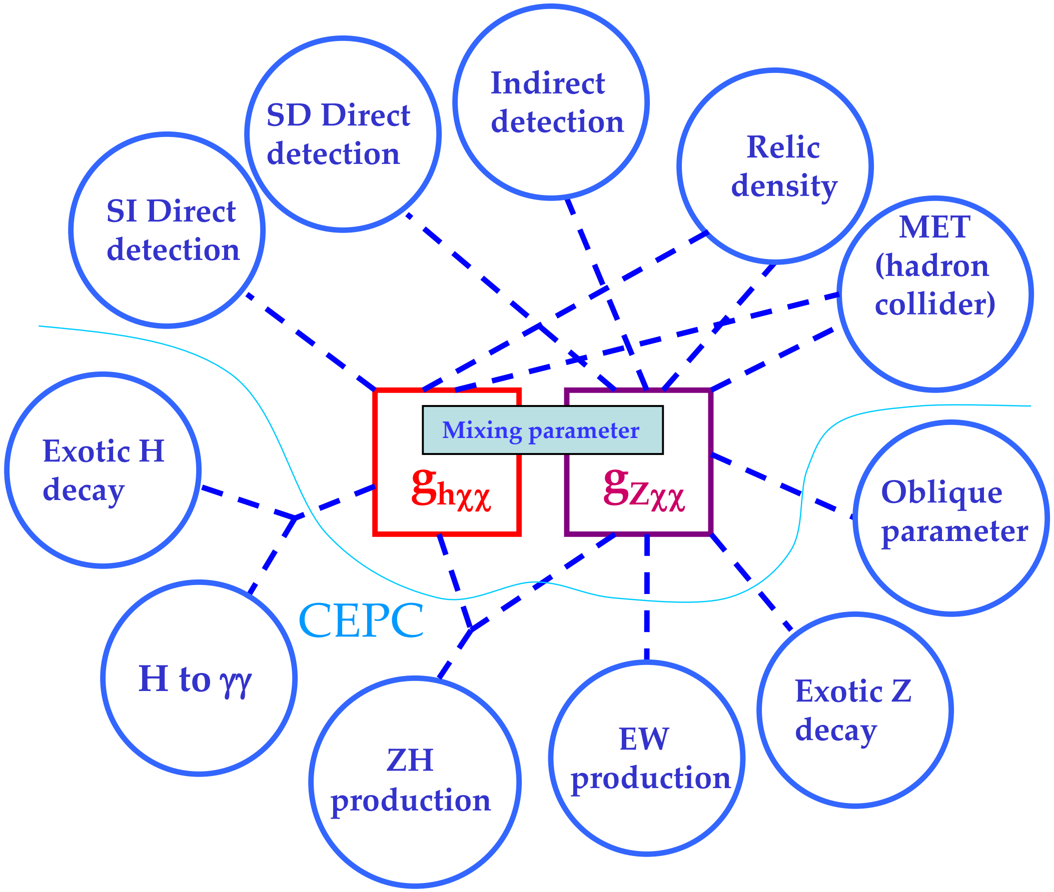
$e^+e^- \to \mu^+\mu^-$



$e^+e^- \to ZZ$

Gao, Bi, Wang, Xiang, Yin, 2112.02519

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