Searching for Dark Matter at CEPC

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Based on an ongoing work in collaboration with:
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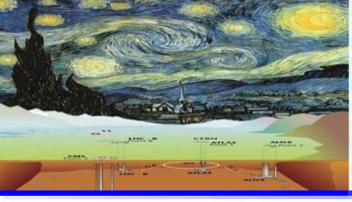
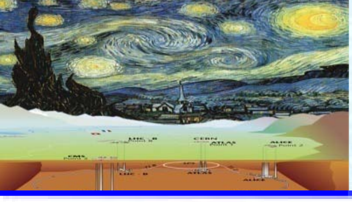
IHEP, 2016.12.15



Outline

- *Introduction*
- *Model*
- *CEPC searches*
- *DM constraints*
- *Conclusion*



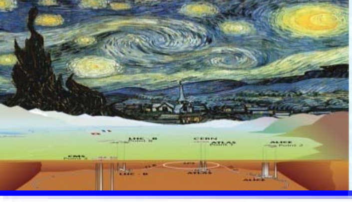
DM searches at e^+e^- colliders

- *Search for light DM, e.g. m<~125GeV at CEPC*
  Search for interactions between the DM and electrons/EW gauge bosons/Higgs
  limited by low CM energies at e^+e^- colliders

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

- *No large QCD background; precise beam energy; polarized beams….*
  Can reconstruct full missing energy
  Precisely measurements of the mass, spin, and other quantum numbers of DM
  Investigate the production mechanism of DM by using these results

- *Complementary to hadron colliders*
  Complementary to direct and indirect DM detection experiments



DM models with additional EW multiplets

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

- Adding one high-dimensional representation: minimal DM model. The lifetime of DM can be longer than that of the Universe. **Cirelli et al , hep-ph/0512090**

- The model may 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…

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

  SDFDM: one singlet + two doublet Weyl spinors

  DTFDM: two doublet + one triplet Weyl spinors

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

  SDFDM-> Bino-higssino in MSSM; singlino-higssino in NMSSM

  DTFDM-> higgsino-wino in MSSM

Singlet-Doublet Fermionic Model

- *Introduce one weyl singlet and two doublets*

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

Gauge invariant Lagrangian

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

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

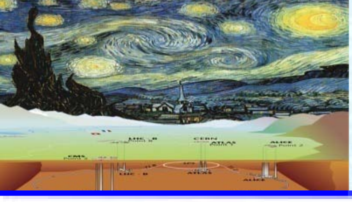
Yukawa coupling

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

Gauge interaction (to the Z)

$$\mathcal{L} \supset \frac{g}{2\cos\theta_w} Z_\mu \left(D_1^{0\dagger} \bar{\sigma}^\mu D_1^0 - D_2^{0\dagger} \bar{\sigma}^\mu D_2^0 - \left(1 - 2\sin^2\theta_w\right) D_1^{-\dagger} \bar{\sigma}^\mu D_1^- + \left(1 - 2\sin^2\theta_w\right) D_2^{+\dagger} \bar{\sigma}^\mu D_2^+ \right)$$

Introduce four parameters: two mass parameters and two yukawa couplings



Mass mixing

- *There are three Majorana fermions and two charged fermions in the dark sector*

$$\mathcal{L}_{\rm mass} = -\frac{1}{2}\begin{pmatrix} S & D_1^0 & D_2^0 \end{pmatrix} \mathcal{M}_{\rm N} \begin{pmatrix} S \\ D_1^0 \\ D_2^0 \end{pmatrix} - m_D D_1^- D_2^+ + \text{h.c.} = -\frac{1}{2}\sum_{i=1}^{3} m_{\chi_i^0}\chi_i^0\chi_i^0 - m_{\chi^\pm}\chi^-\chi^+ .$$

- *Mass mixing matrix*

$$\mathcal{M}_{\rm N} = \begin{pmatrix} m_S & \frac{1}{\sqrt{2}}y_1 v & \frac{1}{\sqrt{2}}y_2 v \\ \frac{1}{\sqrt{2}}y_1 v & 0 & -m_D \\ \frac{1}{\sqrt{2}}y_2 v & -m_D & 0 \end{pmatrix}, m_{\chi^\pm} = m_D, \chi^- = D_1^-, \chi^+ = D_2^+$$

- *Interactions of mass eigenstates with the Z and Higgs*

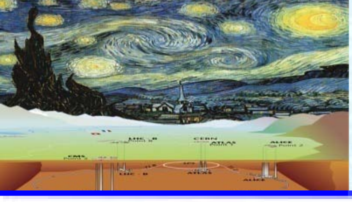
$$\mathcal{L}_{\rm gauge} = eA_\mu \bar{\Psi}^\pm \gamma^\mu \Psi^\pm + \frac{e}{2c_W s_W}(c_W^2 - s_W^2) Z_\mu \bar{\Psi}^\pm \gamma^\mu \Psi^\pm + \frac{e}{4c_W s_W} Z_\mu (\mathcal{O}_{ij}\bar{\Psi}_i\gamma^\mu P_L \Psi_j - \mathcal{O}_{ij}^* \bar{\Psi}_i \gamma^\mu P_R \Psi_j)$$

$$\mathcal{O}_{ij} = \mathcal{N}_{2i}^* \mathcal{N}_{2j} - \mathcal{N}_{3i}^* \mathcal{N}_{3j} .$$

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

$$\mathcal{L}_{\rm Yuk} = -\frac{1}{\sqrt{2}}(y_1 \mathcal{N}_{1i}\mathcal{N}_{2j} + y_2 \mathcal{N}_{1i}\mathcal{N}_{3j})\bar{\Psi}_i P_L \Psi_j h + \text{h.c}$$

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



Custodial symmetry

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

Define SU(2) doublets

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

The lagrangian can be rewritten as

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

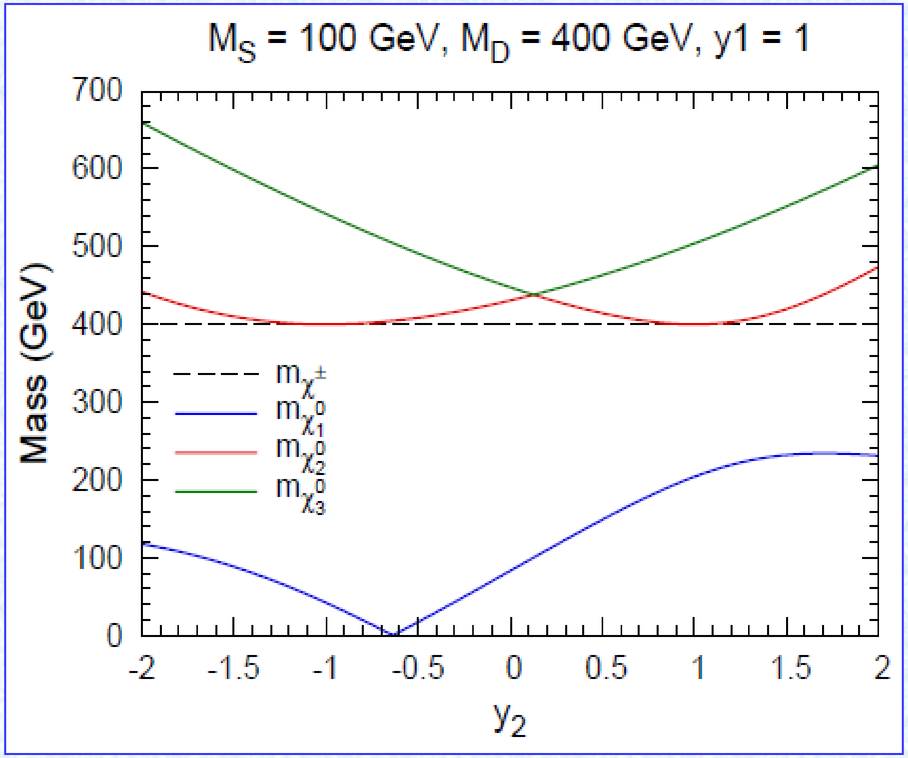
The components of D receive the same Dirac mass contribution. Thus each neutral particles has equal D components. In this case, the coupling $Z\chi_1\chi_1$ tends to be 0.

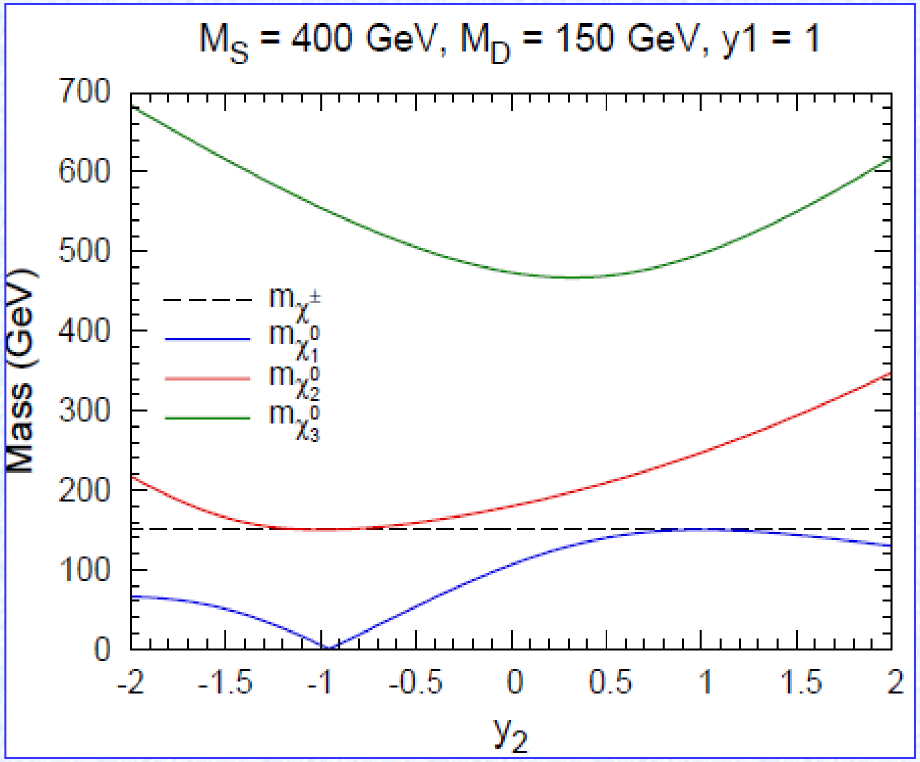
$$g_{Z\chi_1^0\chi_1^0} = -\frac{g}{2c_W}(|\mathcal{N}_{21}|^2 - |\mathcal{N}_{31}|^2)$$

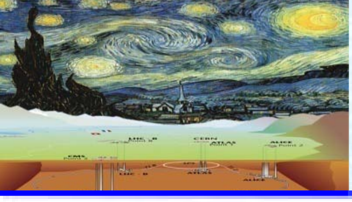
The yukawa coupling $h\chi_1\chi_1$ can also be 0 in the limit y_1=y_2, if $m_D < m_S$

This feature is helpful to loosen the direct detection limits

Mass spectrum



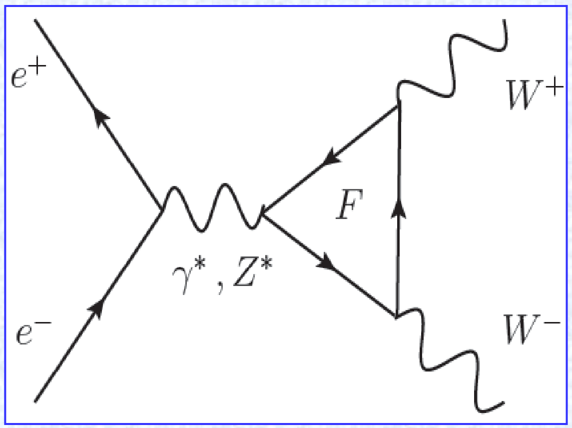


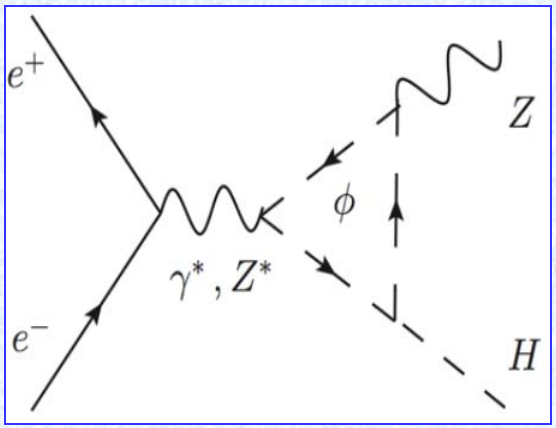


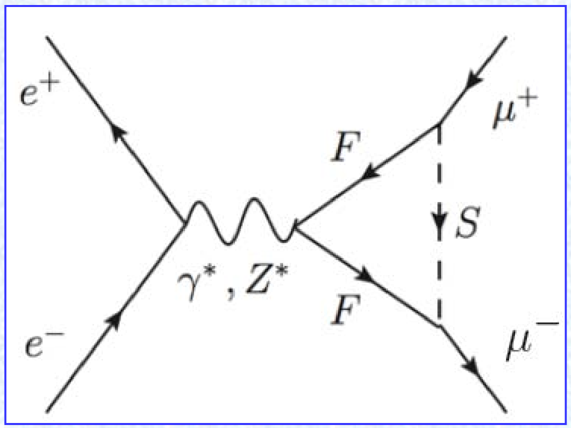
Probing DM at CEPC via loop effects

- *New particles give direct corrections to SM processes, which can be measured to a level of ~O(10^{-3})*

Cao et al, 1604.07536

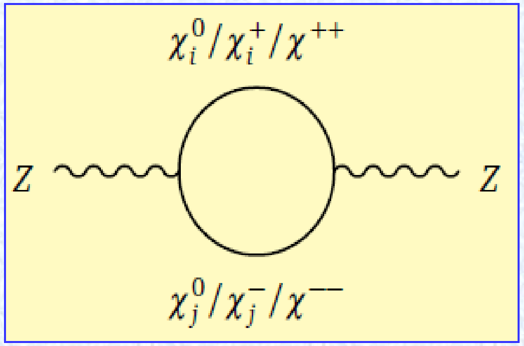


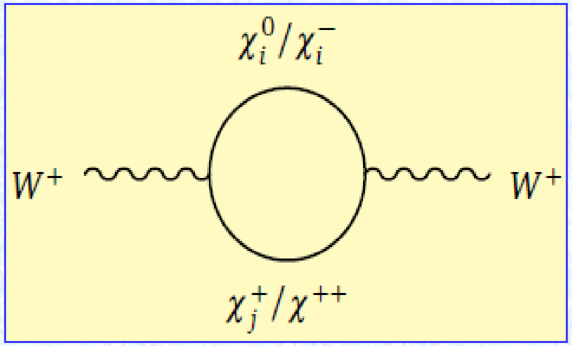




- *Also give oblique corrections to gauge boson propagators*

Search for new particles via the precision measurements and global fitting

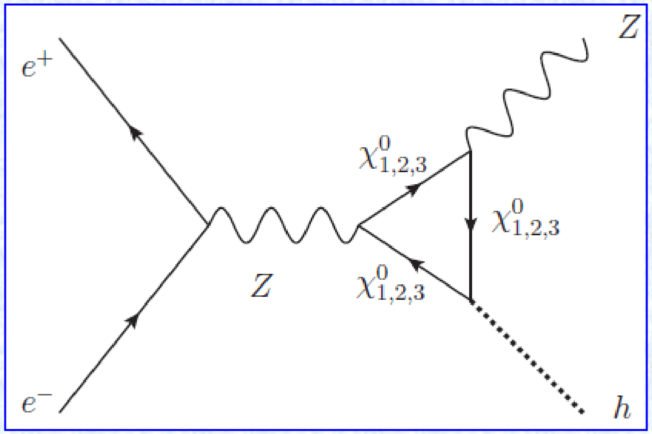


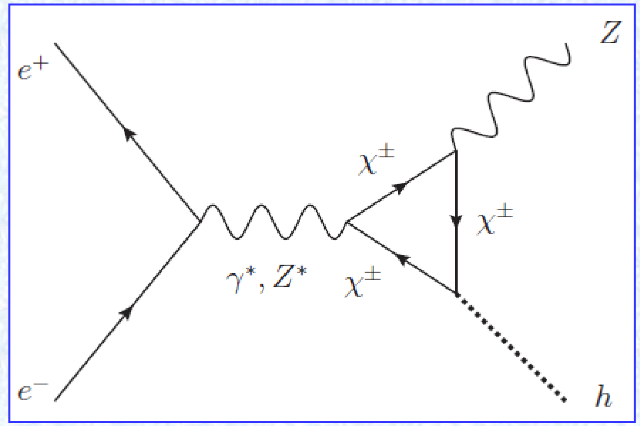


Cai et al, 1611.02186

Probing DM at CEPC via loop effects

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



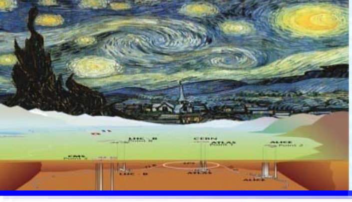


$$M_W \frac{1}{sc^2}\left[1 + \delta Z_e + \frac{2s^2 - c^2}{c^2}\frac{\delta s}{s} + \frac{1}{2}\frac{\delta M_W^2}{M_W^2} + \frac{1}{2}\delta Z_H + \delta Z_{ZZ}\right]$$

We use the FeynArts, FormCalc, and LoopTools to calculate corrections to the Zh production cross section ($\Delta\sigma/\sigma = (\sigma_{NP} - \sigma_{SM})/\sigma_{SM}$)

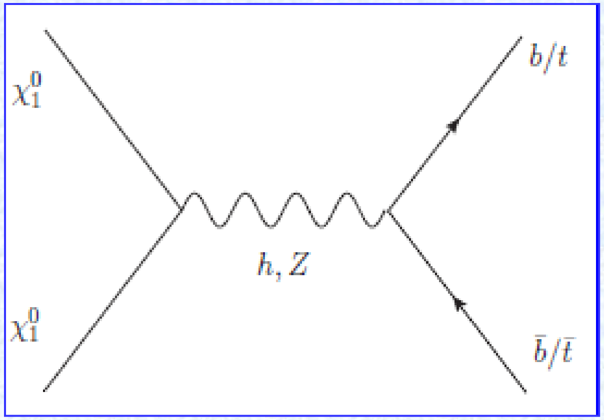
- *It is possible to measure $\Delta\sigma/\sigma|_{Zh}$ to a level of ~0.5% at CEPC (with $5ab^{-1}$ of data)*

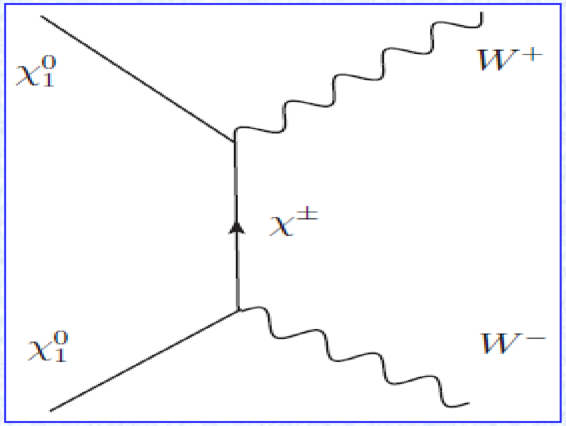
- *We also consider the relevant phenomenology at collider and DM detection experiments*



Relic density

- *In the early universe, DM particles mainly annihilate into*
  1).bb or tt (if kinematics allowed) via the s-channel exchange of the Higgs and Z bosons.
  2).WW , ZZ via the t-channel exchange of the new particles

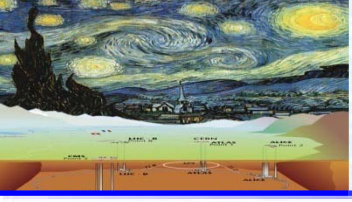




- *The* ***coannihilation*** *process can be important for the degenerate mss spectrum in the dark sector*

- *We use the MadDM (along with FeynRules and MadGraph) to calculate the DM relic density. All annihilation and coannihilation channels have been considered.*

- *We only require* $\Omega h^2 < 0.1$



Direct detection

- *Nuclear recoil signatures induced by the DM scattering off target nuclei*

$$\mathcal{L} \supset \frac{1}{2} g_{h\chi_1^0\chi_1^0} h \bar{\chi}_1^0 \chi_1^0 + \frac{1}{2} g_{Z\chi_1^0\chi_1^0} Z_\mu \bar{\chi}_1^0 \gamma^\mu \gamma_5 \chi_1^0$$

- *Spin-independent (**SI**) scattering: mainly induced by the Higgs mediated scalar interaction. Stringent constraints from XENON, LUX, PANDAX….*

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

- *Spin-dependent (**SD**) scattering: mainly induced by the Z mediated axial-vector interaction. Constraints from DD (e.g. COUPP, PICO…) and high energy neutrino experiments*

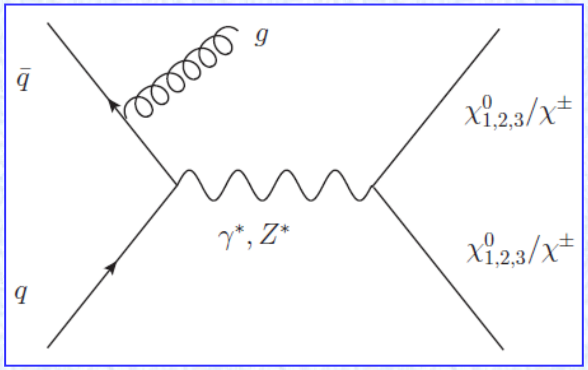
$$g_{Z\chi_1^0\chi_1^0} = -\frac{g}{2c_W}(|\mathcal{N}_{21}|^2 - |\mathcal{N}_{31}|^2)$$

- *We use the latest PANDAX results to set constraints*

PANDAX, 1607.07400, 1611.06553

Direct collider searches

- *DM particles can be directly produced at colliders. The corresponding signature is the **mono-jet** from initial state radiation*



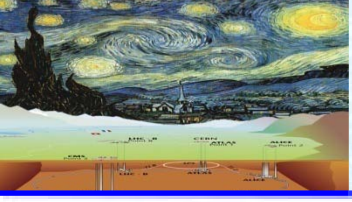
- *If other new fermions are degenerate with DM and light, they would be produced and decay into DM and soft SM particles at colliders, which are difficult to trigger and reconstruct. These processes may also contribute mono-jet signatures*

- *We consider all these production processes in the analysis, and use the ATLAS monojet results (at 8TeV of 20fb^{-1}) to set constraints*

ATLAS, 1502.01518

- *It will be possible to produce heavy new fermions at future hadron colliders, and search for them in many final states (0/1/3 leptons, disappearing track…)*

Low, Wang, 1404.0682



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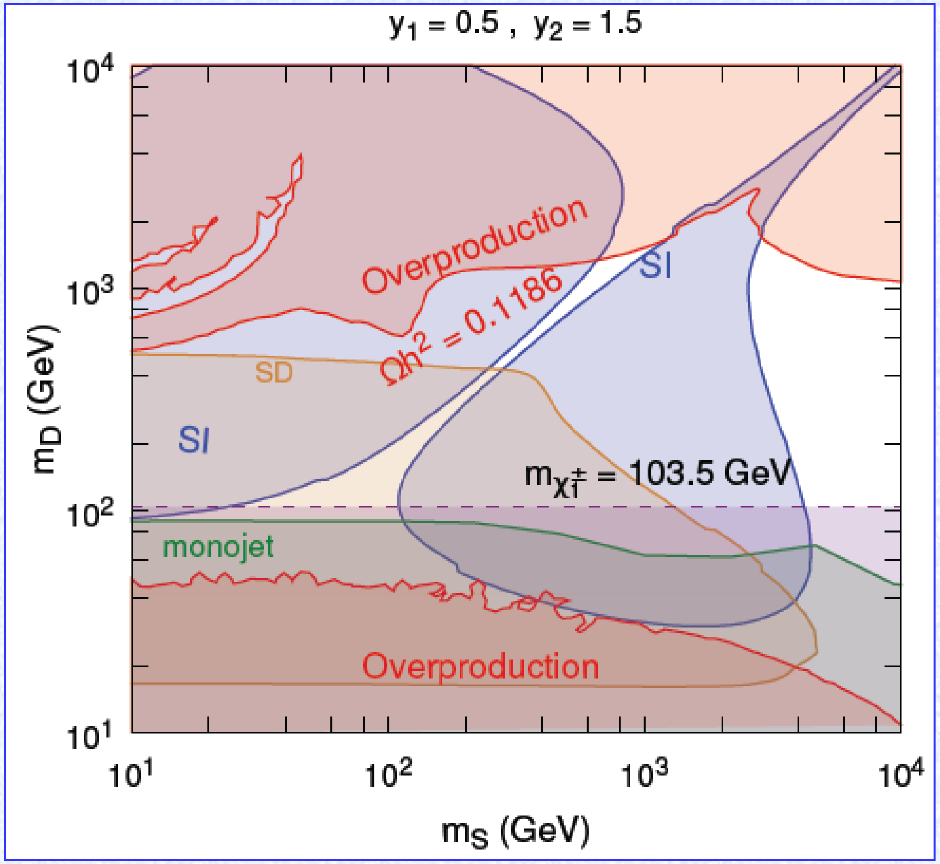

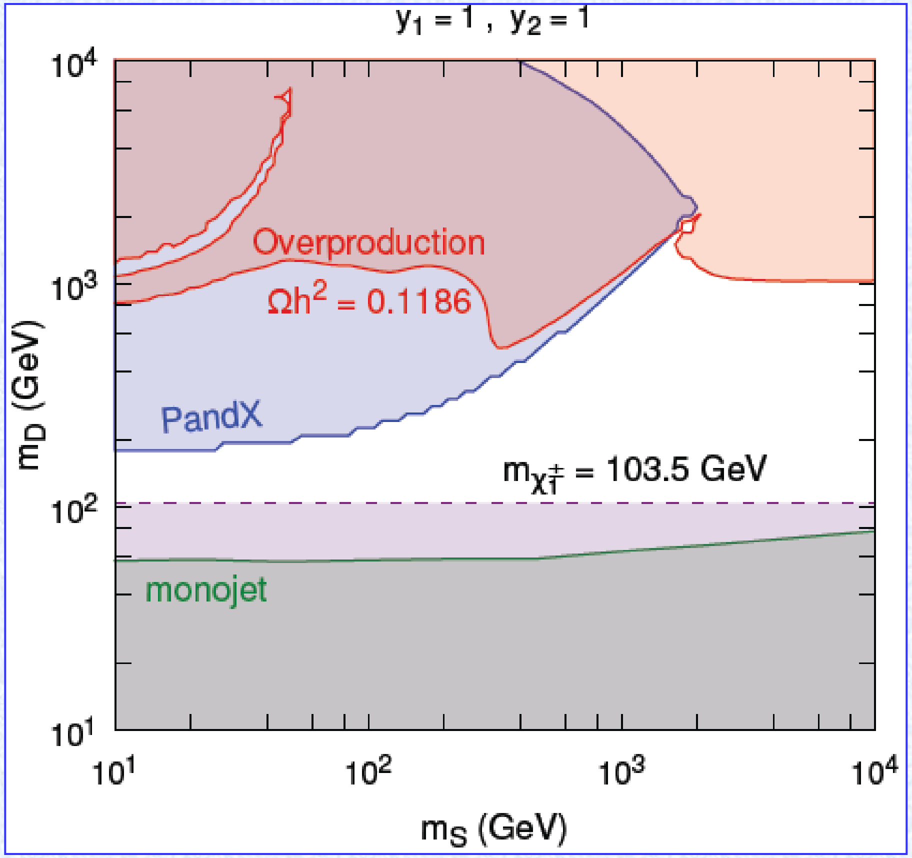

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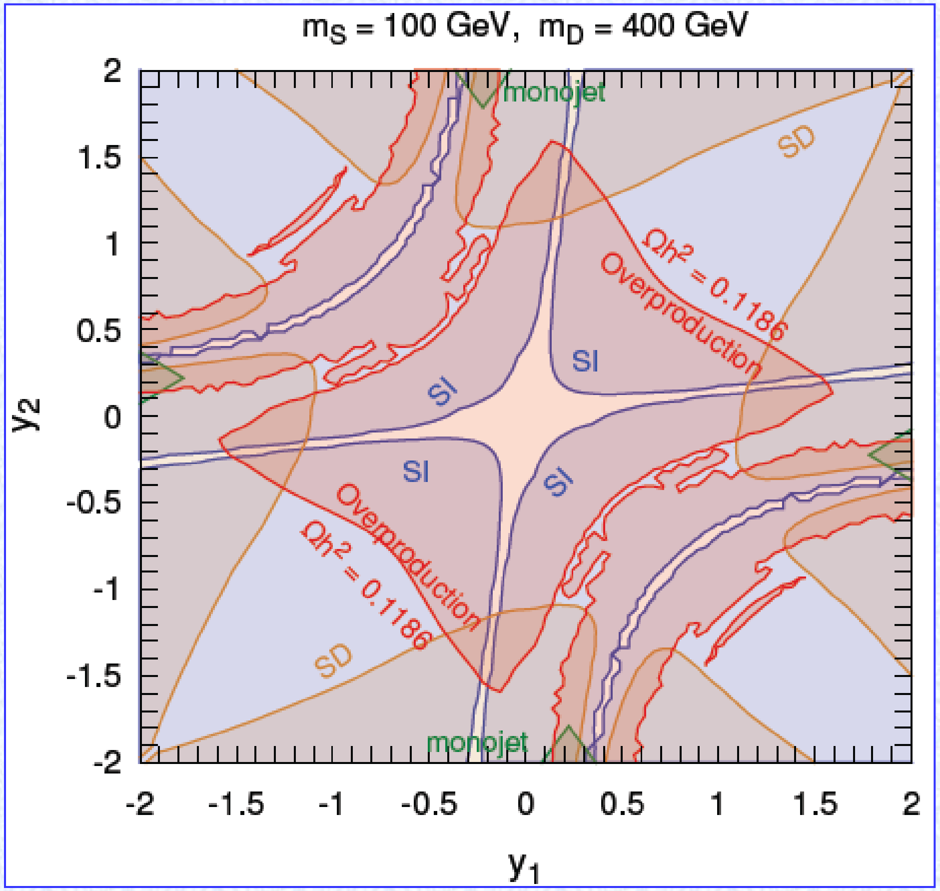
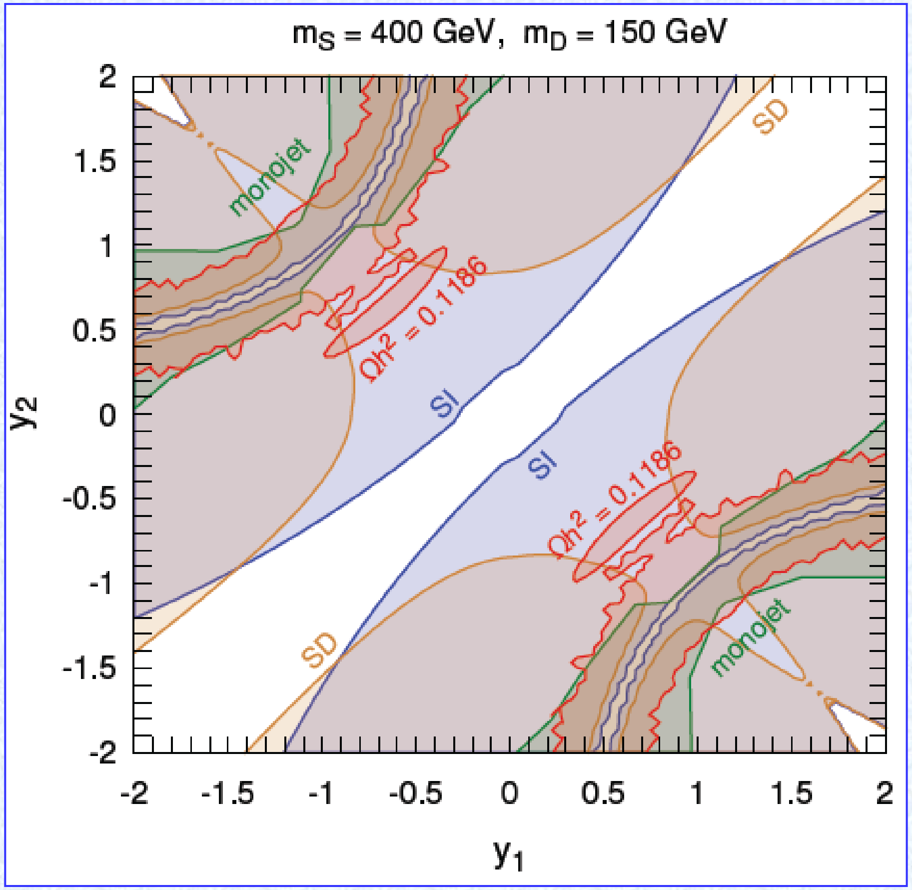
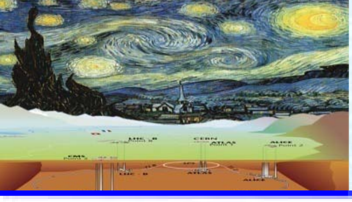
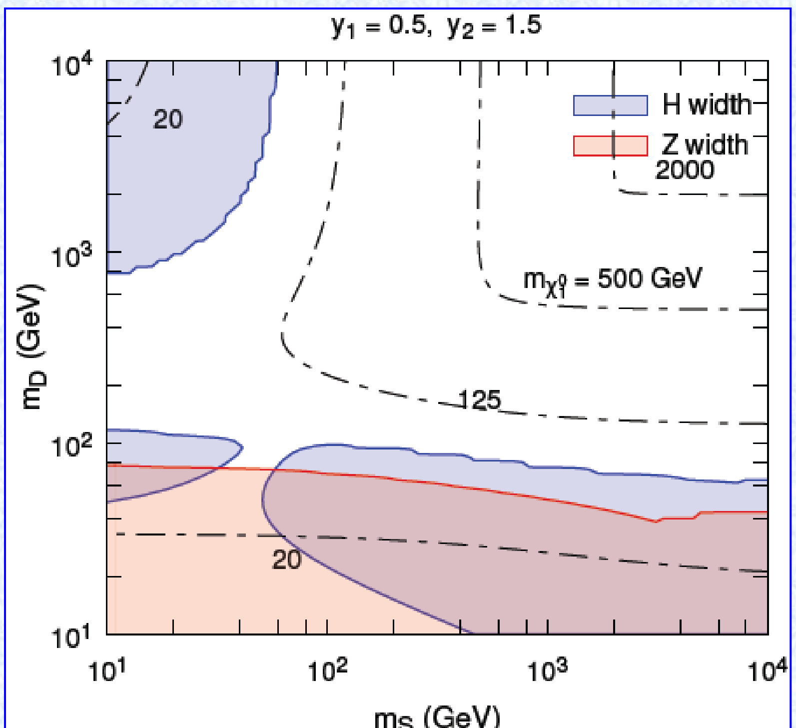


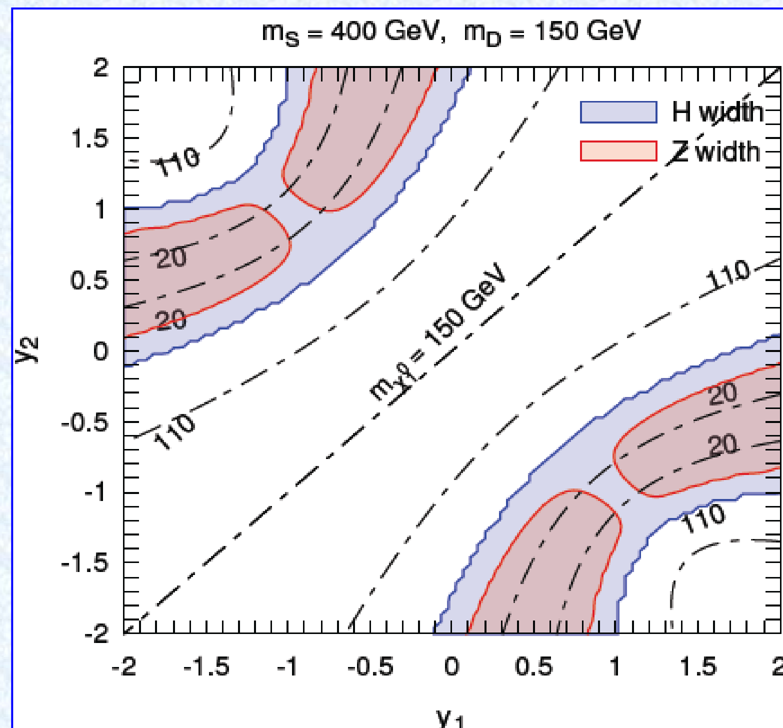




Higgs and Z decays

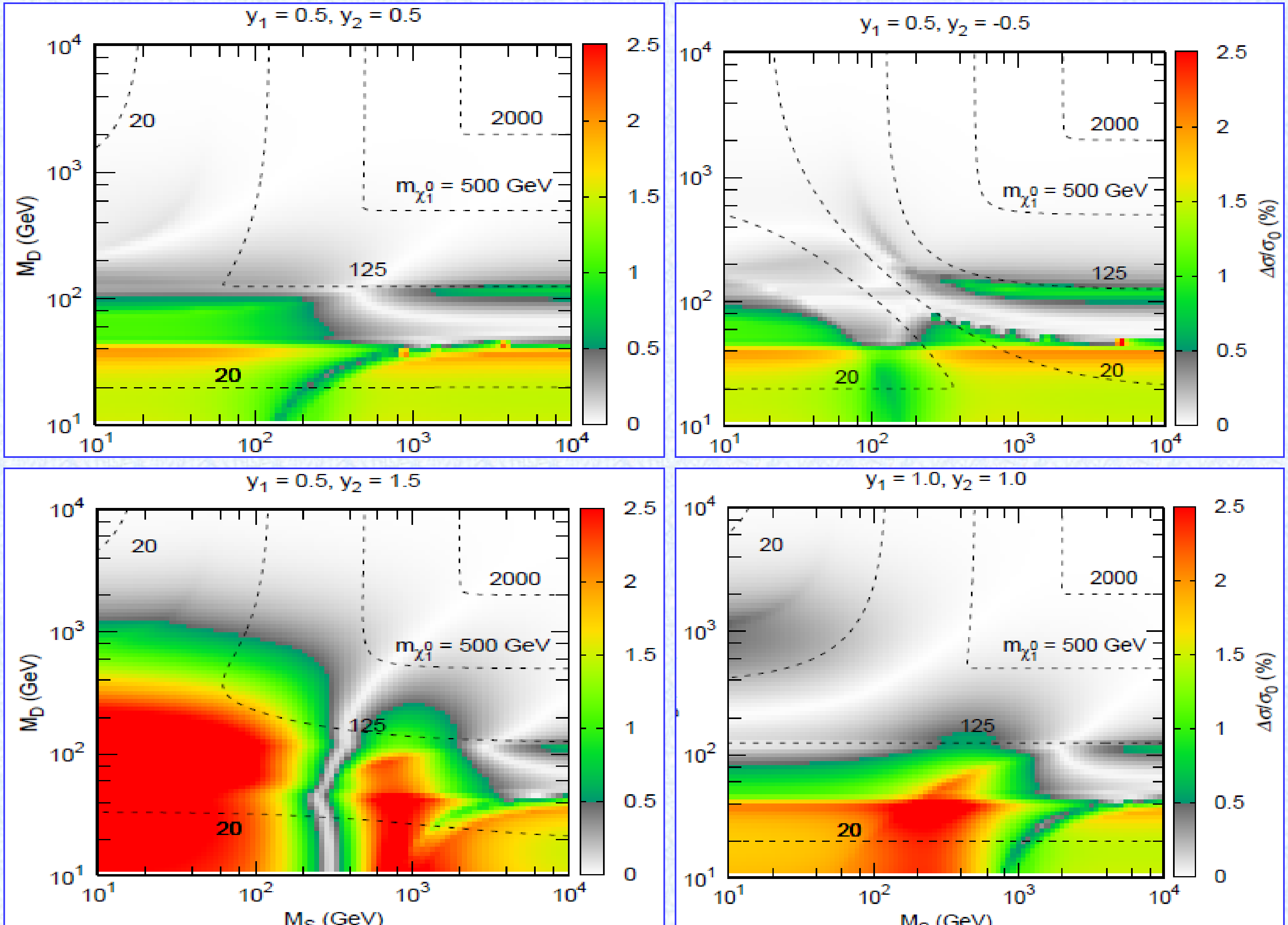
- *If new charged particles couple to the Higgs, they could modified the **Higgs decay width to di-photons** via triangle loops. $\Delta\Gamma/\Gamma$ can be test to be a level of ~9%*
- *If the kinematics is allowed, the Higgs and Z could decay into DM particles. Such **invisible decays** are constrained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





For instance, we require $\Gamma(Z\text{->}inv) < 2$ MeV *and* $\Gamma(h\text{->}inv)/\Gamma_h < 2.8\%$ *(of 5 ab^{-1})*

Searches at CEPC



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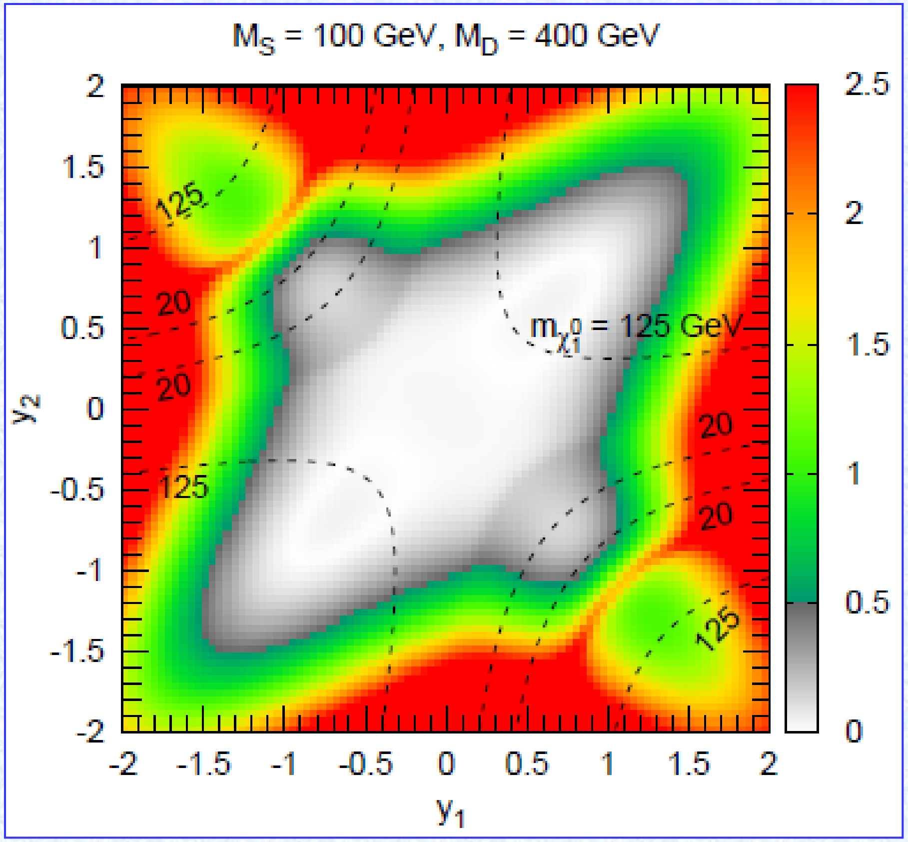
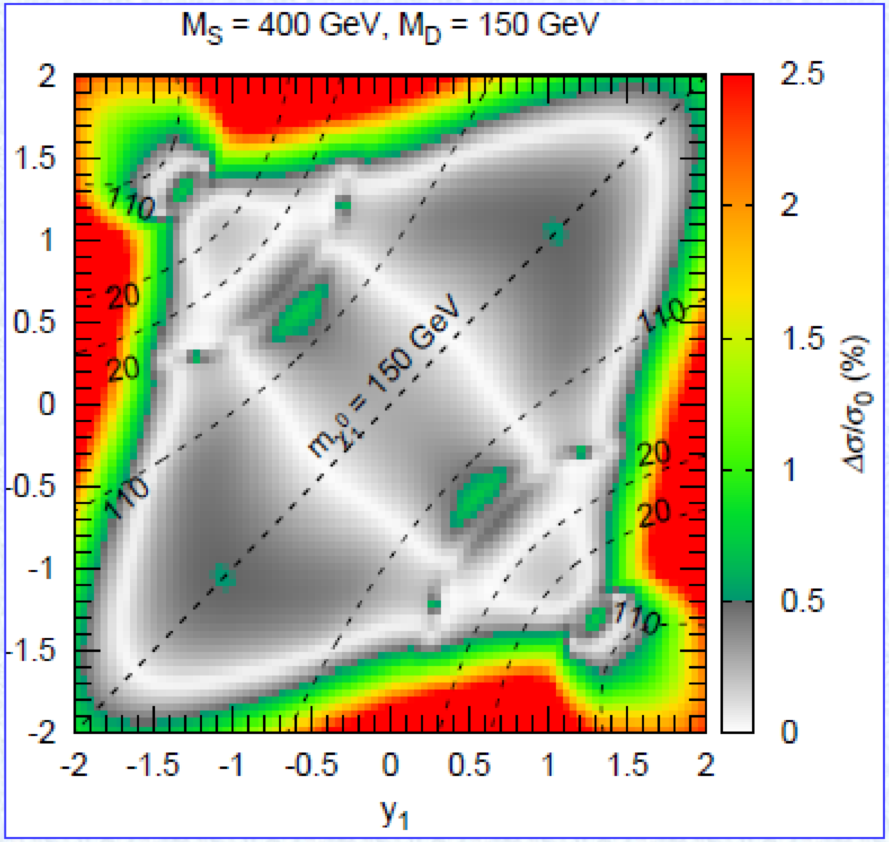
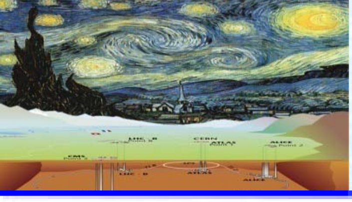






Doublet-Triplet Fermionic Model

- *Introduce one weyl triplet and two doublets*

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

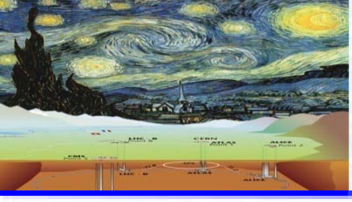
Yukawa interactions

$$\mathcal{L}_{\text{Yuk}} = -\frac{1}{\sqrt{2}}(y_1 \mathcal{N}_{1i}\mathcal{N}_{2j} + y_2 \mathcal{N}_{1i}\mathcal{N}_{3j})\bar{\Psi}_i P_L \Psi_j h + (y_1 \mathcal{C}^L_{1j}\mathcal{C}^R_{2i} - y_2 \mathcal{C}^L_{2j}\mathcal{C}^R_{1i})\bar{\Psi}^\pm_i P_L \Psi^\pm_j h + \text{h.c.}$$

The Higgs couplings to new charged particles can modify the Higgs decay width to photons

Gauge interactions

$$\begin{aligned}\mathcal{L}_{\text{gauge}} =& e A_\mu \delta_{ij} \bar{\Psi}^\pm_i \gamma^\mu \Psi^\pm_j + \frac{e}{2 c_W s_W} Z_\mu (\mathcal{O}'^L_{ij} \bar{\Psi}^\pm_i \gamma^\mu P_L \Psi^\pm_j + \mathcal{O}'^R_{ij} \bar{\Psi}^\pm_i \gamma^\mu P_R \Psi^\pm_j) \\ &+ \frac{e}{4 c_W s_W} Z_\mu (\mathcal{O}_{ij} \bar{\Psi}_i \gamma^\mu P_L \Psi_j - \mathcal{O}^*_{ij} \bar{\Psi}_i \gamma^\mu P_R \Psi_j)\end{aligned}$$



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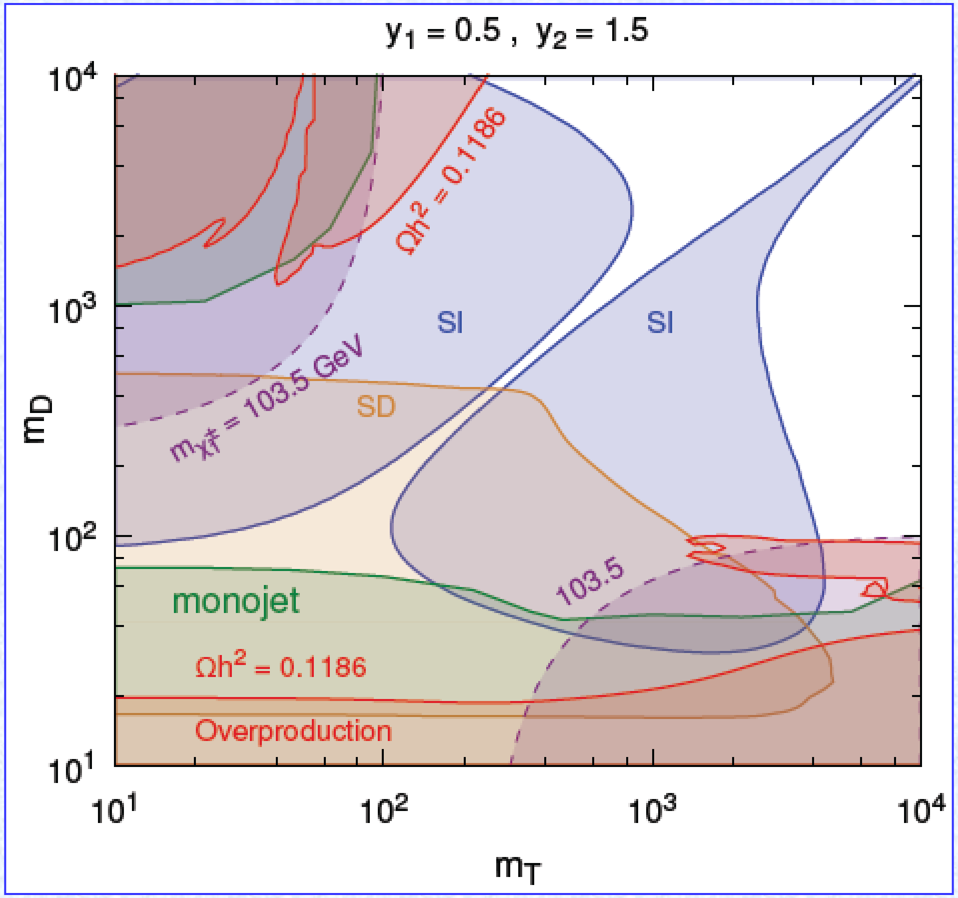
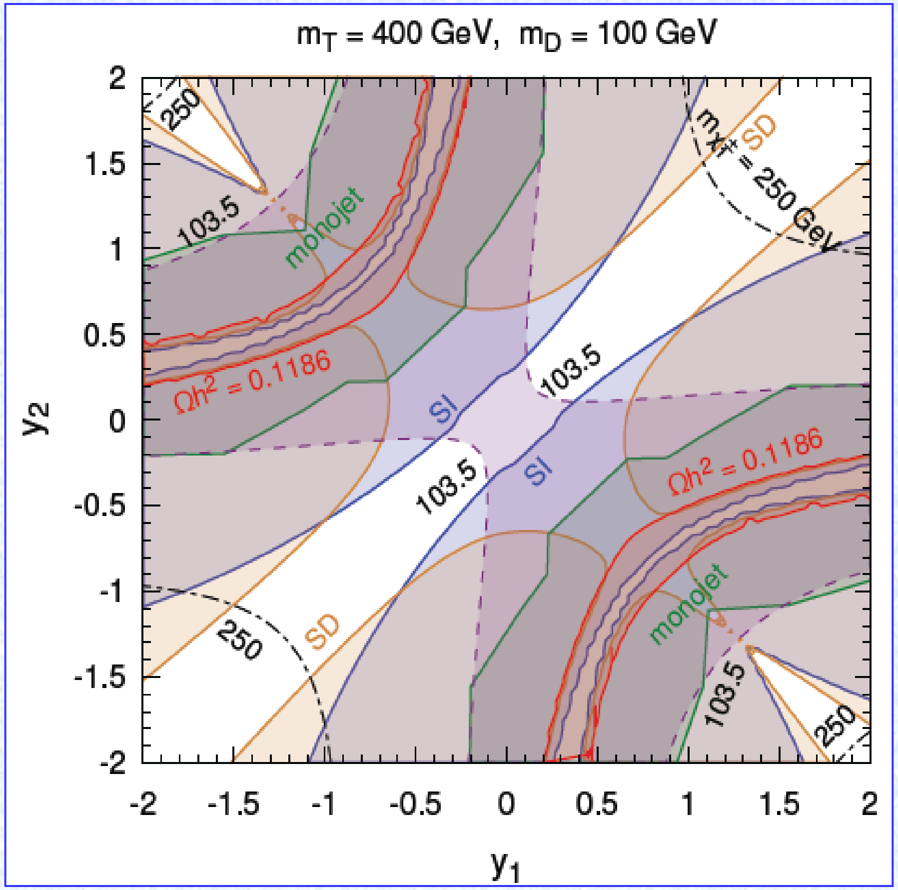
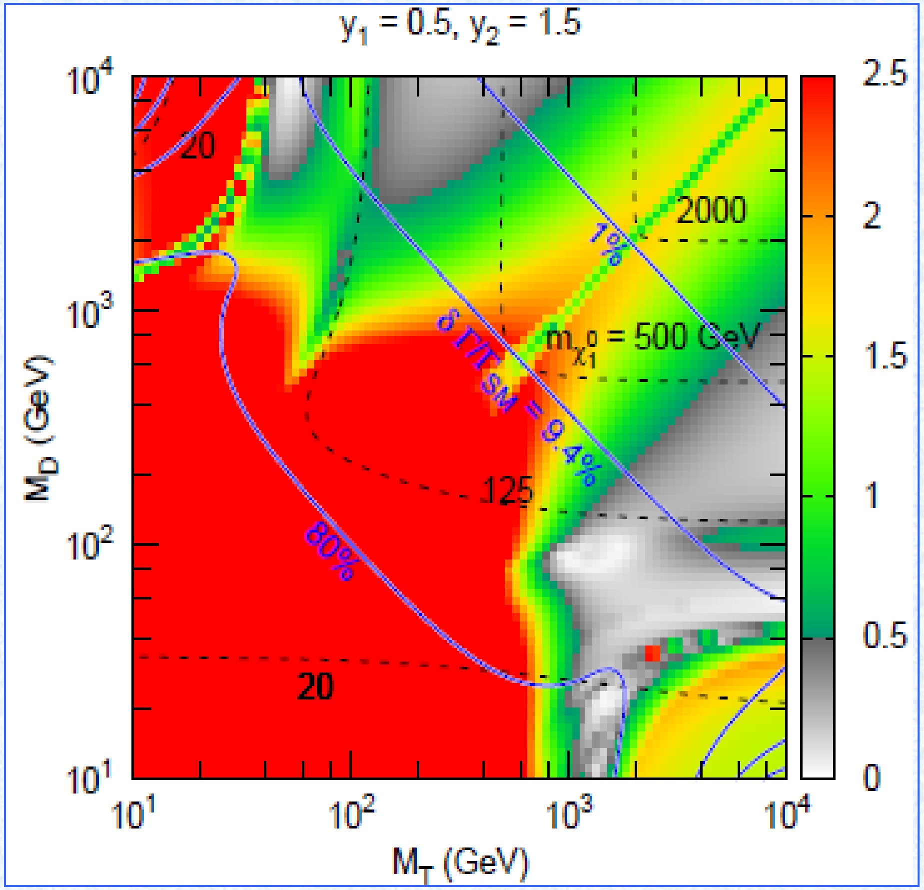
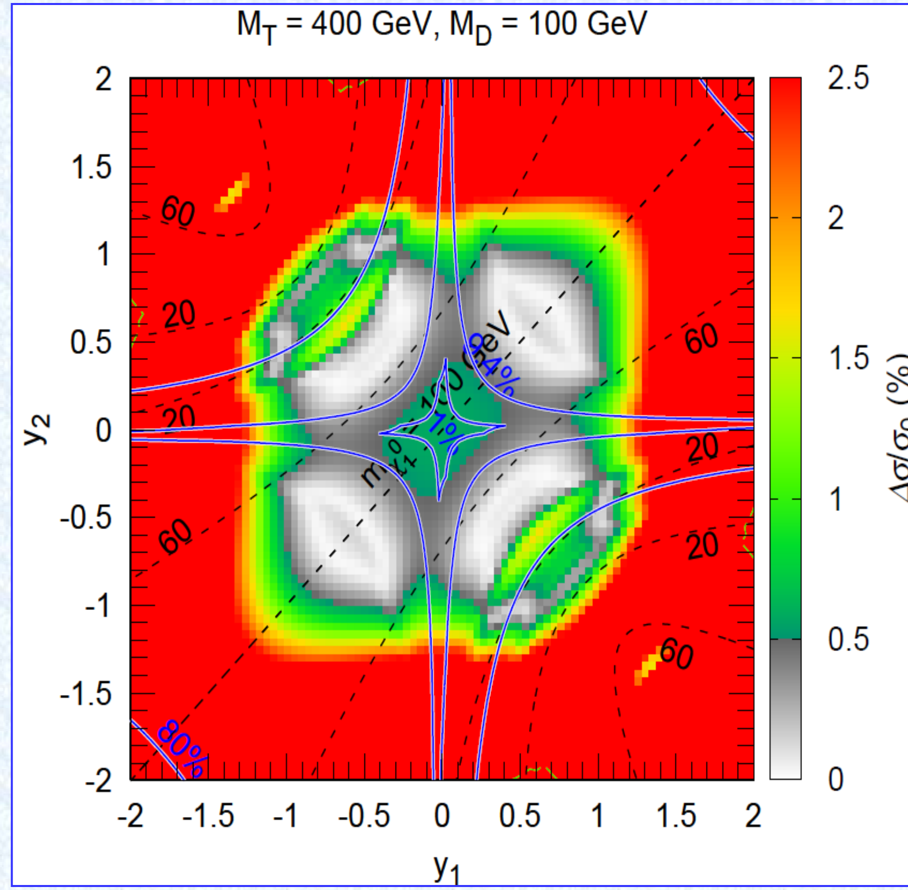
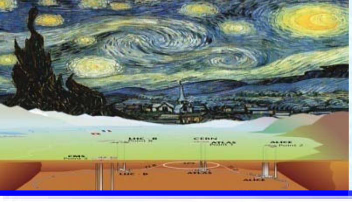




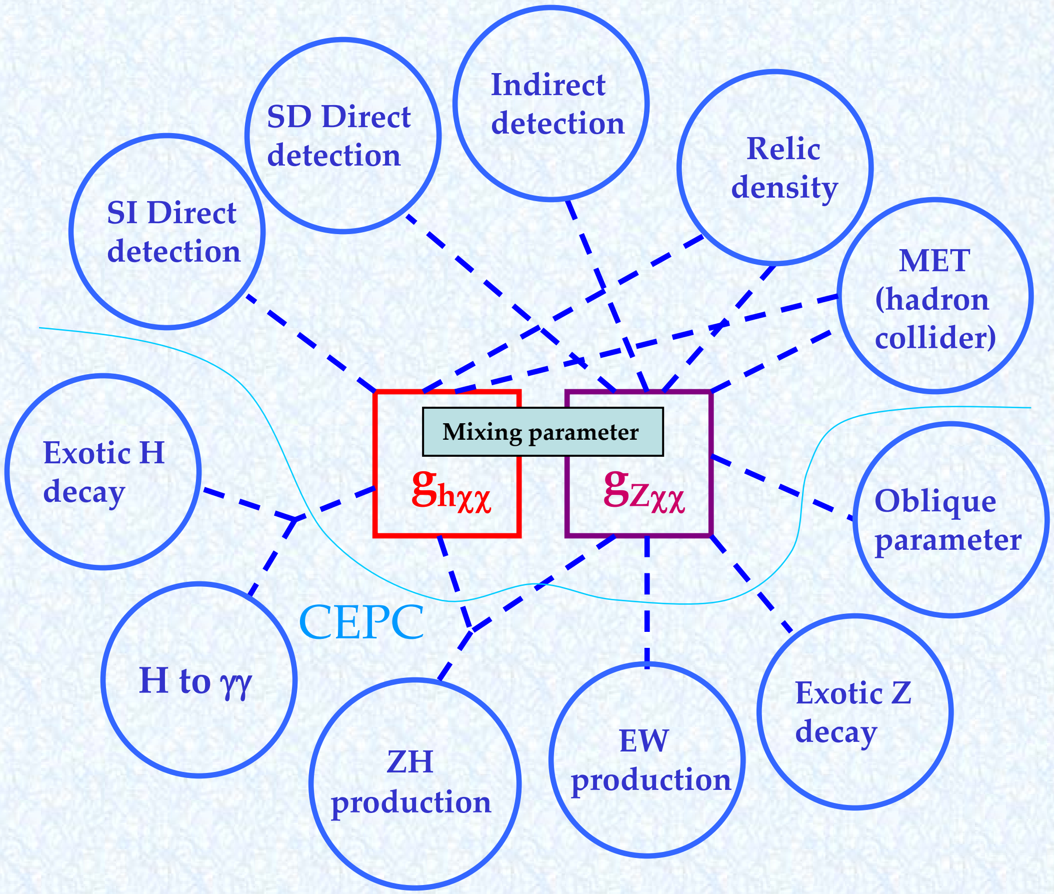
Searches at CEPC



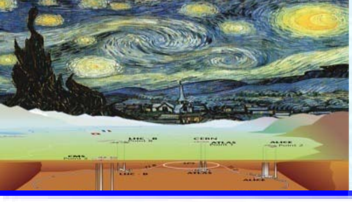




Conclusions



- *It is possible to probe new particles via loop effects at CEPC*
- *We consider a kind of DM models containing additional EW Fermionic multiplets, and focus on the relevant phenomenology at CEPC*
- *The significant correction to ZH production cross section requires moderate interactions connecting new particles to Higgs and Z. These interactions can be constrained by collider and DM detection experiments*



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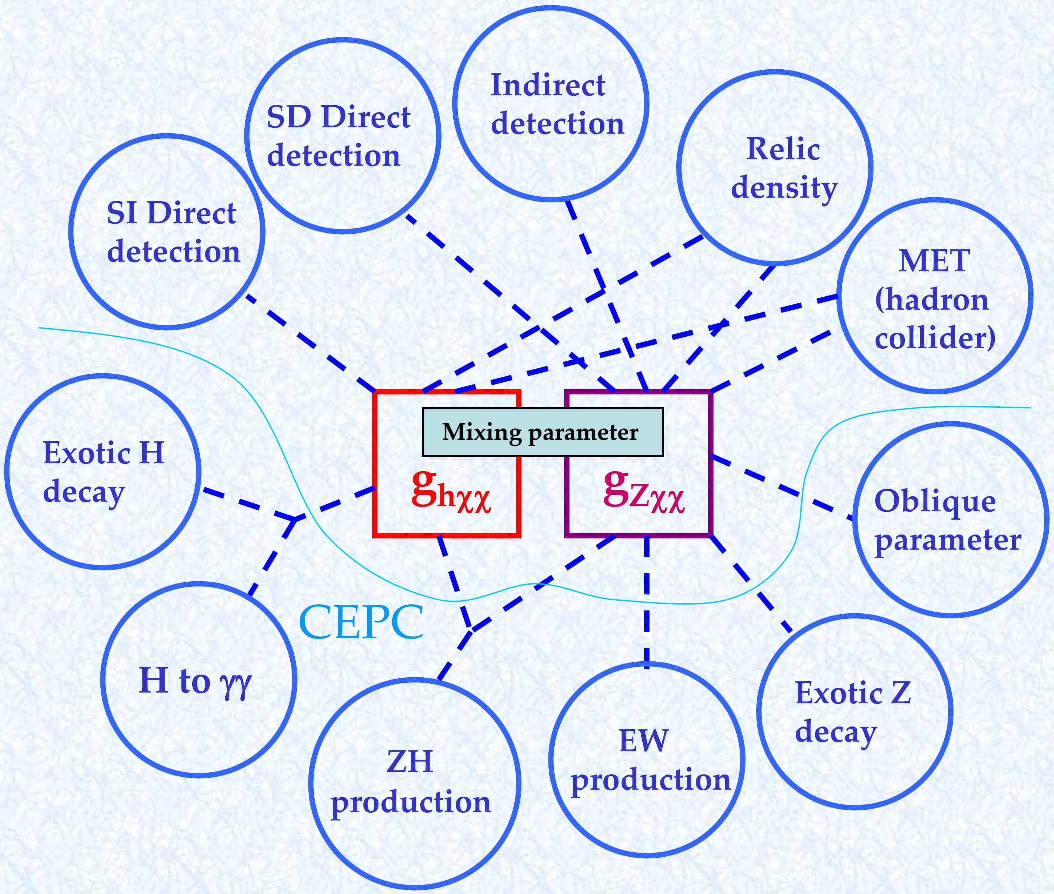

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Thank you