Exploring Dark Matter at the CEPC via Loop Effects

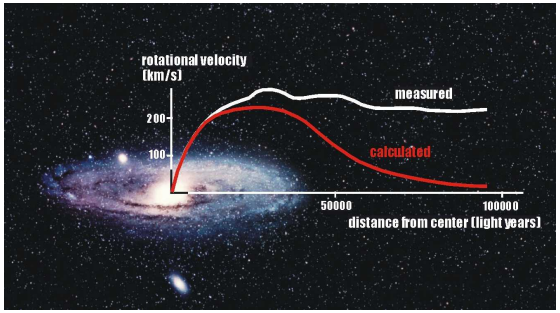
Qian-Fei Xiang (向仟飞)

Institute of High Energy Physics, CAS

Beijing, Peking University, Dec 17, 2016

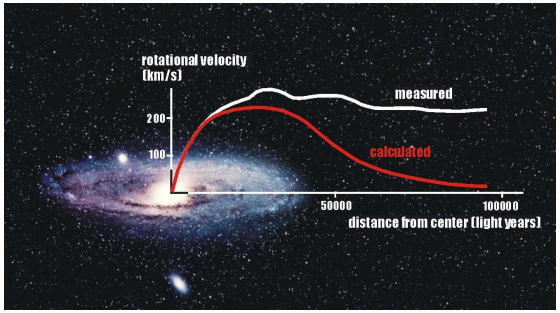
Outline

Evidences of Dark Matter

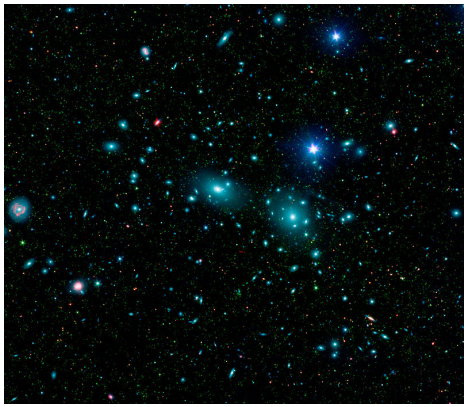


Rotation curves

Evidences of Dark Matter

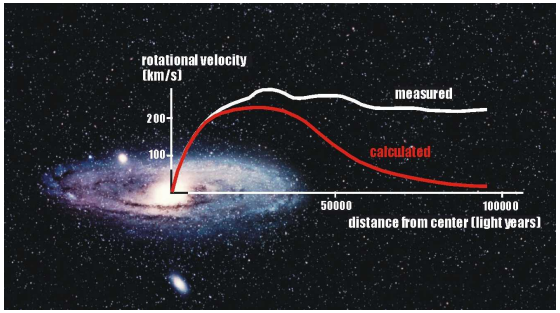


Rotation curves

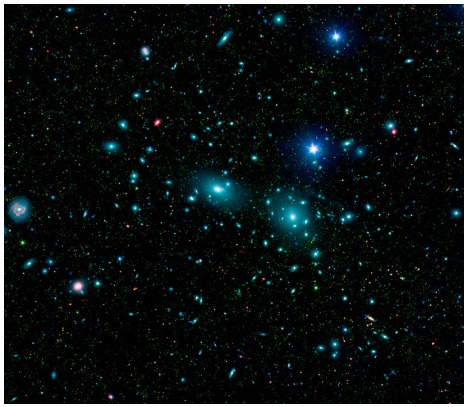


Coma Cluster

Evidences of Dark Matter



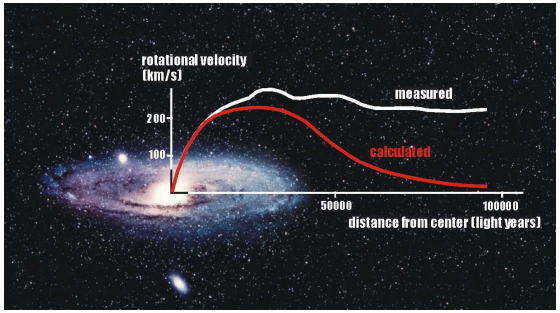
Rotation curves



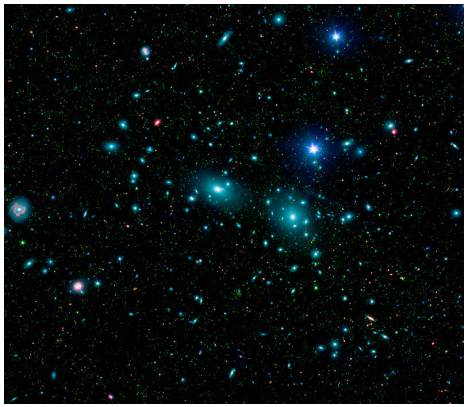
Coma Cluster

The Bullet Cluster

Evidences of Dark Matter

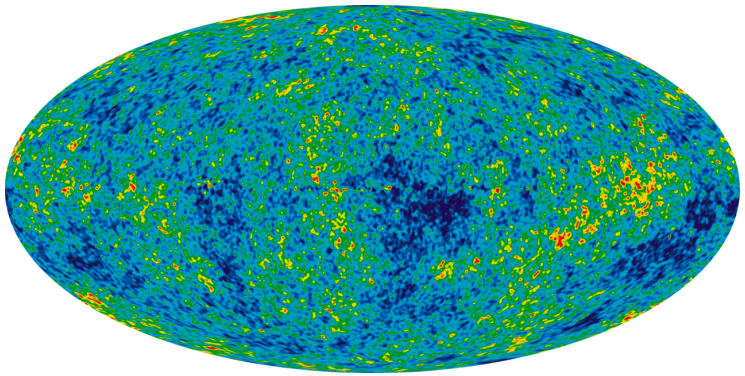


Rotation curves



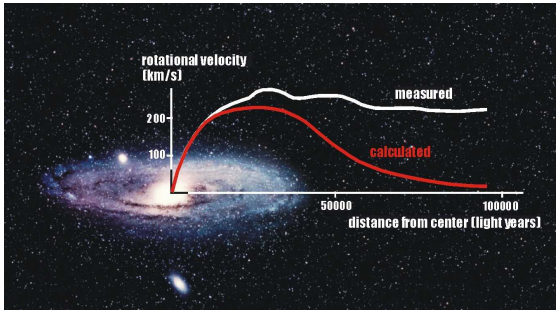
Coma Cluster

The Bullet Cluster

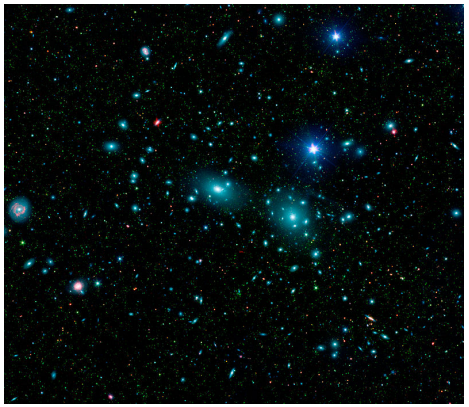


The Cosmic Microwave Background

Evidences of Dark Matter

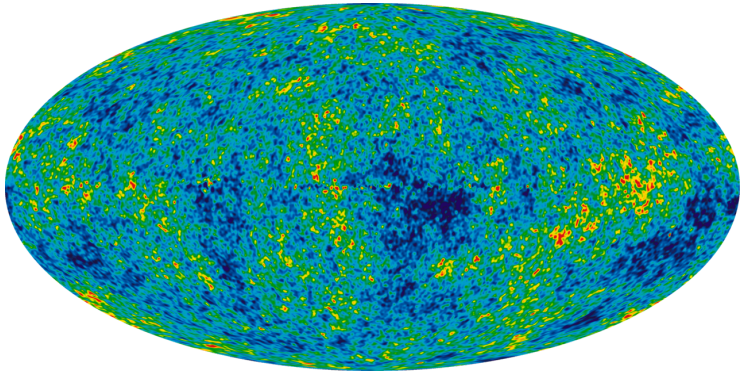


Rotation curves

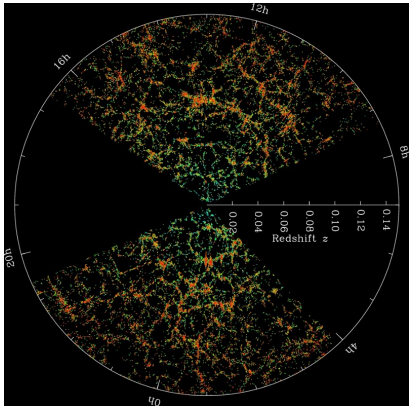


Coma Cluster

The Bullet Cluster

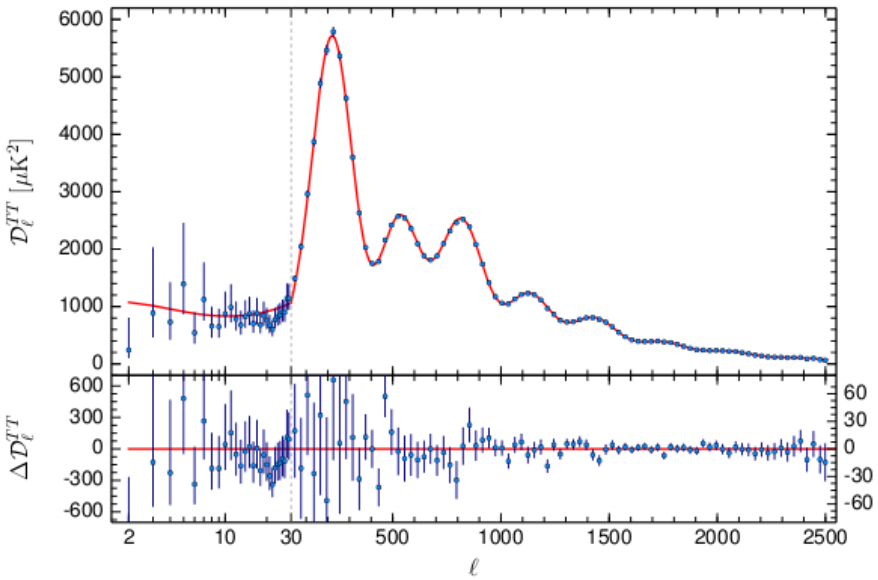


The Cosmic Microwave Background

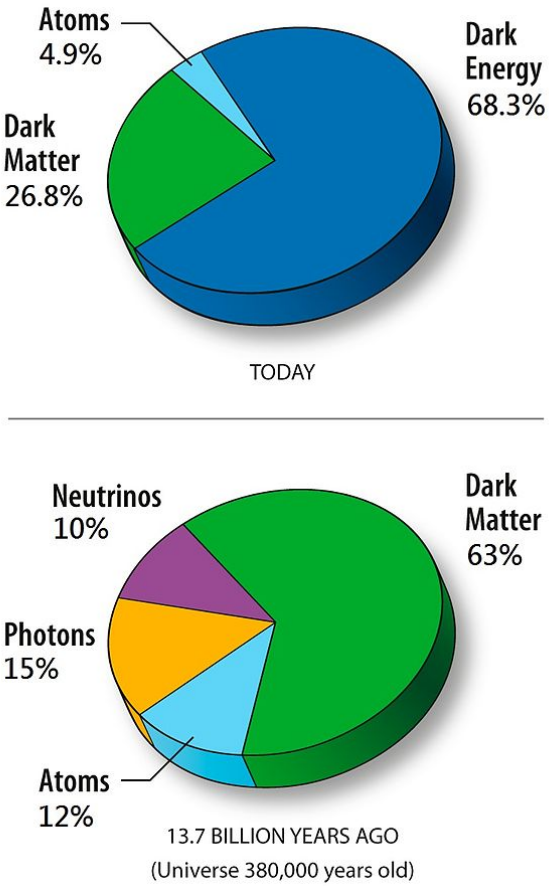


Large-Scale Structure Formation

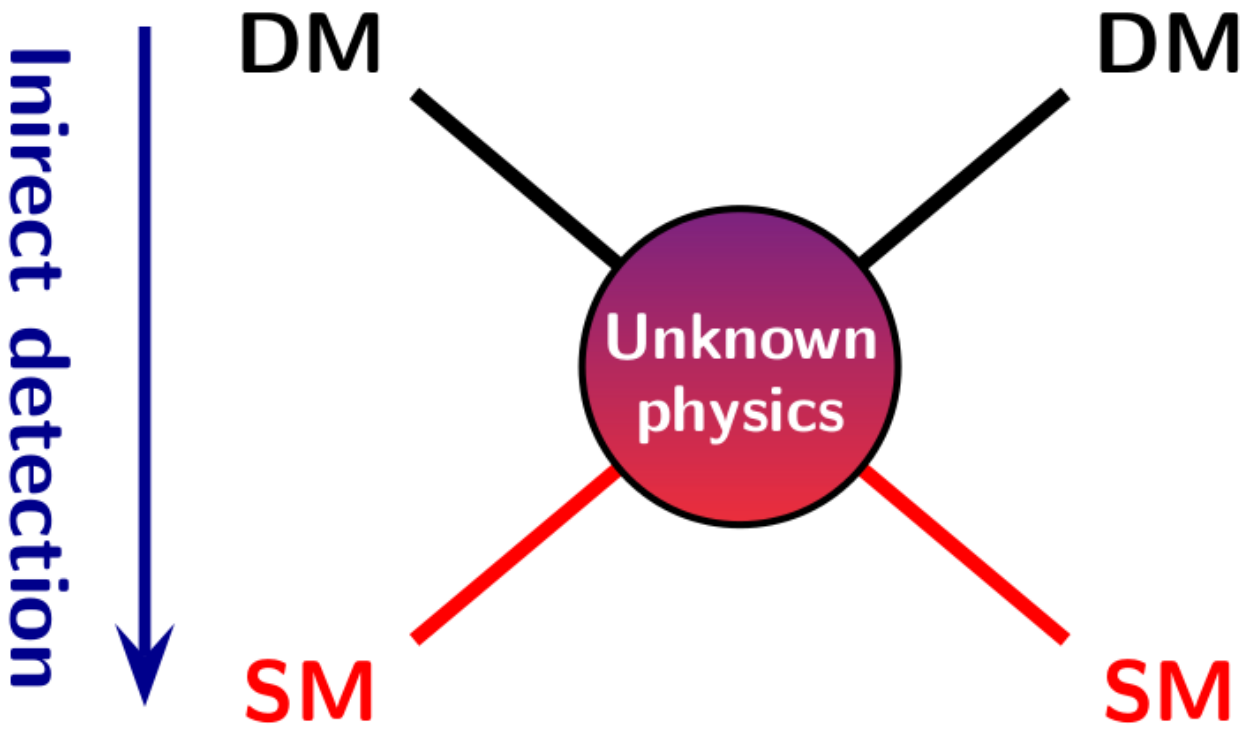
Dark Matter



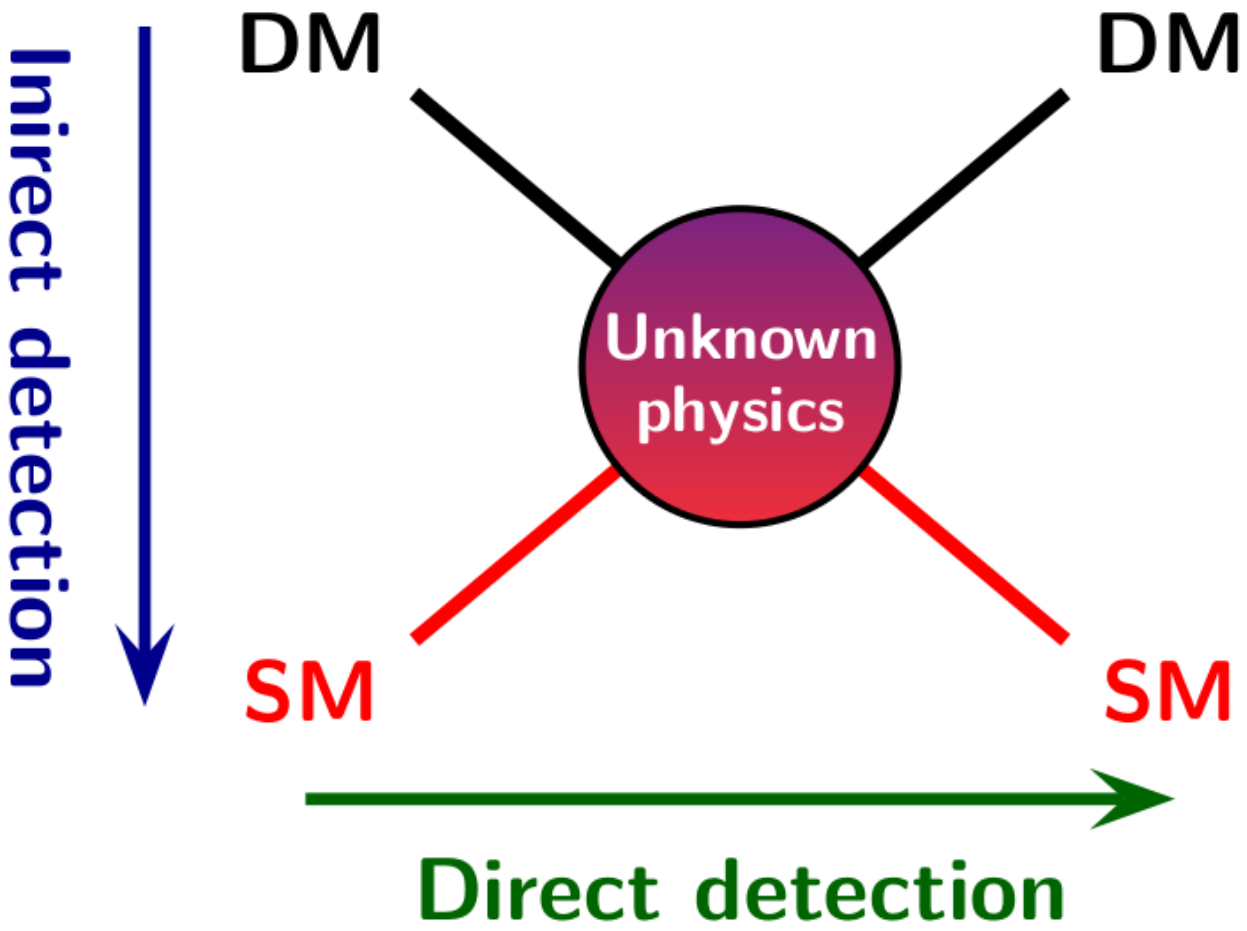
The temperature power spectrum.
Planck 2015, arXiv:1502.01589



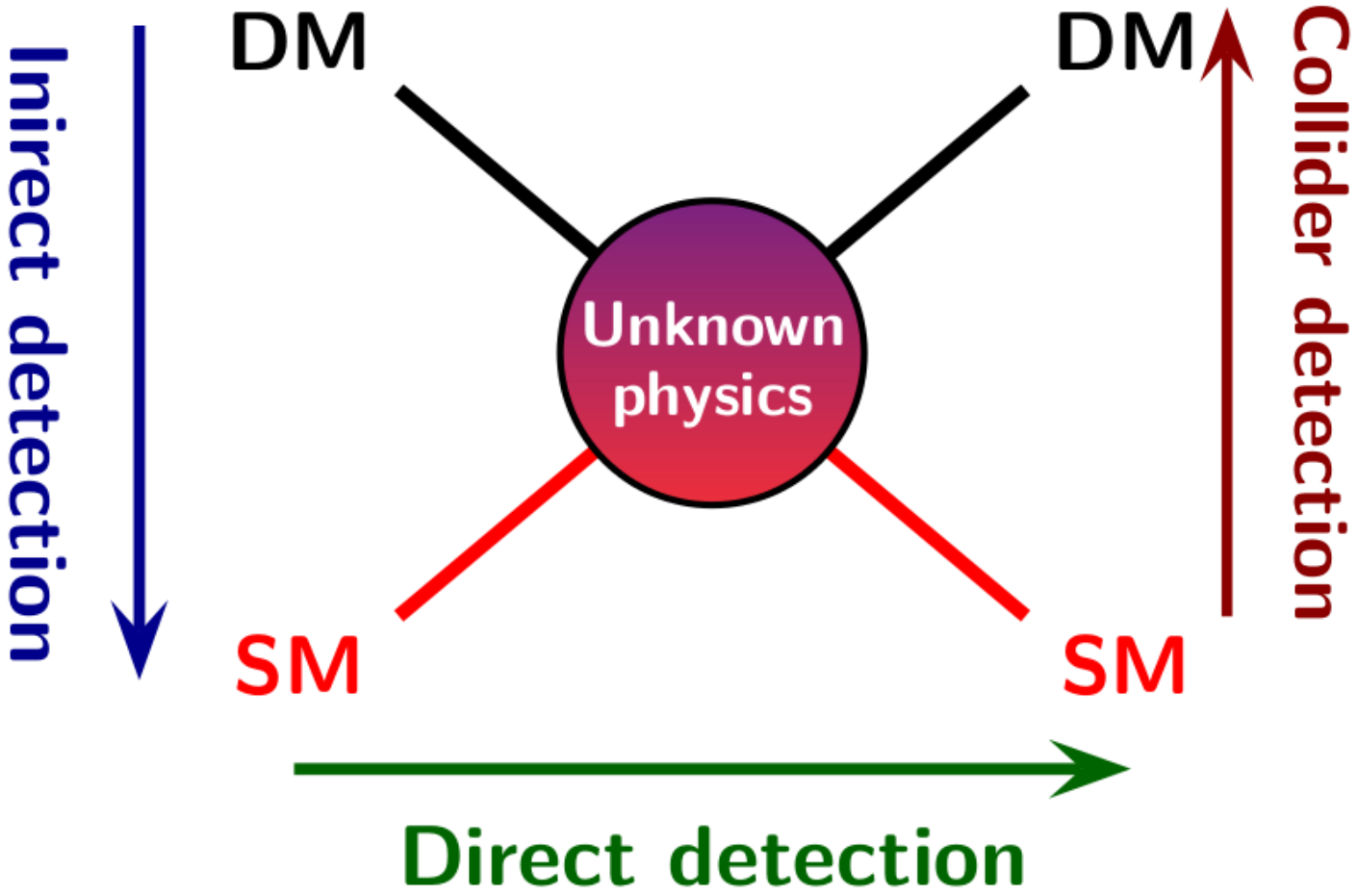
Dark Matter searches



Dark Matter searches



Dark Matter searches



Singlet-Doublet Fermionic Dark Matter (SDFDM)

Introduce left-handed Weyl fermions in the dark sector:

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

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

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

Yukawa couplings: $\mathcal{L}_{\rm HSD} = y_1 H_i S D_1^i - y_2 H_i^\dagger S D_2^i + \text{h.c.}$

Custodial symmetry limit $y = y_1 = y_2$ $\Rightarrow$ $\mathrm{SU}(2)_{\rm L} \times \mathrm{SU}(2)_{\rm R}$ invariant form:

$$\mathcal{L}_{\rm D} + \mathcal{L}_{\rm HSD} = i\mathcal{D}_A^\dagger \bar{\sigma}^\mu D_\mu \mathcal{D}^A - \frac{1}{2}[m_D \epsilon_{AB} \epsilon_{ij} (\mathcal{D}^A)^i (\mathcal{D}^B)^j + \text{h.c.}] + [y \epsilon_{AB} (\mathcal{H}^A)_i S (\mathcal{D}^B)^j + \text{h.c.}]$$

$\mathrm{SU}(2)_{\rm R}$ doublets: $(\mathcal{D}^A)^i = \begin{pmatrix} D_1^i \\ D_2^i \end{pmatrix}$, $(\mathcal{H}^A)_i = \begin{pmatrix} H_i^\dagger \\ H_i \end{pmatrix}$

SDFDM: State Mixing

The dark sector involves 3 Majorana fermions and 1 singly charged fermion

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

$$\mathcal{M}_{\rm N} = \begin{pmatrix} m_S & \frac{1}{\sqrt{2}}y_1 v & \frac{1}{\sqrt{2}}y_2 v \\ \frac{1}{\sqrt{2}}y_1 v & 0 & -m_D \\ \frac{1}{\sqrt{2}}y_2 v & -m_D & 0 \end{pmatrix}, \quad \begin{pmatrix} S \\ D_1^0 \\ D_2^0 \end{pmatrix} = \mathcal{N}\begin{pmatrix} \chi_1^0 \\ \chi_2^0 \\ \chi_3^0 \end{pmatrix}$$

$$\mathcal{N}^{\rm T}\mathcal{M}_{\rm N}\mathcal{N} = {\rm diag}(m_{\chi_1^0}, m_{\chi_2^0}, m_{\chi_3^0}), \quad \chi^+ = D_2^+, \quad \chi^- = D_1^-$$

Couplings of the **DM candidate** χ_1^0 to the Higgs and Z bosons:

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

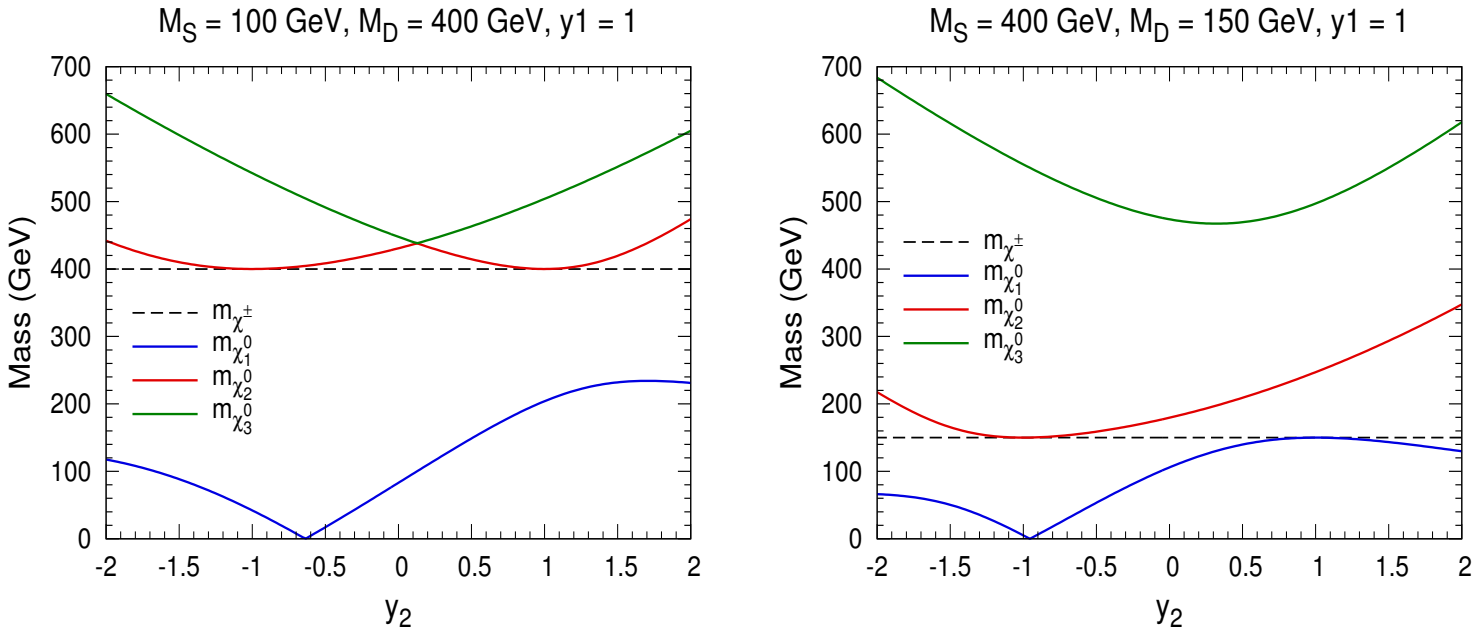
$$g_{h\chi_1^0\chi_1^0} = -\sqrt{2}(y_1\mathcal{N}_{21} + y_2\mathcal{N}_{31})\mathcal{N}_{11}, \quad g_{Z\chi_1^0\chi_1^0} = -\tfrac{g}{2c_{\rm W}}(|\mathcal{N}_{21}|^2 - |\mathcal{N}_{31}|^2)$$

Custodial symmetry limit $y_1 = y_2 \;\Rightarrow\; g_{Z\chi_1^0\chi_1^0} = 0$

$y_1 = y_2$ and $m_D < m_T \;\Rightarrow\; g_{h\chi_1^0\chi_1^0} = 0$

SDFDM spectrums

Particle mass as functions of y_1.



(a) $M_S = 100GeV$, $M_D = 400GeV$ (b) $M_S = 400GeV$, $M_D = 150GeV$

- $m_{\chi^\pm} = m_D$.
- $y_1 = y_2$, or $y_1 = -y_2$, the mass of one neutral particle equals to the mass of $\chi^\pm$. Hard to detect at colliders directly.

Relic density

- $T >> m_{\chi_1^0}$, DM particles are in thermal equilibrium with SM particles.
- $T < m_{\chi_1^0}$, number density of DM becomes exponentially suppressed
- The number density of DM is governed by the Boltzmann equation:

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -<\sigma_{\chi\chi}v>(n_\chi^2 - n_{\chi,eq}^2)$$

- Numerically, this yields an abundance of:

$$\Omega h^2 = 0.11 \times \left(\frac{2.2\times10^{-26}cm^3/s}{<\sigma_{\chi\chi}v>_{freeze}}\right)$$

Relic density

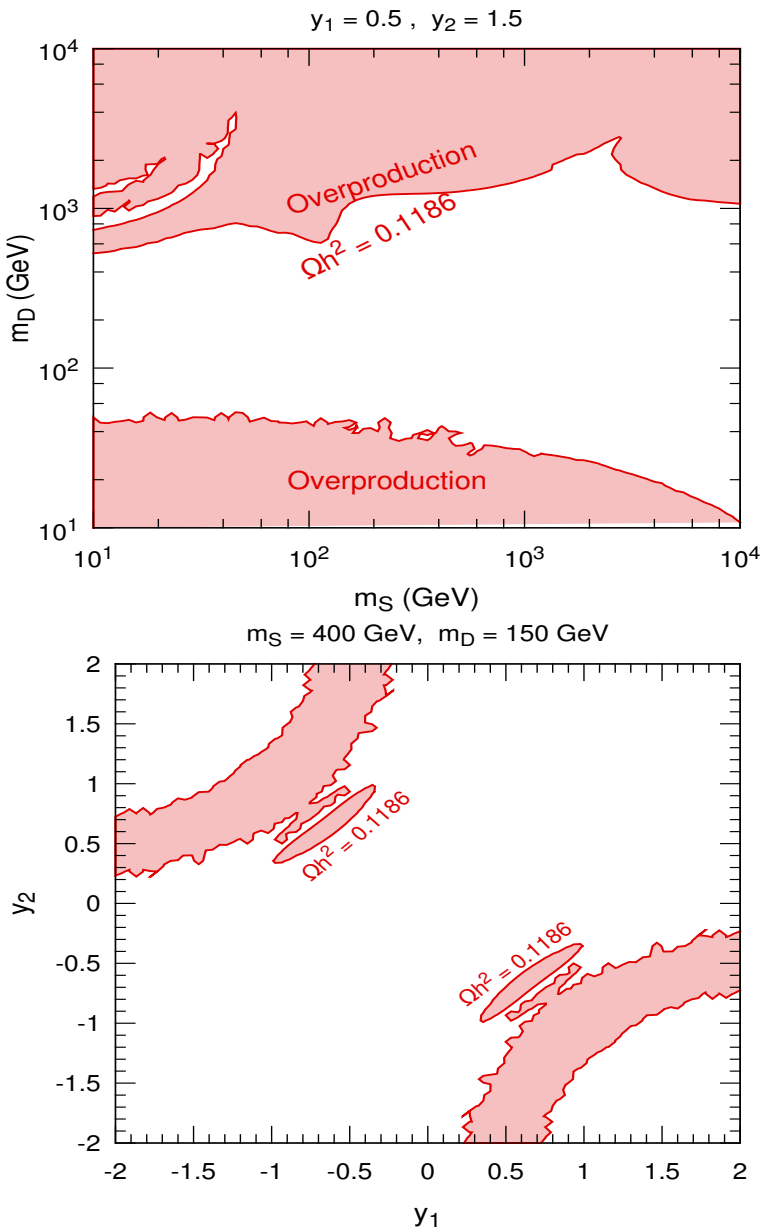
- $T >> m_{\chi_1^0}$, DM particles are in thermal equilibrium with SM particles.
- $T < m_{\chi_1^0}$, number density of DM becomes exponentially suppressed
- The number density of DM is governed by the Boltzmann equation:

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -<\sigma_{\chi\chi}v>(n_\chi^2 - n_{\chi,eq}^2)$$

- Numerically, this yields an abundance of:

$$\Omega h^2 = 0.11 \times \left(\frac{2.2\times10^{-26}cm^3/s}{<\sigma_{\chi\chi}v>_{freeze}}\right)$$

- require $\Omega h^2 \leq 0.1186$. Planck[1502.01589] $m_{\chi_0^1}$ can only contribute to part of observed DM abundance, or some non-thermal production mechanics is needed.

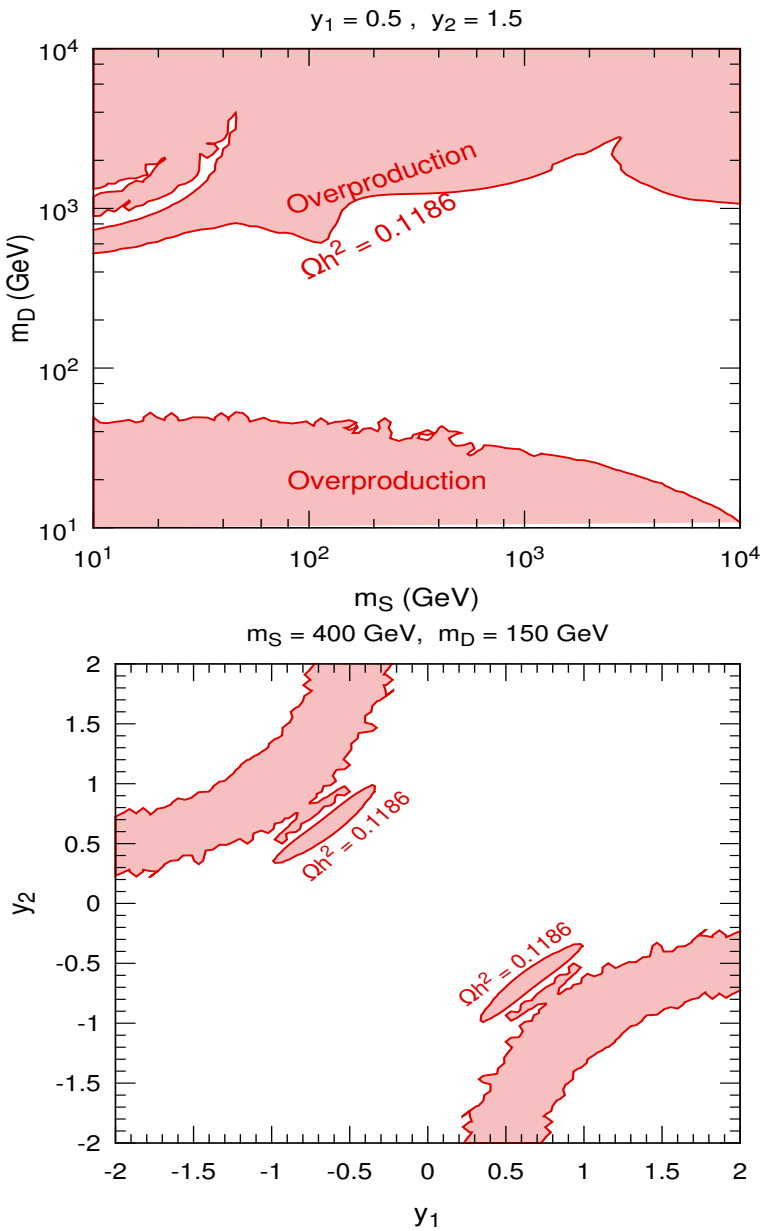


Direct detection

The couplings of the DM candidate χ_1^0 to the Higgs and Z bosons

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

induce **spin-independent (SI)** and **spin-dependent (SD)** scatterings between DM and nuclei, respectively



Direct detection

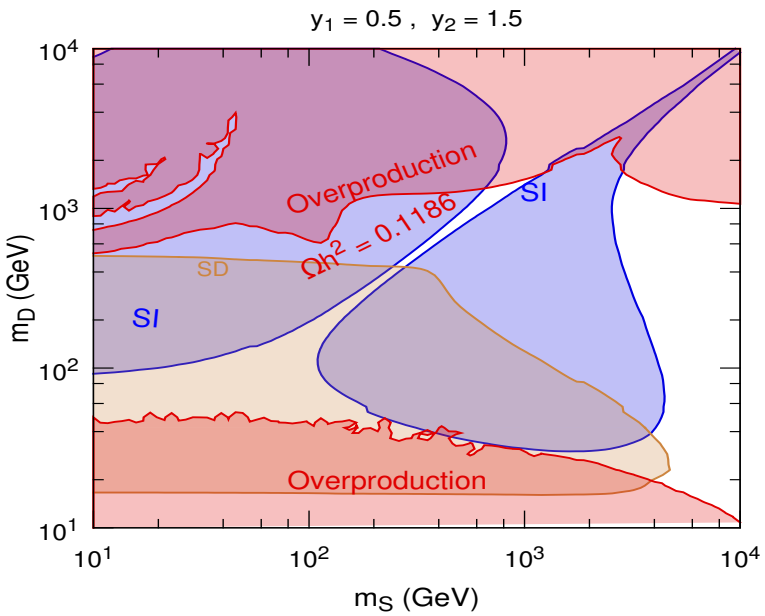
The couplings of the DM candidate χ_1^0 to the Higgs and Z bosons

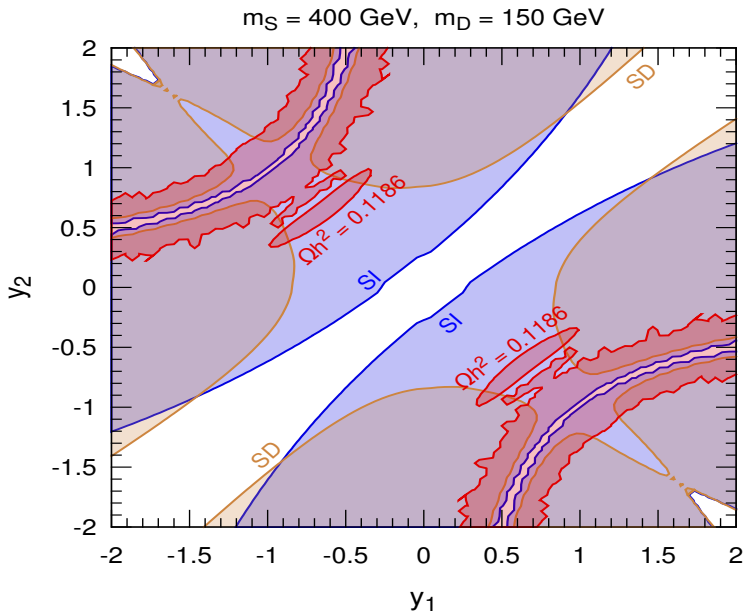
$$\mathcal{L} \supset \frac{1}{2} g_{h\chi_1^0\chi_1^0} h \bar{\chi}_1^0 \chi_1^0 + \frac{1}{2} g_{Z\chi_1^0\chi_1^0} Z_\mu \bar{\chi}_1^0 \gamma^\mu \gamma_5 \chi_1^0$$

induce **spin-independent (SI)** and **spin-dependent (SD)** scatterings between DM and nuclei, respectively

Most stringent constraints from current direct detection experiments:

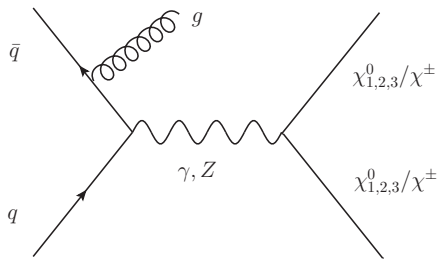
- **SI:** PandaX-II [1607.07400], LUX [1608.07648]
- **SD:** PandaX-II (proton)[1611.06553], LUX (neutron) [1602.03489], PICO (proton) [1503.00008, 1510.07754]





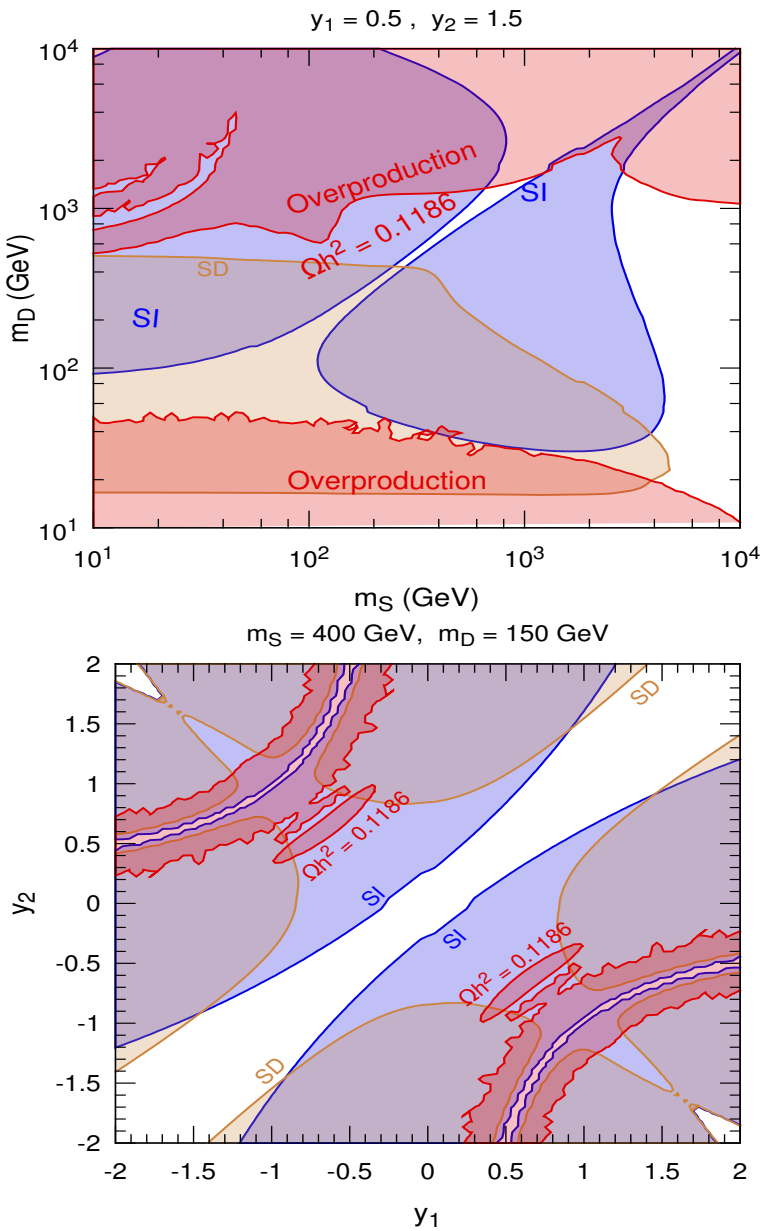
Colliders constrains

New light particles could be produced directly at high energy colliders:



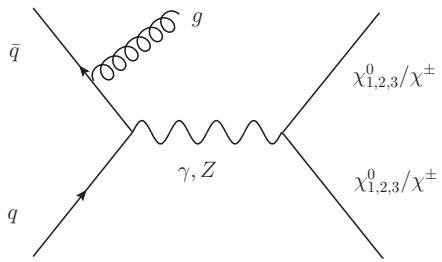
We consider all possible processes:

$$pp \to \chi_i^0 \chi_j^0, \chi_i^0 \chi^\pm, \chi^\pm \chi^\pm$$



Colliders constrains

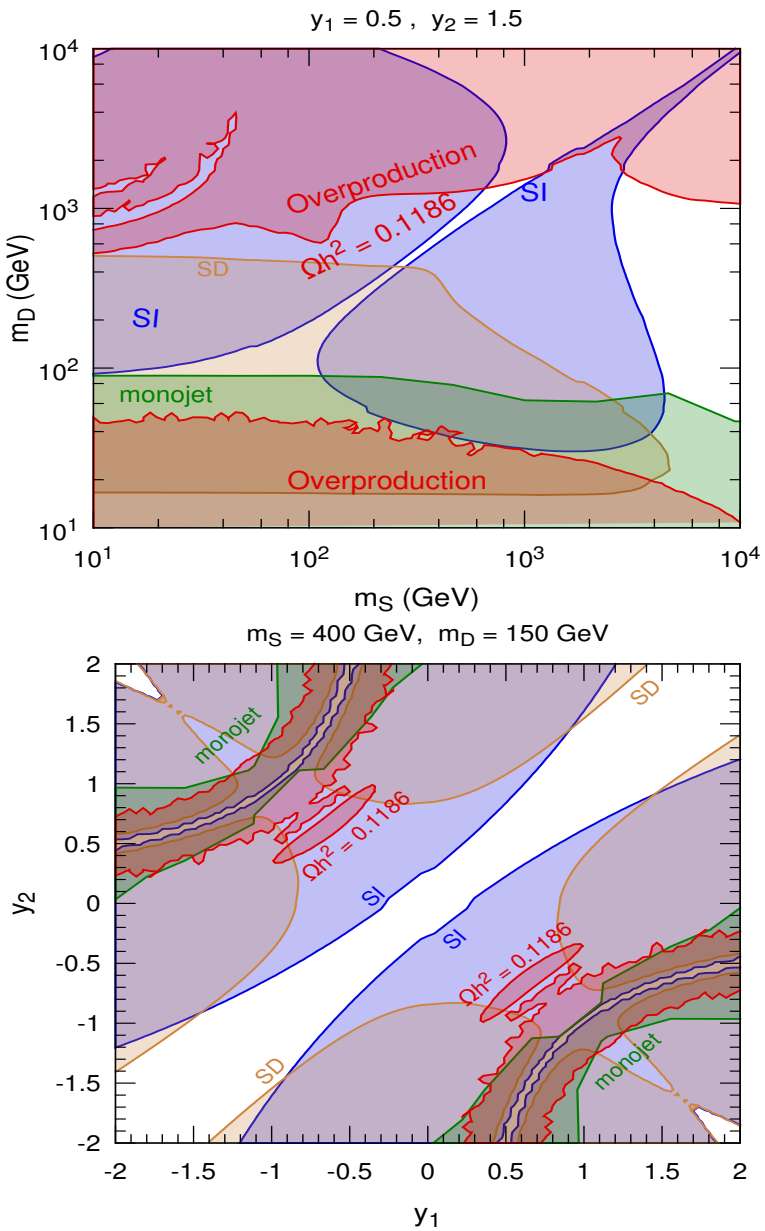
New light particles could be produced directly at high energy colliders:



We consider all possible processes:

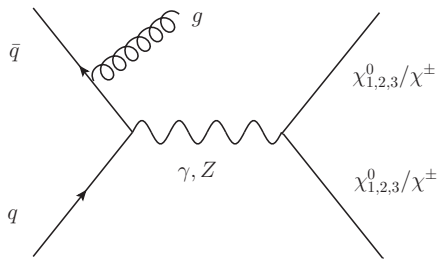
$$pp \to \chi_i^0 \chi_j^0, \chi_i^0 \chi^\pm, \chi^\pm \chi^\pm$$

LHC monojet search at 8 TeV with 20.3 data. [1502.01518]



Colliders constrains

New light particles could be produced directly at high energy colliders:

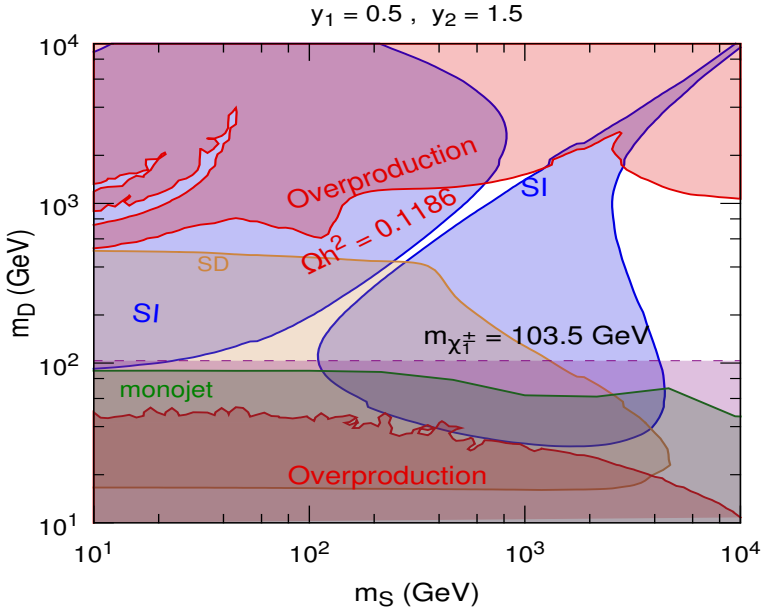


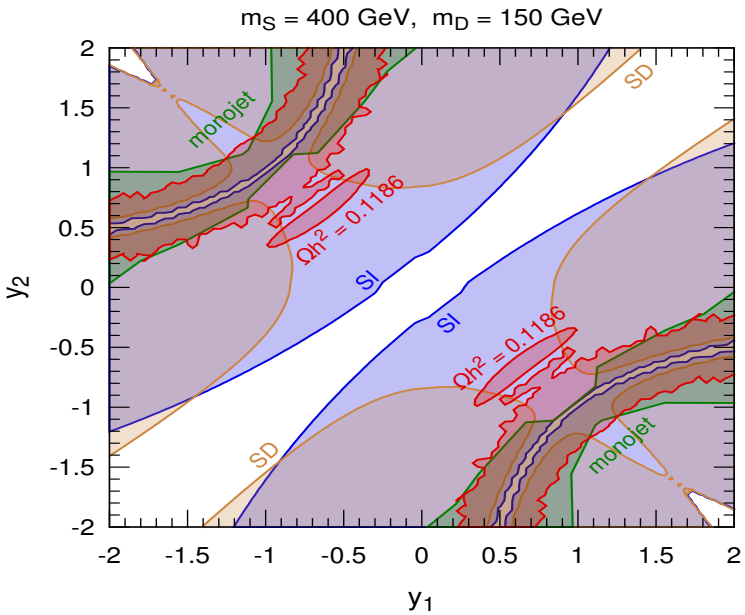
We consider all possible processes:

$$pp \to \chi_i^0 \chi_j^0, \chi_i^0 \chi^\pm, \chi^\pm \chi^\pm$$

LHC monojet search at 8 TeV with 20.3 data. [1502.01518]

In addition, LEP charged particles searches require $m_{\chi^\pm} \leq 103.5$ [0509008].
In our model SFFDM, $m_{\chi^\pm} = m_D$.



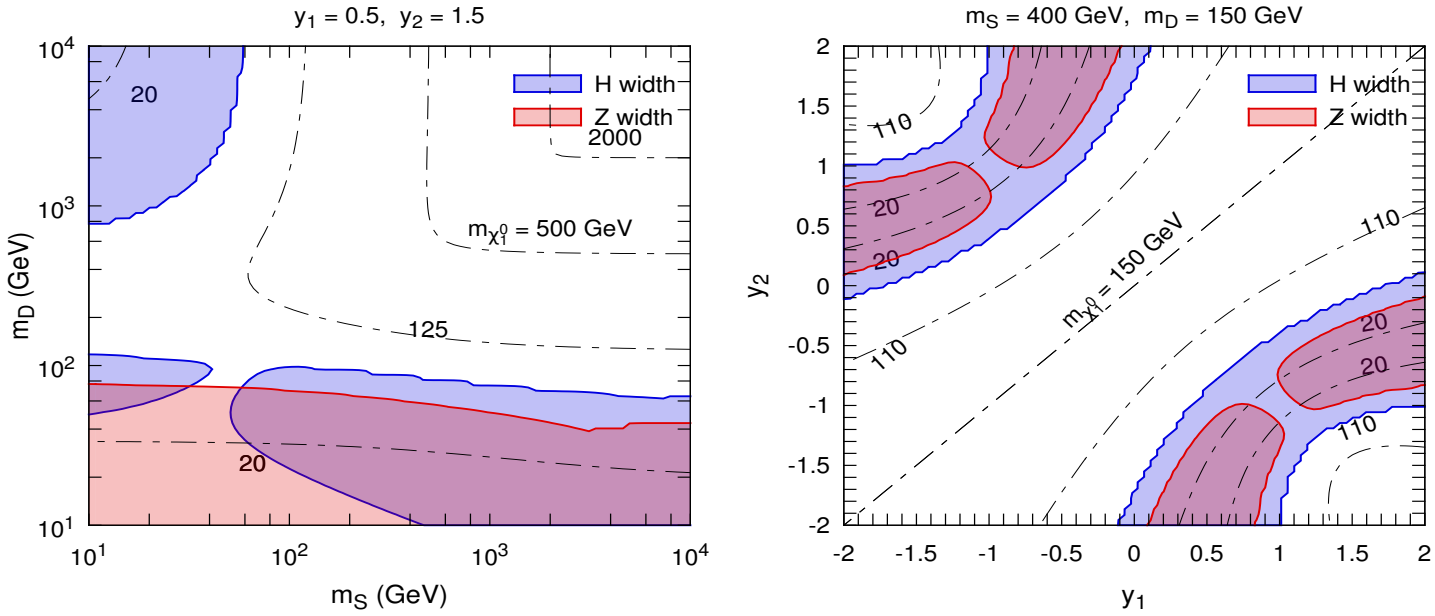


Higgs and Z decays

- 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.
- If new charged particles couple to the Higgs, they could modify the Higgs decay width to di-photon via triangle loops. $\Delta\Gamma/\Gamma$ could be tested at a level of 9%.

Higgs and Z decays

- 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.
- If new charged particles couple to the Higgs, they could modify the Higgs decay width to di-photon via triangle loops. $\Delta\Gamma/\Gamma$ could be tested at a level of 9%.

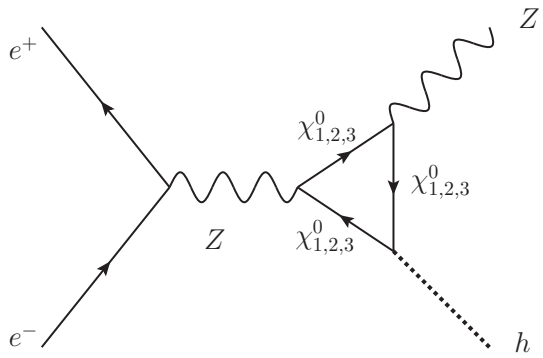


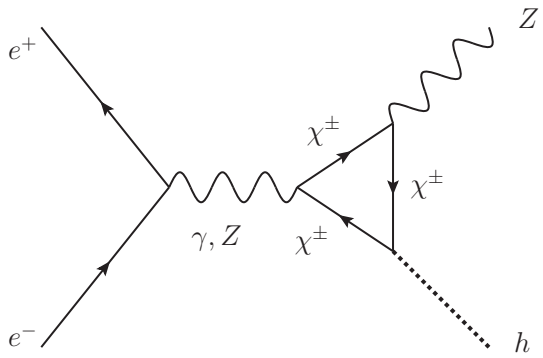
We require $\Gamma(Z \to \text{inv}) < 2$ MeV, LEP [0509008].
and $\Gamma(h \to \text{inv})/\Gamma_h < 0.28\%$, [CEPC-pre-CDR].

Corrections

We consider the **loop corrections** of new particles to the associated Zh production.

This process is affected by both the gauge and yukawa interactions.

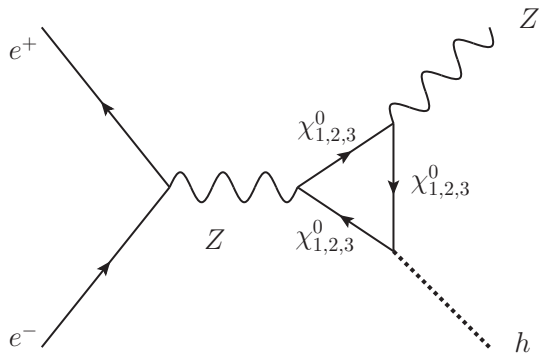


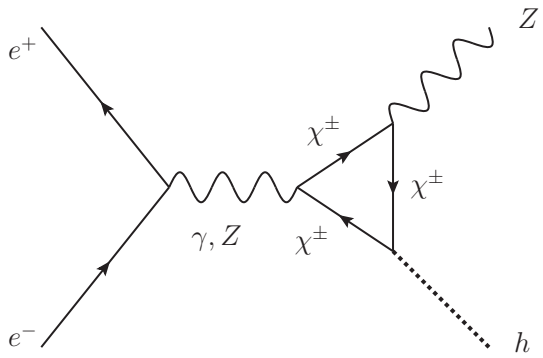


Corrections

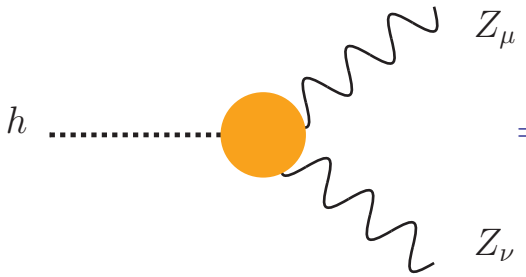
We consider the **loop corrections** of new particles to the associated Zh production.

This process is affected by both the gauge and yukawa interactions.





Formally, the coupling of h to ZZ is :

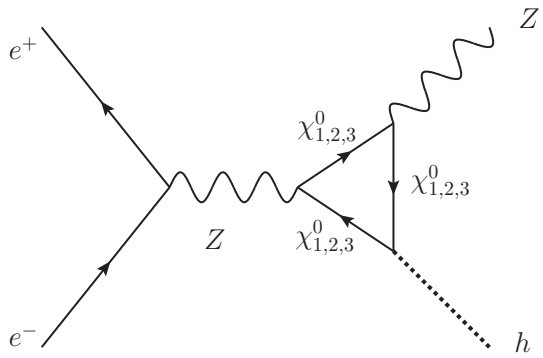


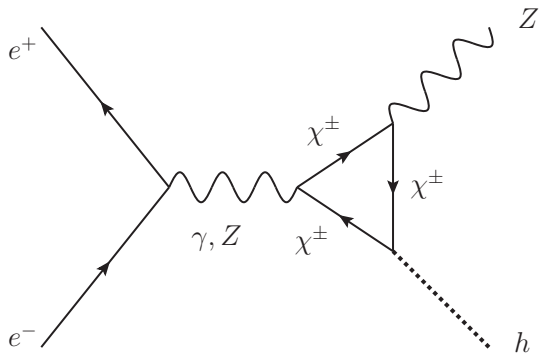
$$= ieg_{\mu\nu}C, \qquad C = M_W \frac{1}{sc^2}[1 + \delta Z_e + \frac{2s^2 - c^2}{c^2}\frac{\delta s}{s} + \frac{1}{2}\frac{\delta M_W^2}{M_W^2} + \frac{1}{2}\delta Z_H + \delta Z_{ZZ}]$$

Corrections

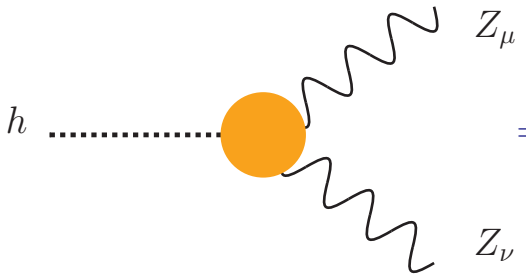
We consider the **loop corrections** of new particles to the associated Zh production.

This process is affected by both the gauge and yukawa interactions.





Formally, the coupling of h to ZZ is :



$$= ieg_{\mu\nu}C, \qquad C = M_W \frac{1}{sc^2}[1 + \delta Z_e + \frac{2s^2-c^2}{c^2}\frac{\delta s}{s} + \frac{1}{2}\frac{\delta M_W^2}{M_W^2} + \frac{1}{2}\delta Z_H + \delta Z_{ZZ}]$$

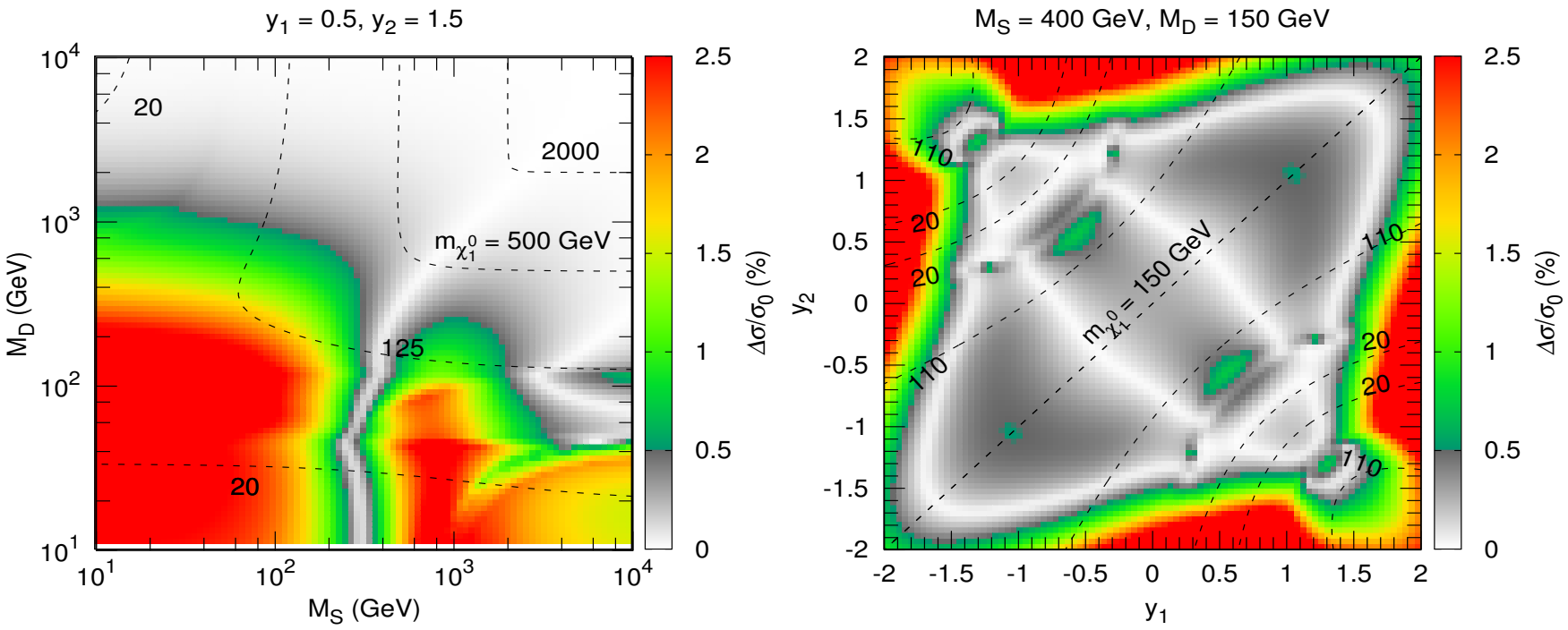
Two cases in which $\Delta\sigma_{ZH}/\sigma_{ZH} = |\sigma_{ZH} - \sigma_{ZH,SM}|/\sigma_{ZH,SM}$ could be enhanced:

- $m_{\chi_i^0} + m_{\chi_j^0} = m_Z(m_H)$, $m_{\chi_i^\pm} + m_{\chi_j^\pm} = m_Z(m_H)$, $m_{\chi_i^0} + m_{\chi_j^\pm} = m_W$
- $m_{\chi_i^0} + m_{\chi_j^0} = \sqrt{s}$, $m_{\chi_i^\pm} + m_{\chi_j^\pm} = \sqrt{s}$

Results

We use **FeynArts**, **FormCalc** to calculate corrections to the Zh production cross section.

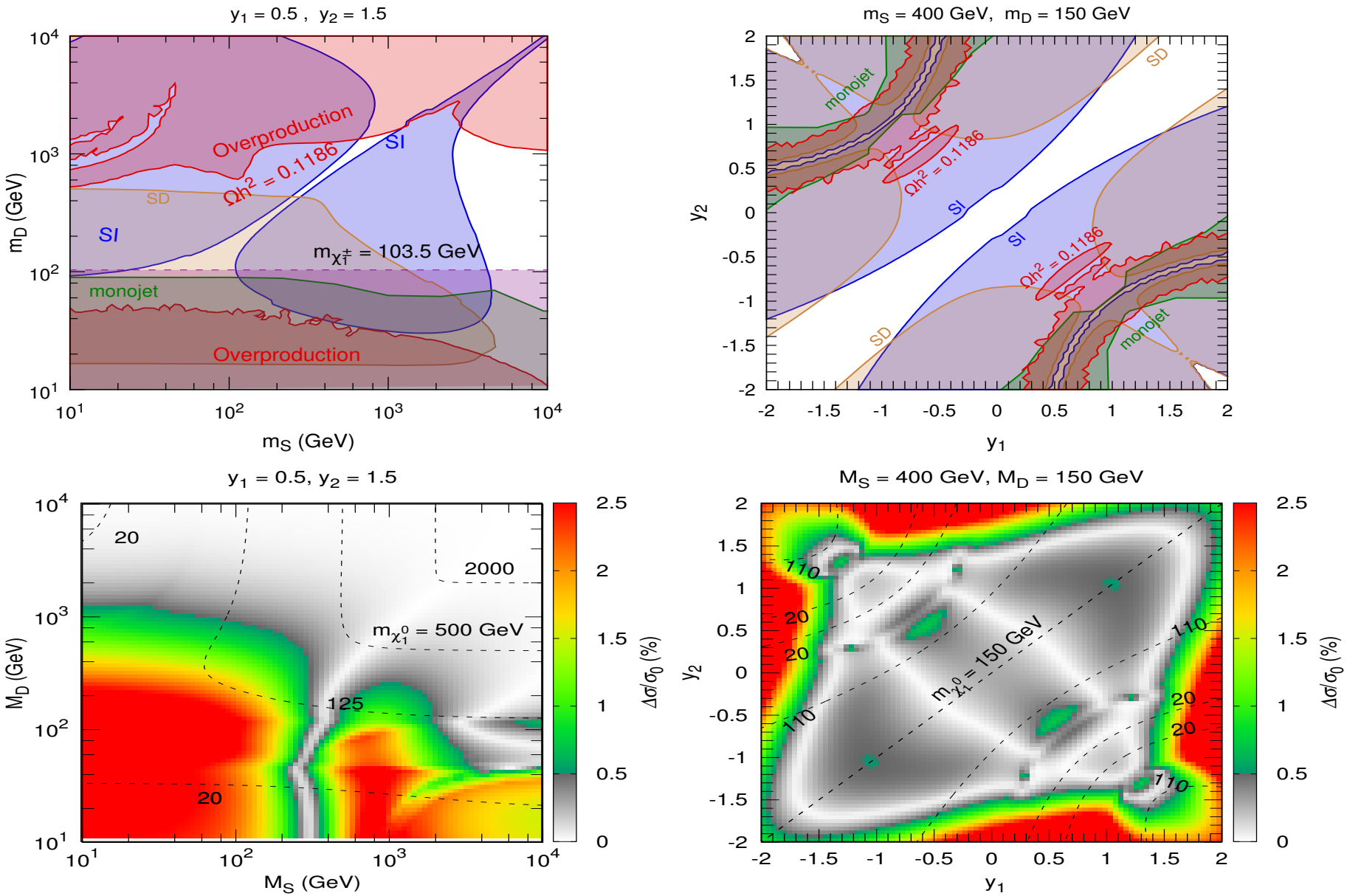
At **CEPC** with 5 ifb data, it can measure $\Delta\sigma_{ZH}/\sigma_{ZH}$ to a level of 0.51%.



Color region is can be explored by CEPC with 5 ifb data.

gray region is beyond the ability of CEPC.

Comparison


y1 = 0.5 , y2 = 1.5
Overproduction
Ωh² = 0.1186
SI
SD
SI
m_χ1± = 103.5 GeV
monojet
Overproduction
m_D (GeV)
m_S (GeV)
m_S = 400 GeV, m_D = 150 GeV
monojet
SD
Ωh² = 0.1186
SI
SI
Ωh² = 0.1186
SD
monojet
y2
y1
y1 = 0.5, y2 = 1.5
20
2000
m_χ1^0 = 500 GeV
125
20
M_D (GeV)
M_S (GeV)
Δσ/σ0 (%)
M_S = 400 GeV, M_D = 150 GeV
110
20
20
m_χ1^0 = 150 GeV
110
110
20
20
110
y2
y1
Δσ/σ0 (%)

Conclusions

- We proposed a DM model with one Weyl $SU(2)_L$ singlet and two Weyl $SU(2)_L$ doublets. After EW vacuum breaking, three neutral particles are obtained with the lightest one could service as the DM candidate.
- We considerd the constrains from relic density, direct detections, and colliders.
- We calculated the corrections to the cross section of Zh associated production. The ability of CEPC with 5 ifb data is comparable to or great than other detections, especially when $y_1 = \pm y_2$, where other detections may lose significance.