Probing Inelastic Dark Matter in Collider Experiments

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Phys.Rev.D 109 (2024) 1, 015018 • e-Print: 2309.00271 [hep-ph]

JHEP 04 (2021) 269 • e-Print: 2101.02503 [hep-ph]

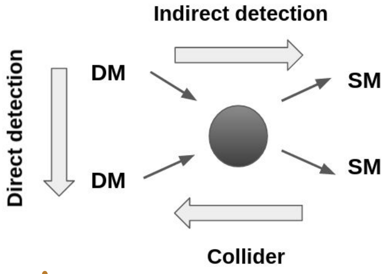
Contents

1. Motivation for inelastic DM models
2. Review of inelastic DM models
3. Search for inelastic DM in various collider experiments
4. Conclusion

Contents

Dark Matter Physics

Weakly interacting massive particles (WIMPs)



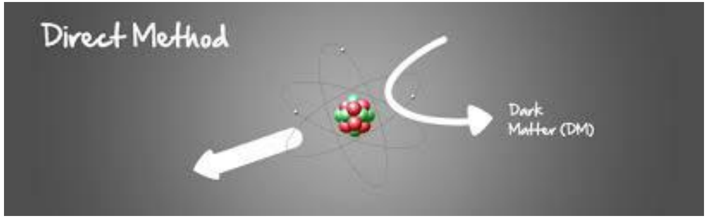
light DM

JHEP 04 (2021) 269

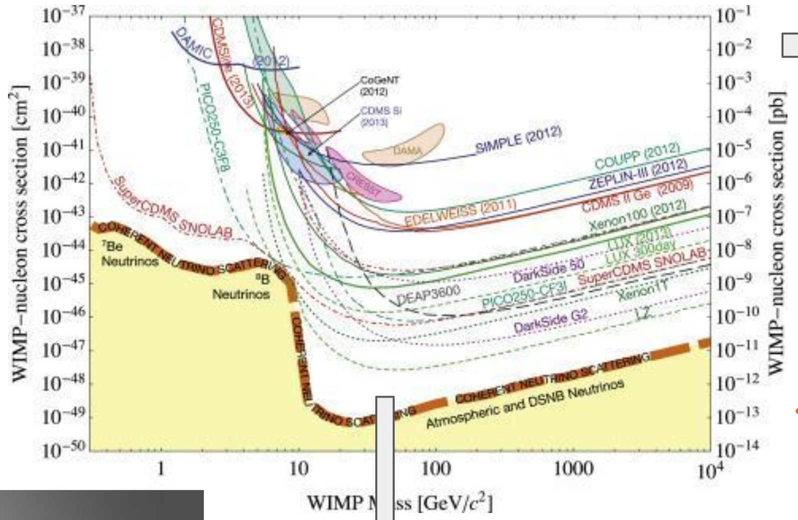
JHEP 04 (2022) 080

JHEP 03 (2022) 005

Phys.Dark Univ. 37 (2022) 101061



DM direct detection



Very heavy DM

1. Co-annihilation
2. pseudoscalar, axial-vector, … mediator
3. leptophilic

suppressed DM nucleon scattering cross section

JHEP 06 (2020) 033 *JHEP* 08 (2021) 073

Motivation : Sub-GeV DM

The fermionic DM :

(1) Vector mediators :

$$\chi\chi \to A'A', \chi\chi \to A' \to f\overline{f}$$ (s-wave)

$$\Rightarrow m_\chi \gtrsim 10\mathrm{GeV}$$ from CMB constraint

Solutions : asymmetric DM, inelastic DM, forbidden DM, freeze-in mechanism models, etc ...

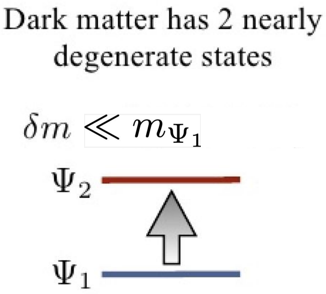
(2) Scalar meidators :

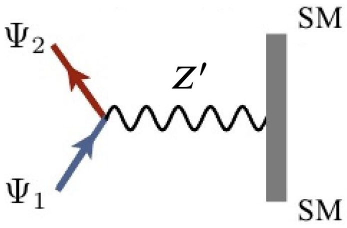
$$\chi\chi \to SS, \chi\chi \to S \to f\overline{f}$$ (p-wave)

$$\Rightarrow m_\chi \gtrsim 10\mathrm{MeV}$$ from BBN constraint

Motivation : Inelastic DM

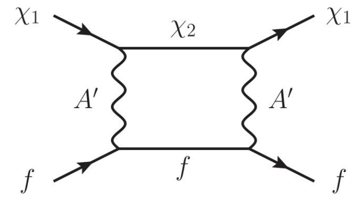
1. The inelastic (or excited) DM model with extra $U(1)_D$ gauge symmetry is one of the most popular dark sector models with light DM candidate.
2. There are at least two states in the dark sector and there is an inelastic transition between them via the new $U(1)_D$ gauge boson.
3. If the mass splitting between these two states are small enough the co-annihilation channel could be the dominant one of DM relic density in early Universe.



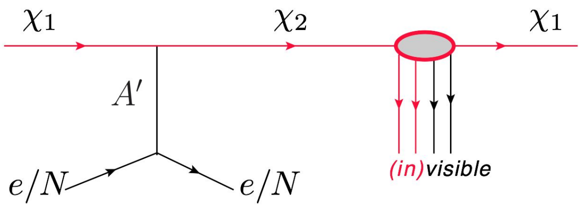


Motivation : Inelastic DM

The constraint from DM and nucleon inelastic scattering is much weaker than the elastic one in the direct detection experiments.

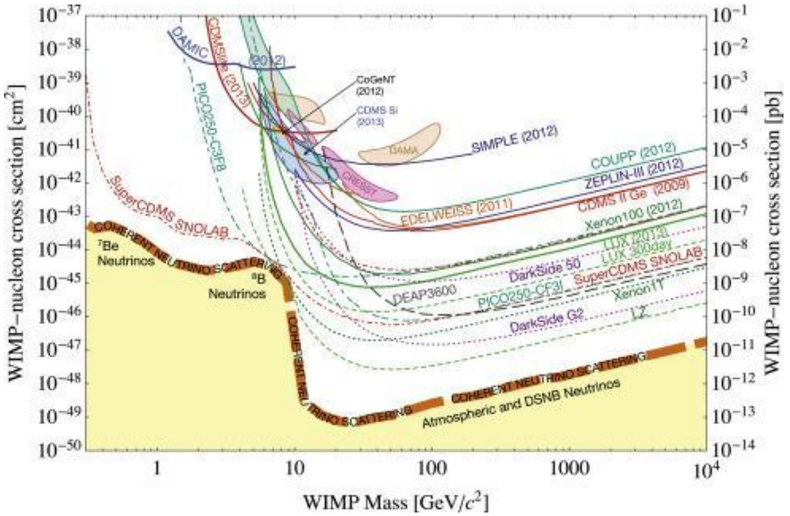


PHYS. REV. D **99,** 015021 (2019)



Phys.Rev.Lett. 119 (2017) 16, 161801

DM direct detection

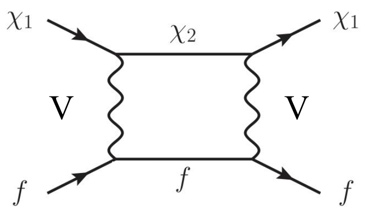


A DM mass heavier than O(TeV) is needed to detect an excitation from χ_1 to χ_2 with the mass splitting O(100 keV).

$$v_{\rm min}^{\rm global} = \sqrt{\frac{2\delta}{\mu}}.$$

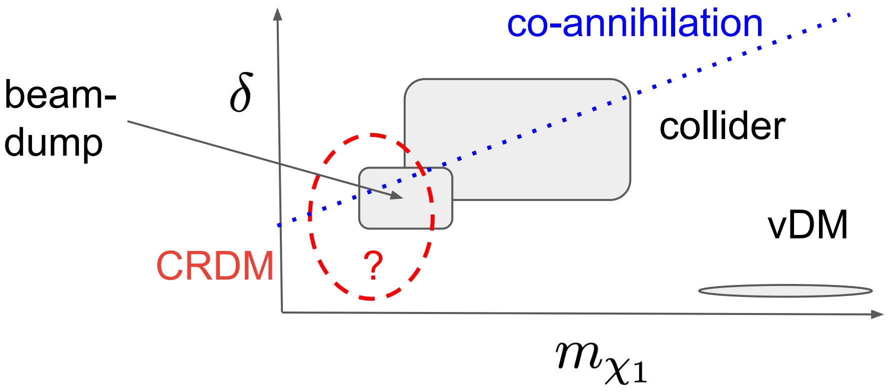
Phys.Rev.D 96 (2017) 10, 102007

The constraint from DM and nucleon inelastic scattering is much weaker than the elastic one in the direct detection experiments.

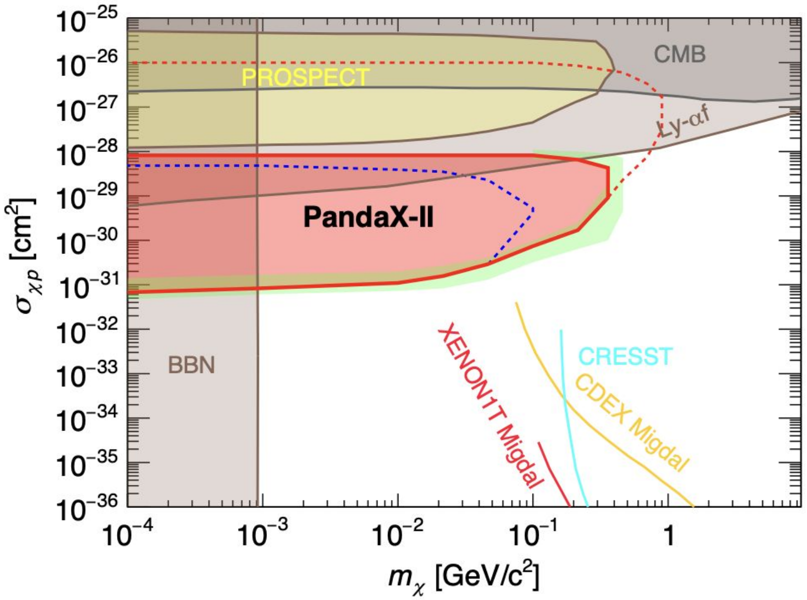


PHYS. REV. D **99**, 015021 (2019)

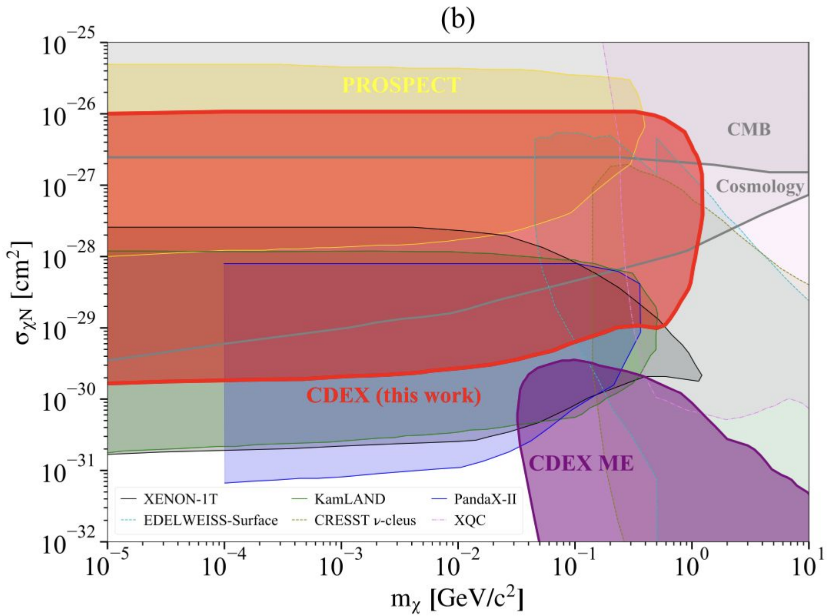
Phys.Lett.B 832 (2022) 137254 **PandaX**



Experimental Results (**Cosmic Ray Boosted Sub-GeV DM**)



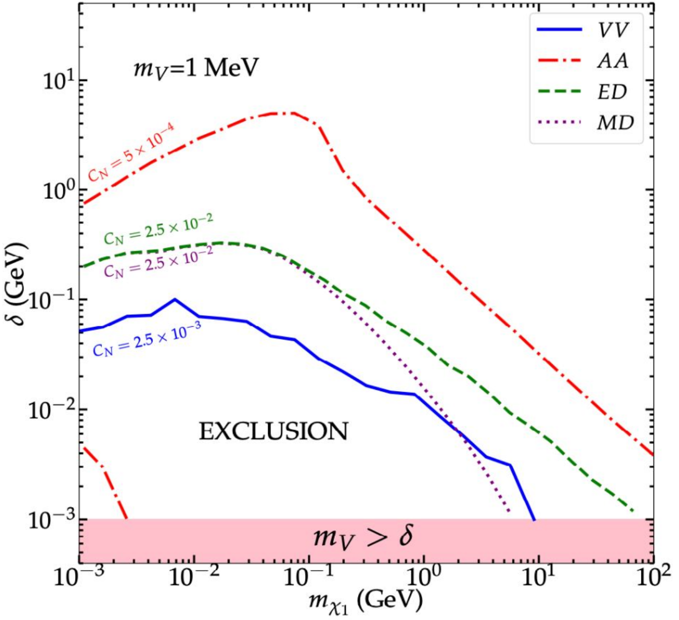
Phys.Rev.Lett. 128 (2022) 17, 171801 **PandaX**



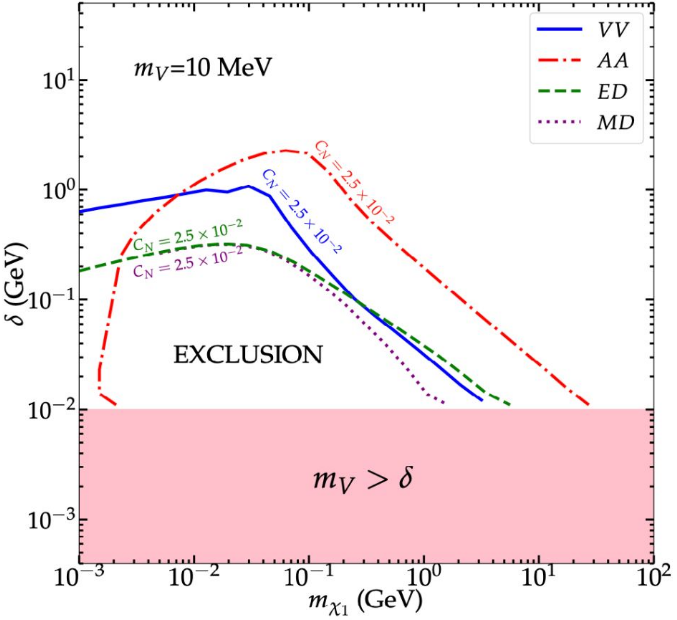
Phys.Rev.D 106 (2022) 5, 052008 **CDEX**

Constraints from PandaX-4T

JC Feng, XW Kang, **CT Lu**, YL Sming Tsai, and FS Zhang
JHEP 04 (2022) 080 e-Print: 2110.08863 [hep-ph]



(c) $m_V = 1\,\mathrm{MeV}$.



(d) $m_V = 10\,\mathrm{MeV}$.

Constraints from PandaX-4T

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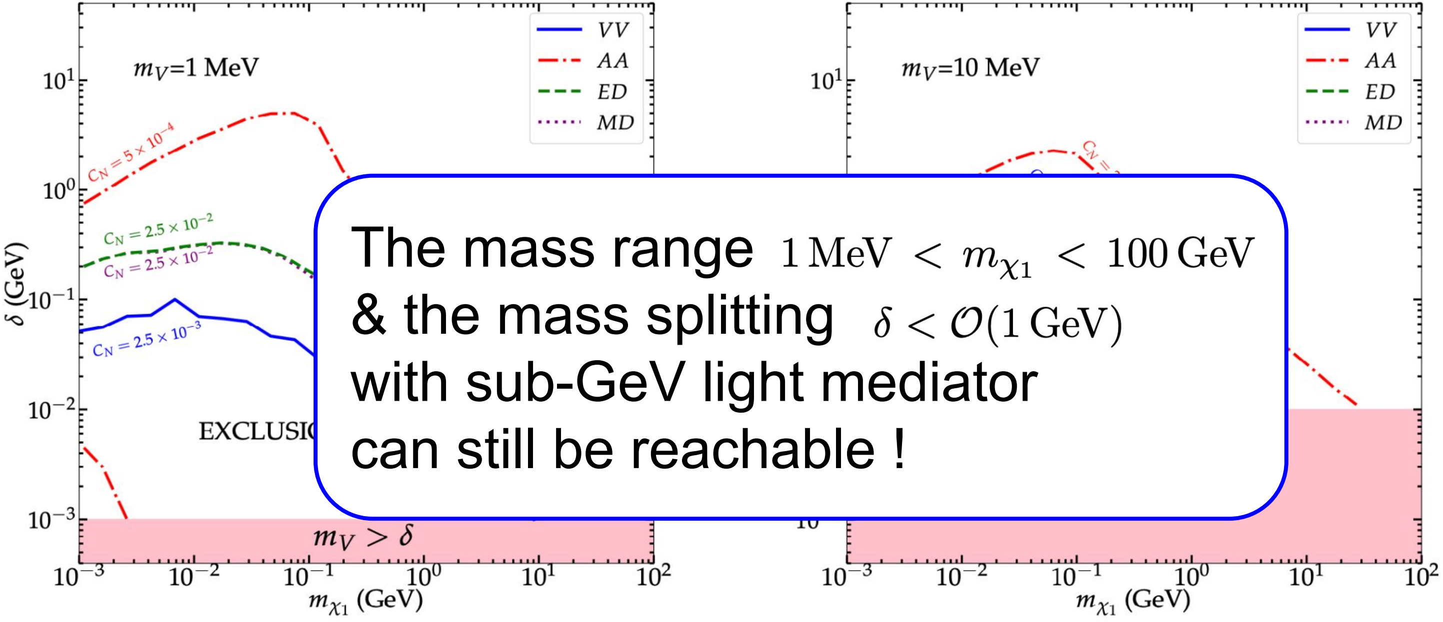

The mass range $1\,\mathrm{MeV} < m_{\chi_1} < 100\,\mathrm{GeV}$
& the mass splitting $\delta < \mathcal{O}(1\,\mathrm{GeV})$
with sub-GeV light mediator
can still be reachable !

(c) $m_V = 1\,\mathrm{MeV}$.　　**(d)** $m_V = 10\,\mathrm{MeV}$.

Contents

Review of inelastic DM models

$Q_D(\Phi) = +2$ and $Q_D(\chi) = +1.$

$$\mathcal{L}_{\text{scalar}} = |D_\mu H|^2 + |D_\mu \Phi|^2 - V(H,\Phi),$$

$$V(H,\Phi) = -\mu_H^2 H^\dagger H + \lambda_H (H^\dagger H)^2 - \mu_\Phi^2 \Phi^*\Phi + \lambda_\Phi(\Phi^*\Phi)^2 + \lambda_{H\Phi}(H^\dagger H)(\Phi^*\Phi),$$

$$\mathcal{L}_\chi = \overline{\chi}(i\not\partial + g_D \not X - M_\chi)\chi - \left(\frac{f}{2}\overline{\chi^c}\chi\Phi^* + H.c.\right),$$

$$\chi_{1,2}(x) = \frac{1}{\sqrt{2}}(\chi(x) \mp \chi^c(x)).$$

$$\mathcal{L}_\chi = \frac{1}{2}\overline{\chi_2}(i\not\partial - M_{\chi_2})\chi_2 + \frac{1}{2}\overline{\chi_1}(i\not\partial - M_{\chi_1})\chi_1 - i\frac{g_D}{2}(\overline{\chi_2}\not X\chi_1 - \overline{\chi_1}\not X\chi_2) - \frac{f}{2}h_D(\overline{\chi_2}\chi_2 - \overline{\chi_1}\chi_1),$$

Review of inelastic DM models

In the unitrary gauge, the scalar fields can be expanded as

$$H(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix} \quad , \quad \Phi(x) = \frac{1}{\sqrt{2}} (v_D + h_D(x))$$

Expand the kinematic mixing term in the first order of epsilon:

$$\mathcal{L}_{X,gauge} = -\frac{1}{4} X_{\mu\nu} X^{\mu\nu} - \frac{sin\epsilon}{2} B_{\mu\nu} X^{\mu\nu}$$

$$\mathcal{L}_{Z' f \bar{f}} = -\epsilon e c_W \sum_f x_f \bar{f} \not{Z}' f$$

$$m_{Z'} \simeq g_D Q_D(\Phi) v_D$$

$$x_l = -1, \; x_\nu = 0, \; x_q = \tfrac{2}{3} \text{ or } \tfrac{-1}{3}$$

Review of inelastic DM models

After the SSB of this $U(1)_D$ gauge symmetry, we expect the accidentally residual Z_2 symmetry, $\chi_1 \to -\chi_1$, can be left such that χ_1 are stable and become DM candidates in our University.

Gauge interaction :

$$-i\frac{g_D}{2}(\overline{\chi_2}\not{X}\chi_1 - \overline{\chi_1}\not{X}\chi_2)$$

The term to trigger the mass splitting :

$$-(\frac{f}{2}\overline{\chi^c}\chi\Phi^* + H.c.)$$

Mass eigenstates and mass splitting :

$$M_{\chi_{1,2}} = M_\chi \mp f v_D \qquad \Delta_\chi \equiv (M_{\chi_2} - M_{\chi_1}) = 2 f v_D$$

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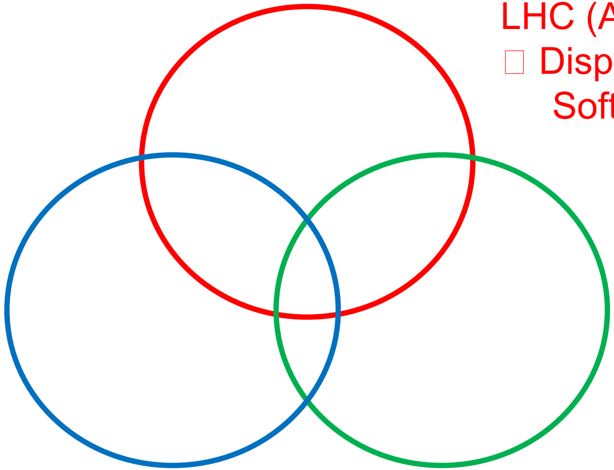
Search for inelastic DM from three frontier experiments

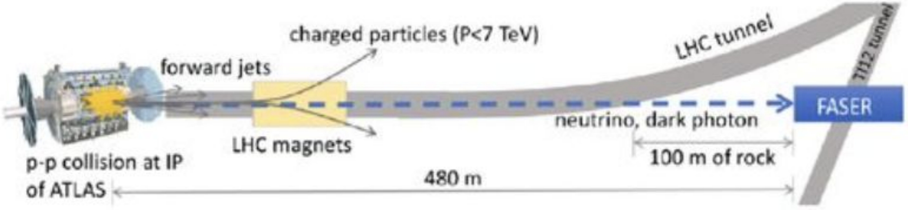


Energy Frontier:
LHC (ATLAS, CMS)
□ Displaced muon-jet,
Soft lepton pair

Lifetime Frontier:
LHC (FASER)
□ Long-lived particles

Intensity Frontier:
Belle II, STCF
□ displaced vertex
□ mono-photon

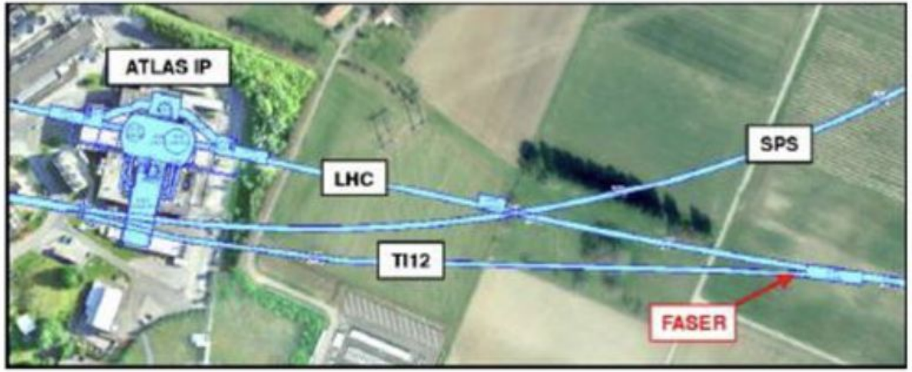
FASER (ForwArd Search ExpeRiment)



process:

$$\mathrm{pp} \rightarrow \chi_2 + \chi_1, \ \chi_2 \text{ travels} \sim 480\mathrm{m},$$

then $\chi_2 \rightarrow \ \chi_1 f\overline{f}$.



$$\textbf{FASER}: L = 1.5\mathrm{m}, \ R = 0.1\mathrm{m},$$

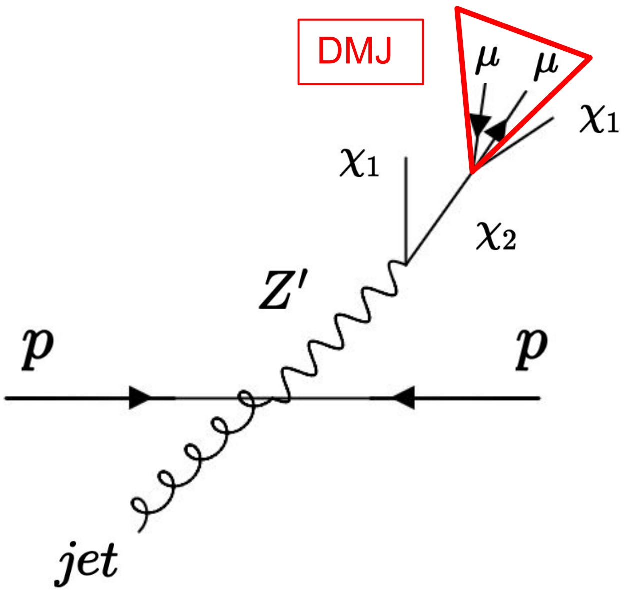
$$\textbf{FASER 2}: L = 5\mathrm{m}, \ R = 1\mathrm{m}.$$

$$E_{\mathrm{vis}} > 100\,\mathrm{GeV}$$

the integrated luminosity, $\mathcal{L}$,

for FASER and FASER 2 is 150 fb^{-1} and 3 ab^{-1}

Displaced Muon-Jet (DMJ)



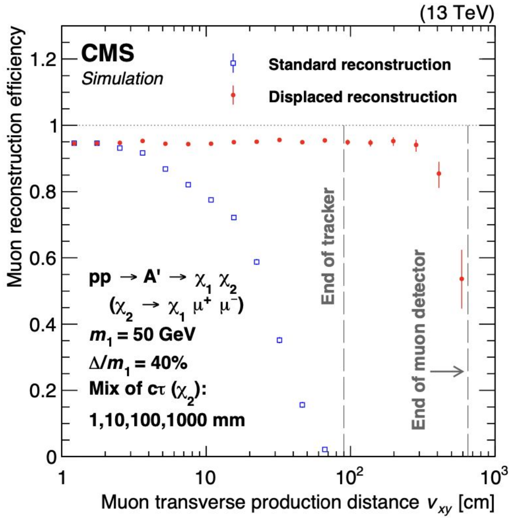
Event selections:

$$p_T^j > 120 \text{ GeV}$$

$$p_T^\mu > 5 \text{ GeV}$$

$$d_\mu > 1 \text{ mm}$$

$$R_{\chi_2}^{xy} < 30 \text{ cm}$$



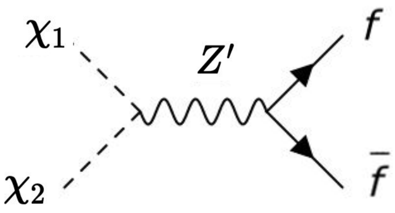
e-Print: 2305.11649 [hep-ex]

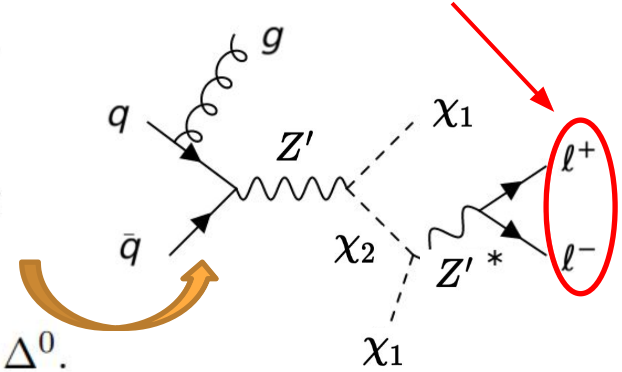
Soft lepton pair

The compressd mass spectrum search at the LHC is closely related to the DM co-annihilation mechanism.

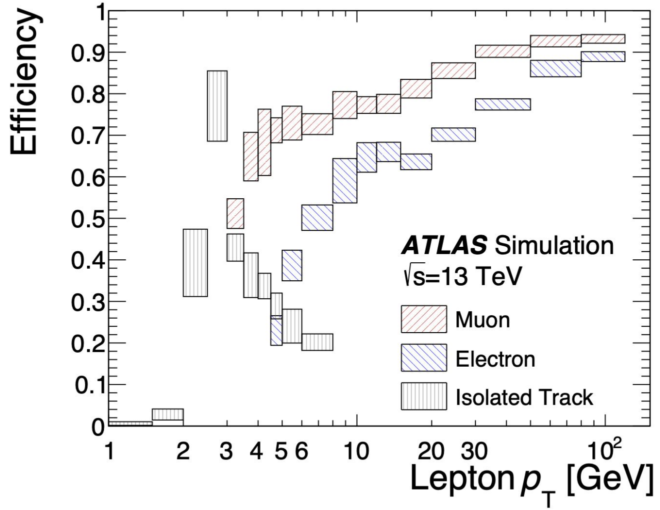
Co-annihilation

LHC signature (soft leptons)





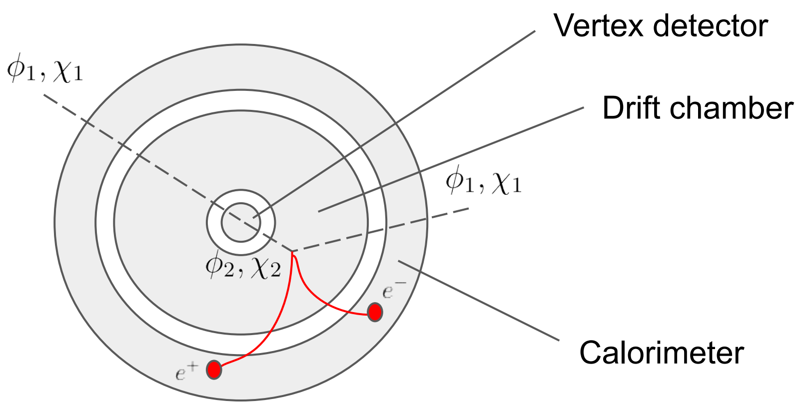
$\chi_1 \chi_2 \to f\bar{f}$ for a small Δ^0.

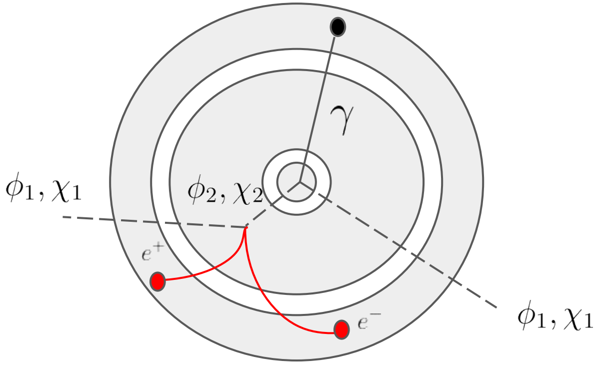


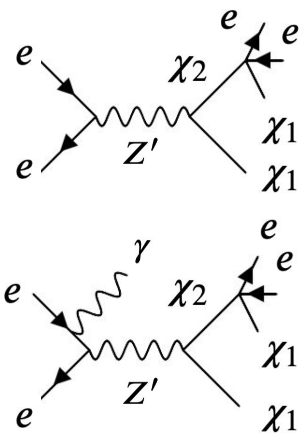
We recast the following ATLAS analysis for the inelastic DM models:

G. Aad et al. (ATLAS), Phys. Rev. D **101**, 052005 (2020), 1911.12606.

Displaced vertex signature examples in Belle II detector (xy-plane)





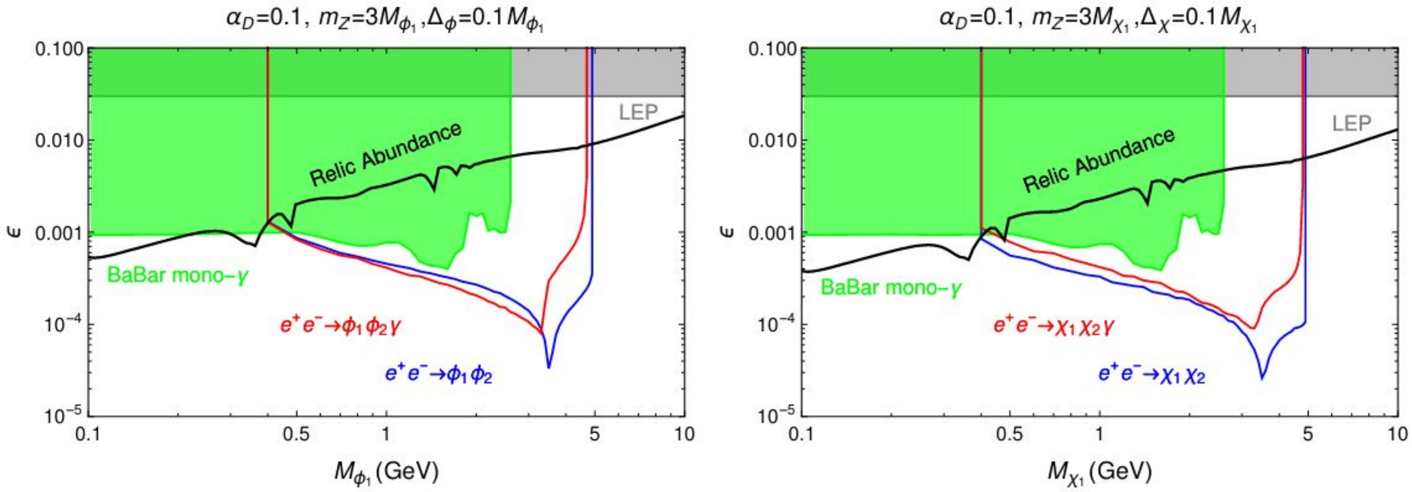


$$e^+e^- \to \phi_1\phi_2 \to \phi_1\phi_1 e^+e^-$$
$$e^+e^- \to \chi_1\chi_2 \to \chi_1\chi_1 e^+e^-$$

$$e^+e^- \to \phi_1\phi_2\gamma \to \phi_1\phi_1 e^+e^-\gamma$$
$$e^+e^- \to \chi_1\chi_2\gamma \to \chi_1\chi_1 e^+e^-\gamma$$

DW Kang, **CT Lu**, P. Ko *JHEP* 04 (2021) 269 e-Print: 2101.02503 [hep-ph]

The future bounds from $e^+e^- \to \phi_1\phi_2(\chi_1\chi_2)$ and $e^+e^- \to \phi_1\phi_2(\chi_1\chi_2)\gamma$ processes



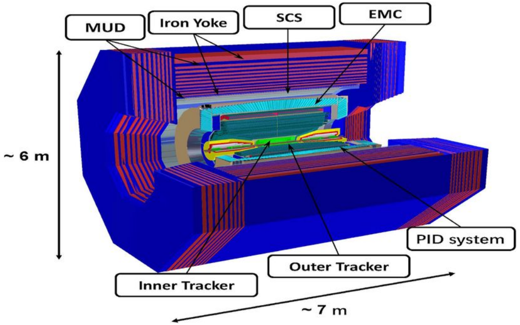
$$L = 50ab^{-1}$$

D.W. Kang, P. Ko, **C.T. Lu**

90% C.L. contours which correspond to an upper limit of 2.3 events with the assumption of background-free

DW Kang, **CT Lu**, P. Ko *JHEP* 04 (2021) 269 e-Print: 2101.02503 [hep-ph]

中国超级陶-粲装置
Super Tau-Charm Facility (STCF)



Designed STCF:

1. Peak luminosity $0.5\text{-}1\times10^{35}\ \mathrm{cm^{-2}s^{-1}}$ at 4 GeV.
2. Energy rang E_{cm} = 2-7 GeV.
3. Single Beam Polarization (Phase II)

Process: **Mono-photon**

$$e^+e^- \to \gamma Z' \to \gamma(\chi_1\chi_2)$$

missing energy

Event selections:

In the barrel region $(|z_\gamma| < 0.8)$

$$E_\gamma > 25\ \mathrm{MeV}$$

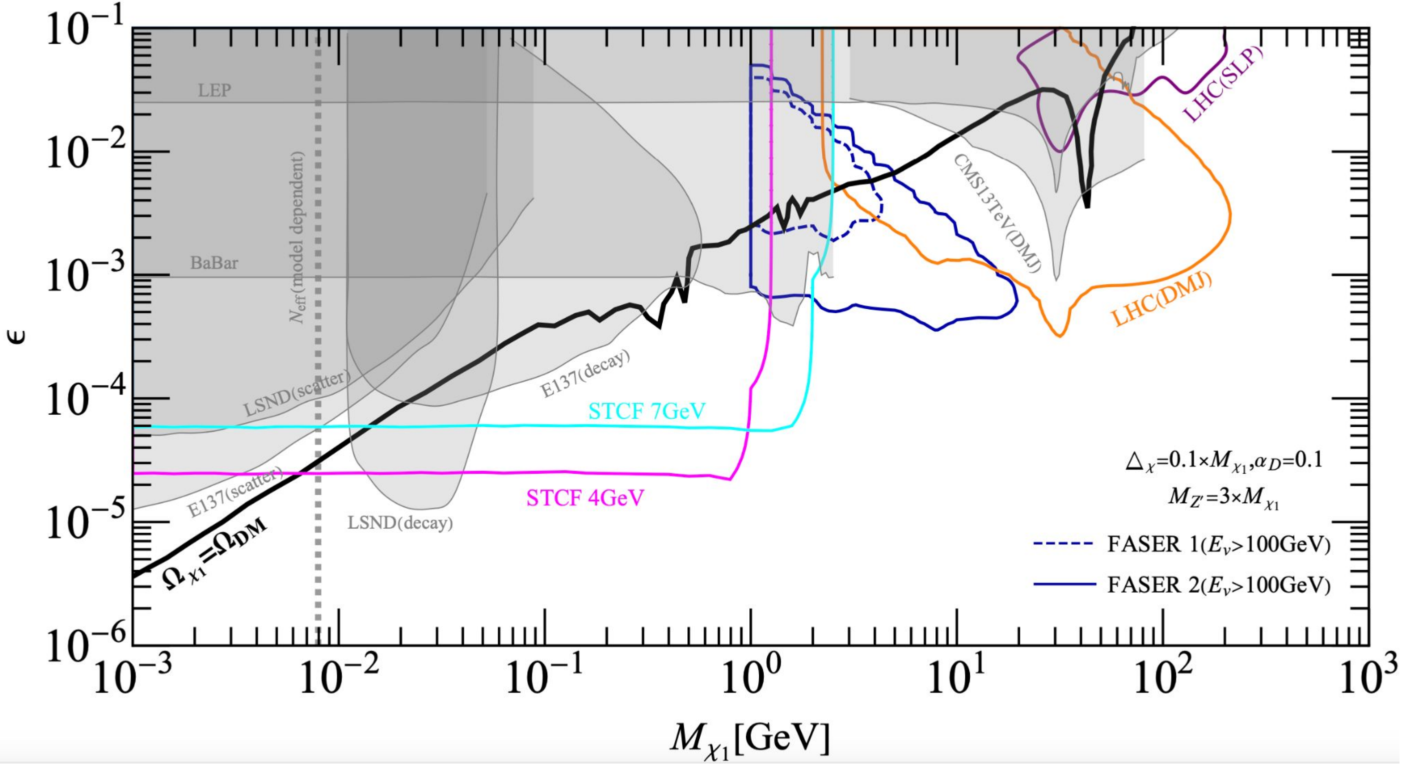
In the end-caps region

$$(0.92 > |z_\gamma| > 0.86)$$

$$E_\gamma > 50\ \mathrm{MeV}$$

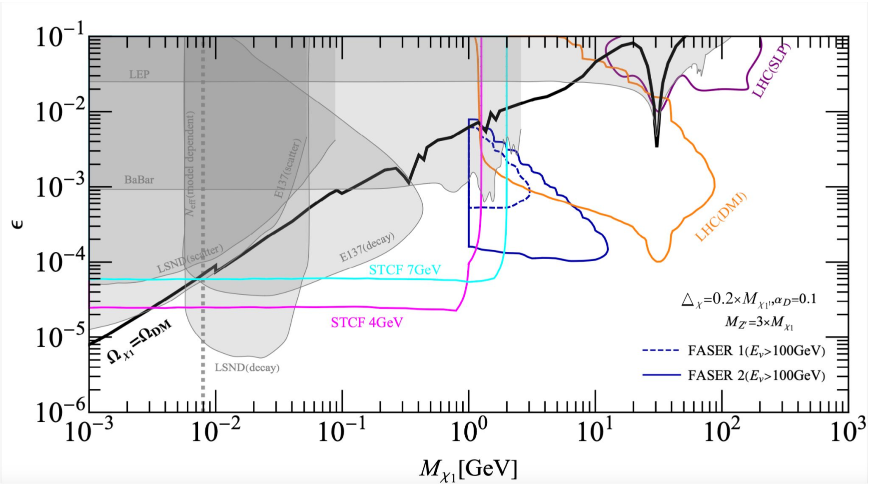
$$z_\gamma \equiv \cos\theta_\gamma$$

Projected Sensitivities of Three Frontier Experiments

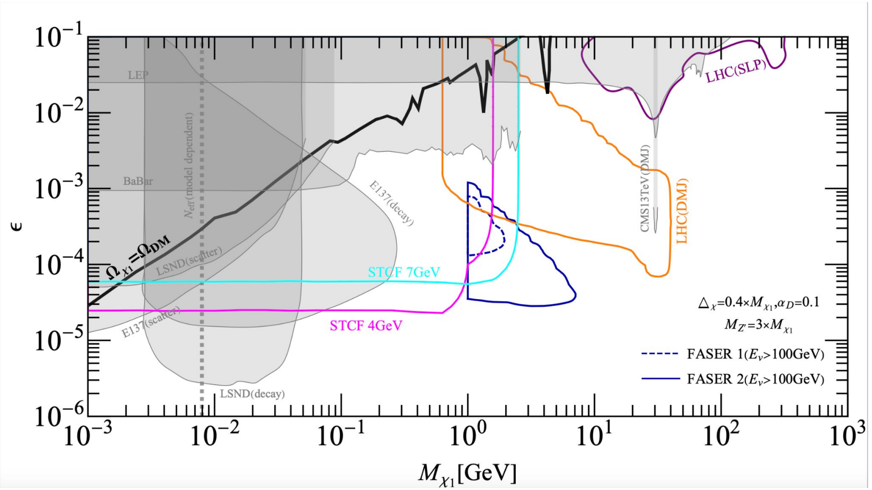


Projected Sensitivities of Three Frontier Experiments

$\triangle_\chi = 0.2 \times M_{\chi 1}$

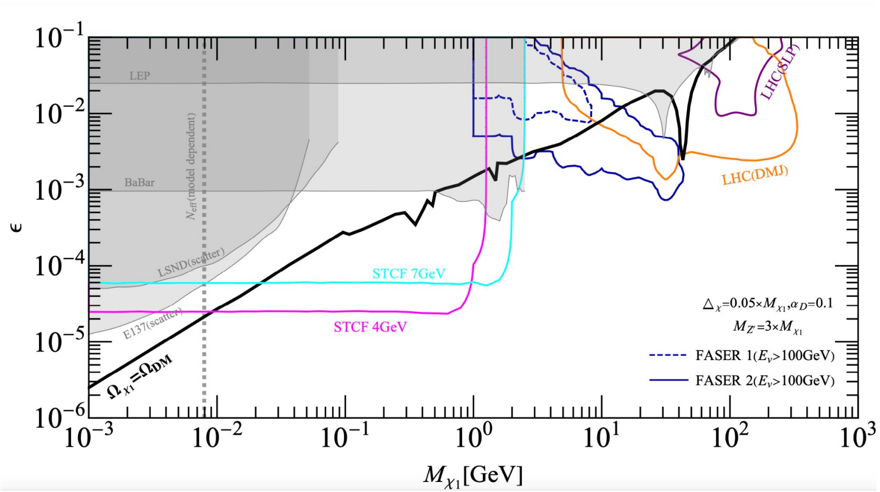


$\triangle_\chi = 0.4 \times M_{\chi 1}$

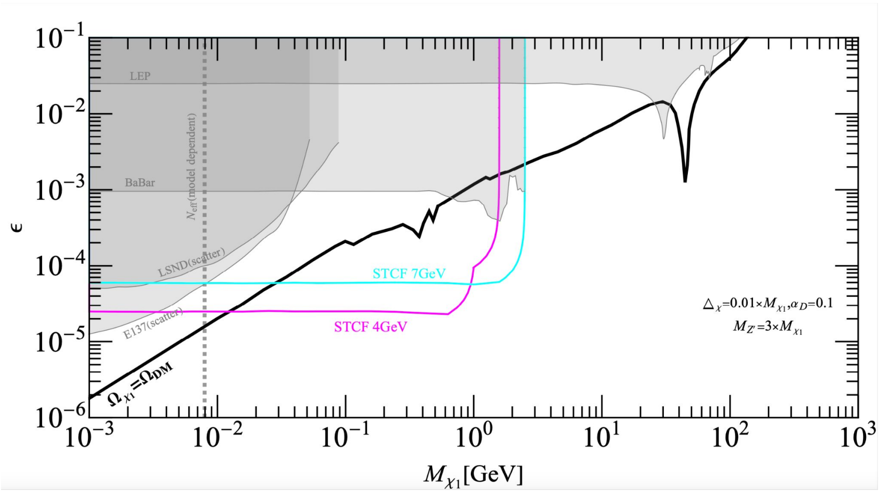


Projected Sensitivities of Three Frontier Experiments

$\triangle_{\chi}=0.05\times M_{\chi 1}$



$\triangle_{\chi}=0.01\times M_{\chi 1}$



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Conclusion

- The inelastic DM model is one kind of simple UV complete DM model to allow the sub-GeV DM candidate. Besides, this model can easily escape the strong DM direct detection constraints.

- We consider the Energy Frontier (LHC), Lifetime Frontier (FASER) and Intensity Frontier (Belle II, STCF) experiments to search for inelastic DM for the DM mass from 1 MeV to 210 GeV.

- In our benchmark settings, we found that the parameter space for the observed DM relic density can be covered by the combination of these experiments.

Thank you
for your attention

Back-up Slides

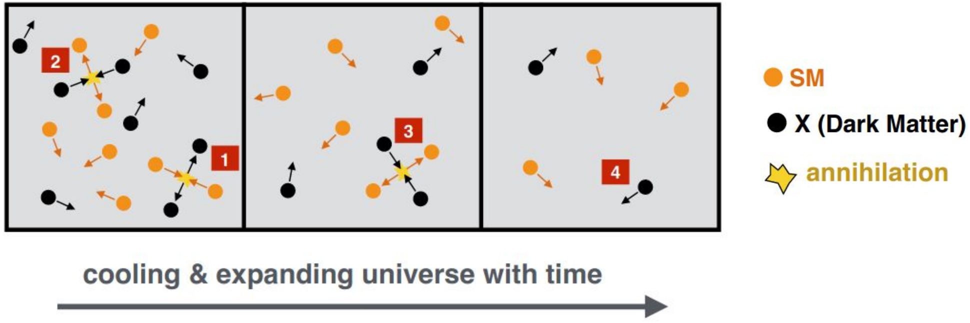
DM thermal history

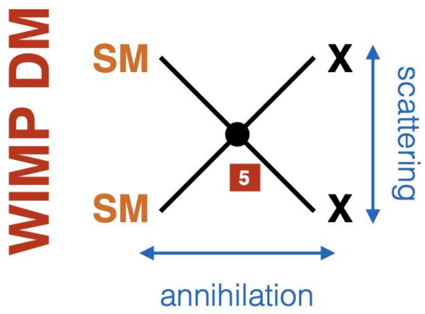
Standard thermal relic

(1) When the temperature $kT \gg m_X c^2$, both the SM and DM were in thermal equilibrium, $\mathrm{SM} + \mathrm{SM} \leftrightarrow X + X$

(2) As the universe cools to $kT \lesssim m_X c^2$, only $X + X \rightarrow \mathrm{SM} + \mathrm{SM}$ is possible and drastically reducing DM abundance.

(3) DM becomes so dilute and the abundance is frozen-out and survies to this day.

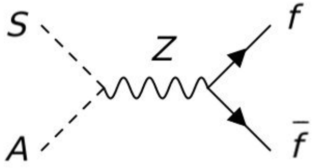




Physics Today, June 2017, page 46

Dark Matter Co-annihilation Process

co-annihilation

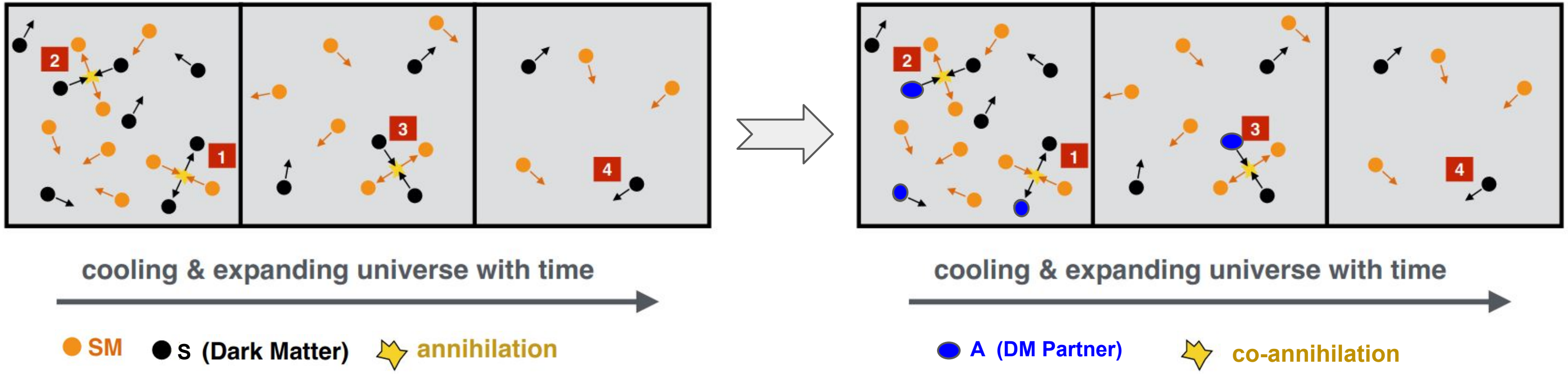


relic density

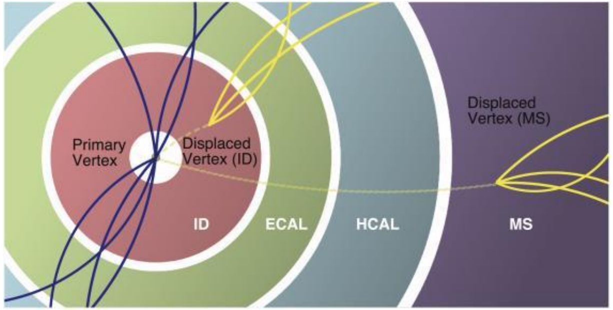
$$\Omega_{DM}h^2 \propto \frac{1}{\langle\sigma v\rangle_f} \propto e^{2\frac{\Delta^0}{T_f}}$$

$$\Delta^0 = m_A - m_S \ll m_S$$

T_f is the temperature at which the co-annihilation freeze-out.



Long-lived particles (LLPs)



JPPNP 3695 (2019)

LLPs in Standard Model (SM) :

1. neutron : mean lifetime = 879.4(6) s $n^0 \rightarrow p^+ + e^- + \bar{\nu}_e + \gamma$
2. charged pion : mean lifetime = 2.6033+-0.0005 x 10^{-8} s

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$

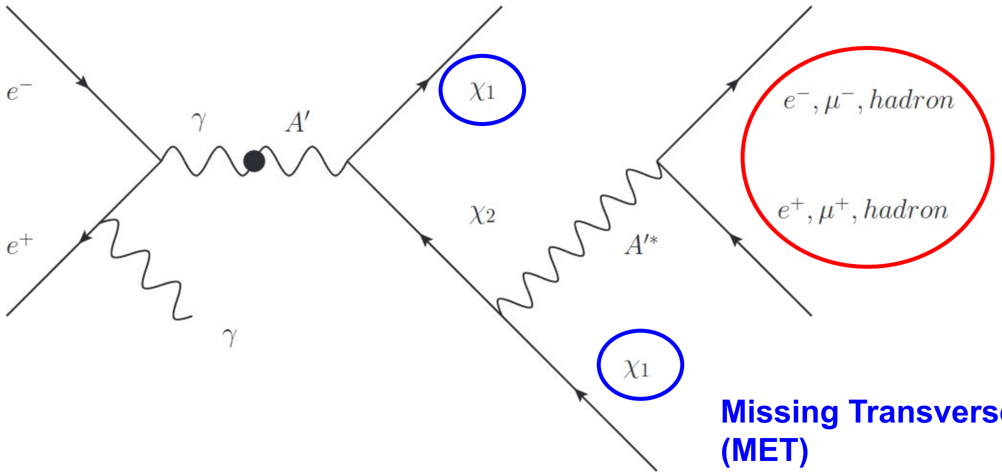
LLPs in the beyond Standard Model (BSM) :

1. Heavy neutral leptons -> neutrino mass and mixing, matter-antimatter asymmetry.
2. Hidden mesons -> dark matter models, twin Higgs models, mirror fermion models.
3. The excited state in inelastic dark matter models.

Motivation : Inelastic DM

The excited DM state can naturally become long-lived and leave displaced vertex inside detectors after it has been produced at colliders such that we can search for such novel signatures !

displaced vertex



Missing Transverse Energy (MET)

$$\Gamma(\chi_2 \to \chi_1 \ell^+ \ell^-) \simeq \frac{4\epsilon^2 \alpha_{\rm em} \alpha_D \Delta^5 m_1^5}{15\pi m_{A'}^4},$$

Motivation : Inelastic DM

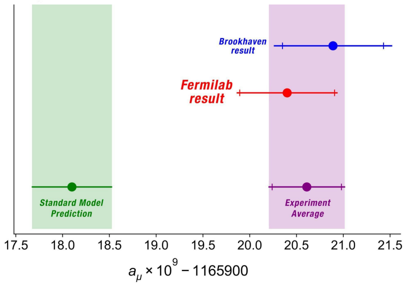
Muon g-2 anomaly

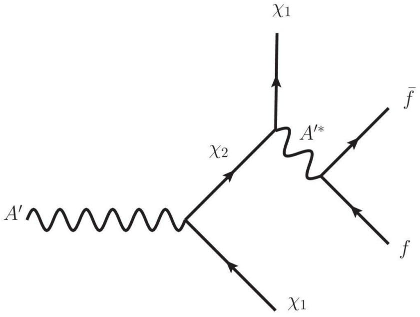
Revisiting the dark photon explanation of the muon anomalous magnetic moment

Gopolang Mohlabeng (Brookhaven) (Feb 13, 2019)

Published in: *Phys.Rev.D* 99 (2019) 11, 115001 • e-Print: 1902.05075 [hep-ph]

Phys.Rev.Lett. 126 (2021) 14, 141801





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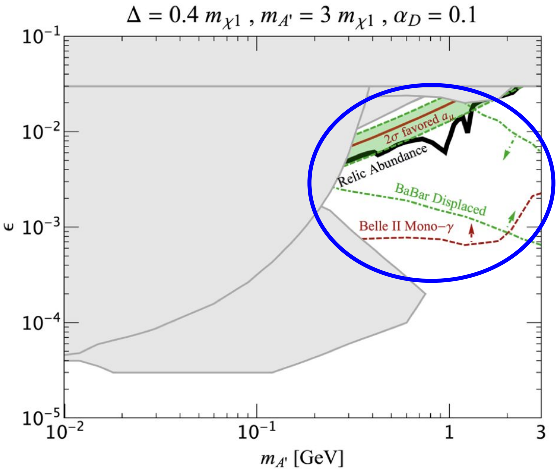
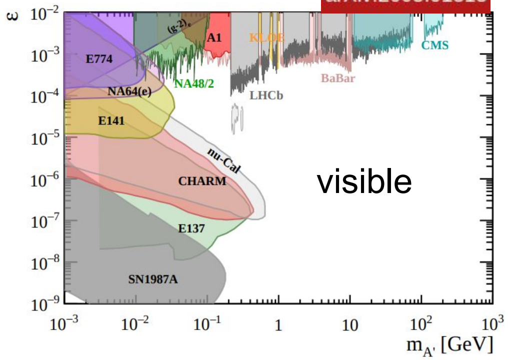


arXiv:2005.01515



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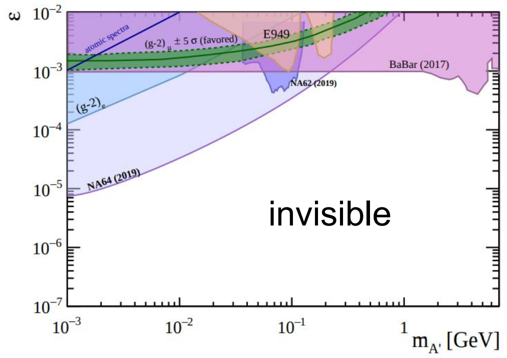

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