非弹性暗物质模型的多手段协同探测

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• Exploring properties of long-lived particles in inelastic dark matter models at Belle II

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

• Revising inelastic dark matter direct detection by including the cosmic ray acceleration J.C. Feng, X.W. Kang, CT Lu, Y.L.S. Tsai and F.S. Zhang,

JHEP 04 (2022) 080 • e-Print: 2110.08863 [hep-ph]

• Probing inelastic dark matter at the LHC, FASER, and STCF CT Lu, J. Tu and L. Wu,

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

Contents

- 1. Motivation for inelastic DM models
- 2. Review of inelastic DM models
- 3. Search for inelastic DM via Synergistic Multi-Experiment Strategies
- 4. Conclusion and outlook

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- **1. Motivation for inelastic DM models**
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Dark Matter Physics

Weakly interacting massive particles (WIMPs)

 10^{-1}

 10^{-2}

 10^{-3}

10-5

10-6

 10^{-8}

 10^{-9}

10-10

10-11

10-12

10-13 10-14

 10^{4}

1000

section [pb] 10^{-4}

cros 10-7

WIMP.



Very heavy DM

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

suppressed DM nucleon scattering cross section

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Motivation : Sub-GeV DM

The fermionic DM :

• Vector mediators :

 $\chi\chi \to A'A', \chi\chi \to A' \to f\overline{f}$ (s-wave) $\Rightarrow m_{\chi} \gtrsim 10 \text{GeV}$ from CMB constraint

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

• Scalar meidators :

$$\chi\chi \to SS, \chi\chi \to S \to f\overline{f}$$
 (p-wave)
 $\Rightarrow m_{\chi} \gtrsim 10 \text{MeV}$ 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.

a



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).

$$v_{
m min}^{
m global}=\sqrt{rac{2\delta}{\mu}}.$$
 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.



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Review of inelastic DM models

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

 $\mathcal{L}_{\text{scalar}} = |D_{\mu}H|^2 + |D_{\mu}\Phi|^2 - V(H,\Phi),$ $V(H,\Phi) = -\mu_H^2 H^{\dagger}H + \lambda_H (H^{\dagger}H)^2 - \mu_{\Phi}^2 \Phi^* \Phi + \lambda_{\Phi} (\Phi^*\Phi)^2$

 $+ \lambda_{H\Phi} (H^{\dagger}H) (\Phi^*\Phi),$

$$\begin{aligned} \mathcal{L}_{\chi} &= \overline{\chi}(i\partial \!\!\!/ + g_D \not\!\!\!/ - M_{\chi})\chi - \left(\frac{f}{2}\overline{\chi^c}\chi\Phi^* + H.c.\right), \\ \mathcal{L}_{\chi} &= \frac{1}{2}\overline{\chi_2}(i\partial \!\!\!/ - M_{\chi_2})\chi_2 + \frac{1}{2}\overline{\chi_1}(i\partial \!\!\!/ - M_{\chi_1})\chi_1 \\ &- i\frac{g_D}{2}(\overline{\chi_2}\not\!\!\!/ \chi_1 - \overline{\chi_1}\not\!\!/ \chi_2) - \frac{f}{2}h_D(\overline{\chi_2}\chi_2 - \overline{\chi_1}\chi_1), \end{aligned}$$

Review of inelastic DM models

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

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

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

$$\mathcal{L}_{Z'f\overline{f}} = -\epsilon e c_W \sum_f x_f \overline{f} Z' f$$
$$x_l = -1, \ x_\nu = 0, \ x_q = \frac{2}{3} \text{ or } \frac{-1}{3}$$

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

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

Review of inelastic DM models

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

Gauge interaction :

$$-i\frac{g_D}{2}(\overline{\chi_2}\,/ \chi_1 - \overline{\chi_1}\,/ \chi_2)$$

The term to trigger the mass splitting :

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

Mass eigenstates and mass splitting :

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

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Search for inelastic DM from four frontier experiments



Intensity Frontier: How to determine the particle nature of DM?



DW Kang, CT Lu, P. Ko	JHEP 04 (2021) 269	e-Print: 2101.02503 [hep-ph]
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If the excited DM is long-lived, can we determine its mass at colliders ?

The crossing point from these events and kinematic endpoint measurement $m_{f\bar{f}}^{max}$ can help us to determine the mass of DM and mass splitting. This method is a first application of

"Kinematic focus point" method to the inelastic DM models.



Energy Frontier: How to cover the detection of heavier DM?



Lifetime Frontier: How to detect long-lived particles?



process:

 $pp \rightarrow \chi_2 + \chi_1, \ \chi_2 \text{ travels} \sim 480 \text{m},$ then $\chi_2 \rightarrow \chi_1 f \overline{f}.$



FASER : L = 1.5m, R = 0.1m, FASER 2 : L = 5m, R = 1m. $E_{\rm vis} > 100 {\rm ~GeV}$ the integrated luminosity, \mathcal{L} ,

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

Projected Sensitivities of Three Frontier Experiments



Cosmic Frontier: How to boost the light inelastic DM?



Can we use the high energy cosmic-ray to boost the light inelastic DM especially for larger mass splitting?



The Cosmic-ray boosted inelastic DM



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

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]



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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), Intensity Frontier (Belle II, STCF) and Cosmic Frontier (DD, ID) experiments to search for inelastic DM for the DM mass from 1 MeV to 210 GeV.
- To cover those blind parameter space with various DM mass and mass splitting, more new search strategies are required. For example, heating neutron stars & cosmic-ray cooling in AGN.

Thank you for your attention

Back-up Slides

Search for DM at the LHC



Motivation : Sub-GeV DM

The scalar DM :

• Vector mediators:

 $\phi \phi \to A'A' \quad (s-wave), \quad \phi \phi \to A' \to f\overline{f} \quad (p-wave)$

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

SIMP, ELDER, Co-SIMP models

- Scalar meidators : Two real scalars model (one for medidator, one for DM candidate)
- Fermion mediators : t-channel models (ex: neutrino portal)

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



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

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



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



Projected Sensitivities of Three Frontier Experiments

 $\Delta_{\chi} = 0.2 \times M_{\chi_1}$

$$\Delta_{\chi}=0.4 \times M_{\chi_1}$$



Projected Sensitivities of Three Frontier Experiments

 $\Delta_{\chi} = 0.05 \times M_{\chi_1}$

 $\Delta_{\chi}=0.01 \times M_{\chi_1}$



Experimental Results (Cosmic Ray Boosted Sub-GeV DM)

