第十六届TeV物理工作组学术研讨会

16th TeV Workshop

Heavy long-lived coannihilation partner from inelastic Dark Matter model and its signatures at the LHC

Reporter：郭金辉

Date：Nov 9，2022

Jinhui Guo, Yuxuan He, Jia Liu, Xiao-Ping Wang, *JHEP 04 (2022), 024, JHEP04(2022)024.*

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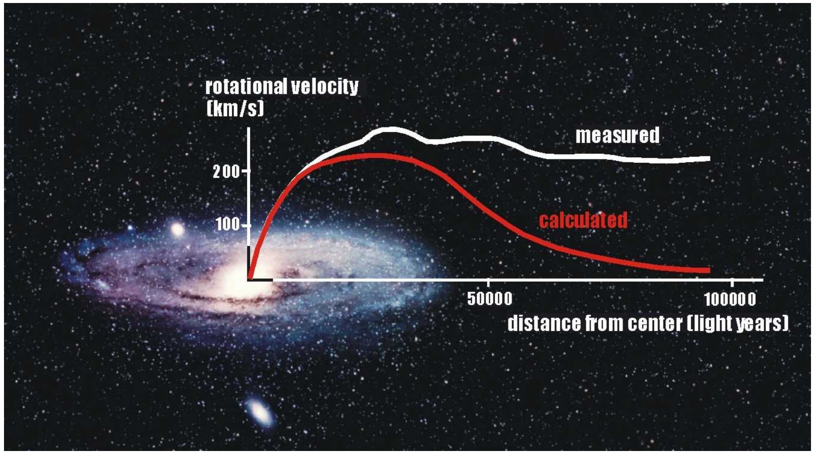
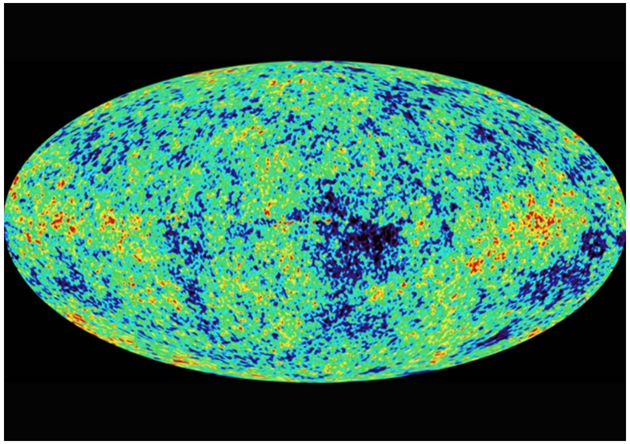
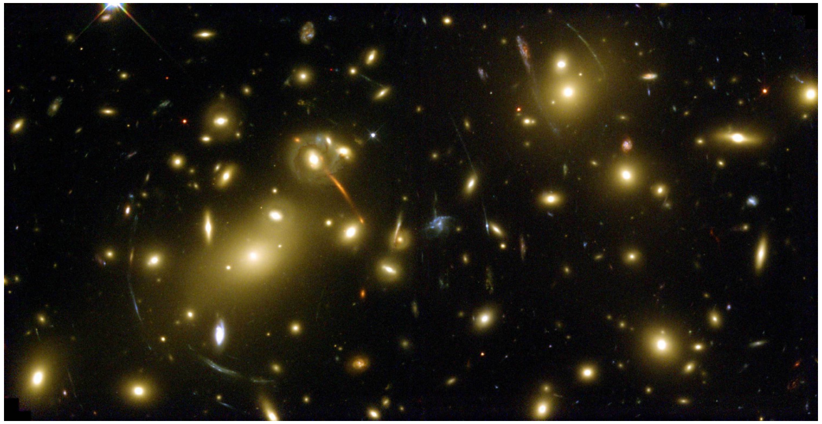
1. Introduction

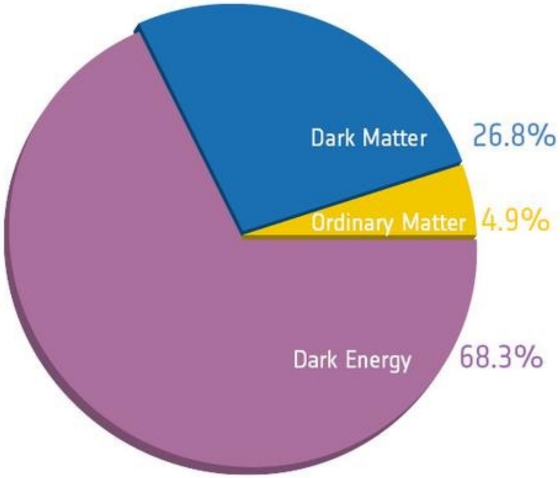
Does dark atter (DM) exist?

Ref: Rubin,V.C., Ford, W.K. & Thonnard, N. 1978, Astrophys. J. 225, L107



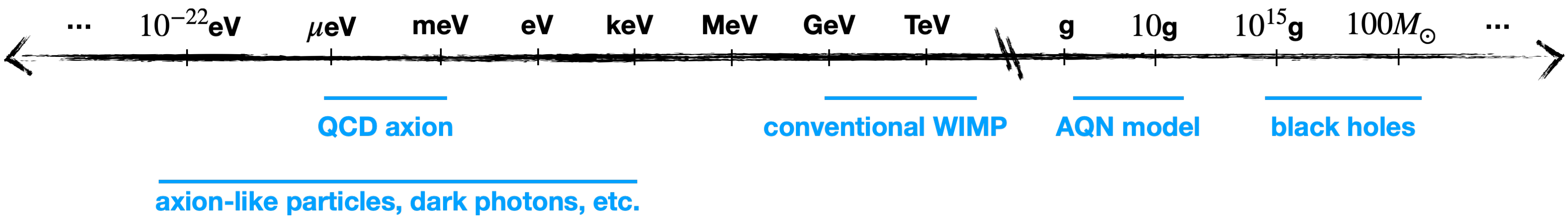




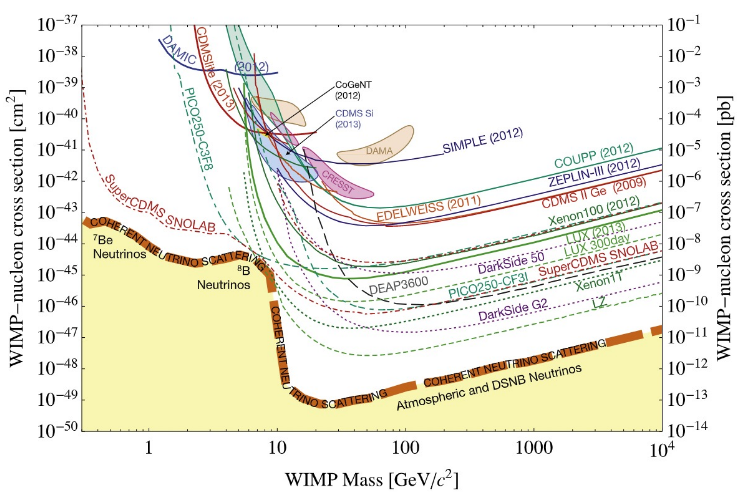


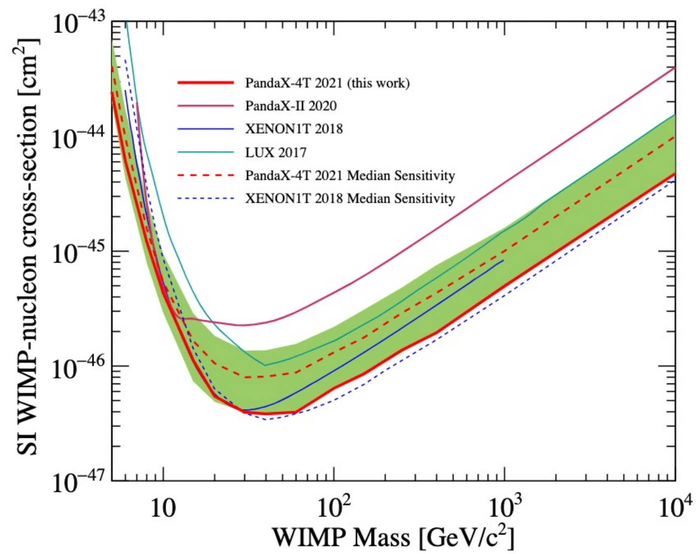
Ref: *ESA and the Planck Collaboration*

Searching for Dark Matter



For the WIMP DM:

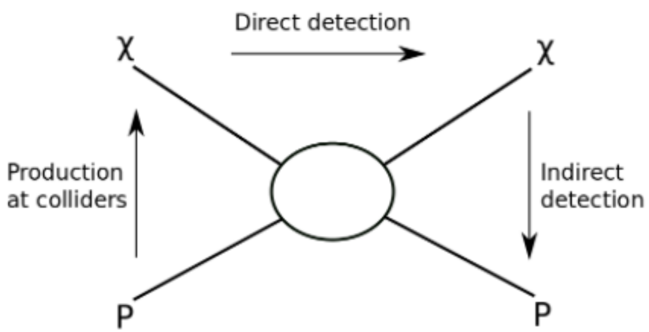


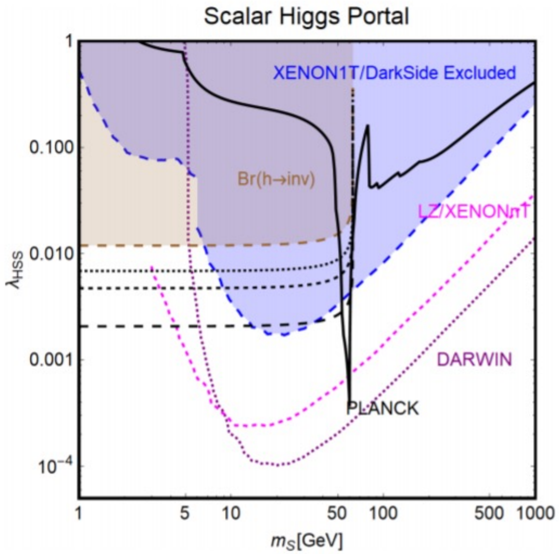


Ref: PHYSICAL REVIEW LETTERS 127, 261802 (2021) by PandaX-4T, J.Cooley

1. Introduction

Dark matter **(in)direct detection** constrains many of WIMP models:





[Ref: G. Arcadi, et. al. Phys.Rept. 842 (2020) 1-180]()

$$\Delta\mathcal{L}_S = -\frac{1}{2}M_S^2 S^2 - \frac{1}{4}\lambda_S S^4 - \frac{1}{4}\lambda_{HSS}\Phi^\dagger\Phi S^2$$

DM: enough cross section

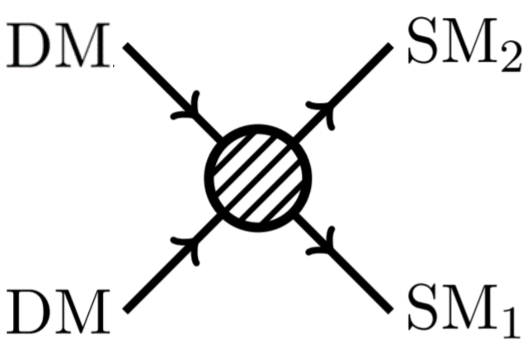
DD: small cross section

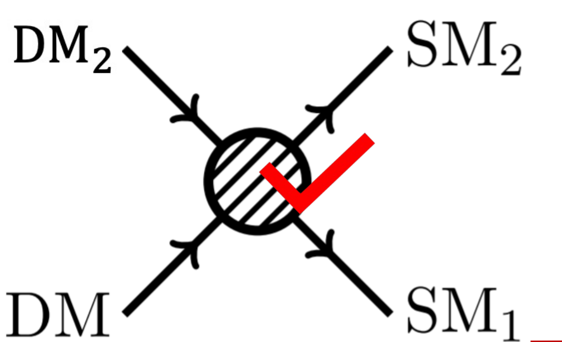
Inelastic DM

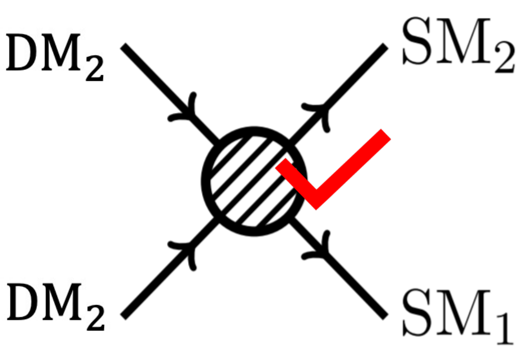
Coannihilation mechanism:

$$\sigma_{eff} = \frac{g_{s_1}^2}{g_{eff}^2}\left(\sigma_{11} + 2\sigma_{12}\frac{g_{s_2}}{g_{s_1}}(1+\Delta)^{3/2}e^{-x_f\Delta} + \sigma_{22}\frac{g_{s_2}^2}{g_{s_1}^2}(1+\Delta)^3 e^{-2x_f\Delta}\right).$$

$$\Delta \equiv \frac{m_2 - m_1}{m_1}$$

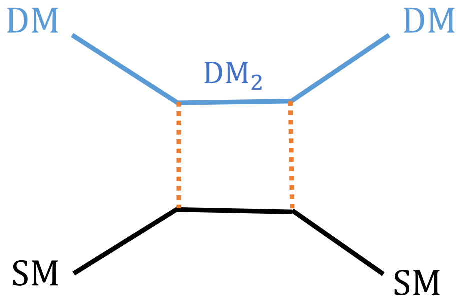




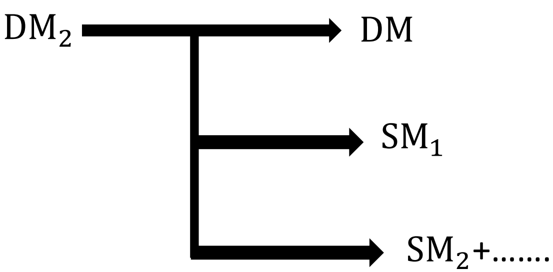


1. Introduction

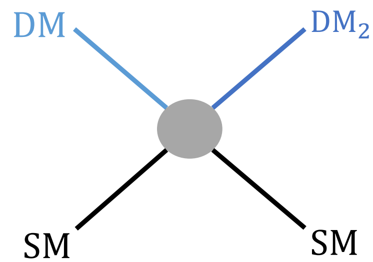
- Elastic scatterings $\sigma(\mathrm{SM}+\mathrm{DM})$



- The DM_2 may be long-lived



- Inelastic scatterings $\sigma(\mathrm{SM}+\mathrm{DM})$

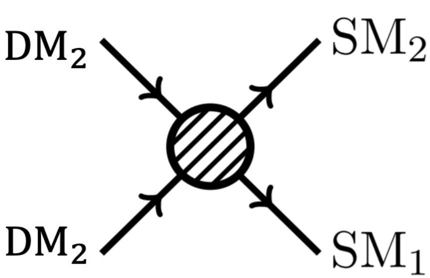


kinematic suppressed!

- Previous studies: coannihilation dominated by σ_{12} and LLP search for light DM.

We focus on the case:

1. $\sigma_{22} \gg \sigma_{12} \gg \sigma_{11} \sim 0$ and m_{DM}>100 GeV
2. Searching for the DM_2's long-lived signature.



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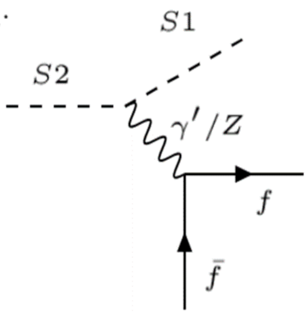
2. Coannihilation inelastic DM Models and Constraints

- The effective Lagrangian is

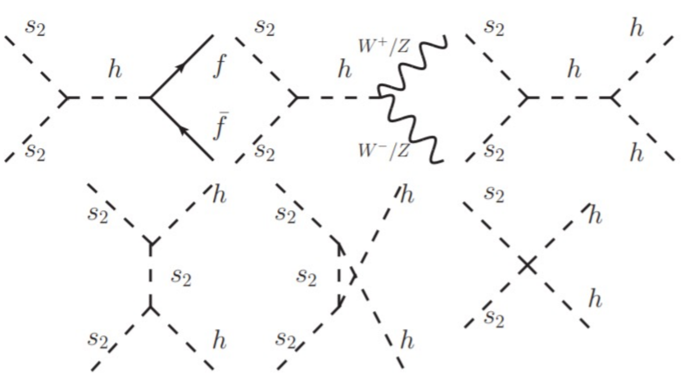
$$\mathcal{L} \supset (D_\mu S)^\dagger (D^\mu S) - \frac{m_1^2}{2} s_1^2 - \frac{m_2^2}{2} s_2^2 - \lambda_{22} s_2^2 \left(H^\dagger H - \frac{v^2}{2} \right) - \frac{1}{4} F'^{\mu\nu} F'_{\mu\nu} - \frac{\epsilon}{2\cos\theta_W} F'^{\mu\nu} B_{\mu\nu} + \frac{m_{A'}^2}{2} A'^\mu A'_\mu .$$

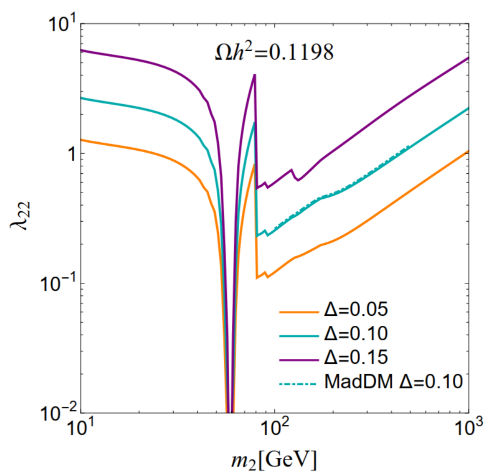


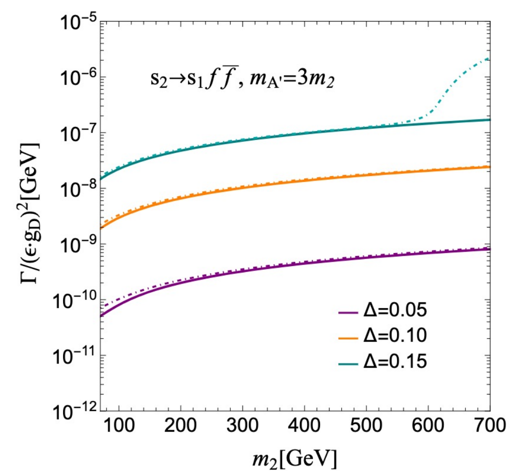
We have $\sigma_{11} = 0, \sigma_{12} \ll \sigma_{22}$. And $\Gamma(s_2)$ is suppressed by $m_{A'} = 3m_2$, ϵ and Δm, which can be a LLP.

With $g_D = 0.1, m_{A'} = 3m_2$, the free parameters: $\{\epsilon, m_2, \Delta\}$

- Dark Matter Relic abundance
- The decay width of s_2



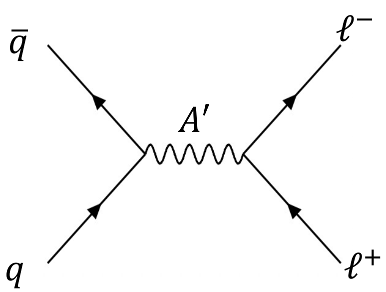




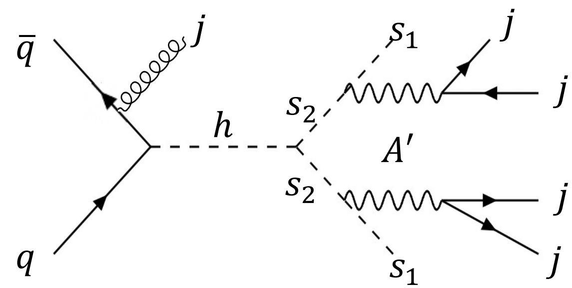
2. Coannihilation inelastic DM Models and Constraints

Constraints on our model:

1. Constraints from LHC



Dilepton resonance search



Monojet plus missing energy

The soft final jets may be not detectable

2. Electroweak precision measurement: heavy massive A' leads to ignorable contribution.

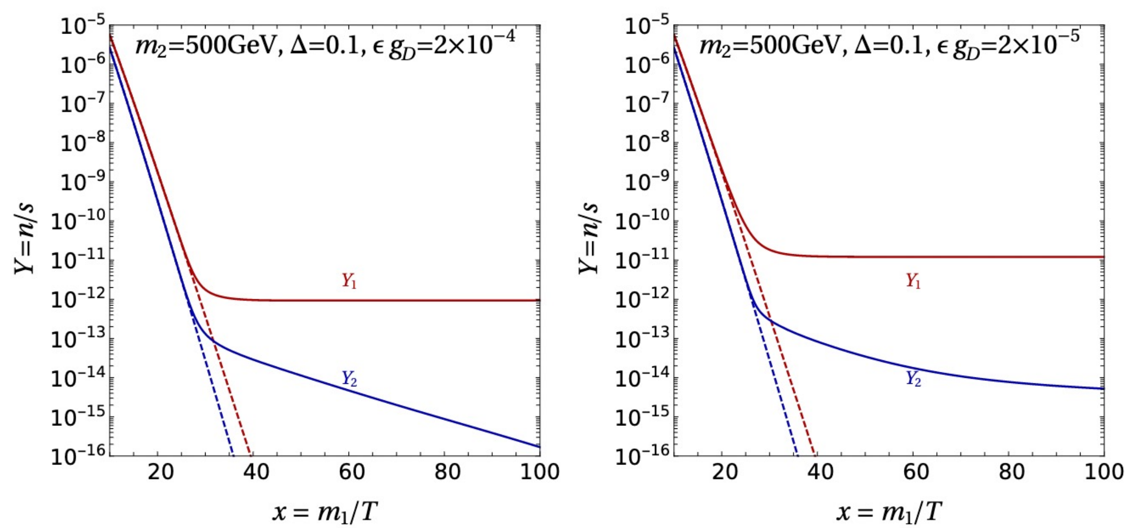
3. Constraints from thermalization requirement

$$s_1 + f \leftrightarrow s_2 + f$$

$$\Gamma(T) = \sum_f n_f^{eq} \langle \sigma_f v \rangle \gtrsim H$$

$$\begin{cases} \dfrac{dY_1}{dx} = -\dfrac{\lambda_f}{x^2} Y_f \left(Y_1 - \dfrac{Y_1^{eq}}{Y_2^{eq}} Y_2\right) + \gamma x \left(Y_2 - \dfrac{Y_2^{eq}}{Y_1^{eq}} Y_1\right), \\ \dfrac{dY_2}{dx} = -\dfrac{\lambda_{22}}{x^2} \left(Y_2^2 - Y_2^{eq2}\right) + \dfrac{\lambda_f}{x^2} Y_f \left(Y_1 - \dfrac{Y_1^{eq}}{Y_2^{eq}} Y_2\right) - \gamma x \left(Y_2 - \dfrac{Y_2^{eq}}{Y_1^{eq}} Y_1\right) \end{cases}$$

$$\lambda = \frac{s(m_1)}{H(m_1)} \langle \sigma v \rangle, \ \gamma = \frac{\langle \Gamma_2 \rangle}{H(m_1)}$$



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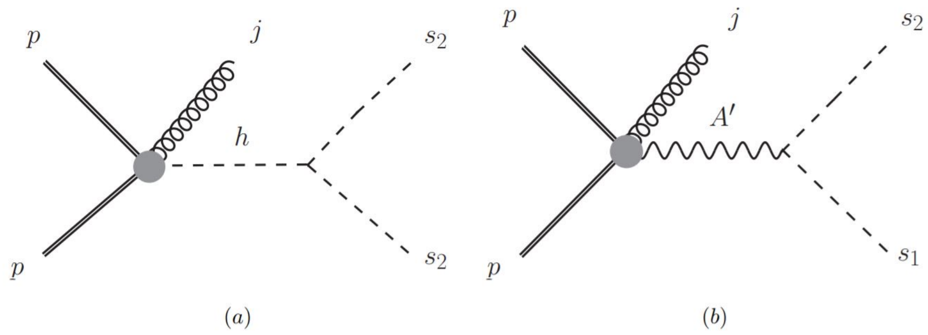
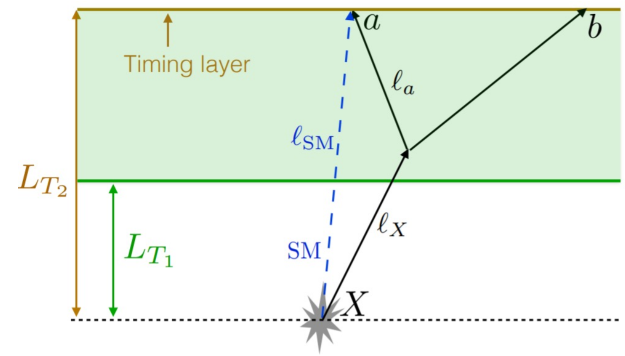
3. LLPs phenomenology in collider

- The generation of LLPs s_2





Ref: J.Liu Z. Liu L.T.Wang PRL 122.13(2019)

- Time delayed signature in LHC

$$\Delta t = L_{s_2}/\beta_{s_2} + L_f/\beta_f - L_{\rm SM}/\beta_{\rm SM}$$

- Basic cuts on signal

1. Displaced muon-jet cuts (DMJ):

$$p_{T,j} > 120\ \text{GeV}, p_{T,\mu} > 5\ \text{GeV}, r_{s_2} < 30\ \text{cm}, d_0^\mu > 1\ \text{mm}$$

2. LLPs cuts:

Ref: E. Izaguirre et.al. PRD93.6(2016)063523

$$p_{T,j} > 120\ (30)\text{GeV}, p_{T,\ell} > 3\ \text{GeV}, |\eta| < 2.4, \Delta t_\ell > 0.3\ \text{ns}, 5\ \text{cm} < r_{s_2} < 30\ \text{cm}, z_{s_2} < 3.04\ \text{m}$$

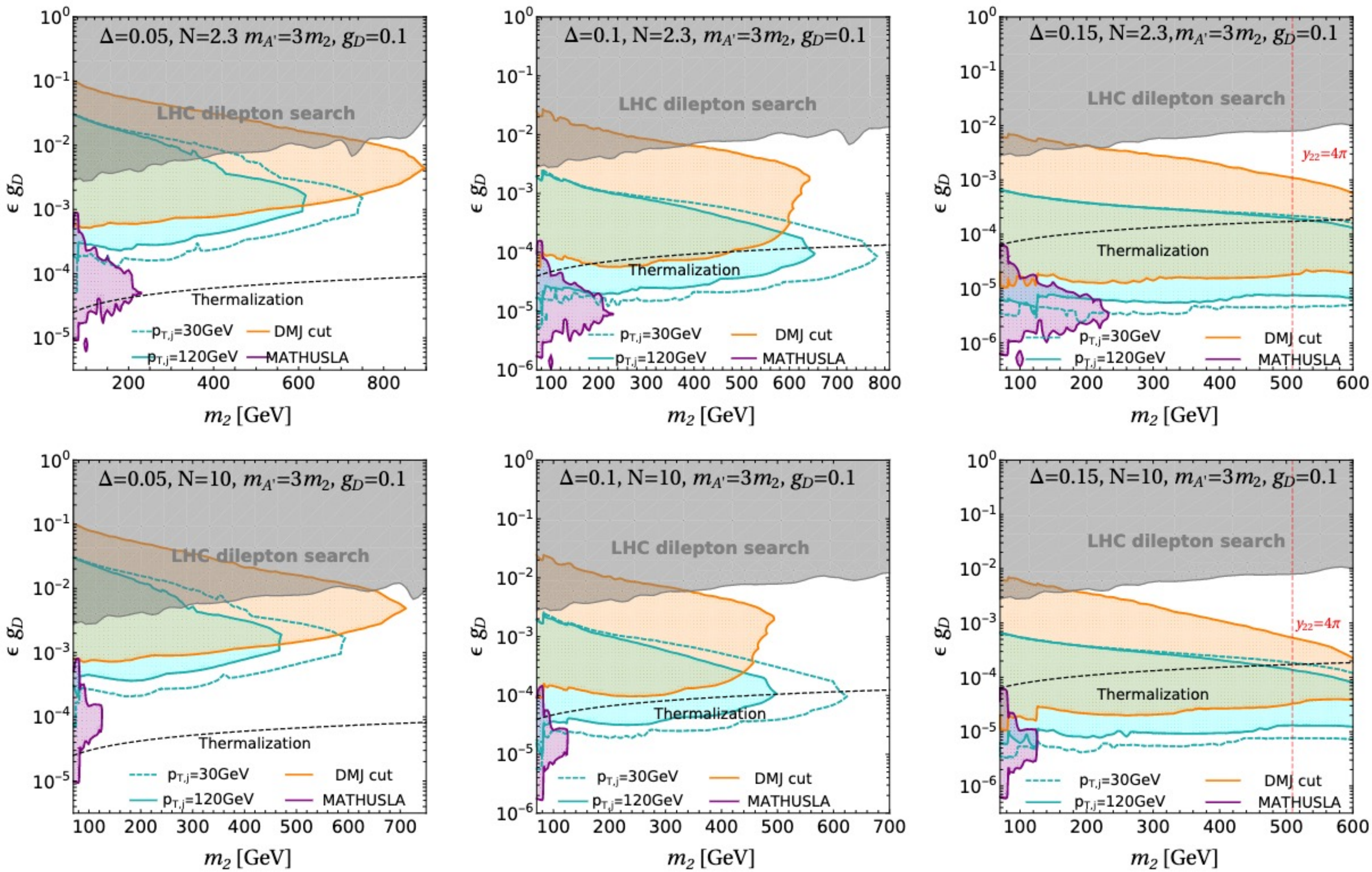
Ref: J.Liu Z. Liu L.T.Wang PRL 122.13 (2019)
A. Berlin F. Kling PRD99.1(2019)015021

3. MATHUSLA

$$100\ \text{m} < x_{s_2} < 120\ \text{m}, -100\ \text{m} < y_{s_2} < 100\ \text{m}, 100\ \text{m} < z_{s_2} < 300\ \text{m}$$

Ref: ATLAS PLB 796 (2019) 68-87

3. LLPs phenomenology in collider



The expected sensitivity at HL-LHC to the scalar-vector model in the $\epsilon g_D, m_2$ plane for $L = 3\ \text{ab}^{-1}$ and $\sqrt{s} = 13$ TeV

Contents

4. Conclusions

- We explore a coannihilation scenario that annihilation between coannihilation partner is the dominant contribution.
- We illustrate this mechanism with simplified scalar DM model.
- And we explore the long-lived signature of partner in HL-LHC.

Thanks!

Backup

Backup

- Derivation of co-annihilation effective cross section

$$\frac{dn_i}{dt} = -3Hn_i - \sum_{j,X} [\langle \sigma_{ij} v \rangle (n_i n_j - n_i^{eq} n_j^{eq}) - (\langle \sigma'_{ij} v \rangle n_i n_X - \langle \sigma'_{ji} v \rangle n_j n_{X'}) - \Gamma_{ij}(n_i - n_i^{eq})] , \quad ($$

$$\frac{dn}{dt} = -3Hn - \sum_{i,j=1}^{N} \langle \sigma_{ij} v \rangle (n_i n_j - n_i^{eq} n_j^{eq})$$

$$n_i n_j \sigma_{ij} \sim T^3 m_i^{3/2} m_j^{3/2} \sigma_{ij} \exp[-(m_i + m_j)/T] ,$$

while the rate for a reaction of type (6b) is

$$n_i n_X \sigma'_{ij} \sim T^{9/2} m_i^{3/2} \sigma'_{ij} \exp(-m_i/T) .$$

So the latter rates are larger by a factor of roughly

$$n_X / n_j \sim (T/m_j)^{3/2} \exp(m_j/T) \sim 10^9 ,$$

K. Griest and D. Seckel PRD 43 (1991)3191-3203

$$r_i \equiv n_i^{eq} / n^{eq} = \frac{g_i (1+\Delta_i)^{3/2} \exp(-x\Delta_i)}{g_{\text{eff}}}$$

$$g_{\text{eff}} = \sum_{i=1}^{N} g_i (1+\Delta_i)^{3/2} \exp(-x\Delta_i)$$

$$\frac{dn}{dt} = -3Hn - \langle \sigma_{\text{eff}} v \rangle (n^2 - n_{\text{eq}}^2) ,$$

where

$$\sigma_{\text{eff}} = \sum_{ij}^{N} \sigma_{ij} r_i r_j = \sum_{ij}^{N} \sigma_{ij} \frac{g_i g_j}{g_{\text{eff}}^2} (1+\Delta_i)^{3/2} (1+\Delta_j)^{3/2} \times \exp[-x(\Delta_i + \Delta_j)] .$$

Backup

Coannihilation inelastic DM Models

- Consider Lagrangian with **complex scalar** $\hat{S} = (\hat{s}_1 + i\hat{s}_2)/\sqrt{2}$

$$\mathcal{L} \supset \left(\partial_\mu \hat{S}\right)^* \left(\partial^\mu \hat{S}\right) - m_S^2 \hat{S}^* \hat{S} - \delta\hat{m}_{ij}^2 \hat{s}_i \hat{s}_j - \hat{\lambda}_{ij} \hat{s}_i \hat{s}_j \left(H^\dagger H - \frac{v^2}{2}\right)$$

Where **U(1) violation** terms $\delta\hat{m}_{ij}^2$ and $\hat{\lambda}_{ij}$ are 2×2 **rank 1** matrices and $\hat{\lambda}_{ij}$ is proportional to $\delta\hat{m}_{ij}^2$. After diagonalizing the mass terms:

$$\mathcal{L} \supset (\partial_\mu S)^\dagger (\partial^\mu S) - \frac{m_1^2}{2} s_1^2 - \frac{m_2^2}{2} s_2^2 - \lambda_{22} s_2^2 \left(H^\dagger H - \frac{v^2}{2}\right)$$

We have $\sigma_{11} = 0, \quad \sigma_{12} = 0$

Only s_2 couple with SM particles, s_1 can not be DM candidate

Backup

- Pure scalar model

Simply assume δm_{ij}^2 and λ_{ij} can not be simultaneously diagonalized but have a **misalignment angle** $\delta\theta$, After diagonalizing mass term:

$$\lambda_{12} \approx -\delta\theta \times \lambda_{22}, \quad \lambda_{11} \approx \delta\theta^2 \times \lambda_{22}$$

And then $$\sigma_{11} \approx 0, \quad \sigma_{12} \ll \sigma_{22}$$

Since λ_{11} is strongly constrained in direct detection, we simply set it to 0. and we have $\lambda_{12} \ll \lambda_{22}$:

$$\mathcal{L} \supset \frac{1}{2}(\partial S_1)^2 + \frac{1}{2}(\partial S_2)^2 - \frac{m^2}{2}S_1^2 - \frac{M^2}{2}S_2^2 - \lambda_{12}S_1S_2(|H|^2 - \frac{v^2}{2}) - \frac{\lambda_{22}S_2S_2}{2}(|H|^2 - \frac{v^2}{2})$$

Where the heavier state S_2 can potentially be LLP due to **small coupling** and **mass splitting**

Coannihilation inelastic DM Models

- Scalar-vector model

Gauging the U(1) Symmetry, introducing dark photon A' , which have kinematic mixing with SM B field:

$$\mathcal{L} \supset (D_\mu S)^\dagger (D^\mu S) - \frac{m_1^2}{2} s_1^2 - \frac{m_2^2}{2} s_2^2 - \lambda_{22} s_2^2 \left(H^\dagger H - \frac{v^2}{2} \right) - \frac{1}{4} F'^{\mu\nu} F'_{\mu\nu} - \frac{\epsilon}{2\cos\theta_W} F'^{\mu\nu} B_{\mu\nu} + \frac{m_{A'}^2}{2} A'^\mu A'_\mu.$$

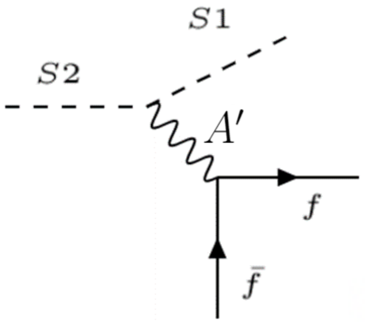
Where $D_\mu S = \partial_\mu S + i g_D A'_\mu S$ introducing coupling between 2 scalars. Diagonalizing mass terms we have:

$$\mathcal{L}_{\rm int} = \tilde{Z}_\mu (g J_Z^\mu - g_D \frac{m_Z^2 \tan\theta_W}{m_Z^2 - m_{A'}^2} \epsilon J_D^\mu) + \tilde{A}'_\mu (g_D J_D^\mu + g \frac{m_{A'}^2 \tan\theta_W}{m_Z^2 - m_{A'}^2} \epsilon J_Z^\mu + e\epsilon J_{\rm em}^\mu) + \tilde{A}_\mu e J_{\rm em}^\mu.$$

s_2 decay mainly mediated by dark photon,

its width is suppressed by **dark photon mass**,

small coupling and **mass splitting.**



Backup

- Scalar-vector model details

realized in UV models with dark Higgs. For instance we consider dark Higgs Φ carrying a opposite charge comparing to S. Terms like $y\mathrm{Im}(S\Phi^*)^2$ can be added to the Lagrangian and generating mass splitting yv_Φ^2. The kinetic mixing between SM Higgs and dark Higgs generates appropriate terms like $\frac{\lambda_{22}S_2S_2}{2}(|H|^2 - \frac{v^2}{2})$ after integrating out Φ field.

$$\begin{pmatrix} Z_\mu \\ A_\mu \\ A'_\mu \end{pmatrix} = \begin{pmatrix} 1 & 0 & \frac{m_{A'}^2 \tan\theta_W}{m_Z^2 - m_{A'}^2}\epsilon \\ 0 & 1 & \epsilon \\ \frac{m_Z^2 \tan\theta_W}{m_{A'}^2 - m_Z^2}\epsilon & 0 & 1 \end{pmatrix} \begin{pmatrix} \tilde{Z}_\mu \\ \tilde{A}_\mu \\ \tilde{A}'_\mu \end{pmatrix}$$

$$\frac{g_D^2}{2}(S_1^2 + S_2^2)\left(\tilde{A}'_\mu + \epsilon\frac{m_Z^2 \tan\theta_W}{m_Z^2 - m_{A'}^2}\tilde{Z}_\mu\right)^2$$

Backup

Existing constraints from Cosmology and LHC

- Direct detection:

  elastic scatterings : very small — E. Izaguirre et.al. PRD93.6(2016)063523; A. Berlin F. Kling PRD99.1(2019)015021

  inelastic scatterings : suppressed by **non-relativistic** velocity.
- Indirect detection:

  s_1 : tiny pair annihilation cross-section.

  s_2 : already decayed in early universe. — E. Izaguirre et.al. PRD93.6(2016)063523
- LHC search: **MET+mono jet, dilepton resonance** search in LHC constrains some of parameter space.
- Electroweak precision measurement (EWPM) is not sensitive to parameter region in our model since A' is very heavy.

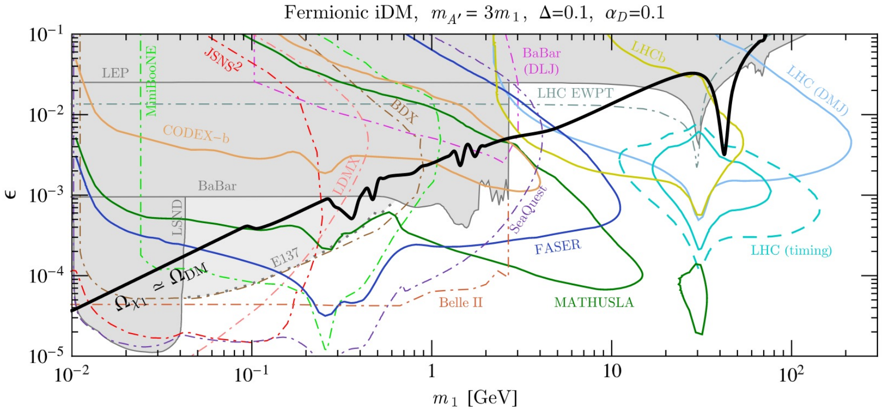
Backup

- Co-annihilation calculation

$$
\begin{aligned}
\langle\sigma v\rangle_s =&\langle\sigma v\rangle_{f\bar{f}} + \langle\sigma v\rangle_{WW} + \langle\sigma v\rangle_{ZZ} + \langle\sigma v\rangle_{hh},\\
\langle\sigma v\rangle_{f\bar{f}} =&\frac{\lambda_{22}^2 m_f^2 (m_2^2 - m_f^2)^{3/2}}{4\pi m_2^3 (4m_2^2 - m_h^2)^2},\\
\langle\sigma v\rangle_{WW} =&\frac{\lambda_{22}^2 (4m_2^4 - 4m_W^2 m_2^2 + 3m_W^4)\sqrt{m_2^2 - m_W^2}}{8\pi m_2^3 (4m_2^2 - m_h^2)^2},\\
\langle\sigma v\rangle_{ZZ} =&\frac{\lambda_{22}^2 (4m_2^4 - 4m_Z^2 m_2^2 + 3m_Z^4)\sqrt{m_2^2 - m_Z^2}}{16\pi m_2^3 (4m_2^2 - m_h^2)^2},\\
\langle\sigma v\rangle_{hh} =&\frac{\lambda_{22}^2 (\lambda_{22} v_h^2 (4m_2^2 - m_h^2) - 4m_2^4 + m_h^4)^2 \sqrt{m_2^2 - m_h^2}}{16\pi m_2^3 \left(8m_2^4 - 6m_2^2 m_h^2 + m_h^4\right)^2}.
\end{aligned}
$$

- Previous studies: coannihilation dominated by σ_{12} and LLP search for light DM.

$$\mathcal{L} \supset \frac{\epsilon}{2\cos\theta_w} A'_{\mu\nu} B^{\mu\nu} \qquad i e_D A'_\mu \bar{\chi}_1 \gamma^\mu \chi_2$$



Ref: PHYSICAL REVIEW D 99, 015021 (2019) by Felix Kling