The exotic Higgs boson decays in inelastic DM models

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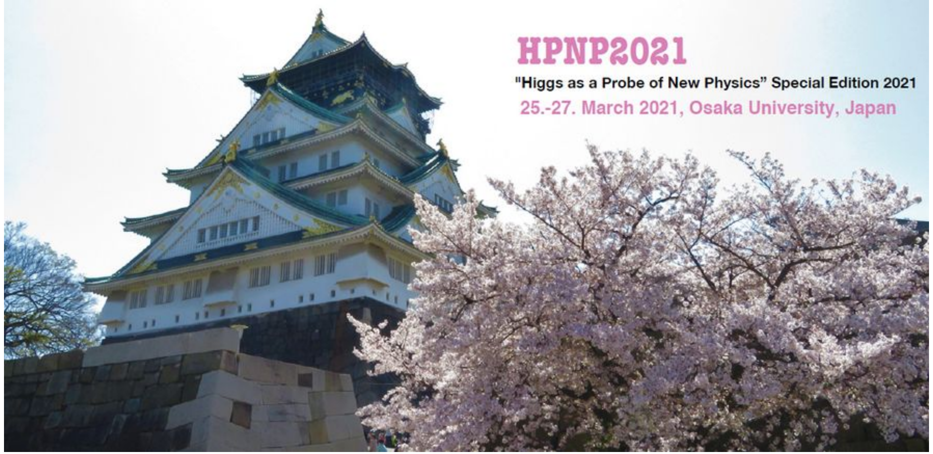

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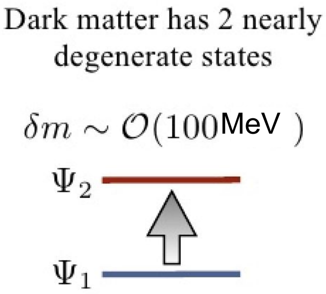
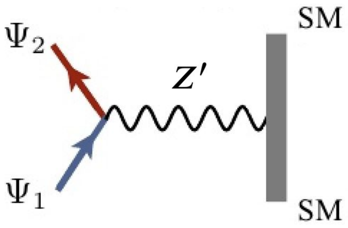
Motivation

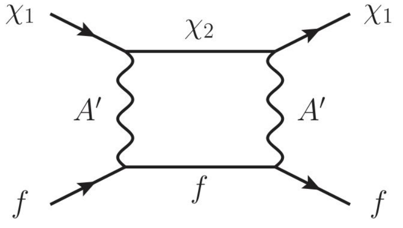
1. The inelastic (or excited) DM model with extra $U(1)_D$ gauge symmetry is one of the most popular dark sector models with light DM candidate.
2. There are at least two states in the dark sector and there is an inelastic transition between them via the new $U(1)_D$ gauge boson.
3. If the mass splitting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





Motivation

1. The co-annihilation production of light DM via thermal freeze-out is still consistent with the CMB constraint for the amount of parameter space.
2. The constraint from DM and nuclear inelastic scattering is much weaker than the elastic one in the direct detection experiments.



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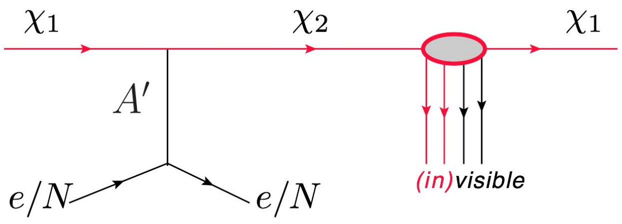

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→ It makes more allowed parameter space in inelastic DM models which can be explored !

Review of inelastic DM models

1. After the SSB of this $U(1)_D$ gauge symmetry, we expect the accidentally residual Z_2 symmetry, $\phi_1 \to -\phi_1$ or $\chi_1 \to -\chi_1$, can be left such that ϕ_1 or χ_1 are stable and become DM candidates in our University.

A. The scalar model	**B. The fermion model**
Φ and $\phi = (\phi_2 + i\phi_1)/\sqrt{2}$ $Q_D(\Phi) = +2 \quad Q_D(\phi) = +1$	Φ and Dirac fermion χ $Q_D(\Phi) = +2 \quad Q_D(\chi) = +1$
$V(H,\Phi,\phi) = -\mu_H^2 H^\dagger H + \lambda_H (H^\dagger H)^2 - \mu_\Phi^2 \Phi^*\Phi + \lambda_\Phi (\Phi^*\Phi)^2 - \mu_\phi^2 \phi^*\phi + \lambda_\phi (\phi^*\phi)^2 + (\mu_{\Phi\phi}\Phi^*\phi^2 + H.c.) + \lambda_{H\Phi}(H^\dagger H)(\Phi^*\Phi) + \lambda_{H\phi}(H^\dagger H)(\phi^*\phi) + \lambda_{\Phi\phi}(\Phi^*\Phi)(\phi^*\phi)$	$V(H,\Phi) = -\mu_H^2 H^\dagger H + \lambda_H (H^\dagger H)^2 - \mu_\Phi^2 \Phi^*\Phi + \lambda_\Phi (\Phi^*\Phi)^2 + \lambda_{H\Phi}(H^\dagger H)(\Phi^*\Phi)$

Ref : 1407.6588, 1910.04311, 2006.16876, 2101.02503, ...

Review of inelastic DM models

A. The scalar model	B. The fermion model
$g_D X_\mu(\phi_2\partial^\mu\phi_1 - \phi_1\partial^\mu\phi_2)$	$-i\frac{g_D}{2}(\overline{\chi_2}\not{X}\chi_1 - \overline{\chi_1}\not{X}\chi_2)$
$(\mu_{\Phi\phi}\Phi^*\phi^2 + H.c.)$	$-(\frac{f}{2}\overline{\chi^c}\chi\Phi^* + H.c.)$
$M_{\phi_{1,2}} = \sqrt{\frac{1}{2}(-\mu_\phi^2 + \lambda_{H\phi}v^2 + \lambda_{\Phi\phi}v_D^2) \mp \mu_{\Phi\phi}v_D}$ $\Delta_\phi \equiv M_{\phi_2} - M_{\phi_1} = \frac{2\mu_{\Phi\phi}v_D}{M_{\phi_1} + M_{\phi_2}}$	$M_{\chi_{1,2}} = M_\chi \mp f v_D$ $\Delta_\chi \equiv (M_{\chi_2} - M_{\chi_1}) = 2 f v_D$

Ref : 1407.6588, 1910.04311, 2006.16876, 2101.02503, ...

Review of inelastic DM models

The common formulae for both scalar and fermion inelastic DM models :

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

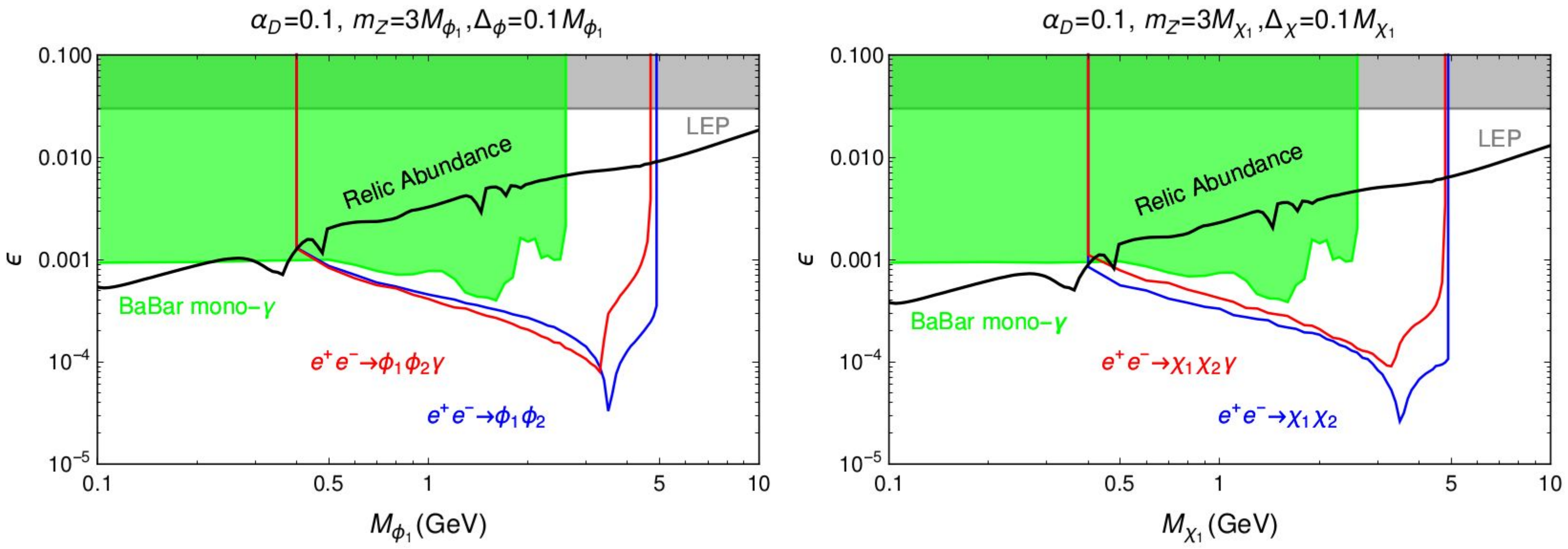
$$\begin{pmatrix} h \\ h_D \end{pmatrix} = \begin{pmatrix} cos\theta & sin\theta \\ -sin\theta & cos\theta \end{pmatrix}\begin{pmatrix} h_1 \\ h_2 \end{pmatrix}$$

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

$$\mathcal{L}_{Z'f\bar{f}} = -\epsilon e c_W \sum_f x_f \bar{f} \not{Z}' f \qquad m_{Z'} \simeq g_D Q_D(\Phi) v_D \qquad x_l = -1,\ x_\nu = 0,\ x_q = \tfrac{2}{3} \text{ or } \tfrac{-1}{3}$$

Intensity Frontier : Belle II

Mono-photon and displaced vertex signatures



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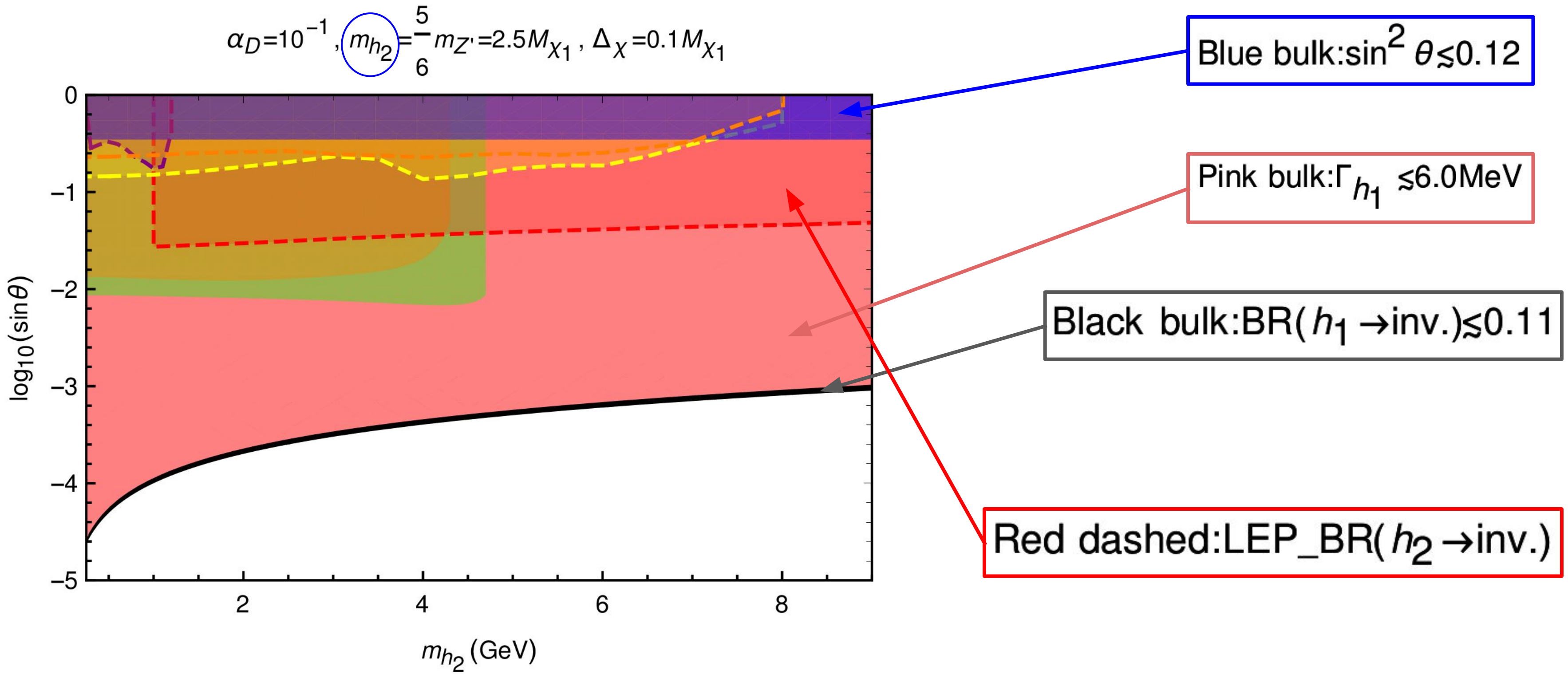
Energy Frontier : LHC

Why SM-like Higgs boson invisible decays or exotic decays detection are important for inelastic DM models ?

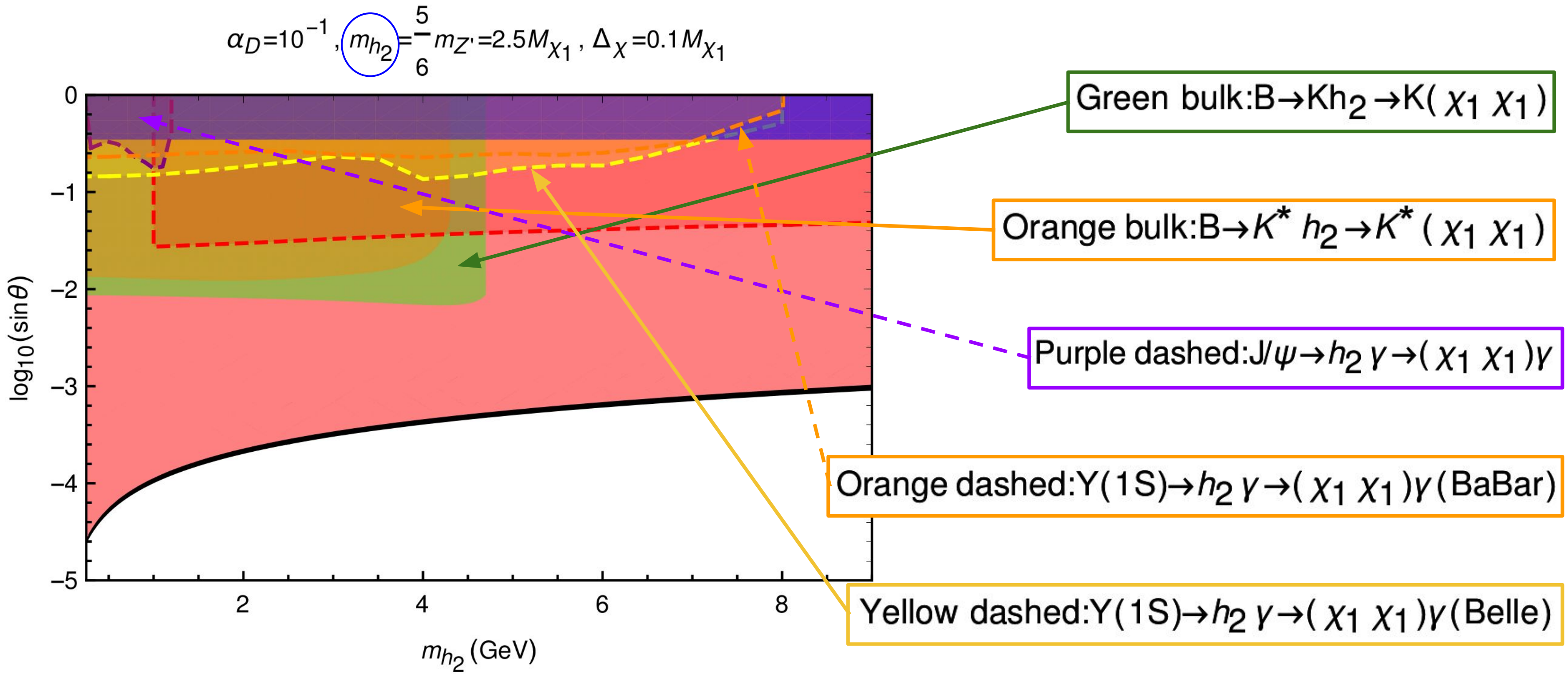
Let's focus on the same parameters settings :

$$\alpha_D = 0.1,\ m_{Z} = 3M_{\phi_1},\ \Delta_\phi = 0.1 M_{\phi_1}$$

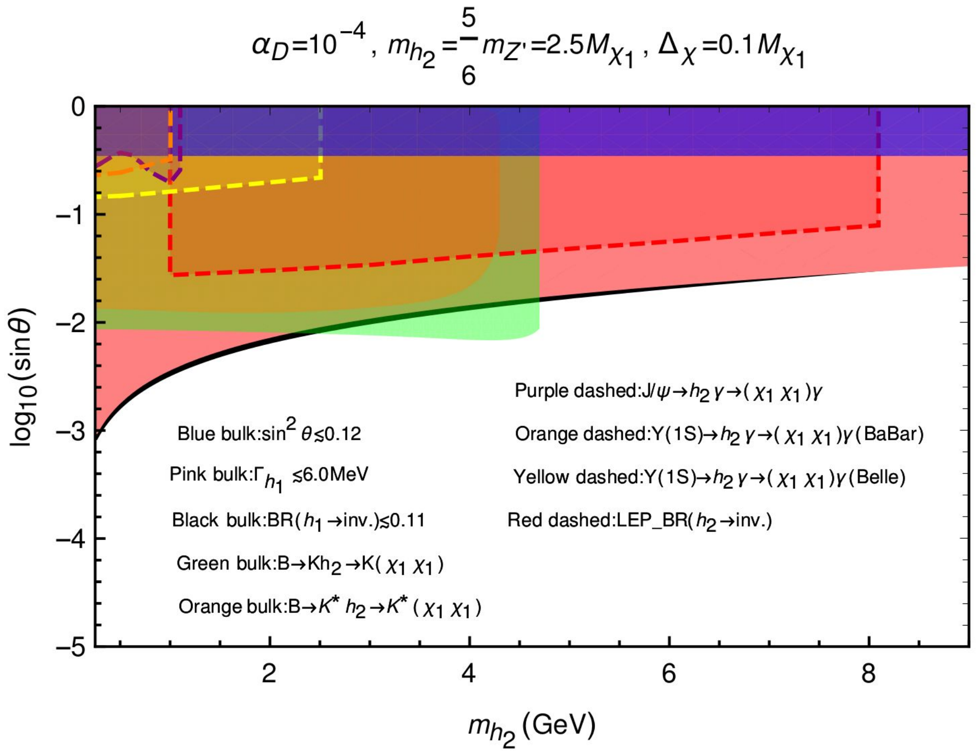
Constraints for inelastic DM models



Constraints for inelastic DM models



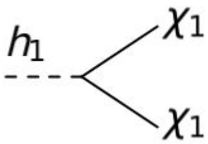
Constraints for inelastic DM models

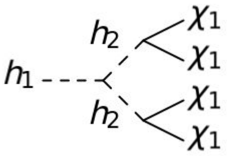


Since α_D is small in this scenario, the DM is either via resonant coannihilation or higgs portal process in the early Universe.

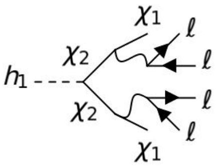
The exotic Higgs boson decay channels

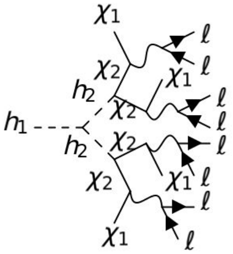
1. Higgs boson invisible decay channels :

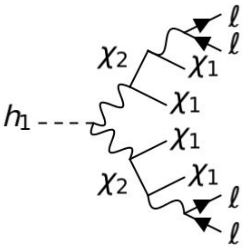


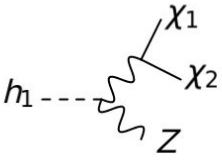


2. Higgs boson exotic decay channels :









Summary

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. Because of the Higgs boson invisible decay and Higgs width measurement constraints, the extra gauge coupling α_D and h-hD mixing angle $\sin\theta$ cannot be large simultaneously.
3. The novel multi-leptons or lepton-jets signatures from Higgs boson exotic decays are proposed and can be searched at the LHC and future colliders.

Thank you
for your attention