Displaced vertices from pseudo-Dirac dark matter

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Based on arXiv:1706.08985 (AD, A. De Simone, T. Jacques and V. Sanz)

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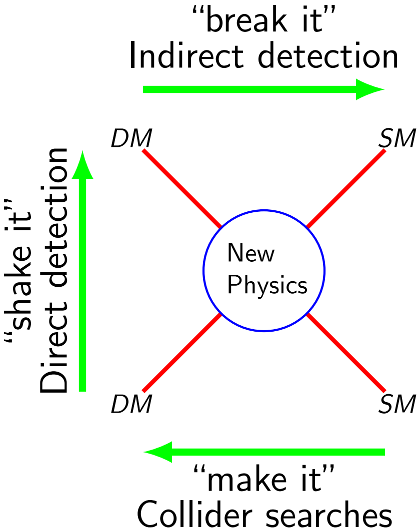
ma per seguir virtute e canoscenza
SISSA

Search strategies



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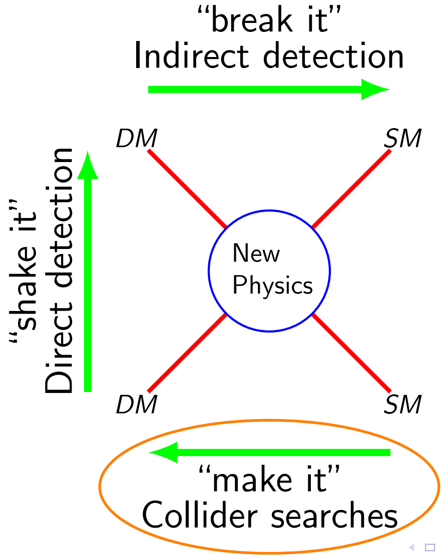

Pseudo-Dirac model

Pseudo-Dirac dark matter simplified model: SM + 2 Majorana fermions coupled to it through a Z' boson.

Despite its simplicity, interesting features:

i) not only standard signatures (monojet), but also "unusual" ones (displaced vertices);

ii) link between collider signatures and cosmological observations;

iii) broken crossing symmetry between $DM - N \leftrightarrow DM - N$ and $DM - DM \leftrightarrow N - N$ interactions;

iv) DM-nuclei scattering cross section helicity/velocity suppressed; DM annihilation cross section unsuppressed.

Model

Starting point: pDDM Lagrangian

$$\mathcal{L}_{\rm pDDM} = \mathcal{L}_0 + \mathcal{L}_{\rm int} \, ,$$

where

$$\mathcal{L}_0 = \bar{\Psi}(i\partial\!\!\!/ - M_D)\Psi - \frac{m_L}{2}\left(\overline{\Psi^c} P_L \Psi + \text{h.c.}\right) - \frac{m_R}{2}\left(\overline{\Psi^c} P_R \Psi + \text{h.c.}\right) ,$$

$$\mathcal{L}_{\rm int} = \bar{\Psi}\gamma^\mu (c_L P_L + c_R P_R)\Psi \, Z'_\mu + \sum_f \bar{f}\gamma^\mu (c_L^{(f)} P_L + c_R^{(f)} P_R) f \, Z'_\mu \, ,$$

f: SM fermion.
"Pseudo-Dirac limit": $m_{L,R} \ll M_D$.

Mass eigenstates (at $0th$ order in $|m_L - m_R|/M_D$):

$$\chi_1 = \frac{i}{\sqrt{2}}(\Psi - \Psi^c) \quad \rightarrow \quad m_1 = M_D - \frac{m_L + m_R}{2}$$
$$\chi_2 = \frac{1}{\sqrt{2}}(\Psi + \Psi^c) \quad \rightarrow \quad m_2 = M_D + \frac{m_L + m_R}{2}\,.$$

χ_1 is the DM candidate; χ_2 is unstable and can decay into χ_1.
In the pseudo-Dirac limit, $\Delta m \equiv m_2 - m_1 \ll m_{1,2}$.

$\mathcal{L}_{int}$ in terms of $\chi_{1,2}$:

$$\mathcal{L}_{\rm int}^{(\chi_1\chi_2)} = i\,\frac{c_R + c_L}{2}\,\bar{\chi}_1\gamma^\mu\chi_2\,Z'_\mu$$

$$\mathcal{L}_{\rm int}^{(\chi_i\chi_i)} = \frac{c_R - c_L}{4}\,\bar{\chi}_i\gamma^\mu\gamma^5\chi_i\,Z'_\mu$$

$$\mathcal{L}_{\rm int}^{(\bar{f}f)} = \sum_f \bar{f}\gamma^\mu\left[\frac{c_L^{(f)} + c_R^{(f)}}{2} - \frac{c_L^{(f)} - c_R^{(f)}}{2}\,\gamma^5\right] f\,Z'_\mu\,,$$

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Different coupling dependence

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Different interaction structure

Decay length

$\chi_2 \to \chi_1 f\bar{f}$ decay length (at rest):

$$L_0 \simeq 2.9\,\mathrm{m}\left[\sum_f N_c^{(f)}(c_L + c_R)^2\left({c_L^{(f)}}^2 + {c_R^{(f)}}^2\right)\right]^{-1}\left(\frac{M_{Z'}}{1\,\mathrm{TeV}}\right)^4\left(\frac{1\,\mathrm{GeV}}{\Delta m}\right)^5.$$

If $M_{Z'} \sim \mathcal{O}\,(\mathrm{TeV})$ and $\Delta m \sim \mathcal{O}\,(\mathrm{GeV}) \Rightarrow L_0 \sim \mathcal{O}\,(\mathrm{m}) \Rightarrow$ possible signal at LHC as displaced vertex!

Actual decay length at LHC: enhanced by the boost factor $\beta\gamma \sim \mathcal{O}(1 - 100)$.

Relic abundance

χ_1 and χ_2 quasi-degenerate in mass $\Rightarrow$ coannihilations are important.

Effective thermal cross section:

$$\langle\sigma v\rangle_{\rm eff} = \frac{1}{1+\alpha^2}\left(\langle\sigma v\rangle_{11} + 2\alpha\langle\sigma v\rangle_{12} + \alpha^2\langle\sigma v\rangle_{22}\right) ,$$

where $\alpha \equiv (1+\Delta m/m_1)^{\frac{3}{2}} e^{-x\Delta m/m_1}$, $\langle\sigma v\rangle_{ij} \equiv \langle\sigma v\rangle_{\chi_i\chi_j\to f\bar{f}}$ and $x \equiv m_1/T$.

By combining effective cross-section and decay length:

$$\frac{\Omega h^2}{0.1194} \simeq 1.26\left(\frac{L_0}{1\ \mathrm{m}}\right)\left(\frac{100\ \mathrm{GeV}}{m_1}\right)^2\left(\frac{\Delta m}{1\ \mathrm{GeV}}\right)^5 .$$

Link between relic abundance and decay length: one of the main predictions of the model.

Relic abundance

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Effective thermal cross section:

Velocity suppressed

$$\langle\sigma v\rangle_{\rm eff} = \frac{1}{1+\alpha^2}\left(\langle\sigma v\rangle_{11} + 2\alpha\langle\sigma v\rangle_{12} + \alpha^2\langle\sigma v\rangle_{22}\right),$$

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Couplings determination

Seven free parameters in the model:

$$\{m_1, \Delta m, M_{Z'}, c_L, c_R, c_L^{(f)}, c_R^{(f)}\}.$$

Assumptions and requirements:

i) without loss of generality, $c_R^{(f)} = -c_L^{(f)}$;

ii) ATLAS dijets constraints on SM-dark sector couplings;

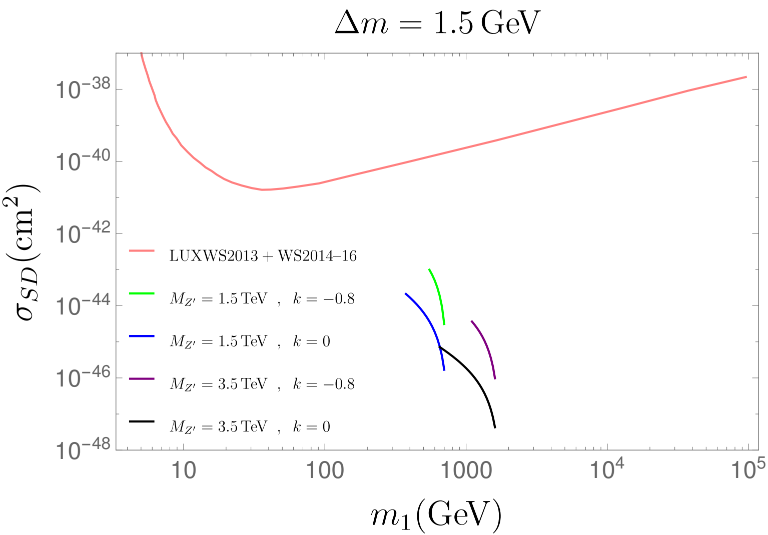
iii) $\Gamma_{Z'}/M_{Z'} \leq 0.2 \quad \Rightarrow \quad$ Breit-Wigner approximation is accurate;

iv) observed DM relic abundance;

v) fix the value of $k \equiv c_R/c_L$.

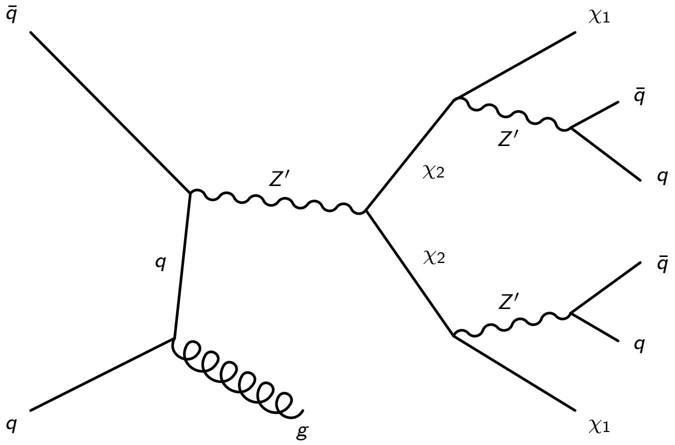
$\Rightarrow$ determination of c_L and c_R for given $\{m_1, \Delta m, M_{Z'}\}$.

Direct detection constraints



Displaced vertices

Strongest DV signals at LHC: $pp \to \chi_2\chi_2 j \to \chi_1\chi_1 jjjjj$.



Expected almost zero background.

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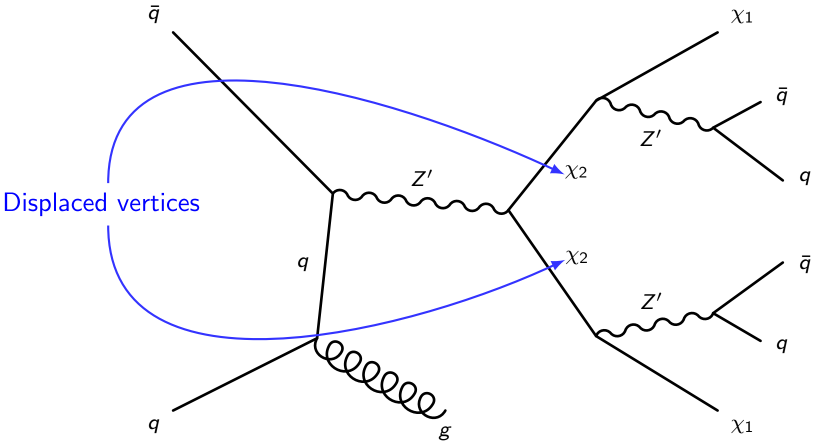
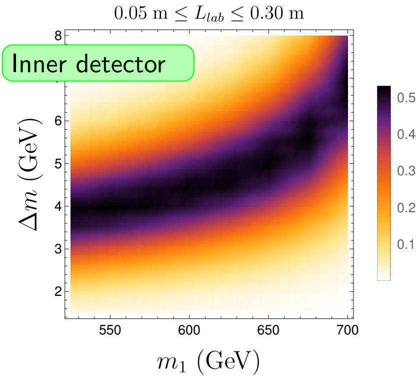
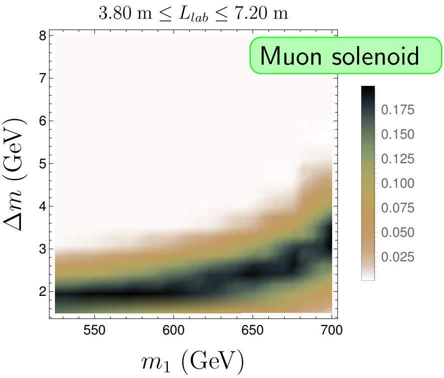


Expected almost zero background.

Probability that χ_2 decays in the detector ($M_{Z'} = 1.5\,\text{TeV}$):

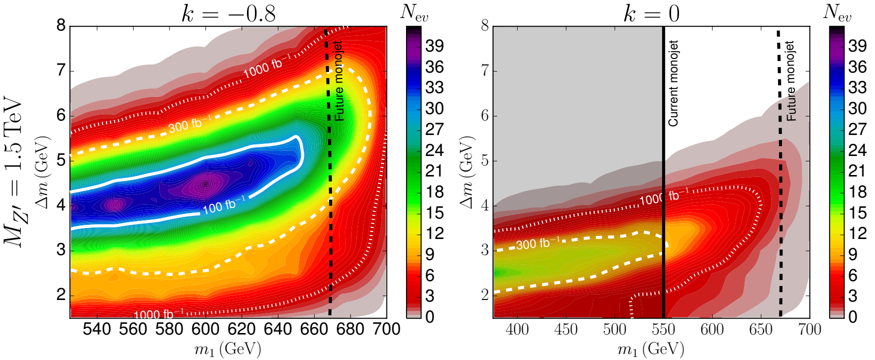




Complementarity DV-monojet

Cuts: $p_T > 200$ GeV , $MET > 300$ GeV.

DV: approximately zero background $\Rightarrow$ 95% C.L. exclusion if $N > 3$.



Conclusions

pDDM model: simple extension of the SM, but interesting features.

Not only standard signatures (monojet), but also “unusual” ones (DV).

Interplay between cosmological observations and collider signatures.

With larger luminosity $\Rightarrow$ exclusion/signal over a wide mass range.

pDDM model may be used as a benchmark for these new searches.

Backup slides

The freezeout temperature is given by $T_F = m_1/x_F$:

$$x_F = 25 + \log\left[\frac{d_F}{\sqrt{g_* x_F}}\, m_1 \langle \sigma v \rangle_{\rm eff}\, 6.4 \times 10^6\, \text{GeV}\right] ,$$

with $d_F = 2$ number of degrees of freedom of χ_1.

The DM cosmological abundance is:

$$\Omega h^2 = \frac{8.7 \times 10^{-11}\, \text{GeV}^{-2}}{\sqrt{g_*} \int_{x_F}^{\infty} dx\, \frac{\langle \sigma v \rangle_{\rm eff}}{x^2}} ,$$

with $g_* \simeq 100$ effective number of relativistic species at T_F.

χ_2 proper decay length in the lab frame: $L_0^{\rm lab} = \beta\gamma L_0$.

Probability that χ_2 travels a distance L before decaying:

$$P(L) = \frac{1}{L_0^{\rm lab}}\, e^{-L/L_0^{\rm lab}}$$

If p_T is the transverse momentum of $\chi_2 \Rightarrow$ transverse decay length $L_{T,0}^{\rm lab} = \frac{p_T}{m_2}\, L_0$.

Probability that χ_2 travels a distance greater than L in the transverse direction:

$$P(L_T^{\rm lab} > L) = \frac{1}{N}\sum_{i=1}^{N} \exp\left\{-\frac{L}{L_{T,0}^{\rm lab}(p_T = p_{T,i})}\right\}\,,$$

N number of simulated events.

χ_2 decay width:

$$\Gamma_{\chi_2\to\chi_1\bar{f}f} = \sum_f \frac{N_c^{(f)}}{480\pi^3}(c_L+c_R)^2\frac{\Delta m^5}{M_{Z'}^4}\Bigg\{\left(1-\frac{3}{2}\frac{\Delta m}{m_1}\right)\left(c_L^{(f)2}+c_R^{(f)2}\right)$$

$$-\frac{m_f^2}{2m_1^2}\Bigg[\left(36c_L^{(f)2}+33c_L^{(f)}c_R^{(f)}+36c_R^{(f)2}\right)+\frac{16m_1^2}{M_{Z'}^2}\left(2c_L^{(f)2}+c_L^{(f)}c_R^{(f)}+2c_R^{(f)2}\right)$$

$$+\frac{10m_1^2}{\Delta m^2}\left(1-\frac{3}{2}\frac{\Delta m}{m_1}\right)\left(c_L^{(f)}+c_R^{(f)}\right)^2-\frac{65}{2}\frac{\Delta m}{m_1}\left(2c_L^{(f)2}+c_L^{(f)}c_R^{(f)}+2c_R^{(f)2}\right)$$

$$-\frac{24m_1\Delta m}{M_{Z'}^2}\left(2c_L^{(f)2}+c_L^{(f)}c_R^{(f)}+2c_R^{(f)2}\right)\Bigg]\Bigg\}+\mathcal{O}\left[\left(\frac{\Delta m}{m_1}\right)^7\right]+\mathcal{O}\left[\left(\frac{m_f}{m_1}\right)^4\right].$$

Z' decay width:

$$\Gamma_{Z'\to\chi_1\chi_2} = \frac{(c_L + c_R)^2}{48\pi} M_{Z'} K \left[1 + \frac{(m_1+m_2)^2}{2M_{Z'}^2}\right]\left(1 - \frac{m_2 - m_1}{M_{Z'}}\right)\left(1 + \frac{m_2 - m_1}{M_{Z'}}\right)$$

$$\Gamma_{Z'\to\chi_i\chi_i} = \frac{(c_R - c_L)^2}{96\pi} M_{Z'} \left(1 - \frac{4m_i^2}{M_{Z'}^2}\right)^{\frac{3}{2}}$$

$$\Gamma_{Z'\to\bar{f}f} = \sum_f N_c^{(f)} \frac{M_{Z'}}{24\pi}\sqrt{1 - \frac{4m_f^2}{M_{Z'}^2}}\left[\left(c_L^{(f)2} + c_R^{(f)2}\right) - \frac{m_f^2}{M_{Z'}^2}\left(c_L^{(f)2} - 6c_L^{(f)}c_R^{(f)} + c_R^{(f)2}\right)\right],$$

where:

$$K \equiv \sqrt{1 - 2\,\frac{m_1^2 + m_2^2}{M_{Z'}^2} + \left(\frac{m_2^2 - m_1^2}{M_{Z'}^2}\right)^2}$$

Thermal cross sections:

$$\langle \sigma v \rangle_{12} = \sum_f \frac{N_c^{(f)}}{32\pi} \frac{(c_L + c_R)^2}{\left(1 - \frac{(m_1+m_2)^2}{M_{Z'}^2}\right)^2} \frac{(m_1+m_2)^2}{M_{Z'}^4} \sqrt{1 - \frac{4 m_f^2}{(m_1+m_2)^2}}$$

$$\left[\left(c_L^{(f)2} + c_R^{(f)2} \right) - \frac{m_f^2}{(m_1+m_2)^2} \left(c_L^{(f)2} - 6 c_L^{(f)} c_R^{(f)} + c_R^{(f)2} \right) \right] + \mathcal{O}\left(\frac{1}{x}\right)$$

$$\langle \sigma v \rangle_{ii} = \sum_f \frac{N_c^{(f)}}{8\pi} \frac{(c_L - c_R)^2}{\left(1 - \frac{2m_i^2}{M_{Z'}^2} \frac{2x_i+3}{x_i}\right)^2} \frac{m_i^2}{M_{Z'}^4} \sqrt{1 - \frac{2m_f^2}{m_1^2} \frac{x_i}{2x_i+3}}$$

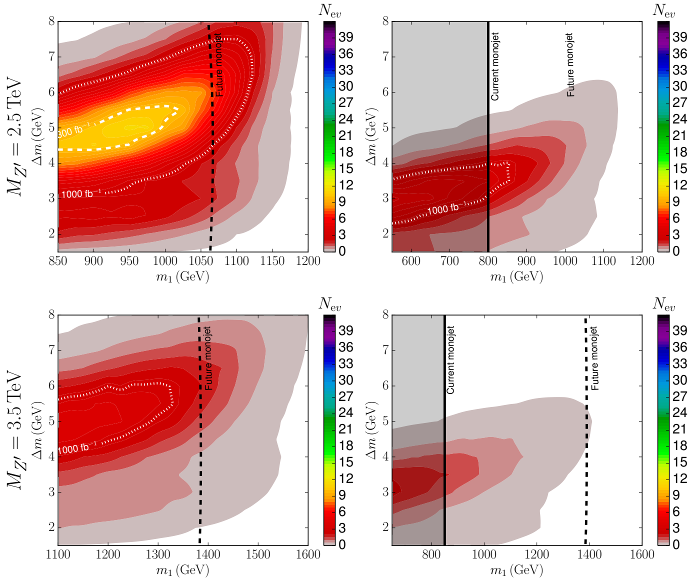
$$\left[\frac{c_L^{(f)2} + c_R^{(f)2}}{x_i} - \frac{m_f^2}{2m_1^2} \left(c_L^{(f)} - c_R^{(f)} \right)^2 \frac{x_i}{2x_i+3} \right] + \mathcal{O}\left(\frac{1}{x}\right)$$

DM-f scattering cross section:

$$\langle \sigma v \rangle_{\chi_1 f \to \chi_1 f} = \sum_f \frac{N_c^{(f)}}{16\pi} (c_L - c_R)^2 (c_L^{(f)} - c_R^{(f)})^2 \frac{\mu^2_{\chi_1 f}}{M^4_{Z'}} v$$

From arXiV:1603.04156, for axial-vector coupling and $c_L^{(f)} = -c_R^{(f)}$:

$$\sigma_{\rm SD} \simeq 2.4 \times 10^{-42}\,\mathrm{cm}^2 \cdot (c_R - c_L)^2 \left(c_L^{(f)}\right)^2 \left(\frac{1\,\mathrm{TeV}}{M_{Z'}}\right)^4 \left(\frac{\mu_{n\chi}}{1\,\mathrm{GeV}}\right)^2 .$$


$M_{Z'} = 2.5$ TeV
$M_{Z'} = 3.5$ TeV
Δm (GeV)
m_1 (GeV)
N_{ev}
Future monojet
Current monojet
300 fb^{-1}
1000 fb^{-1}