Searching for Sub-GeV Dark Matter at Fixed Target Neutrino Experiments

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[B. Batell, P. dN, D. McKeen, M. Pospelov, A. Ritz '14, to appear]
Motivation

Experimental limits for WIMP-Nucleon cross section

A Low Mass Dark Matter Scenario

Dark sector containing scalar DM $\chi$ and vector mediator $V$, with $m_V > 2m_\chi$.

$$\mathcal{L} = |D_\mu \chi|^2 - m_\chi^2 \chi^2 - \frac{1}{4} V_{\mu\nu}^2 + \frac{1}{2} m_V^2 V_\mu^2 + g_B V_\mu J_B^{\mu} - \frac{\kappa}{2} V_{\mu\nu} F^{\mu\nu} + \ldots$$

$$D_\mu = \partial_\mu - i g_B q_B V_\mu = \partial_\mu - i e' V_\mu$$

- Dark vector mediator interacts with SM through kinetic mixing with photon, coupling to baryonic current, or some combination of the two.

$$\mathcal{L} \supset V_{\mu} \left( g_B J_B^{\mu} - \kappa e J_{EM}^{\mu} \right)$$

- Five free parameters: $m_\chi$, $m_V$, $\kappa$, $g_B$ and $e'$.
  - $e'^2 = 4\pi\alpha'$ when we consider only kinetic mixing.
  - $e'^2 = 4\pi\alpha_B$ when we add coupling to baryons.
Fixed Target Neutrino Experiments

Experiments involve impacting a target with $\sim 10^{20} - 10^{22}$ protons to produce a high intensity neutrino beam.

- Neutrinos produced from decays of charged mesons.
- Can select for neutrino or antineutrino beams through the use of magnetic focusing horns.

- Non-neutrinos are removed from the beam before it reaches the target to reduce background.

- Several fixed target neutrino experiments were investigated: LSND, MiniBooNE, T2K.
Dark Matter Beams

Production of a dark matter beam through:

- Radiative decays of pseudoscalar mesons: $\pi^0$, $\eta$, $\eta'$.
- Coupling to vector mesons: $\rho$, $\omega$, $\phi$.
- Direct parton-level production: $p + N \rightarrow V^* \rightarrow \chi\bar{\chi}$

Detection through NCE scattering off electrons or nucleons. Very similar to neutrino NCE scattering.
Reducing Backgrounds: The MiniBooNE Off-Target Run

Neutrinos provide the primary background in these searches.

- Can discriminate between neutrinos and dark matter by differences in their timing, energy, and angular distributions.
- Neutrino production can be dramatically reduced by performing an off-target or beam dump run.
  - Unfortunately not compatible with neutrino running.
- The MiniBooNE experiment is currently conducting such a run, expects to collect $1-2 \times 10^{20}$ POT (PAC proposal [arXiv:1211.2258v1, with R. Van de Water]).
MiniBooNE Kinetic Mixing - $\chi N \rightarrow \chi N$

PRELIMINARY
MiniBooNE Kinetic Mixing - $\chi^e \rightarrow \chi^e$

PRELIMINARY
T2K P0D Kinetic Mixing

\[ N_X \rightarrow N_X \quad m_X = 10 \text{ MeV} \quad \alpha' = 0.1 \quad \text{POT} = 5 \times 10^{21} \]

\[ N_X \rightarrow N_X \quad m_V = 1 \text{ GeV} \quad \alpha' = 0.1 \quad \text{POT} = 5 \times 10^{21} \]

\[ m_V (\text{GeV}) \]

\[ \sigma_N (\text{cm}^2) \]

PRELIMINARY
Summary

- Thermal relic WIMP with a sub-GeV mass and interactions mediated by a light U(1)′ vector boson provides a viable dark matter candidate.
- This candidate escapes many of the best limits imposed by standard direct, indirect and collider searches.
  - While new limits are being placed on the parameter space, a great deal of viable parameter space remains unconstrained. Electron fixed target experiments could reduce this further.
- Variants on this model, such as a baryonically coupled U(1)$_B$ vector boson, can escape many of these new constraints.
- Fixed Target Neutrino Facilities possess good sensitivity to these hidden-sector scenarios.
  - Capable of probing regions of the hidden-sector parameter space currently inaccessible to other techniques while using a straightforward counting approach.
- Running a Fixed Target Neutrino Experiment in an off target mode could provide new sensitivity, while requiring far fewer POT.
  - A test of this approach is being conducted by the MiniBooNE experiment
Acknowledgements

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Kinetic Mixing Constraints

[arXiv:1205.2671 [hep-ex]]

Aoyama’12, [arXiv:1205.5368 [hep-ph]], Endo’12,
[arXiv:1209.2558 [hep-ph]].
[arXiv:1309.5084[hep-ph]]
Choosing a Portal

For $m_V > 2m_\chi$

- **U(1)' Mediator - Vector Portal**
  - **Fermionic DM** - s-wave annihilation and an increased dark matter number density due to the low dark matter mass results in a visible distortion of the CMB. Also leads to a more visible signal from galactic center. [Padmanabhan & Finkbeiner et al '05; Slatyer et al '08]
  - **Scalar DM** - p-wave annihilation allows this scenario to be viable for small $\kappa$, as the annihilation rate is suppressed by an additional factor of $v$. A small $v$ heavily suppresses the dark matter annihilation rate.

- **Scalar Mediator - Higgs Portal**
  - **Scalar DM** - s-wave annihilation excludes this scenario for the reasons given previously.
  - **Fermionic DM** - p-wave annihilation renders this model viable. However, fermionic DM requires a large mixing, which could affect $B$ decays. [Bird, Kowalewski & Pospelov 2006]