Next Generation Proton Beam Dump Searches for Dark Matter

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Basic proton beam - target - detector setup

Neutrino beam

$$\pi^+ \rightarrow \mu^+ \nu_\mu$$

10m - 100km
A dark matter beam!

[BB, Pospelov, Ritz '09]
[deNiverville, Pospelov, Ritz '11]
[deNiverville, McKeen, Ritz '12]
New forces \rightarrow \text{viable light thermal relic dark matter} \\
\text{Scalar DM: p-wave annihilation, CMB ok} \\
\text{Dark photon can address g-2 anomaly}
Production of the Dark Matter beam

Decays of mesons:

Direct production

Detection via scattering

\( \chi - e^- \) elastic

\( \chi - \text{nucleon elastic} \)

\( q - \bar{q} \) deep inelastic

(not studied yet)
Low Mass WIMP Searches with a Neutrino Experiment: A Proposal for Further MiniBooNE Running

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MiniBooNE

- 8.9 GeV proton beam
- 1.8 \times 10^{21} Protons on Target (POT) delivered
- Beryllium target, 71 cm length, 1 cm diameter; 1.7 interactions lengths
- 50 m long decay volume (filled with air)
- Detector: 12 m diameter sphere, 800 tons of mineral oil, 1520 PMTs
- Magnetic Horn focuses charged hadrons
Proton Beam | Target | Absorber | Dirt | Detector

\[ p \]

540 m
Beating down the neutrino background

The signature of dark matter is a neutral current scattering event

Very similar to neutrino induced neutral current event!

Focus beam onto an absorber!

8 GeV protons

25 m deployable absorber

50 m absorber

Dirt

Detector

Neutrino background reduced by up to 2 orders of magnitude!
Neutrino Rate Reduction with Beam Off Target Running (1 week test run)

- Estimated neutrino rate reduction:
  - 50m absorber one week beam off target run (~5.54e18 POT):
    \[(\text{events/POT})^{\nu \text{ mode}} / (\text{events/POT})^{\text{beam off target}} = 42 \pm 7\]
  - 50m MC: \[(\text{events/POT})^{\nu \text{ mode}} / (\text{events/POT})^{\text{beam off target}} = 36\]
  - 25m MC: \[(\text{events/POT})^{\nu \text{ mode}} / (\text{events/POT})^{\text{beam off target}} = 72\]

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data from R. Van De Water
MiniBooNE Sensitivity

[Aguilar-Arevalo et al., arXiv:1211.2258]

See also talk by R. Van de Water at Snowmass IF5 Meeting

https://indico.fnal.gov/contributionDisplay.py?contribId=38&sessionId=4&confId=6248
OscSNS

- 1 GeV protons at Spallation Neutron Source,
- $2.2 \times 10^{23}$ POT/yr
- liquid mercury target
- detector: 60m back of the target, cylindrical, 800 tons mineral oil

Sensitivity to $\chi_e \rightarrow \chi e$

Factor of 2-3 improvement in $\kappa$

[BB, Essig, Surujon, to appear]
NuMi/MINOS

- Fermilab Main Injector, 120 GeV protons
- \(\sim 10^{21}\) POT
- Near Detector: Layered steel & plastic scintillator, 4.8m x 3.8m 16.6m, 965 m from target \(\theta_{\text{det}} \sim 0.2^\circ\)

In principle there is sensitivity, however...

- New ideas needed to overcome large neutrino background
- Studies of deep inelastic scattering do not yet exist

Yield for \(\chi\bar{N} \rightarrow \chi N\) elastic scattering

[deNiverville, McKeen Ritz, ’11]
NOvA

- Fermilab Main Injector, 120 GeV protons
- \( \sim (6-10) \times 10^{20} \) POT/yr
- Near Detector: Off-Axis 14.6 mrad, liquid scintillator cells
  \( 2.8 \text{ m} \times 4.1 \text{ m} \times 14.3 \text{ m}, \sim 1 \text{ km from target}, \theta_{\text{det}} \sim 0.2^\circ \)

LBNE

- Fermilab Main Injector, 120 GeV protons
- \( \sim 5 \times 10^{20} \) POT/yr
- Near Detector: Straw Tube tracker + ECAL
  \( 3.5 \text{ m} \times 3.5 \text{ m} \times 7.5 \text{ m}, \ 500 \text{ m from target}, \theta_{\text{det}} \sim 0.4^\circ \)

Dedicated studies needed!

Again, main obstacle is the neutrino neutral current background
Project X: New high-intensity proton source

3 MW at 3 GeV $\rightarrow$ potential for $\sim 10^{23} \frac{\text{POT}}{\text{yr}}$
Overcoming the neutrino background

- Neutrinos produced from meson decays in the decay pipe
MiniBooNE proposal: run protons into the dump

Neutrino background reduced by factor of $\sim 50$
Still, neutrinos produced through proton - air reactions in decay pipe

\[ pA \rightarrow \pi^+ X \]

\[ \pi^0, \eta^0 \rightarrow \gamma V \]

\[ V \rightarrow \chi \chi^* \]
Optimally, dump should be positioned immediately following beam line.

Evacuated beam line

Neutrino background potentially reduced by factor of ~ 2-3 orders of magnitude!
Currently, none of the existing or proposed experiments can run in such a mode

Either

- Design a dedicated beam line/dump experiment (requires new detector)
- Adapt existing proposals, e.g. add spur line to LBNE:
Timing

Dark matter is heavier than neutrinos - arrives at the detector later!
e.g. at MiniBooNE

8 GeV protons

RWM

Neutrons produced in p-Air interactions traveling at c and in phase with beam RF structure

π⁰ and η produced by protons quickly decay producing WIMPs (X)

540 m = 1800 nsec at c

WIMPs can travel slower than c
Timing

\[ p_L = 1.5 \text{ GeV} \]

<table>
<thead>
<tr>
<th>Timing cut (nsec)</th>
<th>Background Reduction (%)</th>
<th>WIMP Velocity ( \beta )</th>
<th>WIMP Mass (MeV)</th>
</tr>
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<tbody>
<tr>
<td>3.0</td>
<td>90</td>
<td>0.9984</td>
<td>85</td>
</tr>
<tr>
<td>4.6</td>
<td>99</td>
<td>0.9974</td>
<td>108</td>
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<tr>
<td>5.9</td>
<td>99.9</td>
<td>0.9967</td>
<td>122</td>
</tr>
</tbody>
</table>
Defocusing

Typically, neutrinos are focused toward the target by a magnetic horn.

Instead, defocus charged particles, using $E$ or $B$ field.
Beyond portals

Portals are the simplest way to couple dark matter to SM, but we should keep an open mind to other possible mediators.

Experiments will put a limit (or see an excess!) on number of neutral current events. Can be interpreted in a variety of ways.

If dark matter couples dominantly to quarks, proton beams will have unique sensitivity. If instead it couples dominantly to electrons, then electron beams will have unique sensitivity.

Given that we know absolutely nothing about how/if DM interacts with the SM, it is important to pursue both approaches!

As an aside: there is interesting work to be done here also on the theory/pheno side, in terms of model building (are there other interesting, viable ways to couple light DM to SM?), and “model independent” characterization of results.
Simplified model: Vector coupled to baryon current

\[ \mathcal{L} \supset -\frac{1}{4} V_{\mu\nu}^2 + |(\partial_\mu - ig_b Q_b V_\mu)\chi|^2 + \bar{q}i\gamma^\mu(\partial_\mu - ig_b \frac{1}{3} V_\mu)q \]

Constraints from precision QED, B-factories & electron fixed targets do not apply

Proton beams have unique sensitivity, e.g. MinBooNE:
Outlook

• Proton and electron beam dumps offer a new way to search for dark matter in a difficult region of parameter space

• Complementary to traditional probes, such as direct detection experiments

• First analysis is underway at MiniBooNE ... limits soon!

• Main obstacle is neutrino neutral current background
  • Dump, Timing, Defocusing... new ideas needed

• Future neutrino experiments could run in a ``Dark matter mode”, or can design dedicated experiments

• Early days! Studies needed for both theory and experiment