Search for Dark Matter in the beam-dump of a proton beam with MiniBooNE

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Outline

Motivation: Sub-GeV dark matter
MiniBooNE detector
Dark Matter search in beam-dump mode
Results
Lessons learned and future perspectives
Conclusions
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Motivation

- Sub-GeV mass range significantly less explored, but theoretically well motivated.
- Accessible, among others, with accelerator beam dump experiments.

What about here?
- nuclear recoils too weak

Sub-GeV Dark Matter

• Evidence of Dark Matter motivates extending the Standard Model to include a “Dark Sector” → new fields with no SM gauge charges.

• DM particles in the Dark Sector couple to the SM via a “mediator”.

• Many possible ways to connect the Standard Model and the Dark Sector, constrained by SM symmetries (called portals):

  - **Vector portal** → vector mediator $V^\mu$
  - **Higgs portal** → scalar mediator $\phi$
  - **Neutrino portal** → fermion mediator $N$

  3 renormalizable portals to the SM

• **Vector portal** models → most viable for thermal, sub-GeV DM.

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Minimal kinetically mixed dark photon

• A minimal extension to the Standard Model:

\[ \mathcal{L}_{V,\chi} = |D_\mu \chi|^2 - m_\chi^2 |\chi|^2 - \frac{1}{4} V_{\mu\nu}^2 + \frac{1}{2} m_V^2 V_\mu^2 + \epsilon V_{\mu\nu} F_{\mu\nu}^\mu + \ldots \]

\[ D_\mu = \partial_\mu - ig_D V_\mu, \quad g_D = \sqrt{4\pi \alpha_D} \]

4 parameters: \( m_\chi, m_V, \epsilon, \alpha_D \)


• \( U(1)_D \) gauge boson ("dark photon") increases the DM annihilation cross section to give the correct relic density.

• Mediator with mass \( O(10^{-3}) \) MeV could resolve the \((g-2)_\mu\) anomaly.

M. Pospelov, Phys. Rev. D 80, 095002 (2009)
Dark Matter Beam and Detection

- Production in high-energy collisions and detection by scattering.

Event rate: $\sim e^4 \alpha_D$, for $m_V > 2m_\chi$ (invisible decay of $V$).

Why a beam dump experiment?

- Neutrino interactions are a background to such DM search.
- A beam dump produces significantly fewer neutrinos.

**Neutrino production target (thin)**

Charged mesons escape and produce $\nu$'s

- $\pi^0$ decay quickly into dark sector
- $\pi^+$ decay with longer lifetime into high-energy neutrinos

**Beam dump (thick target)**

- $\pi^0$ decay quickly into dark sector
- $\pi^+$ absorbed before decay to $\nu$'s (or DAR to low-energy $\nu$'s)
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The MiniBooNE detector

- 800 tons of mineral oil (CH$_2$)
- Cherenkov detector with some scintillation from trace fluors
- 1280 inner and 240 veto PMTs
- Ran for $>10$ yr in $\nu$ and $\bar{\nu}$ modes and has published 27 papers.
- The detector is well understood
MiniBooNE before ”-DM”

- Ran for over 10 years:
  - $\nu$-mode ($6.7 \times 10^{20}$ POT)
  - $\bar{\nu}$-mode ($11.5 \times 10^{20}$ POT)
- 11 oscillation papers
- 14 cross section and flux papers
- 19 Ph.D. Theses

See our website for a full list of publications. [http://www-boone.fnal.gov/](http://www-boone.fnal.gov/)
Booster Neutrino Beam (BNB)

- Beam: 8 GeV protons
- Target: Be
- Distance to MiniBooNE: 541 m
- Stable and well understood
CCQE and NCE events

CCQE: Charged-Current Quasi-Elastic
Single $\mu$ events + decay $e$

NCE: Neutral-Current Elastic
Low hits activity with no $\mu$ or $\pi$

- First double differential cross-section measurement.
- Absolute and relative (to CCQE) cross-sections.

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Beam Dump (Off Target) mode

- Reduce $\nu$ production by steering beam to miss the target.
- Beam impacts on the beam dump
- Charged mesons absorbed in the steel beam dump before decaying $\rightarrow$ reduces the neutrino flux.

MiniBooNE target assembly

Target | Decay Pipe | Beam Dump | MiniBooNE Detector

- $p$ on Be in Air
- $\pi^0$ and $\gamma$ from $\nu$ decay
- $\chi^+$ from charged meson decay
- $\chi$ in Steel
- $N$ in Earth

50 m | 4 m | 487 m
Neutrino flux reduction

Off-Target flux: \( \Phi_{\text{off}} = (1.19 \pm 1.1) \times 10^{-11} \text{v/(POT \cdot cm}^2) \), \( 0.2 < E_v < 3 \text{ GeV} \)

Comp. to \( \nu \)-Mode: - Flux reduced by factor of \(~30\)
- Event rate reduced by factor of \(~50\).
Off Target beam stability

- Ran 9 months, Nov 2013 to Sep 2014, collected $1.86 \times 10^{20}$ POT.
- $\nu$/POT decreased by ~50 compared to $\bar{\nu}$ Mode.
N-DM event selection

Single $p/n$ track with a few hundred MeV kinetic energy.

- 1 Track (single recoil) in beam timing window
- Event is centralized contained
  - No activity in the veto
  - Within tank fiducial volume
- Signal above visible energy and number of hits threshold.
- PID: Nucleon or electron

Based on the $\bar{\nu}$ NCE cross section analysis.

Dark Matter generator

- Used BdNMC to generate $T_N^{true}$ event lists.
- Produced event lists $m_\nu \in [0.01,0.1]$ GeV and $m_\chi \in [0.001,m_\nu/2]$ GeV
- Included $\pi^0/\eta$-decay and Bremsstrahlung channels.

- $\pi^0/\eta$ event lists from beam MC used to generate $\pi^0$ and $\eta$ distributions.

Fit strategy

- Use 4 distributions:
  - CCQE <sub>ν</sub> neutrino-Mode
  - CCQE<sub>Off</sub> BDump-Mode
  - NCE<sub>ν</sub> neutrino-Mode
  - NCE<sub>Off</sub> BDump-Mode (signal)

- CC ratios help reduce flux uncertainties.
- NC ratios help reduce neutrino cross section uncertainties.
Simultaneous Fit

Covariance matrix
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**NCE\textsubscript{Off} distribution**

- Data consistent with background-only.
- Systematics dominated.
- Constrain samples reduce systematic error to 13%.

### #events and uncertainty

<table>
<thead>
<tr>
<th>Source</th>
<th>#events</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam unrelated bkg</td>
<td>697</td>
<td></td>
</tr>
<tr>
<td>Beam rel: (\nu\text{det}) bkg</td>
<td>775</td>
<td></td>
</tr>
<tr>
<td>Beam rel: (\nu\text{dirt}) bkg</td>
<td>107</td>
<td></td>
</tr>
<tr>
<td><strong>Total Bkg</strong></td>
<td>1579</td>
<td>34% (pred. sys.)</td>
</tr>
<tr>
<td><strong>Data</strong></td>
<td>1465</td>
<td>3% (stat.)</td>
</tr>
<tr>
<td><strong>Fit Results</strong></td>
<td>1548</td>
<td>13% (fit effective error)</td>
</tr>
</tbody>
</table>
Only considered on-shell decays \( (m_V > 2m_\chi) \)

CL limit on \( \epsilon^4 \alpha_D \) for a given \( m_V \) and \( m_\chi \).

Slice to compare to other experiments.
Results

- **In most of par. space:** exclude model solutions to the $(g-2)_\mu$ anomaly
- **in some of par. space:** exclude model solutions matching the relic density.
- **Overall:** new regions of parameter space excluded.
- **Cover most of the gap between** $1 \text{ MeV} < m_\chi < \text{direct detection.}$
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• Understand the Backgrounds
  - Used a decade worth of data to reduce systematic errors.
  - Large detector w/veto → reduce events from dirt around it.
  - Beam-unrelated backgrounds measured with 12 (2) Hz random trigger in off-target (ν) Mode.

• Nuclear physics must be considered
  - Final sensitivity affected by uncertainties from nuclear effects (eg. binding energy, Pauli blocking).
  - Honest sensitivity estimate must include a decent nuclear model.

• Correlations can be very helpful
  - Include sideband analyses (samples may be correlated)
  - Correlations → constrained systematic uncertainties in signal sample.
Future MB analyses

- Proton beam is comprised of 81 ns RF pulses (buckets)
- Massive dark matter will propagate sub-luminal
- Characteristic intra-bunch timing improve “high” mass dark matter sensitivity
## Future MB analyses

### Electron-DM Elastic

- MiniBooNE searched for $\nu_\mu \rightarrow \nu_e$ oscillations.
- Excellent electron tracker.
- $\nu_e + e \rightarrow \nu_e + e$ is dominant background $\rightarrow$ clean SM prediction.
- Connected to low-energy excess from oscillation search.

### $\Delta$ Resonance ($\pi^0$)

- Neutral pion $\pi^0$ decays to 2 energetic photons.
- Main background to $\nu_e$ oscillation $\rightarrow$ well studied.
- Hard to fake with beam-unrelated backgrounds.
- Estimate 1-10 total “strobe” events.
Future: a dedicated beam dump

- Off-tgt mode ν’s also from:
  - proton beam halo “scraping” against material
  - Proton interactions with air in the decay pipe
- Idea: *
  - remove BNB target and focusing horn.
  - Replace with dedicated steel dump at end of beam pipe.

* A non-trivial upgrade to the BNB → convert/enhance the Short Baseline Neutrino (SBN) program to a sub-GeV DM search program?
(see talk by R. Van de Water @ Cosmic Visions Workshop 2017)
Short Baseline Neutrino (SBN) program

- Motivated by LSND/MiniBooNE to study $\nu$ oscillations. To begin operations in 2018.
- Short Baseline Near Detector (SBND) $\rightarrow$ Ideal for beam dump sub-GeV DM search.
DM search with SBND

e & \pi^0 channel

• SBDN closer to target ⇒ increased signal rate (≈x9).

• Signal/Background estimates robust, learned from MB N-DM search.

• \pi^0 (e) good at high (low) masses - complementary to each other.

• Improve on current MiniBooNE limit by an order of magnitude.

• Require improved beam dump
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- MiniBooNE collected data \((1.86 \times 10^{20} \text{ POT})\) in beam-off-target mode to search for sub-GeV dark matter.


- First of its kind proton beam dump search with a large well characterized neutrino detector (dedicated collab).

- Nucleon-DM elastic scatter analysis is complete e-DM and inelastic \(\pi^0\) channels are underway.

- Future opportunities (e.g. DM search with SBN) are being explored.
Thank you for your attention!

Backups
## Previous beam dump / Fixed Target experiments – Proton Beams

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Location</th>
<th>approx. Date</th>
<th>Amount of Beam ($10^{20}$ POT)</th>
<th>Beam Energy (GeV)</th>
<th>Target Mat.</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>CHARM</td>
<td>CERN</td>
<td>1983</td>
<td>0.024</td>
<td>400</td>
<td>Cu</td>
<td>[16]</td>
</tr>
<tr>
<td>PS191</td>
<td>CERN</td>
<td>1984</td>
<td>0.086</td>
<td>19.2</td>
<td>Be</td>
<td>[17, 18]</td>
</tr>
<tr>
<td>E605</td>
<td>Fermilab</td>
<td>1986</td>
<td>$4 \times 10^{-7}$</td>
<td>800</td>
<td>Cu</td>
<td>[19]</td>
</tr>
<tr>
<td>SINDRUM</td>
<td>SIN, PSI</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>$\nu$-Cal</td>
<td>IHEP Serpukhov</td>
<td>1989</td>
<td>0.0171</td>
<td>70</td>
<td>Fe</td>
<td>[20–22]</td>
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<tr>
<td>LSND</td>
<td>LANSCE</td>
<td>1994-1995</td>
<td>813</td>
<td>0.798</td>
<td>H$_2$O, Cu</td>
<td>[23]</td>
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<tr>
<td></td>
<td></td>
<td>1996-1998</td>
<td>882</td>
<td></td>
<td>Cu, W</td>
<td></td>
</tr>
<tr>
<td>NOMAD</td>
<td>CERN</td>
<td>1996-1998</td>
<td>0.41</td>
<td>450</td>
<td>Be</td>
<td>[18, 24]</td>
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<tr>
<td>WASA</td>
<td>COSY</td>
<td>2010</td>
<td>0.550</td>
<td></td>
<td>LH2</td>
<td>[25]</td>
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<tr>
<td>HADES</td>
<td>GSI</td>
<td>2011</td>
<td>0.32 pA*t</td>
<td>3.5</td>
<td>LH$_2$, No, Ar+KCl</td>
<td>[26]</td>
</tr>
<tr>
<td>MiniBooNE</td>
<td>Fermilab</td>
<td></td>
<td></td>
<td></td>
<td>Be</td>
<td>[27]</td>
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<tr>
<td></td>
<td></td>
<td>2003-2008</td>
<td>$6.27$</td>
<td></td>
<td>Be</td>
<td>[28]</td>
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<tr>
<td></td>
<td></td>
<td>2005-2012</td>
<td>$11.3$</td>
<td>$8.9$</td>
<td>Be</td>
<td>[29]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2013-2014</td>
<td>$1.86$</td>
<td></td>
<td>Steel</td>
<td></td>
</tr>
</tbody>
</table>

Table by R.T. Thornton, Indiana University Nuclear Physics Seminar, Nov. 21, 2014
Future MB analyses

Electron Scattering  \(\pi^0\) production  Leptophobic Model

- Will exclude new parameter space in vector portal kinetic mixing theory.
- Produced Model Independent Fit (MIF) for use with other theories.
- MIF used to set CL in leptophobic theory (very significant exclusion).
- Timing analysis underway to improve sensitivity to heavier masses.
- Future MiniBooNE analysis is promising.
Leptophobic Dark Matter

- It is possible that dark matter couples dominantly to quarks.
- Many constraints are evaded - proton beams have a significant advantage!
- Simplified model (based on local $U(1)_B$ baryon number)

\[ \mathcal{L} = i \bar{\chi} \gamma^\mu D_\mu \chi - m_\chi \bar{\chi} \chi - \frac{1}{4} (V_B^{\mu \nu})^2 + \frac{1}{2} m_V^2 (V_B^\mu)^2 + \frac{g_B}{3} V_B^\mu \sum_i \bar{q}_i \gamma_\mu q_i + \ldots \]

\[ D_\mu = \partial_\mu - ig_B q_B V_B^\mu \]


- 4 new parameters: $m_\chi, m_V, \alpha_B, q_B$
- $U(1)_B$ is “safe” - preserves approximate symmetries of SM (CP, P, flavor)
- Gauge anomalies can be canceled by new states at the weak scale
BdNMC

[deNiverville, Chen, Pospelov, Ritz]
https://github.com/pgdeniverville/BdNMC/releases

- Publicly available proton beam fixed target DM simulation tool developed by Patrick deNiverville (U. Victoria) and collaborators.

Detailed DM production model:

Neutral mesons decays

Bremsstrahlung + vector meson mixing

Direct production

Several DM scattering processes included

Elastic NC nucleon or electron scattering

Inelastic NC neutral pion - like scattering

Deep Inelastic scattering