Hunting for Boosted DM

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Physics Motivation?
Surface ν Detectrors: SBN

- Short-Baseline Neutrino (SBN) Program @ Fermilab

Physics @ SBN: ν oscillation, sterile ν, etc.

- E spectrum & flavor of ν's produced by the Booster Neutrino Beam

- Development of the LAr-TPC technology for DUNE
ProtoDUNE: a prototype of the Deep Underground Neutrino Experiment (DUNE) @ CERN

- SP: single-phase
- DP: dual-phase

Physics @ DUNE: neutrino, BSM, etc.

- To test the long-term stability & operation
- To calibrate beam & cosmic-ray responses
MicroBooNE: on-going since July 2015 (BNB: operational since October 2015)
ICARUS: planned to start of operation in 2019
SBND: planned to start of operation in 2019/2020
ProtoDUNE: operation from September 2018 & now planned to take cosmic-origin data for new physics searches (~2 year)
Surface ν Detectors

Other Physics Motivation?

Any physics potential with the SBN/ProtoDUNE detectors, especially BSM physics?
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- Signal events would get buried inside the huge cosmic backgrounds.
- Search for cosmic-origin new physics signal @ surface detectors is hopeless.
- Solution: Installing detectors deep under the ground!
I. Signals leaving appreciable tracks: the source direction is inferred from the track.
   → Restricting to events coming through the Earth from the opposite side of the detector location.
   → Potential backgrounds in that direction are significantly suppressed while signals are intact. (Similar to up-going $\nu$ searches @ SK, IceCube, NOvA, etc.)

Kim, Kong, JCP, Shin [1804.07302]

II. A signal with many unique features (e.g. iBDM): Possible to isolate signal events from cosmic background events efficiently.
   (due to good detector performance: positon/angular/energy resolution, etc.)

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Target Approach

Earth Shielding
(Benchmark: Boosted DM)
Two-component BDM Scenario

G. Belanger, JCP (2011)

\[ \frac{Z_2}{U(1)'} \rightarrow \frac{Z'_2}{U(1)''} \]
Two-component BDM Scenario

G. Belanger, JCP (2011)

“Assisted Freeze-out” Mechanism

- Heavier relic $\chi_0$: hard to detect it due to tiny coupling to SM
- Lighter relic $\chi_1$: hard to detect it due to small relic

$\chi_1$: Negligible, Non-relativistic relic
Two-component BDM Scenario

$x_0 x_0 \rightarrow x_1 x_1$ (current universe): **Relativistic!!** ($\gamma_1 = m_0/m_1$)

(Note that relic $x_1$ is non-relativistic.)

$Z_2/U(1)'$   $Z'_2/U(1)''$

$x_0$   $x_1$   $x_1$   $x_0$

$\lambda_1$   $\lambda_0$

(relic)

(Galactic Center)

(becomes boosted)

(Laboratory)

G. Belanger, *JCP* (2011)

[Agashe, Cui, Necib, Thaler (2014)]
 Expected Signatures

- **Ordinary elastic** scattering (eBDM): only electron/proton recoil ➔ **single track**
- Tracks will **pop-up** inside the fiducial volume.
- Focus on e-recoil. But, Straightforwardly applicable to p-recoil (up to form factor, DIS, etc.)

Fiducial vol. of detector
Flux of BDM & its Detection

- Flux of boosted $\chi_1$ around the Earth

$$F_{\chi_1} \propto \frac{\langle \sigma v \rangle_{\chi_0 \chi_0 \rightarrow \chi_1 \chi_1}}{m_0^2}$$

from the number density of DM $\chi_0$, $n_0 = \rho_0 / m_0$

- Setting $\langle \sigma v \rangle_{\chi_0 \chi_0 \rightarrow \chi_1 \chi_1} \sim 10^{-26}$ cm$^3$/s & assuming NFW DM halo profile,

$$F_{\chi_1} = O(10^{-1} - 10^{-6}) \text{ cm}^{-2} \text{s}^{-1}$$ for $m_0 = \sim 30$ MeV to $\sim 10$ GeV

✓ Not small enough for small-volume ($\sim 1$ ton) detectors to have signal sensitivity (e.g., conventional WIMP detectors: Xenon1T, LZ, COSINE-100(+2 ton LS), ...)

✓ Big enough for sub-kton (e.g. ProtoDUNE, SBN) to observe signal events (better position/angle/vertex resolution & particle identification, lower $E_{th}$ compared to Super-Kamiokande)
Earth Shielding

- **BG**: Cosmic muons
- **Signal**: Boosted DM

- Background and signal events are coming from everywhere.
- Half of them travel through the Earth.
Earth Shielding

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- ✔ Background and signal events are coming from everywhere.
- ✔ Half of them travel through the Earth.
- ✔ Backgrounds cannot penetrate the Earth while signals can!
Earth Shielding

- **BG**: Cosmic muons
- **Signal**: Boosted DM

✓ Background and signal events are coming from everywhere.
✓ Half of them travel through the Earth.
✓ Backgrounds cannot penetrate the Earth while signals can!

- Accept only **events traveling through the Earth** (i.e., coming out of the bottom surface) at the price of half statistics (for a cumulatively isotropic signal);
  - **direction** inferred from recoil track
  ➣ Essentially, **no cosmic-origin BGs** except Atm neutrino BG (cf. observation of upward-muons induced by muon neutrinos created by DM annihilation [NOvA Collaboration, in progress])
Expected Signatures (Reminder)

- Ordinary elastic scattering (eBDM): only electron/proton recoil ➔ single track
- Tracks will **pop-up** inside the fiducial volume.
- Focus on e-recoil. But, Straightforwardly applicable to p-recoil (up to form factor, DIS, etc.)

Fiducial vol. of detector
Potential Backgrounds

Active vol.
Potential Backgrounds

- **Low E particles** ($\lesssim 30$ MeV) can be removed/suppressed by taking a fiducial vol. smaller than the active vol. (Fiducial vol.: e.g. $\sim 170$ t/$300$ t for ProtoDUNE DP/SP)

$\sim 35$ cm from active volume boundary

(DUNE CDR-Vol.4)
Potential Backgrounds

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- **High E particles** (e.g., muon) create tracks incoming outside the fiducial vol., which can be rejected by a trigger and the post-analysis.

$\Rightarrow$ A large flux is expected for the detectors placed on the ground, e.g., ProtoDUNE, SBN.
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  - **A large flux** is expected for the detectors placed on the ground, e.g., ProtoDUNE, SBN.

- **(Atmospheric) neutrinos** are (potentially) irreducible.
  - $\sim 40$ single-track $e$-like events/yr/kt
Low E particles (≤ 30 MeV) can be removed/suppressed by taking a fiducial vol. smaller than the active vol. (Fiducial vol.: e.g. ~170 t/300 t for ProtoDUNE DP/SP)

High E particles (e.g., muon) create tracks incoming outside the fiducial vol., which can be rejected by a trigger and post-analysis.

(Airshelpheric) neutrinos are (potentially) irreducible.

→ ~40 single-track e-like events/yr/kt
 Effective Data Collection for 1yr-Run

\( \nu \) 40 neutrino-induced e-like, single-track events/yr/kt

\( \mathcal{F}_{\chi_1} \sim \bar{D}_f \times (10^1 - 10^6) \text{cm}^{-2} \text{yr}^{-1} \)

\( D_f \): effectively a certain fraction of day when the Earth Shielding effect can be utilized, with respect to the source core.
(e.g. for Sun: effectively, half year for one year run \( D_f = 1/2 \))
Number of Signal Events

- Number of signal events $N_{\text{sig}}$ is

$$N_{\text{sig}} = \sigma_\varepsilon \cdot D_f \cdot \mathcal{F} \cdot t_{\text{exp}} \cdot N_e$$

- $\sigma_\varepsilon$: scattering cross section between $\chi_1$ (BDM) and electron (target)
- $D_f$: data collection fraction of day
- $\mathcal{F}$: flux of incoming (boosted) $\chi_1$
- $t_{\text{exp}}$: exposure time
- $N_e$: total number of target electrons

Realistic experimental effects such as cuts, $E_{\text{th}}$ are absorbed into $\sigma_\varepsilon$. 

Controllable! (once a detector is determined)
1-year exposure: effectively half-year data collection \((D_f = 1/2)\) is assumed.

The limits from all-sky data: DM halo model-independent (up to total flux) and obtained w/o any particular model assumption to describe the interaction between SM particles & BDM.

Angular cuts improve the experimental sensitivities at the cost of DM halo model-dependence (optimal \(\theta_C\) values differ detector-by-detector & run time).
Mass spectra: dark photon decays into DM pairs, i.e., $m_X > 2m_1$

1-year data collection from the entire sky and $g_{11} = 1$ are assumed.

A wide range of **unexplored** parameter space can be probed even with surface-based detectors.

\[
\mathcal{L}_{\text{int}} \equiv -\frac{\epsilon}{2} F_{\mu\nu} X^{\mu\nu} + g_{11} \bar{\chi}_1 \gamma^\mu \chi_1 X_\mu + g_{12} \bar{\chi}_2 \gamma^\mu \chi_1 X_\mu + h. c.
\]

Based on **Assisted FO** set-up [Belanger, JCP (2011)]
Dark X Parameter Space: Visible X Decay

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Based on Assisted FO set-up
[Belanger, JCP (2011)]
MHP Dark Matter Post-Workout Muscle Growth Accelerator, Blue Raspberry, 3.22 Pound

Flavorful Dark Sector?!

Price: $36.09 ($11.21 / Pound) & FREE Shipping. Details

In Stock. Ships from and sold by Amazon.com. Gift-wrap available.

2 Flavors: Blue Raspberry

- Blue Raspberry

Want it tomorrow, Aug. 9? Order within 3 hrs 35 mins and choose One-Day Shipping at checkout. Details

About the product
- The ultimate post workout muscle growth accelerator
- 600% increase in protein synthesis
- Absorbs faster than whey isolate
Conclusion

- (light) BDM search is promising & provides a new direction to study DM phenomenology.
- Huge cosmic-ray BG can be well controlled with the “Earth Shielding” effect.
- **Surface detectors** possesses excellent sensitivities to a wide range of (light) BDM
  - allows a deeper understanding in non-minimal dark sector physics.
- **Surface detectors** can provide alternative avenue to probe dark photon parameter space.

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Focus of this talk!

<table>
<thead>
<tr>
<th>Scattering</th>
<th>$v_{DM}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$v_{DM} \ll c$</td>
</tr>
<tr>
<td><strong>elastic</strong></td>
<td>Direct detection</td>
</tr>
<tr>
<td><strong>inelastic</strong></td>
<td>inelastic DM (iDM)</td>
</tr>
</tbody>
</table>
Back-Up
Muon Flux inside the Earth

- $N_\mu$ at sea level is $\sim 100 \, m^{-2}s^{-1}sr^{-1} = 3 \times 10^9 \, m^{-2}yr^{-1}sr^{-1}$. [Particle Data Group (2015)]

- $N_\mu$ at 20 km.w.e. $\approx 7$ km below sea level is $\sim 10^{-9} \, m^{-2}s^{-1}sr^{-1}$, i.e., suppressed by a factor of $\sim 10^{11}$.

  \begin{align*}
  \text{(Potential) muon-induced BG is negligible for muons incident at } \theta > \theta_{cr}.
  \end{align*}

\begin{align*}
\theta_{cr} \approx \frac{7 \, \text{km}}{2R_\oplus} \approx 0.03^\circ
\end{align*}

Almost horizontal plane

Flattened by neutrino-genic muons

[Particle Data Group (2015)]
Effect of Earth’s Rotation

(a) Diagram showing different positions of the Earth and the direction of the signal.

(b) Diagram explaining the rotation axis and detector latitude.

(c) Diagram illustrating the positions of points P1 and P2 on the horizon and at different instants.
**Benchmark Model**

\[
\mathcal{L}_{\text{int}} \equiv -\frac{\epsilon}{2} F_{\mu\nu} X^{\mu\nu} + g_{11} \tilde{\chi}_1 \gamma^\mu \chi_1 X_\mu + g_{12} \tilde{\chi}_2 \gamma^\mu \chi_1 X_\mu + h.c.
\]

- **Vector portal (kinetic mixing)** [Holdom (1986)]
- **Fermionic DM**
  - \(\chi_2\): a heavier (unstable) dark-sector state
  - Flavor-conserving \(\Rightarrow\) elastic scattering (eBDM)
  - Flavor-changing \(\Rightarrow\) inelastic scattering (iBDM)
- **Various models** conceiving BDM signatures
  - BDM source: GC, Sun (capture), dwarf galaxies/assisted freeze-out, semi-annihilation, decaying, etc.
  - Portal: vector portal, scalar portal, etc.
  - DM spin: fermionic DM, scalar DM, etc.
  - iBDM-inducing operators: two chiral fermions, two real scalars, dipole moment interactions, etc.

Based on **Assisted FO set-up** [Belanger, JCP (2011)]
**Potential BGs: Neutrinos**

Table 4.3: Atmospheric neutrino event rates including oscillations in 350 kt · year with a LArTPC, fully or partially contained in the detector fiducial volume.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Event Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>fully contained electron-like sample</td>
<td>14,053</td>
</tr>
<tr>
<td>fully contained muon-like sample</td>
<td>20,853</td>
</tr>
<tr>
<td>partially contained muon-like sample</td>
<td>6,871</td>
</tr>
</tbody>
</table>

\[ \sim 40.2 / \text{yr/kt}: \text{may contain multi-track events} \]

**Single-track candidates:** \(32.4 + 8.8 = 41.2 / \text{yr/kt}\), while total e-like events are \(49.9 / \text{yr/kt}\). (Note that SK takes e-like events with \(E > \sim 10 \text{ MeV}\).)

⇒ Potential BGs for elastic scattering signal (eBDM) events

**Multi-track candidates:** \(5.2 / \text{yr/kt}\)

⇒ Most extra tracks come from mesons which can be identified at LArTPC.

⇒ Very likely to be background-free for inelastic scattering signal (iBDM) events

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[DUNE CDR-Vol.2 (2015)]
(Mainly) focusing on “Non-relativistic” weakly interacting massive particles (WIMPs) search

- $E_{\text{recoil}} \sim m v^2$
- $\sim 1 - 100 \text{ keV}$
- $(v/c \sim 10^{-3})$

- Detectors designed to be sensitive to this $E$ range

- No solid observation of WIMP signals
- A wide parameter respace already excluded
- Close to the neutrino “floor”
- Need new ideas!
**Boosted DM (BDM) Signatures**

\[ F_{\chi_1} = \sim 10^{-1} - 10^{-6} \text{ cm}^{-2}\text{s}^{-1} \]

with \( m_0 = E_1 = \sim 30 \text{ MeV} - 10 \text{ GeV} \)

- \( \chi_0 \): heavier DM
- \( \chi_1 \): lighter DM
- \( \gamma_1 \): boost factor of \( \chi_1 \)
- \( \chi_2 \): massive unstable dark-sector state
- \( \phi \): mediator/portal particle

**Approach I**
(Kim, Kong, JCP & Shin, [arXiv:1804.07302])

**Approach II**
(in collaboration with Chatterjee et al., [arXiv:1803.03264])

(a) Elastic scattering (\textbf{eBDM}) (cf. eBDM at HK/DUNE/PINGU/Xenon1T/... [Agashe et al. (2014); Kong, Mohlabeng, JCP (2014); Necib et al. (2016); Alhazmi, Kong, Mohlabeng, JCP (2016); Giudice, Kim, JCP, Shin (2017); many more])

(b) Inelastic scattering (\textbf{iBDM}) (cf. iBDM at HK/DUNE/Xenon1T/... [Kim, JCP, Shin (2016); Giudice, Kim, JCP, Shin (2017); Aoki, Toma (2018)])
More familiar parameterization is possible with the below modification.

\[ \sigma_\epsilon \mathcal{F} \geq \frac{N^{90}}{D_f t_{\text{exp}} N_T} \quad 90\% \text{ C.L.} \]

\[ \mathcal{F} = \frac{1}{2} \cdot \frac{1}{4\pi} \int d\Omega \int_{\text{los}} ds \langle \sigma v \rangle_{\chi_0 \chi_0 \rightarrow \chi_1 \chi_1} \left( \frac{\rho(s, \theta)}{m_0} \right)^2 \]

\[ = 1.6 \times 10^{-4} \text{ cm}^{-2} \text{ s}^{-1} \times \left( \frac{\langle \sigma v \rangle_{\chi_0 \chi_0 \rightarrow \chi_1 \chi_1}}{5 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}} \right) \times \left( \frac{\text{GeV}}{m_0} \right)^2 \]

\[ \equiv \mathcal{F}_{\text{ref}}^{180^\circ} \times \left( \frac{\langle \sigma v \rangle_{\chi_0 \chi_0 \rightarrow \chi_1 \chi_1}}{5 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}} \right) \times \left( \frac{\text{GeV}}{m_0} \right)^2 \]

\[ \sigma_\epsilon \geq \frac{N^{90}}{D_f t_{\text{exp}} N_T \mathcal{F}_{\text{ref}}^{\theta_C}} \left( \frac{5 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}}{\langle \sigma v \rangle_{\chi_0 \chi_0 \rightarrow \chi_1 \chi_1}} \right) \left( \frac{m_0}{\text{GeV}} \right)^2 \]

\[ \sigma_\epsilon \text{ vs. } m_0 \quad (\text{just like } \sigma \text{ vs. } m_{\text{DM}} \text{ in conventional WIMP searches}) \]

\[
\begin{array}{|c|c|c|c|c|}
\hline
\text{Detector} & \text{N}^{90} & \text{N}_{\text{BG}} \\
\hline
\text{All sky} & 30^\circ & \text{All sky} & 30^\circ \\
\hline
\text{ProtoDUNE-DP} & 4.86 & 2.67 & 4.22 & 0.28 \\
\text{ProtoDUNE-SP} & 5.50 & 2.79 & 6.02 & 0.40 \\
\text{ProtoDUNE-total} & 6.69 & 3.04 & 10.24 & 0.69 \\
\text{MicroBooNE} & 3.34 & 2.42 & 1.10 & 0.074 \\
\text{SBND} & 3.54 & 2.44 & 1.14 & 0.094 \\
\text{ICARUS} & 5.50 & 2.79 & 6.02 & 0.40 \\
\text{SBN Program-total} & 6.24 & 2.94 & 8.53 & 0.57 \\
\hline
\end{array}
\]

\[ D_f=1/2 \text{ is assumed.} \]
A 0.5 kt-\( V_{\text{fid}} \) detector and \( 2m_1 > m_X \) (i.e., visibly-decaying X) and \( g_{11} = 1 \) are assumed.

Results with 1-year & 2-year (effectively \( \frac{1}{2} \)-year & 1 year assumed) exposures.

Full ProtoDUNE/SBN can cover the parameter space uncovered by SK! (especially, the region where the relevant recoil E is lower than ~100 MeV.)

The analysis with an angle cut allows to probe more parameter space, as expected.
Detection of BDM

- Flux of boosted $\chi_1$ near the earth

$$F_{\chi_1} \propto \frac{\langle \sigma v \rangle_{\chi_0 \chi_0 \rightarrow \chi_1 \chi_1}}{m_0^2}$$

from the number density of DM $\chi_0$, $n_o = \rho_o/m_0$

- Setting $\langle \sigma v \rangle_{\chi_0 \chi_0 \rightarrow \chi_1 \chi_1} \sim 10^{-26}$ cm$^3$s$^{-1}$ and assuming the NFW DM halo profile, one can obtain $F_{\chi_1} \sim 10^{-6} \sim 8$ cm$^{-2}$s$^{-1}$ for $\chi_0$ of weak-scale mass, $m_0 \sim O(10-100$ GeV).

- Low flux $\Rightarrow$ No sensitivity in conventional DM direct detection experiments

  $\Rightarrow$ Large volume (neutrino) detectors

motivated: SK/HK, DUNE, IceCube, ...

- Sources

  - GC: Agashe et al. (2014); Necib et al. (2016); Alhazmi, Kong, Mohlabeng, JCP (2016); etc.
  
  - Sun: Berger et al. (2014); Kong, Mohlabeng, JCP (2014); Alhazmi, Kong, Mohlabeng, JCP (2016); etc.
  
  - Dwarf galaxies: Necib et al (2016)