(In)elastic (Boosted) Dark Matter Searches and Monte Carlo Simulation

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Current Status of Dark Matter Searches

- No observation of DM signatures via non-gravitational interactions while many searches/interpretations designed/performed under WIMP/minimal dark-sector scenarios ⇒ merely excluding more parameter space in dark matter models

[Cushman, Calbiati, McKinsey (2013); Baudis (2014)]

[CMS mono-photon search (2014)]

Time to change our approach?!
Conventional vs. Nonconventional Approaches

- Conventional/traditional approaches for DM searches:
  - Weak-scale mass
  - Weakly coupled
  - Minimal dark sector
  - Elastic scattering
  - Non-relativistic

- Nonconventional/modified approaches for DM searches:
  - Other mass scales, e.g., sub-GeV, MeV, keV, ...
  - Weaker connection to the SM, e.g., vector portal (dark photon), scalar portal, ...
  - “Flavorful” dark sector, e.g., more DM species, unstable heavier dark-sector states, ...
  - Inelastic scattering
  - Relativistic

Inelastic boosted/relativistic DM searches
Inelastic “Relativistic”/Boosted Dark Matter

- Generic model framework [DK, Park, Shin (2016)]

- $\chi_1$: "boosted" DM

- Fixed target: $e^-, p$, etc.

- $\chi_2$: heavier dark sector state: unstable

- Target recoiling: visible

- $\chi_1$: undetected

- Secondary signatures: some are visible

- Probing heavier dark-sector states

- Target recoil (like in typical DM direct detection exp.) + secondary visible signatures $\Rightarrow$ more handles, (relatively) background-free (no secondary signatures in usual backgrounds)

- Complementary to standard DM direct searches
Boosted/Relativistic Dark Matter: Cosmic Frontier

- Signals coming from the universe today, nontrivial model building required
  - Semi-annihilation in e.g., $Z_3$ models [D’Eramo, Thaler (2010)]
  - Fast-moving DM via induced nucleon decays [Huang, Zhao (2013)]

- Incoming flux of boosted DM is typically small.

Underground large-volume detectors, e.g.,
Super/Hyper-K, DUNE [Agashe, Cui, Necib, Thaler (2014); Huang, Zhao (2013); Necib, Moon, Wongjirad, Conrad (2016); Berger, Cui, Zhao (2014); Kong, Mohlabeng, Park (2014); Alhazmi, Kong, Mohlabeng, Park (2016); DK, Park, Shin (2016)]

Surface-based detectors, e.g.,
ProtoDUNE, SBN Program [Chatterjee, DK, et al. (2018); DK, Kong, Park, Shin in progress]

Conventional WIMP detectors (with some model variation), e.g., Xenon, Lux-Zeplin [Giudice, DK, Park, Shin (2017)]
Boosted/Relativistic Dark Matter: Intensity Frontier

- Signals coming from colliders, additional model building not always necessary
- If dark sectors (containing dark matter) are more “weakly” connected to the SM sector, high intensity experiments are also motivated, e.g., fixed target experiments.
  - BDX, NA64, MicroBooNE, SeaQuest, LDMX, T2HKK, DUNE, SHiP, and many more

- Quite a few phenomenological studies/proposals in the context of dark photon decays, elastic/inelastic scattering of DM, etc. [LoSecco et al. (1980); Bjorken, Essig, Schuster, Toro (2009); Batell, Pospelov, Ritz (2009); deNiverville, Pospelov, Ritz (2011); Izaguirre, Knjaic, Schuster, Toro (2014); Izaguirre, Kahn, Knjaic, Moschella (2017); Berlin, Gori, Schuster, Toro (2018); Bonivento, DK, Park, Shin in progress, and many more]
Two-component Boosted DM Scenario

- A possible relativistic source: BDM scenario (cosmic frontier), stability of the two DM species ensured by separate symmetries, e.g., $Z_2 \otimes Z'_2$, $U(1) \otimes U(1)'$, etc.

- Dominant relic

- Freeze-out first

- Freeze-out later

- Negligible, non-relativistic relic

- “Assisted” freeze-out mechanism
  
  [Belanger, Park (2011)]

- $Y_0$  
  
- $Y_1$  
  
- $x = m_{Y_i}/T$
“Relativistic” Dark Matter Search

Heavier relic \( \chi_0 \): hard to detect it due to tiny/negligible coupling to SM

Lighter relic \( \chi_1 \): hard to detect it due to small amount

Galactic Center at the universe today

Laboratory

\[ \gamma_1 = \frac{m_0}{m_1} \]

[Agashe, Cui, Necib, Thaler (2014)]
Boosted DM Detection

- Flux of boosted $\chi_1$ near the earth
  \[ \mathcal{F}_{\chi_1} \propto (\text{interaction strength}) \times (\chi_0 \text{ number})^2 \]
  \[ \sim 0.8 \times 10^{-7} \text{ cm}^{-2} \text{ s}^{-1} \left( \frac{\langle \sigma v \rangle_{\chi_0 \chi_0 \rightarrow \chi_1 \chi_1}}{10^{-26} \text{ cm}^3 \text{ s}^{-1}} \right) \left( \frac{20 \text{ GeV}}{m_0} \right)^2 \]
  from DM number density

- Setting $\langle \sigma v \rangle_{\chi_0 \chi_0 \rightarrow \chi_1 \chi_1}$ to be $\sim 10^{-26} \text{ cm}^3 \text{ s}^{-1}$ and assuming Navarro-Frenk-White DM halo profile, a standard profile, one finds
  \[ \mathcal{F}_{\chi_1} \sim 10^{-7} \text{ cm}^{-2} \text{ s}^{-1} \text{ for WIMP mass-range } \chi_0 \text{ [e.g., } \mathcal{O}(20 \text{ GeV})] \]

- No sensitivity in conventional dark matter direct detection experiments $\Rightarrow$ large-volume (neutrino) detectors motivated
  - ✔ Super-/Hyper-Kamiokande (SK/HK)
  - ✔ Deep Underground Neutrino Experiment (DUNE)
Benchmark Model

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

- **Vector portal** (e.g., “dark photon” scenario) [Holdom (1986)]
- **Fermionic DM**
  - \( \chi_2 \): a heavier (unstable) dark-sector state
  - Flavor-conserving interaction \( \Rightarrow \) elastic scattering (can be **suppressed or even vanishing**)
  - Flavor-changing interaction \( \Rightarrow \) inelastic scattering

- Not restricted to this model: various models conceiving BDM signatures
  - BDM source: galactic center, solar capture, dwarf galaxies, assisted freeze-out, semi-annihilation, fast-moving DM etc. [Agashe et al. (2014); Berger et al. (2015); Kong et al. (2015); Alhazmi et al. (2017); Super-K (2017); Belanger et al. (2011); D’Eramo et al. (2010); Huang et al. (2013)]
  - Portal: vector portal, scalar portal, etc.
  - DM spin: fermionic DM, scalar DM, etc.
  - iBDM-inducing operator: two chiral fermions, two real scalars, dipole moment interactions, etc. [Tucker-Smith, Weiner (2001); Giudice, DK, Park, Shin (2017)]
Inelastic BDM (iBDM) at Large-Volume Detectors

\[
\frac{d\sigma}{dE_T} = \frac{m_T}{8\pi\lambda(s, m_T^2, m_1^2)} |M|^2,
\]

\[
|M|^2 = \frac{8(\epsilon e_{12})^2 m_T}{2m_T(E_2 - E_1 - m_X)^2} \times [M_0(F_1 + \kappa F_2)^2 + M_1 \{(F_1 + \kappa F_2)\kappa F_2 + (\kappa F_2)^2\}(E_1 - E_2 + 2m_T)^2].
\]

(F_1 = 1, F_2 = 0 for electron)

\[
M_0 = \left[ m_T(E_1^2 + E_2^2) - \frac{(\delta m)^2}{2}(E_2 - E_1 + m_T) \\
+ \frac{m^2(T)(E_2 - E_1)}{2m_T} + m_1^2E_2 - m_2^2E_1 \right],
\]

\[
M_1 = m_T \left\{ \left( E_1 + E_2 - \frac{m_2^2 - m_1^2}{2m_T} \right)^2 \\
+ (E_1 - E_2 + 2m_T) \left( E_2 - E_1 - \frac{(\delta m)^2}{2m_T} \right) \right\},
\]

\[
\delta m \equiv m_2 - m_1.
\]

\[
M_2 \leq \sqrt{m_T^2 + 2E_1m_T + m_1^2} - m_T.
\]

\[
\cos \theta = \frac{E_TE_2 + (m_T^2 + m_2^2 - s)/2}{\sqrt{(E_2^2 - m_2^2)(E_T^2 - m_T^2)}}
\]

- \( \theta \) (roughly) determines angular separation between the primary (target recoil) and the secondary \((e^+e^-)\) pair signals.
Discovery Potential with e-scattering

- GeV/sub-GeV mass and sizable boost factor of dark-sector particles preferred by kinematics
- $e^-$-scattering preferred $\leftarrow$ smaller threshold energy, $e^-$ as a fundamental particle
- $e^+e^-$ from the secondary: highly collimated (not separable in most favored parameter region)
- $e^-$ from the primary: collimated, but separable with detectors of good angular resolution
- High chance to observe two separable charged tracks

[DK, Park, Shin (2016)]
Discovery Potential with $p$-scattering

- GeV/sub-GeV mass and decent boost factor of dark-sector particles preferred by kinematics
- (Typically) Larger threshold energy, $p$ could be broken apart, atomic form factor
- $e^+e^-$ from the secondary: separated
- $p$ from the primary: separated from the secondary particles
- High chance to observe three separable charged tracks

[DK, Park, Shin (2016)]
Recall, in a minimal boosted DM scenario, if flux over the whole sky is $\mathcal{O}(10^{-7})$ cm$^{-2}$ s$^{-1}$, it is promising and achievable!

Comparable/better signal sensitivity at DUNE! ⇒ More investigation needed! [De Roeck, DK, Moghaddam, Park, Shin, Whitehead, in progress]
More Applications

- Similar physics opportunities at surface-based detectors, e.g., NOvA, SBN Program, ProtoDUNE, etc.
- Challenge: enormous cosmic-origin backgrounds (typically from muons)
- Solution:
  - Many signal features of iBDM [Chatterjee, DK et al. (2018)]
  - “Earth Shielding” for elastic BDM (at the cost of half statistics) [DK, Kong, Park, Shin in progress]

- Similar physics opportunities at conventional WIMP detectors or (small-volume) neutrino detectors, e.g., Xenon, DarkSide, CUORE, etc.
- Challenge: “small” volume w.r.t the flux of boosted DM
- Solution: model modification to increase the flux
  \[ \mathcal{F}_{\chi_1} \propto m_0^{-2} \]
  - Good resolution, sensitivity to low-energy (MeV-range) signals
  - Phenomenological study at WIMP detectors with their detector specifics considered [Giudice, DK, Park, Shin (2017)]
(In)elastic BDM Searches in Various Experiments

Detectors are **complementary** to one another rather than superior to the others!
Event Simulation for Cosmic-frontier Searches

- Boosted/relativistic DM injection
  - (Usually) boosted DM comes with a fixed boost factor
- Parton-level Calculation
  - Phase-space gen.
  - Standard parton-level calculators
- Event Generation
  - Standard event generators
  - GENIE
- Detector Response
  - LArSoft
  - GEANT4

- Electron scattering: good enough with standard parton-level calculators (or even phase-space generator) to describe leading behaviors of BDM-initiated events
- Proton scattering: several effects even before detector responses, e.g., atomic form factor, deep inelastic scattering (DIS of iBDM \cite{DK, Machado, Park, Shin, in progress}), Δ-resonances regime, nucleon effects etc.
- GENIE (see also Berger's talk for more details)
  - The above-mentioned effects are fully considered.
  - Resonance model in \cite{Rein, Sehgal (1981)} (inputs from lattice QCD needed?)
  - Elastic BDM has been implemented, iBDM is being implemented.
Event Simulation for Intensity-frontier Searches

- Boosted/relativistic DM injection
- Parton-level Calculation
- Event Generation
- Detector Response

- Boosted/relativistic DM injection
- Parton-level Calculation
- Event Generation
- Detector Response

- Ex) vector portal
- Meson ($\pi/\eta$) decays
- Bremsstrahlung
- Drell-Yan

- Phase-space gen.
- Standard parton-level calculators
- Standard event generators
- GENIE
- LArSoft
- GEANT4

- BdNMC [deNiverville (2017)],
  - All production mechanisms are considered.
  - Target and detector characteristics can be set.
  - Pre-simulated data is used.

- Fixed target experiments with the latest MadGraph

[deNiverville, Chen, Pospelov, Ritz (2017)]
Conclusions

- Boosted/relativistic dark matter searches at the cosmic/intensity frontier are promising.
- They may provide an alternative avenue to explore dark sector physics (including dark matter).

- Theoretical/phenomenological studies have been actively conducted and in progress.
- There are many ongoing/projected experiments in which they can be tested/probed.

- Many existing MC tools can be utilized for boosted/relativistic DM physics, and an increasing amount of effort to develop dedicated MC tools has been made.
- More active interactions with MC-tool community are highly expected/encouraged!
Thank you!
Background Considerations

- **Potential sources**

  - Cherenkov radiation (CR) by electron/muon is distinguished from that by proton.
  - Electron-preferred scenarios:
    - CR by an N.C. electron
    - CR by a C.C. electron/muon/tau
    - CR by at least, a C.C. proton unless broken

  - Proton-preferred scenarios: opening angles among recoil proton, decayed electrons are large enough to resolve
Background Considerations

- More challenging cases: broken nuclei

\[ \nu_\ell \rightarrow \ell \rightarrow p/n \rightarrow \pi^+ \rightarrow \mu^+ \nu \rightarrow e^+ \nu \nu \nu \]

- Similar expectations for neutral currents
- (Dedicated study in progress)
Background Considerations

More challenging cases: broken nuclei

\[ \nu_\ell \rightarrow \ell \rightarrow W \rightarrow p/n \pi \]

- \( \pi^+ \rightarrow \mu^+ \nu \rightarrow e^+ \nu \nu \nu \)

- Expecting again that (quality) track-based particle identification allows us to distinguish multi-track background events from signal ones.
- A dedicated study is needed.

Particle tracks created by a neutrino interaction in liquid argon in the ArgoNeuT.
Flux of Neutrino

[Ruppin et al., (2014)]