BSM Targets at a Target-less DUNE

Snowmass Community Summer Study Workshop

July 23rd, 2022

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Physics goals of near detectors:

**Primary role: Understanding Systematic Uncertainties**

- High beam luminosity + Large fiducial mass
- Ideal to investigate rare/new neutrino interactions
- \( \sigma < 10^{-44} \text{ cm}^2 \)
- Test SM predictions
- Search for BSM physics
Question:

• How can we fully leverage DUNE to search for New Physics?

• Can DUNE probe compelling new physics beyond the reach of high energy colliders?
Neutrino Experiments as Dark Sector factories!

The huge fluxes of neutrinos and photos can be used for BSM searches

- Heavy Neutral Leptons, Dark Photon, light DM, etc

Berryman et al, PRD (2018)
Breitbach et al, JHEP (2022)
De Romeri et al, PRD (2019)
Magill et al, PRL (2019)

Zahra Tabrizi, NTN fellow, Northwestern
• **Direct Search of Dark Sectors:**
  
  – Light Dark Matter
  
  – Axion-Like Particles

• **Conclusion**
“What is Dark Matter?”

We don’t know!

There could be several kinds, making up a whole “dark sector”
“Where is Dark Matter?”

We don’t know!

“How is Dark Matter?”

They all ask “What is Dark Matter?” and “Where is Dark Matter?”, but nobody asks “How is Dark Matter?”

TOM GAULD for NEW SCIENTIST
Photons at the target kinetically produce Dark Photons, which decay into dark matter:

\[
\mathcal{L} \supset -\frac{\varepsilon}{2} F_{\mu\nu} F_{\mu\nu}^\prime + \frac{M_{A'}^2}{2} A_\mu A'^\mu + |D_\mu \phi|^2 - M_\phi^2 |\phi|^2
\]

- \( D_\mu = \partial_\mu - ig_D A'_\mu \), \( g_D = \sqrt{4\pi \alpha_D} \)

**DM production**

\[ \propto \varepsilon^2 \]

**DM detection**

\[ \propto \varepsilon^2 \]

\( \mathcal{D} \) event rate \( \sim \varepsilon^4 \alpha_D \)

De Romeri, Kelly, Machado, PRD (2019)

(also Beam bremsstrahlung and Resonance production)

7/23/22

Zahra Tabrizi, NTN fellow, Northwestern
Light Dark Matter

**DM signal:** elastic scattering on electrons

How can we get rid of neutrinos in a neutrino detector?

But so do neutrinos!

$\sim 9,400 \nu - e$ events / year!
Light Dark Matter

- **Challenge:** elastic neutrino-electron scattering is a huge background!

Breitbach, Buonocore, Frugiuele, Kopp, Mittnacht, JHEP (2022)

- **Going to off-axis increases DM signal/background**

De Romeri, Kelly, Machado, PRD (2019)
Light Dark Matter

De Romeri, Kelly, Machado, PRD (2019)

See talk by Kevin Kelly
Light Dark Matter

Scalar DM $\phi$, $\alpha_D = 0.1$, $M_{A'} = 3M_\phi$

spectral analysis ($\Delta E = 250$ MeV)

De Romeri, Kelly, Machado, PRD (2019)

Breitbach, Buonocore, Frugiuele, Kopp, Mittnacht, JHEP (2022)

See talk by Kevin Kelly
• Impinging protons directly to the dump area;
• Shorter distance between the source point and the detector → more DM signal;
• Charged mesons absorbed in the Al beam dump before decay;
• The $\nu$ flux decreases by 3 orders of magnitude → Only 0.5 $\nu$-e background in 3 mo-0.6 MW!

See talk by Wooyoun Jang

Brdar, Dutta, Jang, Kim, Shoemaker, ZT, Thompson, Yu
arXiv: 2206.06380
Target-less DUNE can probe the parameter space for thermal relic DM in only 3 months!
Axion-Like Particles (ALPs)

- (pseudo)scalars, strongly motivated by theory and cosmology;

- Why is CP conserved in QCD? Solution to the strong CP problem (QCD axion);

- DM candidates;
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- DM candidates;

Excluded by astrophysics

QCD axion range

D. Cadamuro, 1210.3196 [hep-ph]
Using photons to produce ALPs:

\[ \mathcal{L}_{a\gamma\gamma} = -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} F_{\mu\nu} \]

**ALP production**

Primakoff scattering

**ALP detection**

Inverse Primakoff scattering

ALP decay
ALPs at Target-less DUNE

- The only lab-based constraints!
- Can probe QCD-axion
- 3 months target-less DUNE can do better than 1 yr GAr

Brdar, Dutta, Jang, Kim, Shoemaker, ZT, Thompson, Yu
PRL (2021)

Brdar, Dutta, Jang, Kim, Shoemaker, ZT, Thompson, Yu
arXiv: 2206.06380
ALPs at Target-less DUNE

Brdar, Dutta, Jang, Kim, Shoemaker, ZT, Thompson, Yu
arXiv: 2206.06380
DIS: FASERv

Kaon/Muon decay: ISODAR, KDAR

Solar neutrinos: Borexino

QE, Resonances: MINOS, NOvA, DUNE

Atmospheric Neutrinos: IceCube

Beta decay and IBD: Reactor Experiments

$\nu \rightarrow l, \nu$

$K^- \rightarrow \bar{u} \rightarrow \pi^0, \mu^-$

$\nu \rightarrow l, \nu$

$\nu \rightarrow l, \nu$

$\mu^{-} \rightarrow W^{-} \rightarrow e^{-}$

$\bar{\nu}_\mu$

$\nu_e$

$^7\text{Be} + e^- \rightarrow ^7\text{Li} + \nu_e$

$^3\text{He} + p \rightarrow ^4\text{He} + e^+ + \nu_e$

$^3\text{He} + p \rightarrow ^2\text{H} + \nu_e$

Cosmic ray

1st Generation
2nd Generation
3rd Generation
4th Generation
Nth Generation

neutron
fission product
energy release
Previous Conditions neutron
fission product
energy release
energy release
Late Conditions

Energy release

 neutron
Neutrino experiments give us a powerful tool to search for new physics, either by direct production or by precision measurements!
Conclusion:

• New generation of neutrino experiments are being built to answer many unknowns in the neutrino sectors;

• We can use the near detectors to directly search for dark sector (e.g.: ALPs, light DM, etc.);

• For several BSM models, near detectors give the best constraints;

• We can remove most of the neutrino background by using the target-less configuration;

• Target-less DUNE can probe the parameter space for thermal relic DM in only 3 months!

• It can also probe the region for QCD axion, and give best lab-based constraint on the parameter space of ALPs
Thanks for your attention
Back up Slides
Production and Detection of Dark Matter

DM production

DM detection

Beam bremsstrahlung

Neutral meson decays

Elastic scattering with an electron

Resonance production
Production and Detection of ALPs

**ALP production**

- Compton
- Associated production
- Resonant production
- ALP-bremsstrahlung

**ALP detection**

- Inverse Compton
- External pair conversion
- Di-lepton decay
Axion Like Particles (ALPs) at DUNE:

Photon Flux from GEANT4 Simulation

V. Brdar, B. Dutta, W. Jang, D. Kim, I. Shoemaker, Z. T., A. Thompson, J. Yu
Axion Like Particles (ALPs) at DUNE:

- Coherent $\pi^0$ production $\nu + A \rightarrow \nu + A + \pi^0$

In GAr:
- We expect $\sim 10^6$ NC events;
- Vetoing events with hadronic activity remove $\sim 80\%$;
- A cut on the opening angle removes the rest;

V. Brdar, B. Dutta, W. Jang, D. Kim, I. Shoemaker, ZT, A. Thompson, J. Yu