BSM Physics Opportunities at DUNE

Workshop on Neutrino-Nucleus Interactions in the Standard Model and Beyond

January 17 – 21, 2022

Jaehoon Yu
University of Texas at Arlington

Outline

• Introduction
• What makes DUNE good for BSM?
• BSM Physics Topics at DUNE
• Backgrounds to BSM
• Conclusions
DUNE Physics Motivation

- The neutrino sector in SM needs a modification to reflect $m_\nu$!
  - Precision measurements of the oscillation parameters
    - Mixing angles and mass hierarchy
  - Studying the CPV in $\nu$ sector and precisely measuring the CP phase
    - Do neutrinos and anti-neutrinos oscillate the same way?
- These could lead to a new symmetry
- The question of the grand unification
  - Energy scale of the unification and nucleon decay
- Understanding particles of astrophysical origin
  - Supernova, blackhole formation, relic neutrinos, dark matter, etc
- These require high statistics samples
  - Large mass, large volume and highly capable (near and far) detectors
  - High intensity neutrino beam facility with a long baseline
BSM@nu, the genesis

• BSM@nu picked up steam after the 2013 U.S. Snowmass exercise
• Must leverage the neutrino facility capabilities for precision oscillation measurements to the next step
• Need to further increase community interests on BSM opportunities and complement those in the EF regime
• Need a strategic plan to strengthen the fundamental measurements, such as $\nu$-N xsec, to support precision measurements
• Need to think about managing and mitigating background from “neutrino interactions”
• Important to play a leadership role in expanding physics opportunities
• Low E capabilities of the detectors could expand BSM kinematic reach
• A paper on ROP covers some of these opportunities (Argüelles et al., https://iopscience.iop.org/article/10.1088/1361-6633/ab9d12 )
Deep Underground Neutrino Experiment (DUNE)

- Per the 2013 – 2014 strategic planning of the communities in the three regions, an effort of building a next generation international neutrino experiment is in progress in the U.S.
- Joint efforts of teams from all three regions – Americas, Europe and Asia – US flagship hosted by Fermilab
- DUNE far detector TDR completed and published in 2020
  - [https://iopscience.iop.org/article/10.1088/1748-0221/15/08/T08008](https://iopscience.iop.org/article/10.1088/1748-0221/15/08/T08008);
  - [https://iopscience.iop.org/article/10.1088/1748-0221/15/08/T08009](https://iopscience.iop.org/article/10.1088/1748-0221/15/08/T08009);
- LAr TPC precision 3D imaging detectors ➔ Potential to employ multiple technologies within one experiment, systematic x-check
  - Fundamental safety and construction infrastructure completed in 2021
  - A full-fledged cavern excavation ongoing!
Anatomy of DUNE

1300km (800 miles)

4 caverns w/ fiducial

$V_A \sim 10\text{kt LAr each}$

$\sim 30\times\text{ICARUS}$
• LAr TPC: The same technology as the FD; reduces systematics from different nuclear effects than FD; 
  \( n^-Ar \) interactions \( (V_A=1.50\text{t}) \) \( \rightarrow 1\times10^{8} n\text{m} \text{CC/year} \) on-axis (~1Hz)

• Magnetized (0.5T) large volume HPAr TPC (10atm) w/ ECAL: \( n^-Ar \) events with low-threshold tracking; \( p\text{m} \) measurements \( (V_f=1\text{t}) \) \( \rightarrow 1\times10^{6} n\text{m} \text{CC/year} \) on-axis

• DUNE-PRISM: Off-axis \( n \) spectrum for systematics; takes ND-LAr and ND-GAr from on-axis up to 30.5m

• SAND(System for On-Axis neutrino Detection): Monitors on-axis \( \nu \) beam flux to the FD; Consists of a straw tube tracker + ECAL equipped with a 0.6T magnet from different nuclear n-axis (~1Hz) events with lower on-axis and ND-GAr from on-axis
Images in DUNE LAr-TPC Prototypes

**Throughgoing μ**

Electromagnetic shower + two muon decays

- $E_{_\text{LEM}} = 31 \text{ kV/cm}$
- $P = 1010 \text{ mbar}$

**Multiple hadronic interactions in a shower**

- $E_{_\text{LEM}} = 32 \text{ kV/cm}$
- $P = 1010 \text{ mbar}$

Run 4696, Ev 103: 2 EM showers and a pion interaction

Nov. 24, 2021

Status of DUNE
Dr. Jaehoon Yu
BSM Physics Topics at DUNE

• High beam power, large detector mass + highly capable, precision near and far detectors with low E threshold make BSM physics viable
  • Signal to background ratio grows by the sqrt of the beam power
  
• Near Detector Searches ➔ Take advantage of high beam power
  • Low mass Dark Matter (LDM)
  • Axion-like Particles (ALP)
  • Heavy Neutral Leptons (HNL)
  • Milli-charge Particles (mCP)
  • Neutrino Trident

• Far Detector Searches ➔ Take advantage of ND, large $V_A$ FD and long baseline
  • Sterile neutrino searches
  • Non-standard Interactions, Non-Unitarity, CPT violation
  • Large Extra Dimensions (LED)
  • Boosted Dark Matter (BDM)/ Inelastic Boosted Dark Matter (iBDM)

• Promote strong collaboration of theorists and experimentalists

• Some of these topics covered in EPJ C.81, 322 (2021)
BSM@ν Physics Signatures at ND

- High intensity proton beams produce large number of photons from brem, DY or neutral mesons decays ➔ Make it possible to contemplate couplings of new U(1) gauge to the SM γ

- Detection through an electron, μ, N(n) recoil or 1, 2 γ final states
• Axion-like particles can be produced via the Primakoff process in high intensity proton beams

• Detection via the inverse Primakoff process either in a scattering with $e/N + \gamma$ or decays of the ALP to two $\gamma$
  - $\nu_e$ CC, NC backgrounds
  - $\nu_\mu$ NC $\rightarrow \pi^0 \rightarrow \gamma\gamma$ bck

• DUNE ND has a potential to fully close the cosmic triangle

• Brdar et al., PRL126, 201801 (2021)
LDM Search and Low E Threshold

- LDM’s produced in the target via coupling of dark photon with a SM $\gamma$ from brem, scalar meson decays or direct $\mathrm{DY}$
  - Identify the signal using $e^-$ or nucleon recoil by LDM via dark photon kinetic coupling with SM $\gamma$
    - Batell et al. [0906.5614],
    - deNiverville et al. [1205.3499]
    - Coloma et al. [1512.03852]
- Ability to identify $e^-$ recoil w/ low E threshold key
  - Expands the LDM mass coverage
  - Recoil $E_e$ peaks at low E for low LDM mass
  - Significant background from $\nu_\mu$ scattering off $e^-$
- Search benefits greatly from DUNE PRISM for neutral meson induced LDM
  - Leverage more rapid reduction of $\nu_\mu$ flux than the signal off-axis (De Romeri et al., PRD100, 095010, 2019)
Milli-Charged Particle Search

- mCP w/ charge < $Q_{\text{quark}}$
- Production via meson decays or DY
- Identify the signal using multiple $e^-$ recoils by mCP and link them to point back to the source position & reject non-beam backgrounds
  - Tested with ArgoNEUT (~0.17m$^3$)
    - Ability to identify $e^-$ recoil w/ ~<$\text{MeV}$ E threshold enables this method possible
    - Enabling virtually background free search
  - DUNE ND V~60m$^3$~350$^3$V_{ArgoNEUT}
  - Difference in the beam E and large POT produce large number of mCP in a broad mCP mass range
  - 570m distance from target to ND could cause matter effect

January 21, 2022
nuNI 2022
Jaehoon Yu
Dark Photon Search

- New U(1) could kinetically mix with a SM $\gamma$ from scalar meson decays or direct DY
- If these dark photons can live sufficiently long to reach the DUNE ND \(\Rightarrow\) Look for their decays to a charged lepton pair
  - $A' \to e^+e^-$
  - Primary background from $\pi^0 \to \gamma\gamma$
    - One of the $\gamma$ mid-ID’s as e and one missed
    - Could a magnet help?
  - $A' \to \mu^+\mu^-$
    - Charged pion production from CC
    - Charged $\pi$ decay product mixing with other low E hadronic activities
- Low E threshold & precise understandings of CCQE and CCRES essential

January 21, 2022

nuNI 2022
Jaehoon Yu
• High intensity proton beams produce heavy neutral leptons from the decays of heavy mesons in the target

• HNL then decays into charged leptons and lighter mesons in the DUNE ND complex → charge lepton + a meson, 2 charged leptons + ν – Vertex requirements would help

• Multiple production and decay channels available for searches

• Coloma et al., (2007.03701)
Signatures of BSM@ν

BSM signal final states include charged leptons (e+/-, μ+/-) and photons, along with nucleus (nucleon) recoil → ν-N interactions. The primary background is ν coherent, NC with π0, νe CC with π0, etc.

<table>
<thead>
<tr>
<th>Process</th>
<th>Signatures</th>
<th>Background</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALP</td>
<td>Scattering: γ+e/ γ+N (n) Decay in flight: γγ</td>
<td>ν coherent, NC with π0, νe CC with π0, etc</td>
</tr>
<tr>
<td>LDM</td>
<td>χe→χe, χN→N'n</td>
<td>NC with π0, νe CC, QE, RES</td>
</tr>
<tr>
<td>mCP</td>
<td>Multiple e- scatterings</td>
<td>νe CC with π0</td>
</tr>
<tr>
<td>Dark Photon</td>
<td>A→e+e-, μ+μ+</td>
<td>ν CC + mis-ID π, Accidental overlap of CC</td>
</tr>
<tr>
<td>HNL</td>
<td>N → νe+e-, νμ-μ+, νeμ, νπ0, eπ, μπ</td>
<td>ν CC + mis-ID π, νe CC with π0</td>
</tr>
<tr>
<td>ν trident</td>
<td>ν→νe+e-, νμ-μ+, νeμ</td>
<td>νμN→νμπN (ν CC)</td>
</tr>
<tr>
<td>BDM/iBDM</td>
<td>χN→e+N</td>
<td>ν coherent, NC with π0, νe CC</td>
</tr>
</tbody>
</table>
Low Energy $\nu$ Interactions

- QE and RES dominate $\nu$-N interactions in DUNE $E_\nu$ range where the two oscillation maxima reside
- QE & RES critical to understanding background to BSM
- Large uncertainties for $\nu$-N x-sec calculations in the critical region
  - Precision calculations w/ improved nuclear models and event generations essential for oscillation physics
  - Planned measurement, such as at e4$\nu$ collaboration could provide critical missing info
  - Need to clearly identify the list of measurements that can help improving calculations and prioritize them to target low hanging fruits first
Tails, tails

- BSM effects extremely rare and are in the tail ends of the SM processes ➔ can easily be masked by SM fluctuations
- Many theoretical predictions and generators forν–N interactions have been in existence and continue making remarkable improvements ➔ but they still have sizeable uncertainties within each and between themselves
We learned at this workshop.

\[ n + n \rightarrow \nu E_{\nu}/10^{-38} \text{cm}^2 \]

\[ E_{\nu}/\text{GeV} \]

\[ Q^2/\text{GeV}^2 \]

2GeV $\nu_\mu + \text{Ar}$
Tails, tails, tails, and tails

• BSM effects extremely rare and are in the tail ends of the SM processes ➔ can easily be masked by SM fluctuations

• Many different theoretical predictions and generators for $\nu-N$ have been in existence and continue improving ➔ but they still have sizeable uncertainties within each and between themselves
  – Significantly reducing the uncertainties critical for B&B osc. physics
  – Essential for estimating backgrounds to BSM searches

• Generators begin to incorporate BSM processes but could take a long time to implement due to insufficient resources ➔ need further strengthening the efforts
  – Strong collaborations between generator teams and experiments a way to boost
  – NP and HEP communities must work together to understand low E processes
  – In addition, we need more concerted efforts and get them done in a timely fashion
Conclusions

• The high intensity proton beams for next generation neutrino experiments enable expanding physics reach beyond that of neutrinos and the SM

• Large scale, precision 3D imaging capability DUNE detectors fit to probe a broad scope of BSM physics
  – Enormous opportunities to search for BSM signatures at DUNE ND and FD combinations

• Accessing yet-to-be-explored kinematic phase space requires precision detectors with as low E threshold as possible
  – Backgrounds from non-beam sources could be well rejected w/ low E electron detection capability and pointing back to the target
  – Neutrino interactions will be the significant background to BSM signatures

• In theory front, it is fundamental
  – To develop innovative tools for BSM signature calculations and generator
  – To significantly improve precision of the neutrino-Nucleus interactions