Beyond the Standard Model at DUNE

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On behalf of DUNE Collaboration

NuFACT2019, August 26~31, 2019
The Grand Hotel Daegu, Korea
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DUNE Overview
DUNE – a fully international experiment

- 1094 collaborators from 184 institutions in 34 countries
- Growing at a rate of about 100 collaborators/year

Armenia, Brazil, Bulgaria, Canada, CERN, Chile, China, Colombia, Czech Republic, Spain, Finland, France, Greece, India, Iran, Italy, Japan, Madagascar, Mexico, Netherlands, Paraguay, Peru, Poland, Portugal, Romania, Russia, South Korea, Sweden, Switzerland, Turkey, UK, Ukraine, USA.
DUNE

- Approximately 4X10 kton fiducial mass liquid-argon Far Detector
- Located at SURF’s 1478 m level with 1300 km baseline
- Near Detector located approximately 575 m from neutrino source
- Wide-band neutrino beam (~ GeV range)
- Flagship physics topics: CPV, supernova neutrinos and BSM physics
The LBNF Beam

- The LBNF (Long Baseline Neutrino Facility) beam is produced at Fermilab.
- It will use 60-120 GeV proton beam at 1.2 MW \((10^4 \text{ POT/s})\), upgradeable to 2.4 MW.
- It can run in neutrino and anti-neutrino modes by switching the polarity of the magnetic horns.
- The wide-band beam enables the use of the first and second oscillation maxima and enhances probing of new BSM physics.

Neutrino Flux at 1300 km (CDR Optimized Beam)
Near Detector (ND)

- Control of systematic uncertainties affecting the long-baseline oscillation analysis by precise measurements of the neutrino flux and interaction cross-sections
Near Detector (ND)

- The preliminary conceptual design includes three sub-detectors (right to left)
  - A LArTPC (50~100 tons) with pixelated readout,
  - A magnetized, high-pressure gaseous TPC (HPgTPC),
  - A magnetized three-dimensional scintillator tracker (3DST).

- The design includes the possibility of taking data at varying off-axis positions, exposing the ND to neutrino fluxes with different spectra.
  - Handle the deconvolution of the neutrino flux and cross-section
Far Detector (FD)
Far Detector (FD)

- 4X10-kton (fiducial) LArTPC modules
- Single and dual-phase detector designs
- Integrated photon detection

Single-phase: charge drifts to wire planes (APAs)

APA: Anode Plane Assembly
CPA: Cathode Plane Assembly
A powerful imaging technology

- Stopping Muon
- MIP Region
- Bragg Peak
- Michel Electron
- Photons

MIP: Minimum Ionizing Particle
BSM Physics at DUNE

• Topics investigated include:
  – Non-standard short-baseline and long-baseline oscillations phenomena:
    • Sterile neutrino mixing
    • Non-standard interactions (NSI)
    • Non-unitarity mixing
    • CPT violation
    • Tau neutrinos
  – BSM at the ND related to the beam and its interactions with the detector:
    • Low mass dark matter
    • Trident neutrinos
  – BSM at the FD benefitting from its large mass and resolution:
    • Boosted dark matter
    • Nucleon decay
Non-standard Oscillation
Sterile Neutrino Mixing

• Sterile (right-handed) neutrinos are a prediction of many BSM models explaining the origin of neutrino masses.

• Active-to-sterile neutrino mixing distorts the standard oscillation probabilities. DUNE will be sensitive to this effect through the combined analysis of the $\nu_\mu$ and $\nu_e$ spectra from both ND and FD.

• Potentially, DUNE could look as well for non-standard $\nu_\tau$ appearance or use the atmospheric sample from the FD.

Mixing probabilities for 3 and 3+1 neutrino models
Non-Standard Interactions (NSI)

- Projected DUNE has sensitivity to various NSI parameters.

Non-standard interactions (NSI) in propagation can be described as new contributions to the MSW effect:

**Matter effect (MSW)**

\[
H = U \begin{pmatrix}
    0 & \Delta m^2_{21}/2E \\
    \Delta m^2_{31}/2E & 0
\end{pmatrix}
U^\dagger + \tilde{V}_{\text{MSW}}, \quad \tilde{V}_{\text{MSW}} = \sqrt{2}G_F N_e \begin{pmatrix}
    1 + \epsilon_{ee}^m & \epsilon_{em}^m & \epsilon_{e\tau}^m \\
    \epsilon_{e\mu}^m & \epsilon_{\mu\mu}^m & \epsilon_{\mu\tau}^m \\
    \epsilon_{e\tau}^m & \epsilon_{\mu\tau}^m & \epsilon_{\tau\tau}^m
\end{pmatrix}
\]

- Shown here the allowed regions (68, 90 and 95% CL) for an exposure of 300 kton·MW·year.

DUNE may potentially improve present constraints on \(|\epsilon_{e\mu}|\) and \(|\epsilon_{e\tau}|\) by at least a factor of 2.
Non-Unitary Mixing

- If neutrinos acquire mass through a (type I) seesaw mechanism, the mixing matrix need not be unitary.
- 300 kton·MW·years with 80 GeV beam flux

\[
N = \begin{pmatrix}
1 - \alpha_{ee} & 0 & 0 \\
\alpha_{\mu e} & 1 - \alpha_{\mu\mu} & 0 \\
\alpha_{\tau e} & \alpha_{\tau\mu} & 1 - \alpha_{\tau\tau}
\end{pmatrix} U^{3\times3}
\]

- Allowed regions at the 1σ, 90%, 2σ CL for non-unitarity mixing parameters for DUNE-only (solid) and DUNE + present constraints (dashed)
- Impact for non-unitarity on the DUNE CPV discovery portal
CPT Violation

\[ P(\nu_\mu \to \nu_e) \neq P(\bar{\nu}_\mu \to \bar{\nu}_e) \Rightarrow \text{CP violation} \]
\[ P(\nu_\mu \to \nu_\mu) \neq P(\bar{\nu}_\mu \to \bar{\nu}_\mu) \Rightarrow \text{CPT violation} \]

- Projected sensitivity of DUNE to CPT violation for an exposure of 300 kton⋅MW⋅year and three different values of \( \theta_{23} \) mixing angle.

- Current experimental bounds:
  \[ \Delta(\Delta m^2_{31}) \equiv \left| \Delta m^2_{31} - \Delta \bar{m}^2_{31} \right| < 3.7 \times 10^{-4} \text{ eV}^2 \]
  \[ \Delta(\sin^2 \theta_{23}) \equiv \left| \sin^2 \theta_{23} - \sin^2 \bar{\theta}_{23} \right| < 0.32 \]

- DUNE can improve current limit on \( \Delta(\Delta m^2_{31}) \) by almost one order of magnitude.

ArXiv: 1712.01714
Tau neutrinos

- Currently, almost all of our knowledge from the tau neutrino sector derives from lepton universality of cross-section and PMNS unitarity of the mixing matrix.

- Tau neutrinos are challenging to select and reconstruct, but they could provide valuable complementary information for BSM physics searches.

- Beam event statistics (for a flat efficiency of 30%):
  - \(~130\ \nu_\tau\)/year and \(~30\ \text{anti-}\nu_\tau\)/year;
  - \(~800\ \nu_\tau\)/year for the high-energy tune of the beam.

- The atmospheric sample gives access to the full first oscillation maximum, improving constraints on the atmospheric parameters.
New Physics at the Near Detector

$\nu_\mu \rightarrow \nu_X$
Low-mass Dark Matter

- Dark matter particles produced in the decay of light mesons reach the DUNE ND, where they are detected via electron scattering.
- The main background (neutrino-electron) can be suppressed taking data off-axis (PRISM).
- Shown here the sensitivity (90% CL) of DUNE for a 7-year (50% neutrino beam, 50% anti-neutrino) run.

ArXiv: 1903.10505
Trident Neutrinos

- Rare SM process, with one neutrino and two leptons of opposite charge in the final state,
  - has been observed with measured cross-section in good agreement with SM.

- SM cross-section is \( \sim 7 \) orders of magnitude smaller than \( \nu_\mu \text{CC}\pi \) background.

- Trident rate is sensitive to the existence of new forces mediated by a light vector boson that could explain the muon g-2 anomaly.
New Physics at the Far Detector
**Boosted Dark Matter**

- Galactic halo can produce dark matter which could interact inelastically in DUNE. 
  ⇒ Dark photon

\[ \chi_0: \text{heavier dark matter} \]
\[ \delta m = m_{\chi^2} - m_{\chi^1} \]

- Dark matter from the core of Sun could interact elastically with the DUNE. 
  ⇒ Lepto-phobic $Z'$

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**Expected 5$\sigma$ discovery reach with 1 year DUNE lifetime**

**Angle between Sun and particles produced**
Nucleon Decay

• DUNE, shielded from cosmic ray, has a high mass and precise particle tracking ⇒ Baryon number violation can be done:
  - Neutron - anti-neutron oscillation
  - \( p \rightarrow \text{anti-} \nu K^+, \; n \rightarrow K^+e^- \)
  - \( p \rightarrow \pi^0 e^+ \)

• Sensitivity using full simulations (including atmospheric neutrinos and final state interactions with the Argon nucleus) is coming for the TDR.
Summary

• The DUNE detectors and the LBNF beam enable a rich experimental program of BSM physics searches, including
  – Non-standard short-baseline and long-baseline oscillation phenomena;
  – Searches for new phenomena/particle at the ND related to the beam and its interactions with the detector;
  – Searches for new phenomena at the FD benefitting from its large mass.

• This is a very active and exciting area of collaboration between experimentalists and theorists/phenomenologists.

• Look for results from finalized studies in the upcoming DUNE Technical Design Report (TDR) later this year.
Thank you for your attentions.

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Back-up
Testing the standard “three-flavour” paradigm

\[ U_{PMNS} = \begin{pmatrix}
  U_{e1} & U_{e2} & U_{e3} \\
  U_{\mu1} & U_{\mu2} & U_{\mu3} \\
  U_{\tau1} & U_{\tau2} & U_{\tau3}
\end{pmatrix} = \begin{pmatrix}
  1 & 0 & 0 \\
  0 & c_{23} & s_{23} \\
  0 & -s_{23} & c_{23}
\end{pmatrix} \begin{pmatrix}
  c_{13} & 0 & s_{13}e^{-i\delta} \\
  0 & 1 & 0 \\
  -s_{13}e^{i\delta} & 0 & c_{13}
\end{pmatrix} \begin{pmatrix}
  c_{12} & s_{12} & 0 \\
  -s_{12} & c_{12} & 0 \\
  0 & 0 & 1
\end{pmatrix} \]

CP Violation in the lepton sector might provide support for \textit{Leptogenesis} as mechanism to generate the Universe’s matter-antimatter asymmetry.

**CP Violation:** \( \delta \neq \{0, \pi\} \)

\( s_{ij} = \sin \theta_{ij} ; \ c_{ij} = \cos \theta_{ij} \)
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CP Violation in the lepton sector might provide support for Leptogenesis as mechanism to generate the Universe’s matter-antimatter asymmetry.

**CP Violation:** \( \delta \neq \{0, \pi\} \quad s_{ij} = \sin \theta_{ij} \; ; \; c_{ij} = \cos \theta_{ij} \)

**Caveat:**
No direct evidence for Leptogenesis, since a model is needed to connect the low-scale CPV observed here to high-scale CPV for heavy neutrinos that lead to Leptogenesis.
Single Phase Concept

Liquid Argon TPC

m.i.p. ionization: 6000 e/mm

Cathode Plane

$E_{\text{drift}} \sim 500V/cm$

170 kV

3.4 m $\rightarrow$ 2.13 ms

time

1D Data-inspired Responses

- U (ind.)
- V (ind.)
- W (col.)

Arbitrary Unit

-30 -20 -10 0 10

Time (us)
Dual Phase TPC

- Larger drift distance (12 m) – higher fields
- Potentially better signal to noise
- Readout/HV access through chimneys on top.

- 153,600 channels
- 80 3x3 m² Charge Readout Planes
Thank you for your attentions.

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