Calibrating the Deep Underground Neutrino Experiment (DUNE)

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Overview

- Introduction to the DUNE detector systems
  - Liquid argon time projection chamber (LArTPC) technology
- Overview of the DUNE physics program
- Calibration procedures under development
  - Focussing on the far detector (FD)
  - Largely similar at the near detector (ND)
**Far detector (FD) complex**
- Located at SURF, SD, USA
- Will utilise LArTPC technology
- Located 1.5 km underground
- Will comprise 4 x 17 kt modules

**Near detector (ND) complex**
- Located at Fermilab, IL, USA
- Comprises LArTPC, gaseous argon (GAr) TPC & non-TPC components
- 574 m from the wideband ν beam source

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Example oscillation probability of a 2.8 GeV incoming neutrino from the 100% muon neutrino beam
The DUNE LArTPC

Example of a neutrino interaction in a LArTPC

The first, horizontal drift, DUNE FD module will house 150 APAs, with 50 TPCs residing between each APA-CPA pair.
DUNE physics

Primary goal:
Precise neutrino oscillation parameter measurements

DUNE $\nu_\mu$ oscillation probability region of interest
DUNE physics

- **CP-phase, $\delta_{\text{CP}}$**
  - Significant CP violation discovery potential over wide range of true $\delta_{\text{CP}}$ values within 10 years

DUNE physics

- CP-phase, $\delta_{CP}$
  - Significant CP violation discovery potential over a wide range of true $\delta_{CP}$ values within 10 years

- Mass ordering
  - Unambiguous measurement of the neutrino mass ordering for all values of $\delta_{CP}$ within the first few years

DUNE physics

- **CP-phase, $\delta_{CP}$**
  - Significant CP violation discovery potential over a wide range of true $\delta_{CP}$ values within 10 years

- **Mass ordering**
  - Unambiguous measurement of the neutrino mass ordering for all values of $\delta_{CP}$ within the first few years

- **Astrophysical neutrino searches**
  - Solar neutrinos
  - Supernova neutrinos

- **Atmospheric neutrino searches**

- **Beyond the Standard Model (BSM) searches**
DUNE physics

Multiple features of the DUNE experimental program will facilitate these measurements, including:

- Unprecedented control of the systematic uncertainties using the near detector system
- Liquid argon technology provides mm-scale resolution of neutrino interactions
- Expertise gained from ProtoDUNE - A multi-system prototype for DUNE
- Calibration of the detector systems
Calibrating the DUNE FD LArTPCs

Calibration approach

- Determine the components of the detector response which measurements depend on
- Calculate the response of the detector to these dependencies using “standard candles”
- Establish the calibration timescale required to achieve **physics precision goals**
  - GeV-scale: < 2% (5%) energy scale uncertainty on leptons (hadrons)
  - MeV-scale: < 5% energy scale uncertainty
- Ultimately, the simulation will be updated such that it better-reflects DUNE data

Calibration sources

- Naturally-occurring
  - Cosmic muons
  - Atmospheric neutrinos
  - Intrinsic radioactive isotopes
- Beam particles
  - Neutrinos
  - Neutrino interaction products
- Hardware systems under development
  - Ionisation laser system
  - Pulsed neutron source
  - Radioactive source deployment system

*Discussed in this talk*
## Detector response dependencies

<table>
<thead>
<tr>
<th>Dependency</th>
<th>Definition</th>
<th>Measurement significance</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Electric field</strong></td>
<td>Goal field strength is <strong>500 V/cm</strong> in each DUNE TPC</td>
<td>Precision map of the uniformity is essential in determining the ionisation electron origin</td>
</tr>
<tr>
<td><strong>Recombination</strong></td>
<td>Ionisation electron recombination with positively-charged argon ions</td>
<td>Impacts the number of electrons reaching the wire planes, E-field-dependent</td>
</tr>
<tr>
<td><strong>Electron lifetime</strong></td>
<td>Drift time before electrons attach to electronegative impurities. Goal: <strong>&gt;3 ms</strong></td>
<td>Impacts the number of electrons reaching the wire planes, purity-dependent</td>
</tr>
<tr>
<td><strong>Electron diffusion</strong></td>
<td>Longitudinal and transverse spread of the electrons as they drift in the TPC</td>
<td>Affects the signal shape and the electron distribution across wires</td>
</tr>
<tr>
<td><strong>Electronics</strong></td>
<td>Gain [mV/fC], wire field response, electronics response</td>
<td>Definition of the absolute energy scale and signal distribution on wires</td>
</tr>
</tbody>
</table>
Cosmic-ray muons

- DUNE FD MC simulations: **4,750 primary muons** in the active volume of a single 17 kt module per day
  - 1.8% (around **90/day**) stop in the detector

- Stopping and through-going muons are standard candles for drift-dependent calibrations
  - Electron lifetime, recombination & detector alignment

- Source of other standard candles
  - $\delta$-ray & Michel electrons

- Electron lifetime can be calculated from the x-position-dependence of the muon charge depositions

- ProtoDUNE achieved **24 ms** electron lifetime\(^1\)

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\(^1\) B. Abi et al 2020 JINST 15 P12004
Cosmic-ray muon energy calibration

- Look at the true-energy dependence of through-going muon track charge depositions
  - Determine how best to mitigating this truth-level dependence in data
  - Quantify any impact on the energy scale in the form of a systematic
Cosmic-ray muon energy calibration

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  - Determine how best to mitigating this truth-level dependence in data
  - Quantify any impact on the energy scale in the form of a systematic

- Use the well-characterised behaviour of stopping muon track energy depositions
  - As a function of residual range, the distance from the end of the track

Absolute energy scale calibration

<table>
<thead>
<tr>
<th>True muon energy [GeV]</th>
<th>Reconstructed dQ/dx [ADC/cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0.1</td>
</tr>
<tr>
<td>10^2</td>
<td>0.2</td>
</tr>
<tr>
<td>10^3</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Stopping muon energy calibration

<table>
<thead>
<tr>
<th>Reconstructed residual range [cm]</th>
<th>Reconstructed dQ/dx [ADC/cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.1</td>
</tr>
<tr>
<td>50</td>
<td>0.2</td>
</tr>
<tr>
<td>100</td>
<td>0.3</td>
</tr>
</tbody>
</table>

DUNE simulation | DUNE work in progress

- Best plane (most hits)
  - Far detector, single phase
  - Through-going muons
    - 2.88 ms corrected lifetime
    - 17 kt, 70 days

- Stopping muons, > 2 m long
  - As a function of residual range, the distance from the end of the track
$\pi^0 \rightarrow \gamma\gamma$

- $\pi^0$ invariant mass is a standard candle
- Used for calibrating the electromagnetic energy reconstruction
- $\pi^0$ are available from multiple sources
  - Only **0.8% (around 40/day)** of the primary cosmic-ray muons produce at least 1 $\pi^0$ in the DUNE FD
  - Around **200 $\pi^0$/day** in total are produced the DUNE FD
- It is difficult to reconstruct the full electromagnetic shower energies of the photon decay products
- Procedures for calibrating with $\pi^0$'s have been developed by other experiments

$$m_{\pi^0} = \sqrt{2E_1E_2(1 - \cos \theta)}$$
Michel and δ-ray electrons

- Used to calculate the low-energy electron energy scale
  - Critical for the astrophysical neutrino program

- **Michel electrons** occur at the end of a stopping muon
  - Low statistics but easy to reconstruct

- **δ-rays** are produced along muon tracks
  - Increased rate with muon energy
  - Extremely high statistics but often very few hits
Radioactive isotopes

- $^{39}$Ar is naturally present in the detector
  - Beta decays have end-point energy of 565 keV
  - Decay rate of ~1 Bq/kg
  - High statistics

- Electron lifetime, recombination and electronic noise effects on the spectrum are largely separable
  - ProtoDUNE have successfully used the relative change in spectra to predict the electron lifetime at the % level

- $^{42}$Ar will be present$^{2,3}$, though less abundant than $^{39}$Ar
  - ~0.1 mBq/kg
  - Higher energies possible, just below 4 MeV

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Ionisation laser system

- Construct drift velocity and electric field maps from track position distortion measurements
- Facilitates a fine-grained estimate of the electric field in space and time
- Multiple periscopes placed in the detector in order to maximise coverage
  - FC-penetrating (1) and non-penetrating (2) designs
- Possible measurements:
  - E-field
  - Drift velocity
  - APA alignment
Pulsed neutron source

- Neutron capture in $^{40}\text{Ar}$: $n + ^{40}\text{Ar} \rightarrow ^{41}\text{Ar} + 6.1 \text{ MeV } \gamma$
  - Well-characterised $\gamma$ cascades from dedicated experiments

- Deuteron-deuteron (DD) source used
  - Possibility for high statistics

- $^{40}\text{Ar}$ has an anti-resonance at 57 keV where the elastic scattering cross-section is low
  - High detector coverage from long-range neutrons

- Possibility for characterising the low energy threshold region of DUNE (5-10 MeV)
  - Valuable for low energy recombination and energy scale calibration measurements
  - Valuable for low energy charge and light calibrations
  - Critical for astrophysical neutrino program

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3arXiv:2203.00740
Summary

● There are many calibration procedures under development for DUNE - Software and hardware-based techniques
● Challenges introduced by the detector response will be carefully addressed in order to,
  - Minimise the systematic uncertainties to achieve the precision goals
  - Eliminate data-MC biases in all physics measurements
● Will leverage ProtoDUNE data where possible in order to mitigate the challenges faced in operating an experiment on the scale of DUNE

Thank you!
Thank you!
Backup slides
BSM in DUNE

- Search for active-sterile neutrino mixing
- Searches for non-unitarity of the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix
- Searches for nonstandard interactions (NSI)
- Searches for violation of Lorentz or charge, parity, and time reversal symmetry (CPT)
- Searches for neutrino trident production
- Search for light-mass dark matter (LDM)
- Search for boosted dark matter (BDM)
Cosmic-ray muons in DUNE

Muon rate [1/(10 kt)/day/GeV]

Muons energy [GeV]

Preliminary

DUNE simulation

Far detector

$\langle E_\mu \rangle = 282$ GeV

3244 $\mu/(10$ kt)/day
Landau-Vavilov

The Landau-Vavilov formula dictates the expected behaviour of muon energy depositions per unit length with respect to its energy and ‘thickness’ (density*pitch).

It should be possible to use this formula in the calibration of the energy scale of the detector.

This could either be defined in an energy-dependent or independent way.

Though energy-dependent is very difficult due to reconstruction complications with through-going muons.

\[
\Delta_p = \xi \left( \frac{\ln \frac{2m_e^2\beta^2\gamma^2}{I}}{I} + \frac{\xi}{I} + j - \beta^2 - \delta(\beta\gamma) \right)
\]

\[
\delta(\beta\gamma) = \begin{cases} 
0, & \text{if } 2 \log_{10}(\beta\gamma) \ln(10) < 5.2146 \\
2 \log_{10}(\beta\gamma) \ln(10) - 5.2146 + 0.19559(3 - \log_{10}(\beta\gamma)), & \text{if } 2 \log_{10}(\beta\gamma) \ln(10) > 5.2146, \\
\log_{10}(\beta\gamma) < 0.2, & \text{if } 0.2 < \log_{10}(\beta\gamma) < 3.0 \\
3.0 < \log_{10}(\beta\gamma) & \end{cases}
\]

At the CR muon average:

\[
p_\mu = 292,000 \text{ MeV/c} \]

\[
\left(\frac{dE}{dx}\right)_{\text{MPV}} = 1.804 \text{ MeV/cm}
\]
## Landau-Vavilov

<table>
<thead>
<tr>
<th>Param.</th>
<th>Value</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>m</td>
<td>0.511 MeV/c^2</td>
<td>Electron mass</td>
</tr>
<tr>
<td>l</td>
<td>188x10^{-6} MeV</td>
<td>Mean excitation energy</td>
</tr>
<tr>
<td>j</td>
<td>0.2</td>
<td>Value from here</td>
</tr>
<tr>
<td>δ(βγ)</td>
<td>See RHS of slide, based on Sternheimer</td>
<td>Density effect coefficient</td>
</tr>
<tr>
<td>β</td>
<td>v/c</td>
<td>Relativistic beta</td>
</tr>
<tr>
<td>γ</td>
<td>p/m_μ</td>
<td>Relativistic gamma</td>
</tr>
<tr>
<td>ξ</td>
<td>(k/2)<em>(Z/A)</em>((x/β^2) MeV</td>
<td>-</td>
</tr>
<tr>
<td>k</td>
<td>0.307075</td>
<td>4π N_A r_e m MeV cm / mol</td>
</tr>
<tr>
<td>x</td>
<td>(p*dp) kg/cm^2</td>
<td>Thickness (density * pitch)</td>
</tr>
</tbody>
</table>

Peak values used to construct plot on RHS

| dp | 0.55 cm | Peak pitch in CR muon sample |

\[ \Delta_p = \xi \left[ \ln \frac{2mc^2\beta^2\gamma^2}{I} + \ln \frac{\xi}{I} + j - \beta^2 - \delta(\beta\gamma) \right] \]

\[ \delta(\beta\gamma) = \begin{cases} 0, & 2 \log_{10}(\beta\gamma) \ln(10) - 5.2146 + 0.19559(3 - \log_{10}(\beta\gamma)), \\ 2 \log_{10}(\beta\gamma) \ln(10) - 5.2146, & \log_{10}(\beta\gamma) < 0.2 \\ 0.2 < \log_{10}(\beta\gamma) < 3.0 \\ 3.0 < \log_{10}(\beta\gamma) \end{cases} \]

At the CR muon average:

\[ p_\mu = 292,000 \text{ MeV/c} \]

\[ \left( \frac{dE}{dx} \right)_{MPV} = 1.804 \text{ MeV/cm} \]
Cosmic-ray muons

- DUNE FD MC simulations: **4,750 primary muons** in the active volume of a single 17 kt module per day
  - 1.8% (around 90/day) stop in the detector

- Stopping and through-going muons are standard candles for drift-dependent calibrations
  - Electron lifetime, recombination & detector alignment

- Source of other standard candles
  - δ-ray & Michel electrons

- Measured a **4% τ_e bias** using a reconstructed approach in the DUNE FD MC simulation
  - The cause is currently being understood

- ProtoDUNE achieved **24 ms** electron lifetime¹

¹B. Abi et al 2020 JINST 15 P12004
Cosmic-ray muons

- Use the well-characterised behaviour of stopping muon energy depositions along the length of the track
- ProtoDUNE were capable of getting excellent agreement in stopping muon $dE/dx$ vs residual range between their calibrated measurements, MC and theoretical expectation

![Graphs showing comparison between data, MC, and theoretical expectation](image)
π^0 \rightarrow γγ

π^0 Invariant mass calculated with different photon selection criteria.

When adding true energy requirements to the photon selections the measured invariant mass bias, Δm, reduces from ~75 MeV/c^2 (56% of the true value) to ~25 MeV/c^2 (19% of the true value).

The width of the measured invariant mass peak also reduces substantially.

Reconstruction-based photon/π^0 selections are under development.

\[ m_{π^0} = \sqrt{2E_1 E_2 (1 - \cos θ)} \]

π^0 selection criteria:
- No requirement on energy or angle

π^0 selection criteria:
- \( E_{true}(γ_1) > 60 \text{ MeV} \)
- \( E_{true}(γ_2) > 40 \text{ MeV} \)
Ionisation laser system

- Construct drift velocity and E-field maps from track position distortion measurements
- Fine-grained estimate of E-field in space and time
- Multiple periscopes in the detector to maximise coverage

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Complexities</th>
</tr>
</thead>
<tbody>
<tr>
<td>High statistics</td>
<td>Field cage aperture required for design 1</td>
</tr>
<tr>
<td>Well defined tracks</td>
<td>Shadowing of FC profiles possible in design 2, if not mitigated</td>
</tr>
<tr>
<td>Possible measurements:</td>
<td>Design-dependent coverage</td>
</tr>
<tr>
<td>● E-field &amp; drift velocity</td>
<td></td>
</tr>
<tr>
<td>● APA alignment</td>
<td></td>
</tr>
<tr>
<td>● Photon system efficiency</td>
<td></td>
</tr>
</tbody>
</table>
Radioactive source deployment system

- Radioactive sources can be deployed within the detector
  - Primarily \(^{58}\text{Ni}\) (9 MeV γ)
  - Also neutron & alpha (6 & 15 MeV γ) sources
  - At known locations with known activity

- Measure the response of the detector to photon signals
  - Within the energy range of interest to the DUNE astrophysical program

- Calibrate response to single isolated solar ν events
  - Determination of radiological background suppression capabilities
External measurements

SBN Program

- 3 LArTPC detectors in the Booster neutrino beam at Fermilab
- Will be running before DUNE switches on
  - Mature calibration procedures defined in each detector with possible applications to the DUNE ND & FDs
- Possibility for use of data in DUNE procedure development
- Substantially different, narrow-band, neutrino energy spectrum
- Both are surface detectors with different detector response parameters, such as space charge

ProtoDUNE

- Multiple iterations
  - Single phase (SP)
  - Dual phase (DP)
- Dedicated DUNE R&D
  - Same E-field
  - Same drift length
- Immediate use of ProtoDUNE data in the DUNE calibration procedure development
- Charged particle beam
  - Not neutrino beam

Pros || Cons

SBND cryostat
SBN Review

ProtoDUNE detector setup diagram