Calibrating the Deep Underground Neutrino Experiment (DUNE)

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CALOR 2022
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The University Of Sheffield.

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)

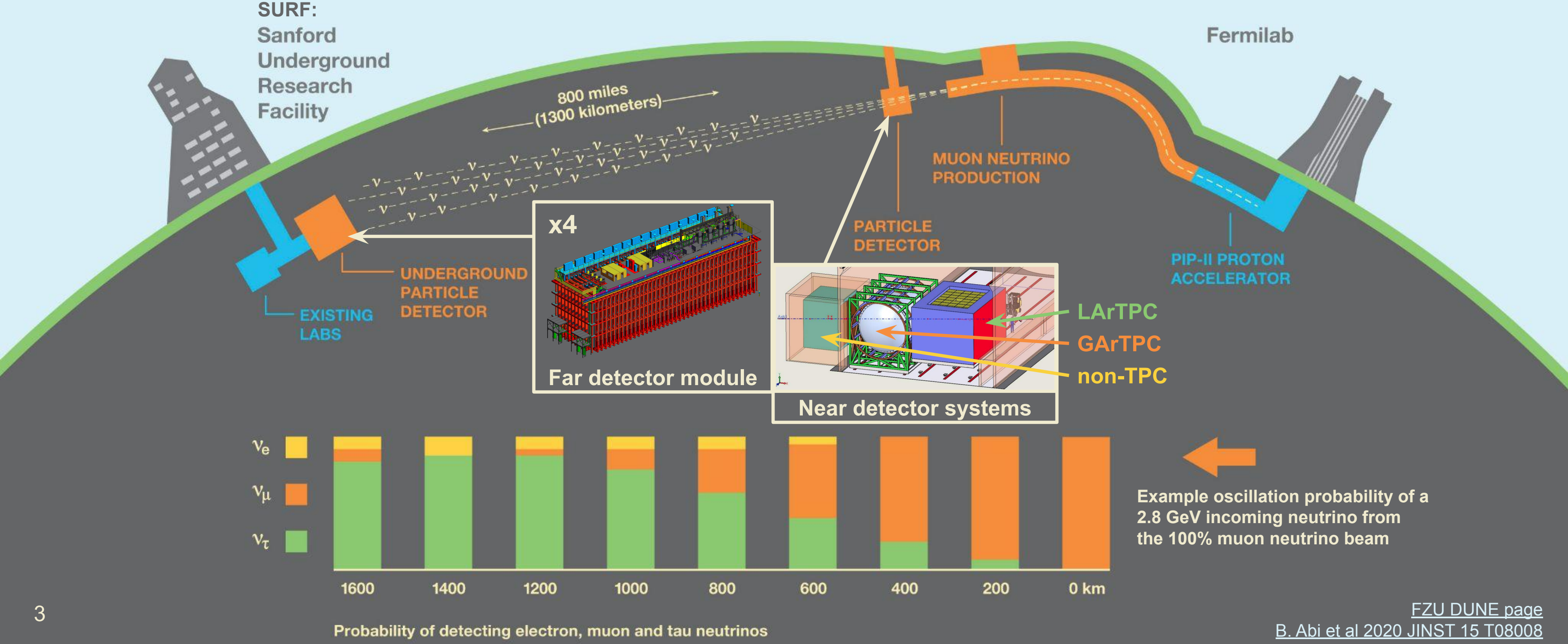
DUNE

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

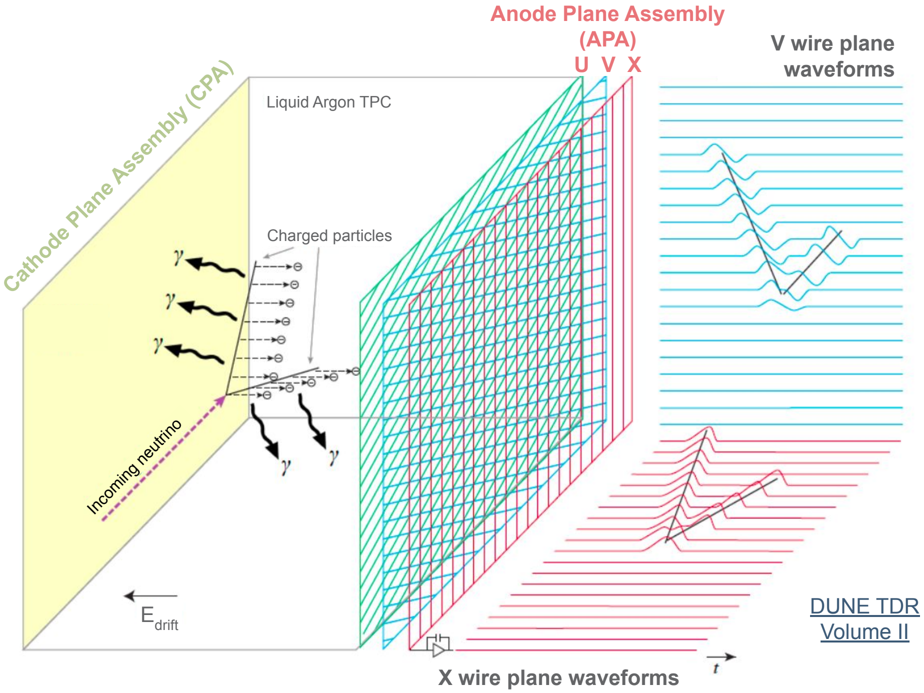
- Located at Fermilab, IL, USA
- Comprises LArTPC, gaseous argon (GAr) TPC & non-TPC components
- 574 m from the wideband ν beam source



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

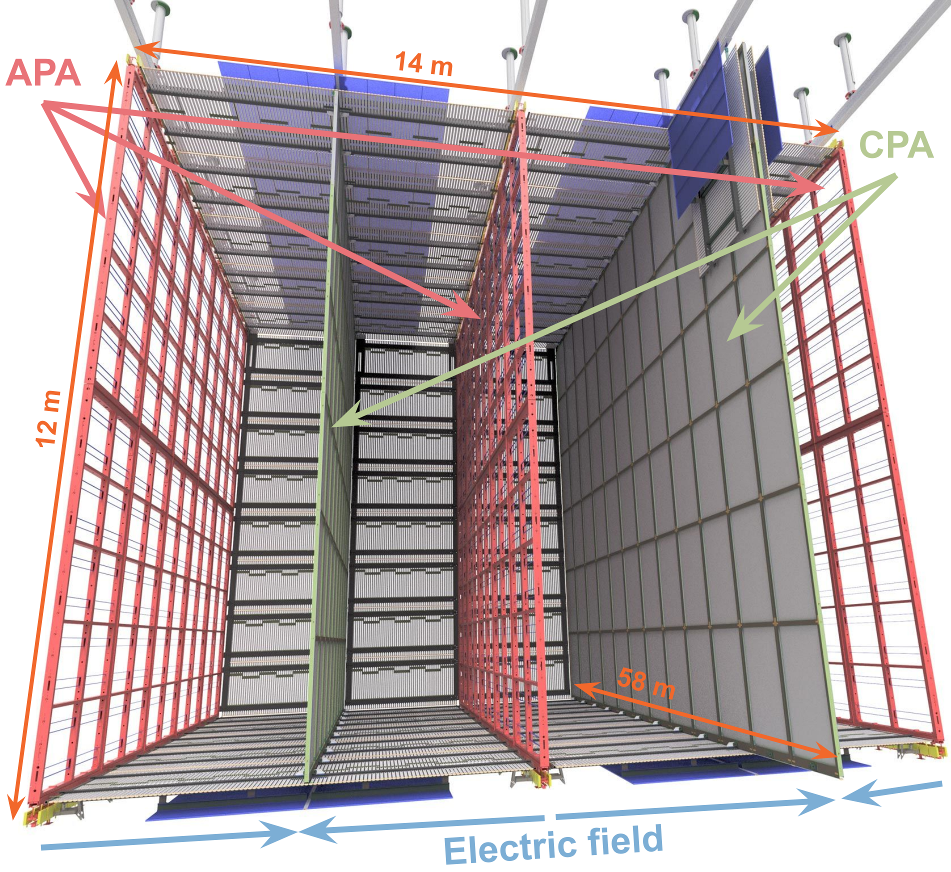
FZU DUNE page
B. Abi et al 2020 JINST 15 T08008

The DUNE LArTPC



DUNE TDR Volume II

Example of a neutrino interaction in a **LArTPC**

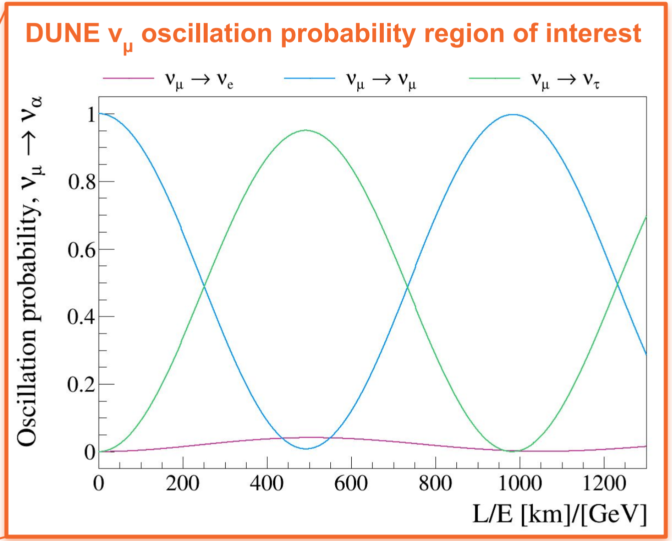


The first, *horizontal drift*, DUNE FD module will house **150 APAs**, with 50 TPCs residing between each APA-CPA pair

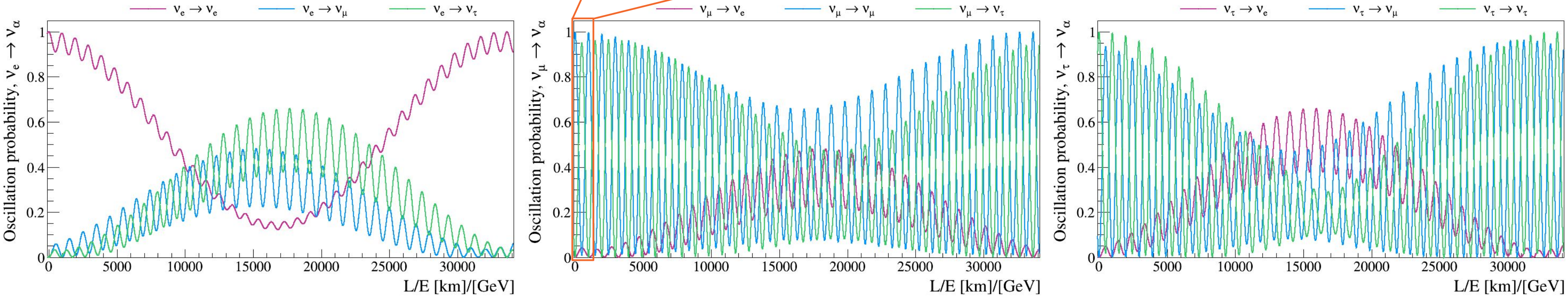
DUNE physics

Primary goal:

Precise neutrino oscillation parameter measurements

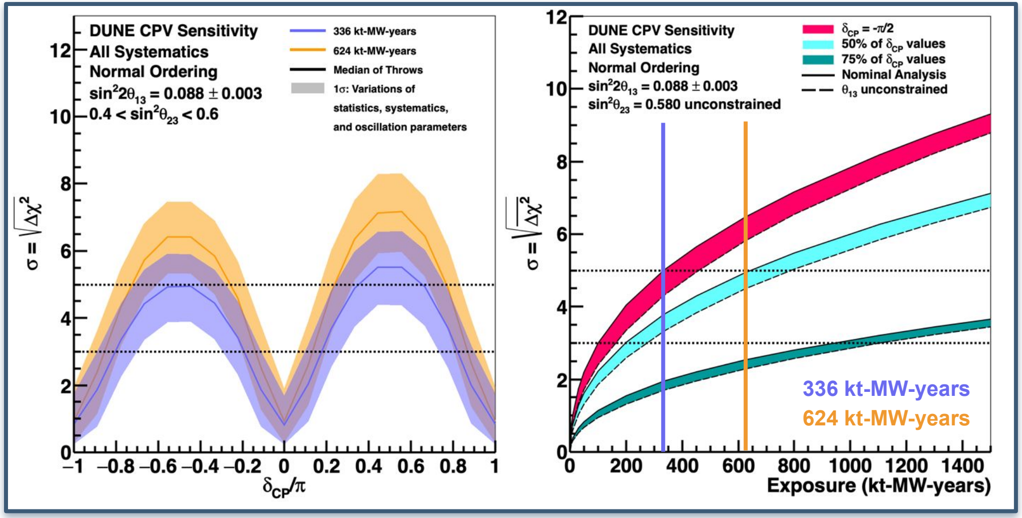


DUNE ν_μ oscillation probability region of interest



DUNE physics

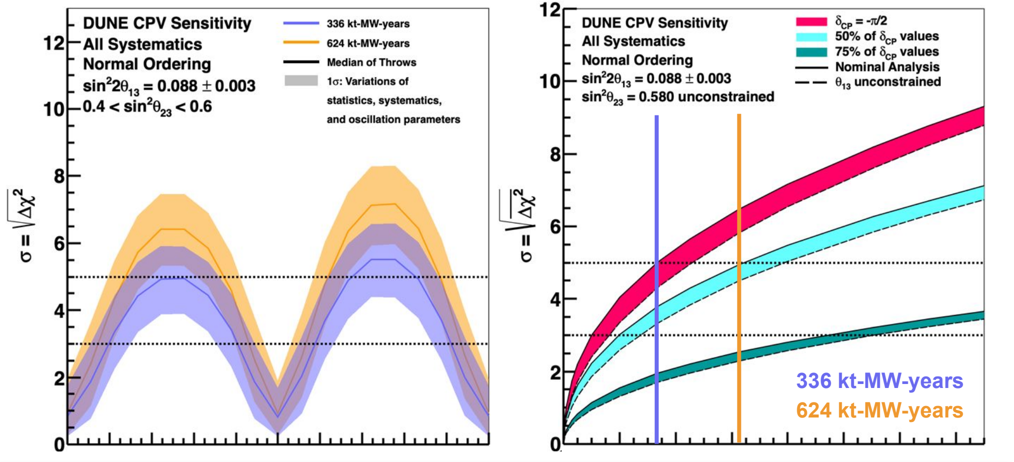
- CP-phase, δ_{CP}
  - Significant CP violation discovery potential over wide range of true δ_{CP} values within 10 years

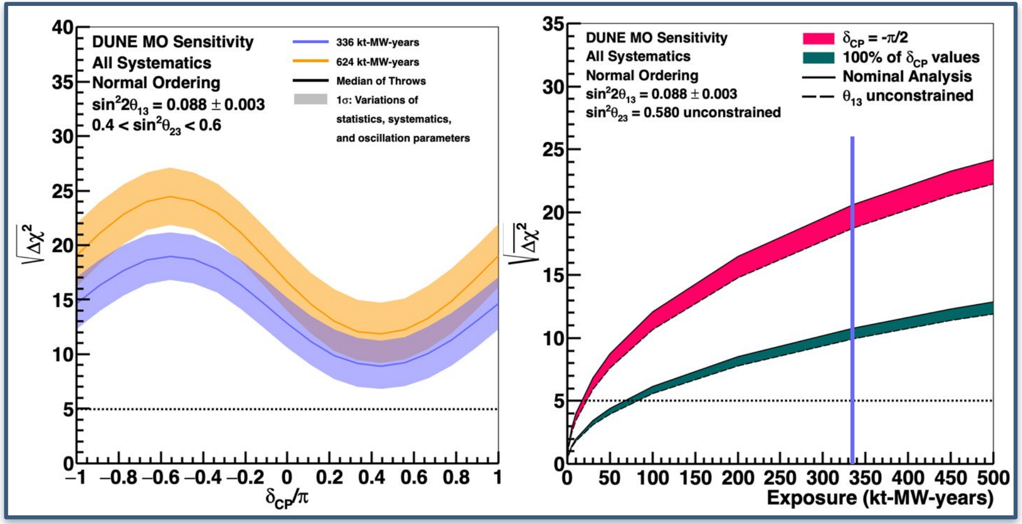


Snowmass Neutrino Frontier: DUNE Physics Summary (2021). arXiv:2203.06100

DUNE physics

- CP-phase, δ_{CP}
    - Significant CP violation discovery potential over a wide range of true δ_{CP} values within 10 years
- **Mass ordering**
    - **Unambiguous measurement of the neutrino mass ordering for all values of δ_{CP} within the first few years**





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- Mass ordering
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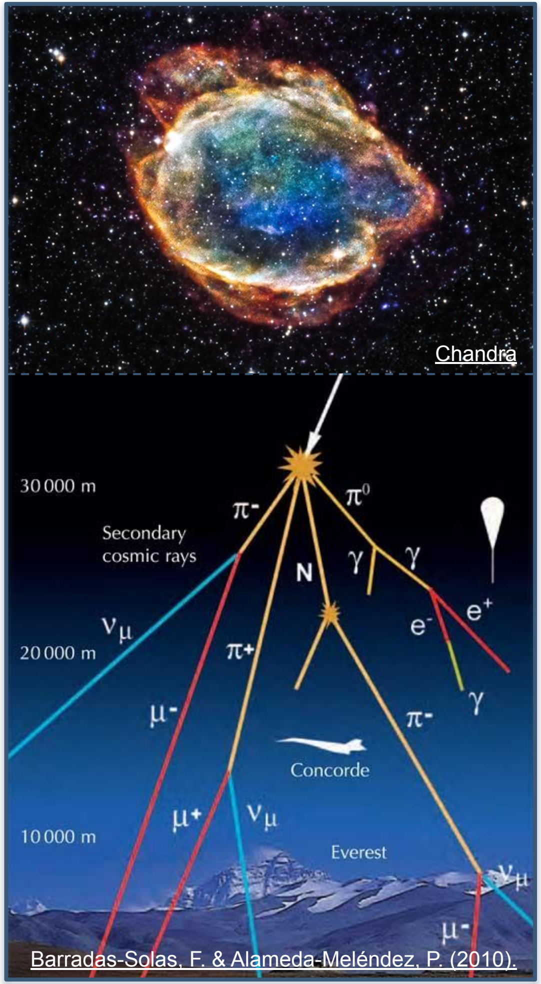
- **Astrophysical neutrino searches**
    - **Solar neutrinos**
    - **Supernova neutrinos**
- **Atmospheric neutrino searches**
- **Beyond the Standard Model (BSM) searches**



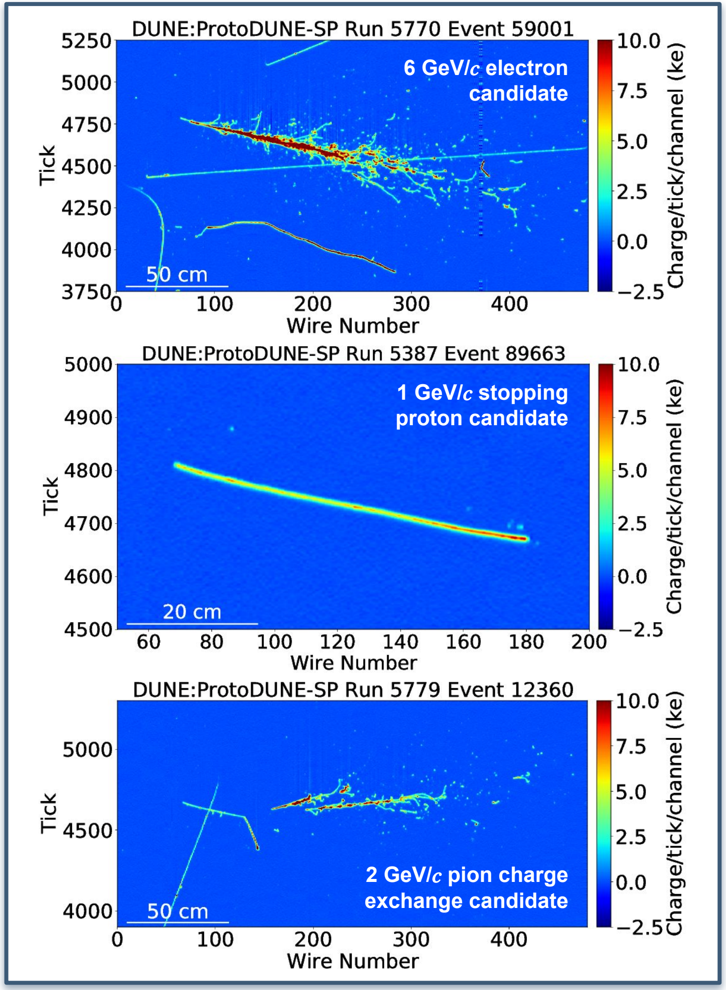
Chandra

Barradas-Solas, F. & Alameda-Meléndez, P. (2010).

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**



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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-occuring
    - **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

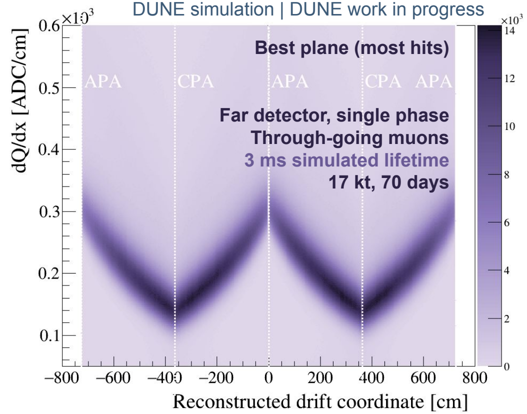
Detector response dependencies

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

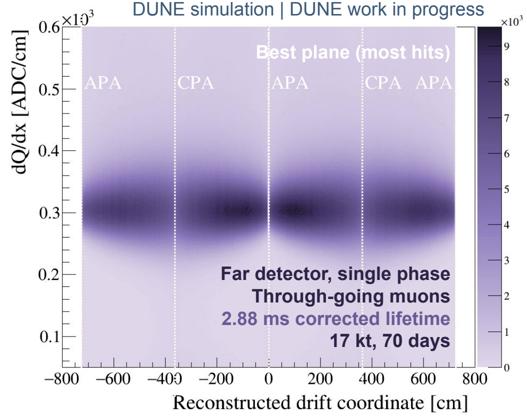
Cosmic-ray muons

- 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
- Electron lifetime can be calculated from the x-position-dependence of the muon charge depositions
- ProtoDUNE achieved **24 ms** electron lifetime[1]

Electron lifetime calculation



Reconstruction-based τ_e measurement: **2.88 ms**

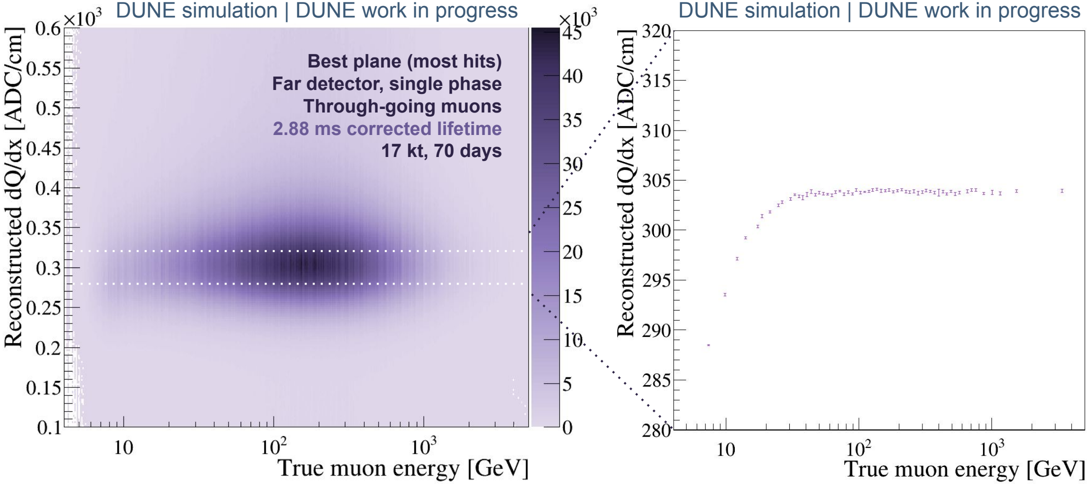


[1] B. Abi et al 2020 JINST 15 P12004

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

Absolute energy scale calibration

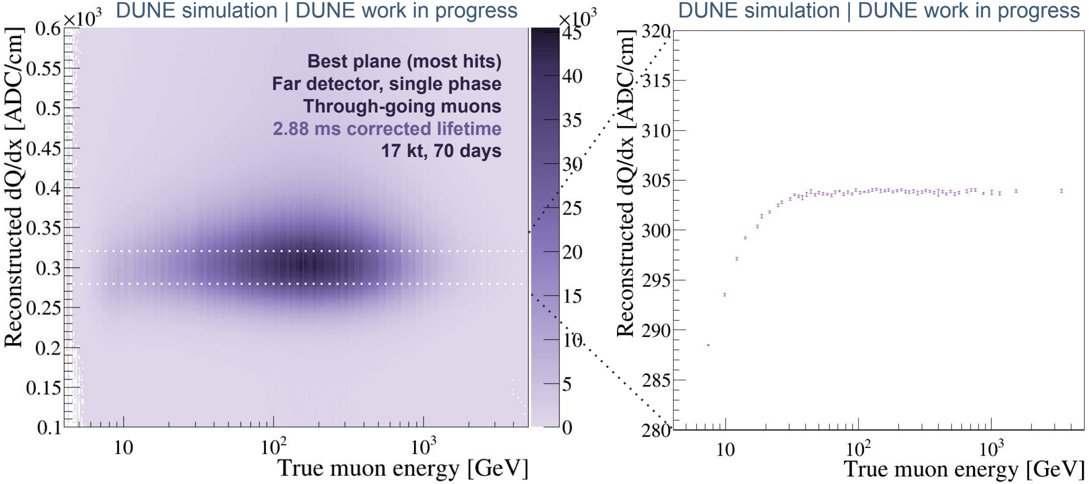


Cosmic-ray muon energy calibration

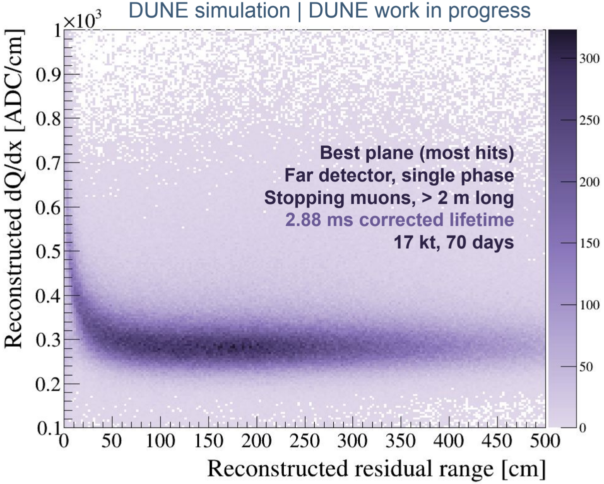
- Look at the true-energy dependence of through-going muon track charge depositions
  - Determine how best to mitigating this truth-level dependence in data
  - Quantify any impact on the energy scale in the form of a systematic

- **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

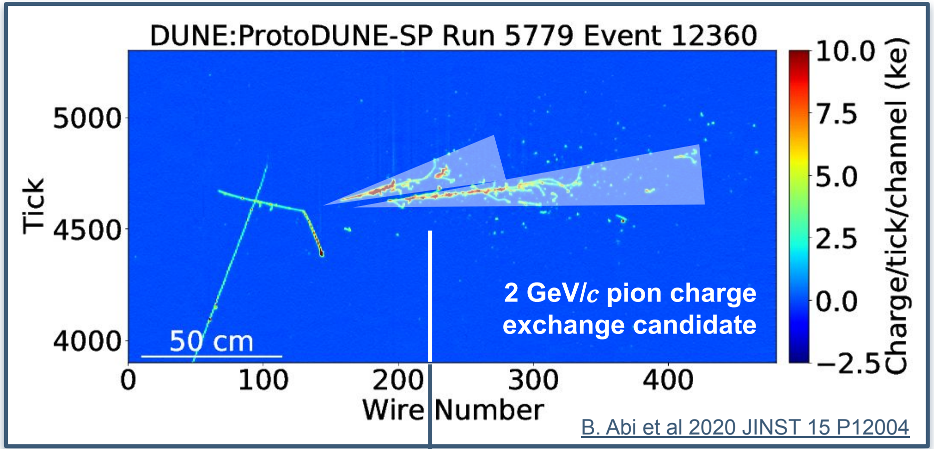


Stopping muon energy calibration



$\pi^0 \rightarrow \gamma\gamma$

- π^0 invariant mass is a standard candle
- Used for calibrating the electromagnetic energy reconstruction
- π^0 are available from multiple sources
    - Only **0.8% (around 40/day)** of the primary cosmic-ray muons produce at least 1 π^0 in the DUNE FD
    - Around **200 π^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 π^0's have been developed by other experiments



2 GeV/*c* pion charge exchange candidate

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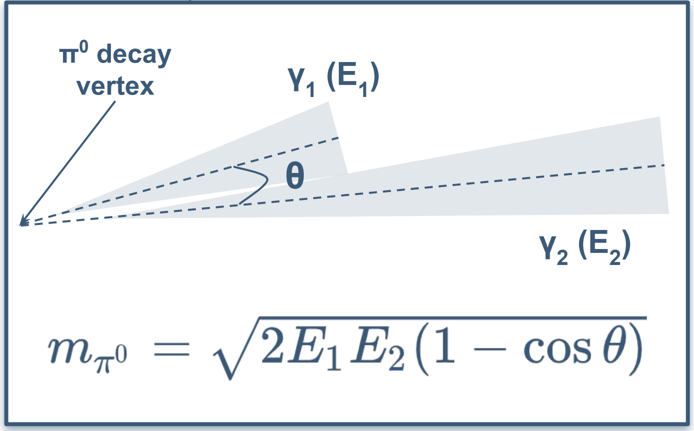
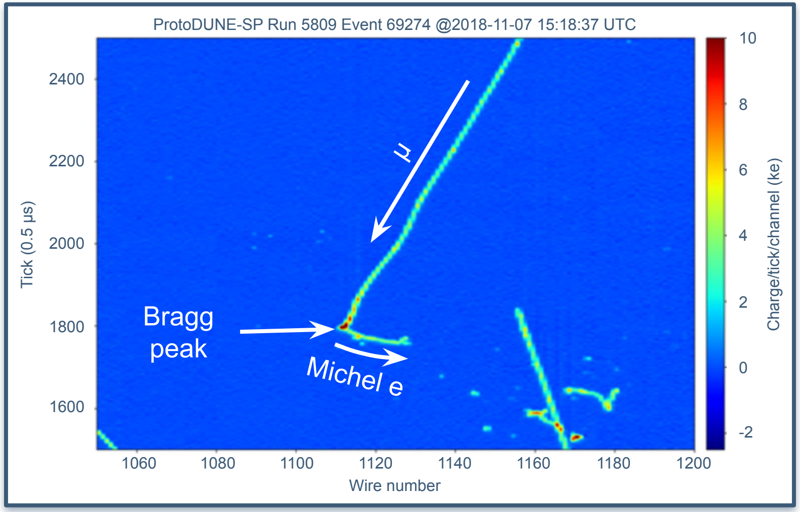


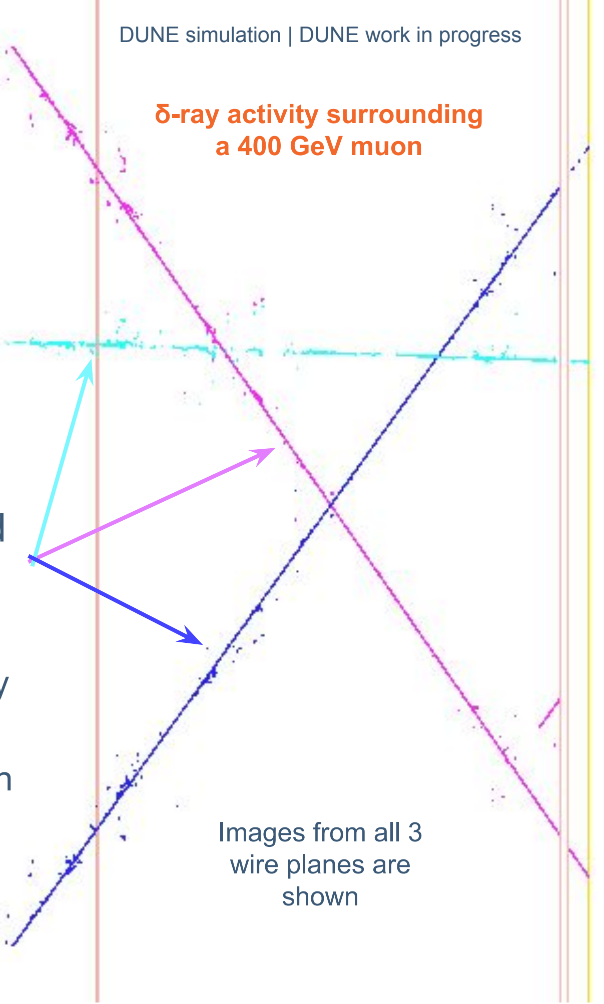
$$m_{\pi^0} = \sqrt{2E_1E_2(1-\cos\theta)}$$

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



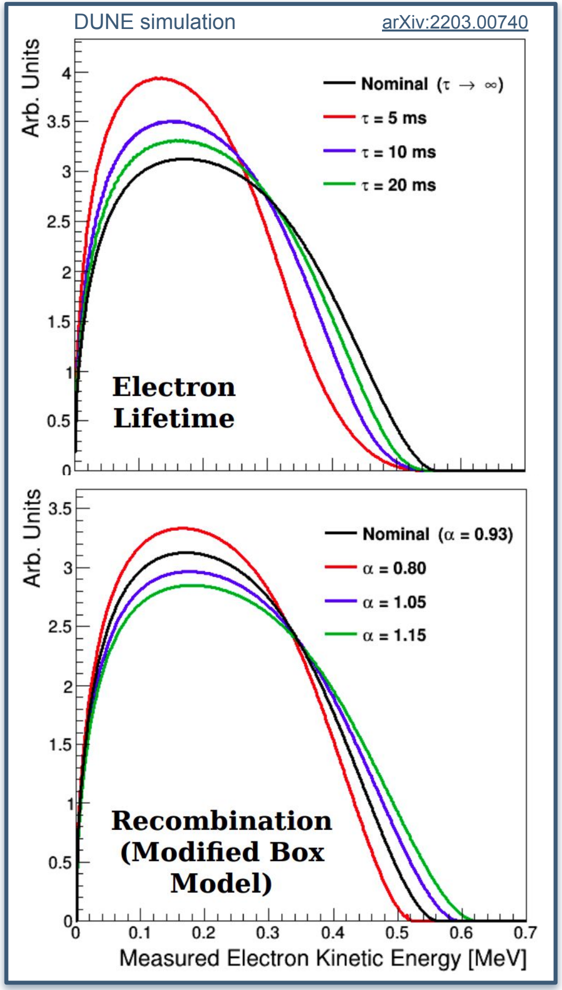
DUNE simulation | DUNE work in progress

δ-ray activity surrounding a 400 GeV muon

Images from all 3 wire planes are shown

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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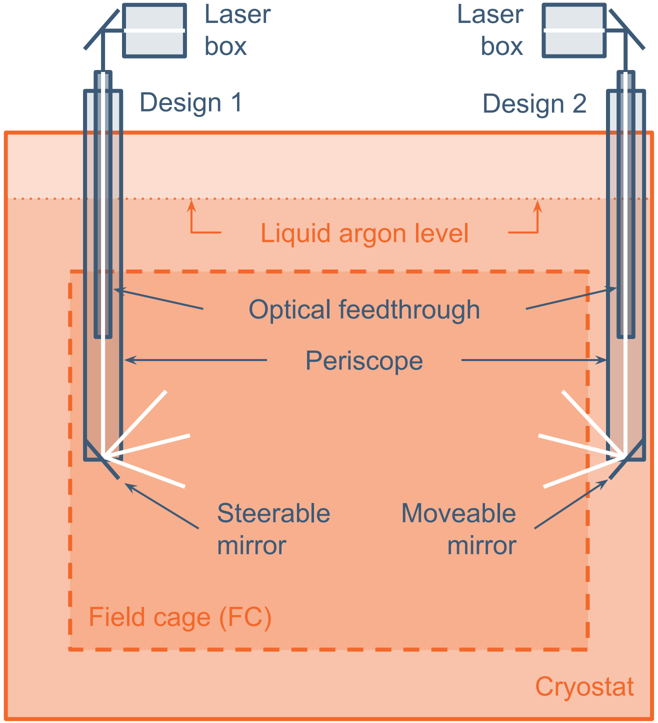
[2] A S Barabash et al 2016 J. Phys.: Conf. Ser. 718 062004, [3] arXiv:2203.00740

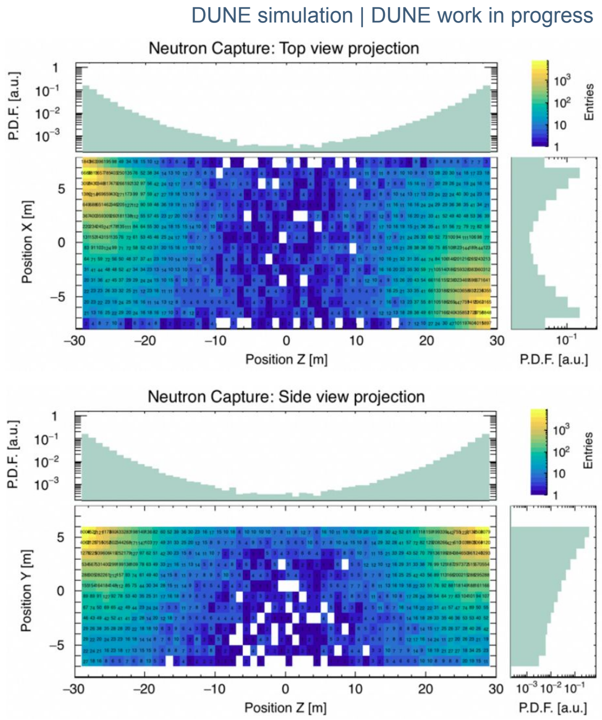
Ionisation laser system

- 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}Ar: **n + ^{40}Ar → ^{41}Ar + 6.1 MeV γ**
    - Well-characterised γ cascades from dedicated experiments
- Deuteron-deuteron (DD) source used
    - Possibility for high statistics
- ^{40}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



Particles 2022, 5(1), 74-83

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[3] arXiv: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!

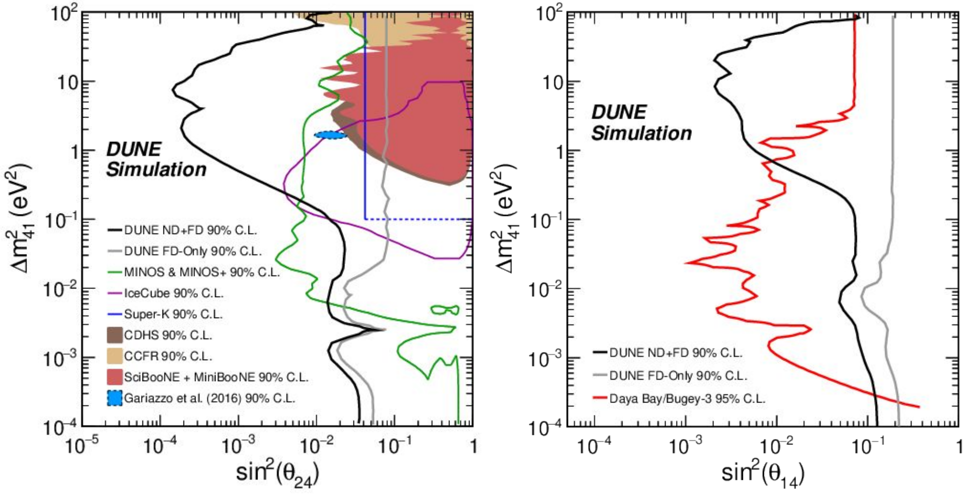
$\nu_{⚧}$ Thank you!

Backup slides

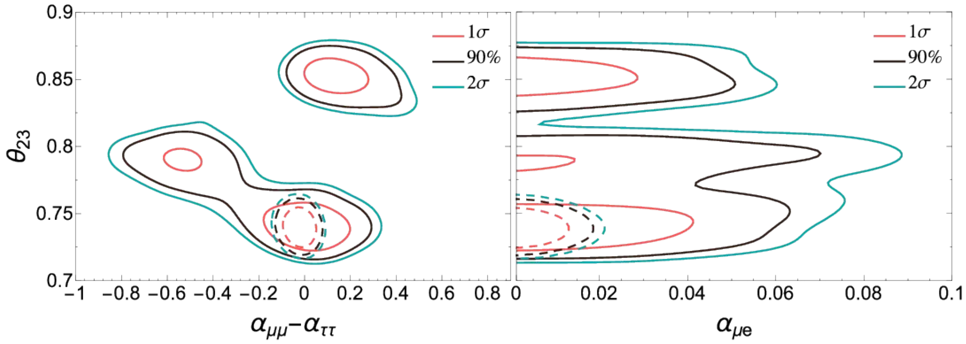
BSM in DUNE

- **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)

Active-sterile neutrino mixing sensitivities

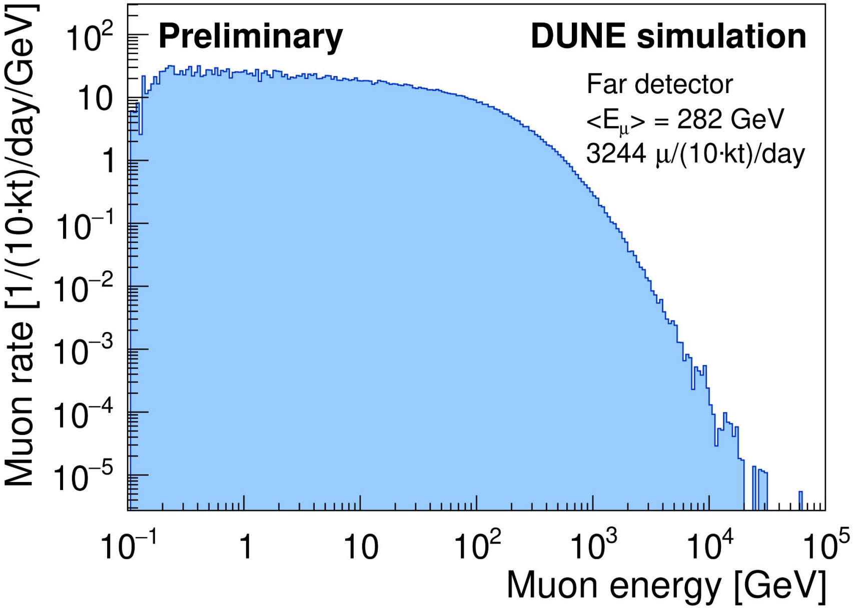


PMNS matrix non-unitarity parameter sensitivities



arXiv:2002.03005v2, Eur. Phys. J. C (2021) 81: 322

Cosmic-ray muons in DUNE



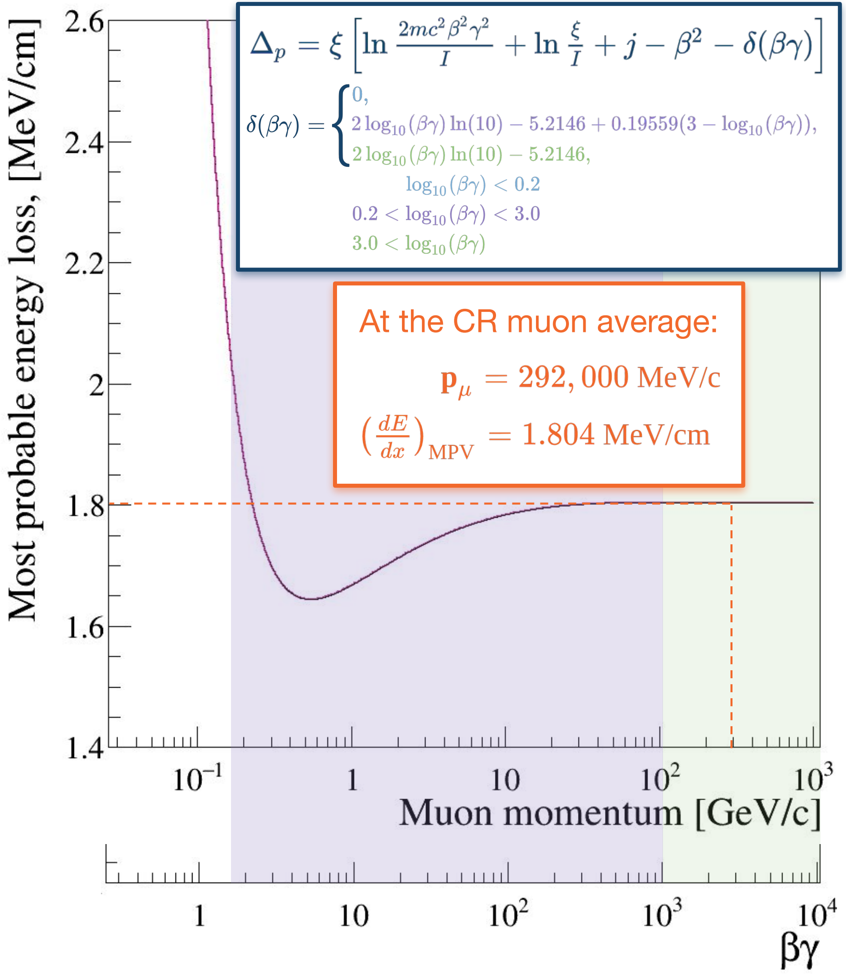
Landau-Vavilov

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.



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

$$\delta(\beta\gamma) = \begin{cases} 0, \\ 2\log_{10}(\beta\gamma)\ln(10) - 5.2146 + 0.19559(3 - \log_{10}(\beta\gamma)), \\ 2\log_{10}(\beta\gamma)\ln(10) - 5.2146, \end{cases}$$

$\log_{10}(\beta\gamma) < 0.2$

$0.2 < \log_{10}(\beta\gamma) < 3.0$

$3.0 < \log_{10}(\beta\gamma)$

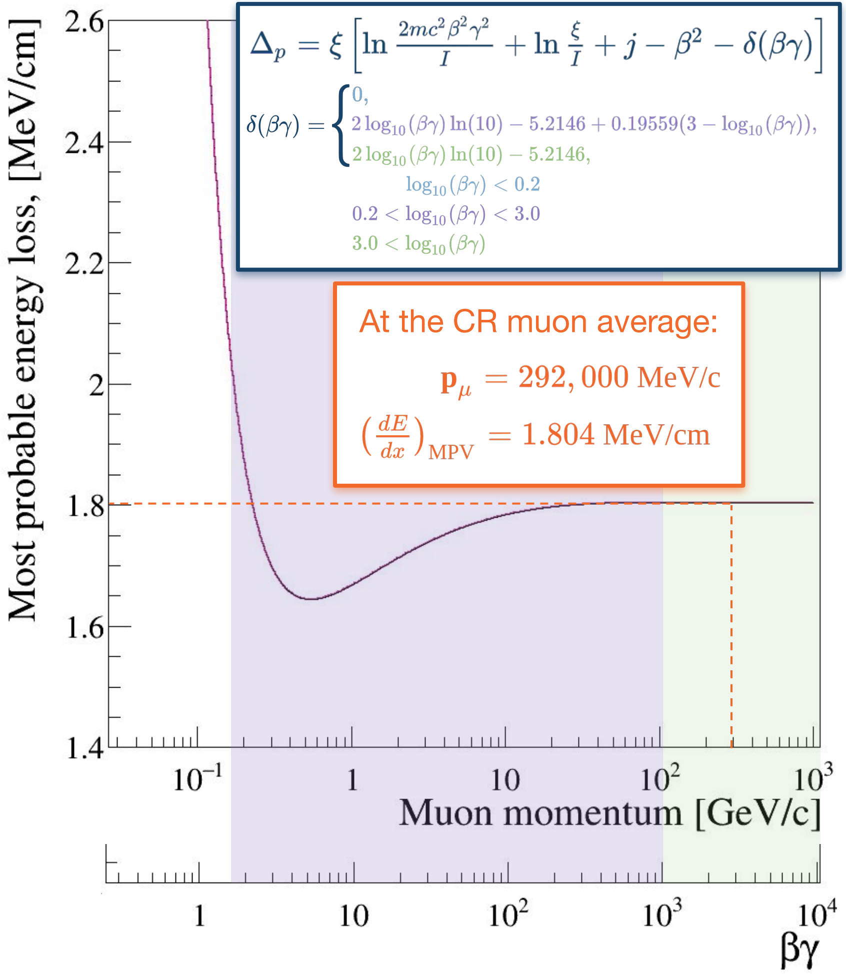
At the CR muon average:

$$\mathbf{p}_{\mu} = 292,000\ \mathrm{MeV/c}$$

$$\left(\frac{dE}{dx}\right)_{\mathrm{MPV}} = 1.804\ \mathrm{MeV/cm}$$

Landau-Vavilov

Param.	Value	Comment
m	0.511 MeV/c^2	Electron mass
I	188x10^{-6} MeV	Mean excitation energy
j	0.2	Value from **here**
δ(βγ)	See RHS of slide, based on Sternheimer	Density effect coefficient
β	v/c	Relativistic beta
γ	p/m$_\mu$	Relativistic gamma
ξ	(k/2)*(Z/A)*(x/β^2) MeV	-
k	0.307075	4π N$_A$ r$_e$ m MeV cm / mol
x	(ρ*dp) kg/cm^2	Thickness (density * pitch)
Peak values used to construct plot on RHS		
dp	0.55 cm	**Peak** pitch in CR muon sample



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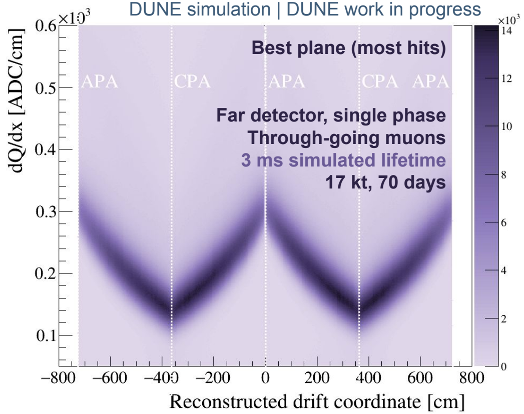
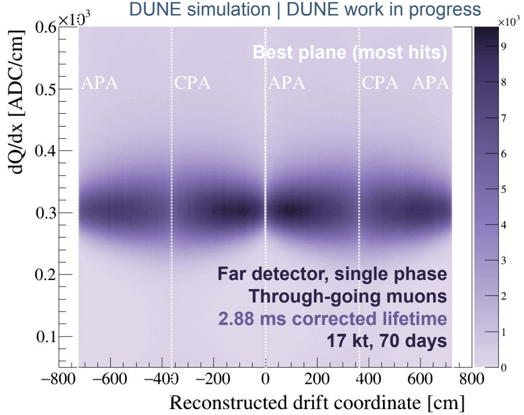
Cosmic-ray muons

- 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 lifetime[1]

Electron lifetime calculation



Reconstruction-based τ_e measurement: **2.88 ms**



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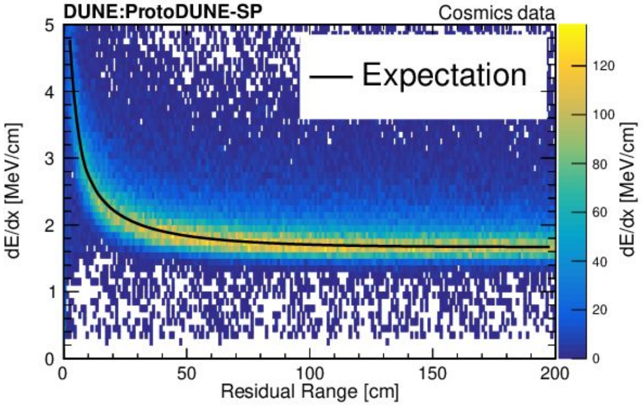
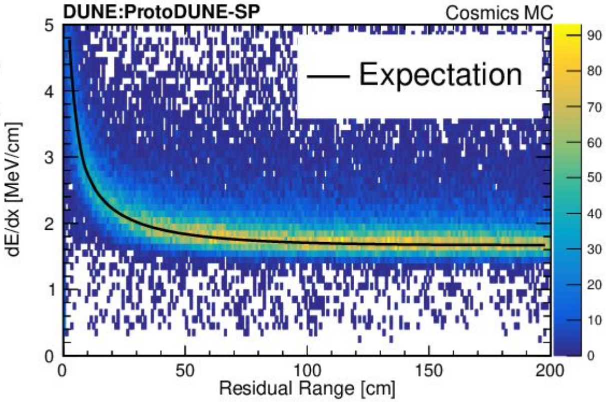
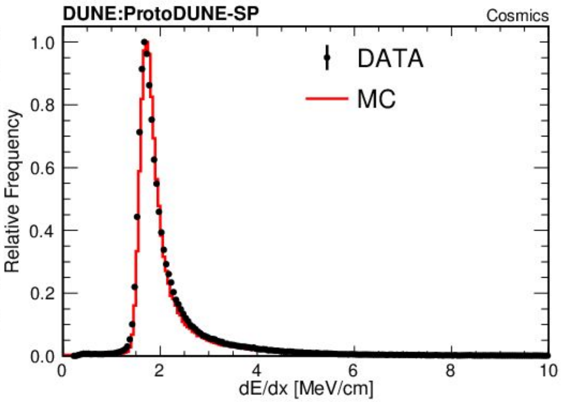
[1] B. Abi et al 2020 JINST 15 P12004

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







B. Abi et al 2020 JINST 15 P12004

$\pi^0 \rightarrow \gamma\gamma$

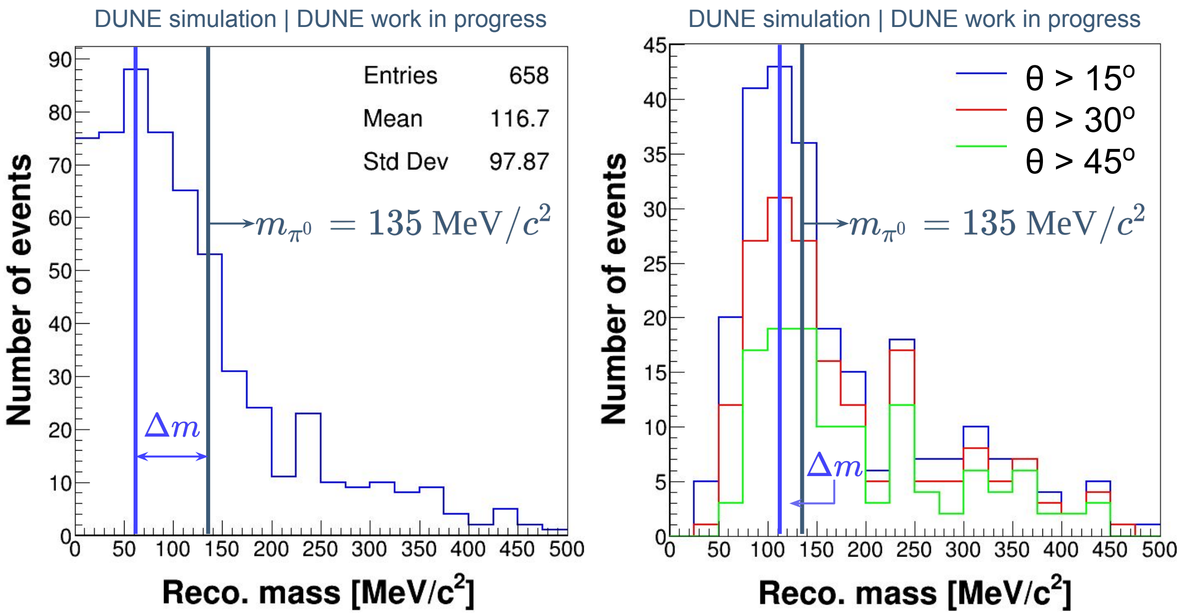
π^0 Invariant mass calculated with different photon selection criteria.

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.

$$m_{\pi^0} = \sqrt{2E_1 E_2 (1 - \cos\theta)}$$



π^0 selection criteria:

- No requirement on energy or angle

π^0 selection criteria:

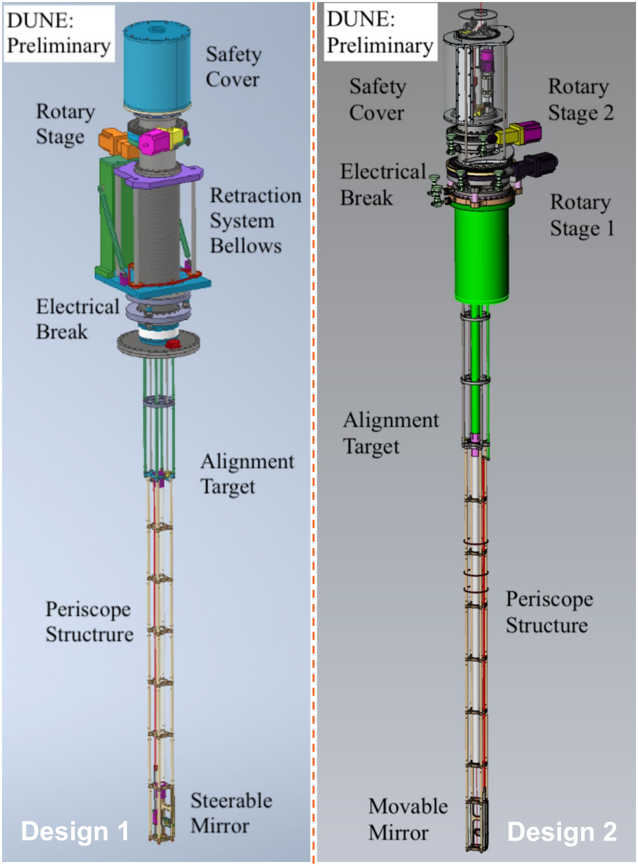
- $E_{true}(\gamma_1) > 60$ MeV
- $E_{true}(\gamma_2) > 40$ MeV

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

Advantages	Complexities
High statistics	Field cage aperture required for design 1
Well defined tracks	Shadowing of FC profiles possible in design 2, if not mitigated
Possible measurements: • E-field & drift velocity • APA alignment • Photon system efficiency	Design-dependent coverage

TPC Calibration

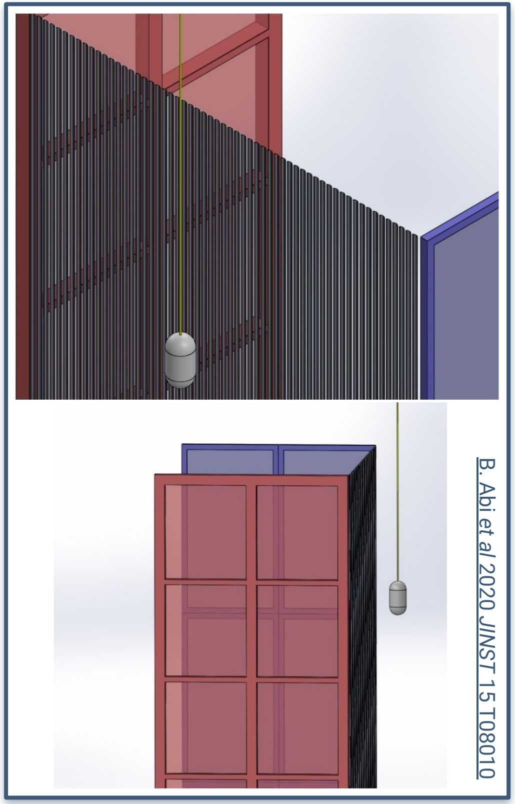


Retraction mechanism
Penetrates the TPC

Located next to the FC
Two eccentric rotation movements

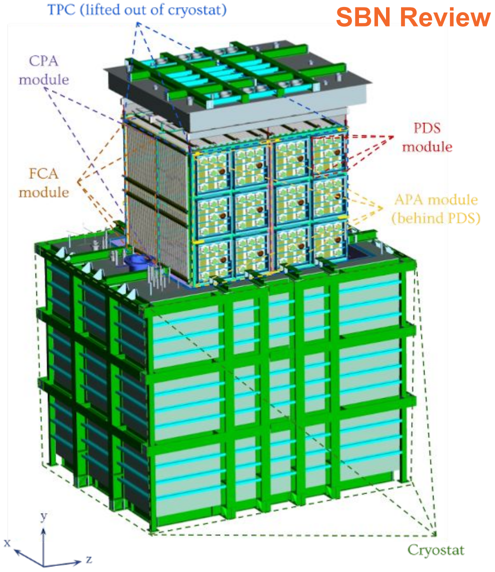
Radioactive source deployment system

- Radioactive sources can be deployed within the detector
  - Primarily **^{58}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



B. Abi *et al* 2020 JINST 15 T08010

External measurements



SBND cryostat
SBN Review

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

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

- Both are surface detectors with different detector response parameters, such as space charge