Neutrinos: The Long and Short of It

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QMUL Seminar 7/1/26

University of Sheffield

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Overview

- The neutrino detector landscape: long and short baselines
- Liquid Argon Time Projection Chambers (LArTPCs)
- The Short Baseline Near Detector (SBND)
- The Deep Underground Neutrino Experiment (DUNE)
- SBND and DUNE at Sheffield

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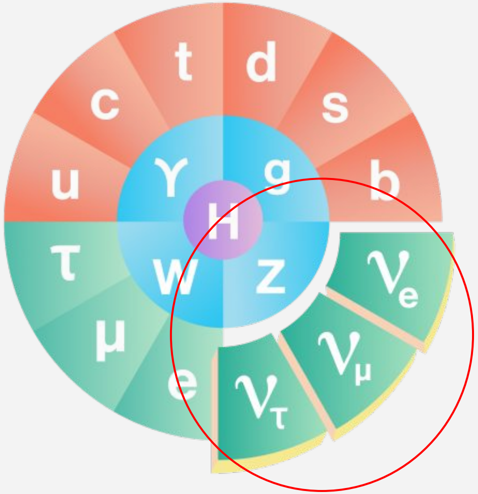
The Neutrino Landscape: Long and Short Baselines

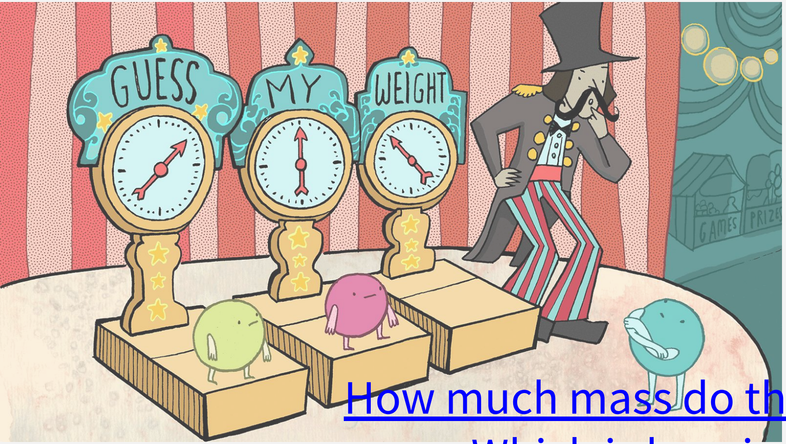
Neutrinos: The Basics



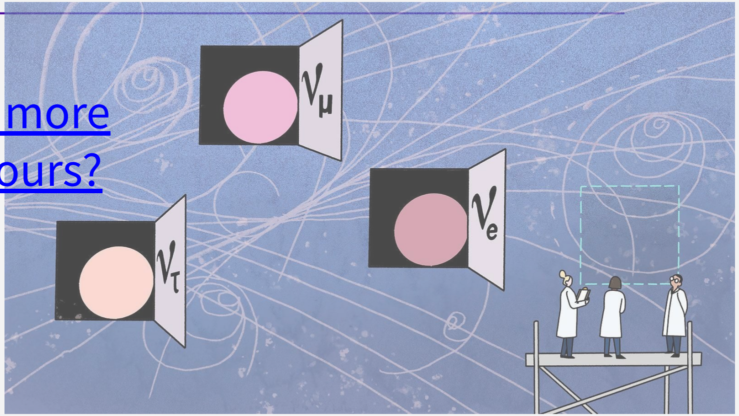
- They come in (at least) three flavours
- They are extremely light
- They have no charge
- They interact via the weak force (and gravity)
- They were postulated in 1930
- The first official detection of one was in the 1950s

Neutrinos (Fermilab)

Neutrinos: (some of) The Questions



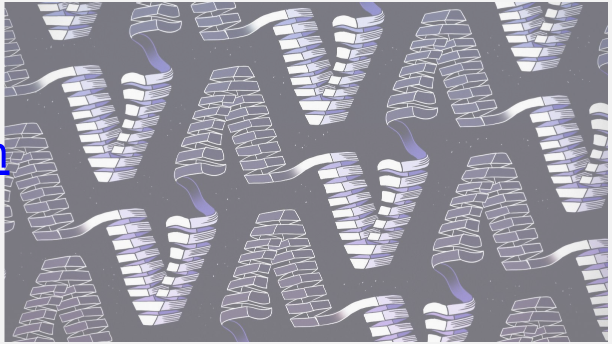
Are there any more neutrino flavours?



How much mass do they have?
Which is heaviest?

What do neutrinos contribute to Charge-Parity Violation?

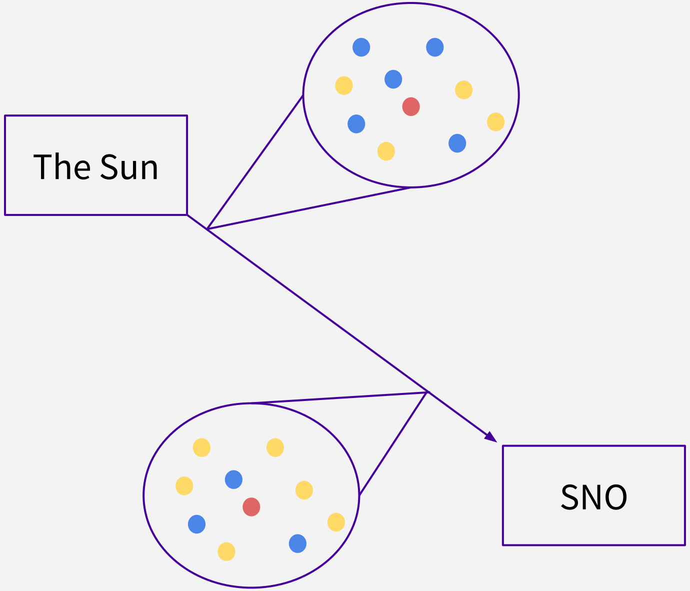
Are they their own antiparticle?



Claim to Fame: Oscillations

The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald "for the discovery of neutrino oscillations, which shows that neutrinos have mass".

Nobel Prize



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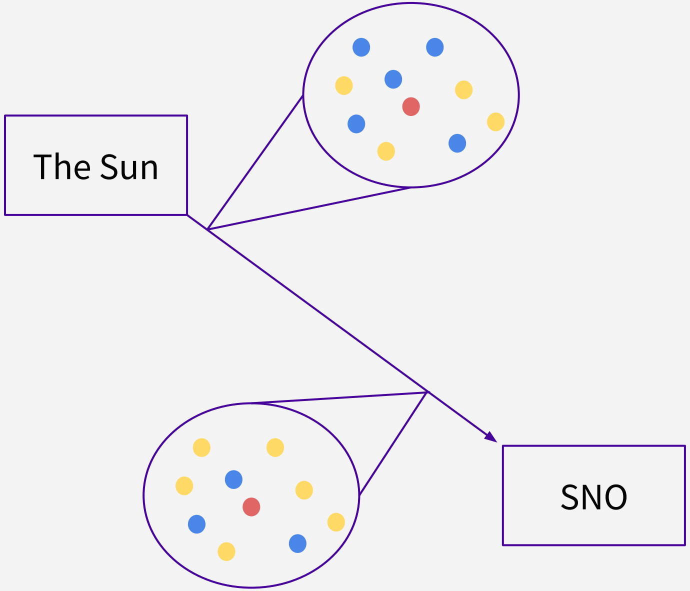

$$P_{\nu_\alpha \to \nu_\beta}(t) = \delta_{\alpha\beta} - \left(4 \sum_{i>j} \mathrm{Re}(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \times \sin^2 \frac{\Delta m^2_{ij} L}{4E}\right) + \left(2 \sum_{i>j} \mathrm{Im}(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \times \sin \frac{\Delta m^2_{ij} L}{2E}\right)$$

Oscillation Parameters

Expand…

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Oscillation Parameters

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \times \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{bmatrix} \times \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

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This is the PMNS matrix. It allows us to relate the **mass and flavour eigenstates** of the neutrinos.

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From these circled parts, we can see there are 6 parameters that must be measured:

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NuFIT 2024

Parameter	Limit	
θ_{12} /°	33.68	+ 0.73 / - 0.70
θ_{23} /°	48.50	+ 0.70 / - 0.90
θ_{13} /°	8.52	+ 0.11 / - 0.11
δ_{CP} /°	177	+ 19 / - 20
Δm^2_{21} /10^{-5} eV^2	7.49	+ 0.19 / - 0.19
$\lvert\Delta m^2_{3l}\rvert$ /10^{-3} eV^2	2.534	+ 0.025 / - 0.023

From these circled parts, we can see there are 6 (4+2) parameters that must be measured:

Neutrino Masses and Other Mysteries

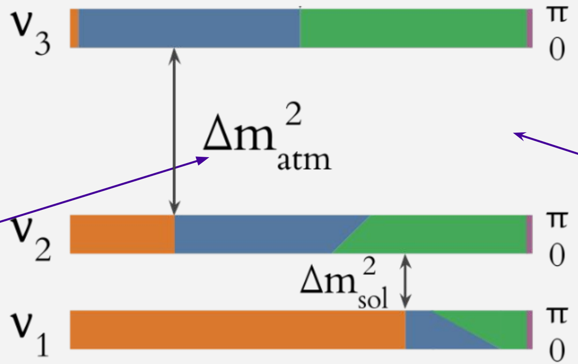
Each neutrino flavour state (e, μ, τ) is actually a mixture of the neutrino mass eigenstates (m1, m2, m3).

=> This is how we know there must be at least one non-zero neutrino mass, otherwise oscillations would not be possible

$$|\nu_\alpha\rangle = \sum_{j=1}^{3} U_{\alpha j} \, |\nu_j\rangle \, ,$$

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix} .$$

We can determine the mass splittings, but not the absolute masses



We also don't know which of the flavours is the heaviest. Two options are proposed, known as the <u>normal hierarchy (NO)</u> and inverse hierarchy (IO)

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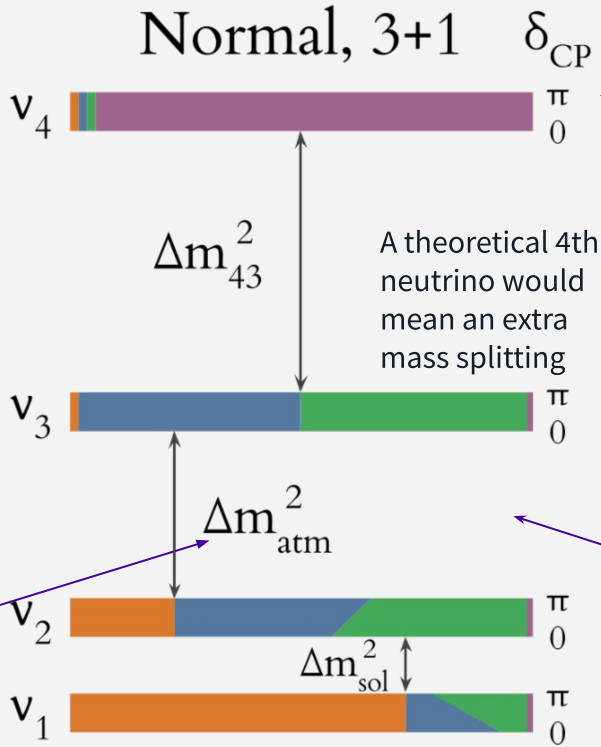
Sterile neutrino: a hypothetical neutrino which only interacts via gravity

The composition can also depend on the amount of VP violation



A theoretical 4th neutrino would mean an extra mass splitting

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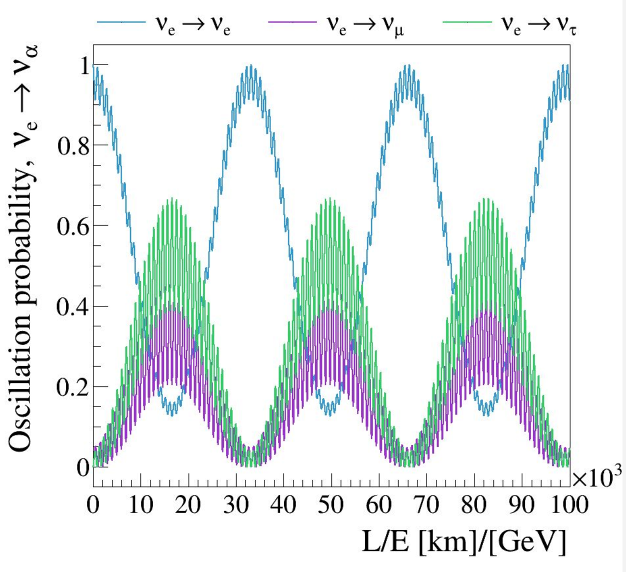
Long Baseline Experiments

Examples:

- DUNE (1300 km)
- Hyper-K (295 km)

These can look at **oscillations**, and are long enough to explore both the **first and second maxima**. These are dominated by matter effects (which will help us deduce the neutrino mass hierarchy) and CP violation respectively, which they can help us **distinguish**

Oscillation probabilities **change** at different baselines and energies



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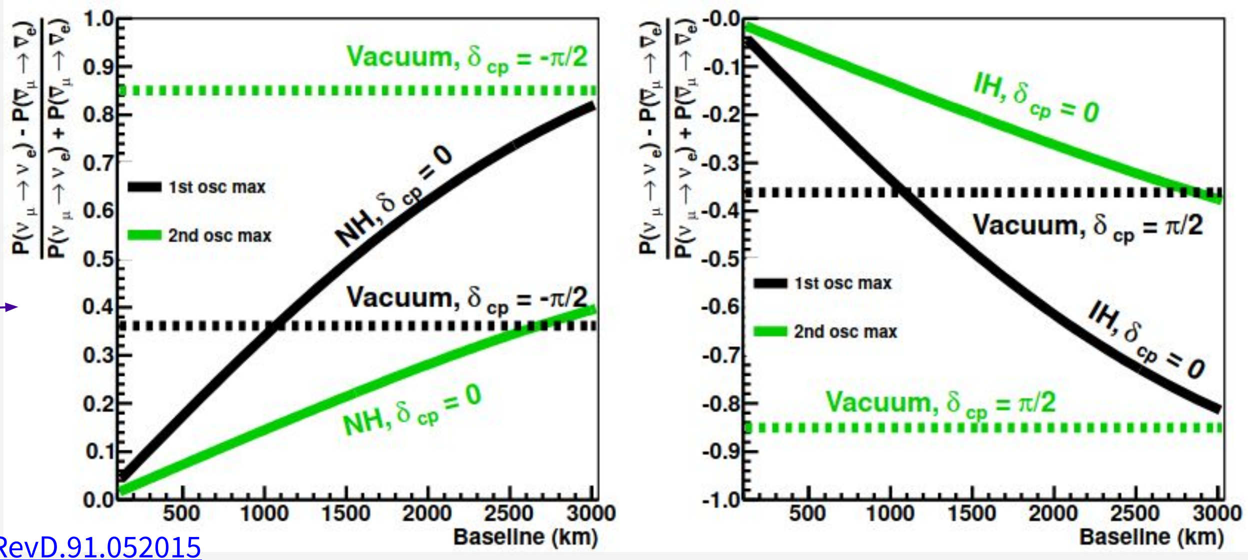
This shows the **CP asymmetry** at different baselines. The difference in the values for each maxima increase as the baseline does



PhysRevD.91.052015

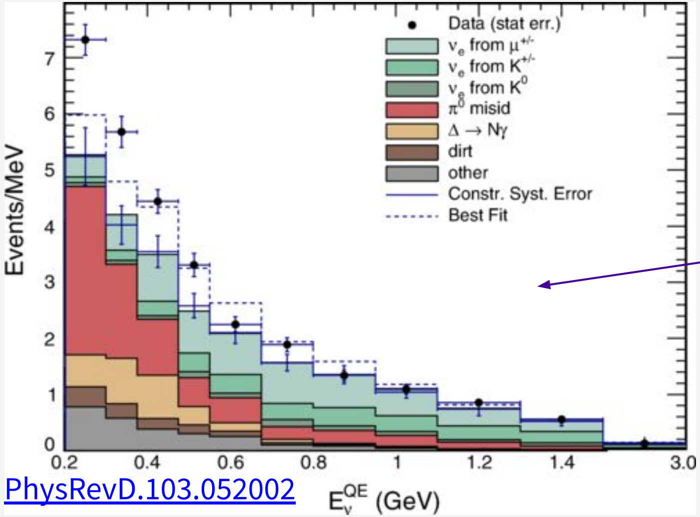
Short Baseline Experiments

Examples:

- MicroBooNE (470m)
- SBND (110m)
- MiniBooNE (470m)
- LSND (30m)

They should not observe an oscillation signal as they aren’t sensitive to the mass splittings.

So if we *do* see something that could be an oscillation, that indicated new physics to investigate!



PhysRevD.103.052002

This MiniBooNE Plot has been the subject of much discussion

If such an excess can be reproduced, one explanation would be 3+N sterile neutrinos

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Liquid Argon Time Projection Chambers (LArTPCs)

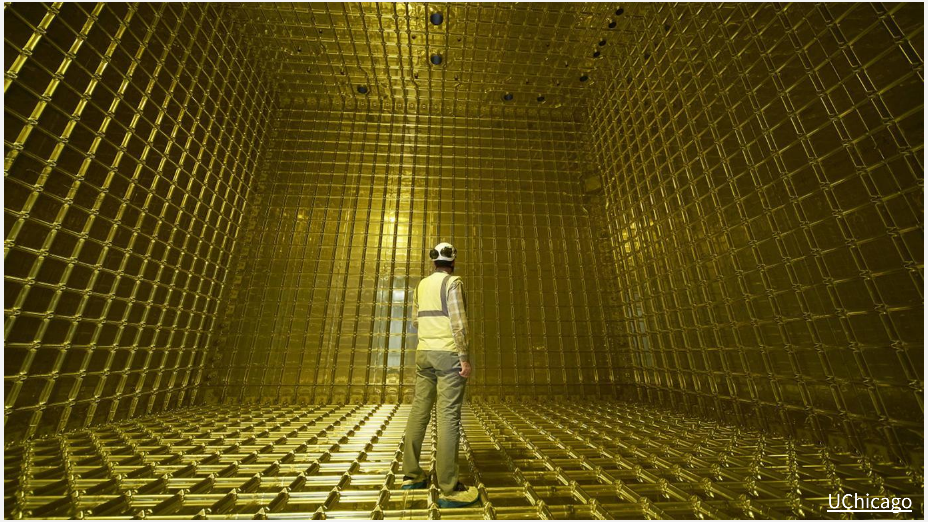
Why Liquid Argon?

Argon is very dense, allowing for a higher event rate

Argon is cheap and readily available

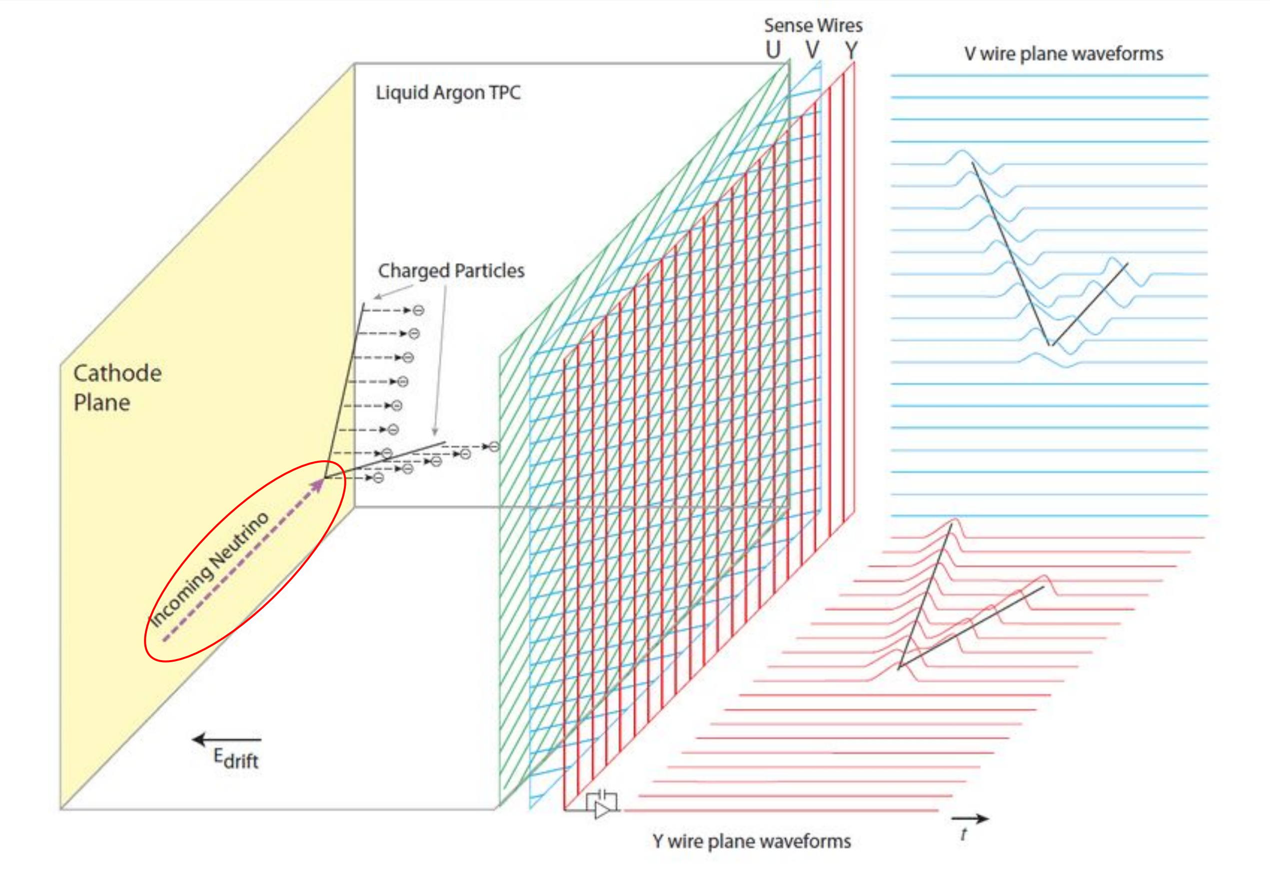
Argon is a noble element and thus chemically inert, so it doesn't absorb signal particles

Argon is transparent to its own scintillation light and produces a lot of it



Time Projection Chamber Operations

Step 1: A neutrino enters the liquid argon

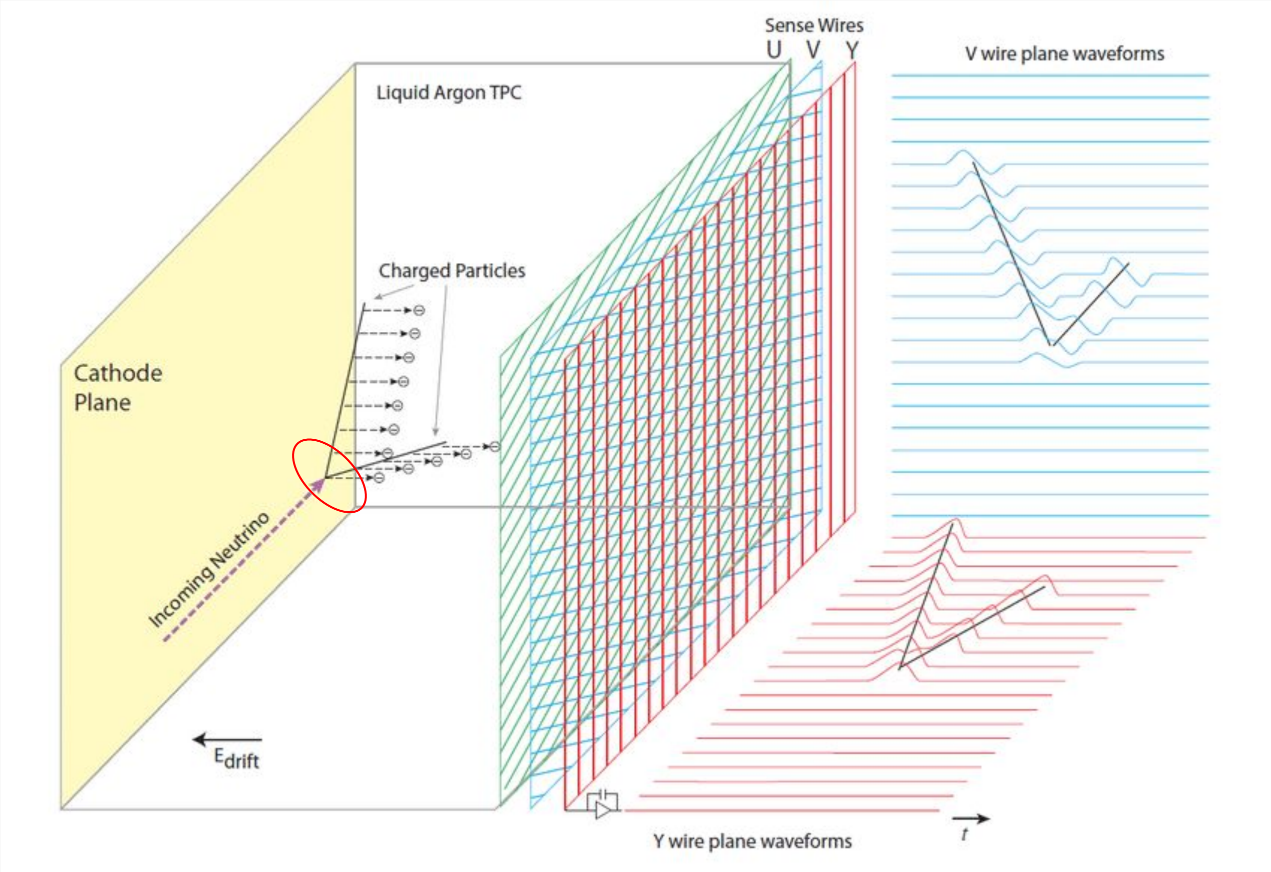


Design and Construction of the MicroBooNE Detector

Time Projection Chamber Operations

Step 1: A neutrino enters the liquid argon

Step 2: The neutrino interacts with an argon nucleus and produces final state particles



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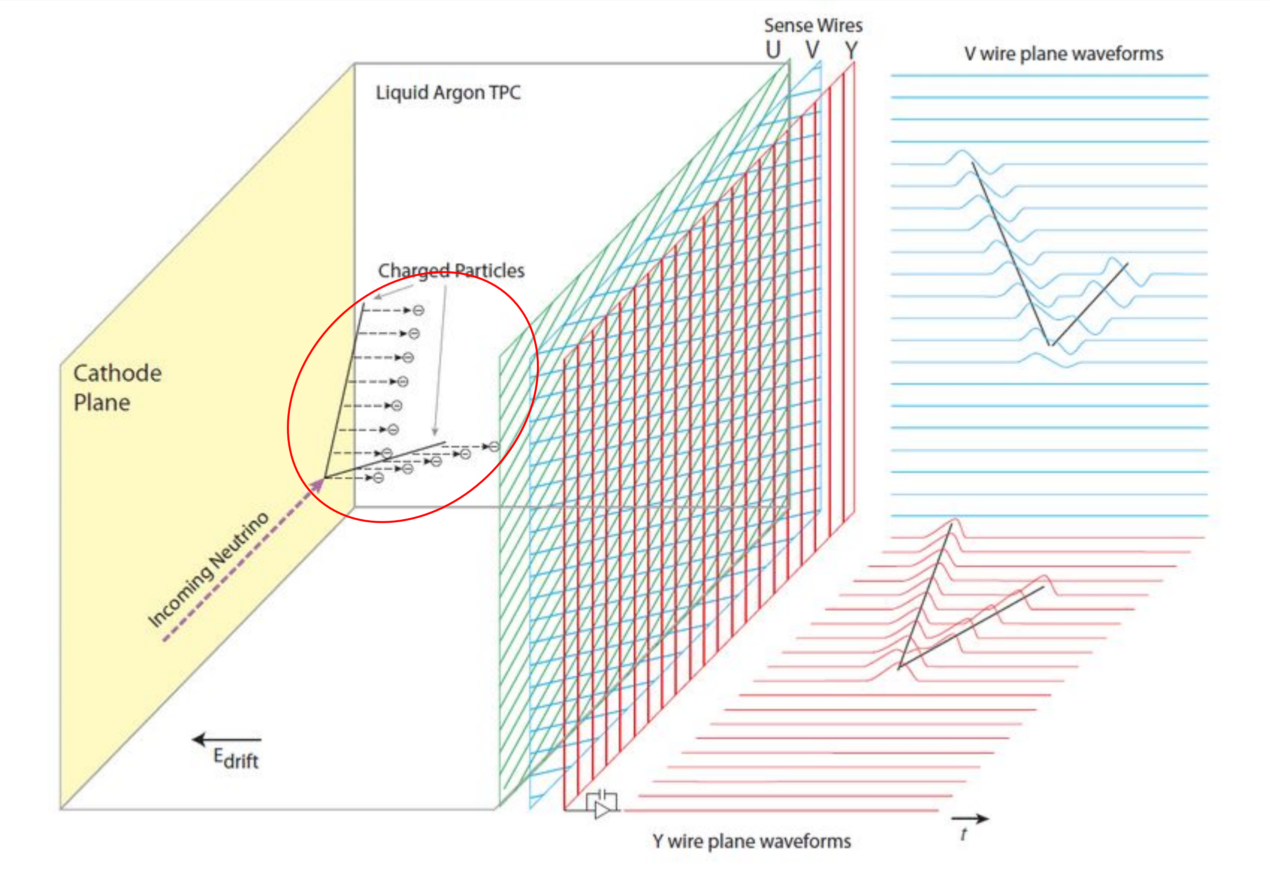

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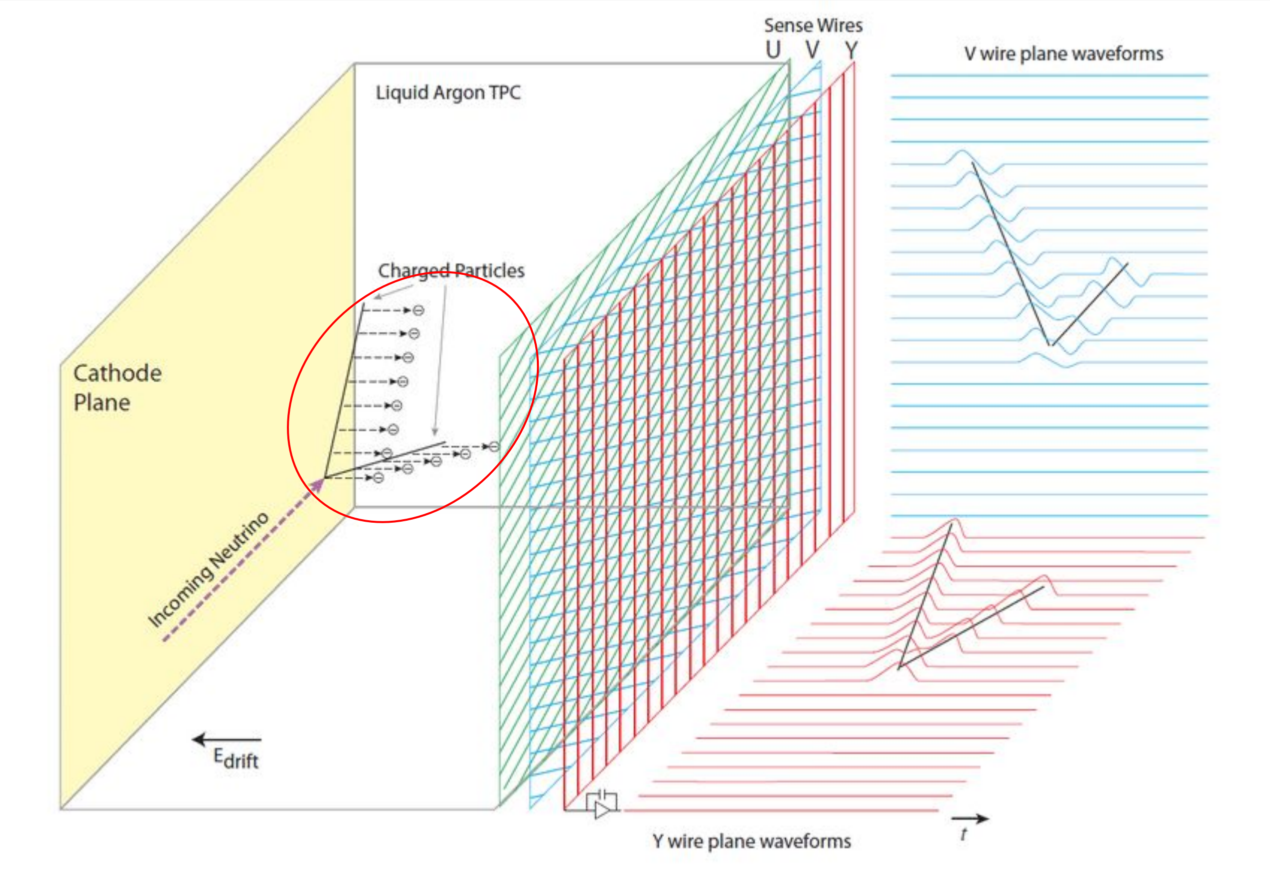

Step 4: Electrons are drifted over to the wire planes by an electric field

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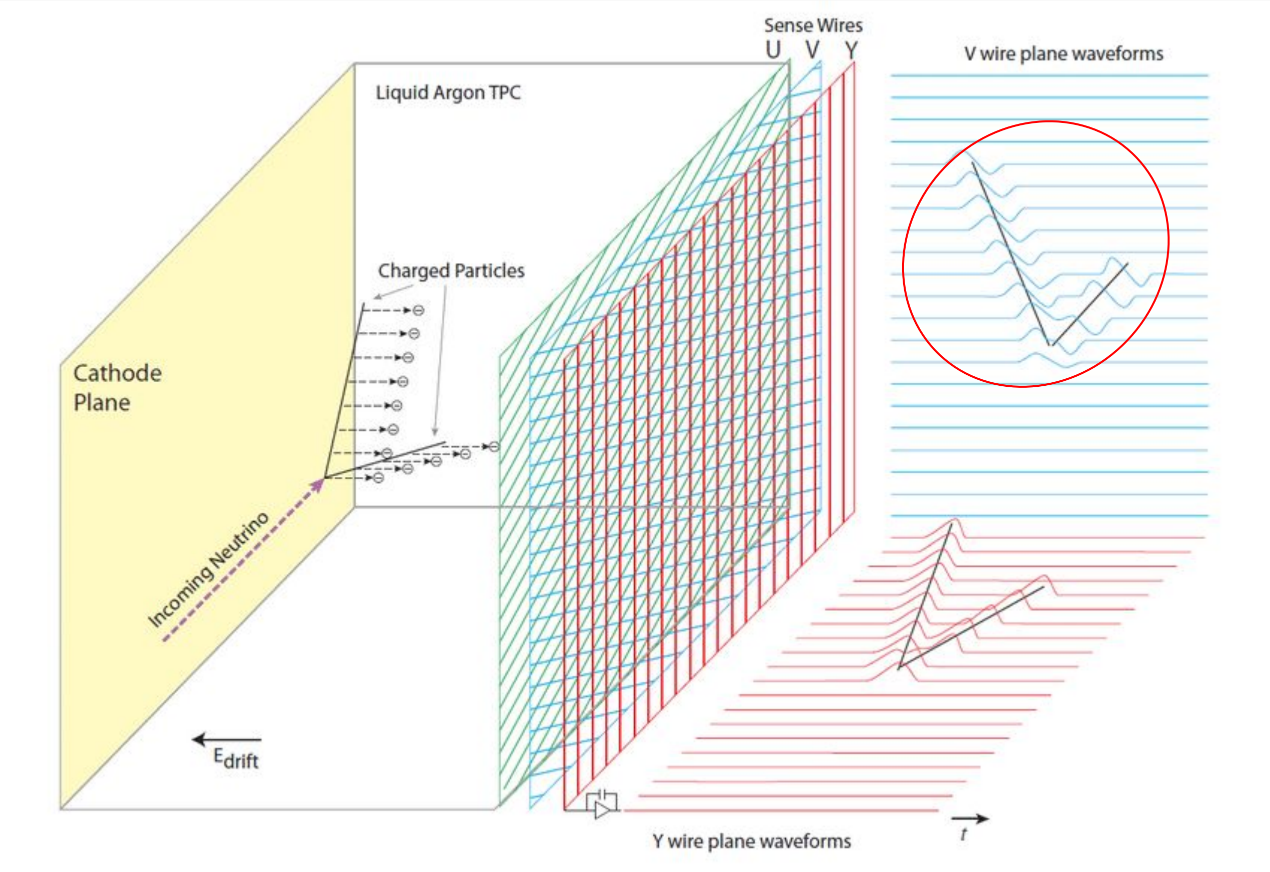

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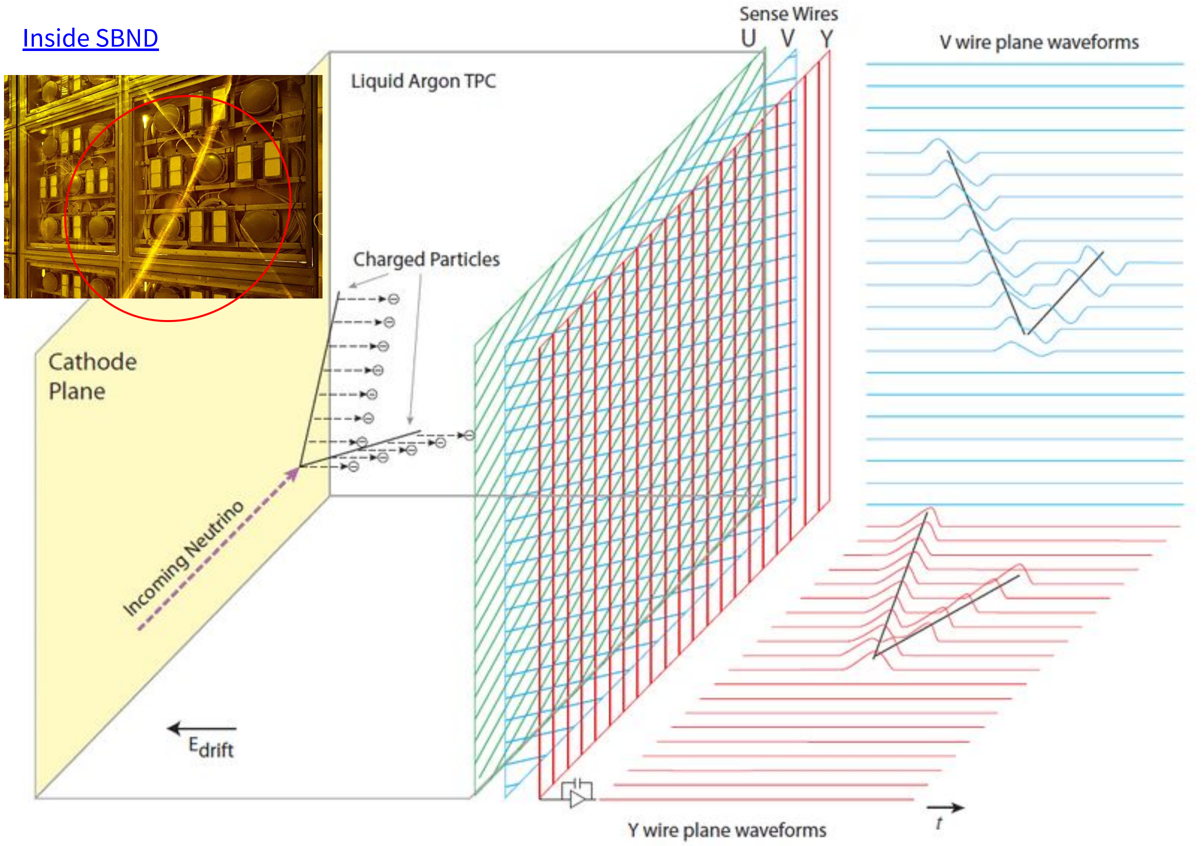
[Inside SBND]



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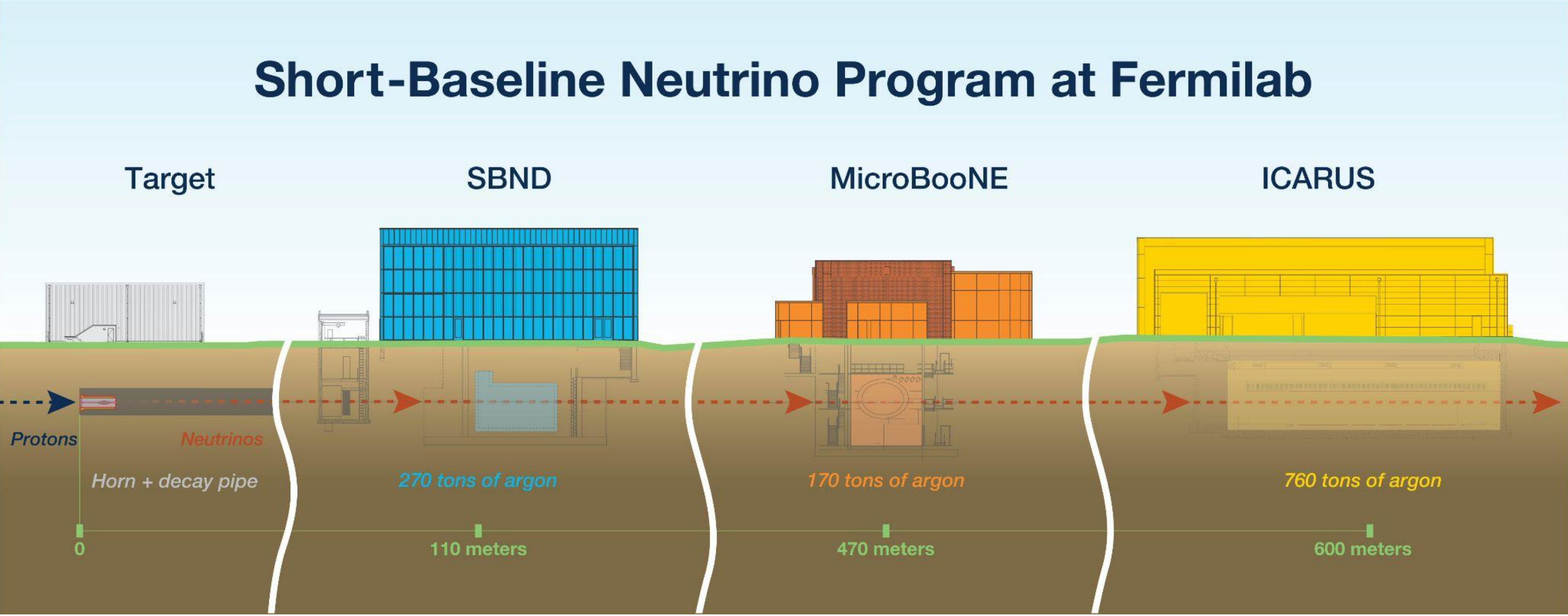
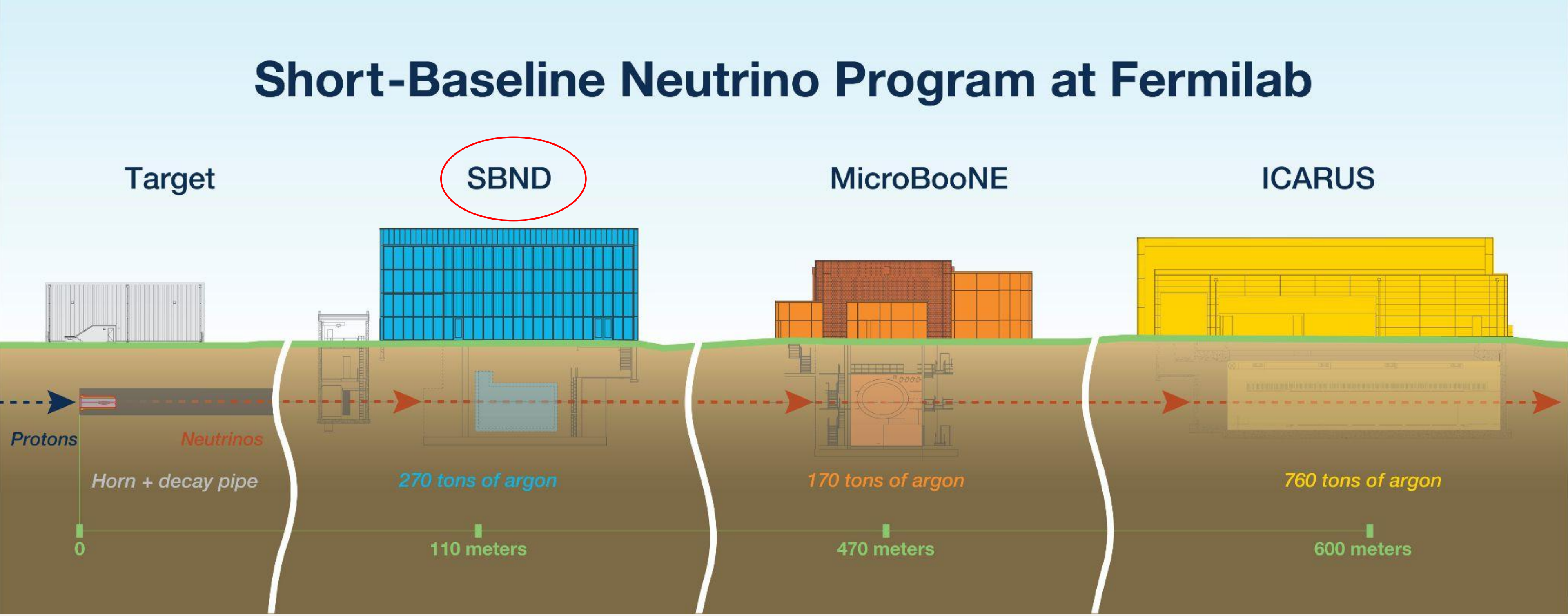
Step 6: Scintillation photons are also collected by the PDS to help with timing and calorimetry

[Design and Construction of the MicroBooNE Detector]

The Short Baseline Near Detector (SBND)



Infographic



Infographic

The Short Baseline Near Detector

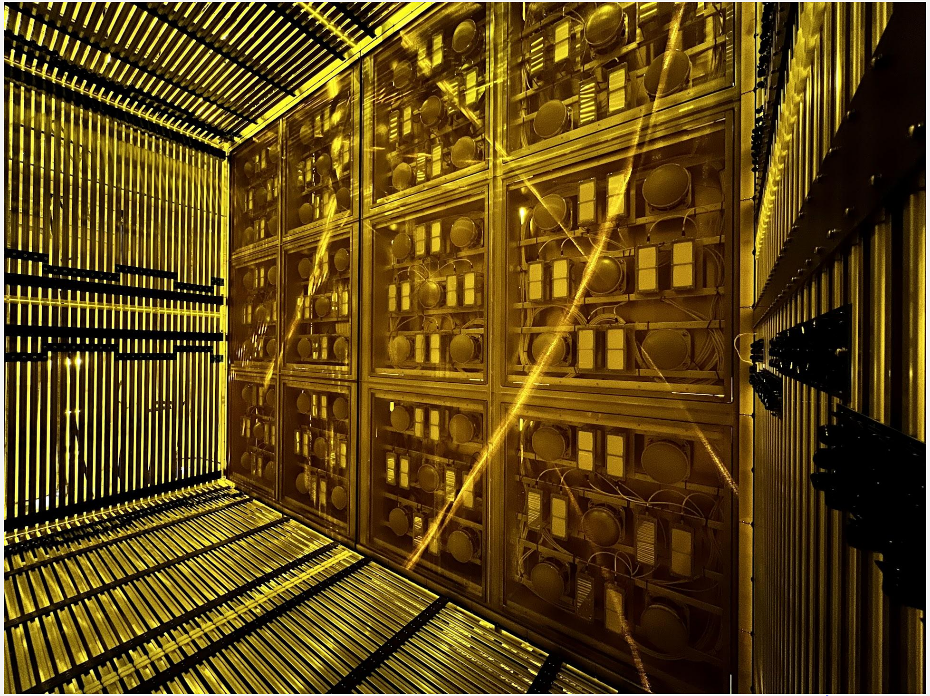
- These three LArTPCs working together form the **Short Baseline Neutrino programme**. SBND acts as its Near Detector.
- SBND is formed of **two LArTPCs sitting back to back**, with the cathode in the centre and an anode on either side
- It began **taking data** in July 2024

SBND being moved

Scientific Goals of SBND

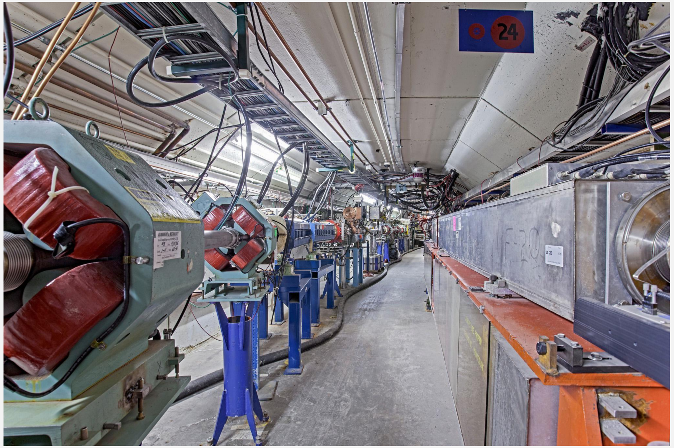
- **Precision studies** of neutrino-argon interactions
- Searches for **Beyond Standard Model** physics
- In particular, searches for **sterile neutrinos**
- The **development** of LArTPC technologies

SBND will produce results on its own as well as as part of the SBN programme

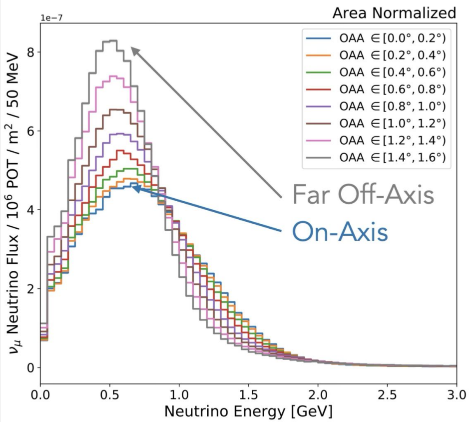


Inside SBND

The Booster Neutrino Beam (BNB)

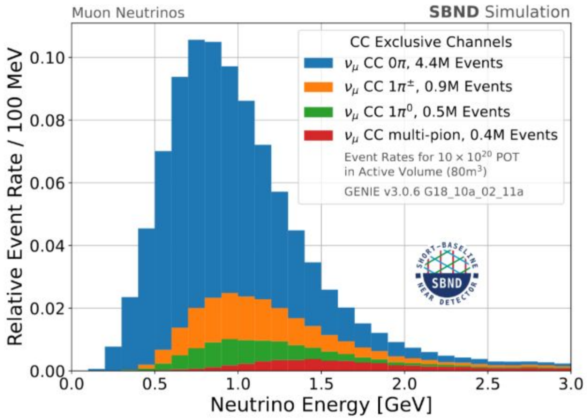


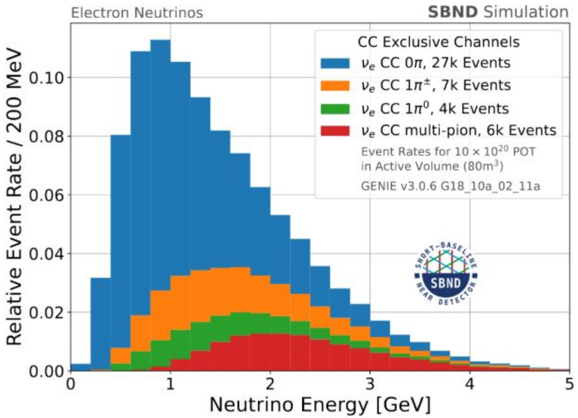
[The Booster Neutrino Beam](#)

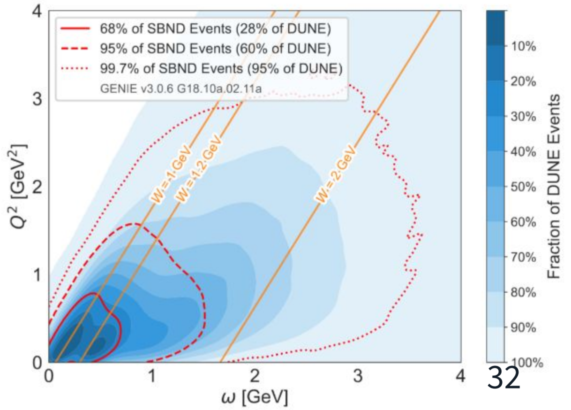


[FERMILAB-PUB-25-0154-PPD](#)

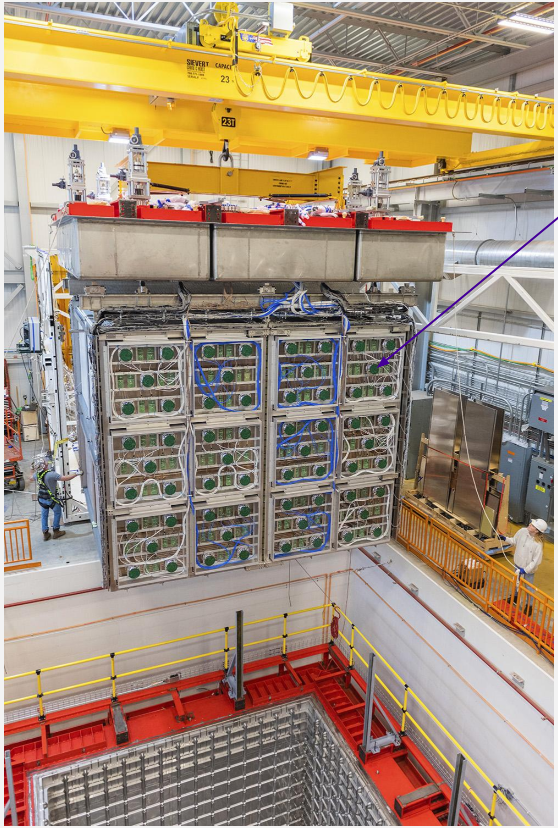
- The BNB is **primarily a ν_μ beam**, although it can be run in antineutrino mode
- Protons produced by the Linac are directed through a booster, then into a target, producing **pions and kaons which then decay** to form the neutrino beam
- We expect (and are seeing!) **>2 million neutrinos** from the BNB to interact with SBND each year







SBND Detector Technology

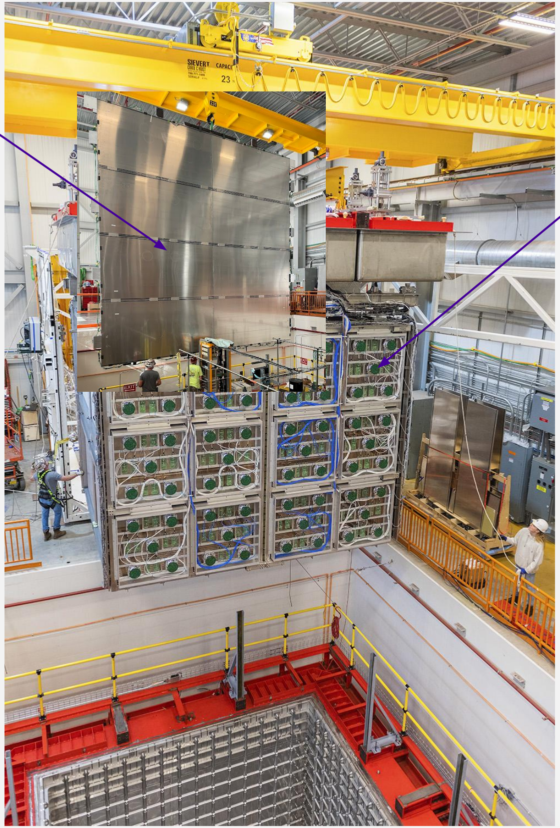


[SBND going into place](#)

Photon Detection System (PDS) which consists of both standard Photomultiplier Tubes (PMTs) and X-ARAPUCAs

SBND Detector Technology

The detector is surrounded by Cosmic Ray Tagger (CRT) planes formed from simulator strips



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The Cathode Plane Assembly (CPA) sits in the centre of the detector, forming two seperate TPCs on either side of it

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Cold electronics have been employed to reduce readout noise

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A field cage surrounds the TPC to maintain the drift field

SBND going into place

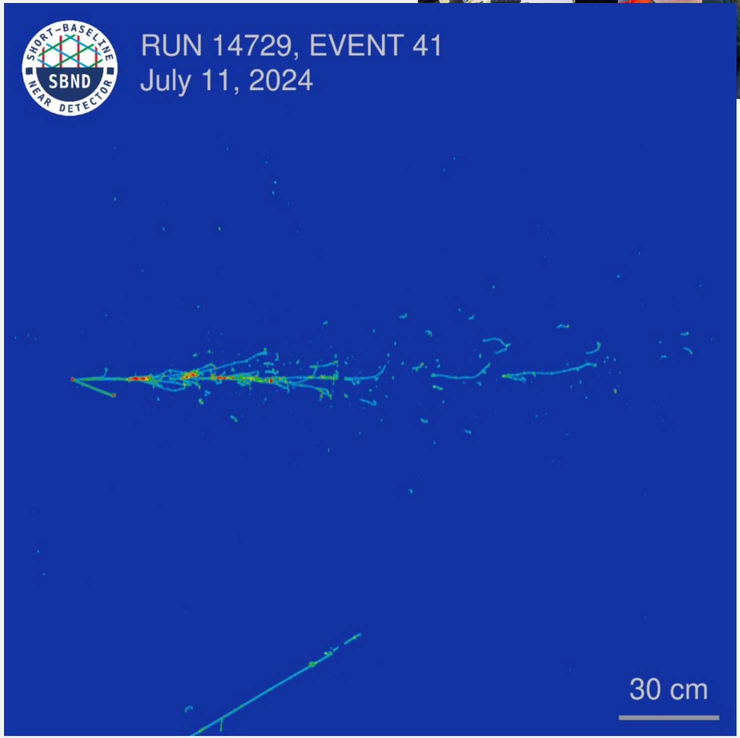
Photon Detection System (PDS) which consists of both standard Photomultiplier Tubes (PMTs) and X-ARAPUCAs

Cold electronics have been employed to reduce readout noise

Current Status

First Data!

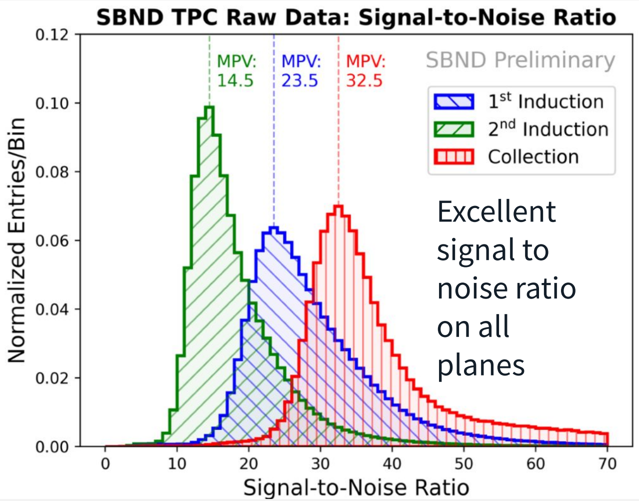
FERMILAB-PUB-25-0154-PPD



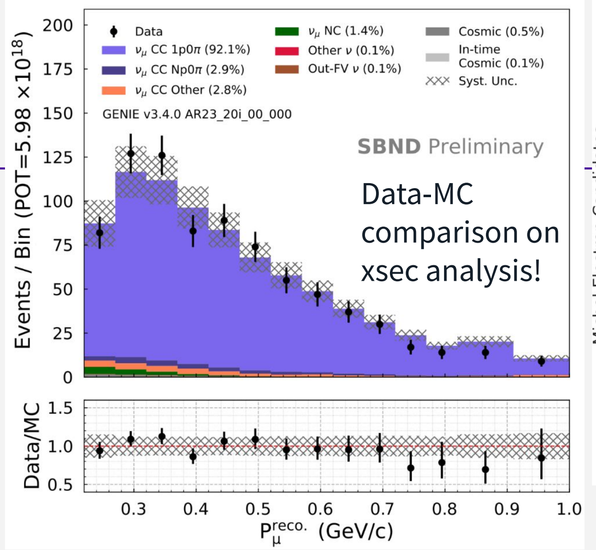
SBND very happy it works!

Many analyses are **currently in progress**, alongside a myriad of other essential work such as **calibration and reconstruction improvements**!

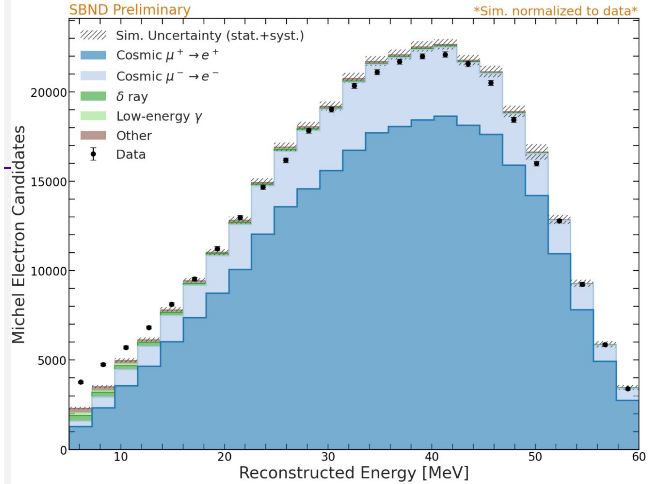
More SBND Latest Results



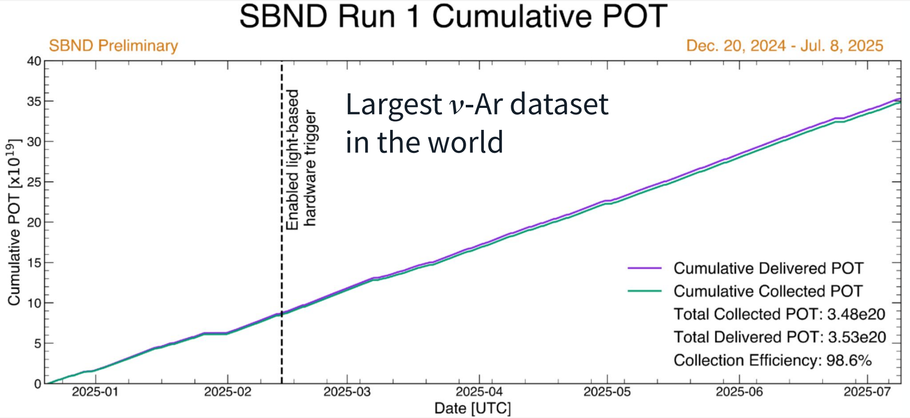
Excellent signal to noise ratio on all planes



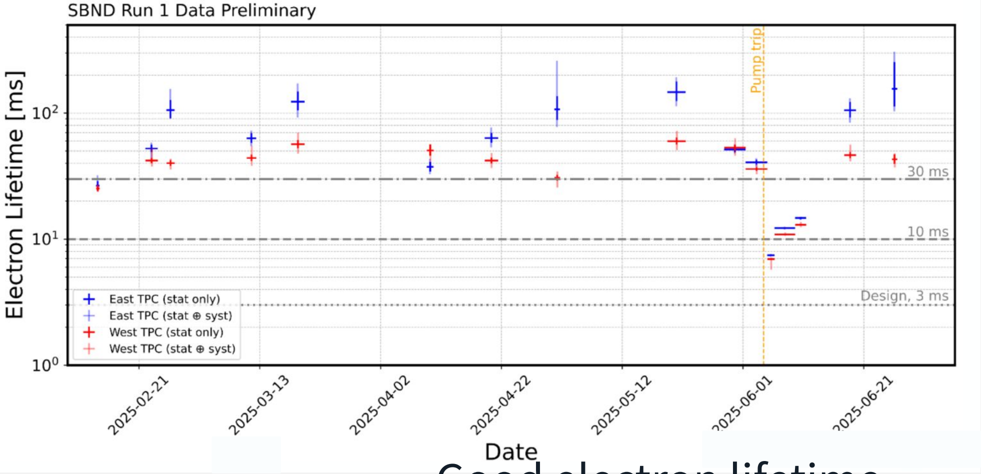
Data-MC comparison on xsec analysis!



Good data/MC agreement seen in calibrations



Largest ν-Ar dataset in the world



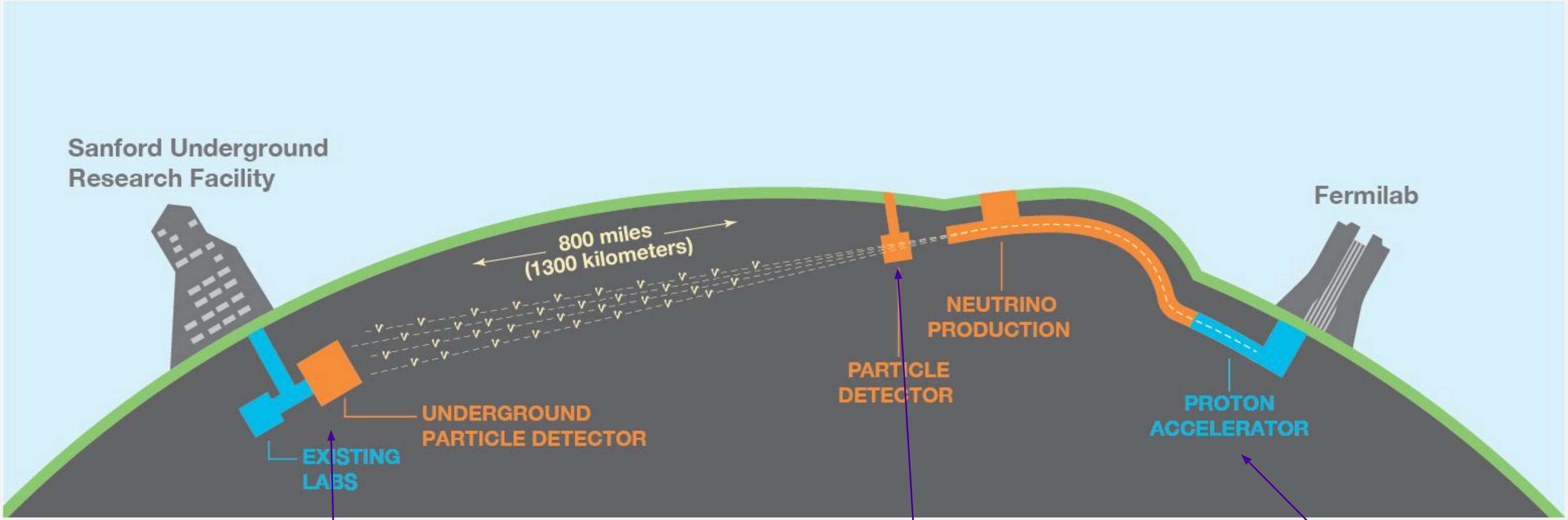
Good electron lifetime

University of Sheffield

The Deep Underground Neutrino Detector (DUNE)

DUNE

https://www.dunescience.org/



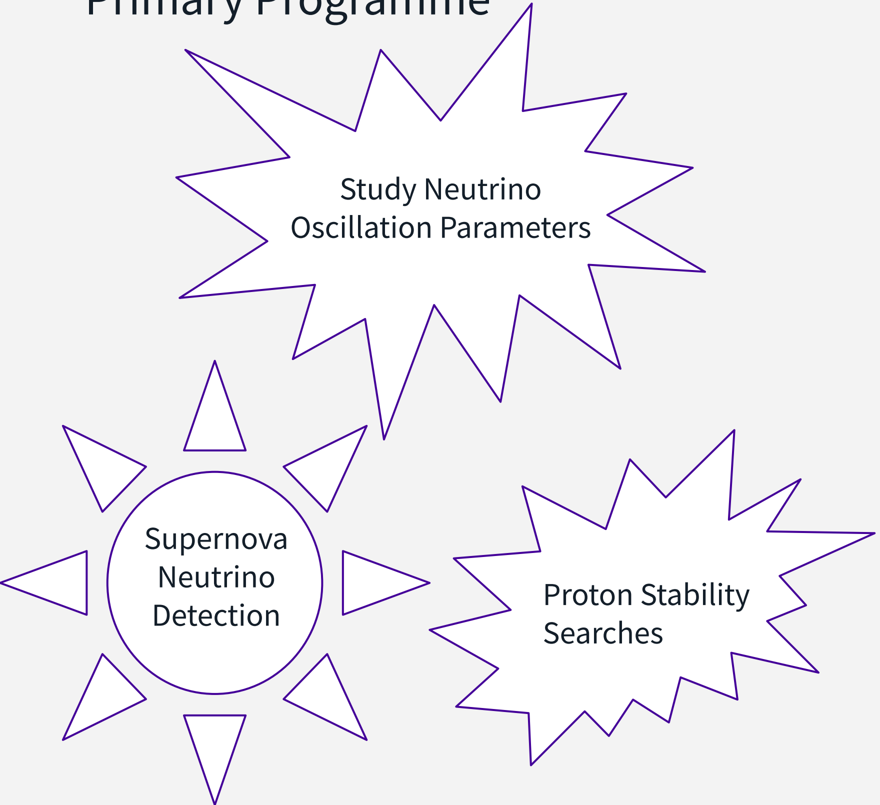
Far Detector

Near Detector

Upgraded NuMI Beam (PIP-II)

Experimental Goals

Primary Programme



Experimental Goals

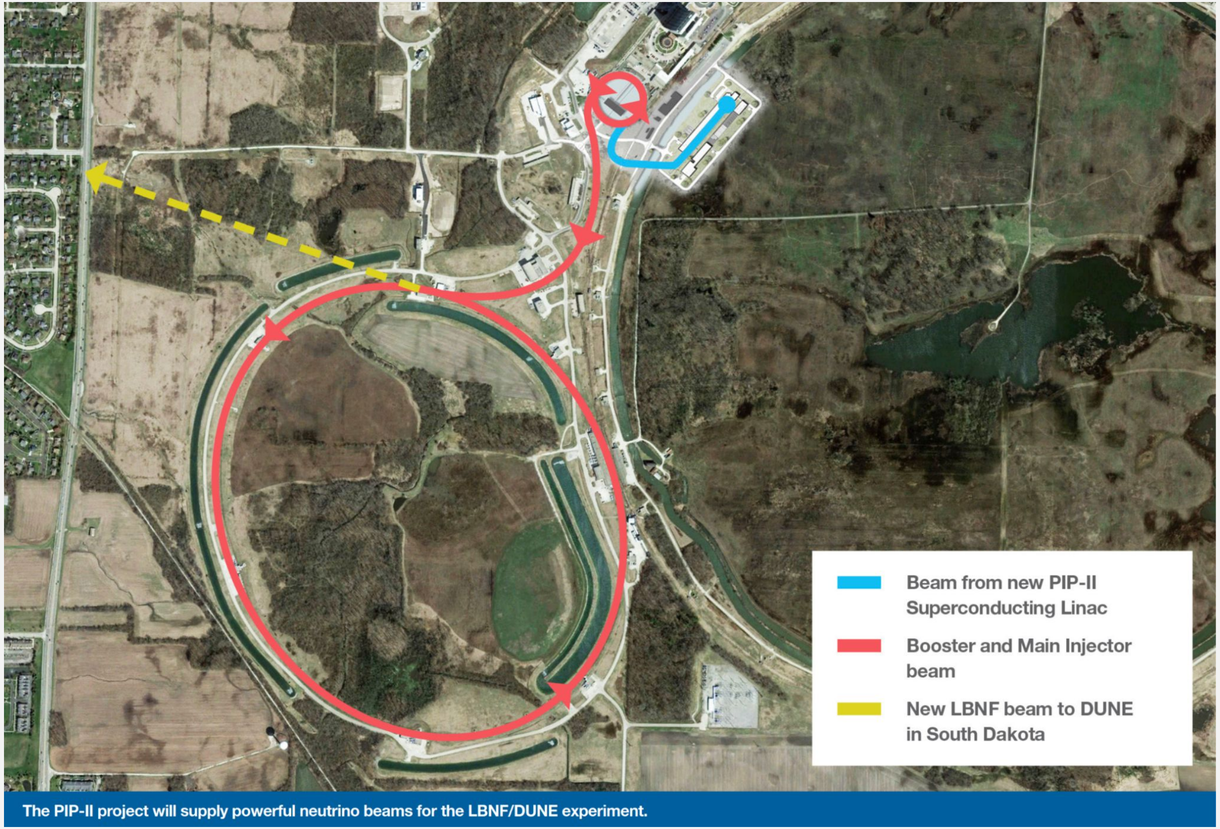
Primary Programme

- Study Neutrino Oscillation Parameters
- Supernova Neutrino Detection
- Proton Stability Searches

Secondary Programme

- Near Detector Physics Studies
- Beyond Standard Model Physics Studies
- Non-Beam Neutrino Oscillations

Beam



- The beam for DUNE will be an **upgraded version** of a the current beam
- The **Proton Improvement Plan (PIP)** is in place to ensure it will reach its potential
  -> I, II, III

[The Plan for PIP-II](#)

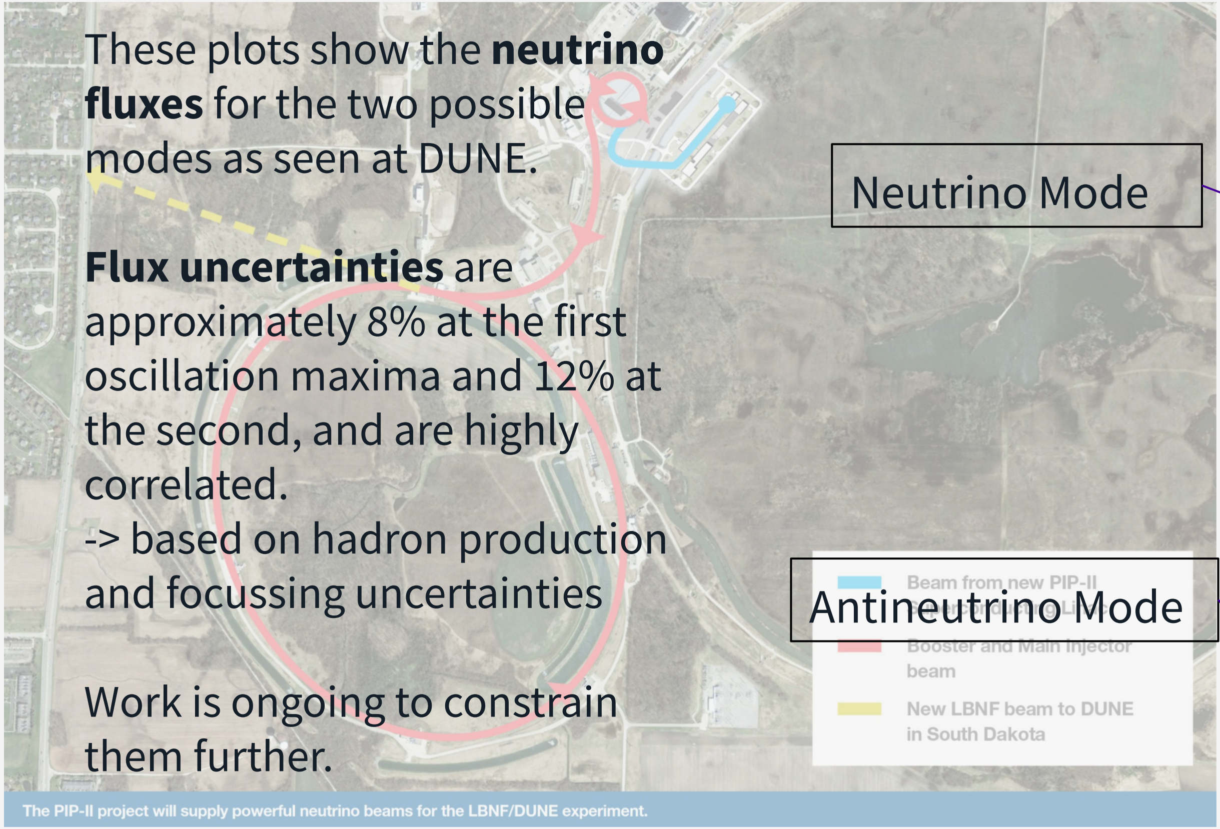
Beam

[arxiv 2002.03005](https://arxiv.org/abs/2002.03005)

These plots show the **neutrino fluxes** for the two possible modes as seen at DUNE.

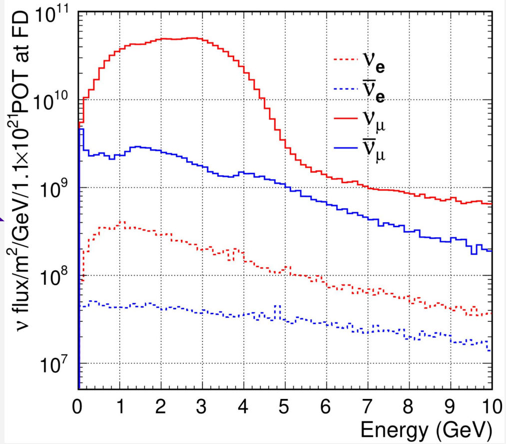
Flux uncertainties are approximately 8% at the first oscillation maxima and 12% at the second, and are highly correlated.
-> based on hadron production and focussing uncertainties

Work is ongoing to constrain them further.

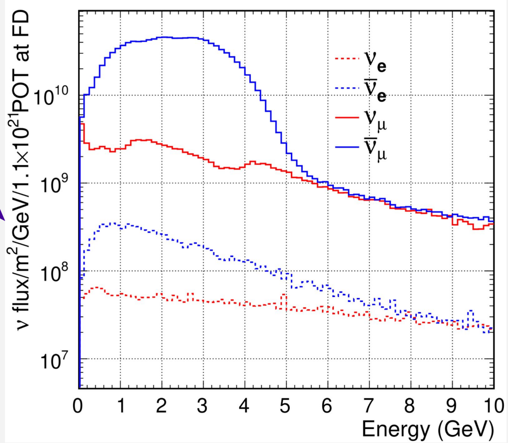


[The Plan for PIP-II]()

Neutrino Mode



Antineutrino Mode

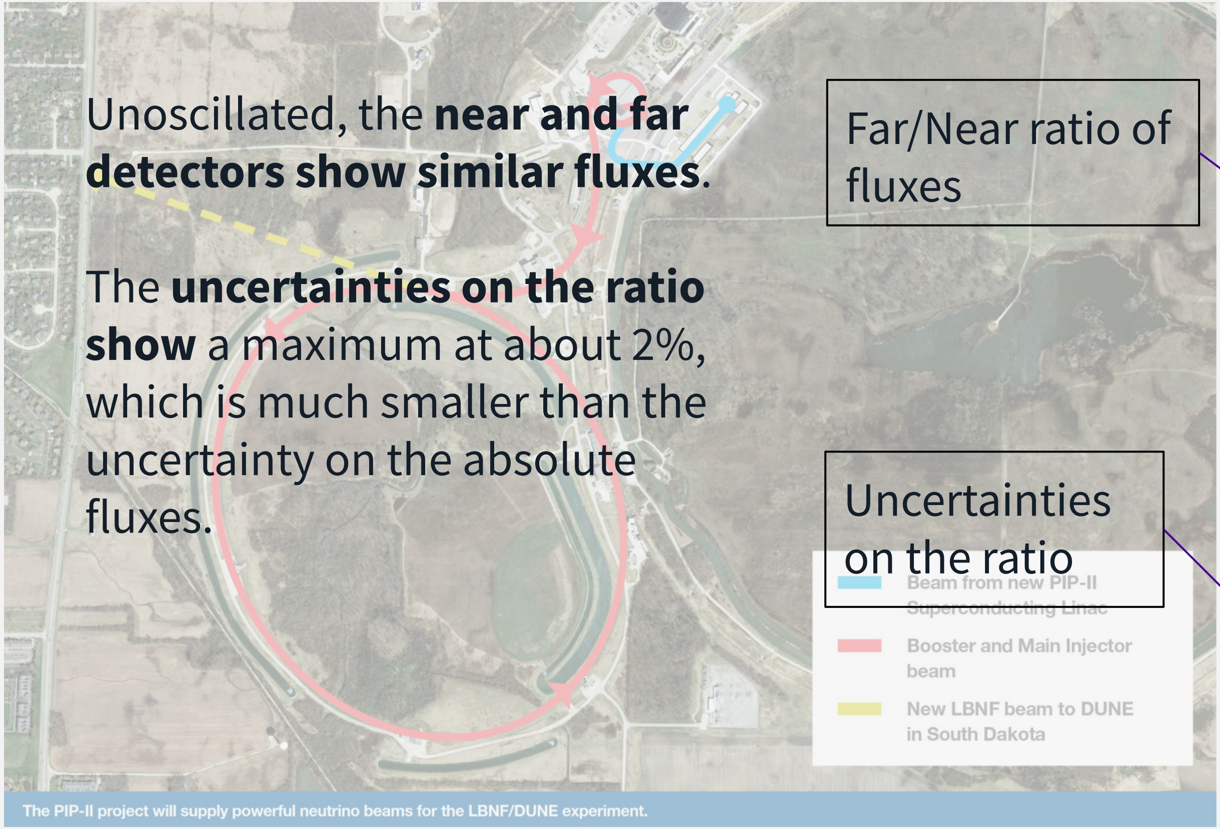


Beam

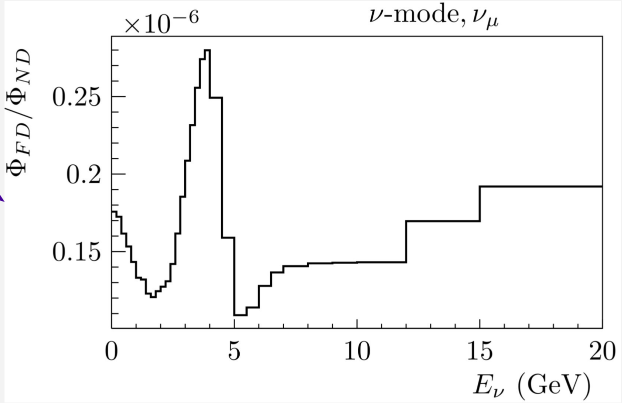
arxiv 2002.03005

Unoscillated, the **near and far detectors show similar fluxes.**

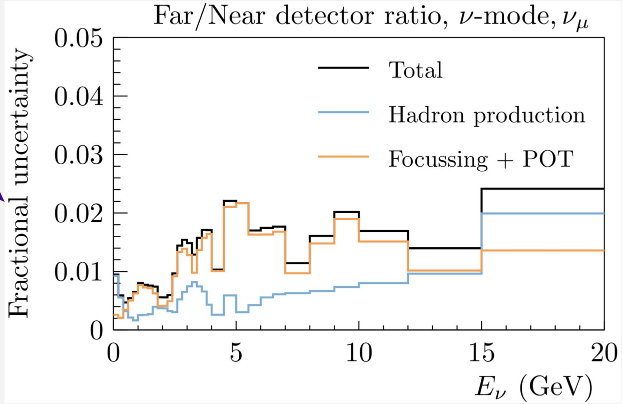
The **uncertainties on the ratio show** a maximum at about 2%, which is much smaller than the uncertainty on the absolute fluxes.



Far/Near ratio of fluxes

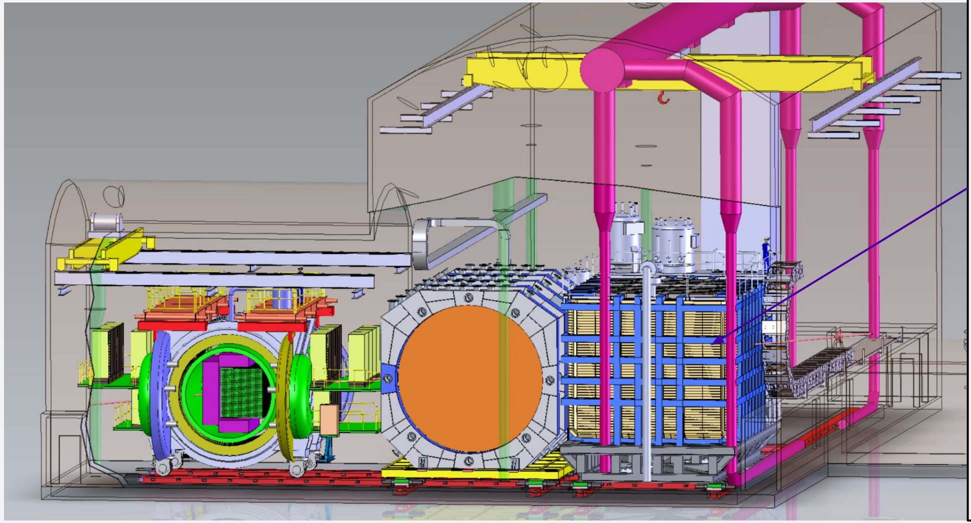


Uncertainties on the ratio



The Plan for PIP-II

Near Detector

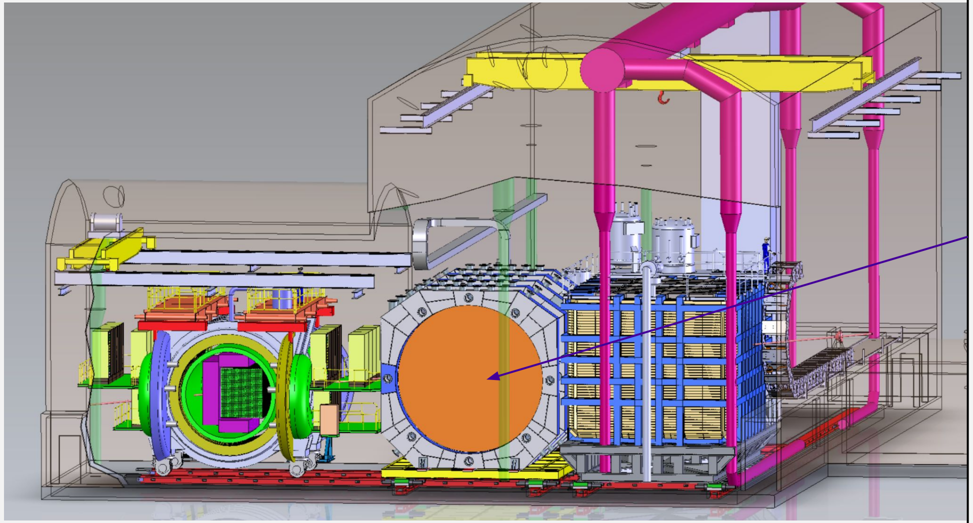


arxiv 2103.13910

ND-LAr

- LArTPC based
- First to meet the beam
- Host to 35 optically isolated modules of 2 TPCs, each with their own readout

Near Detector

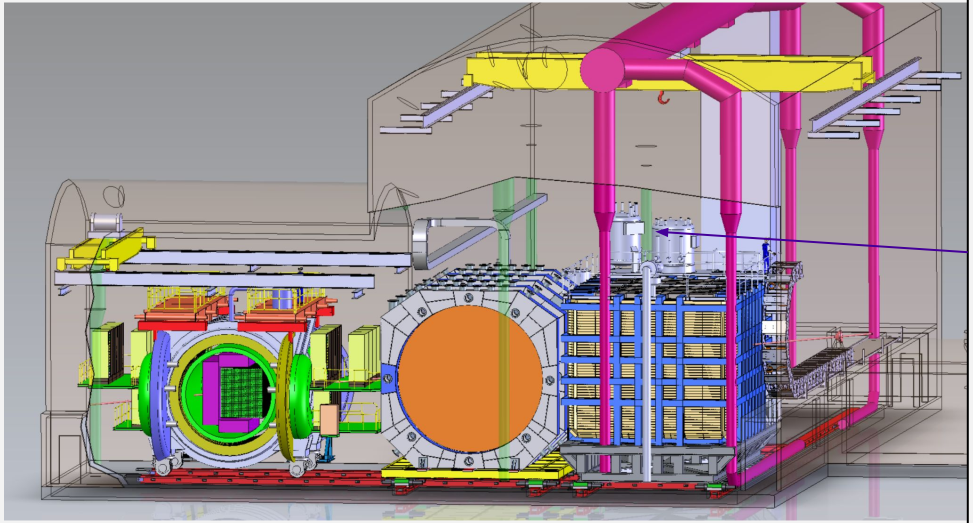


[arxiv 2103.13910](https://arxiv.org/abs/2103.13910)

The Muon Spectrometer (TMS)

- The centre position is initially TMS, with plans to replace it with ND-GAr (lower particle tracking/extended ND acceptance limits)
- This detector will investigate particles exiting ND-LAr

Near Detector



arxiv 2103.13910

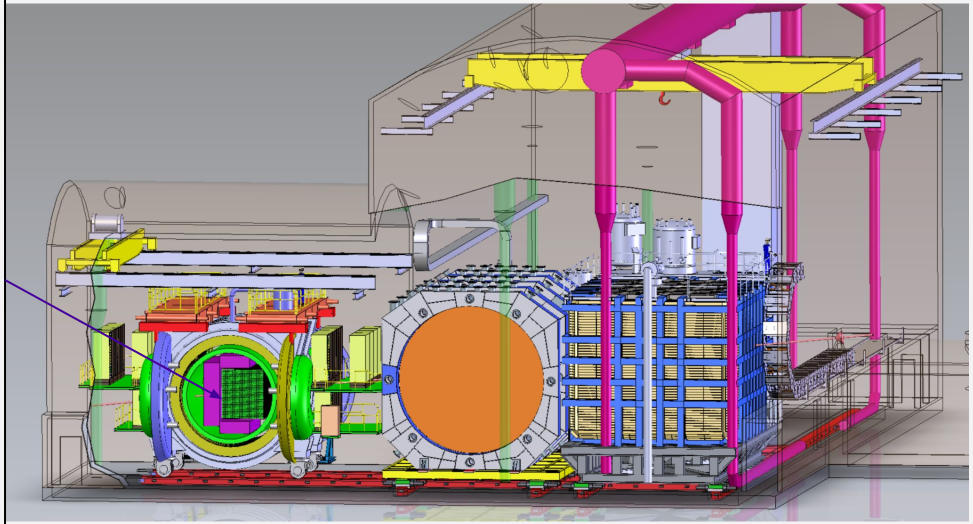
The Precision Reaction Independent Spectrum Measurement (PRISM) Concept

- The ND-LAr and ND-GAr detectors will be able to move off-axis
- This provides an extra degree (or 2.8) of freedom
- Allows for linear combinations of flux to be considered

Near Detector

System for On-Axis Neutrino Detection (SAND)

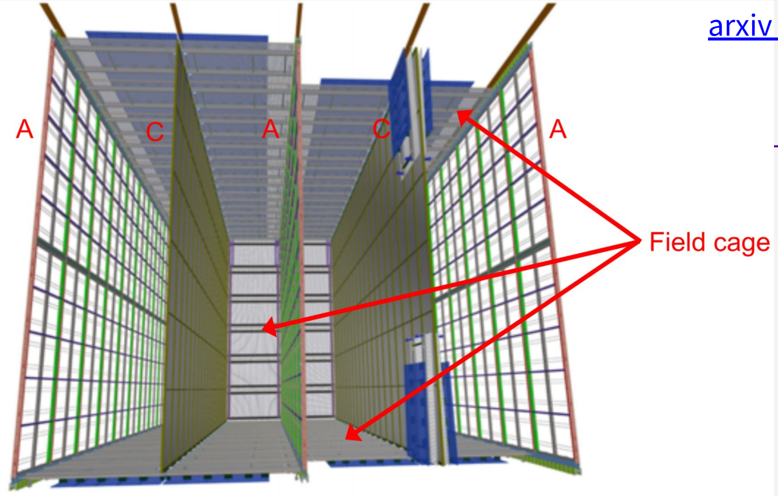
- Serves as a beam monitor, always remaining on-axis
- LAr target, ECAL with inner tracker, and solenoid



arxiv 2103.13910

Far Detector

arxiv 2002.03005

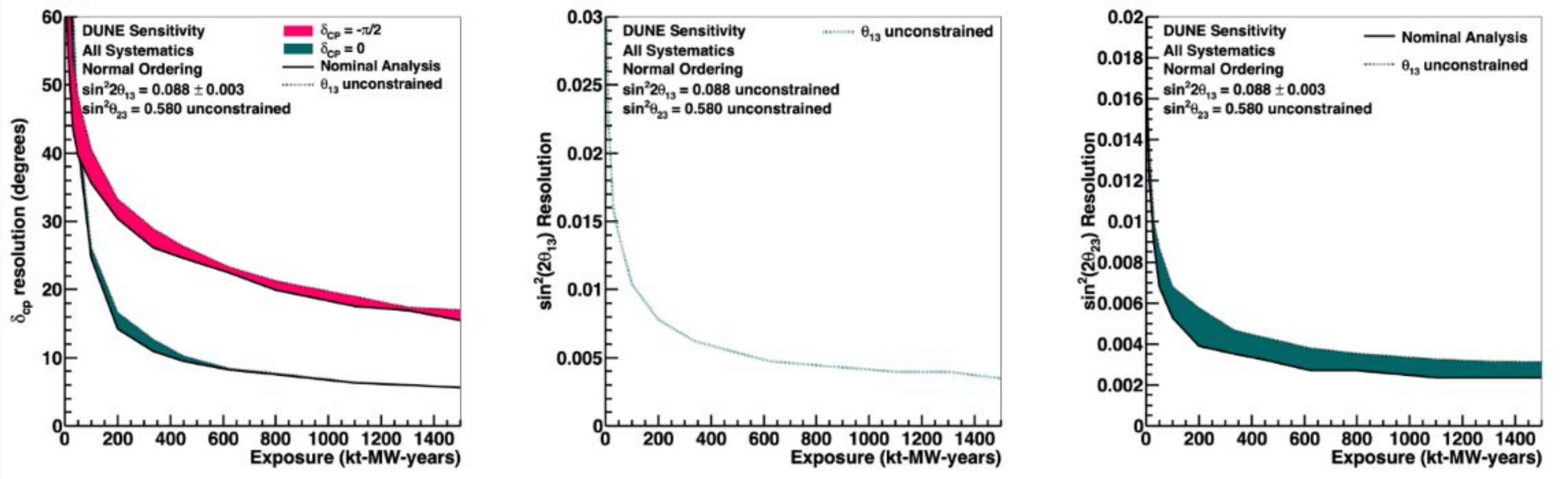


- Construction of the Far Detector caverns at SURF is **currently ongoing**
- **Four separate modules** will work together to form the detector
- The modules will have an active volume of 10 kt of liquid argon across **four drift regions**
- Due to the very large scale, this work was **prototyped at CERN**, with the protoDUNE detectors

APAs arriving at SURF

Phase Format

- The DUNE Project has been set up to work in **two sections**: Phase I and Phase II
- **Phase I** is currently well underway!
- **Phase II** involves adding the last two modules to the FD, upgrading the ND, and enhancing the energy of the beam
- This should allow both the **statistics and systematics** of the experiment to be improved

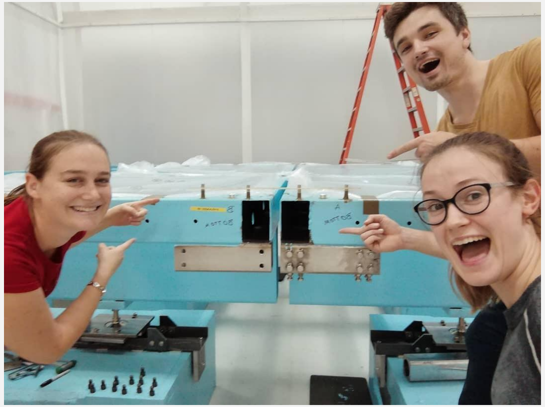


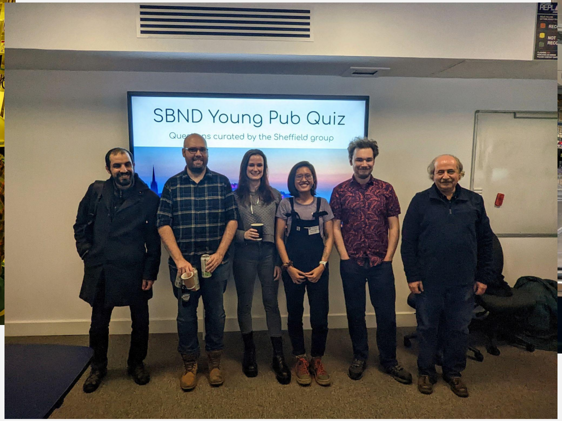
[arxiv 2408.12725](https://arxiv.org/abs/2408.12725)

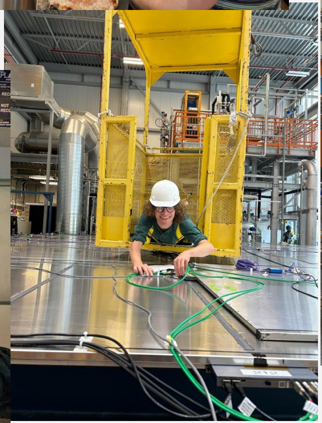
University of Sheffield

Sheffield at DUNE and SBND

Sheffield has a long history of involvement at SBND…



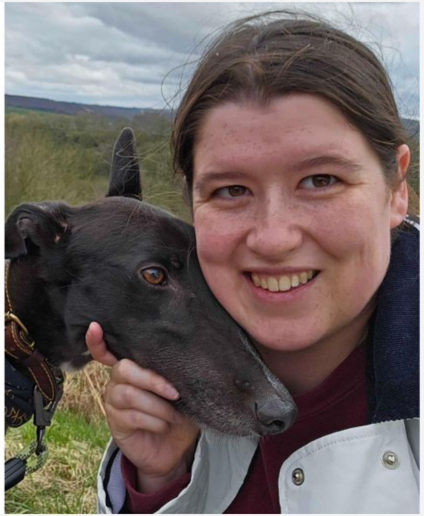




Sheffield at DUNE...

- Anna Beever is working on nuclear cluster production/measurements, Anthony Ezeribe is working on APA production, while Rhiannon Smith-Jones and I are working on calibration
- We're going to talk a little about **calibration**, as that's what I do (and have approved plots for!)



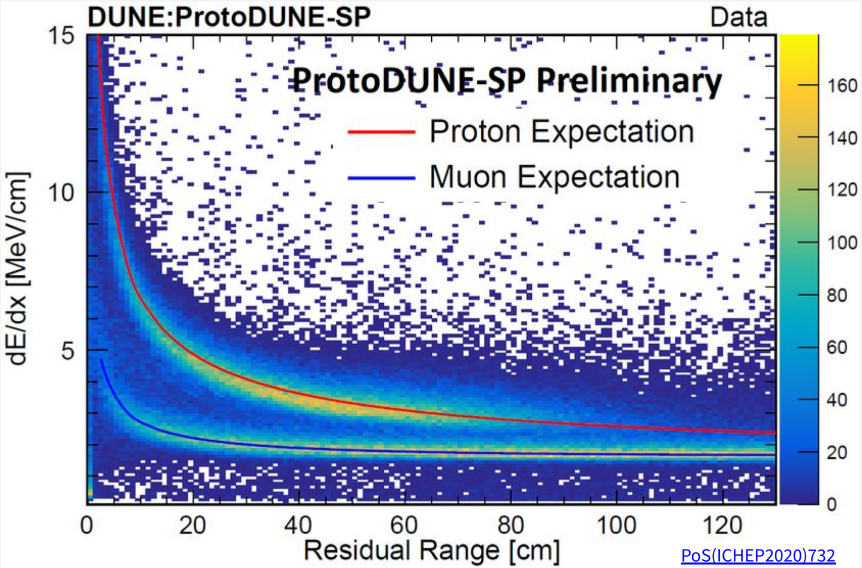



Why do we need Calibration?

- We need to **calibrate data** in order to quantify our understanding of detector and reconstruction performance metrics and systematic uncertainties -> space charge effects, recombination, diffusion, etc…

- Particles with **well known energy spectra** can be used as standard candles for translating observed results into corrected variables
-> good calibration is essential for PID

- The way this is generally done is to **calculate theoretical and reconstructed values then compare the two**, tuning variables in the reconstruction calculation to define a mapping between them



PoS(ICHEP2020)732

The aim of this calibration is to move **from dQ/dx** (charge per unit length) **to dE/dx** (energy per unit length) which can be used in particle identification

Stopping Muon Calibration

purity = 99.4%
efficiency = 67.6% (4280 tracks)

Track Selection

Divide track into 5 cm **bins in residual range**

Modified Box Model (MBM)

Calculate a dE/dx value with a chosen C_{cal} value and the MBM **then fit** a plot of the dE/dx vs entries to find the MPV values in each residual range bin

$$\left(\frac{dE}{dx}\right) = \left(\exp\left(\frac{\left(\frac{dQ}{dx}\right)_{\text{calibrated}}}{C_{\text{cal}}}\frac{\beta' W_{\text{ion}}}{\rho\mathcal{E}}\right) - \alpha\right)\left(\frac{\rho\mathcal{E}}{\beta'}\right)$$

Recombination-Scaling Model (RSM)

Plot reco dQ/dx entries in each residual range bin and fit to find an **MPV value**

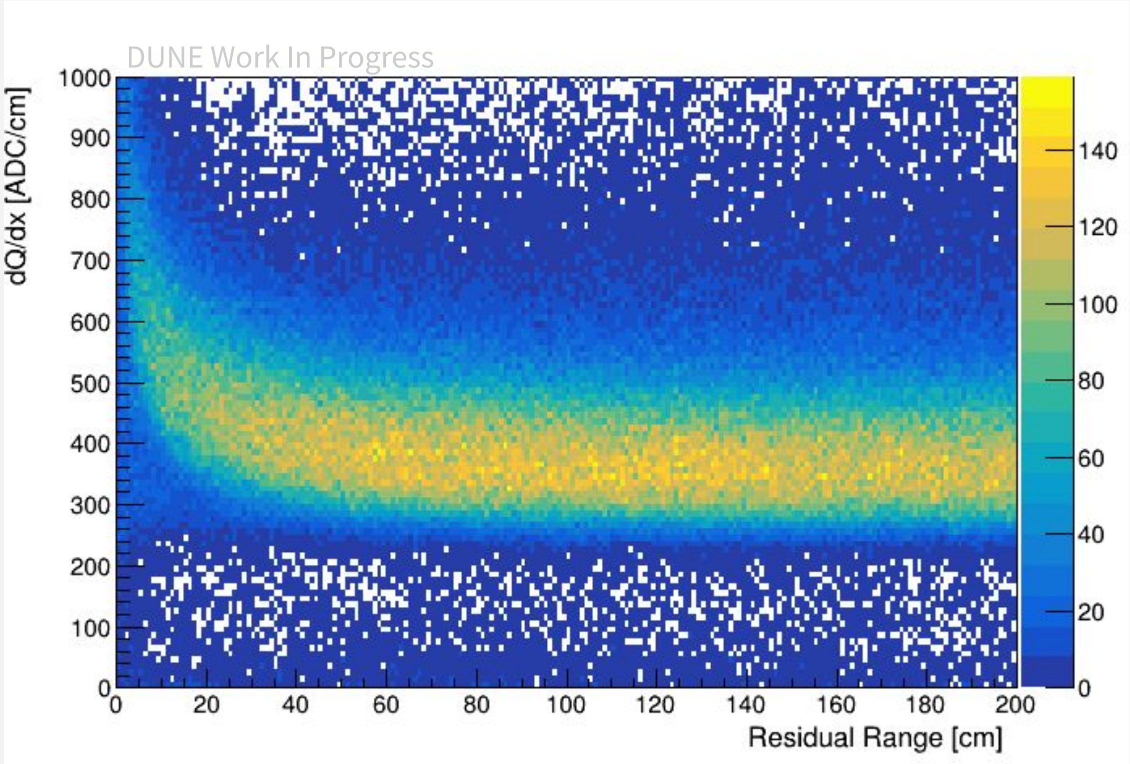
Calculate a **theoretical dE/dx value** in each bin of residual range

Compare χ^2 distributions to find the best C_{cal} value (lowest χ^2 sum across bins)

Plot a ratio of theoretical dE/dx to reco dQ/dx **and fit** to find a conversion equation

$$A + B(1/r) + C(r)$$

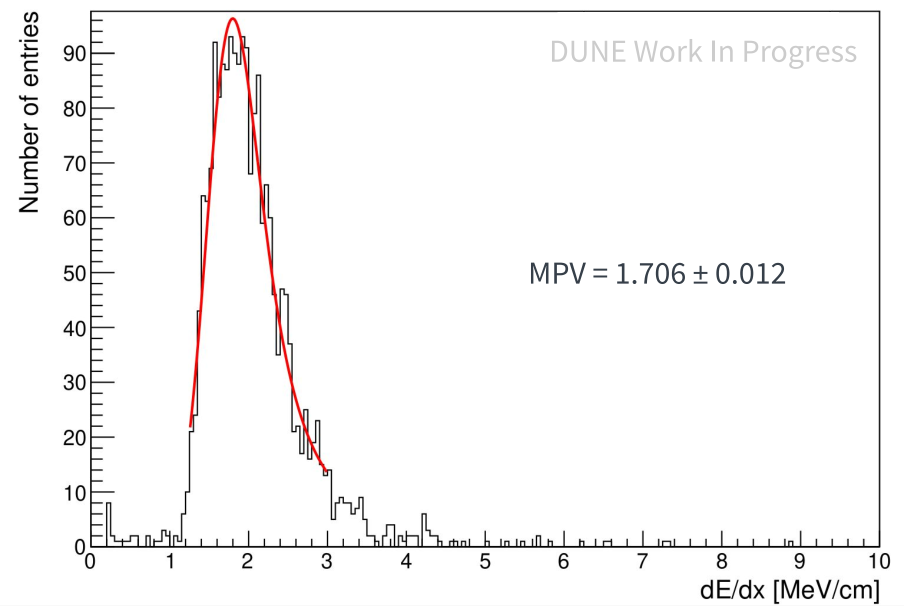
dQ/dx Vs Residual Range (Reconstructed Selected Events)



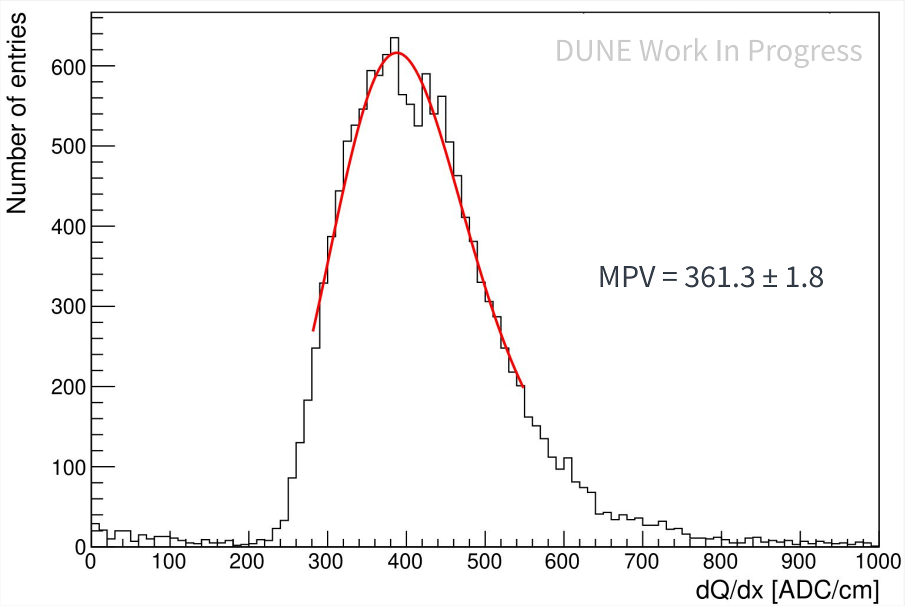
Recombination reduces the Bragg Peak

Fit for Most Probable Value

Modified Box Model



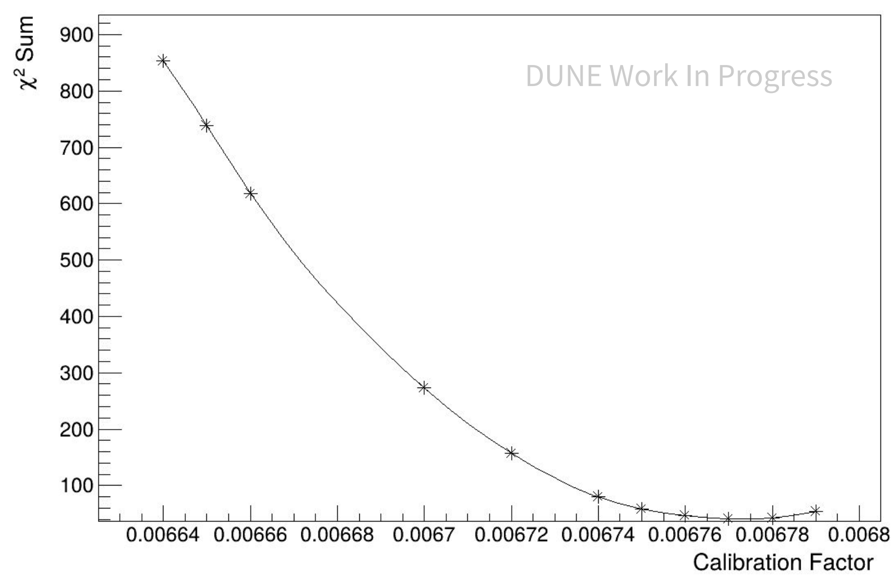
Recombination-Scaling Model



Fit using a Landau-Gaussian

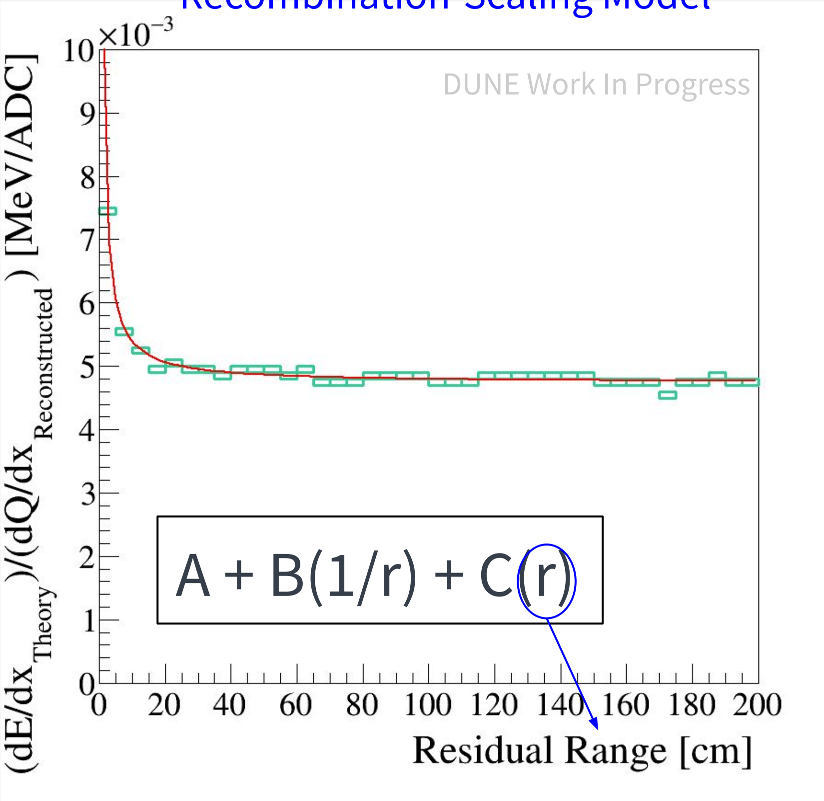
Find the Best Parameter Values

Modified Box Model



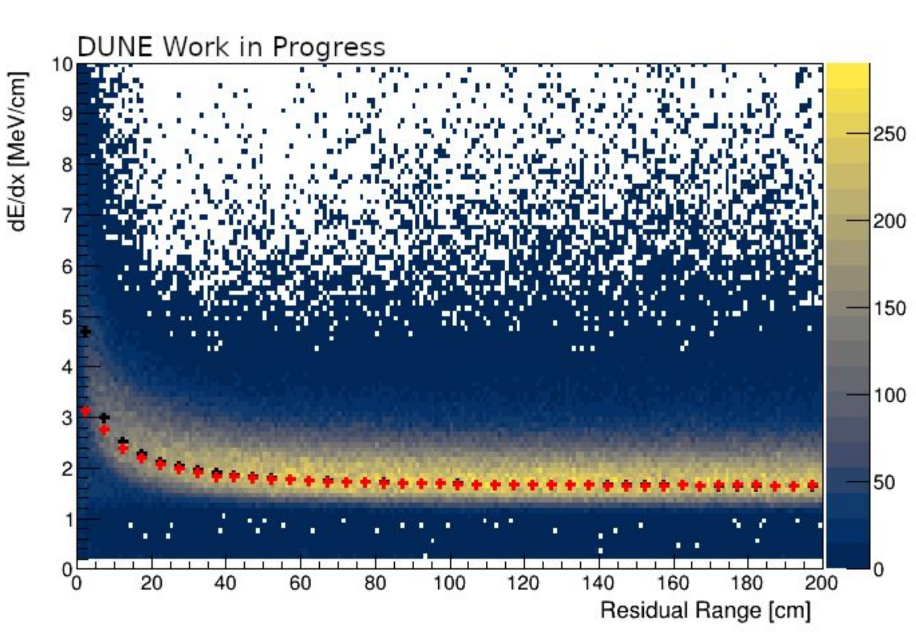
$$\left(\frac{dE}{dx}\right) = \left(\exp\left(\frac{\left(\frac{dQ}{dx}\right)_{\text{calibrated}}}{C_{\text{cal}}}\frac{\beta' W_{\text{ion}}}{\rho\mathcal{E}}\right) - \alpha\right)\left(\frac{\rho\mathcal{E}}{\beta'}\right)$$

Recombination-Scaling Model

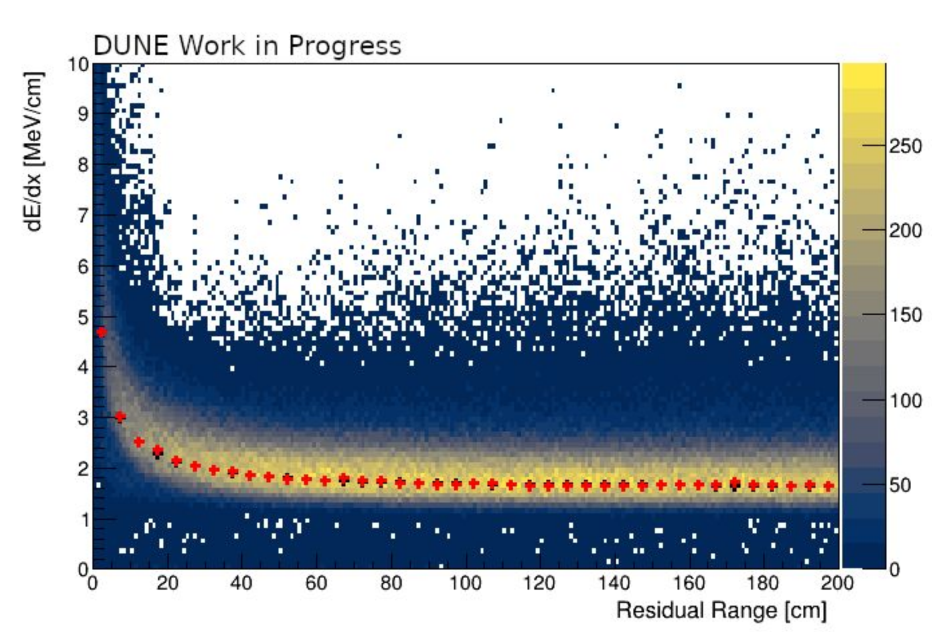


Plot dE/dx against Residual Range

Modified Box Model

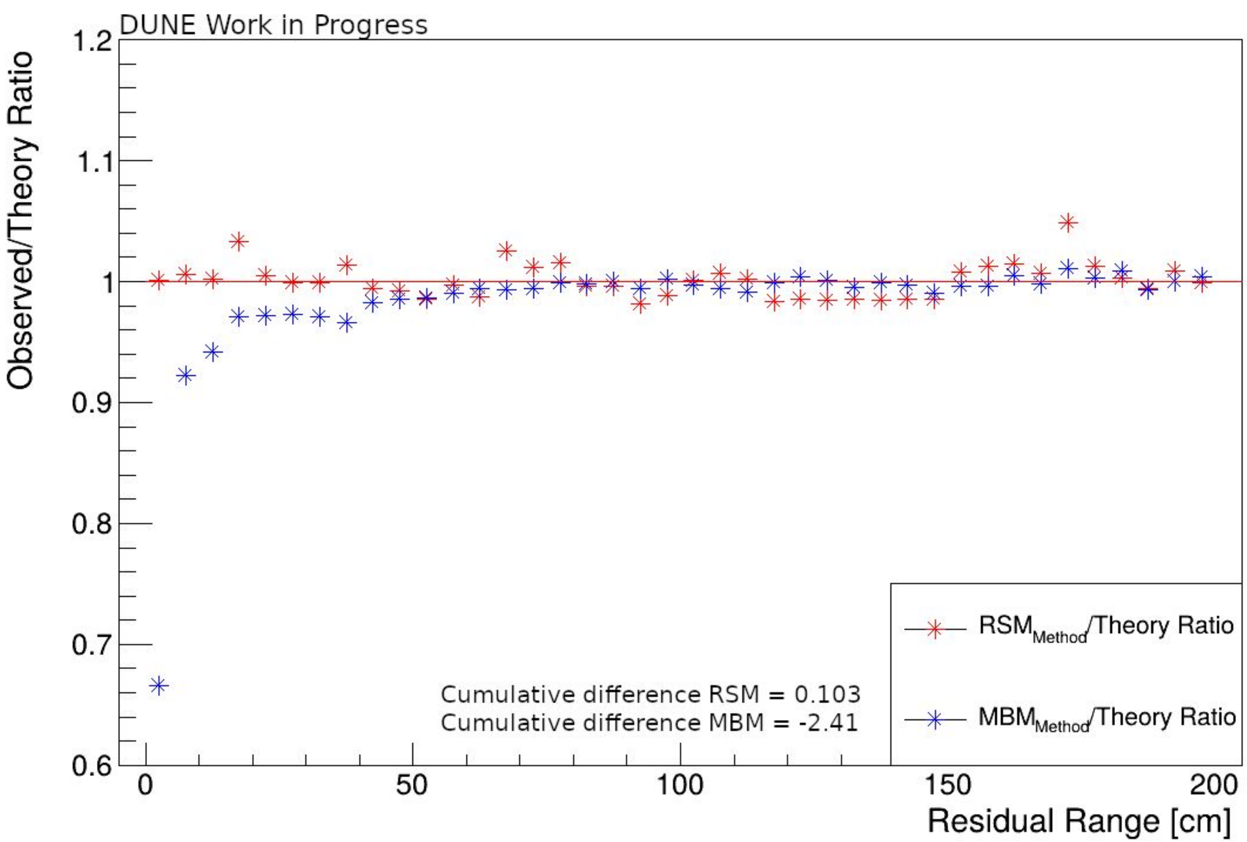


Recombination-Scaling Model



Red = most probable values for each bin; Black = theoretical values for each bin

Compare!



Conclusions:

- Both methods work well for moving from charge to unit length to energy per unit length for stopping muons!
- It will be tested with appropriate protoDUNE data once available

Conclusions

- There are still a lot of open questions in neutrino physics which are currently being investigated
- We have some exciting developments coming up for both short and long baseline neutrino experiments
- Thank you!!

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www.sheffield.ac.uk