# Constraining an Oscillation Analysis using Detector Systematics for the DUNE Liquid Argon Near Detector

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IOP APP/HEPP Meeting

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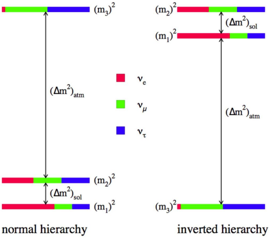
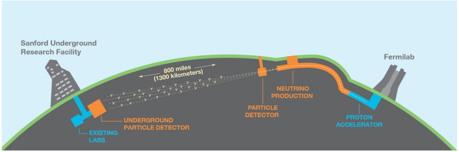
# Open Problems in Neutrino Physics

- Neutrino Mass Hierarchy:
  - Unknown ordering of mass eigenstates: Normal ($\nu_1 < \nu_2 < \nu_3$) or Inverted ($\nu_3 < \nu_1 < \nu_2$)
  - Crucial for understanding neutrino mass generation
- Precise Measurement of $\delta_{CP}$ in the Lepton Sector:
  - Difference in behaviour between neutrinos and antineutrinos
  - Could explain some of the matter-antimatter asymmetry of the universe
  - CP violating phase $\delta_{CP}$ in the PMNS matrix is poorly constrained
  - Long-baseline experiments are designed to precisely measure $\delta_{CP}$



# Deep Underground Neutrino Experiment

- The Deep Underground Neutrino Experiment (**DUNE**) is a next generation Neutrino Experiment being built in the Sanford Underground Research Facility (**SURF**) in South Dakota
- As part of the Long Baseline (**LBL**) neutrino programme, a new $\overset{(-)}{\nu}_{\mu}$ beam is also being built at Fermilab in Illinois
- DUNE consists of 2 detector complexes, a Near Detector Complex (**ND** located $\sim$ 574m from the beam) and a Far Detector Complex (**FD** located $\sim$ 1300km from beam)



# DUNE Near Detector Complex

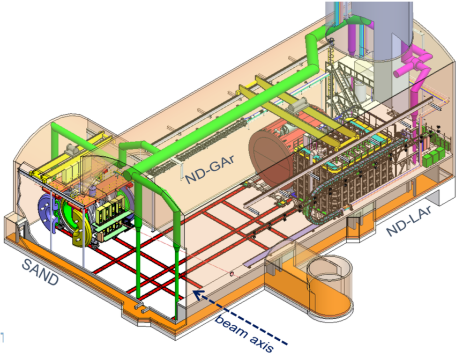
$$N_\nu(E_{rec}) = \int dE_\nu \times \underbrace{P_{osc}(E_\nu, L; \theta)}_{\substack{\text{Neutrino}\\\text{Osc Prob}}} \times \underbrace{\Phi(E_\nu)}_{\nu\text{ Flux}} \times \underbrace{\sigma_{\nu:Ar}(E_\nu, E_{rec})}_{\substack{\nu\text{-Ar}\\\text{Cross-Section}}} \times \underbrace{D(E_{rec})}_{\substack{\text{Detector}\\\text{Efficiencies}}}$$

- The ND Complex has three primary purposes:
    - Measure flux and monitor flux variations over time by determining the unoscillated $\nu$ flux
    - Constrain the $\nu$-Ar cross section model
    - Constrain detector systematics by having similar technologies and operating in a high rate environment in both detectors to transfer measurements to the FD

# Near Detector Complex

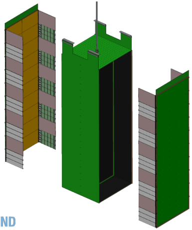
The ND Complex is comprised of three detectors:

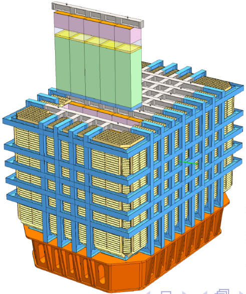
- **ND-LAr**: Liquid Ar target like FD
  - Has downstream spectrometer (TMS in Phase I, ND-GAr in phase II)
- **ND-GAr**: Magnetised Gaseous Ar target (Phase II)
- **SAND**: On-axis Beam Monitor
- **PRISM**: ND-LAr, TMS and ND-GAr move to sample different flux



# ND-LAr

- ND-LAr will use a 7×5 modular array (each module is $1 \times 1 \times 3\ m^3$) with dead regions between the modules comprised of filler material and ASICs
- It will have a 130t of Liquid Argon, having the same target material as the FD
- Each module will include two $50cm$ drift TPC volumes
- It will include a pixelated charge readout system as well as a 25% optical light readout system





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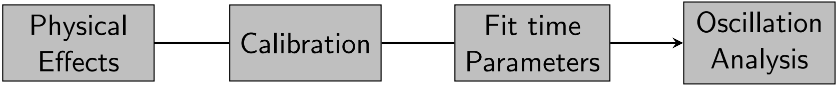
# Detector Systematic Uncertainty Model



Physical Effects

Calibration

Fit time Parameters

Oscillation Analysis

- Take physical effects we know about
- Calibration effort measures size of each of these effects
- Variations in prediction of spectrum for each sample for each fit variable
- Parameterised in a way we can vary at fit time
  - If effects are large and parameterisable they can be varied at fit time
  - Sub-leading or unvariable can be grouped into overall energy scale and resolution uncertainties or similar

# Previously Used Energy Uncertainties

- For the first Technical Design Report (TDR) LBL analysis a standard calorimetric energy uncertainty formula was used
- The uncertainty on the recreated energy depends on the reconstructed particle type

$$E'_{rec} = E_{rec} \times (1 + p_0 + p_1\sqrt{E_{rec}} + \frac{p_2}{\sqrt{E_{rec}}})$$

- $E'_{rec}$ is the smeared (shifted) reconstructed energy
- $E_{rec}$ is the nominal reconstructed energy
- $p_0$, $p_1$ and $p_2$ are the free fit parameters with one set per particle species

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# Energy Scale Uncertainties

| Particle | $p_0$ | $p_1$ | $p_2$ |
|---|---|---|---|
| all (except muons) | 2% | 1% | 2% |
| $\mu(range)$ | 2% | 2% | 2% |
| $\mu(curvature)$ | 1% | 1% | 1% |
| p, $\pi^{\pm}$ | 5% | 5% | 5% |
| e, $\gamma$, $\pi^0$ | 2.5% | 2.5% | 2.5% |
| n | 20% | 30% | 30% |

Table: Energy response uncertainties of various particles where $p_0$, $p_1$, and $p_2$ correspond to the energy response parameterisation (DUNE TDR Volume 2)

These values use data taken from other experiments including calorimetric based experiments (NO$\nu$A, MINER$\nu$A) as well as LArTPC's (LArIAT, MicroBooNE, ArgoNeuT) to estimate the particle species uncertainties

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# Reconstruction

- Within DUNE there are two reconstruction algorithms that are being developed:
    - SPINE (*mlreco*)
    - Pandora
- These have also been used on various other experiments as ways of reconstructing particle tracks and showers
- For each of these reconstruction techniques, there is a requirement to study and estimate the resolutions and biases.
- Energy Reconstruction techniques determining how to apply systematics, i.e. $\mu^{\pm}$ uses track length whereas $\pi^{\pm}$ uses calorimetry to reconstruct energy

# Energy Scale & Resolution

Energy Scale Uncertainty:

- Compare reconstructed energy ($E_{\text{reco}}$) to true energy ($E_{\text{true}}$) using simulation
- Apply calibration factors and assess deviations
- Fit systematic shifts across different energy bins

Energy Resolution Uncertainty:

- Parametrise resolution using appropriate fits to functions of ($E_{\text{reco}}, E_{\text{true}}$)

# $dE/dx$ through Dead Regions

- Energy will be lost by particles passing through areas that would not be picked up by the pixels
- The filler material has been chosen to have a similar $dE/dx$ to LAr, but the PCBs and ASICs would be different
- The angle and position of the particle depositing energy can be used to calculate an uncertainty (or calibrated out) of the total energy of that particle

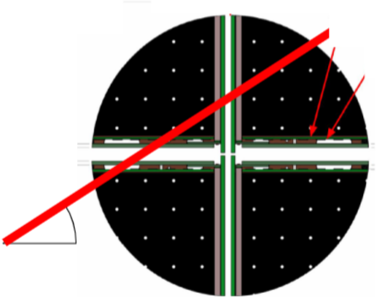

Figure: A particle going through the LAr at an angle through the ASICs and Filler Material

# Space Charge Effects

- In LAr TPCs the electric field is designed to be perfectly uniform throughout the active volume
- Large concentrations of $e^-$ and $Ar^+$, produced by successive interactions, produce spatial distortions inside the detector leading to displacement in the reconstructed position of events

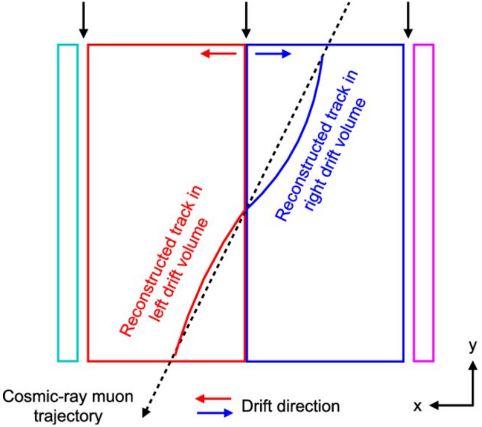

Figure: Example of a space charge distortion of a track due to concentration of Ions in a TPC

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# Conclusion and Next Steps

- Systematic uncertainties will be calculated for all particle species
- Paradigm shift from an era of statistically to systematically limited neutrino measurements within the neutrino sector
- A more detailed and realistic understanding of detector systematics is essential to feed into future oscillation analyses and elsewhere

# Thank You!

Questions?

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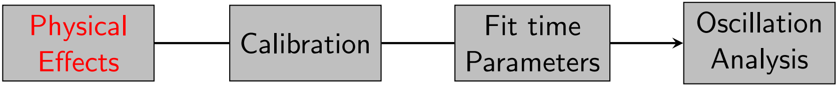
# New Proposed Workflow


Physical Effects

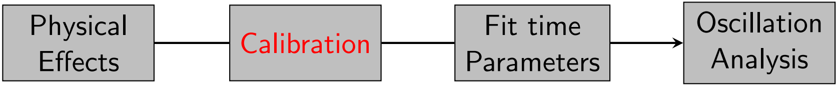
Calibration

Fit time Parameters

Oscillation Analysis

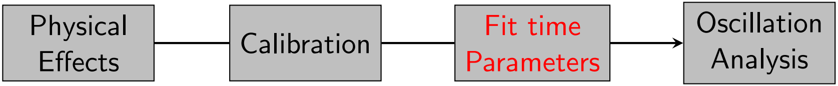
- Establish a list of particles and their properties that we need uncertainties on
- Rank the magnitude of these effects and understand which to include directly in fit and which to group

# New Proposed Workflow



- Use 2×2 data and other calibration methods to establish by how much these effects affect the uncertainties on the energy scale/resolution
    - Snowstorm is one technique that could be used to do this for some effects (see Andrew Cudd's work, and IceCube paper)
    - However to my understanding, Snowstorm will probably not be ready for use in the ND TDR so we need to come up with alternative ways of finding detector uncertainties
    - Other effects which vary kinematic parameters may need other treatment

# New Proposed Workflow



- Many experiments for their 'sub-leading grouped parameters' measure Energy scale and resolution per particle species with uncertainty varying depending on some other variables (see muon example later)
    - Key point for CAF production, we can only have effect depend at fit time on a variable we have access to at fit time e.g. if you need distance to wall put it in the CAFs
- While physical effect identification is ongoing in detector groups LBL can start adding this more sophisticated 'rest of the effects' treatment
- Can move step by step from TDR treatment to new treatment without being left with no uncertainty model if we don't finish in time for ND TDR deadline

# Example of workflow

- Choose a particle to start working on for detector systematics e.g. muons, $\mu^{\pm}$
- Rank biggest physical effects and discuss their implications e.g. muon containment and resolution due to distance to wall
- Work with Calibration and Prototypes groups to establish how varying this affects a variable like $E_{rec}$ e.g. pick distance to wall and angle as key variables then 10cm away from a wall the energy scale uncertainty is $x$, 20cm away it's $y$ etc.
- Once enough effects have been added, the values from the previous table can be updated slowly for each of the particles

# Example of a workflow

- Like in the above example, every single physical effect does not need to be directly coded into the OA fitter
- We will have a process for deciding which are and which aren't with presentations at scheduled meetings where all stakeholder groups are present
- For larger individual physical effects, we can discuss if they can be calculated at the fitting time

# Containment

- Not all particles will remain contained inside the fiducial volume of the detector and some will leave the detector
- The total energy cannot be reconstructed on the events that leave the detector
- Particles that leave in the forward direction will pass through the TMS where the energy of the escaped particles energy can be measured (there is an uncertainty on that measurement too)
- Other particles may escape and not pass through the TMS, meaning that the energy of the particle is lost

# Electric Field Non-Uniformity

- Around the edge of the fiducial volumes and around the edge of the walls the field is non-uniform
- The resolution and energy reconstruction at the edges of the detector would be distorted adding to energy scale and resolution uncertainties
- There is also an uncertainty on the high voltage measurement between the anode and cathode in the TPC

# Other Considered Effects

These are some other effects have been considered but not yet fully developed:

- Channel Efficiencies
- Field Responses
- Pixel Responses
- Short Track $dE/dx$

# Summary

- Making more realistic ND-LAr detector systematics needs to be a priority as we move closer to the ND TDR and physics analysis for 2×2
- Establishing a workflow allows for a clear understanding of who is doing what
- A more detailed "Physical Effects and Uncertainties" talk is being written so we can begin to look at the intricacies of what each of these effects will look like for the big picture

# Realistic approach to ND-LAr Detector Systematics

- In the TDR, the detector systematics are only estimates of the Energy Scale Uncertainties
- These systematics were part of the Oscillation Analysis fits in both the frequentist and bayesian approach
- A realistic approach to calculating detector systematics are paramount to ensure more realistic uncertainties on the analysis of oscillation parameters as DUNE collects more data and the experiment matures

# Particle Gun

- Full productions of ND-LAr CAFs are not yet ready whilst there is still a massive push to ensure all the steps of production are finalised for analysis before the ND TDR in October
- Work began in November 2024 to create a particle gun production allowing for the detector systematic uncertainties of each particle to be studied individually
- A particle gun was successful in **edep-sim** using a Geant4 macro input file with the ability to change particle type, energy range and energy distributions using environment variables as well as particle direction and vertex creation by way of editing the input macro file