DUNE-IN2P3 analysis meeting *March 27, 2024*

Detector systematics & oscillation parameter estimation

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Outline

- **Detector & reconstruction systematics for oscillation parameter estimation**
  - What are the current uncertainties?
  - How were they chosen?
  - Ideas to improve them, can ProtoDUNE help?

- **Notes:**
  - Only discussing beam (anti)neutrinos in here
  - Focusing on the far detector
  - This is gathering information from previous work from here and there, not everything is documented
  - To be used as a basis for discussion and future work

TDR analysis

- **Long-baseline neutrino oscillation physics potential of the DUNE experiment**
  - arXiv:2006.16043
  - Journal article adapted from the technical design report (TDR)

- **Event selection**
  - MC simulation of FD w/ HD (no VD, « single phase » era)
  - Events are classified as $\overset{(-)}{\nu}_\mu$ or $\overset{(-)}{\nu}_e$ with a convolutional visual network (hit pattern recognition): arXiv:2006.15052
  - $E(\nu_\mu)$ = energy of the longest reconstructed track + hadronic energy
    - ↳ contained track: $E(\mu)$ from range
    - ↳ not contained track: $E(\mu)$ from multiple Coulomb scattering
  - $E(\nu_e)$ = energy of the highest energy shower + hadronic energy

hadronic energy → charge of hits not in longest track / high energy shower

Energy resolution

- **Neutrinos:**
  - $E(\nu) \simeq 15 - 20\,\%$
- **Muons:**
  - $E(\mu) = 4\,\%$ (contained tracks)
    $E(\mu) = 18\,\%$ (exiting tracks)
- **Electrons:**
  - $E(e) = 4\% \oplus 9\,\%\,\sqrt{E(e)}$ + non-Gaussian tail due to shower leakage, anticorrelated with the hadronic energy measurement
- **Hadronic energy:**
  - $E(h) = 34\,\%$, with possible improvements by:
    - identifying individual hadrons
    - adding masses of charged pions
    - applying particle-specific recombination corrections

Detector uncertainties

- **Energy scale & particle response uncertainty:**

reweighed reconstructed energy ← E'_{rec}

E_{rec} → nominal reconstructed energy

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

p_0, p_1, p_2 → fit free parameters with a priori constraint

Detector uncertainties

- **A priori values on free parameters:**

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

Particle type	Allowed variation		
	p_0	p_1	p_2
all (except muons)	2%	1%	2%
μ (range)	2%	2%	2%
μ (curvature)	1%	1%	1%
p, $\pi^{\pm}$	5%	5%	5%
e, γ, π^0	2.5%	2.5%	2.5%
n	20%	30%	30%

The scale of these assumed uncertainties is motivated by what has been achieved in recent experiments, including calorimetric based approaches (NOvA, MINERvA) and LArTPCs (LArIAT, MicroBooNE, ArgoNeuT). The DUNE performance is expected to significantly exceed the performance of these current surface-based experiments. NOvA [44] has achieved $< 1\%$ (5%) uncertainties on the energy scale of muons (protons).

Detector uncertainties

- **A priori values on free parameters:**

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n	20%	30%	30%

- Details from Chris Marshall presentation on November 2023 at the calibration meeting:

- Overall energy scale is a calibration uncertainty: relationship between deposited energy and measured energy
  - It might vary with energy, so allow some shape freedom
  - This would be uncorrelated ND to FD

(e.g. due to uncertainties in the electric field)

Detector uncertainties

- **A priori values on free parameters:**

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- Details from Chris Marshall presentation on November 2023 at the calibration meeting:

- Numbers are educated guesses:
  - 2% is a typical energy scale uncertainty for running experiments
  - 5% is a typical particle response residual uncertainty from e.g. MINERvA test beam
  - 2.5% is the residual uncertainty from the π0 mass peak in MINERvA
  - Neutrons we have no idea
  - We have no idea what the energy-dependent parameters should be so we made them the same

Detector uncertainties

- **A priori values on free parameters:**

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- Details from Chris Marshall presentation on November 2023 at the calibration meeting:

- Particle response in LAr: relationship between true particle kinematics and deposited energy
  - Could constrain this with ProtoDUNE
  - Also might vary with energy, so allow some shape freedom
  - This would be largely correlated ND to FD

Detector uncertainties

- **A priori values on free parameters:**

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

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- Details from Chris Marshall presentation on November 2023 at the calibration meeting:

→ (p, $\pi^{\pm}$; e, γ, π^0)
- Particle response in LAr: relationship between true particle kinematics and deposited energy
  - Could constrain this with ProtoDUNE
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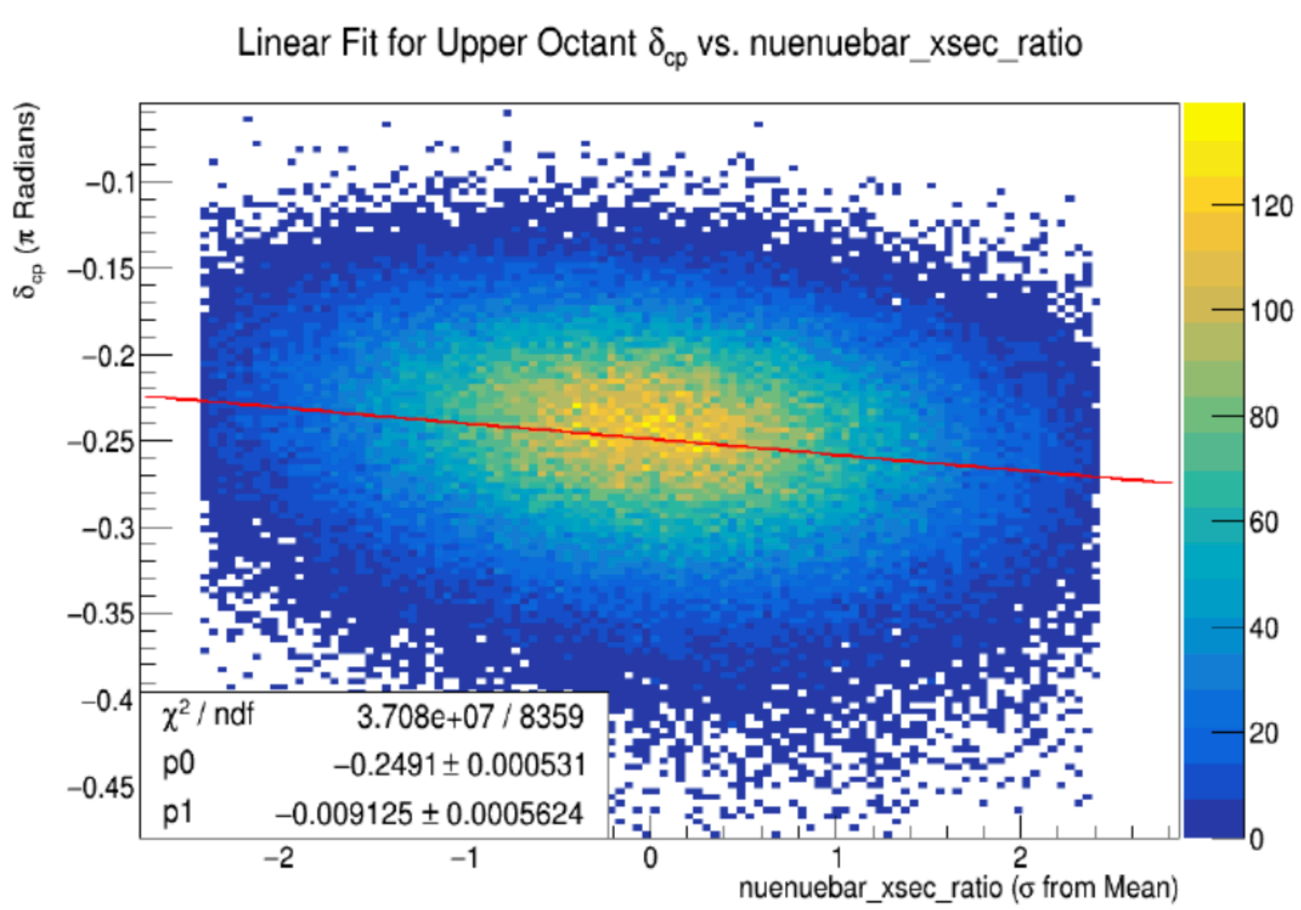
Impact on oscillation parameters

- Chris Marshall presentation on November 2023 at the calibration meeting:

New-ish idea: look at post-fit correlations as a proxy



- Choose a particular point in true oscillation parameter space where systematics are important
- Perform O(100k) random simulated experiments where every uncertainty parameter is thrown (including stats)
- Look at correlations between *thrown* value of a parameter and *measured* value of δ_{CP}

Impact on oscillation parameters

- Chris Marshall presentation on November 2023 at the calibration meeting:

Deeper look at energy parameters

- Largest slopes for δ are:
  - 1) 2.8 Energy scale p2
  - 2) 2.6 EM energy scale p2
  - 3) 2.3 Energy scale p0
  - 4) 2.2 EM energy scale p0
  - 5) 1.3 EM energy scale p1
  - 6) 0.8 Muon energy scale p2
  - 7) 0.7 Muon energy resolution
  - 8) 0.6 Neutron energy resolution

➡ Energy scale have larger effect than cross-section and flux uncertainties that are well constrained by the near detectors data

Impact on oscillation parameters

- Chris Marshall presentation on November 2023 at the calibration meeting:

Looking forward: biggest needs in next ~1-2 years

- Revisit the energy scale/response uncertainties:
  - Are the numbers still reasonable?
  - Does the allowed shape vs. energy make any sense?
- Implement proper calibration uncertainties in the FD
  - Field non-uniformity, recombination, etc.
  - Can we calculate weights/shifts during the regular reco process? Do we need alternative samples?
- Implement proper calibration uncertainties in the ND
  - This is a todo item in the ND sim/reco group, but might benefit from more expertise