Systematic uncertainties in DUNE

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Precision Time Structure Workshop
2 November, 2019
Outline

- A generic long-baseline oscillation measurement, and how systematic uncertainties arise
- The DUNE near detector
- Flux uncertainty in DUNE
- Neutrino interaction & energy reconstruction uncertainties
Neutrino oscillation probability

- The goal of any neutrino oscillation experiment:
  - Measure the flux of neutrinos of flavor $\beta$ at a distance $L$
  - Compare it to the flux of neutrinos of flavor $\alpha$ at the source
  - As a function of neutrino energy
  - Disappearance ($\alpha = \beta$) and appearance ($\alpha \neq \beta$)

\[ P(\nu_\alpha \rightarrow \nu_\beta) = \frac{\Phi_{\nu_\beta}(E_\nu, L)}{\Phi_{\nu_\alpha}(E_\nu, 0)} \]
We measure neutrino interactions, not fluxes directly

![Diagram showing neutrino source and far detector connected by distance L, with neutrinos ν_α and ν_β]

\[ N(E_\nu) = \Phi(E_\nu) \times \sigma(E_\nu) \times \epsilon(E_\nu) \]

- Observed interaction rate, \( N \), depends on fluxes, but also cross sections (\( \sigma \)), and detector acceptance (\( \epsilon \))
- Cross sections, in particular, are highly uncertain
Energy reconstruction is challenging

- And the observed rate is measured as a function of reconstructed energy, which is connected to neutrino energy $E_\nu$ by some smearing matrix $D$

- This matrix dependent on your particular detector, but also depends strongly on neutrino interactions

$$N(E_{reco}) = \int \Phi(E_\nu) \times \sigma(E_\nu) \times \epsilon(E_\nu) \times D(E_\nu \rightarrow E_{reco}) dE_\nu$$
Uncertainties are reduced with near detector measurements

\[
N_{far}(E_{reco}) = \int \Phi(E_\nu, L) \times \sigma(E_\nu) \times \epsilon(E_\nu) \times D(E_\nu \rightarrow E_{reco}) dE_\nu
\]

\[
N_{near}(E_{reco}) = \int \Phi(E_\nu, 0) \times \sigma(E_\nu) \times \epsilon(E_\nu) \times D(E_\nu \rightarrow E_{reco}) dE_\nu
\]

- Near detector in the same flux, with the same nuclear target, and a similar detector technology, will constrain many uncertain parameters
But there is no magical “cancellation”

\[
N_{\nu_\beta}^{\text{far}}(E_{\text{reco}}) = \int \Phi_{\nu_\beta}(E_\nu, L) \times \sigma_{\nu_\beta}(E_\nu) \times \epsilon_{\nu_\beta}^{\text{far}}(E_\nu) \times D_{\nu_\beta}^{\text{far}}(E_\nu \rightarrow E_{\text{reco}}) dE_\nu
\]

\[
N_{\nu_\alpha}^{\text{near}}(E_{\text{reco}}) = \int \Phi_{\nu_\alpha}(E_\nu, 0) \times \sigma_{\nu_\alpha}(E_\nu) \times \epsilon_{\nu_\alpha}^{\text{near}}(E_\nu) \times D_{\nu_\alpha}^{\text{near}}(E_\nu \rightarrow E_{\text{reco}}) dE_\nu
\]

- There are many differences between the observed interaction rates at the near and far detectors, which lead to systematic uncertainties:
  - Fluxes are different primarily due to oscillations
  - Cross sections are strongly energy-dependent, potentially different nucleus, or different neutrino flavor
  - Even if ND and FD are “functionally identical,” acceptance and energy reconstruction will be somewhat different due to the sizes
But there is no magical “cancellation”

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\]

- All of these terms depend on $E_{\nu}$, so this product cannot be factorized
- Even if the ND and FD were literally identical, the flux differences mean that nothing actually cancels
- Independent knowledge of flux and cross sections is very helpful
But there is no magical “cancellation”

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- All of these terms depend on $E_\nu$, so this product cannot be factorized
- Even if the ND and FD were literally identical, the flux differences mean that nothing actually cancels
- Independent knowledge of flux and cross sections is very helpful
- 40 kt fiducial LAr TPC far detector at SURF, 1300 km baseline
- Upgraded conventional neutrino beam at Fermilab, peaked at 2.5 GeV
- Near detector system at Fermilab is critical for constraining systematic uncertainties
The DUNE Near Detector

- LAr TPC functionally similar to far detector
- Magnetized, high-pressure gaseous Ar TPC with high-performance calorimeter
- Magnetized plastic scintillator tracker & on-axis beam monitor
Movable detectors for on- and off-axis measurements

- LAr + HPgTPC system will move up to 33m off axis to sample different energy spectra in the same beam
- Next talk will provide details about what this does for uncertainties
DUNE ND philosophy

- **LAr TPC**
  - High rate (30M $\nu_\mu$ CC, 5k $\nu$+e elastic events/yr) enables many simultaneous exclusive measurements, and a direct flux constraint
  - Similar technology to FD enables use of PRISM technique to directly probe energy response in different fluxes

- **High-pressure gaseous Ar TPC**
  - Excellent PID, $4\pi$ coverage, sign selection, very low thresholds $\rightarrow$ study $\nu$-Ar interactions in exquisite detail, much better than FD

- Robust monitoring of beam spectrum vs. time
Flux uncertainties in DUNE

- Absolute flux uncertainty is ~8% and dominated by hadron production uncertainties

- This includes currently available constraints from hadron production experiments (i.e. NA49), but not future constraints (i.e. EMPHATIC, NA61), or in situ measurements (i.e. ν+e elastic, low-ν)
Near/Far flux ratio

- Near/Far ratio has ~20-50% deviations from unity, before accounting for oscillations.
- Leads to an uncertainty that is ~0.5% in the peak, but rising to ~2% in the falling edge, and dominated by focusing effects.
- This cannot be constrained by the near detector.
Neutrino-electron elastic scattering

\[
\frac{d\sigma}{dy} (\nu e^- \rightarrow \nu e^-) = \frac{G_F^2 m_e E_{\nu}}{2\pi} \left[ \left( \frac{1}{2} - \sin^2 \theta_W \right)^2 + \sin^4 \theta_W (1 - y)^2 \right]
\]

\[E_e \theta_e^2 < 2m_e\]

• Pure electroweak process with known cross section at tree level
• Signal is a single, forward electron with no other particles
• MINERvA has demonstrated using ν+e to constrain the NuMI flux

$\nu + e$ flux constraint: \(~5\% for MINERvA, \sim 2\% for DUNE\)
Cross section uncertainties

- DUNE has evaluated ~60 cross section uncertainties, affecting quasi-elastic scattering, resonance production, deeply inelastic scattering, nuclear effects, $\nu_\mu/\nu_e$ differences
- Starts with, but greatly expands on GENIE reweighting framework
- Used in oscillation fits in forthcoming physics TDR
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I'm going to spare you the details, and instead explain more qualitatively how cross section uncertainties impact DUNE.
Cross section uncertainties

- DUNE is sensitive to effects that impact the rate of $\nu_\mu$ and $\nu_e$ CC interactions at the Far Detector as a function of reconstructed neutrino energy.

\[
\sin^2 2\theta_{23} = 0.580 \\
\Delta m^2_{32} = 2.451 \times 10^{-3} \text{ eV}^2
\]

3.5 years (staged)

- Signal $\nu_\mu$ CC
- $\nu_\mu$ CC
- NC
- $(\nu_e + \nu_\mu)$ CC
- $(\nu_e + \nu_\mu)$ CC

\[
\sin^2 2\theta_{13} = 0.088 \\
\sin^2 2\theta_{23} = 0.580
\]

3.5 years (staged)

- Signal $(\nu_e + \nu_\mu)$ CC
- Beam $(\nu_e + \nu_\mu)$ CC
- NC
- $\nu_\mu$ CC
- $\nu_e$ CC

\[
\delta_{CP} = -\pi/2 \\
\delta_{CP} = 0 \\
\delta_{CP} = +\pi/2
\]
Cross section uncertainties

- $\nu_\mu$ and $\nu_e$ total CC cross sections
- But also exclusive cross sections, which change the makeup of the final state, and thus impact how much of the neutrino energy is visible to DUNE
Neutrino energy reconstruction

- Muon energy is reconstructed by range for fully-contained events
- Hadronic energy is reconstructed calorimetrically
- \( E_\nu = E_\mu + E_{\pi^\pm} + E_{\pi^0} + E_p + E_n + ... \)
Leptons, pions, and protons are all seen by DUNE, and can be reconstructed, albeit with somewhat different response functions

$$E_ν = E_μ + E_{π^±} + E_{π^0} + E_p + E_n + \ldots$$
• Neutrons show up as small blips in the detector, and their energy is mostly lost, i.e. “missing energy”

\[ E_\nu = E_\mu + E_{\pi^\pm} + E_{\pi^0} + E_p + E_n + \ldots \]
• If you change the composition of the final state, i.e. if there are more neutrons and fewer protons, then the reconstructed energy will be impacted

\[ E_v = E_\mu + E_{\pi^\pm} + E_{\pi^0} + E_p + E_n + \ldots \]
Neutrino energy reconstruction impacts oscillation parameters

- $\nu_\mu$ disappearance parameters are especially sensitive to energy misreconstruction
  - Absolute scale shift directly pulls $\Delta m^2$
  - Resolution uncertainties fill in the “dip” and drive $\sin^2 2\theta_{23}$
- Uncertainties in reconstructed energy can be due to detector effects (i.e. calibration uncertainties) or cross sections (i.e. neutron production uncertainties)
Example: 20% of final-state proton energy becomes neutrons

- Suppose the kinetic energy of final-state protons is decreased 20% (i.e. by giving energy to neutrons)
- Results in a ~3% shift in best-fit $\Delta m^2$
- In the next talk, Mike will describe how our ND design mitigates this type of uncertainty
- Similar effects could be obtained with shifts to detector absolute energy scale, for example
Important cross section & reconstruction systematics for $\delta_{CP}$

- Appearance spectra are less sensitive to absolute energy reconstruction.
- But several other effects have significant impact on appearance:
  - Absolute EM energy scale in FD.
  - Cross section uncertainties that only impact $\nu_e$, i.e. effects in phase space forbidden in $\nu_\mu$ CC.
  - Cross section uncertainties that affect $\nu_e/\bar{\nu}_e$ ratio.
  - Beam $\nu_e$ is $\sim$5% of total sample in the peak (thanks, large $\theta_{13}$!)
  - NC backgrounds are <5%, but large uncertainties on NC $\pi^0$.

\[ \sin^2 2\theta_{13} \]
Event mixture in DUNE oscillation sample is very different from T2K

- GENIE “DefaultPlusValenciaMEC” on Ar
- DUNE oscillation peak region is roughly 40% $0\pi$, 40% $1\pi$, 20% $2+\pi$
  - Compared to T2K $\sim85\% \ 0\pi$
- Huge amount of theory work has dramatically improved our modeling of CC$0\pi$ – we need this same commitment to $1\pi$, $2\pi$, SIS/DIS, etc. for DUNE

\begin{align*}
0.4 < E_\nu < 0.8 \text{ GeV} & \quad 2.3 < E_\nu < 2.7 \text{ GeV} & \quad 4.0 < E_\nu < 4.5 \text{ GeV}
\end{align*}
Detector acceptance (LAr ND)

- LAr ND has reduced acceptance due to non-containment of muons and/or hadronic showers, but is designed such that there are no holes in the accepted phase space.
- Differences in ND and FD acceptance will need to be corrected, but this is largely due to geometric effects.
- HPgTPC in ND will also have $4\pi$ acceptance.
Far detector selection efficiency

- $\nu_e$ CC in neutrino mode
- Full MC with CVN event selection (solid curve) is comparable to fast MC from CDR (dashed curve)
- 85-90% efficient in the region where most events are expected
- Must ensure that this efficiency is robust against interaction & detector models
Summary

• DUNE is sensitive to systematic uncertainties due to the flux prediction, neutrino interaction model, energy reconstruction, and detector acceptance & efficiency

• Highly-capable multi-system near detector is designed to reduce these uncertainties, as well as to resolve broad categories of potential effects (unknown unknowns)
Backups
Flux uncertainty principal component analysis

- The largest HP & focusing uncertainties show up as principal components of the full flux covariance.
- The largest 30 components are treated as nuisance parameters in DUNE TDR sensitivity analysis.
Energy resolution is quite good in a region of $(E, \theta)$, basically where $E\theta^2$ is very small.

Effectively, select a subsample of good, and unbiased energy resolution and measure shape from it.

Requires very high statistics.
**ν+e scattering signal and backgrounds in E,θ**

- **Signal** is subject to kinematic constraint $E_e \theta_e^2 < 2m_e$
- **Dominant background** is $\nu_e$ CC at very low $Q^2$
- **But background shape** in $E, \theta$ is very different from signal, and realistic uncertainties on background shape still do not produce signal-like distribution
2D templates for $\nu + e$ signal

Each template is a bin of neutrino energy, and adds events in $(E, \theta)$.
DUNE ND ν+e statistics

- DUNE LAr ND at ~50t F.V. will have ~15k events in 3 years, even with very conservative thresholds
- >100x more statistics than MINERvA LE analysis
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GENIE ReWeight

GENIE reweight parameters affecting
CC quasi-elastic
CC resonance production
CC deep inelastic scattering
Final-state interactions
Neutral currents
DUNEint not covered in GENIE

Additional parameters:

CC QE
CC Resonance
2p2h
Scaling C → Ar
ν_e/ν_μ or ν_e/ν_e

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Additional parameters affecting non-resonant pion production

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NR_nubar_p_NC_1Pi
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Example 1: uncertainty on “2-particle 2-hole” interactions

- MINERvA and NOvA see an enhancement in cross section that is consistent with multinucleon 2p2h scattering, i.e. $\nu_\mu(np) \rightarrow \mu^{-}nn$

- MINERvA can fit in 4 different ways: as 1p1h, nn only, pp only, 2p2h

- Implemented parameter moves events between nn $\rightarrow$ 2p2h $\rightarrow$ 1p1h
Example 2: Interference in single pion production

- CC1π is important contribution to DUNE oscillation signal
- GENIE's Rein-Sehgal resonant pion model lacks interference with non-resonant processes
- Our model includes this effect using the “MK model,” which includes resonant, non-resonant, and interference terms
- Result in different $W$ distribution and different hadron ejection
- Difference is treated as uncertainty
Example 3: Suppression in CC1π at low momentum transfer

- MiniBooNE, MINERvA, NOvA, MINOS see a suppression at low $Q^2$ for single pion production
- Evaluated from a fit to MINERvA data compared to our version of GENIE
- DUNE cross section uncertainty includes physics beyond GENIE
Lesson from NOvA: significant MC tuning will be required to match ND

- Out-of-the-box GENIE RFG (top-left), with empirical 2p2h added (bottom left)
- Improved models and extensive cross section model tuning (right)
Event mixture in DUNE oscillation sample is different from T2K, NOvA

- DUNE oscillation maximum occurs where QE, resonant, and DIS interactions are all significant
Post-fit systematics in TDR

- Left panel is flux & FD detector effects, right panel is cross sections
- Generally very weakly constrained by FD alone, but become very constrained by ND
Far detector event selection: FHC $\nu_e$ CVN probability

- FHC event probabilities from CVN
- Cut at 0.85 for this analysis
- Selects oscillated and intrinsic electrons