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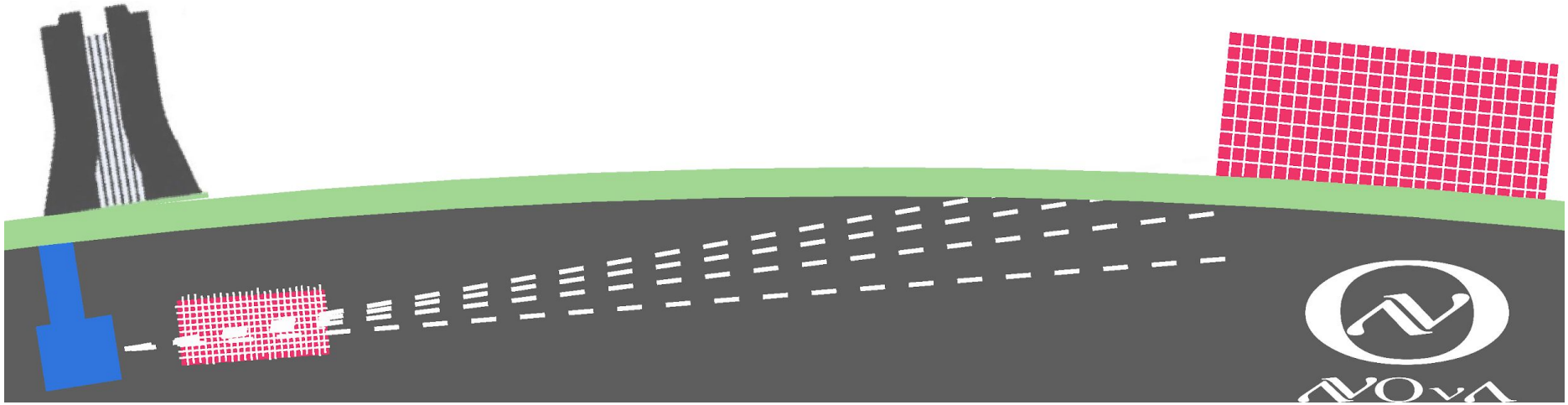
NOvA's far detector predictions and key systematic uncertainties

New Perspectives 2019

Fermilab

NOvA detectors

- **Long-baseline** neutrino oscillation experiment.
- Near detector (ND) ~100 m underground, at Fermilab.
- Far detector (FD) on surface in northern Minnesota.
- Two **functionally similar** detectors 809 km apart.



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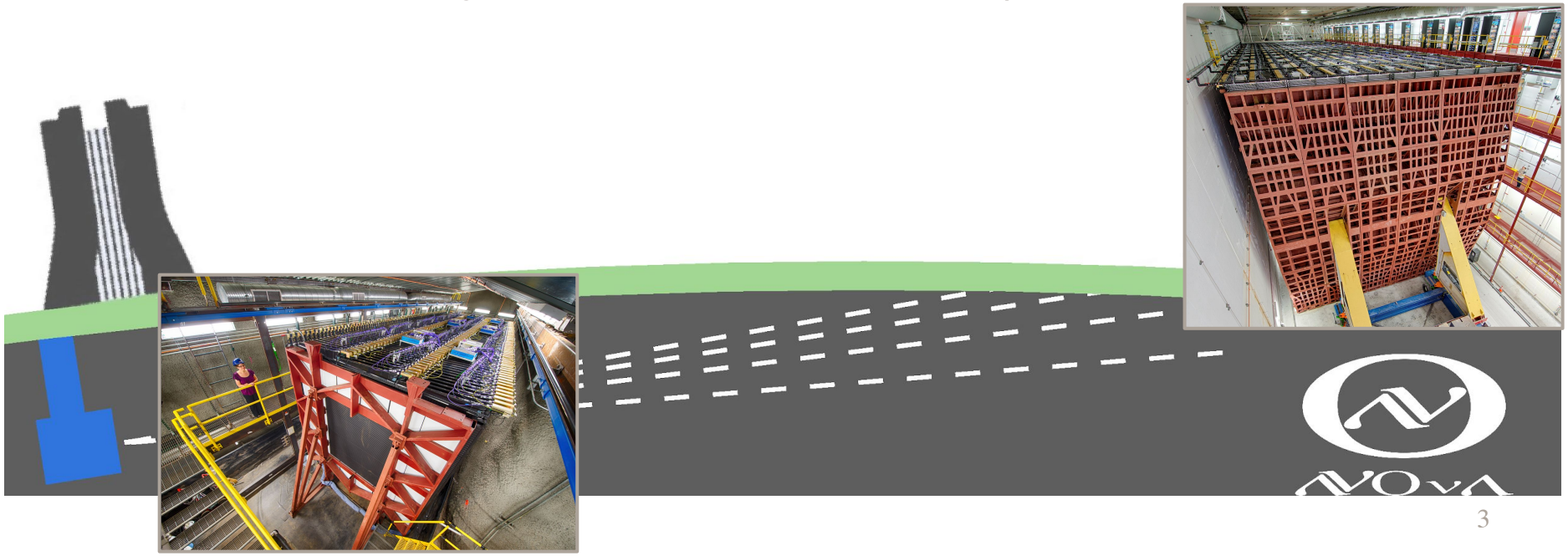
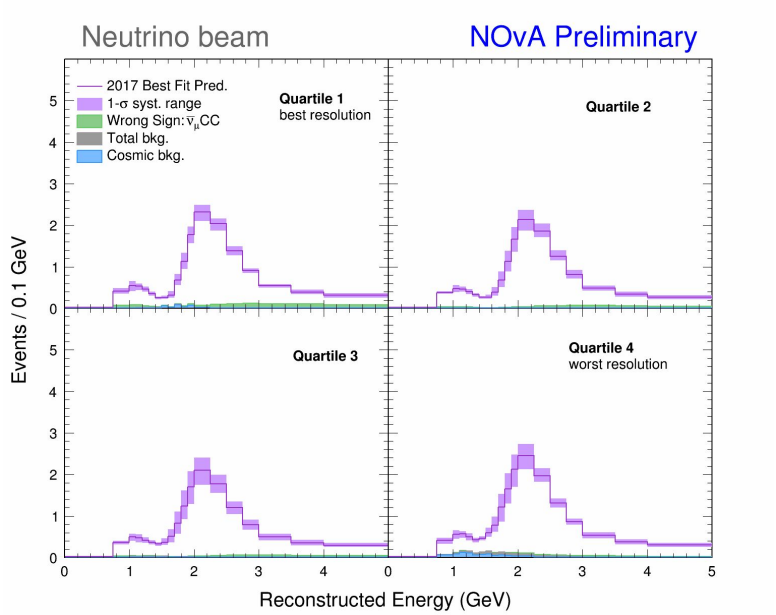


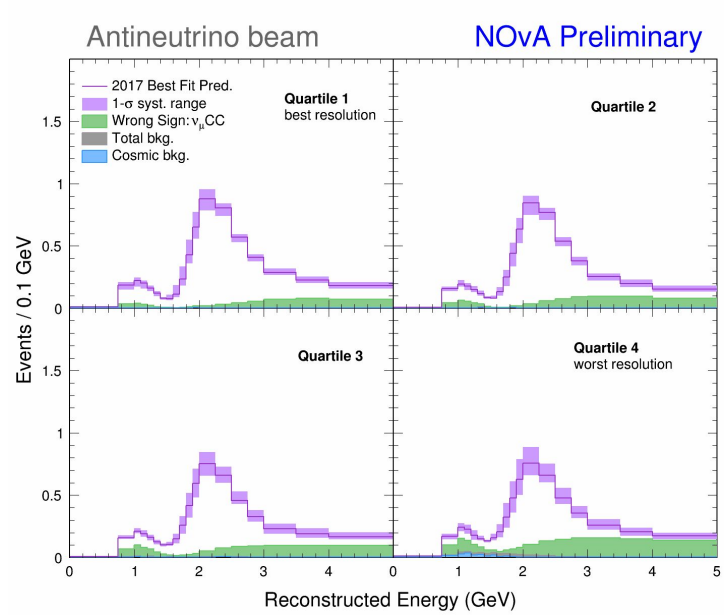
Three-flavor oscillations fit

1. Accurate far detector predictions.
   - ν and $\bar{\nu}$ beam running modes.
   - ν_μ-disappearance and ν_e-appearance selected samples.

ν ν_μ



$\bar{\nu}$ ν_μ



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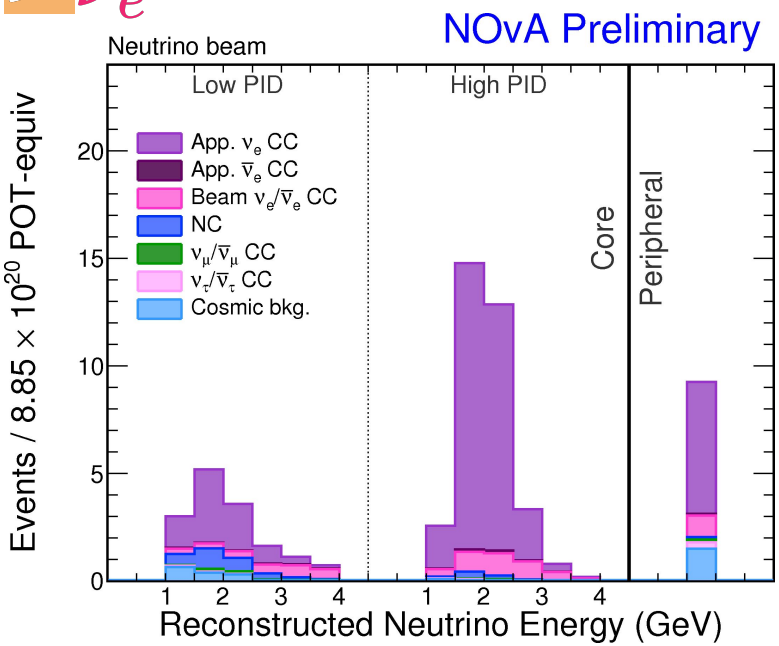
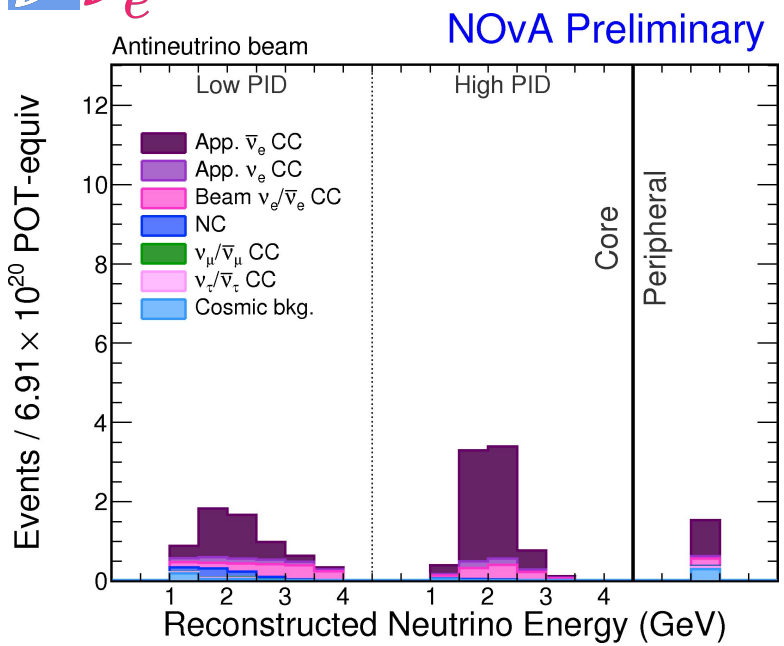
$\nu\ \nu_e$



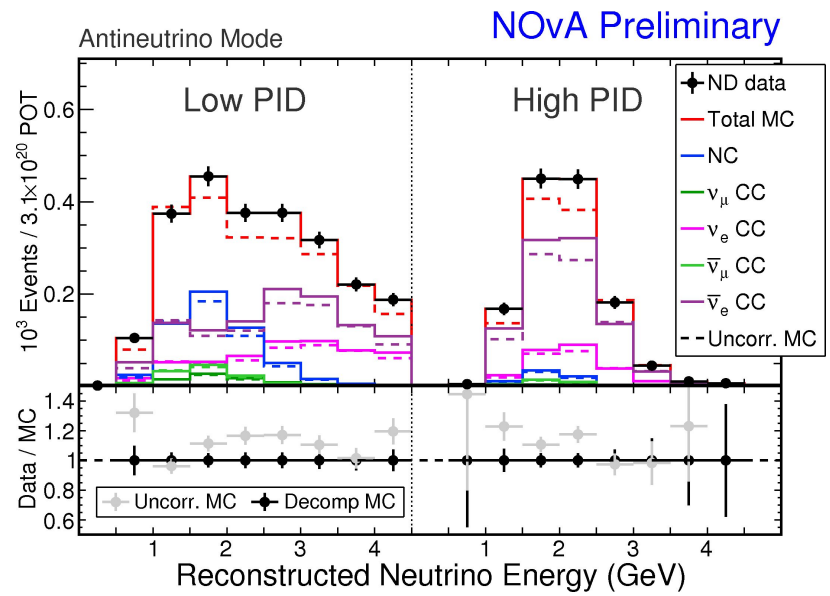
$\bar{\nu}\ \nu_e$



ν_e

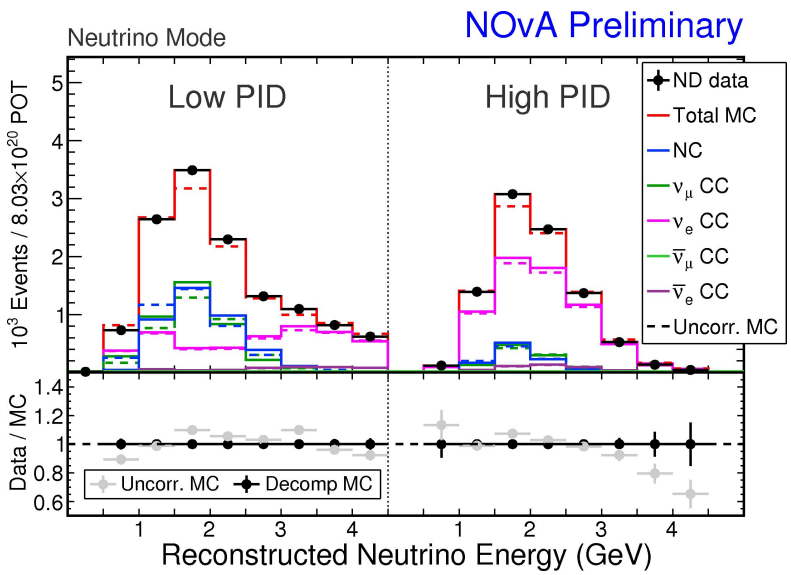
Data-driven ND techniques

- Three main beam backgrounds that we can study in ND data:
  - beam ν_e-CC
  - ν_μ-CC
  - NC
- Data-driven techniques scale ND MC to fit ND data, so we can then use it to correct our FD MC.
- For antineutrino beam backgrounds retain their proportions during scaling



ν_e

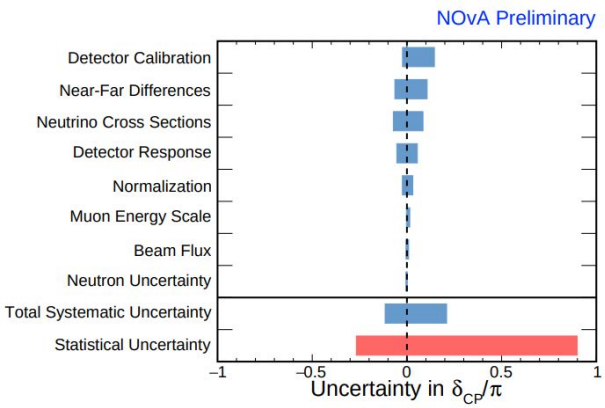
Data-driven ND techniques

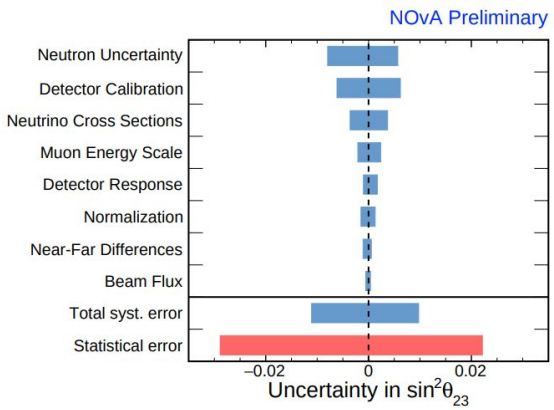


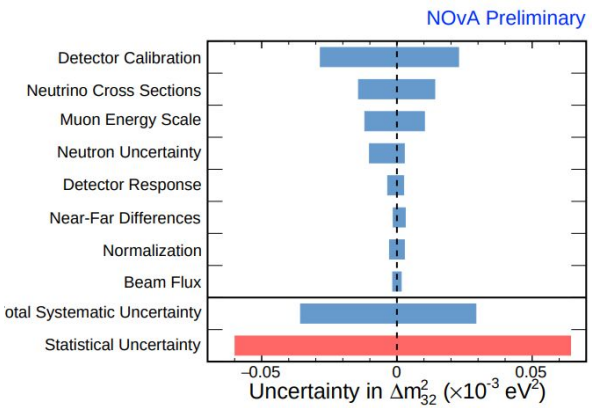
- For neutrino beam data we use a combination of two data-driven techniques to adjust ND MC to fit the ND data.
- Beam ν_e-CC events:
  - Same parents as ν_μ-CC: lower energy νs → from π, higher energy νs → from K.
  - (Un)contained events constrain π(K) flux.
- ν_μ-CC:
  - Estimate fraction from number of Michel electrons.
- NC takes the remaining portion.

Three-flavor oscillations fit

1. Accurate far detector predictions.
   - ν and $\bar{\nu}$ beam running modes.
   - ν_μ-disappearance and ν_e-appearance selected samples.
2. Comprehensive understanding and treatment of systematics.







Systematic shifts

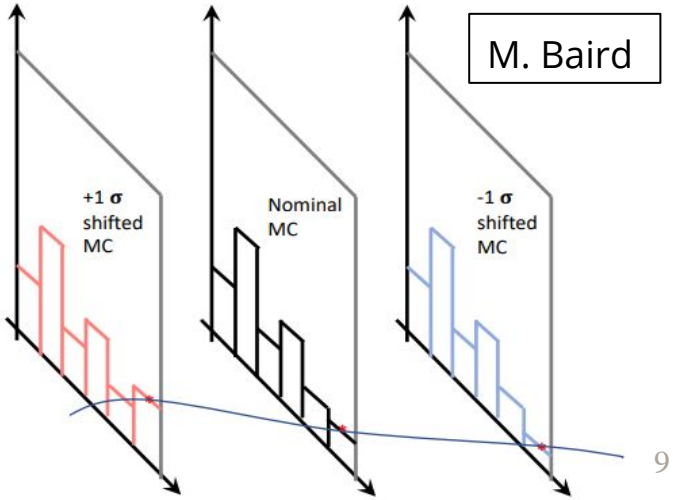
We process our systematics in three different ways:

1. **Direct** → re-weight according to event type to create systematically shifted spectra. (E.g. flux, cross-section).
2. **Recomputed event** → recalculation of reconstructed energy. (E.g. muon energy scale).
3. **File-based** → re-simulated event sample, for each shift. (E.g. light level, calibration).

For each one we generate shifts at:

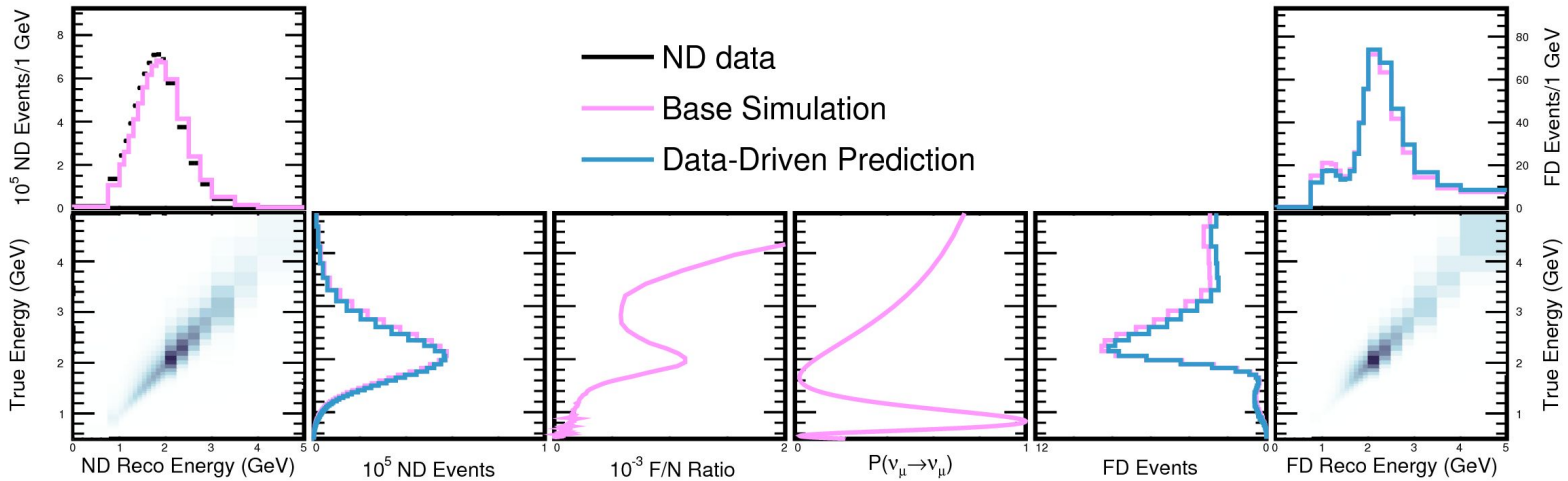
- **±1σ**, **±2σ**
- **±1σ** for file-based systematics.

Then **interpolate** between shifted points.



Generating FD predictions

To evaluate the effect of a systematic shifts on our FD prediction, we propagate our nominal MC and each shift through the extrapolation procedure using our corrected ND MC .



- Selected ν_μ ND events (**4 quartiles**) → FD ν_μ signal prediction.

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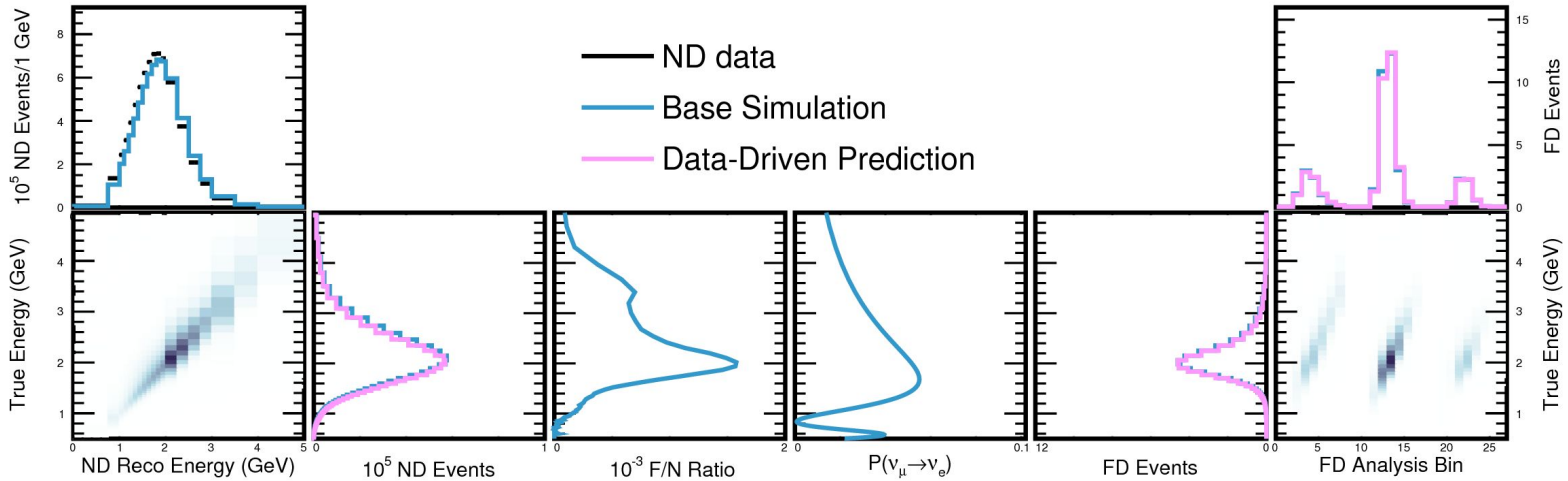
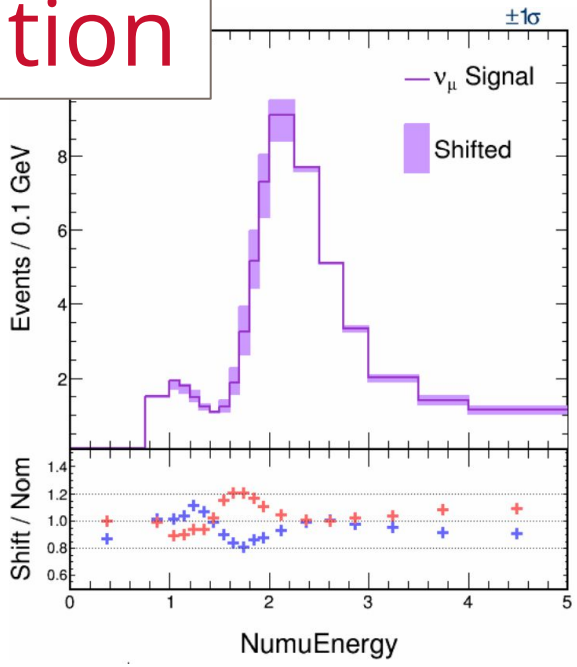
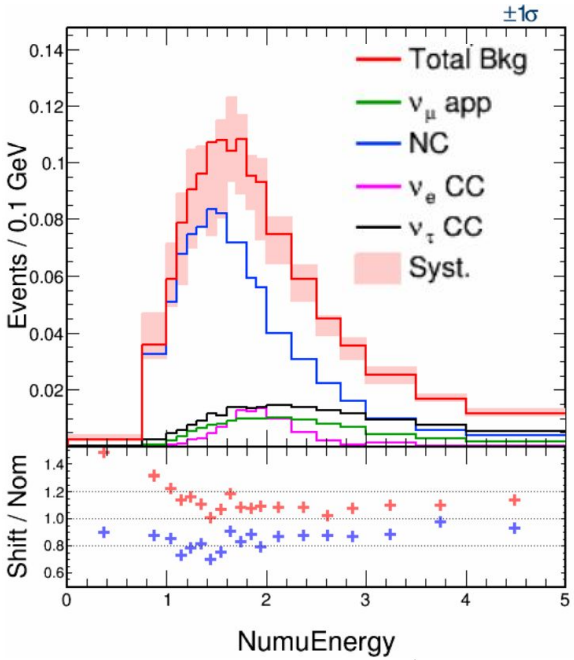


- Selected ν_μ ND events (**4 quartiles**) → FD ν_μ signal prediction.
- Selected ν_μ ND events → FD ν_e signal prediction.
- Selected ν_e/ν_μ/NC ND events → FD ν_e background prediction.

Calibration

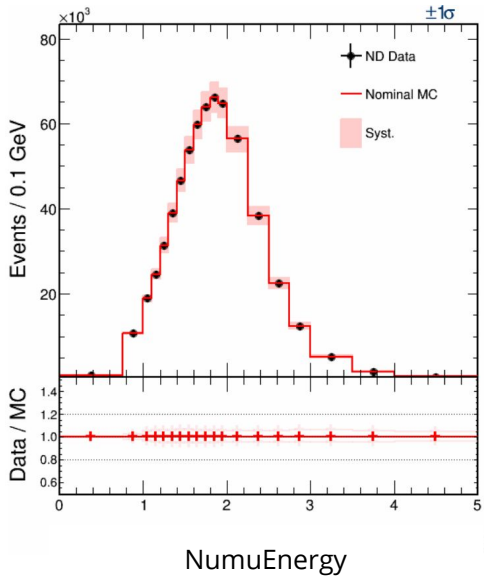
FD prediction
signal





FD prediction
Background

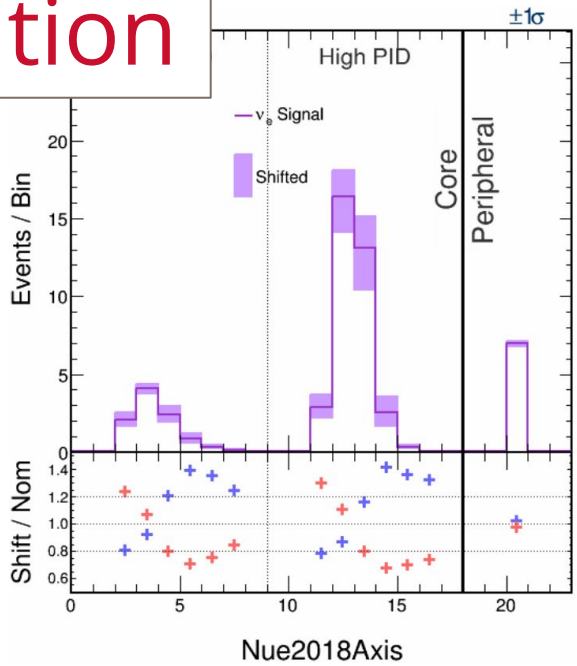
ND spectrum
signal
[fake data]

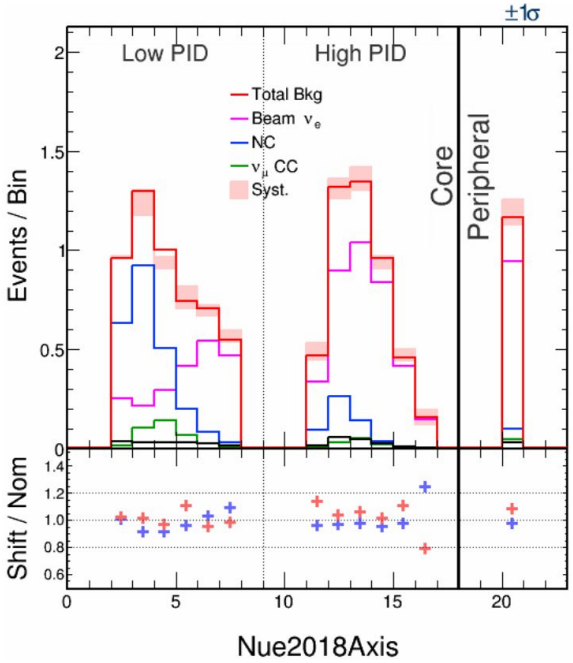


- Extrapolated FD prediction & ND spectra
- One of our largest systematics

Calibration

FD prediction
signal





FD prediction
Background

ND spectrum
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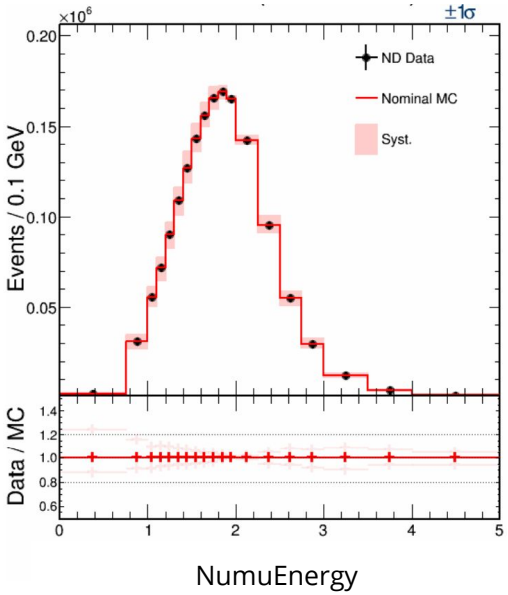
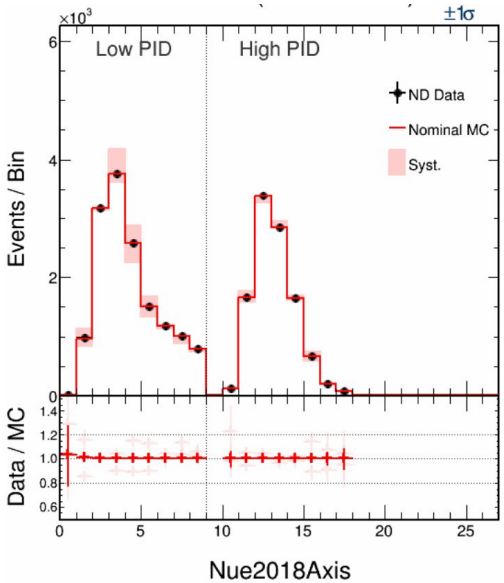
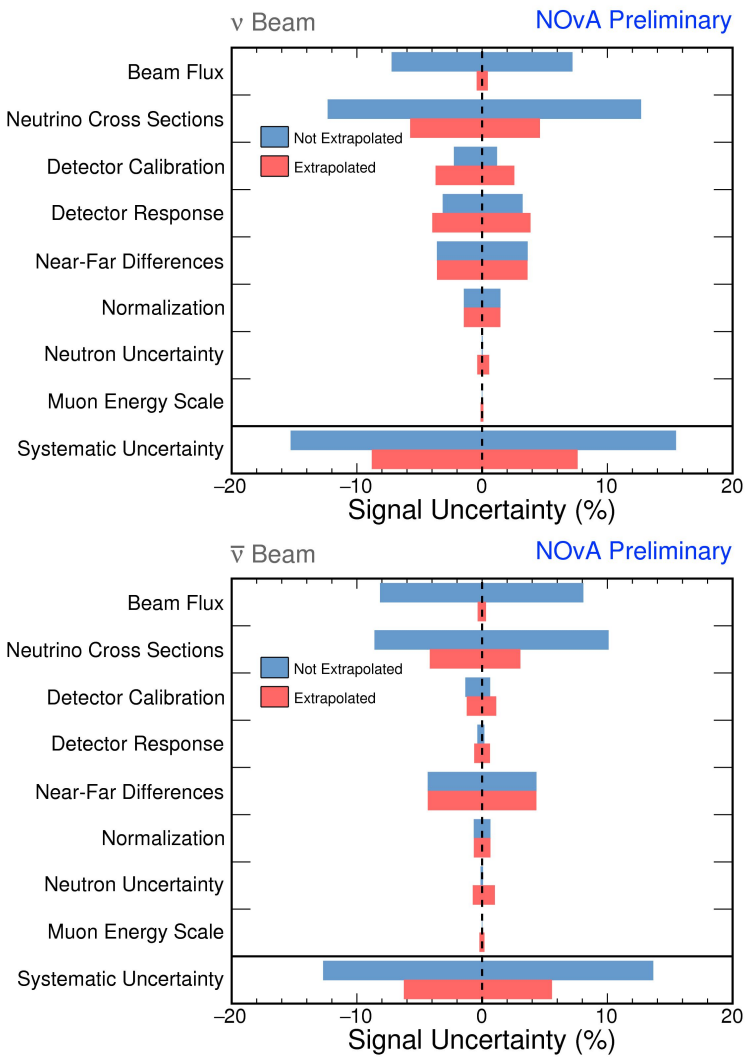




ND spectrum
Background
[fake data]

Extrapolated systematics



- Key systematic uncertainties by impact on selected ν_e-appearance events.
- **Detector calibration** and **neutrino cross sections** are consistently our most important systematics.
- Significant reduction in **beam flux** and and **neutrino cross section** systematics after extrapolation.
- Some systematics such as **Near-Far differences** are unaffected by extrapolation.

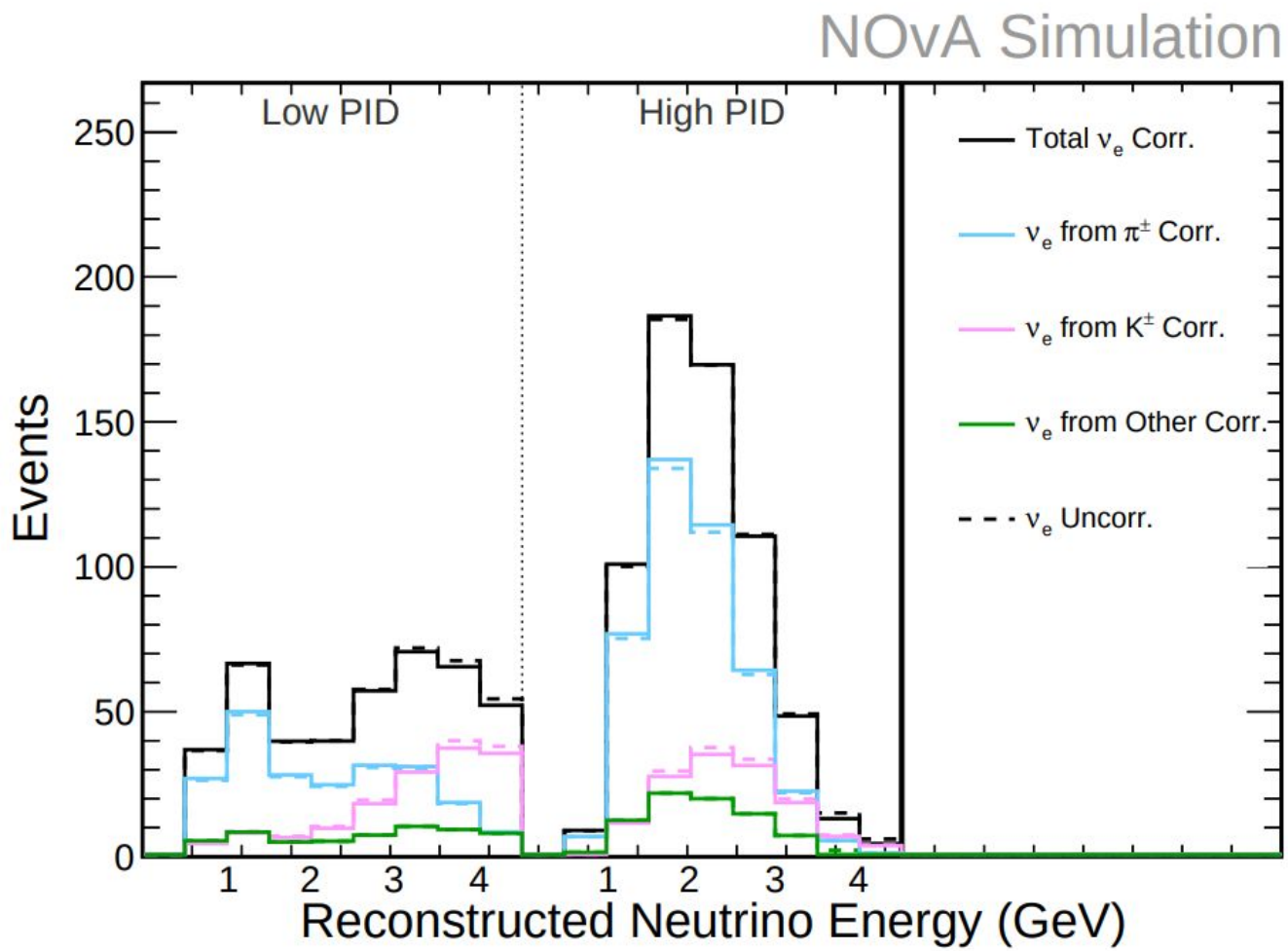
Conclusions

- Three-flavor neutrino oscillations joint fit requires accurate FD predictions and treatment of systematic shifts.
- NOvA uses data-driven ND techniques to improve FD predictions.
- Propagate multiple samples, including systematic shifts, to generate FD predictions.
- Compare systematic shifts to Nominal MC across 100s of individual systematics uncertainties before including them in the fit.

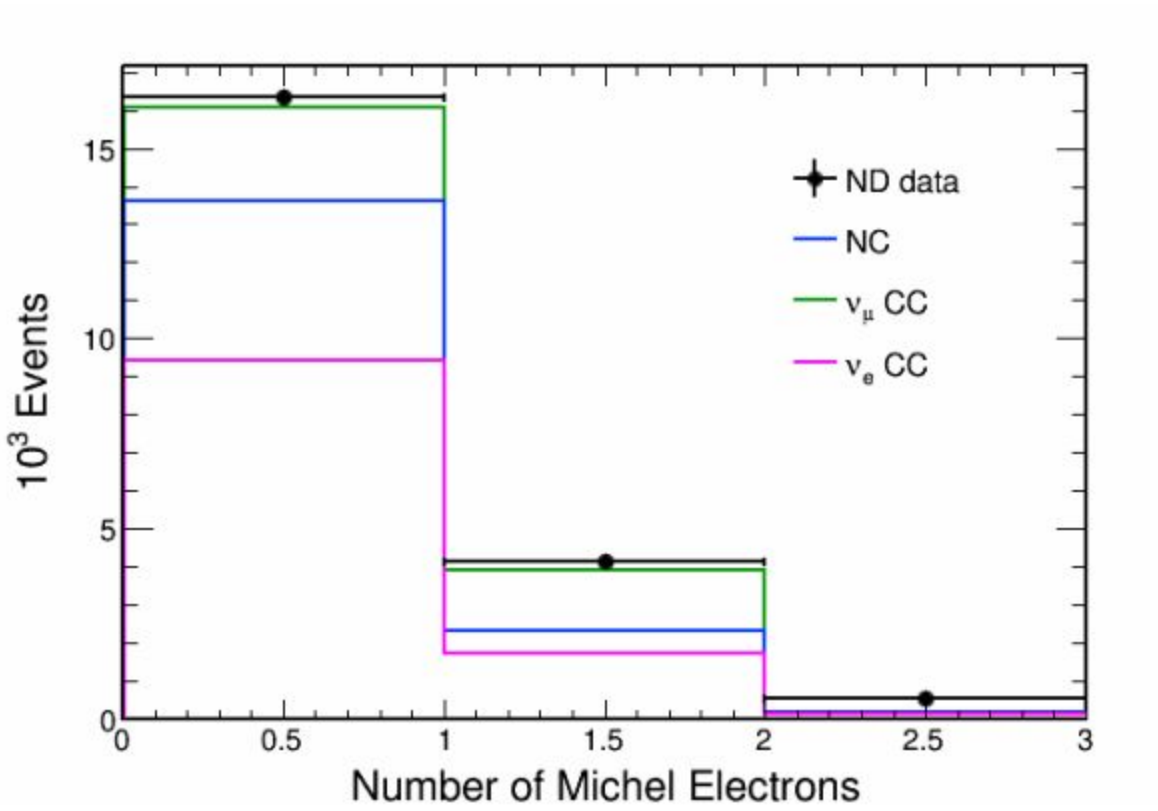
http://novaexperiment.fnal.gov

Extra slides

Beam Nue decomposition



Michel electron decomposition



Systematics groups

- **Detector calibration**
  - **absolute** → shift ND and FD in **same** direction.
  - **relative** → shift ND and FD in **opposite** directions.
- **Near-far differences** includes acceptance, ND to FD kinematics and Michel electron tagging systematics.
- **Neutrino cross sections** includes over 70 cross section and GENIE systematic shifts.
- **Detector response** includes light level and Cherenkov systematics.
- **Normalization** systematics.
- **Muon energy scale** has both **relative** and **absolute** variants in the same form as the detector systematics.
- **Beam flux** includes five PPFX principal components.
- **Neutron uncertainty** systematic.

χ^2 test

We actually study the effect of **over 100** systematics, **over half** of which are cross-section/GENIE systematics.

Cross section systematics that we do not float individually in the fit are included in one of the **five** small-GENIE principal components.

To determine which GENIE/cross section systematics to include in the principal component analysis (PCA) we use a χ^2 test.

We calculate the χ^2 between the nominal extrapolated FD reconstructed energy spectrum and the corresponding **±1σ** shifted spectra → considering ν_μ and ν_e and both beam running modes.

We use this metric over a ratio of event counts as it better quantifies the impact of systematics that only affect the shape of the FD spectrum.

Cross-section systematics

- We start with **over 70** cross section systematics.
- After ordering by χ^2 (considering ν_μ and ν_e and both beam running modes and the positions of other non-cross section systematics) we define a list of **24** to float as individual systematics in the joint fit.
- We include the remaining cross section systematics via components of the GENIE PCA.
- Sensitivity studies showed that **five** principal components (PCs) were sufficient.
- The following slides show the size of the **24 individual** cross section and **five GENIE PC** shifts → ordered by impact on oscillation parameters.
- Followed by FD predictions for a few key **individual** cross-section systematics have a high impact in both:
  - χ^2 → do not go into GENIE PCA.
  - Oscillation parameter sensitivity.

Flux systematics

- We include **all** flux systematics via a PCA.
- As with GENIE PCA, sensitivity studies showed that **five** principal components were sufficient.
- In the following slides we show FD predictions for the flux PC 01, which has the most impact.

Near-far differences

Although functionally similar our two detectors differ in some ways → notably their size.

- This leads to slight differences in kinematics → meaning some (cross section) systematics do not cancel to the full extent after extrapolation.
- These systematics aim to account for unmodeled kinematic differences that could produce an important effect after extrapolation.

Acceptance:

- A 1.3% (4.1%) shift on the (anti)neutrino mode nominal prediction to account for differences extrapolating from different regions of the ND.
  - e.g. top vs bottom, inside vs outside.

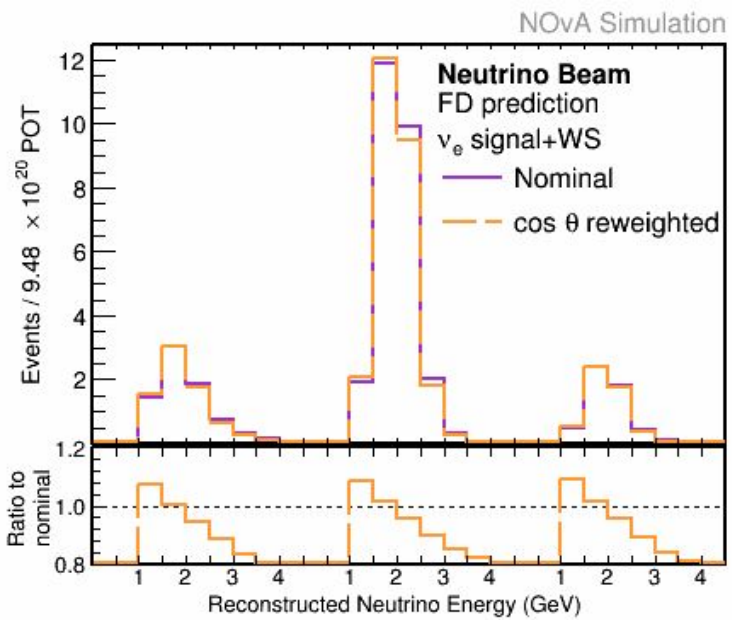
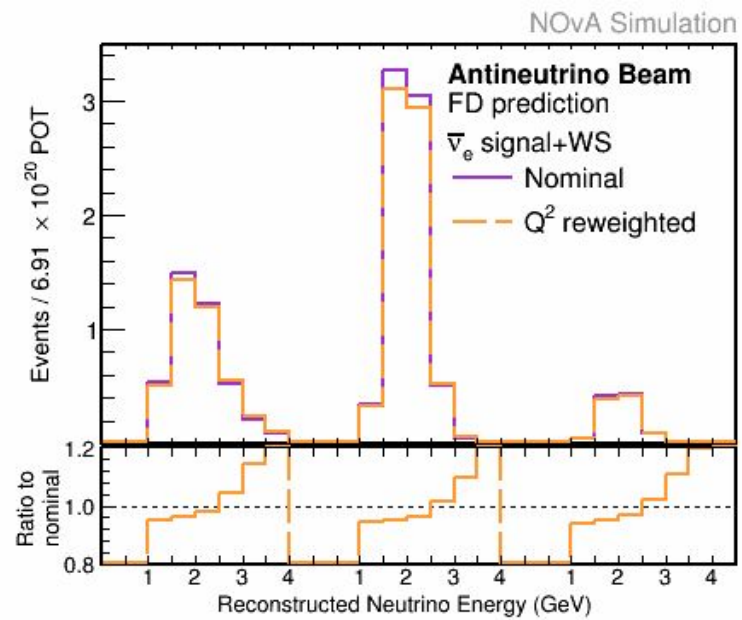
ND to FD kinematics:

Excluding ND containment effects, ND ν_μ events, from which FD ν_e signal distribution is estimated, have different kinematics (particularly in Q^2).

- Estimated by re-weighting ND data & MC to FD signal MC, in different kinematic variables.
- Leads to a 1.5% (2.7%) shift on nominal for (anti)neutrino mode.

Near-far differences

These plots show the largest shifts in extrapolated FD signal spectrum after re-weighting ND data & MC to FD kinematic distributions.

The kinematic variables were:

- cos θ_{numi} in neutrino beam mode.
- Q^2 in antineutrino beam mode.