Predicting the Far Detector Event Rate for the first NOvA ν_e Appearance Analysis

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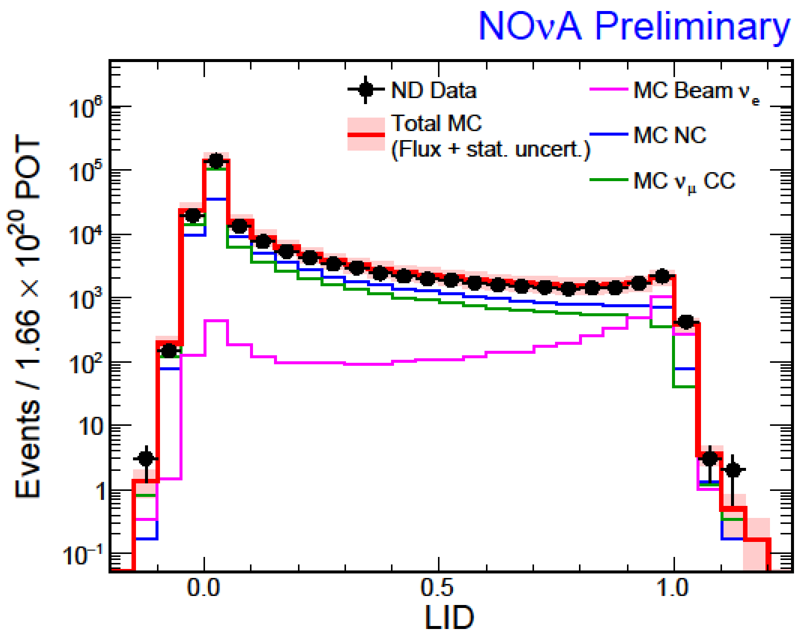
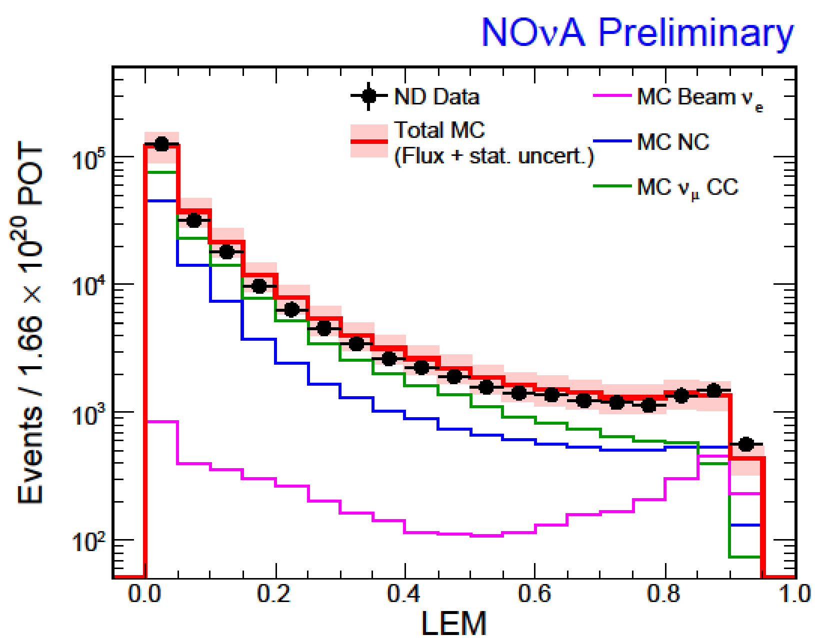
- The Numi Off-Axis ν_e Appearance experiment (NOvA) is a two detector oscillation experiment
    - 14 mrad off-axis gives us a tightly peaked beam centered at 2 GeV
    - Fine-grained, low-Z detector provides good electromagnetic shower reconstruction
    - ND 1 km downstream of the target helps evaluate systematic uncertainties
- This talk describes how to use NOvA's ND data to build a data-driven extrapolation to predict our expected FD event counts

ν_e Selection

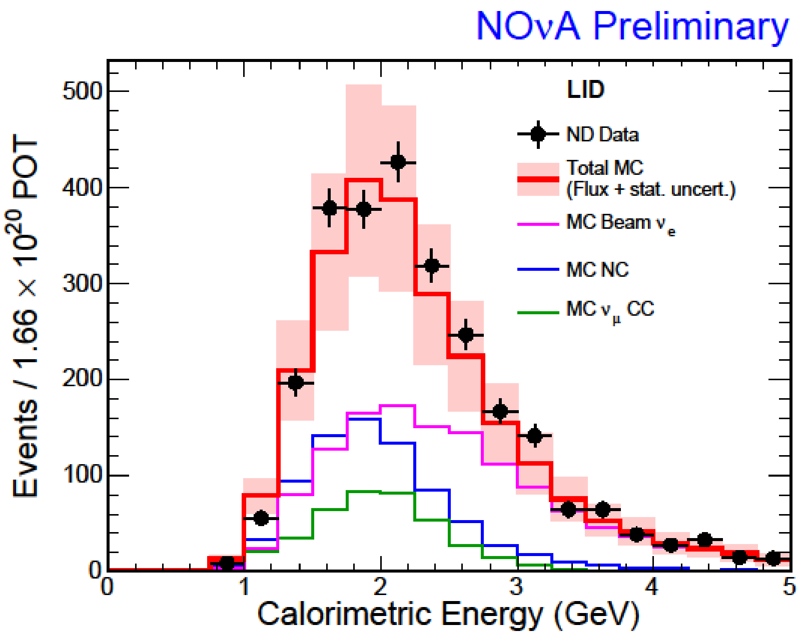
- Two ν_e CC PID's were developed: LID and LEM (see Jianming Bian's talk for more on our PID's)
  - Both PID's show good ND data and MC agreement
- Both PID's are very similar in signal efficiency and cosmic rejection
- ND Spectrum extrapolates to the beam background in our FD
  - Studying ND allows for a high stats prediction of our background
- Any excess over the predicted background is interpreted as ν_e appearance

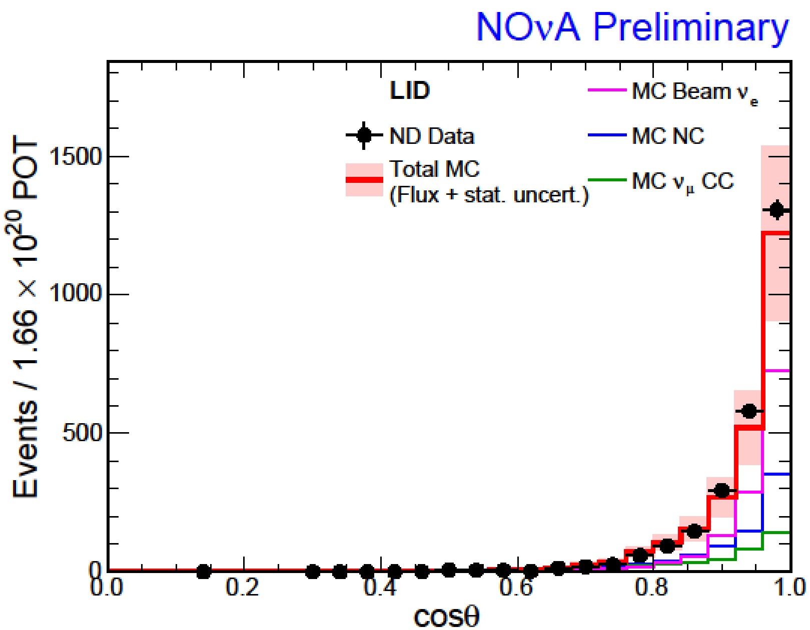




ND ν_e Sample

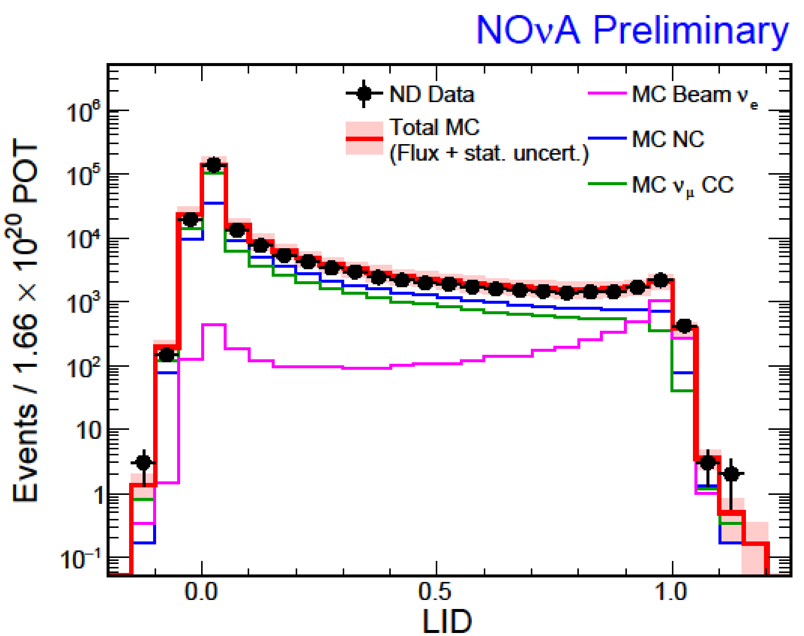
- The ND neutrino energy distribution is modelled well
  - Shape agrees within uncertainty
- There is a small overall normalization discrepancy
  - Data sees 5% more events
- This discrepancy propagates through the extrapolation increasing the predicted background
  - We built a ND to cancel these types of uncertainties using a Far / Near extrapolation

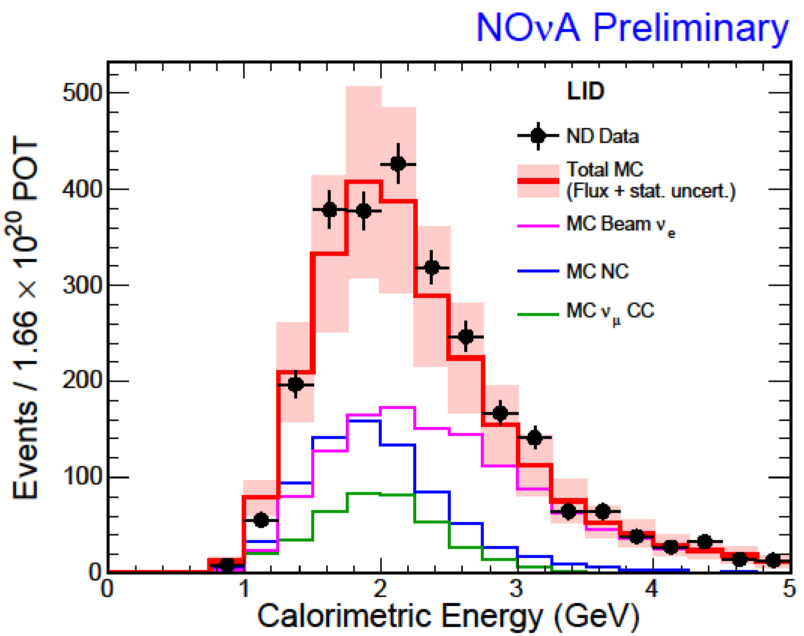




Near Detector Background

- In the ND, all ν_e CC-selected events are background events
- ND data gives a data-driven correction for the MC normalization
  - Scale up each component in MC by the data / MC ratio improves the background prediction
- This assumes that the simulation perfectly predicts the ratio of ND ν_e CC : NC : ν_μ CC interactions
  - We studied this assumption's impact on our analysis – details in following slides



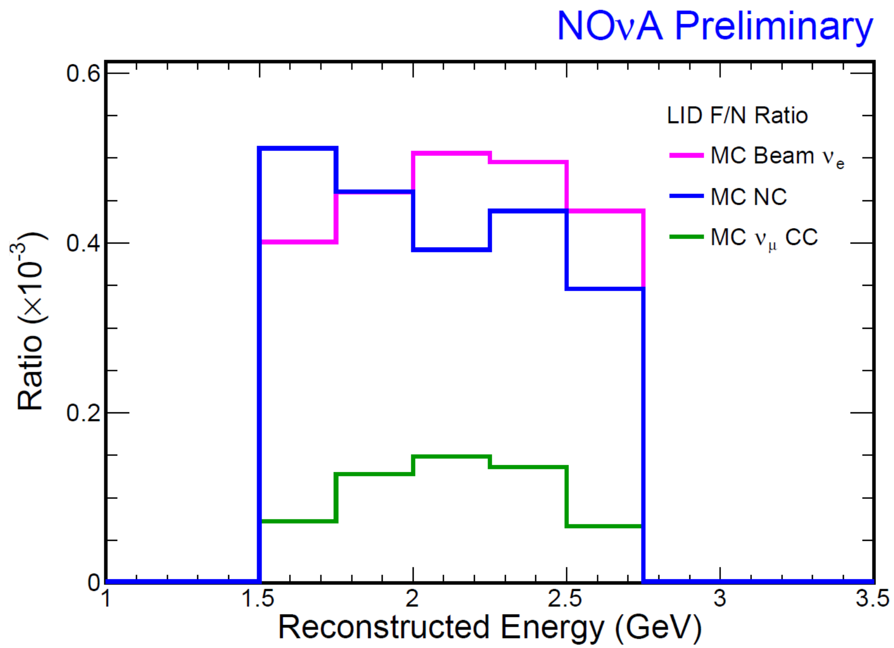


Far Detector Background Prediction

- To extrapolate the background measured in the ND, we first calculate a far over near ratio in MC

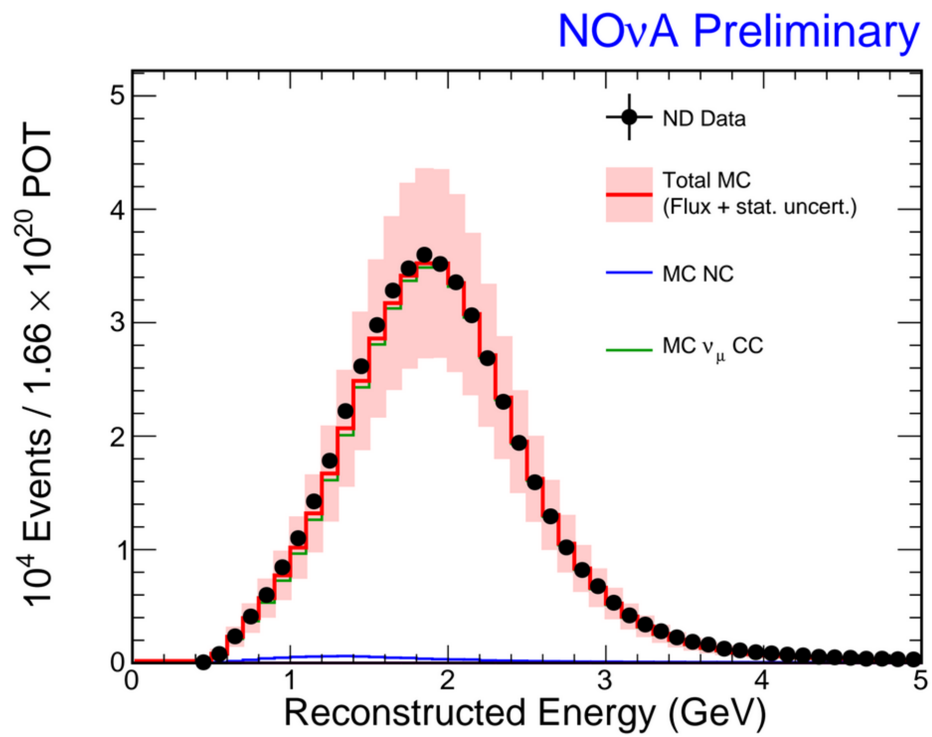
$$FD_i^{Pred} = \frac{FD_i^{MC}}{ND_i^{MC}} ND_i^{Data}$$

- The NC and beam ν_e CC components dominate the FD spectrum and are relatively flat in energy
- The ν_μ CC component is much lower because of oscillations
- After extrapolation, we predict:



	Beam Bkgd	ν_μ CC	Beam ν_e	NC	ν_τ CC
LID	0.88	0.05	0.46	0.35	0.02
LEM	0.94	0.06	0.46	0.40	0.02

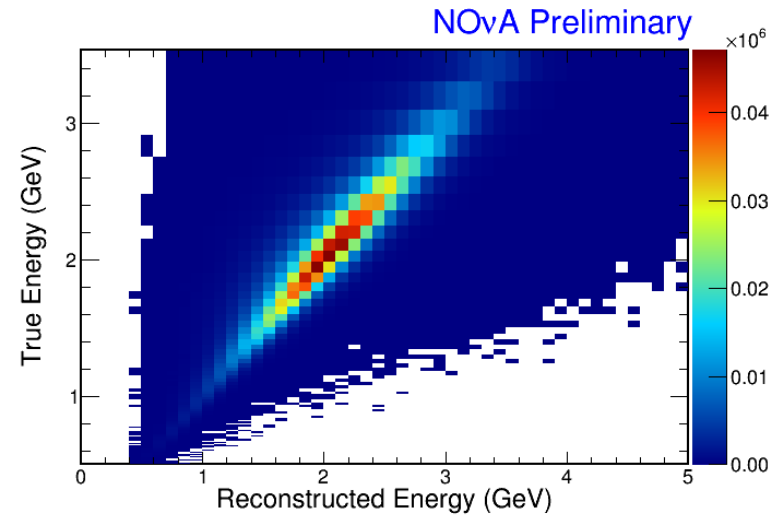
Near Detector ν_μ Spectrum

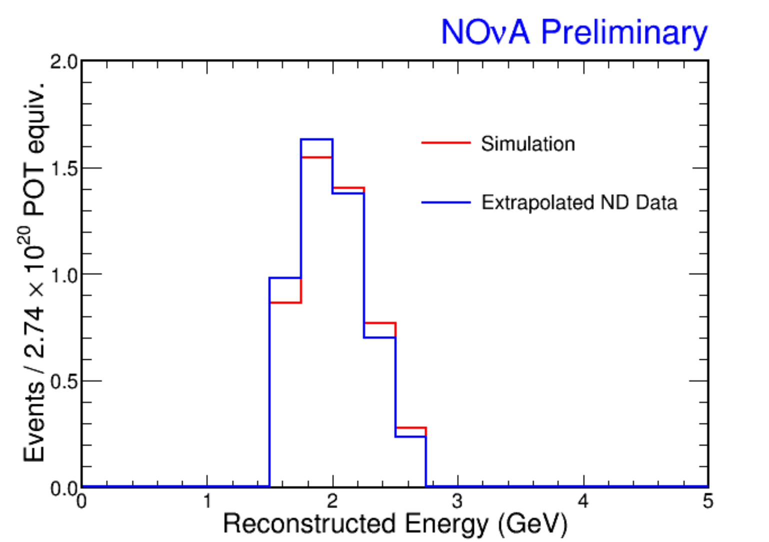


- The signal for the ν_e appearance analysis is ν_e from $\nu_\mu \to \nu_e$ transitions
  - The ND ν_μ CC's allows us to predict our expected FD ν_e CC signal
- The ν_μ CC selected sample is very pure
- The ND integrals of data and MC agree on the 1% level, so our extrapolation doesn't significantly affect the signal prediction
- A discrepancy in hadronic energy has been observed in the ND ν_μ CC sample (see Kirk Bays's talk for more)
  - The effect was tested as a systematic uncertainty for the ν_e appearance analysis and was determined to have a negligible effect

Far Detector Signal Prediction

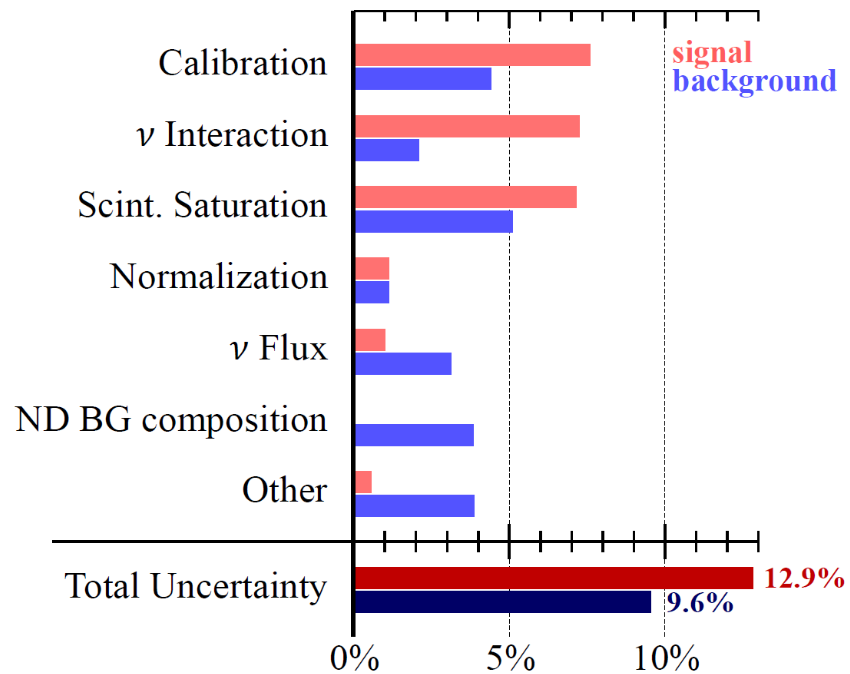
- For the signal, we construct a migration matrix
  - Maps the ND reconstructed energy spectrum to an estimate for true neutrino energy
- We then multiply by the far over near ratio as a function of true energy
  - These reweights depend on the particular oscillation parameters
- After reweighting, we unfold the migration matrix back into reconstructed energy
  - Providing a FD predicted signal spectrum
- We expect about 5 signal events for LID and LEM after extrapolating our ND data
  - Assuming the reactor constraint and no matter effects or CP violation





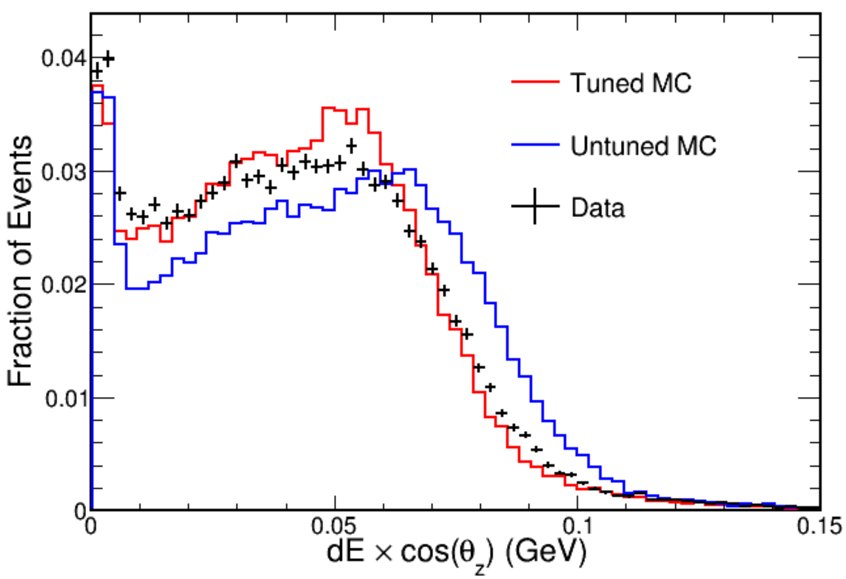
Extrapolation and Systematics

- A two detector experiment allows for the canceling or reduction of many systematic uncertainties such as beam flux and neutrino interaction modeling
  - The residual systematic uncertainties are evaluated by extrapolating our ND data with our nominal simulation and a systematically modified simulation
- For the appearance measurement, we consider a number of systematic effects
  - Calibration
  - Birks-Chou modelling
  - ND background composition
  - Neutrino interaction models
  - Overall normalization
  - Beam uncertainties
  - And more



Non-linearity in Detector Response

- The Birks-Chou Law gives an empirical description of non-linearity for scintillator detector response
- We tuned effective Birks-Chou constants using a high stats ND ν_μ CC QE sample
  - Obvious proton tracks from QE events allow studies based on high track dE/dx

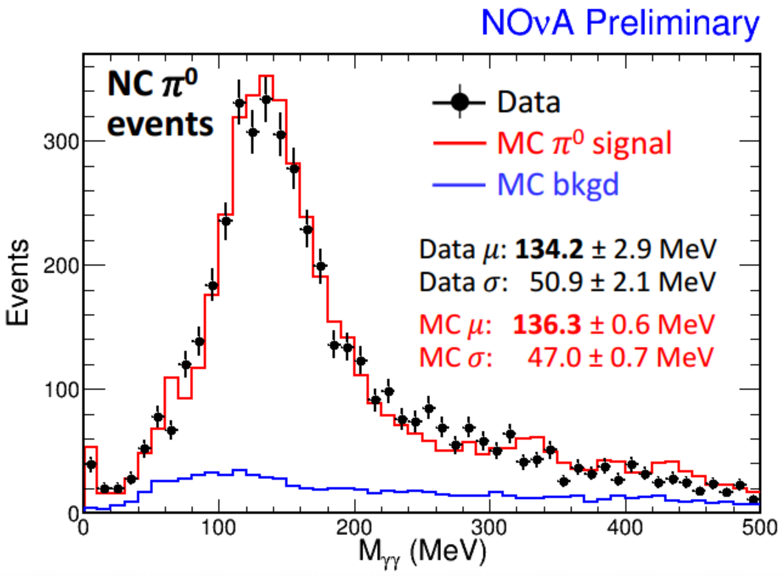


$$\mathrm{LY} = A\frac{\frac{dE}{dx}}{1 + k_B\frac{dE}{dx} + k_C\left(\frac{dE}{dx}\right)^2}$$

- The Data prefers effective constants:
  - k_B = 0.04 g/MeV cm^2
  - k_C = -0.0005 g/MeV^2 cm
- These are higher than expected for this parameterization of pseudocumene
- We treat the difference between our numbers and typical values as a systematic

Absolute Calibration

- Our calibration is built on dE/dx from stopping cosmic muons
- Developed a two cross-check samples
- The π^0 mass peak is a great test for the ν_e analysis – tests EM calorimetry
  - Means are off by (1.5±2.1)%



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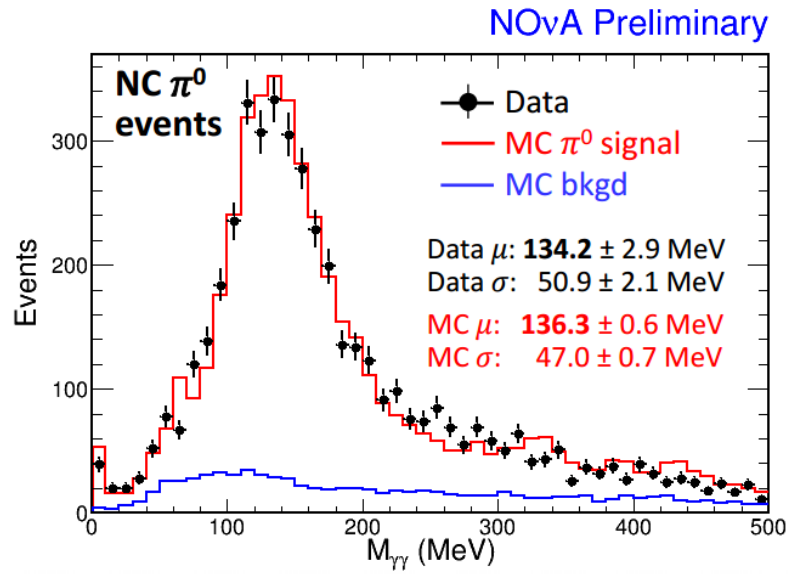
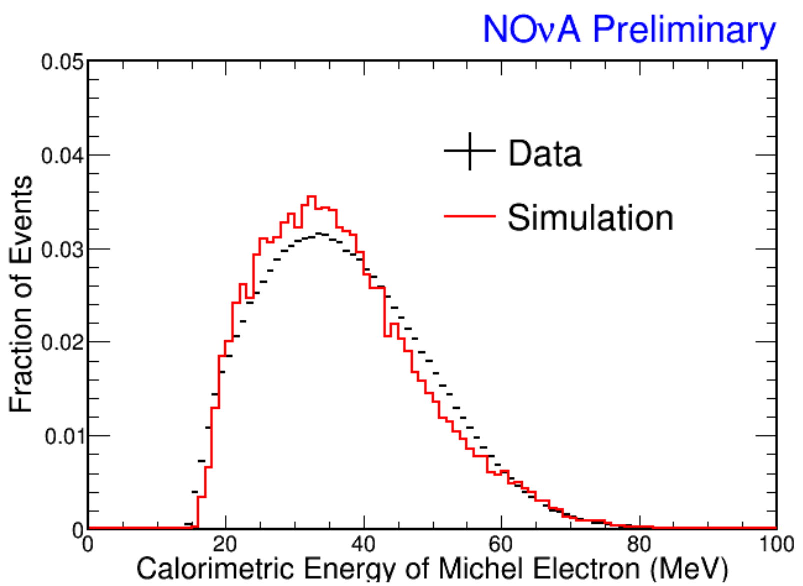




- Michel electrons – high stats sample
  - In the FD, data is 1.9% high
  - In the ND, MC is 1.8% high
- Distributions of dE/dx are well modeled even at energies much lower than signal neutrinos
- We assign a 5% absolute calibration systematic cover these discrepancies

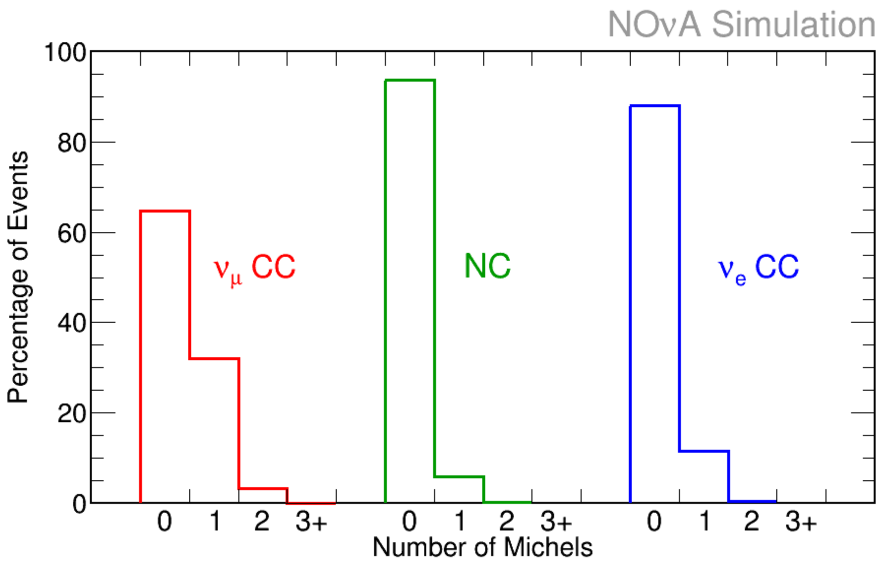
ND Background Composition Systematic

- The extrapolation assumes that our simulation perfectly models the ratio of ND ν_e CC : NC : ν_μ CC interactions
- It is possible to study the effect of changing these ratios on the background prediction by attributing the entire data / MC discrepancy to each of ν_e CC, NC, and ν_μ CC separately
- This gives three background predictions
  - The maximum difference between our nominal background prediction and each of these is taken as a systematic uncertainty
- This gives a 3.9% (3.6%) systematic error on the background for LID (LEM)

Ratio to Nominal	ν_e CC Excess	NC Excess	ν_μ CC Excess
LID	1.008	1.009	0.961
LEM	1.025	1.010	0.964

ND Background Composition Check

- ν_μ CC's have a significant number of Michels because of the decay of the primary muon
- This provides a convenient handle for estimating the ν_μ CC component in the ND



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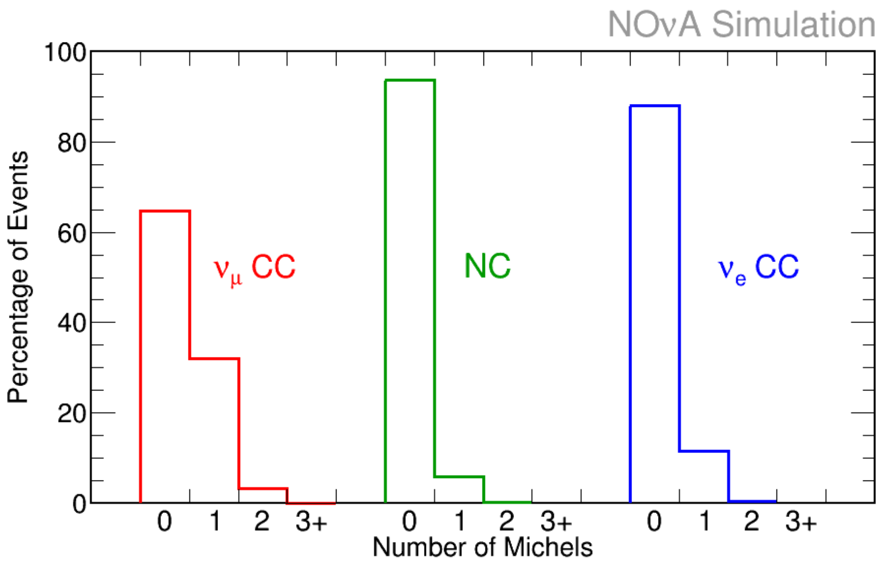

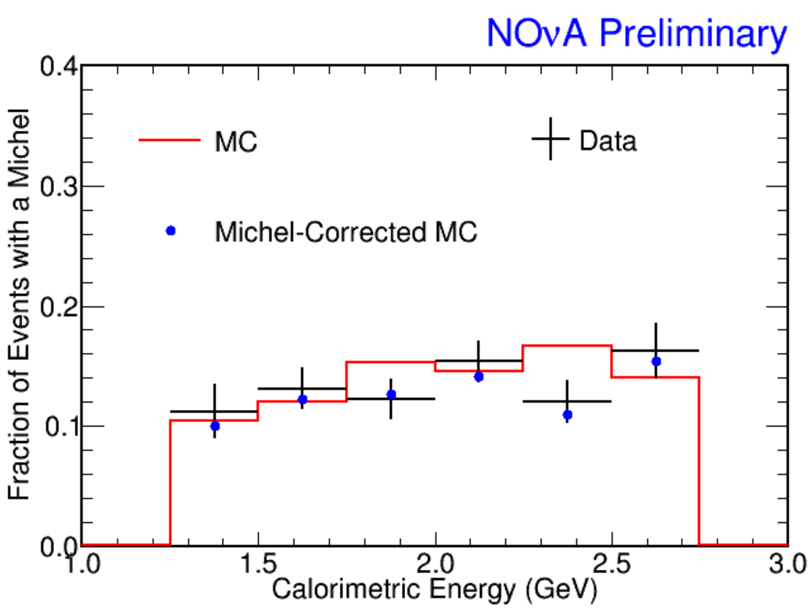

- We see fewer Michels in data than MC implying a lower fraction of ν_μ CC interactions
- Michel-corrected MC predicts 3.1% more FD background
- Very close to the budgeted 3.9% indicating our composition systematic uncertainty is robust

Summary

- Developed a data-driven FD extrapolation using NOvA ND data to estimate the expected FD data and beam background for the first ν_e appearance analysis
- Thoroughly checked the ND data and evaluated the largest contributing sources of systematic uncertainties on the FD signal and background predictions
- Using these methods, we expect
  - 4.94 ± 0.64 signal events on a background of 0.94 ± 0.09 for LID
  - 5.13 ± 0.56 signal events on a background of 1.00 ± 0.10 for LEM

	Signal	Total Bkgd	ν_μ CC	Beam ν_e	NC	ν_τ CC	Cosmics
LID	4.94	0.94	0.05	0.46	0.35	0.02	0.06
LEM	5.13	1.00	0.06	0.46	0.40	0.02	0.06