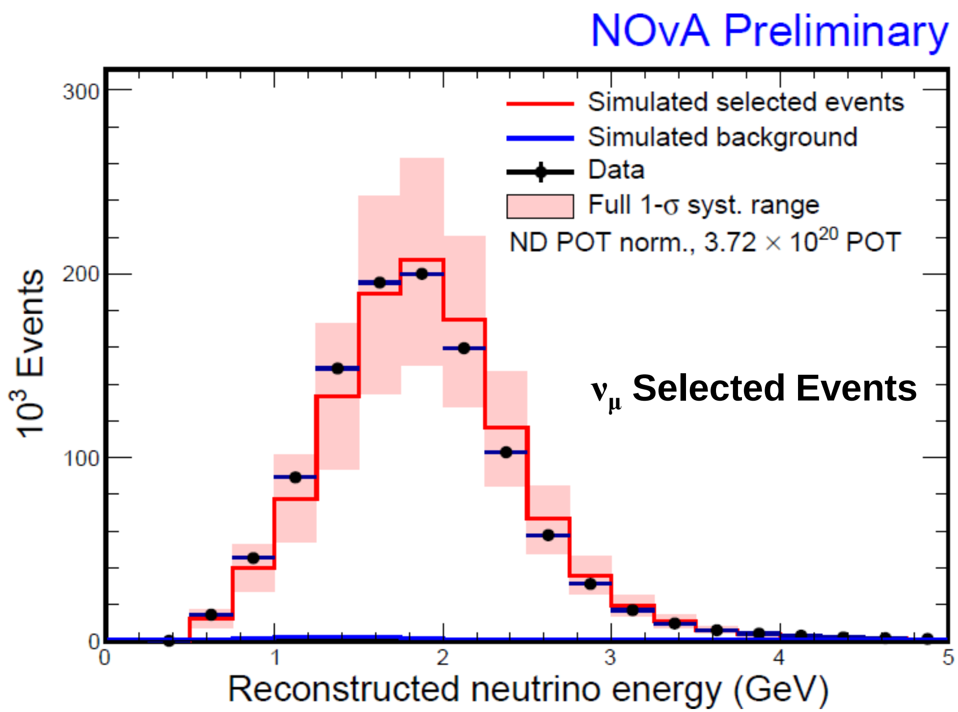
NOνA Near Detector Constraints

Gregory Pawloski
University of Minnesota

Why not just one detector

If we relied on simulation-only to produce a prediction then we would have large systematic uncertainties that would prevent precision measurements

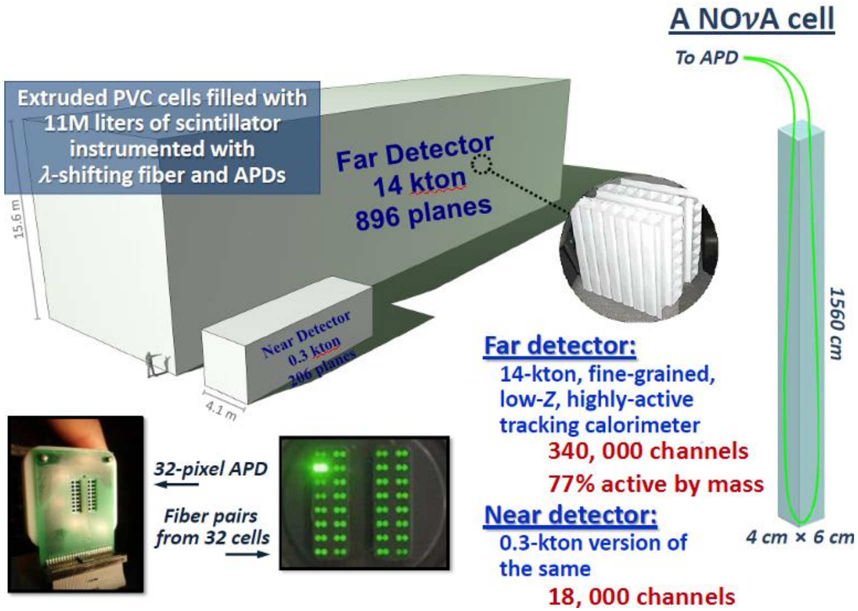


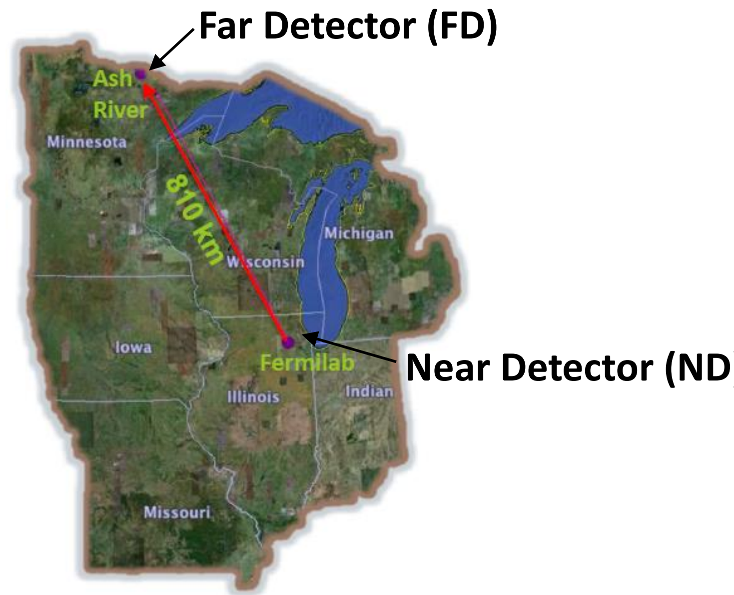
"Out-of-the box" simulation agrees well with data (but big uncertainties)

Most of this uncertainty comes from the uncertainty on flux and cross-sections

- **FLUGG (flux)**
- **GENIE (neutrino interaction)**

Functionally Identical Detectors





For a given energy, neutrinos will have the same:

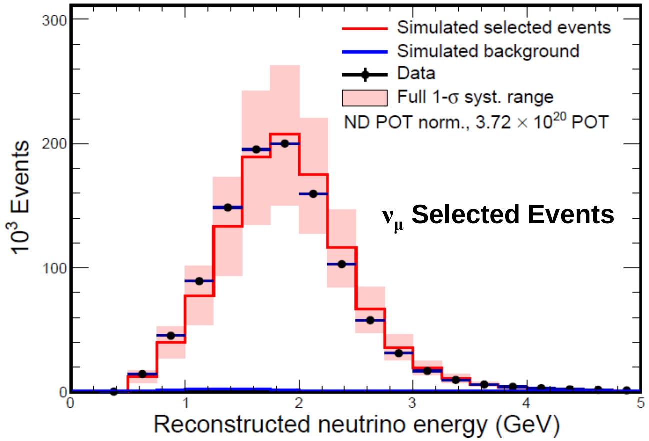
- **Cross-sections**
- **Detector/algorithm performance (efficiencies, calibrations)**

Neutrino flux geometrically related at the FD and ND

If it all were exactly identical

Making the FD prediction would be trivial

Assume you had zero background and perfect calibration



For a ν_μ disappearance analysis you would:

1) Select the ND data
2) Reweight events by survival probability
3) Compare prediction to FD data.

However… there are differences

- **Flux (detectors sample different solid angles)**
- **Slight detector differences**

There are backgrounds

- **Components of selected events oscillate differently or not at all**
- **For ν_μ disappearance, beam backgrounds are tiny**
  - **Just use simulation (with uncertainties) and subtract off**
- **For ν_e appearance, beam backgrounds are relevant**

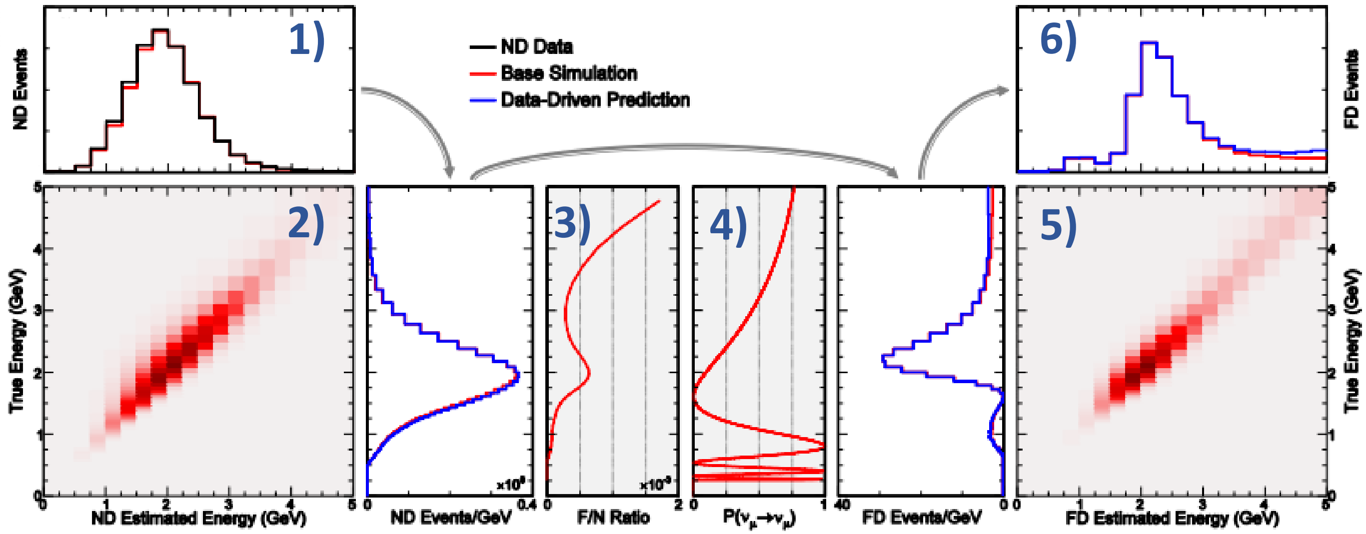
Reco E has to be mapped to true E

- **Oscillation depends on true E**

Far/Near Ratio Extrapolation

How do you convert a ND ν_μ spectrum into a FD prediction

1) Select events in ND (use data and subtract off NC background from simulation)
2) Map ND reco E to true E (use simulation)
3) Apply ratio of FD events to ND events in bins of true E (use simulation)
   Takes into account differences between two detectors
4) Apply oscillation probability on FD true E events (use simulation)
5) Map FD true E to reco E (use simulation)
6) Add simulated backgrounds & cosmics to get Oscillated FD prediction



Don't need to separately measure flux, cross-section, efficiencies, etc in ND

Systematics accounted for by altering simulation at steps 2, 3, 4, and 5

ν_μ Oscillation Uncertainties

Systematic	Effect on $\sin^2(\theta_{23})$	Effect on Δm^2_{32}
Normalisation	± 1.0%	± 0.2 %
Muon E scale	± 2.2%	± 0.8 %
Calibration	± 2.0 %	± 0.2 %
Relative E scale	± 2.0 %	± 0.9 %
Cross sections + FSI	± 0.6 %	± 0.5 %
Osc. parameters	± 0.7 %	± 1.5 %
Beam backgrounds	± 0.9 %	± 0.5 %
Scintillation model	± 0.7 %	± 0.1 %
All systematics	**± 3.4 %**	**± 2.4 %**
Stat. Uncertainty	**± 4.1 %**	**± 3.5 %**

Flux & Cross section uncertainties mostly cancel in FD/ND ratio

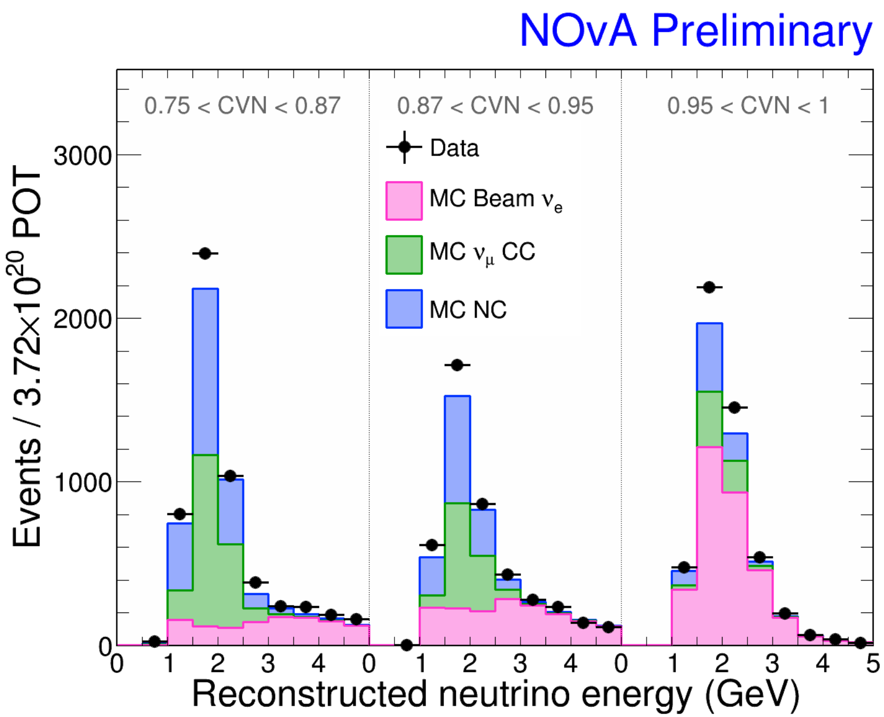
Absolute energy calibration & relative energy calibration between detectors most important

What about $\nu_\mu \rightarrow \nu_e$

For the oscillation of $\nu_\mu \rightarrow \nu_e$ the signal is not present in the ND

ND events are the intrinsic background to the appearance signal

The FD signal spectrum depends on the ND ν_μ spectrum



ν_μ–CC background component oscillates away in the FD, but NC component will not

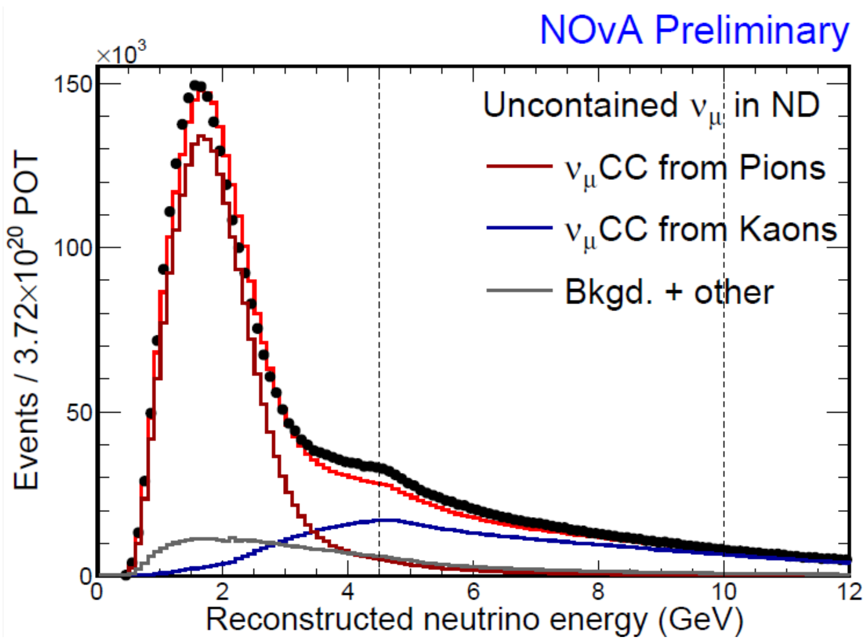
Have to determine proportion of ND data that is each component

Then you can extrapolated each component with FD/ND ratio

What about $\nu_\mu \rightarrow \nu_e$

Constraining the ν_e–CC background events with observed ν_μ–CC events

ν_μ in beam is produced with an associated anti-muon which decays producing intrinsic ν_e

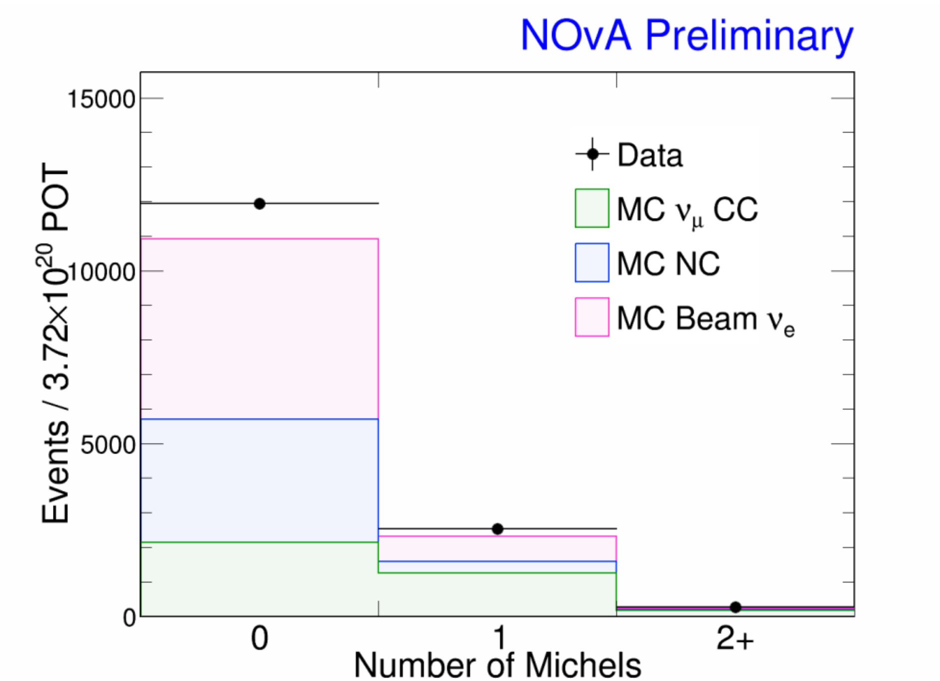


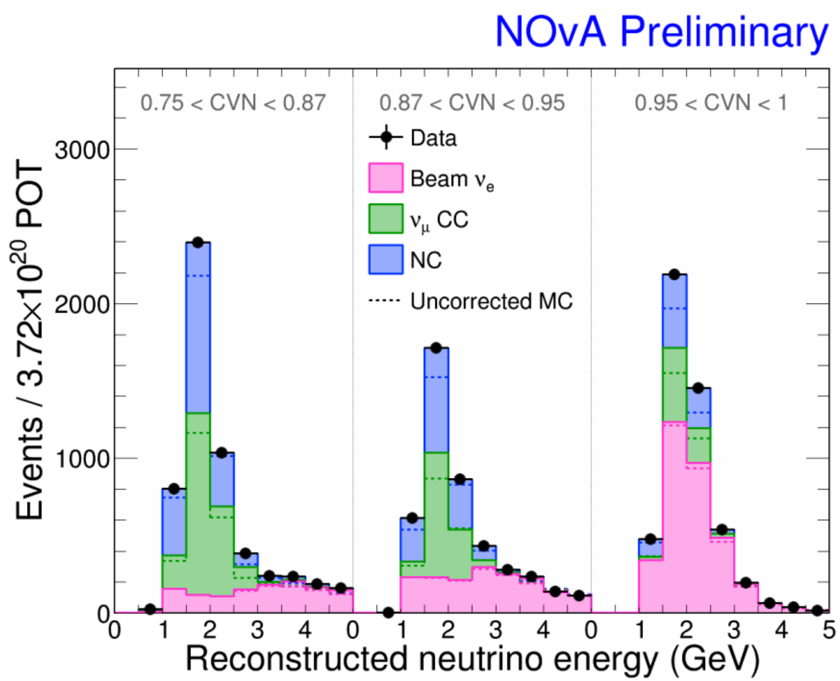
Measure observed ν_μ–CC spectrum in data and note parent of ν_μ
Scale corresponding contribution to beam ν_e production

17% increase in ν_e from ancestor kaon production from target
3-4% decrease in ν_e from ancestor pion production from target

What about $\nu_\mu \rightarrow \nu_e$

Constraining the fraction of ν_μ–CC background events to NC and intrinsic beam ν_e





The muon from a ν_μ–CC background event will produce an extra Michel electron

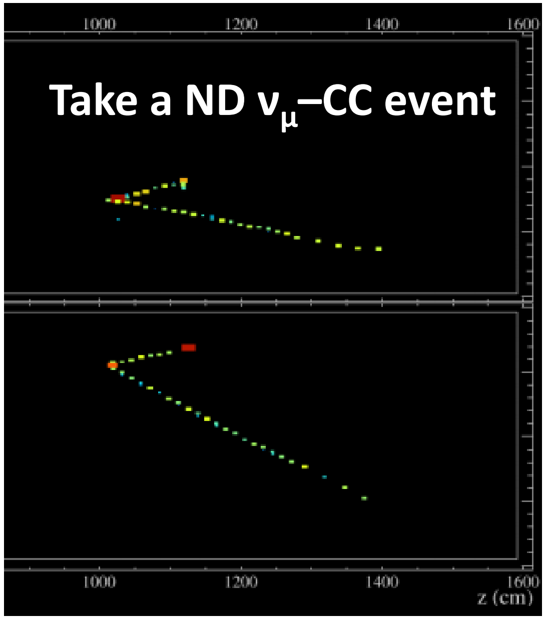
By looking at the number of Michel electrons associated with selected event we can rescale the ν_μ–CC relative to the NC events to fit the ND data

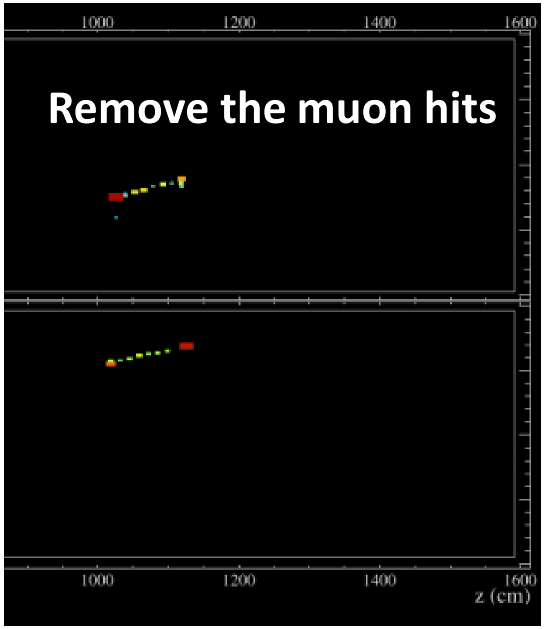
ν_e FD Signal Efficiency

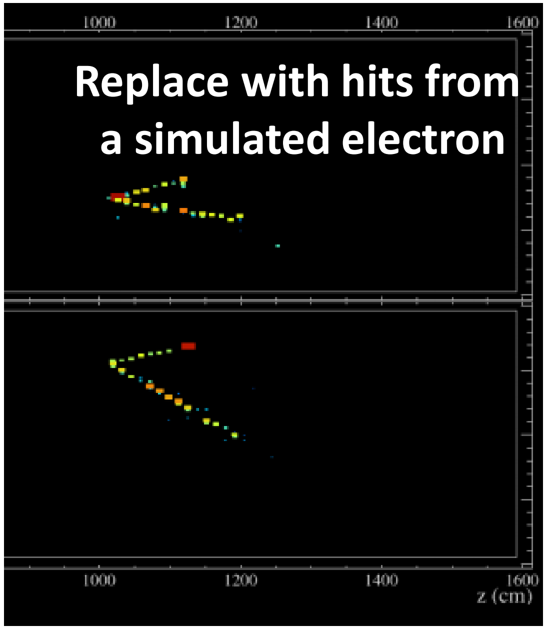
The ν_μ flux will oscillate into the signal ν_e component

The selected ν_μ–CC spectrum in the ND is used to predict the FD ν_e–CC spectrum by using a Far/Near ratio extrapolation procedure

We verify the simulation of the ν_e–CC selection efficiency by using ND data

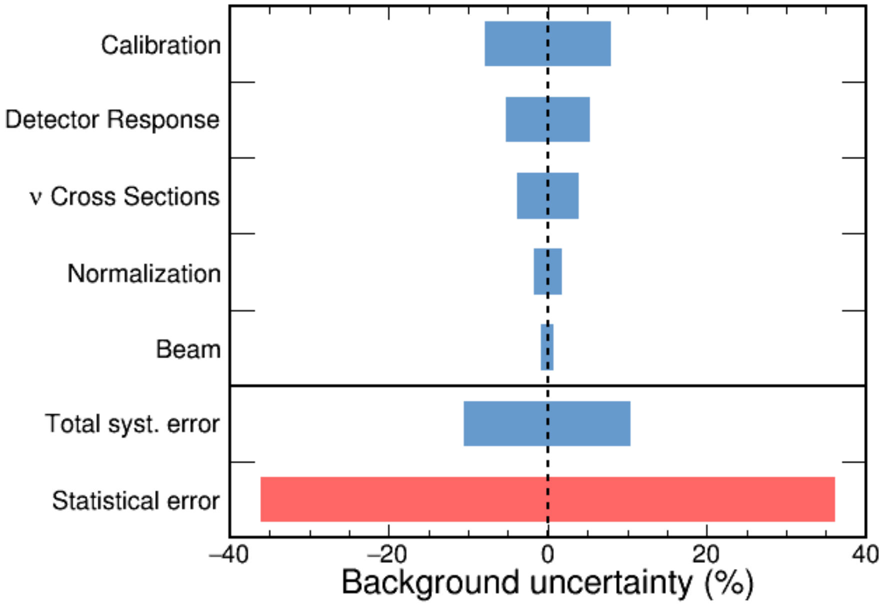


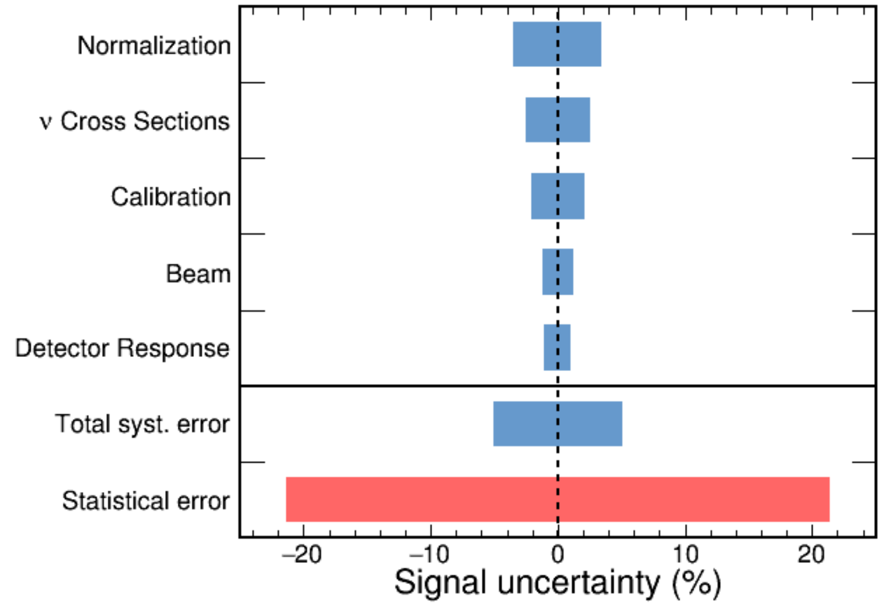




Measured signal efficiency matches simulation at 1% level

ν_e Oscillation Uncertainties





Summary

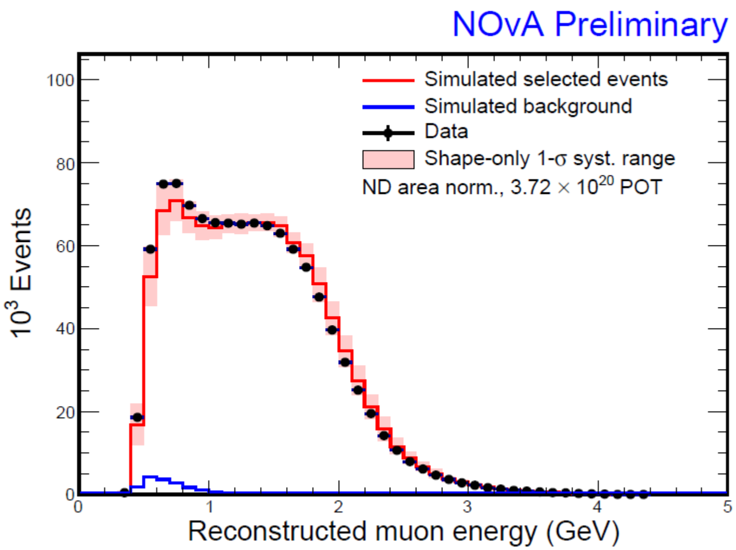
Without extra constraints (*eg* a Near Detector), the uncertainties from cross sections and flux would be prohibitive for the oscillation analyses.

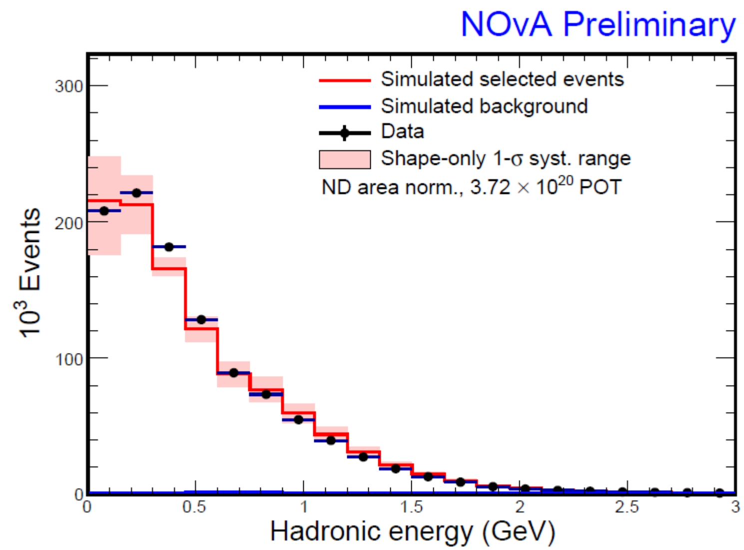
By using functionally identical technologies, Far/Near ratios can be used to produce FD predictions from ND data.

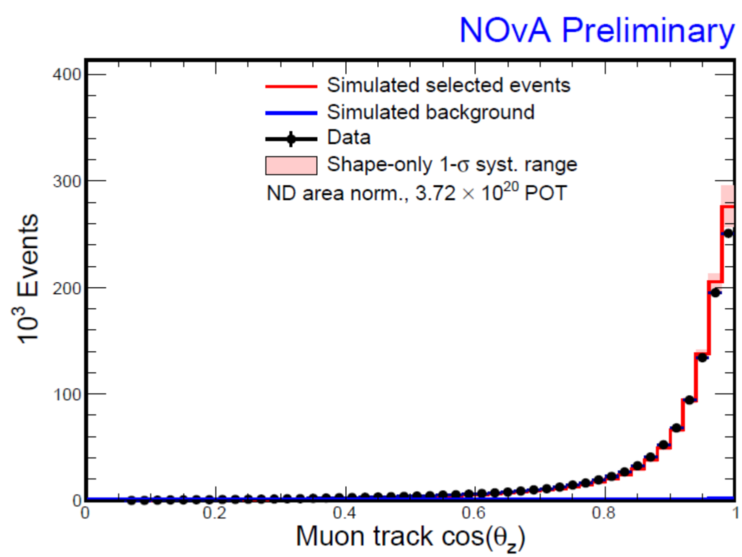
Uncertainties on cross section, flux, and selection are reduced.

Backup

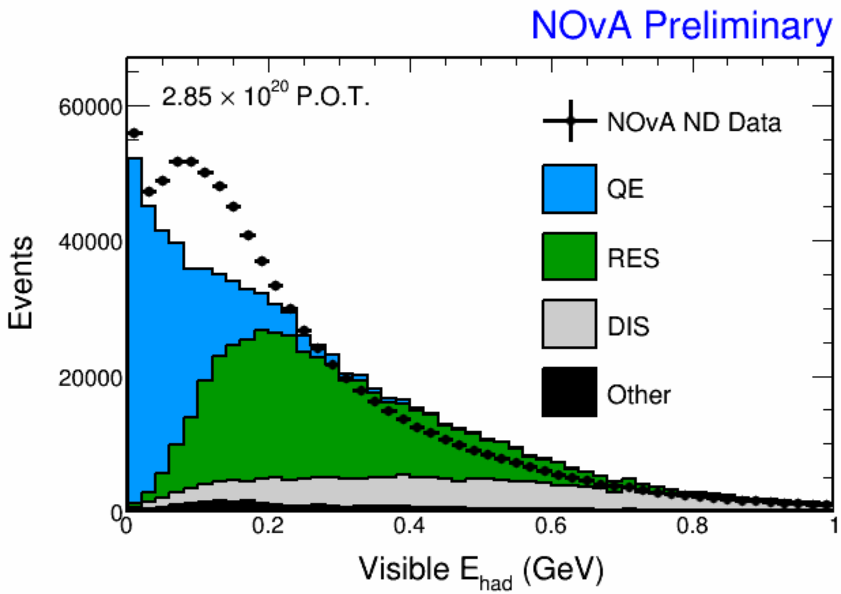
Good Data-MC agreement

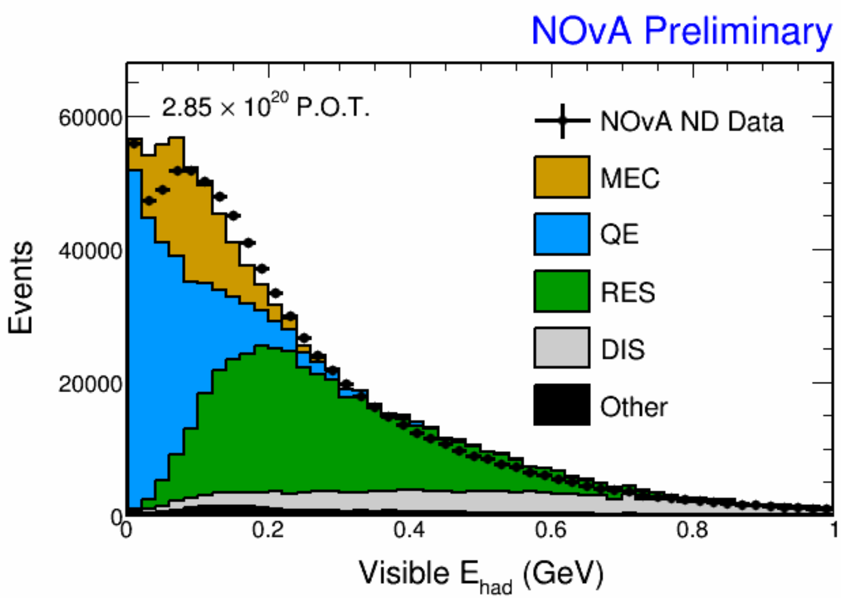






GENIE MEC


NOvA Preliminary
2.85 × 10^20 P.O.T.
NOvA ND Data
QE
RES
DIS
Other
Events
Visible E_had (GeV)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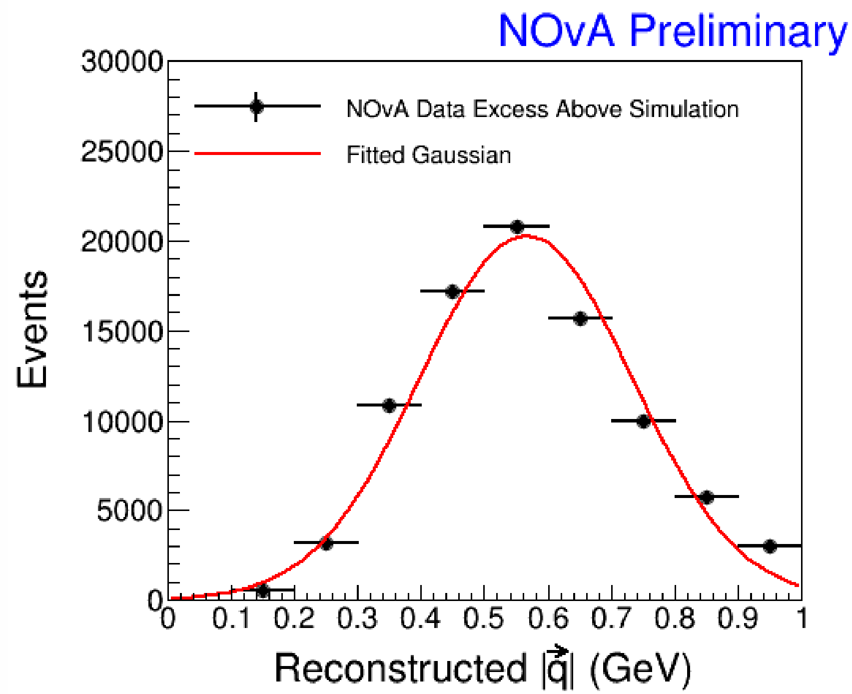
NOvA Preliminary
NOvA Data Excess Above Simulation
Fitted Gaussian
Events
Reconstructed |q⃗| (GeV)