SYSTEMATIC UNCERTAINTIES FOR OSCILLATION ANALYSES IN MINOS AND NOVA

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DUNE Near Detector Workshop

LONG-BASELINE EXPERIMENTS

- Precision is achieved by placing a detector close to the source (Near Detector) and one at or close to the oscillation maximum (Far Detector).

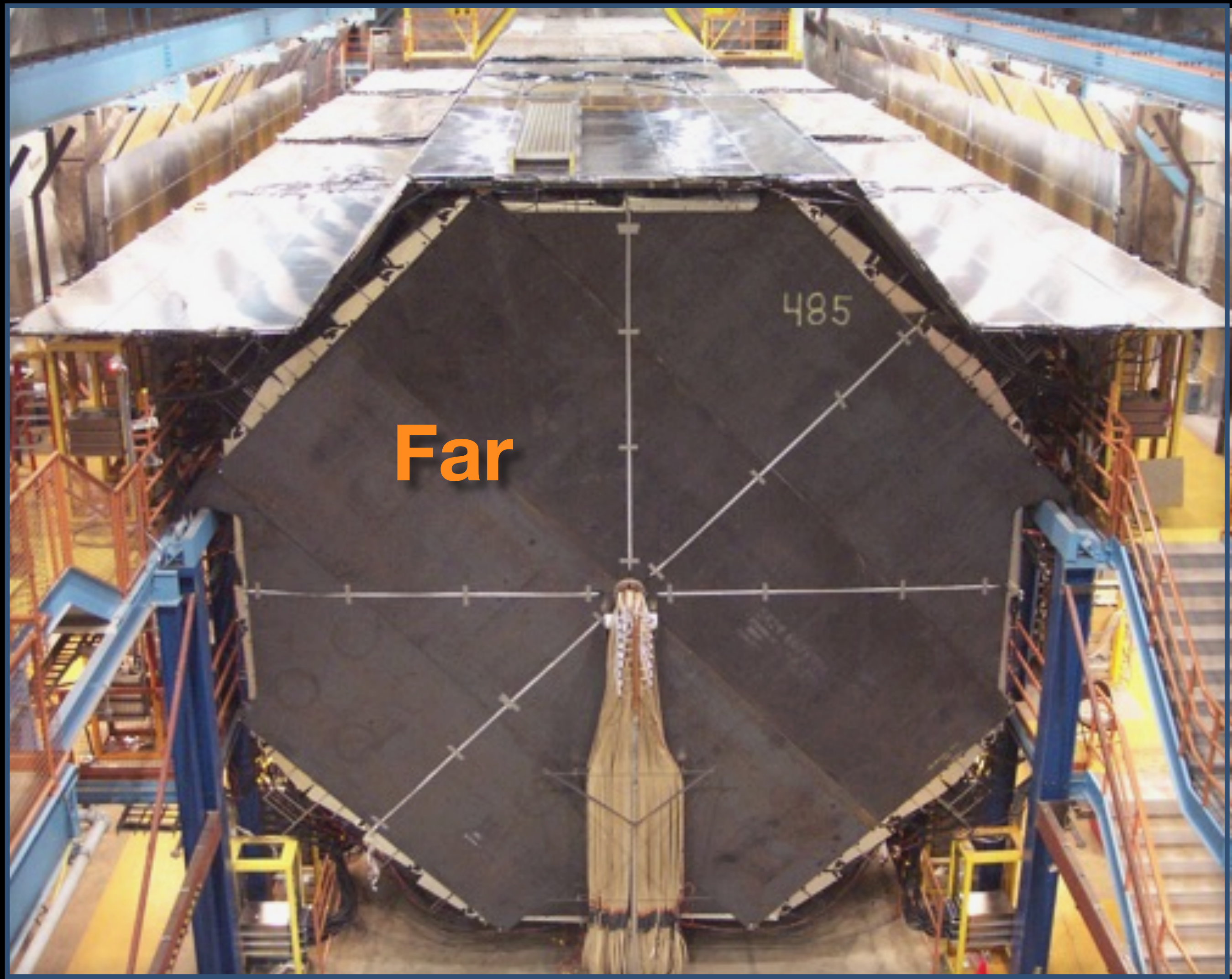
$$ND(\nu_\mu) = \boxed{\Phi(E_\nu) \times \sigma(E_\nu, A)} \times \epsilon_{ND}$$
$$FD(\nu_\mu) = \boxed{\Phi(E_\nu) \times \sigma(E_\nu, A)} \times \epsilon_{FD} \times P_{osc}$$

- The neutrino spectrum is measured at the ND (before oscillations), this is a combination of neutrino flux, cross section and efficiency.
- The measured spectrum is used to make a prediction of the expectation at the FD before considering oscillations.
- **In the case of functionally similar detectors the flux combined with the cross sections uncertainties largely cancel.**
- **Even some aspects of the efficiency might cancel in the case of similar detector response.**

UNDERSTANDING THE FLUX, CROSS SECTIONS AND DETECTOR EFFICIENCIES IS ESSENTIAL FOR HIGH PRECISION

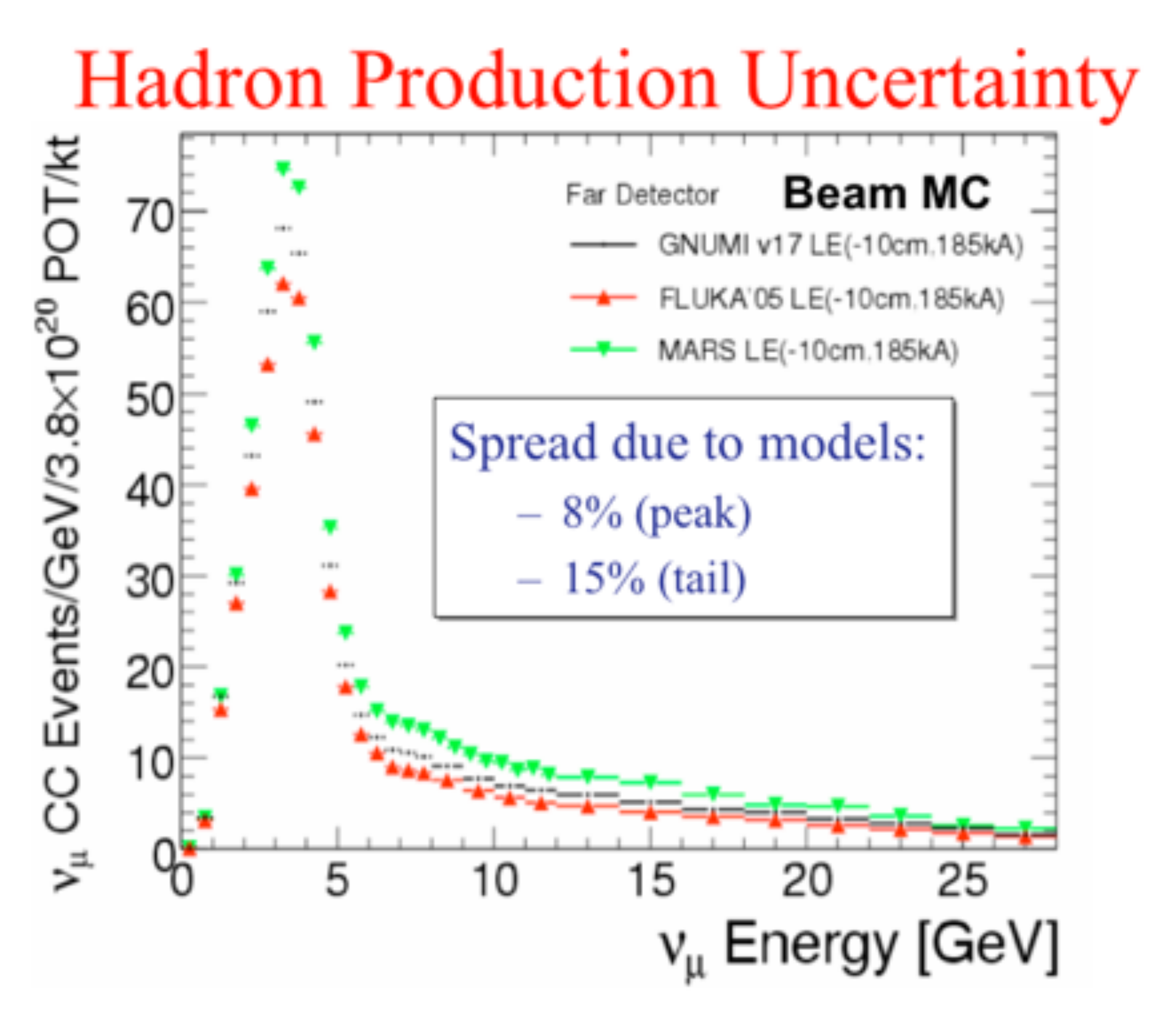
THE MINOS/NOVA DETECTORS

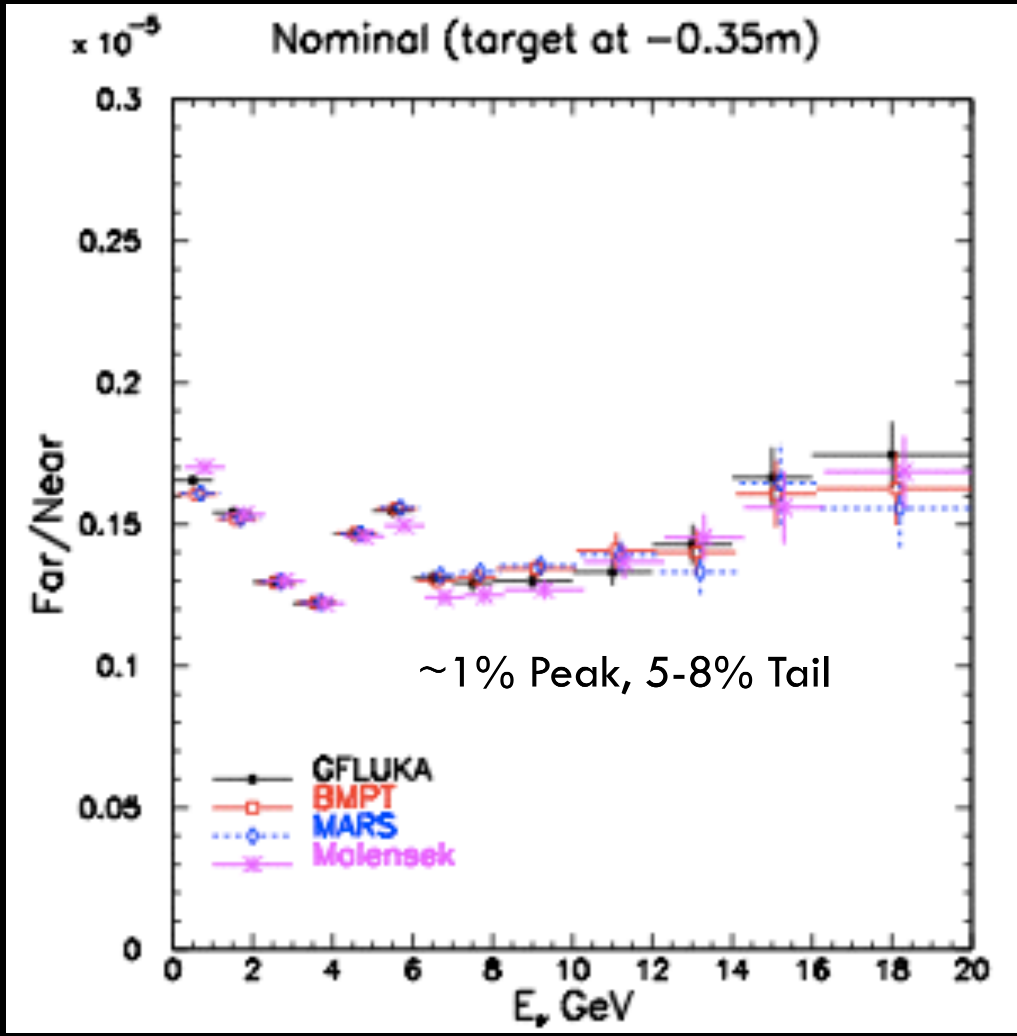
- Both MINOS and NOVA have functionally identical: **Near and Far detectors**
  - Same materials, same construction.
  - Differences in electronics to accommodate different rates.
  - Minor differences in detector response due to distance to electronics and other factors.



Beam flux: Hadron production uncertainties

MINOS - on axis

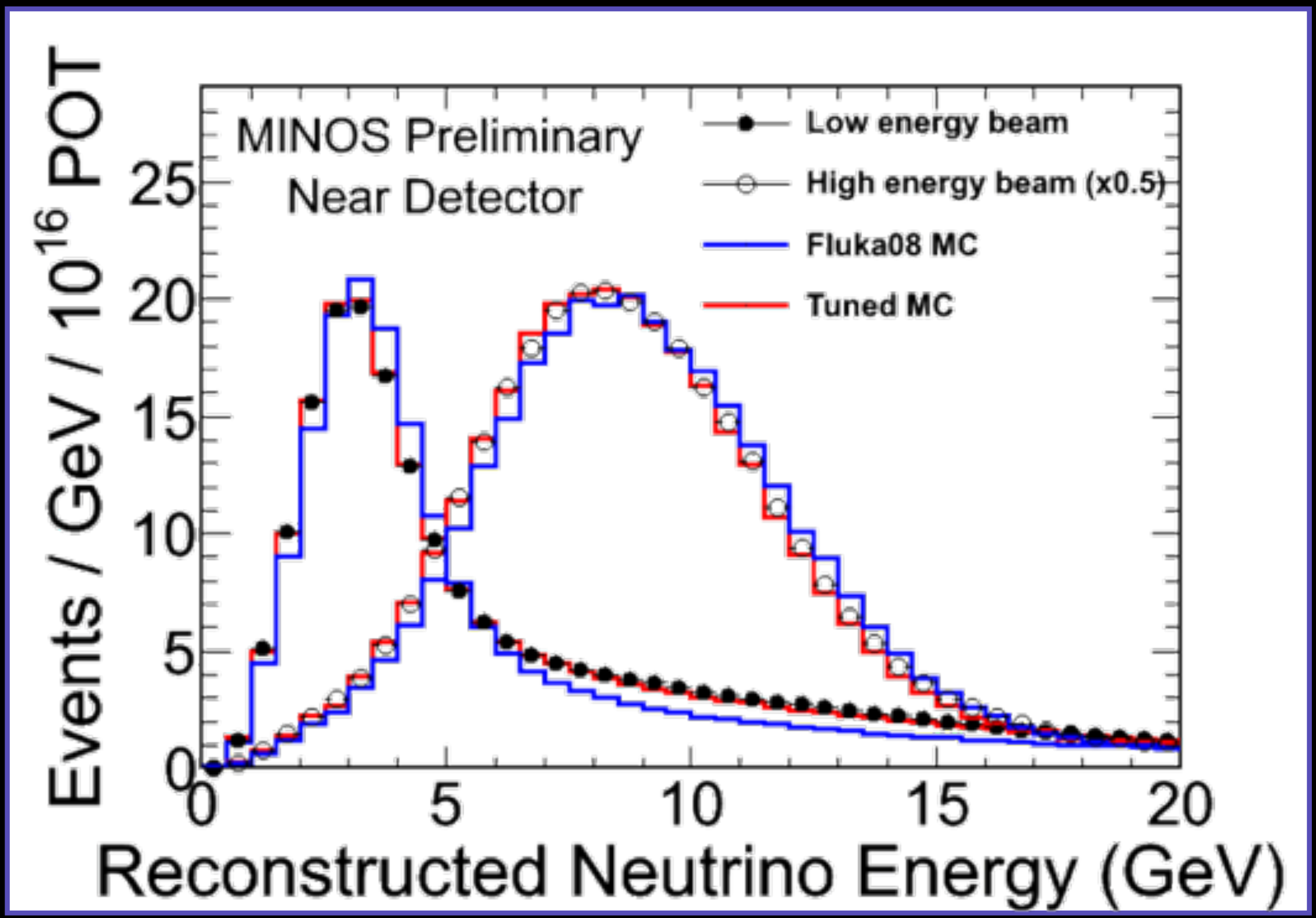




- Uncertainties in the neutrino flux cause large uncertainties in the ND simulated spectrum, but the errors largely cancel in the Far to Near Comparison.
- Note that uncertainties in hadron production just based on modeling is not sufficient.
- Additional flux uncertainties arise from focusing and alignment uncertainties: 10% Near only, 3% in Near/Far.

P. Vahle SBL talk 2012

MINOS NEAR DETECTOR DATA



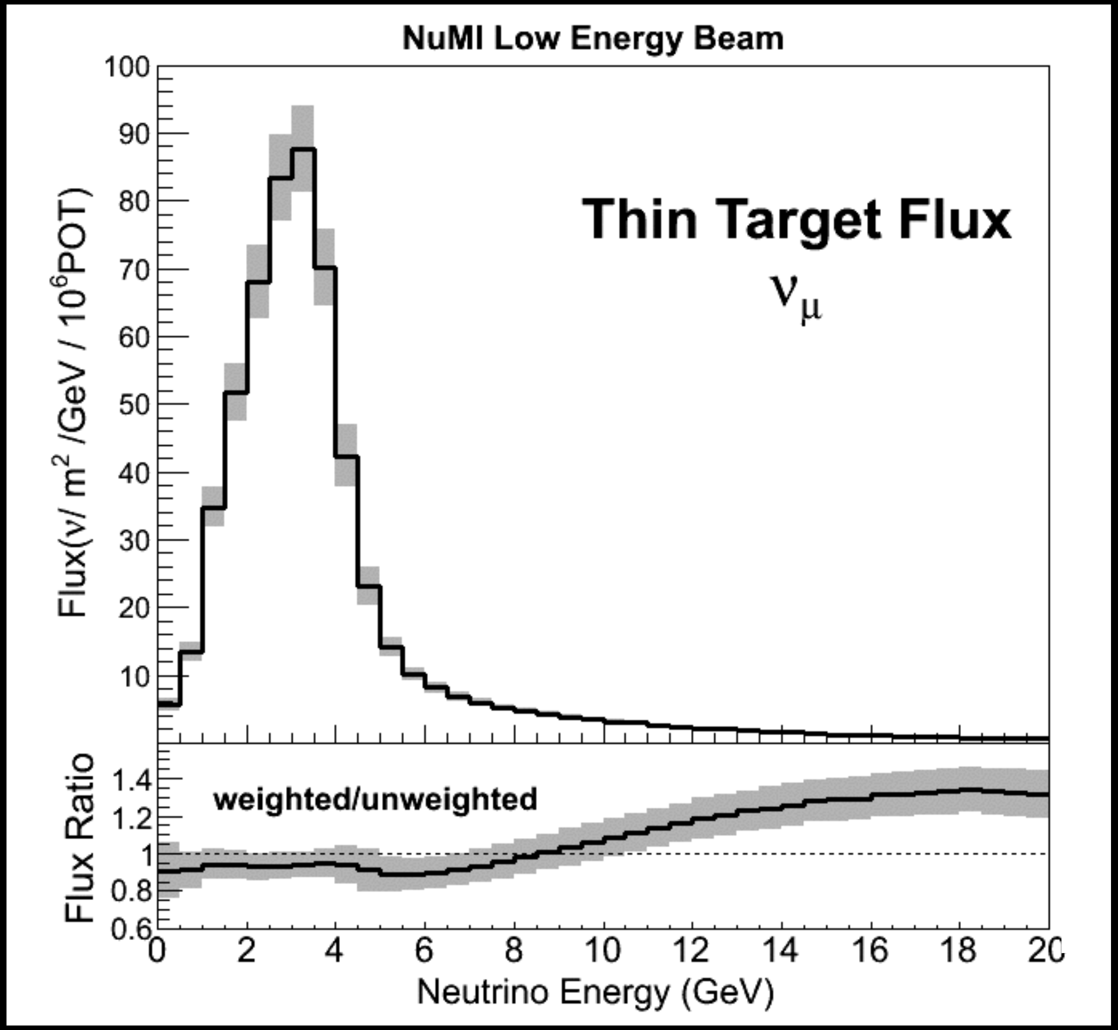
- The beam spectrum can be tuned by varying relative positions of target and magnetic horns.
- **MINOS uses ν_μ CC events in ND to constrain flux using 7 beam configurations.**
- NA49 data used to constrain π+/π− and π/K ratios in fits.

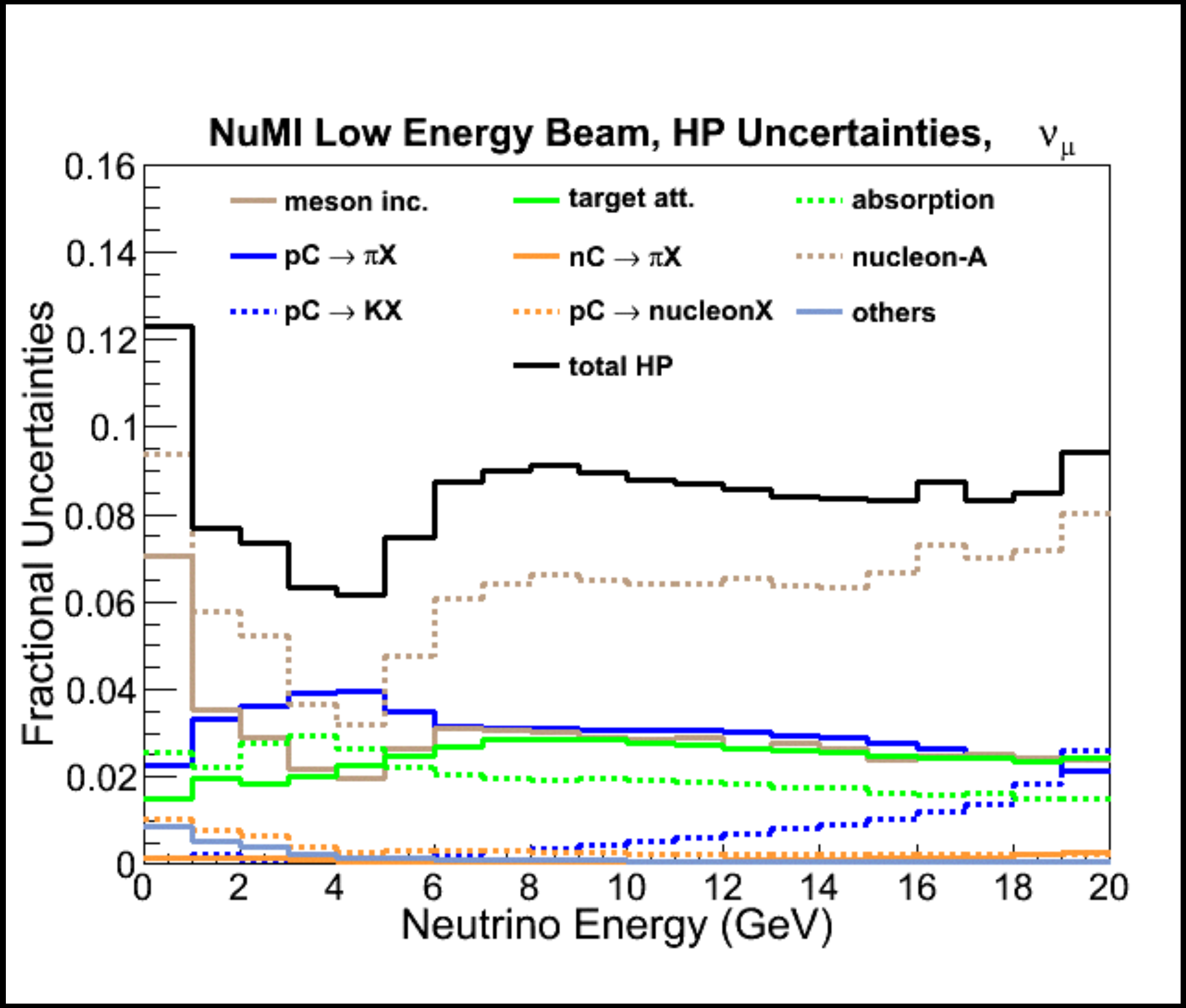
- Majority of data is from the low energy beam.
- High energy beam improves statistics in energy above the oscillation dip.
- Additional exposure in other beam configurations for commissioning and systematic studies.
- Remaining data/MC discrepancies <5%.

FLUX UNCERTAINTIES IN MINERVA

L. Aliaga - APS 2017

- MINERvA published the flux prediction for LE NuMI beam based on thin target data correction (Phys. Rev. D **94**, 092005).





- Note that this is the dominant error for cross section systematics. Down to 6-8% in the peak and <10% in the tail.

PROSPECTS FOR NOVA FLUX

L. Aliaga - APS 2017

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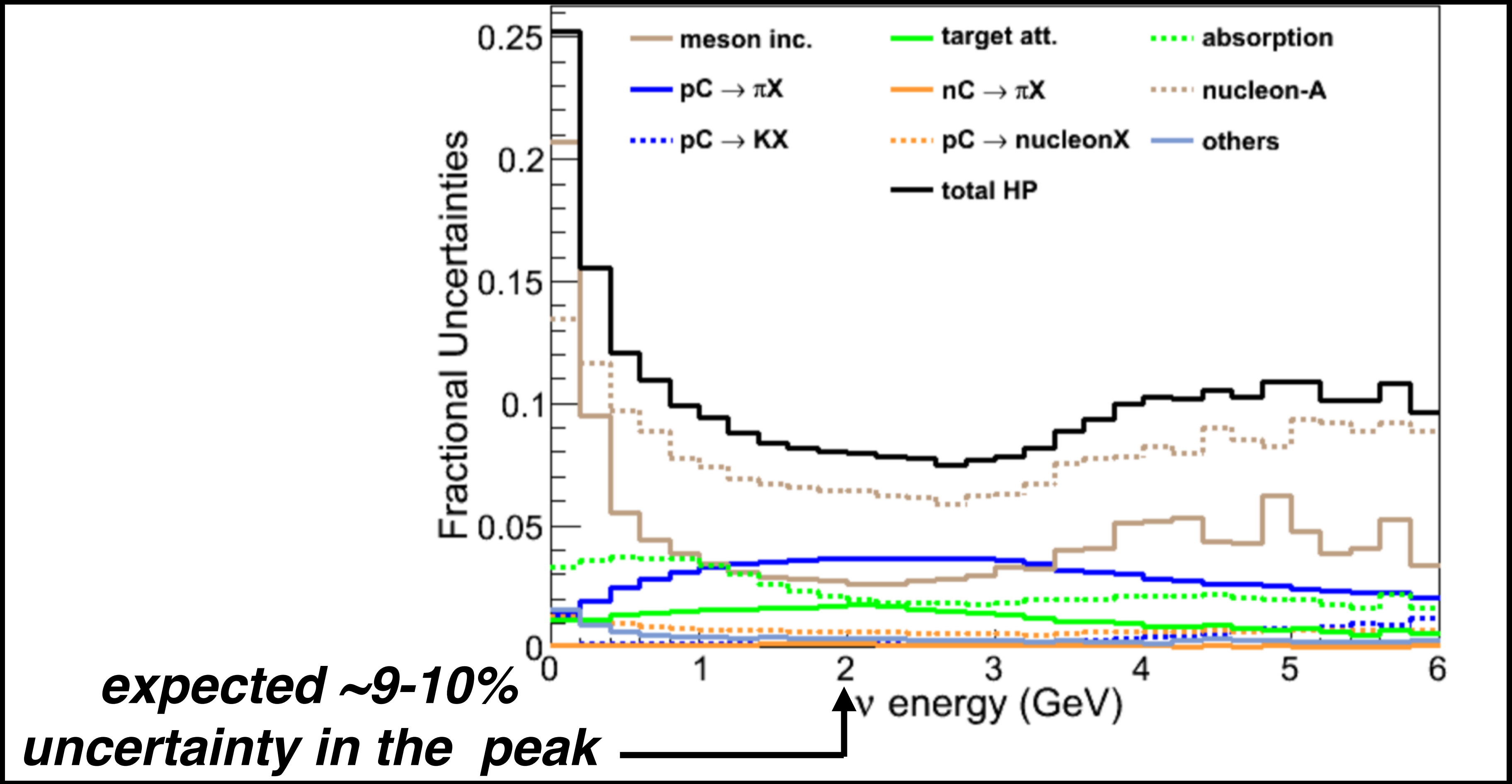
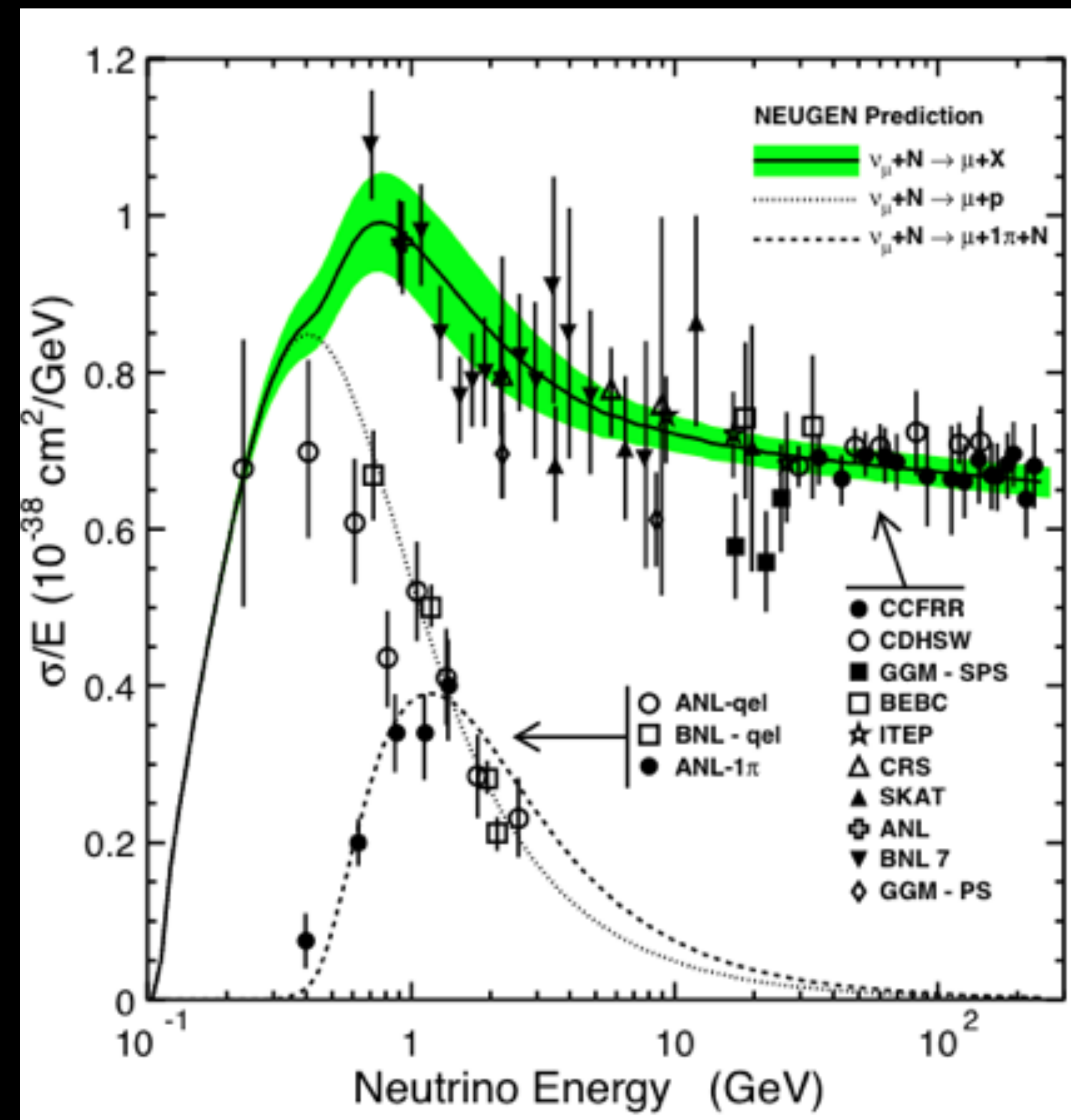


- Using similar method for NOvA would expect 9-10% uncertainty in the peak. Far/Near reduction to be determined.

CROSS SECTION UNCERTAINTIES

- Uncertainties determined from comparison of MC to independent data.
- Fits to both inclusive and exclusive channel data, in different invariant mass regions.
- 3% on the normalization of the DIS ($W > 1.7 GeV/c^2$) cross-section.
- 10% uncertainty in the normalization of the single-pion and quasi-elastic cross-sections.
- 20% uncertainty in the relative contribution of non-resonant states to the 1π and 2π production cross-sections for $W < 1.7 GeV/c^2$.
- More sophisticated treatment by GENIE still results in relative large uncertainties.
  - Agreement of models with high statistics data in Near Detectors still leaves much to be desired.

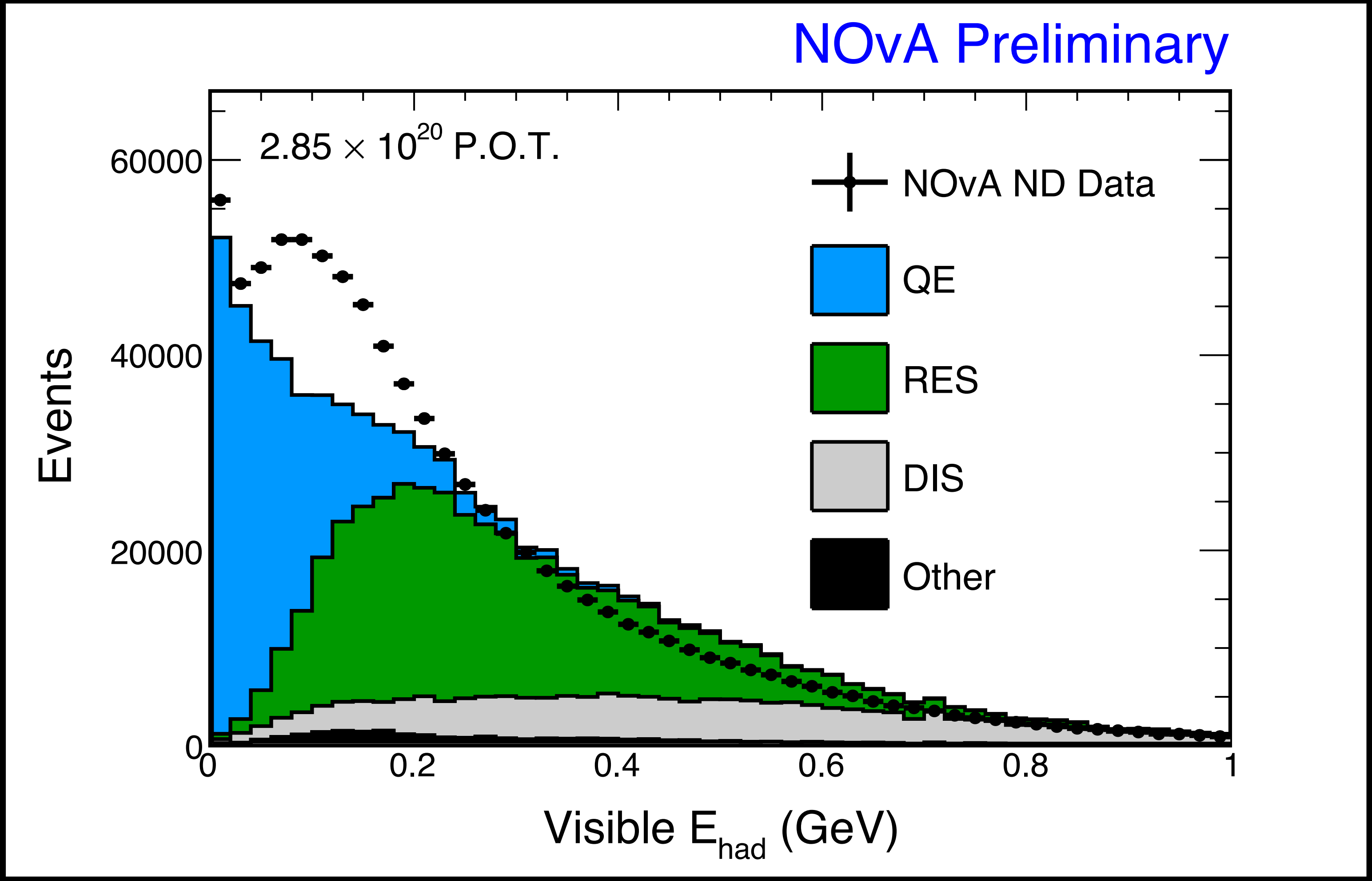
MINOS days



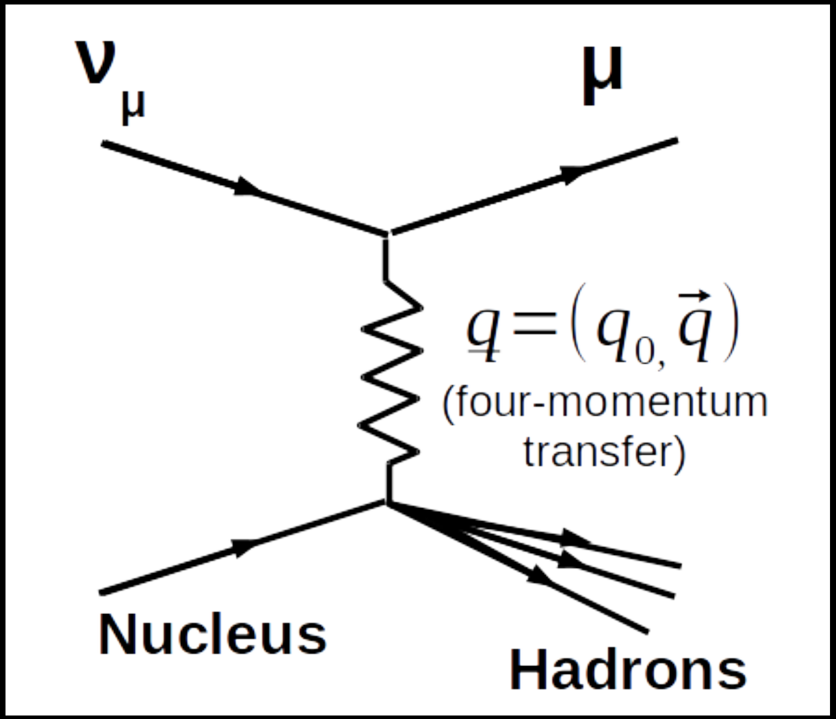
P. Vahle SBL talk 2012

SURPRISES IN NUCLEAR MODELING

- NOvA's Near Detector hadronic energy distribution suggests unsimulated process between quasi-elastic and delta production.



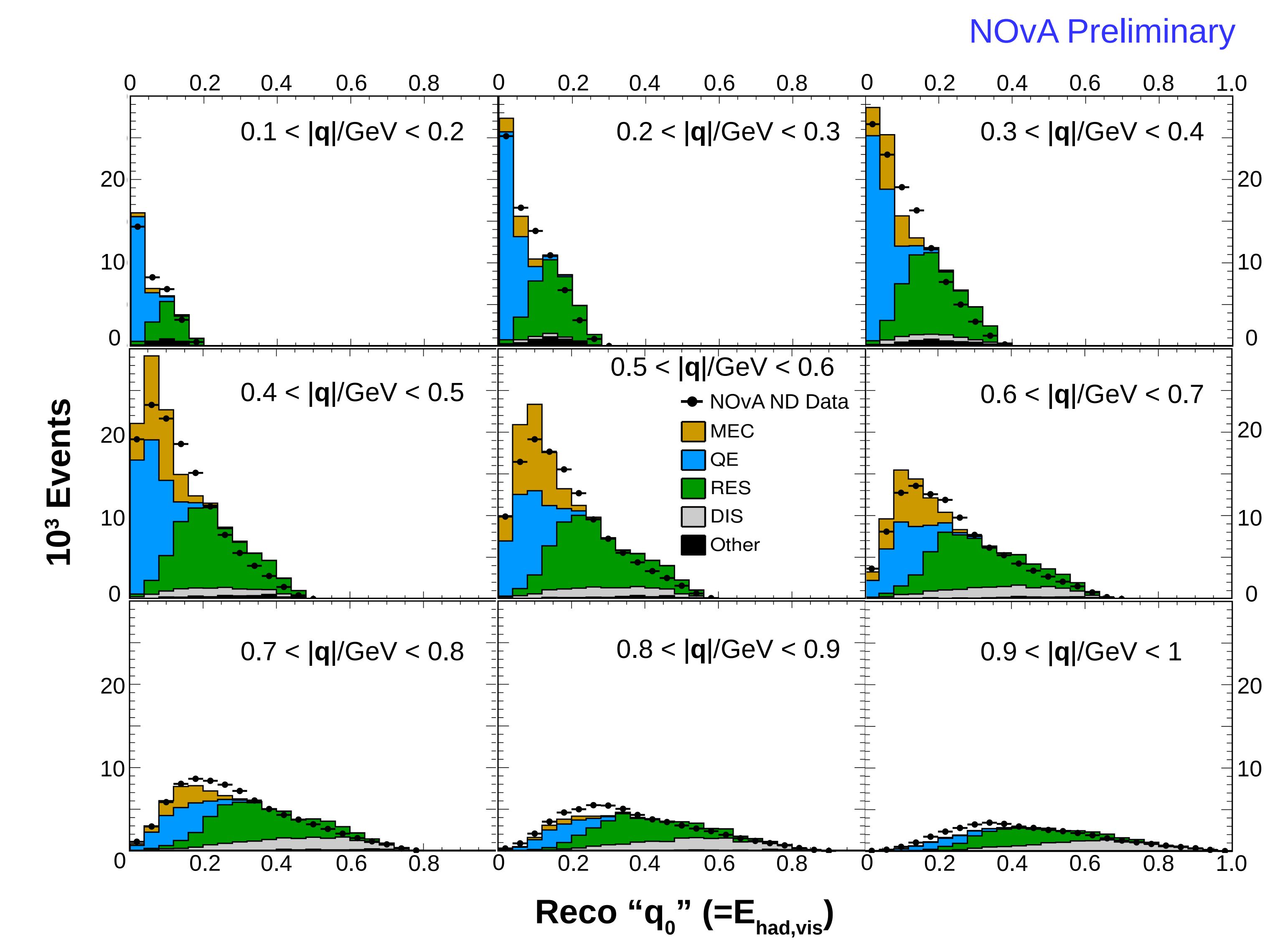
Similar conclusions from MINERvA data reported in P.A. Rodrigues et al., PRL 116 (2016) 071802



Potentially: 2-particle, 2-hole (2p2h) events where neutrino is scattering off a nucleon-nucleon pair

IMPROVED NUCLEAR MODELING

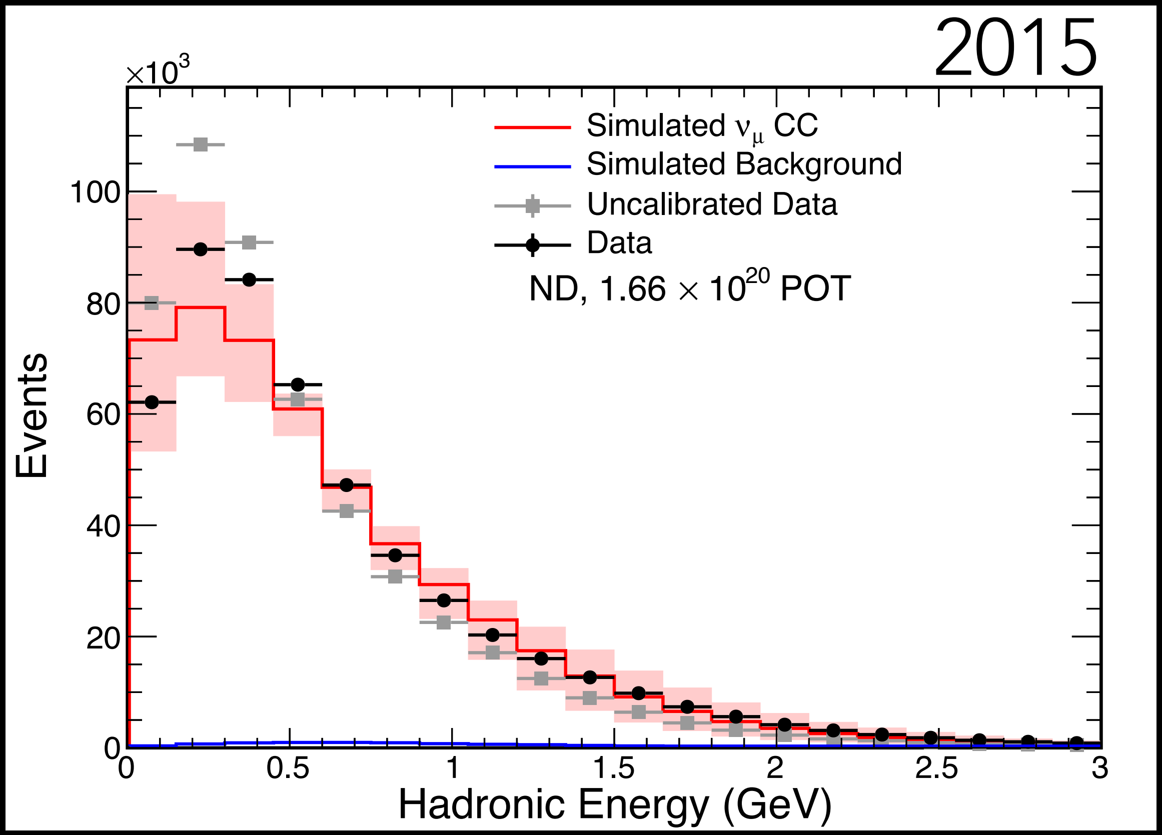
- Enabled GENIE's empirical Meson Exchange Current model (1).
- Reweighted to matched observed excess as a function of momentum transfer.
- Weight single non-resonant pion production down by effectively 50%.
- Take 50% systematic uncertainty on MEC component (2).
- Impacts the hadronic energy scale and quasi-elastic cross section systematic uncertainties.

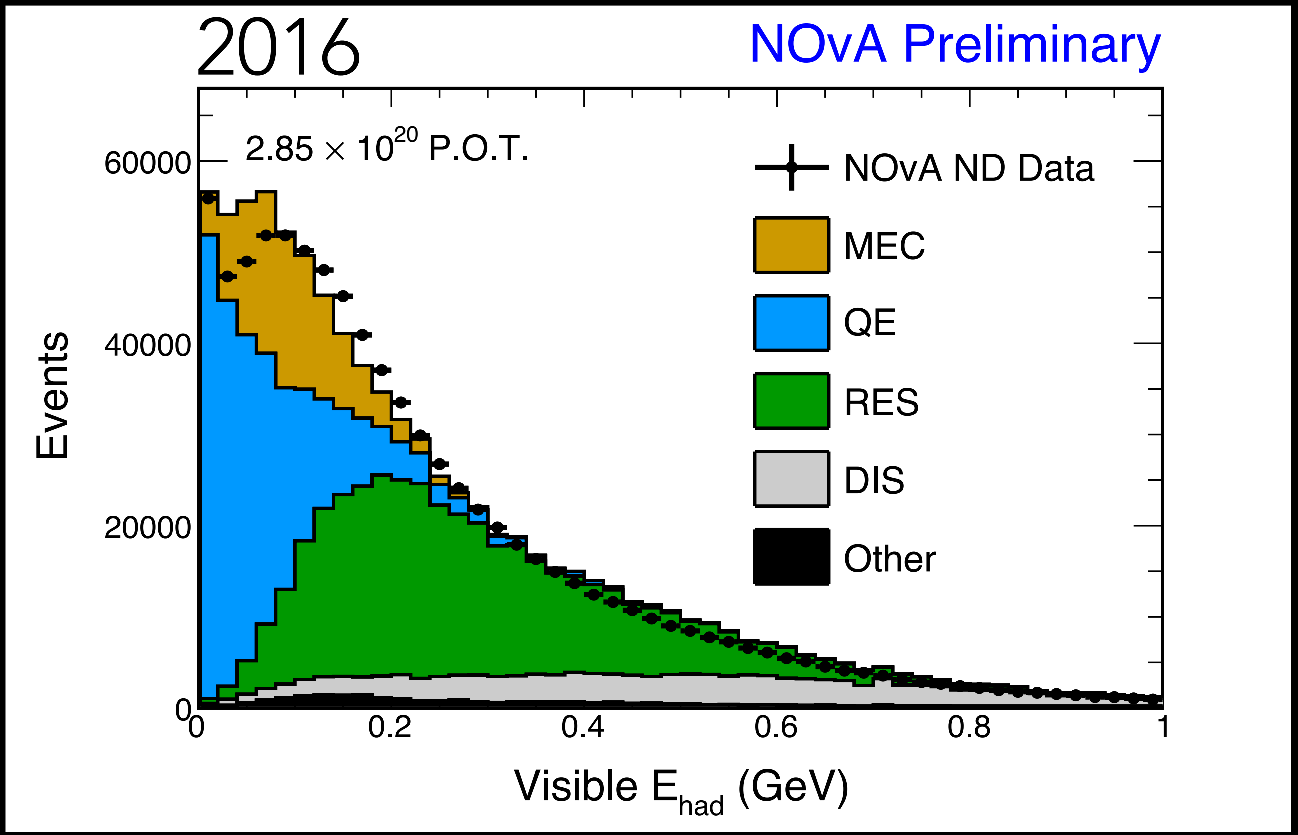


[1]S. Dytman, based on J. W. Lightbody, J. S. OConnell, Comp. in Phys. 2 (1988) 57
[2]P.A. Rodrigues et al., arXiv:1601.01888

Being able to identify nuclear processes on same nucleus as Far Detector, key to extrapolating this.

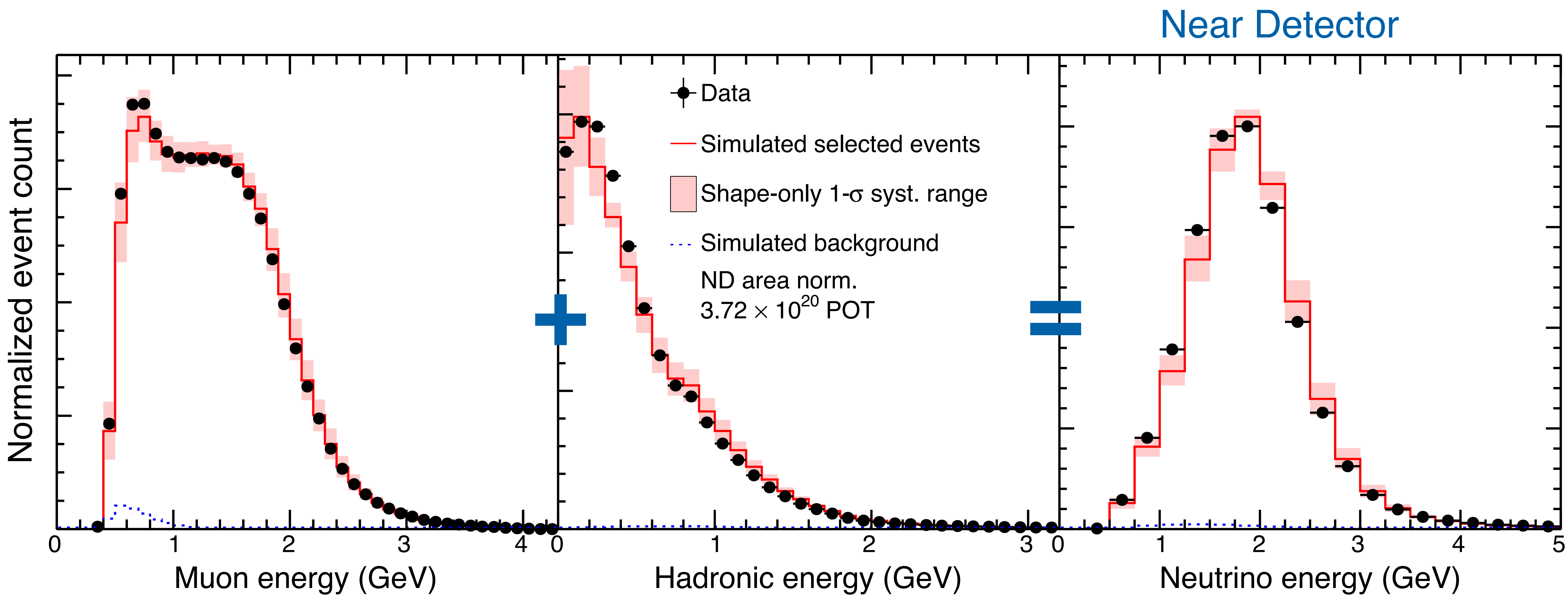
IMPACT OF NUCLEAR MODELING





- In 2015 analysis NOvA observed a substantial discrepancy in ND hadronic energy. Applied empirical 14% hadronic scaling and took entire 14% as a systematic.
  - Assumed to be a combination of cross section/extrapolable detector response.
- Improved simulation and more study identified this as mostly missing 2p2h component. Justified in extrapolating before, reduced systematic uncertainty after adding MEC model.

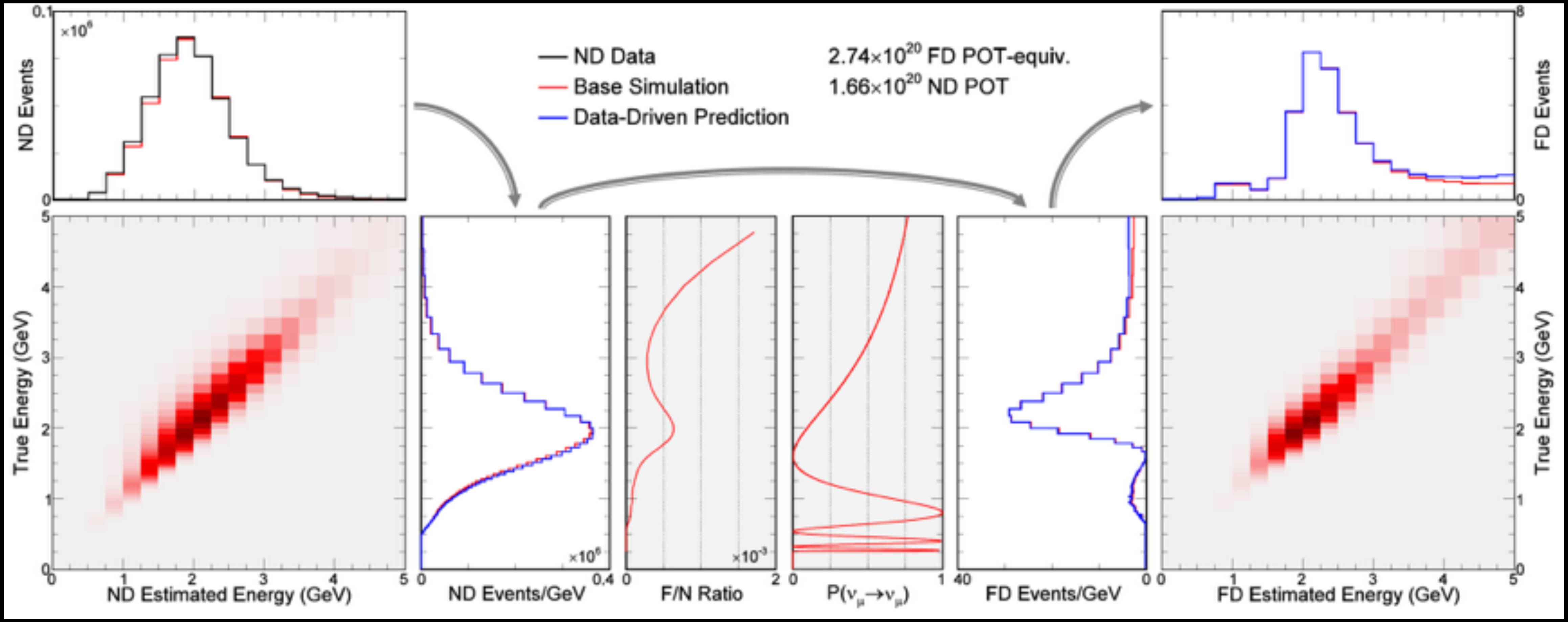
NEUTRINO ENERGY ESTIMATION



- Data vs MC show good agreement for muon neutrino selected events.
  - Muon particle are well described by our MC.
  - Muon dE/dx used in length-to-energy conversion
  - Hadronic energy estimated calorimetrically from off-track hits.
  - **Significant improvement due to effective scintillator light tuning and MEC modeling added.**
- This results in 7% overall neutrino energy resolution.

DATA-DRIVEN FAR DETECTOR MUON NEUTRINO PREDICTION (IN NOVA)

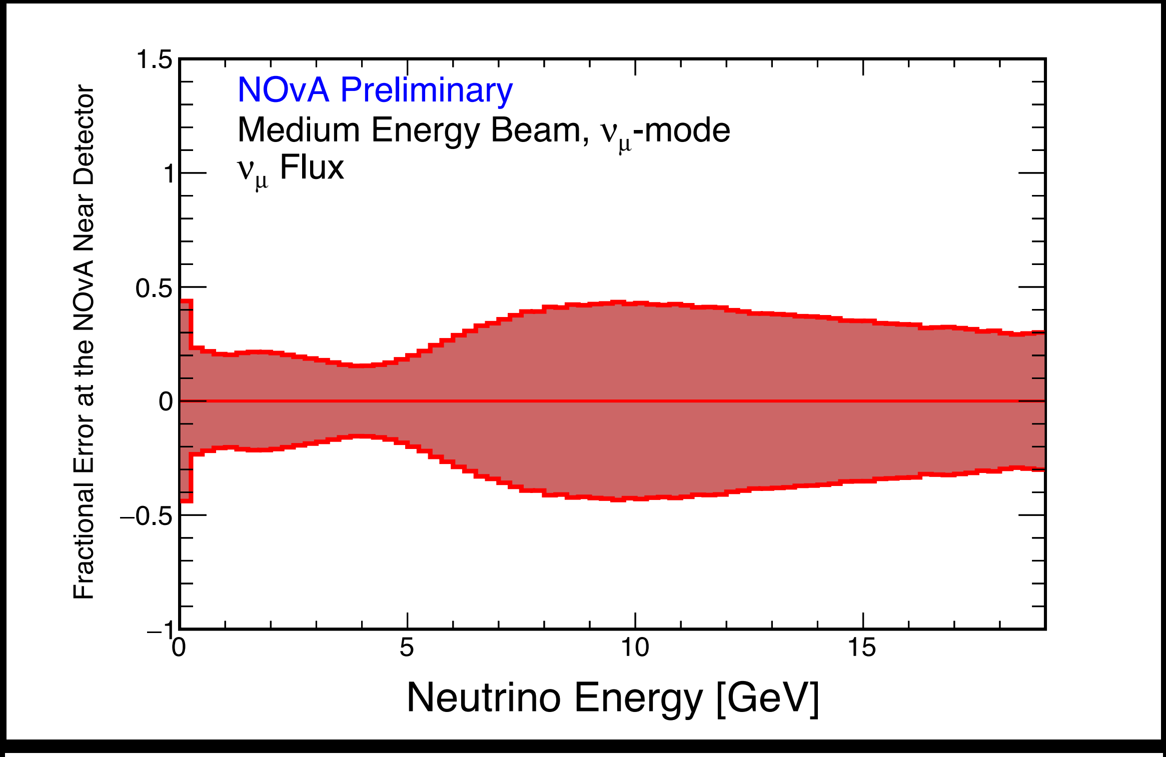
- Estimate the underlying true energy distribution of selected ND events.
- Multiply by expected Far/Near event ratio and $\nu_\mu \rightarrow \nu_\mu$ oscillation probability as a function of true energy.
- Convert FD true energy distribution into predicted FD reconstructed energy distribution.
- Systematic uncertainties assessed by varying all MC-based steps.

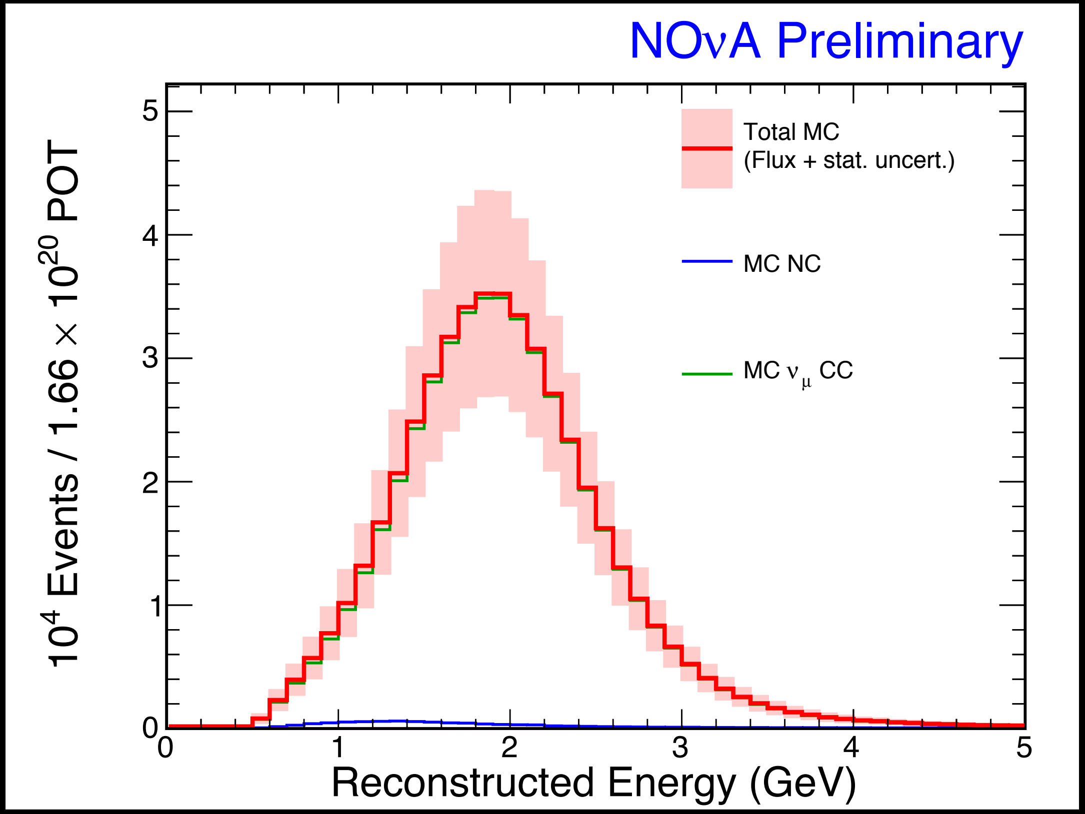


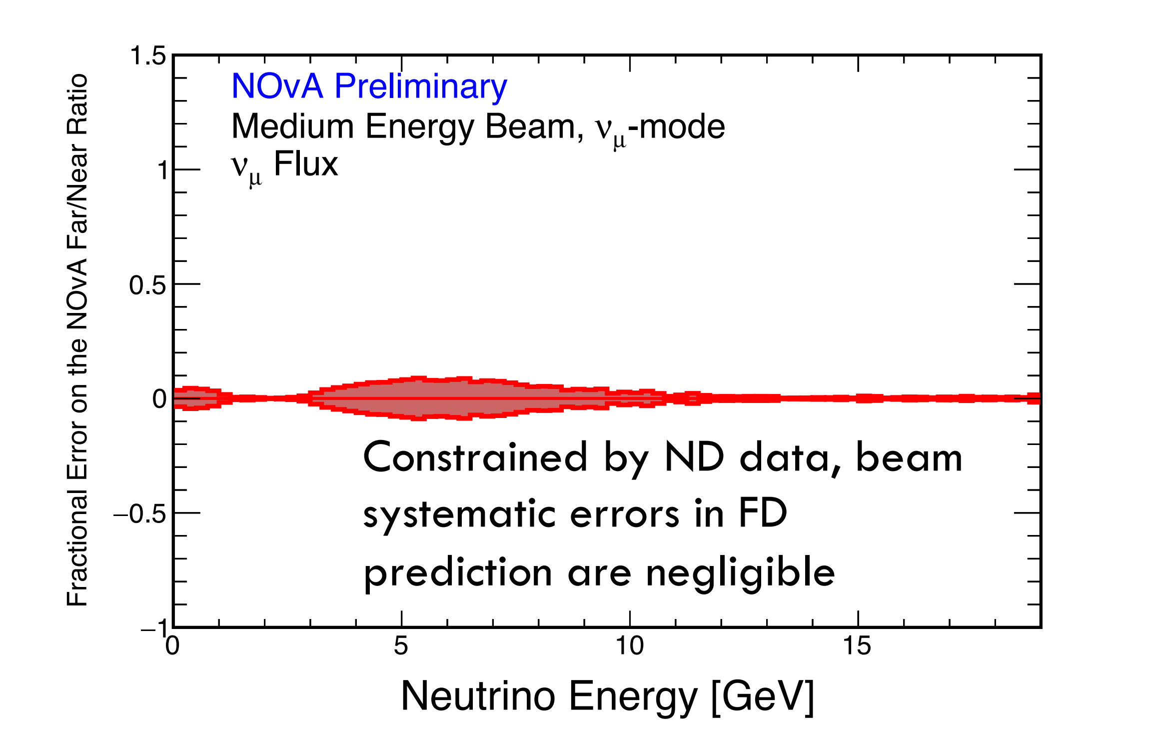
Other extrapolations possible and might have an impact on uncertainties of prediction.

SYSTEMATIC UNCERTAINTIES

- The two **functionally-identical** detector technique in NOvA largely reduces several uncertainties typical of accelerator neutrino experiments:
  - Hadron production uncertainty in the neutrino target and beam line focusing errors cause +/-20% changes in normalization, but peak energy shifts by less than 1.5%.

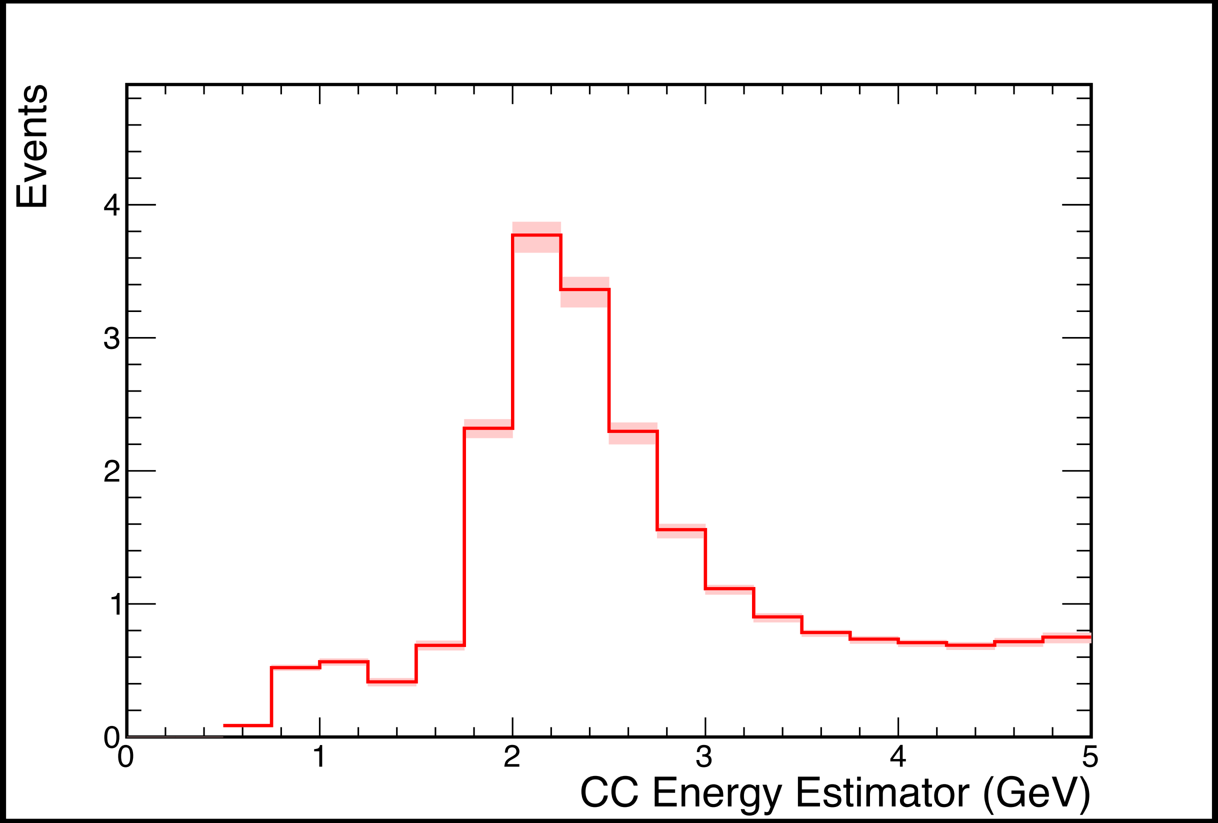


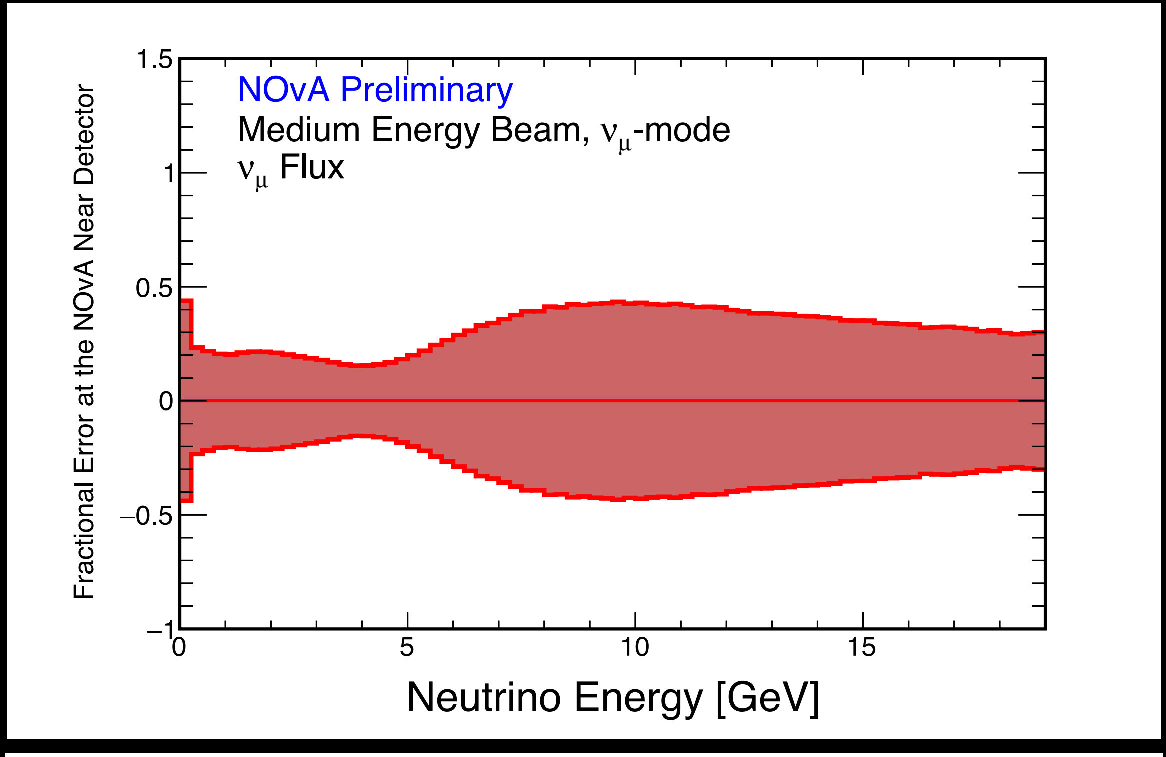


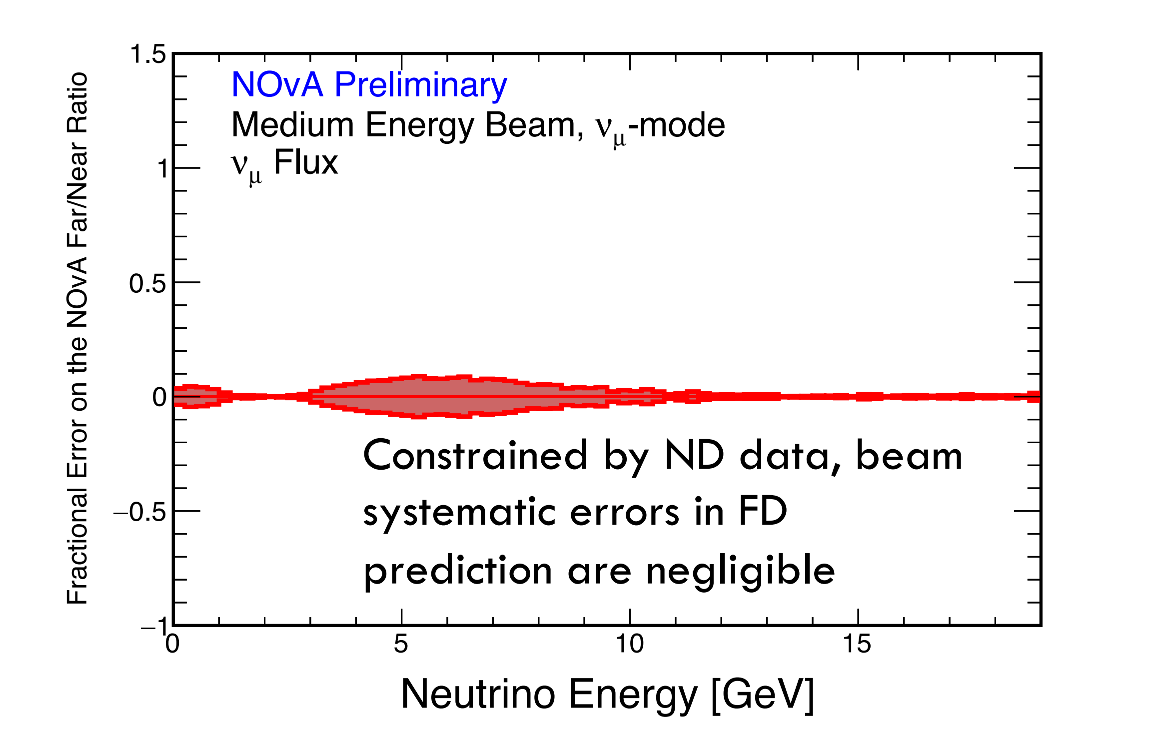


SYSTEMATIC UNCERTAINTIES

- The two **functionally-identical** detector technique in NOvA largely reduces several uncertainties typical of accelerator neutrino experiments:
  - Neutrino interaction uncertainties also cancel in the extrapolation, leaving a residual 3.5% change in number of events. Largest contributions from modifying axial mass in QE and RES cross section parameterization
  - ND beam peak moves by less than 1%.



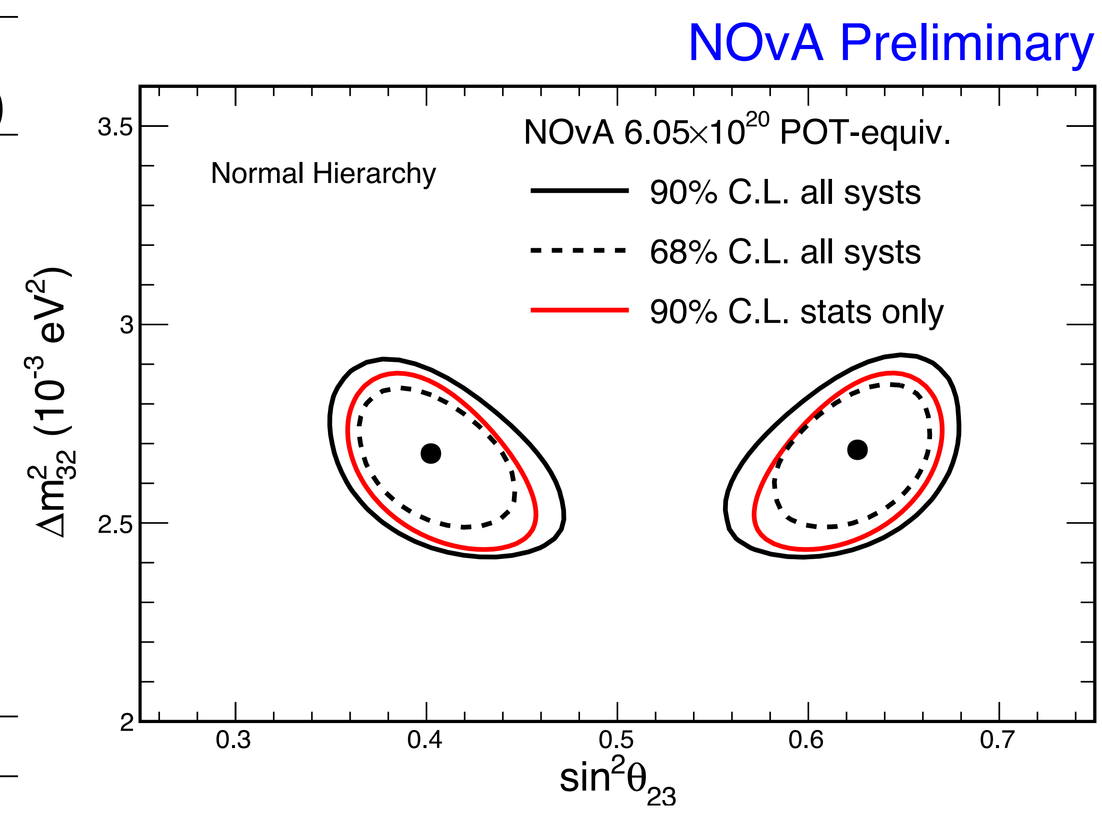




From NOvA's first analysis

SYSTEMATIC UNCERTAINTIES

Source of uncertainty	Uncertainty in $\sin^2\theta_{23} (\times 10^{-3})$	Uncertainty in Δm^2_{32} $(\times 10^{-6}$ eV$^2)$
Absolute muon energy scale [$\pm 2\%$]	+9 / -8	+3 / -10
Relative muon energy scale [$\pm 2\%$]	+9 / -9	+23 / -14
Absolute hadronic energy scale [$\pm 5\%$]	+5 / -5	+7 / -3
Relative hadronic energy scale [$\pm 5\%$]	+10 / -11	+29 / -19
Normalization [$\pm 5\%$]	+5 / -5	+4 / -8
Cross sections and final state interactions	+3 / -3	+12 / -15
Neutrino flux	+1 / -2	+4 / -7
Beam background normalization [$\pm 100\%$]	+3 / -6	+10 / -16
Scintillation model	+4 / -3	+2 / -5
δ_{CP} $[0 - 2\pi]$	+0.2 / -0.3	+10 / -9
Total systematic uncertainty	+17 / -19	+50 / -47
Statistical uncertainty	+21 / -23	+93 / -99



- Most systematics significantly cancel in Far/Near extrapolation.
- Table quotes increase in 68% contours relative to stat-only fit.
- Including MEC in simulation reduces hadronic energy systematic.
- Systematics included as pull terms in the fit.

From NOvA's latest analysis

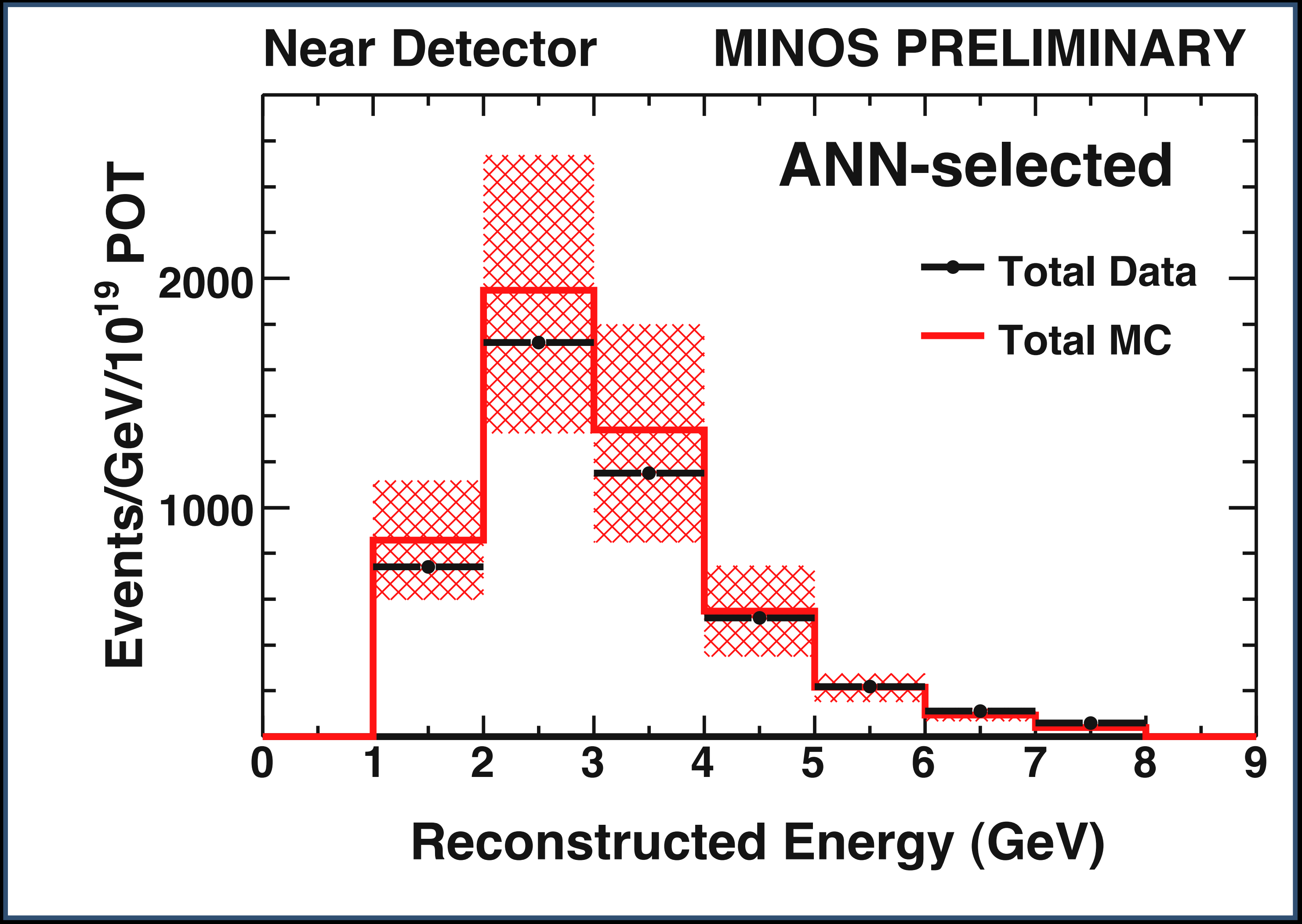
Appearance analysis challenges

- Electron neutrino appearance analyses are different than muon neutrino disappearance analyses:
  - Cannot cancel systematic uncertainties on the signal directly as the signal is not observed at the near detector.
  - Potentially larger backgrounds due to electromagnetic showers in neutral currents.
  - Intrinsic beam electron neutrino contamination.
  - Other systematic uncertainties are more relevant such as hadronic shower uncertainties.

How do we use the near detector then?

MINOS NEAR DETECTOR DATA

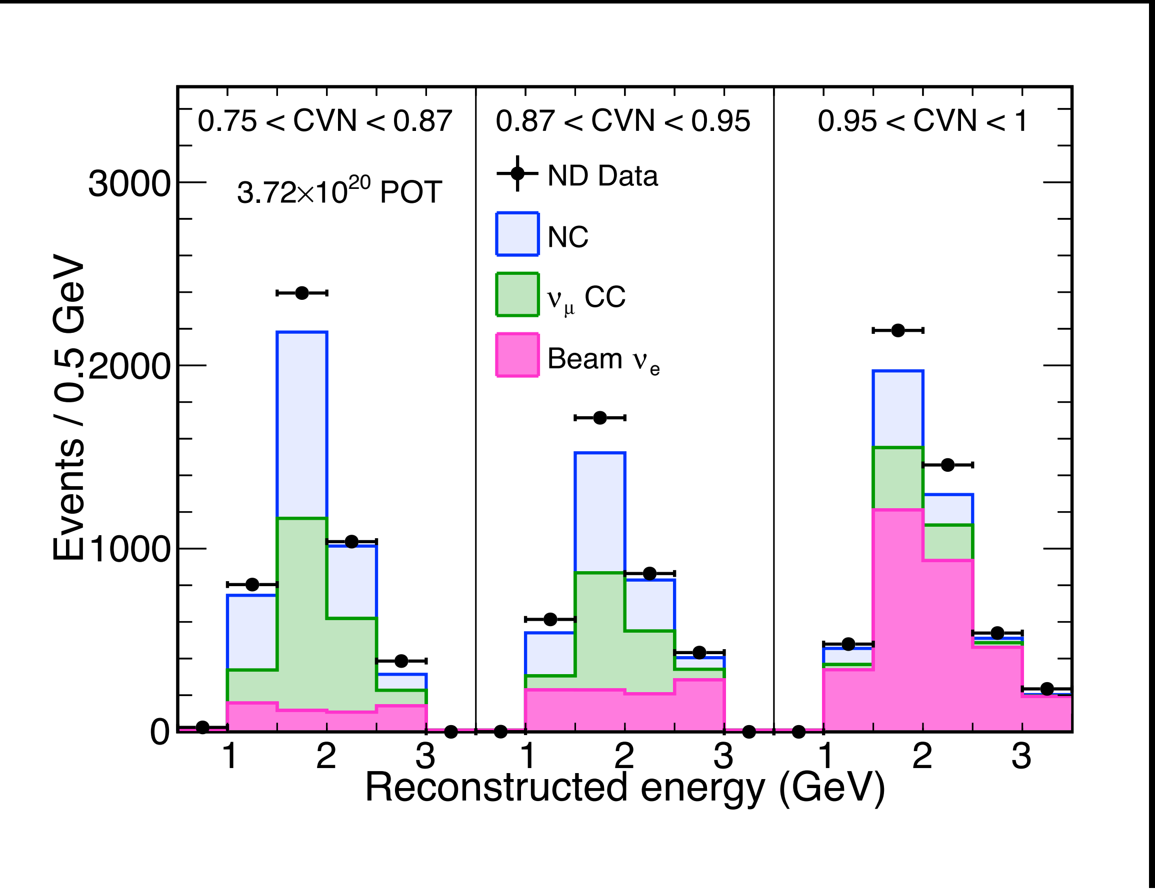
- Near Detector provides a high-statistic data sample to **estimate the background**.
- Simulation originally predicted backgrounds ~20% higher than observed.
- Hadronization and final state interactions uncertainties give rise to large uncertainties in ND prediction.
- External data sparse in region of interest.
- Improvements to nuclear rescattering model in MC reduced data/MC discrepancies in later analyses.

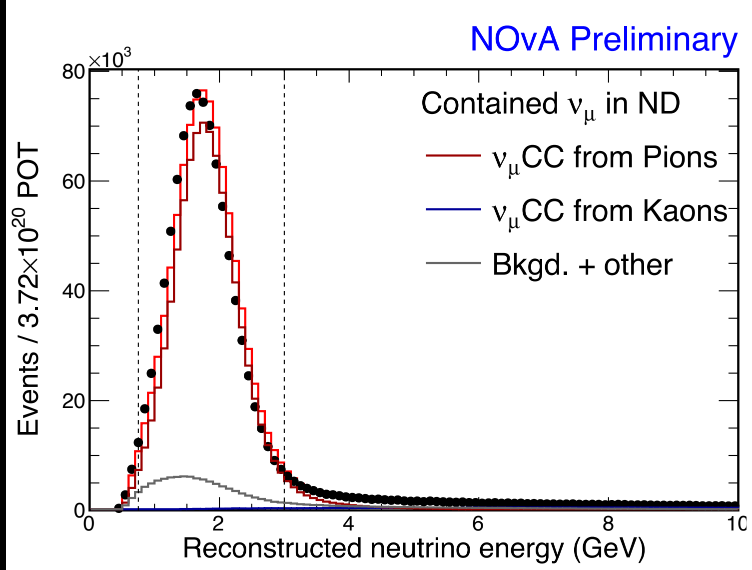


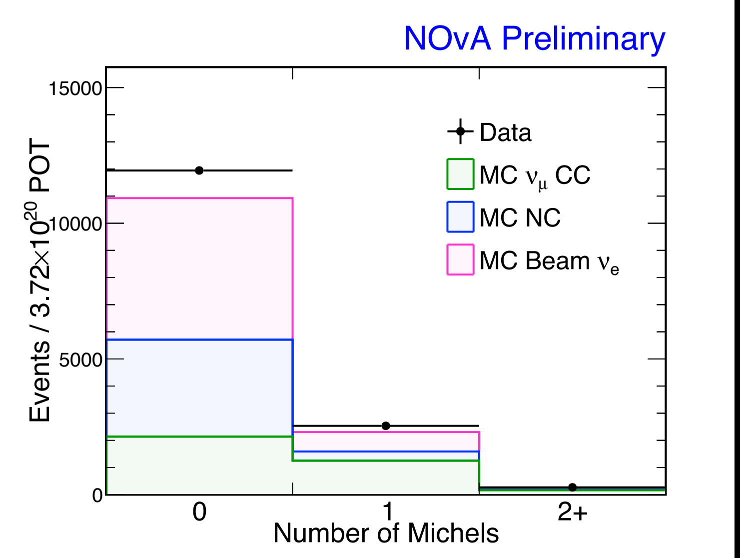
- MINOS developed **data-driven methods** to measure the different background components.

PREDICTING THE BACKGROUND IN THE FD

- Calorimetric energy per electron neutrino selection bin (shown for NOvAs second analysis) shows a small excess.
- As in MINOS, NOvA has developed data driven methods to separate background components and do appropriate corrections to simulation.
  - Adjust beam ν_e 3% up, NCs 17%, ν_μ CC 10%.
  - Note FD background is almost entirely intrinsic ν_e and NC π^0.
- ND data is translated to FD background expectation in each energy bin, using Far/Near ratios from simulation.



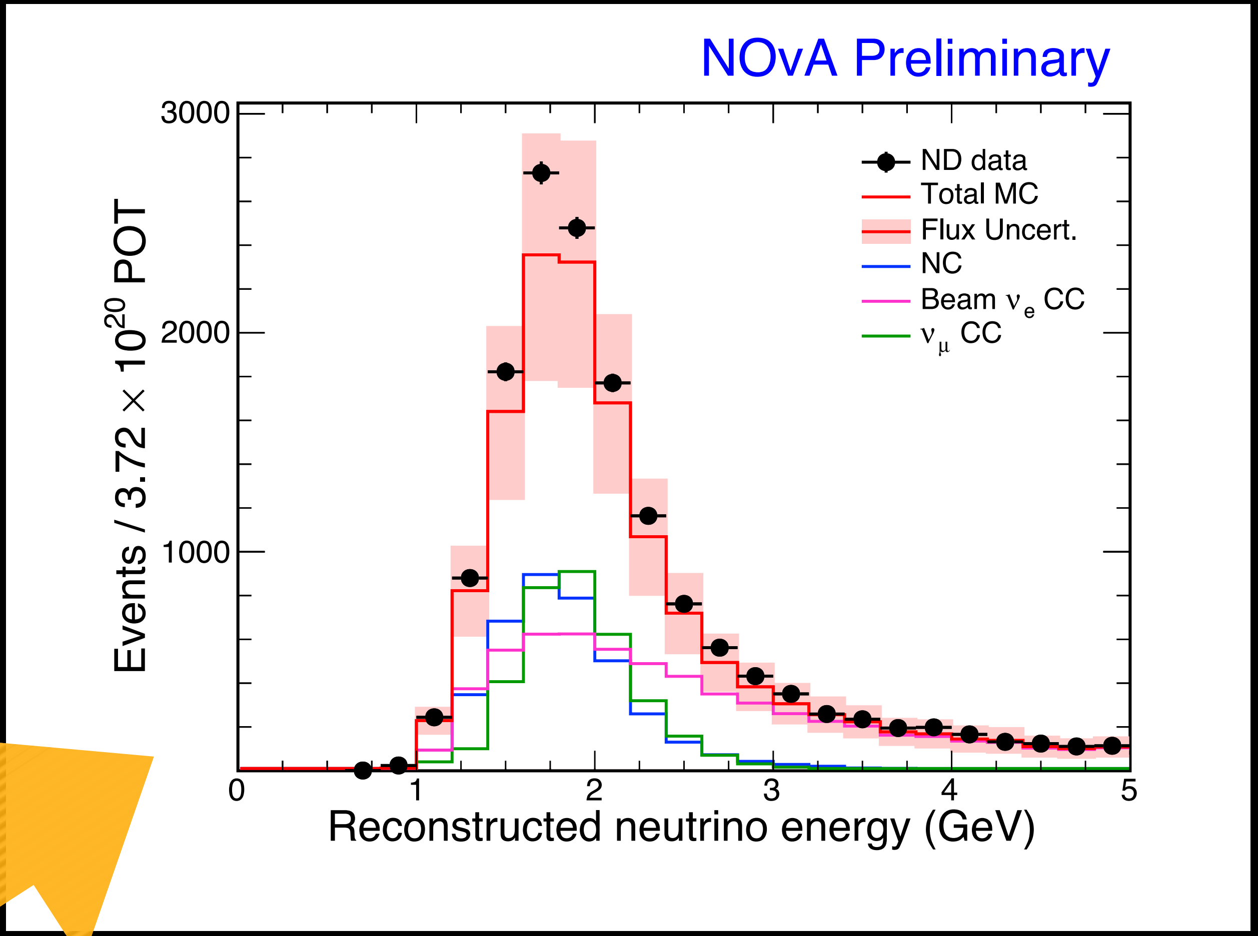


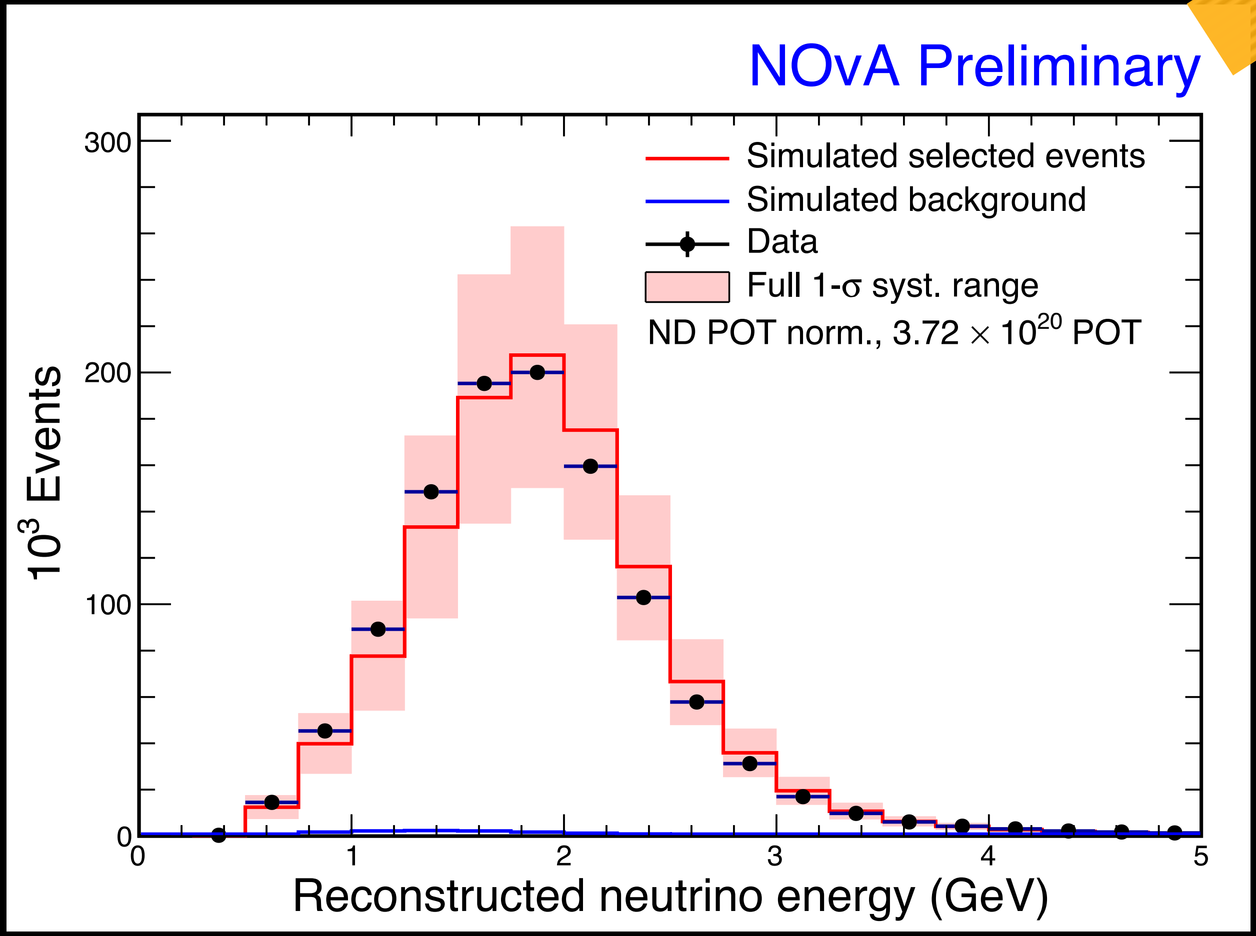


The luxury of flux x cross section

PREDICTING THE SIGNAL IN THE FD

- FD signal expectation is predicted using the ND-selected ν_μ CC spectrum using same technique as for muon neutrino disappearance.





- Since the source of FD ν_e signal is ND ν_μ, it requires we know the ν_e/ν_μ cross-section ratio well.
- Only direct comparison with the same detector at these energies is from MINERvA (QE-only): arXiv:1509.05729.

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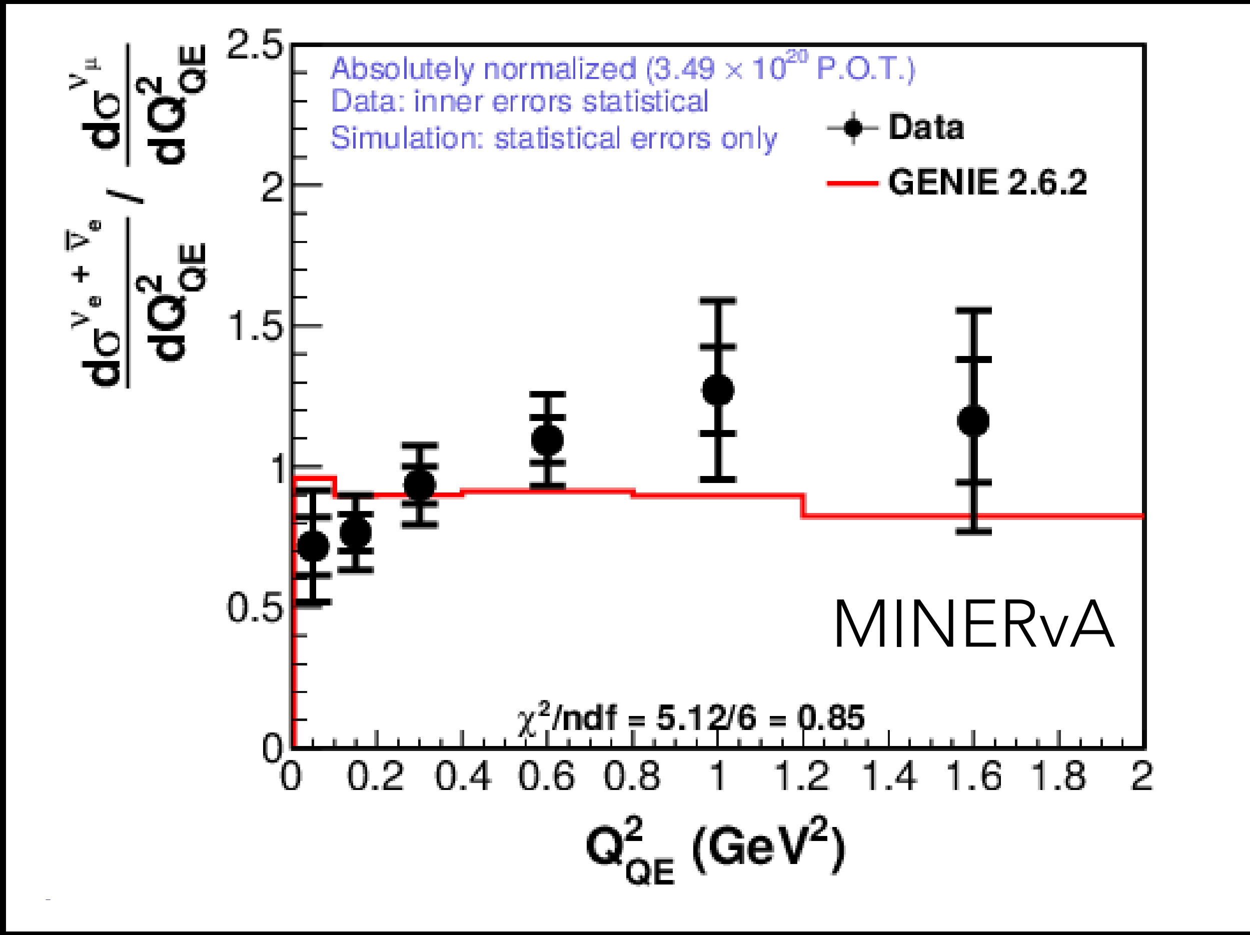

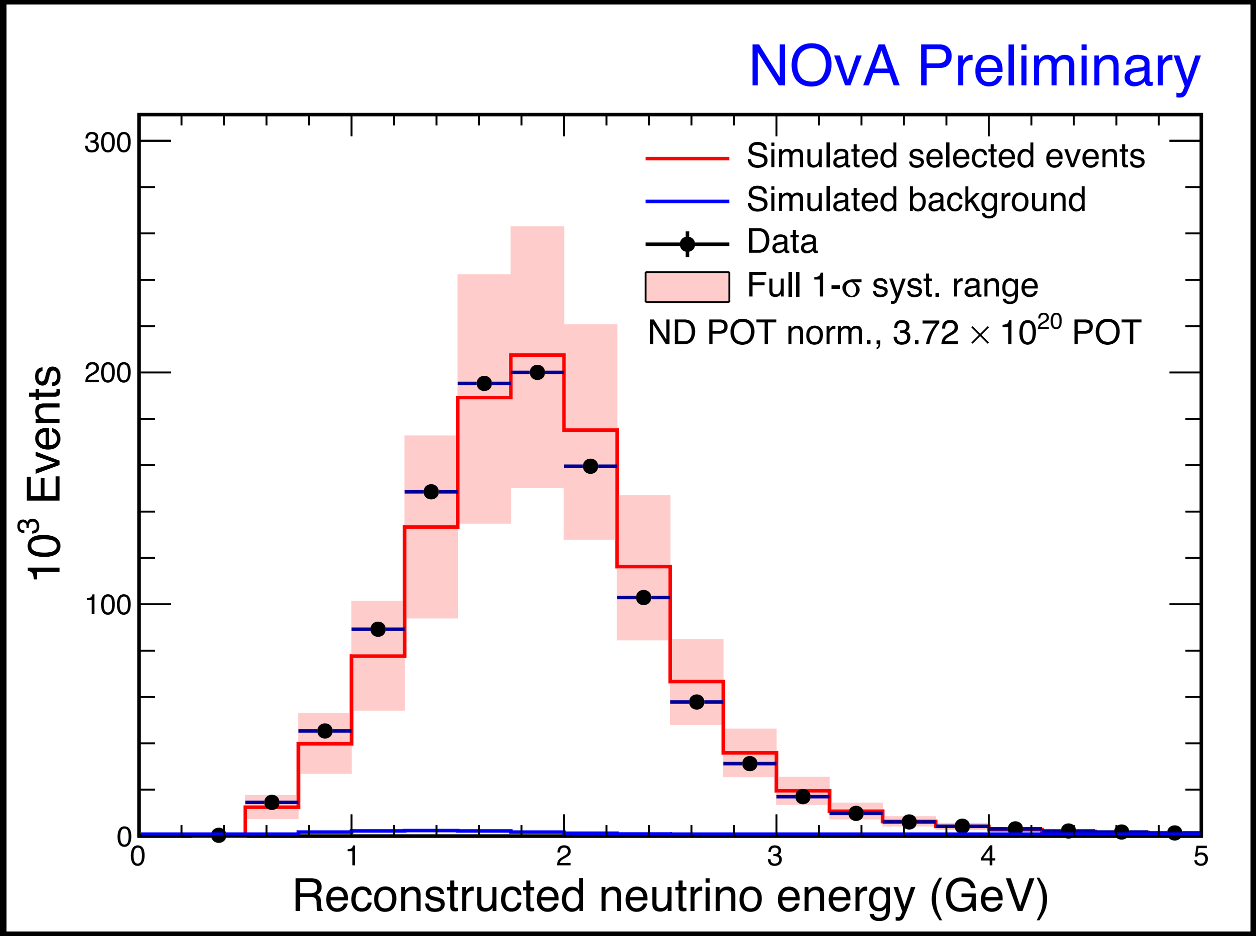

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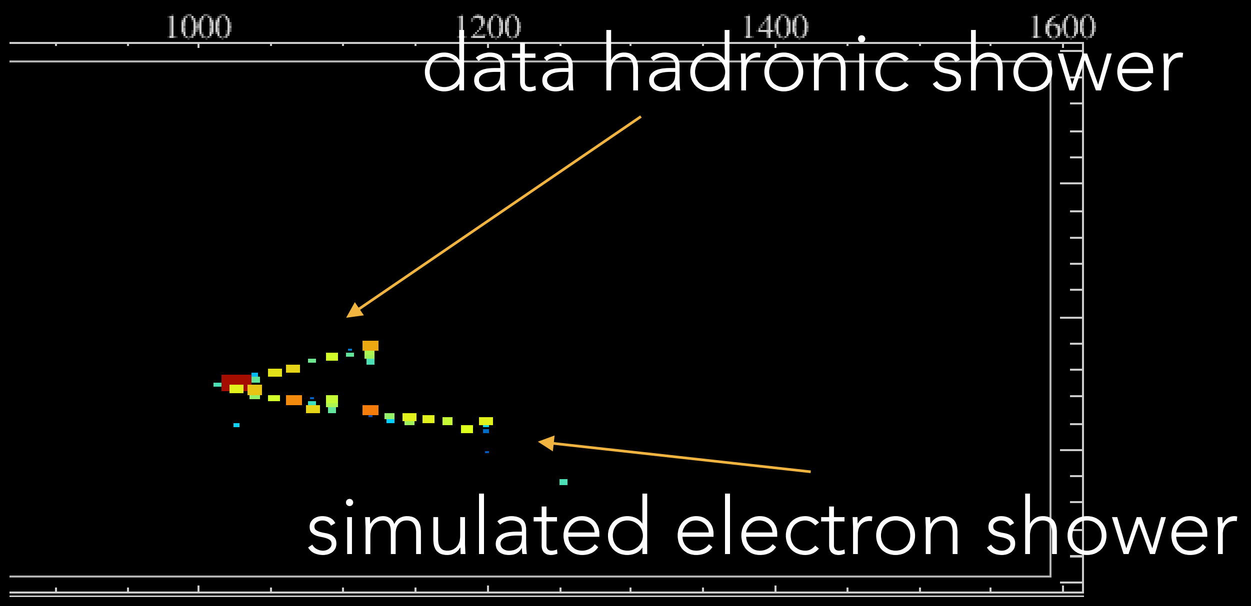
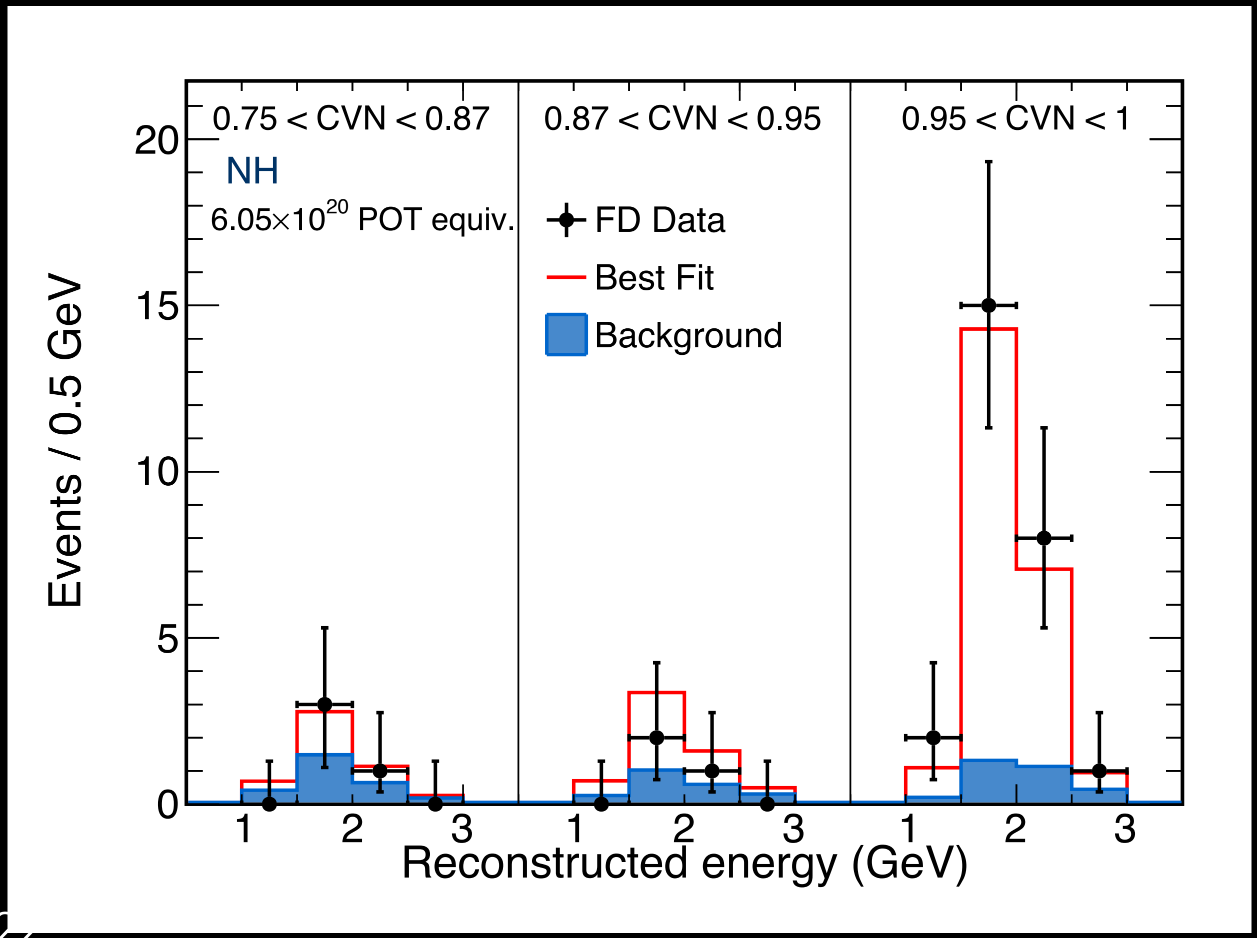
Knowing breakdown of efficiencies per neutrino interaction mode is important

COMBINED FAR DETECTOR PREDICTION

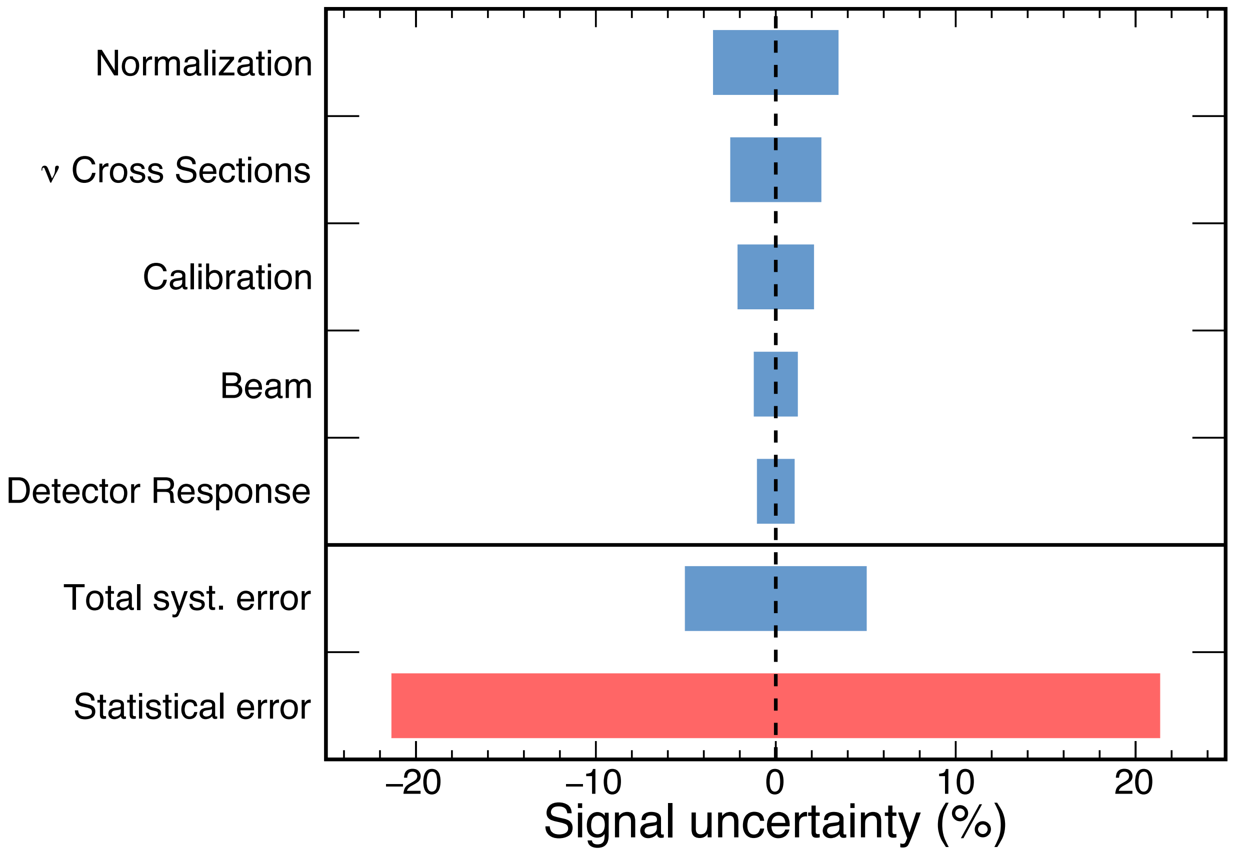
- Signal efficiency checked with hadronic shower data: muon removed data sample, replace simulated electron.
  - EM showers should be well modeled, all discrepancies would come from hadronic side.
  - NOvA finds ~1% data/MC difference when MEC included.
  - Detector response x hadronic model.
- Where do the model dependencies come from?
  - ND sees a different spectrum to FD.
  - ND is substantially smaller and thus containment sculpts kinematics.
  - Correcting for/estimating these effects leans on MC.

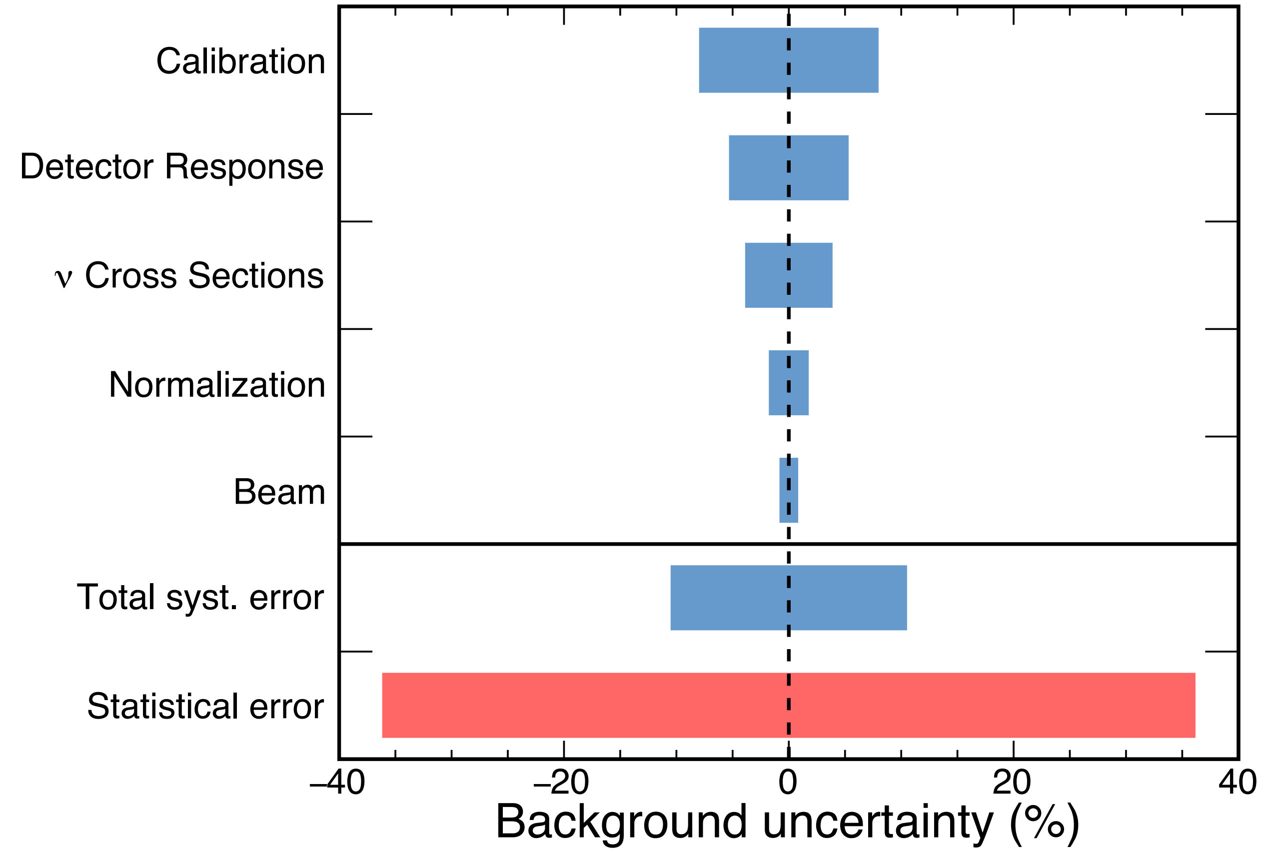




Backhouse - PINS 2017

SYSTEMATIC UNCERTAINTIES FOR APPEARANCE





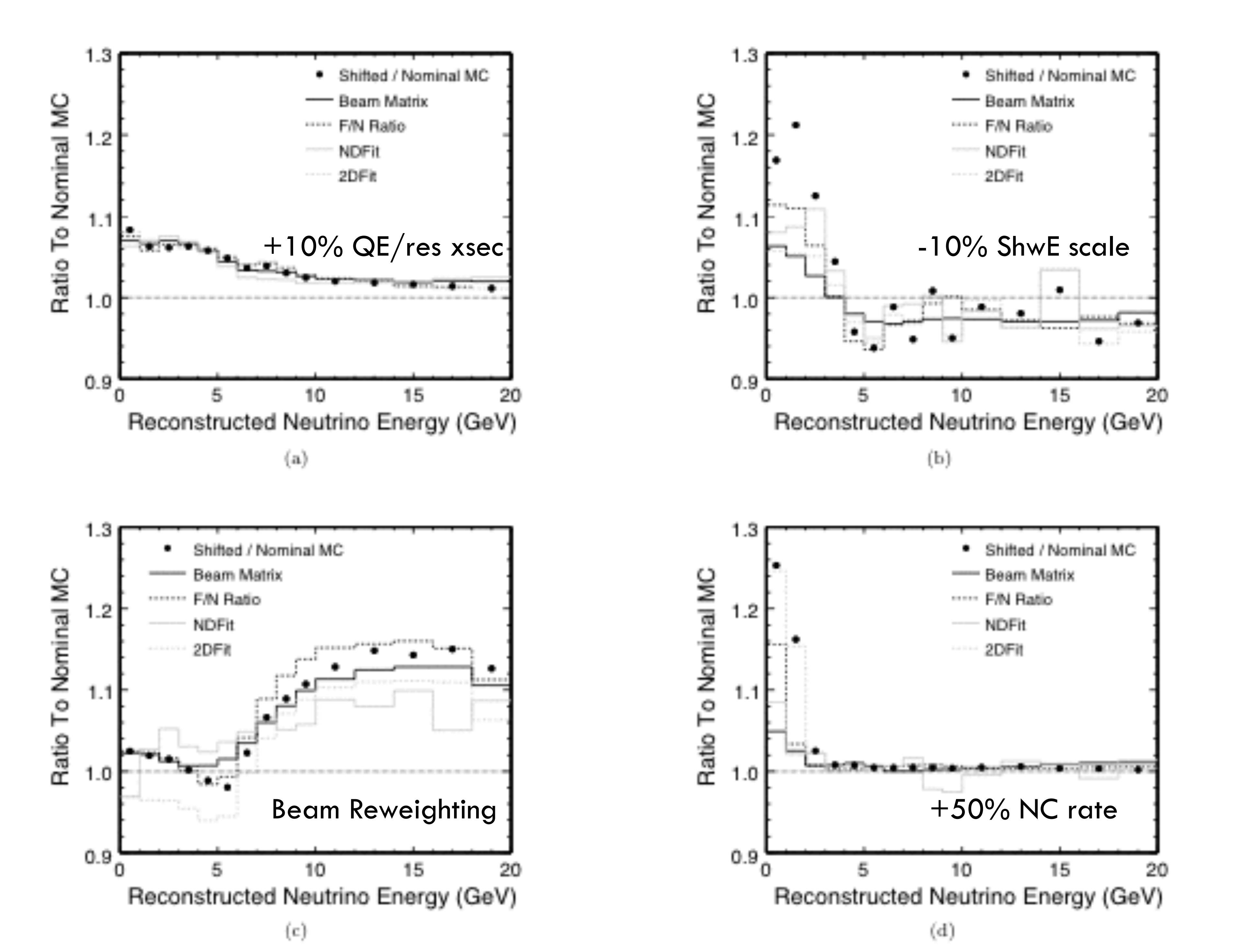
- Extrapolate FD predictions with special MC samples for each effect.
- Uncertainty quoted as difference between shifted and nominal predictions.
- Multiple sources of systematic error considered, including GENIE at 1 sigma plus MEC scale.
- Background effectively constrained using ND, from 30% to <5%.

MY NEAR DETECTOR WISH LIST

- The extrapolation Near to Far using functionally similar detectors allows for significant first order systematic uncertainties cancellations in flux x cross section and even detector response. It is a challenge to disentangle these. Therefore my ND wish list includes:
    - Excellent lepton particle ID/energy resolution
    - Excellent hadronic shower energy resolution
        - 4pi containment of hadronic showers
    - Same nucleus/material as far detector
        - Important for neutrino interaction surprises
    - Able to deal with flux/intensity at near site
    - Similar detector response than far detector (hard I know)

BACKUP

DIFFERENT EXTRAPOLATION MODELS
From MINOS

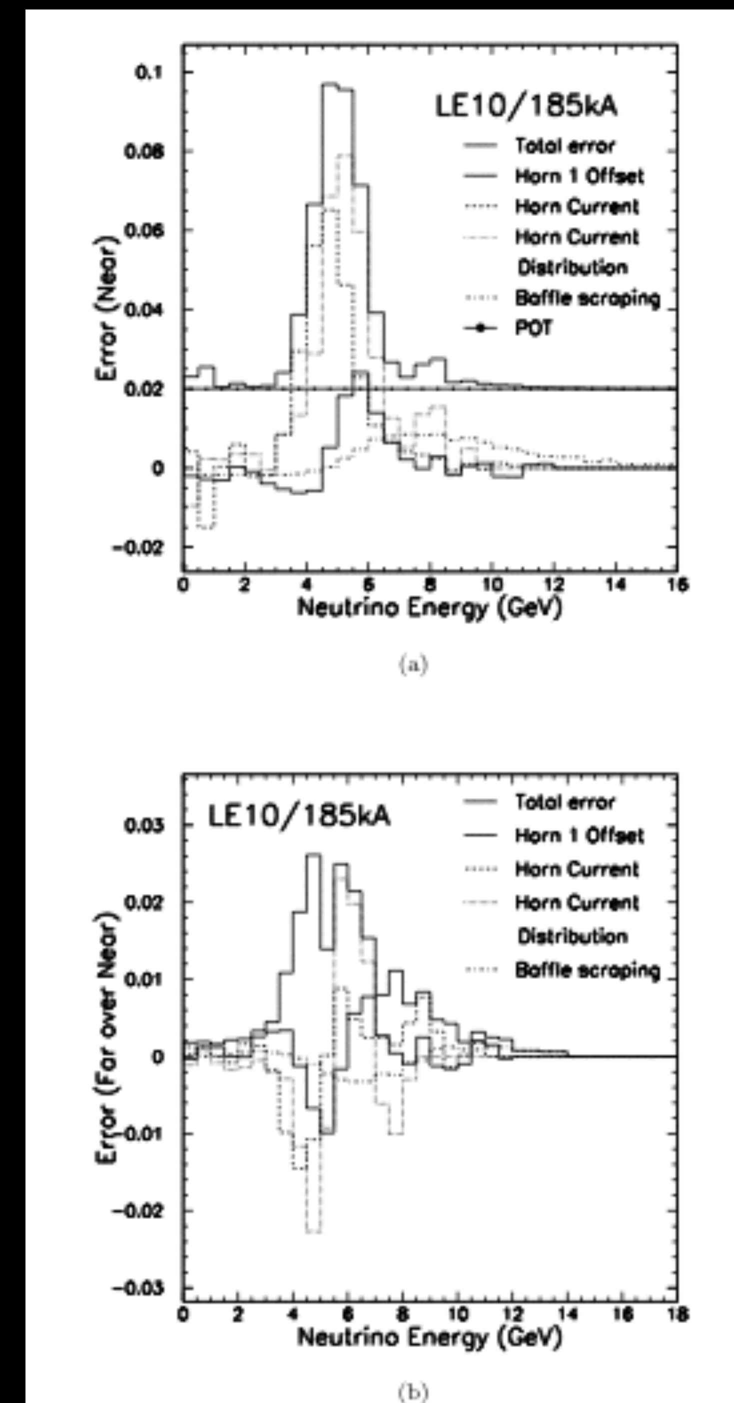


- Some uncertainties are more sensitive to different extrapolation methods (depends on knobs): F/N Ratio and NDFit are currently used by NOvA and T2K respectively.

Beam flux: systematics

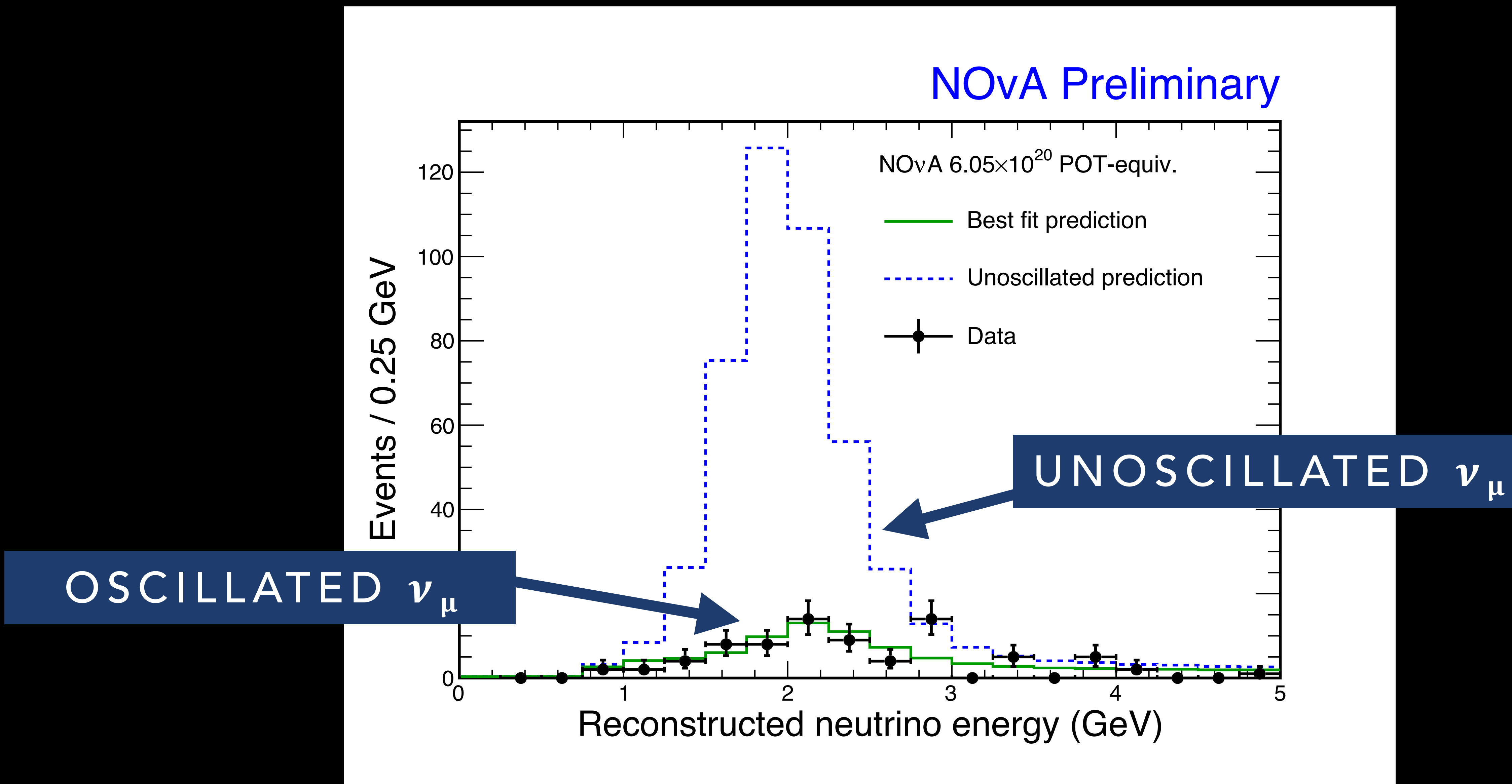
MINOS - on axis

- Additional flux uncertainties arise from focusing and alignment uncertainties.
- Errors in flux estimated using comparisons between nominal (pbeam) simulation and systematically offset simulation sets.
- Offsets determined from beam survey measurements, target scans, hadron/muon monitoring, etc. (Documented in R. Zwaska thesis, UT Austin, 2005).
- Uncertainties go from 10% total in Near only down to <3% at the peak for Far/Near.



P. Vahle SBL talk 2012

MUON NEUTRINO ENERGY SPECTRUM

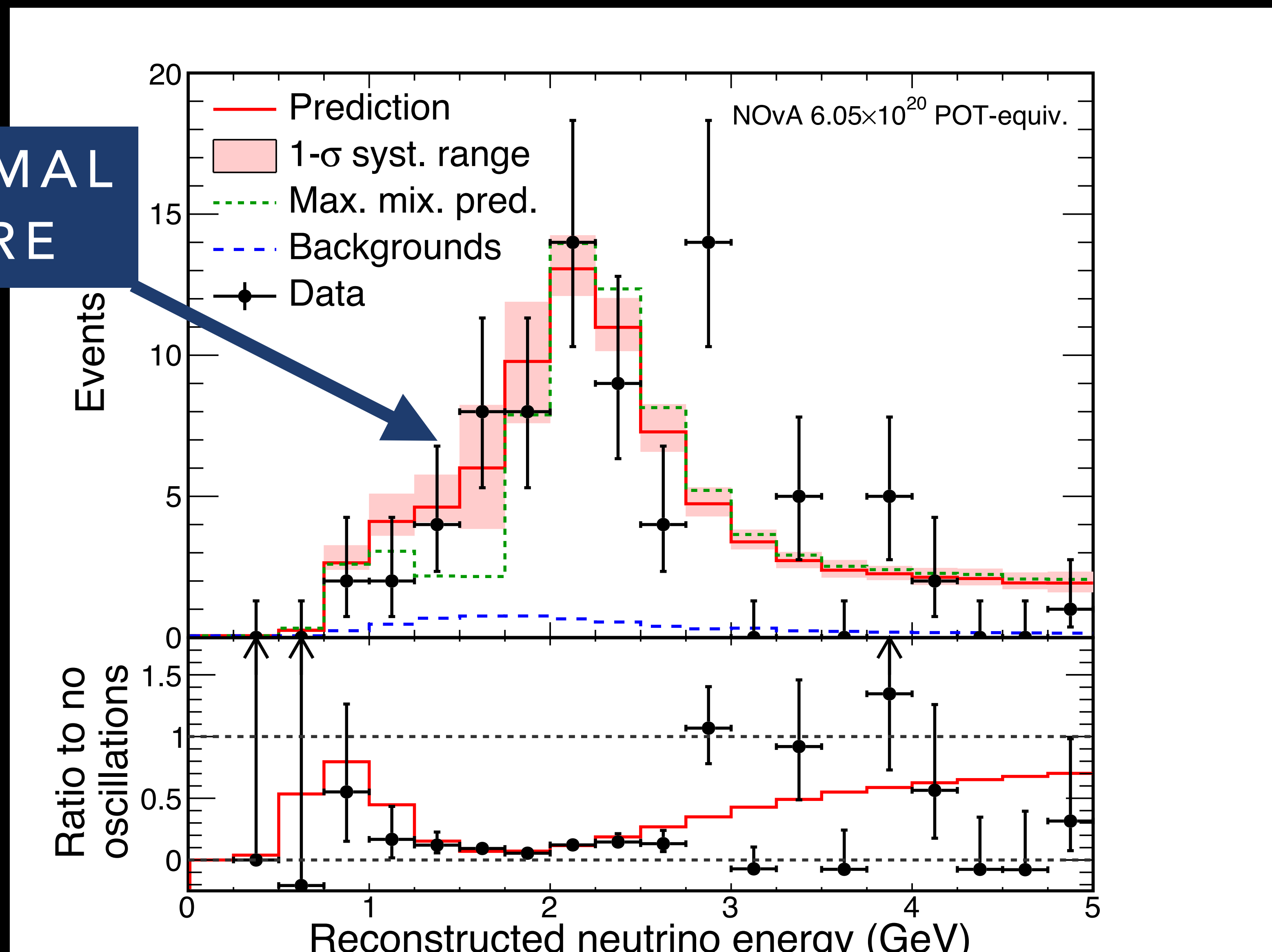


- Expect 473±30 events before oscillations.
- Observe 78 events (expect 82 at best fit oscillated prediction).

MUON NEUTRINO ENERGY SPECTRUM

zooming into the oscillated spectrum

NON MAXIMAL SIGNATURE



- Expect 473±30 events before oscillations.
- Observe 78 events (expect 82 at best fit oscillated prediction).

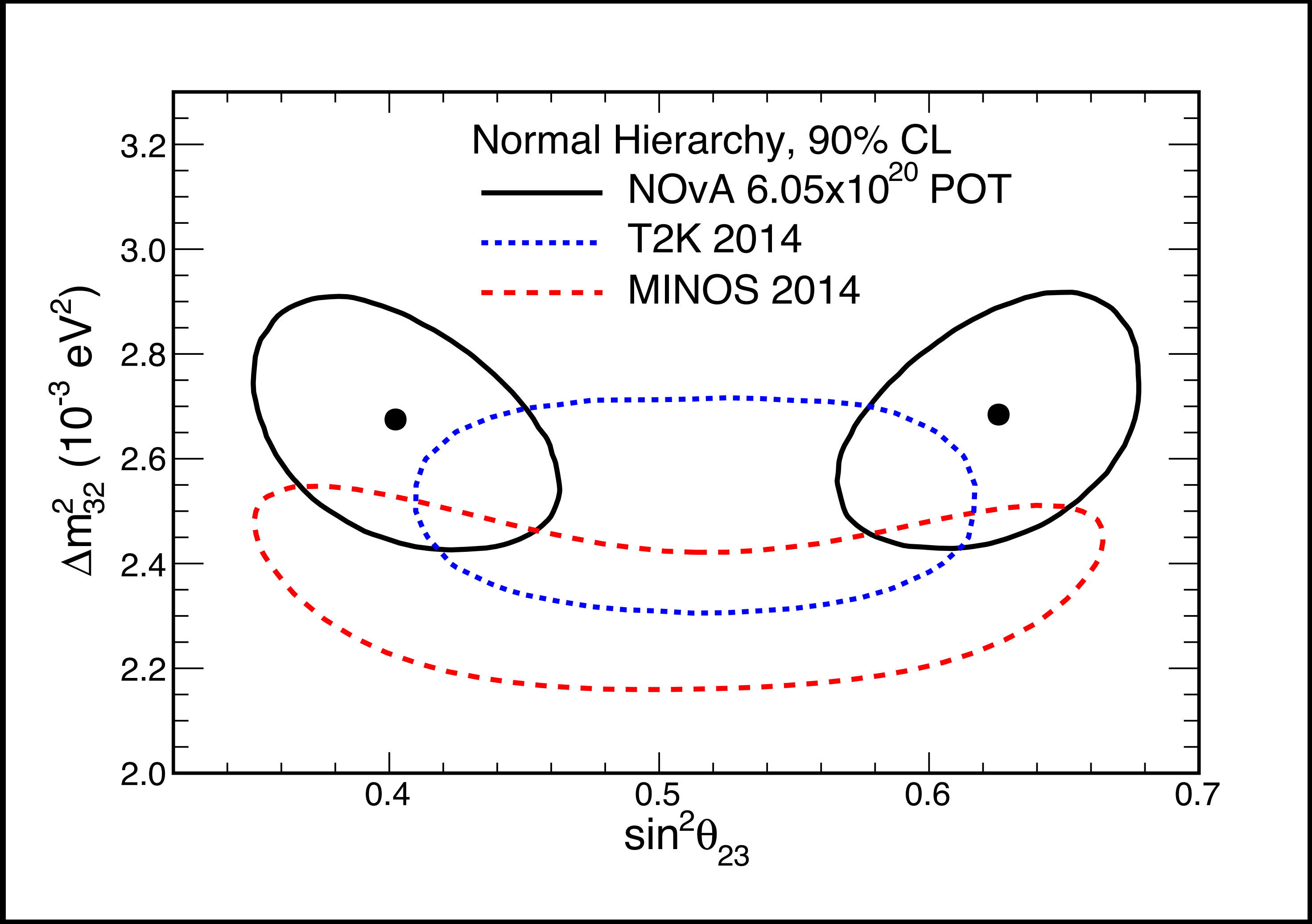
NOVA MUON NEUTRINO DISAPPEARANCE RESULTS

- A 3-flavor fit to the ν_μ selected spectrum provides the allowed parameter space.

- Dominant systematic effects:
  - Normalization, NC background, flux, muon and hadronic energy scales, cross section, detector response and noise.
- Parameter measurements (NH):

$$|\Delta m^2_{32}| = 2.67 \pm 0.11 \times 10^{-3} \mathrm{eV}^2$$

$$\sin^2\theta_{23} = 0.404^{+0.030}_{-0.022} (0.624^{+0.022}_{-0.030})$$

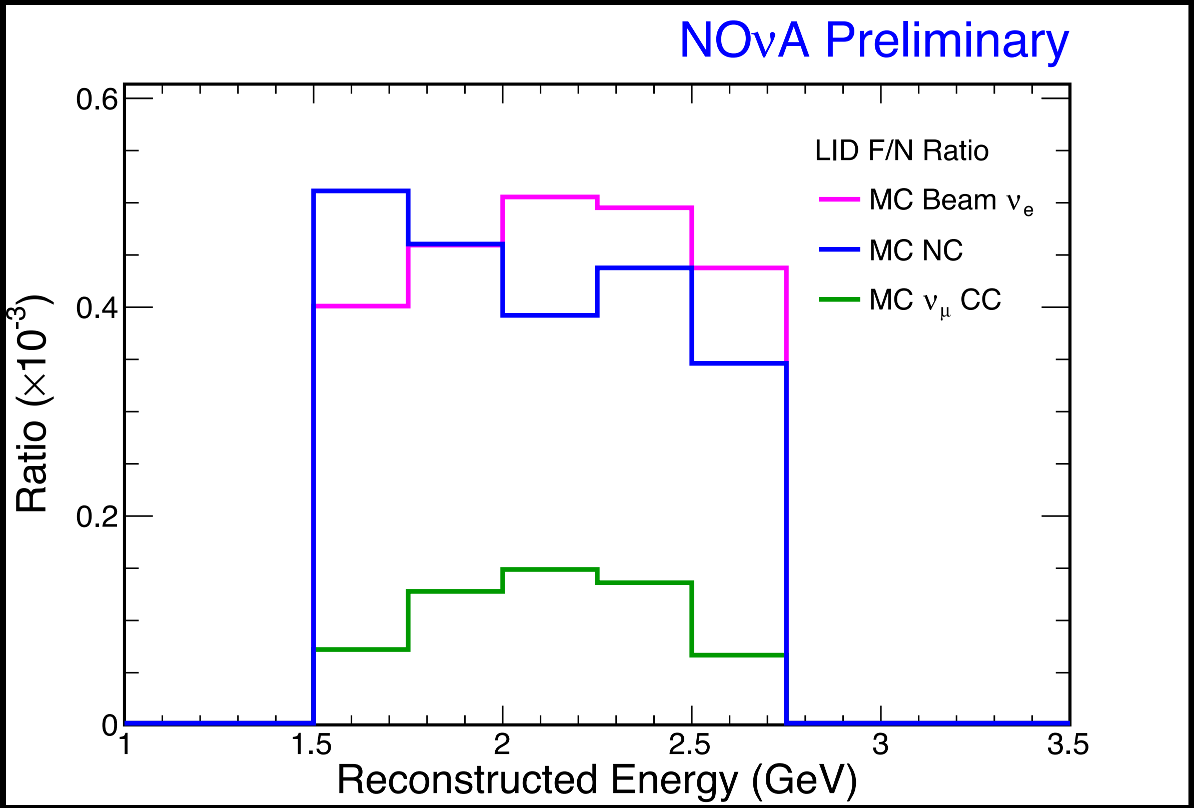


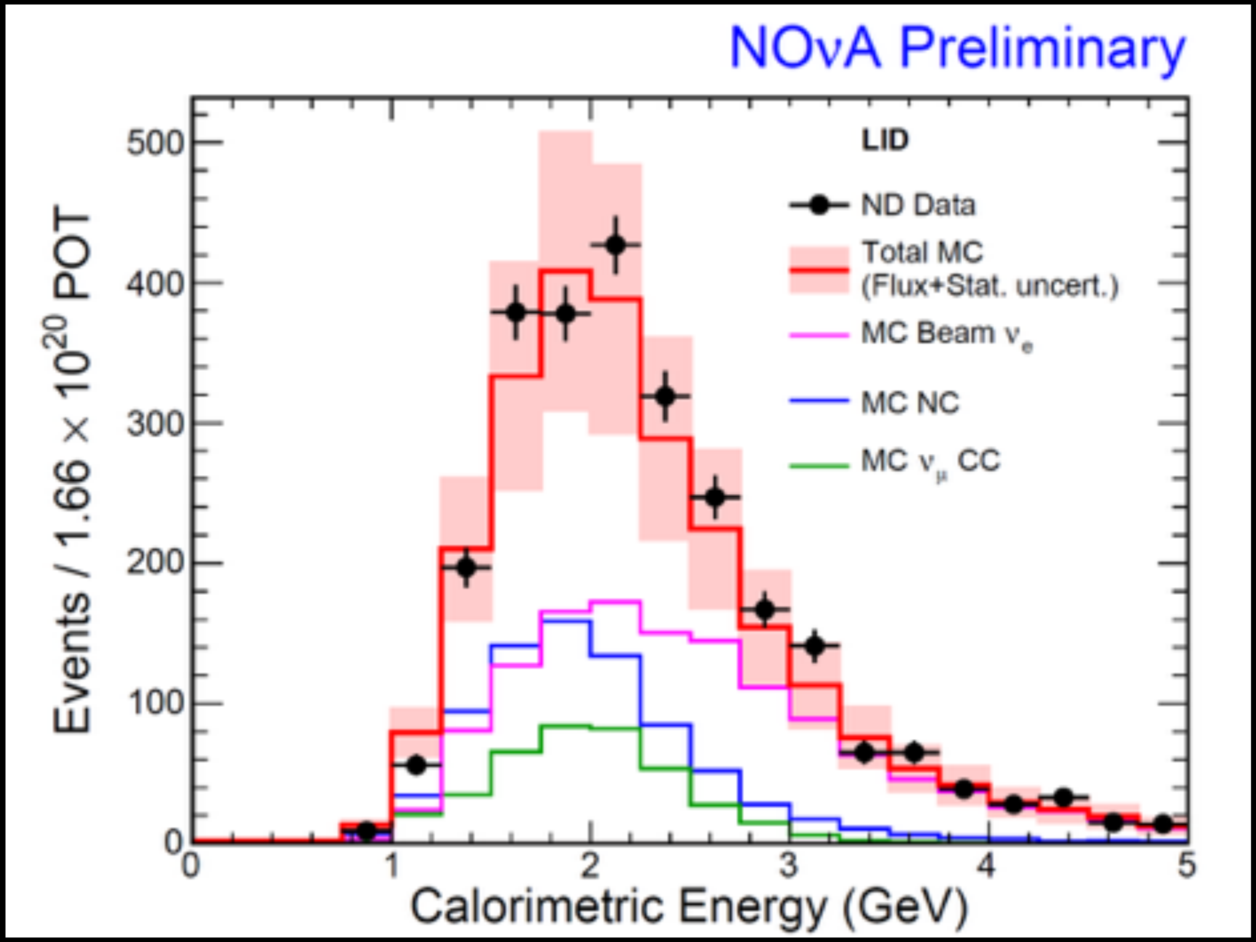
MAXIMAL MIXING EXCLUDED AT 2.6σ

arXiv:1701.05891 (accepted for publication in PRL)

PREDICTING THE BACKGROUND IN THE FD

- Calorimetric energy after electron neutrino selection (shown for NOvAs first analysis) shows good agreement.





- ND data is translated to FD background expectation in each energy bin, using Far/Near ratios from simulation.
- A small 5% excess in data was observed in the ND which was used as a correction to the FD background prediction.

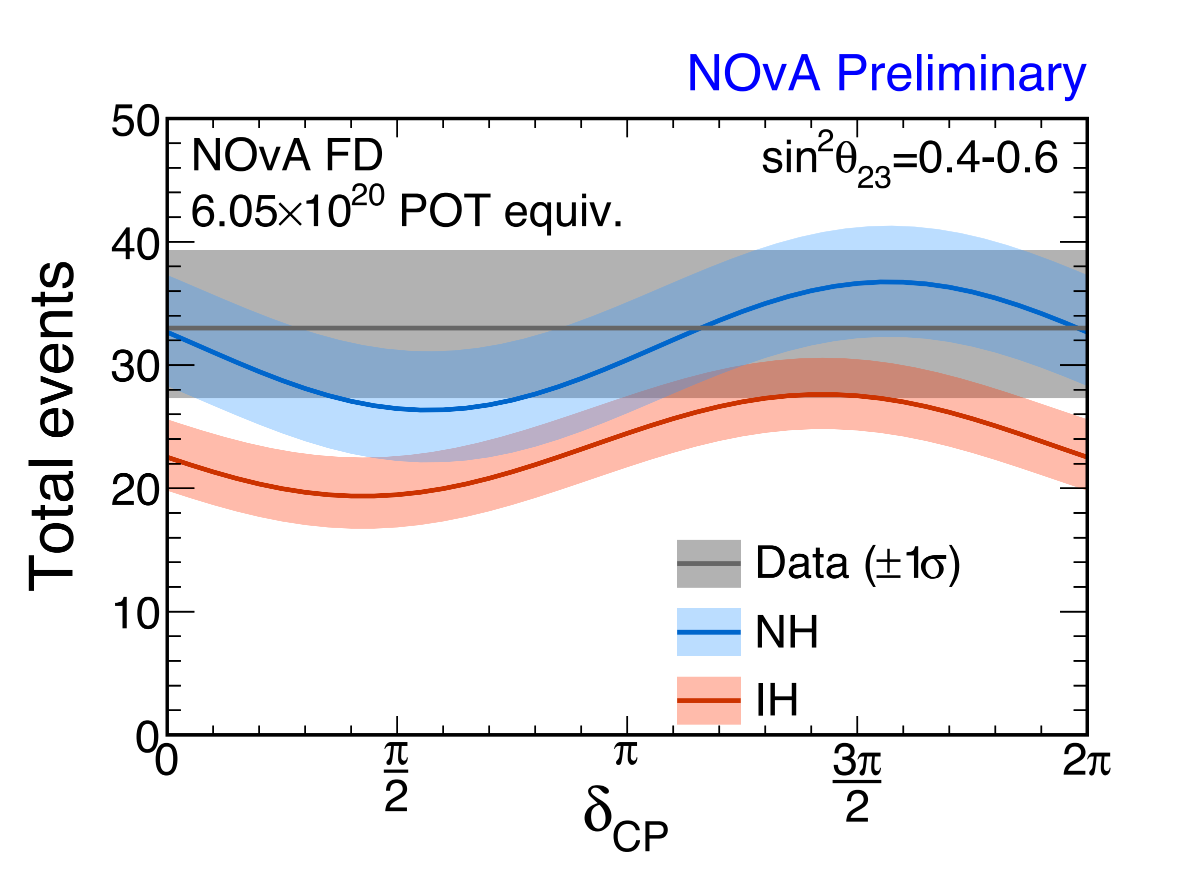
From NOvA's first analysis

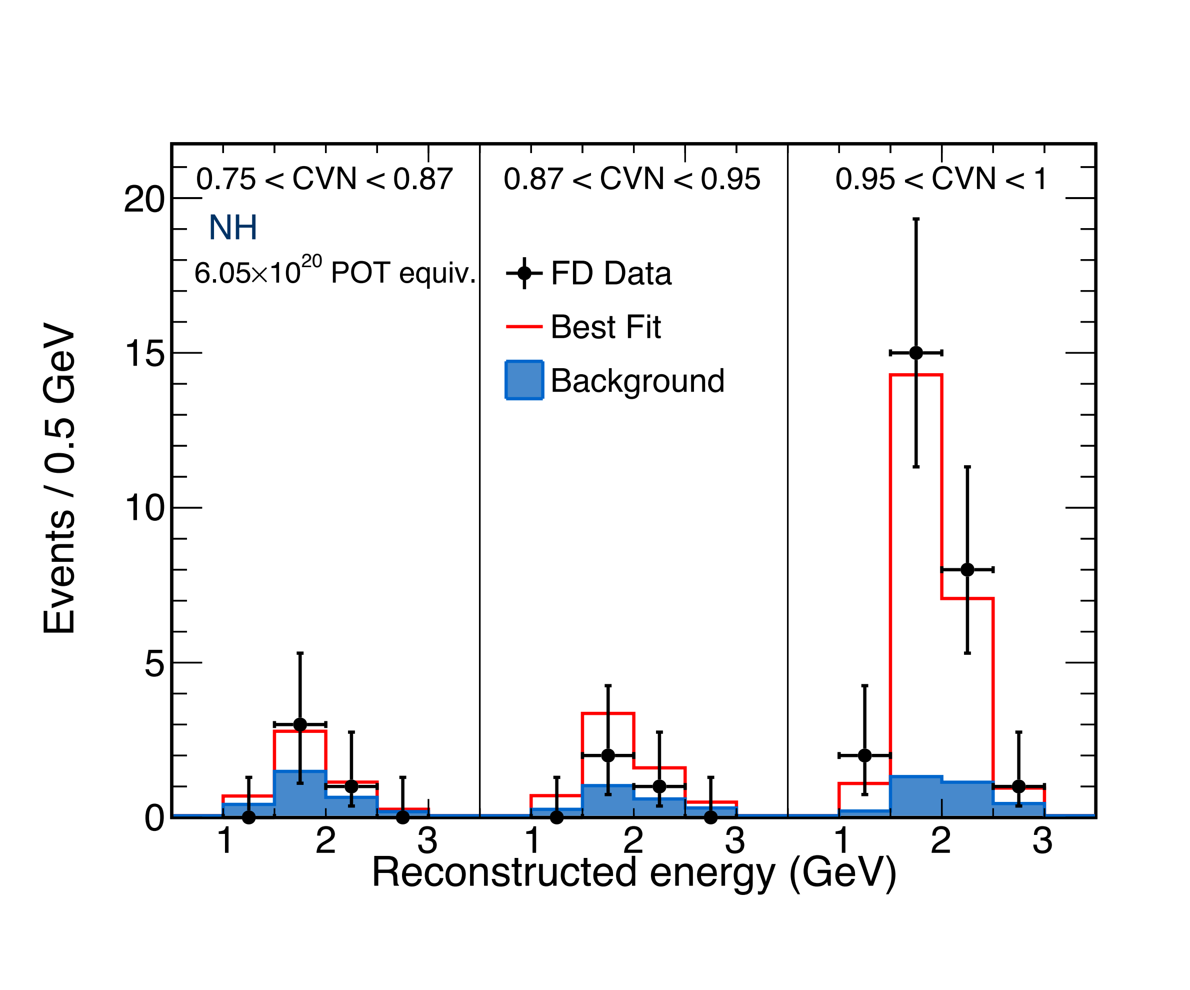
NOVA ELECTRON NEUTRINO APPEARANCE RESULTS

- Observe 33 events for 8.2 expected background events.
- Range of expectation (for maximal mixing):

NH, $3\pi/2$,	IH, $\pi/2$,
36	19

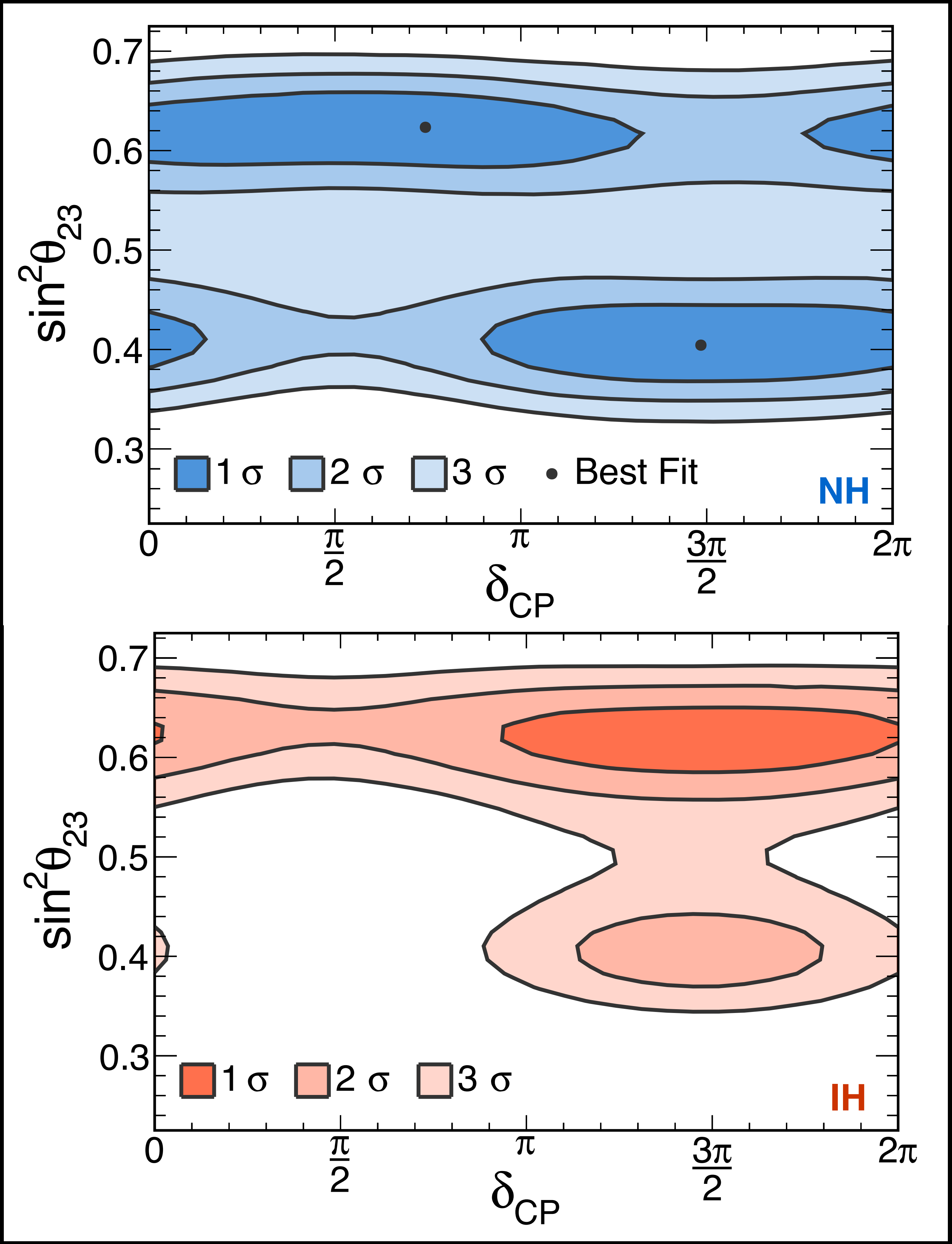
- **Electron neutrino appearance observed at > 8 σ.**





NOVA ELECTRON NEUTRINO APPEARANCE RESULTS

- Fitting the electron neutrino appearance spectrum with muon neutrino disappearance data which for NOvA hints at a non maximal mixing angle.
- Both octants and hierarchies are allowed at 1σ.
  - Very small χ^2 difference (0.47) between IH and NH.
- **NOvA sees a 3σ exclusion at IH, lower octant around δ_{CP}=π/2.**



LBNE systematic uncertainties

- The dominant systematic uncertainties on the appearance signal prediction.
- For the MINOS uncertainties absolute refers to the total uncertainty.
- The LBNE uncertainties are the total expected uncertainties on the appearance signal which include both correlated and uncorrelated uncertainties in the three-flavor fit.

Source of Uncertainty	MINOS Absolute/ν_e	T2K ν_e	LBNE ν_e	Comments
Beam Flux after N/F extrapolation	3%/0.3%	2.9%	2%	MINOS is normalization only. LBNE normalization and shape highly correlated between ν_μ/ν_e.
		Detector effects		
Energy scale (ν_μ)	7%/3.5%	included above	(2%)	Included in LBNE ν_μ sample uncertainty only in three-flavor fit. MINOS dominated by hadronic scale.
Absolute energy scale (ν_e)	5.7%/2.7%	3.4% includes all FD effects	2%	Totally active LArTPC with calibration and test beam data lowers uncertainty.
Fiducial volume	2.4%/2.4%	1%	1%	Larger detectors = smaller uncertainty.
		Neutrino interaction modeling		
Simulation includes: hadronization cross sections nuclear models	2.7%/2.7%	7.5%	$\sim 2\%$	Hadronization models are better constrained in the LBNE LArTPC. N/F cancellation larger in MINOS/LBNE. X-section uncertainties larger at T2K energies. Spectral analysis in LBNE provides extra constraint.
Total	**5.7%**	**8.8%**	**3.6 %**	**Uncorrelated ν_e uncertainty in full LBNE three-flavor fit = 1-2%.**