EXTRAPOLATION TECHNIQUE AND SYSTEMATIC UNCERTAINTIES IN THE NOVA MUON NEUTRINO DISAPPEARANCE ANALYSIS

Meeting of Department of Particles and Fields, Ann Arbor
August 7th 2015

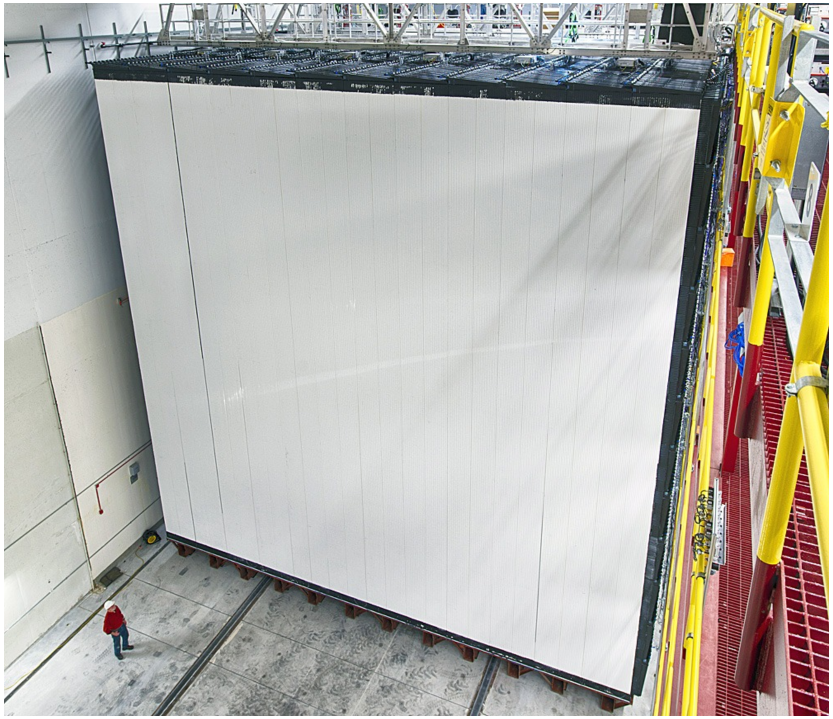
Louise Suter, Argonne National Laboratory
for the NOvA collaboration

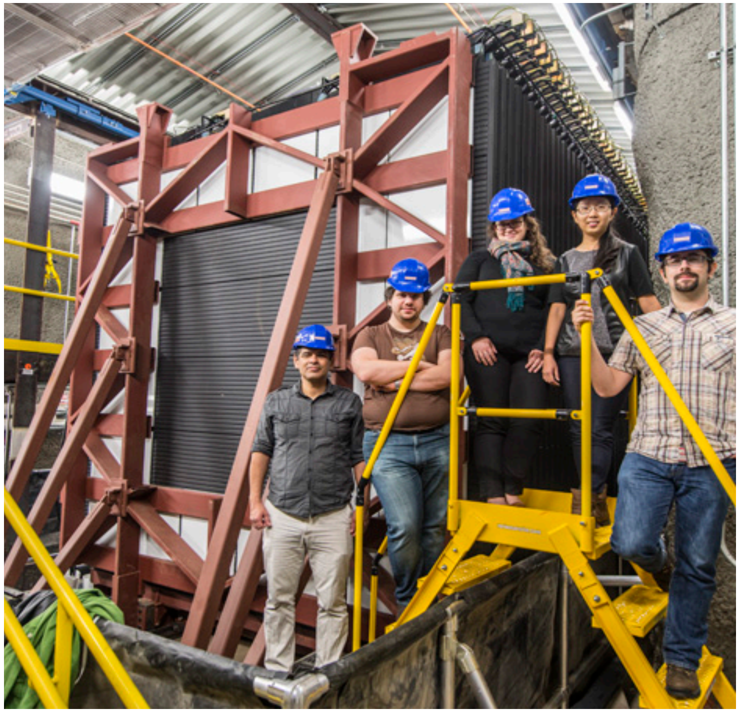
NOvA

Argonne
NATIONAL LABORATORY

Far Detector

Near Detector



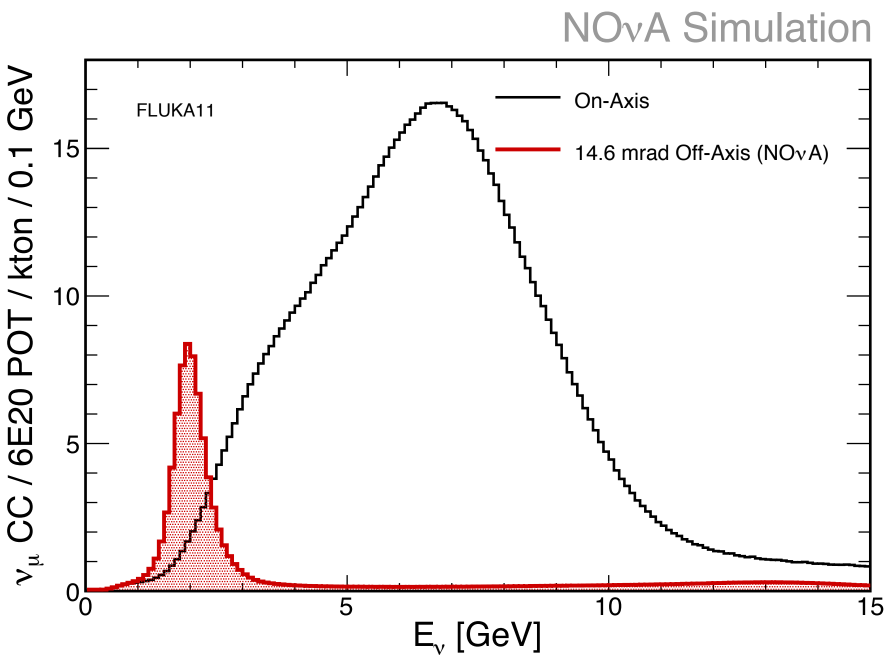


Two identical detectors

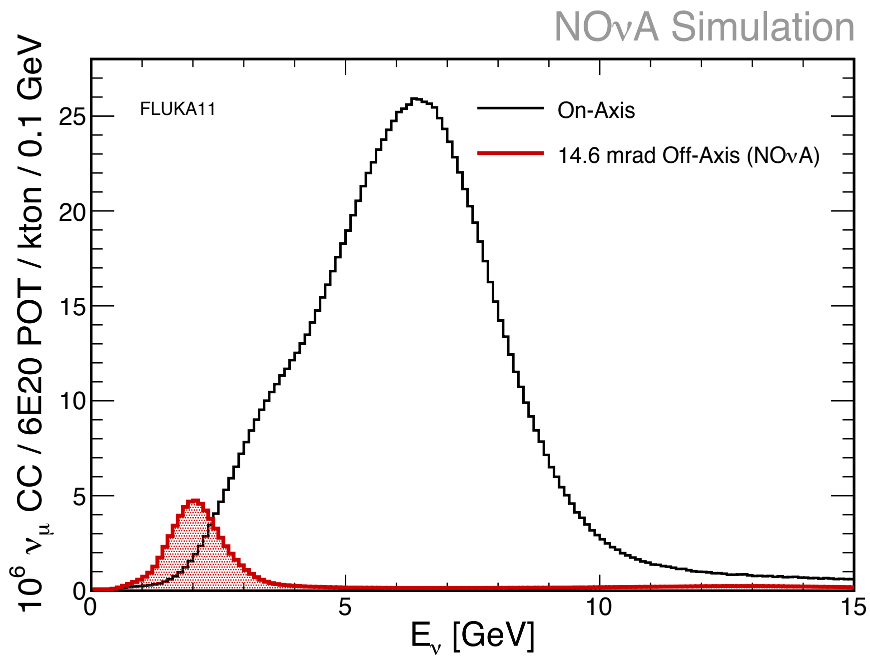
- Measure ν rates after oscillation
- **Use of a ratio measurement allows for cancelation of most systematics**

- Large flux used to characterize ν beam before oscillation
- Use data to predict expected rate at FD

Far Detector



Near Detector

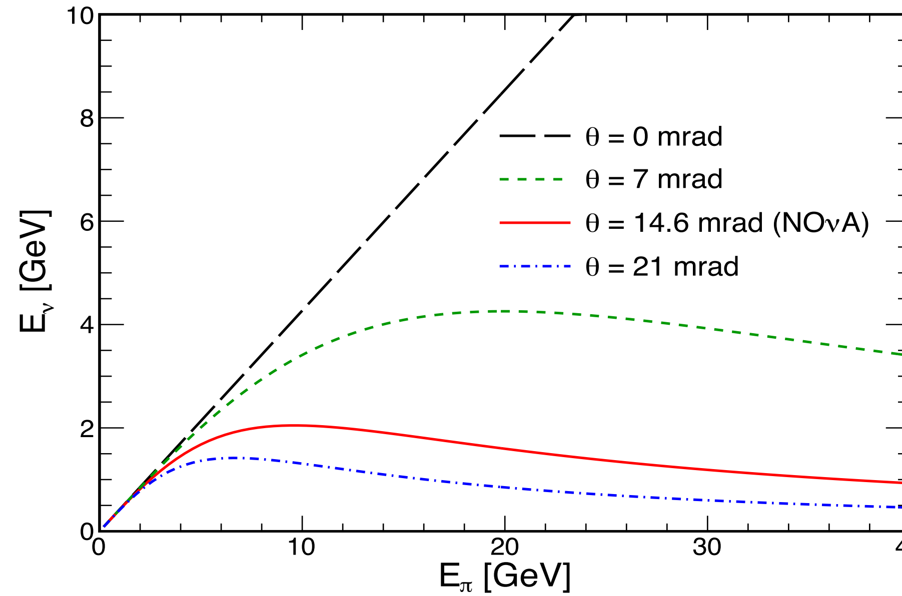


Difference in flux

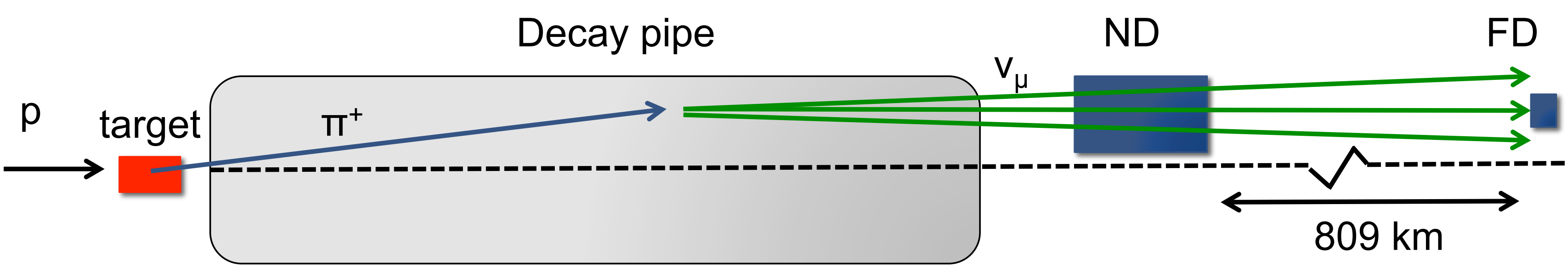
- Measure ν rates after oscillation
- **Use of a ratio measurement allows for cancelation of most systematics**

- Large flux used to characterize ν beam before oscillation
- Use data to predict expected rate at FD

- The ND and FD have similar but not identical spectrum
- Neutrino energy relies on the angle between π decay and ν interaction in detector
  - Off-axis the dependence on pion energy becomes flat
- The ND sees decays from a broader range of angles, whereas the FD sees a point source

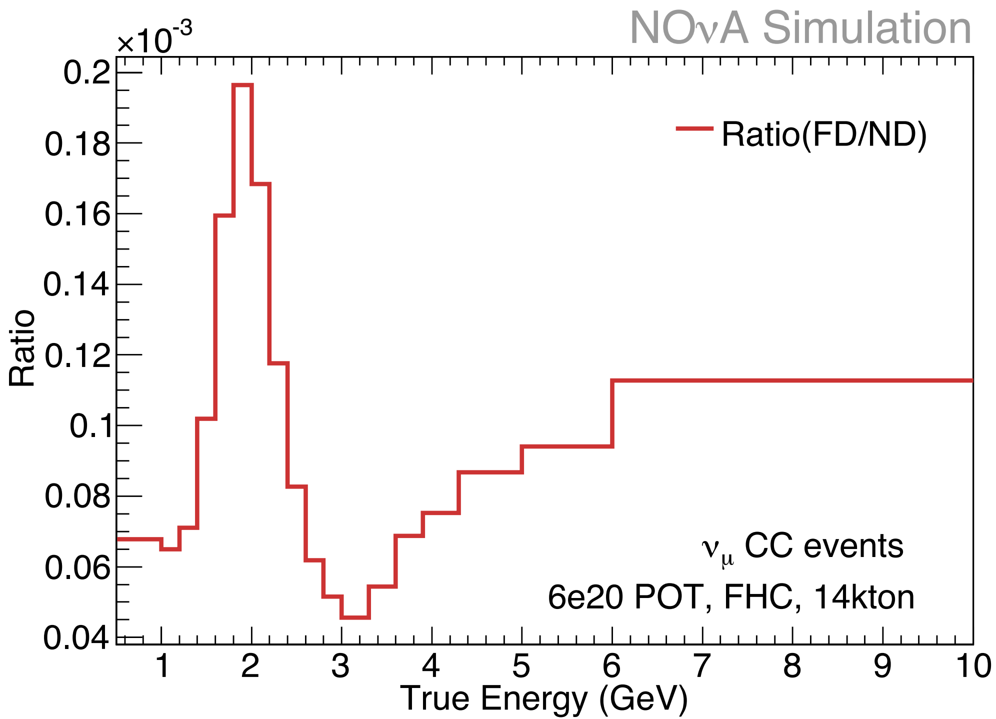


$$E_\nu = \frac{\left(1 - \frac{m_\mu^2}{m_{\pi,K}^2}\right) E_{\pi,K}}{1 + \gamma^2\theta^2}$$



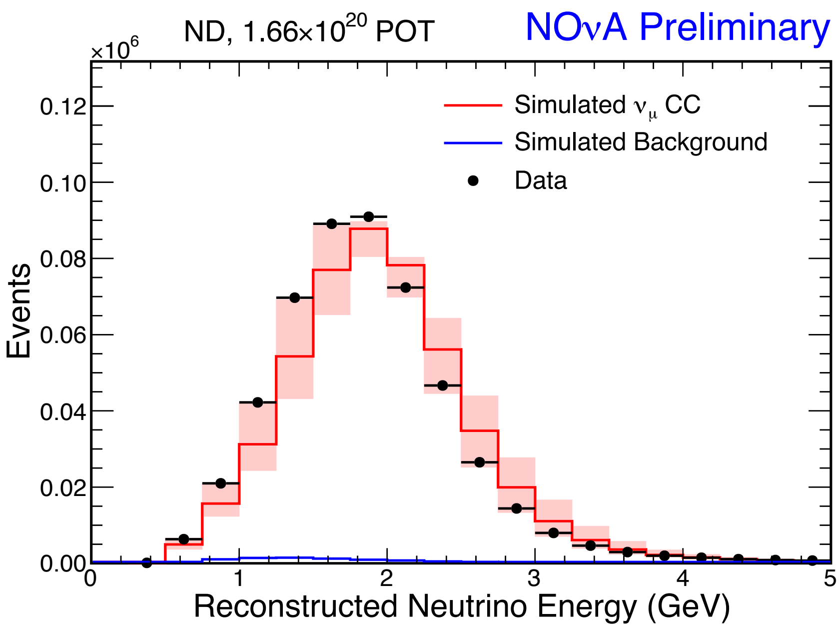
Extrapolation method

- Having a ND enables a data-driven method to predict the ν_μ energy spectrum at the FD
  - Removes the dependence on MC simulation of the flux
  - Identical detector construction cancels detector dependent systematic uncertainties
- Bin-by-bin direct extrapolation using Far/Near ratio method



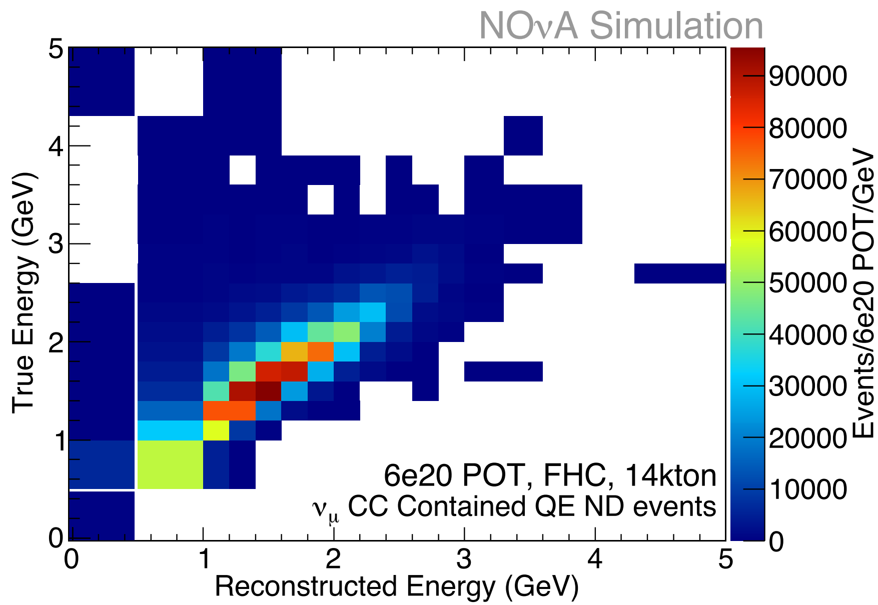
The Far/Near ratio extrapolation method

1. Starting from observed ND reconstructed energy spectrum
2. Use simulated ND migration matrix to transform to true energy spectrum
3. Apply FD/ND flux ratio
4. Apply oscillation prediction (or null prediction)
5. Use FD migration matrix to translate back to reconstructed energy



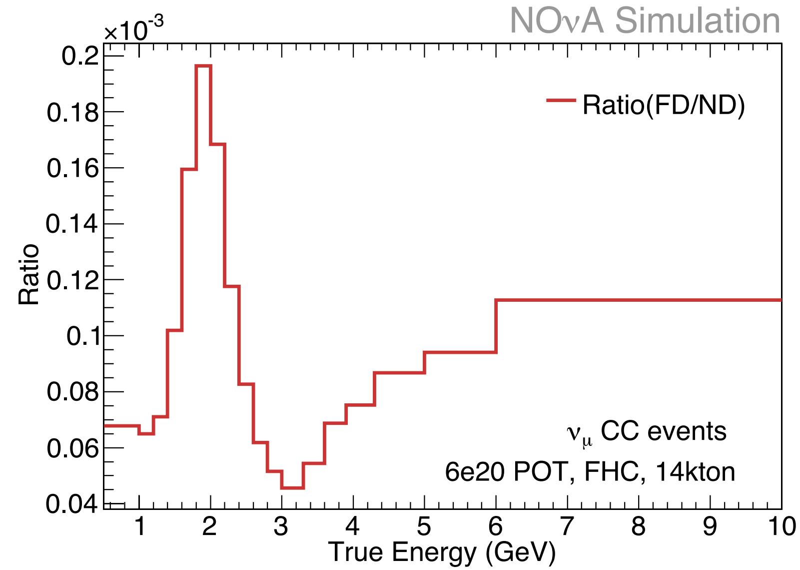
The Far/Near ratio extrapolation method

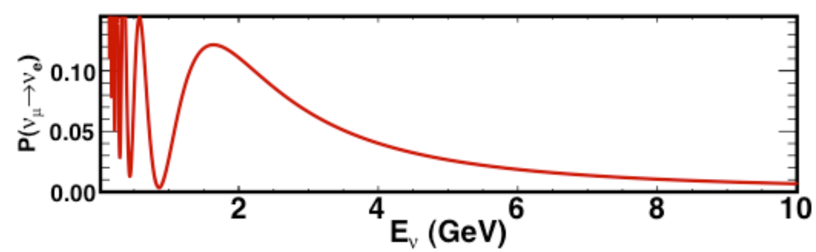
1. Starting from observed ND reconstructed energy spectrum
2. Use simulated ND migration matrix to transform to true energy spectrum
3. Apply FD/ND flux ratio
4. Apply oscillation prediction (or null prediction)
5. Use FD migration matrix to translate back to reconstructed energy



The Far/Near ratio extrapolation method

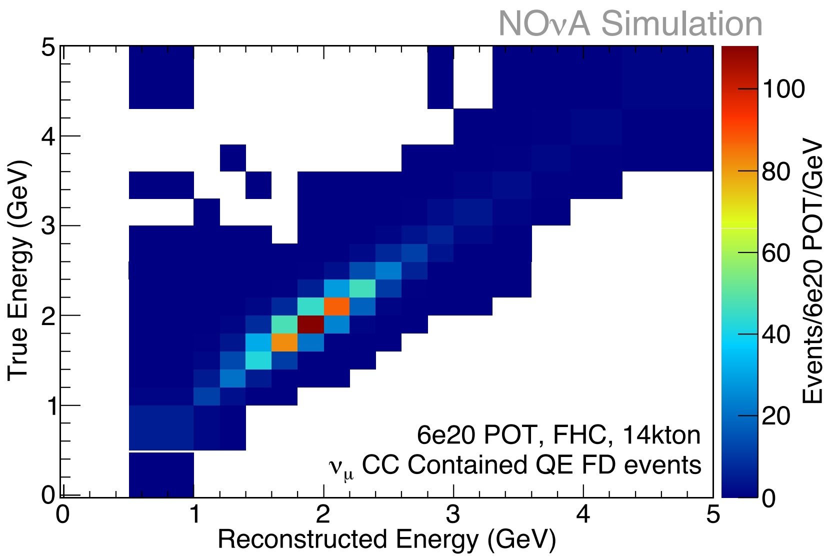
1. Starting from observed ND reconstructed energy spectrum
2. Use simulated ND migration matrix to transform to true energy spectrum
3. Apply FD/ND flux ratio
4. Apply oscillation prediction (or null prediction)
5. Use FD migration matrix to translate back to reconstructed energy





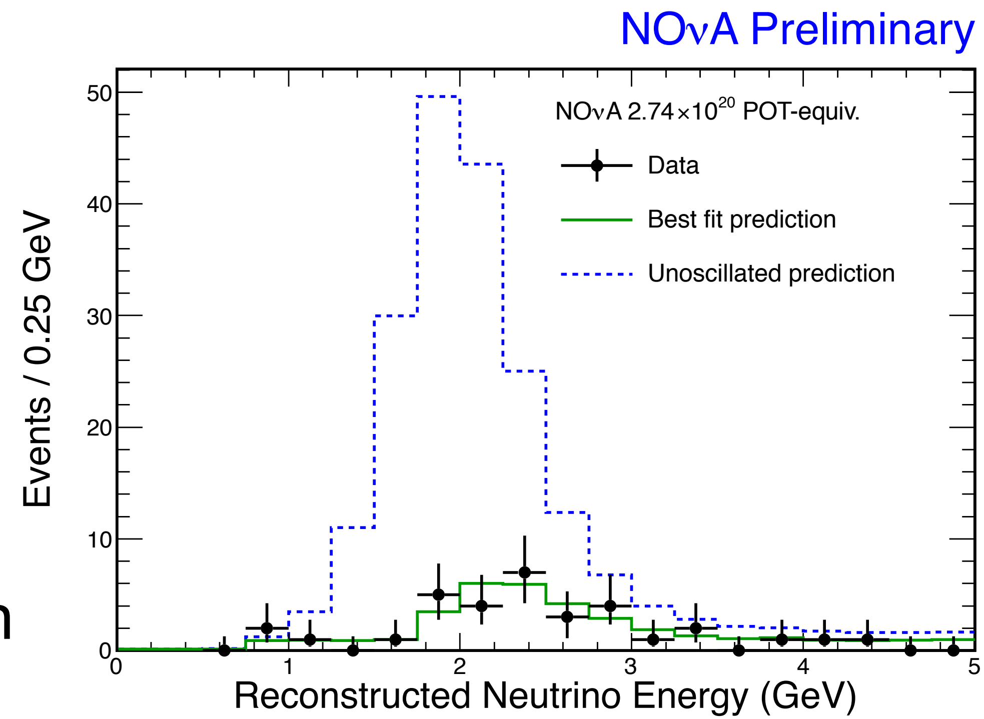
The Far/Near ratio extrapolation method

1. Starting from observed ND reconstructed energy spectrum
2. Use simulated ND migration matrix to transform to true energy spectrum
3. Apply FD/ND flux ratio
4. Apply oscillation prediction (or null prediction)
5. Use FD migration matrix to translate back to reconstructed energy



Predictions and systematic uncertainties

- To extract oscillation parameters we minimize χ^2 between observed FD data best fit and ND prediction under different oscillation predictions
- All uncertainties are included in producing best fit
- Full three flavor parameterization is used, with the other oscillation parameters and their uncertainties marginalized over



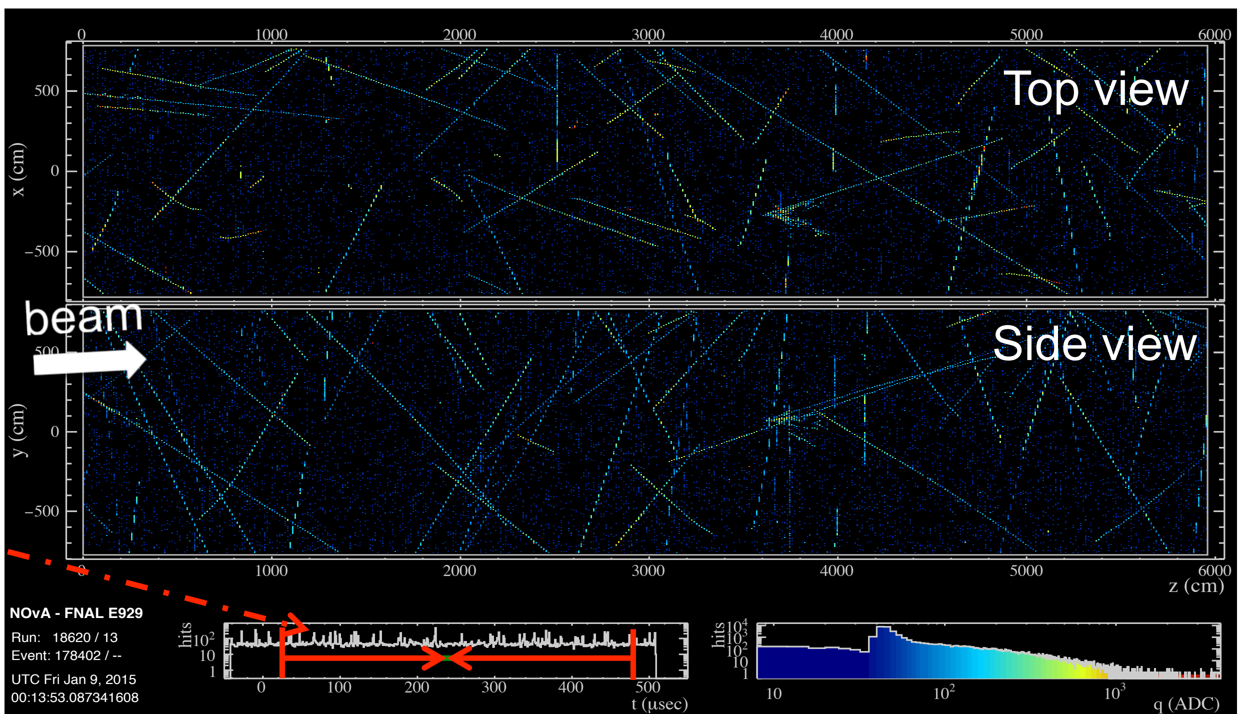
Feldman-Cousins corrections will be included for future iterations

Backgrounds uncertainties

- Neutral Current and ν_τ backgrounds are estimated from simulation. 100% uncertainty taken on these small rates

- Rate of cosmic events is determined from minimum-bias data outside the neutrino beam spill
- Statistical uncertainty of sample is negligible thanks to having a much larger sample larger minimum-bias sample (35x) than beam sample

Large minimum-bias window surrounding beam spill

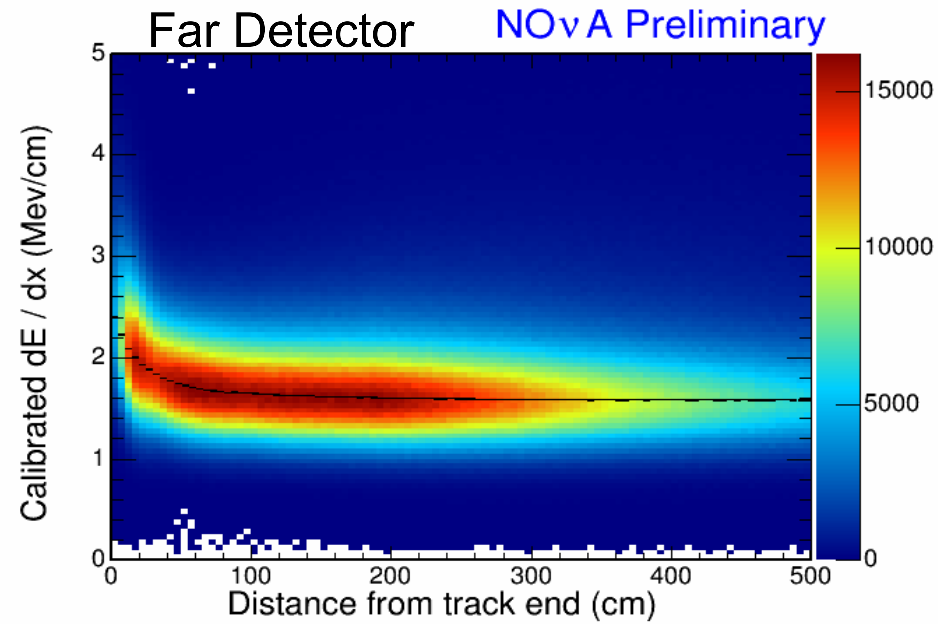


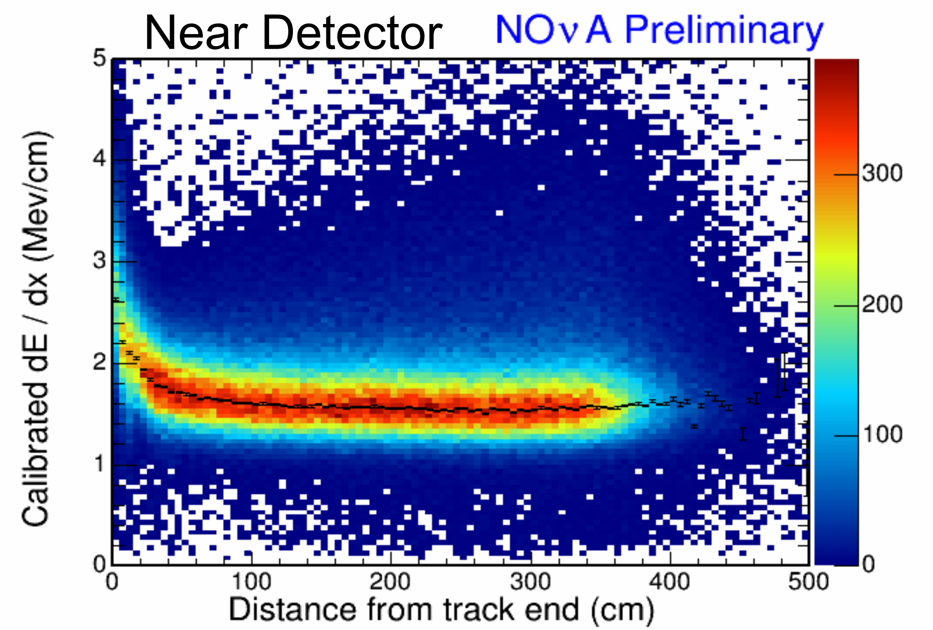
Calibration uncertainty

Hadronic Energy Scale

- Stopping muons provide standard candle for setting absolute energy scale
- Uncertainty estimated from maximum difference between the multiple probes of calibration available propagated through the full analysis framework
  - Michele e^- spectrum, π^0 mass, dE/dx of μ, p

5% percent absolute and relative calibration uncertainty

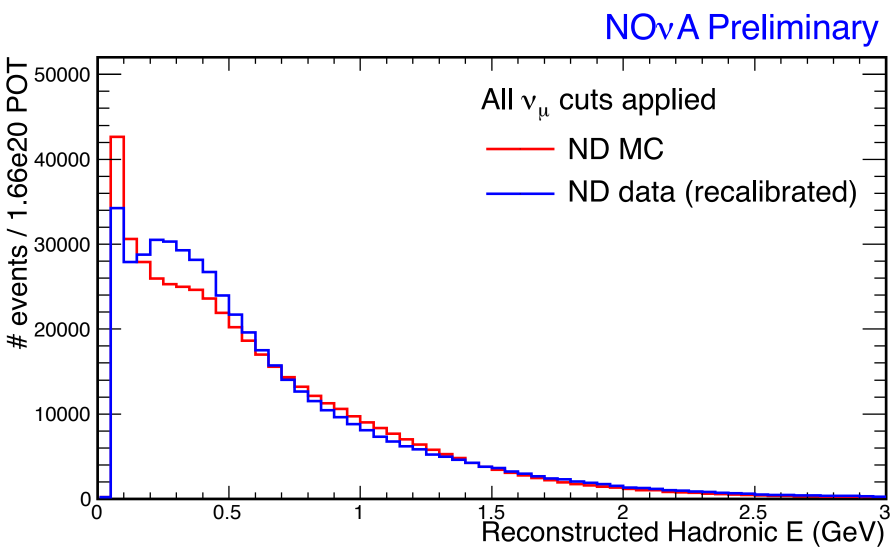


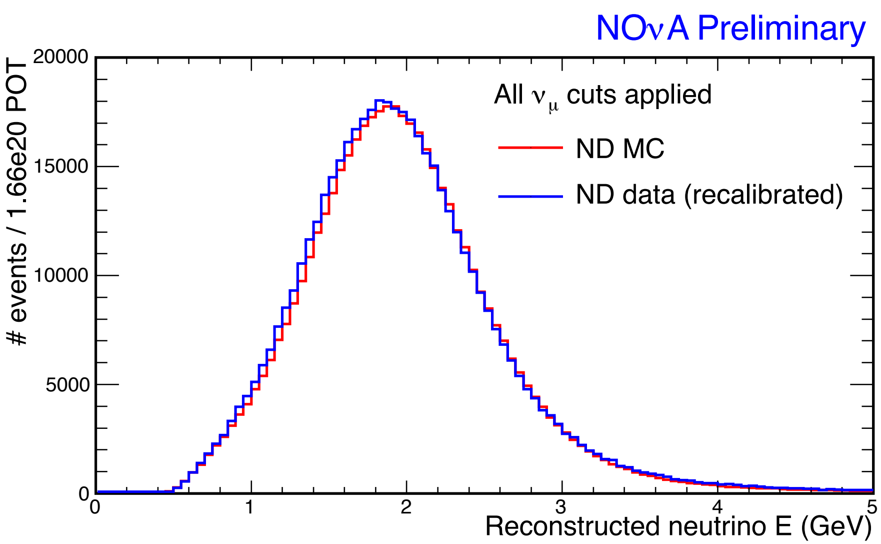


Calibration uncertainty

Absolute hadronic energy scale

- Determine 21% hadronic energy correction (6% on E_ν) using ND data
- Hadronic energy scale determined from tuning data to very well known off-axis E_ν energy peak
- We conservatively take a 100% absolute uncertainty on this correction
- This is our largest systematic uncertainty





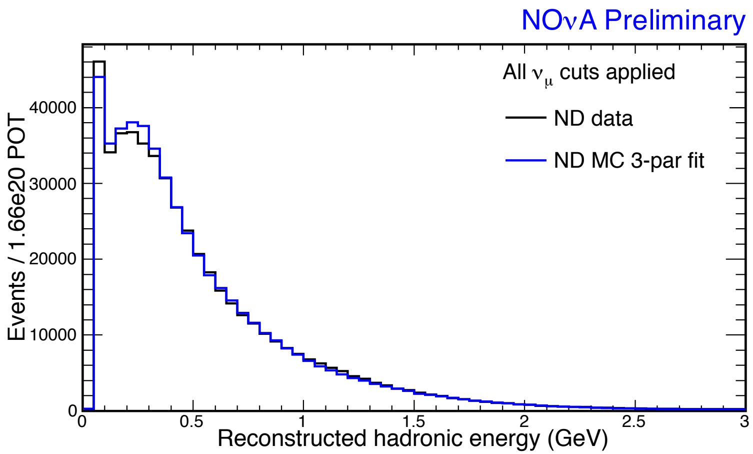
Combined to give a 22% total absolute hadronic energy uncertainty

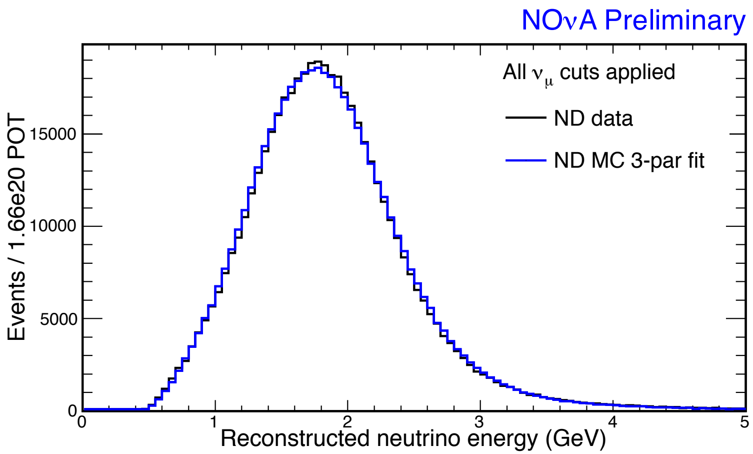
Calibration uncertainty

Relative hadronic energy scale

- Estimate relative uncertainty due to the different detector acceptances
- As 21% scale is calculated using ND data may be optimized for only ND
- Investigated by allowing the normalization and the energy scale of DIS, RES and QE events (as defined by GENIE) to float
- Do a three parameter simultaneous fit of E_{μ}, E_{had} and normalization
- Take the difference between the one-parameter scaling used and this interaction-dependent scaling to determine the relative uncertainty

Determine a 2% relative uncertainty and 1% relative normalization uncertainty



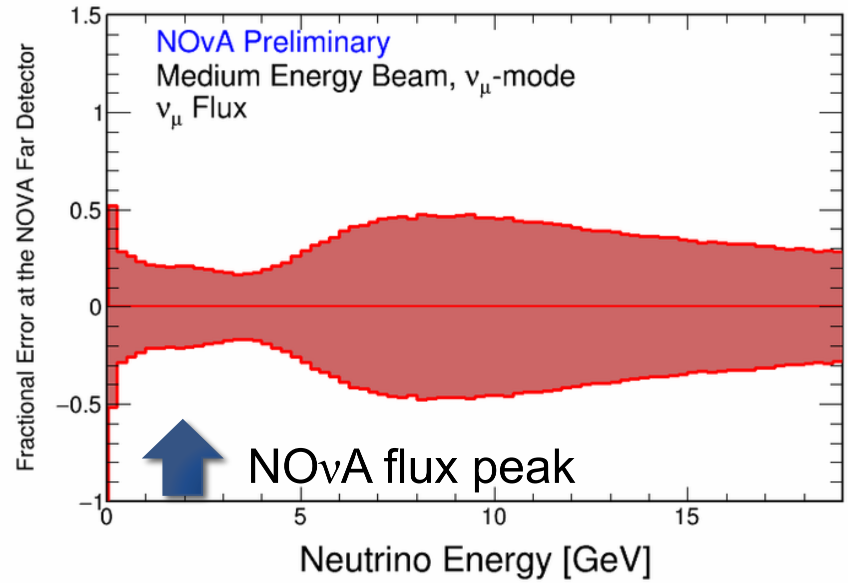


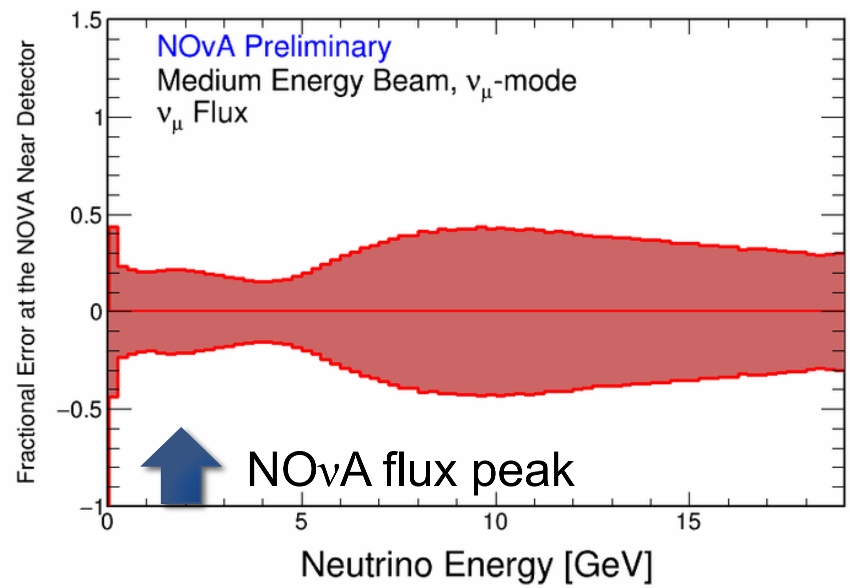
Combined to give a 5% total relative hadronic energy uncertainty

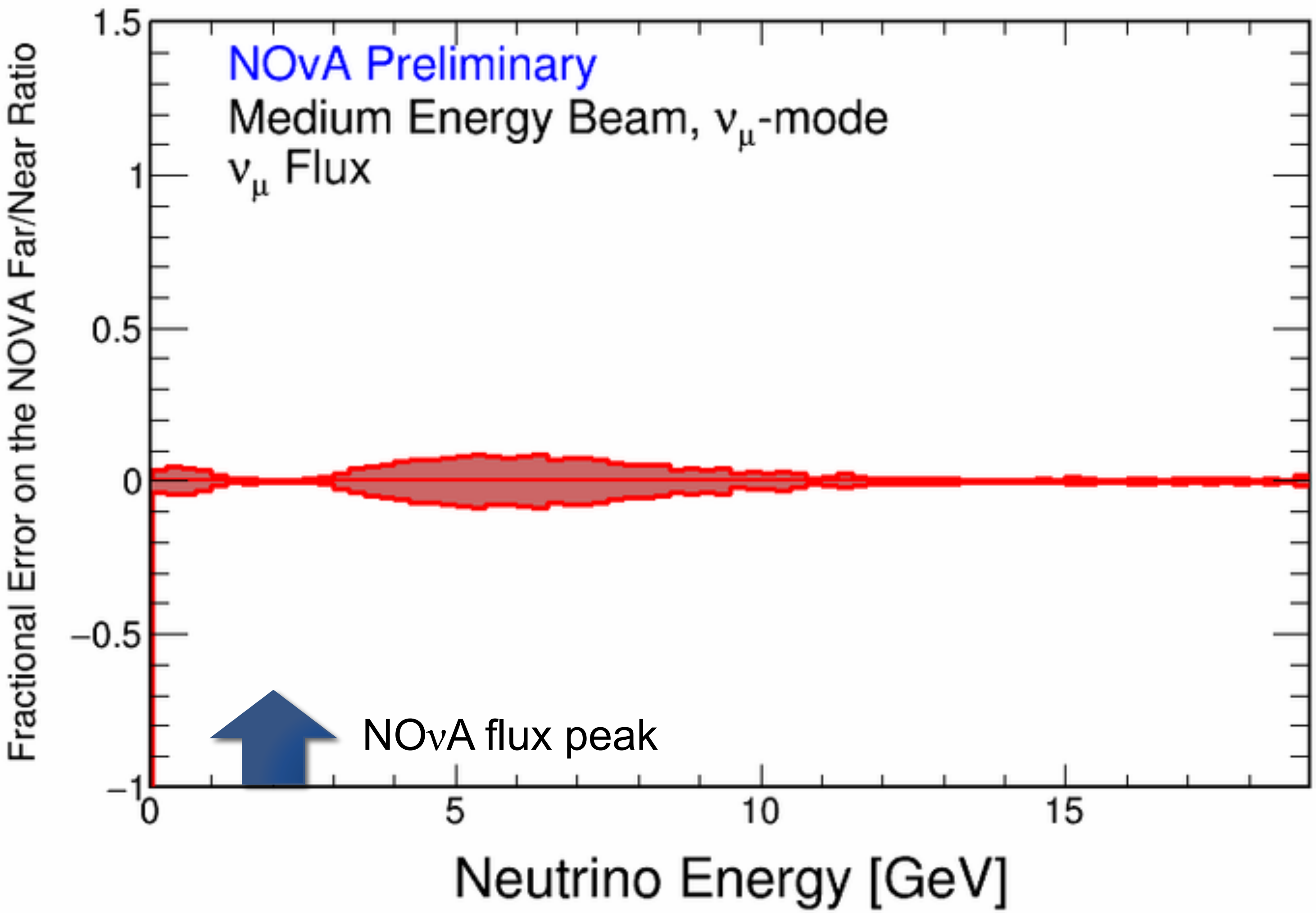
Flux uncertainties

- NOνA flux modeled using FLUKA/ FLUGG
- For each detector the flux uncertainty is large (~20% at 2 GeV peak) and dominated by the hadron production uncertainties
  - Estimated by comparing the NuMI target MC predictions to the the thin-target data from NA49
- Hadron transport uncertainties were also investigated
  - NuMI target and horn positions, horn current and magnetic field uncertainties, and beam spot size and position
- Determined to be small compared to hadron production uncertainties

Details in K. Mann talk 4pm yesterday





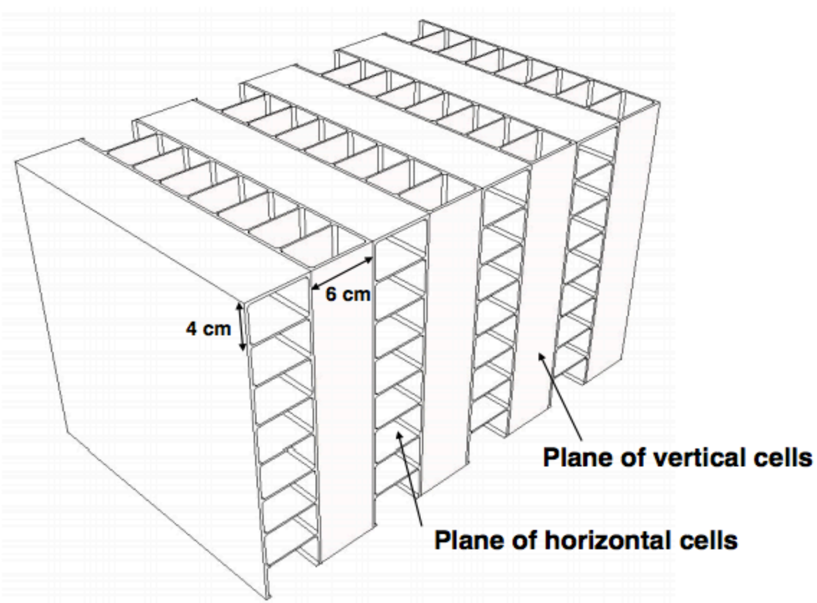


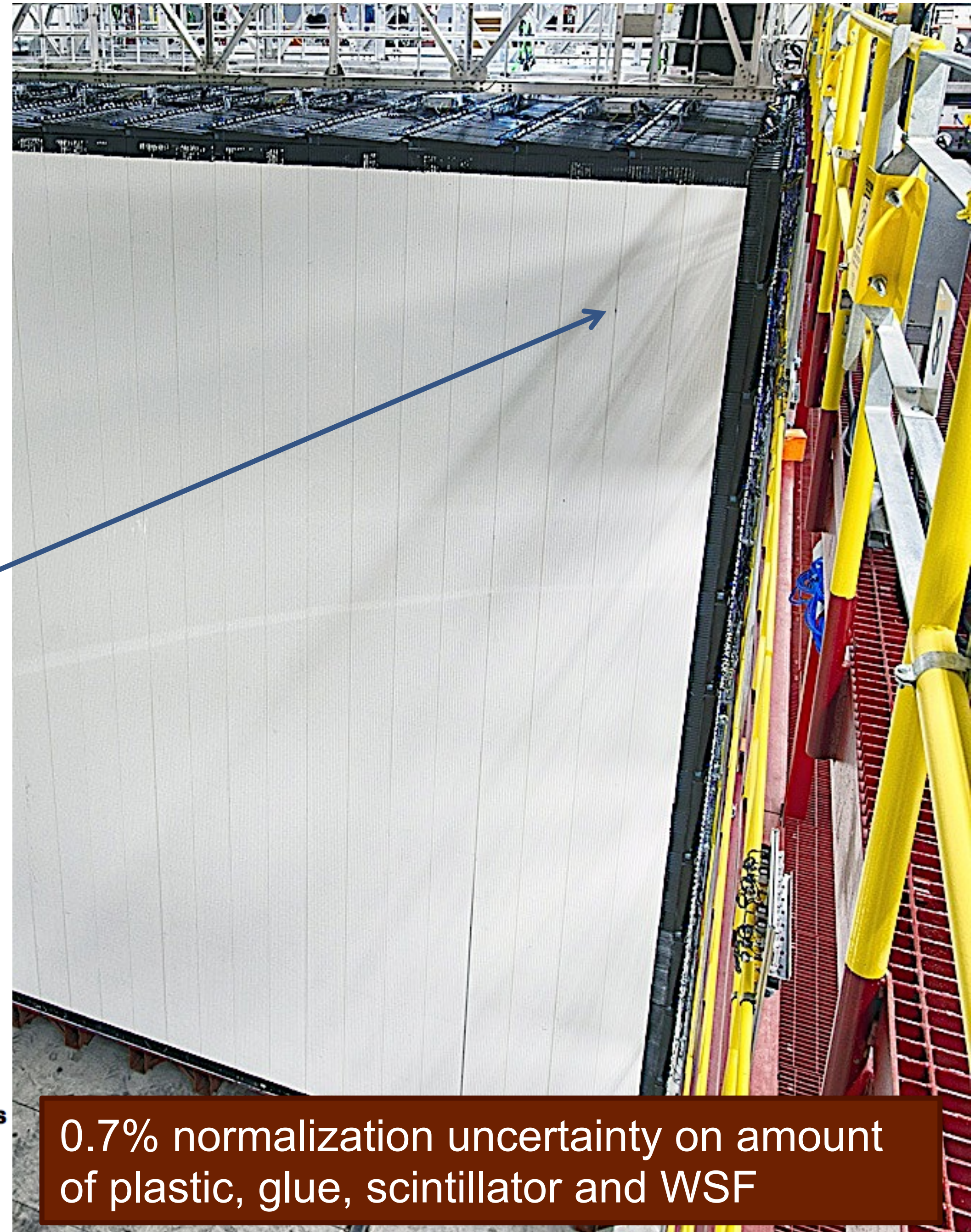
Flux uncertainties are highly correlated between the two detectors.

In F/N ratio flux uncertainty reduced to percent level

Absolute Normalization

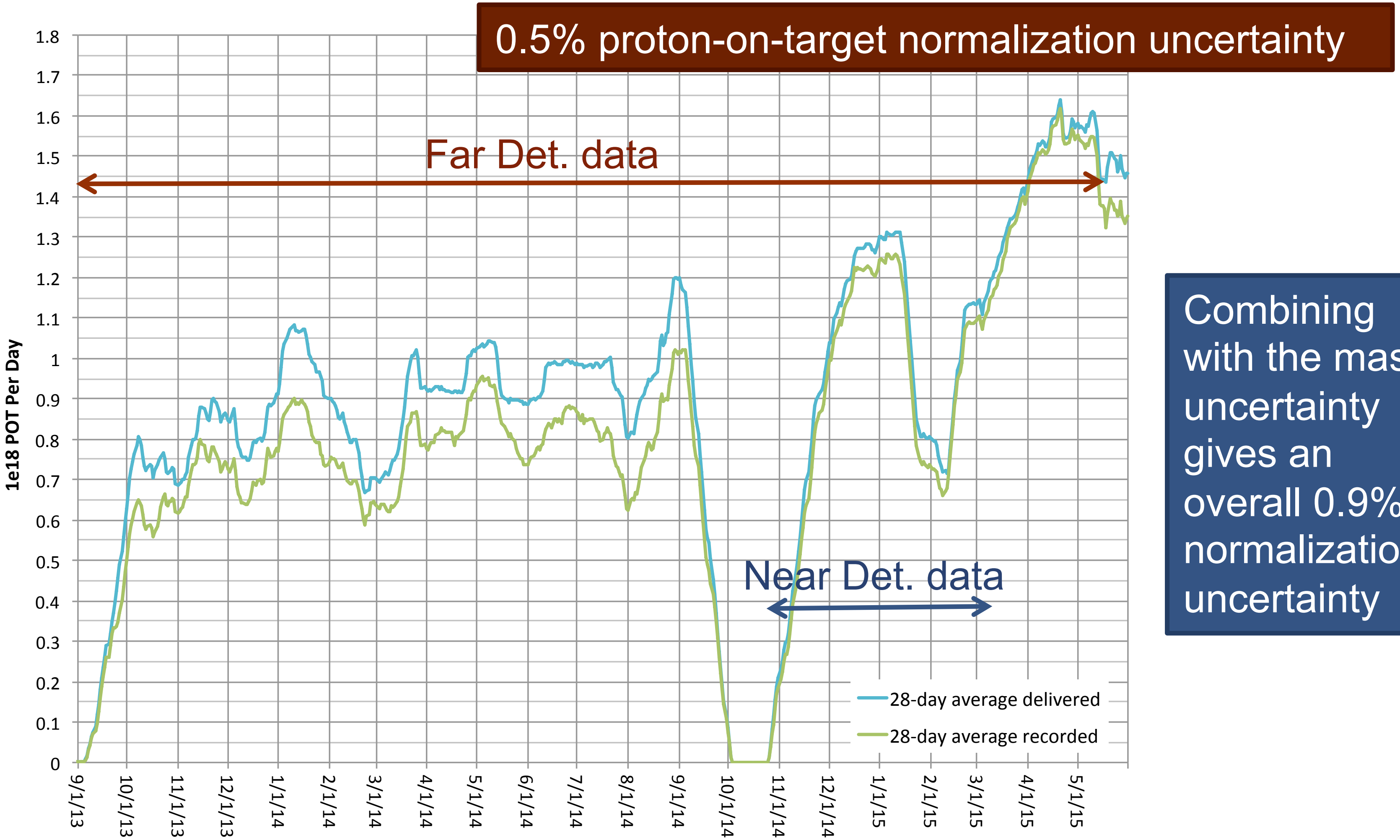
- Mass uncertainty leads to uncertainty in the exposure
- Constructed from PVC cells filled with liquid scintillator containing WSF
- One plane is glued together from individual 12 units





0.7% normalization uncertainty on amount of plastic, glue, scintillator and WSF

Absolute Normalization



Combining with the mass uncertainty gives an overall 0.9% normalization uncertainty

- As detector data taking was over different periods if there had been a POT mis-measurement could results in normalization skew
  - NuMI beam has been shown to be very stable

Neutrino Interactions

- Use GENIE to study uncertainty on cross sections and final state particles exiting the nucleus
- Study effect on the ν_μ CC energy spectrum of 1 and 2σ variations of the 67 parameters provided in GENIE
- Only 6 seen to have a noticeable effect
  - The axial masses for both the charged and neutral current quasi-elastic and resonant cross sections
  - The vector mass for the charged and neutral current resonant cross sections
- The 6 largest, and an effective parameter that includes the effect of the other 61 parameters added in quadrature, are added as penalty terms in the fit

10-25% uncertainty on neutrino interaction dynamics, mostly cancels in F/N ratio

Systematic uncertainties summary

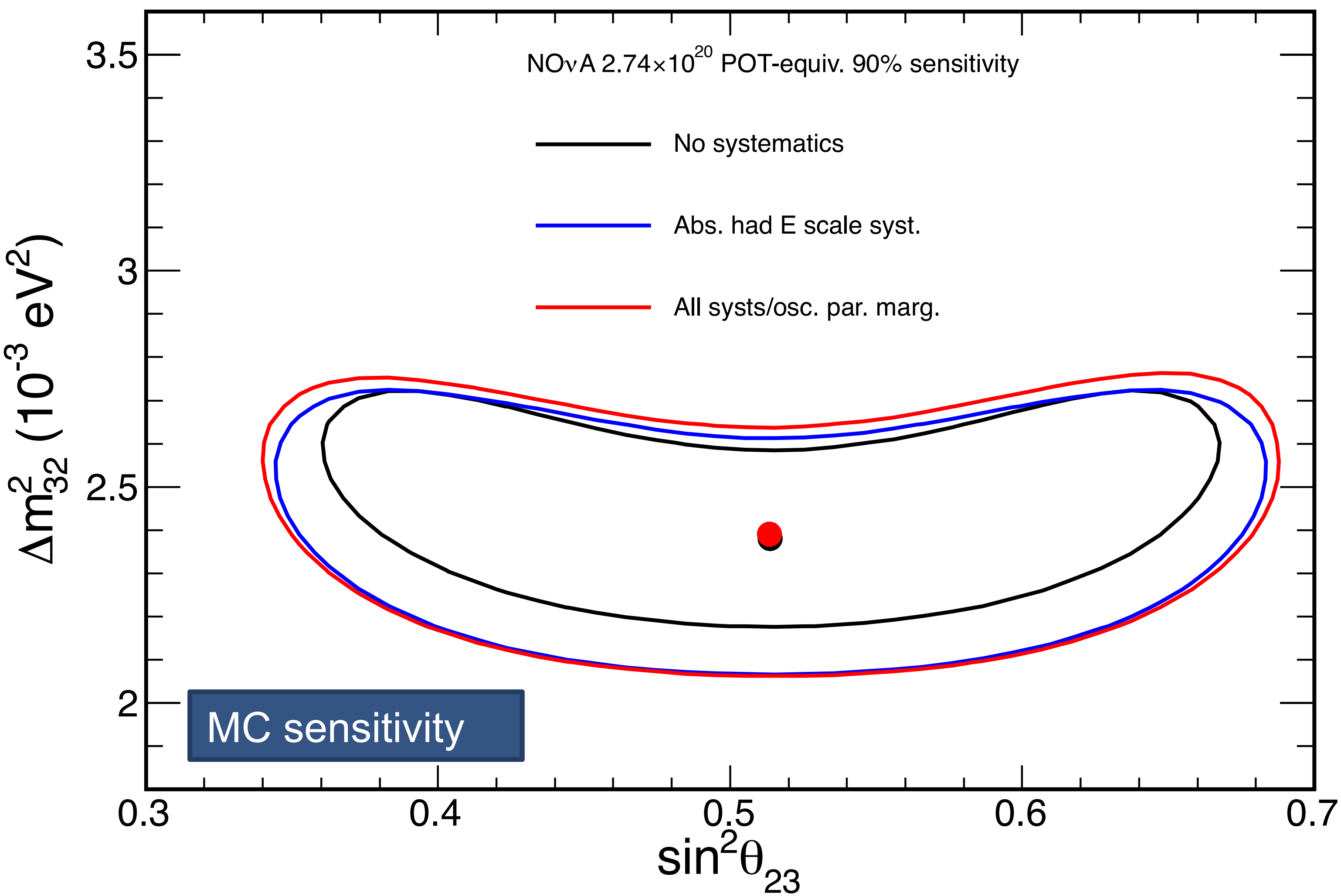
Systematic	Value @ 1σ	Best fit (σ)
Bkg. (NC and ν_τ)	100%	0.06
Absolute Normalization	1.3%	0.0004
Absolute Hadronic energy scale	22%	-0.67
Absolute energy scale	1%	0.06
Beam	Energy dependent (20% @ 2 GeV)	-0.02
Relative Normalization	1.3%	-0.03
Relative Hadronic energy scale	5.4%	0.05
GENIE M_a	15-25%	-0.06
GENIE M_v	10%	-0.06

Oscillation parameters marginalized over in fit
δ_{CP} = Unconstrained, $\Delta m^2_{21} = (7.53 \pm 0.18)\times 10^{-5}$, $\sin^2 2\theta_{13} = 0.086 \pm 0.005$, $\sin^2\theta_{12} = 0.846 \pm 0.021$

ν_μ oscillation probability

$$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \sin^2(\Delta m^2_{32} L/4E)$$

NOνA Preliminary

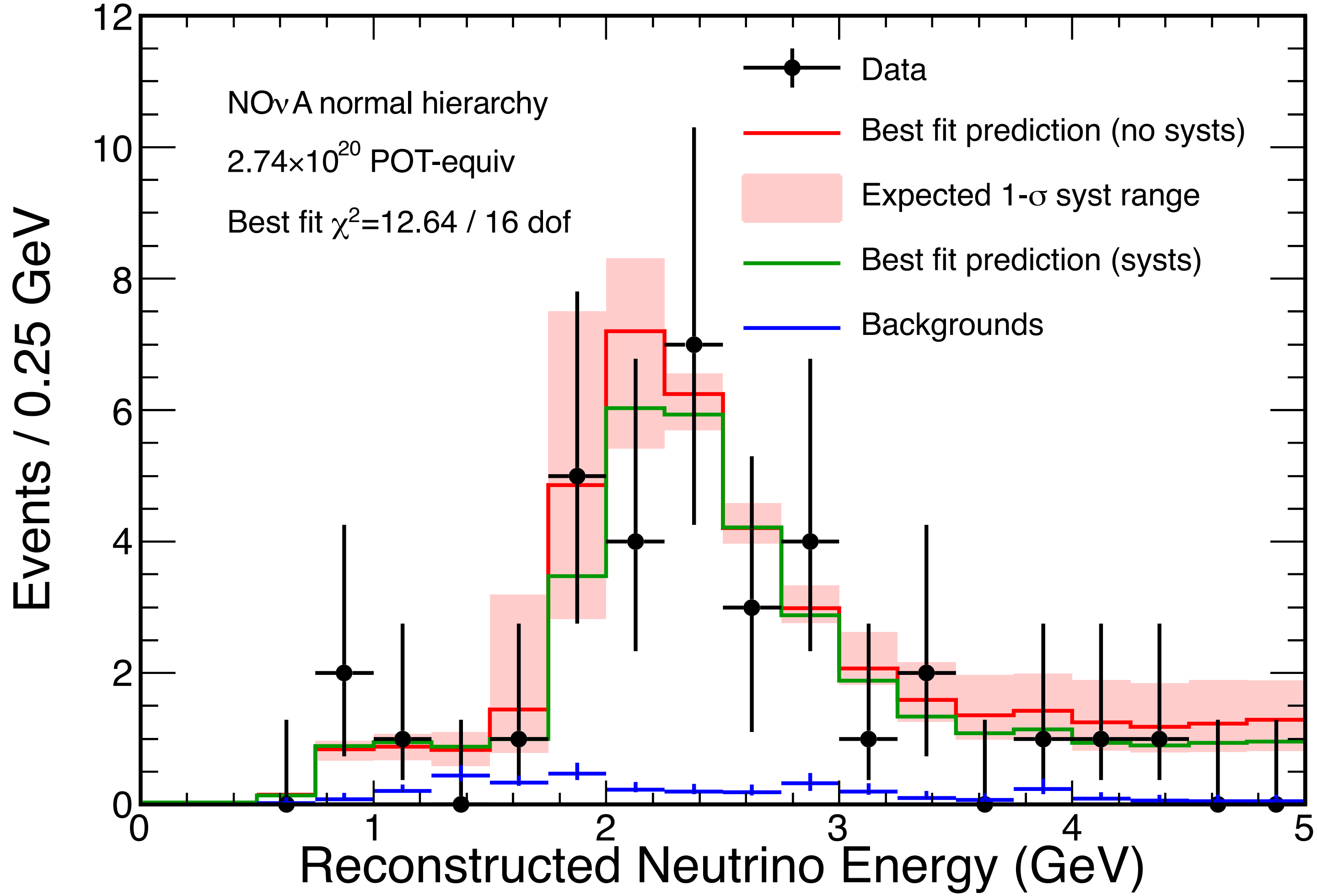


Analysis statistically limited and all systematic uncertainties dominated by the absolute hadronic energy scale

ν_μ oscillation probability

$$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2 2\theta_{23}\, \sin^2(\Delta m^2_{32} L/4E)$$

NOνA Preliminary



Allowing best fit to float with all systematics pulls down on the peak and pull high energy tail down

ν_μ oscillation probability

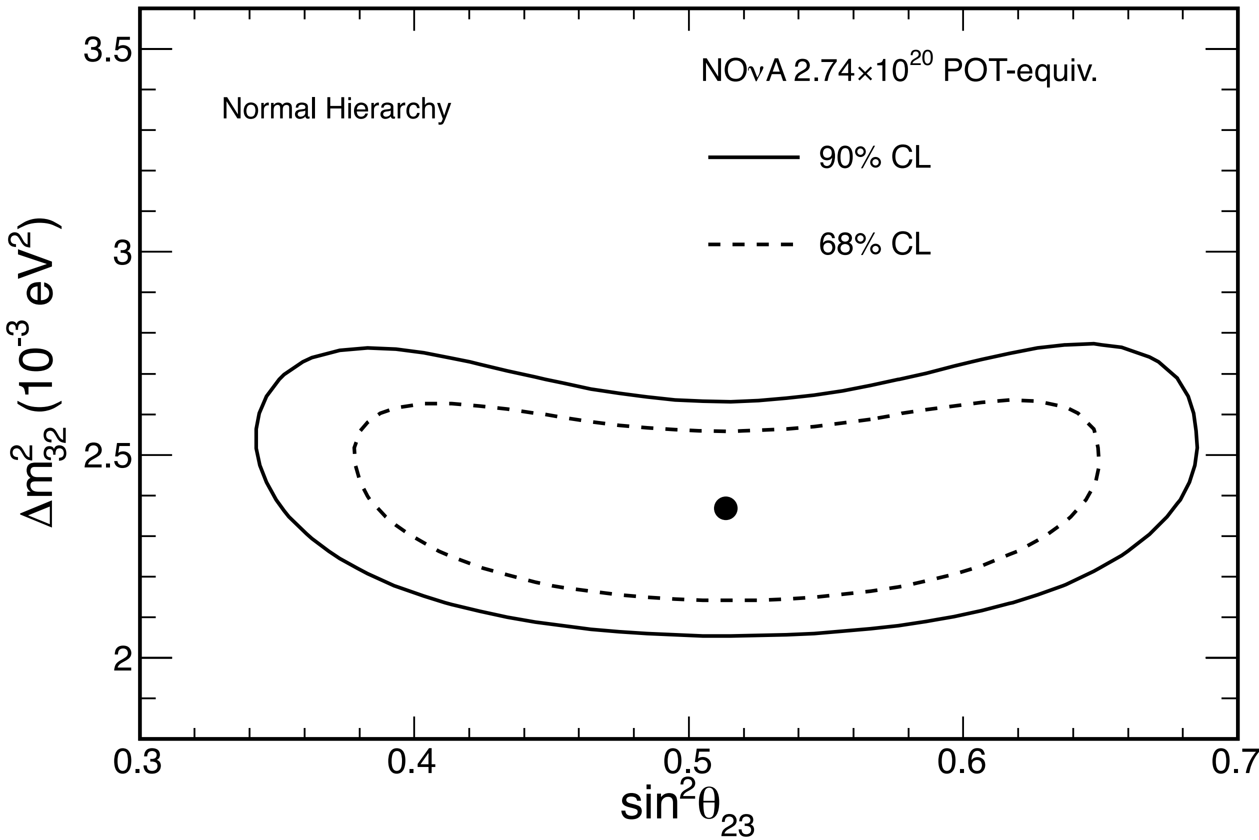
$$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \sin^2(\Delta m^2_{32} L/4E)$$

NOvA Preliminary

$$\Delta m^2 = \begin{cases} +2.37^{+0.16}_{-0.15} \\ -2.40^{+0.14}_{-0.17} \end{cases} \times 10^{-3}\ \mathrm{eV}^2$$

$$\sin^2(\theta_{23}) = 0.51 \pm 0.10$$

6.5% measurement uncertainty

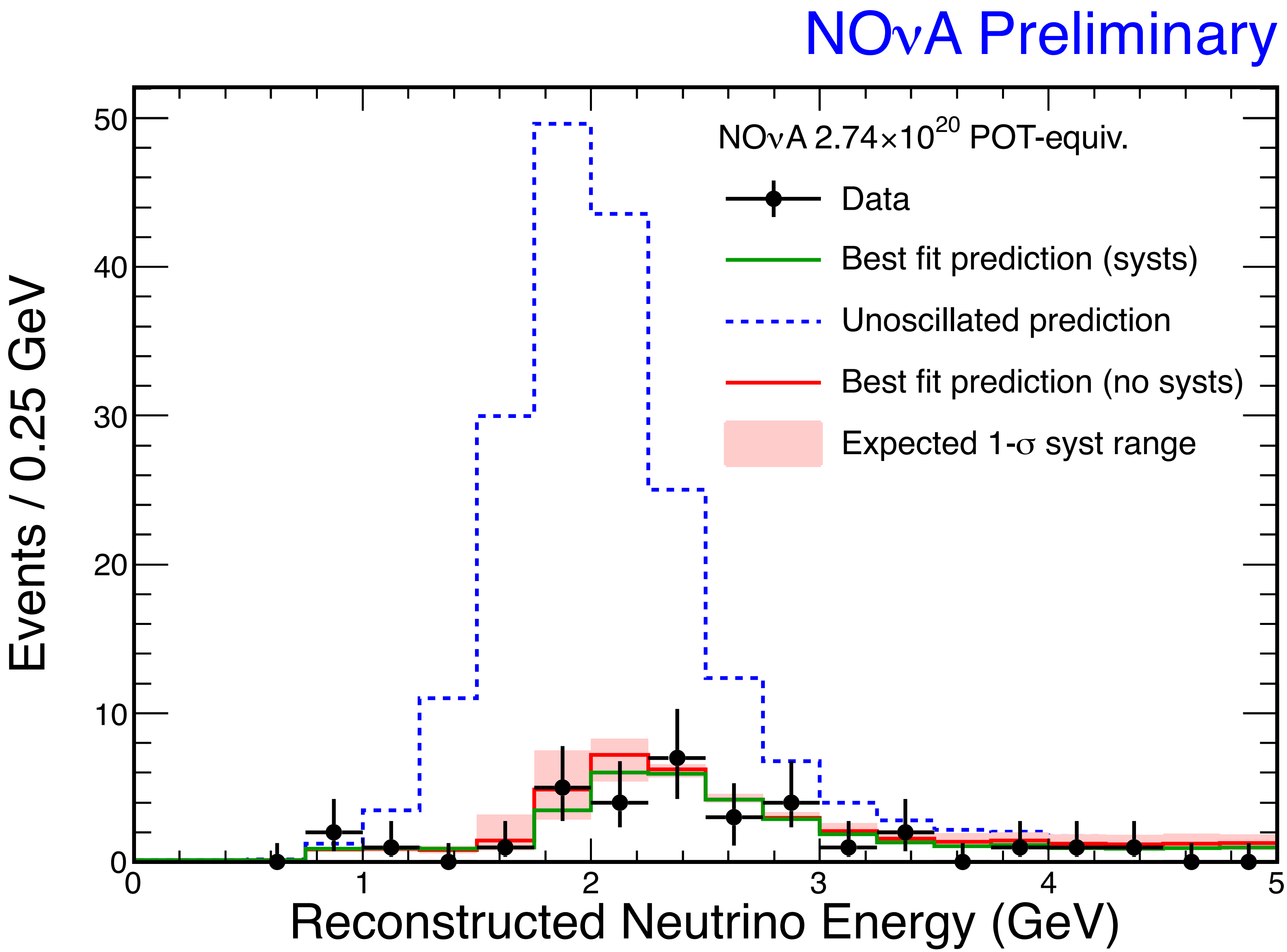


- Fully quantifying the hadronic response will be essential for the next generation of results
- With only **7.6% of the nominal final statistics** NOνA is already competitive with the world limits

Conclusions

- The first results of NOνA have been presented with 2.74×10^{20} POT-equivalent collected between July 2013 and March 2015
- NOνA has showcased its ability to produce world class physics and to be a leader in precision atmospheric neutrino oscillations measurements
- The NOνA results are statistically limited, so most systematic uncertainties are negligible. Minimizing systematics will become important as we look to the future
- NOνA is poised to become a leader in precision neutrino physics and has the majority of its data still to be recorded

Backup

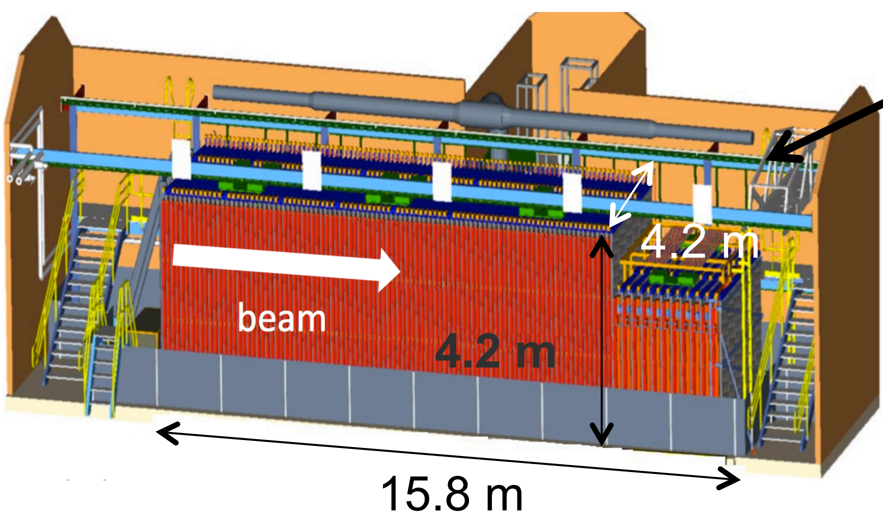

NOνA Preliminary
NOνA 2.74×10^20 POT-equiv.
Data
Best fit prediction (systs)
Unoscillated prediction
Best fit prediction (no systs)
Expected 1-σ syst range
Events / 0.25 GeV
Reconstructed Neutrino Energy (GeV)
0
10
20
30
40
50
0
1
2
3
4
5

Osc. parameter	Value	Best fit (σ)
δ_{CP}	Unconstrained	1.2275
Δm^2_{21}	$(7.53 \pm 0.18)\times10^{-5}$	7.53e10^{-5}
$\sin^2 2\theta_{13}$	0.086 ± 0.005	0.086
$\sin^2\theta_{12}$	0.846 ± 0.021	0.0846

Detector Response modeling

- Uncertainty arise from GEANT modeling of the detector
  - Estimated by comparing alternative GEANT4 physics lists that use different models to simulate hadronic interactions and nuclear deexcitation
- The calometric energy scale, the amount of Birk's suppression and the modeling of deficient hardware were also investigated and determined to be negligible

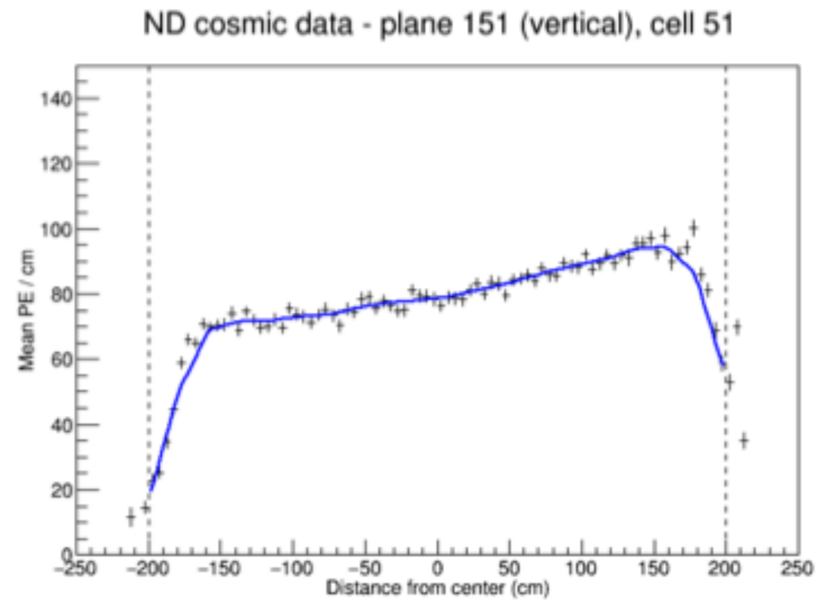
semi-active region, modules alternated with 4" steel plates

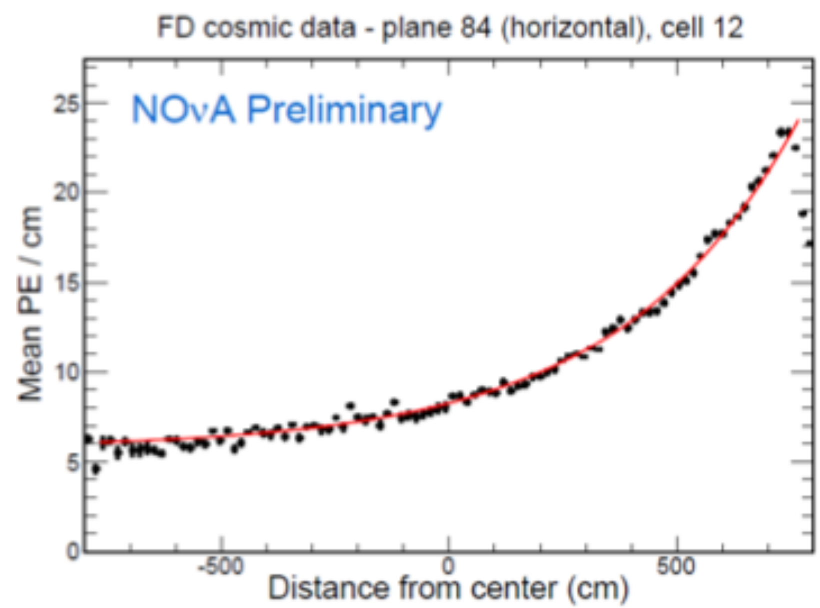


1% uncertainty both normalization and energy scale

Attenuation uncertainty

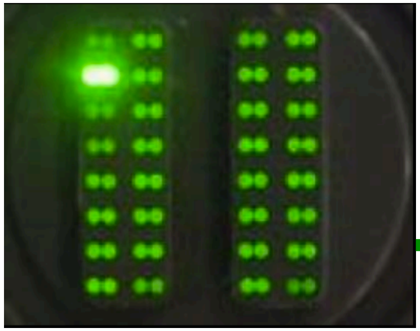
- Biggest calibration correction applied to the NOvA detectors is due to attenuation in the wavelength shifting fiber
- Muons (cosmic or ν induced) are used to probe detector response
- Investigated the tuning of the simulated light levels, photon transport and electronics response in the detectors
  - Alter light levels by 20% while simultaneously adjusting the calibration constants in the opposite direction
- Determined effect to be negligible

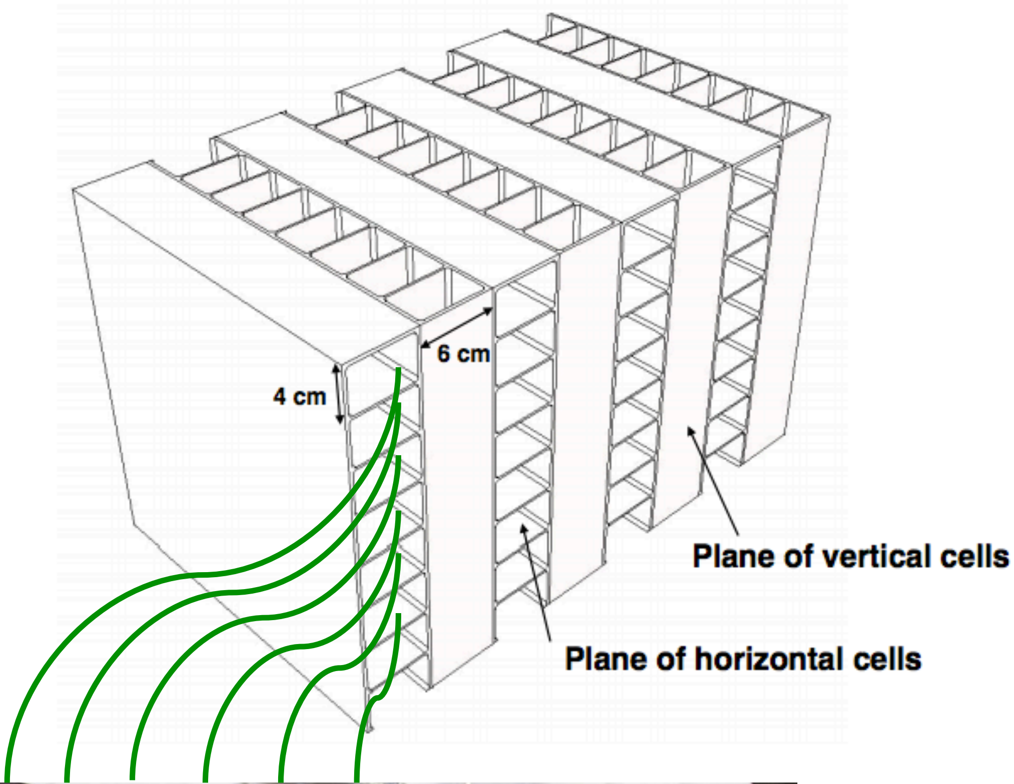




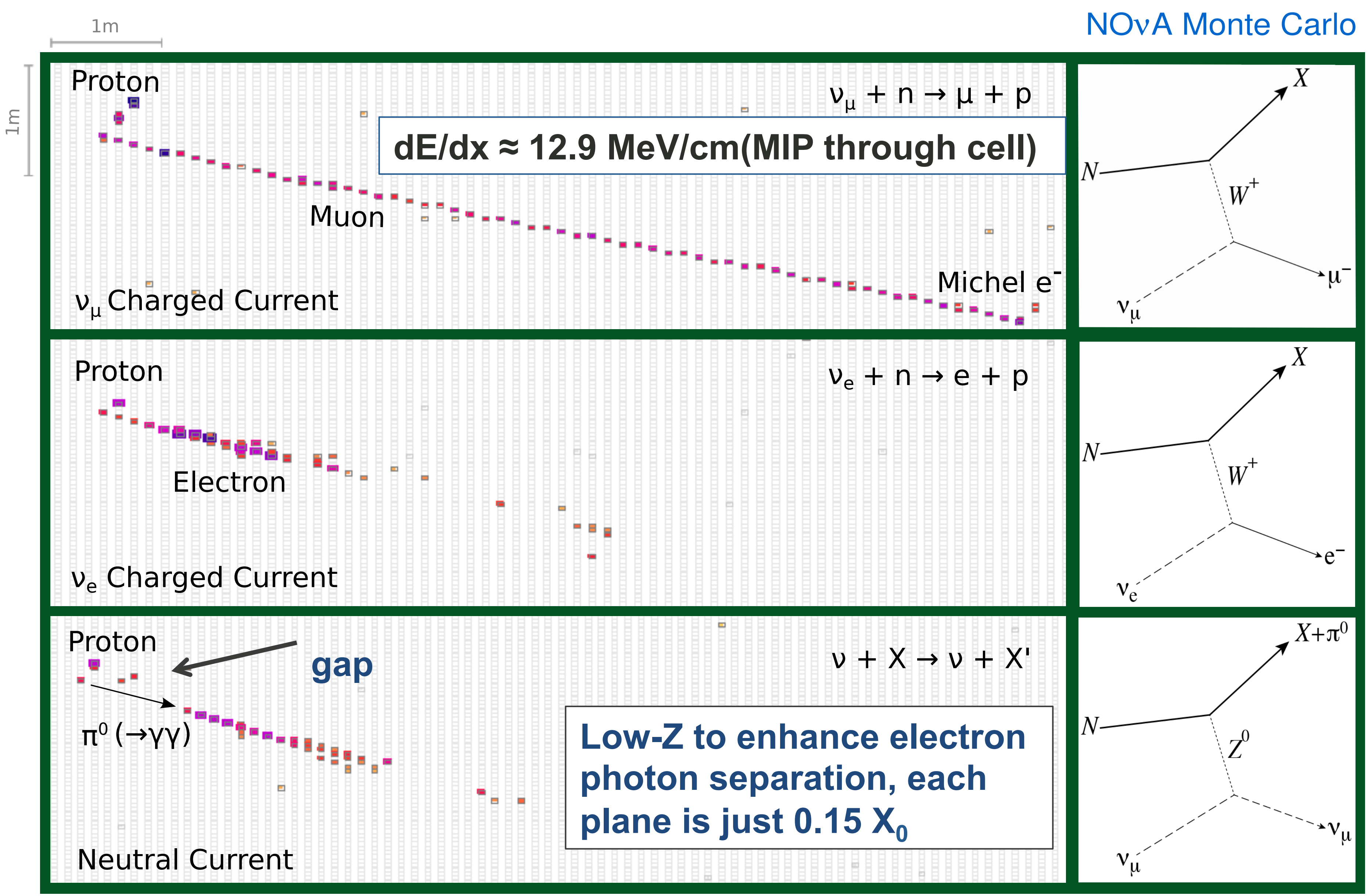
32 pixel APD

32 WSF loops

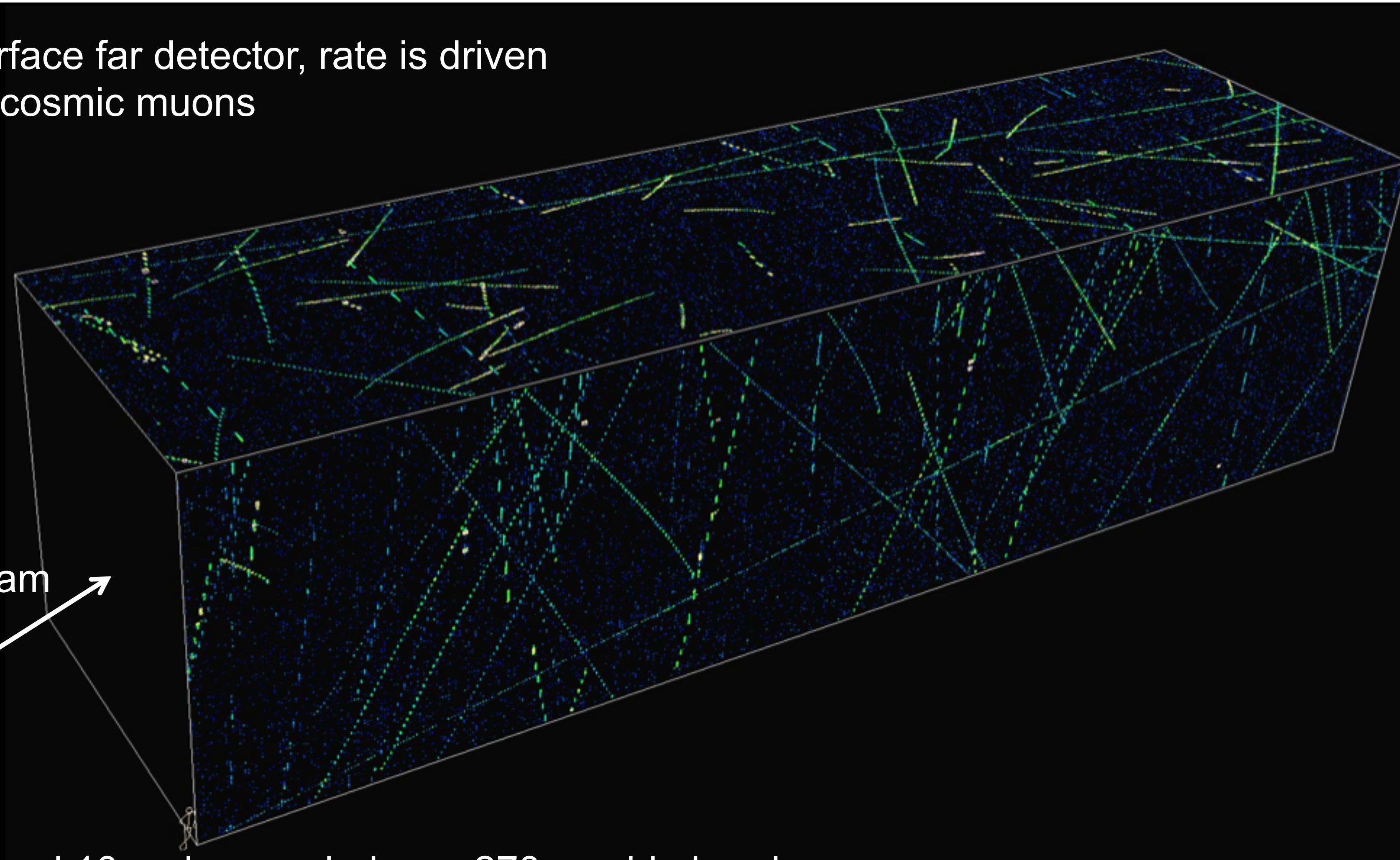




Each cell has loop of wavelength shifting fiber read out in groups of 32 by a 32 pixel Avalanche Photodiode

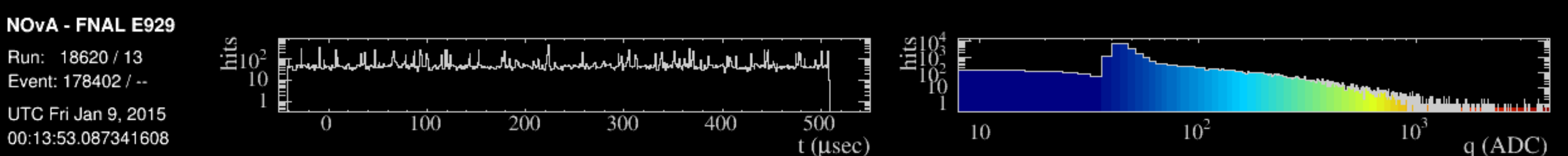

NOνA Monte Carlo
1m
1m
Proton
$\nu_\mu + n \rightarrow \mu + p$
dE/dx ≈ 12.9 MeV/cm(MIP through cell)
Muon
Michel e$^-$
ν_μ Charged Current
X
N
W^+
μ^-
ν_μ
Proton
$\nu_e + n \rightarrow e + p$
Electron
ν_e Charged Current
X
N
W^+
e^-
ν_e
Proton
gap
$\nu + X \rightarrow \nu + X'$
$\pi^0 (\rightarrow\gamma\gamma)$
Low-Z to enhance electron photon separation, each plane is just 0.15 X_0
Neutral Current
$X+\pi^0$
N
Z^0
ν_μ
ν_μ

Surface far detector, rate is driven by cosmic muons



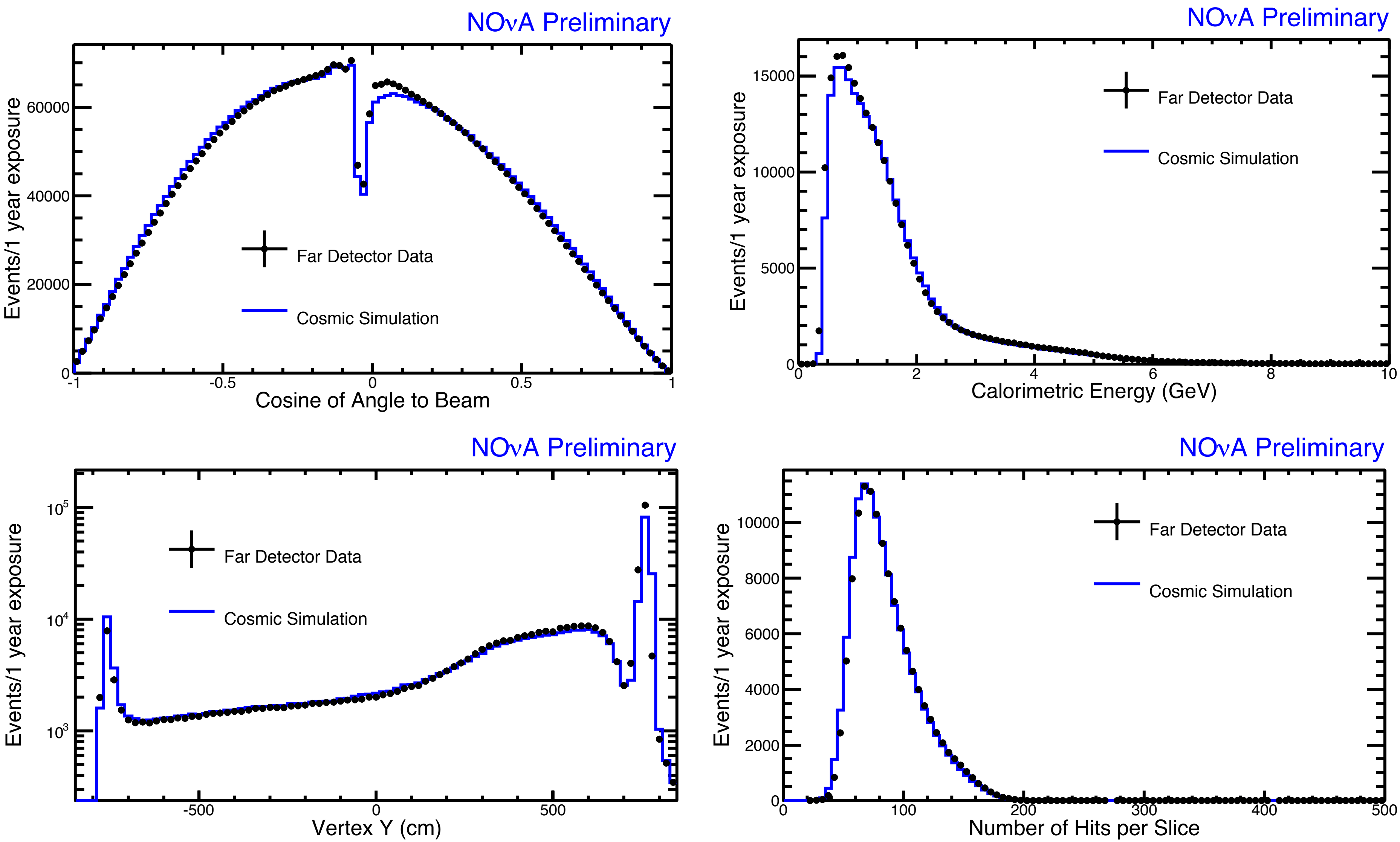
Beam

Record 10 μs beam window ± 270 μs side band



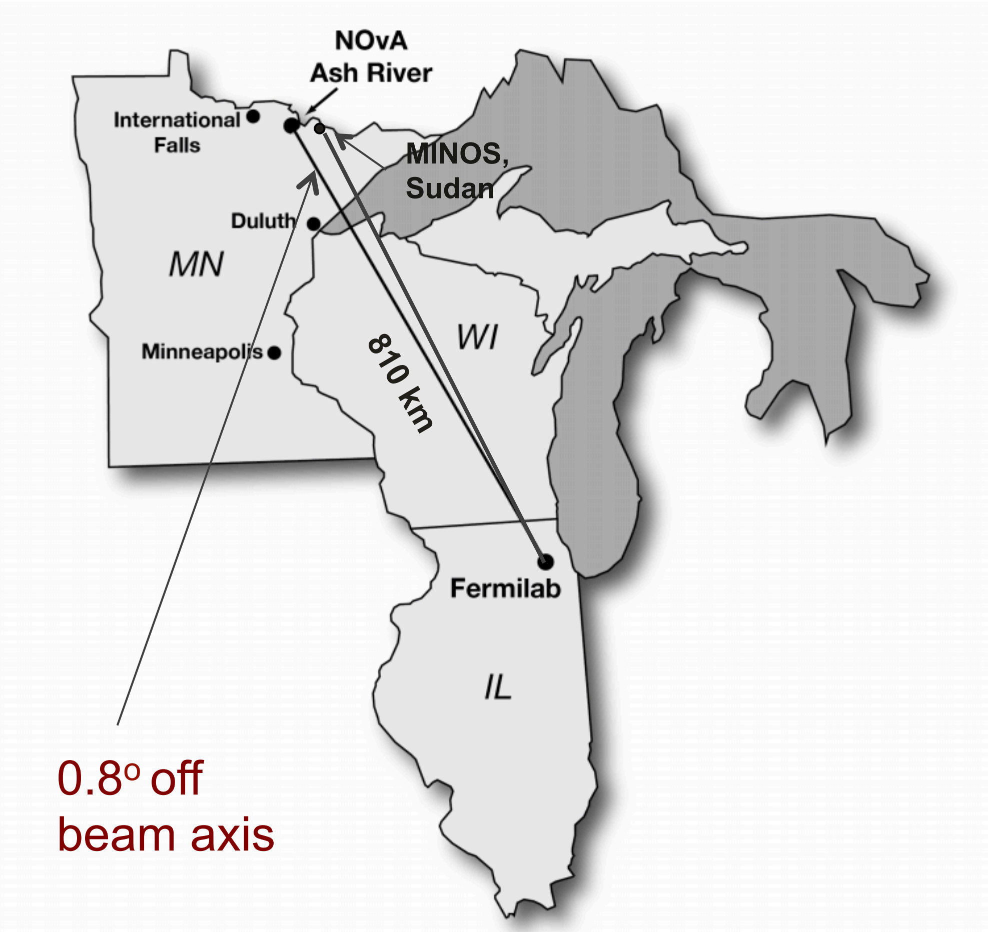
Color denotes charge deposited

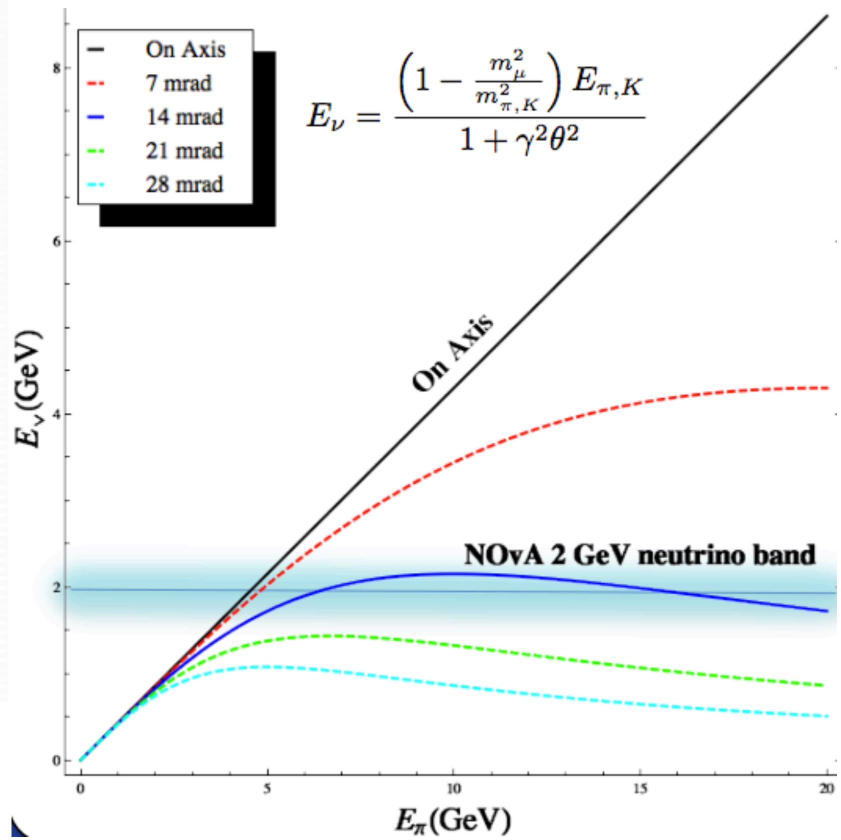
Comparison of cosmic data and MC



Off-axis Detector Location

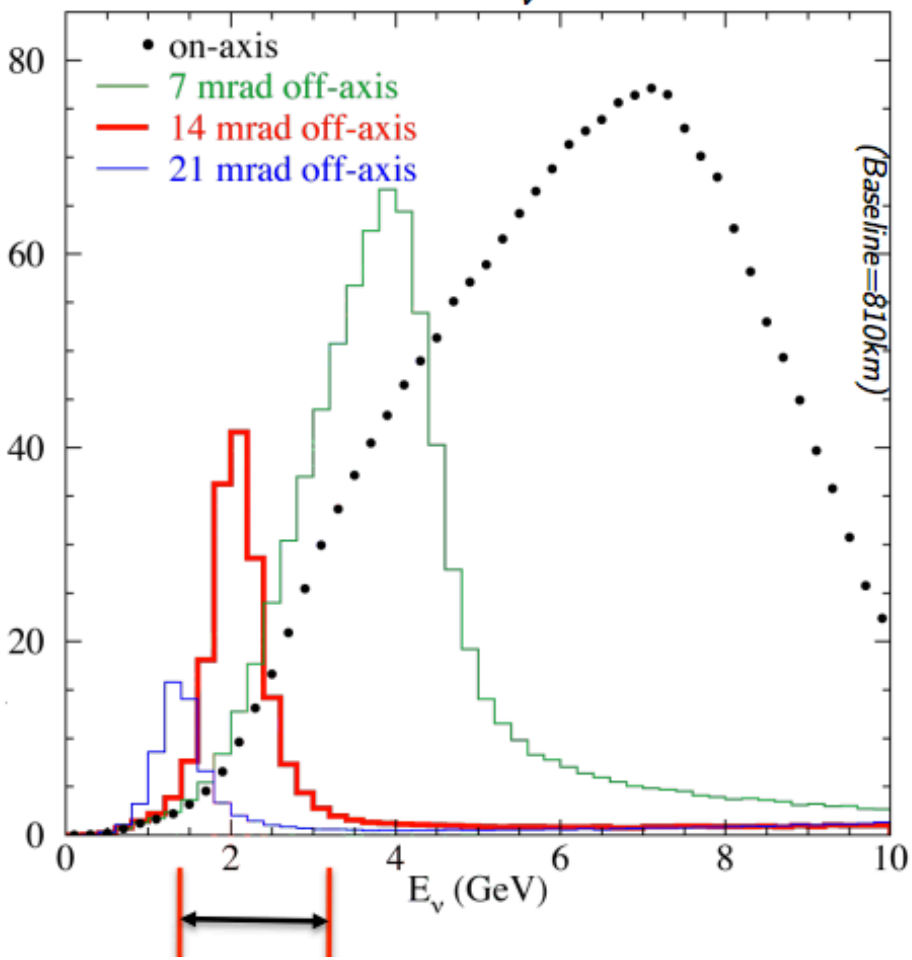
For pion decay in flight beams, the neutrino energy spectrum can be narrowed significantly by selecting an off axis location





Off-axis Detector Location

Far Detector Flux × σ_ν



Narrow peak centered at the energy of the first oscillation maxima

For pion decay in flight beams, the neutrino energy spectrum can be narrowed significantly by selecting an off axis location

- Off-axis flux is reduced as

$$F = \left(\frac{2\gamma}{1+\gamma\theta^2}\right)^2 \frac{A}{4\pi z^2}$$

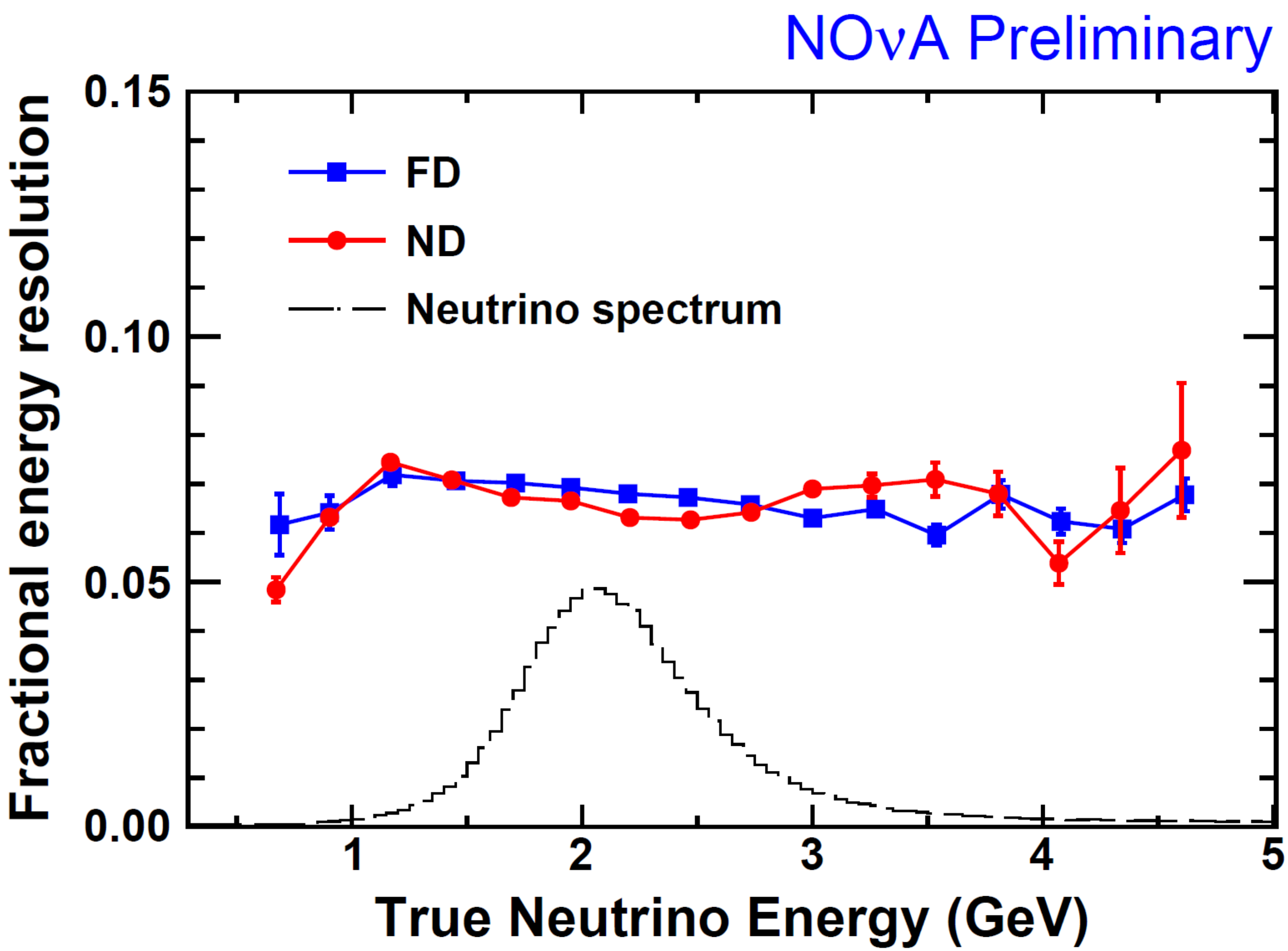
- Energy of neutrino energy flattens out as

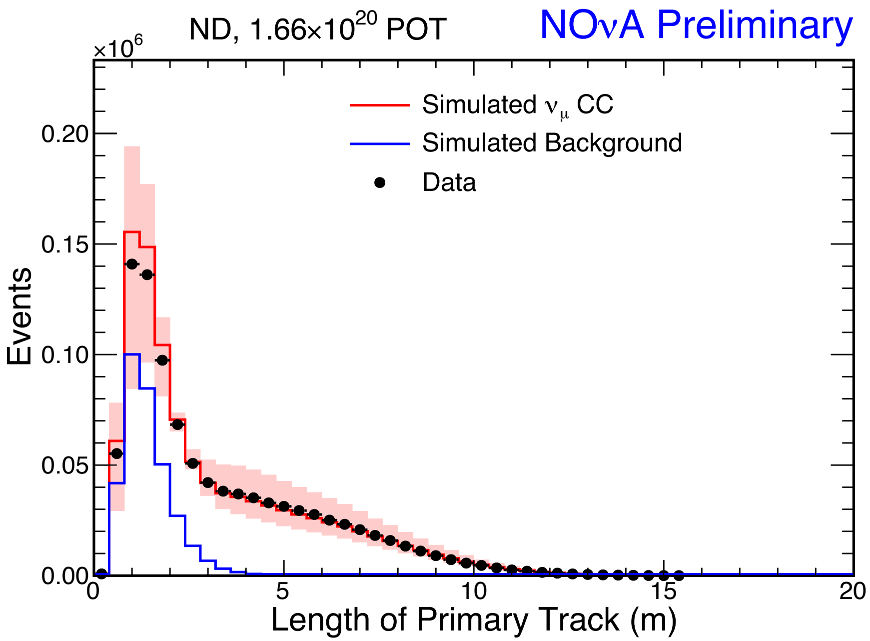
$$E_\nu = \frac{\left(1 - \frac{m_\mu^2}{m_{\pi,K}^2}\right) E_{\pi,K}}{1+\gamma^2\theta^2}$$

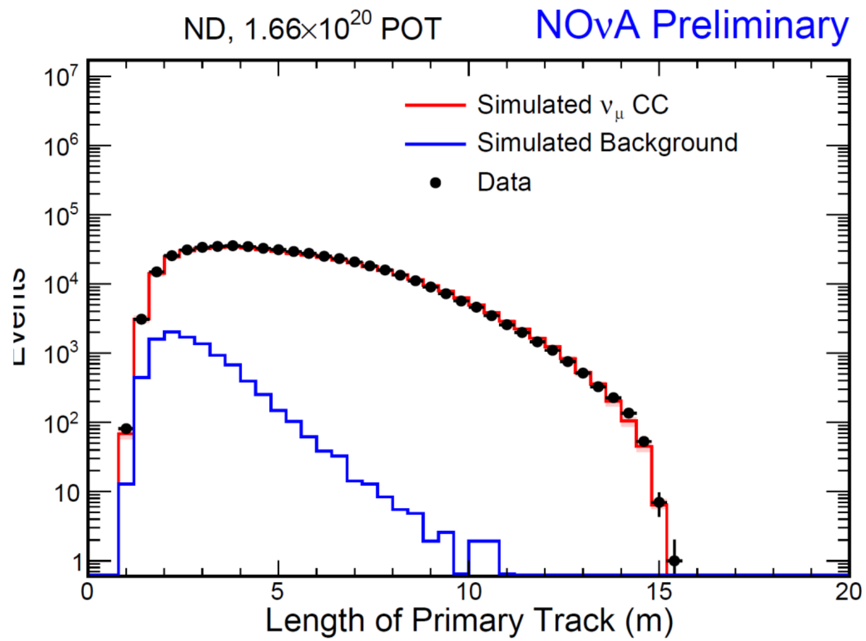
- Narrow band beam peaked at 2 GeV
- Far Detector location optimized for maximum oscillation with a baseline of 810 km

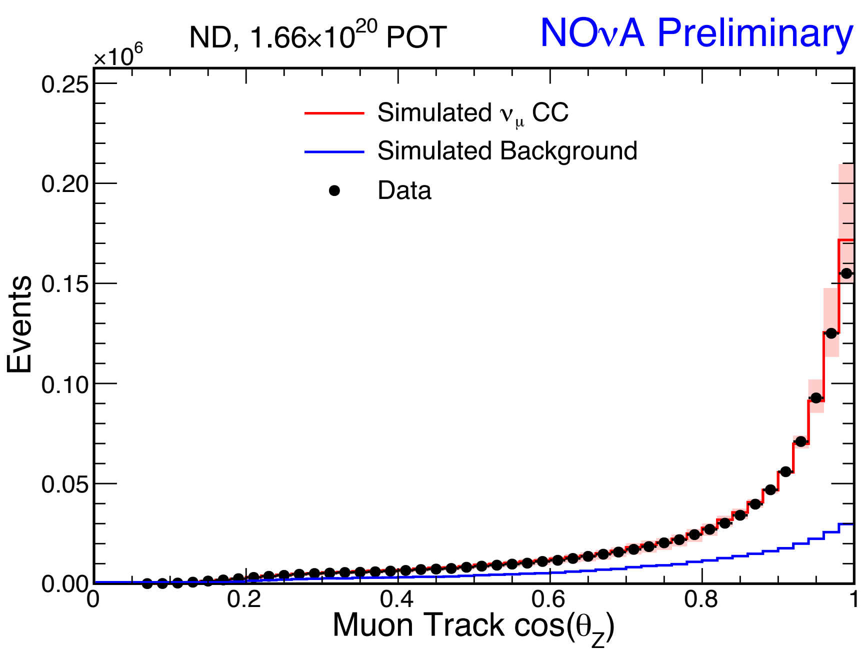
$$E_\nu = \frac{|\Delta m_{32}^2| L}{2\pi} \approx 2 \text{ GeV}$$

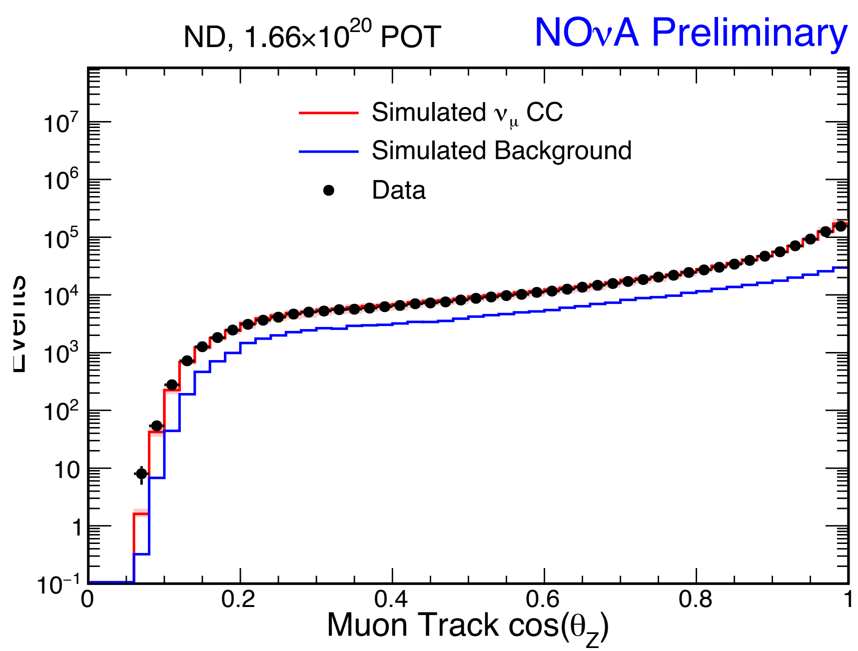
Energy resolution

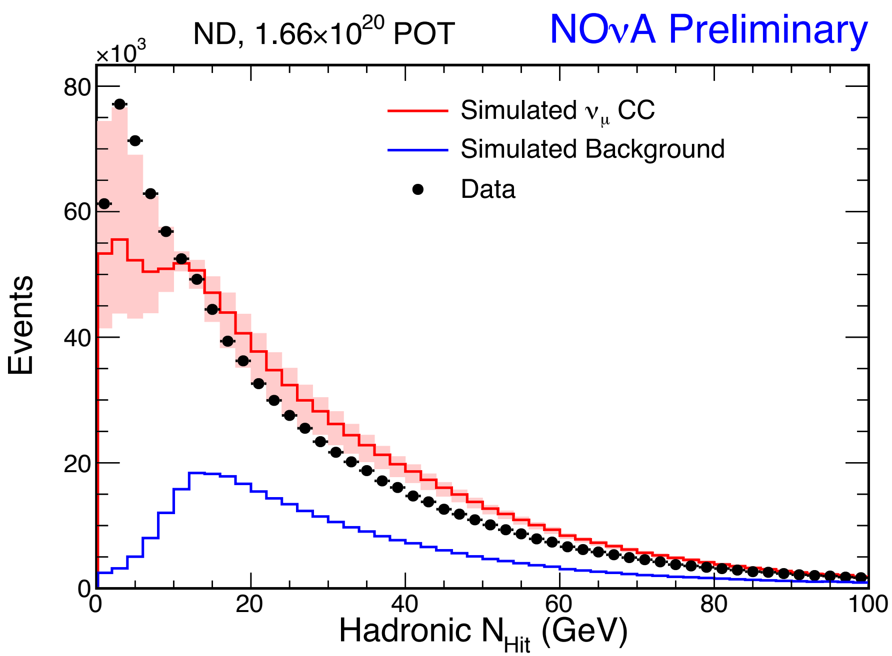


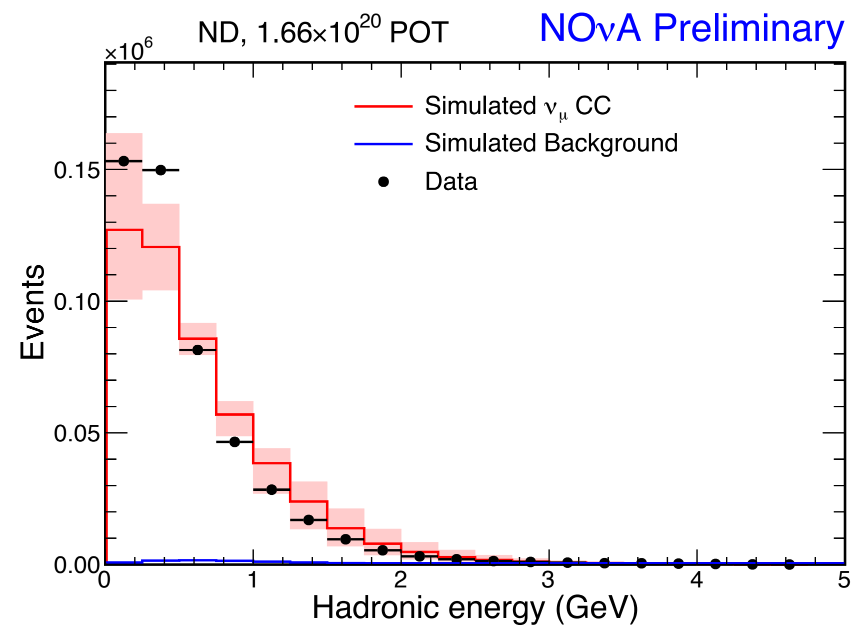

ND, 1.66×10^20 POT
NOνA Preliminary
×10^6
Events
Simulated νμ CC
Simulated Background
Data
Length of Primary Track (m)

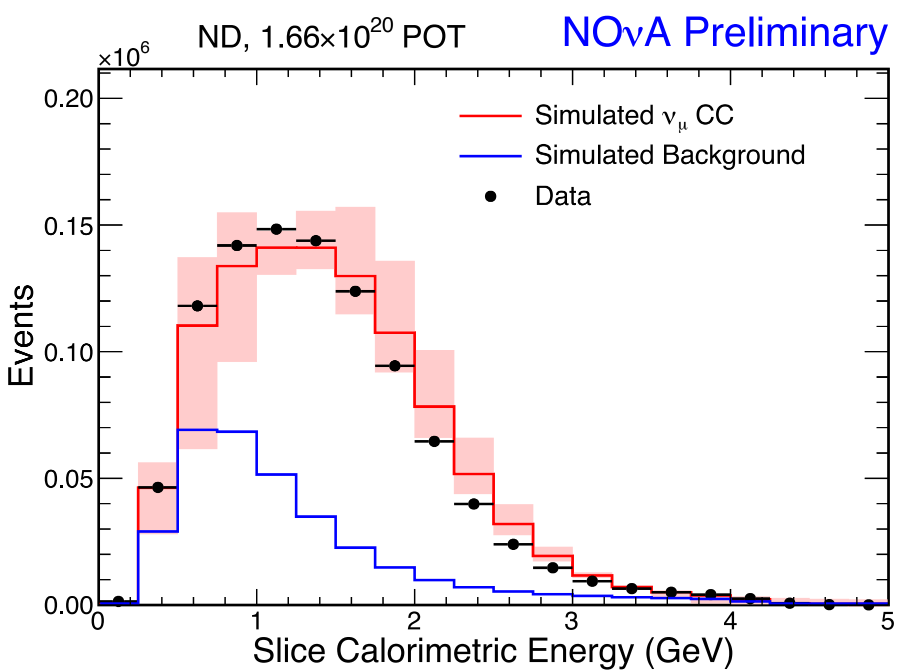

ND, 1.66×10^20 POT
NOνA Preliminary
Simulated νμ CC
Simulated Background
Data
Length of Primary Track (m)

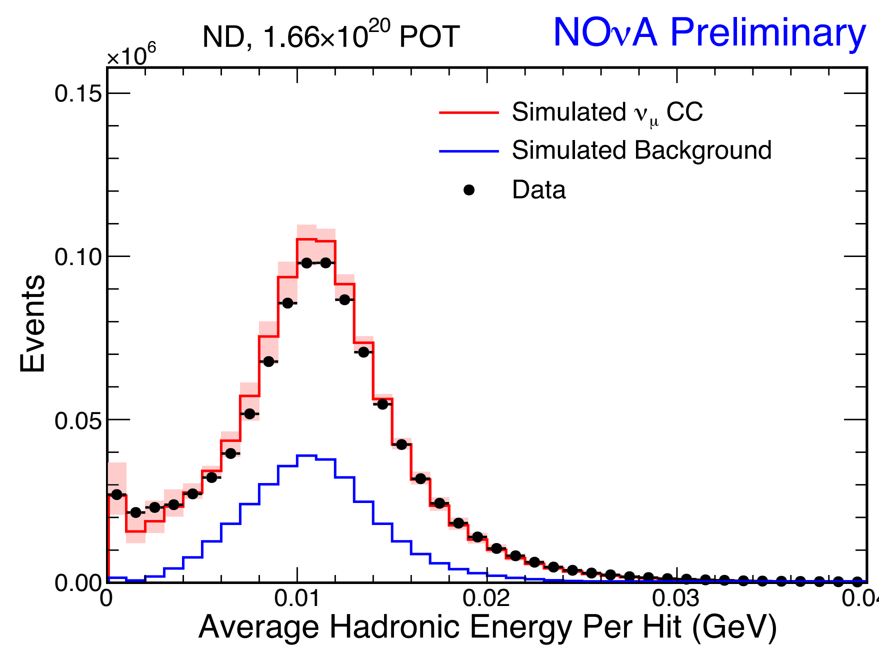

ND, 1.66×10^20 POT
NOνA Preliminary
×10^6
Events
Simulated νμ CC
Simulated Background
Data
Muon Track cos(θZ)


ND, 1.66×10^20 POT
NOνA Preliminary
Simulated νμ CC
Simulated Background
Data
Muon Track cos(θZ)


ND, 1.66×10^20 POT
NOνA Preliminary
×10^3
Simulated νμ CC
Simulated Background
Data
Events
Hadronic N_Hit (GeV)


ND, 1.66×10^20 POT
NOνA Preliminary
×10^6
Simulated νμ CC
Simulated Background
Data
Events
Hadronic energy (GeV)


ND, 1.66×10^20 POT
NOνA Preliminary
×10^6
Simulated νμ CC
Simulated Background
Data
Events
Slice Calorimetric Energy (GeV)


ND, 1.66×10^20 POT
NOνA Preliminary
×10^6
Simulated νμ CC
Simulated Background
Data
Events
Average Hadronic Energy Per Hit (GeV)

Uncertainties on hadron production from NA49