

NOvA ν_μ disappearance measurements of $\sin^2\theta_{23}$ and Δm^2_{32}



ICHEP 2016 — Chicago, IL — Aug 6, 2016

Keith Matera, on behalf of the NOvA Collaboration

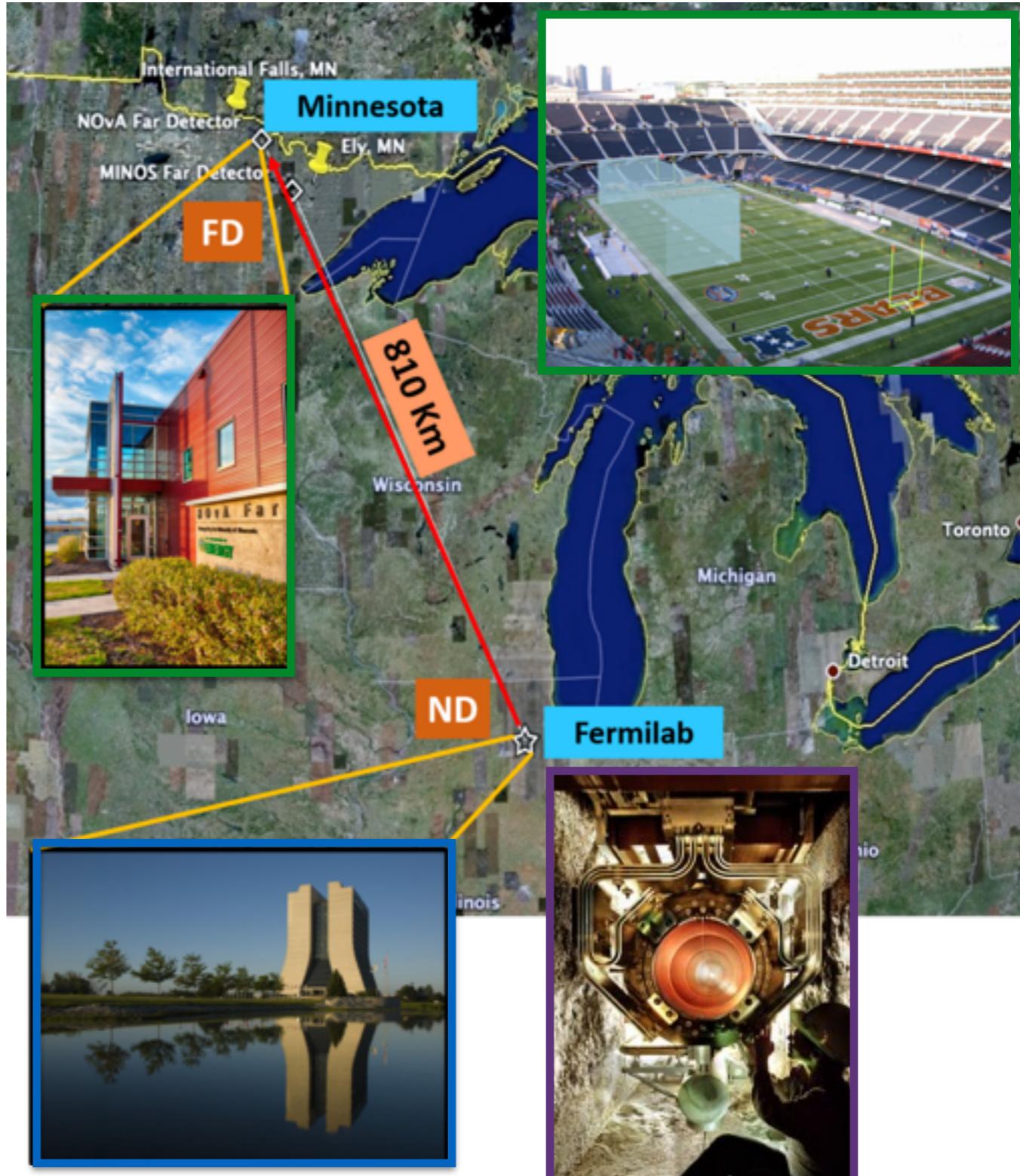
What do you need for a long-baseline accelerator neutrino experiment?

- Long baseline
- Powerful neutrino beam
- Large Far Detector (FD) to look for oscillations

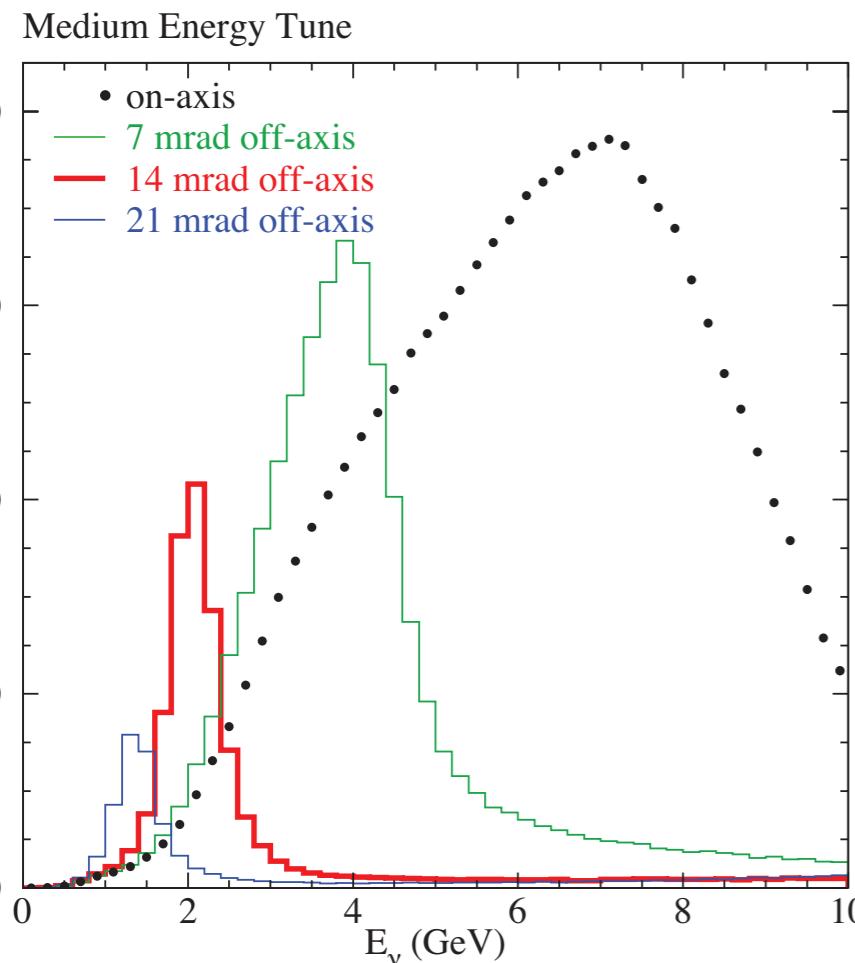
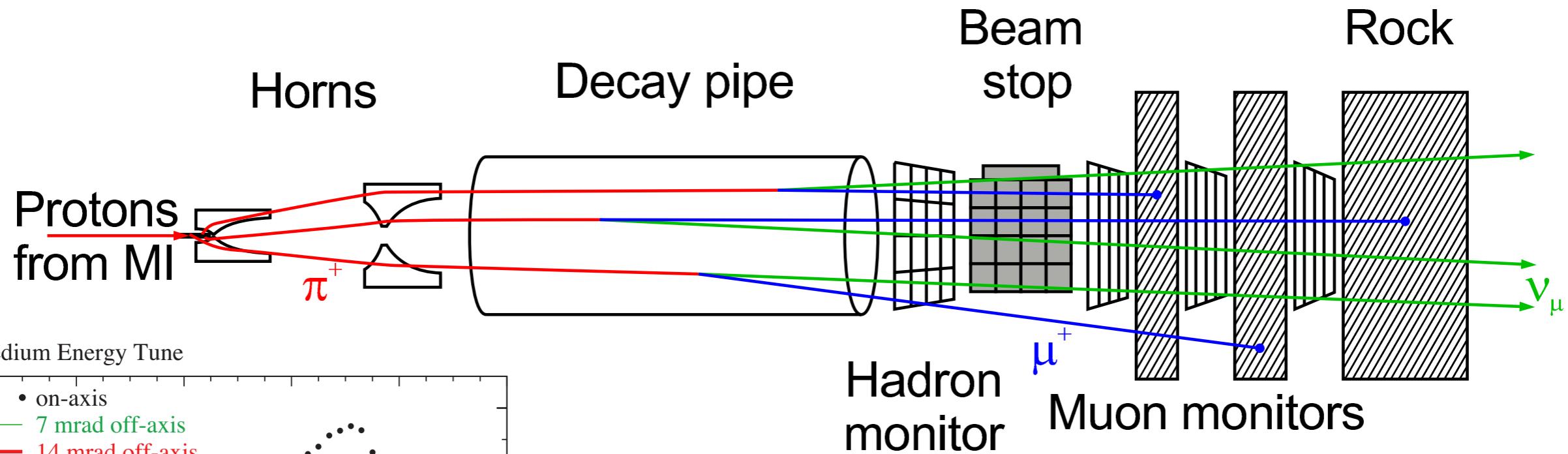
$$\begin{array}{ll} \nu_\mu \rightarrow \nu_\mu & \bar{\nu}_\mu \rightarrow \bar{\nu}_\mu \\ \nu_\mu \rightarrow \nu_e & \bar{\nu}_\mu \rightarrow \bar{\nu}_e \end{array}$$

- Smaller Near Detector (ND) to measure flux before oscillations.

- And one more thing...



The Fermilab NuMI beam accelerates 120 GeV protons onto a graphite target

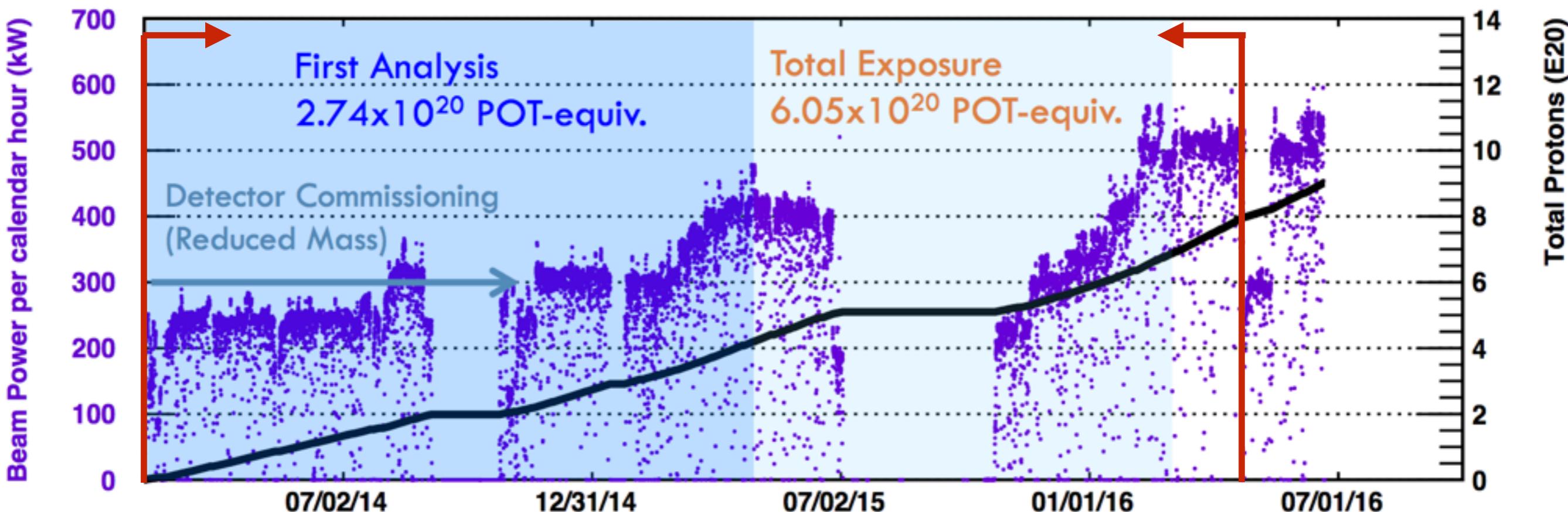


π^\pm are selected by two focusing horns, and decay into neutrinos/antineutrinos

At 14.6 mRad off axis, neutrino energy peaks from 1-3 GeV, and is mostly independent of pion energy

The NuMI beam achieved 700 kW design intensity in tests on June 13

Continued at ~560 kW until summer shutdown



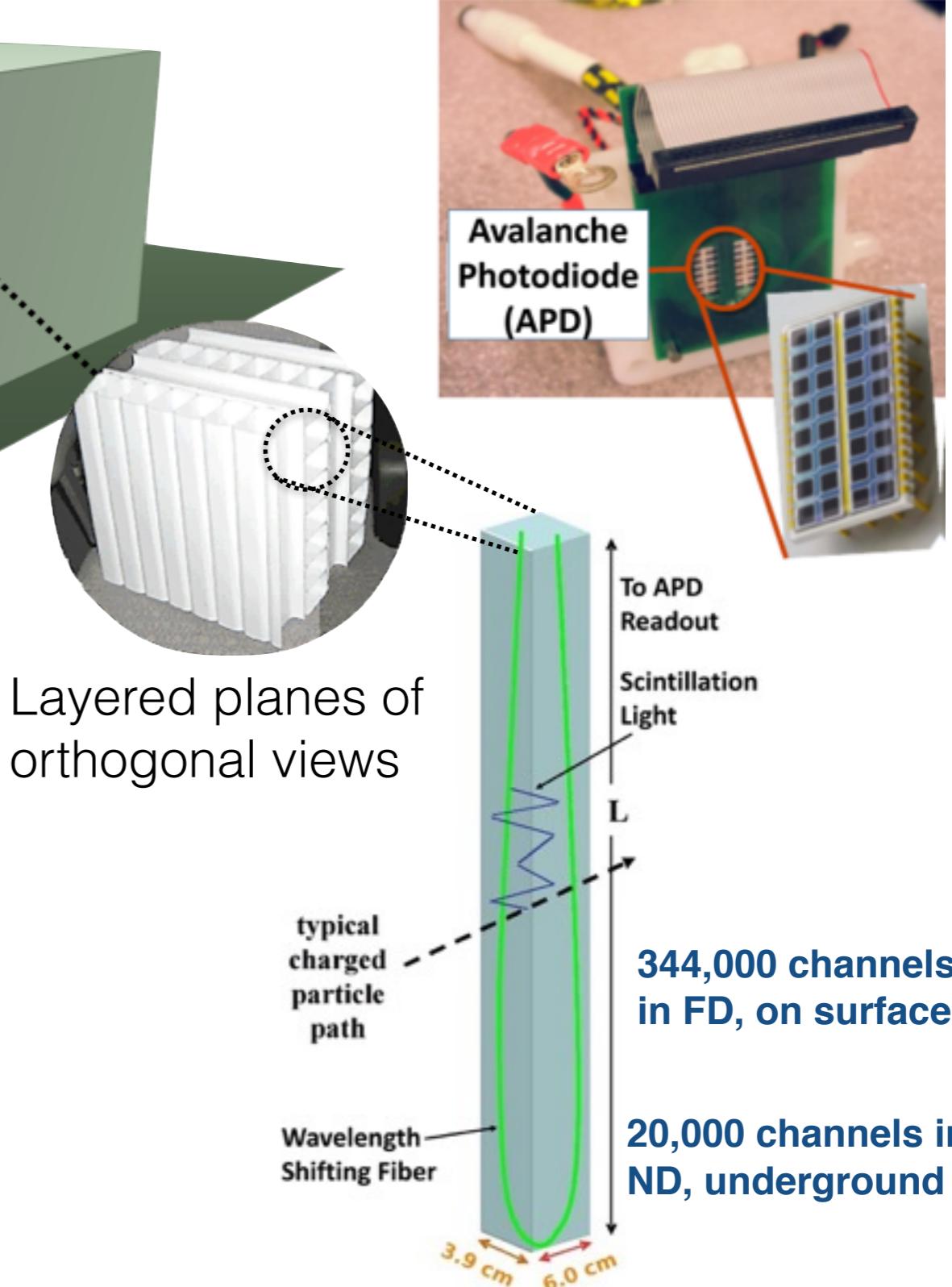
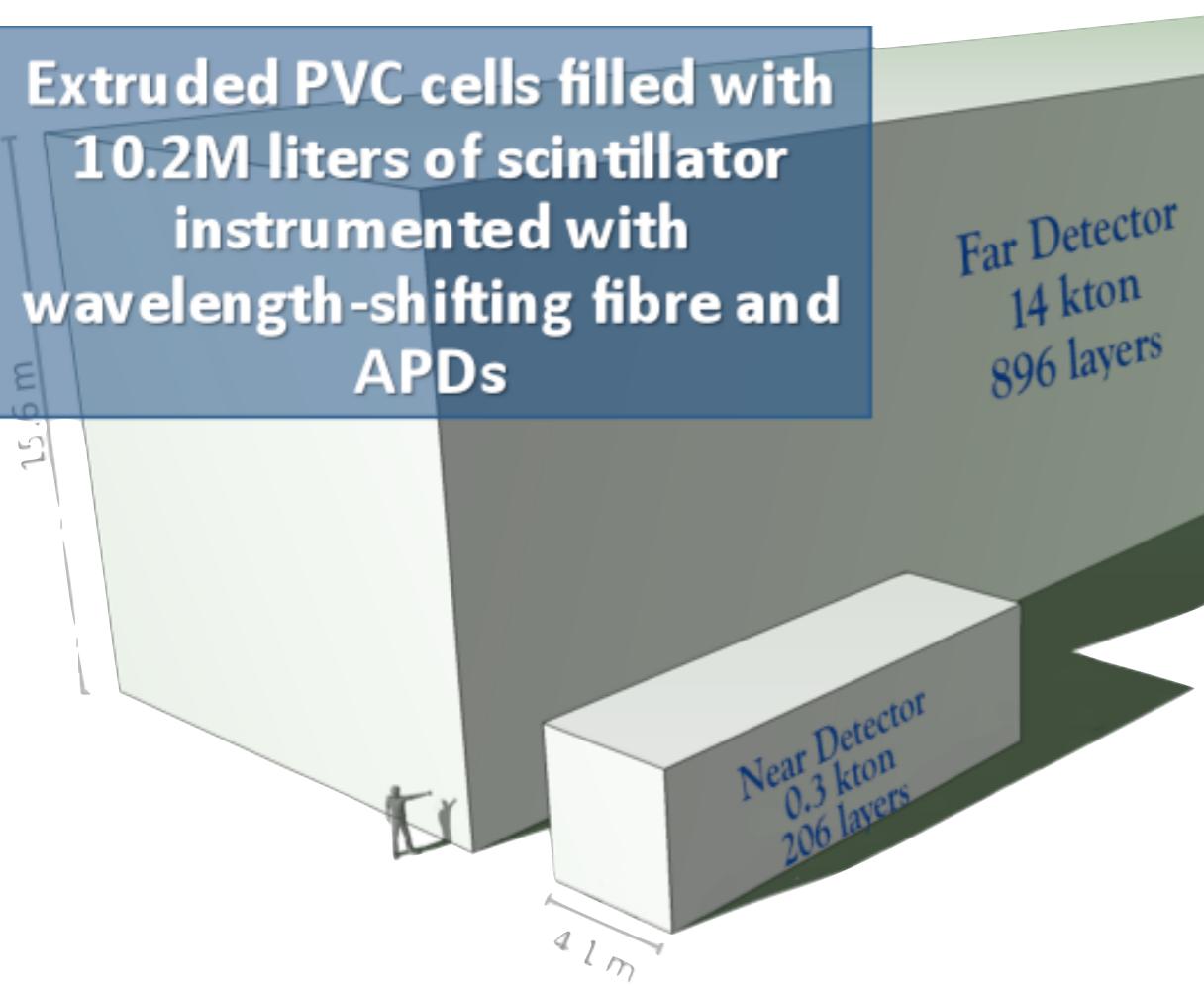
NOvA Second Analysis uses data from Feb 6 2014 to May 2 2016

6.05×10^{20} POT in full 14 kton detector

(More than double the exposure of the 2015 analysis)

Functionally-identical PVC-cell Near and Far Detectors filled with 10.2M liters of scintillator

Extruded PVC cells filled with
10.2M liters of scintillator
instrumented with
wavelength-shifting fibre and
APDs



Low-Z materials, 65% active

DAQ runs with zero deadtime

Triggers on beam, SNEWS, exotics,
cosmic ray calibration samples

Wonderful 200+ collaborators spanning 41 institutions and 7 countries



Argonne, Atlantico, Banaras Hindu, Caltech, CUSAT, Czech Academy of Sciences, Charles, Cincinnati, Colorado State, Czech Technical University, Delhi, Dubna, Fermilab, Goias, IIT-Guwahati, Harvard, IIT-Hyderabad, Hyderabad, Indiana, Iowa State, Jammu, Lebedev, Michigan State, Minnesota-Twin Cities, Minnesota-Duluth, INR Moscow, Panjab, SDMT, South Carolina, SMU, Stanford, Sussex, Tennessee, Texas-Austin, Tufts, UCL, Virginia, Wichita State, William and Mary, Winona State.

NOvA's physics goals include long baseline oscillation

ν_μ CC

Disappearance

This talk!

Suppression of signal
as a function of energy

Measurements of:

$$|\Delta m_{32}^2| \quad \sin^2(2\theta_{23})$$

2015 analysis results:
Phys.Rev.D93.051104

ν_e CC

Appearance

J. Bian's talk @ 14:20

Matter effects enhance
appearance (NH) ~30%
over 810 km baseline

Sensitivity to:

Mass Hierarchy

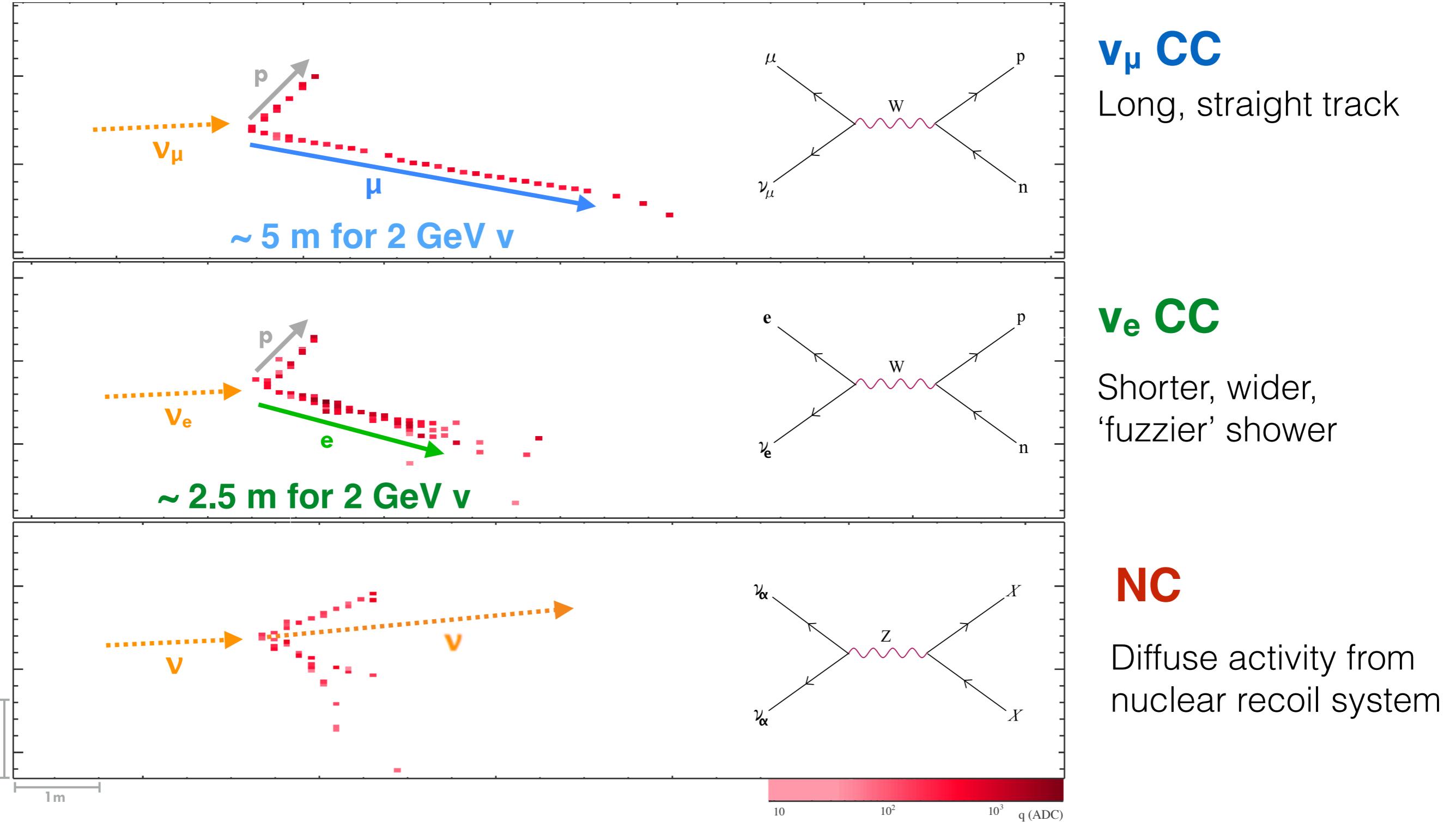
Octant of θ_{23}

δ_{CP}

2015 analysis results:
PRL.116.151806



NOvA's great granularity produces distinct event topologies



Cosmic ray muons are our standard candle for calibration and energy scale

Cells individually corrected for:

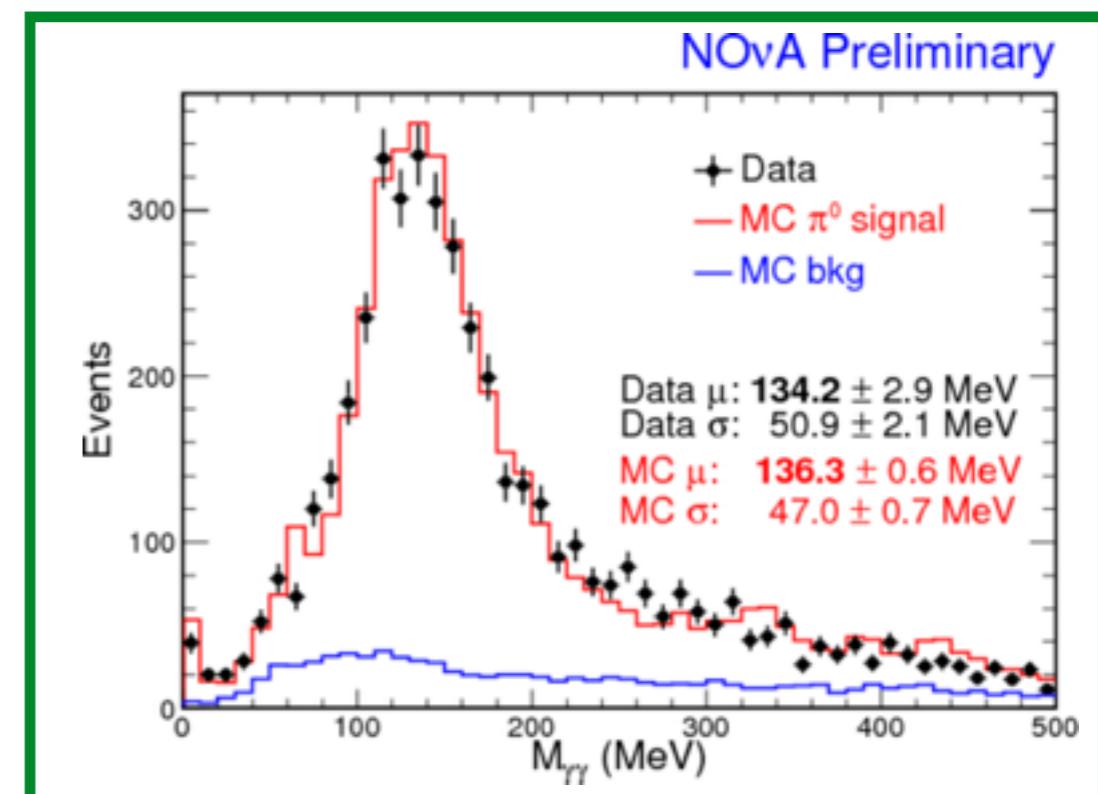
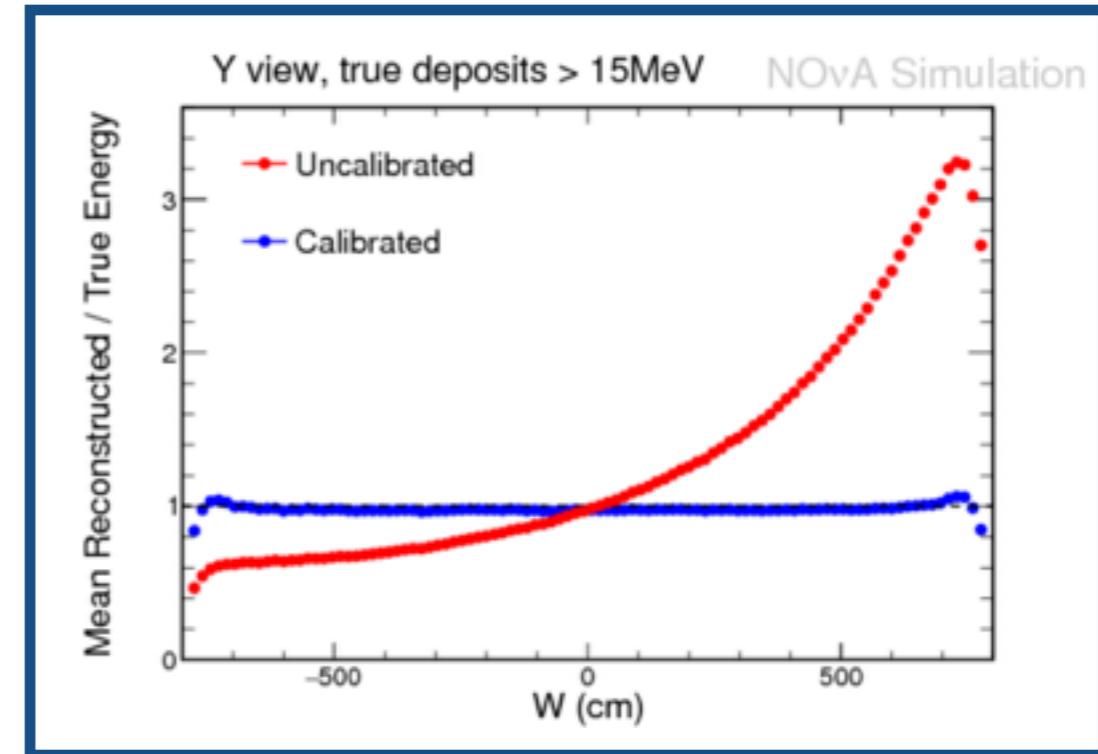
- Light attenuation along cell length
- Shadowing due to detector bulk
- Threshold effects far from readout

Energy scale set by dE/dx near the end of stopping muons

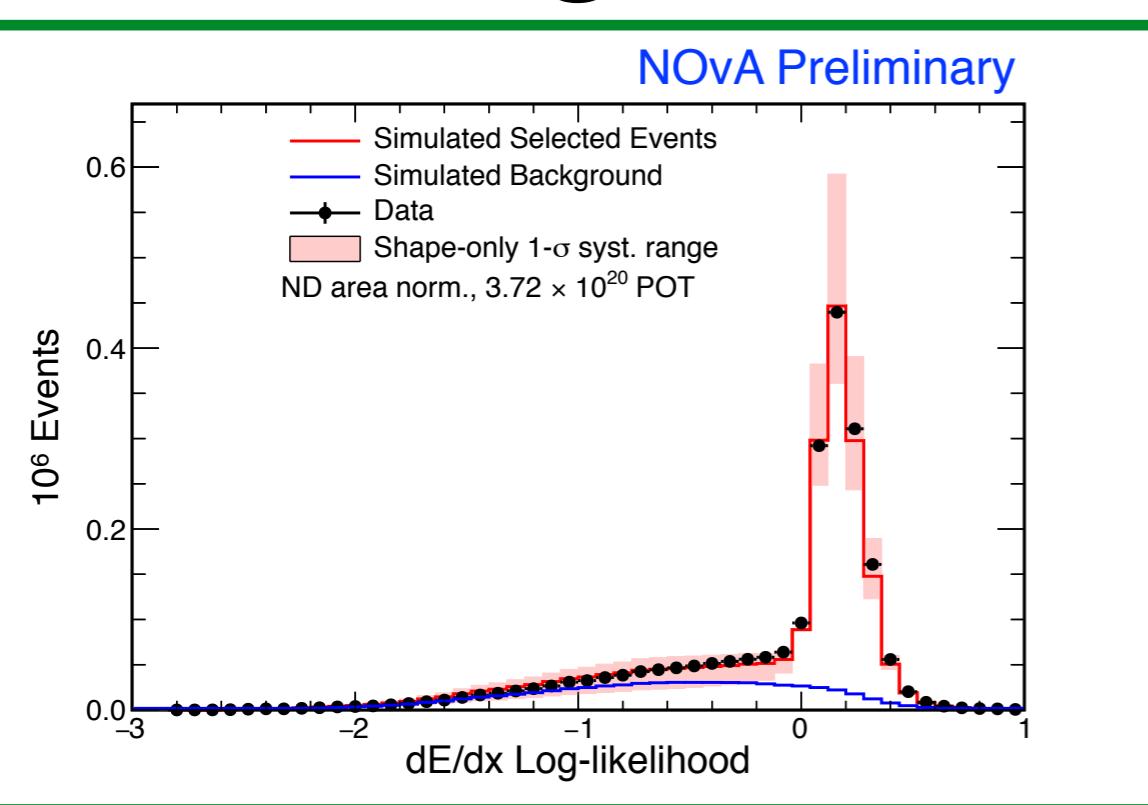
- Cross-checks, including π^0 mass peak, Michel e^- spectrum, beam muon dE/dx
- Take 5% absolute and relative errors

Attenuation Calibration of the NOvA Detectors (372)

P. Singh



Goal: isolate a pure sample of ν_μ charge-current events < 5 GeV



Suppress NC and cosmic events

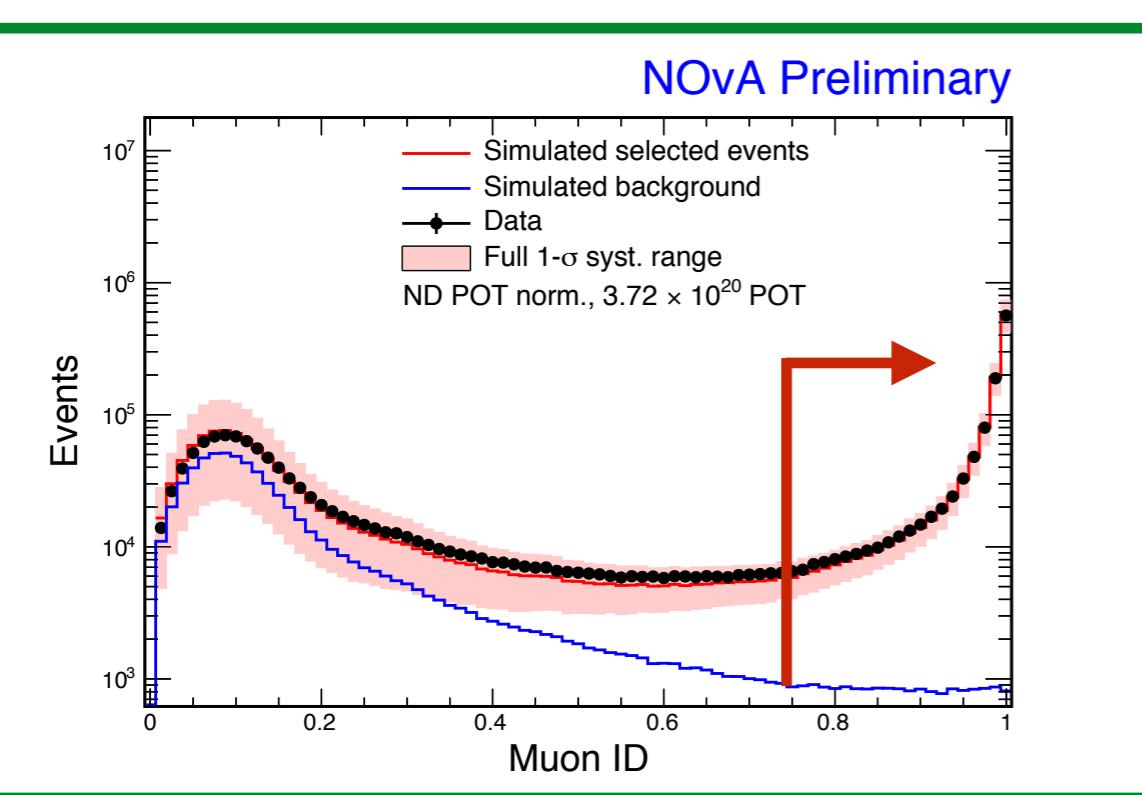
Containment cuts

Remove events with activity close to detector walls

Four variable kNN used to identify muons:

- Track length
- dE/dx along track
- Scattering along track
- Track-only plane fraction

Selection 81% efficient for ν_μ signal, 95% pure



A $10 \mu\text{s}$ beam spill window provides cosmic rejection at $O(10^5)$ — cosmic cuts at another $O(10^7)$

Cosmic rates in data

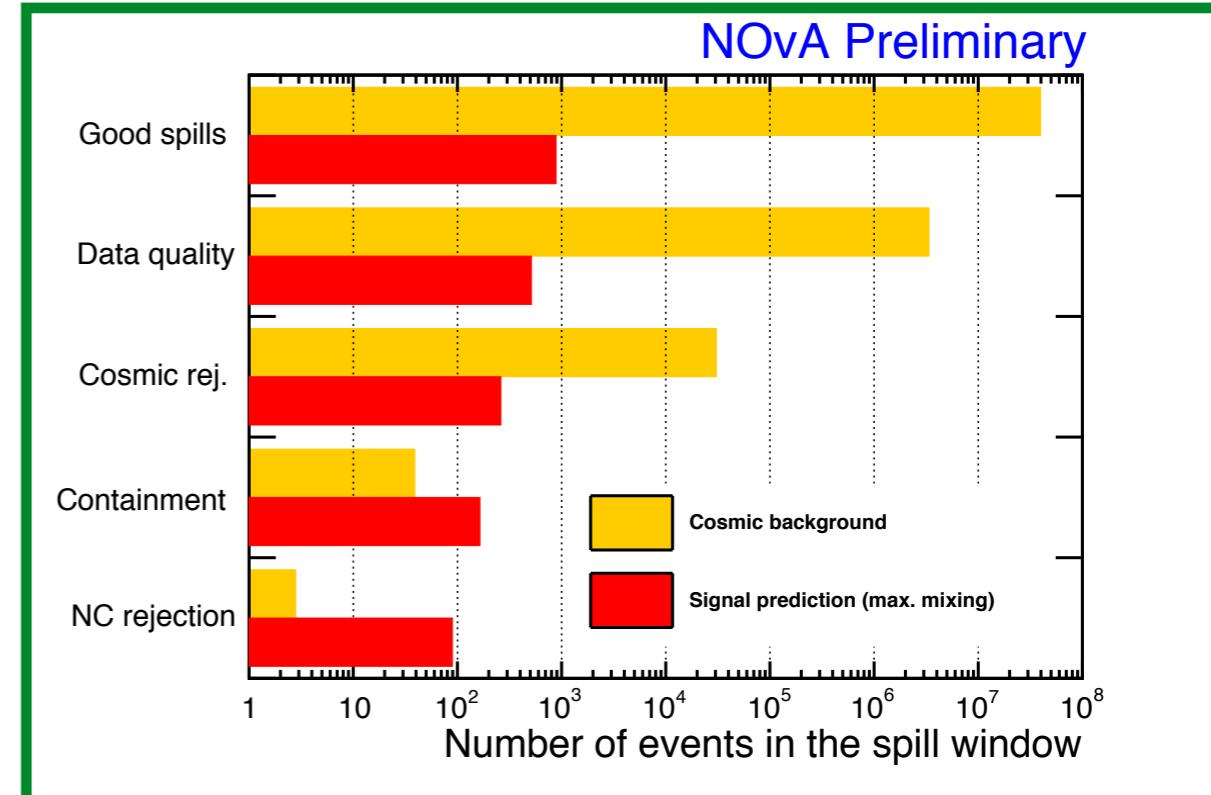
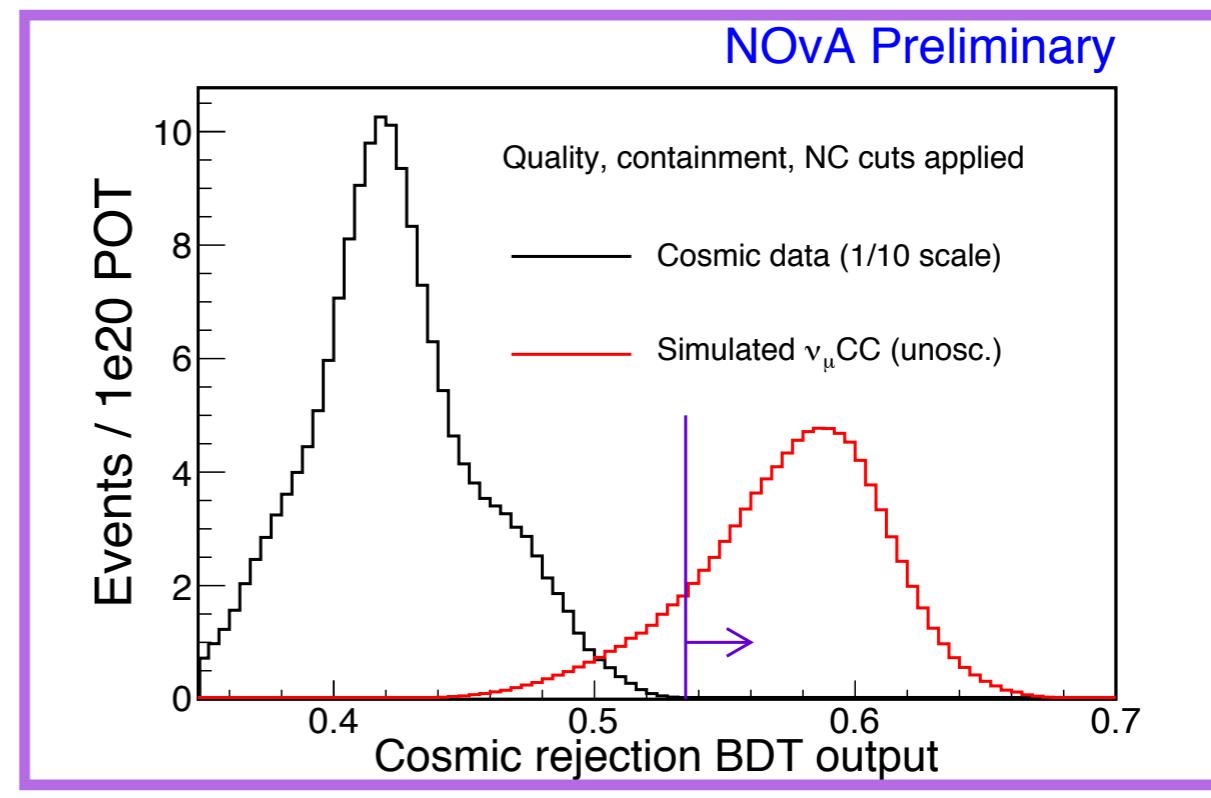
are measured in time windows adjacent to the spill

Event topology and a BDT
(boosted decision tree) provide another factor **$O(10^7)$ reduction** in cosmics. BDT uses:

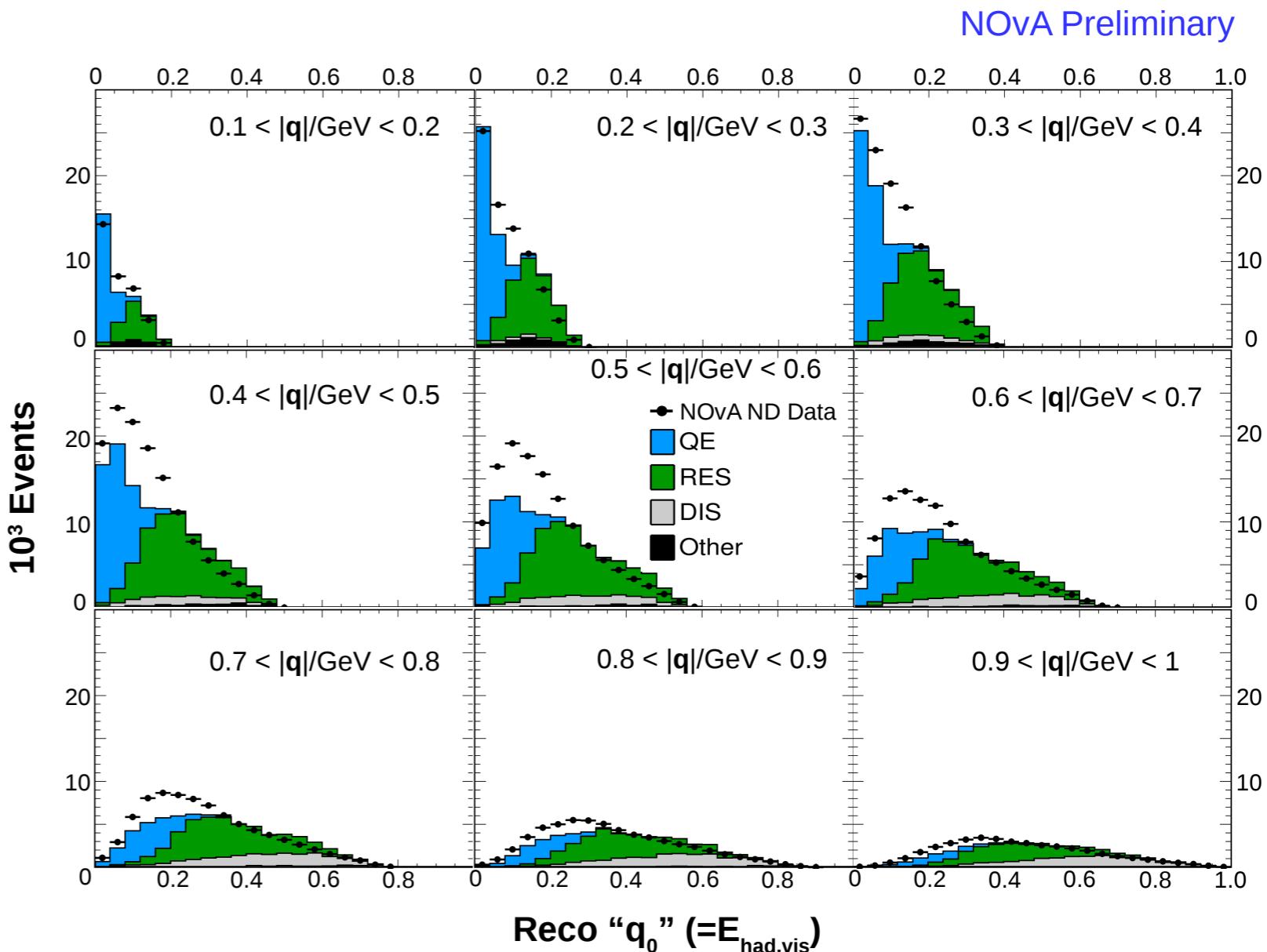
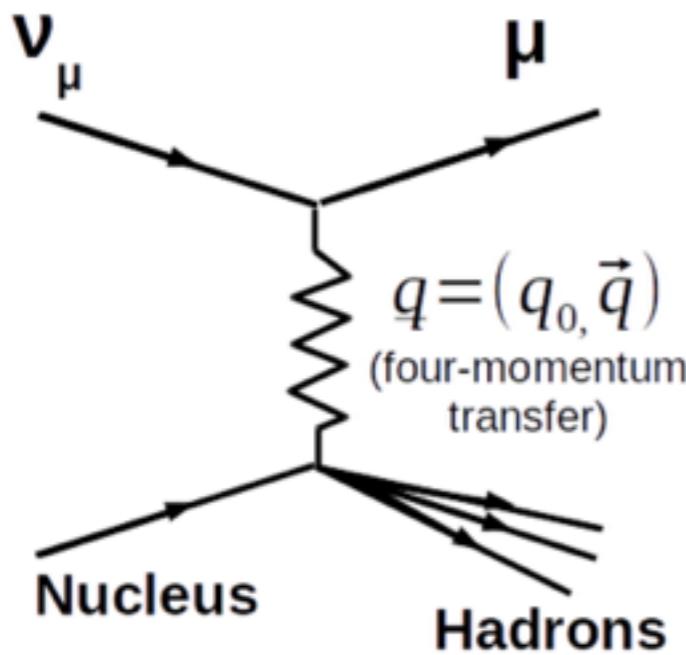
- Track direction
- Track start and end points
- Track length
- Energy
- Number of hits

NOvA Muon Neutrino Selection (1664)

V. Bychkov and L. Corwin



Impact of Near Detector: data suggests an unsimulated process between QE and Δ production



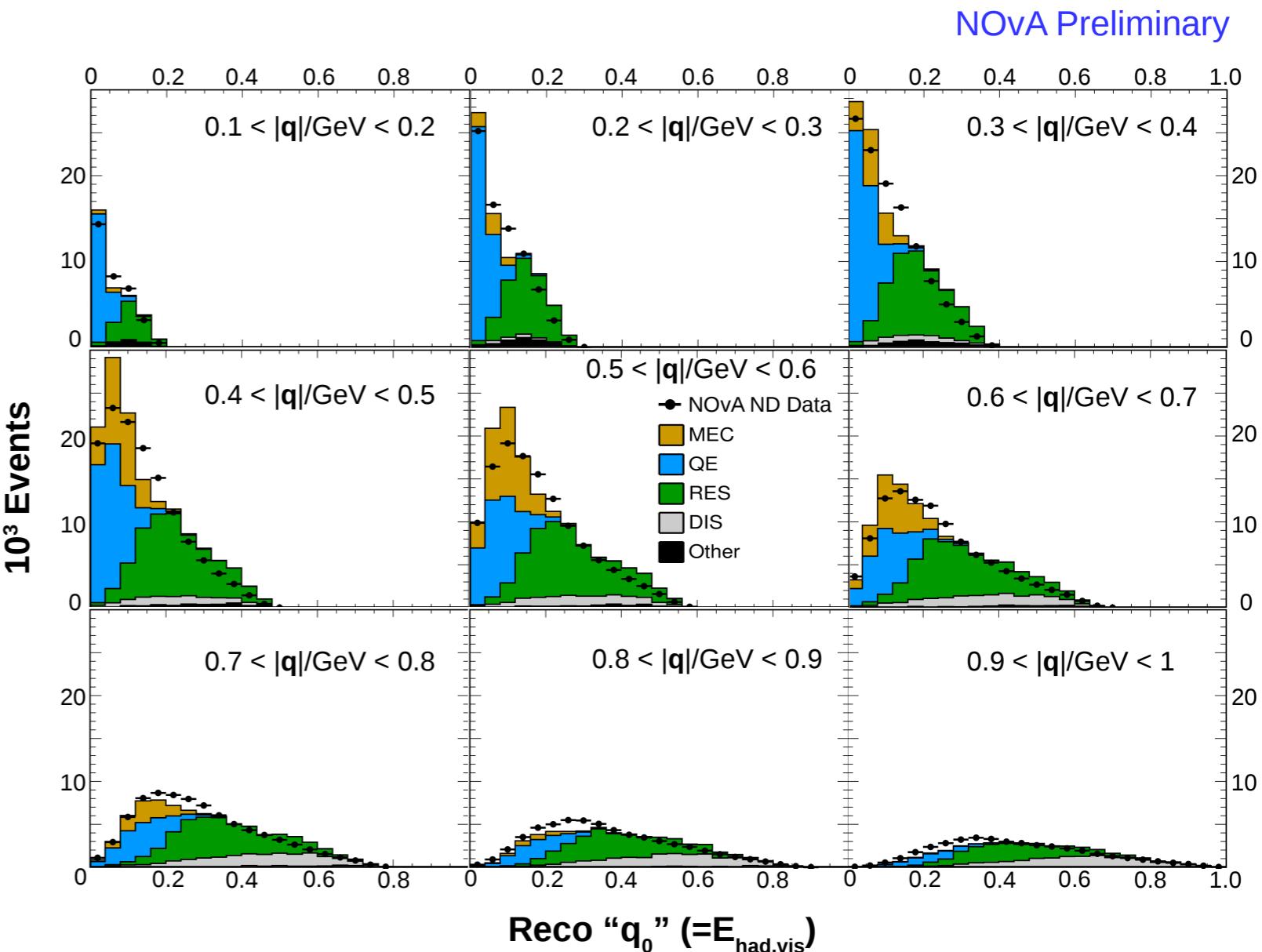
MINERvA reported a similar excess in their data
P.A. Rodrigues et al., PRL 116 (2016) 071802

We enable GENIE's empirical Meson Exchange Current model

We reweight the model to match our observed excess as a function of \mathbf{p} transfer

This reduces our largest systematic uncertainties

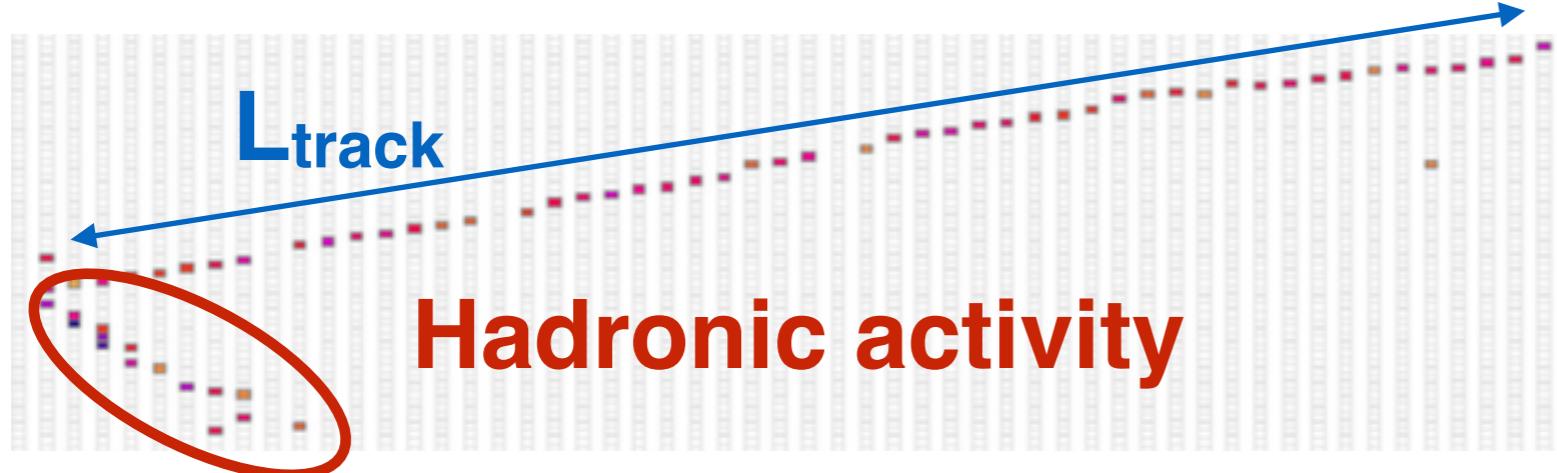
- Hadronic energy scale
- QE cross-section modeling



Reduce single non-resonant pion production by 50%
(P.A. Rodrigues et al, arXiv:1601.01888.)

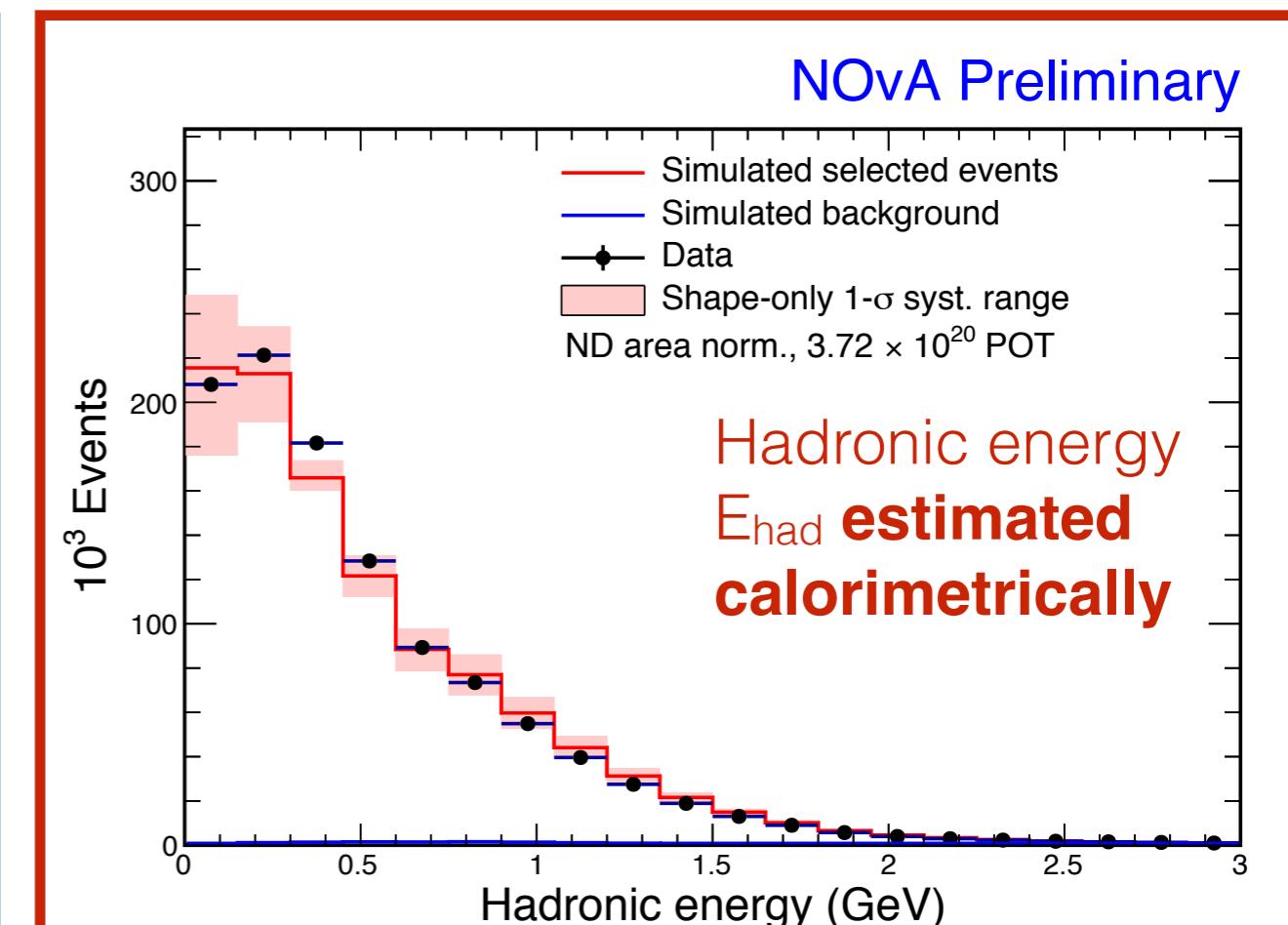
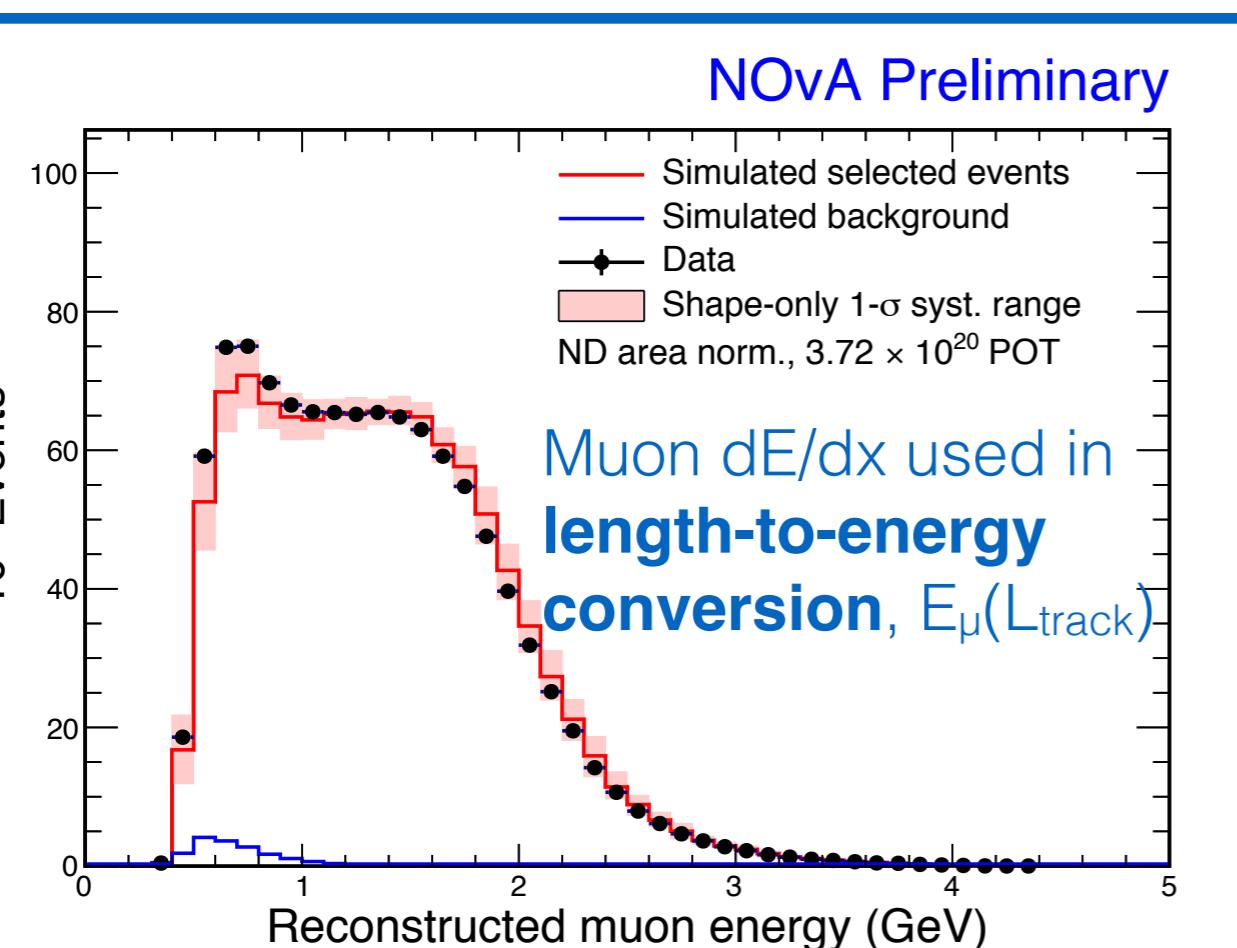
Take 50% systematic uncertainty on MEC component

Neutrino energy is reconstructed as $E_\mu(L_{\text{track}}) + \text{hadronic contributions}$

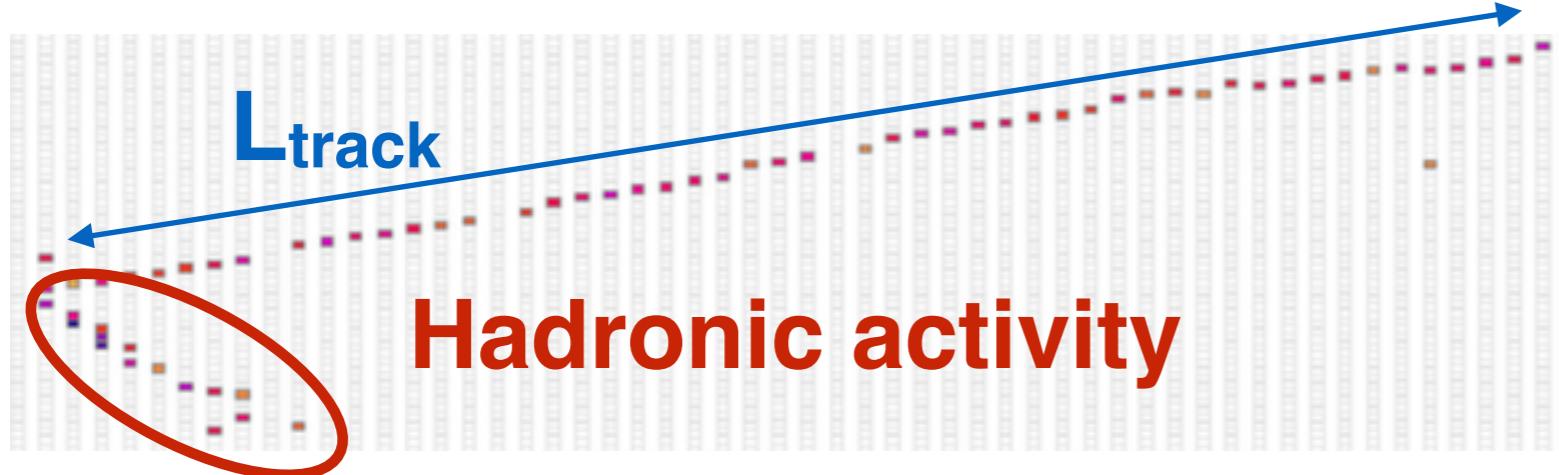


$$E_\nu = E_\mu(L_{\text{track}}) + E_{\text{had}}$$

(E_ν resolution $\sim 7\%$)

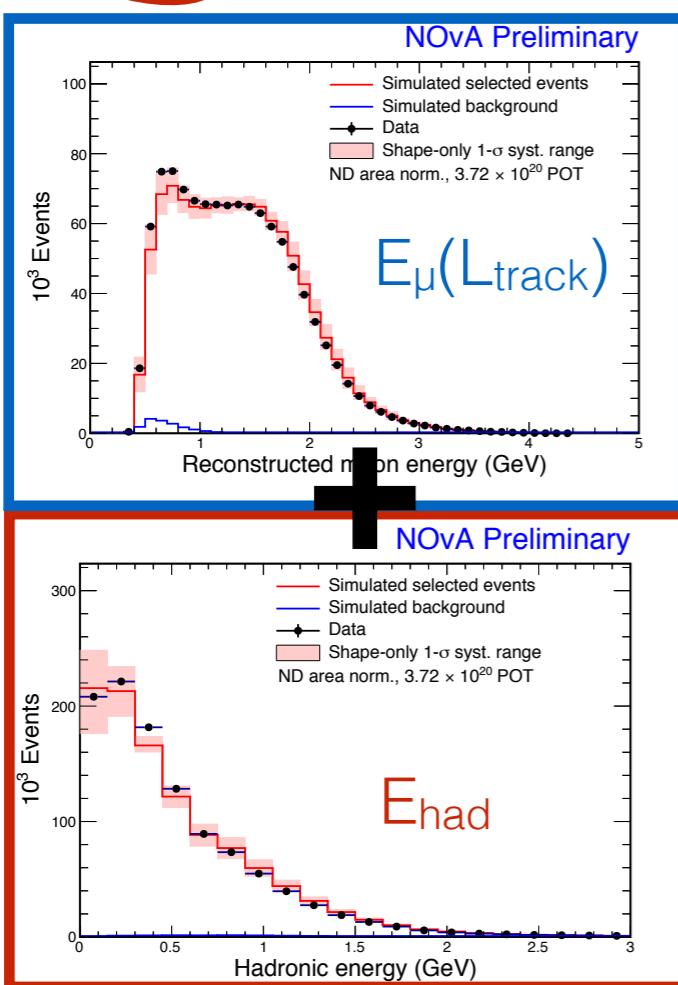


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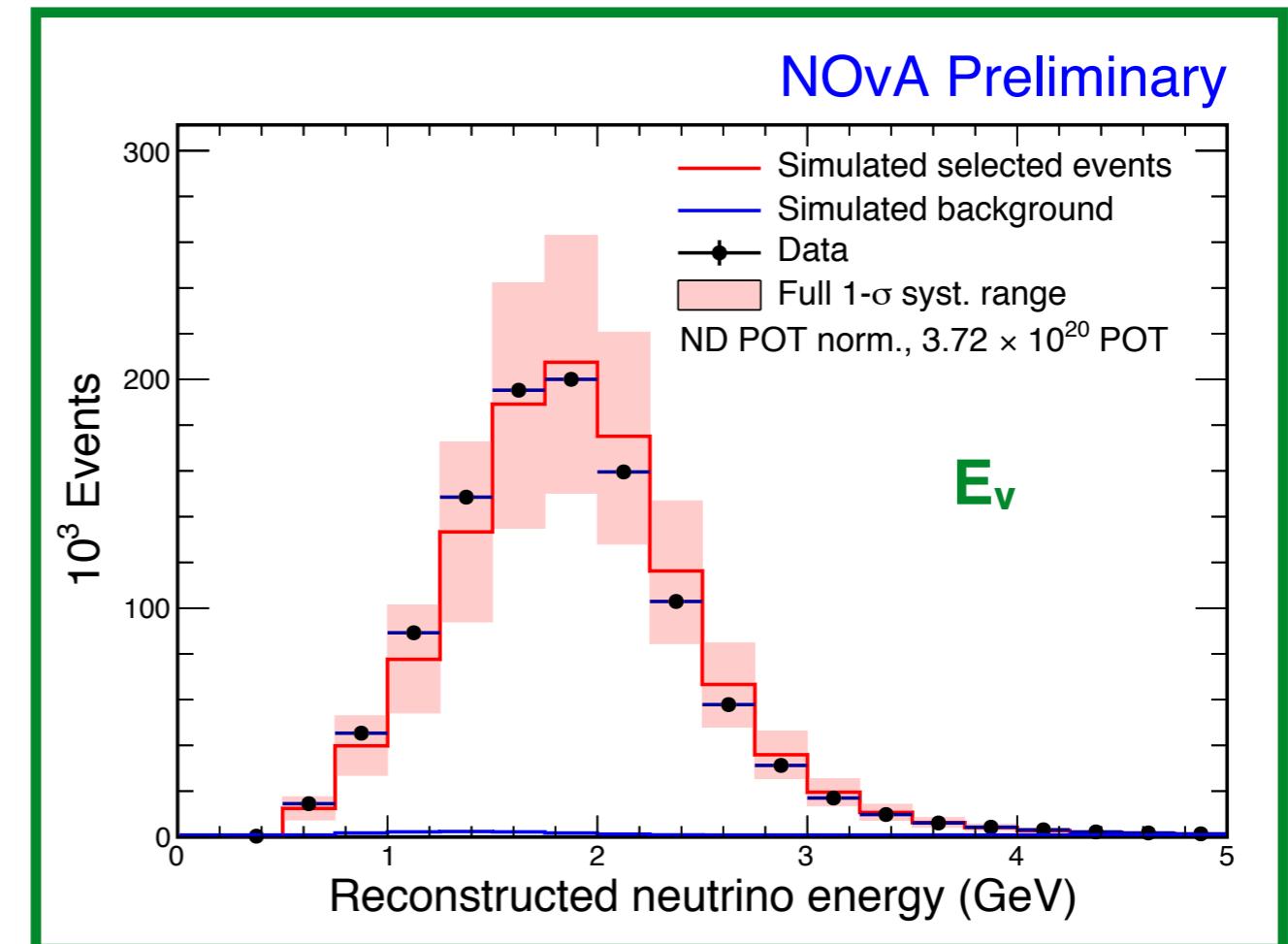


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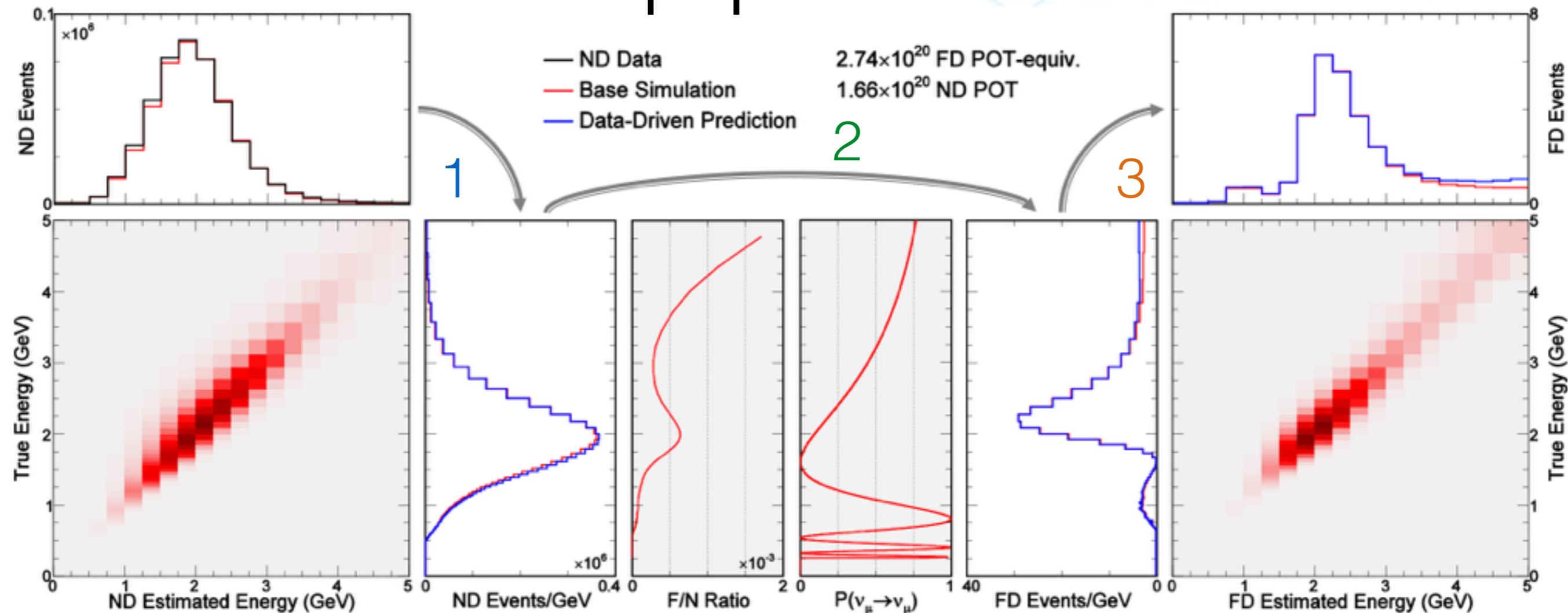
(E_ν resolution $\sim 7\%$)



=



ND to FD extrapolation is a three step process



- 1) Convert ND reconstructed energy to true energy
- 2) Use Far/Near ratio to convert to FD true energy spectrum
- 3) Translate back to reconstructed energy

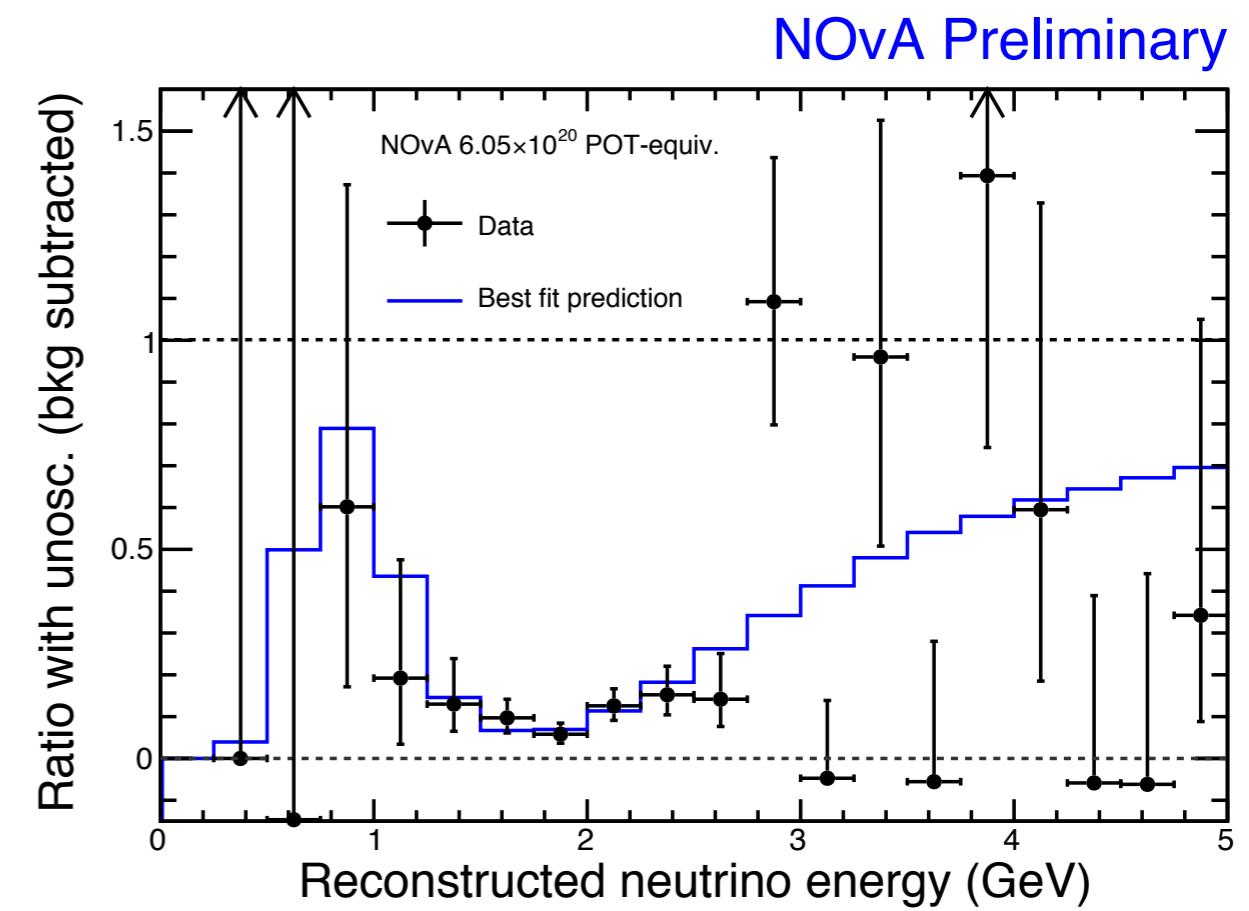
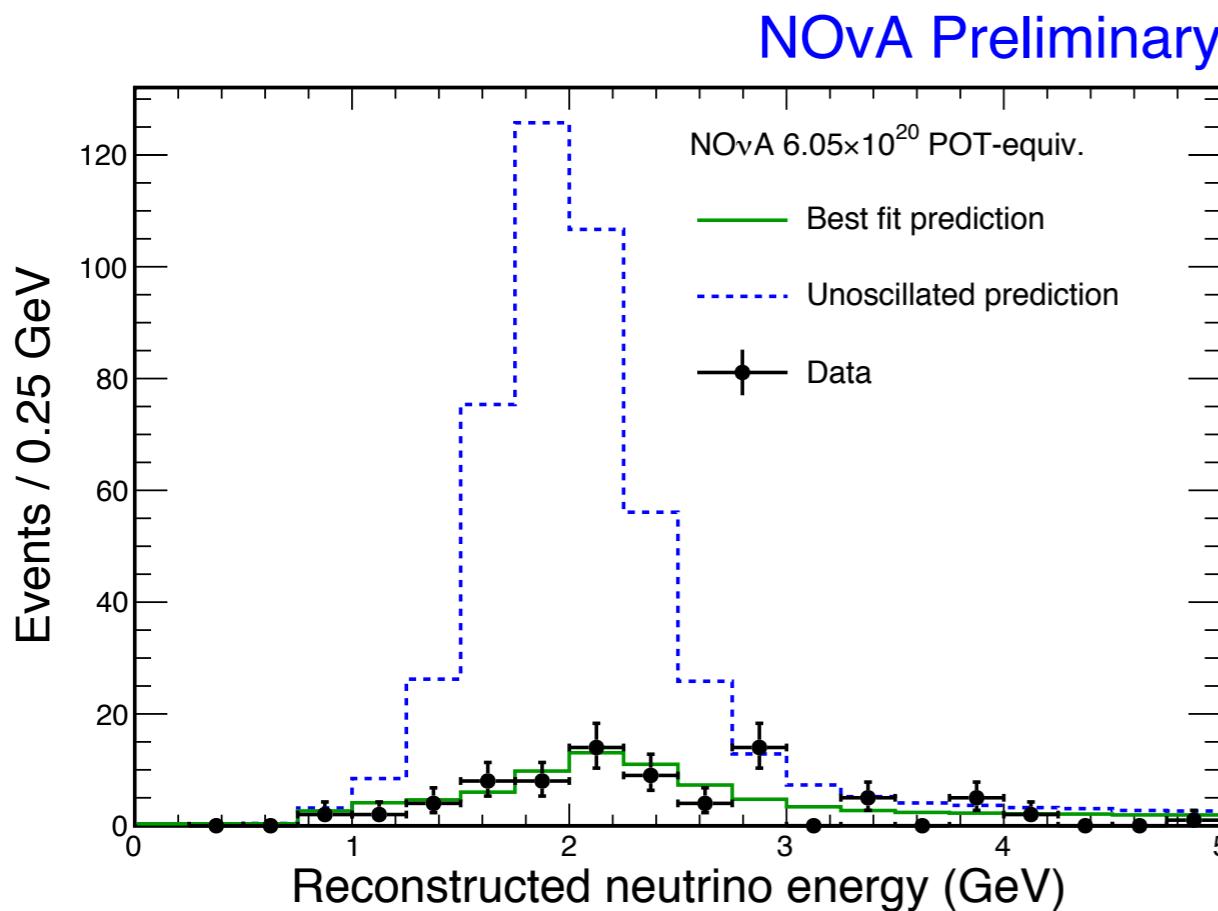
We consider multiple possible sources of systematic error

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

In each case:

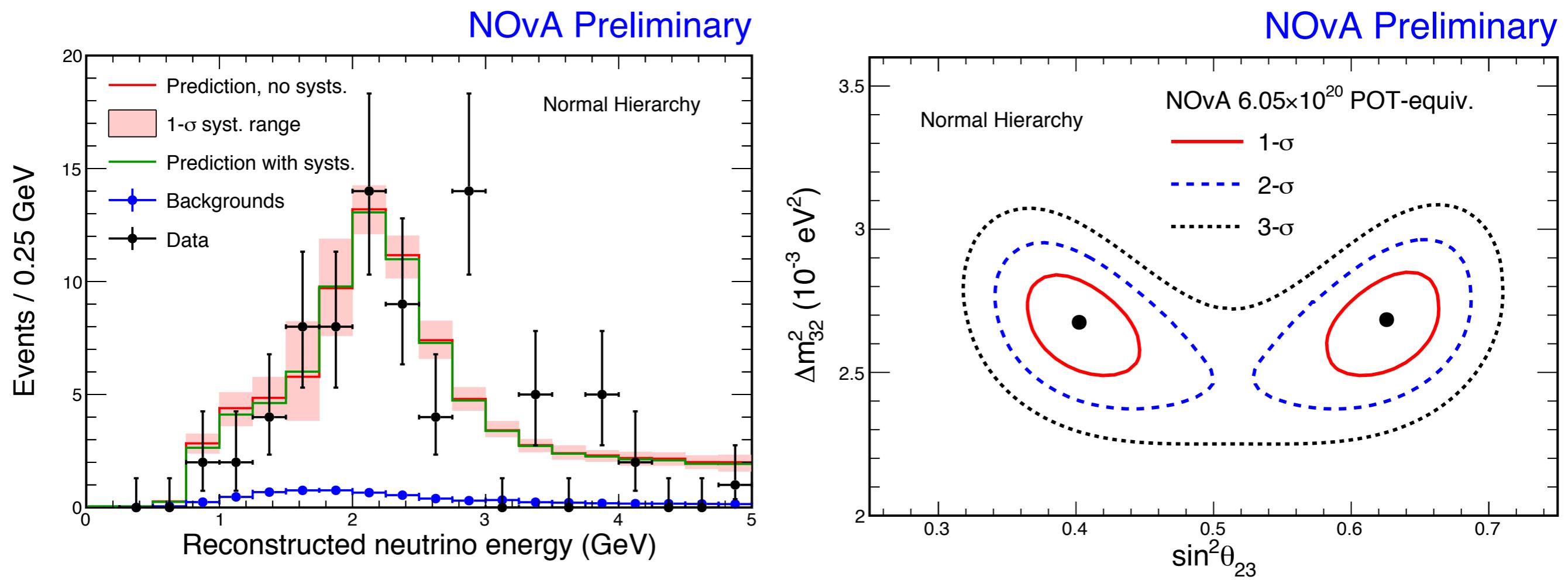
- The effect is propagated through the extrapolation
- We include those effects as pull terms in the fit
- The increase (in quadrature) of the parameter measurement error is recorded

We expect 473 FD ν_μ CC events without oscillation, and observe 78



82 predicted at the best fit point,
including 3.7 beam background and 2.9 cosmic events

Our best fit excludes maximal mixing at 2.5σ

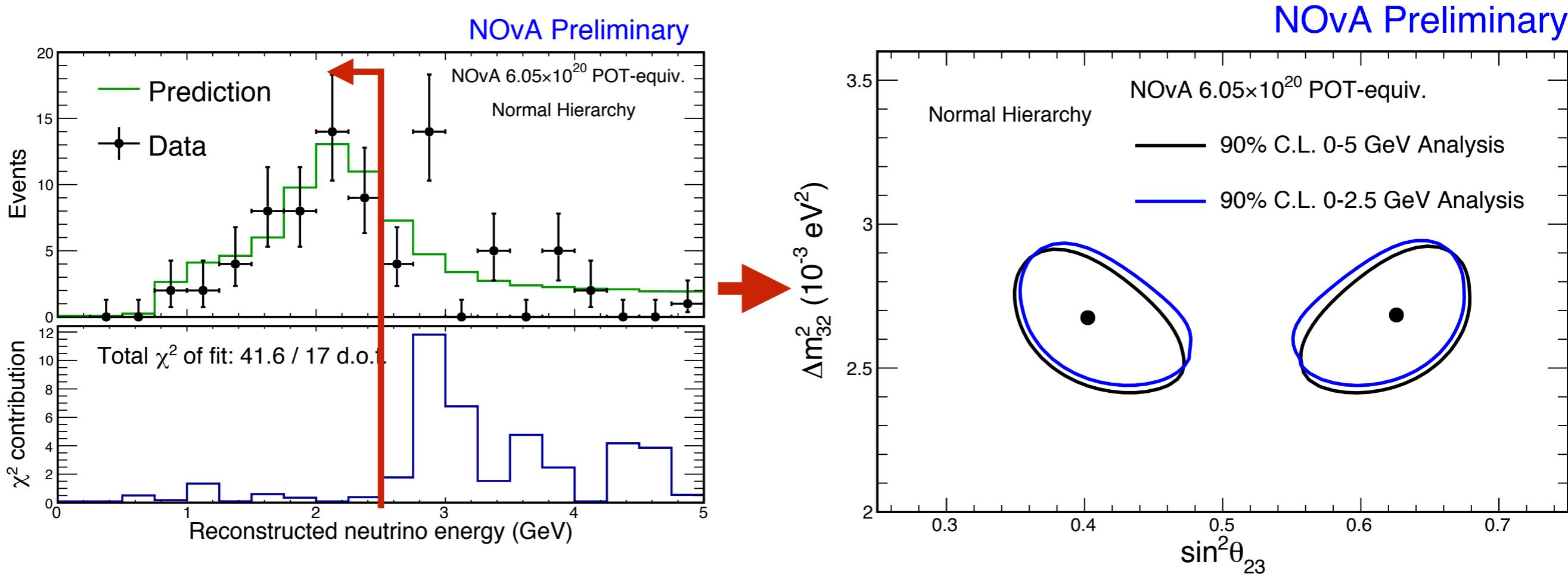


Our best fit is at:

$$\Delta m_{32}^2 = (2.67 \pm 0.12) \times 10^{-3} \text{ eV}^2 (\text{NH})$$

$$\sin^2(\theta_{23}) = 0.40^{+0.03}_{-0.02} (0.63^{+0.02}_{-0.03})$$

Our best fit $\chi^2/\text{DOF} = 41.5/17$
is driven by the region above 2.5 GeV



There is no significant pull in the oscillation fit
from bins in the region above 2.5 GeV

The non-maximal fit is driven by bins in the oscillation dip (1-2 GeV)

Forcing maximal mixing gives us:

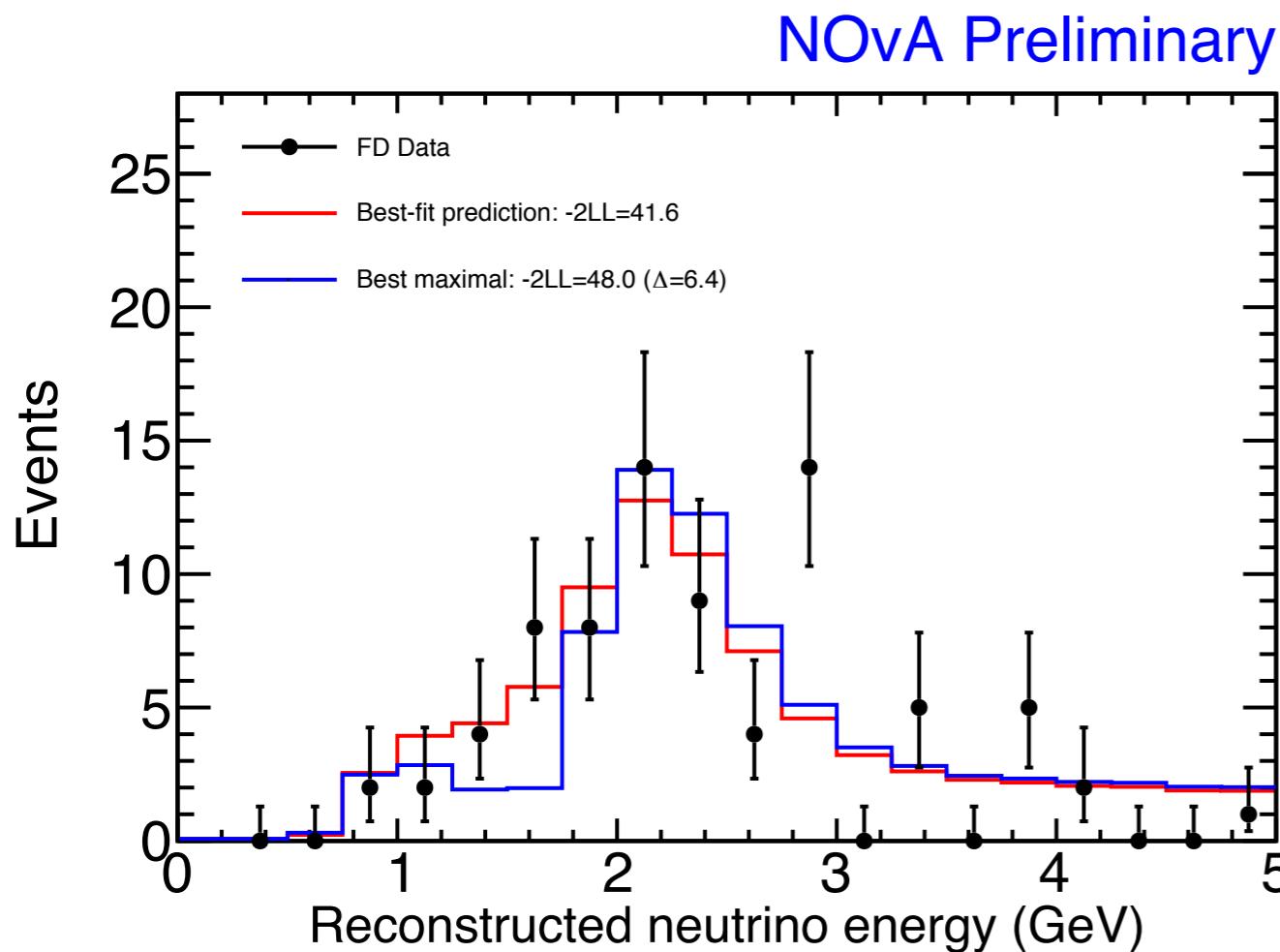
$$\Delta m_{32}^2 = (2.46) \times 10^{-3} \text{ eV}^2$$

with χ^2 at 6.4 above the non-maximal fit

(Compare to

$$\Delta m_{32}^2 = (2.67 \pm 0.12) \times 10^{-3} \text{ eV}^2$$

for non-maximal mixing)



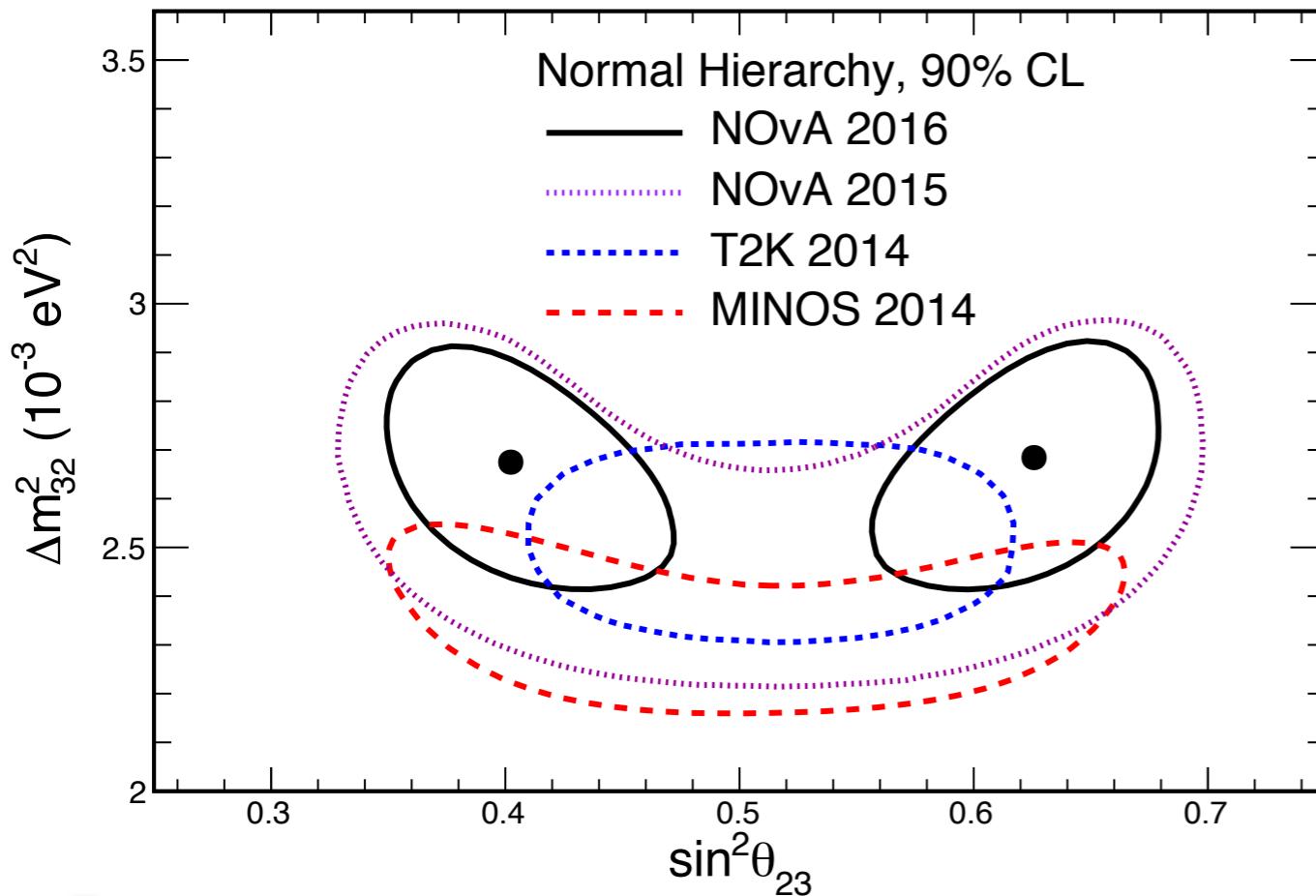
Takeaway

Our best fit:

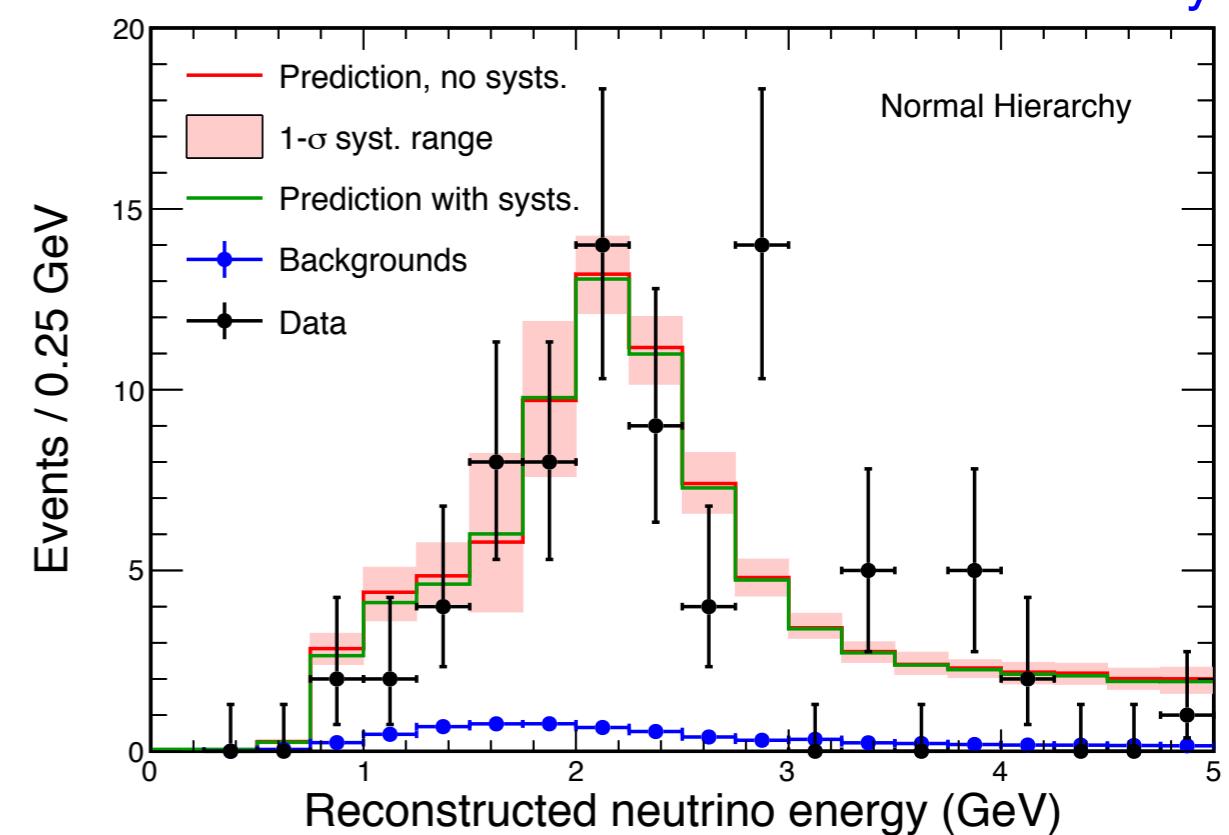
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NOvA Preliminary



NOvA Preliminary



- 1) We observe ν_μ disappearance
- 2) We exclude maximal mixing at 2.5σ
- 3) Inclusion of GENIE's empirical MEC model, tuned to NOvA data, fills in an excess (and improves our systematics)
- 4) Tune in for our ν_e appearance talk (coming up next)!

Visit the poster session to explore many other interesting NOvA studies!

**Cross-section measurements with the NOvA ND
(Poster 1666)**

K. Sachdev

Constraints on the Neutrino Flux in NOvA using the Near Detector Data (Poster 1334)

K. Maan

Neutrino Induced Neutral Current Coherent π^0 Production in The NOvA Near Detector (Poster 520)

H. Duyang

**Attenuation Calibration of the NOvA Detectors
(Poster 372)**

P. Singh

NOvA Muon Neutrino Selection (Poster 1664)

V. Bychkov and L. Corwin

Extrapolation, Systematics and Results for the NOvA Disappearance Analysis (Poster 1464)

J. Lozier

Systematic Uncertainties in the NOvA Electron Neutrino Appearance Analysis (Poster 418)

E. Niner

**Cosmic Electromagnetic Showers in NOvA Detector
(Poster 1516)**

N. Yadav

Search for highly-ionizing particles in the NOvA Far Detector (Poster 1322)

C. Principato

Looking amongst the neutrinos for Lightweight Dark Matter in the NOvA Near Detector (Poster 1015)

F. Jediny, B. Wang

Search for Magnetic Monopoles with the NOvA Far Detector (Poster 981)

E. Song

Looking for Sterile Neutrinos with NOvA (Poster 1665)

S. Yang

Neutrino Identification with a Convolutional Neural Network in the NOvA Detectors (Poster 950)

A. Radovic

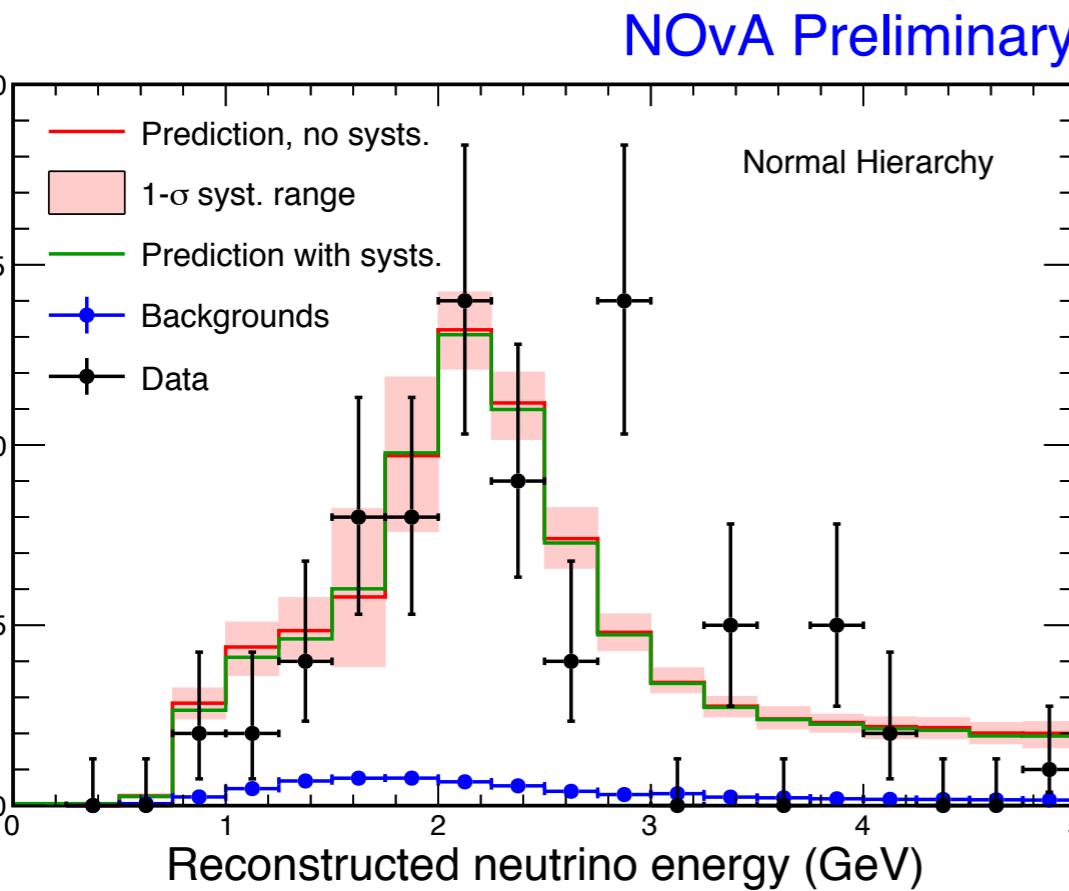
Backup

1-D Profiles

Recall our best fit:

$$\Delta m_{32}^2 = (2.67 \pm 0.12) \times 10^{-3} \text{ eV}^2 (\text{NH})$$

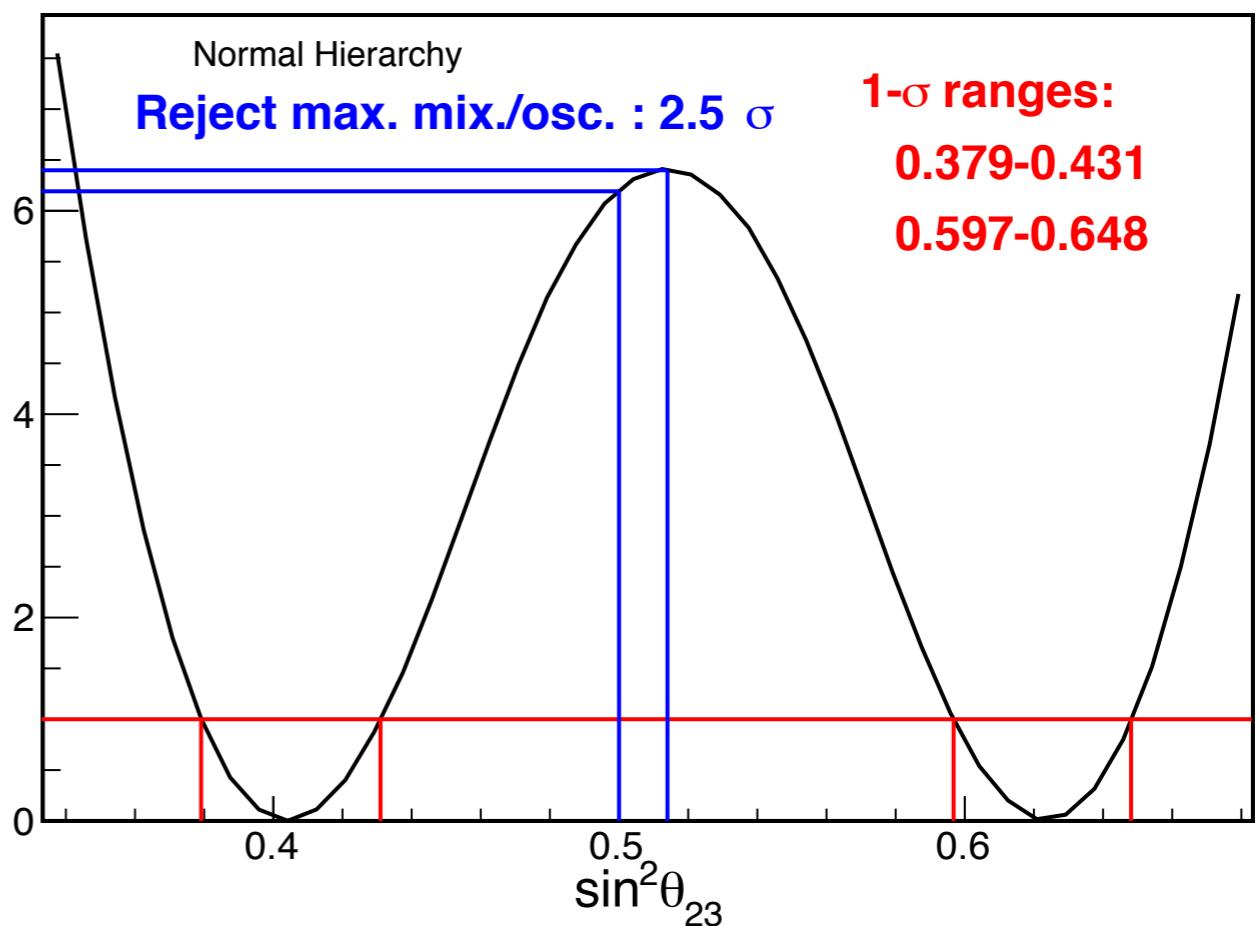
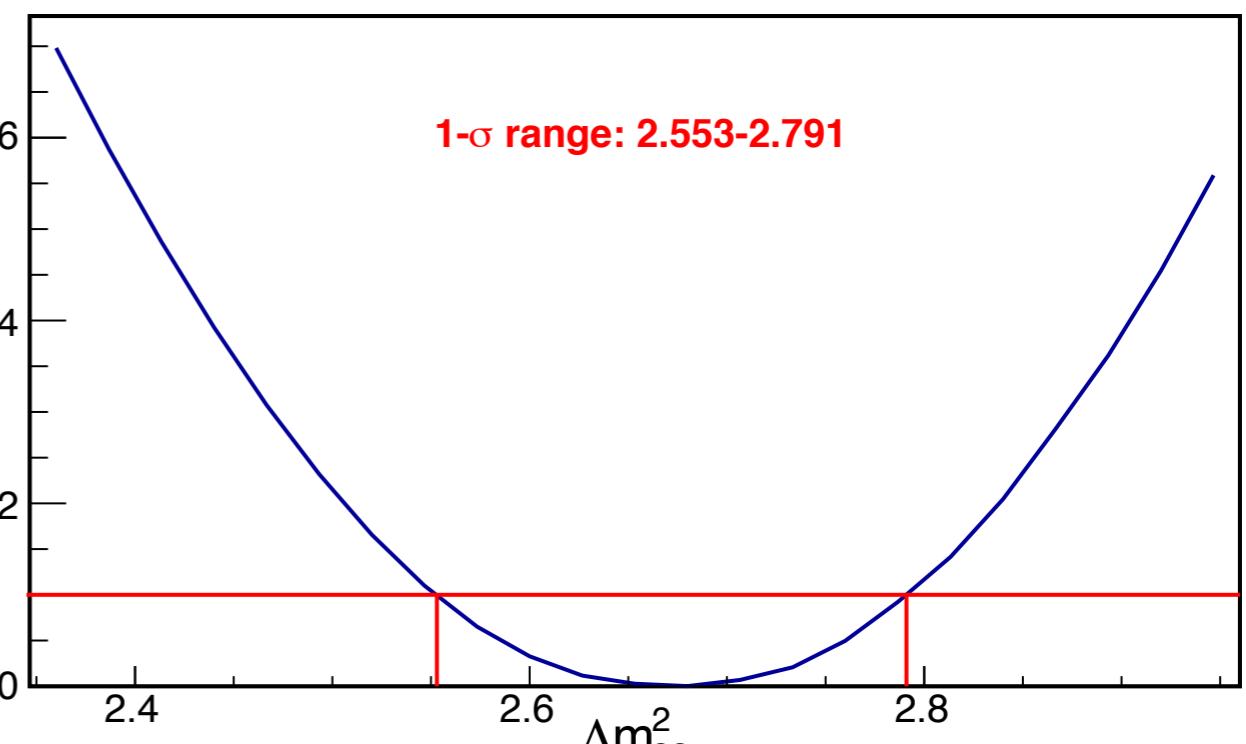
$$\sin^2 \theta_{23} = 0.40^{+0.03}_{-0.02} (0.63^{+0.02}_{-0.03})$$



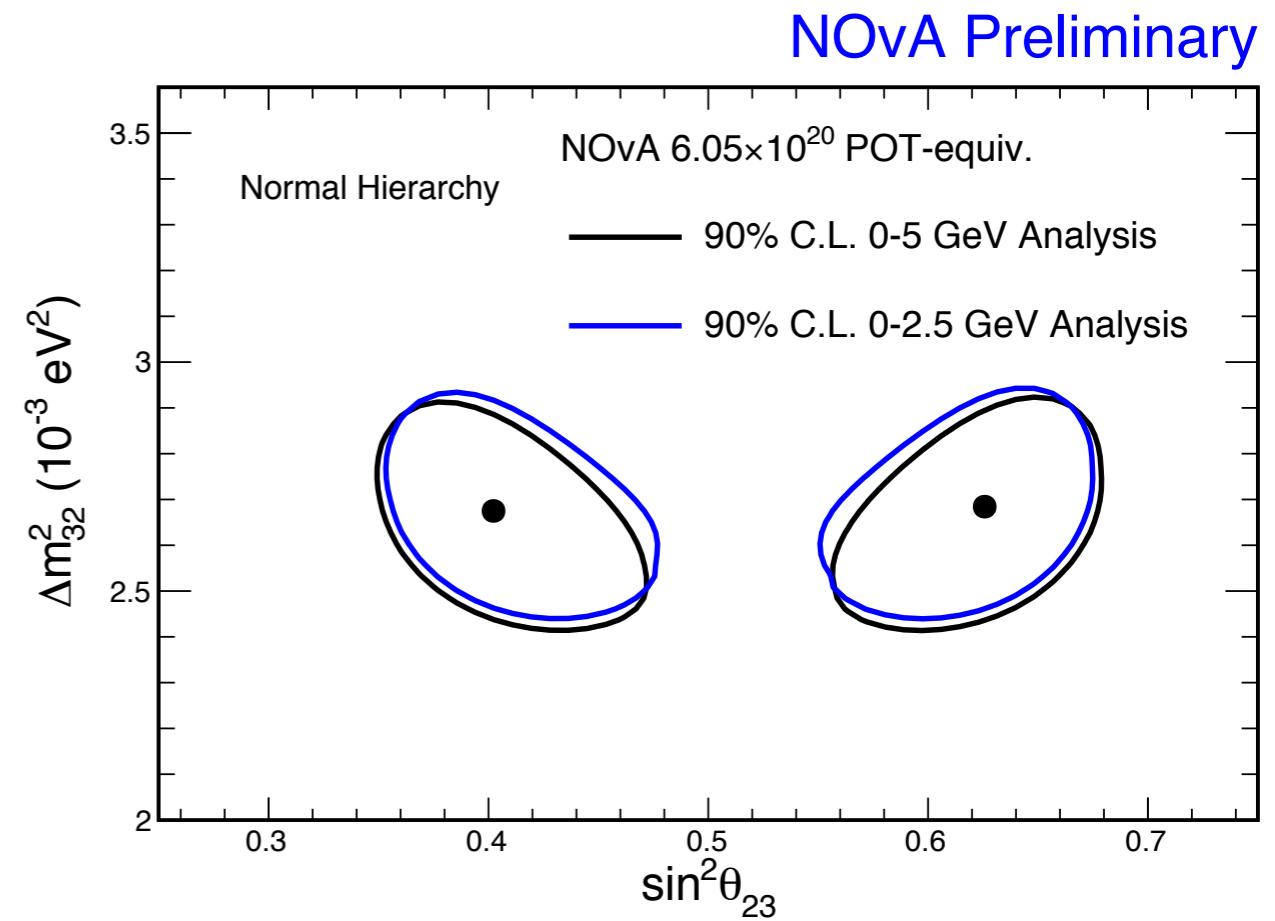
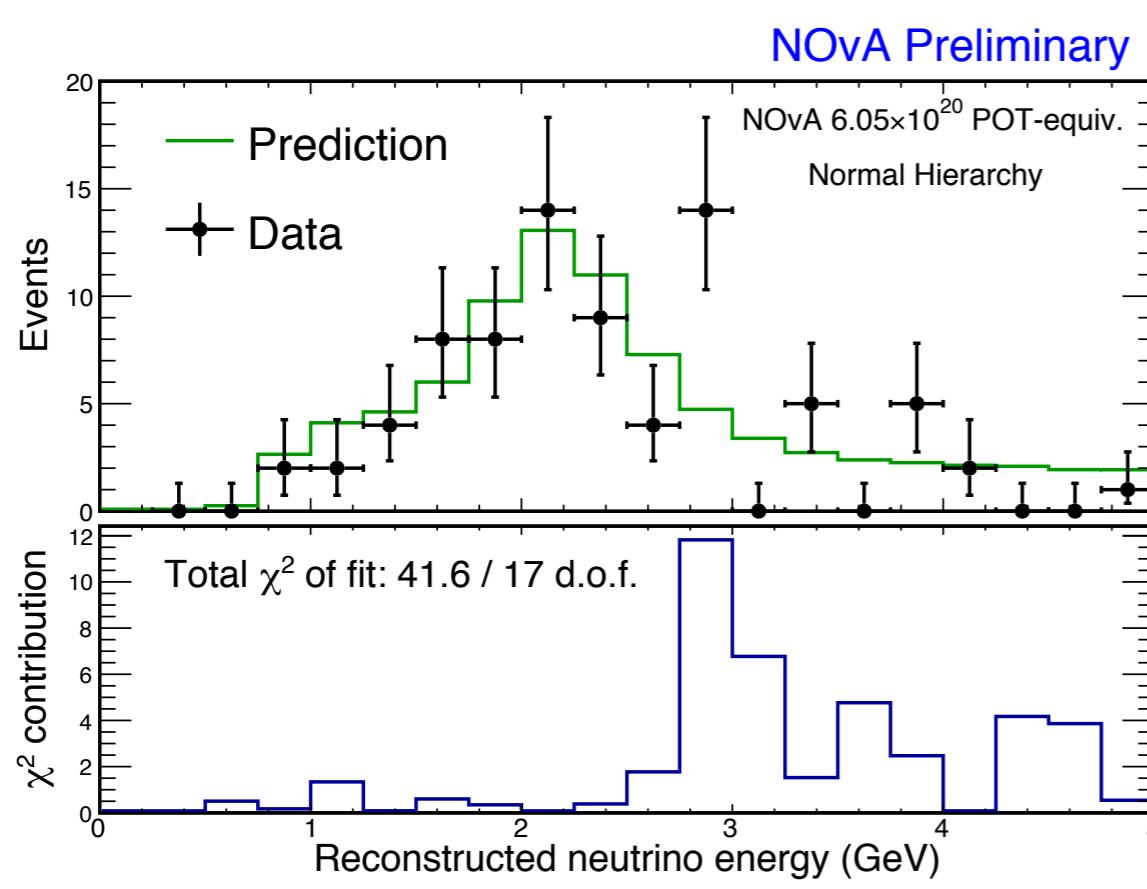
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K. Matera, ICHEP 2016



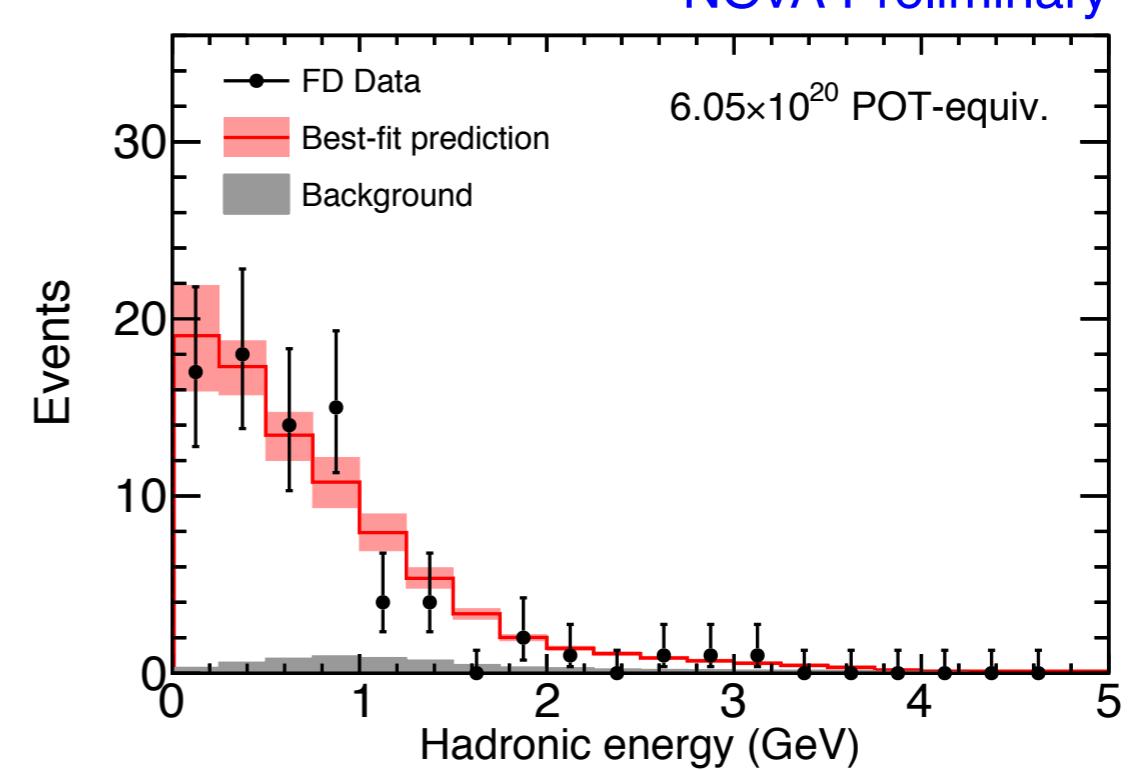
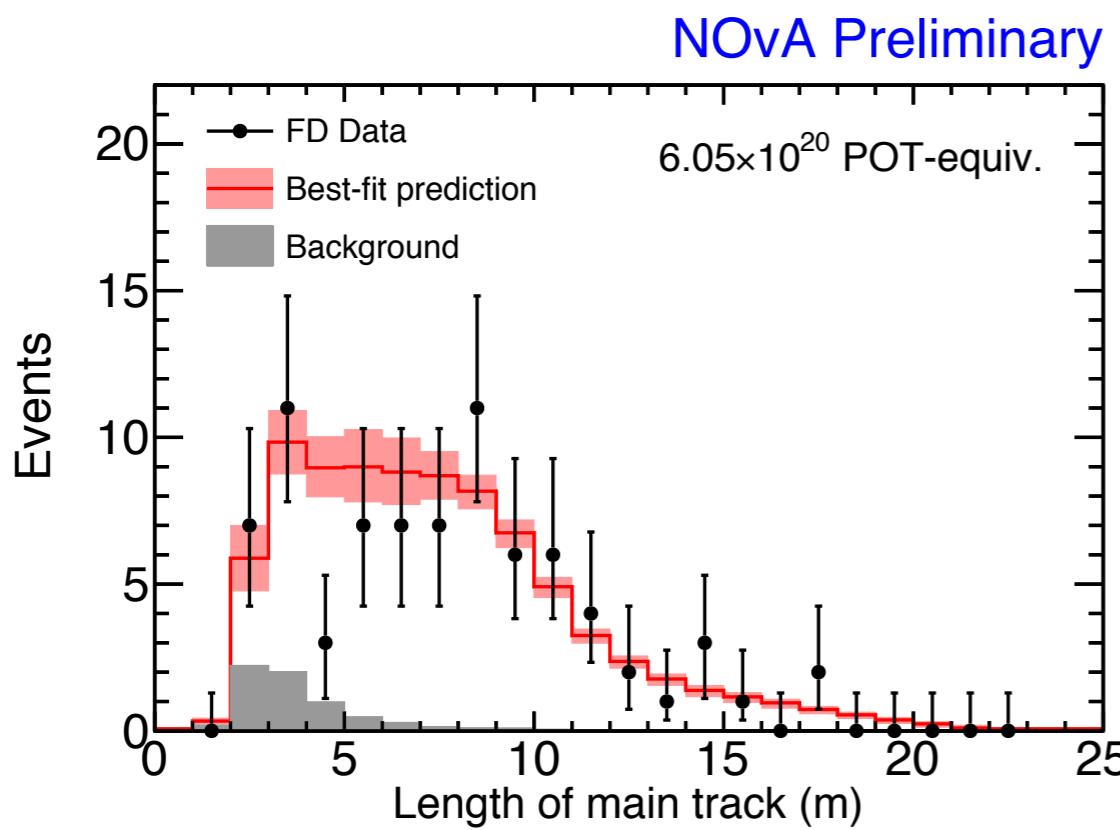
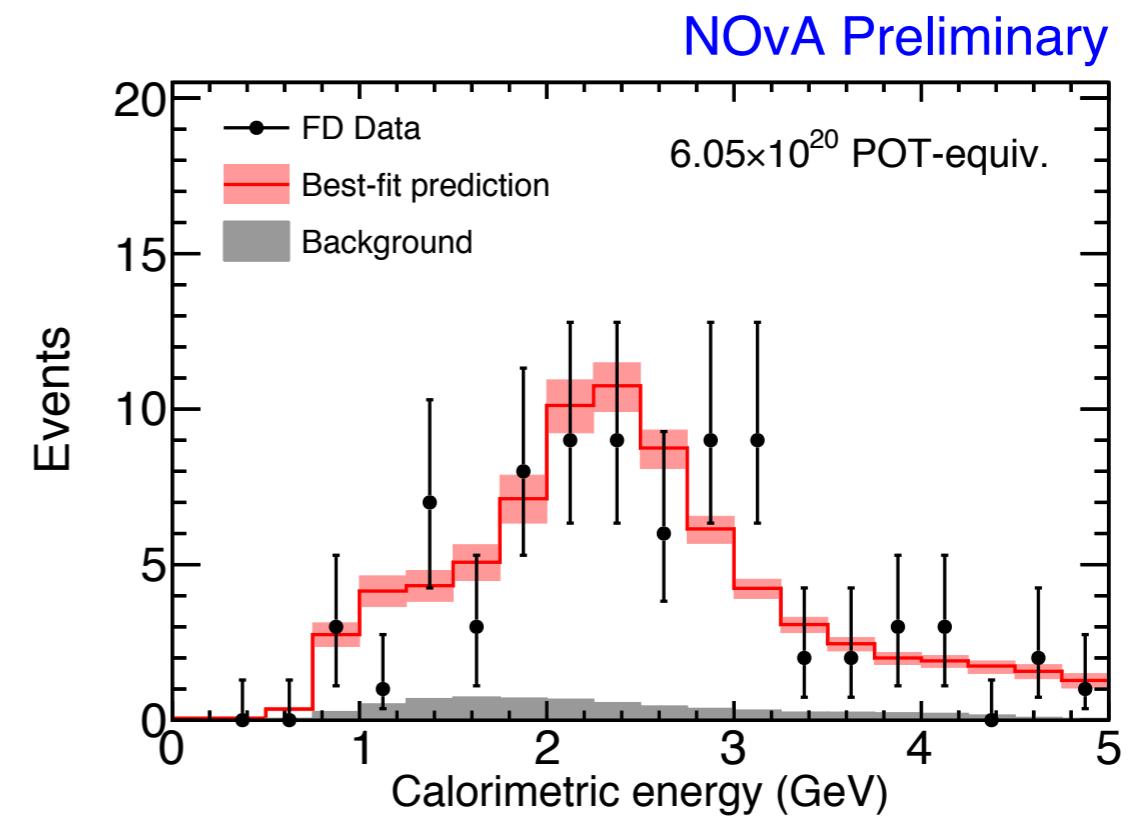
Fit Checks



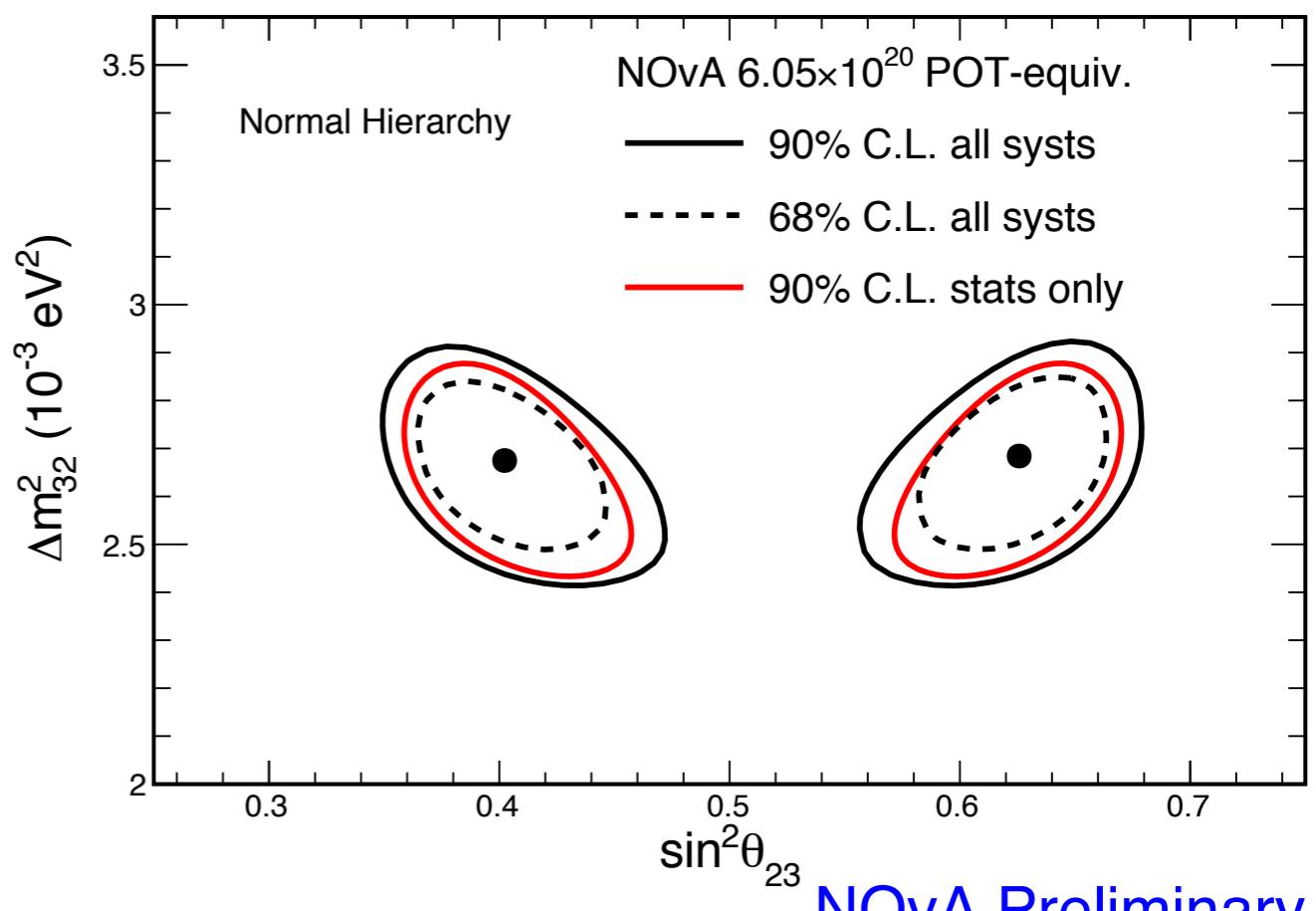
Performing the fit below 2.5 GeV improves χ^2 substantially, but does not much change fit results, sensitivity, or exclusion of maximal mixing.

Fit Checks

Our best fit oscillation prediction matches other distributions well

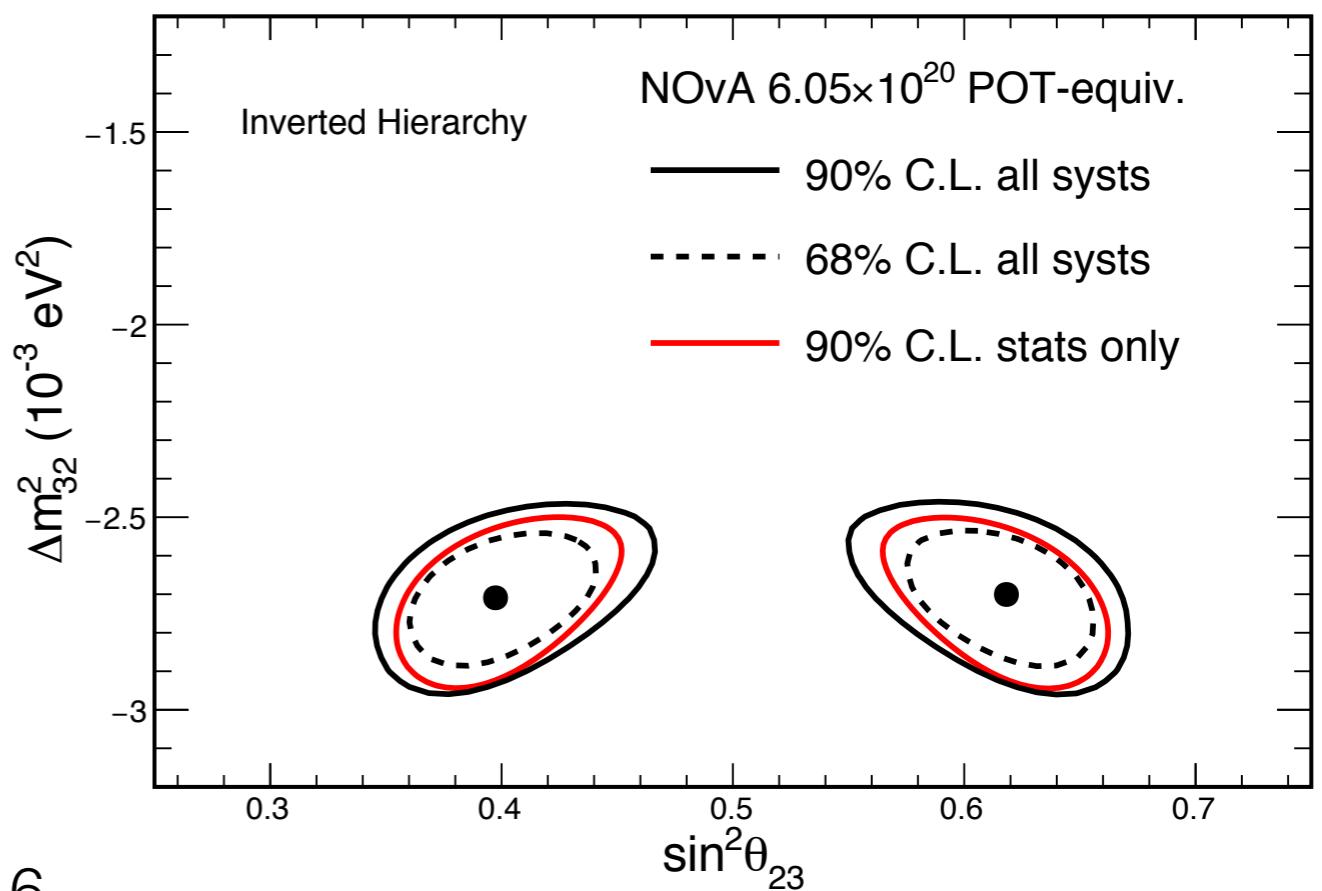


NOvA Preliminary

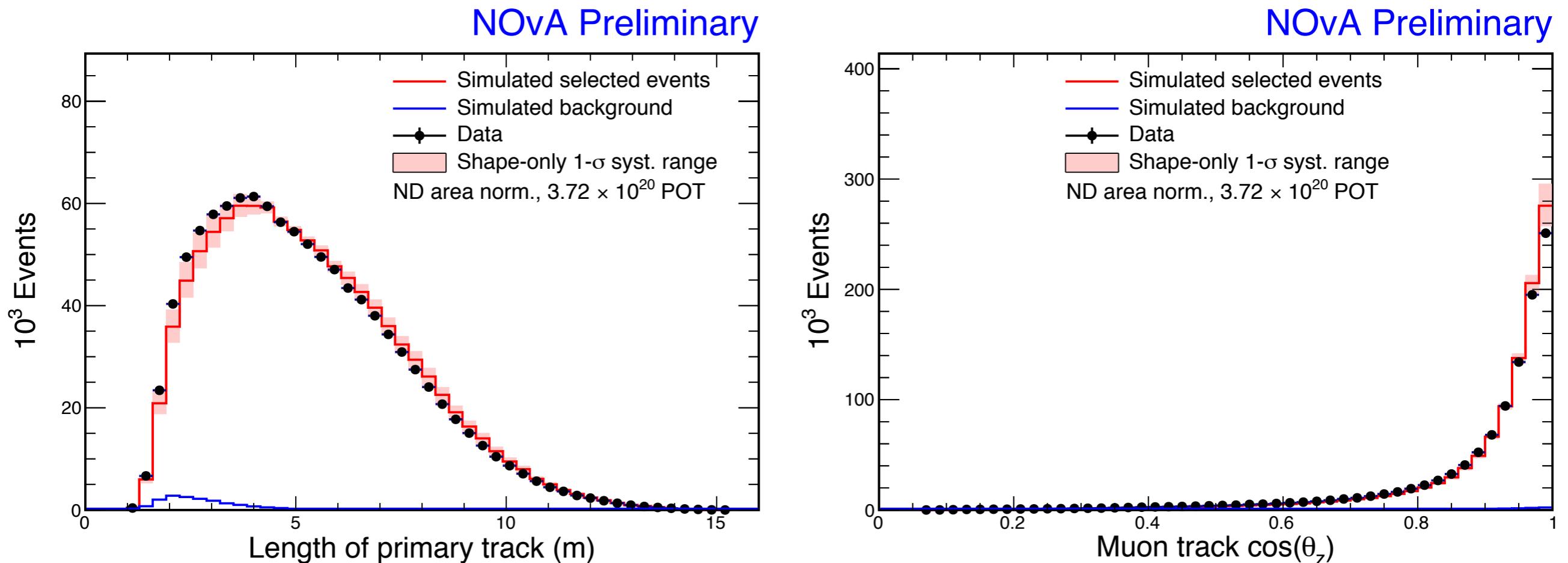


Inverted hierarchy contours

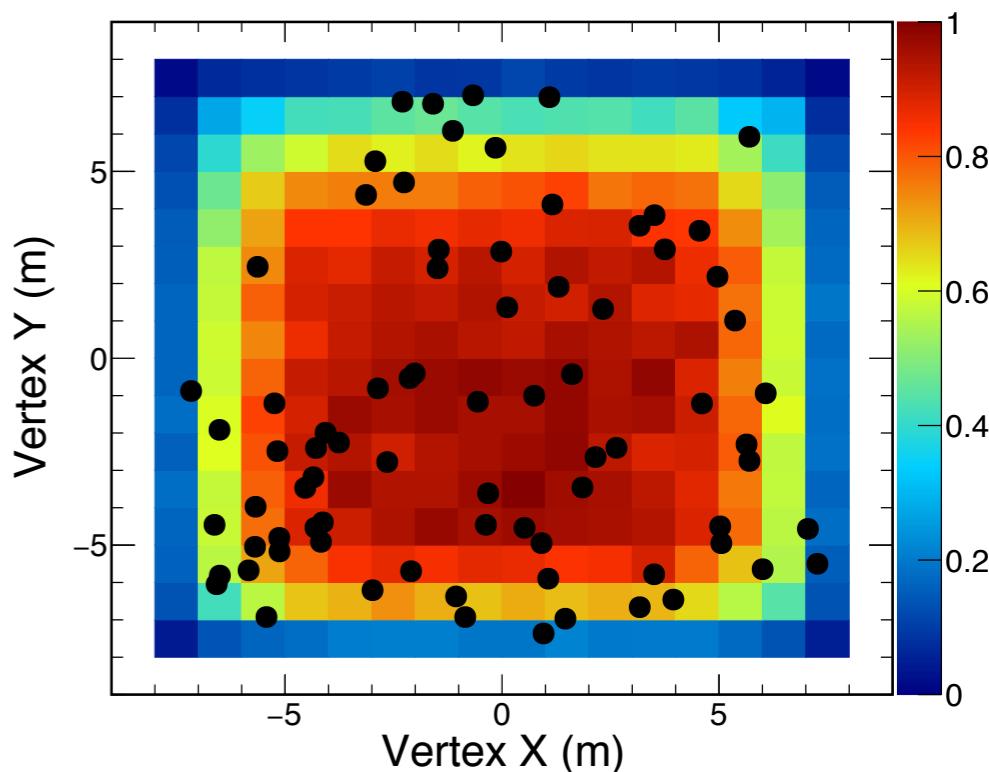
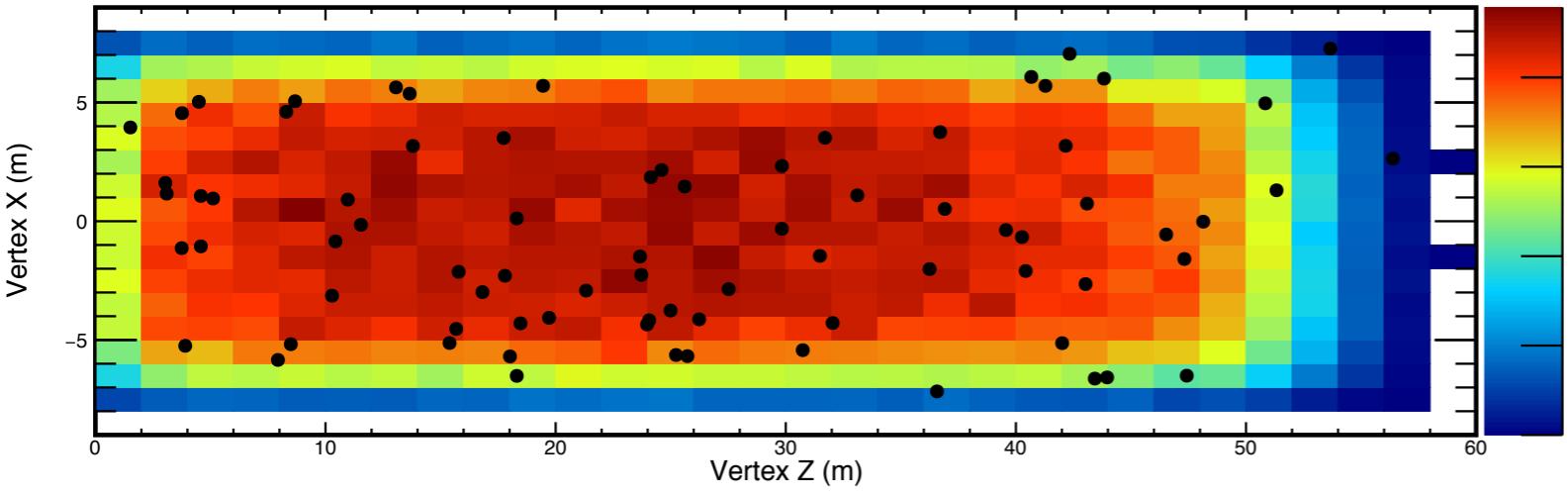
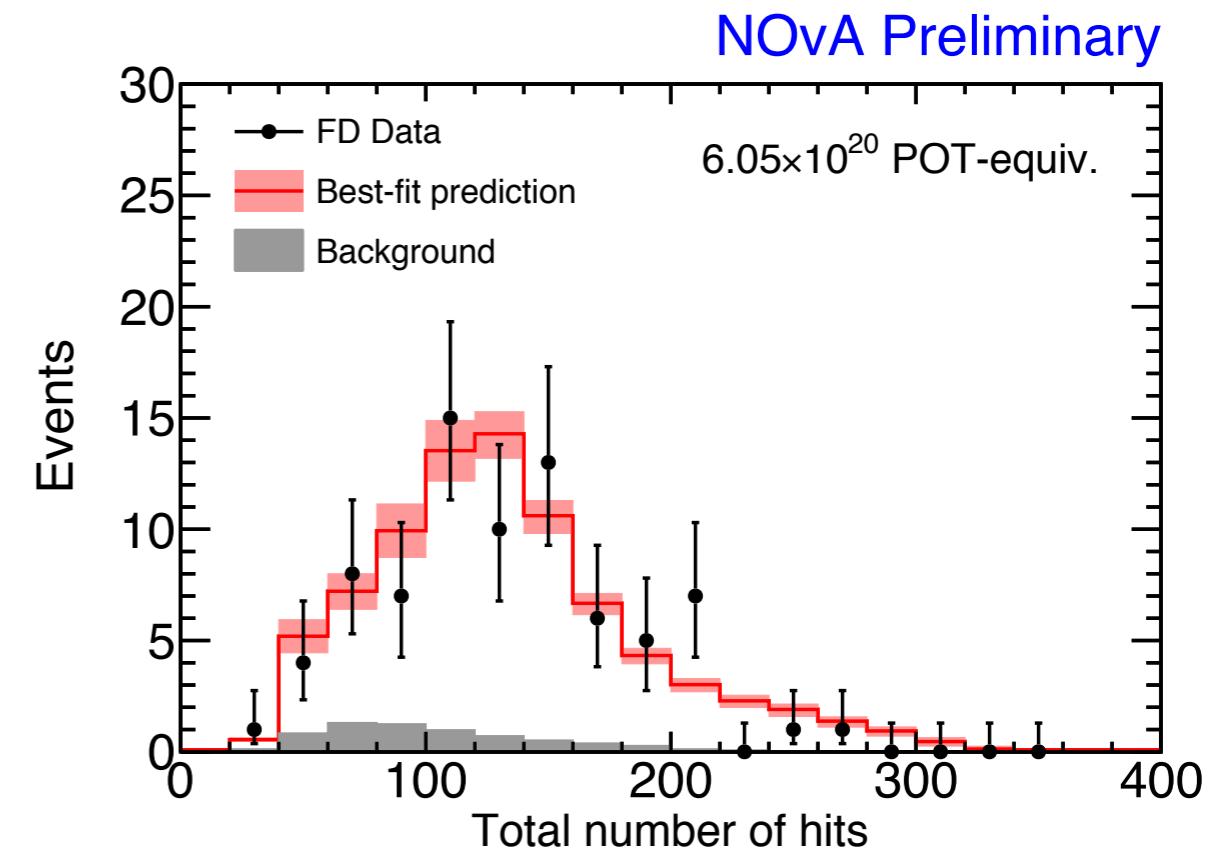
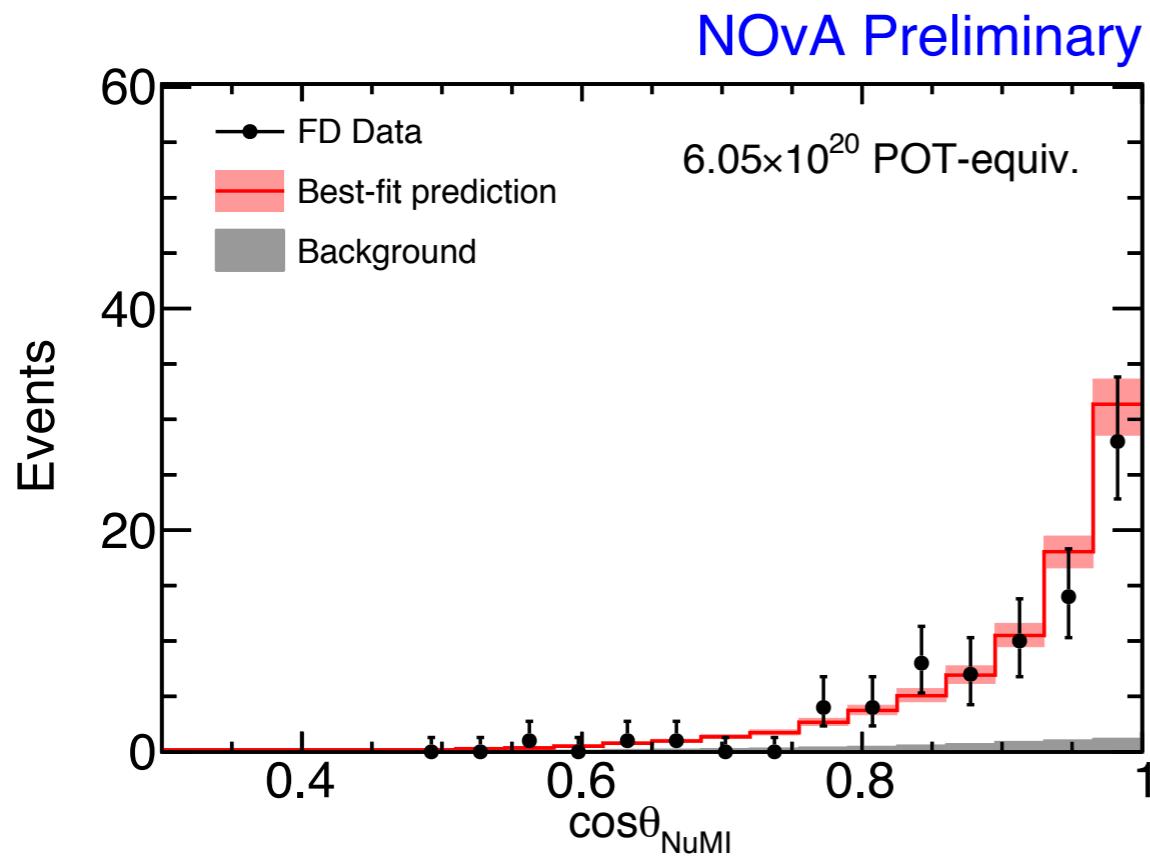
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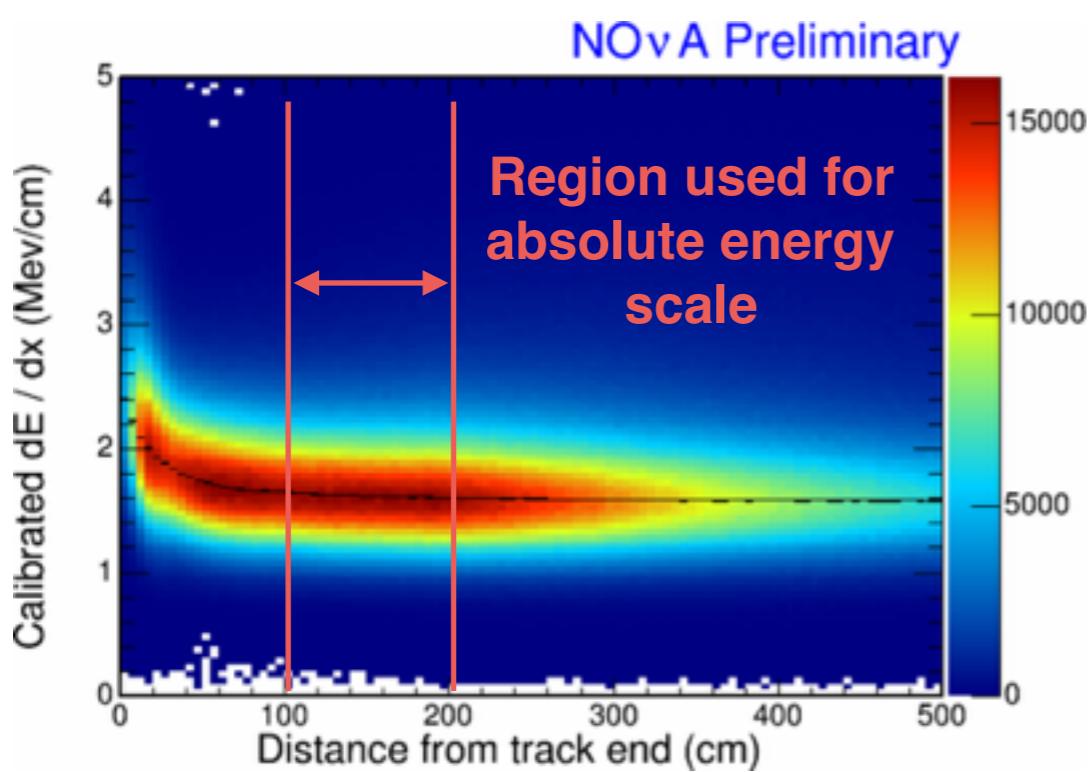
Muon selection



Muon neutrino FD data



Calibration



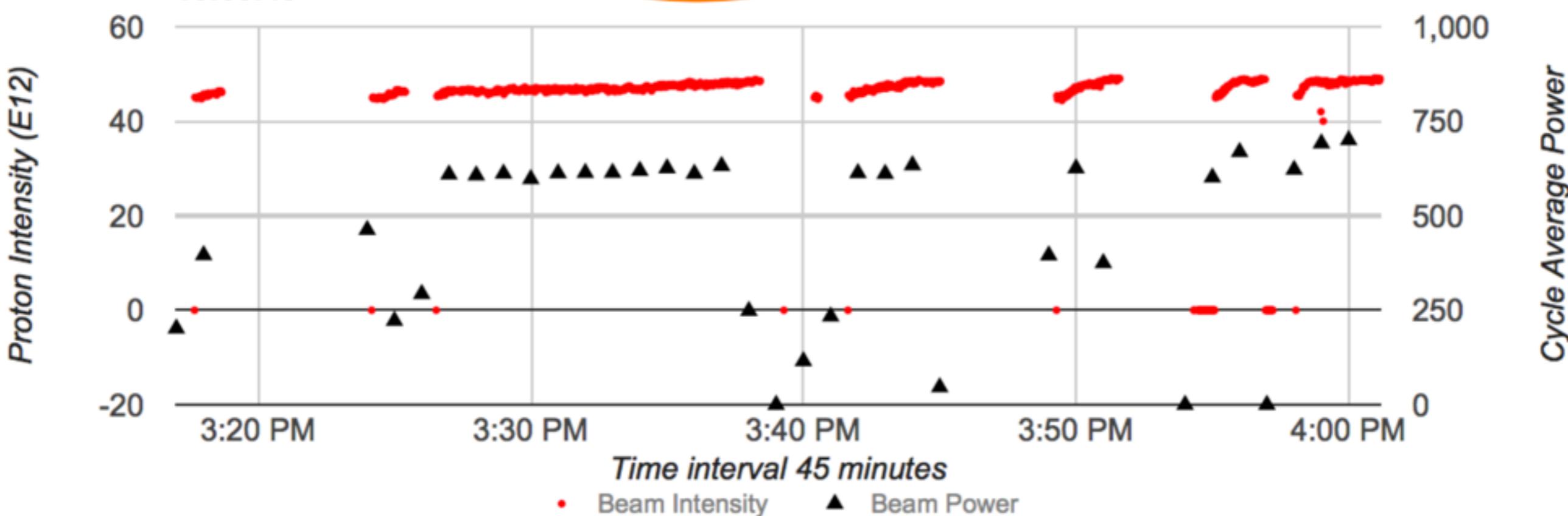
Stopping cosmic muon tracks are used as our standard candle.

dE/dx is approximately constant and well predicted in the region 100-200 cm from the end of the track.

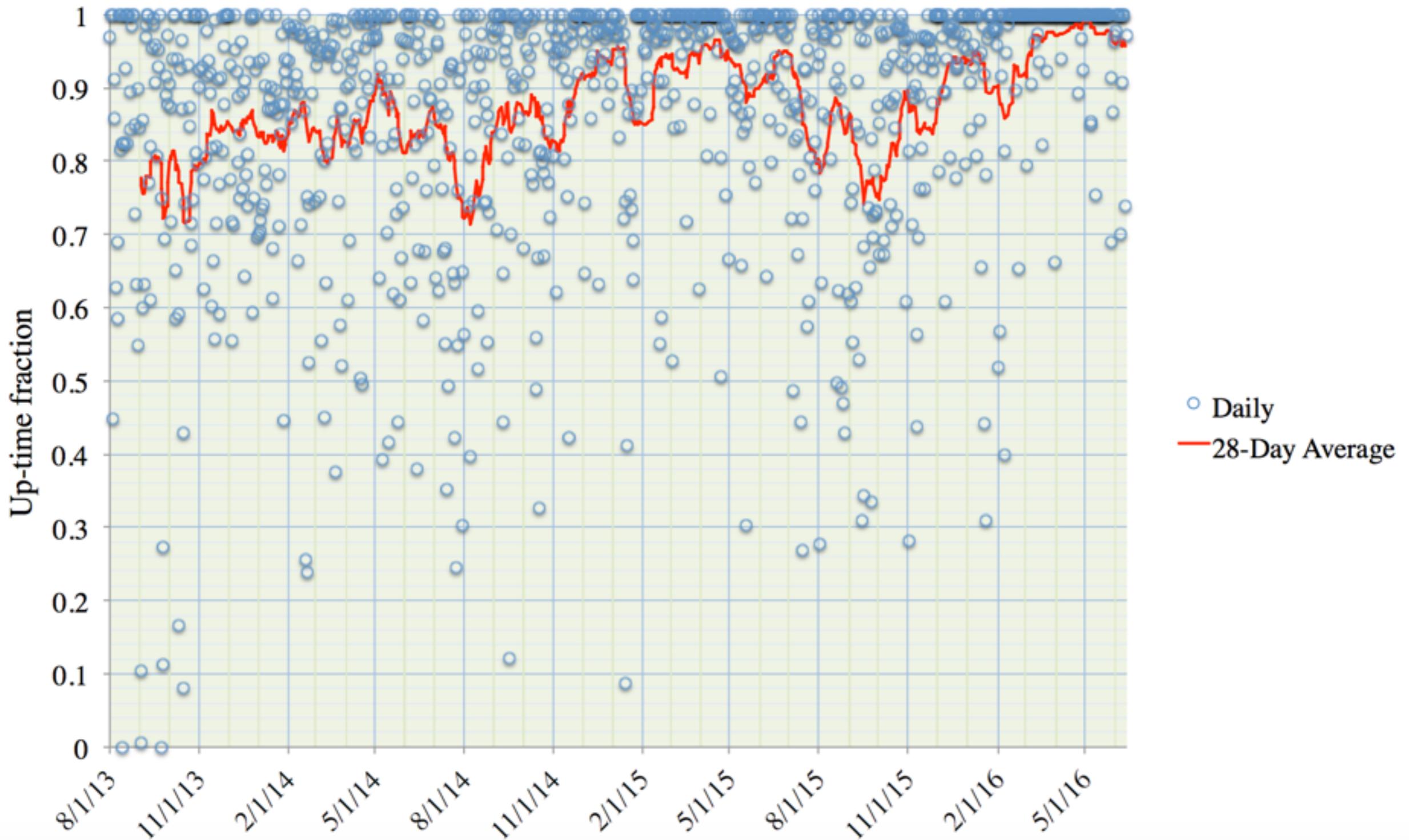
Beam Performance

Achieved design power 700kW!

**Beam Intensity =48.55 E12 Pwr =700.27 KW (DT=1.33300 s) - A9 event 2016-06-13
16:00:49**

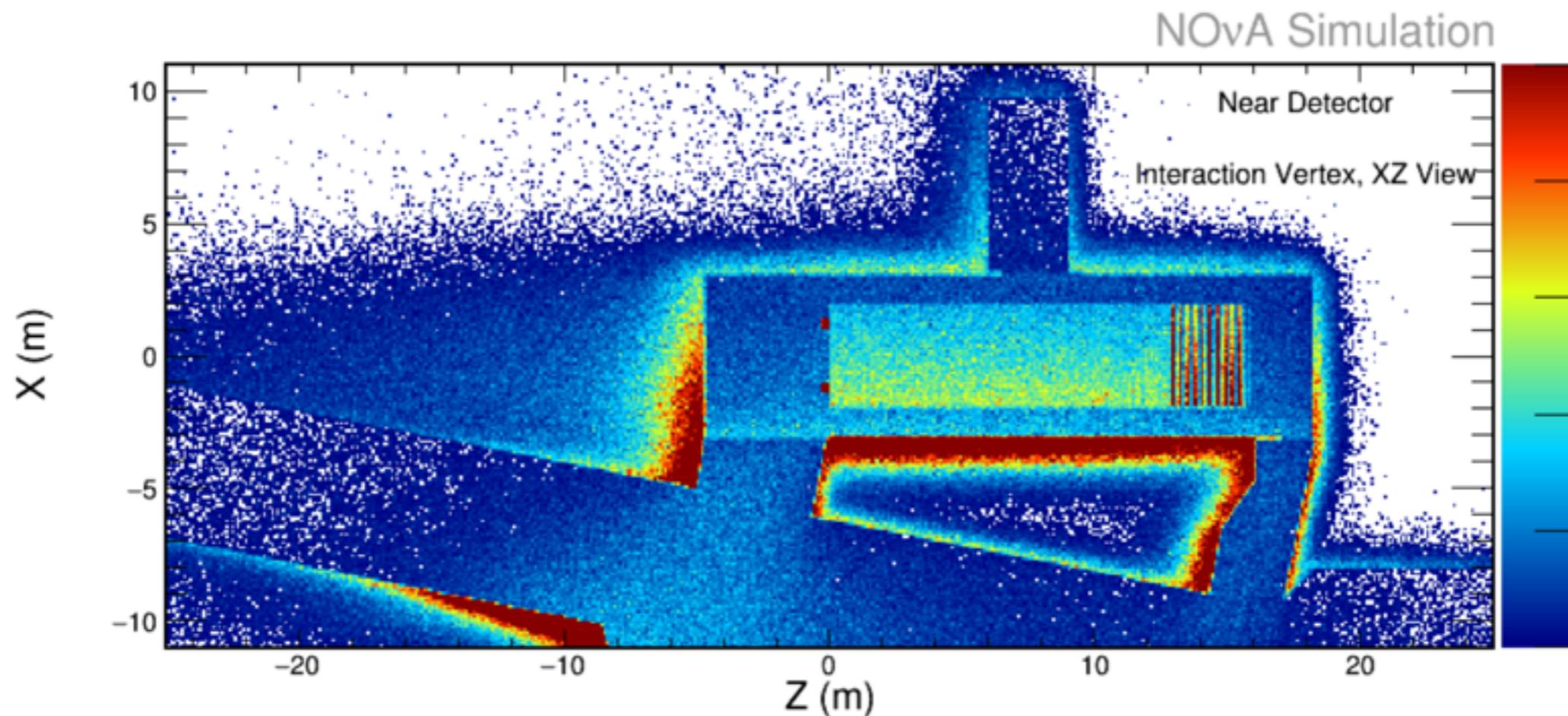


Detector Performance



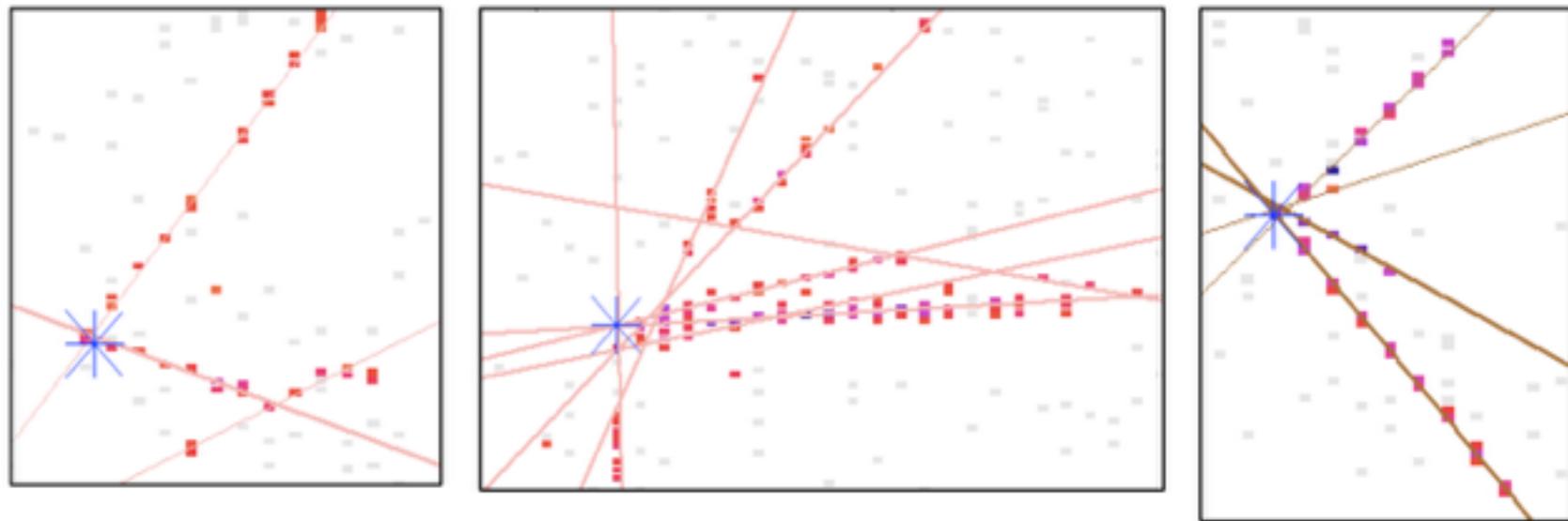
Simulation

- Beam line production, propagation, and neutrino flux: FLUKA/Flugg
- Cosmic Ray flux: CRY
- Neutrino interaction and FSI: GENIE
- Detector simulation: Geant4
- Detector response: custom simulation routines

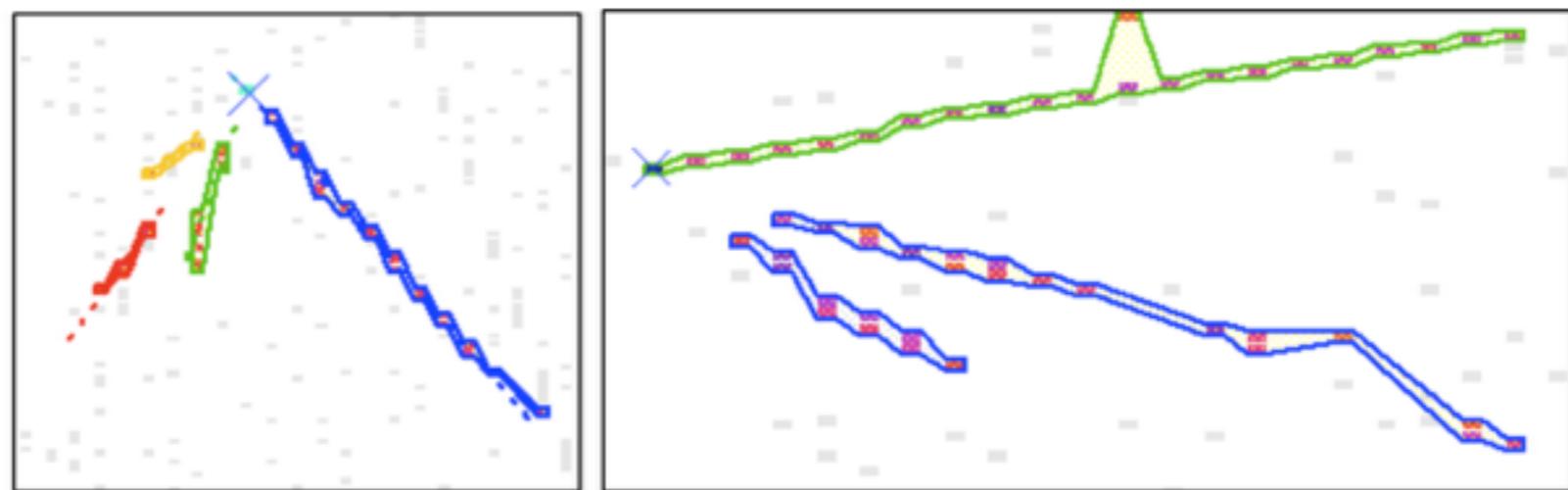


Reconstruction

Vertexing: Find lines of energy depositions w/ Hough transform CC events: 11 cm resolution



Clustering: Find clusters in angular space around vertex. Merge views via topology and prong dE/dx

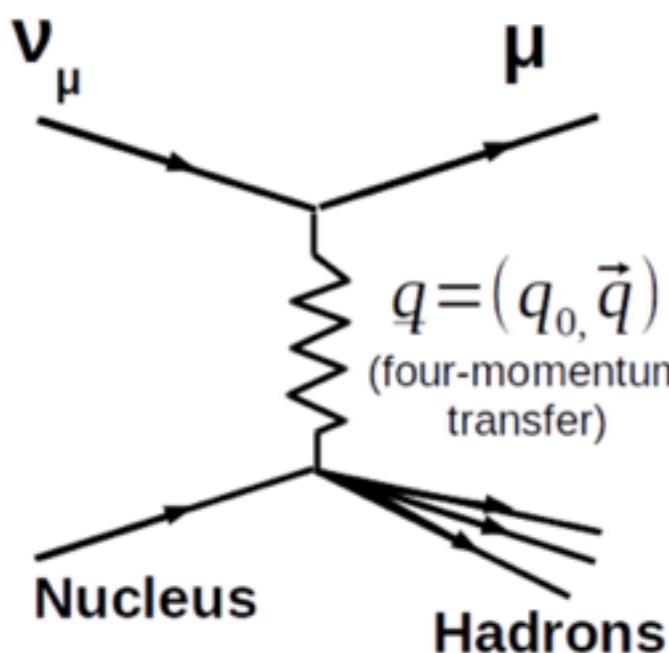
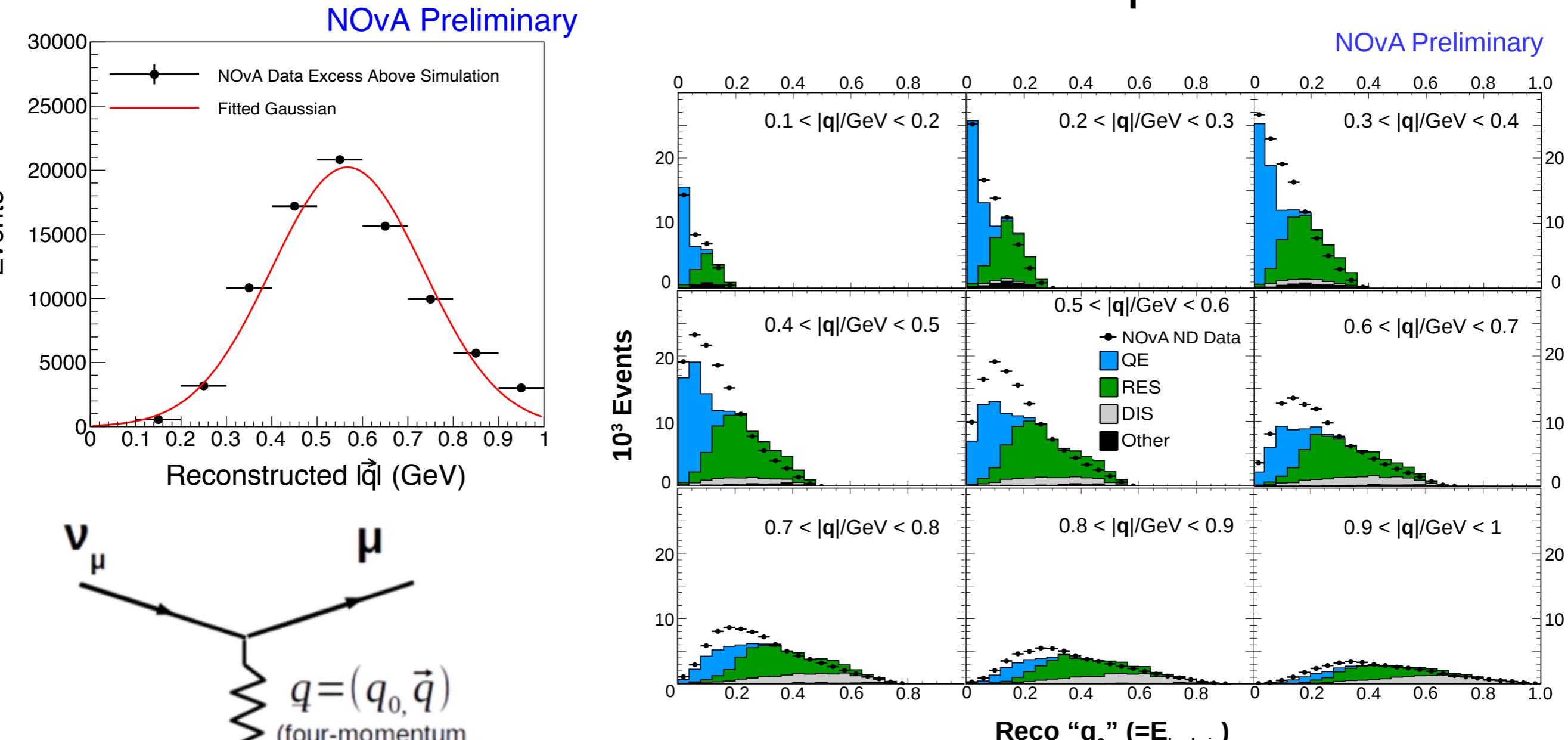


Tracking: Trace particle trajectories with **Kalman filter** tracker.

Also, **cosmic ray tracker**: lightweight, fast, and for large calibration samples, online monitoring.



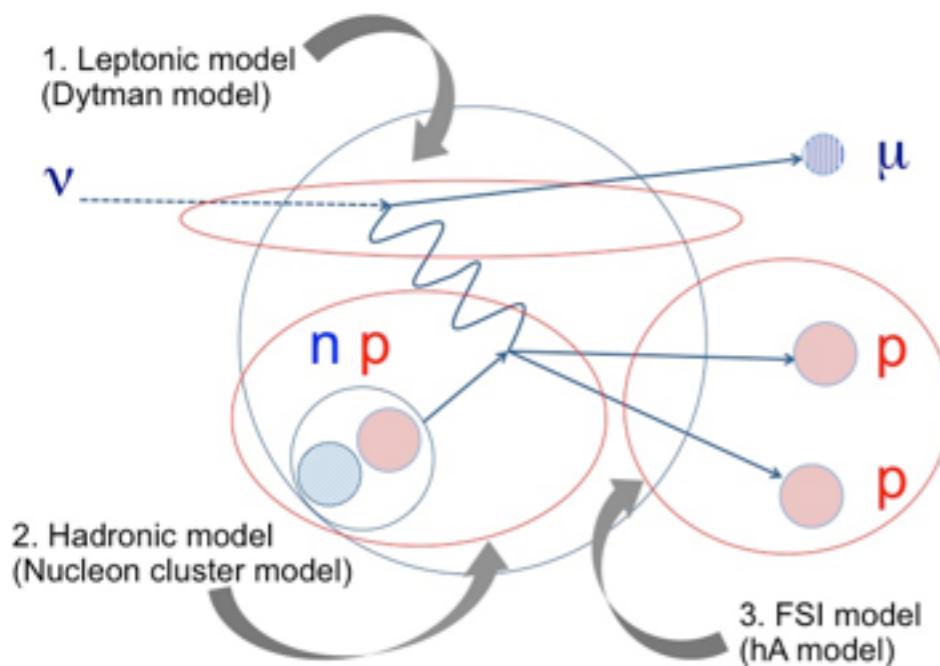
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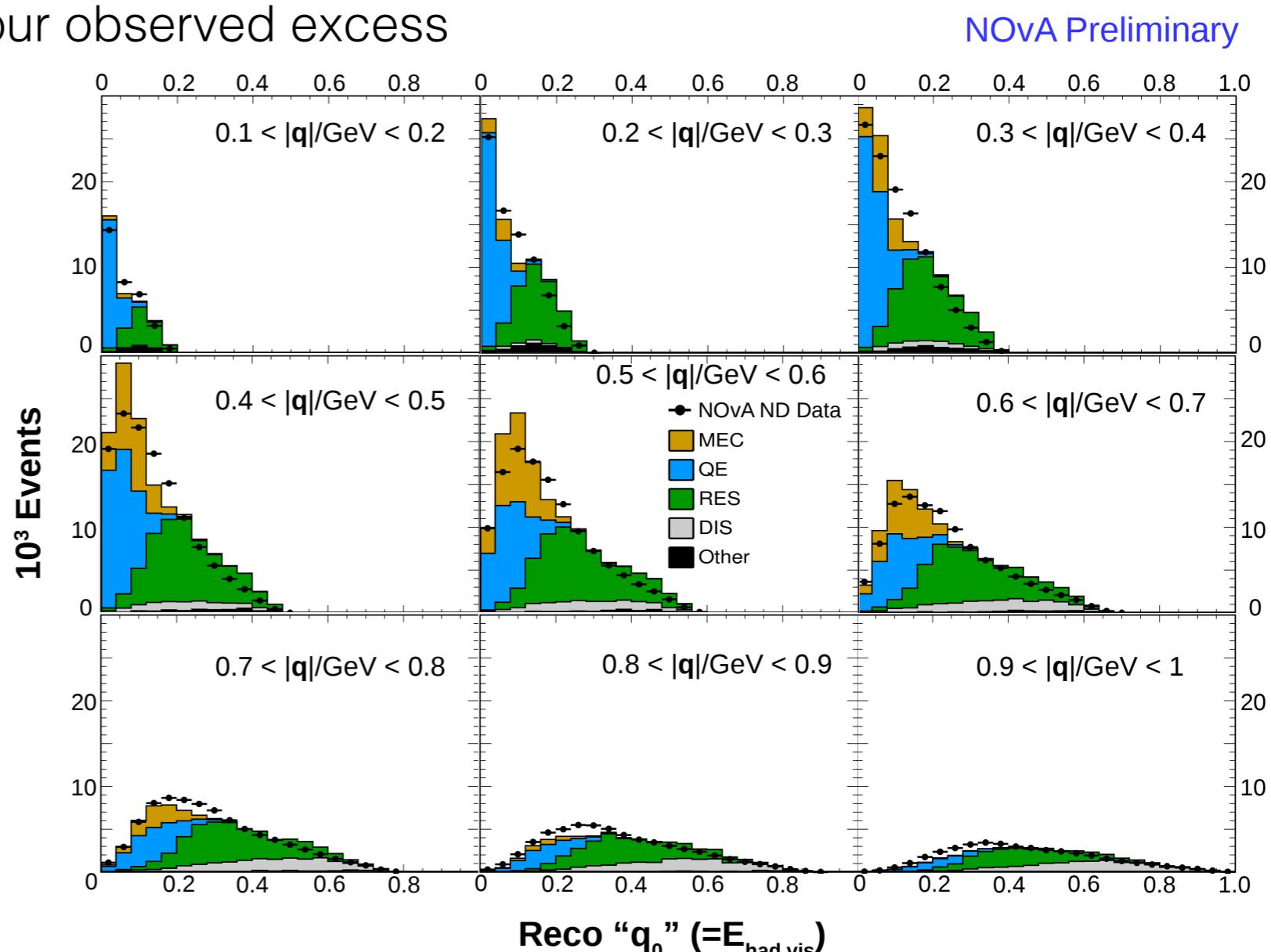
We reweight the model to match our observed excess as a function of \mathbf{p} transfer



Reduce single non-resonant pion production by 50%

(P.A. Rodrigues et al, arXiv: 1601.01888.)

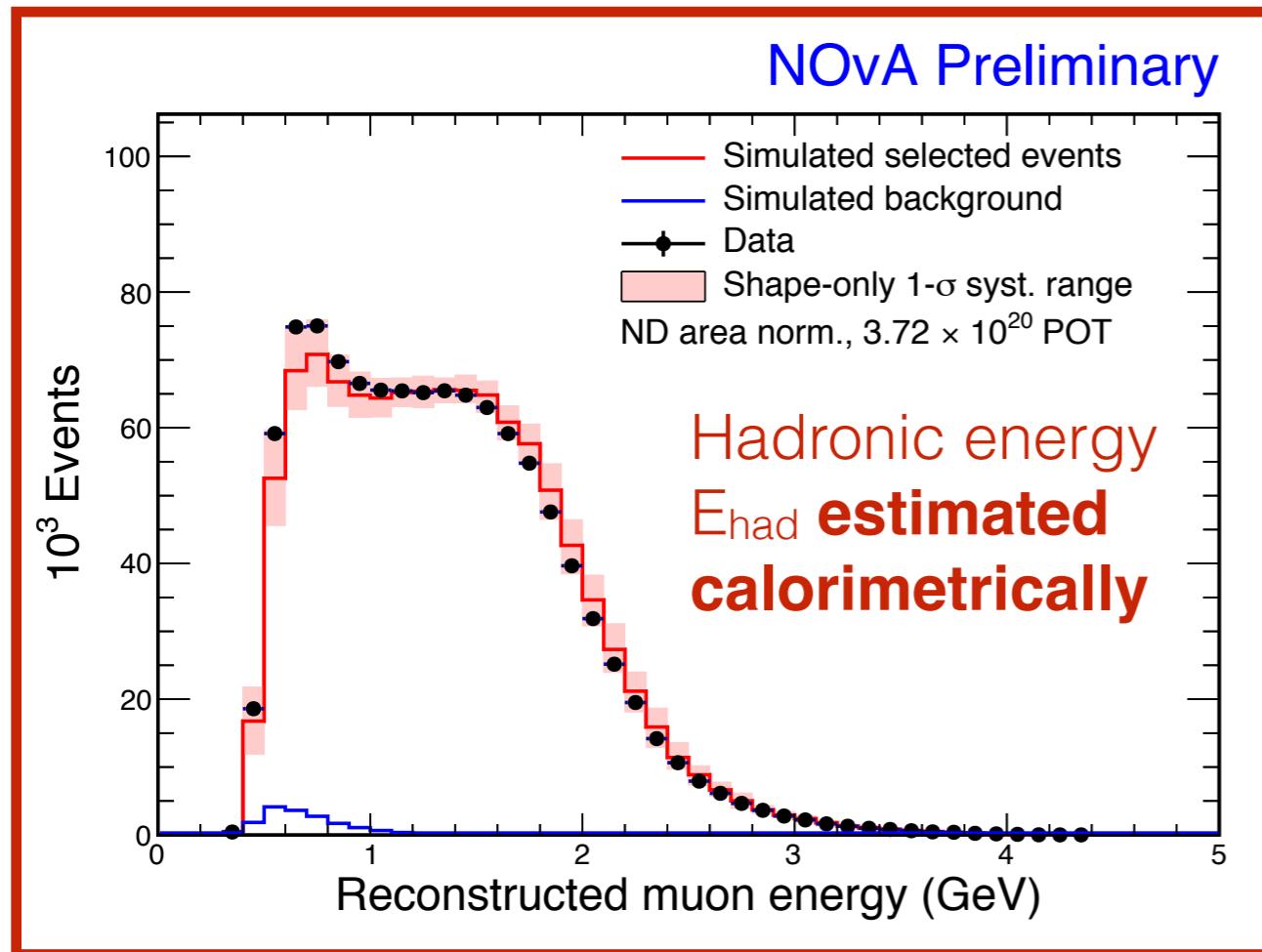
Take 50% systematic uncertainty on MEC component



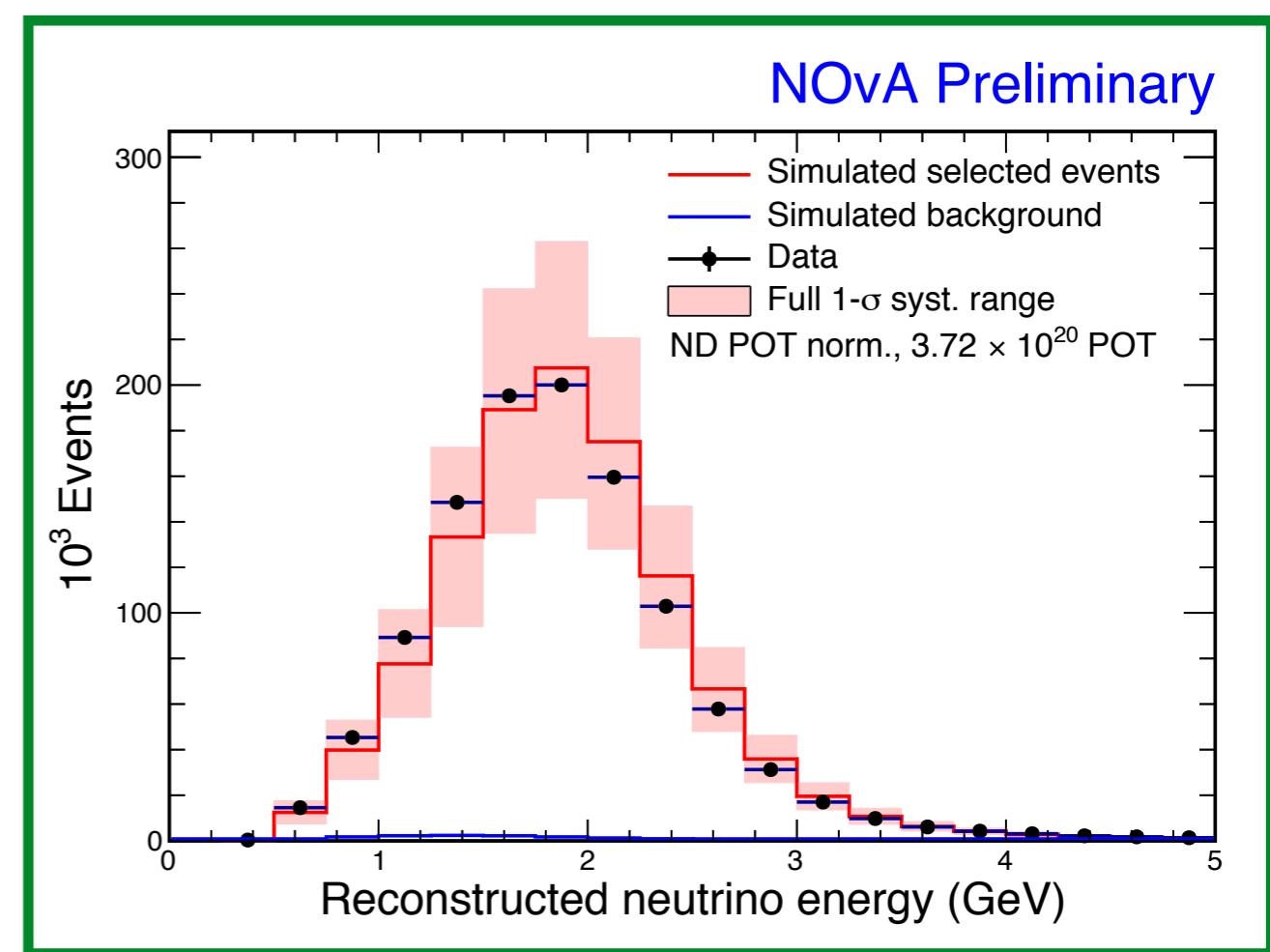
This reduces our largest systematic uncertainties

- Hadronic energy scale
- QE cross-section modeling

The addition of MEC events improves the simulated hadronic energy distribution



The hadronic energy scale uncertainty was reduced from 14% to 5%



The reconstructed ND neutrino energy spectrum is next unfolded, and used to extrapolate ND data for a FD prediction

$$E_\nu = E_\mu(L_{\text{track}}) + E_{\text{had}}$$