The NOvA Near Detector

Mark Messier
Indiana University
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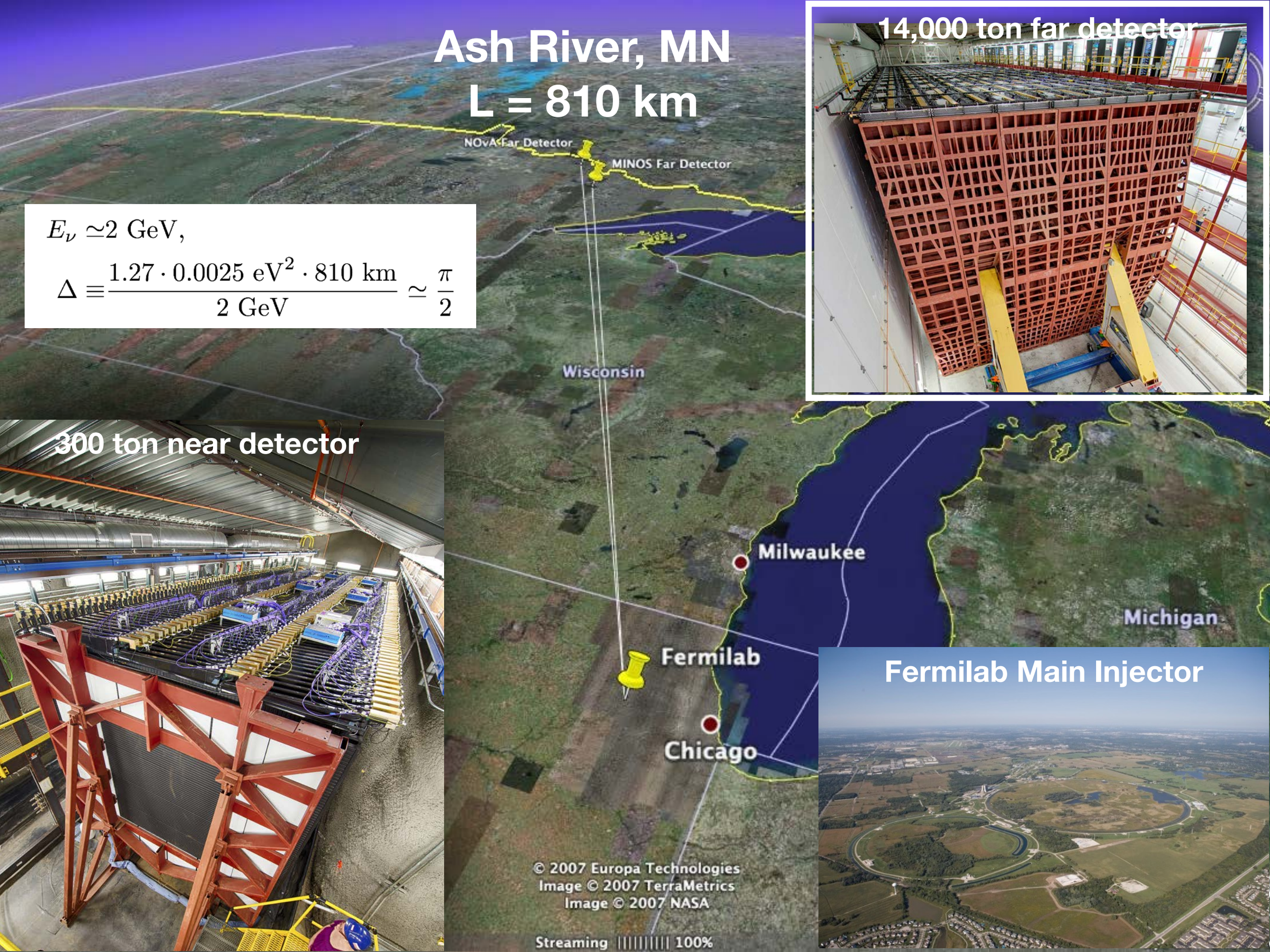
Ash River, MN
L = 810 km

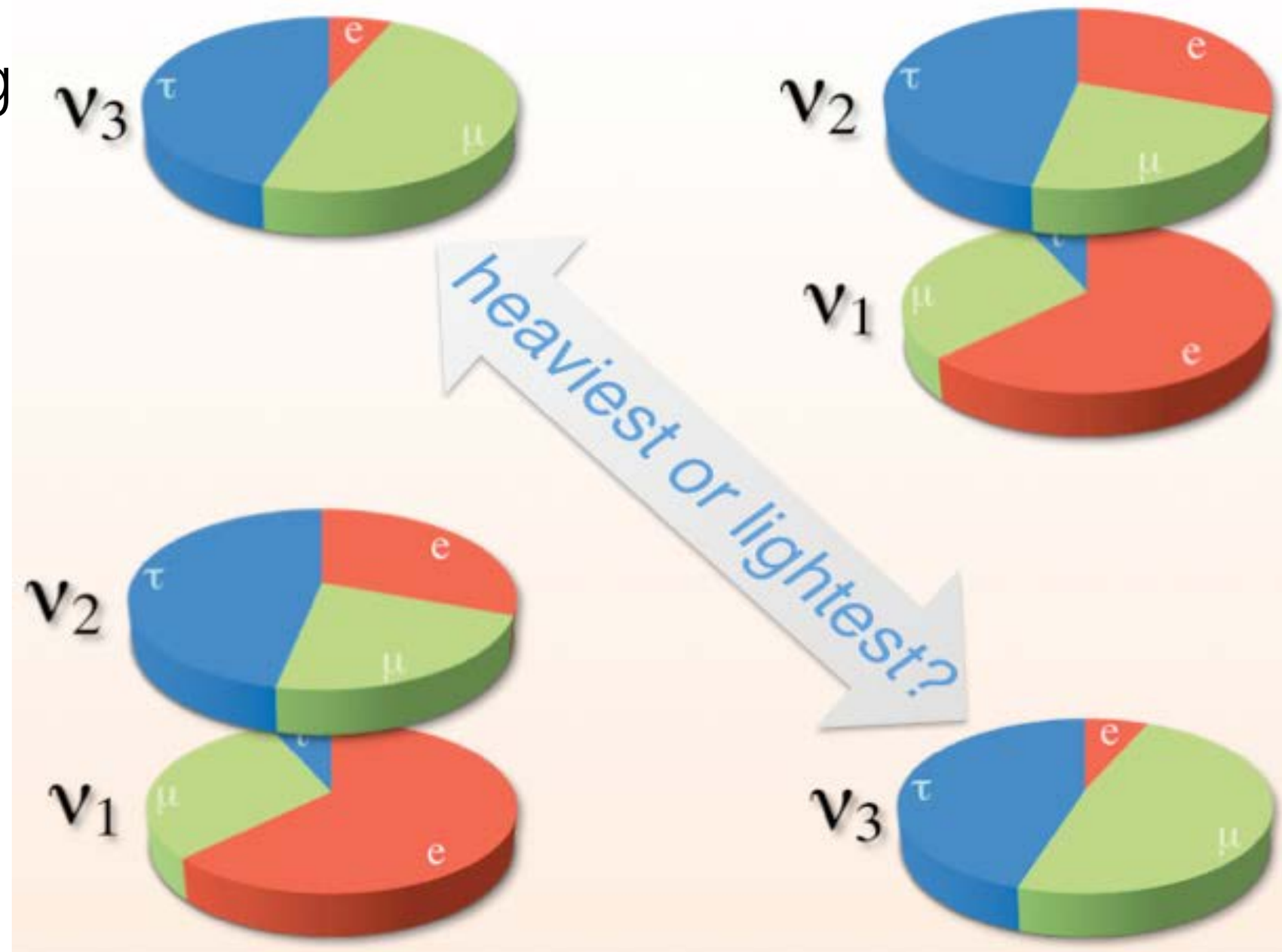
$$E_\nu \simeq 2 \text{ GeV},$$

$$\Delta \equiv \frac{1.27 \cdot 0.0025 \text{ eV}^2 \cdot 810 \text{ km}}{2 \text{ GeV}} \simeq \frac{\pi}{2}$$

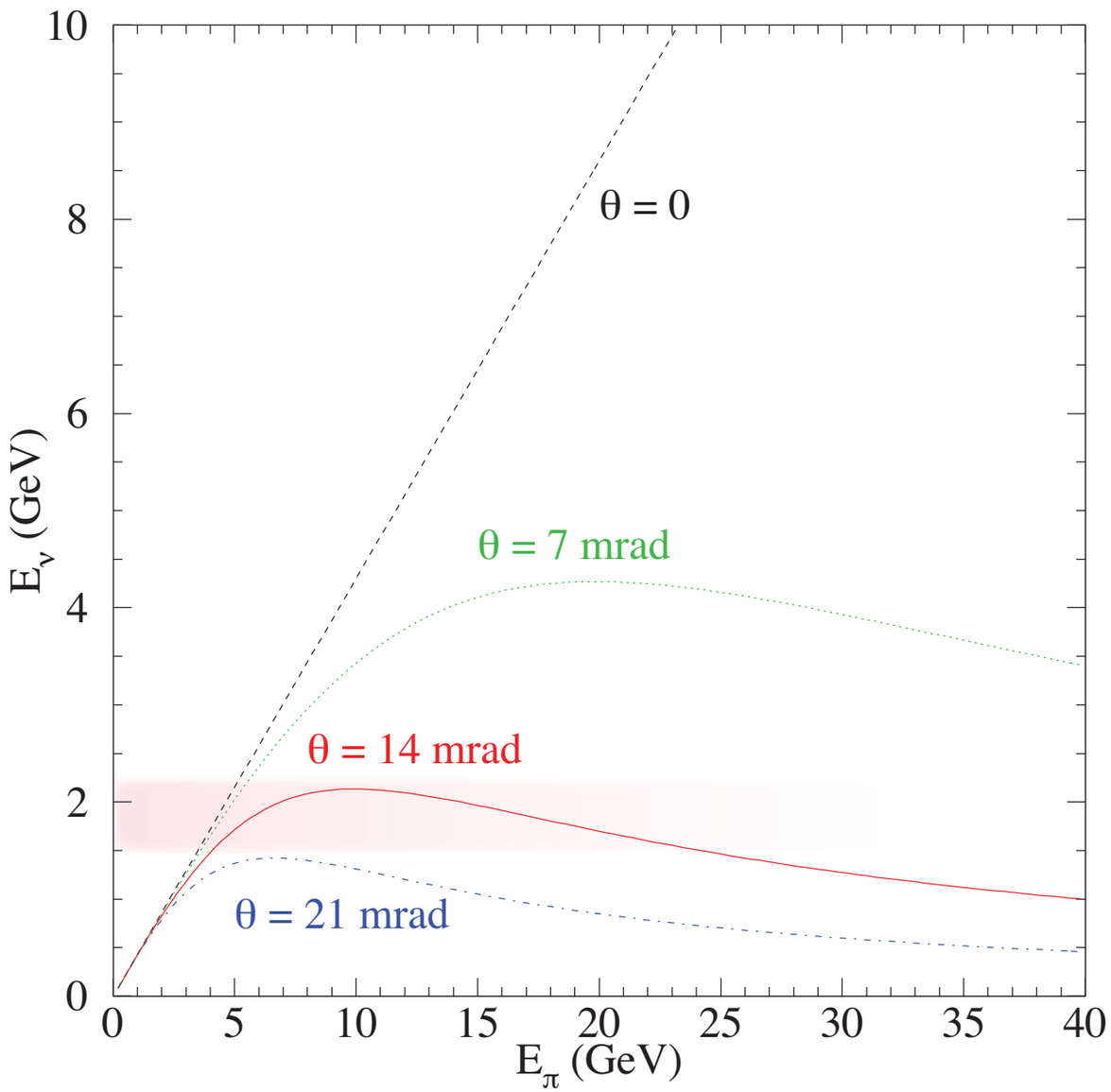


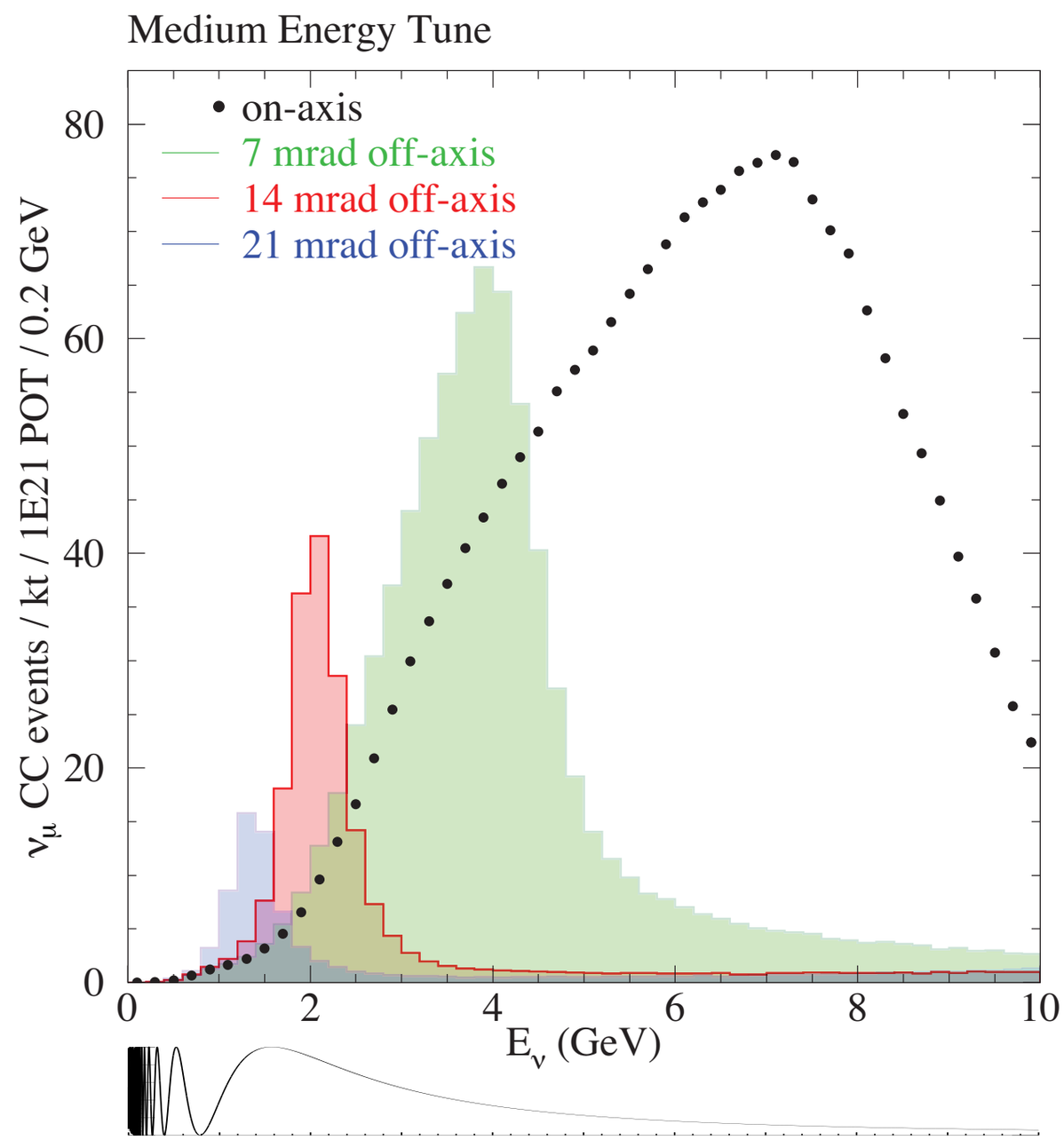
NOvA Physics Program

- Mass ordering
- Nature of ν_3 - θ_{23} octant
- Is CP violated?
- Is there more to this picture?



$$E_\nu = \frac{m_\pi^2 - m_\mu^2}{m_\pi^2} \frac{E_\pi}{1 + \gamma^2 \theta_{\mathrm{Lab}}^2}$$





Selecting neutrino energy

Angle is energy

NOvA beam angle is 14 mad

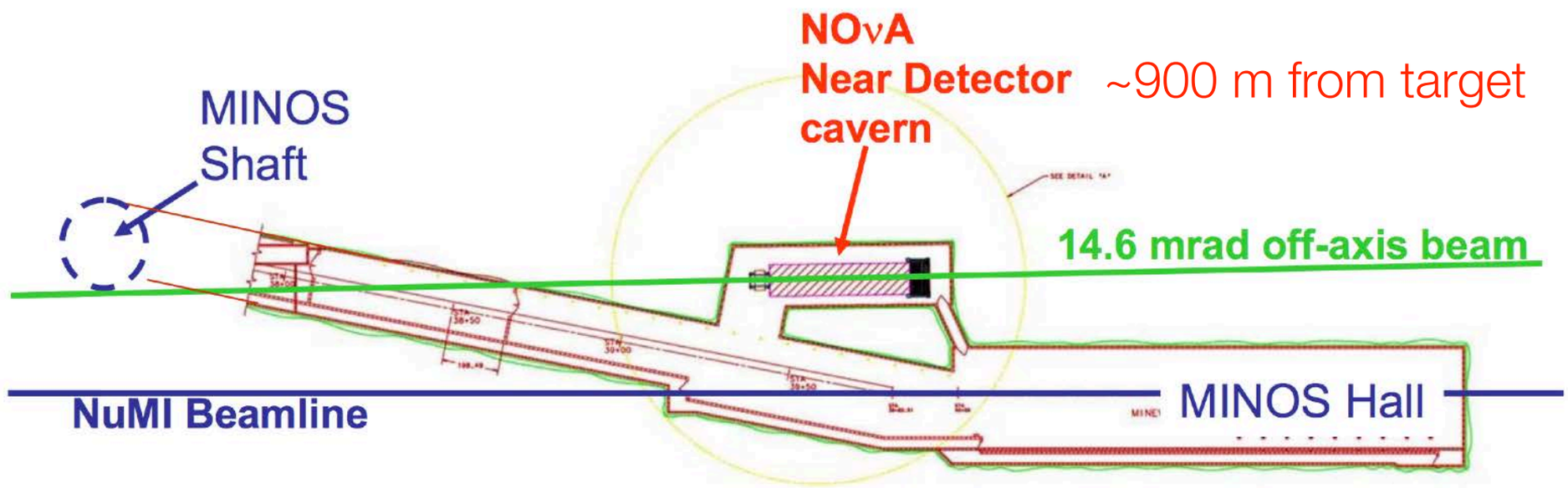
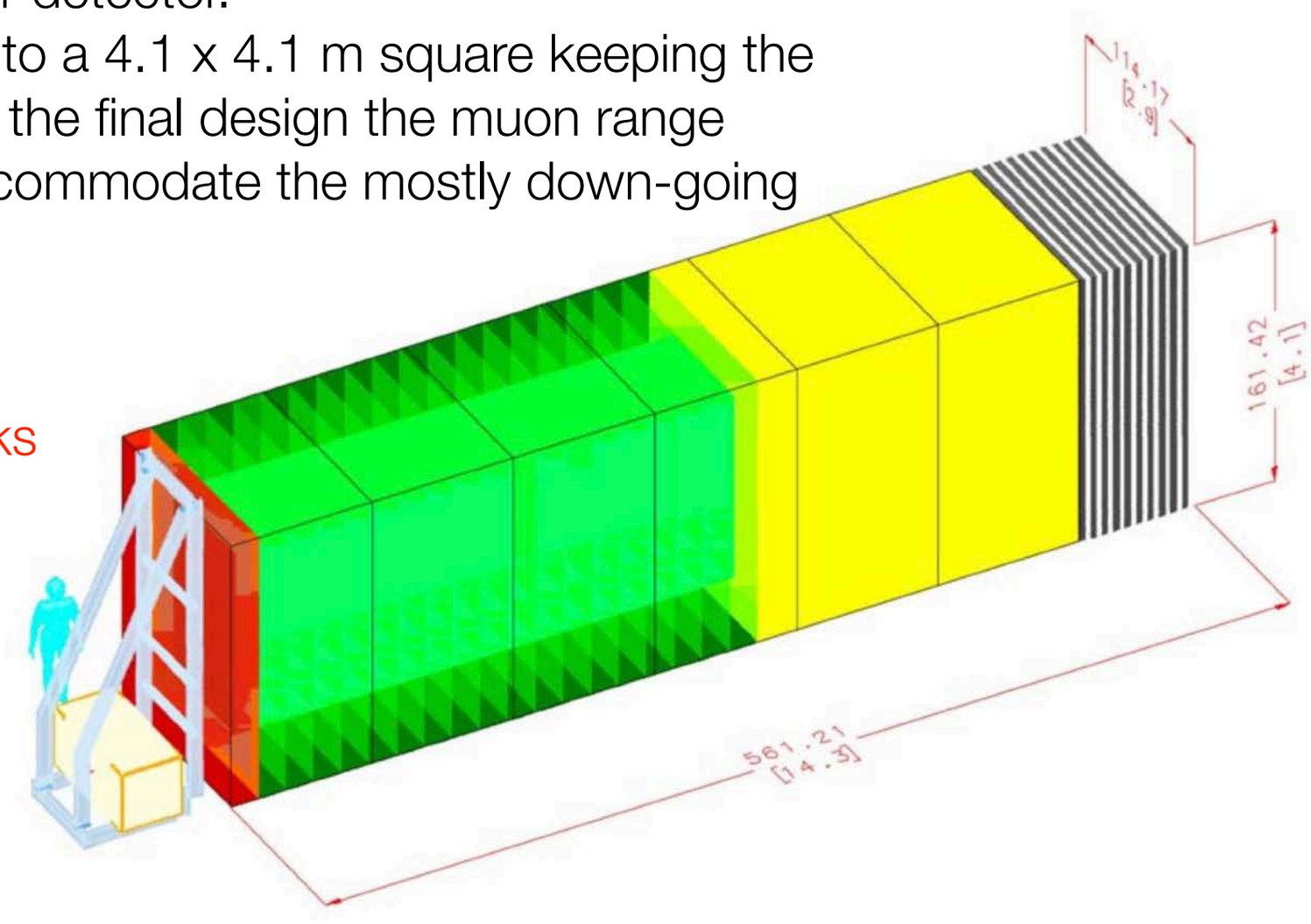
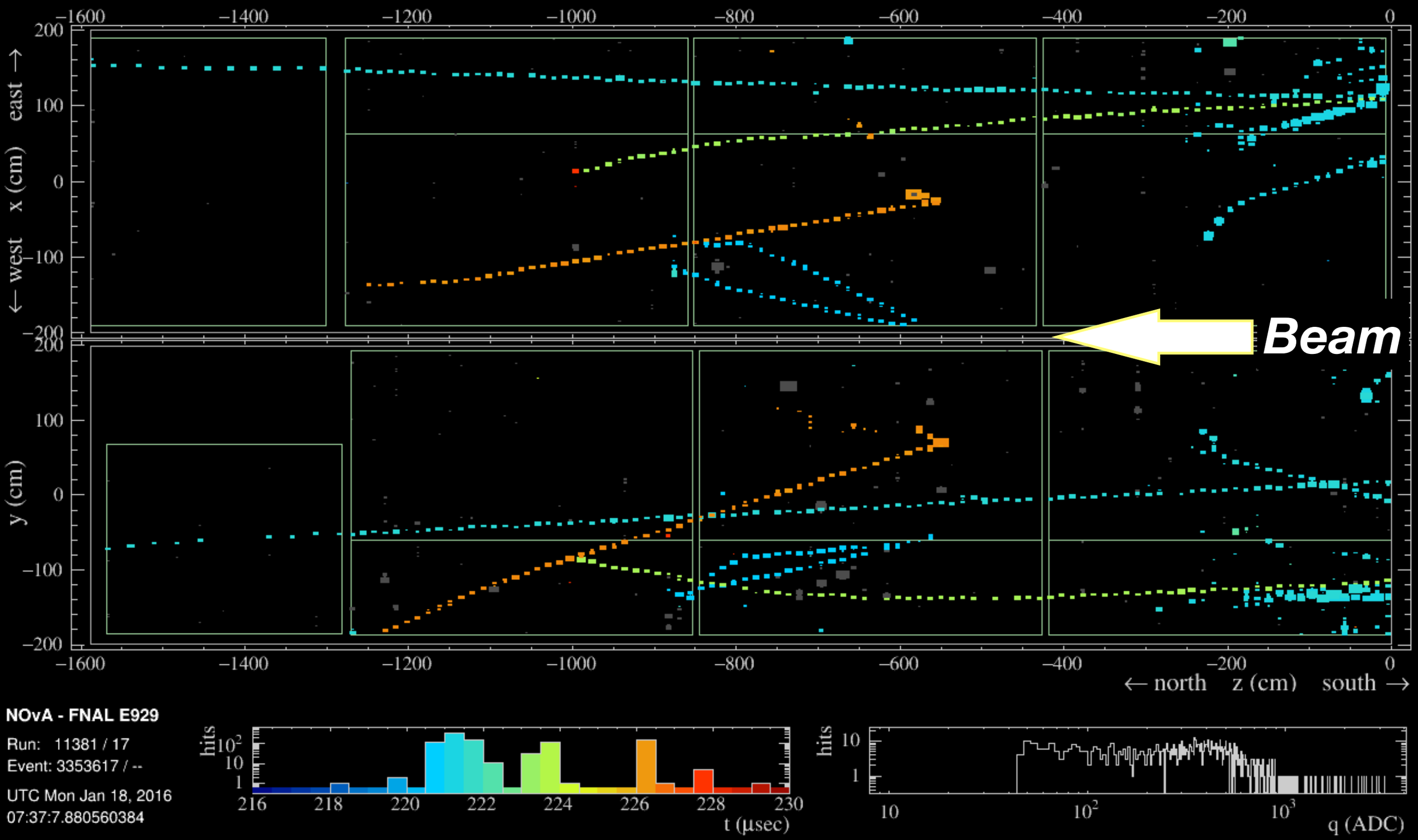


Fig. 5.9: A detailed plan view of the MINOS access tunnel from the vertical MINOS shaft to the MINOS hall. The new NOνA cavern is indicated.

Original design of the NOvA near detector.
Final design widened the profile to a 4.1 x 4.1 m square keeping the cavern dimensions the same. In the final design the muon range stack was built on its side to accommodate the mostly down-going beam muons.

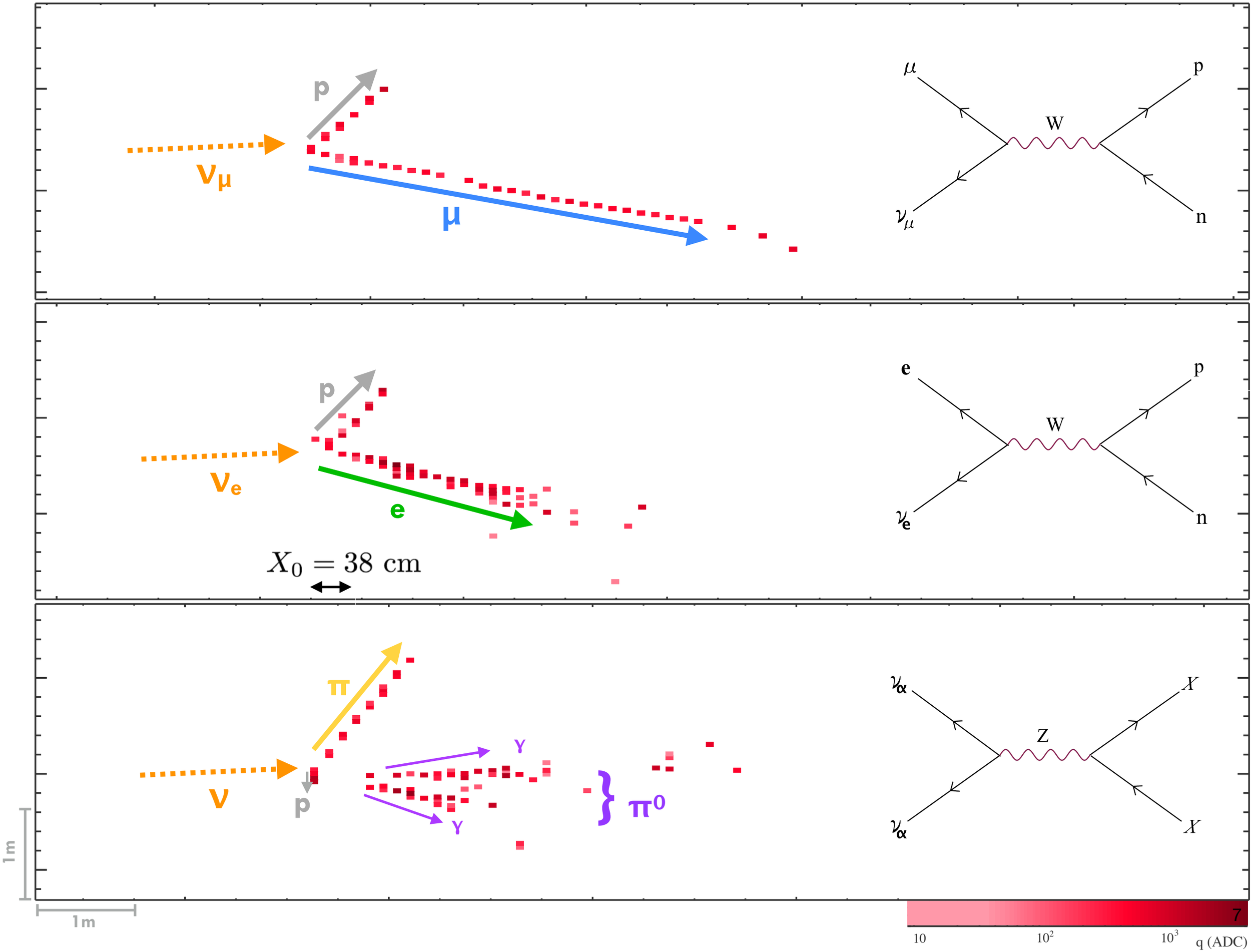
Basic units are:
Red : veto against entering tracks
Green: Target volume.
Yellow: Shower containment
Black/white: Muon ranger.





NOvA Near Detector

Neutrinos recorded by the NOvA Near Detector in a single pulse of the NuMI beam.
Pulled from live event stream
http://nusoft.fnal.gov/nova/public/


p
νμ
μ
μ
p
W
νμ
n
p
νe
e
X0 = 38 cm
e
p
W
νe
n
π
ν
p
γ
γ
π0
1m
1m
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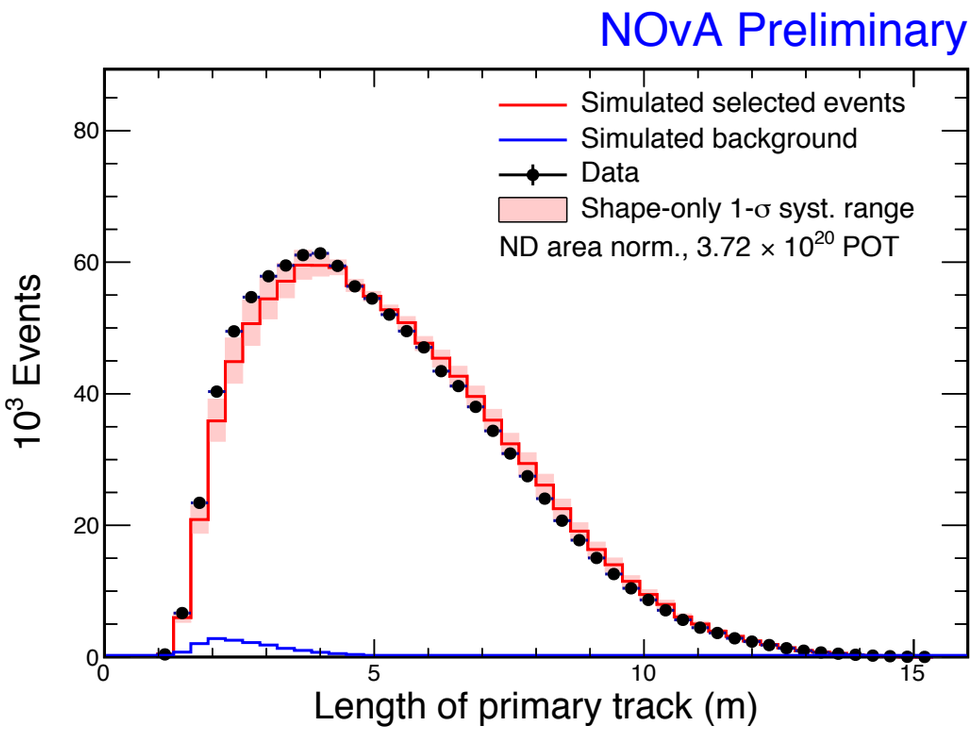
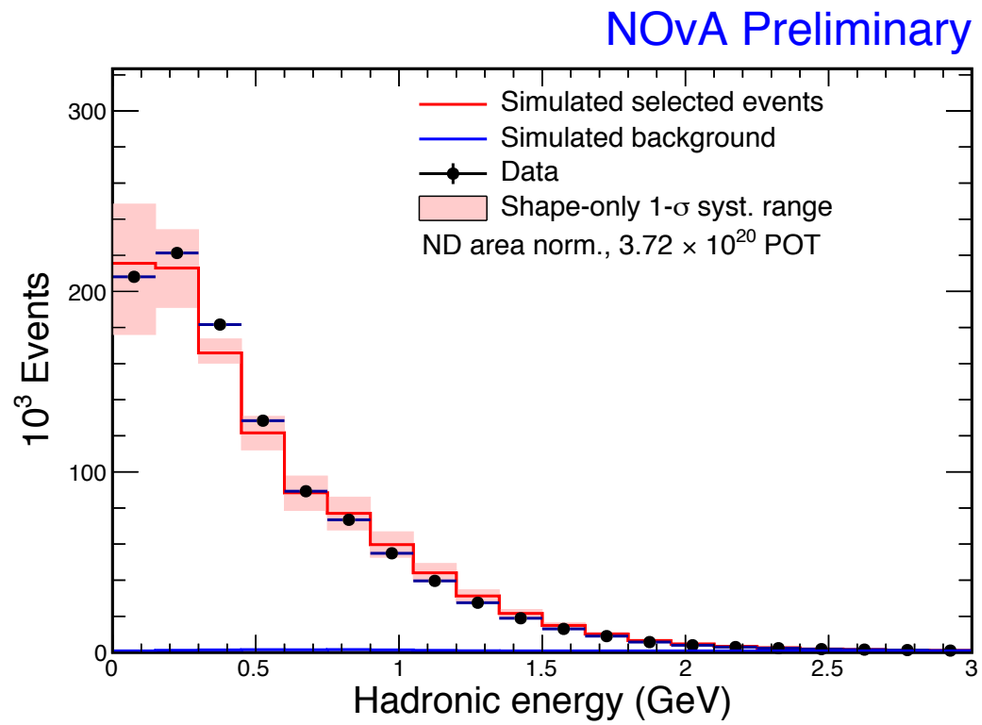
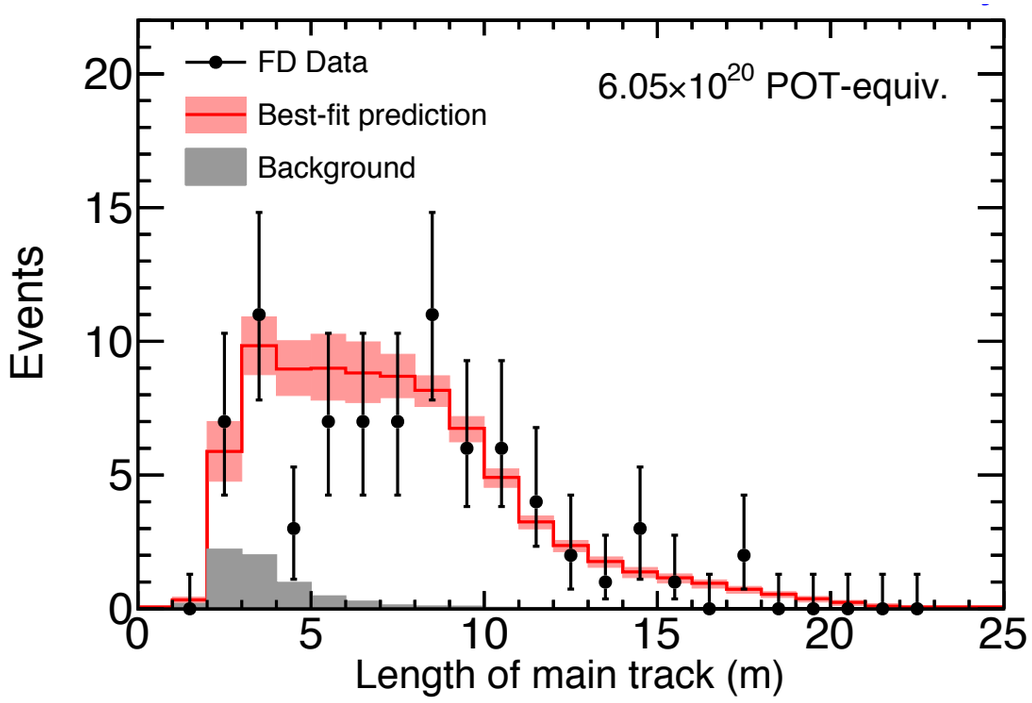
X
Z
να
X
10
10^2
10^3
q (ADC)

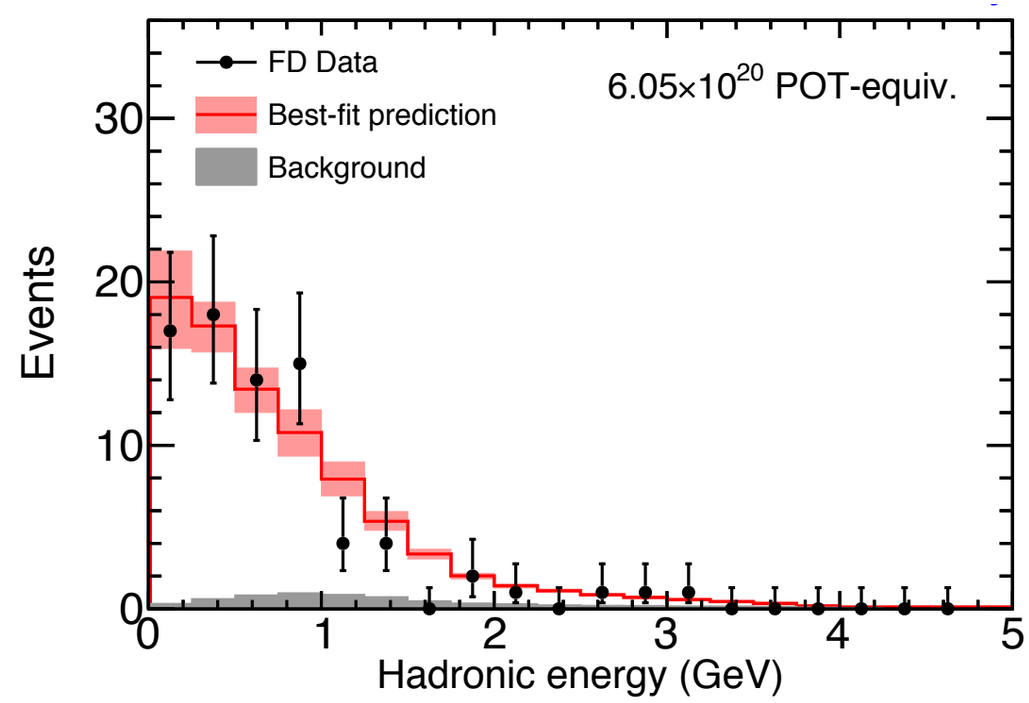
ND:





FD:

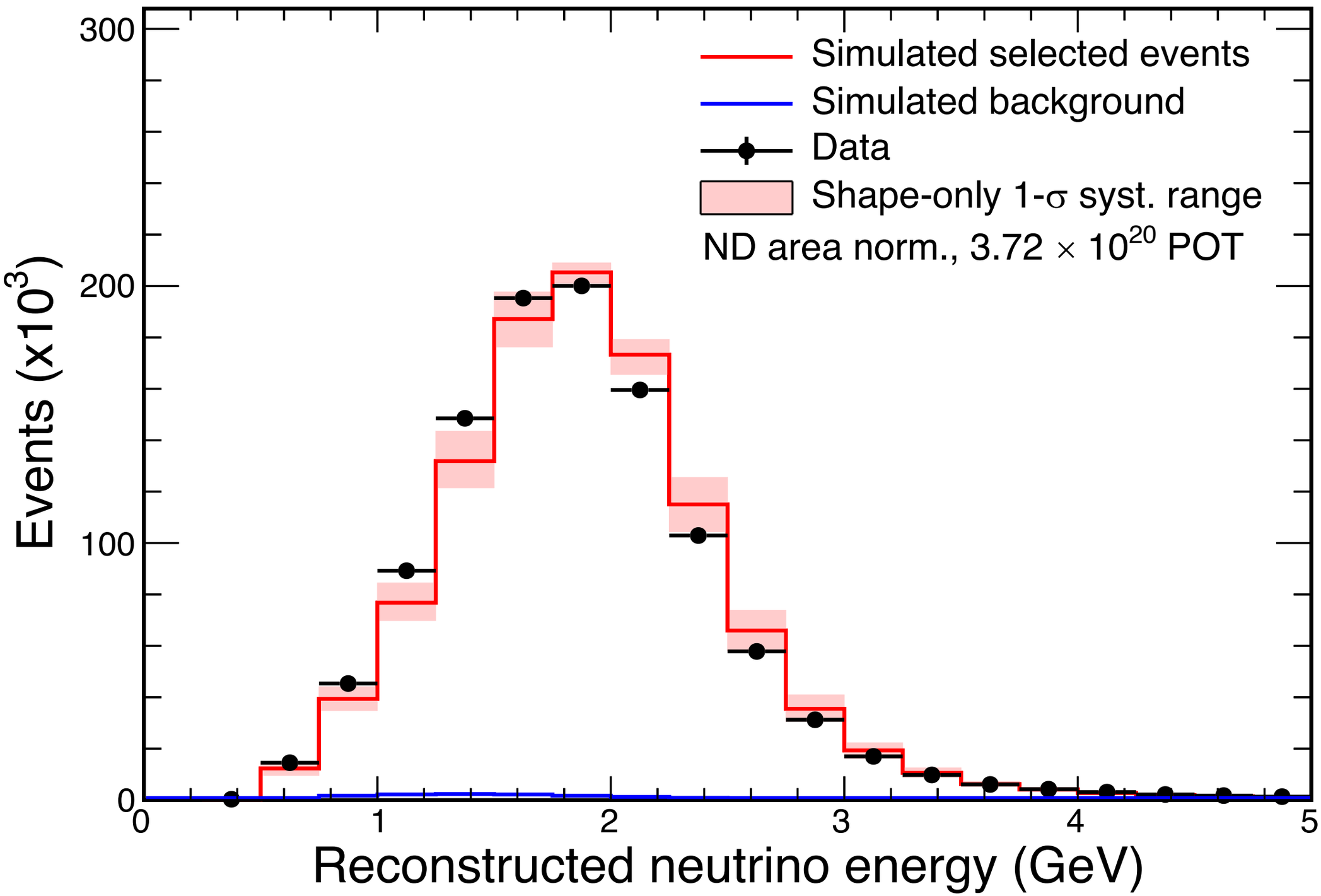




Muon neutrino energy reconstruction

Track length + hadronic energy

3.2% muon energy resolution
28% hadronic energy resolution
7% neutrino energy resolution



NOvA Near detector muon neutrino spectrum

1.1 million contained muon neutrino events

General comments on the NOvA near detector

The NOvA near detector was designed under a rather stringent set of constraints.

- **Total project cost**: NOvA was build during a time of peak oil prices and we were constantly worried about costs. We prioritized the far detector mass at several key cost decision points. The near detector was the cheapest option that we deemed adequate to the job.

- **Technology**: Related to costs. We never considered doing anything but duplicating the far detector design. This allowed components for the near detector to be built in the same production lines at the far detector components. This saved money and effort and also served the physics. It guaranteed the same target nucleus mix which aids the cancelation of neutrino cross-section uncertainties and also made the detection efficiency and energy resolutions nearly identical to the far detector which greatly reduces near-far uncertainties. I would have liked to have one region of the ND build with finer segmentation that the far detector ("SciNOvA") but this idea never took root.

- **Space**: Space in the NuMI underground areas was very tight. The cavern we opted to build is rather small and originally only accommodated a 2x3 module design. We were able to modify the layout late in the project and use contingency to expand to a 3x3 design. This extra width has proved invaluable to provide better kinematic coverage of the far detector neutrino interactions by those in the near detector.

- **Off-axis**: As NOvA is off-axis, flux shape uncertainties are extremely small and the near-to-far extrapolation is rather robust against very large excursions of the NuMI operational parameters. This makes the NOvA near detector a terrible beam monitor, but again serves the physics. NuMI was built for the on-axis MINOS experiment and all MINOS's requirements on control of the NuMI beam operations were over spec'ed for NOvA.

Scientific performance requirements for the NOvA detector

1. **At least 20 ton fiducial volume located about 1 km from the NuMI target with sufficient transverse and longitudinal size for neutrino event containment**

2. **Segmentation in the fiducial volume identical to the far detector**

3. **Orientation identical to the Far Detector**

4. **Energy resolution of 8% for electron-neutrino charged-current events at 2 GeV.**

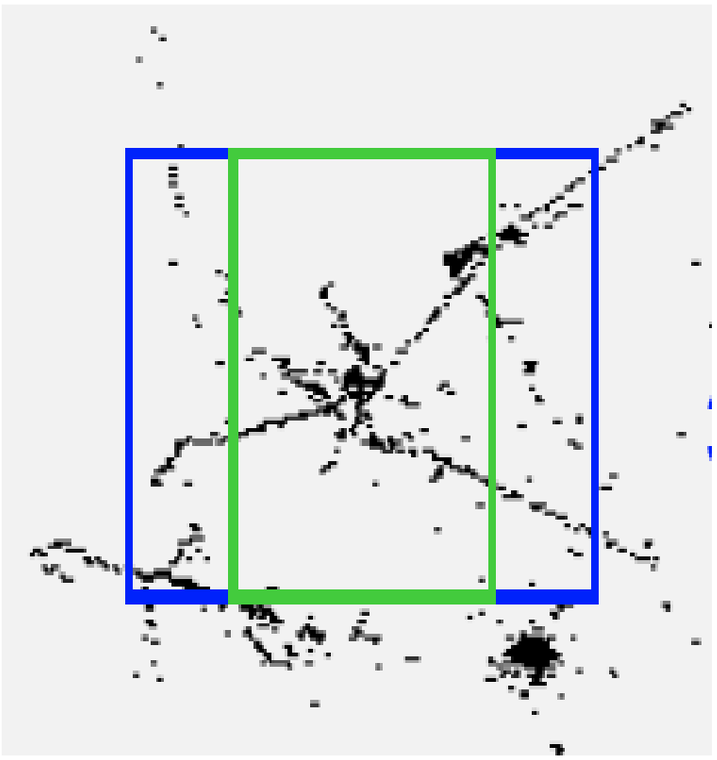
5. **Energy resolution of 4% for muon-neutrino quasi-elastic events at 2 GeV.**

Note: We took the scientific performance requirements to more-or-less be a contract between the collaboration and the project and between the project and DOE. We tried to keep them to an essential minimum to ensure that we (project + collaboration) retained flexibility and didn't have too many key performance parameters to track and document.

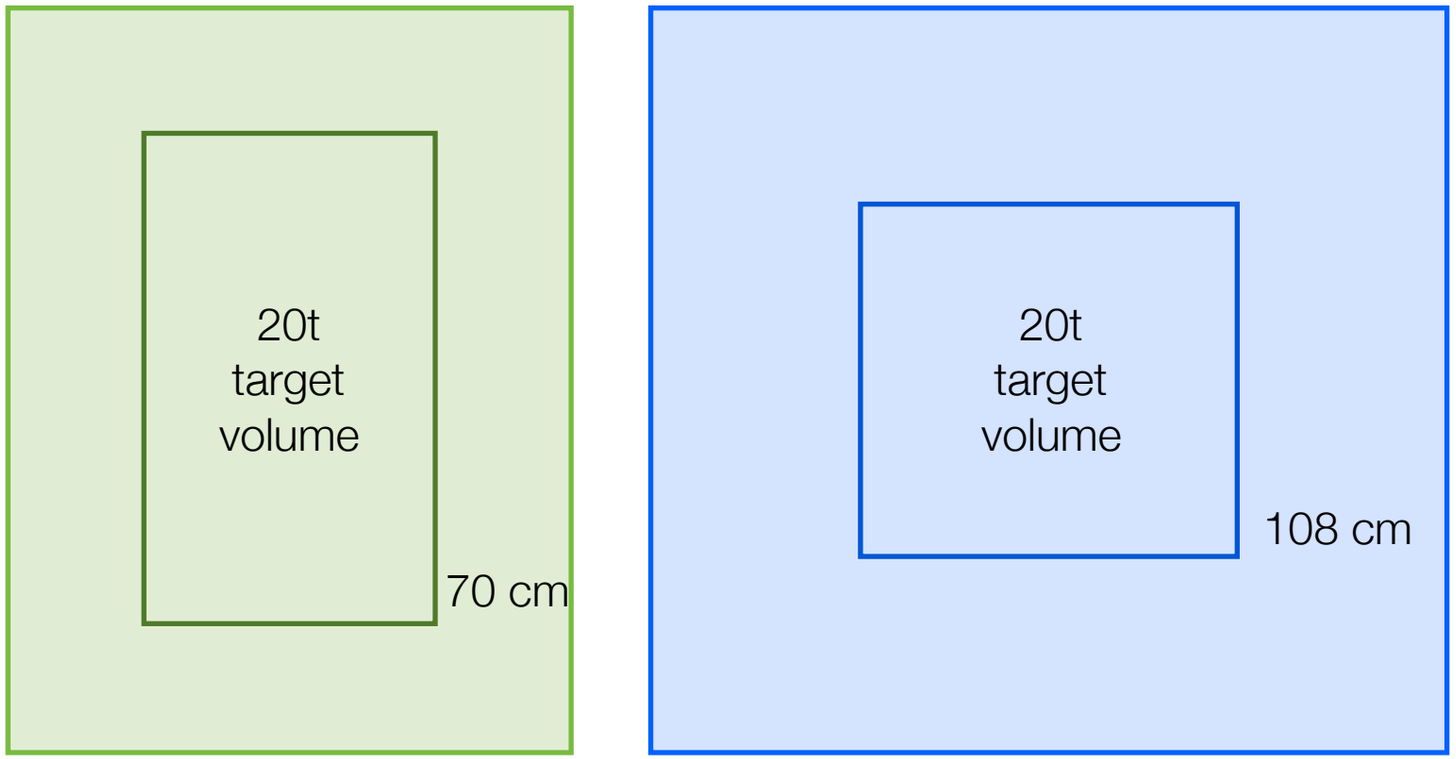
At least 20 ton fiducial volume…

The motivation for this was a more-or-less back of the envelope calculation of the event rates at the near and far detectors. In the NOvA far detector we expected about 40 electron-neutrino events per year. In the near detector we wanted at least a factor of 40 more than this to ensure that the statistical error on electron neutrino background extrapolated from the near detector to be less than 2% in the first year and therefore negligible compared to other sources of uncertainties which we expected to total 5-10%. With 10,000+ electron neutrino candidates we also expected to have enough events to make distributions to study energy spectrum, PID performance, and other possible sources of biases.

…with sufficient transverse and longitudinal size for neutrino event containment



An example neutrino event centered on 2x3 and 3x3 near detector profiles



Detector front views

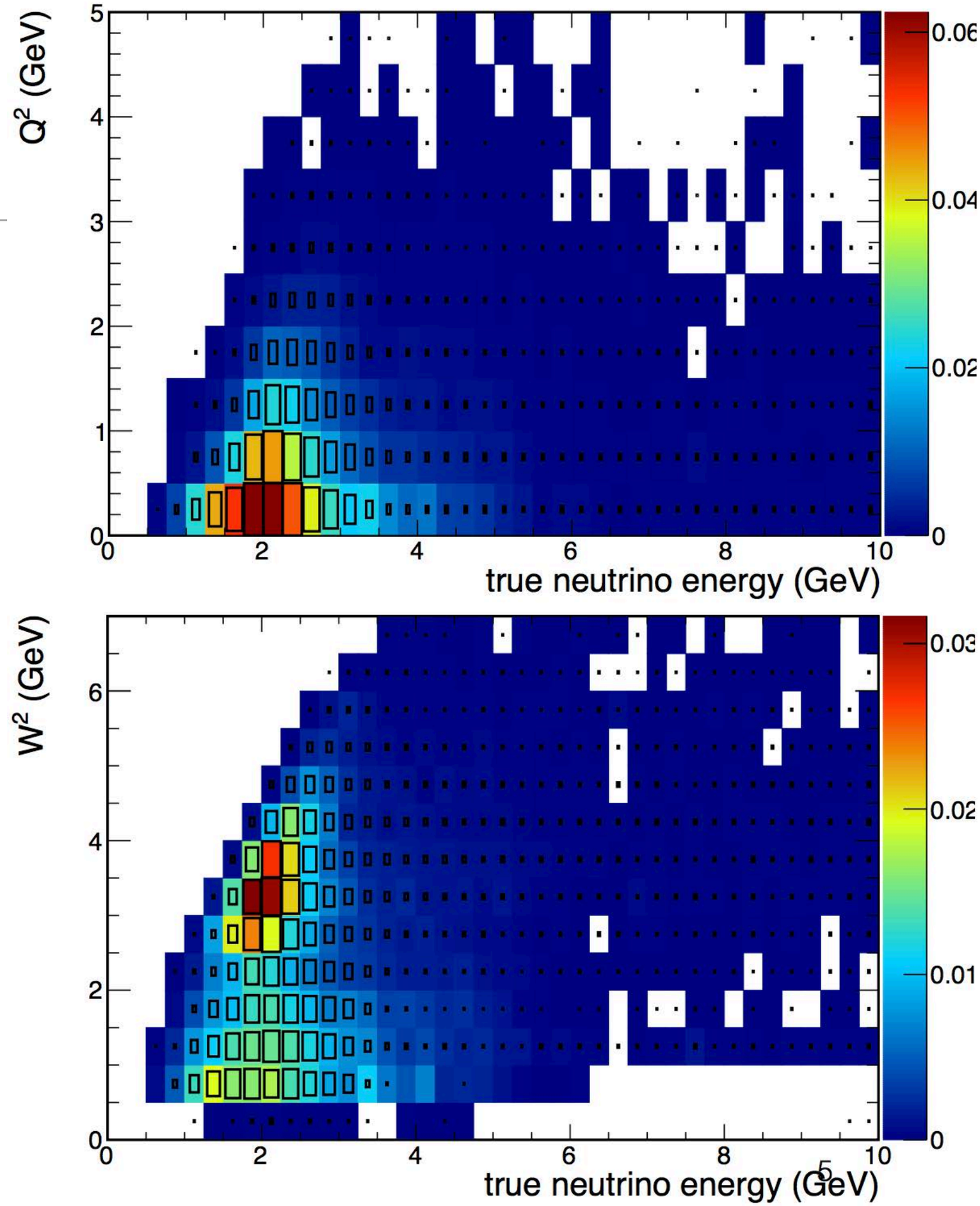
	2x3	3x3
Fraction of ν_e events which are 95% contained or better	61%	95%
Fraction of NC π^0 events which are 95% contained or better	44%	90%

Comparison of backgrounds to the electron neutrino search

- Color shows the background events selected by the NOvA electron neutrino appearance search in the near detector.

- Boxes show the background event rates selected at the far detector (no appearance signal).

- Generally the coverage of the ND matches the FD which reduces uncertainties in the extrapolation from near to far



Energy resolution of 8% for electron-neutrino charged-current events at 2 GeV… 4% for muon-neutrino QE events.

- In the nue case this was a mix of what we believed was achievable and what would not overly degrade the advantages of the narrow-band beam's ability to reject NC backgrounds based on their energy spectrum. The NOvA neutrino beam spectrum has a width of ~30% so keeping the energy resolution of the detector small compared to 30% ensured that we would not have to open up the signal energy window much beyond the edges of the beam spectrum which would allow additional NC backgrounds to enter the sample.

- In the case of numu CC, Fermi momentum of the struck nucleons gives an irreducible ~4-5% spread in reconstructed neutrino energy and we thought we could build a detector capable of not degrading that resolution too much further. In the end, this proved hard to meet for all but a very select group of numu CC events.

Role of near detector in flux determination

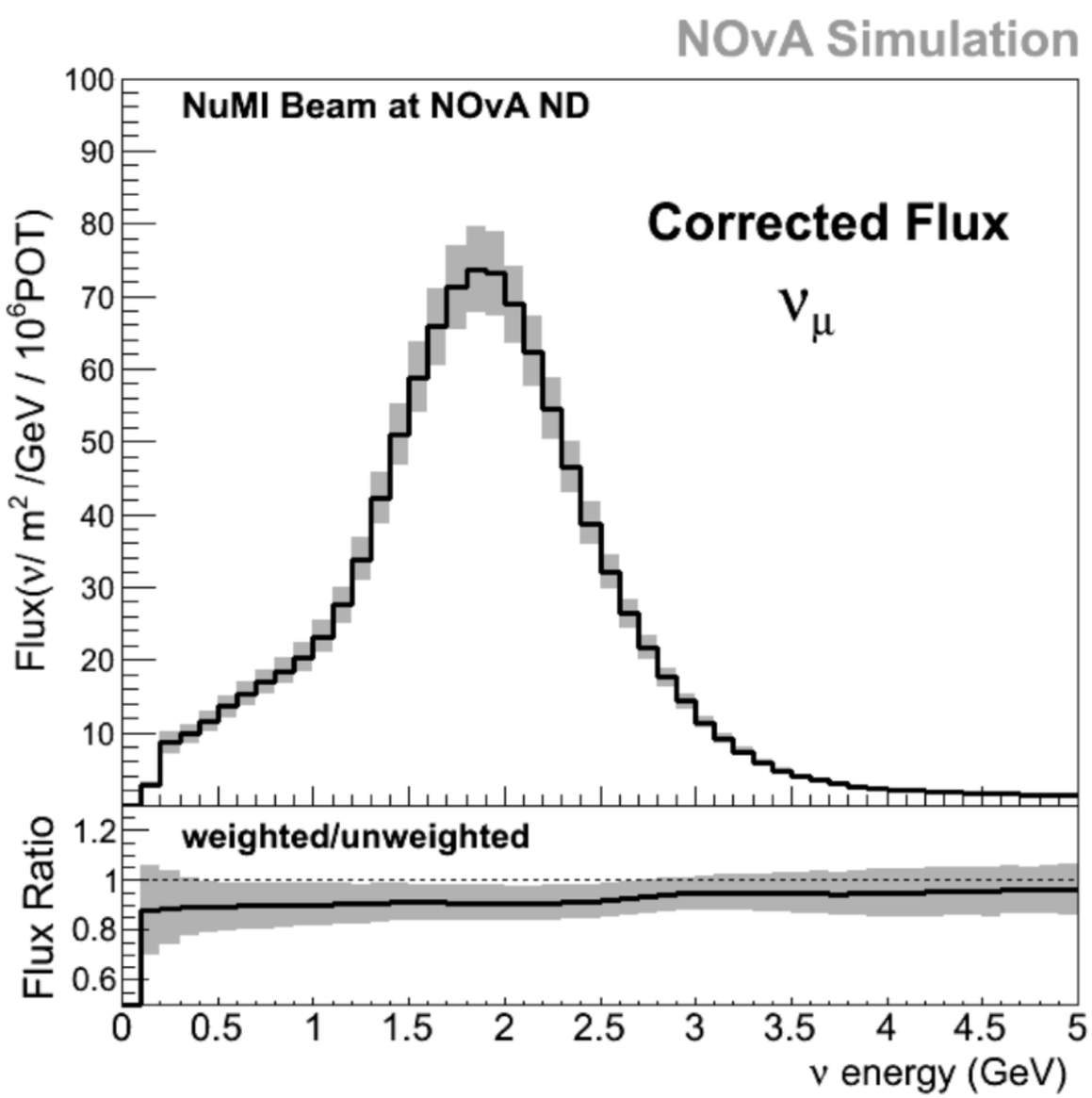
- The NOvA near detector is primarily used to constrain and tune neutrino cross-sections and detector performance.

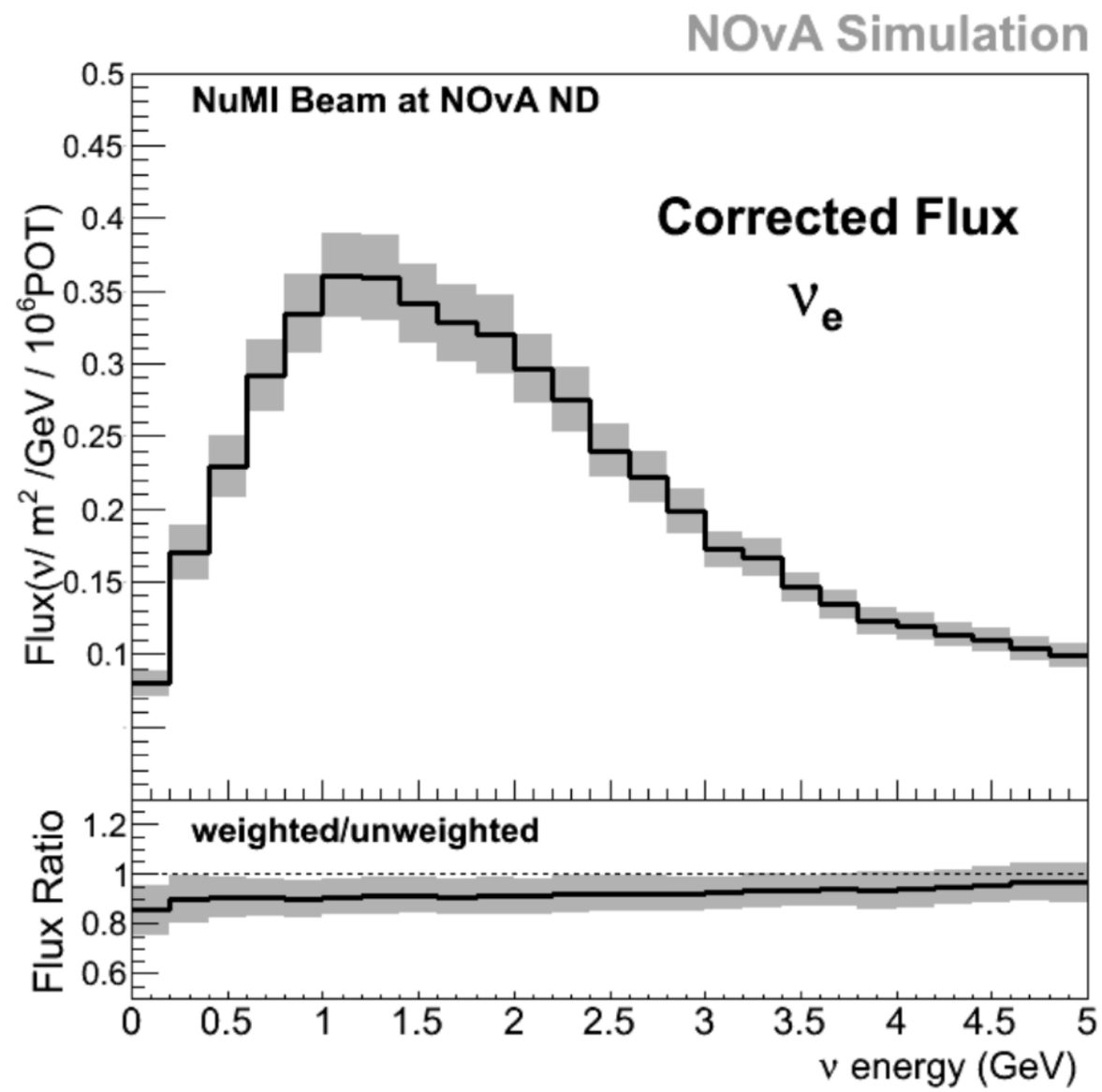
- To date, NOvA does not use its near detector extensively to tune or constrain the neutrino flux. We rely on the PPFX calculation (http://vms.fnal.gov/asset/detail?recid=1939282) of the beam flux which was done for MINERvA's on-axis case and translate that to off-axis. As discussed before, the on-axis case has much more sensitivity to the neutrino flux.

- PPFX uses a variety of constraints from hadron production experimented (Barton, NA61, NA49, MIPP) and a variety of hadron production models, the "low nu" method, and neutrino-electron scattering in the on-axis detectors to predict the flux for MINERvA, MINOS+, and also NOvA with an error band.

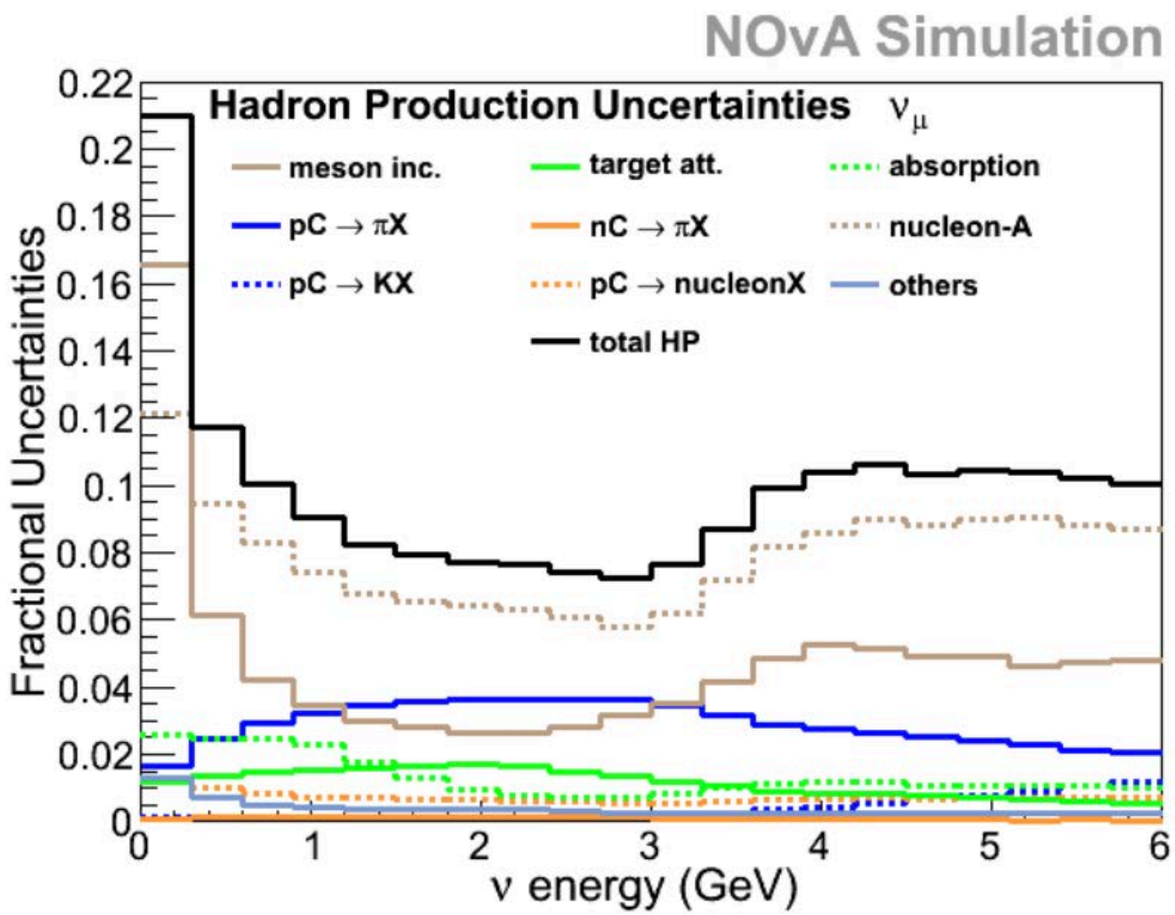
- Exceptions: NOvA uses an in-situ constraint on the kaon flux and is investigating the use of neutrino-electron scattering for a flux constraint.

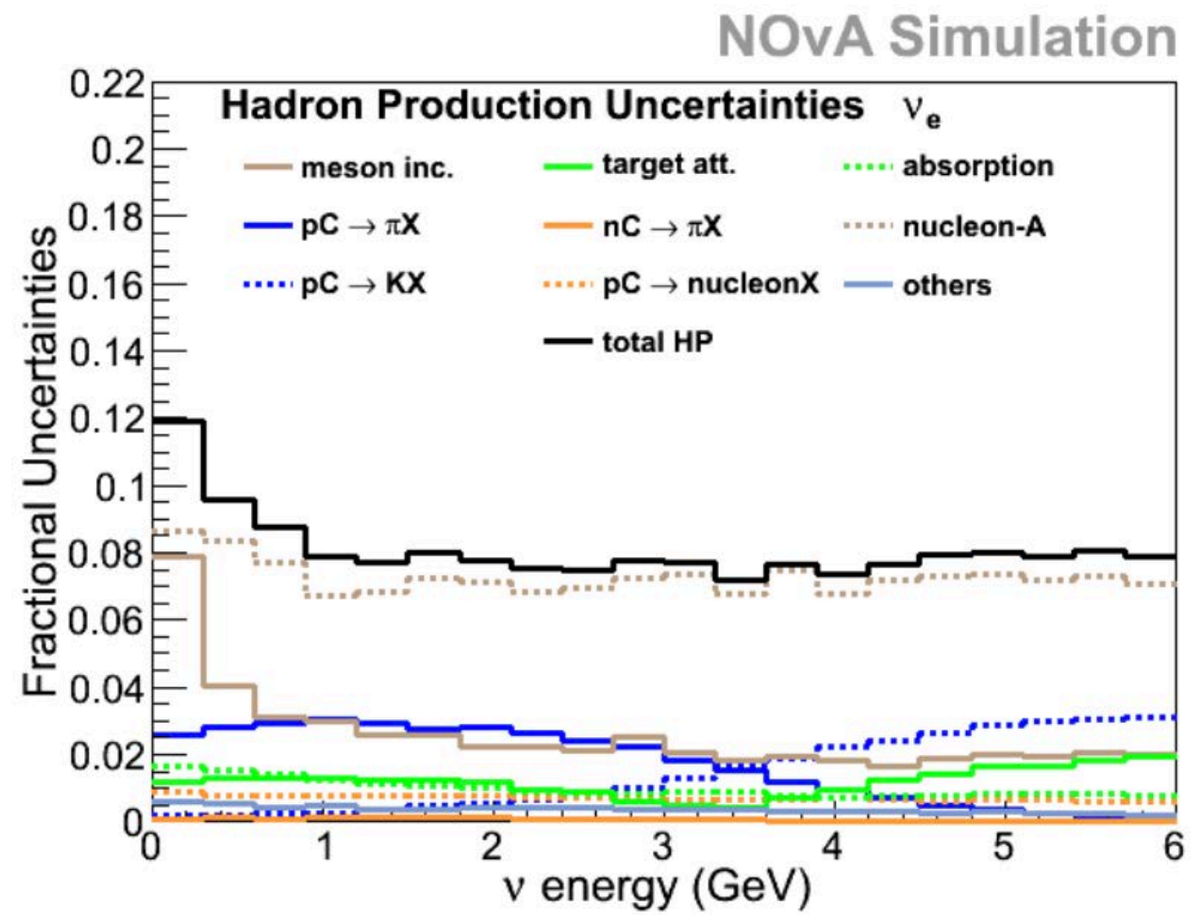
PPFX Flux Predictions for NOvA

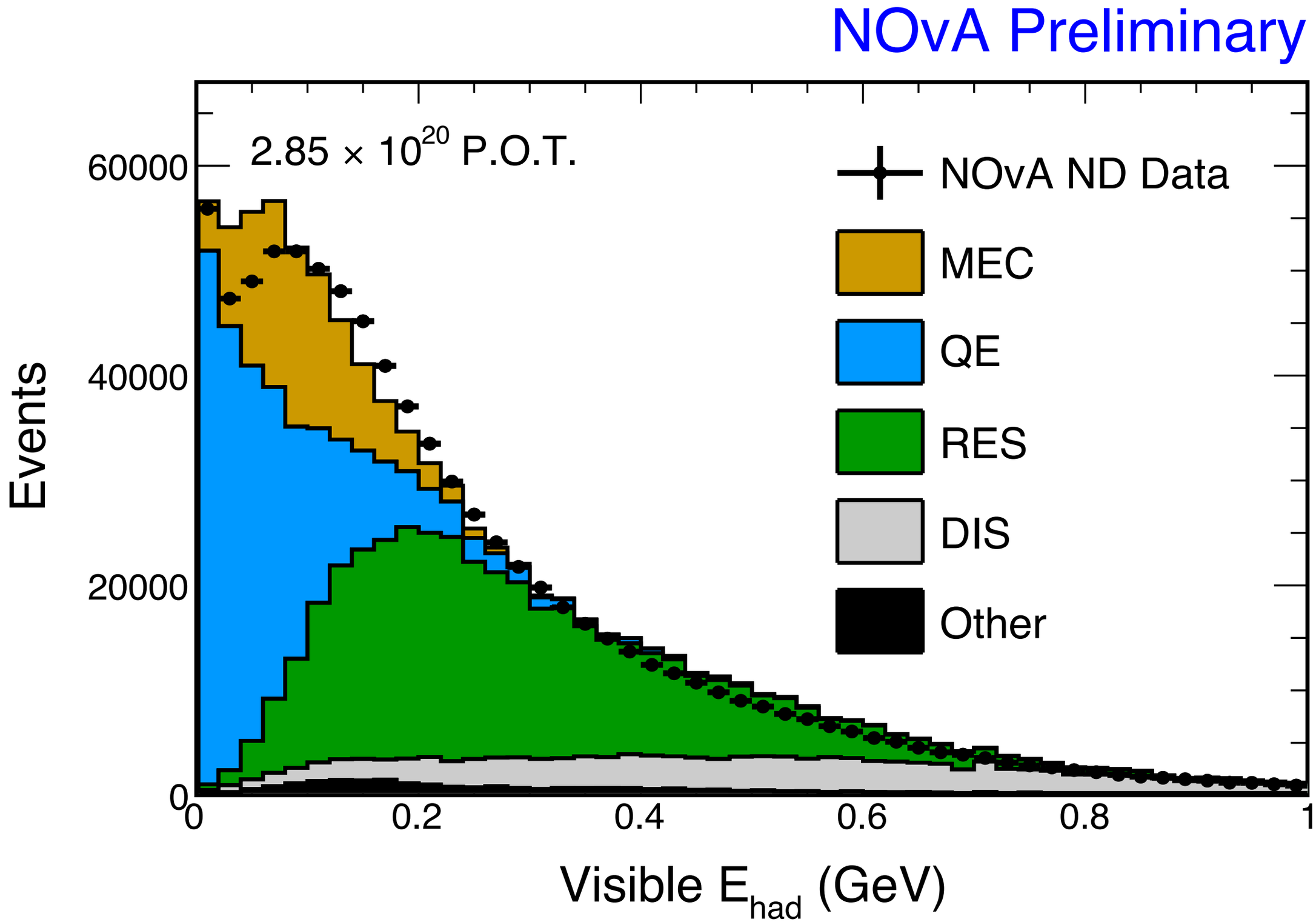




PPFX Flux Predictions for NOvA



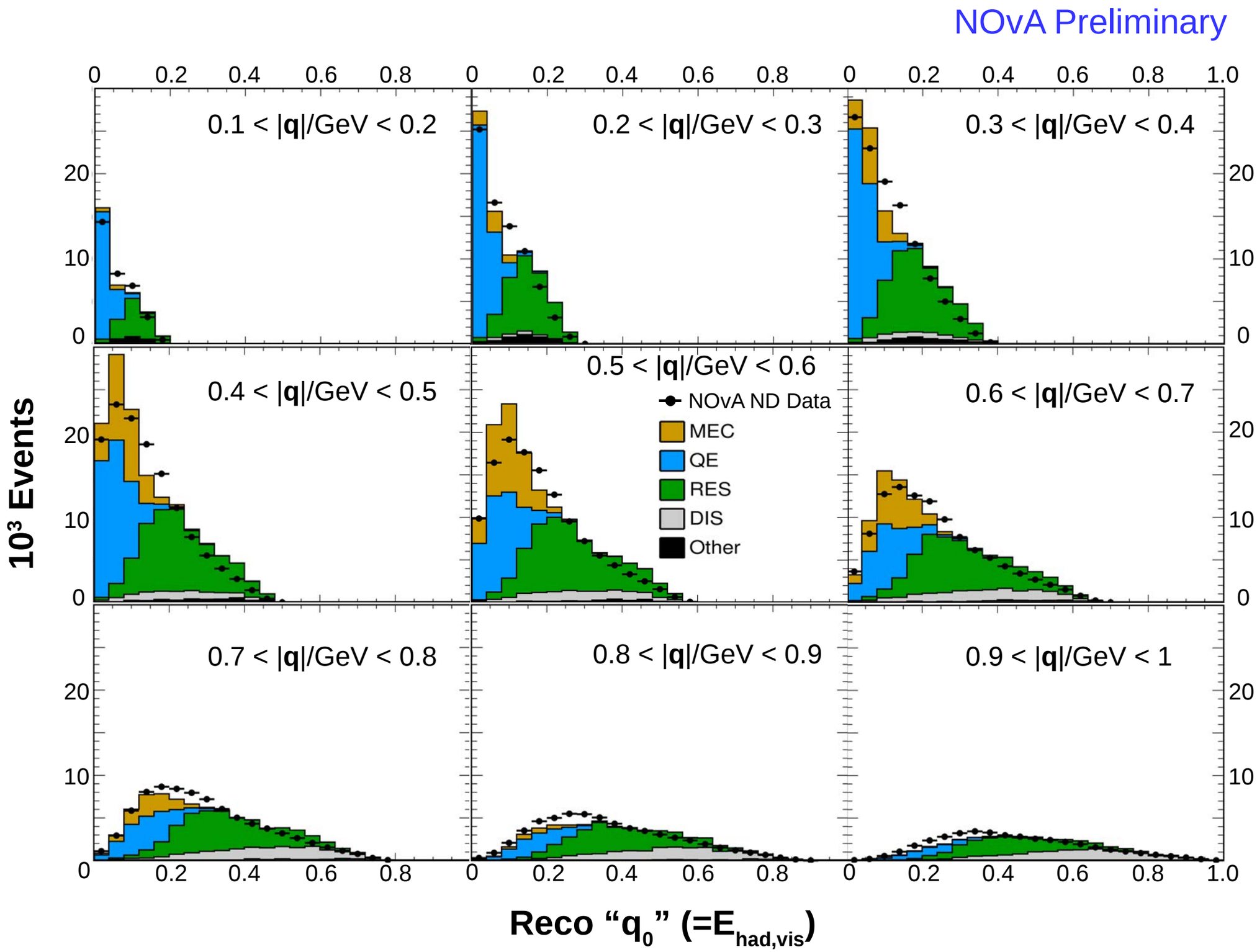




Hadronic energy

Second muon neutrino analysis

Agreement not perfect but much better so that this is no longer leading systematic after near-far extrapolation

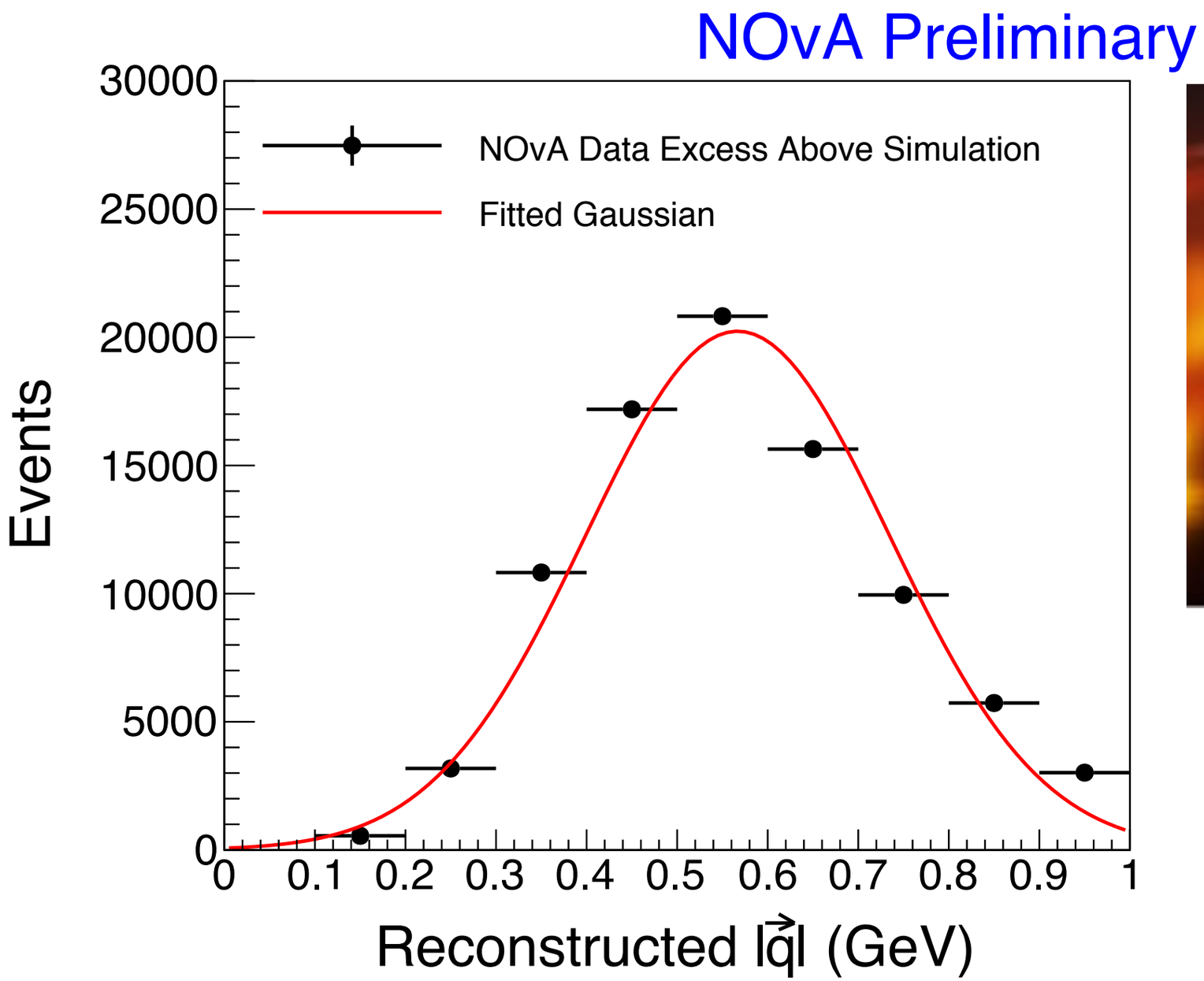


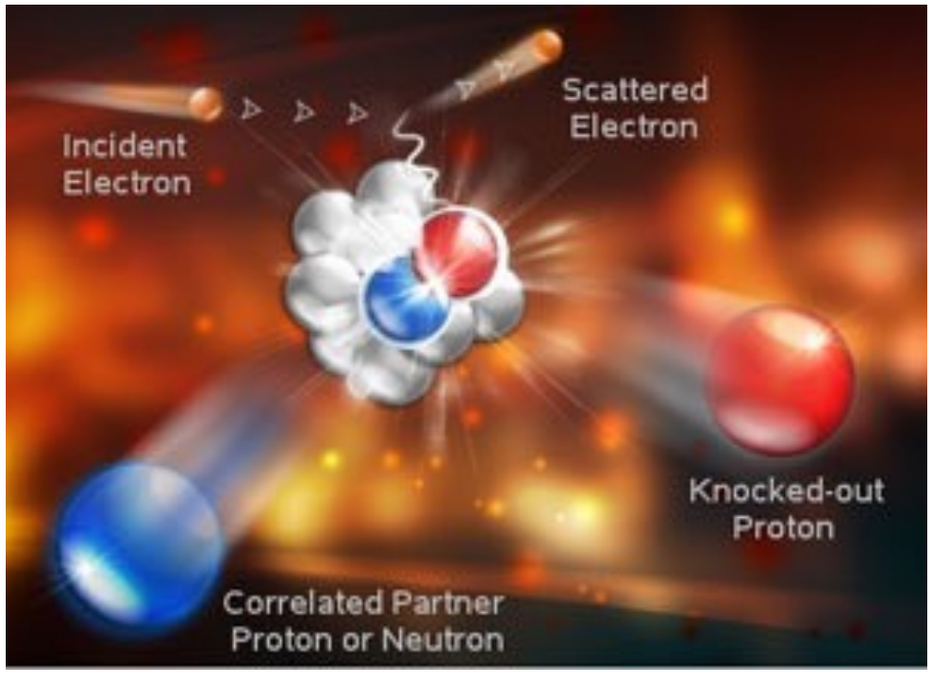
Hadronic energy in slices of momentum transfer

Empirical model of meson exchange current coded into GENIE by S. Dytman guided by MINERvA data

[1] P.A. Rodrigues et al., PRL 116 (2016) 071802 (arXiv:1511.05944)
[2] S. Dytman, based on J. W. Lightbody, J. S. OConnell, Comp. in Phys. 2 (1988) 57
[3] P.A. Rodrigues et al., arXiv:1601.01888

Short range nucleon correlations?

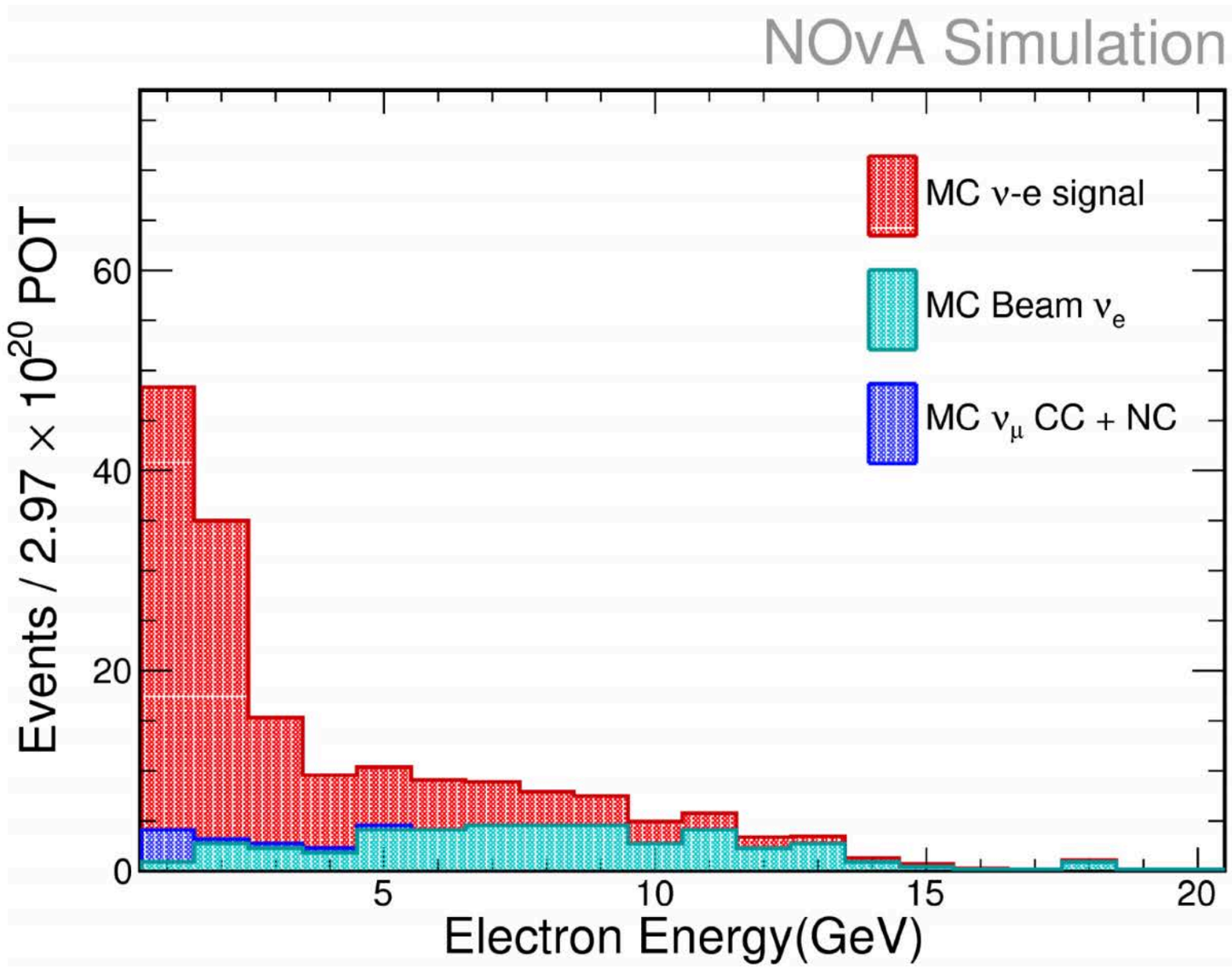




https://www.jlab.org/highlights/phys.html

Neutrino-electron scattering

- Neutrino electron scattering has a well predicted cross-sectio and has no confusion from nuclear effects.
- The cross-section is, however, very low (down by factor of 10,000 compared to neutrino-nucleon)
- Expect about a 10% constraint on total flux from this in future.



A general note on scientific performance requirements

- Composing the scientific performance requirements requires some care. In the case of NOvA the project took these as a contract between the collaboration and the project and between the project and the DOE. They were used to evaluate changes to the designs; designs which reduced cost and still met the scientific performance requirements were generally incorporated.

- That said, the collaboration and project benefitted from flexibility to adjust scope and performance inside the stated requirements.

- In my opinion, you want to keep these two tensions in mind when writing the scientific performance requirements.

  - They are a set of “boundaries” that the project should not cross and therefore communicate a set of priorities from the collaboration to the project

  - On the other hand, they should be written in a way that allows both the collaboration and project flexibility.

- To that end I think you want the scientific performance requirement to be essential and not very numerous. The project will have to track these and the collaboration will be accountable to them at the end of the project to verify that they have been met. Also, they will constrain options when the collaboration and project has to make adjustments. The more there are, the tighter will be the constraints when cost, schedule, scope problems inevitably arise.

	NOvA	DUNE
Beam spectrum	Off-axis : Greatly limits the impact of neutrino flux uncertainties.	On-axis where flux uncertainties play a bigger role.
Detector	NOvA is a fast detector making it possible to use identical technology at near site.	LAr detectors are slow and may have trouble keeping up with the beam intensity.
	Any options beyond duplicating the far detector were cost non-starters to ensure FD mass was prioritized.	Perhaps scope is large enough to increase ND capabilities?
Facilities	NOvA had to fit into existing NuMI facilities.	Underground areas are green field.
Physics program	NOvA's CD0 was only for neutrino oscillations. We knew we would have a cross-section program but optimizing for it was not an option.	DUNE is a larger experiment designed to be multi-purpose from the start.

My personal take on the differences between NOvA and DUNE regarding the near detector