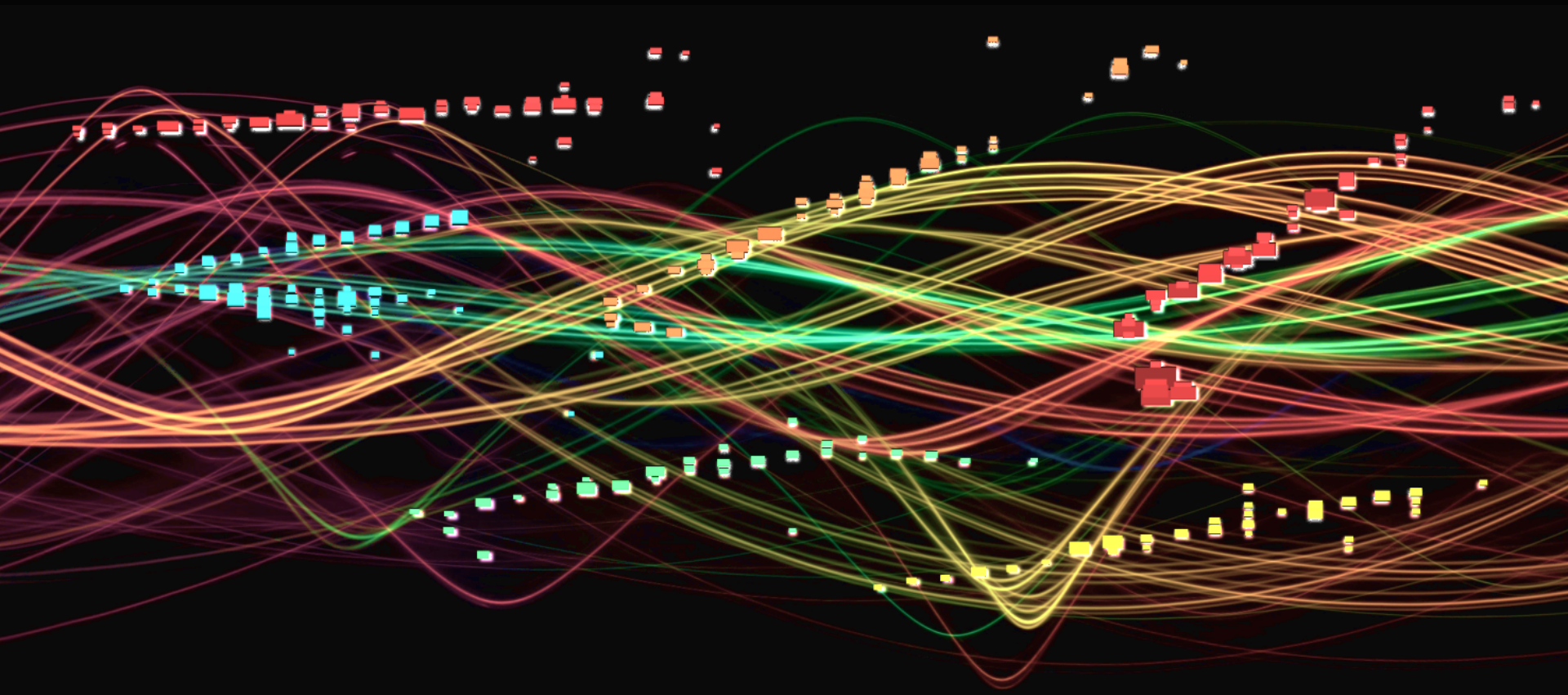


NOvA Systematics

Mathew Muether – Wichita State University

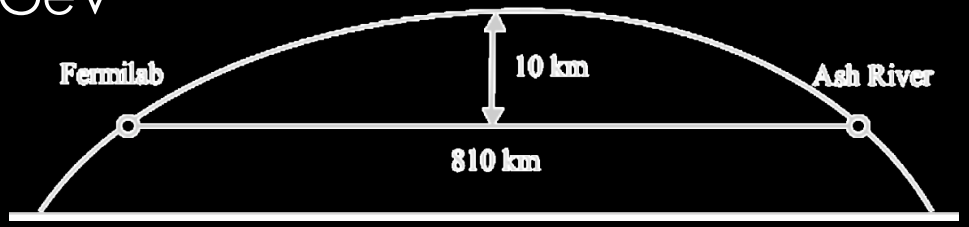
NuINT15 – Osaka, Japan - November 16, 2015

OUTLINE

- Review NOvA design and first oscillation results.
- Describe dominant systematics from first analysis.
- Discuss steps to improve upon the first reported systematics.
  - Including a brief descripition of the NOvA ND Physics program.

NOVA PROGRAM

- Long-baseline neutrino oscillation experiment; 14 mrad Off-axis @ L/E ~ 400 km/GeV



- Near detector to characterize the beam
- Far detector for oscillation study

- Physics goals:

$\nu_\mu \rightarrow \nu_e$ apperance

- Measure θ_{13}
- ν mass ordering
- CP violating phase

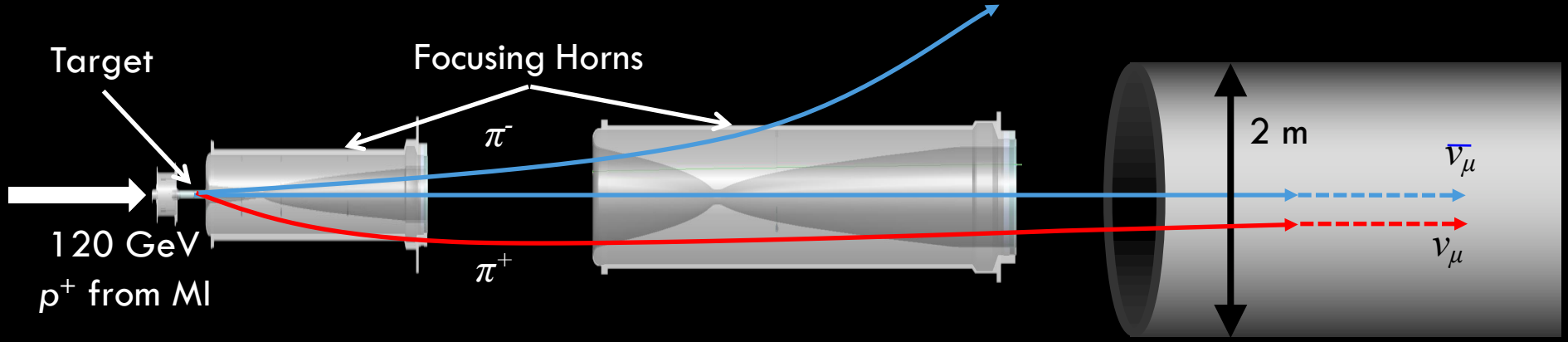
$\nu_\mu \rightarrow \nu_\mu$ disapperance

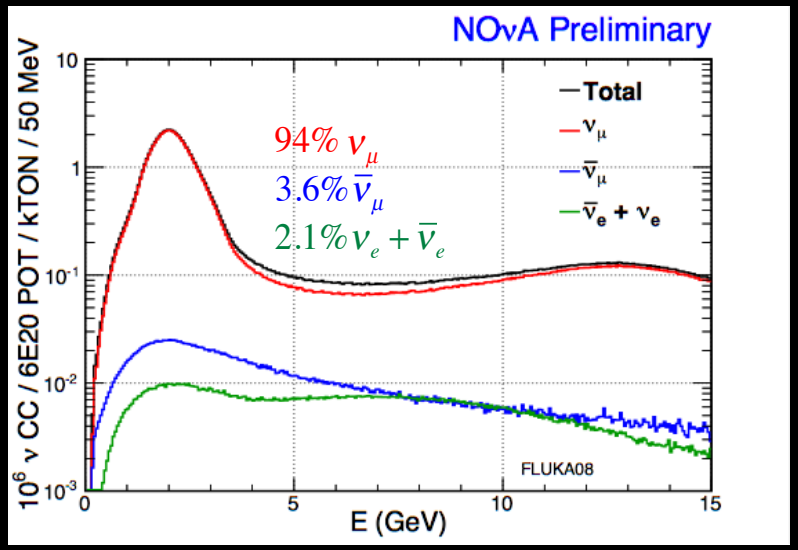
- Precision measurement of θ_{23}, $|\Delta m_{32}^2|$

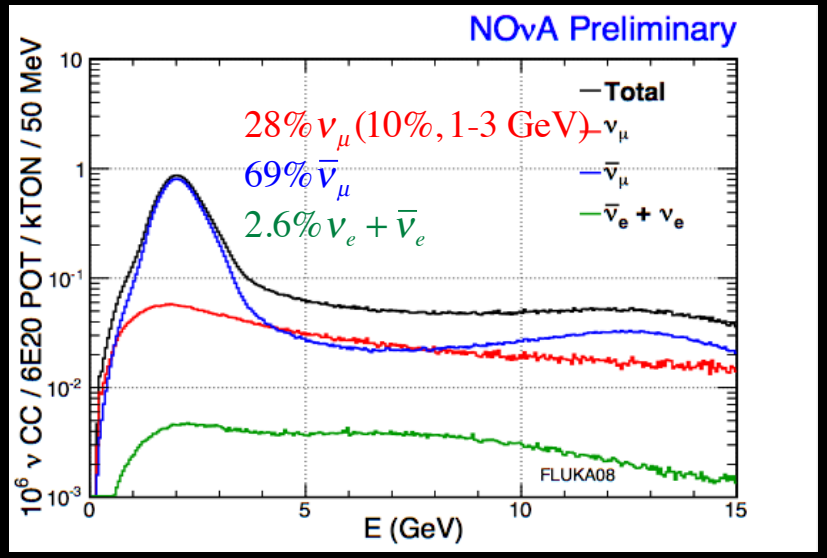
Cross-sections from near detector

Other exotics

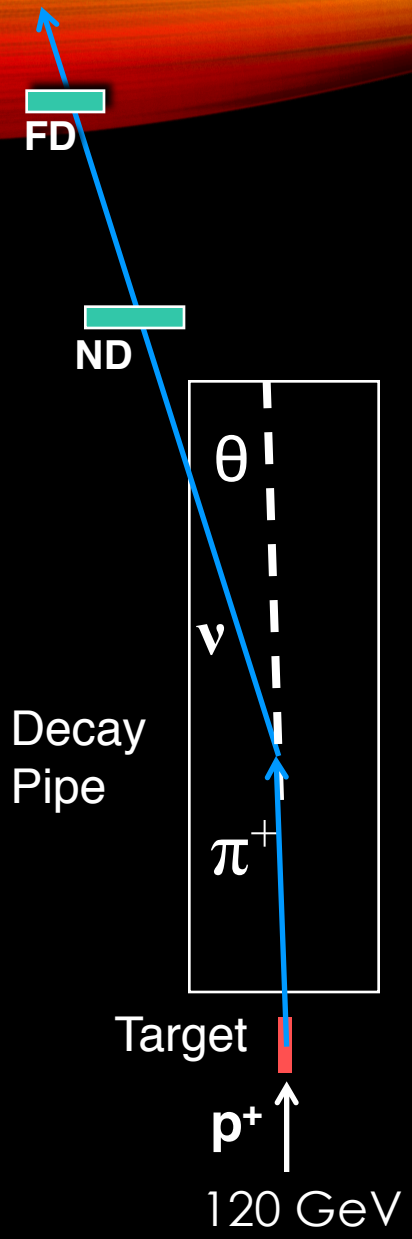
GENERATING NEUTRINOS

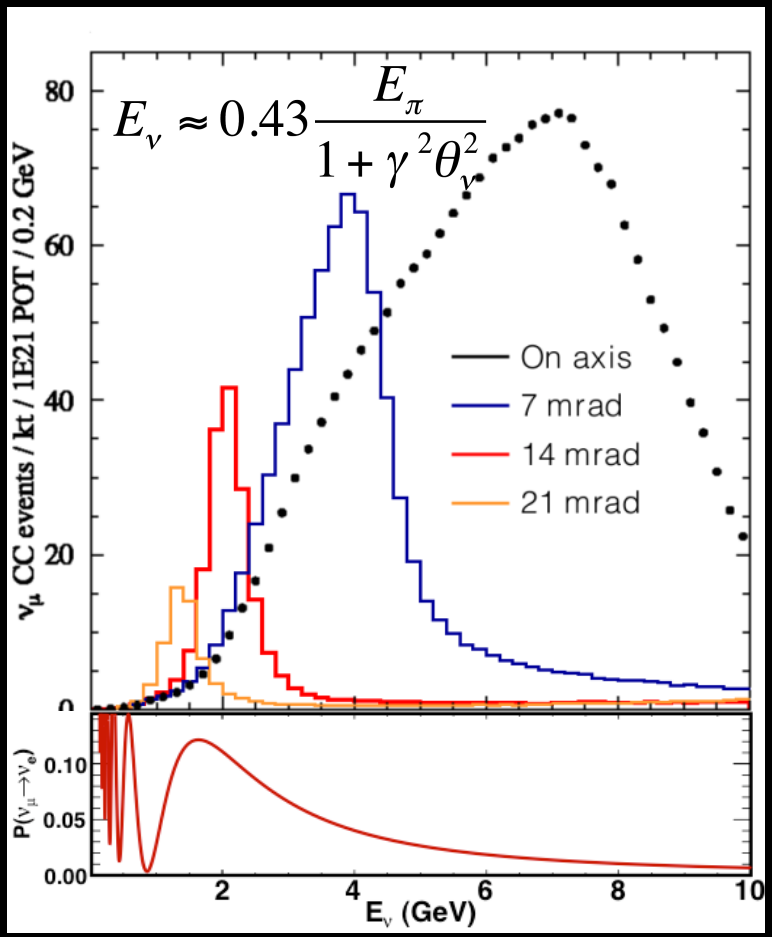






NUMI OFF-AXIS BEAM





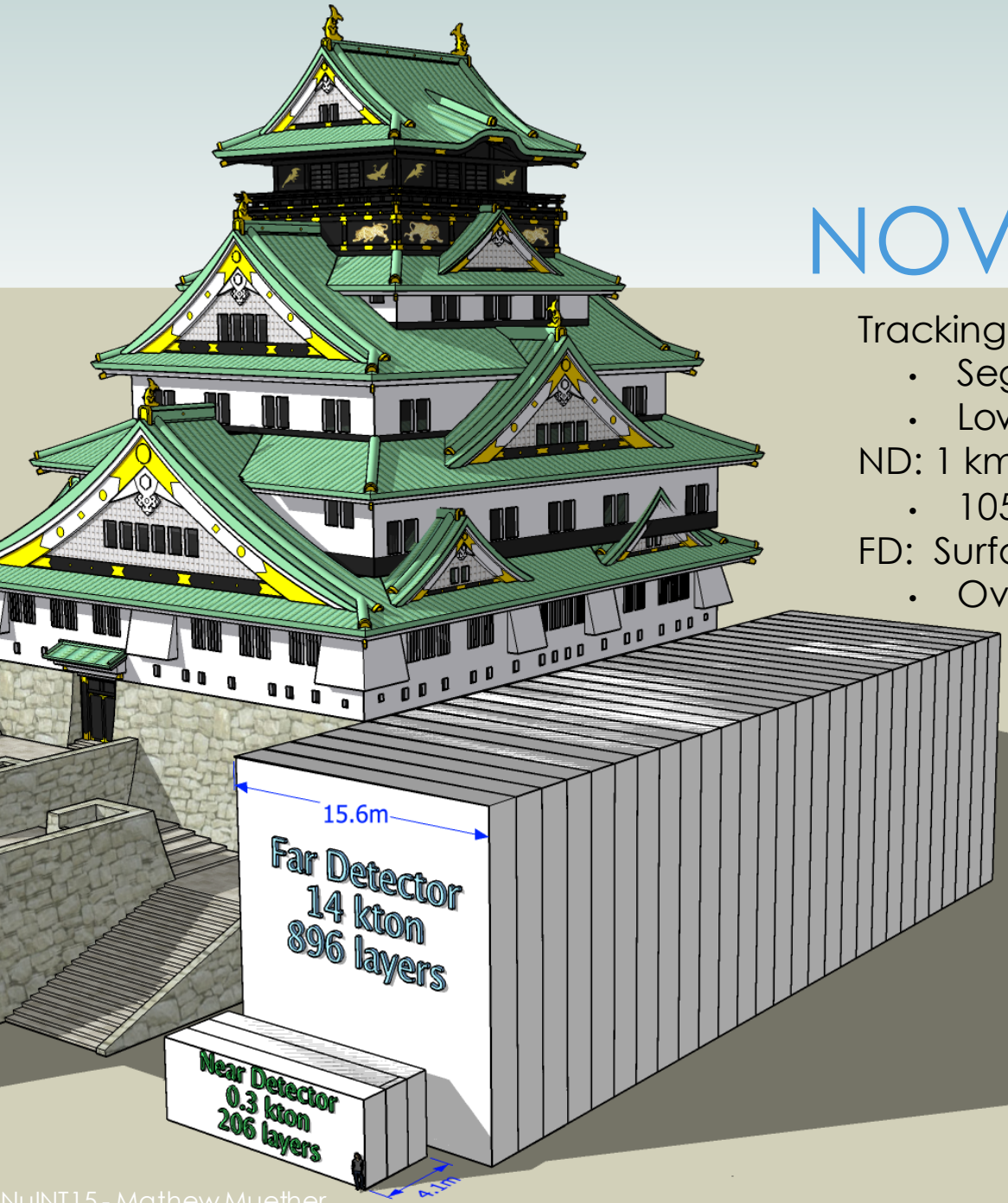
- The 14 mrad off-axis beam is narrow band
- Increased flux near oscillation maximum
- Reduced high energy neutral current background events

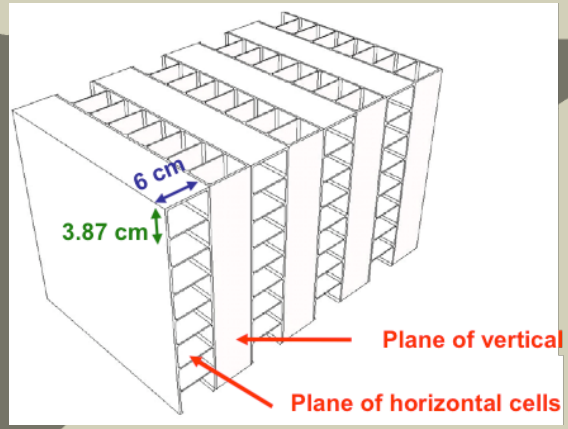
NOVA DETECTORS

Tracking calorimeters for electron ID:
- Segmented (Alternating X/Y)
- Low Z 65% Active Volume

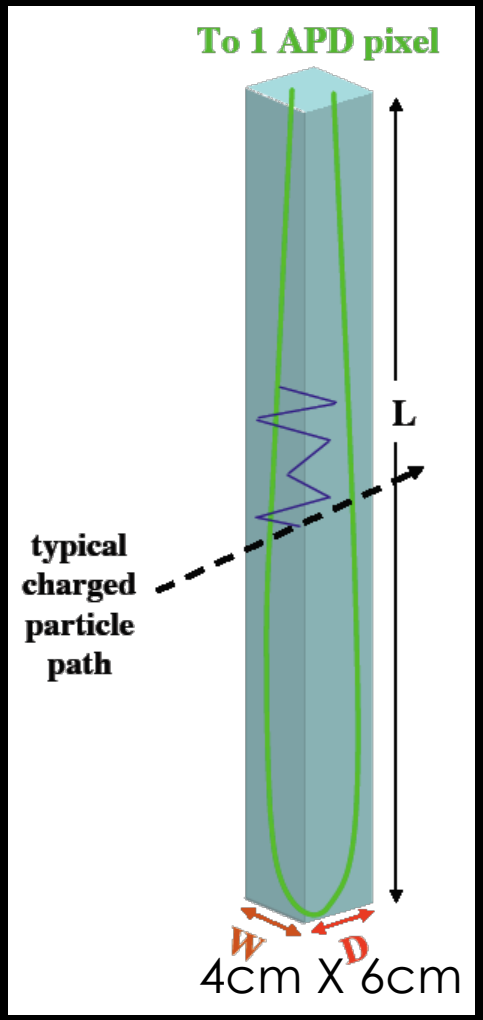
ND: 1 km from NuMI
- 105 m underground

FD: Surface Detector
- Overburden >10 radiation lengths

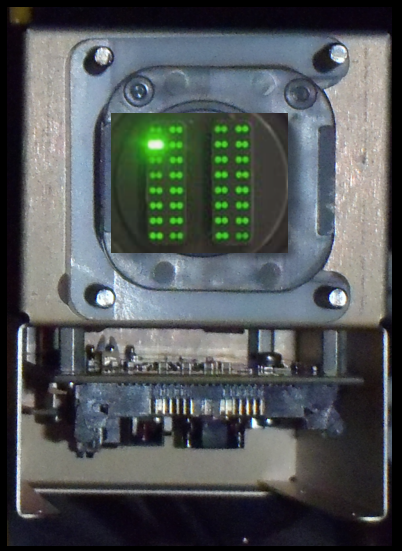


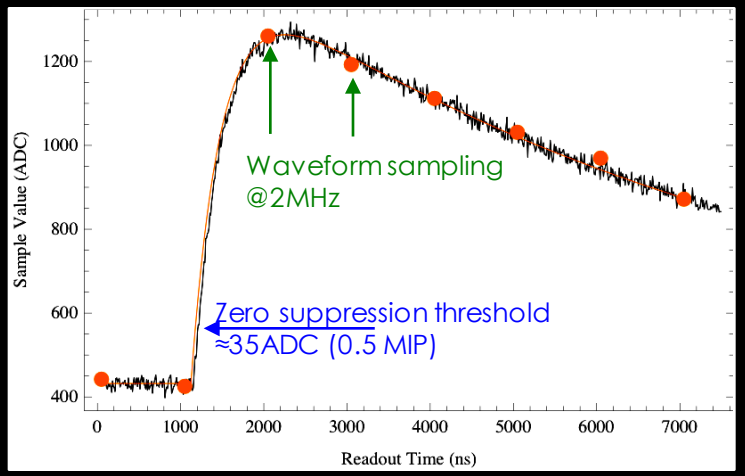


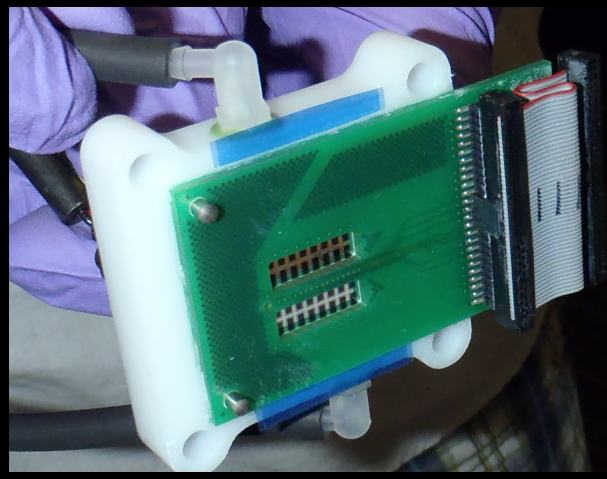
DETECTOR TECHNOLOGY



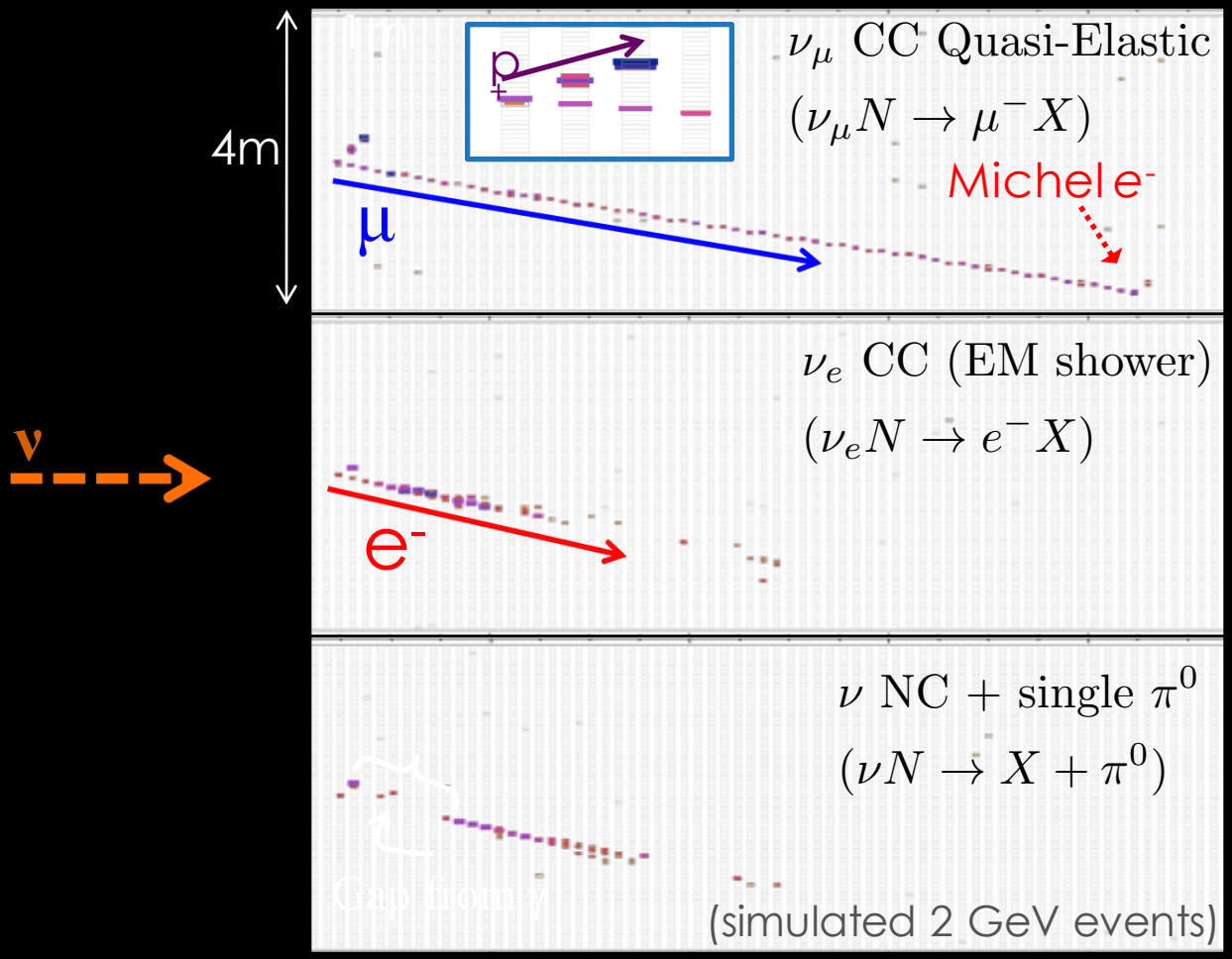
- Extruded PVC cells of LS
- Instrumented with WLS fiber
- APD converts photo to e
- Signal digitized by on module front end electronics (FEBs)
- 25 PE for MIP crossing FD far end
- ~7 sample per X_0

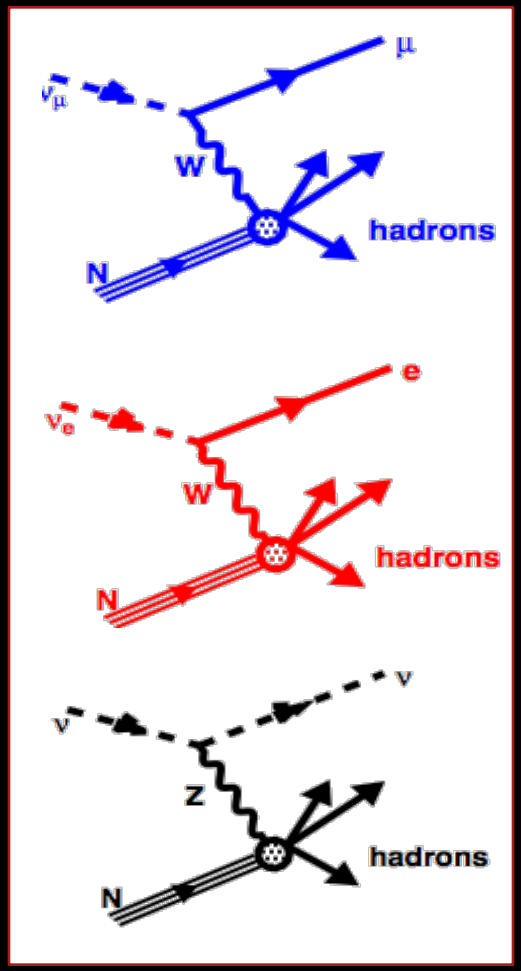






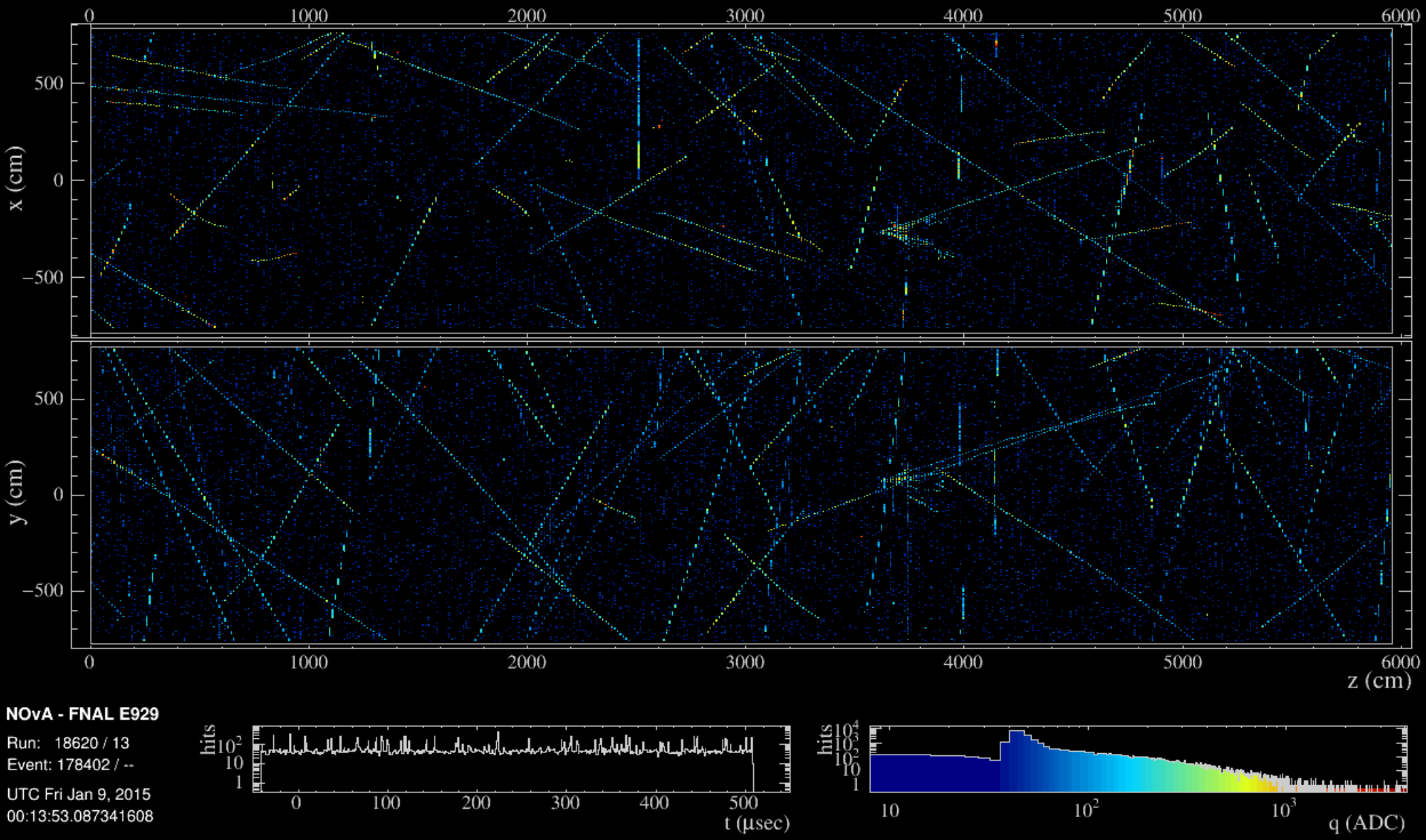
EXPECTED EVENT TOPOLOGIES





FAR DETECTOR

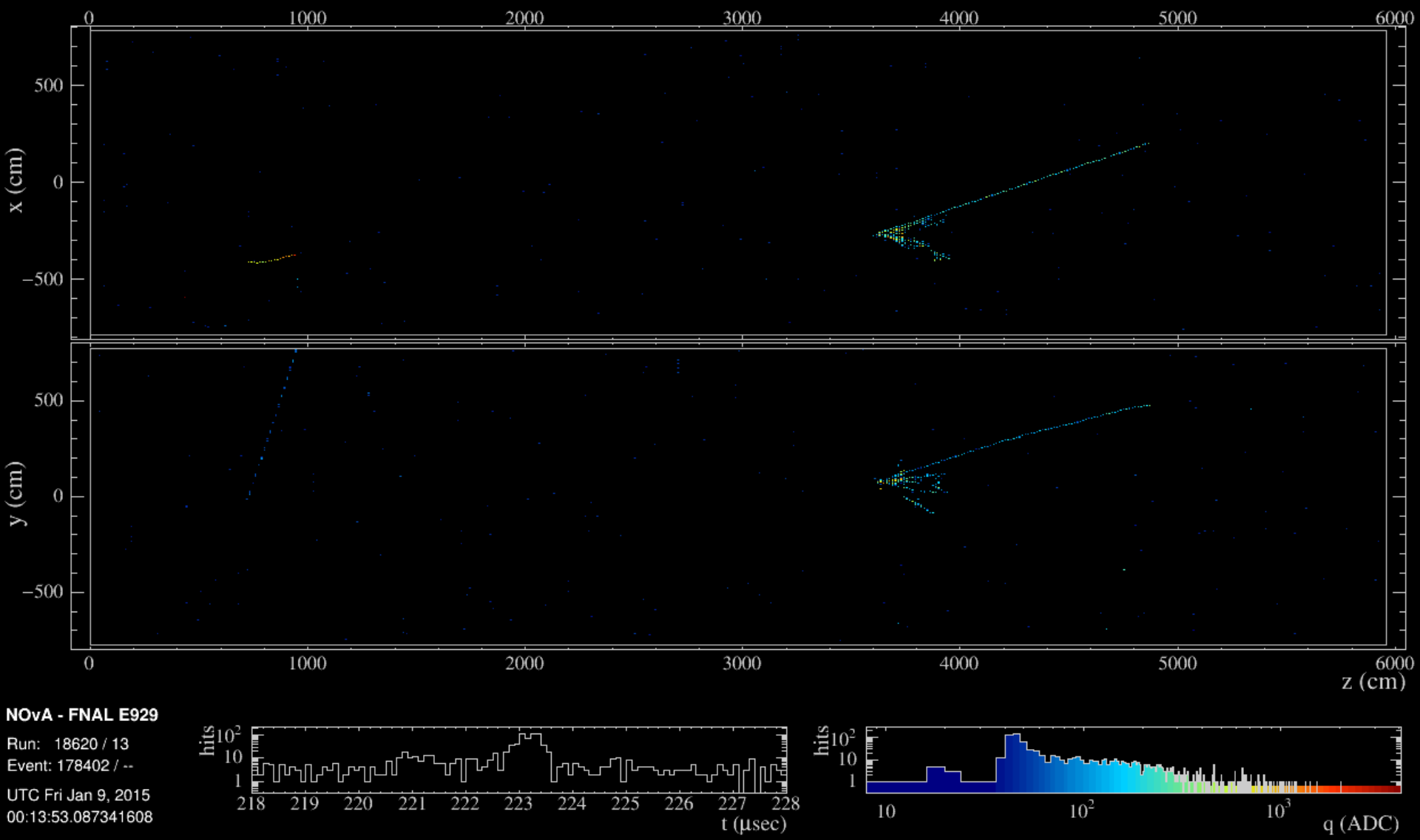

10
MADE
IN
AMERICA
2014



NOvA - FNAL E929

Run: 18620 / 13
Event: 178402 / --

UTC Fri Jan 9, 2015
00:13:53.087341608

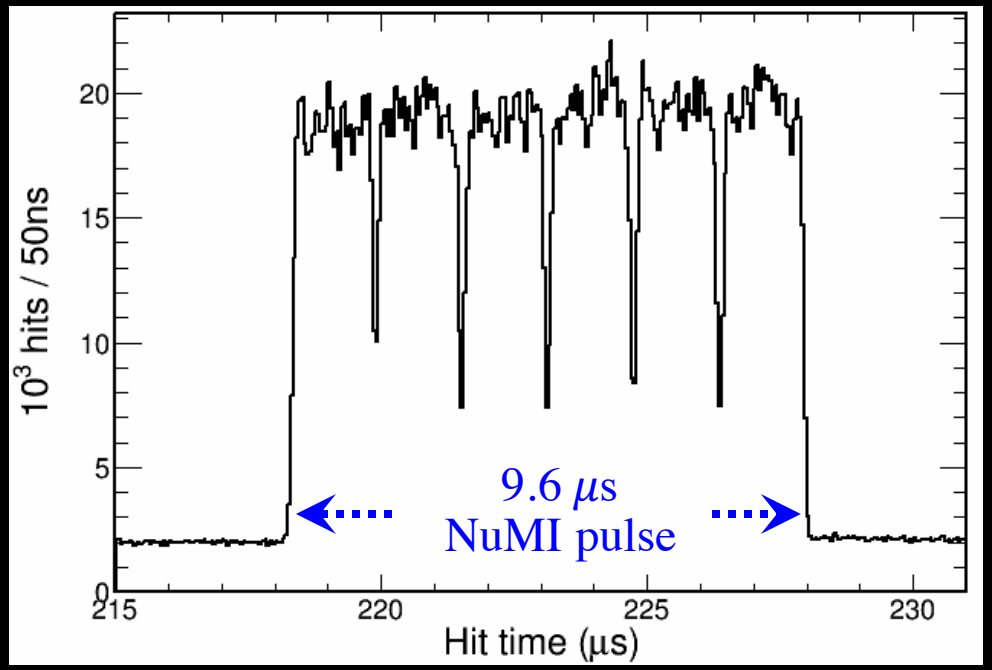


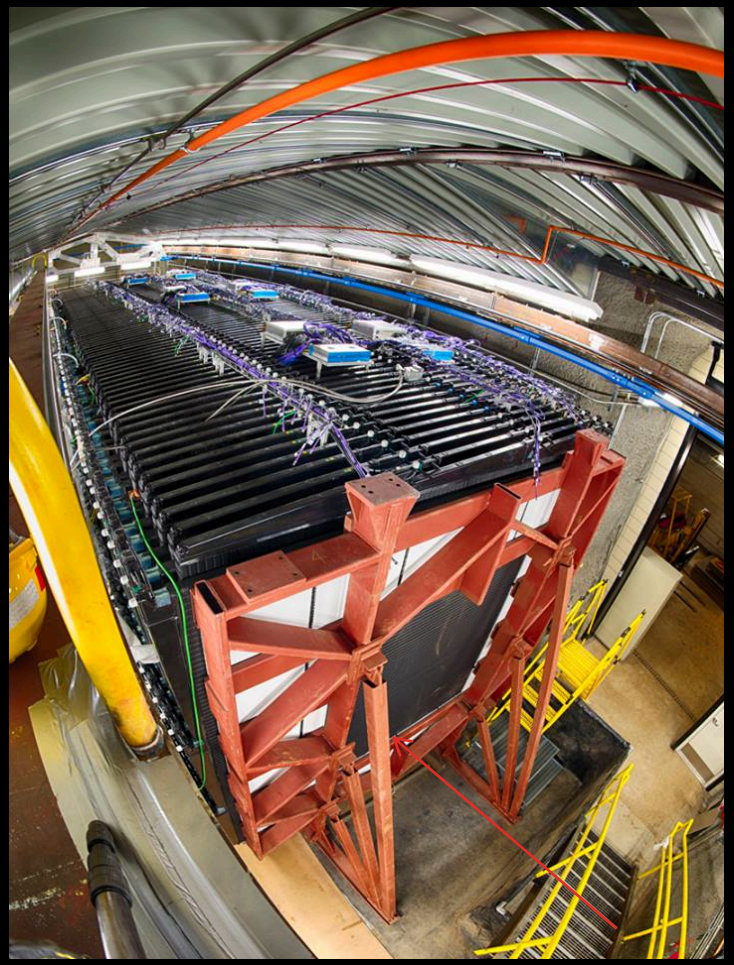
NOvA - FNAL E929

Run: 18620 / 13
Event: 178402 / --

UTC Fri Jan 9, 2015
00:13:53.087341608

NEAR DETECTOR





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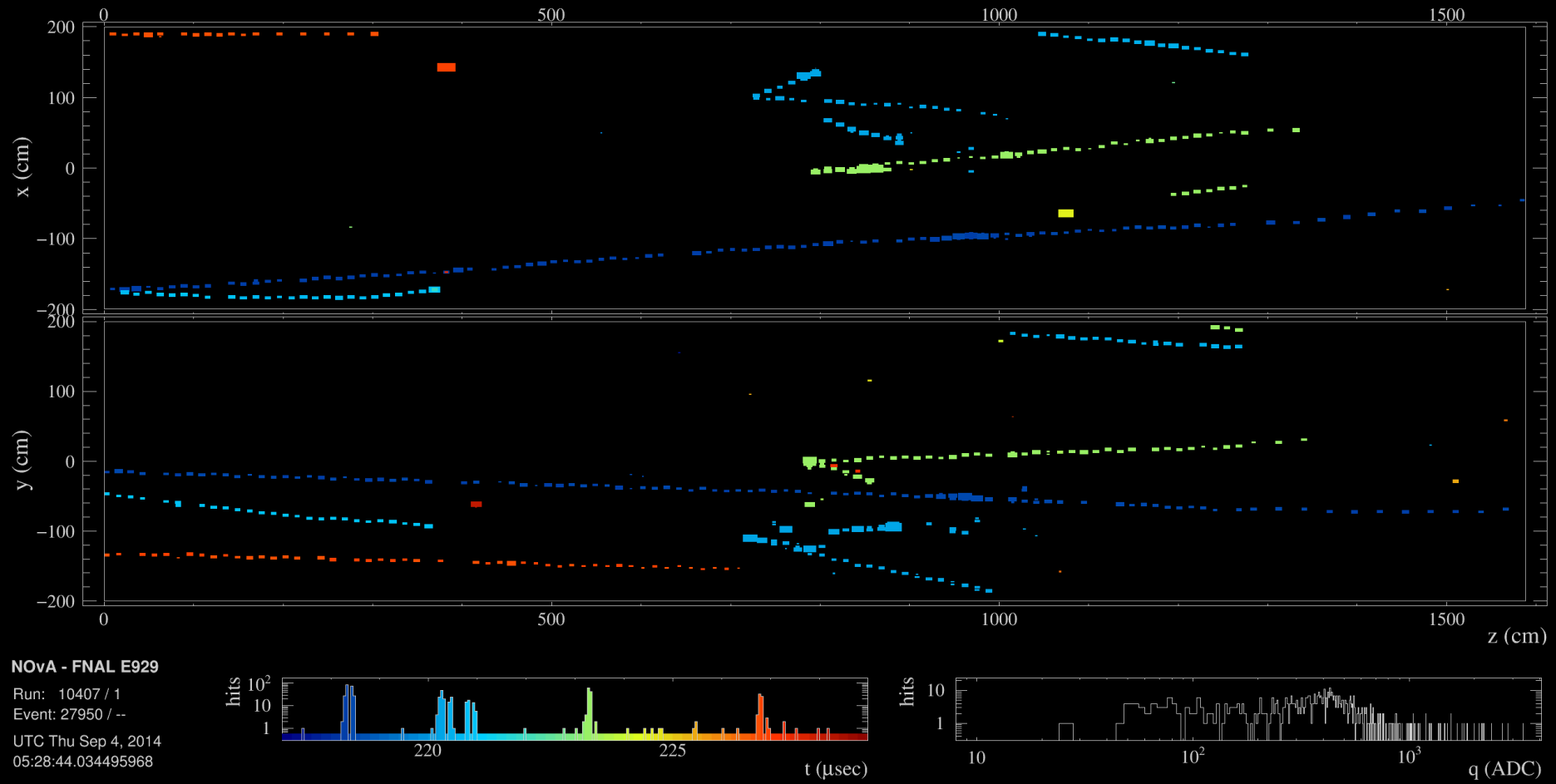
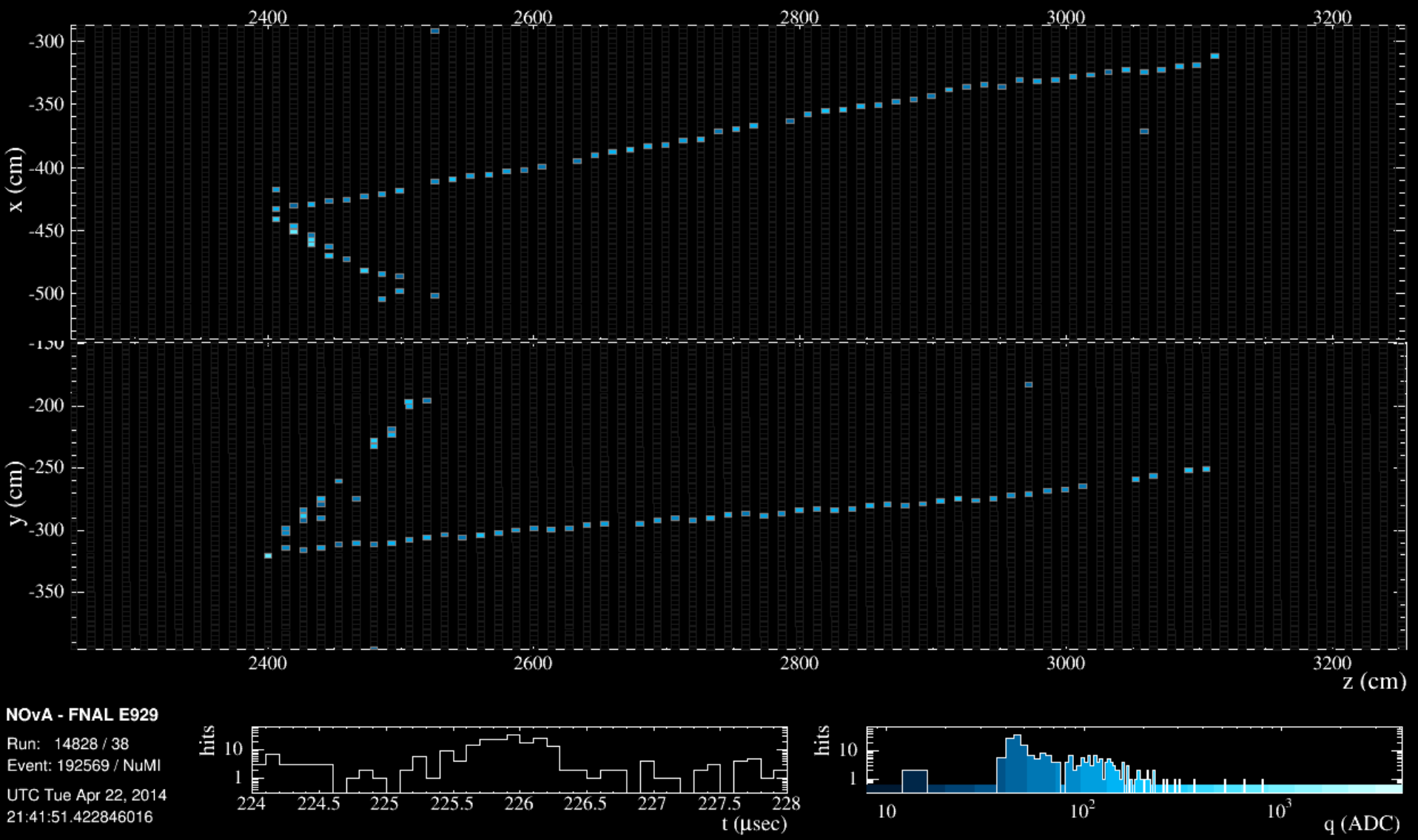


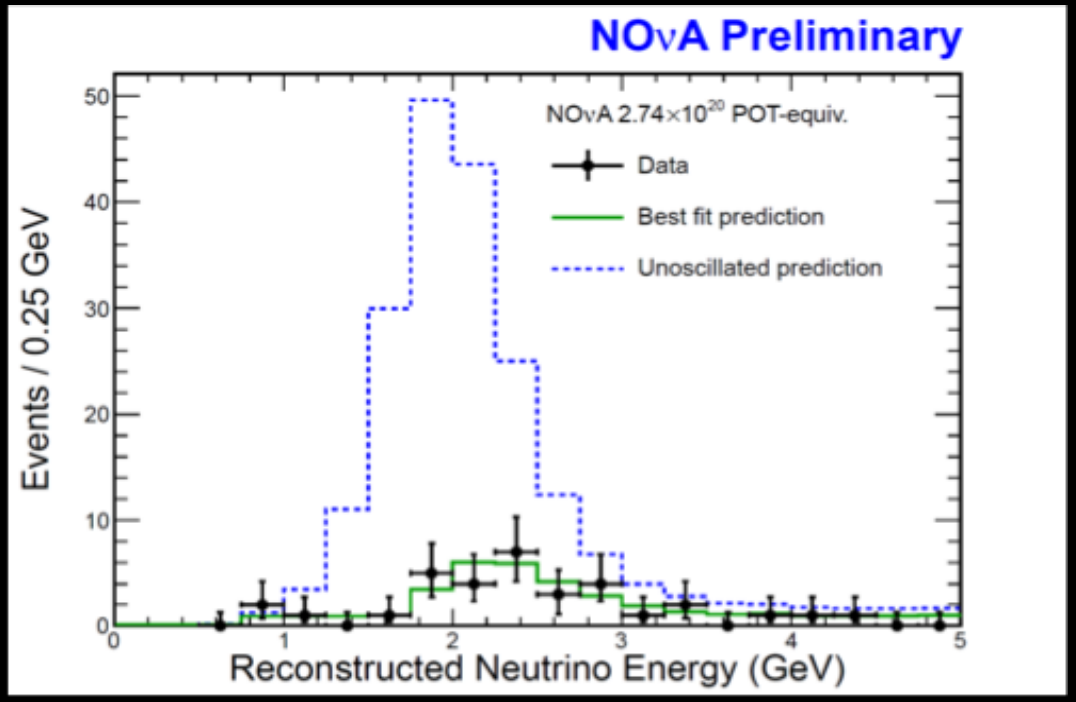
FIRST OSCILLATION ANALYSES

NOvA ν_μ Charged-current candidate

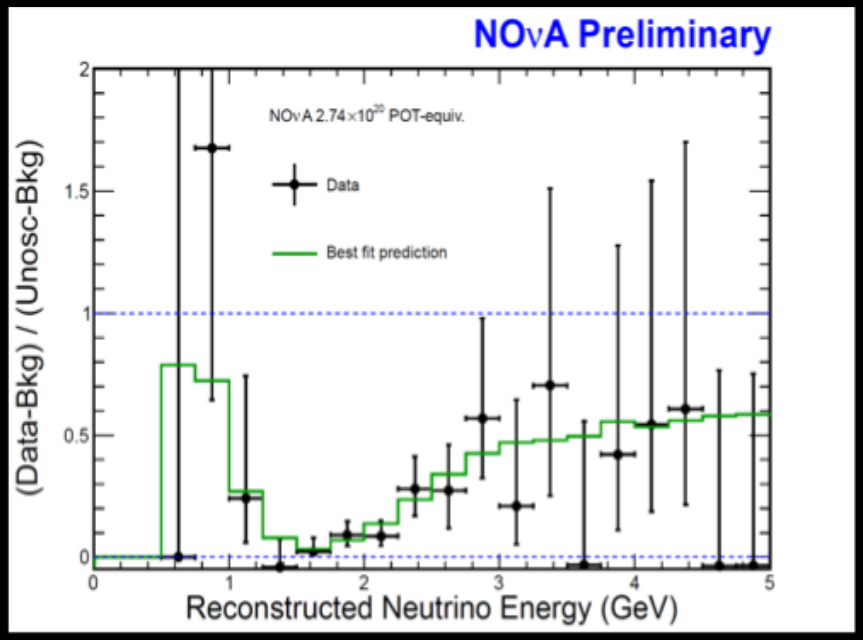


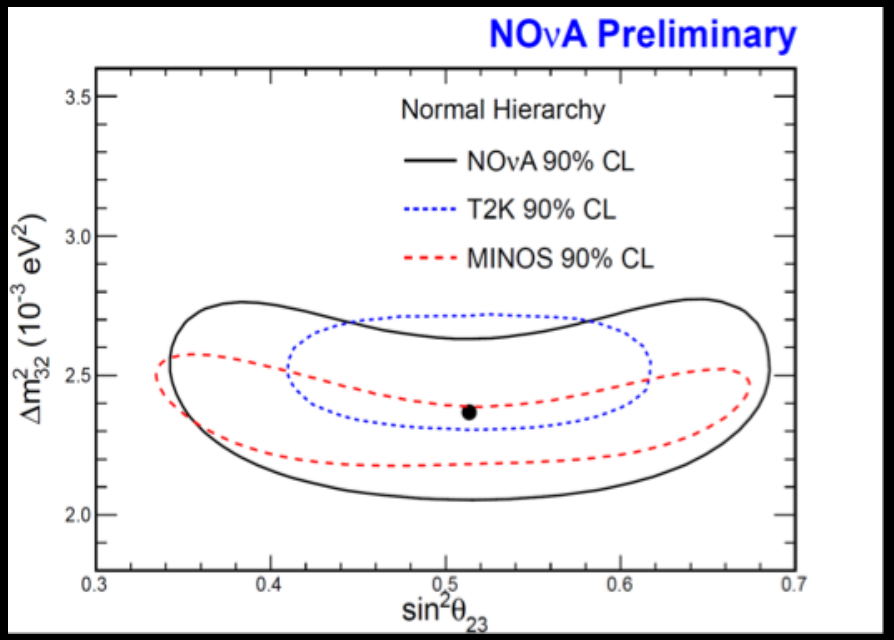
NOVA FAR DETECTOR MUON NEUTRINO SPECTRUM

- Isolate a pure sample of ν_μCC events less than 5GeV
- Containment cuts: require a buffer of no cell activity around the event
- 4-variable kNN used to identify muons
  - track length
  - *dE/dx* along track
  - scattering along track
  - track-only plane fraction
- 201 events expected before oscillations
- 33 events observed

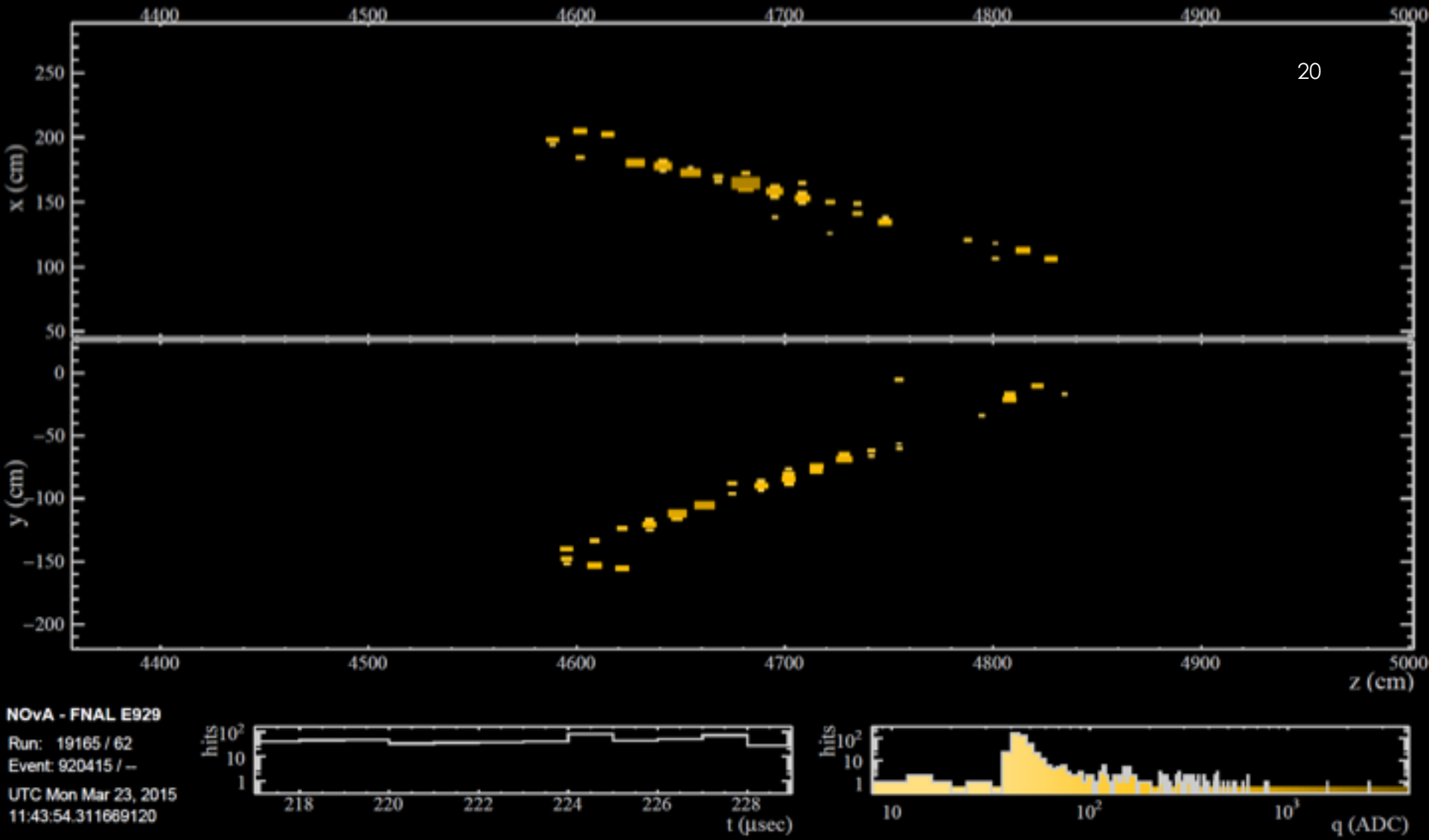


NOVA MUON NEUTRINO DISAPPEARANCE





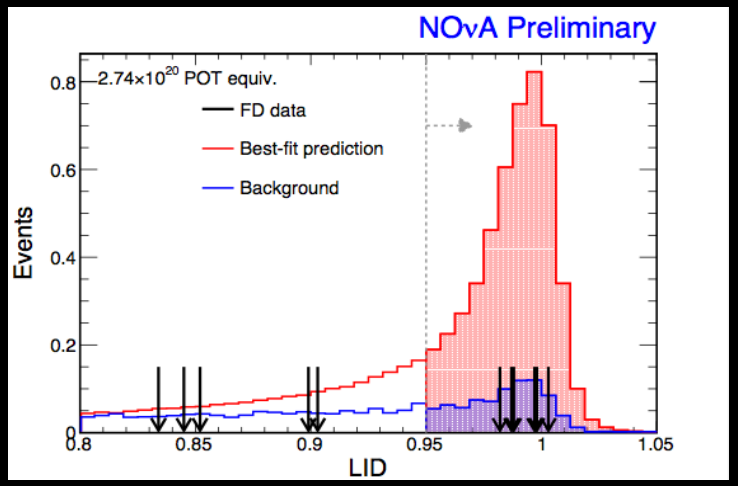
$$\Delta m^2_{32} = +\,2.37^{+0.16}_{-0.15}\ \text{[normal ordering]}$$
$$\Delta m^2_{32} = -\,2.40^{+0.14}_{-0.17}\ \text{[inverted ordering]}$$
$$\sin^2\theta_{23} = 0.51 \pm 0.10$$

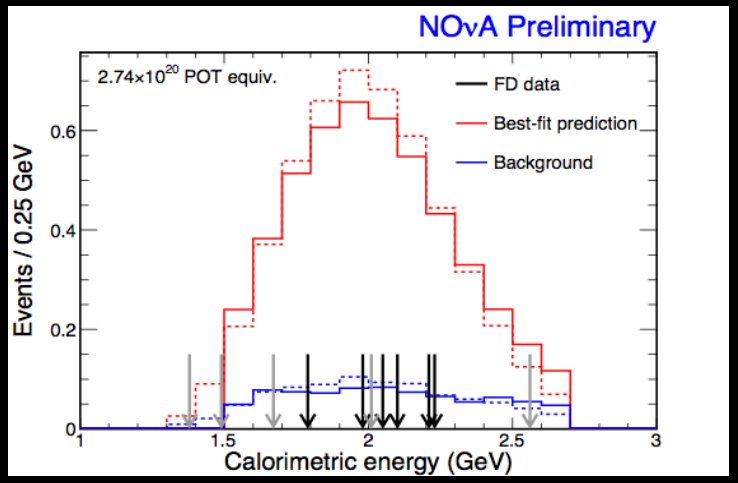


NOvA ν_e Candidate

ELECTRON NEUTRINO APPEARANCE

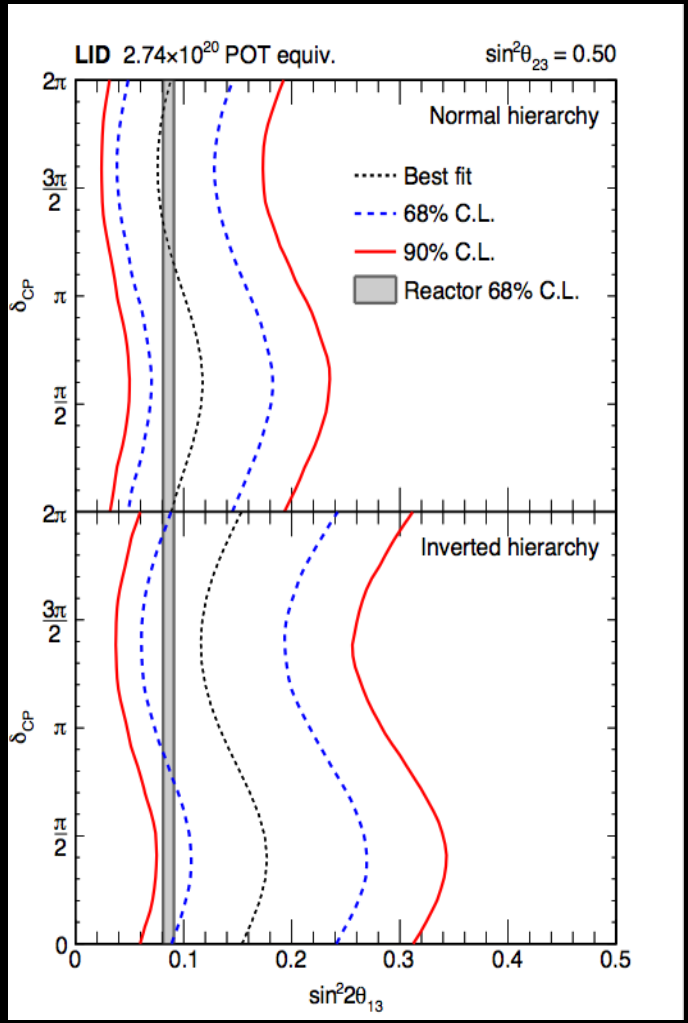
- Events: **6 (LID)** and **11 (LEM)** Expected **background is 1 event** for each. These are **3.3σ** and **5.5σ** significant excesses over background.
- Top plot shows the LID particle IDs for the 11 selected events. The LID&LEM events are to the right of the dashed line. The 5 LEM-only events are shown to the left. Bottom plot shows the energy spectrum of the 11 events. LID are in black, LEM in gray.





ELECTRON NEUTRINO APPEARANCE

- Results show good consistency between NOvA and reactor experiments (gray band) for normal (top) and inverted mass ordering (bottom).
- Agreement is ~1σ better for the normal ordering
- Uncertainties on these initial results are statistics limited.
- Understanding our systematics will become importantfor future analyses.

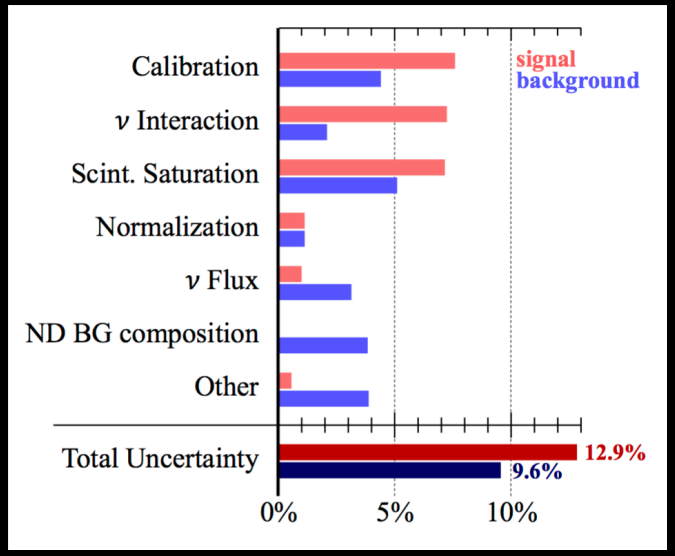


DOMINANT SYSTEMATICS

Uncertainties assessed

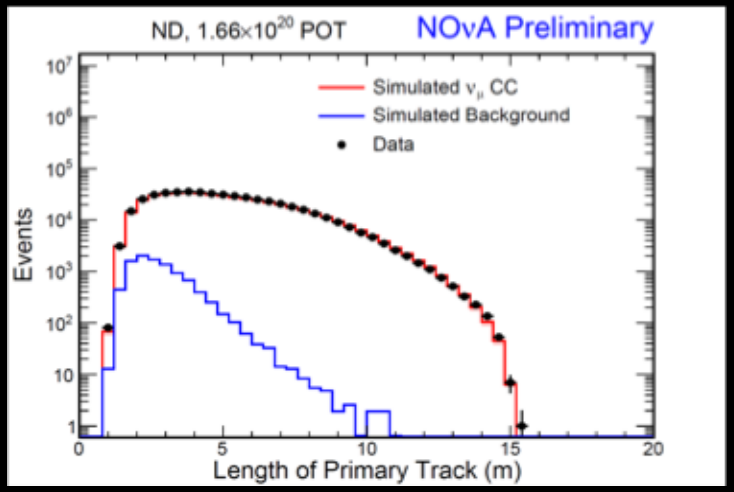
- Hadronic energy *(21%, ~equiv. to 6% on E_ν)*
  - *Dominates for nu_mu appearance measurement*
- Neutrino flux *(NA49 + beam transport model)*
- Neutrino interactions *(GENIE)*
- Absolute, relative normalization *(1%, 2%)*
- NC and ν_τ CC background rate *(100% each)*
- Multiple calibration and light-level systematics *(Hit energy, fiber attenuation, threshold effects)*
- Oscillation parameter uncertainties *(current world knowledge)*

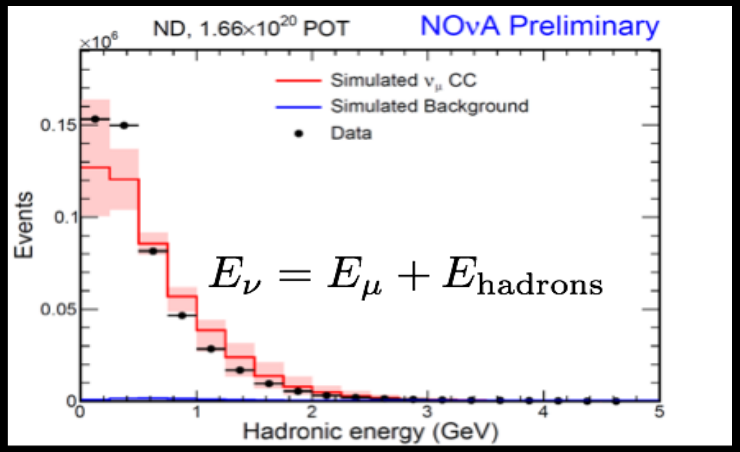
Nue Systematics

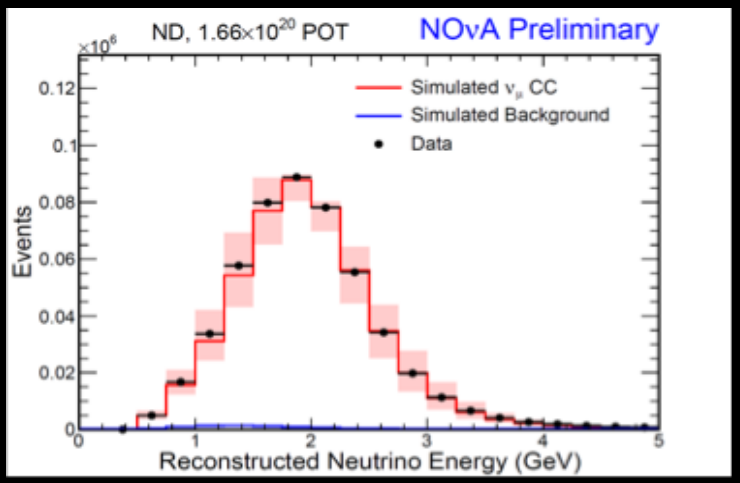


ND/FD Design mitigates many dominate errors related to flux and nu interactions. Not so for XS measurements.

E_{HAD} SYSTEMATIC



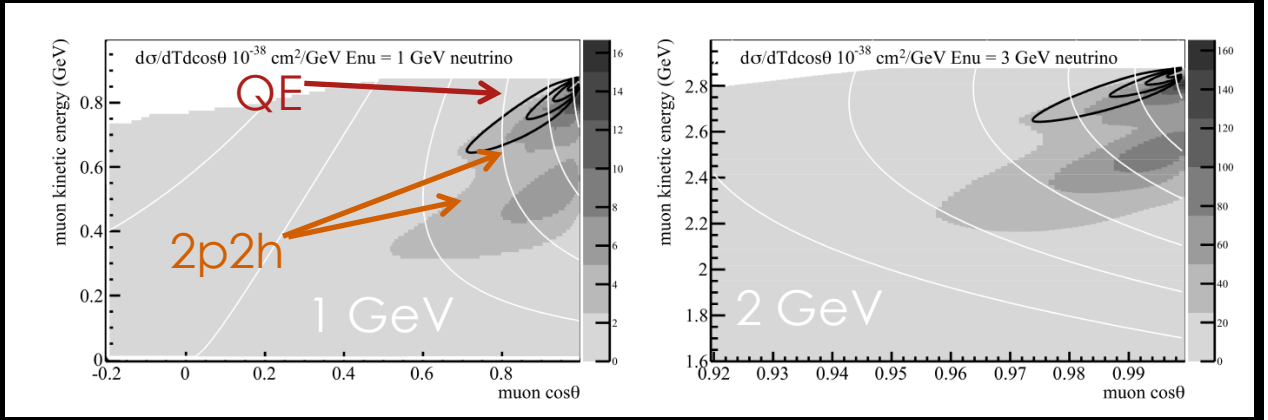




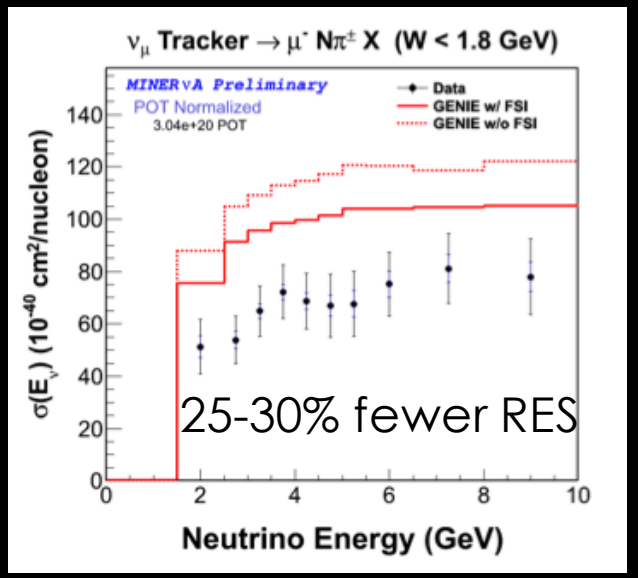
- Muon variables agree well
- Monte Carlo puts 21% more energy into hadron system than seen in data
- Recalibrated the hadronic energy scale to match peaks of the data and MC.
  Correction taken as a systematic on the absolute energy scale
  (6% overall neutrino energy scale uncertainty).

E_{HAD} SYSTEMATIC

- First analyses use conservative systematics
- Need to understand the the discrepancy for future analyses
  - Calibration, detector response, Neutrino interaction modeling, flux modeling
- External data hints at possible contributions
  - Missing 2p2h in Genie
  - MINERvA sees fewer 1pi events than Genie



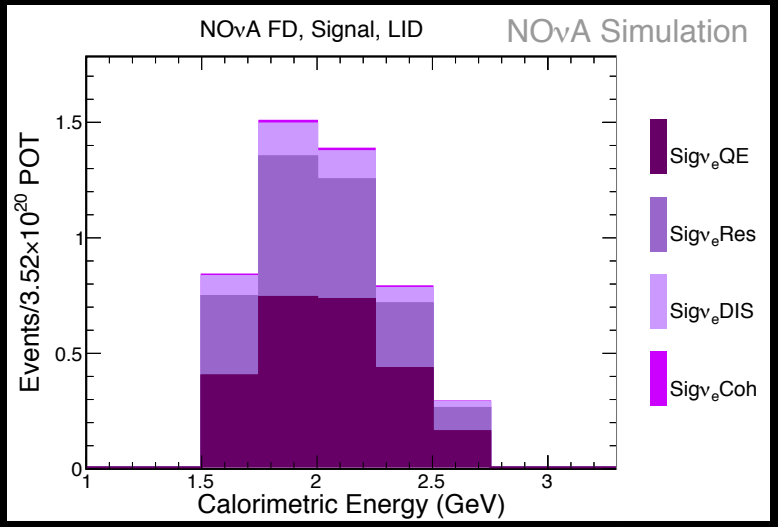
R. Gran et al., PRD 88:113007 (2013)



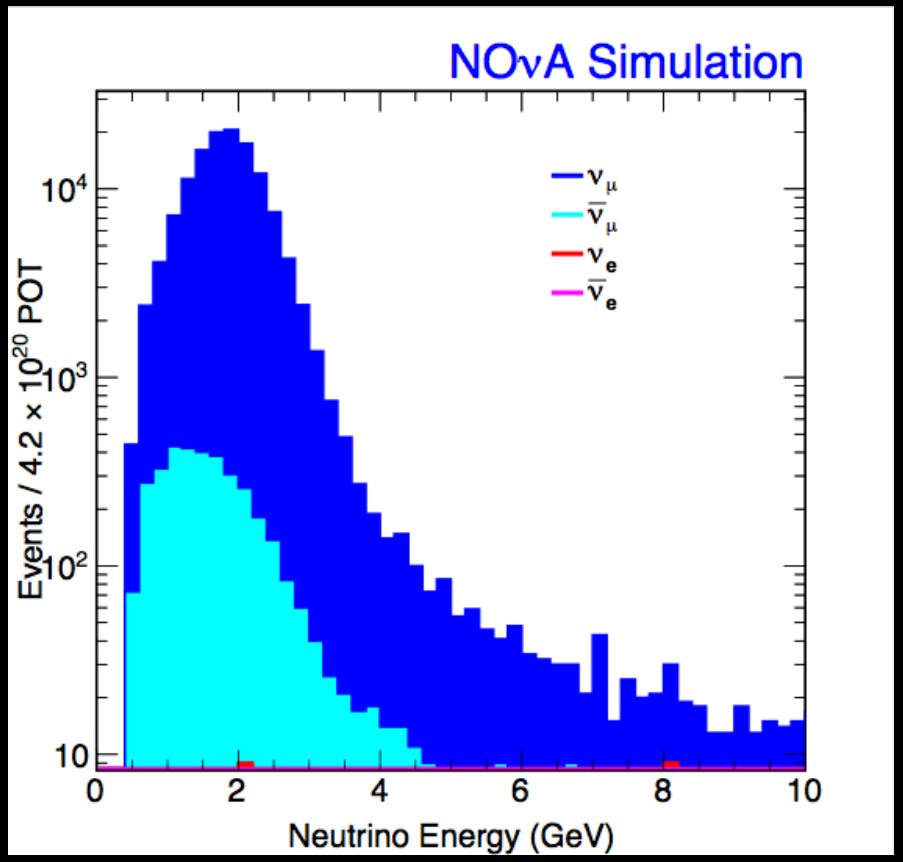
C. McGivern, FNAL JTEPS, June 26, 2015
B. Eberly, arXiv:1406.6415

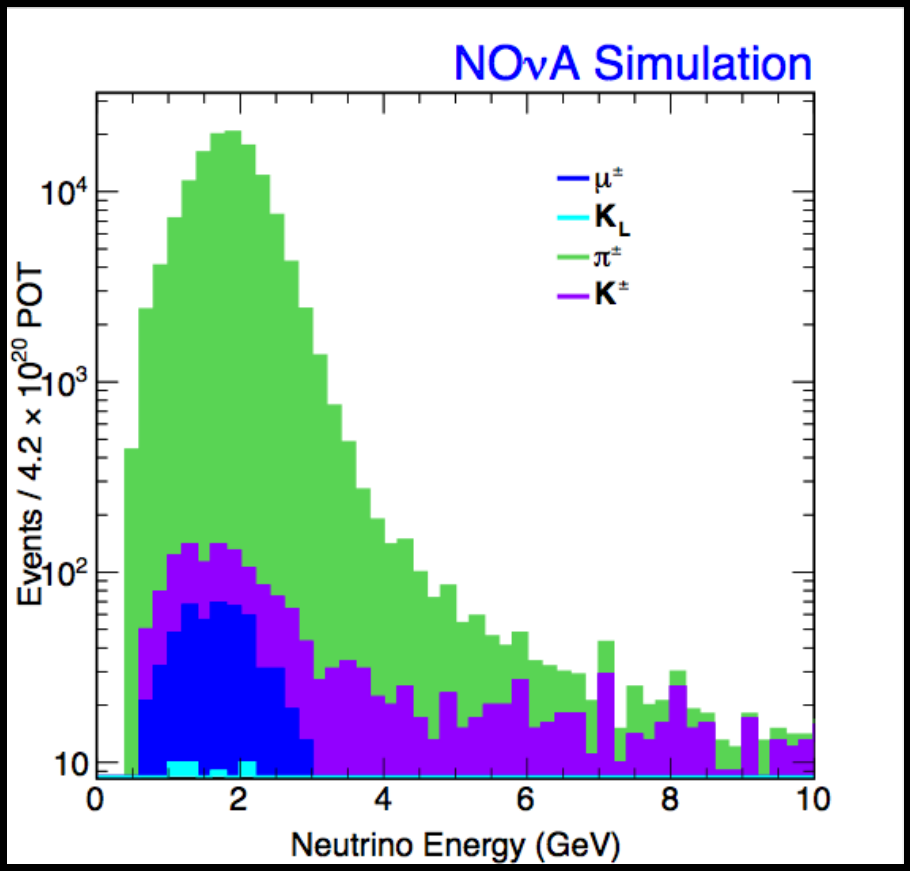
NEUTRINO INTERACTION MODELING

- For first oscillation analyses signal selection efficiency not benchmarked in ND
- Selection efficiency varies by process type
  - QE selection efficiency is 2x RES selection efficiency, which is 2x DIS selection efficiency
- Uncertainties in relative components implies uncertainty in signal selection efficiency
- NOvA will measure the Interaction processes directly with near detector.

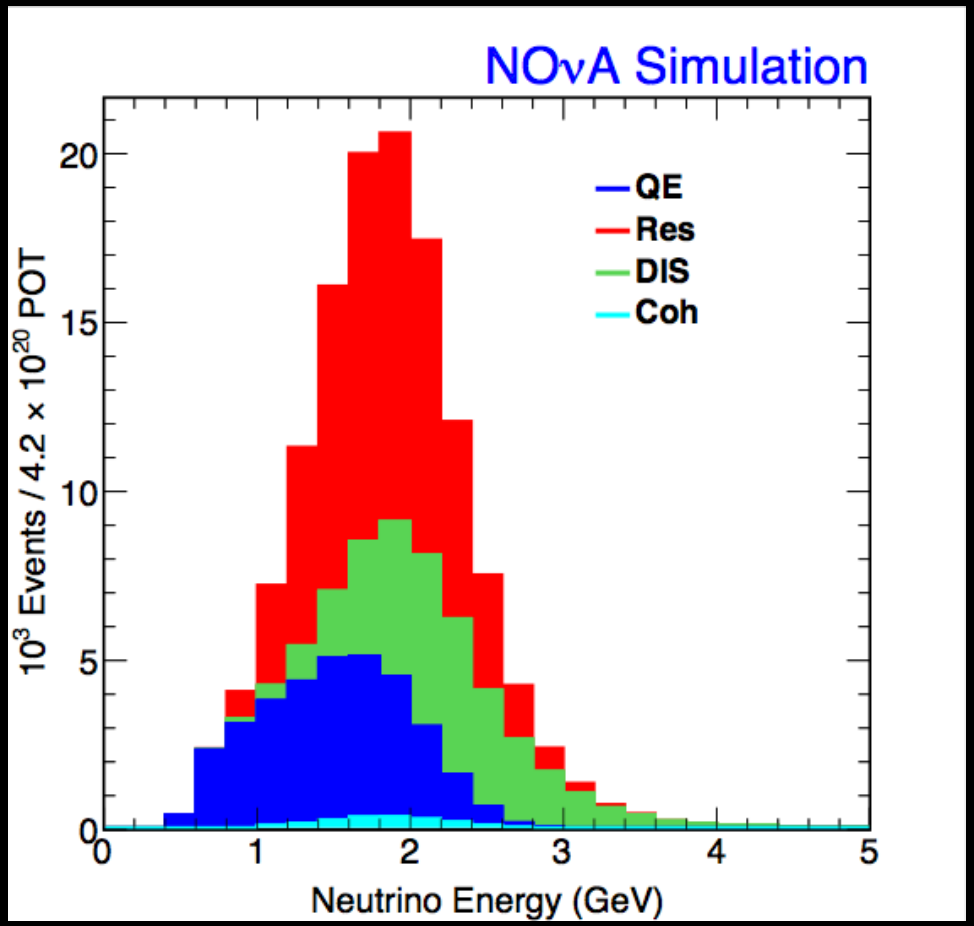


ν_μ CC INTERACTIONS



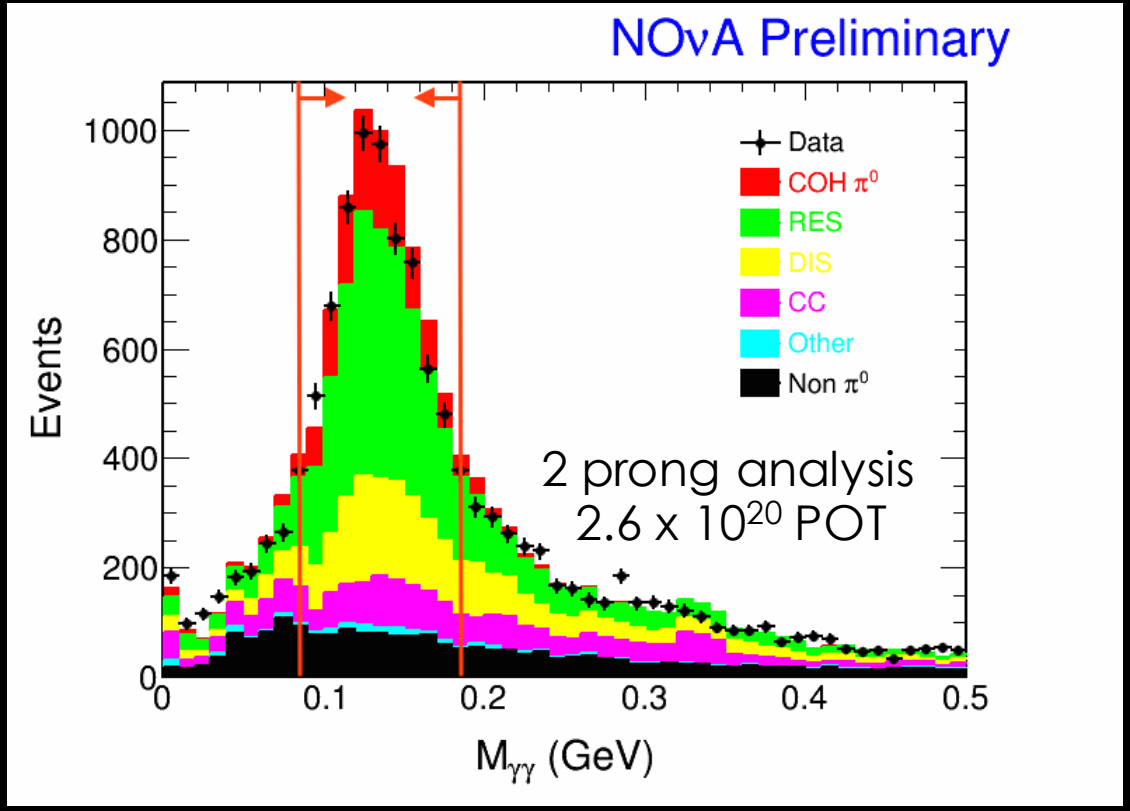


ν_μ CC INTERACTIONS



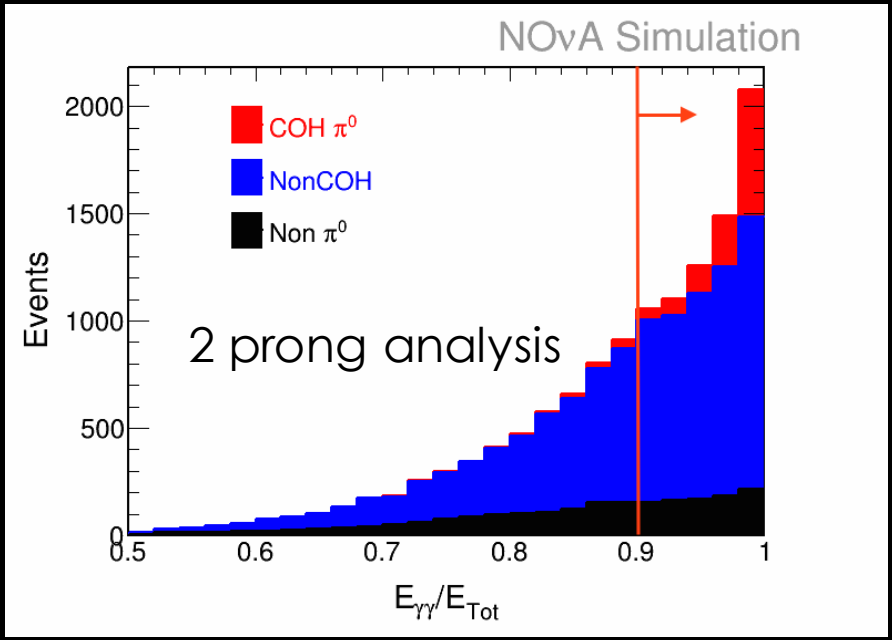
- NOvA has access to all interction types with a narrow-band beam.

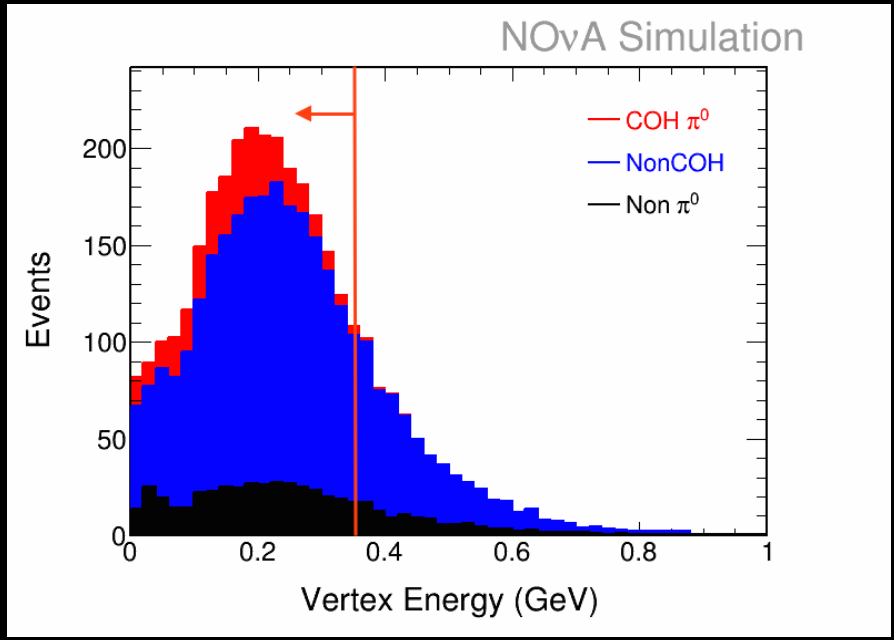
NC COHERENT π^0



We see plenty of π^0s (used as calibration cross check). We want to separate COH from non-COH

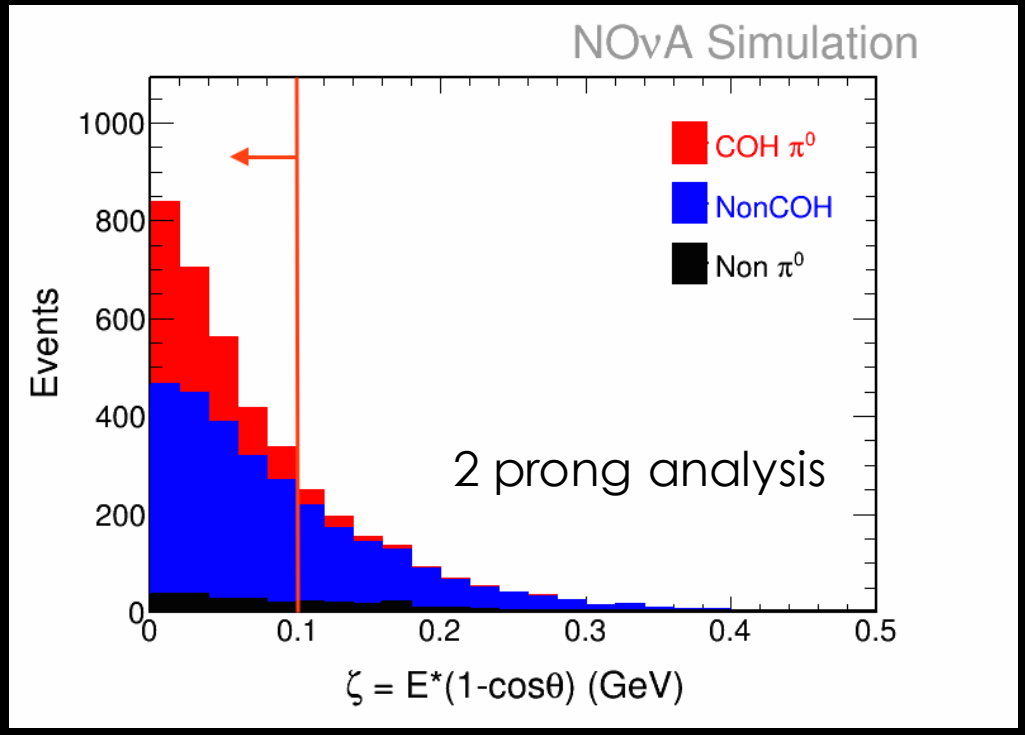
NC COHERENT π^0





COH interactions have only a single π^0 in the final state. All energy should be in the shower and associated with a reconstructed vertex.

NC COHERENT π^0



Require event to have a very forward-going shower in the final state.

- As with many ND physics measurements, background contraints are critical.
- Control sample dominated by background will be used to tune background normalization and shape to *data*.
- Single prong analysis also being investigated.
- Expect results this winter.

OTHER MEASUREMENTS

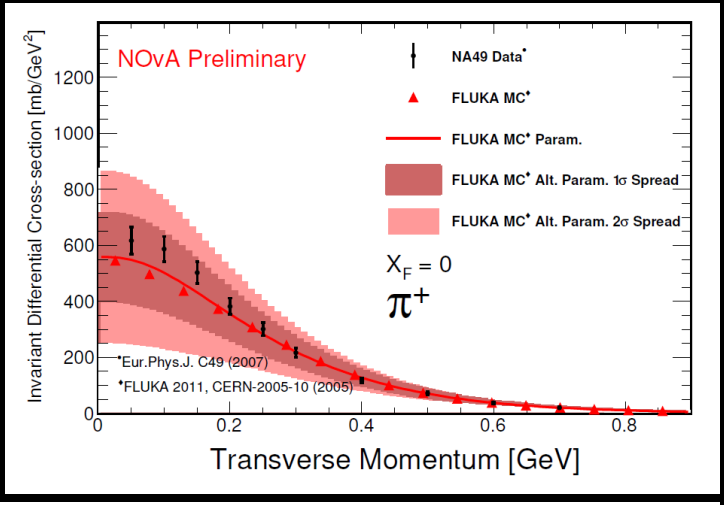
- Many other NOvA neutrino interaction studies are underway including:
  - Electron Neutrino Charged-Current Inclusive Cross Section (Talk by Xuebing Bu, 11/17)
  - ν_μ CC QE and CC inclusive cross section measurements
  - Charged pion production.
  - Plan to study both neutrino and anti-neutrino enhanced datasets.

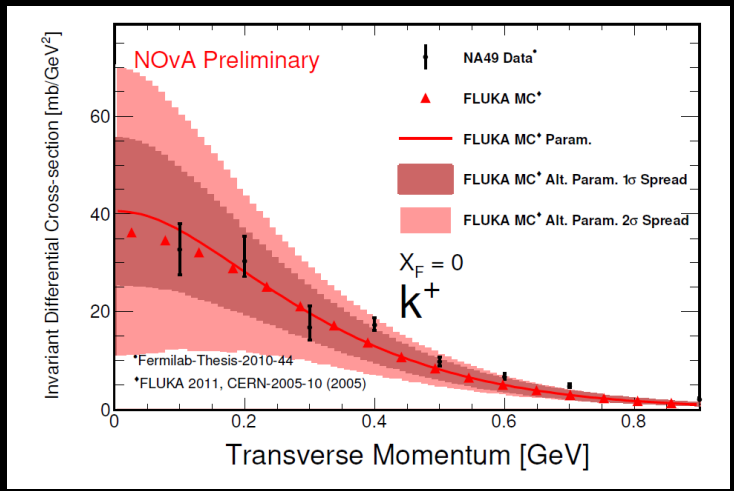
FLUX UNCERTAINTIES

- Full beam geometry simulated with Fluka(11.2c.0) and Flugg(2009_3)
- Hadron production errors come from comparison of NA49 thin target data with Simulation
- Focusing and beam line errors are also include

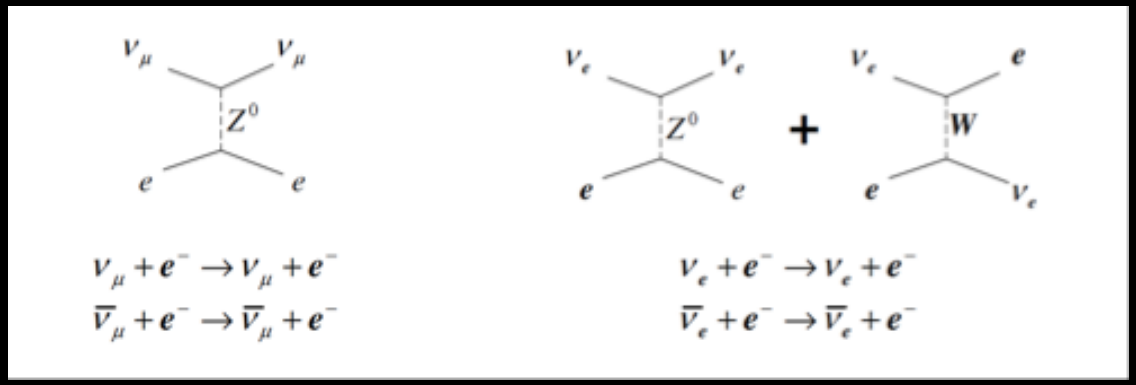
Improvements:

- External MIPP hadron production data promise to reduce normalization. (See inclusive beam nu_e talk for a first implementation.)



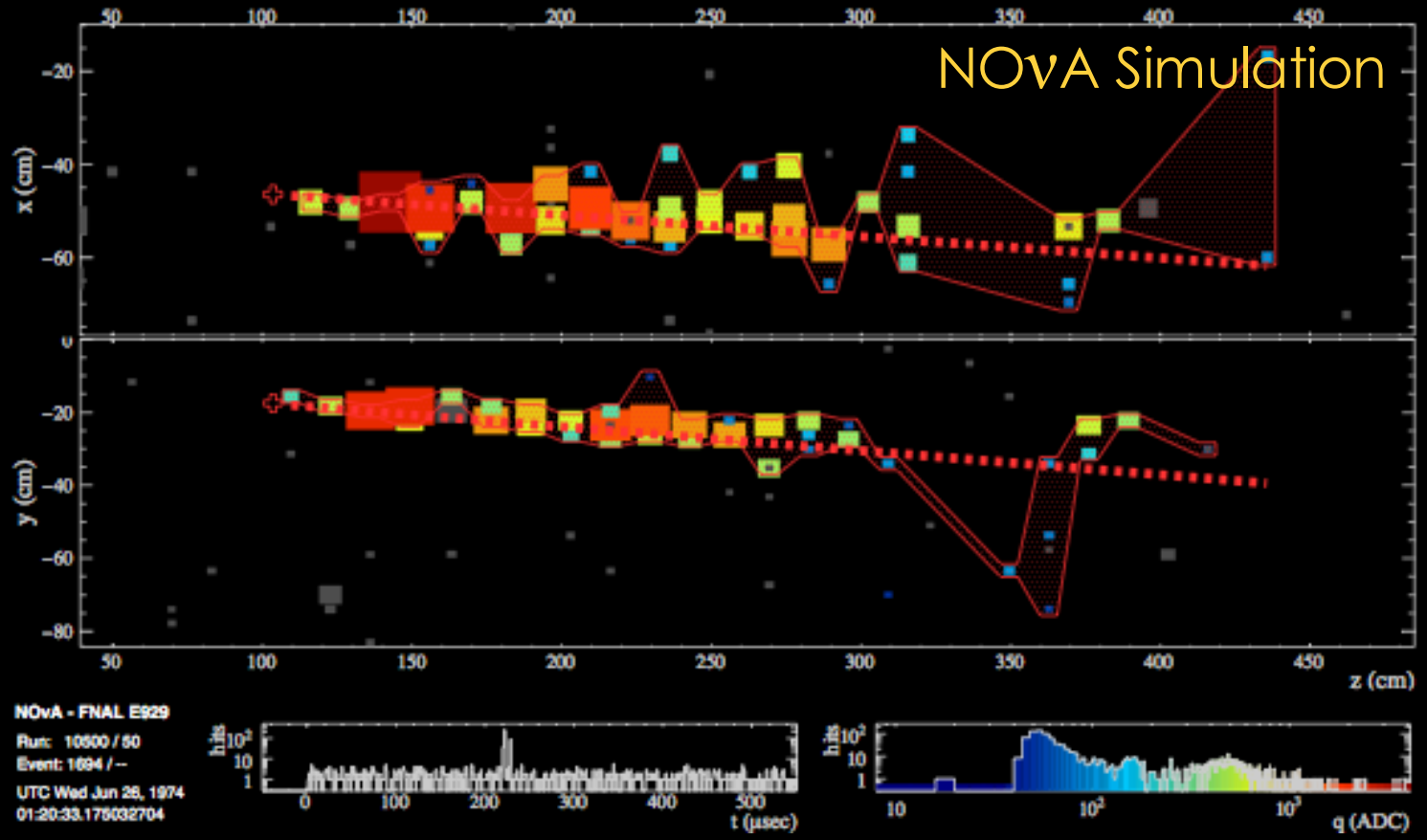


ν + ELECTRON INTERACTIONS

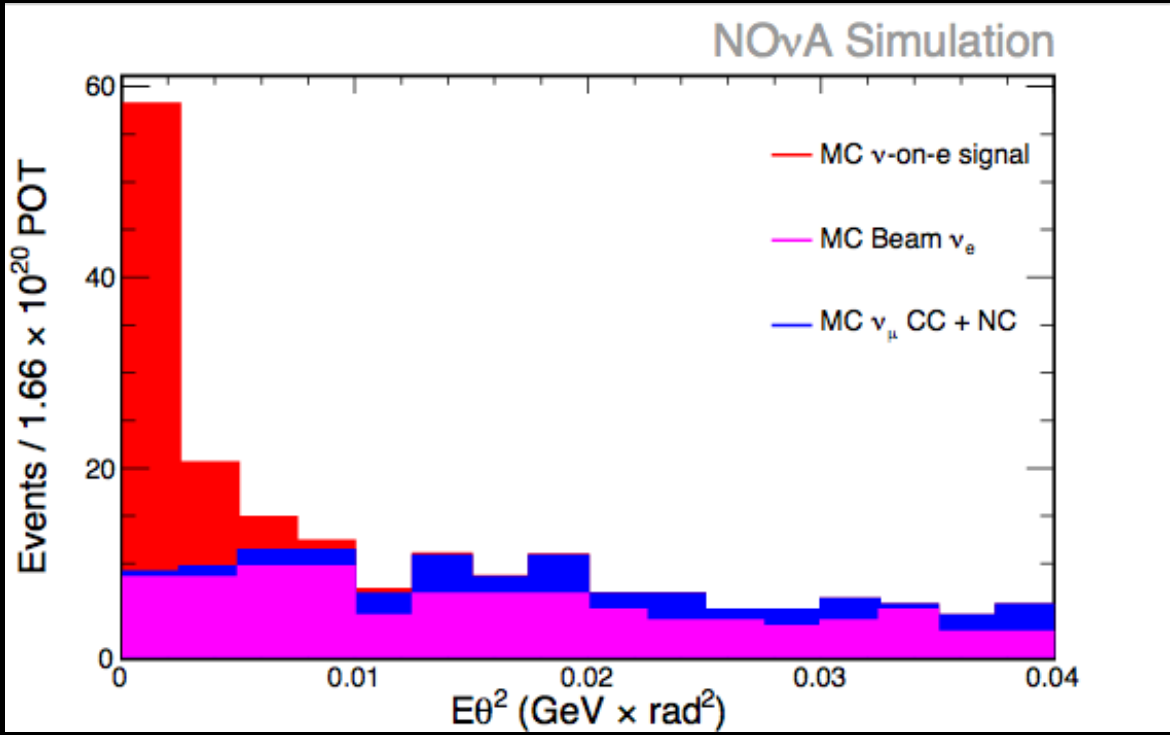


- Purely leptonic process, cross section is calculable
- Very forward-going electron shower signal topology.
- Can be used to constrain ν flux
- Challenge: cross section is ~10^{-4} of ν+A , need excellent background rejection

ν + ELECTRON INTERACTIONS



ν + ELECTRON INTERACTIONS



- After containment, single shower, energy and PID cuts the ν + electron signal is evidenced at forward angles.

CONCLUSION

NOvA systematics are dominated by

- Hadronic energy scale uncertainties
- Neutrino interactions uncertainties *(GENIE)*
- Neutrino flux *(NA49 + beam transport model)*

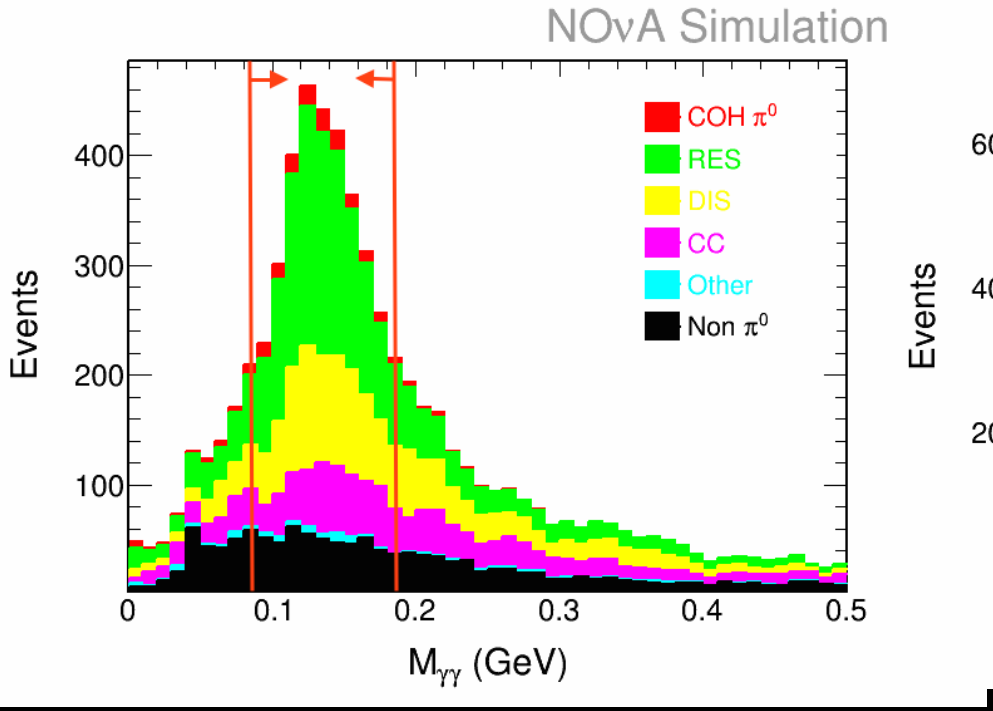
Studies are underway on multiple front to improve upon these limitations as statistics increase.

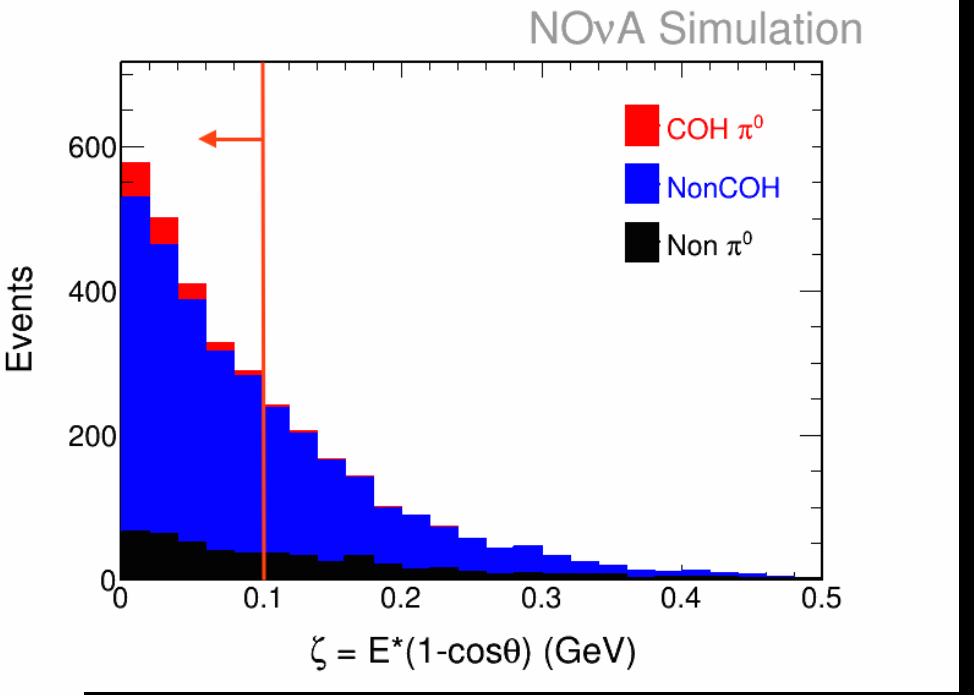
We have an active ND physics program studying a broad range of interaction channels.

On behalf of the NOvA collaboration, **thank you** and please watch for updates.

www-nova.fnal.gov

NC COHERENT π^0 PRODUCTION

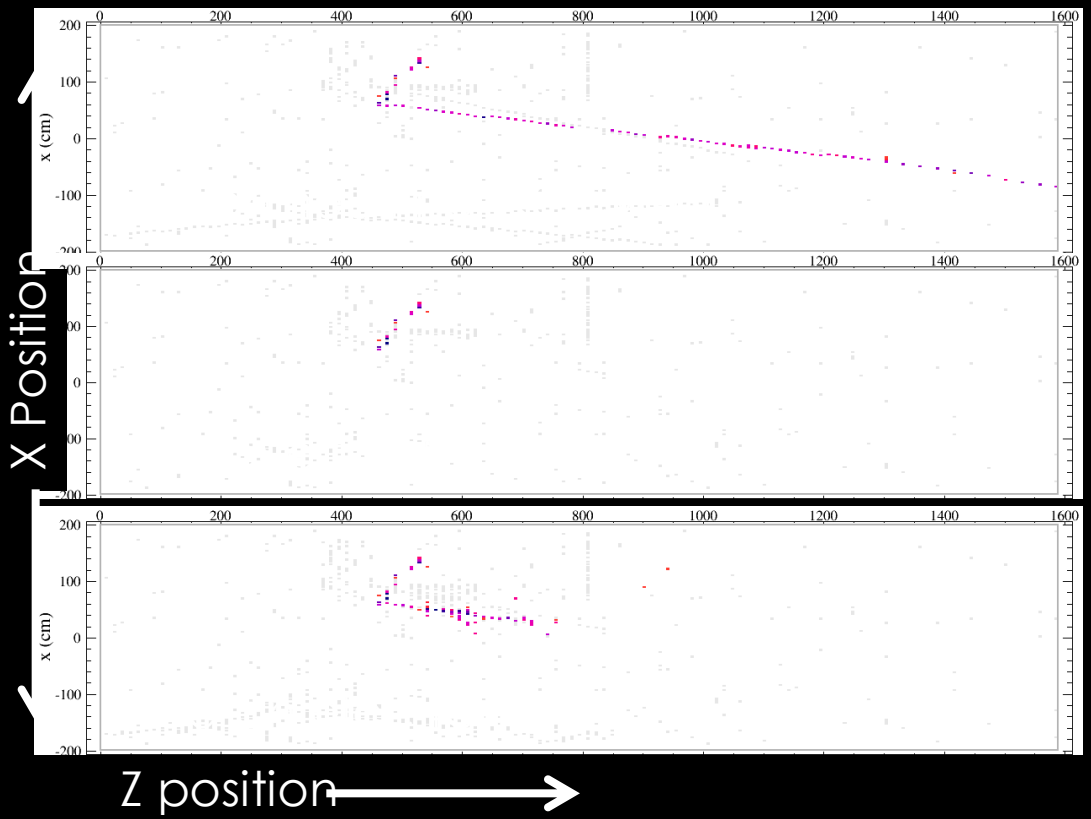




We see plenty of π^0s (used as calibration cross check), now want to separate COH from nonCOH

MUON REMOVAL—ELECTRON ADDITION

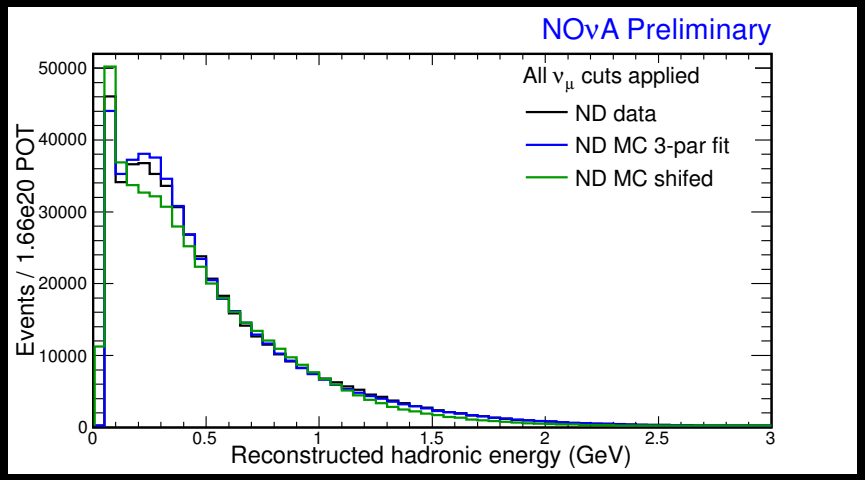
K. Sachdev, Ph.D. Thesis, U. Minn (2015)

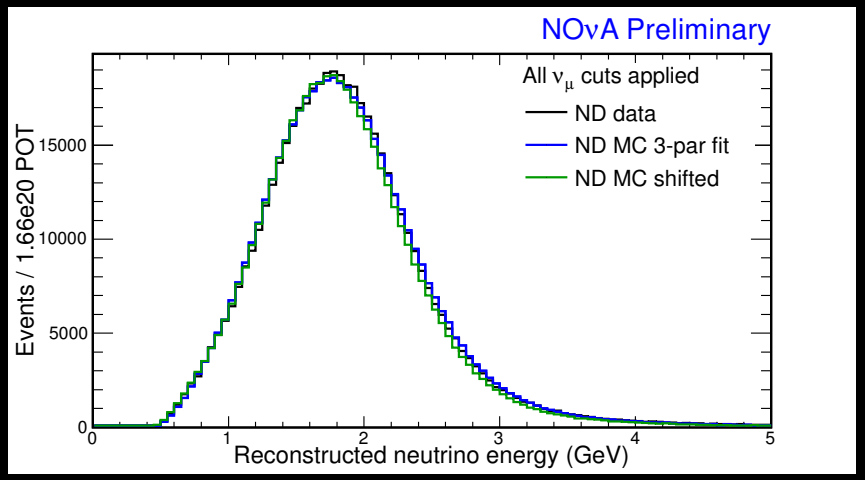


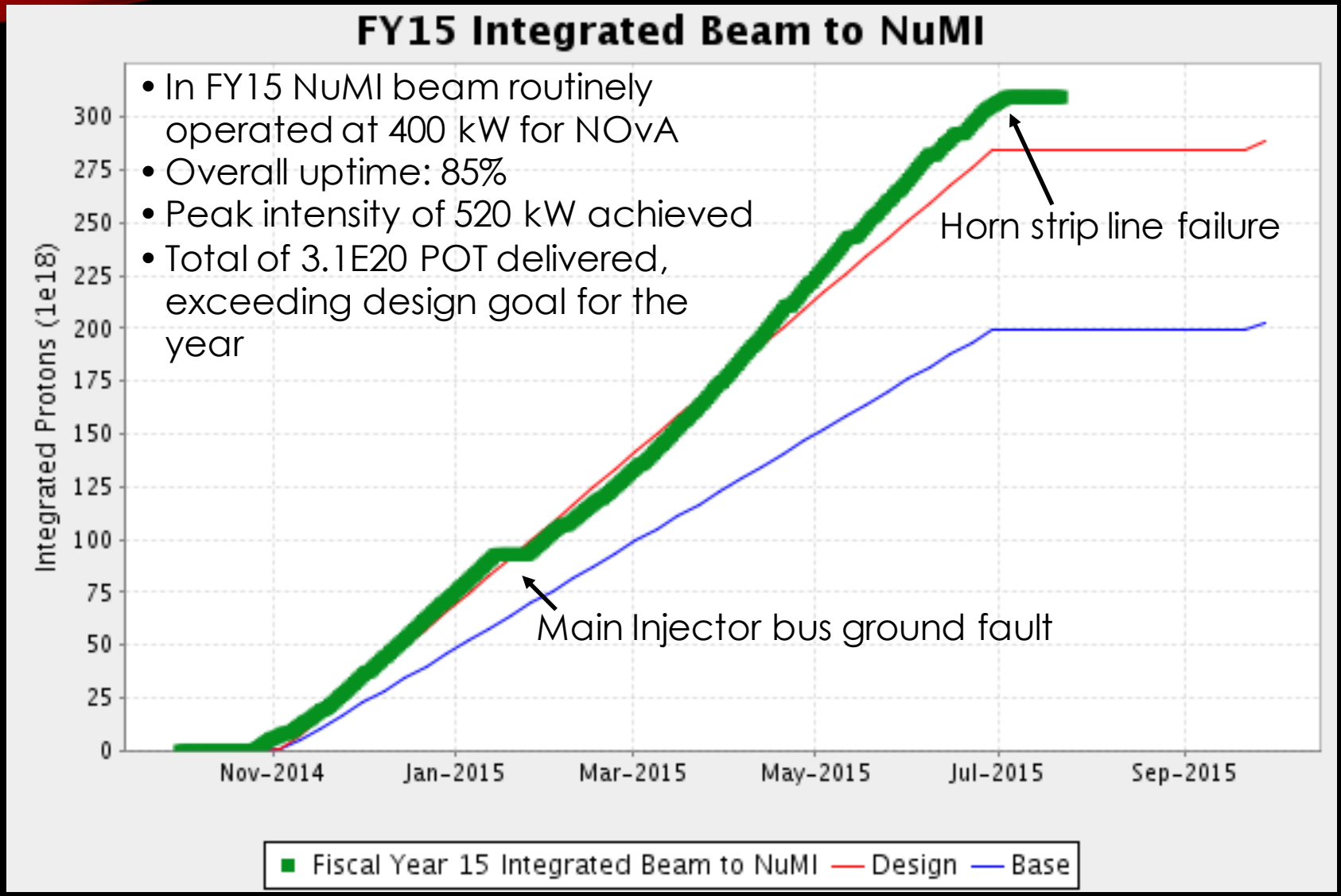
- We can study our signal efficiency in hybrid ND events
  - Remove the hits associated with a muon track in selected numu CC event
  - Insert a simulated electron with the same kinematics as the removed muon
  - Reconstruct the hybrid event
- Comparing distributions between data and MC will help constrain the selection efficiency of electron neutrino events
- Understanding ND/FD acceptance effects still ongoing

HADRONIC ENERGY SYSTEMATIC

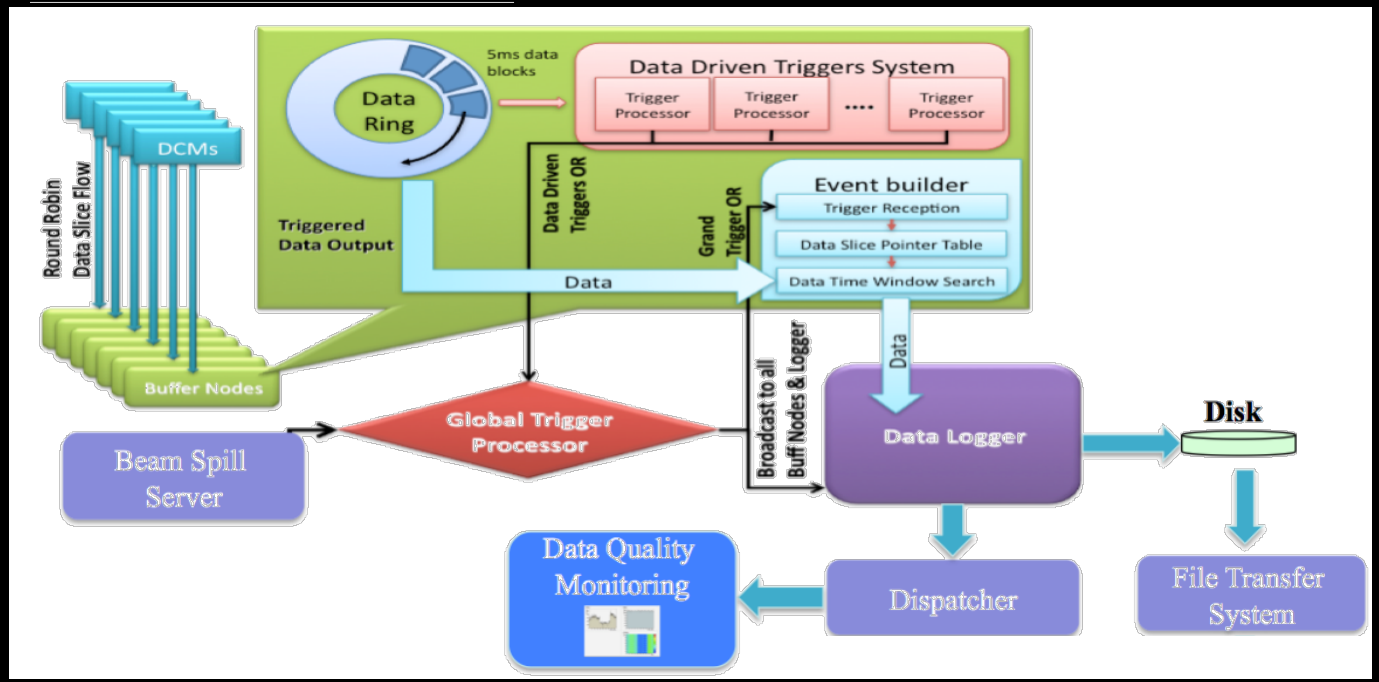
- Additionally a detector-to-detector relative energy systematic
- Assume different models to correct E_{had}
  - Allow energy scale and normalization of each process type (QE/RES/DIS) to vary
  - 2% difference in hadronic energy scale between two correction methods used as systematic



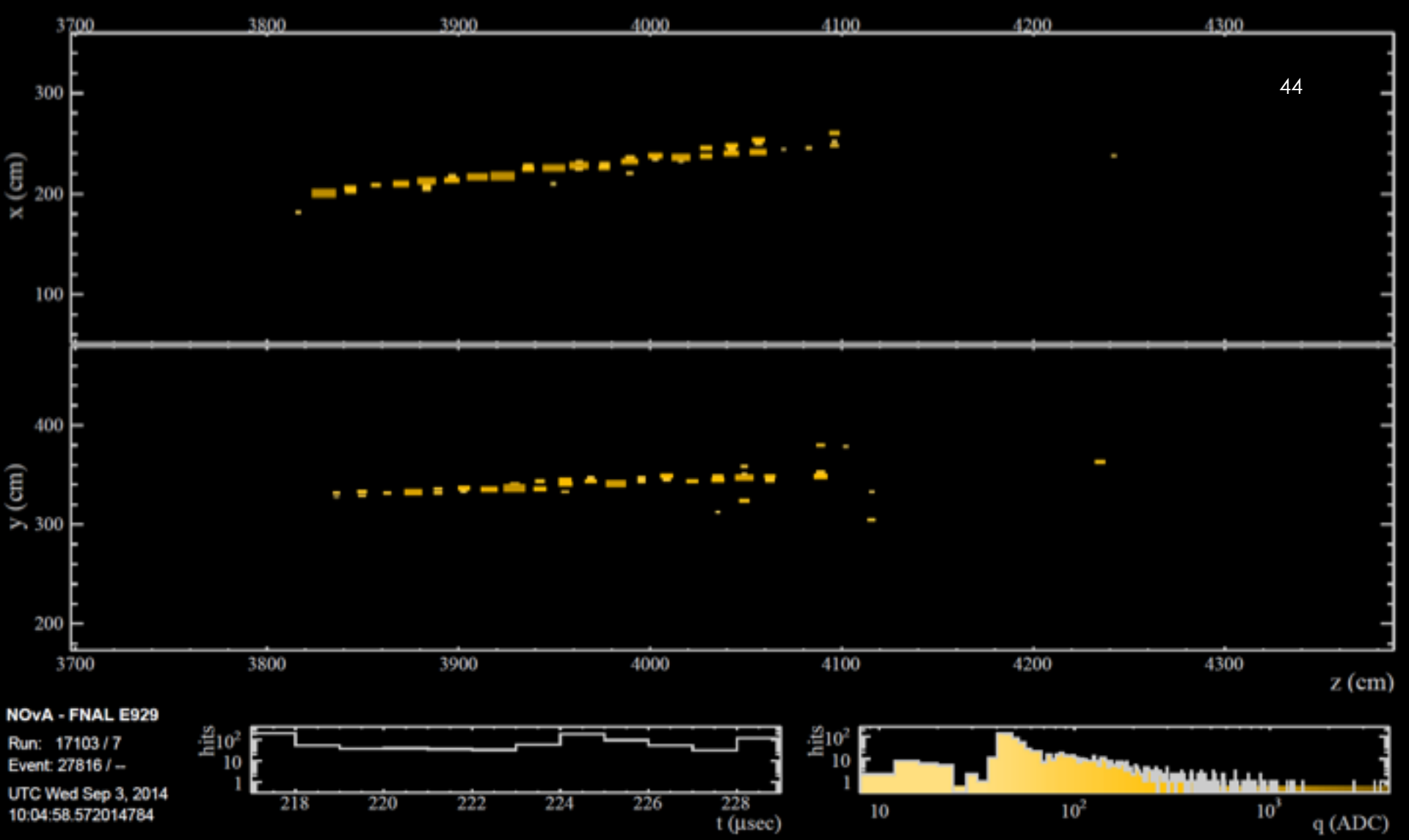



FY15 Integrated Beam to NuMI
• In FY15 NuMI beam routinely operated at 400 kW for NOvA
• Overall uptime: 85%
• Peak intensity of 520 kW achieved
• Total of 3.1E20 POT delivered, exceeding design goal for the year
Horn strip line failure
Main Injector bus ground fault
Integrated Protons (1e18)
300
275
250
225
200
175
150
125
100
75
50
25
0
Nov-2014
Jan-2015
Mar-2015
May-2015
Jul-2015
Sep-2015
Fiscal Year 15 Integrated Beam to NuMI
Design
Base

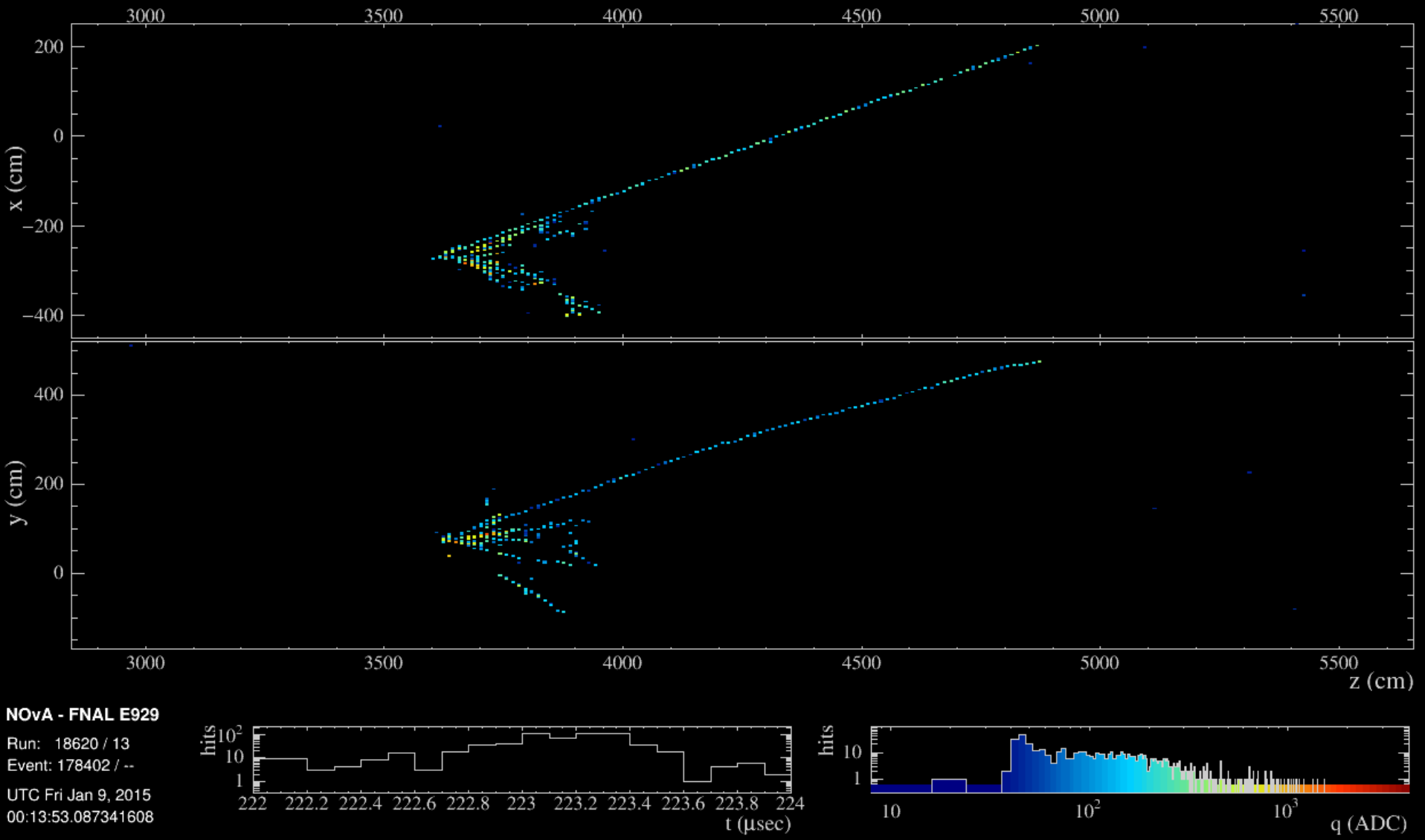
DATA ACQUISITION



- FEBs pass the data to a processing farm.
- Data buffered for at least 20 seconds.
- Beam spill timing signals initiates data storage.
- Synchronized to external timing system to GPS



NOvA ν_e Candidate


3000
3500
4000
4500
5000
5500
200
0
−200
−400
x (cm)
400
200
0
y (cm)
z (cm)
NOvA - FNAL E929
Run: 18620 / 13
Event: 178402 / --
UTC Fri Jan 9, 2015
00:13:53.087341608
hits
10^2
10
1
222
222.2
222.4
222.6
222.8
223
223.2
223.4
223.6
223.8
224
t (μsec)
hits
10
1
10
10^2
10^3
q (ADC)