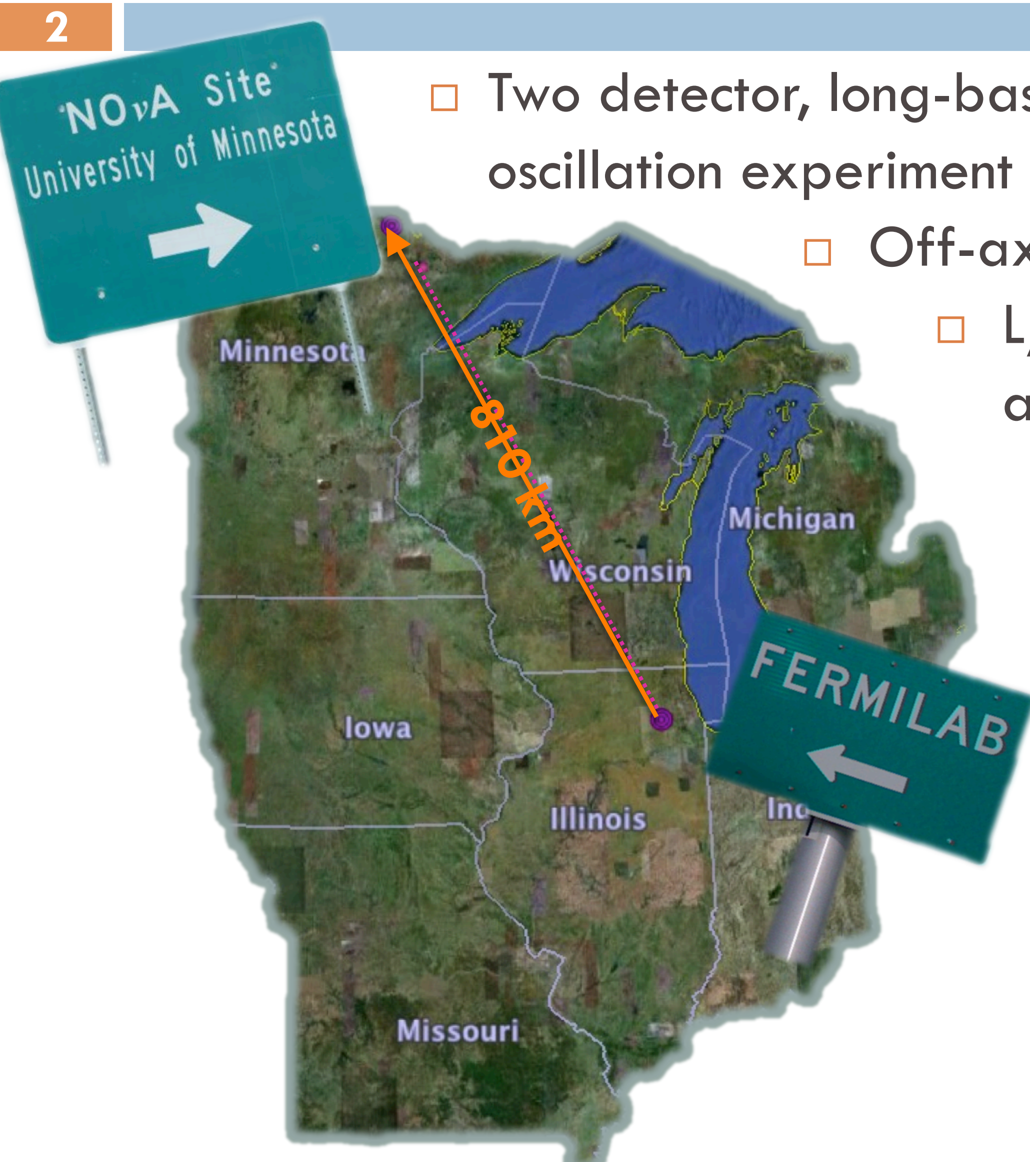
NOVA STRATEGY FOR CONTROLLING SYSTEMATICS

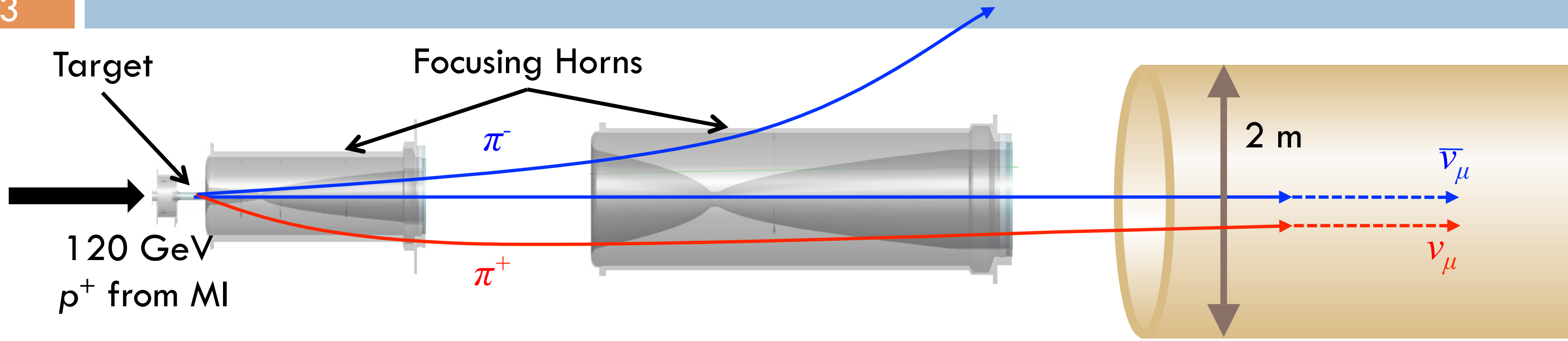
A. Sousa for P. Vahle, NNN15, Oct. 29, 2015

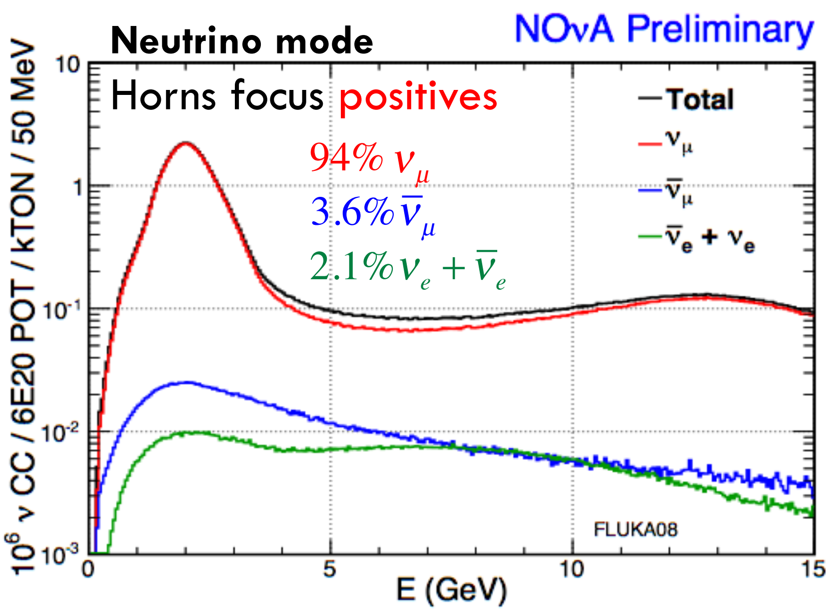
The NOvA Experiment

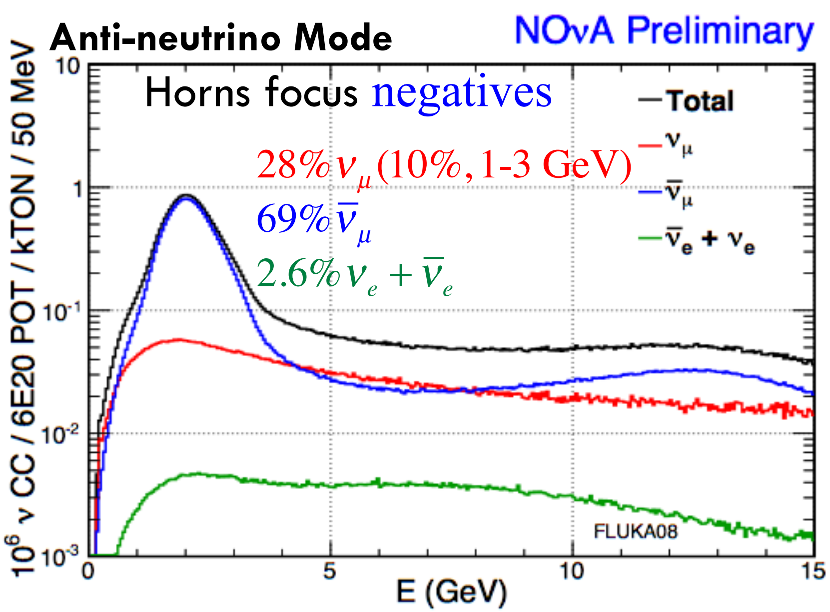


- Two detector, long-baseline neutrino oscillation experiment
  - Off-axis neutrinos from NuMI beam
    - L/E~400 km/GeV, atmospheric Δm^2
      - Physics goals:
        - Search for $\nu_\mu \to \nu_e$ transitions (with both neutrinos and antineutrinos)
        - determine mass hierarchy
        - constrain CP violating phase
        - precision measurements of Δm^2, θ_{23} from ν_μ disappearance

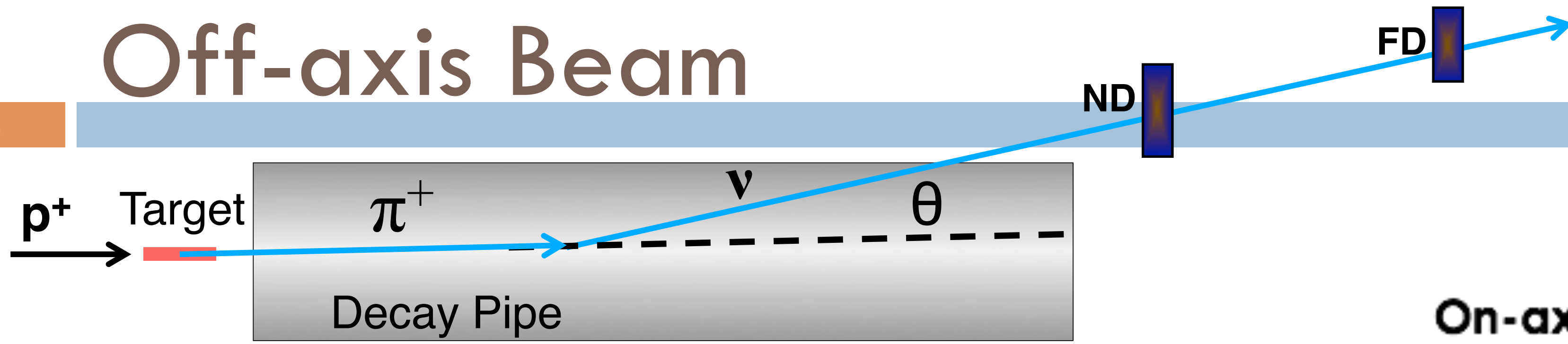
Making a Neutrino Beam



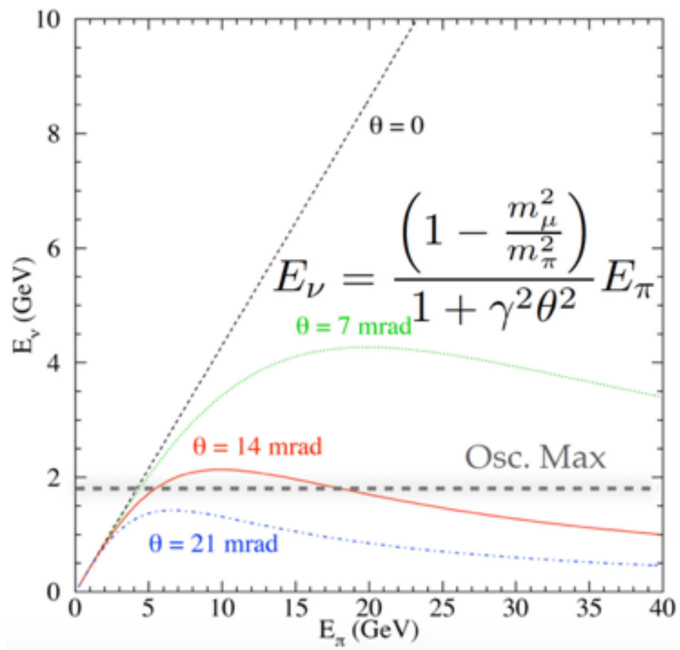


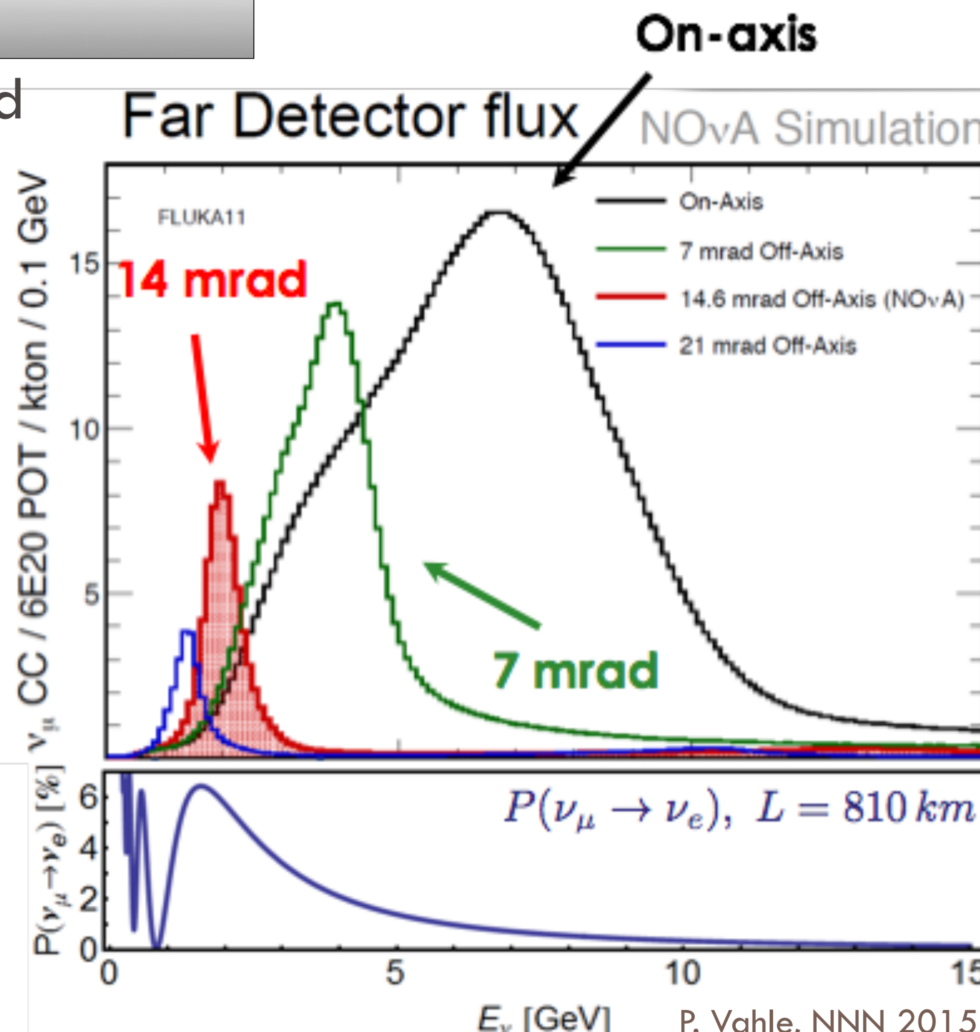


Off-axis Beam



- At 14 mrad off-axis, narrow band beam peaked at 2 GeV
  - Near oscillation maximum
  - Few high energy NC background events





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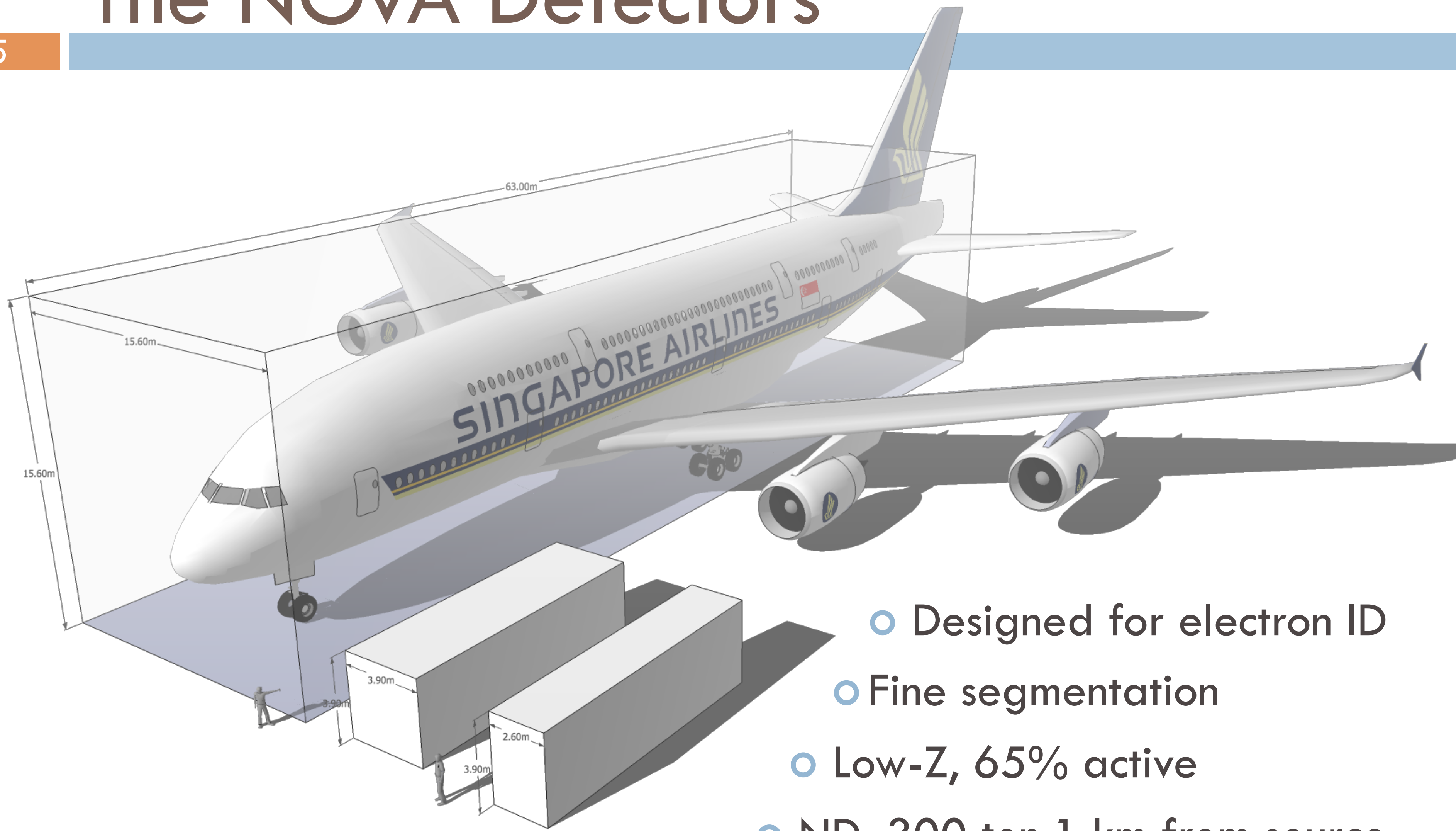
The NOvA Detectors



- Designed for electron ID
- Fine segmentation
- Low-Z, 65% active
- ND: 300 ton,1 km from source
- FD: 14 kton, 810 km from source

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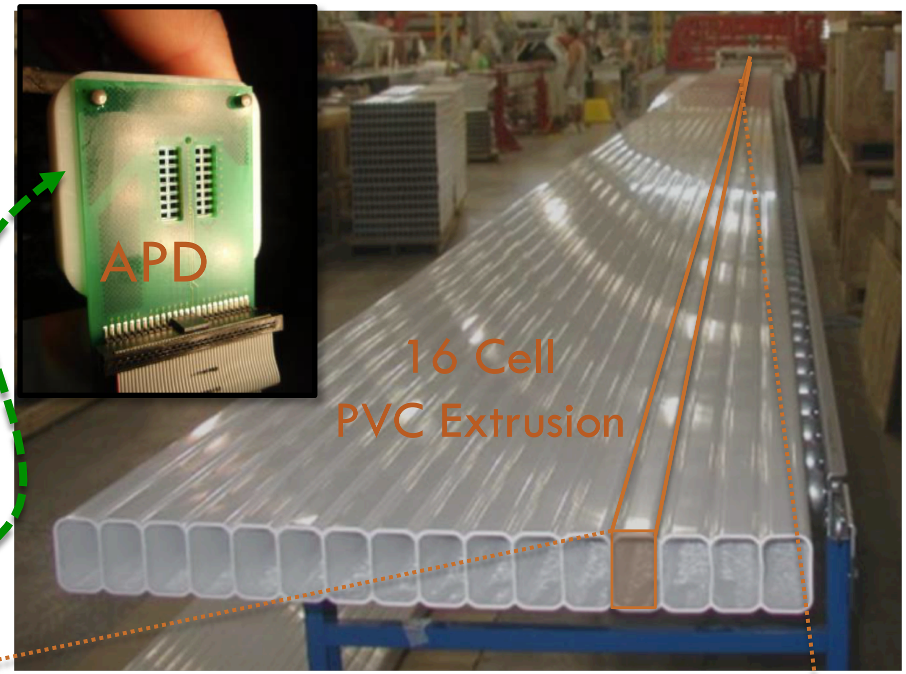
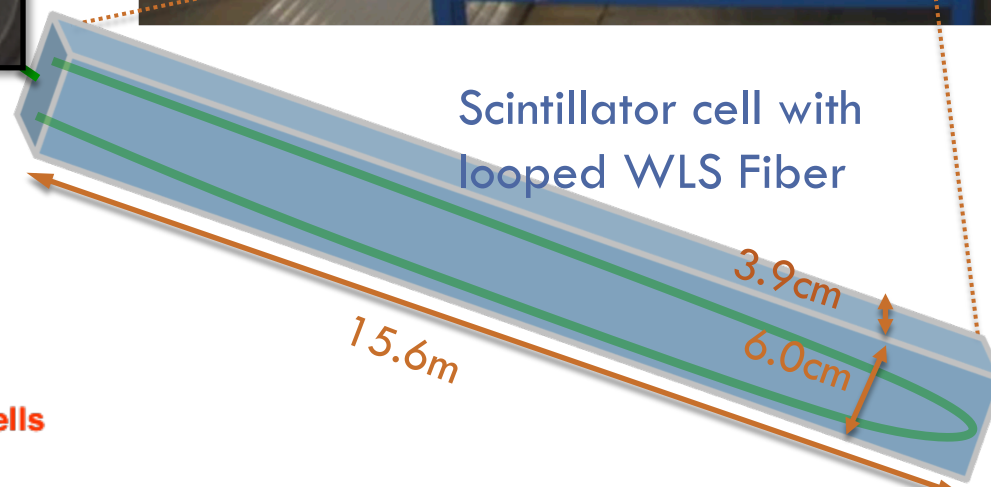
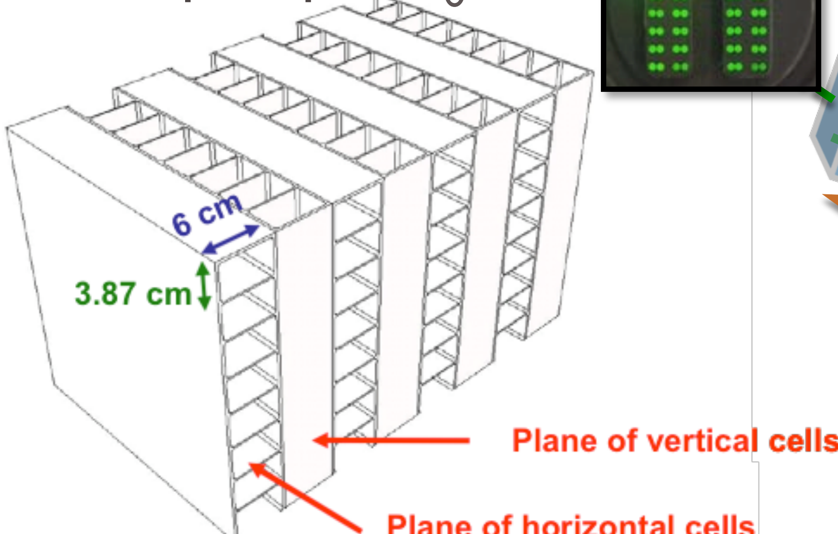
Detector Technology

- PVC extrusion + Liquid Scintillator
  - mineral oil + 5% pseudocumene
- Read out via WLS fiber to APD
  - FD has 344,064 channels
  - muon crossing far end~25 PE
- Layered planes of orthogonal views
- ~7 samples per X_0







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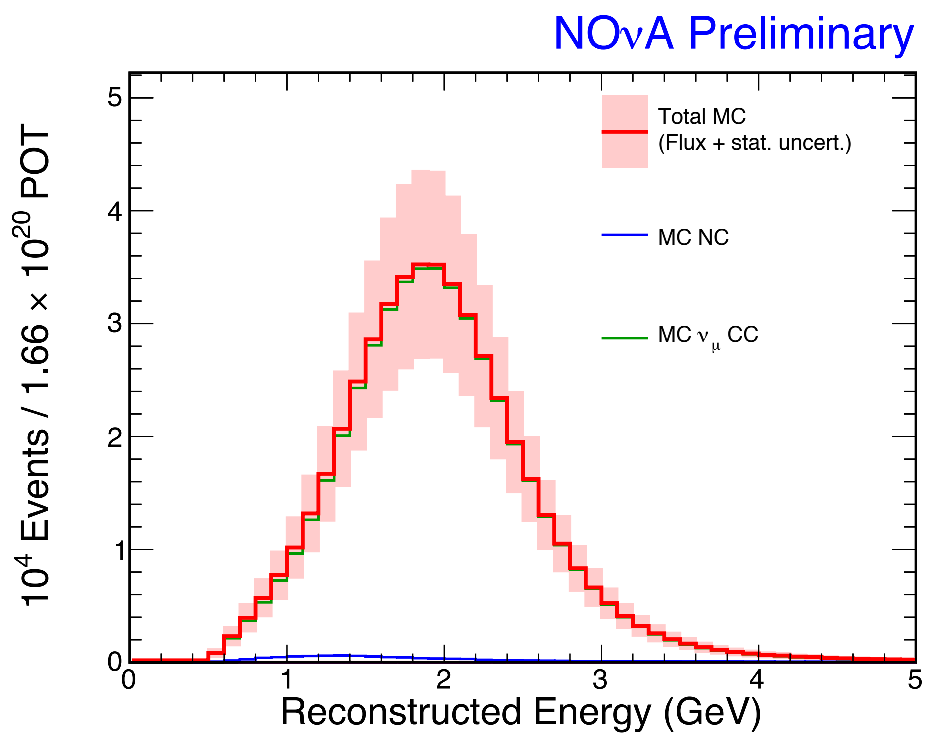
Systematic Control

- Combining 2 functionally identical detectors with an off-axis beam mitigates many of the dominant errors associated with 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%.

MIPP hadron production data and MINERvA flux measurement promise to reduce normalization uncertainty by more than a factor of 2.



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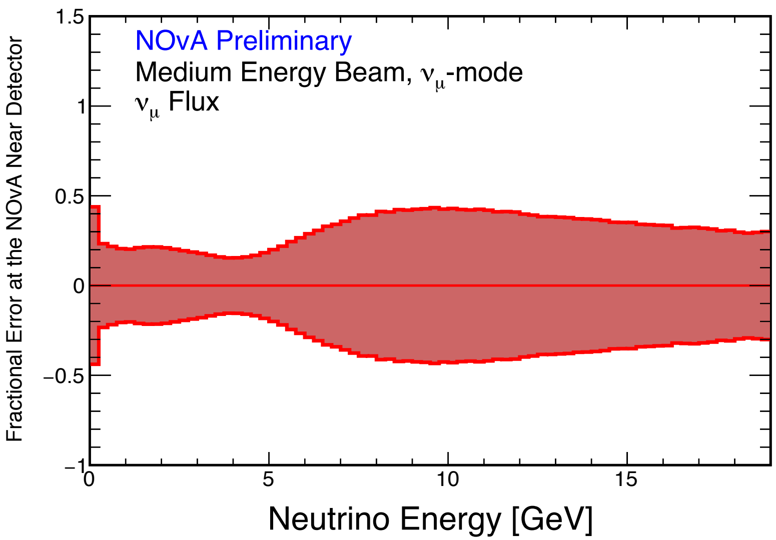

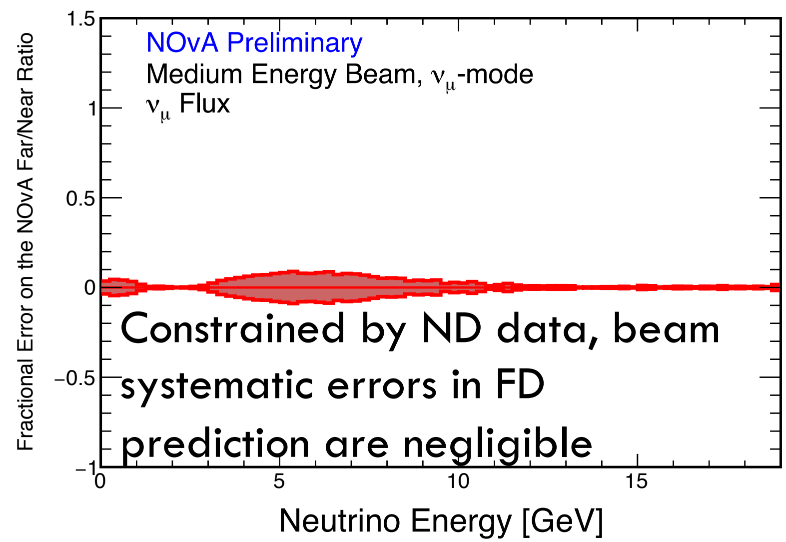

Systematic Control

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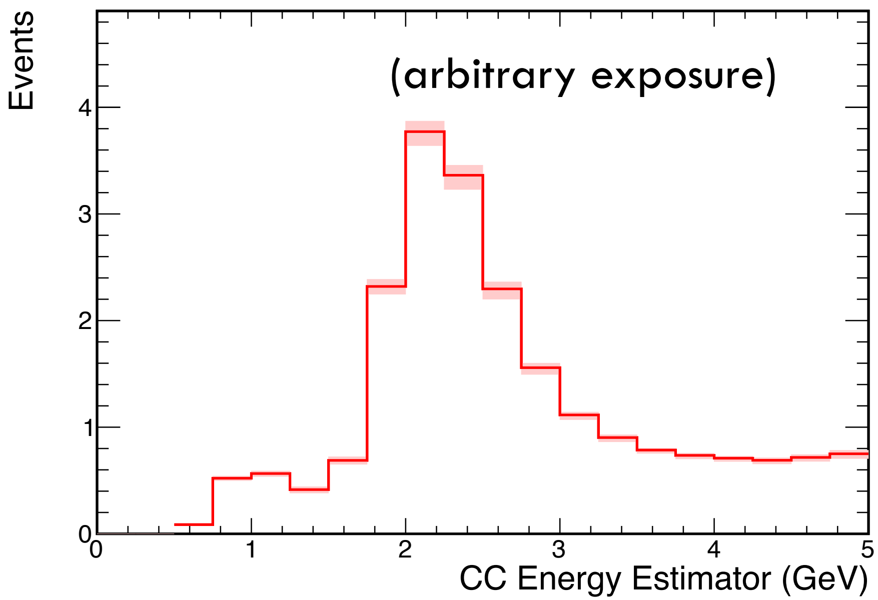


Neutrino interaction uncertainties also cancel in the extrapolation, leaving a residual 3.5% change in number of events

Largest contributions from modifying axial mass in QE and RES cross section parameterization

ND beam peak moves by less than 1%

Interaction uncertainties from Genie Users Manual, arXiv:1510.05494

Which Systematics do matter?

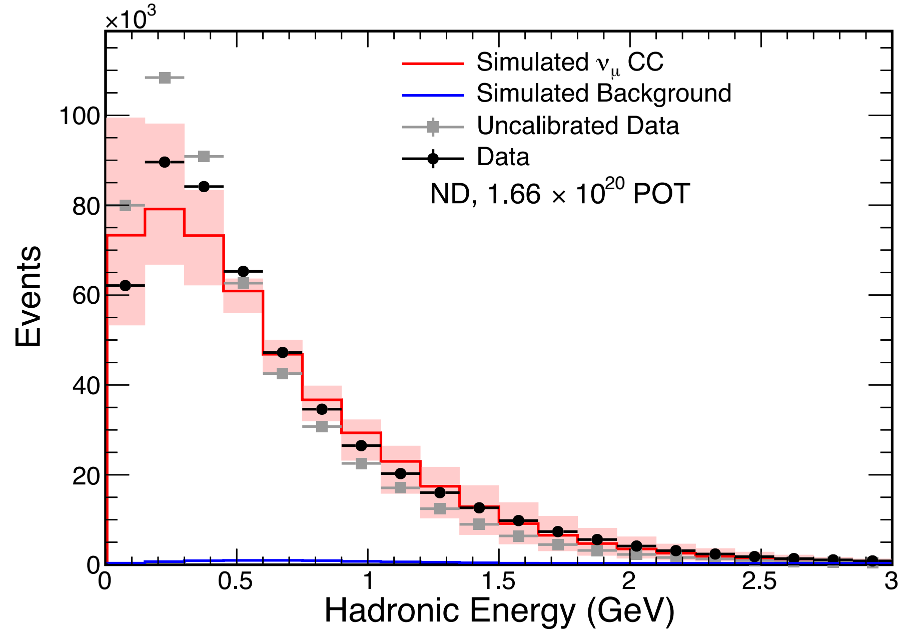
Source	$\delta(\sin^2\theta_{23})$ (±%)	$\delta(\Delta m^2)$ (±%)
Absolute Calorimetric Energy Calibration [±22%]	7.7	3.1
Relative Calorimetric Energy Calibration [±5.4%]	3.7	0.8
Cross Sections and FSI [±(15-25)%]	0.6	0.7
NC and CC Backgrounds	3.2	0.7
Detector Response	1.3	0.7
Flux [±21%]	1.6	0.4
Exposure [<±2%]	0.3	0.2
Oscillation Parameters	2.1	2.2
Total Systematic	9.2	4.1
Statistical	19	5.0

- Errors on mass splitting and mixing angle dominated by hadronic energy calibration/simulation
- NC backgrounds contribute to mixing angle systematic uncertainty

Hadronic Energy Systematic

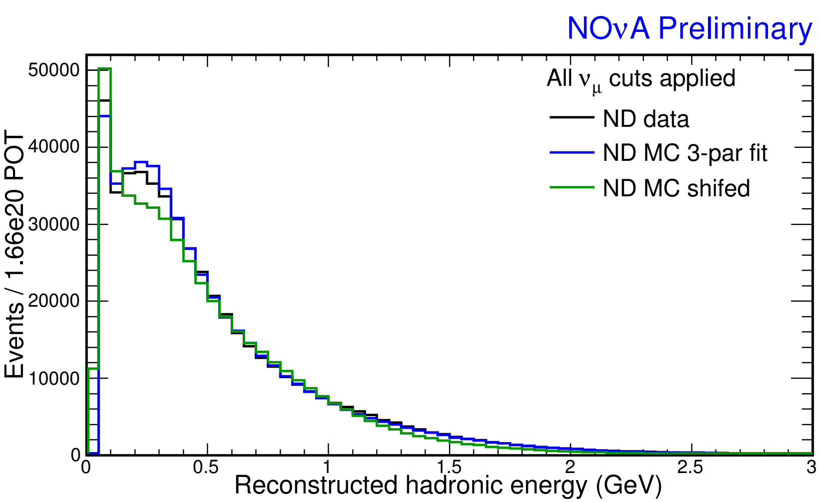
$$E_\nu = E_\mu + E_{had}$$

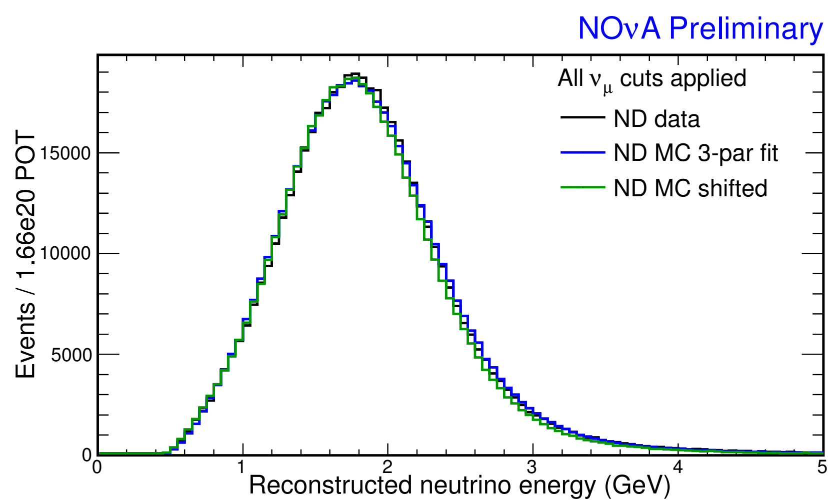
- While the muon simulation matches data, the simulated hadronic system has 21% more energy than in data.
- The hadronic energy scale is recalibrated so the total energy peak of the data matches the MC.
  - Correction taken as a systematic on the absolute energy scale
  - This results in 6% overall neutrino energy scale uncertainty.



Hadronic Energy Systematic

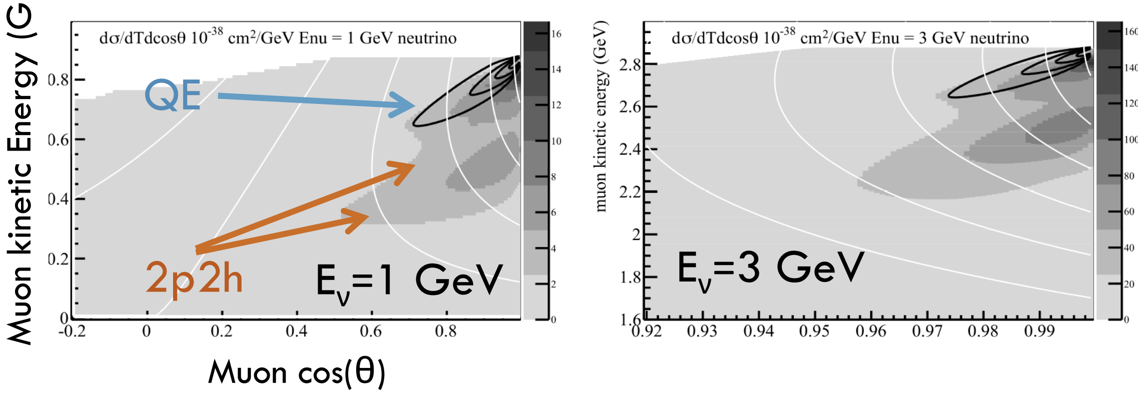
- Additionally implies a detector-to-detector **relative** energy systematic
- Assume different models to correct E_{had}
  - Allow energy scale and normalization of each process type (QE/RES/DIS) to vary
  - 2% difference in hadronic energy scale between two correction methods used as systematic



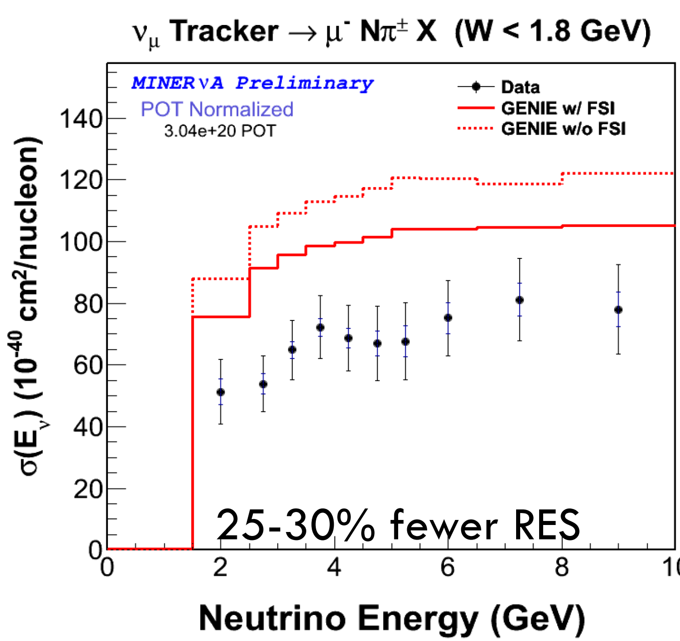


Mitigating the E_{had} Systematic

- First analyses have the luxury of conservative systematics
- Need to understand the source of the discrepancy for future analyses
  - Calibration vs. detector response vs. Neutrino interaction modeling
- External data provide some hints
  - Missing 2p2h in Genie
  - MINERvA sees fewer 1pi events than Genie



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

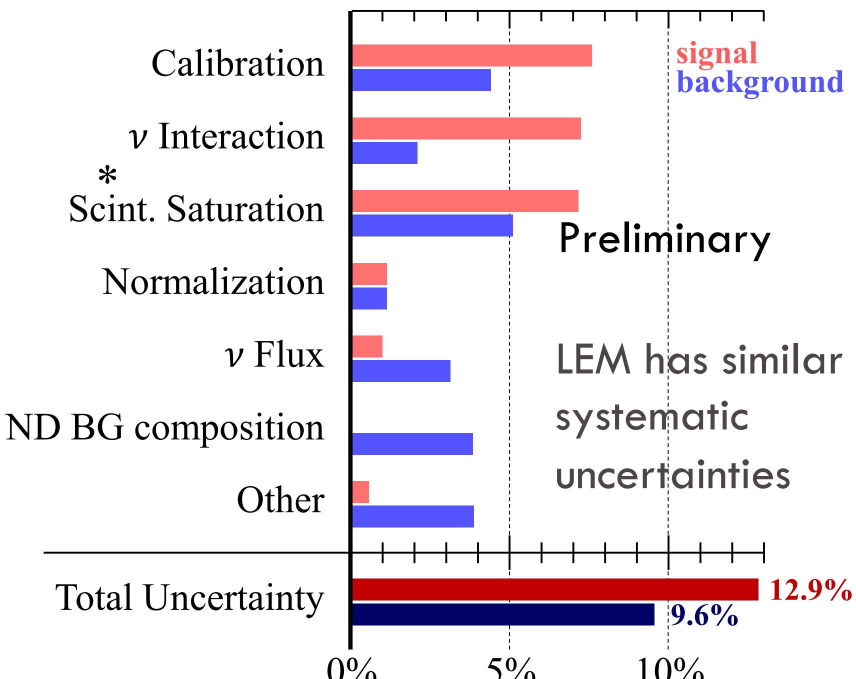


C. McGivern, FNAL JTEPS, June 26, 2015

B. Eberly, arXiv:1406.6415

Which systematics do matter?

- Nue Systematics assessed by modifying the simulation used in the extrapolation
- Variation in the BG and signal prediction taken as the size of the systematic



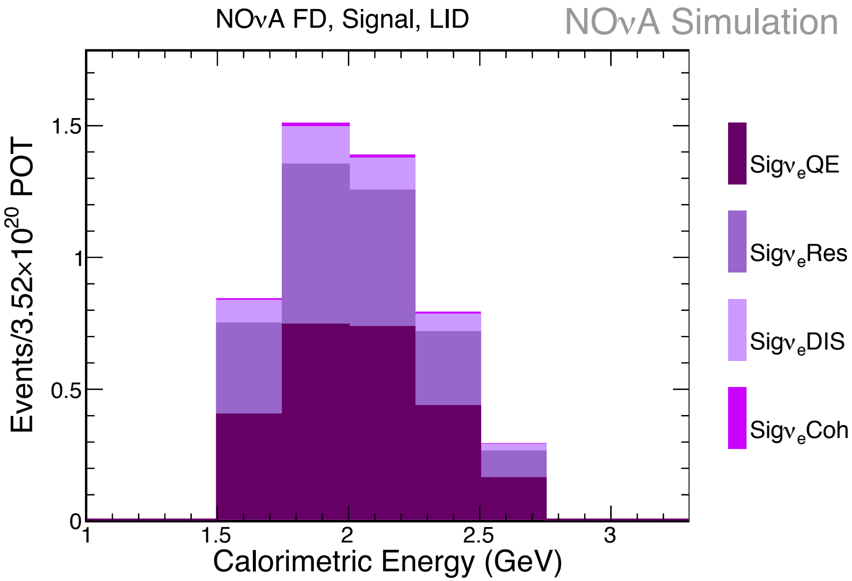
*will be larger in published version

With ~1 BG event and ~6 signal events expected, signal systematics are most important.

Signal systematics dominated by neutrino interaction uncertainties, detector response modeling, energy calibration.

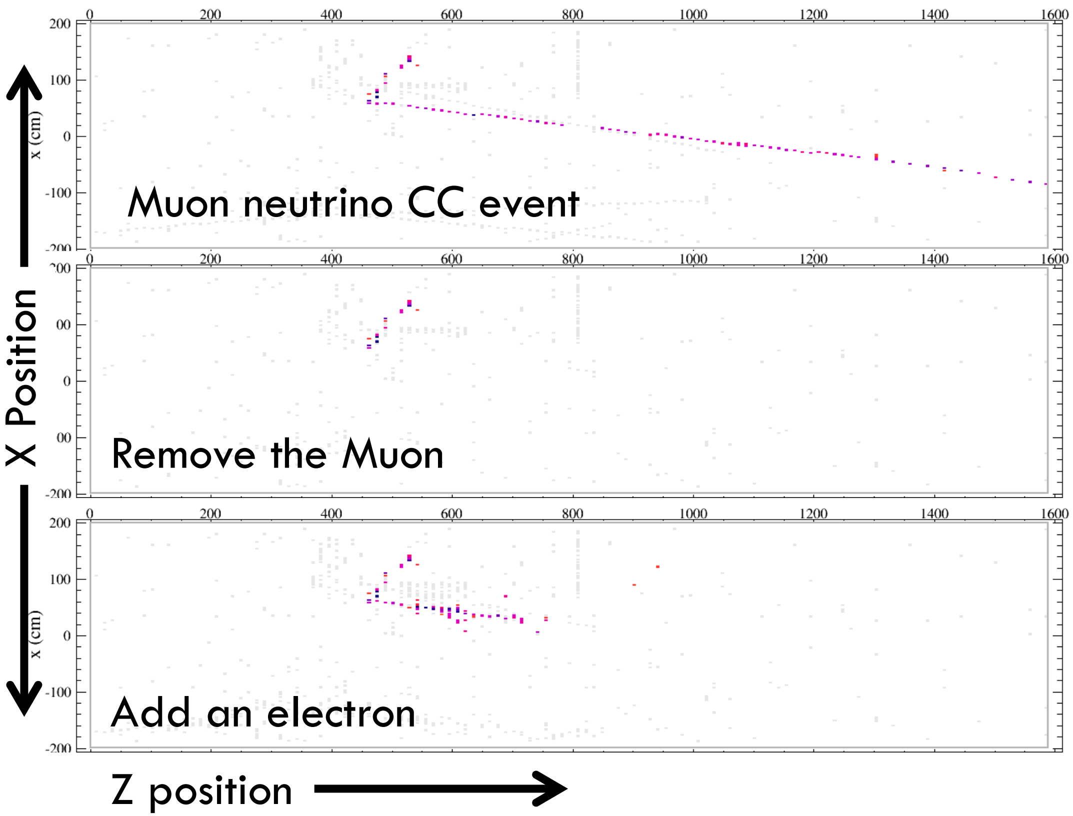
Neutrino Interaction Modeling

- Signal selection efficiency not benchmarked in ND
- Selection efficiency changes for each 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



Muon Removal—Electron Addition

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

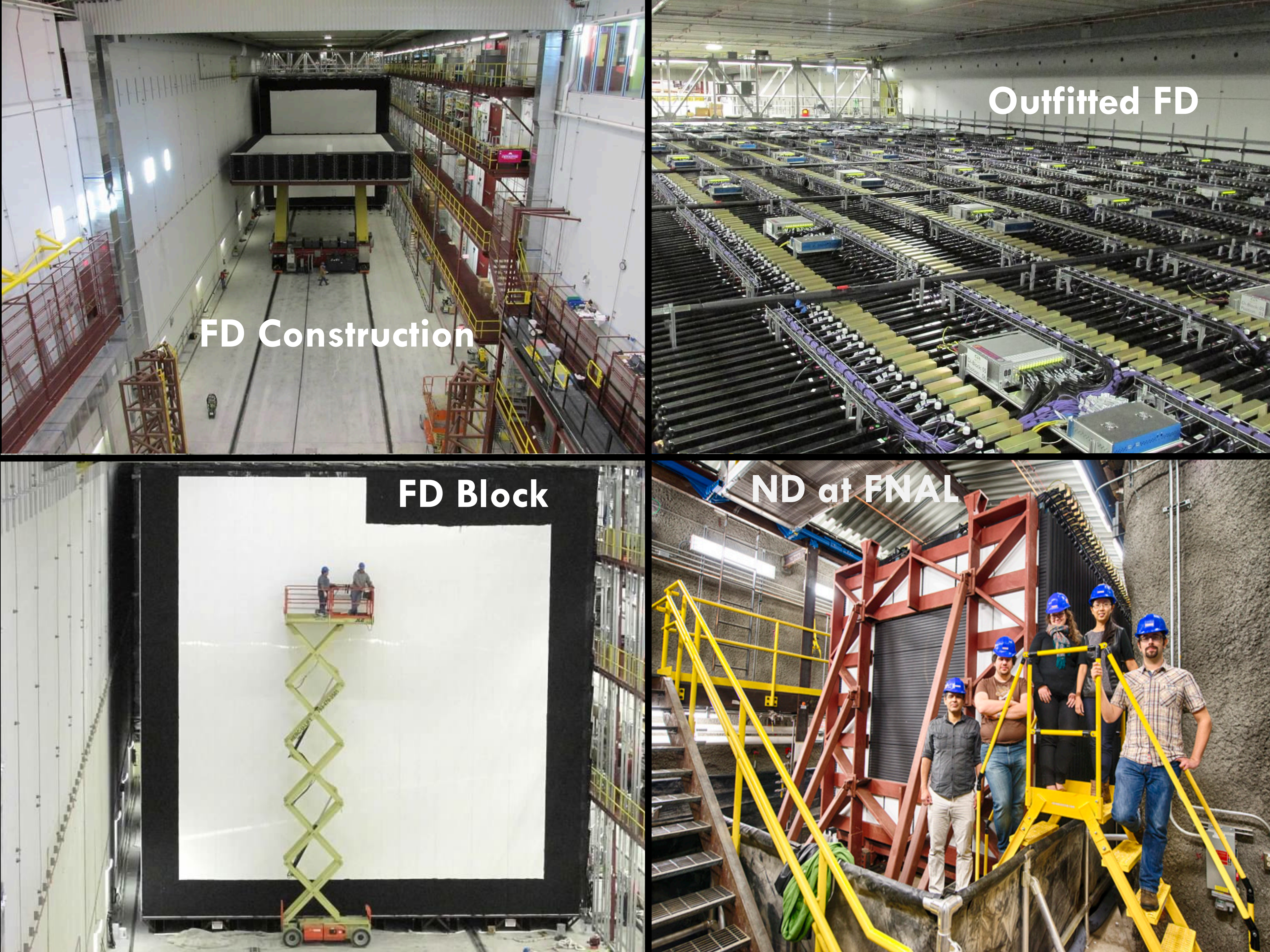


- We can study our signal efficiency in hybrid ND events
  - Remove the hits associated with a muon track in selected numu CC event
  - Insert a simulated electron with the same kinematics as the removed muon
  - Reconstruct the hybrid event
- Comparing distributions between data and MC will help constrain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

Summary

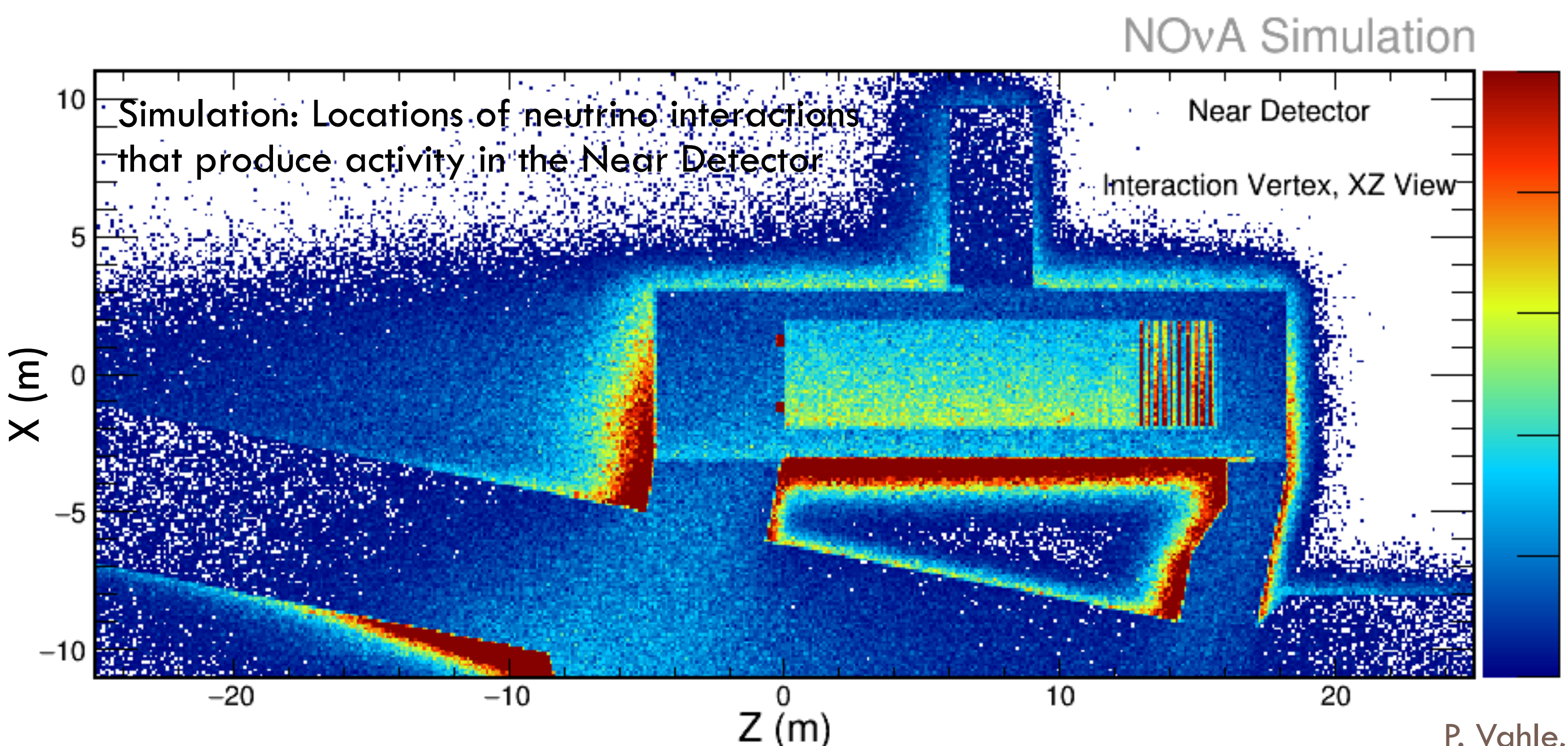
- Off-axis beam and functionally identical detectors mitigate many of the larger errors associated with accelerator neutrino experiments
- NOvA adopted conservative estimates of systematic uncertainties in our first analysis
- Future analyses will benefit from new external data on neutrino interactions and internal data-driven constraints.

Backup


FD Construction
Outfitted FD
FD Block
ND at FNAL

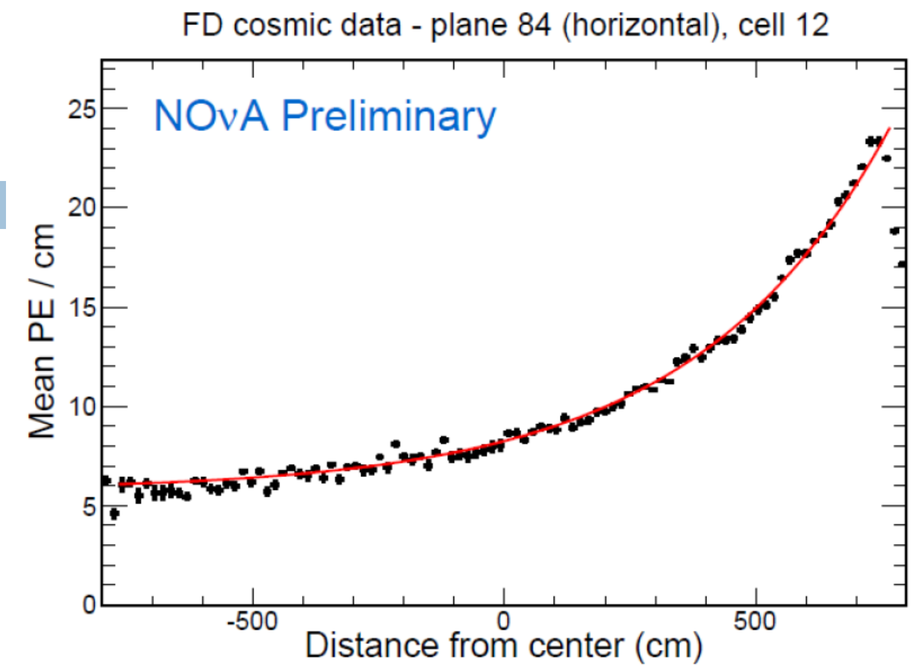
Simulation

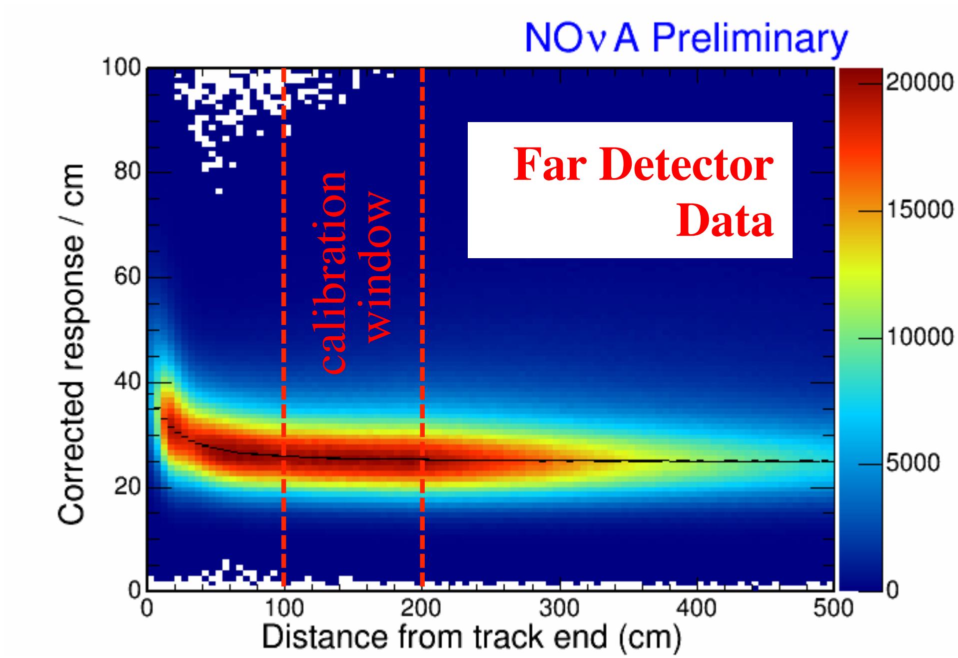
- Beam hadron production, propagation; neutrino flux: **FLUKA/FLUGG**
- Cosmic ray flux: **CRY**
- Neutrino interactions and FSI modeling: **GENIE**
- Detector simulation: **GEANT4**
- Readout electronics and DAQ: **Custom simulation routines**



Calibration

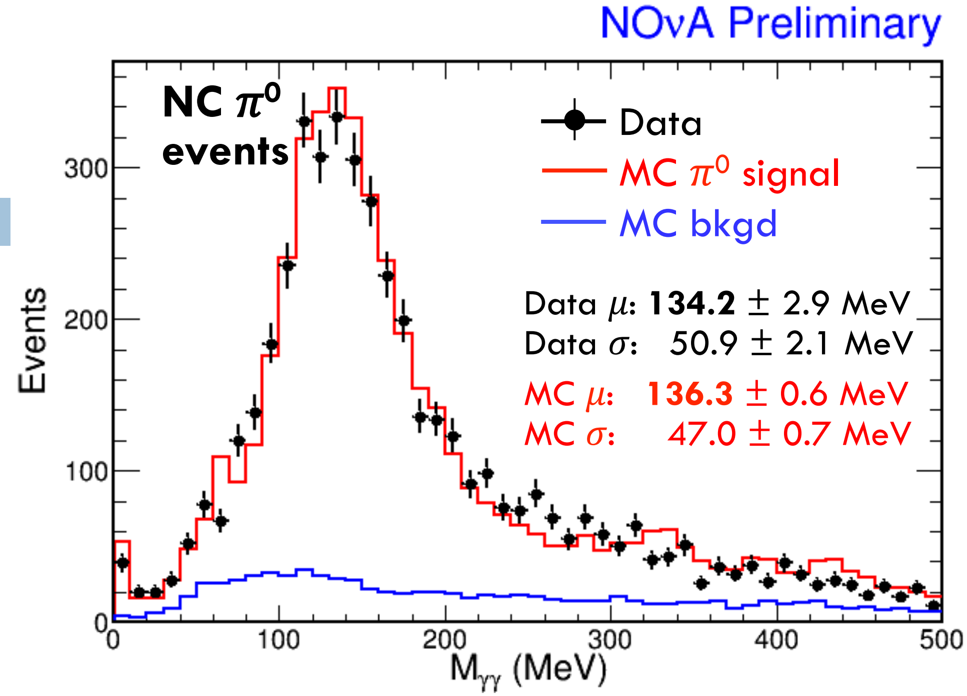
- Calibration achieved using cosmic rays
- Light levels drop by a factor of 8 across a FD cell
- Stopping muons provide a standard candle

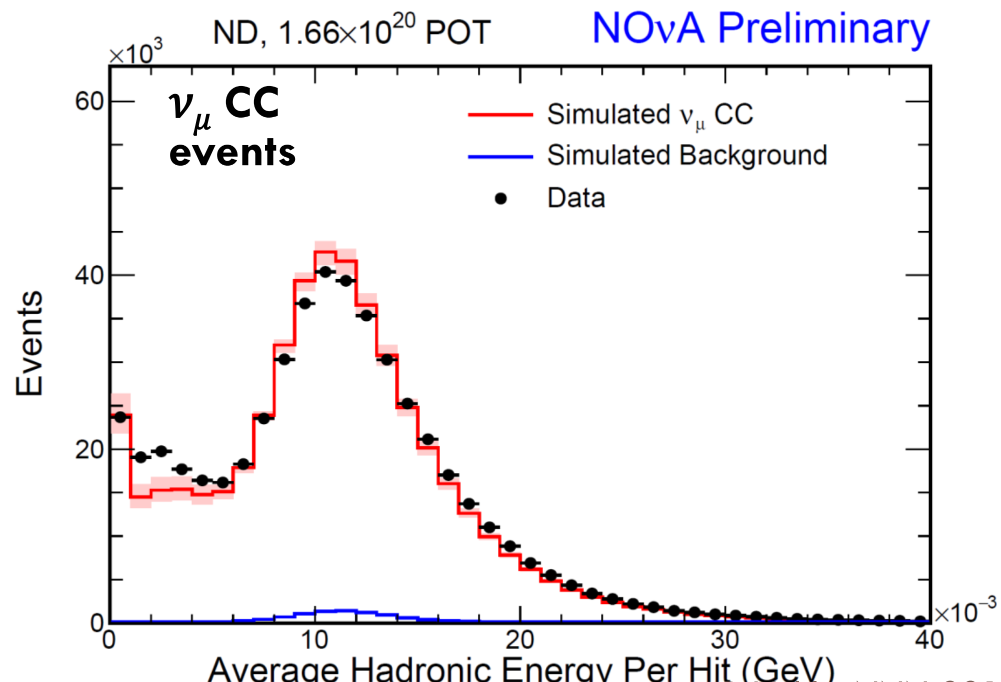




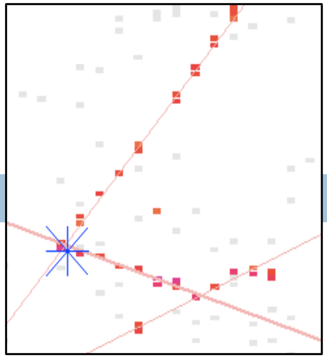
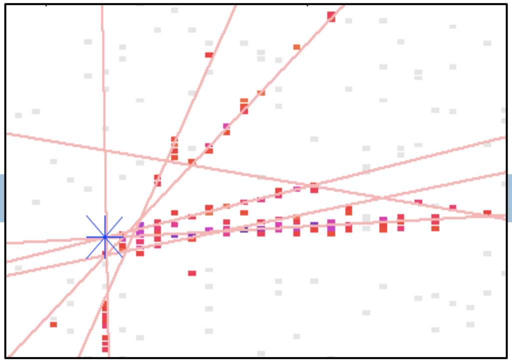
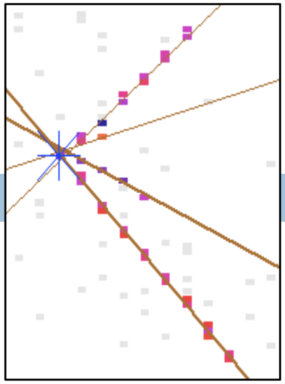
Energy Scale

- Near Detector
  - cosmic μ dE/dx [~vertical]
  - beam μ dE/dx [~horizontal]
  - Michel e^- spectrum
  - π^0 mass
  - hadronic shower E-per-hit
- Far Detector
  - cosmic μ dE/dx [~vertical]
  - beam μ dE/dx [~horizontal]
  - Michel e^- spectrum
- All agree to 5%



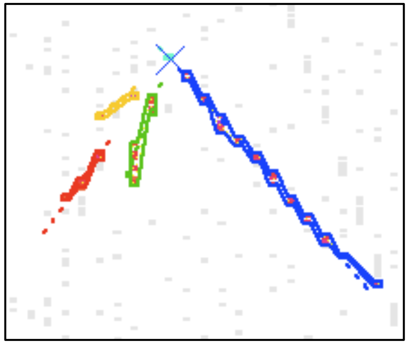
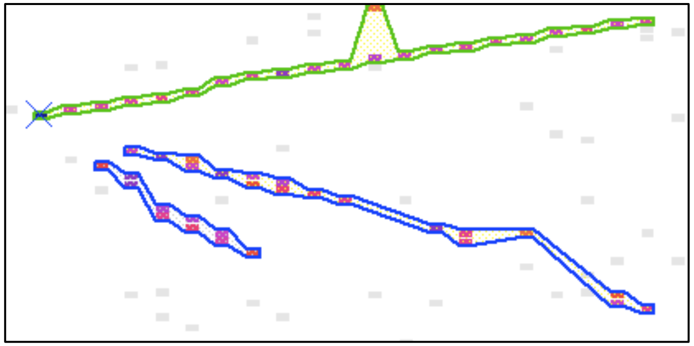


Reconstruction

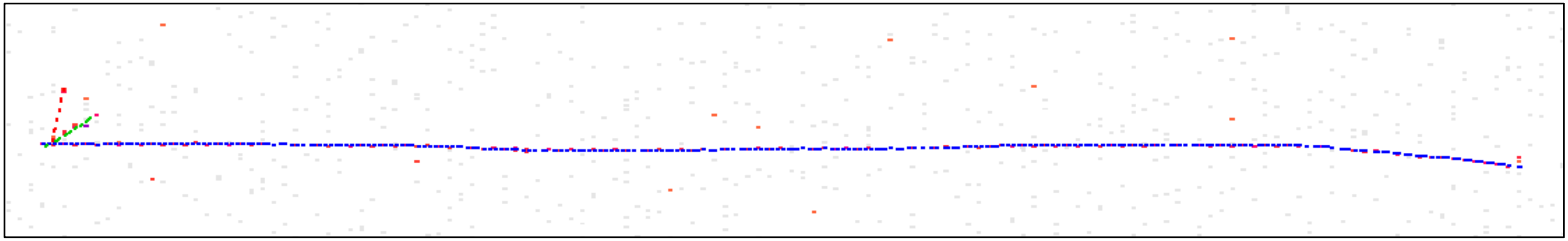
Vertexing: Find **lines of energy depositions** w/ Hough transform

CC events: 11 cm resolution

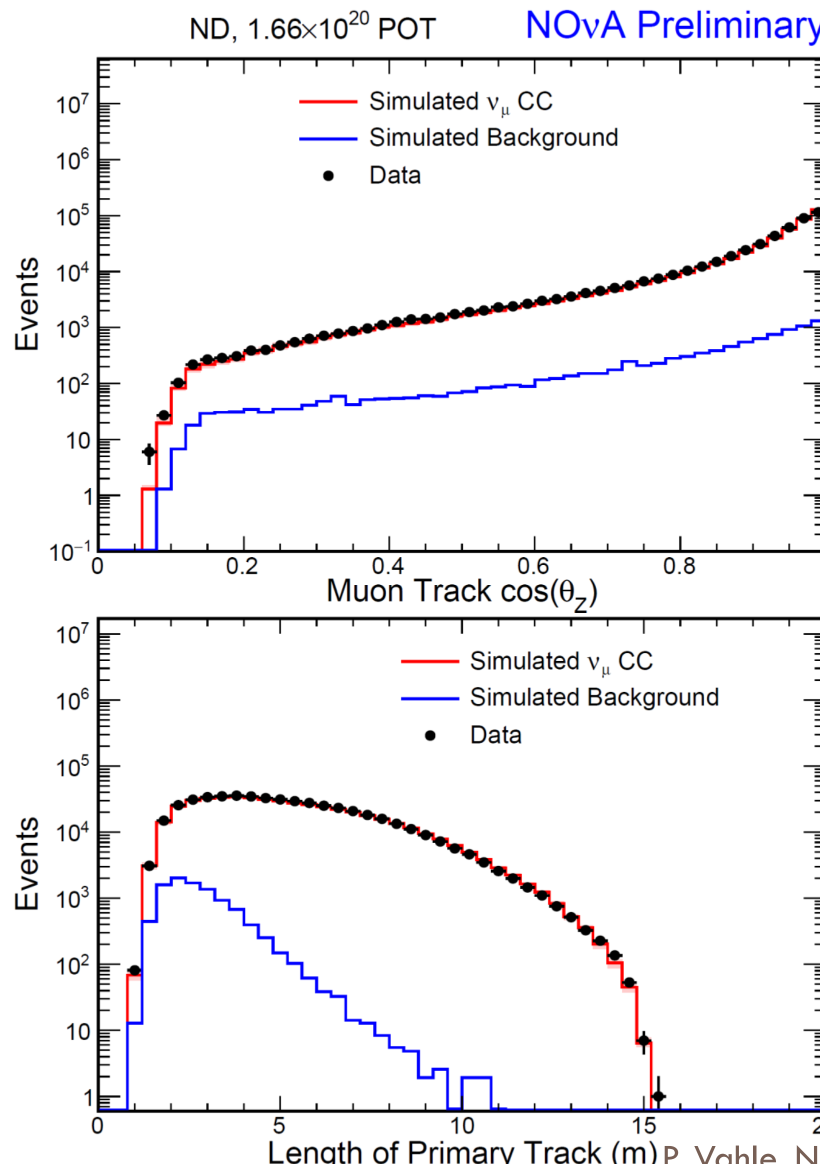
Clustering: Find **clusters in angular space** around vertex. **Merge views** via topology and prong *dE/dx*

Tracking: Trace particle trajectories with **Kalman filter** tracker (below). Also have a **cosmic ray tracker**: lightweight, very fast, and useful for large calibration samples and online monitoring tools.



Selecting Muon Neutrinos

- Goal: Isolate a pure sample of ν_μCC events less than 5GeV
  - Select events with long tracks
  - Suppress NC and cosmic backgrounds
- Containment cuts require a buffer between walls and event
- 4-variable kNN used to identify muons
  - track length
  - dE/dx along track
  - scattering along track
  - track-only plane fraction
- ND Data matches simulation well for muon variables

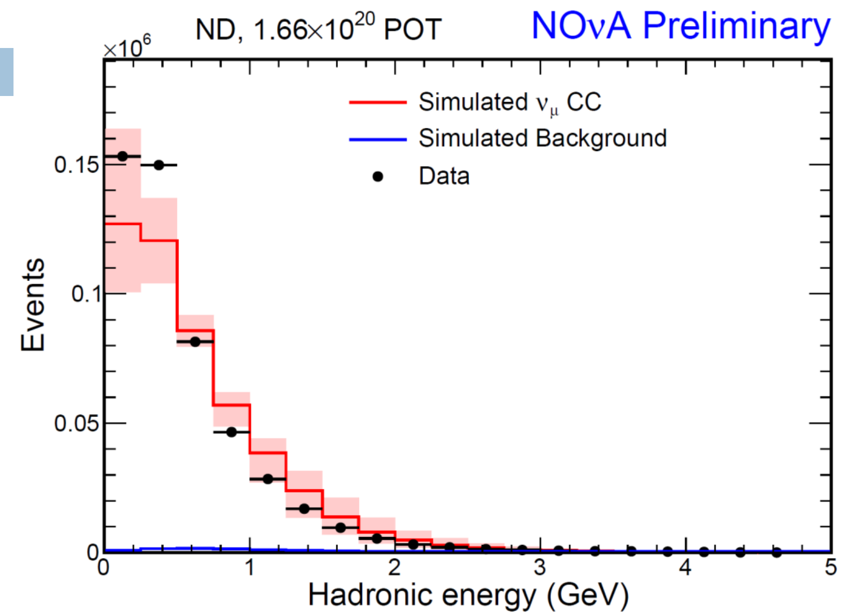


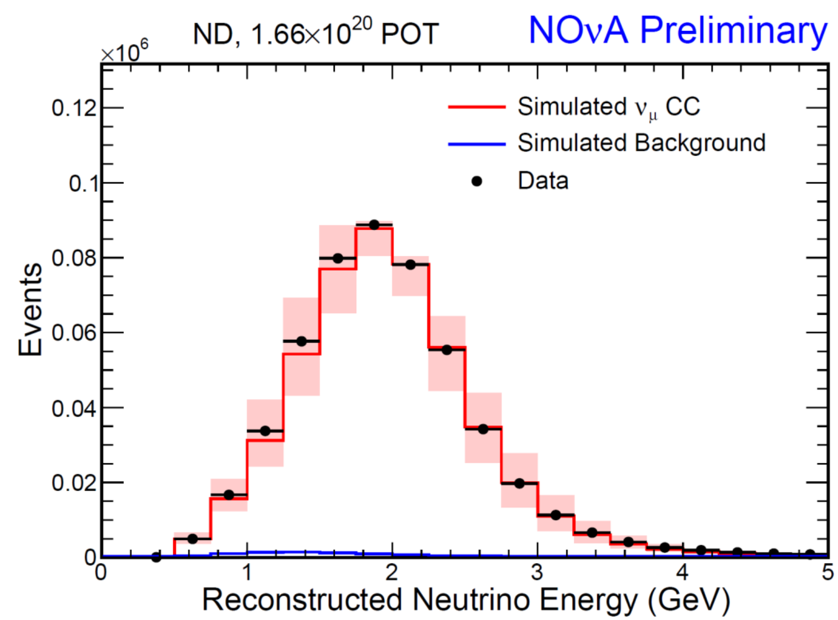
P. Vahle, NNN 2015

Energy Estimation

$$E_\nu = E_\mu + E_{had}$$

- While the muon simulation matches data, the simulated hadronic system has 21% more energy than in data.
- The hadronic energy scale is recalibrated so the total energy peak of the data matches the MC.
  - Correction taken as a systematic on the absolute energy scale
  - This results in 6% overall neutrino energy scale uncertainty.
- ND reconstructed energy distribution is used to produce a data driven prediction of the FD spectrum





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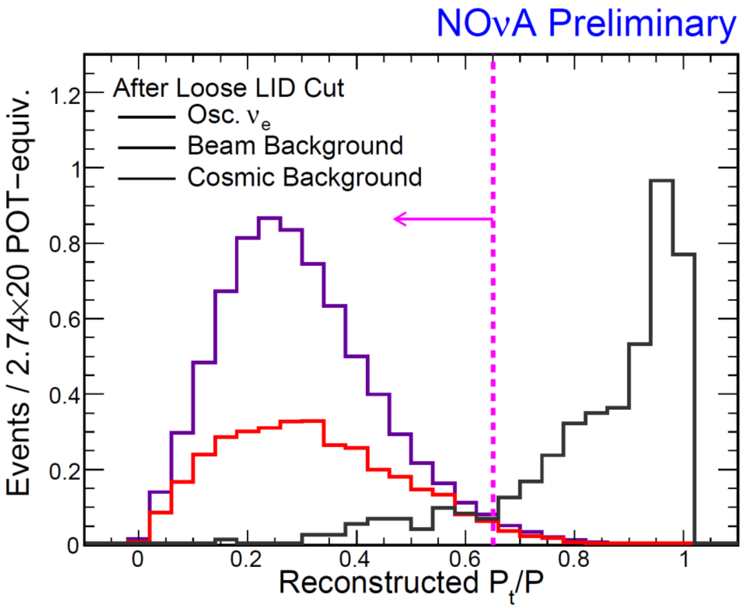
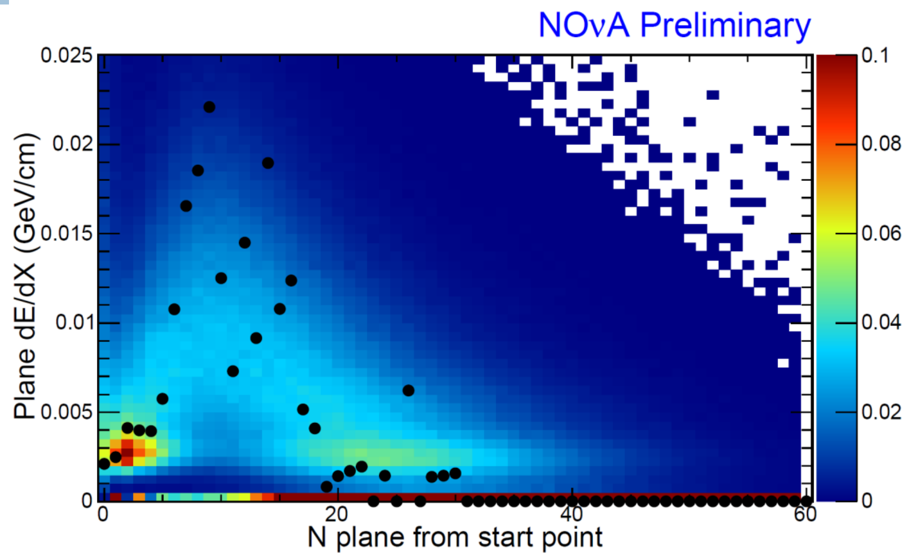
Selecting Electron Neutrinos



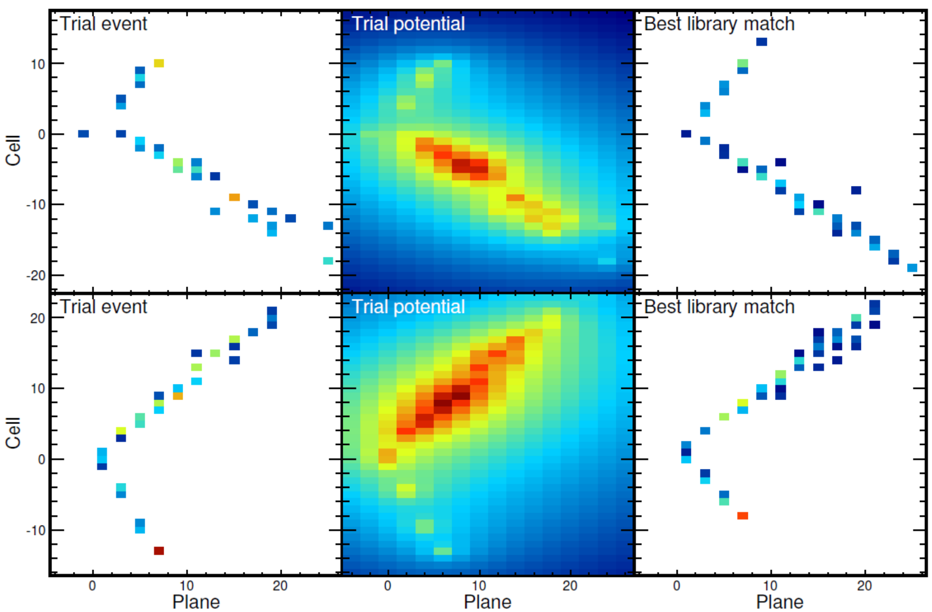
- Goal: Isolate a pure sample of ν_eCC events
  - Select events with electromagnetic showers
  - Suppress backgrounds from NC/ν_μCC/beam ν_e and cosmic events
- Basic cuts to remove obvious backgrounds:
  - Fiducial and Containment
  - Reconstructed p_T/p
    - remove very vertical events
  - Shower length
  - Number of hits
  - Calorimetric energy

Selecting Electron Neutrinos



LID:

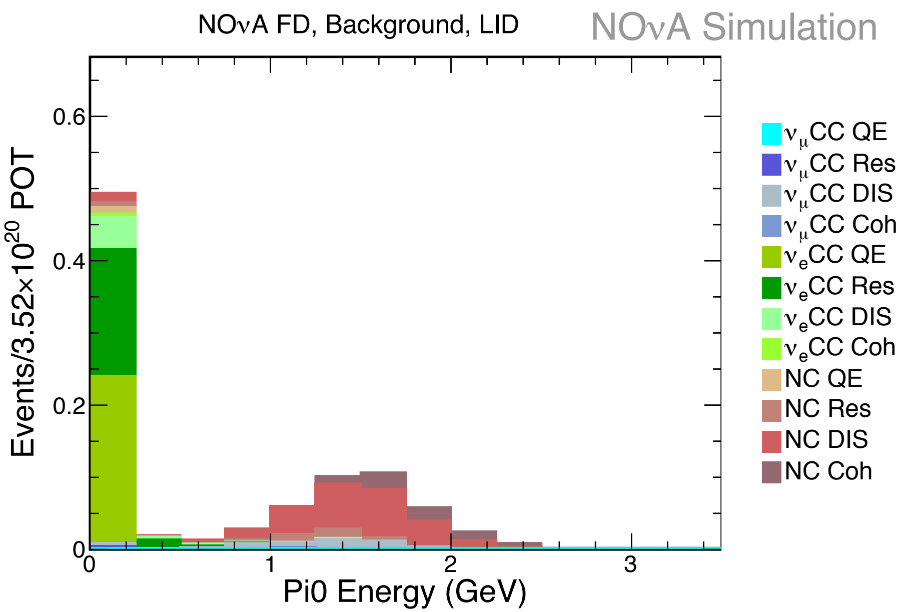
- Compare dE/dx in transverse and longitudnal slices to simulated e/μ/pi/p+ distributions



LEM:

- Pattern of energy deposition of entire event compared to a simulated event library

Background characteristics

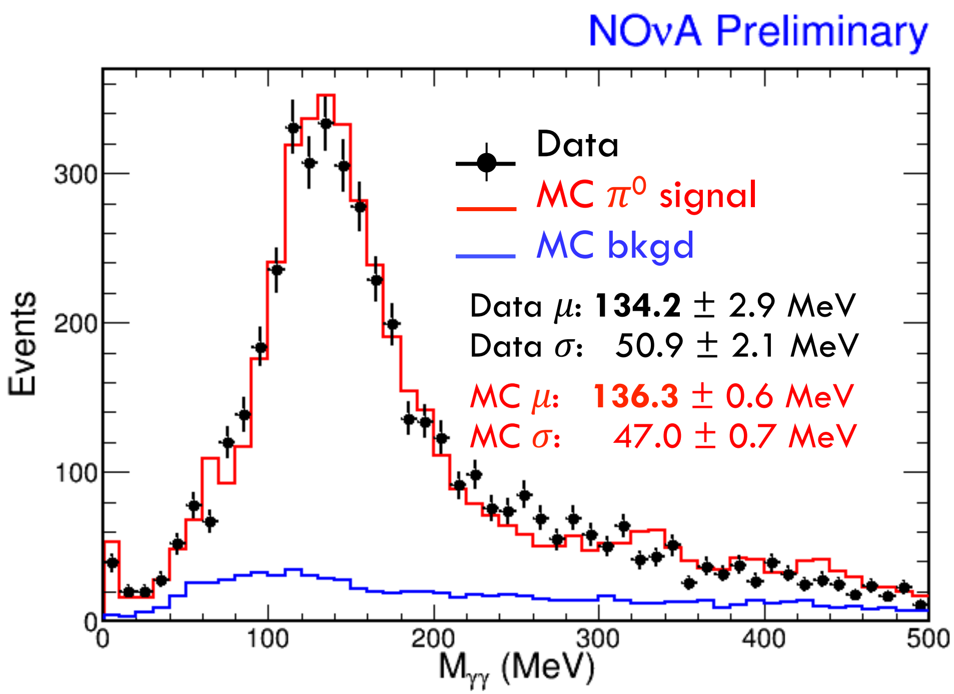


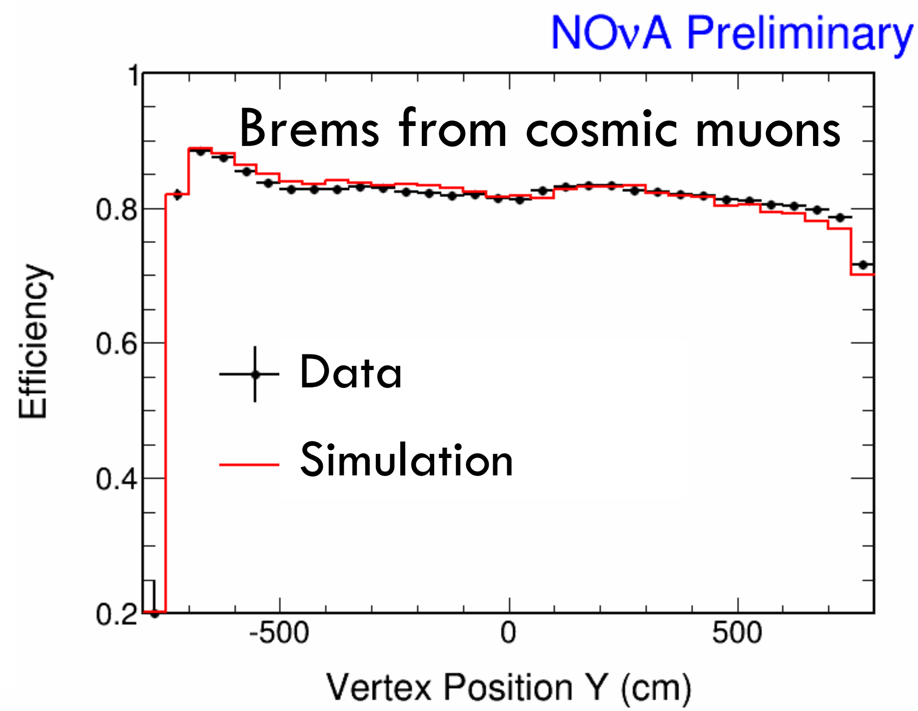
- Both selection techniques achieve good sensitivity to ν_e appearance
  - 35% signal selection efficiency (wrt containment)
  - Reject 99.7% of NC backgrounds
  - better than 1 in 10^8 cosmic rejection
  - 62% expected overlap of the signal
- Selected BG dominated by beam ν_e and NC DIS events
  - Most NC events have an energetic π^0

Before unblinding, we chose the more traditional LID as the primary selector

Signal Prediction

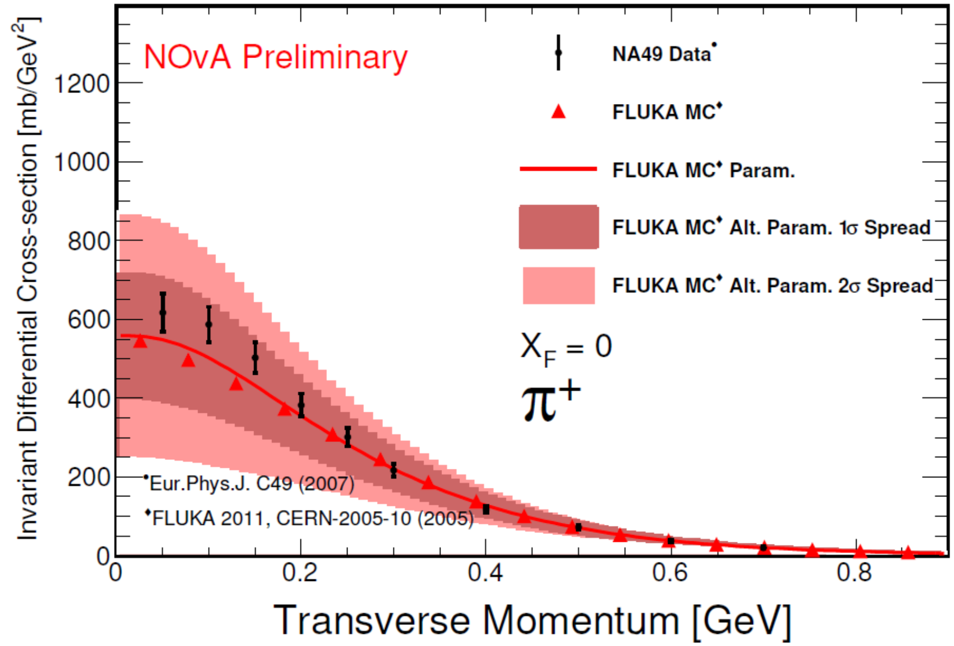
- Signal predictions based on ND ν_μCC energy spectrum
- No direct benchmark of simulation of signal events
- Independent EM samples show good data/MC agreement

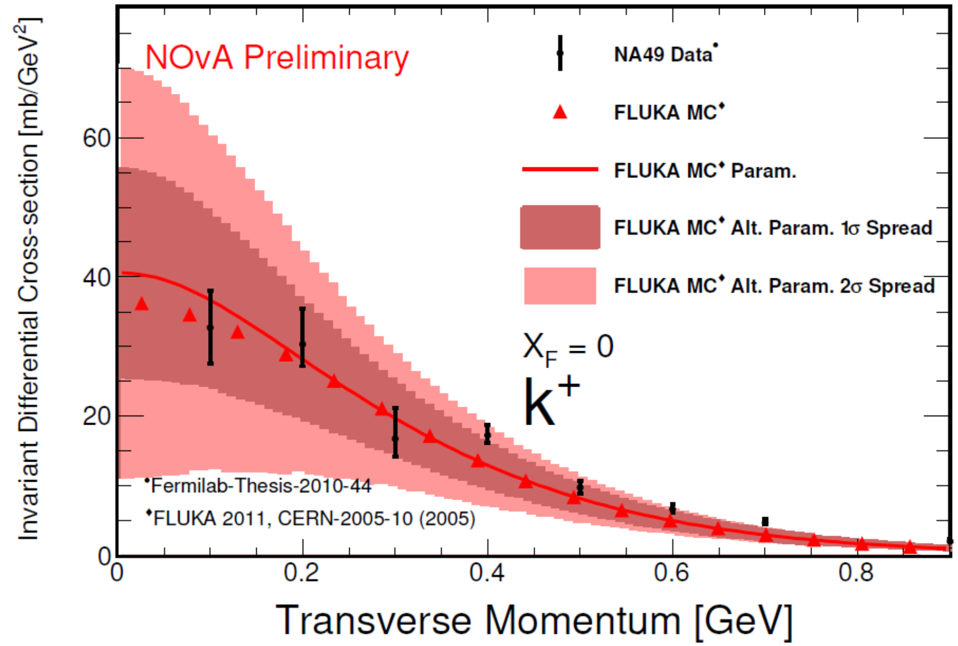




Flux Errors

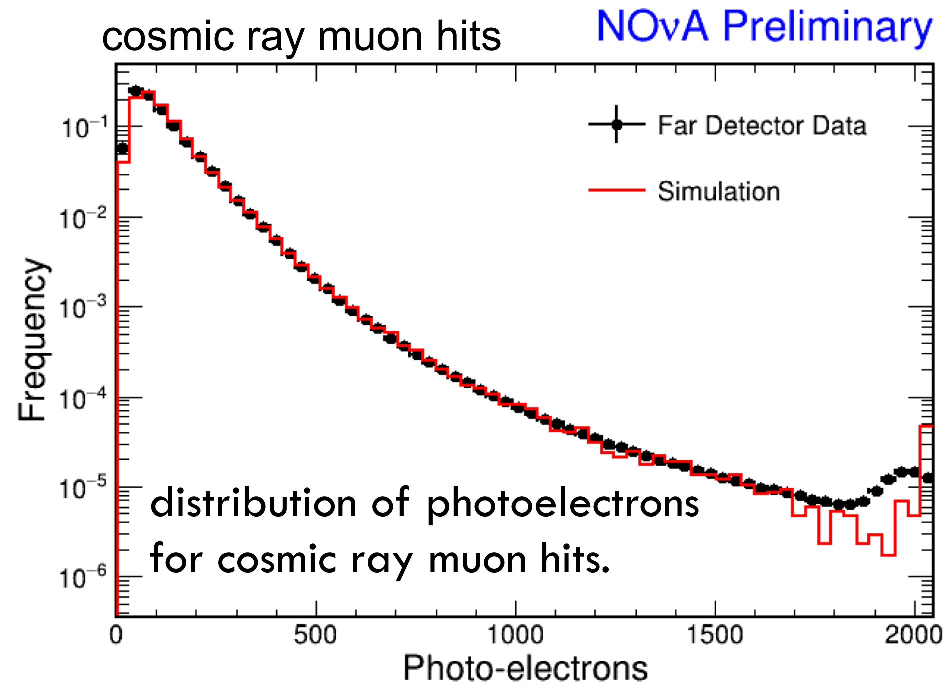
- Full beam geometry simulated with Fluka(11.2c.0) and Flugg(2009_3)
- Hadron production errors come from comparison of NA49 thin target data with Simulation
- Focusing and beam line errors include
  - Horn current miscalibration
  - Horn position/misalignment
  - Current distribution
  - Beam position on target
  - Proton beam spot size
  - Target position

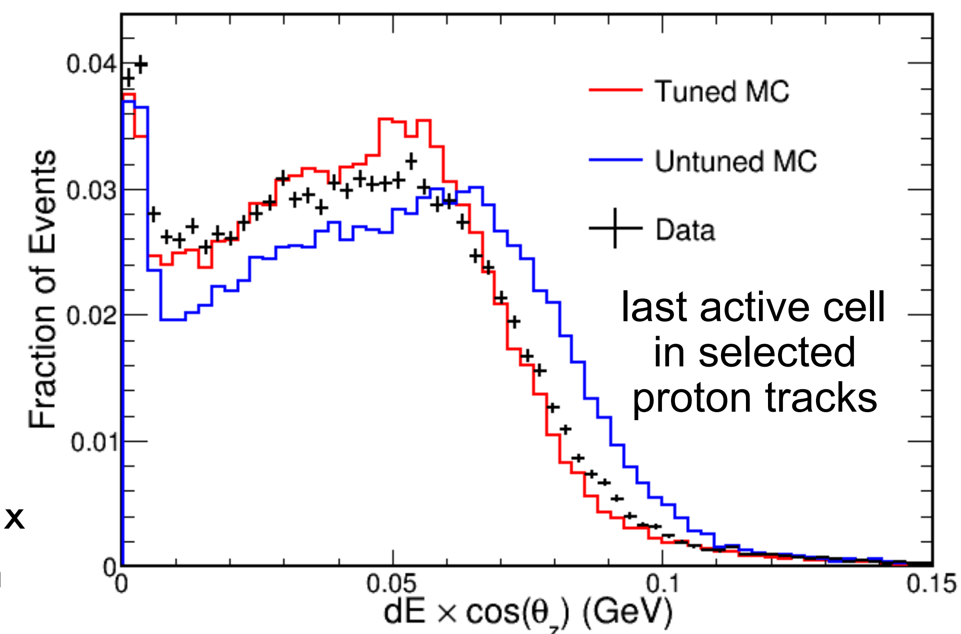




Detector Response Modeling

- **Detailed modeling includes:**
- fiber attenuation
- light collection losses at cell ends
- scintillator saturation
- fiber length variation across modules
- run-by-run matching of inactive channels
- APD characteristics
- amplifier noise
- full digitized traces
- readout electronics noise
- signal shaping, digitization,
  zero suppression





Our Data require more scintillator saturation in simulation for high dE/dx hits than usual. Tune model to proton tracks.