NOvA Analysis Strategies

Pitt PACC SBN Workshop

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The NOvA Experiment

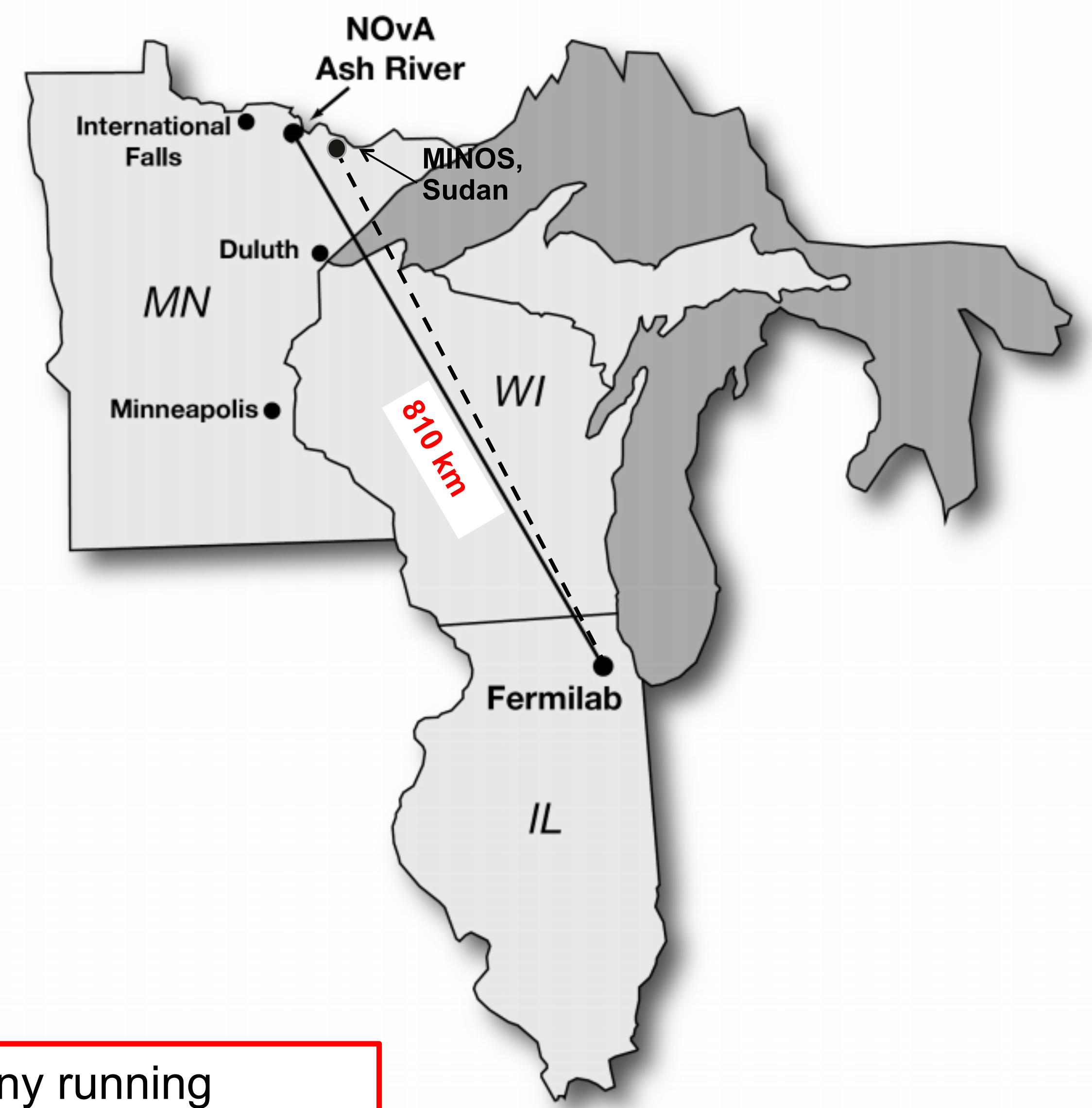
Two detector, long-baseline neutrino oscillation experiment.

Off-axis neutrinos from NuMI beam

L/E~400 km/GeV, atmospheric Δm^2

Physics goals:

- Search for $\nu_\mu \rightarrow \nu_e$ transitions (with both neutrinos and antineutrinos)
- determine mass hierarchy
- constrain CP violating phase
- precision measurements of
  - Δm^2, θ_{23} from ν_μ disappearance



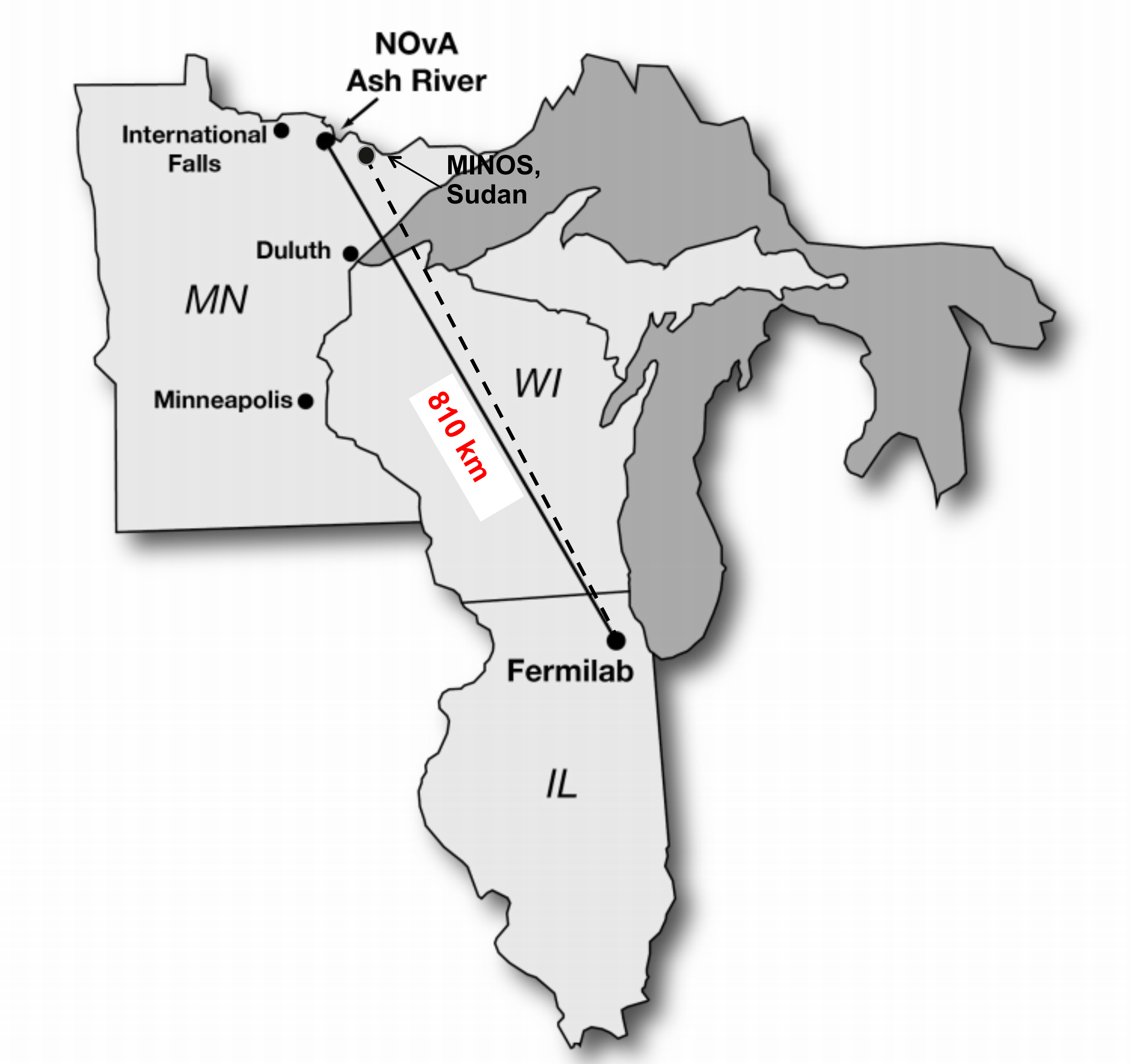
Longest baseline of any running accelerator neutrino experiment at 810km

Increased baseline increases sensitivity to mass hierarchy

The NOvA Experiment

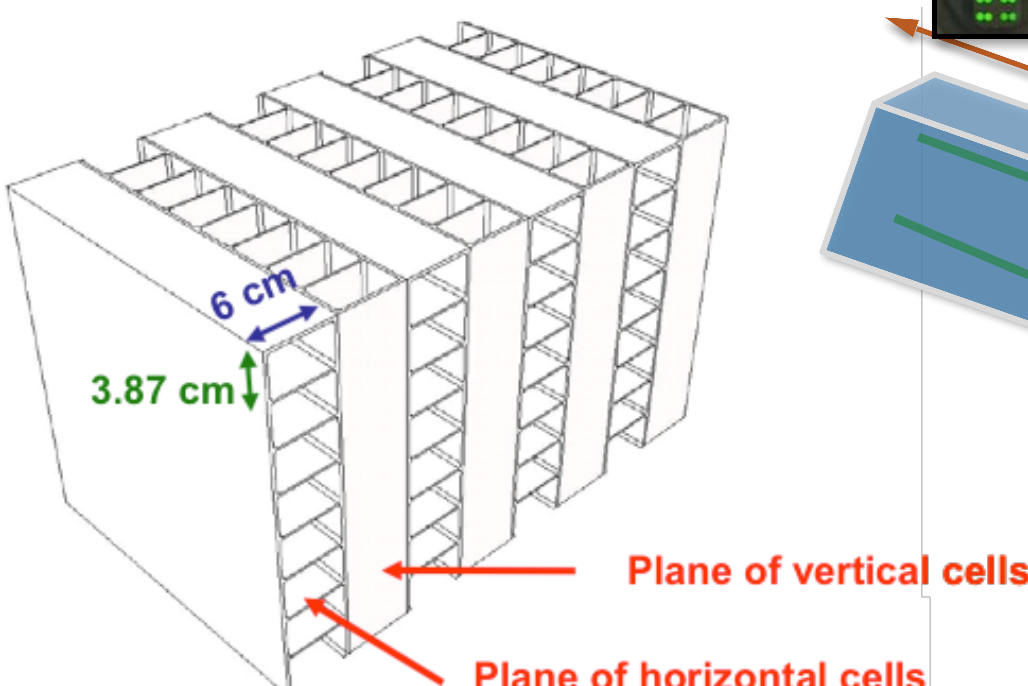
Design philosophy:

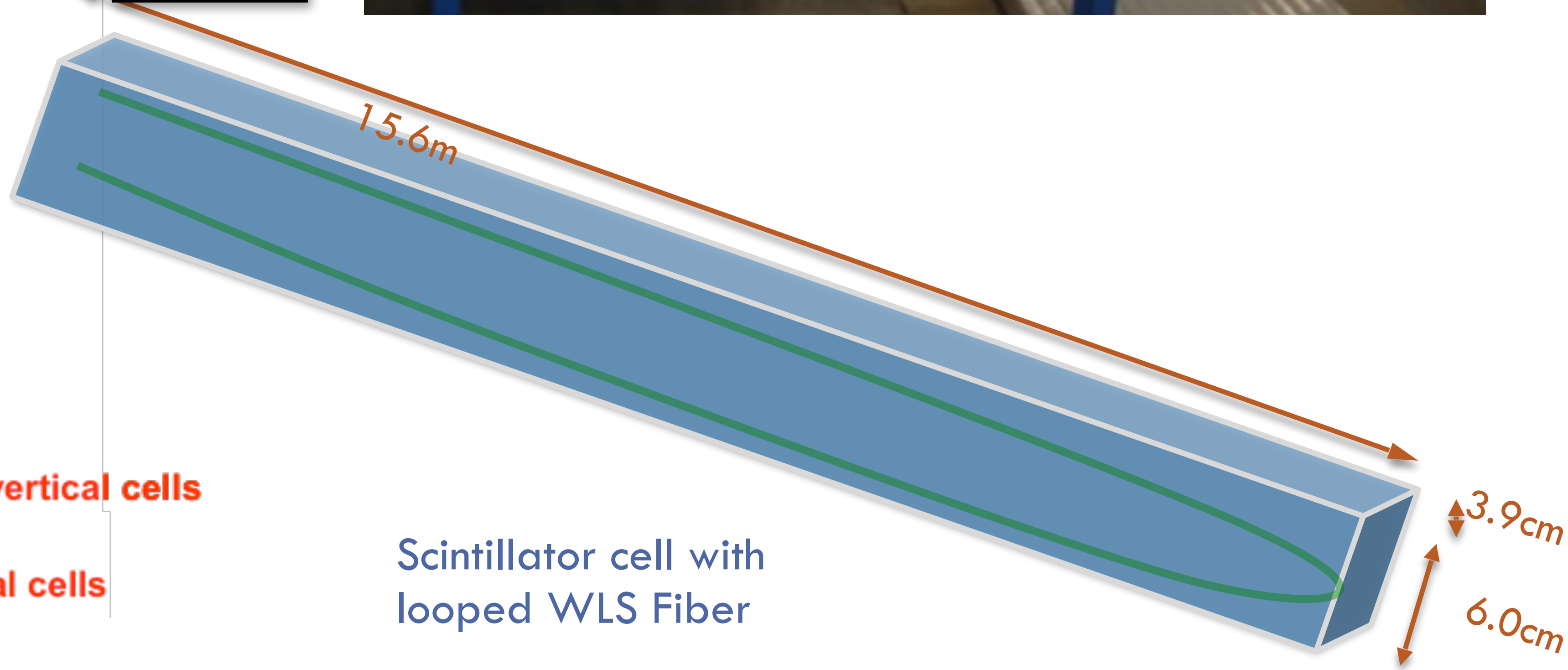
Combining 2 functionally identical detectors with an off axis beam mitigates many of the dominant errors associated with accelerator neutrino experiments



Detector Technology

- PVC extrusion + Liquid Scintillator
  mineral oil + 5% pseudocumene
- Read out via WLS fiber to APD
  FD has 344,064 channels
- Layered planes of orthogonal views

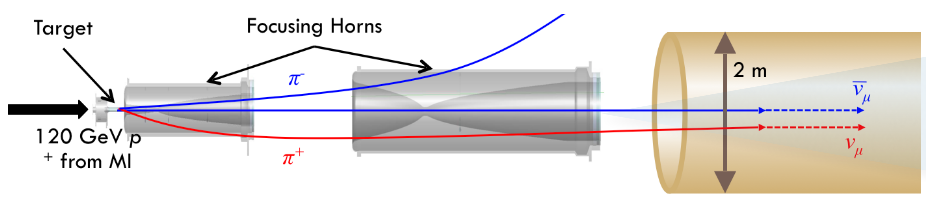




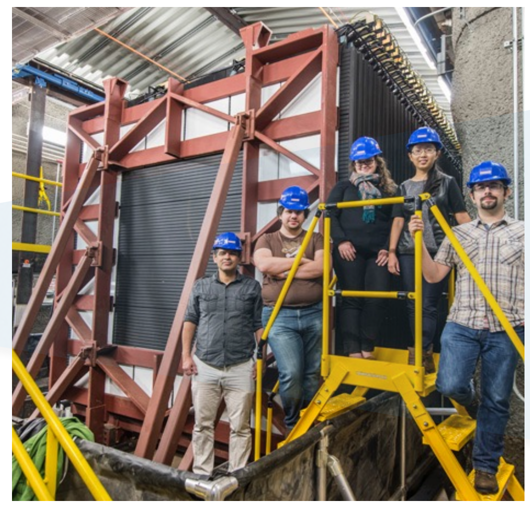
NOvA Detectors

NOvA Experiment

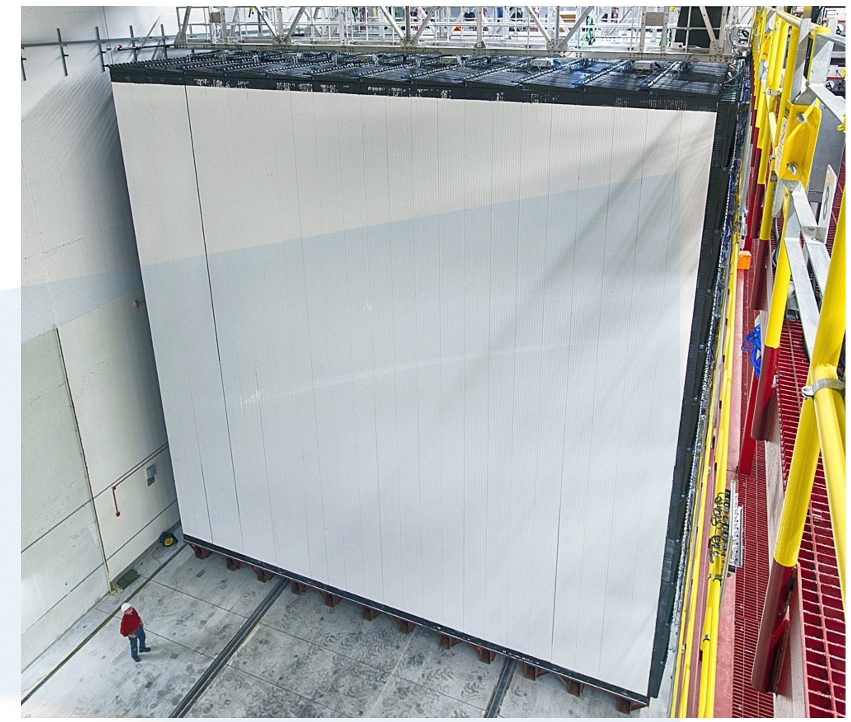
NuMI Beam



Near Detector



Far Detector



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

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

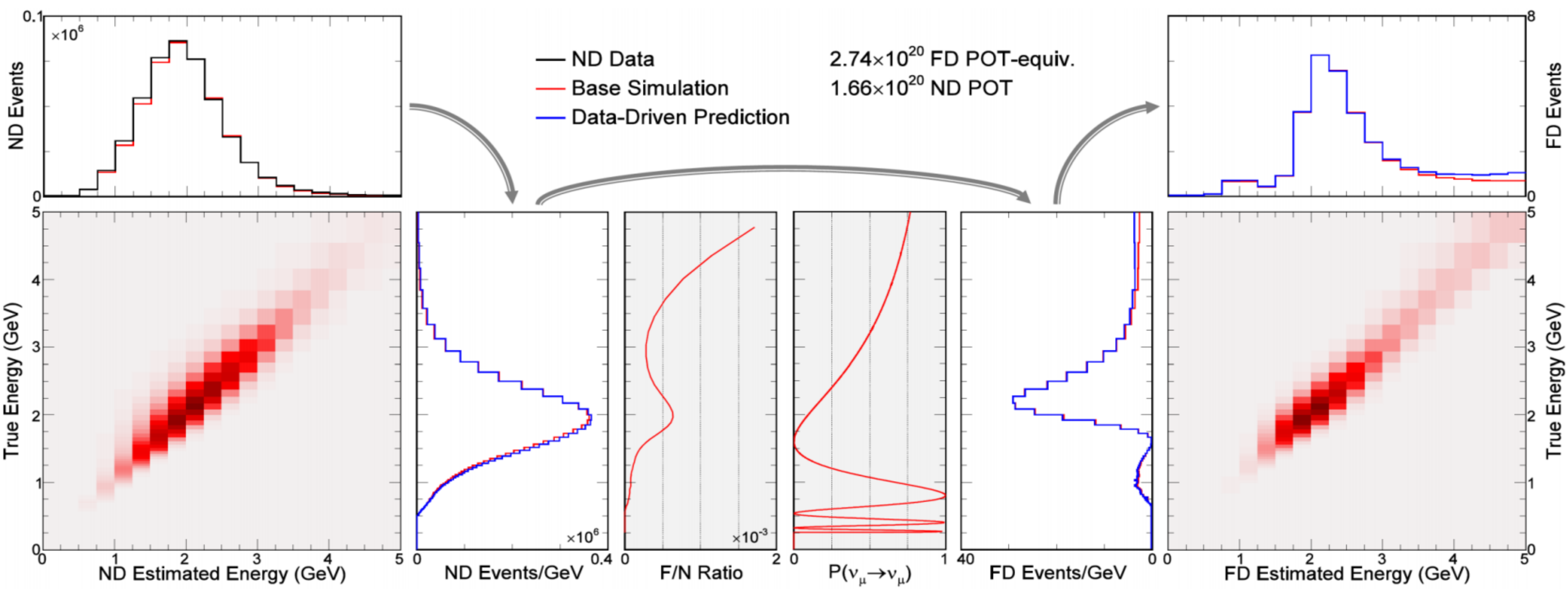
Inputs: Flux and cross sections Simulation,
ND data,
Past experiments,
NOvA Calibration sample etc.

Output:
FD prediction

Far Detector Prediction

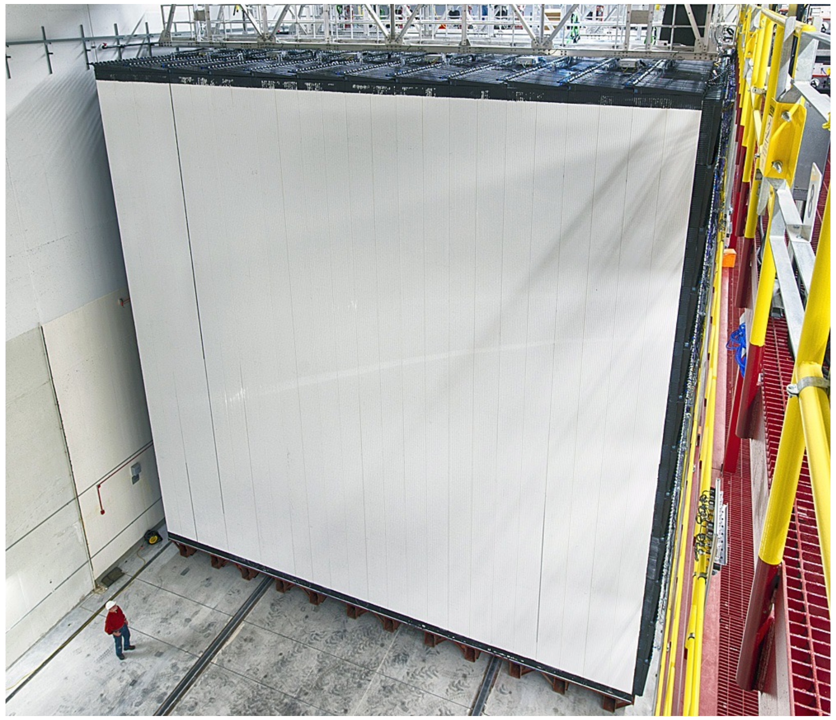
1) Estimate the underlying true energy distribution of selected ND events
2) Multiply by expected Far/Near event ratio and $\nu_\mu \rightarrow \nu_\mu$ oscillation probability as a function of true energy
3) Convert FD true energy distribution into predicted FD reco energy distribution

Systematic uncertainties assessed by varying all MC-based steps

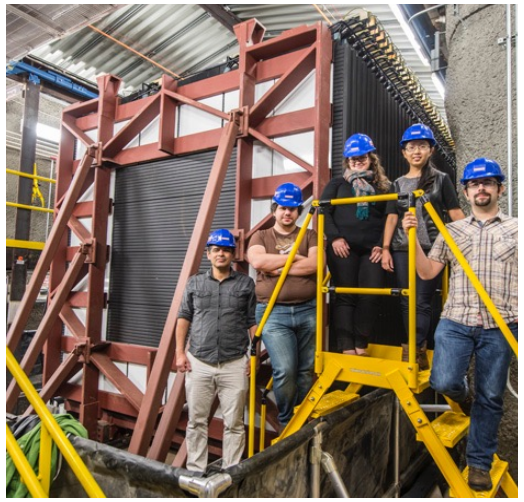


NOvA Experiment

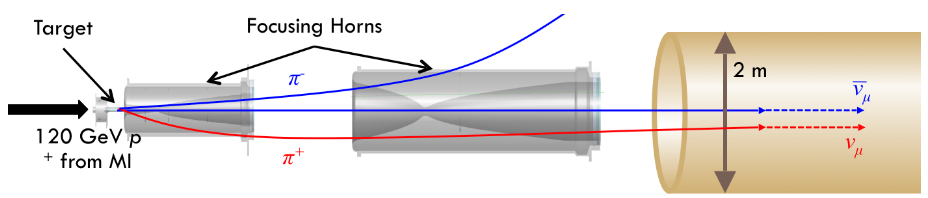
Far Detector



Near Detector



NuMI Beam



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- **Use of a ratio measurement allows for cancelation of most systematics**

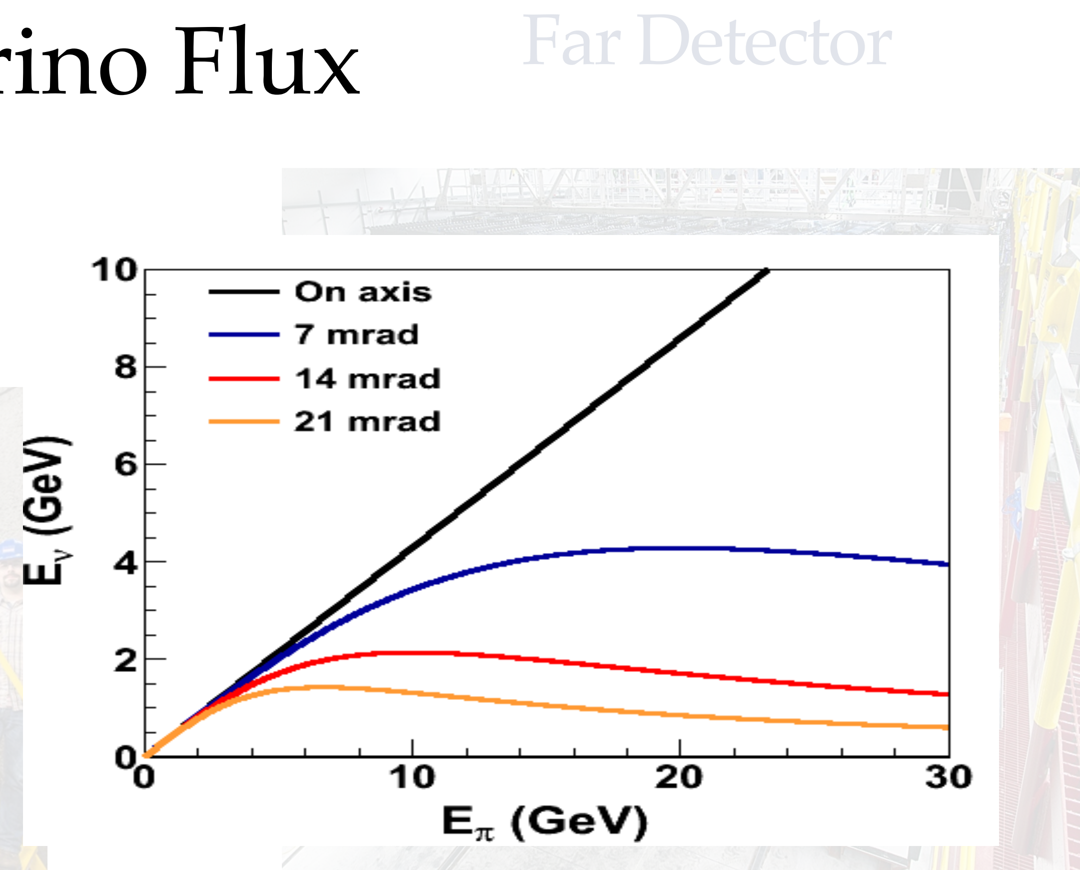
Inputs: Flux and cross sections
Simulation,
ND data,
Past experiments,
NOvA Calibration sample etc.

External
Internal
Data driven

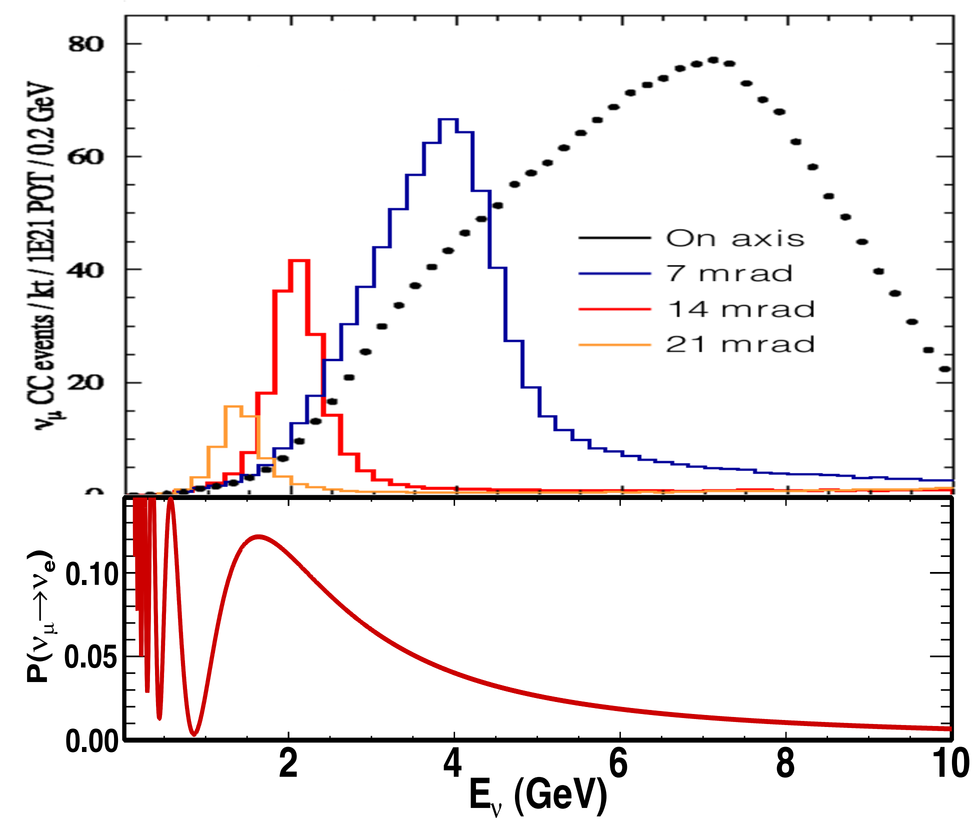
Output:
FD prediction

Systematics: Neutrino Flux

- 14 mrad off-axis beam
- Neutrino energy relies on the angle between π decay and ν interaction in detector
  - Off-axis the dependence on pion energy becomes flat



- Location reduces NC and ν_e CC backgrounds in the oscillation analyses while maintaining high flux at 2 GeV.



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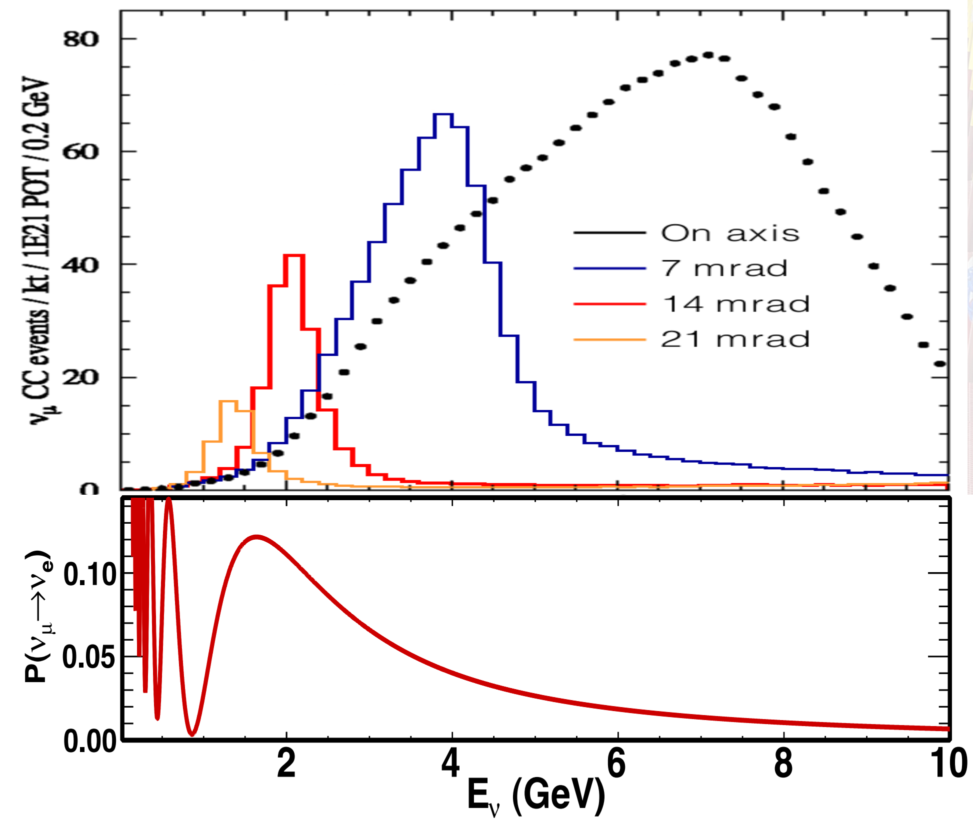
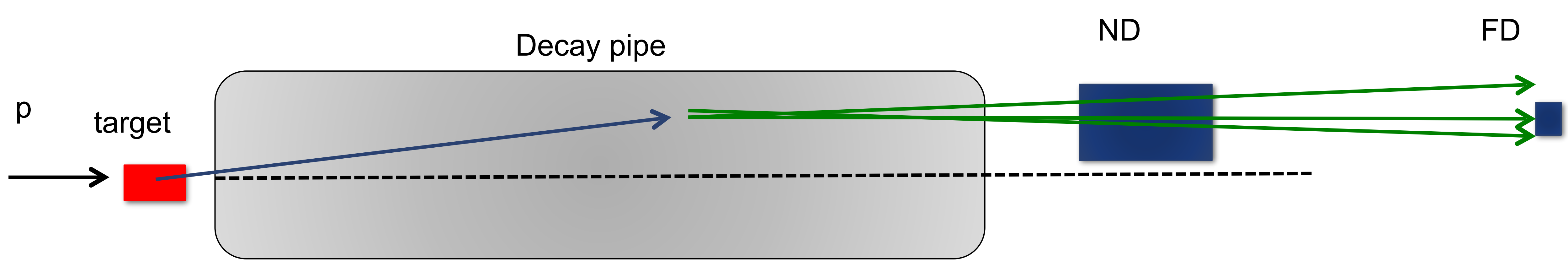


- Location reduces NC and ν_e CC backgrounds in the oscillation analyses while maintaining high flux at 2 GeV.
- **The ND and FD have similar but not identical spectrum**

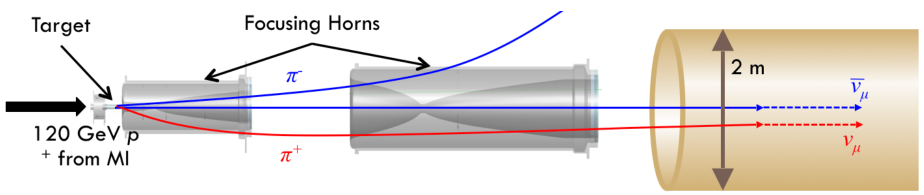


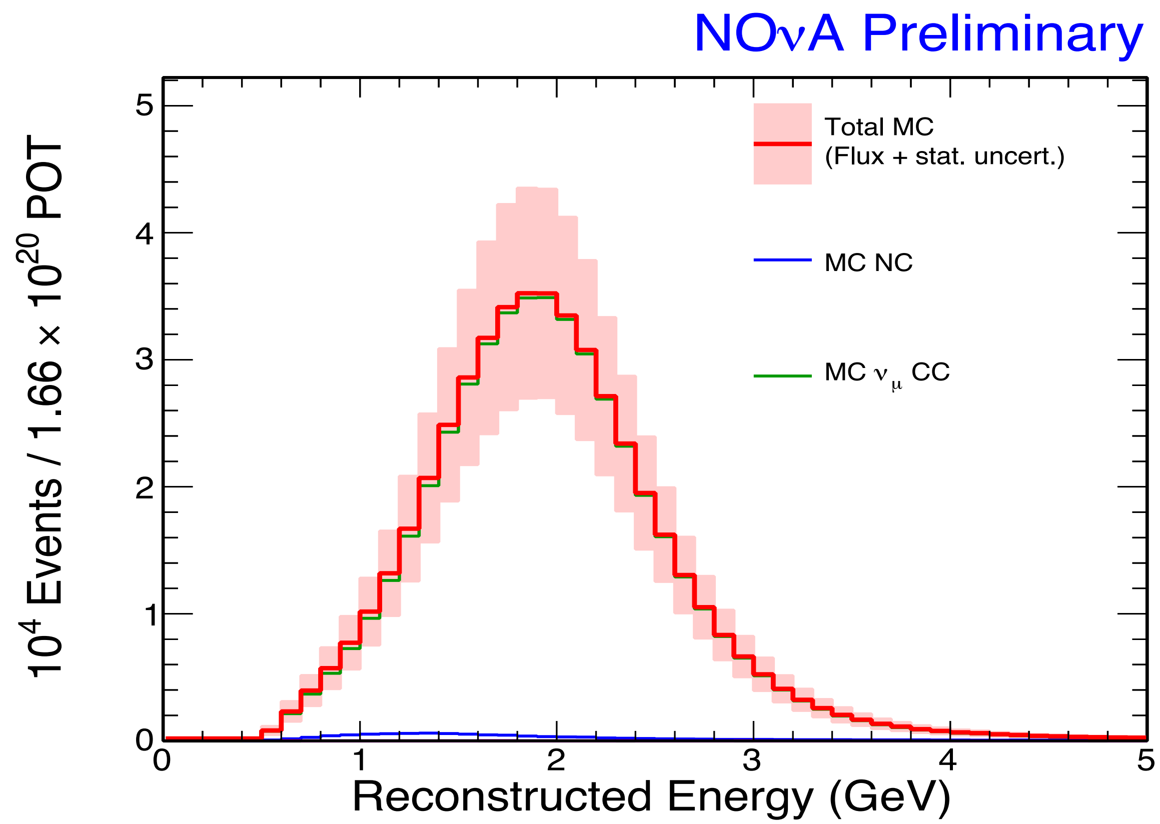
Systematics: Neutrino Flux

Far Detector

Near Detector

NuMI Beam





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%.

Possible future improvements:
MIPP hadron production data and MINERvA flux, NuMI X

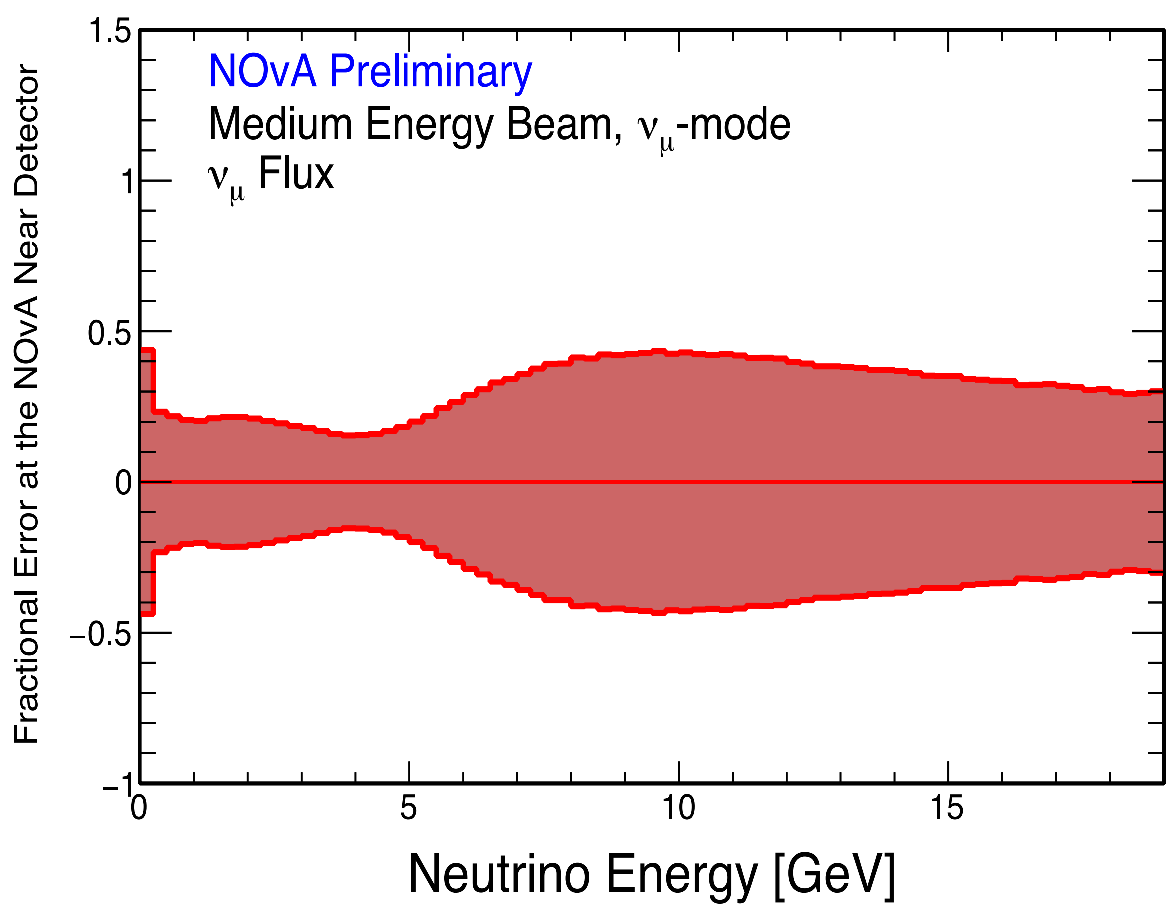
External

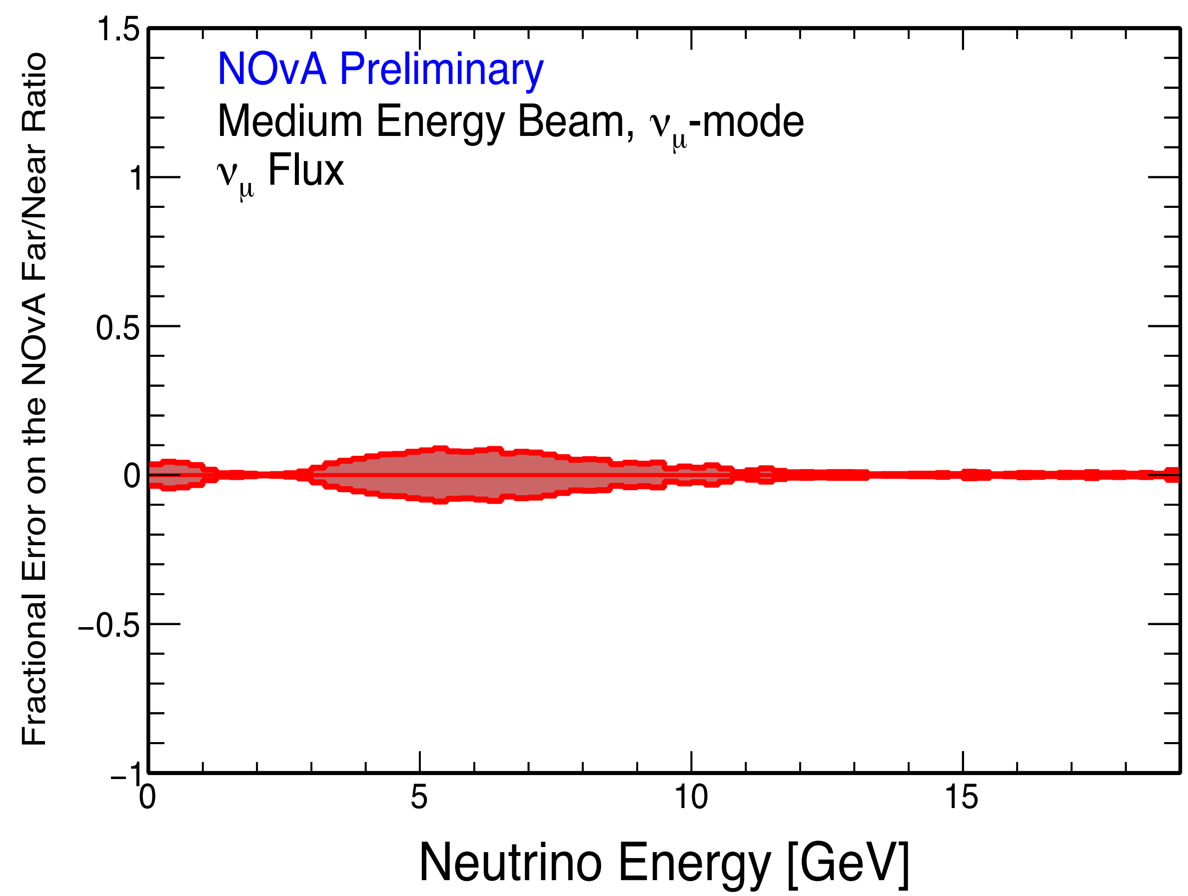
Beam ν_e elastic cross section

Internal, Data driven

Systematics: Neutrino Flux

Constrained by ND data, beam systematic errors in FD prediction are negligible



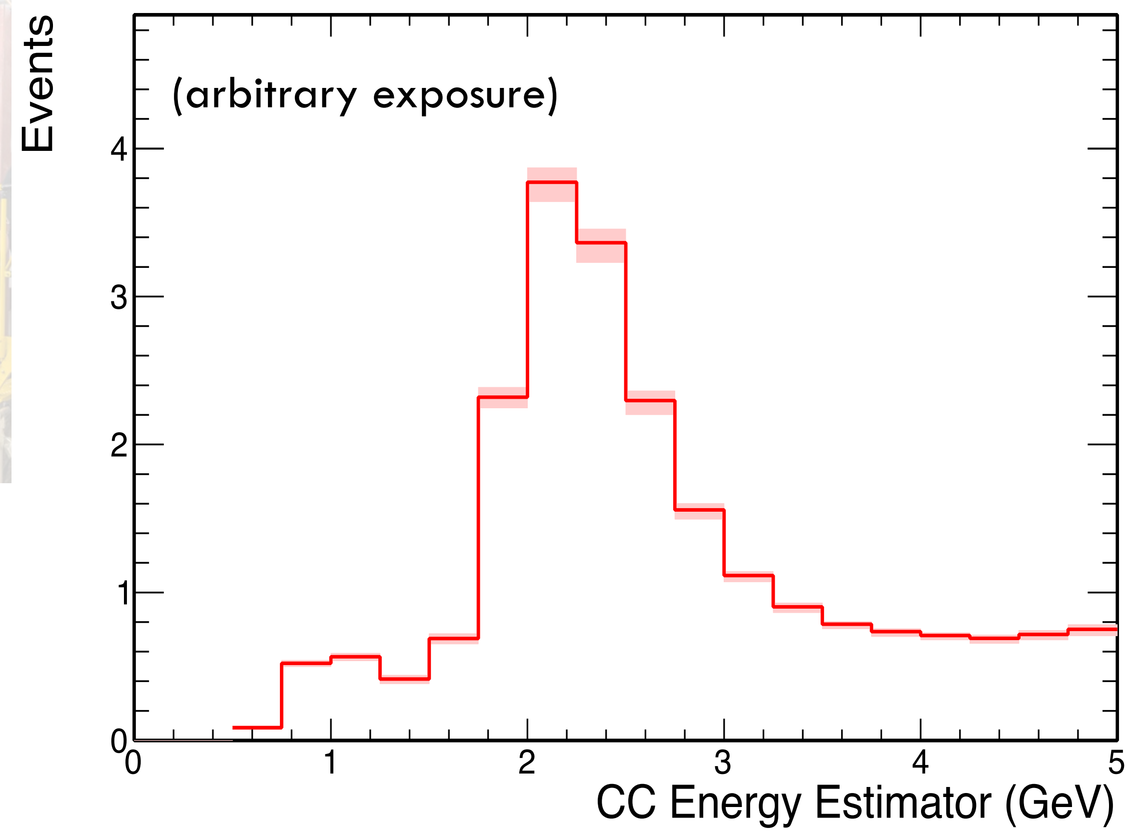


Systematics: Neutrino Interaction

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

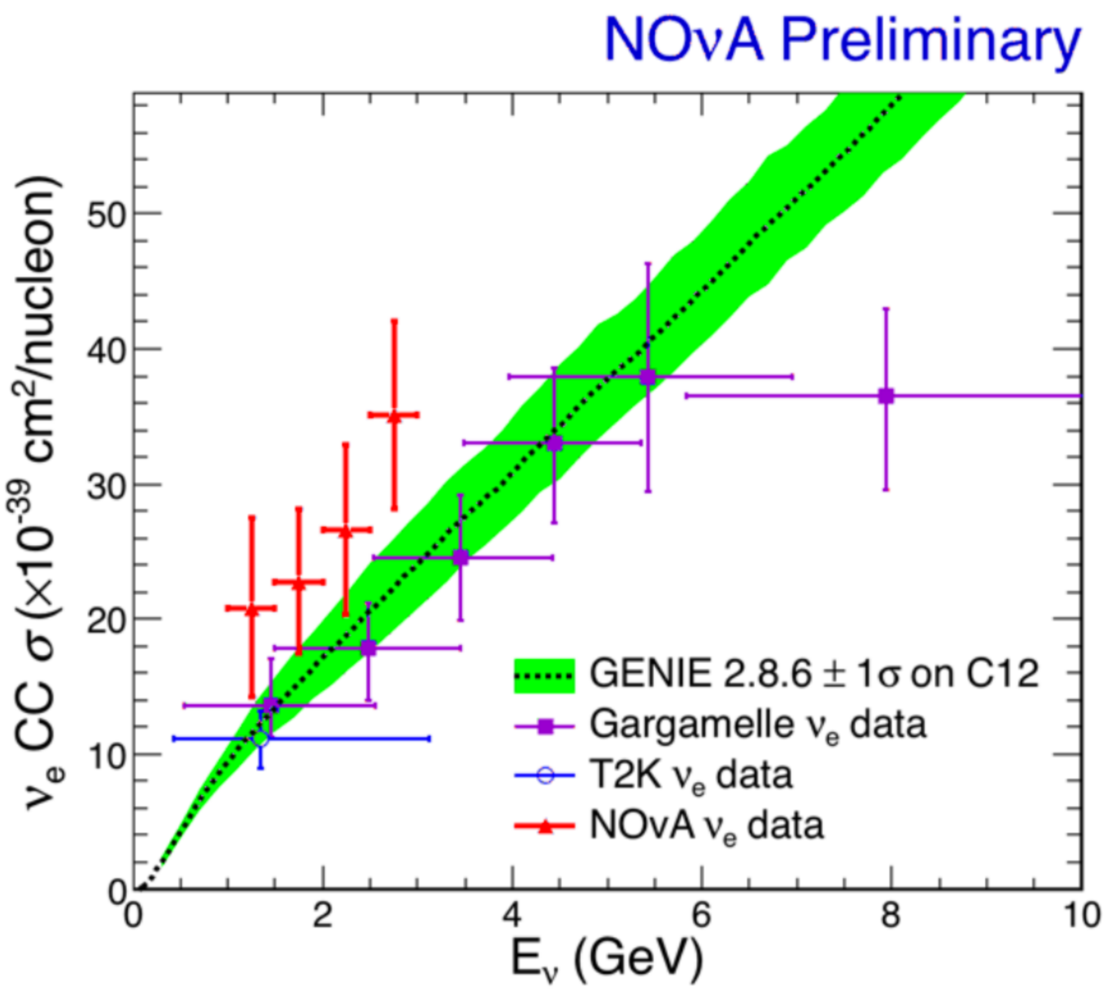
Possible future improvements:

Data from Minerva, MiniBooNE — External

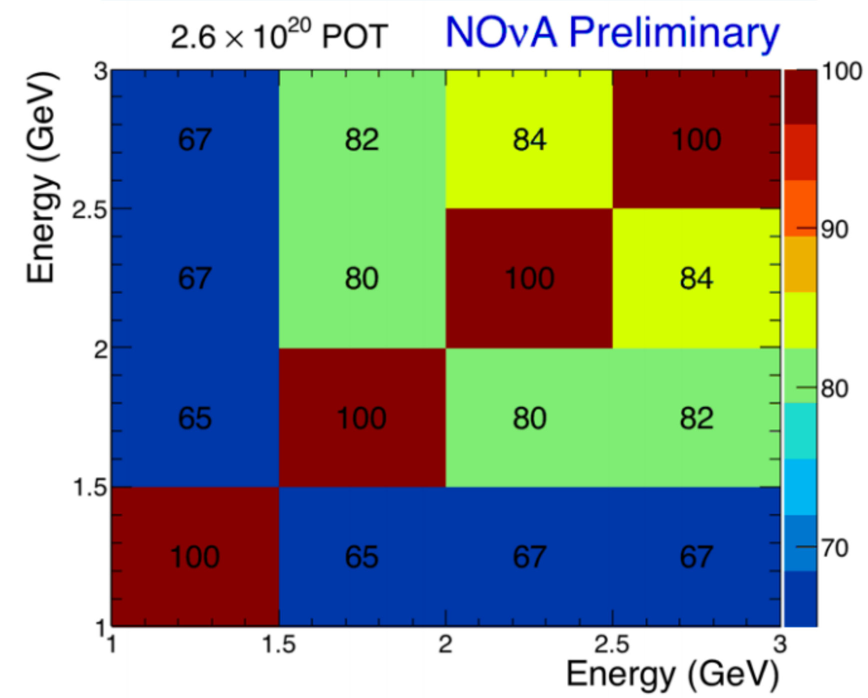
Cross section measurements in NoVA — Internal, Data driven

GENIE modelling 2p2h etc. — Internal

Neutrino Cross sections from NOvA



Bin to bin correlation matrix:



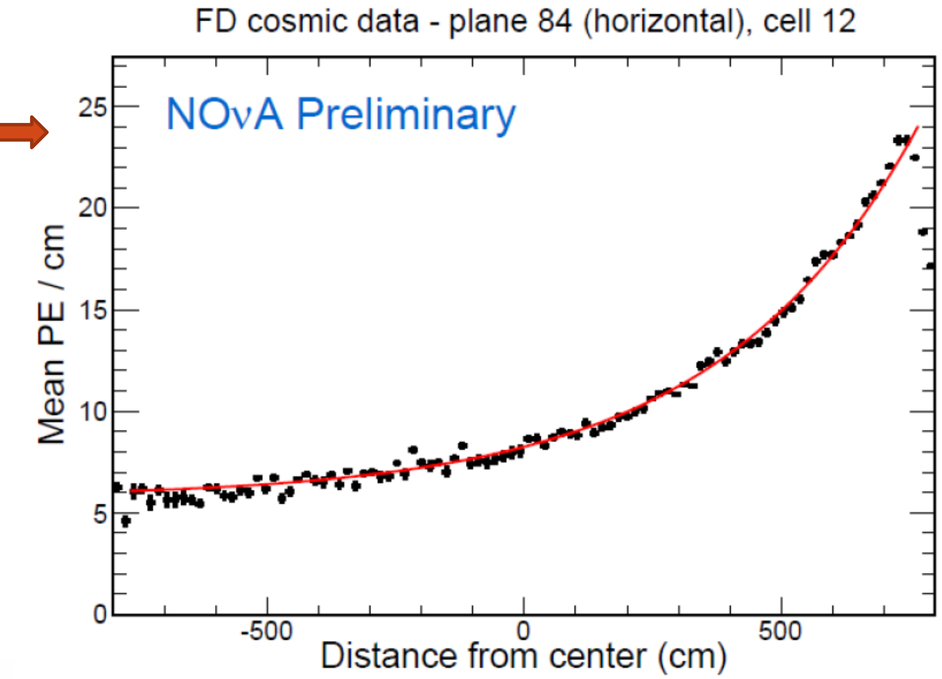
Mass weight of detector component:

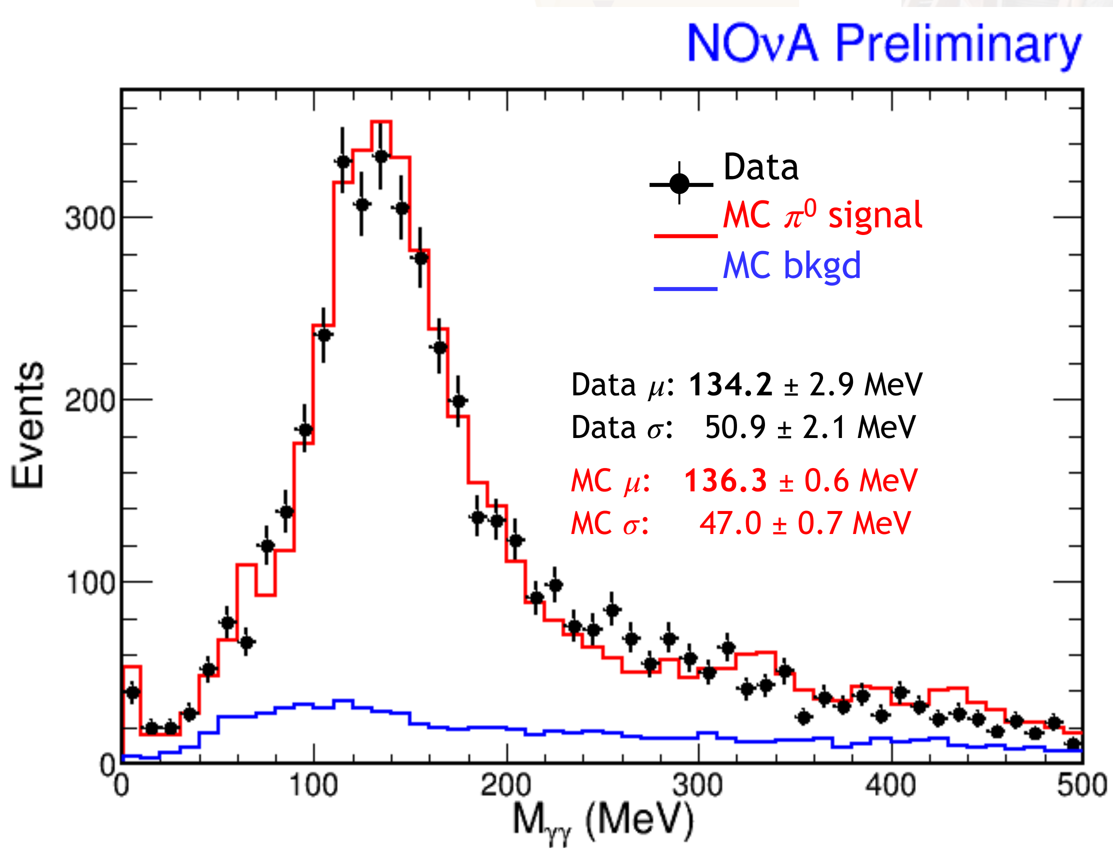
C12	Cl35	H1	Ti48	O16	Others
66.8%	16.4%	10.5%	3.3%	2.6%	0.4%

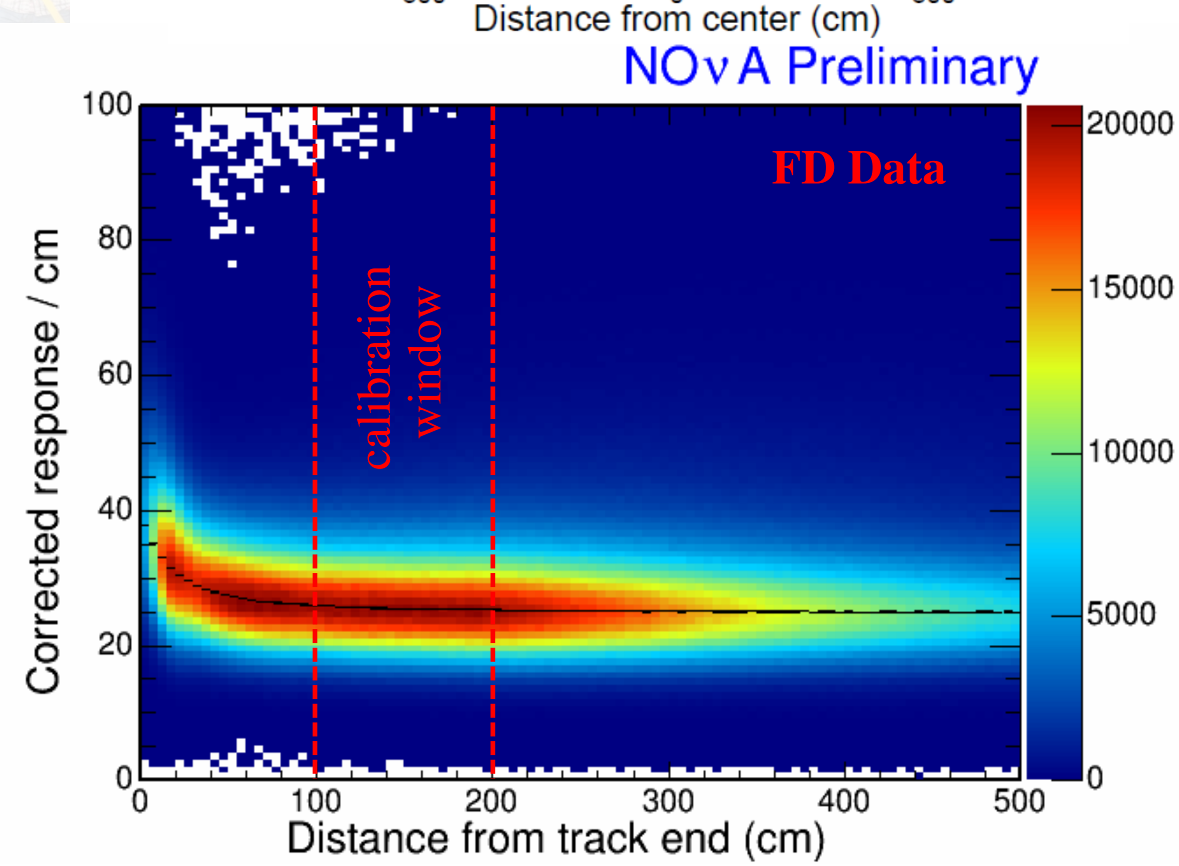
The measured inclusive cross section from Gargamelle, T2k, and NOvA as shown. There is also shown the predicted cross section for nue on carbon from GENIE. There is large correlation between the energy bins for NOvA results (see Top table). Our detector material is dominant by the carbon, chlorine, and hydrogen.

Systematics: Detector effects

- Biggest effect that needs correction is attenuation in the WLS fiber: Example FD cell
- Stopping muons provide a standard candle for setting absolute energy scale (bottom right)
- Multiple probes of Energy scale
  - Michel e- spectrum, π^0 mass (below), μ dE/dx
  - All agree within ±5%







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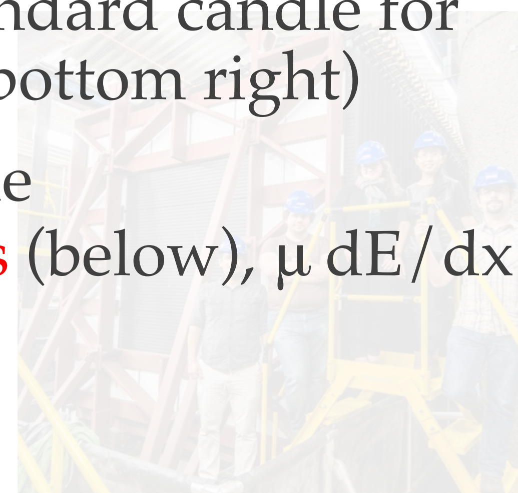
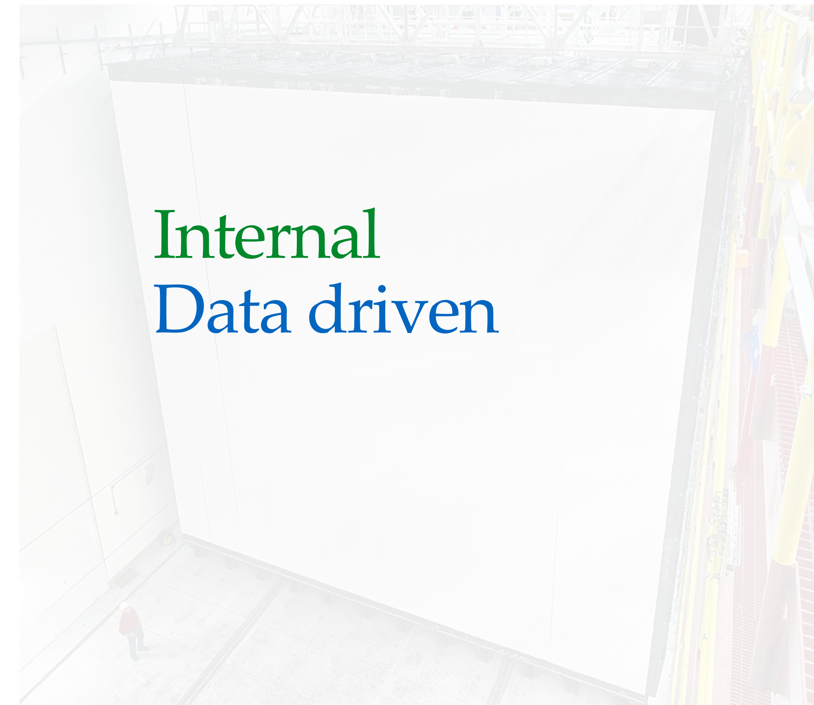




Internal
Data driven

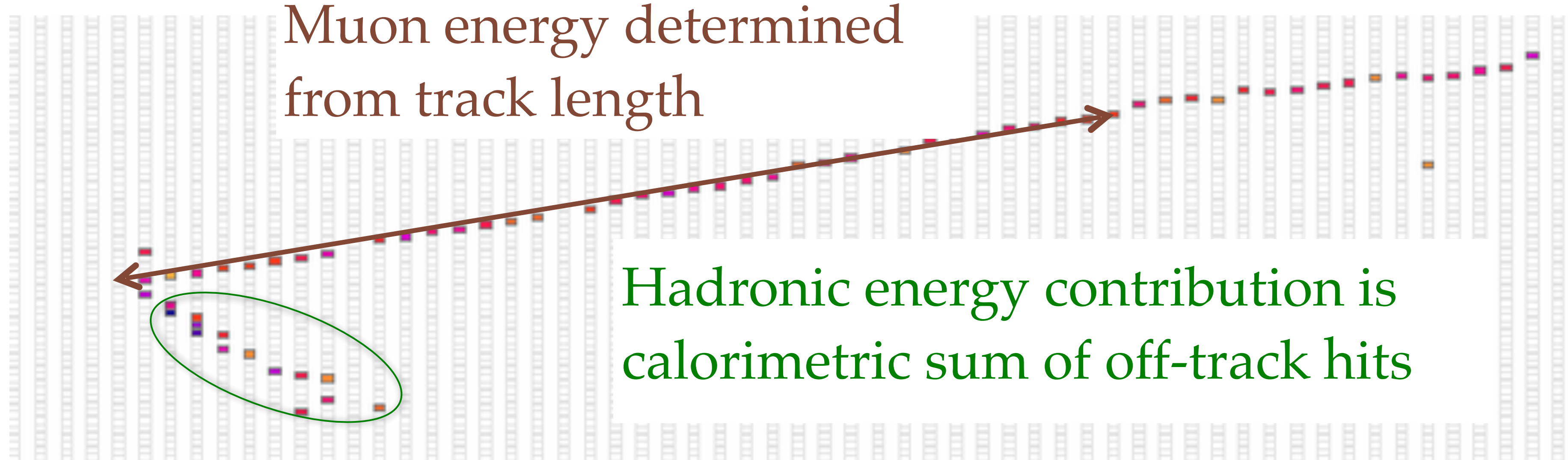
Possible future improvements:

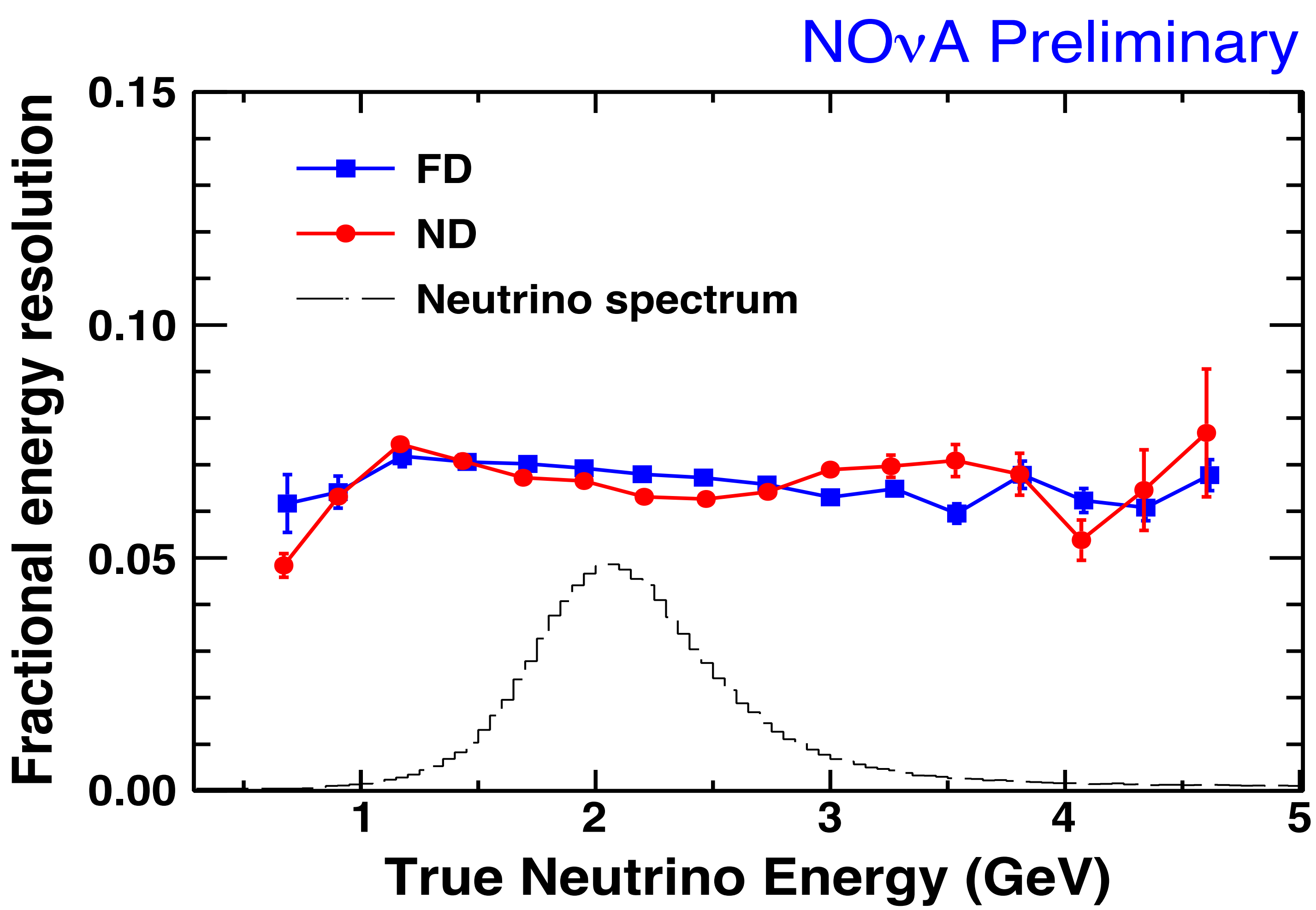
- GEANT simulation
- Test beam

personal note: alignment, geometry often overlooked

NOvA: Energy Estimation

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



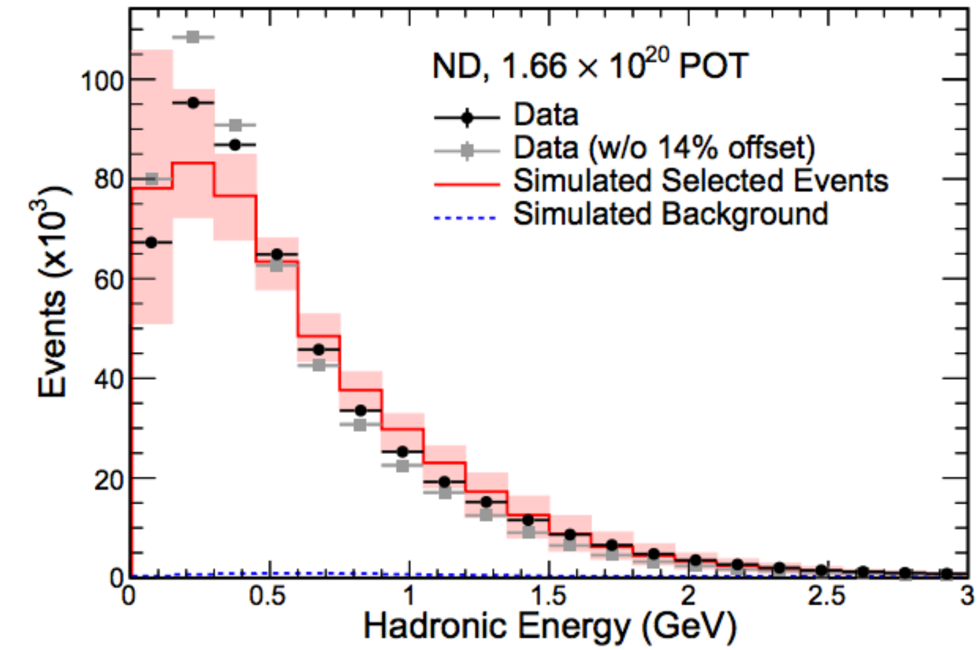


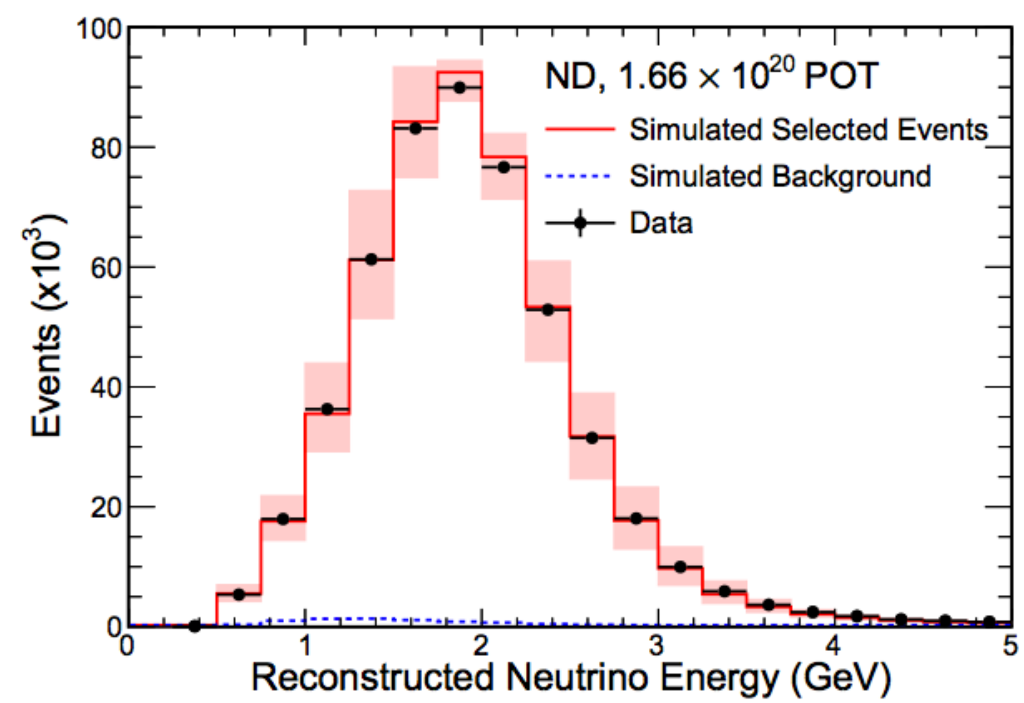
Energy resolution at 2 GeV beam peak is ~7%

NOvA: Energy Estimation

$$E_\nu = E_\mu + E_{\text{hadrons}}$$

- Good agreement for muon simulation but the simulated hadronic system has 14% more energy than in data.
- Neutrino energy is well known from π-decay kinematics in off-axis beam
- 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
- Additionally implies a detector-to-detector relative energy systematic





Source of Uncertainty	Fractional Uncertainty $\sin^2\theta_{23}$ ($\pm$%)	Fractional Uncertainty Δm^2_{32} ($\pm$%)
Absolute Calorimetric Energy Calibration (14.9%)	4.1	2.6
Relative Calorimetric Energy Calibration (5.2%)	3.4	0.6
Muon Energy Scale (2%)	2.2	0.8
Cross Sections and Final State Interactions (15 – 25%)	0.8	0.6
NC and ν_τ CC Backgrounds (100%)	3.0	0.6
Particle-Transport Modeling	1.5	0.6
Beam Flux (21%)	1.3	0.3
Normalization (1.4%)	0.4	0.2
Other Oscillation Parameters	1.8	2.2
Total Systematic Uncertainty	6.8	3.7
Statistical Uncertainty	17.0	4.5

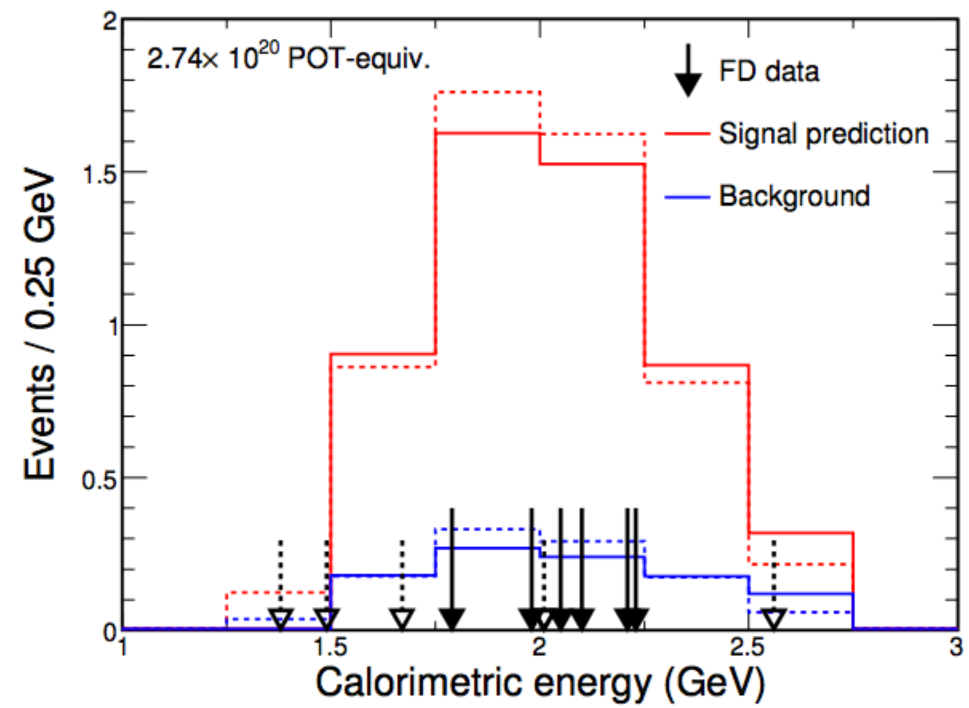
TABLE I. Impact of the sources of uncertainty on the expected sensitivity of the measured values for $\sin^2\theta_{23}$ and Δm^2_{32} evaluated at the test point of $\sin^2\theta_{23} = 0.5$ and $\Delta m^2_{32} = 2.5 \times 10^{-3}\,\mathrm{eV}^2$.

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

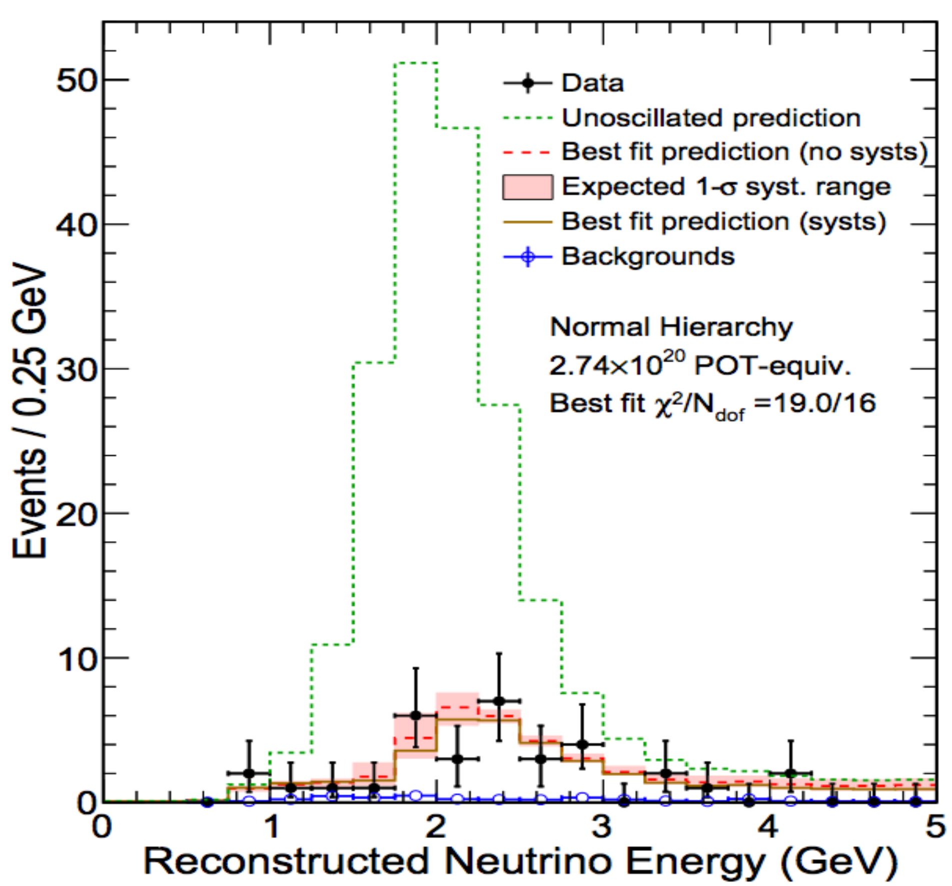
First NOvA Results

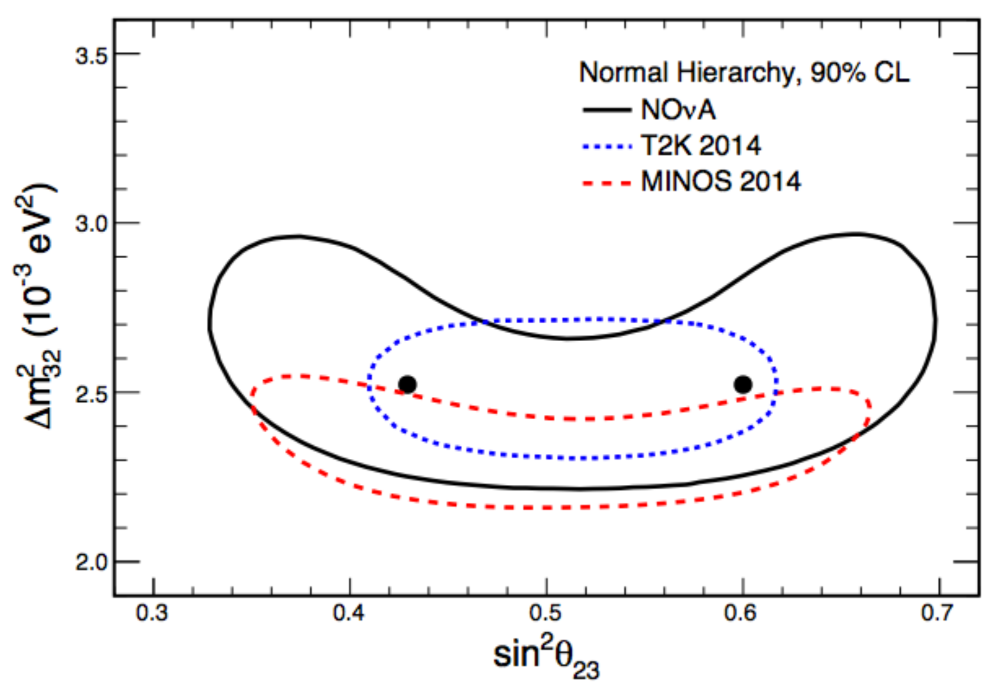
First analysis papers :
arXiv:1601.05022
arXiv:1601.05037

electron neutrino appearance



muon neutrino disappearance



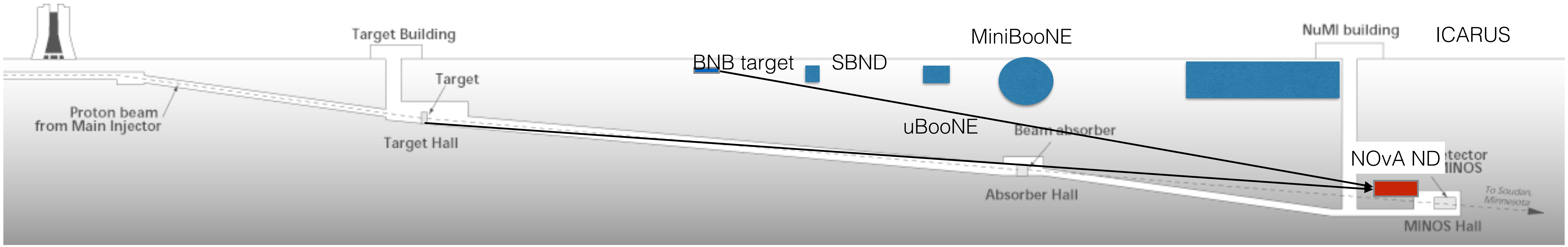


NOvA Summary

- First NOvA analyses have the luxury of conservative systematics.
- Future analyses will have multiple handles to mitigate systematics further

Wait there's more…

Using multiple beams and detectors



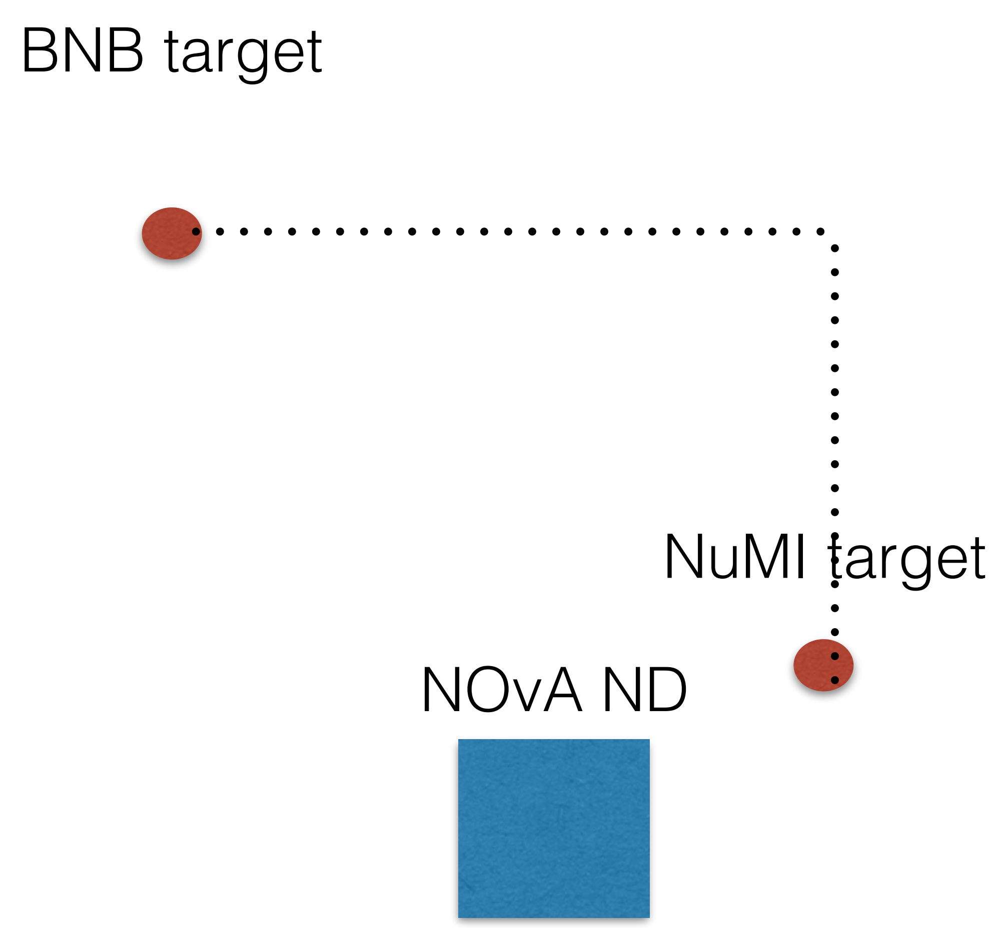
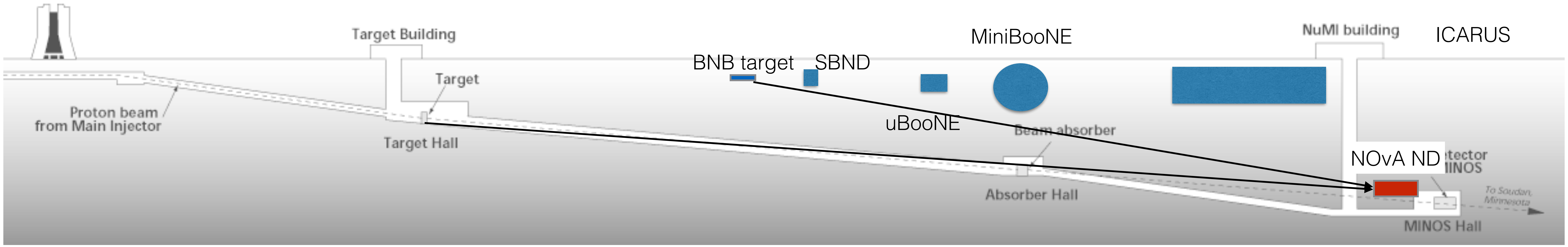


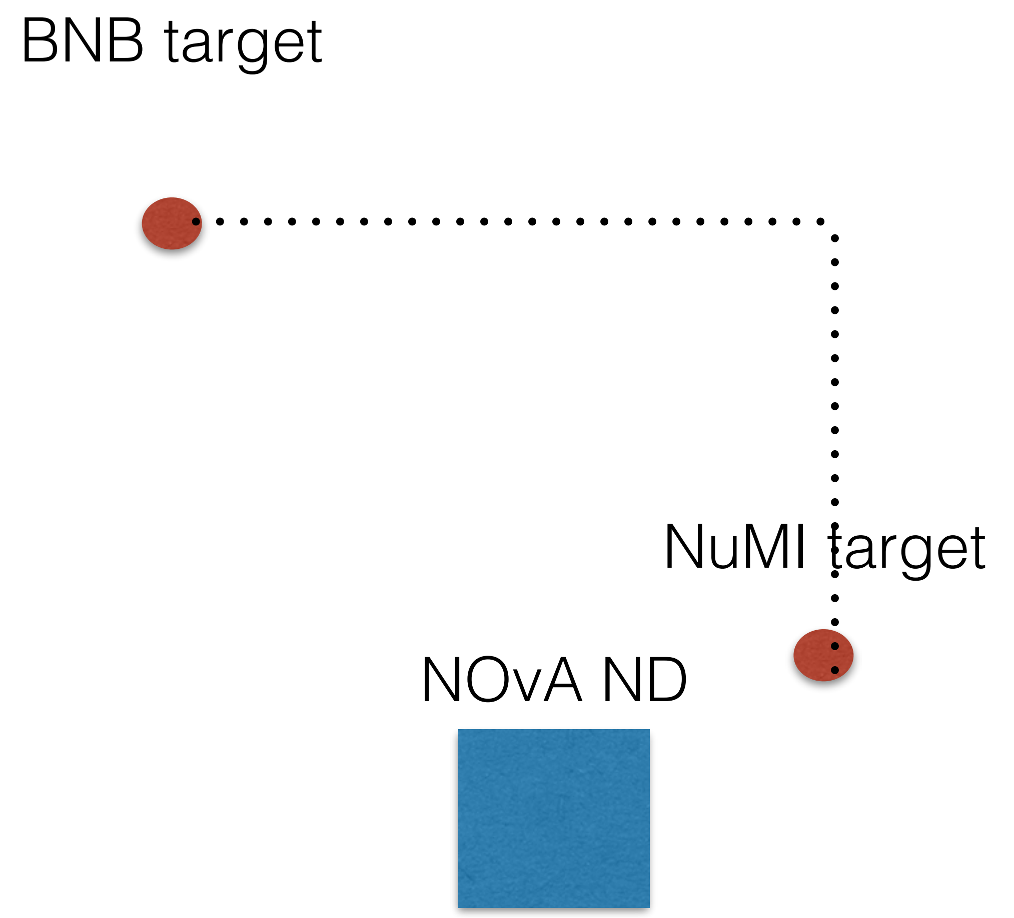
Diagram is for illustrative purposes only, not to scale

Using multiple beams and detectors



Writing the L/E's…

- MiniBooNE (BNB) L/E~0.5 km /0.8 GeV ~0.6
- NOvA ND (NuMI) L/E~1km /2 GeV ~0.5
- NOvA ND (BNB) L/E~0.8km /1.4 GeV ~0.6
- NOvA in a position to study low-energy excess
- Do MiniBooNE excess scale with energy
  - 0.2 - 0.5 GeV -> 0.4 - 1.0 GeV in NOvA ND



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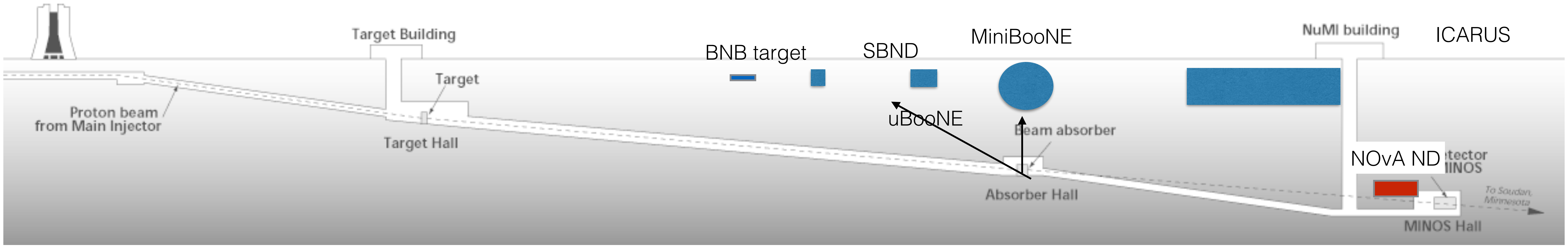
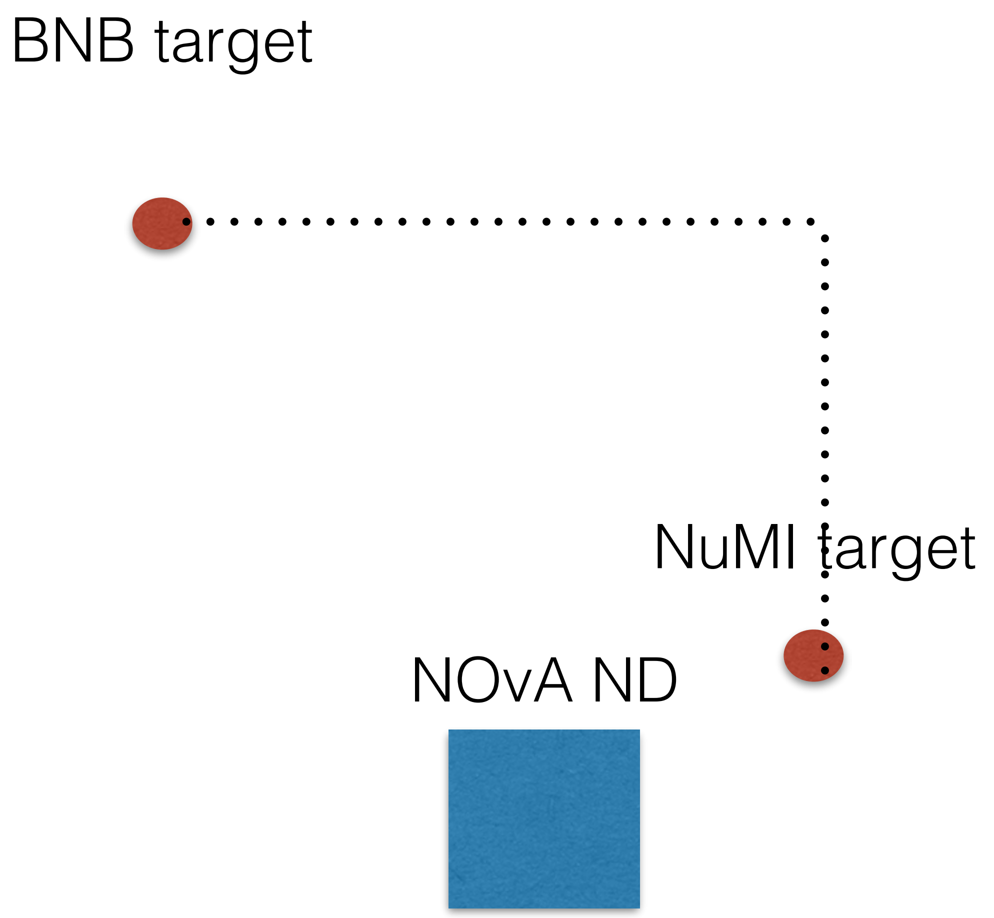


Other studies

- Check energy scale in NOvA ND (kaon DIF)
- Cross section measurements (two beams one detector)
- Mono-energetic kaon DAR beam from NuMI dump (MB, SBND)
- Exotics : Beam produced dark matter



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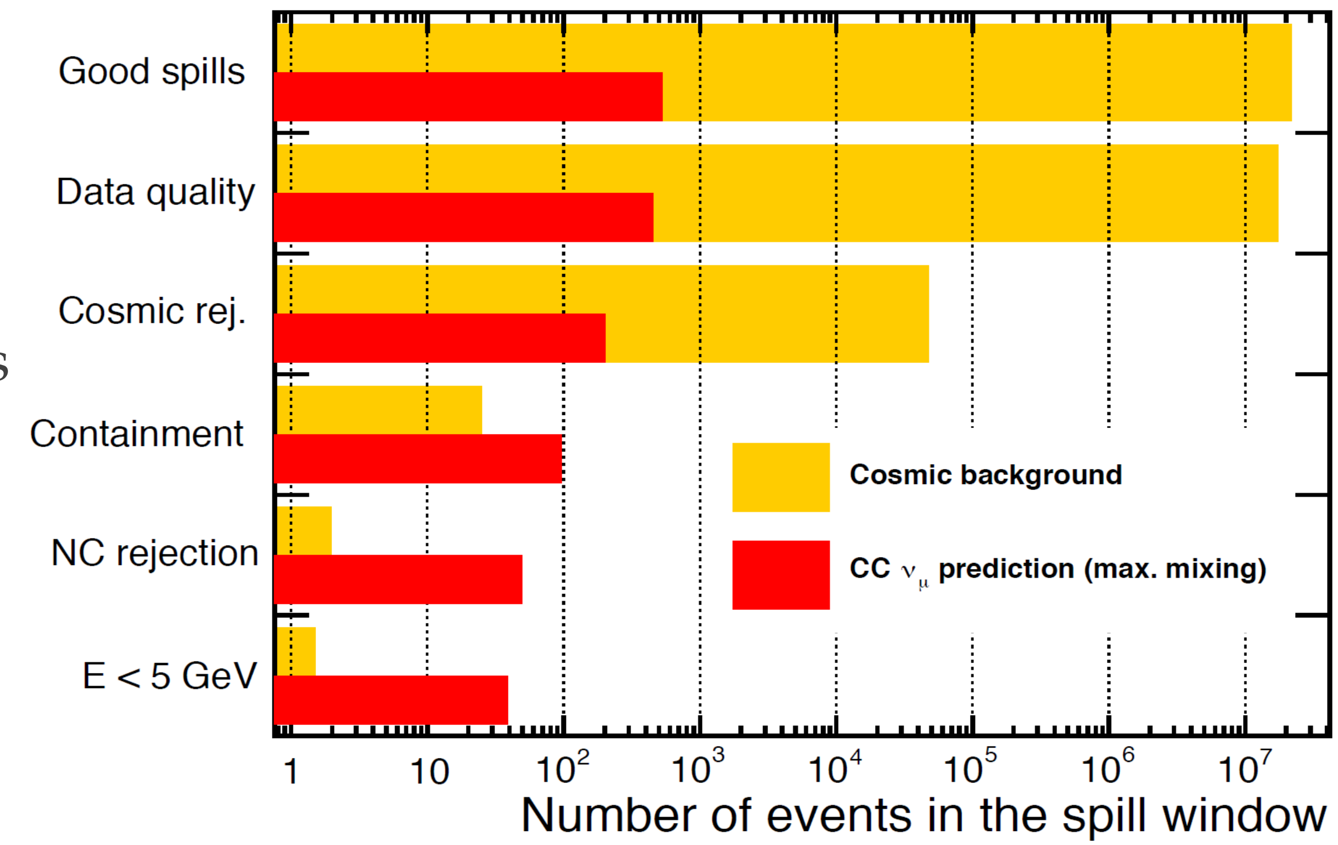
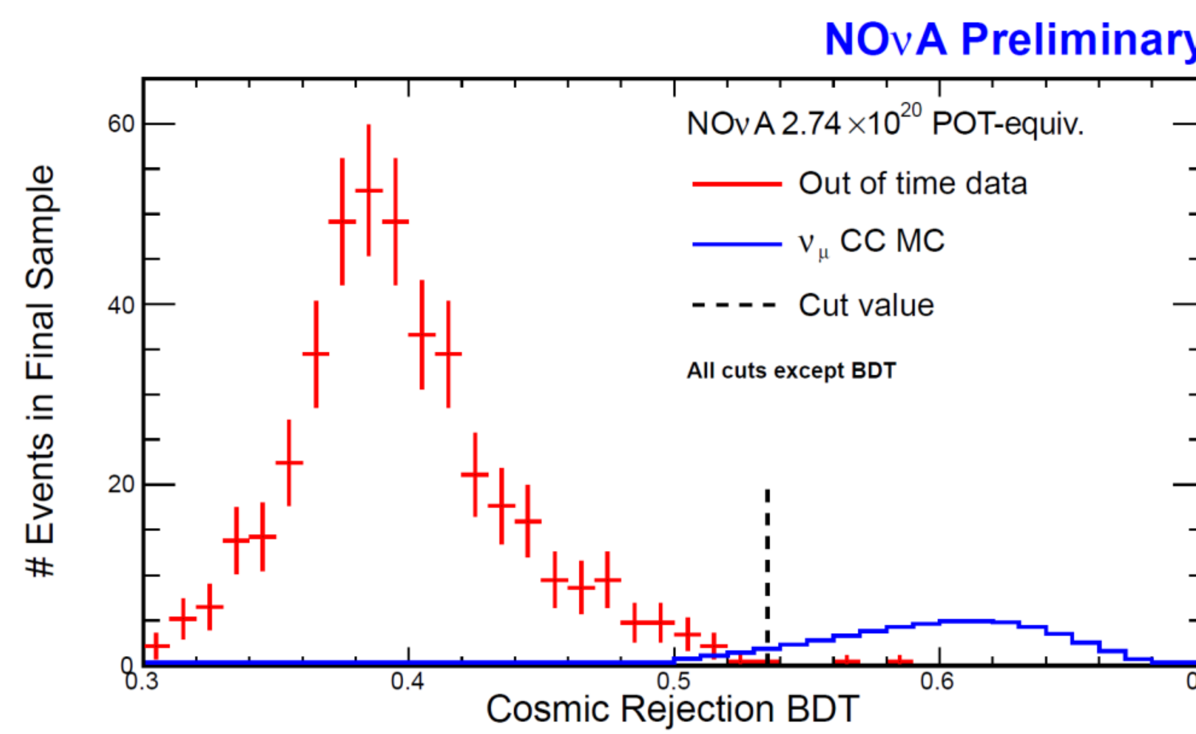
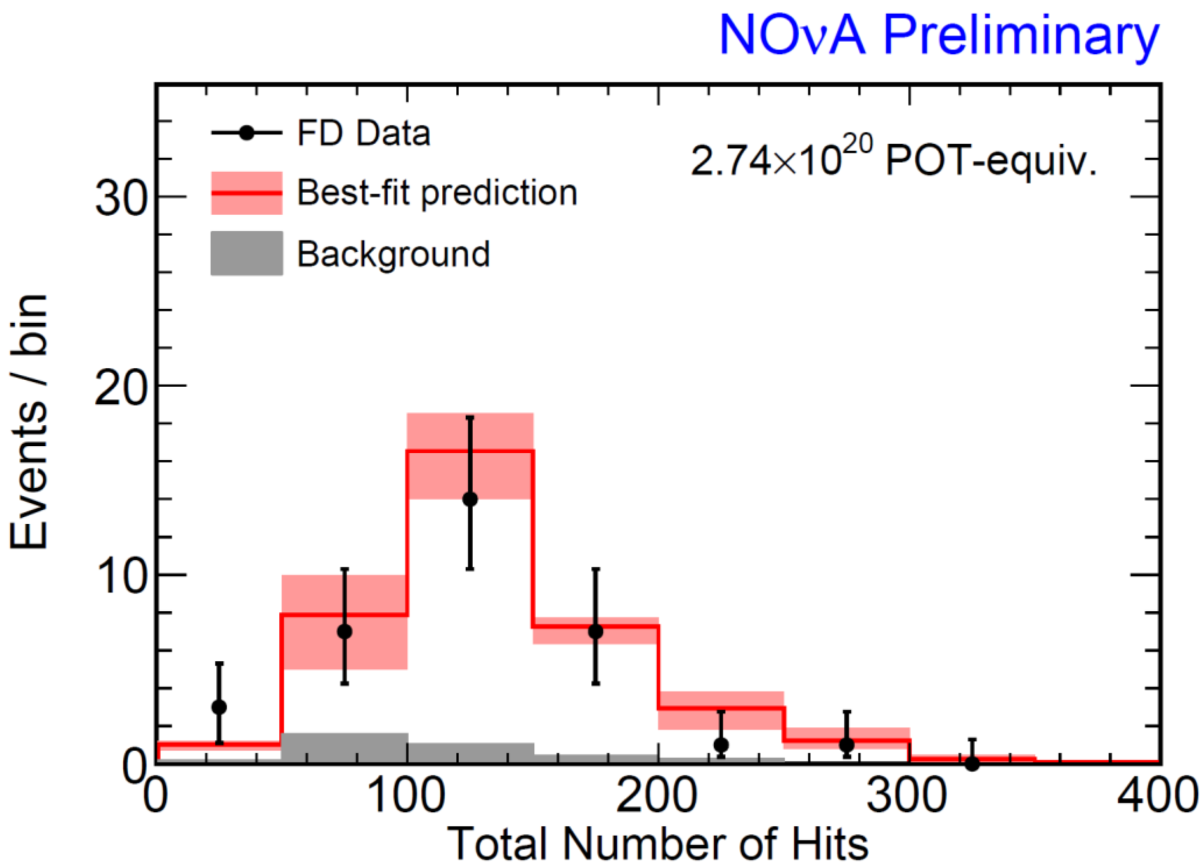
Backups

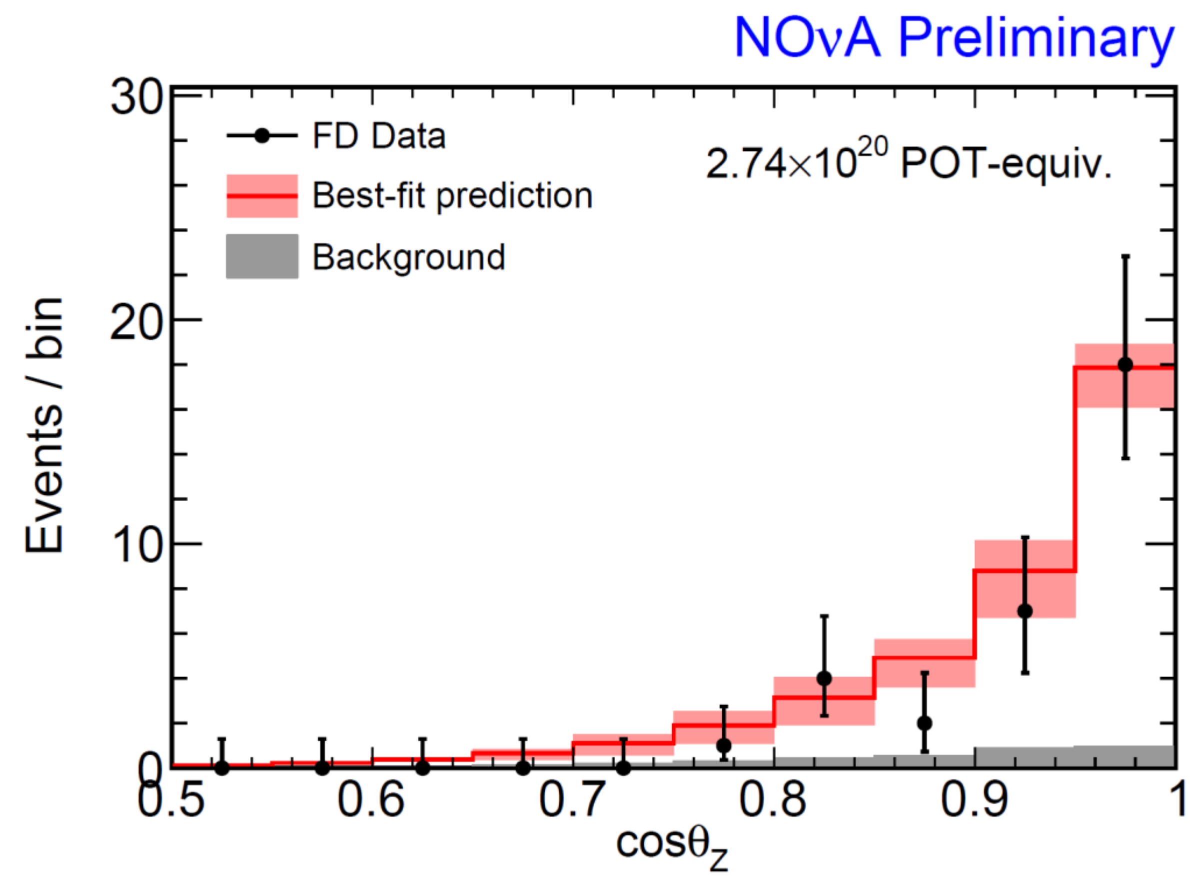
Cosmic Rejection

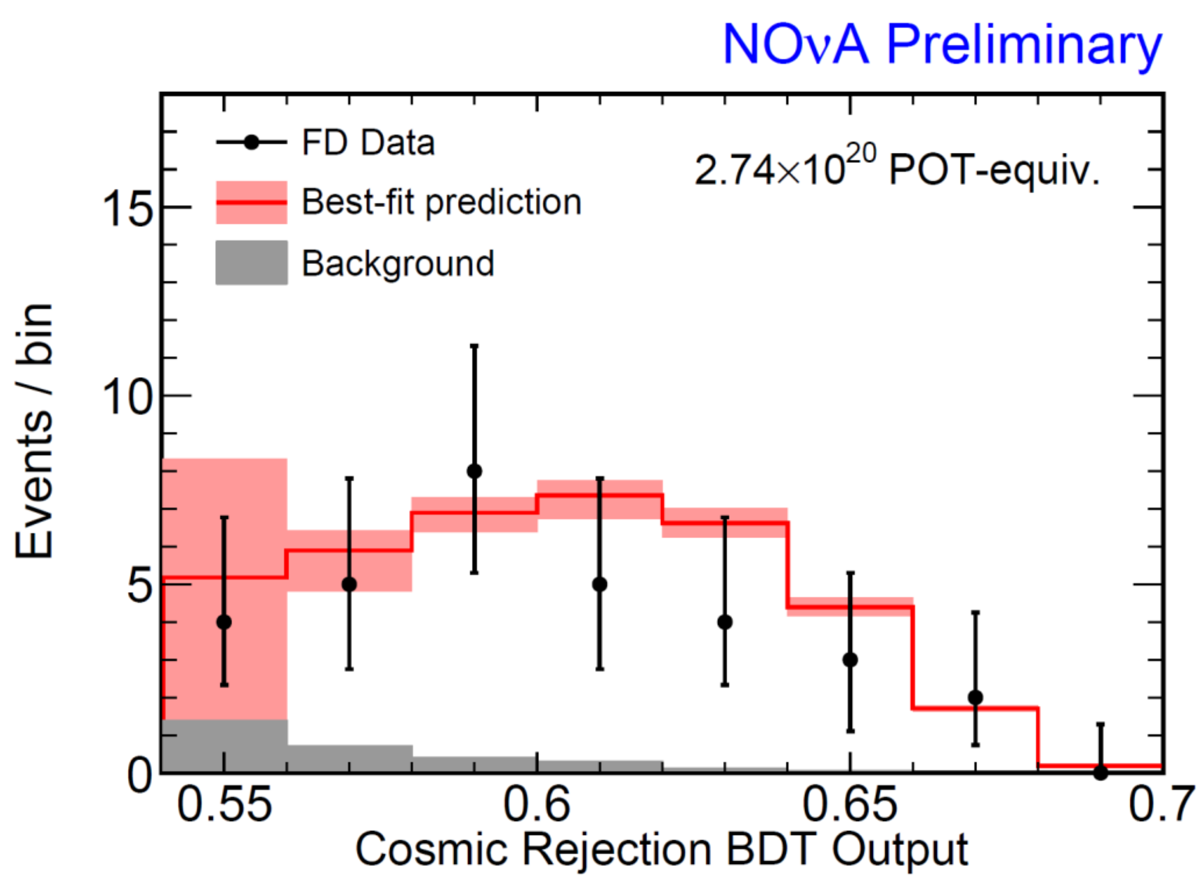
- Cosmic rate is ~150kHz
- Rejection factor from
  - beam timing: 10^5 (pulsed beam, 9.6us every 1.3s)
  - event topology: 10^7
- Final cosmic background rate is measured directly using beam-off FD data
- Use a cosmic rejection decision tree to reduce cosmic background; based on reconstructed track direction, position, and length; and energy and number of hits in event
- Expected cosmic background:
  - **1.4 events**

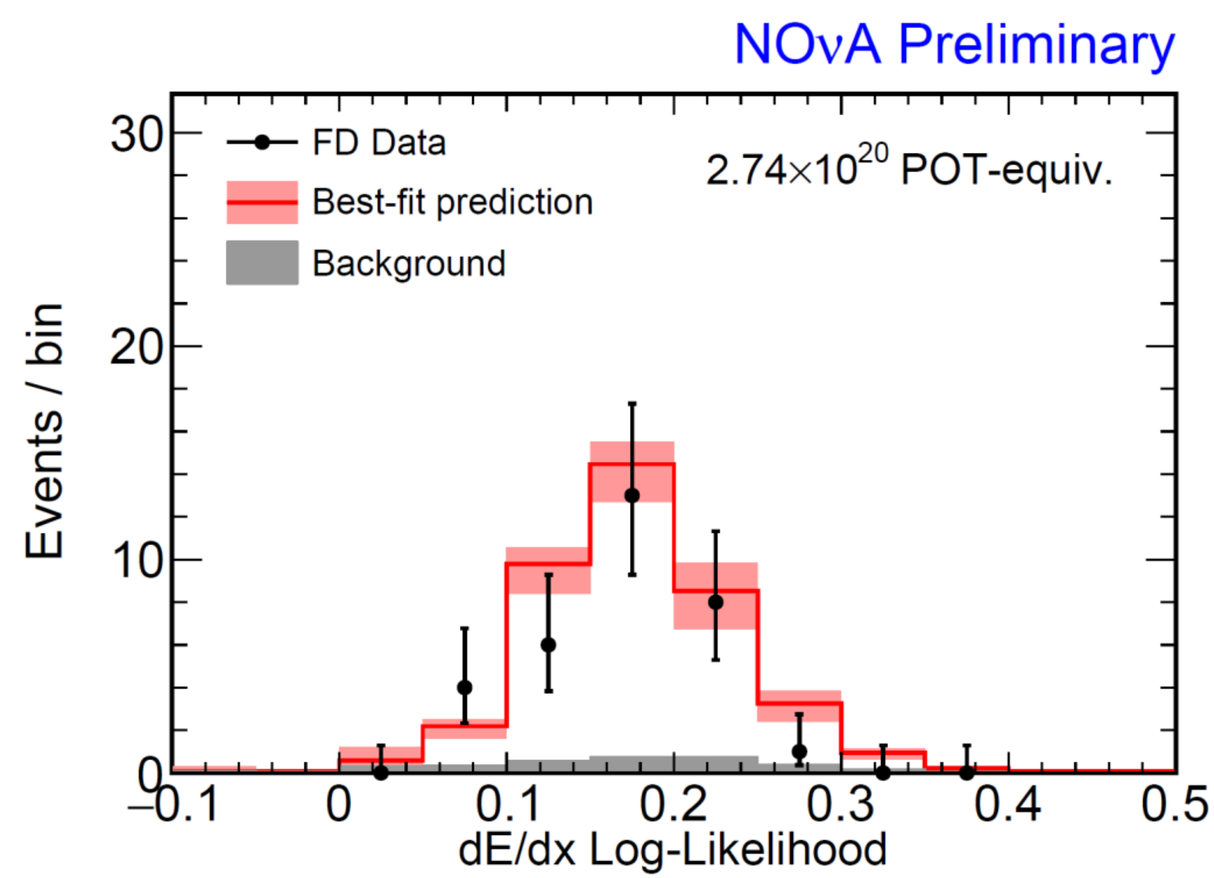





NOvA Preliminary
FD Data
Best-fit prediction
Background
2.74×10^20 POT-equiv.
Events / bin
Total Number of Hits


NOvA Preliminary
FD Data
Best-fit prediction
Background
2.74×10^20 POT-equiv.
Events / bin
cosθ_Z

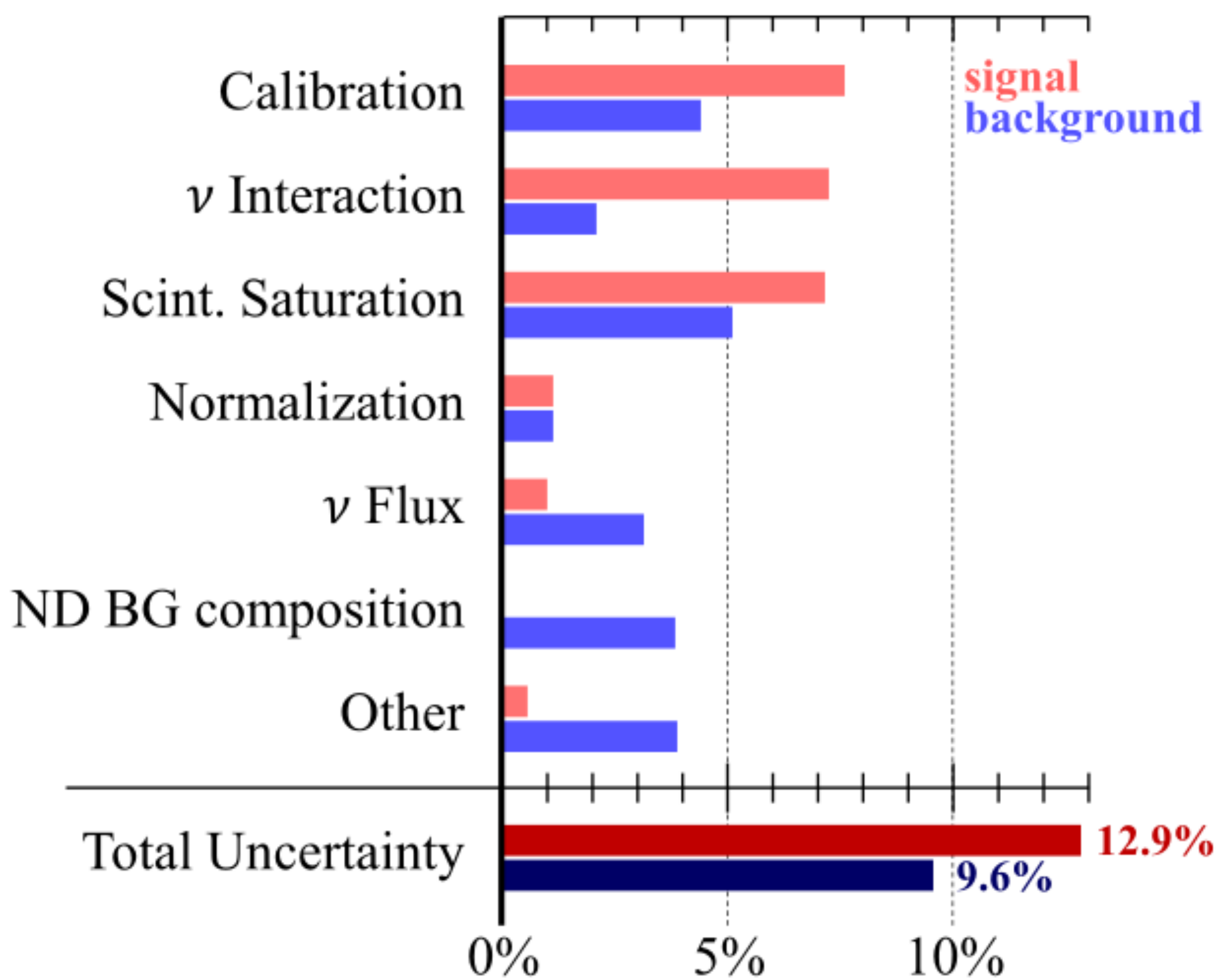

NOvA Preliminary
FD Data
Best-fit prediction
Background
2.74×10^20 POT-equiv.
Events / bin
Cosmic Rejection BDT Output


NOvA Preliminary
FD Data
Best-fit prediction
Background
2.74×10^20 POT-equiv.
Events / bin
dE/dx Log-Likelihood

Systematic Uncertainties

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

LID



LEM has similar systematic uncertainties