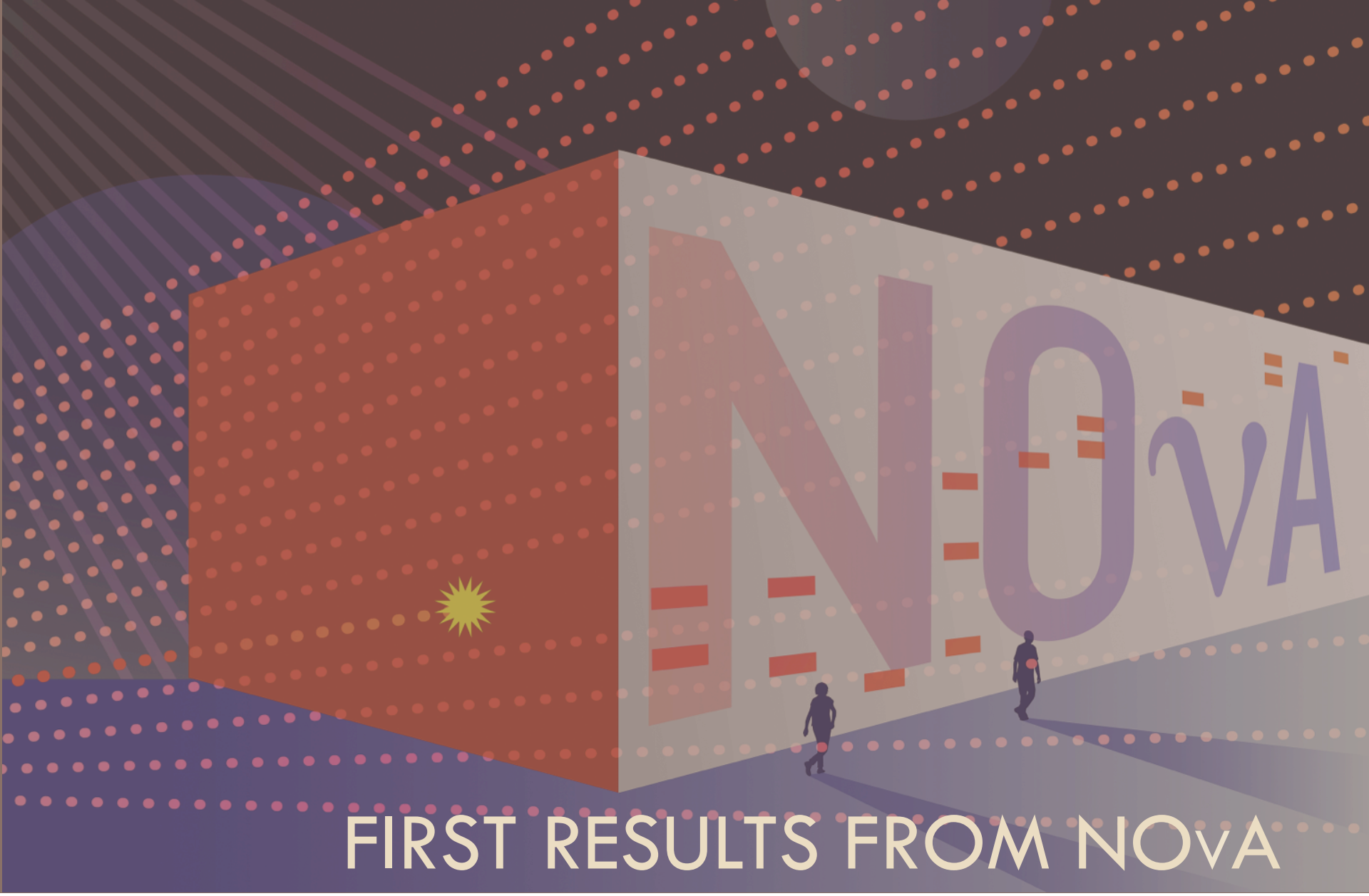


FIRST RESULTS FROM NOvA

Patricia Vahle, for the NOvA collaboration
College of William and Mary

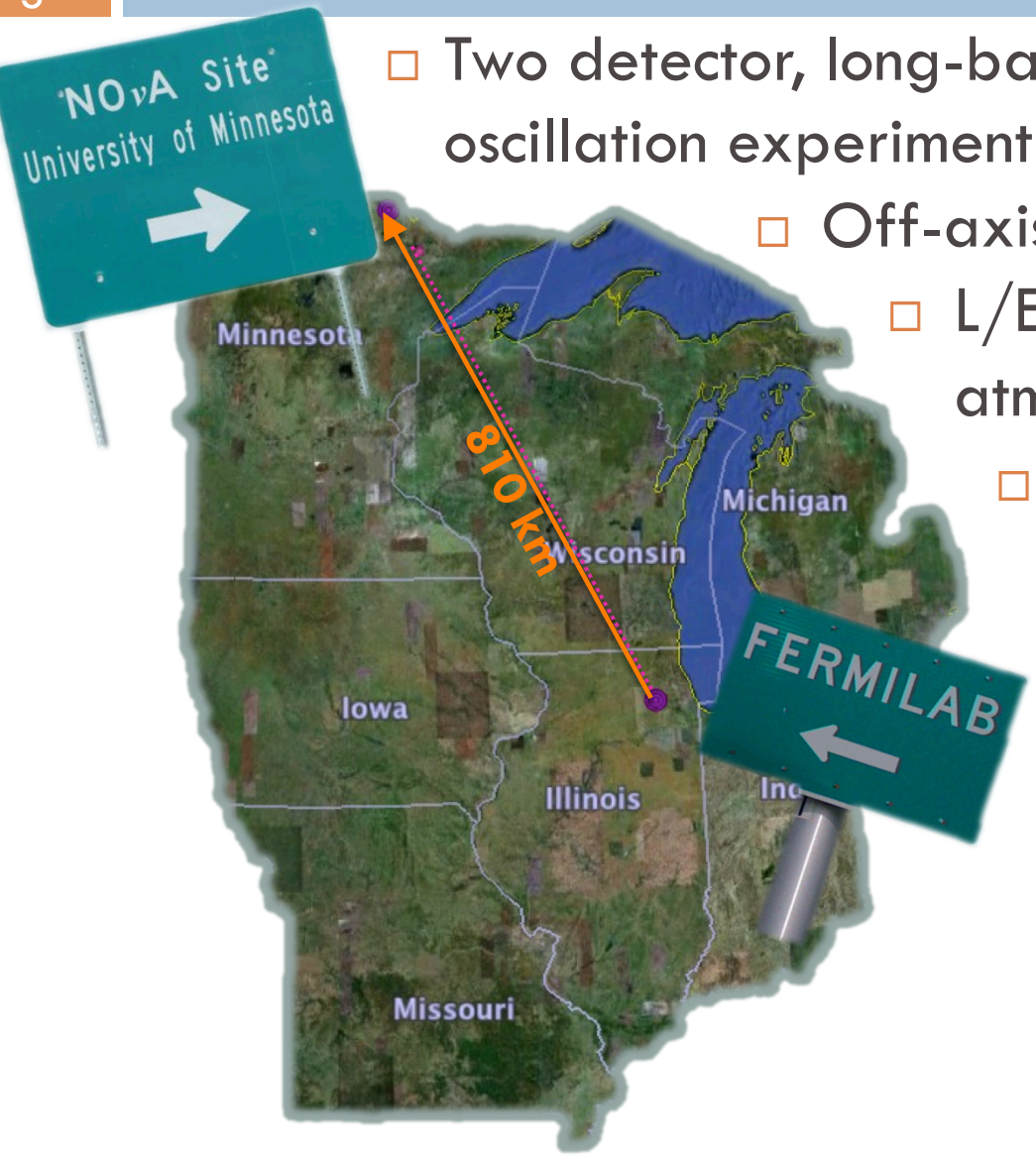
Personal Note

NEUTRINOS
FROM THE LAB, THE SUN,
AND THE COSMOS

SSI
2000

- 15 years ago I was a (very) young graduate student at this school
- Talks were given on actual transparencies
- Gary Feldman gave the long-baseline lectures

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:
        - precision measurements of Δm^2, θ_{23} from ν_μ disappearance
        - Search for $\nu_\mu \rightarrow \nu_e$ transitions (with both neutrinos and antineutrinos)
        - Measure θ_{13}
        - determine mass hierarchy
        - constrain CP violating phase

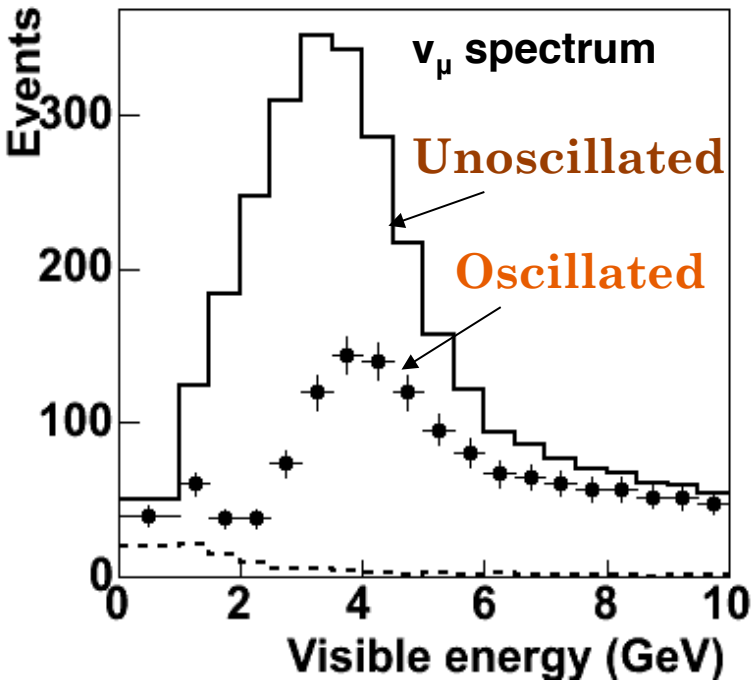
ν_μ Disppearance

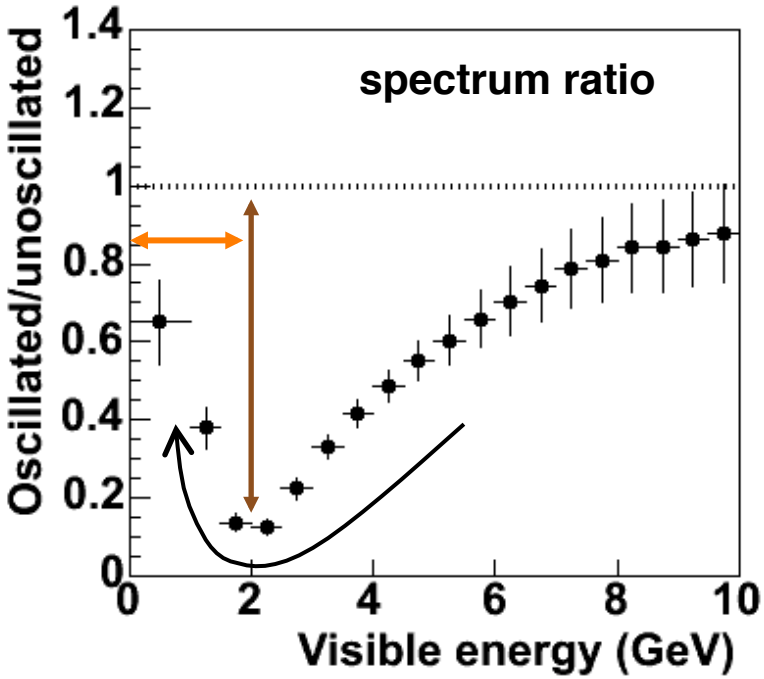
- At L/E~400 km/GeV, dominant oscillation mode is $\nu_\mu \rightarrow \nu_\tau$

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2(2\theta)\sin^2(1.27\Delta m^2 L/E)$$

Monte Carlo

(Input parameters: $\sin^2 2\theta = 1.0$, $\Delta m^2 = 3.35 \times 10^{-3}$ eV^2)





ν_e Appearance

- At L/E~400 km/GeV, dominant oscillation mode is $\nu_\mu \rightarrow \nu_\tau$
- A few percent of the missing ν_μ could change into ν_e

$$P\left(\nu_\mu \rightarrow \nu_e\right) = \left| \sqrt{P_{atm}}\, e^{-i\left(\frac{\Delta m^2_{32} L}{4E} + \delta_{cp}\right)} + \sqrt{P_{sol}} \right|^2$$

$$P_{atm} = \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) \qquad P_{sol} \approx \cos^2\theta_{23} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right)$$

"Atmospheric" Term
Depends on Δm^2 and θ_{13}

"Solar" Term
<1% for current accelerator experiments

ν_e Appearance

- At L/E~400 km/GeV, dominant oscillation mode is $\nu_\mu \rightarrow \nu_\tau$
- A few percent of the missing ν_μ could change into ν_e

$$P\left(\nu_\mu \rightarrow \nu_e\right) = \left| \sqrt{P_{atm}}\, e^{-i\left(\frac{\Delta m^2_{32} L}{4E} + \delta_{cp}\right)} + \sqrt{P_{sol}} \right|^2$$

$$2\sqrt{P_{atm}}\sqrt{P_{sol}}\cos\left(\frac{\Delta m^2_{32} L}{4E}\right)\cos\delta_{CP} \mp 2\sqrt{P_{atm}}\sqrt{P_{sol}}\sin\left(\frac{\Delta m^2_{32} L}{4E}\right)\sin\delta_{CP}$$

Interference Term

- for neutrinos

+ for antineutrinos

$$\text{if } \delta_{CP} \neq 0,$$

$$P\left(\nu_\mu \rightarrow \nu_e\right) \neq P\left(\bar{\nu}_\mu \rightarrow \bar{\nu}_e\right)$$

ν_e Appearance

- At L/E~400 km/GeV, dominant oscillation mode is $\nu_\mu \rightarrow \nu_\tau$
- A few percent of the missing ν_μ could change into ν_e

$$P(\nu_\mu \rightarrow \nu_e) = \left| \sqrt{P_{atm}}\, e^{-i\left(\frac{\Delta m^2_{32} L}{4E} + \delta_{cp}\right)} + \sqrt{P_{sol}} \right|^2$$

$$P_{atm} = \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{31} L}{4E} - aL\right) \left(\frac{\frac{\Delta m^2_{31} L}{4E}}{\left(\frac{\Delta m^2_{31} L}{4E} - aL\right)} \right)^2$$

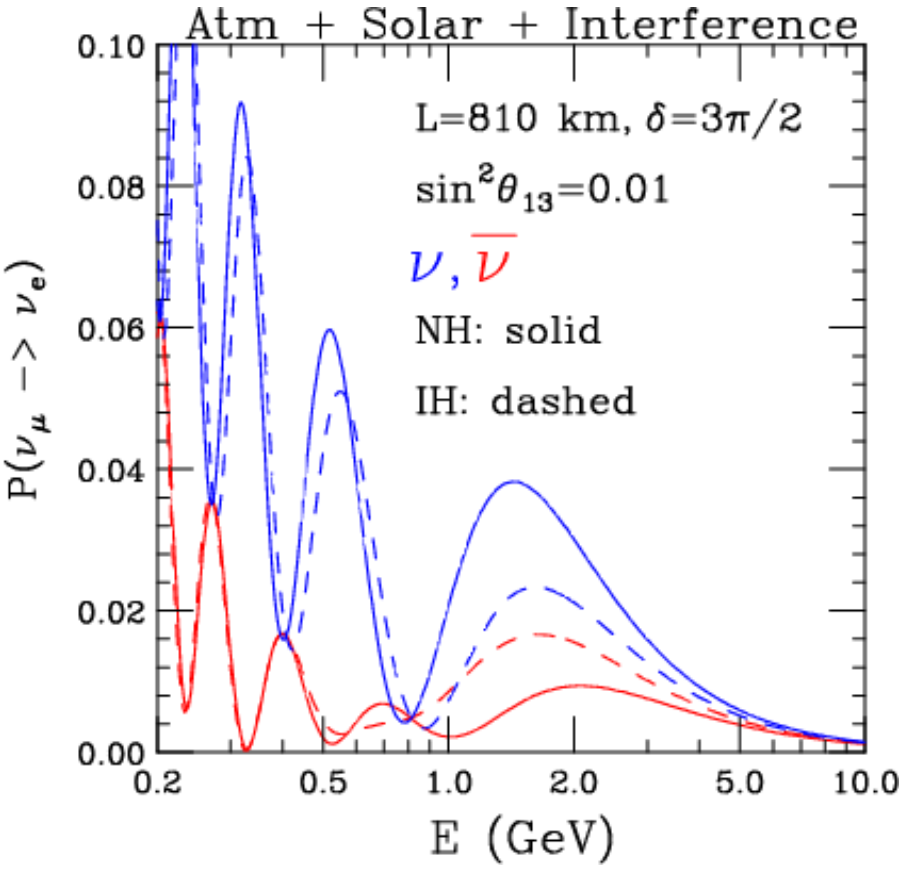
$$P_{sol} \approx \cos^2\theta_{23} \sin^2 2\theta_{12} \sin^2(aL) \left(\frac{\frac{\Delta m^2_{21} L}{4E}}{aL} \right)^2$$

$$a = \pm \frac{G_F N_e}{\sqrt{2}} \approx (4000 \text{ km})^{-1}$$

In matter, additional term in Hamiltonian from ν_e + e CC scattering modifies oscillation probability, depends on mass hierarchy (ordering), a ~30% effect in NOvA

ν_e Appearance

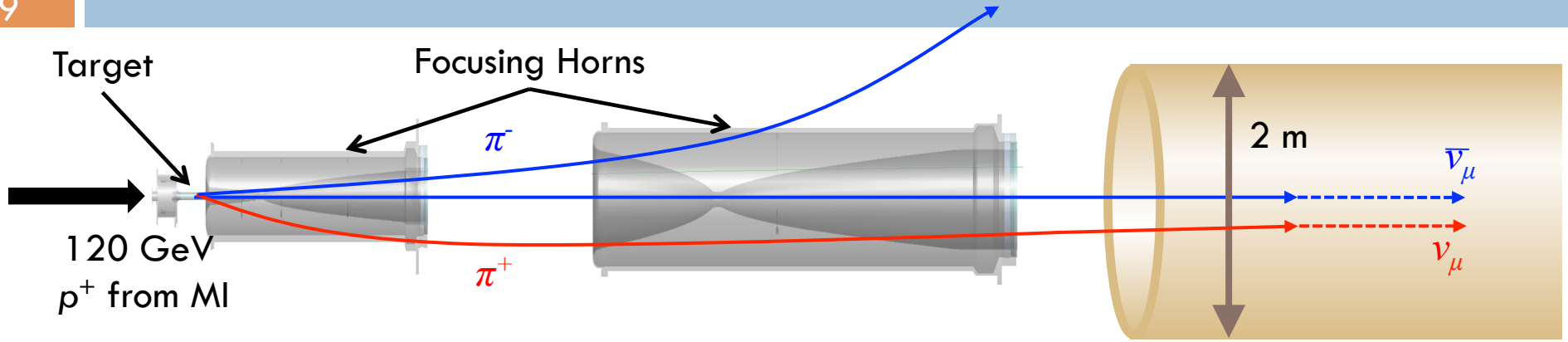
- At L/E~400 km/GeV, dominant oscillation mode is $\nu_\mu \rightarrow \nu_\tau$
- A few percent of the missing ν_μ could change into ν_e

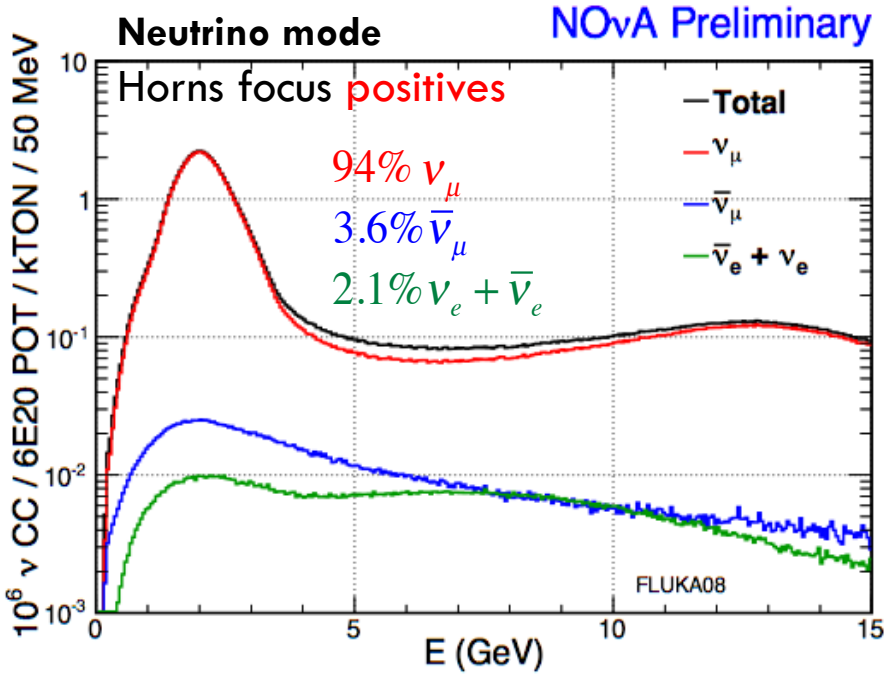


From S. Parke, "Neutrino Oscillation Phenomenology" in Neutrino Oscillations: Present Status and Future Plans

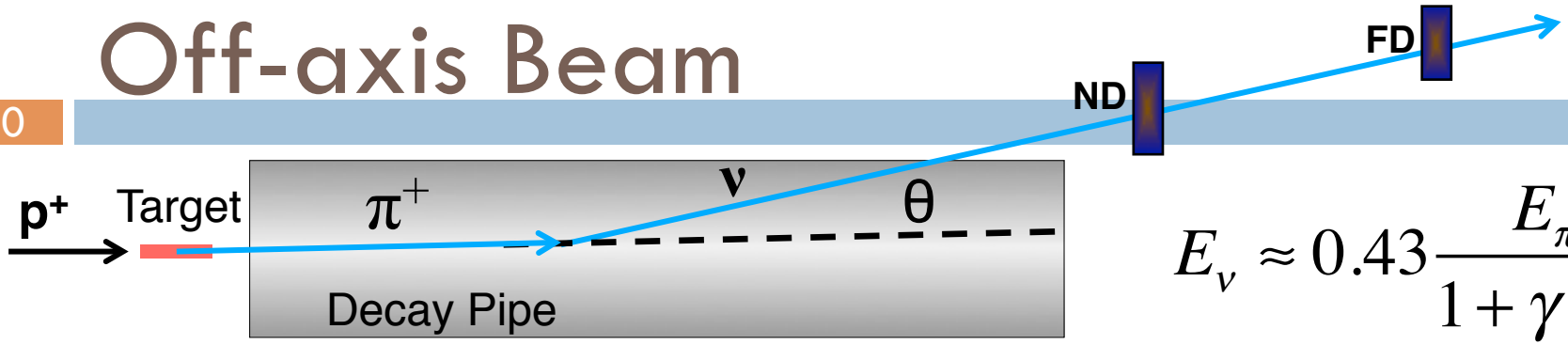
Today, I'll show you first results from neutrino mode running, both muon neutrino disappearance and electron neutrino appearance

Making a Neutrino Beam



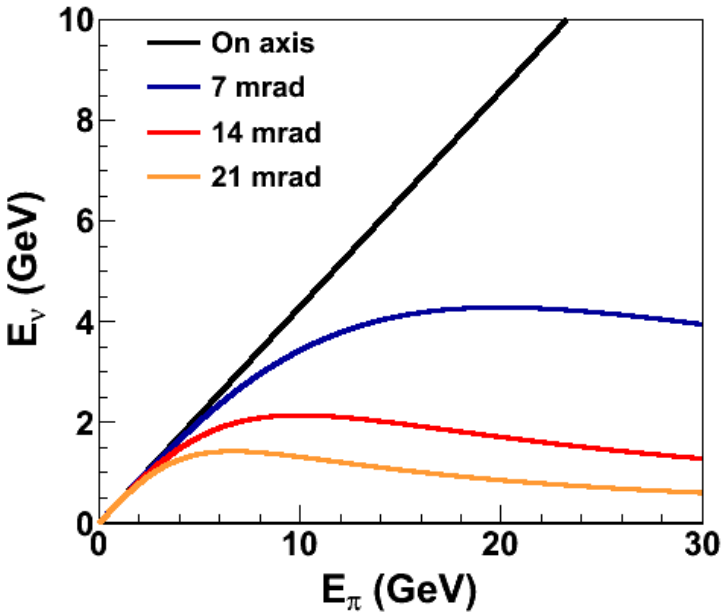


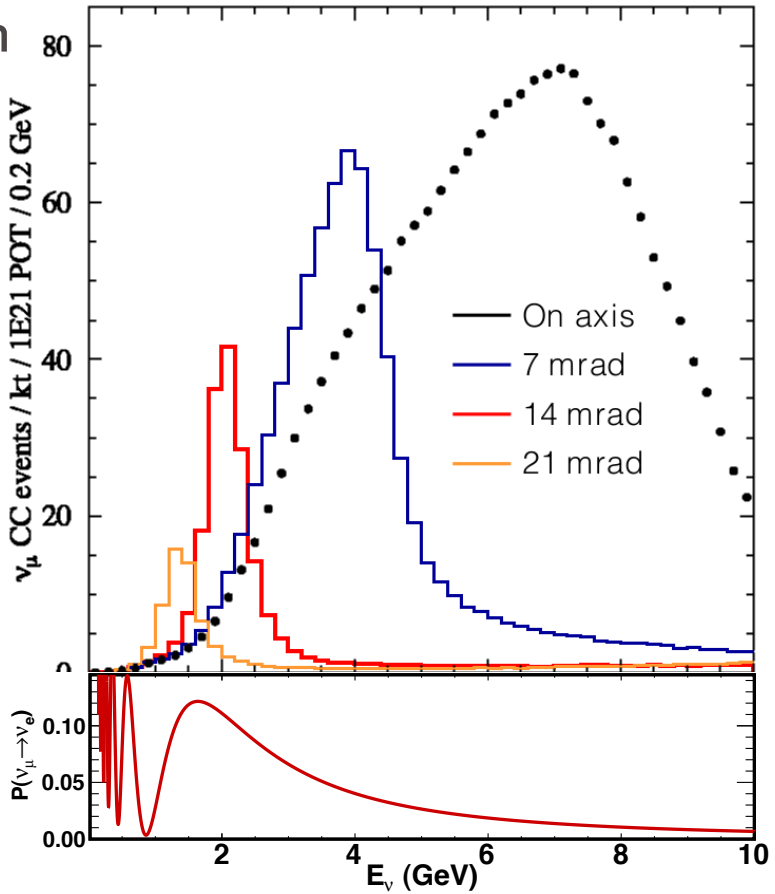
Off-axis Beam



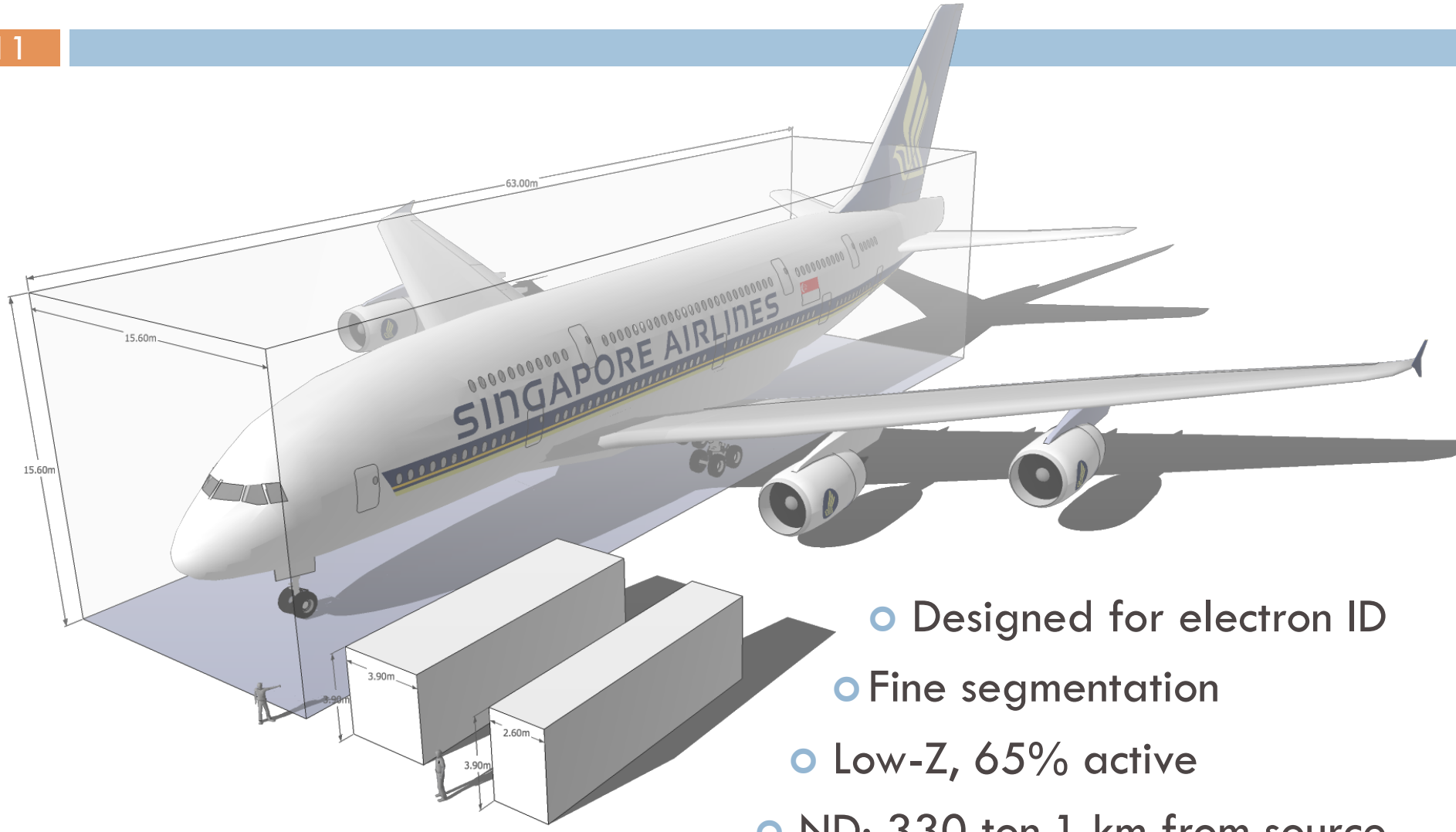
$$E_\nu \approx 0.43 \frac{E_\pi}{1+\gamma^2\theta_\nu^2}$$

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





The NOvA Detectors

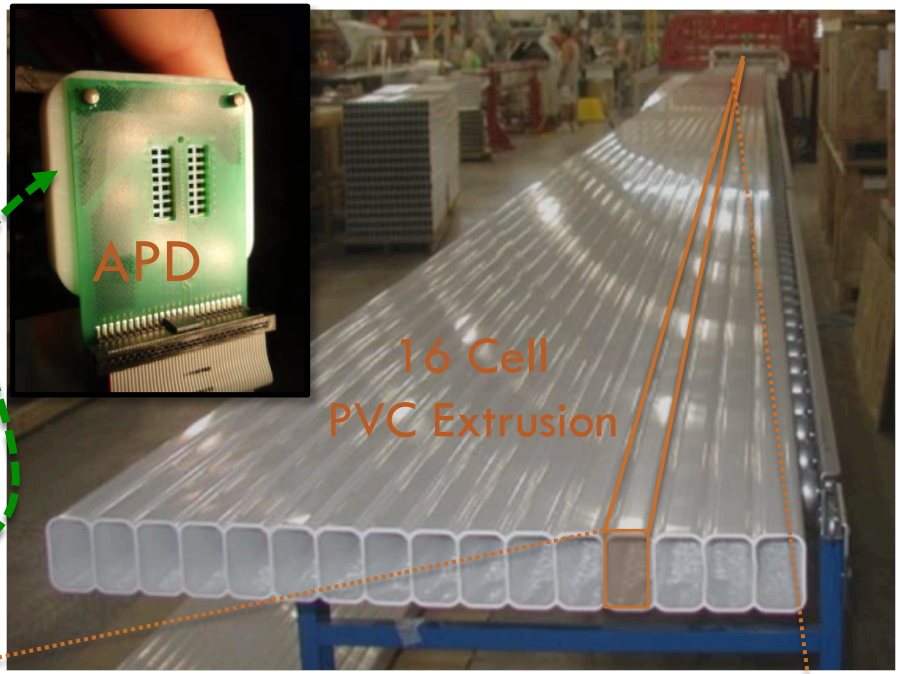


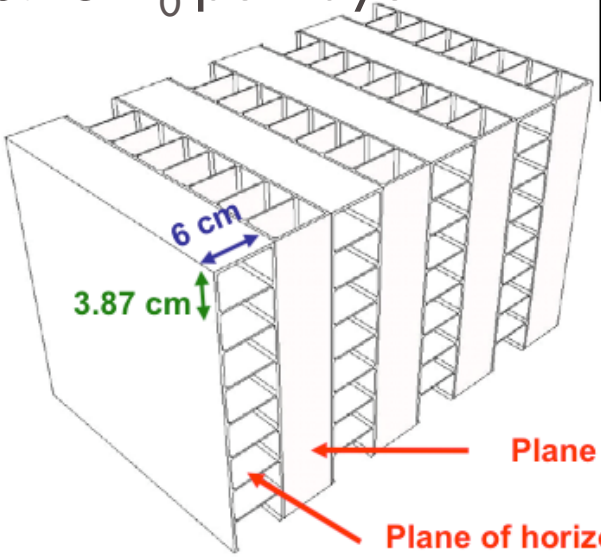
- Designed for electron ID
- Fine segmentation
- Low-Z, 65% active
- ND: 330 ton,1 km from source
- FD: 14 kton, 810 km from source

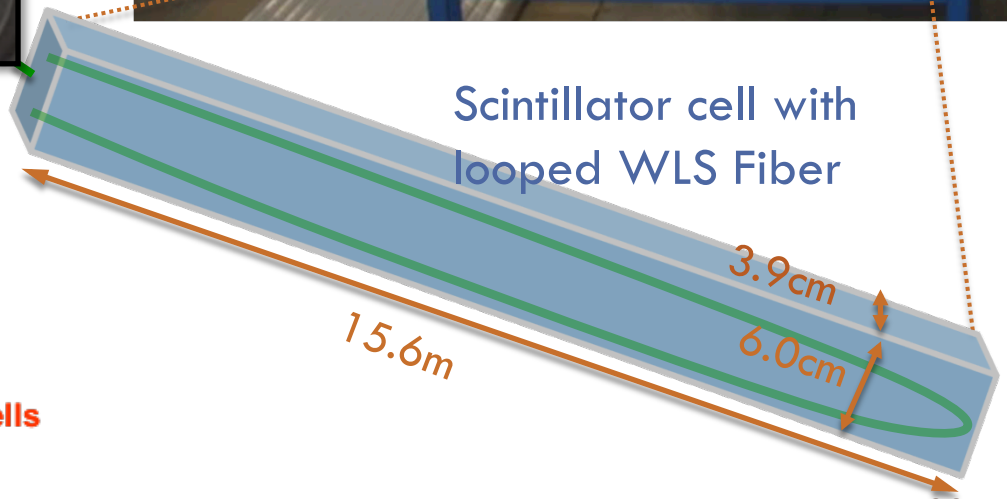
P. Vahle, SSI 2015

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
- 0.15 X_0 per layer

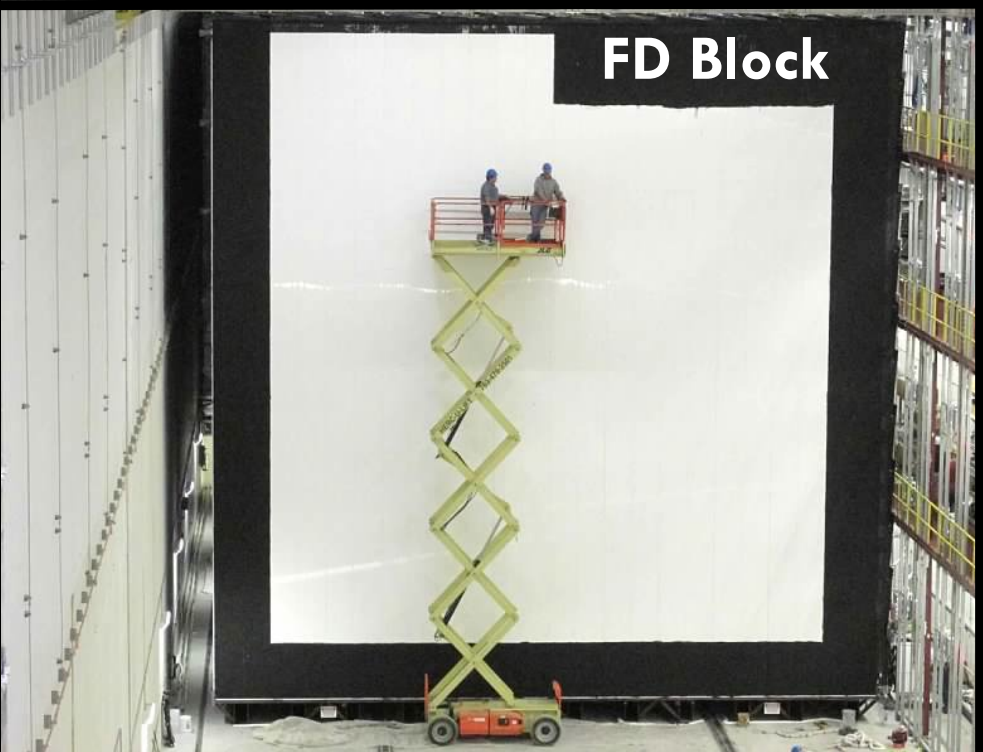


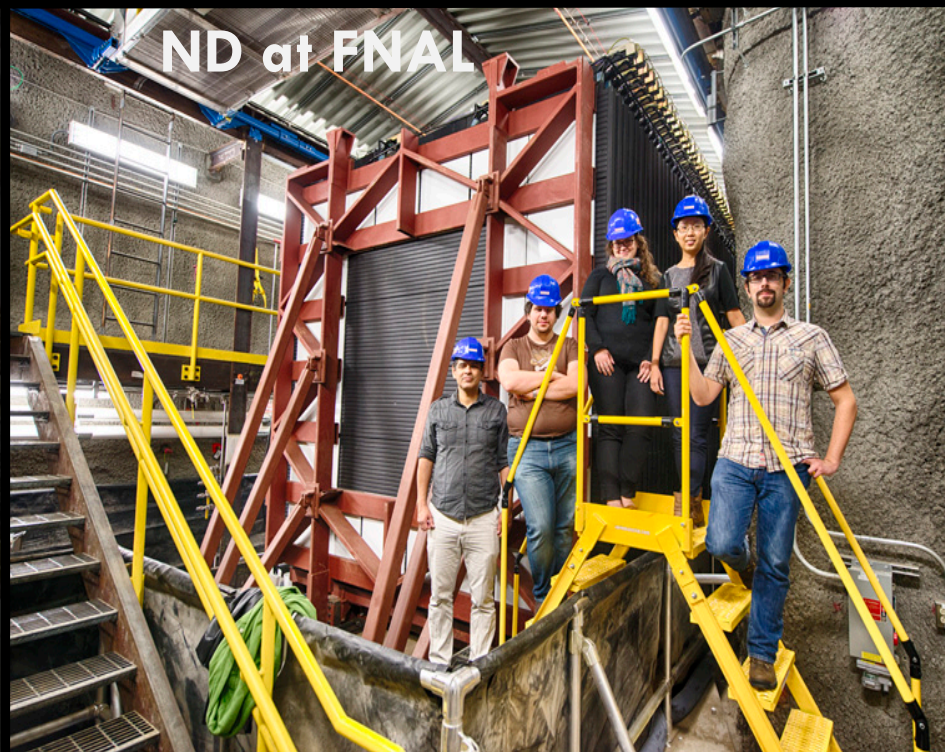




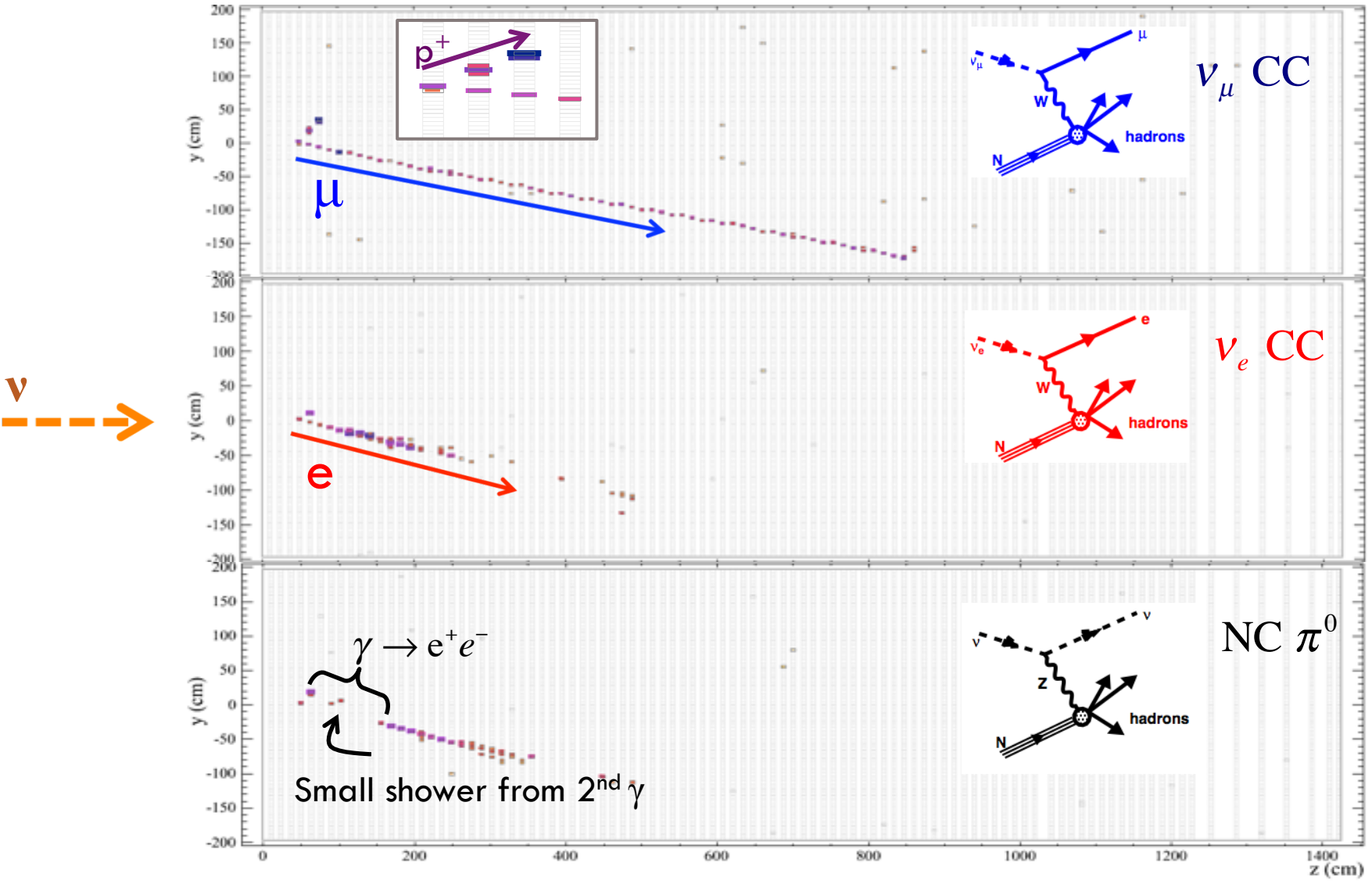

FD Construction

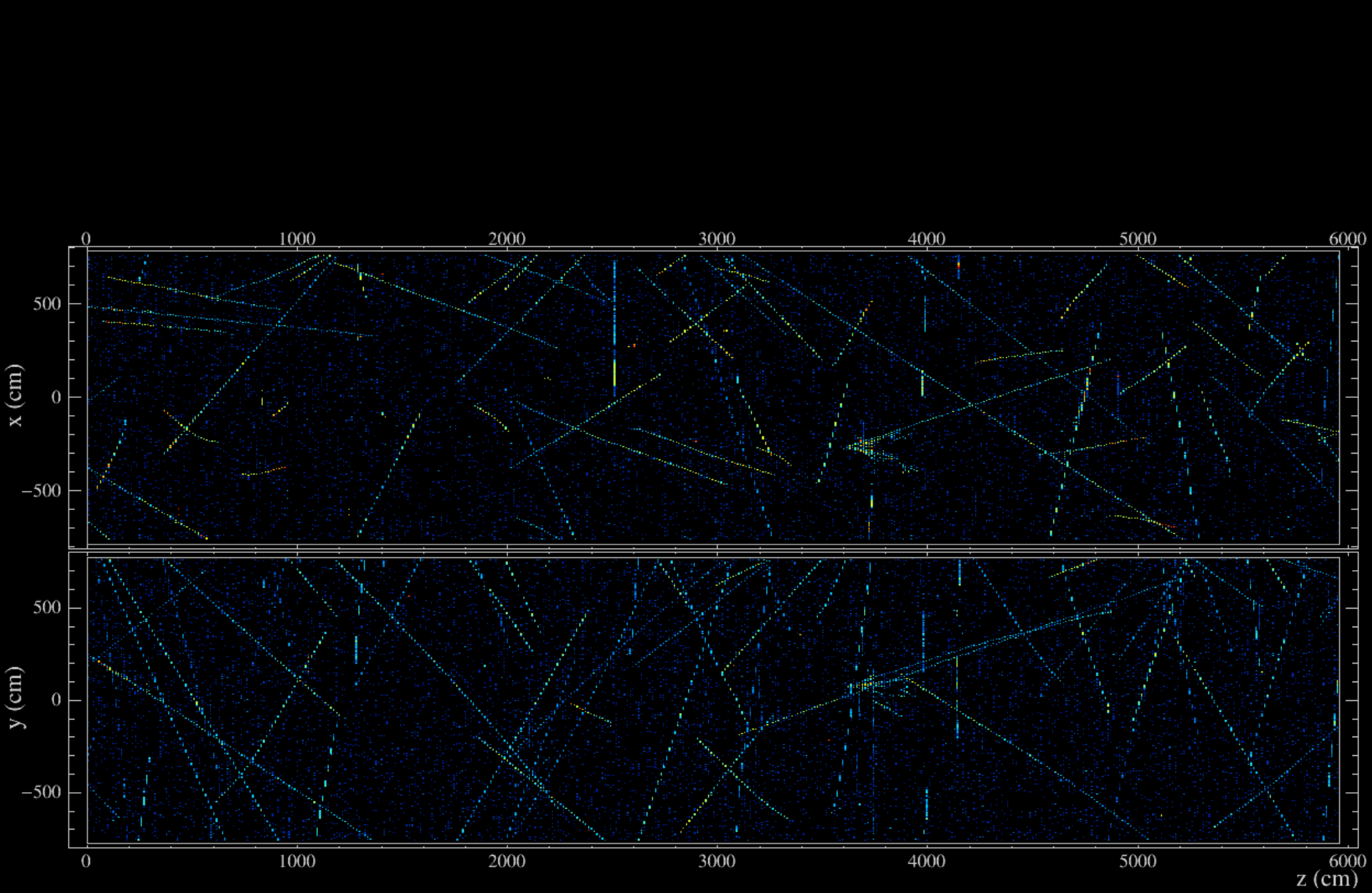

Outfitted FD


FD Block


ND at FNAL

MC Events in NOvA

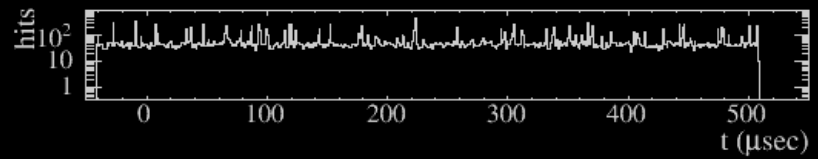


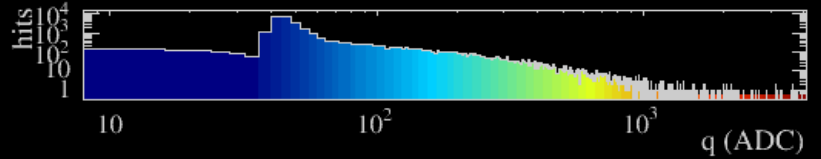


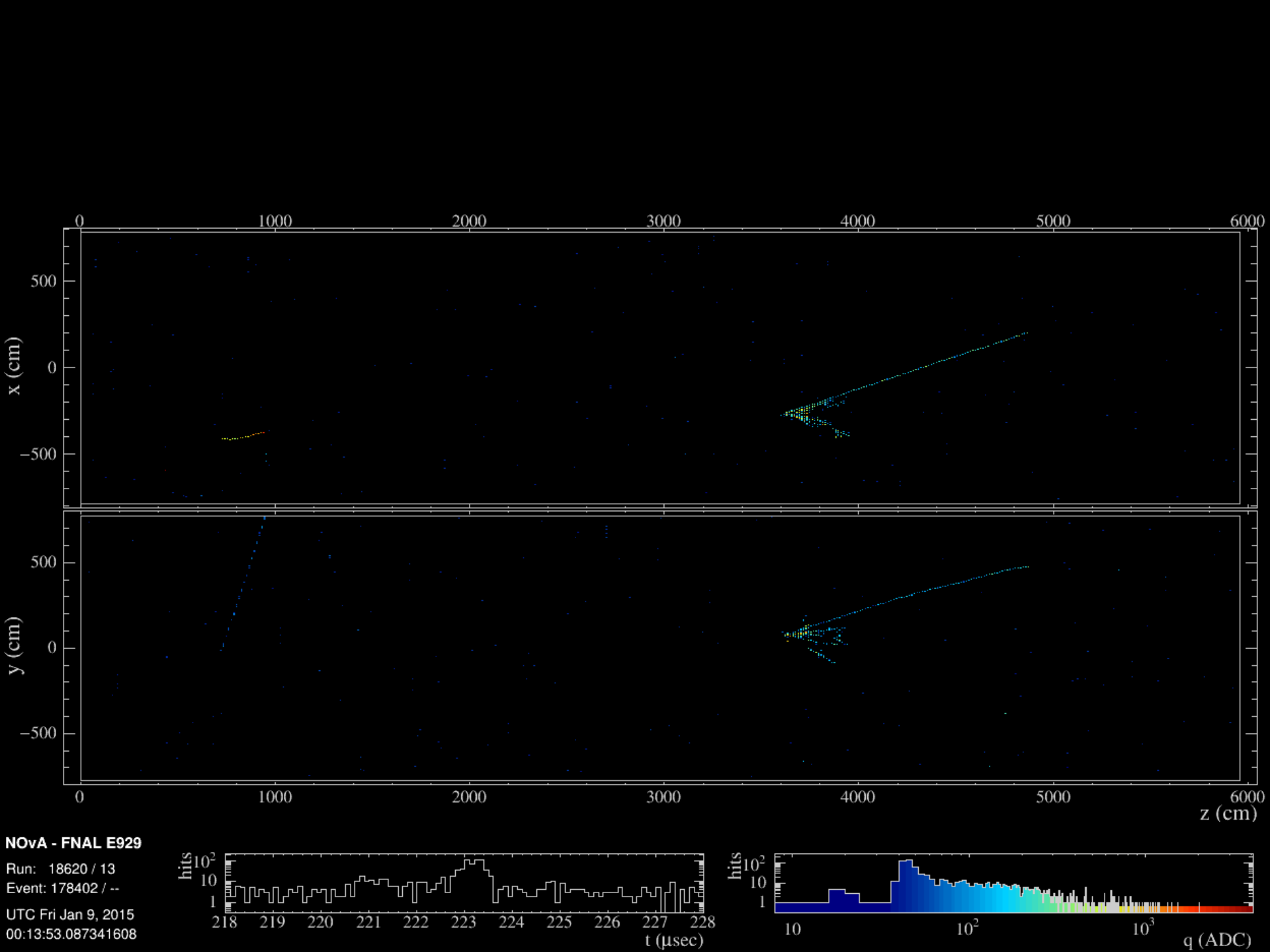
NOvA - FNAL E929

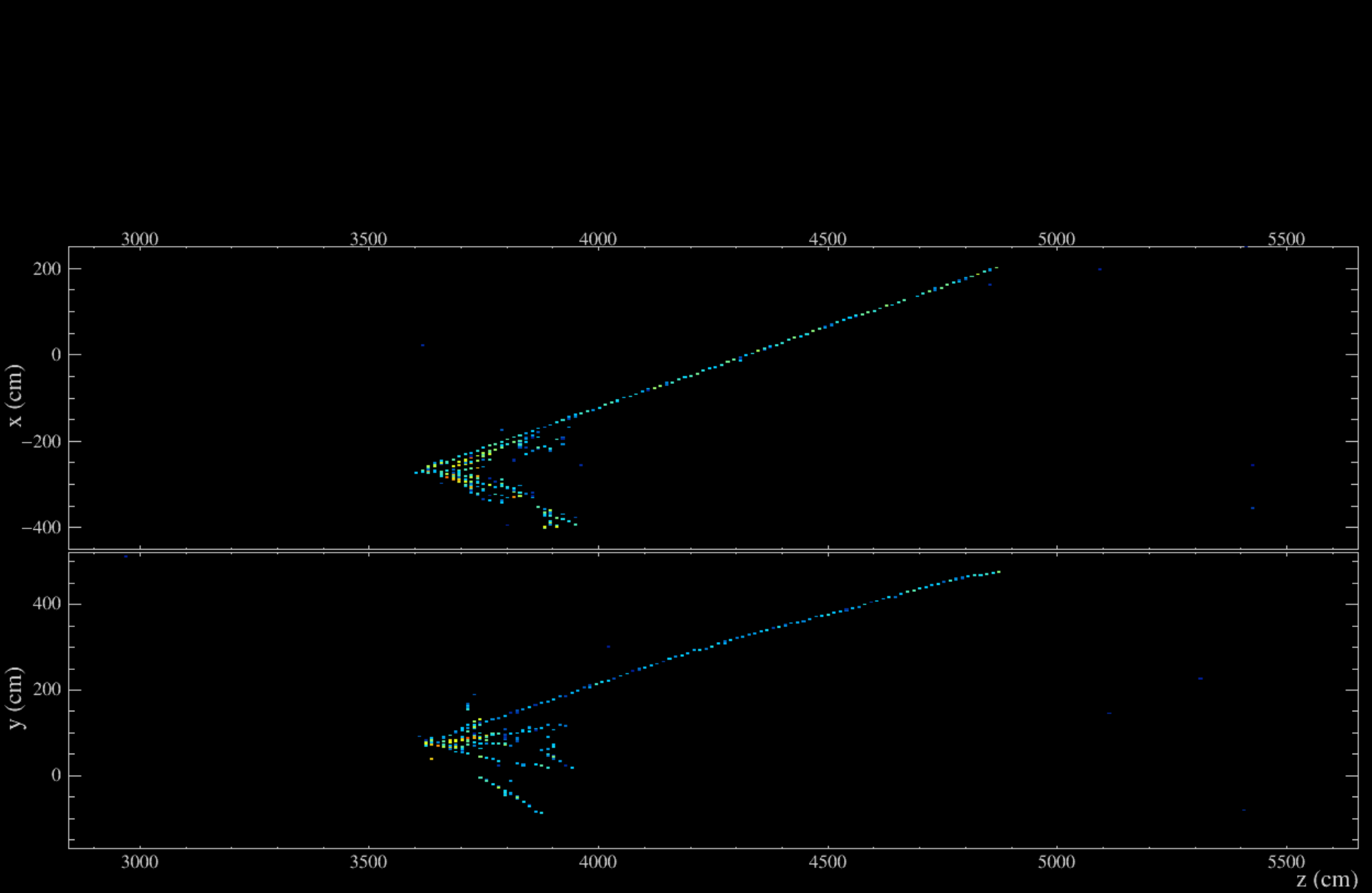
Run: 18620 / 13
Event: 178402 / --

UTC Fri Jan 9, 2015
00:13:53.087341608





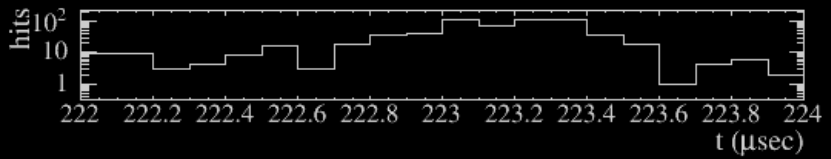

0
1000
2000
3000
4000
5000
6000
500
0
−500
x (cm)
y (cm)
z (cm)
NOvA - FNAL E929
Run: 18620 / 13
Event: 178402 / --
UTC Fri Jan 9, 2015
00:13:53.087341608
hits
10^2
10
1
218
219
220
221
222
223
224
225
226
227
228
t (μsec)
10^2
10^3
q (ADC)

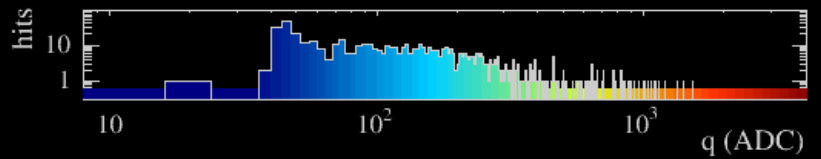


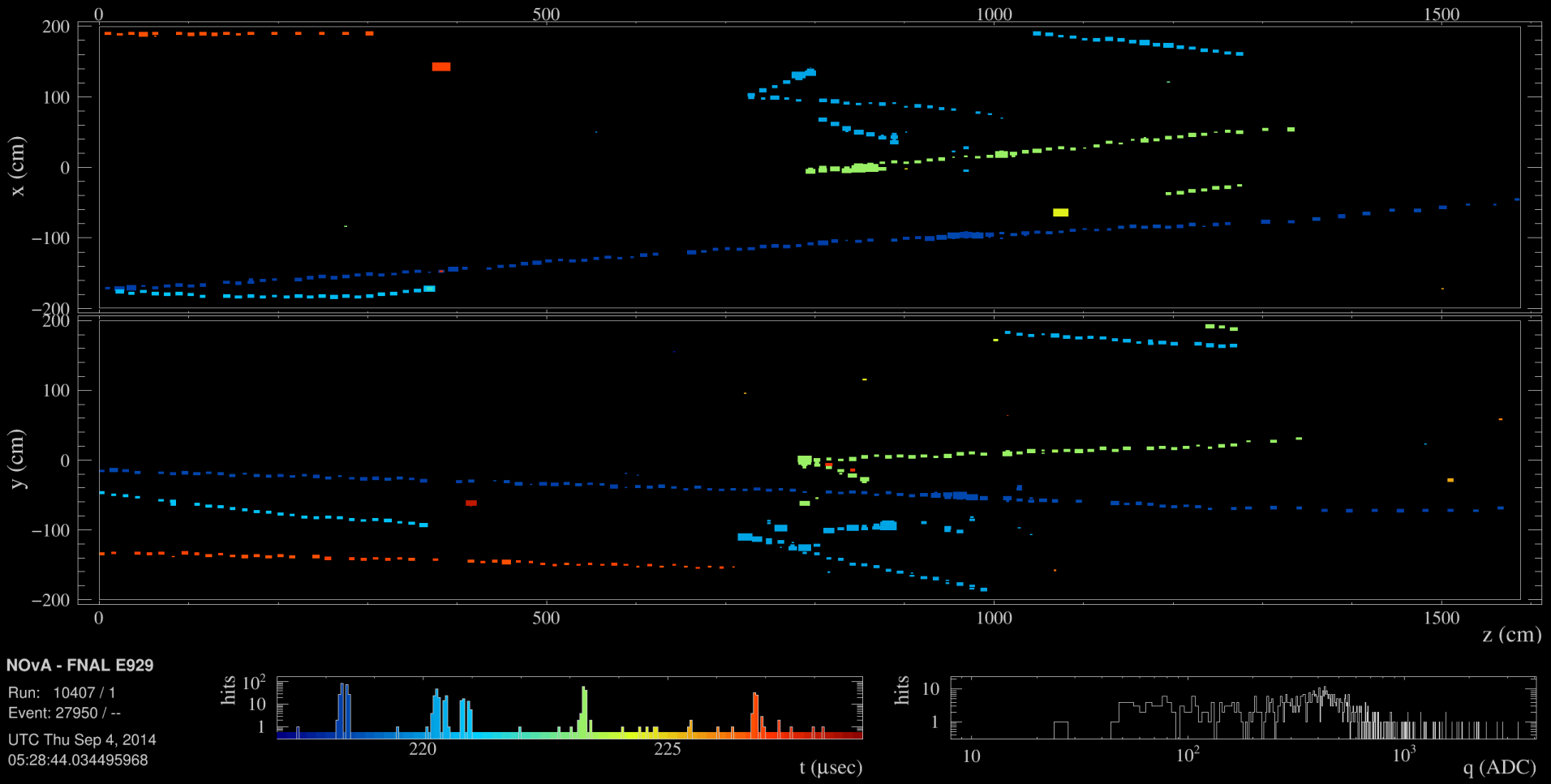
NOvA - FNAL E929

Run: 18620 / 13
Event: 178402 / --

UTC Fri Jan 9, 2015
00:13:53.087341608





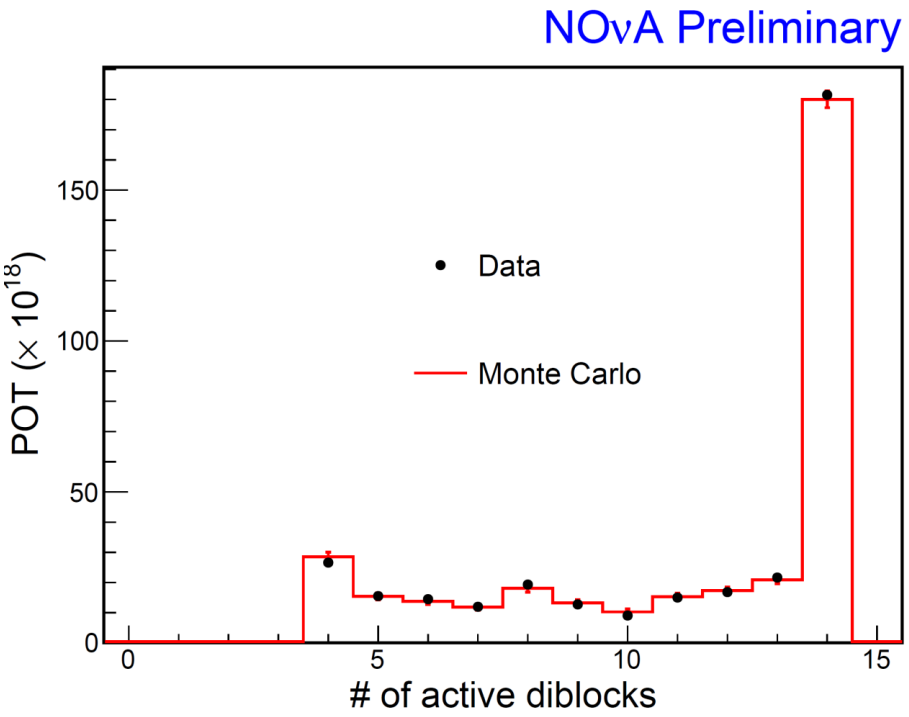


NOvA - FNAL E929

Run: 10407 / 1
Event: 27950 / --

UTC Thu Sep 4, 2014
05:28:44.034495968

Data Collected



3.45×10^{20} POT Recorded

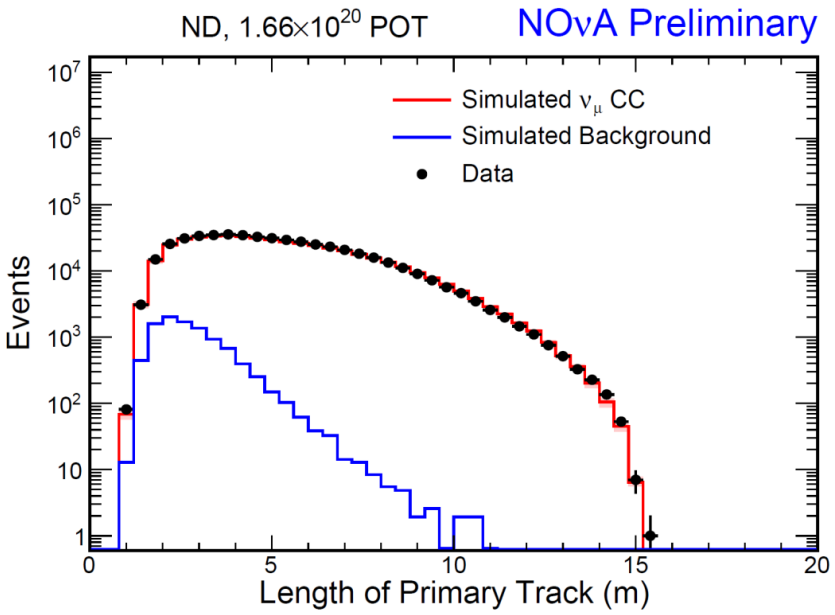
Average 79.4% of full detector mass

2.74×10^{20} POT-equiv

- We began collecting physics data during the construction phase
- As soon as each Far Detector "diblock" (1 kton) was fully commissioned it was added
- FD size is not static throughout our data set
- Full suite of FD configurations is simulated in our analyses

Selecting Muon Neutrinos

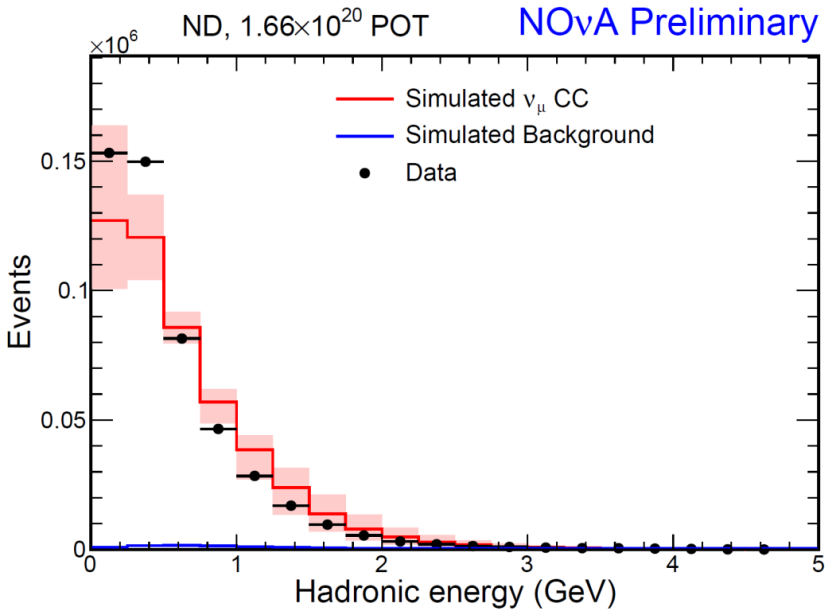
- Goal: Isolate a pure sample of ν_μCC events less than 5GeV
  - Select events with long tracks
  - Suppress NC and cosmic backgrounds
- 4-variable kNN used to identify muons
  - track length
  - dE/dx along track
  - scattering along track
  - track-only plane fraction
- ND Data matches simulation well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

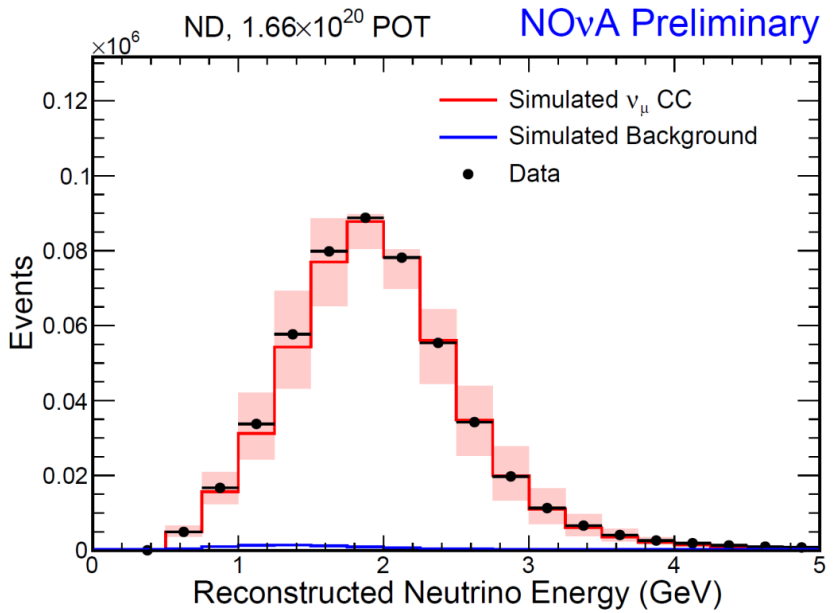


Energy Estimation

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

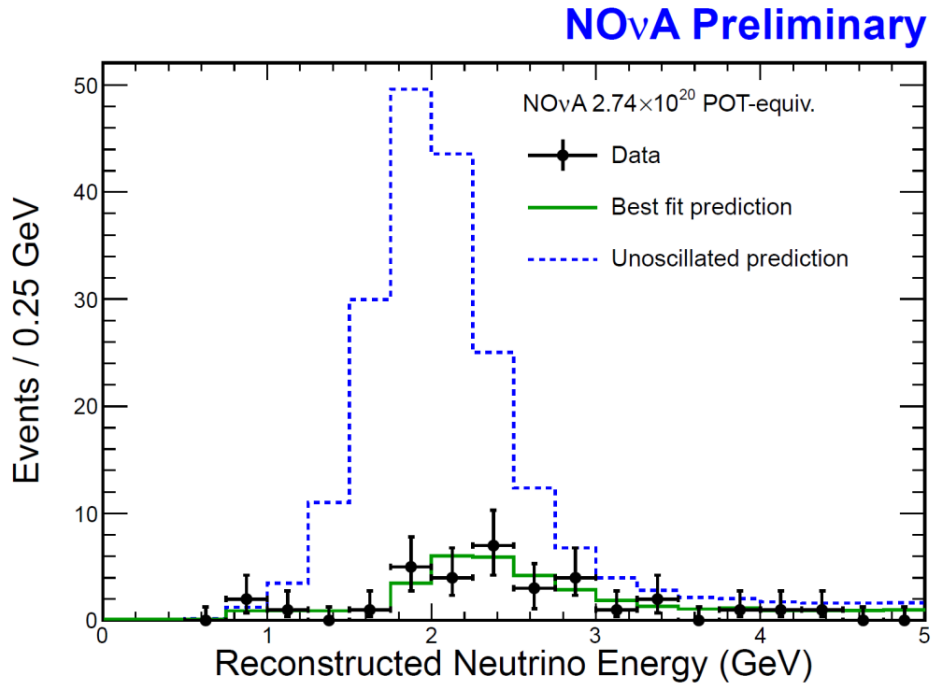
- While the muon simulation matches data, the simulated hadronic system has 21% more energy than in data.
- The hadronic energy scale is recalibrated so the total energy peak of the data matches the MC.
  - Correction taken as a systematic on the absolute energy scale
  - This results in 6% overall neutrino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

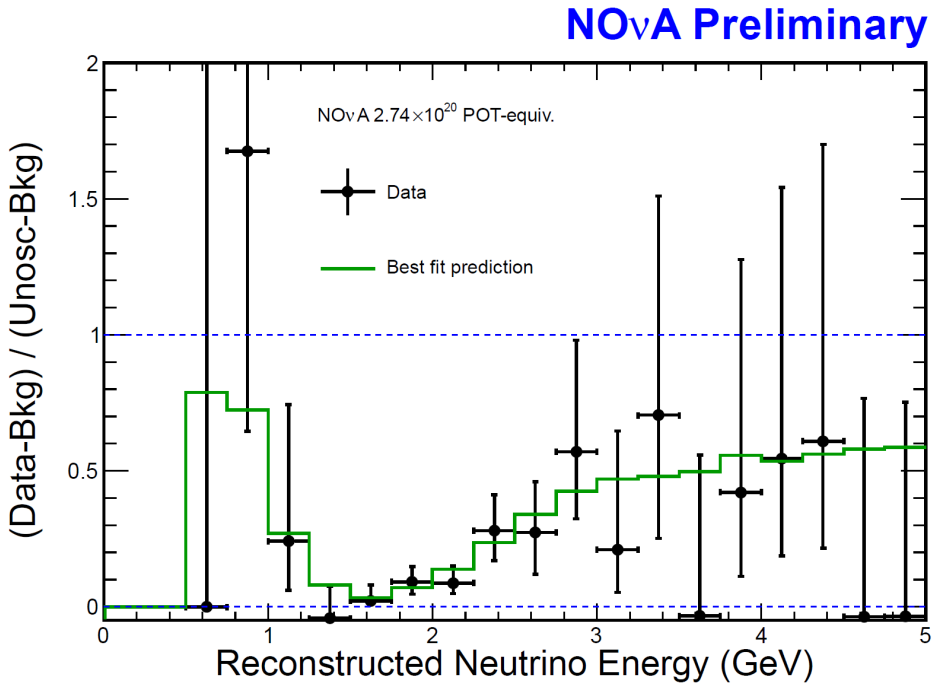




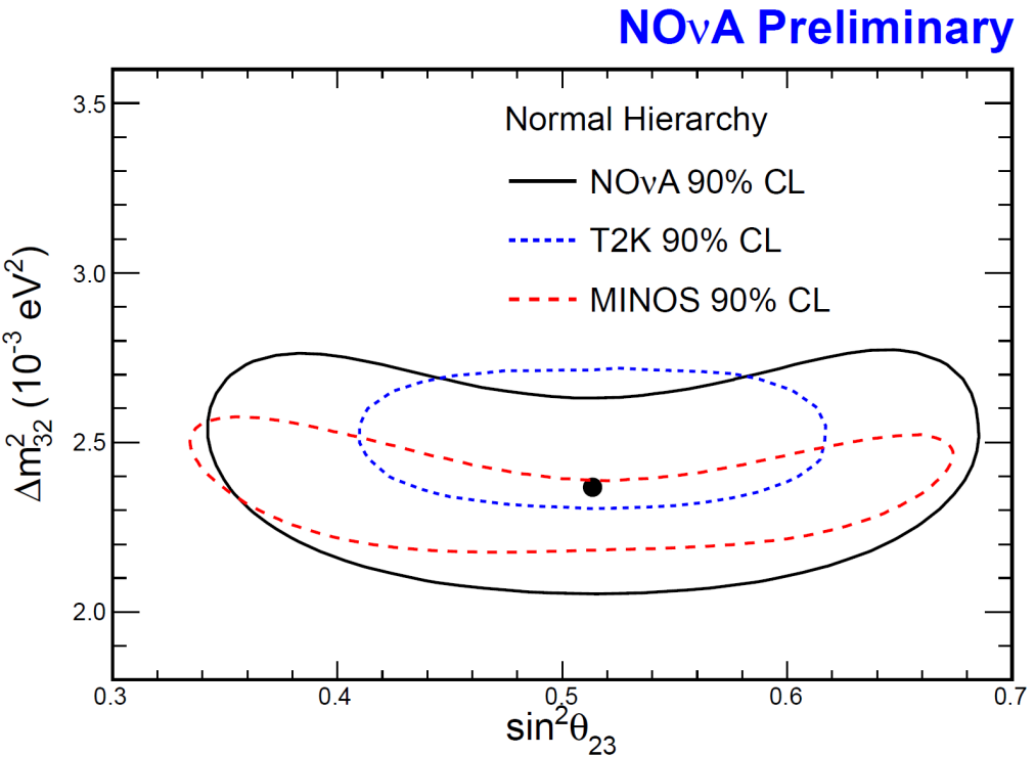
ν_μ Disappearance Results

- Expect 201 events without oscillations
  - Including 2 beam background and 1.4 cosmic events
- We observe 33 events
- Oscillations fit the data well, $\chi^2/N_{dof}=12.6/16$





ν_μ Disappearance Results



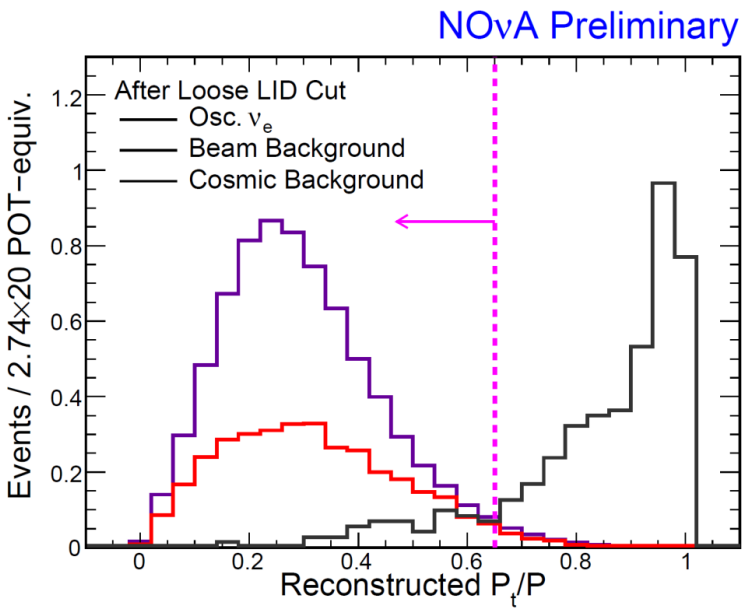
Best fit:

$$\Delta m^2_{32} = \begin{cases} +2.37^{+0.16}_{-0.15} \times 10^{-3}\ \text{eV}^2 & \text{NH} \\ -2.40^{+0.14}_{-0.17} \times 10^{-3}\ \text{eV}^2 & \text{IH} \end{cases}$$

$$\sin^2\theta_{23} = 0.51 \pm 0.10$$

- Good compatibility with both MINOS and T2K
- Systematics included as nuisance parameters
  - Hadronic energy
  - Flux, normalization, cross sections, NC bkg rate, calibration, solar oscillation parameters

Selecting Electron Neutrinos

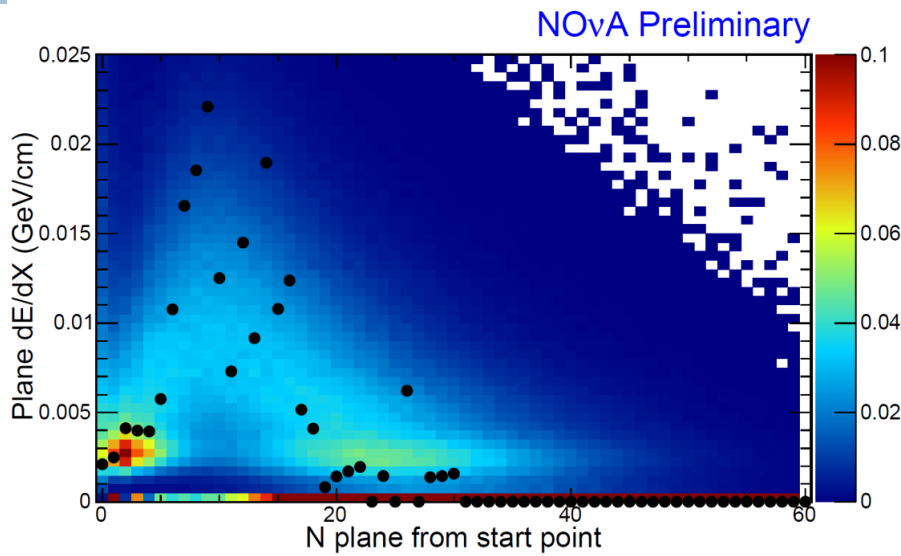


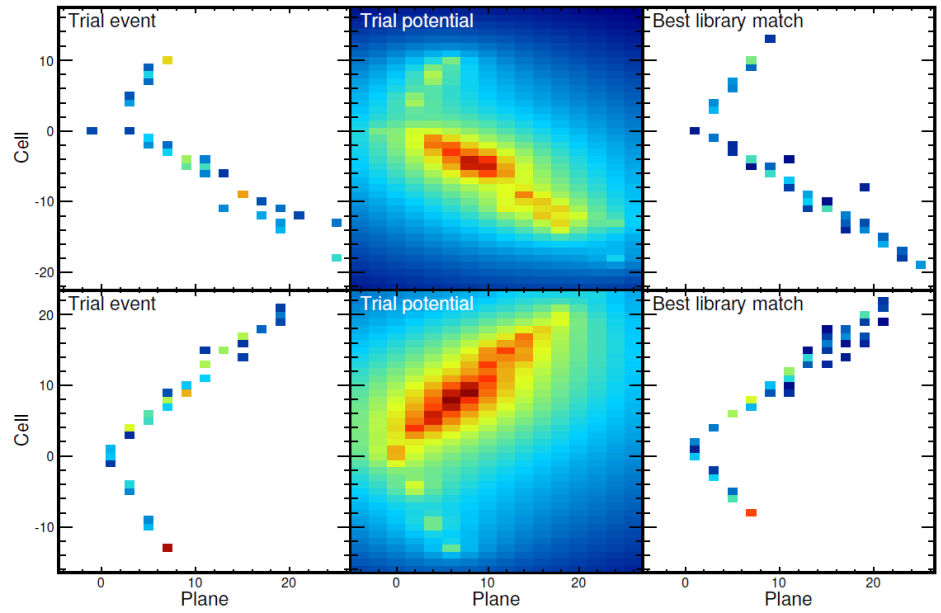
- Goal: Isolate a pure sample of ν_eCC events
  - Select events with electromagnetic showers
  - Suppress backgrounds from NC/ν_μCC/beam ν_e and cosmic events
- Basic cuts to remove obvious backgrounds:
  - Fiducial and Containment
  - Reconstructed p_T/p
    - remove very vertical events
  - Shower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

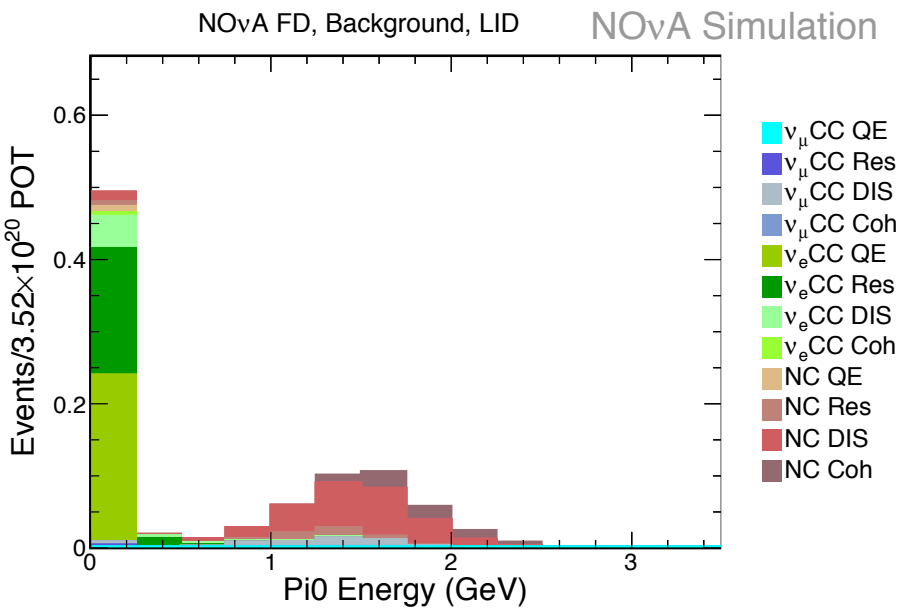




LEM:

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

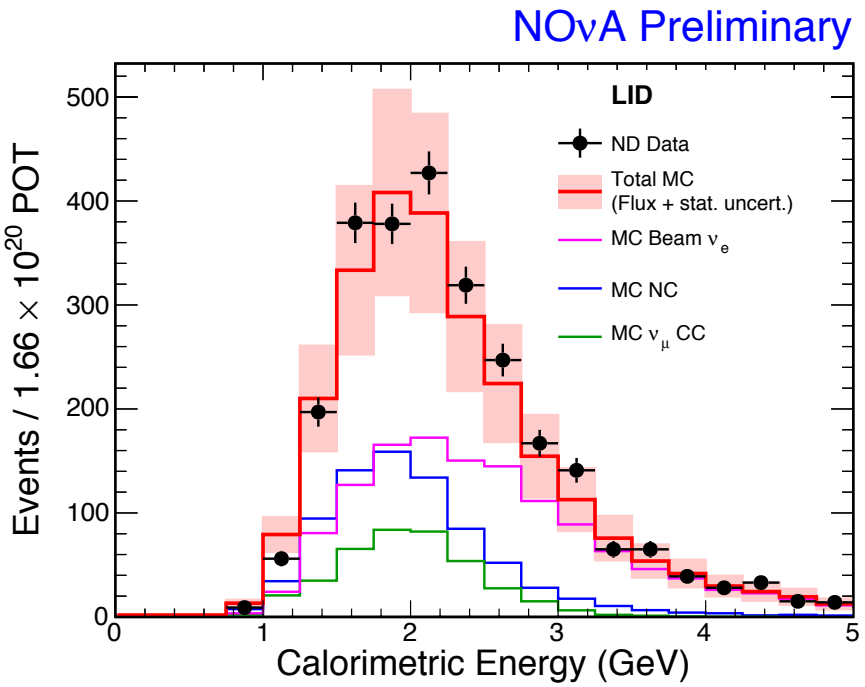
Background characteristics



- Both selection techniques achieve good sensitivity to ν_e appearance
  - 35% signal selection efficiency (wrt containment)
  - Reject 99.7% of NC backgrounds
  - better than 1in 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

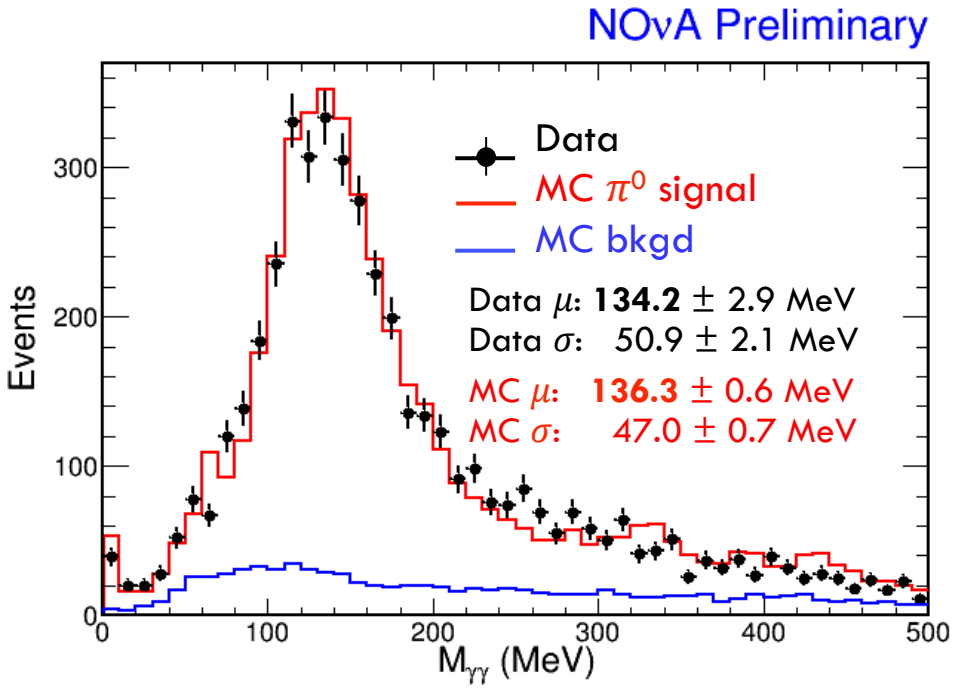
Predicting the FD Background



- Good agreement between ND data and simulation after selection
  - Data selects ~5% more events than simulation
- Use simulated F/N ratio in bins of energy to extrapolate ND data
  - Scale each background component equally
- Cut and count analysis—integrated number of events

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



The Prediction

- We expect about 1 background event
  - Few percent dependence on oscillation parameters

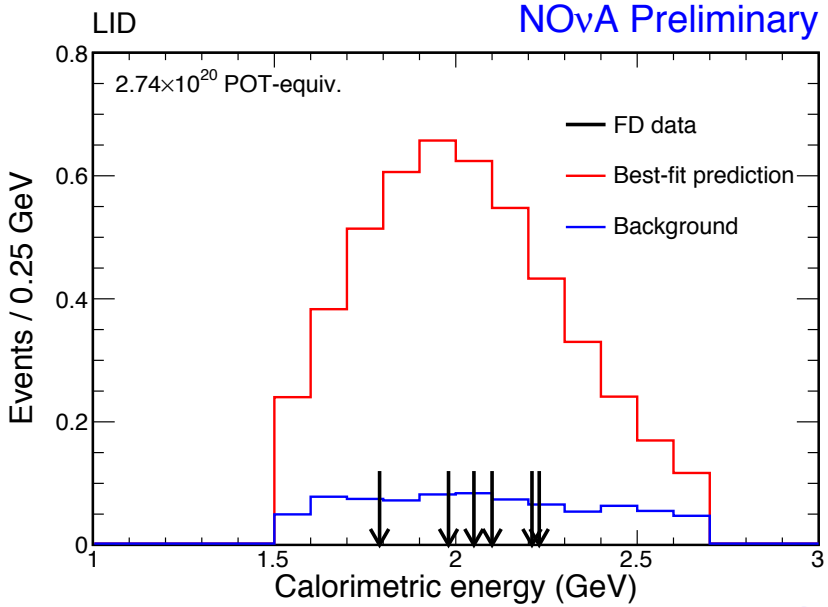
	Total Bkg	Beam ν_e	NC	ν_μ CC	ν_τ CC	Cosmic
LID	**0.94 ± 0.09**	**0.47**	**0.36**	**0.05**	**0.02**	**0.06**
LEM	1.00 ± 0.11	0.46	0.40	0.07	0.02	0.06

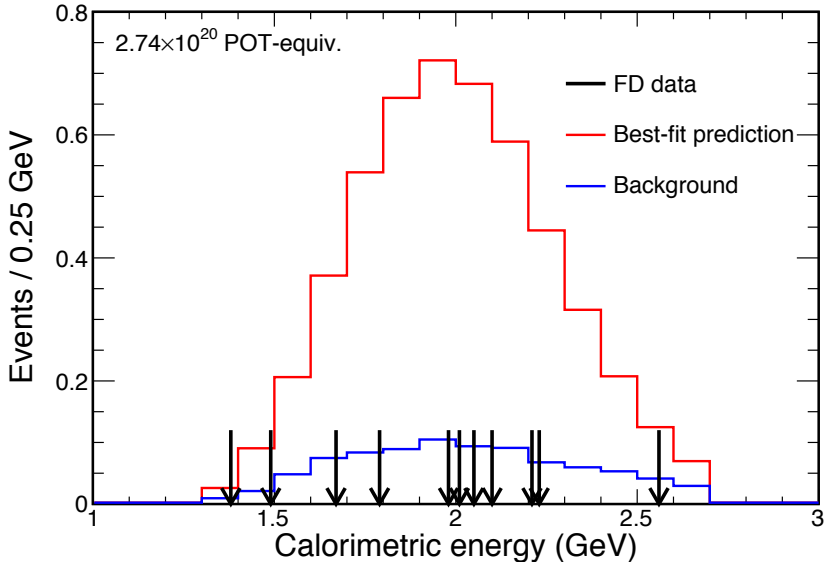
- Signal prediction depends on oscillation parameters

	NH $\delta_{CP}=3\pi/2$	IH $\delta_{CP}=\pi/2$
LID	**5.62 ± 0.72**	**2.24 ± 0.29**
LEM	5.91 ± 0.59	2.34 ± 0.23

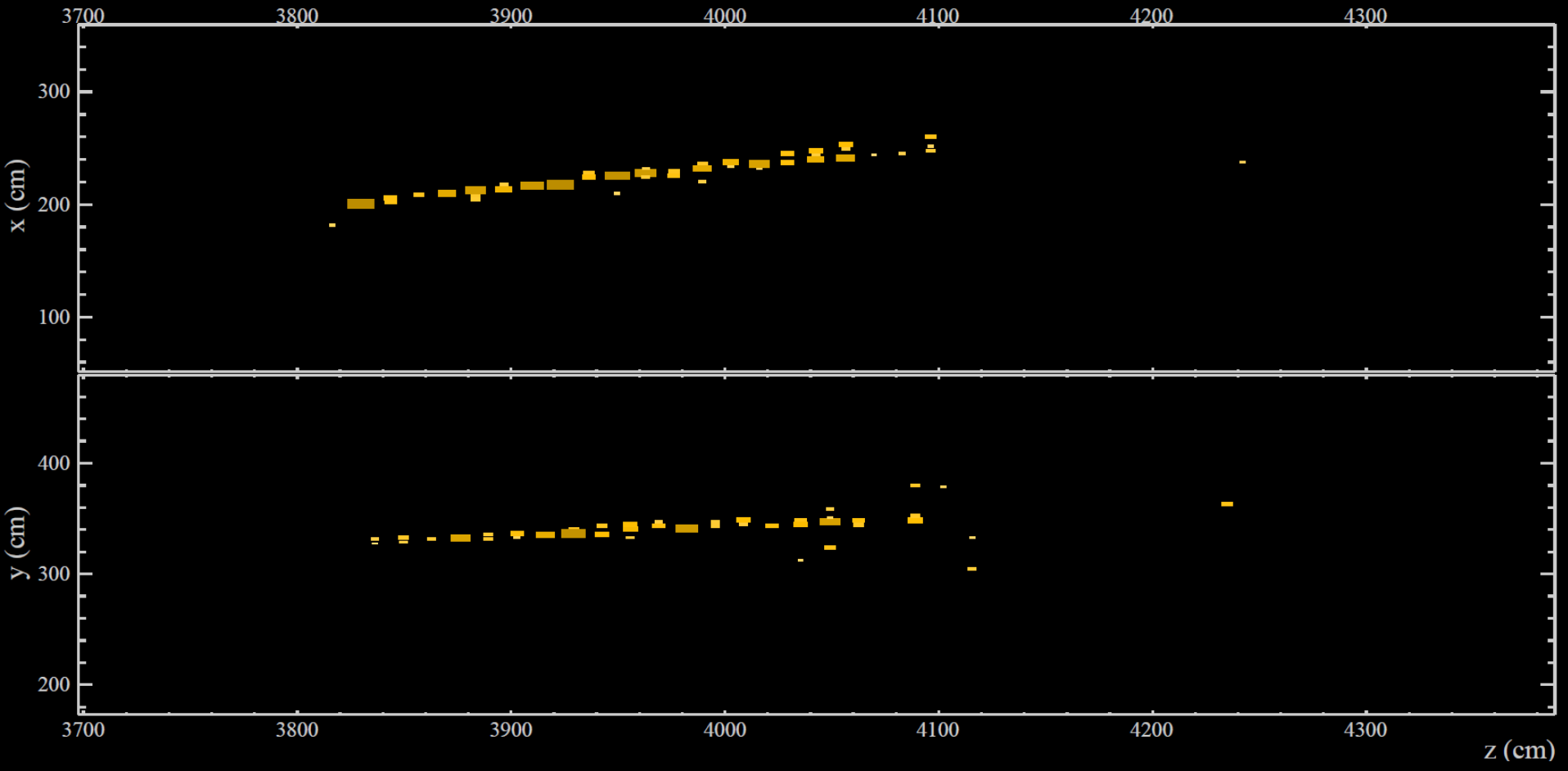
- 13% signal and 10% bkg systematic from calibration uncertainties, mismodeling of neutrino interaction and detector response non-linearity

ν_e Appearance Results





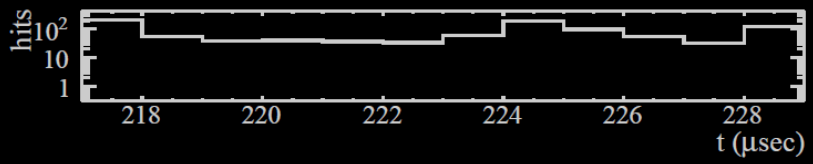
- LID:
  - Select 6 events
  - 3.3σ significance for ν_e appearance
- LEM:
  - Select 11 events
  - 5.5σ significance for ν_e appearance
- All 6 LID events selected by LEM
  - Trinomial probability of selecting this combination (11:6/5/0) is 9.2%

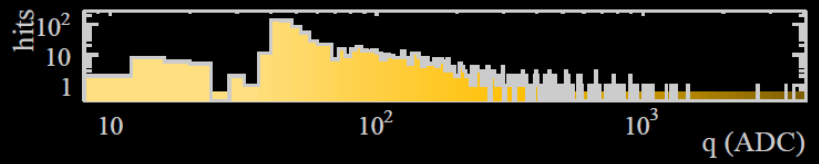


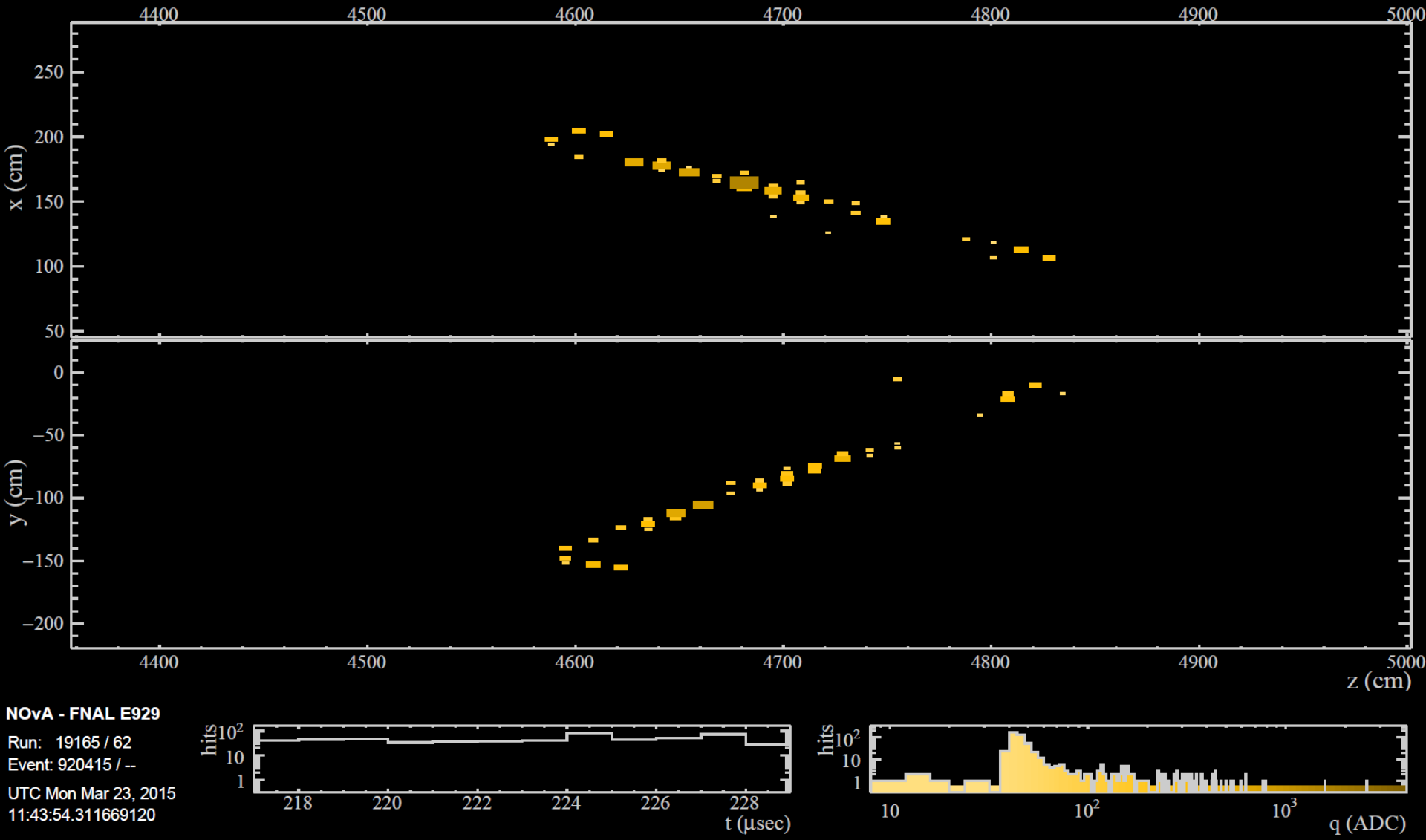
NOvA - FNAL E929

Run: 17103 / 7
Event: 27816 / --

UTC Wed Sep 3, 2014
10:04:58.572014784



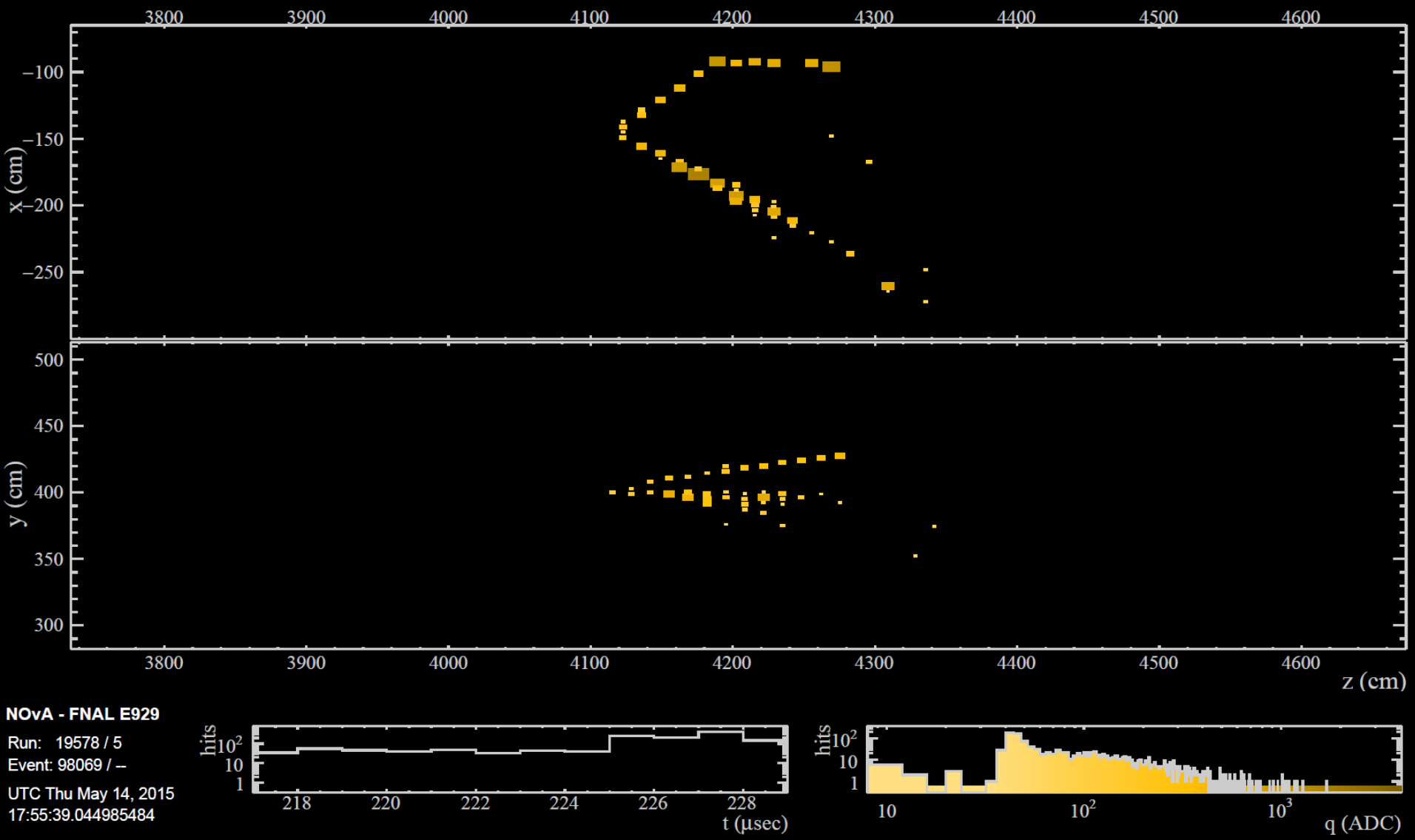




NOvA - FNAL E929

Run: 19165 / 62
Event: 920415 / --

UTC Mon Mar 23, 2015
11:43:54.311669120

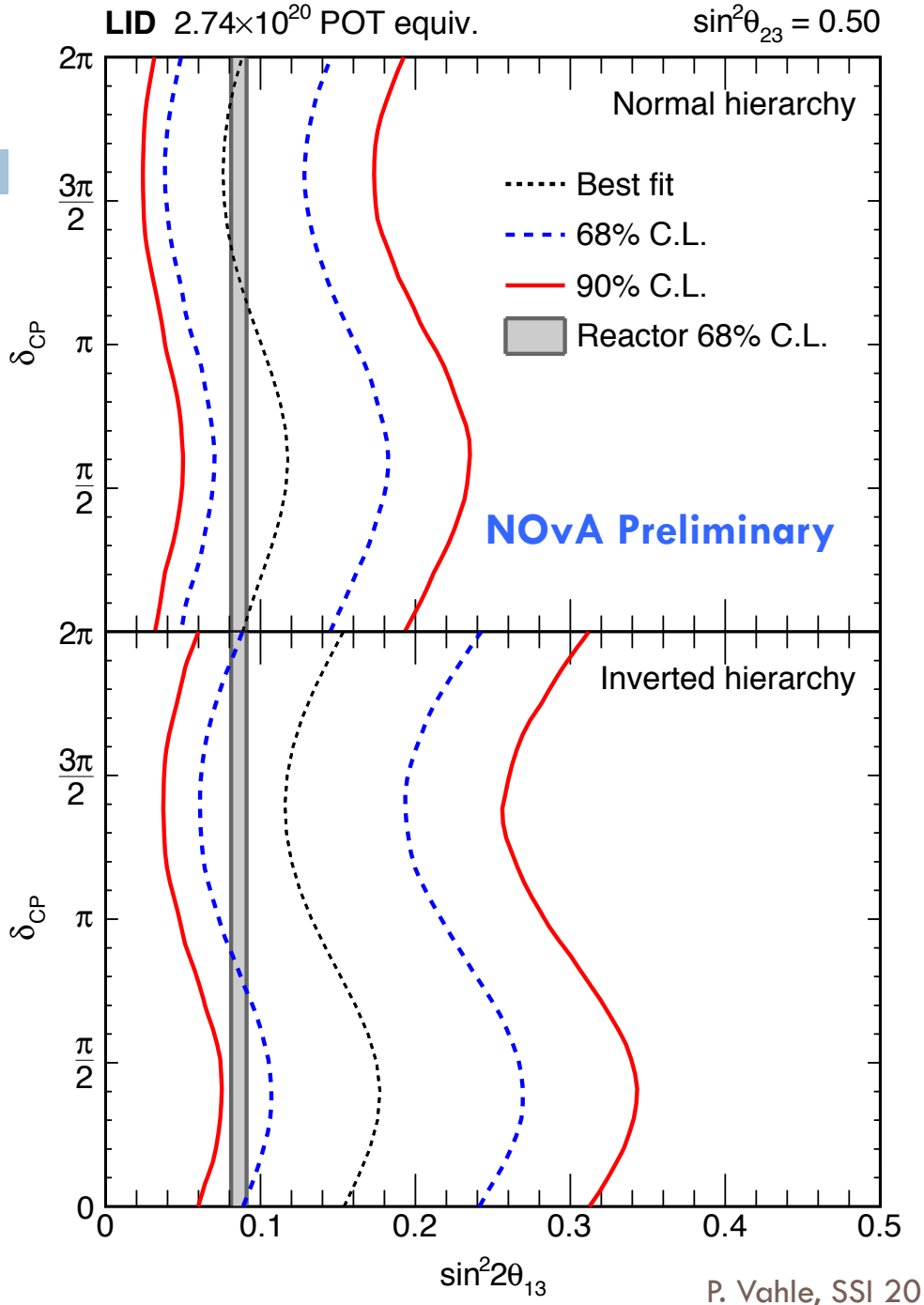


NOvA - FNAL E929

Run: 19578 / 5
Event: 98069 / --
UTC Thu May 14, 2015
17:55:39.044985484

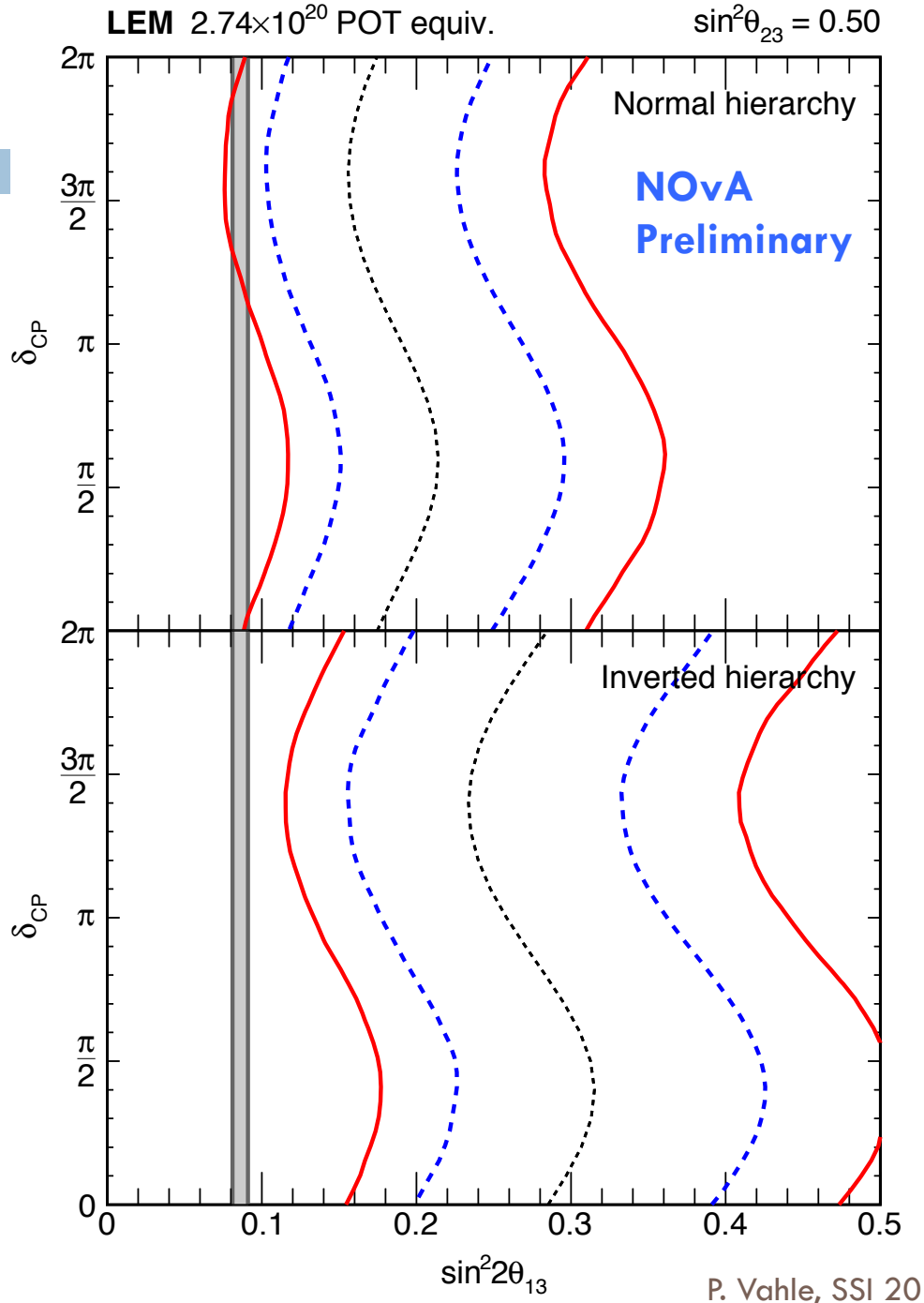
ν_e Appearance Results

- Contours determined using Feldman-Cousins procedure
  - Include errors on solar parameters
  - Atmospheric Δm^2 varied within new NOvA errors
  - $\sin^2\theta_{23}$ held fixed at 0.5
- LID results in good agreement with reactor measurements



ν_e Appearance Results

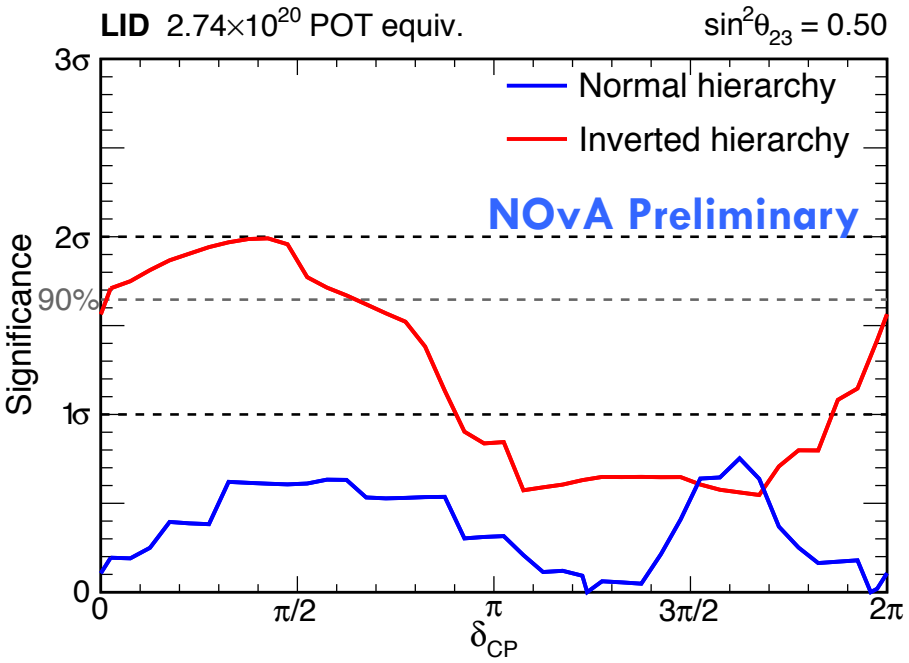
- LEM curves shift right
- Some tension with reactor results, particularly in IH

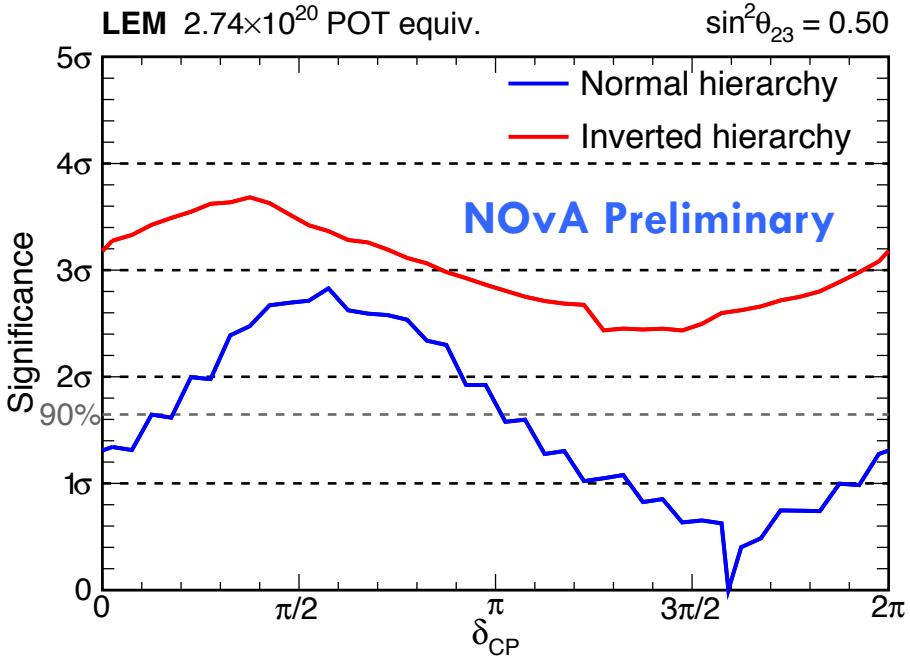


ν_e Appearance Results

- Additionally assuming $\sin^2 2\theta_{13}=0.086\pm0.05$
- LID shows mild tension with IH, $0<\delta_{CP}<0.8\pi$
- LEM disfavors IH at greater than 2σ for all δ_{CP}

(both statements hold even for $0.4<\sin^2\theta_{23}<0.6$)





Jagged structure due to discrete nature of counting experiment

Summary

- NOvA observes muon neutrino disappearance
  - 6.5% measurement of the atmospheric mass splitting
  - θ_{23} consistent with maximal mixing
  - Only 1/13th of proposed exposure
- NOvA observes electron neutrino appearance
  - ν_e appearance signal at 3.3σ for primary selector, 5.5σ for secondary selector.
  - Some preference for normal hierarchy
- Beam returns in October
  - 400-500 kW running
  - Plan to increase to 700kW by March 2016
  - Double the exposure by next summer
  - Lots more data to come!

Backup Slides

Neutrinos Have Mass!

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \mathbf{U}^\dagger \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

$$P(\nu_\alpha \rightarrow \nu_\beta) = \left| \sum_j U^*_{\beta j} e^{-i\frac{m_j^2 L}{2E}} U_{\alpha j} \right|^2$$

- $\nu_e, \nu_\mu, \nu_\tau \leftrightarrow \nu_1, \nu_2, \nu_3$
  - Flavor States: creation and detection
  - Mass States: propagation
- A neutrino created as one flavor can later be detected as another flavor, depending on:
  - distance traveled (L)
  - neutrino energy (E)
  - difference in the squared masses ($\Delta m^2_{ij} = m^2_i - m^2_j$)
  - The mixing amplitudes ($U_{\alpha i}$)

The PMNS Mixing Matrix

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- (12) Sector: Reactor + Solar, L/E~15,000 km/GeV

$$^{\dagger}\Delta m^2_{21} = 7.50^{+0.19}_{-0.20} \times 10^{-5}\ \text{eV}^2 \qquad \tan^2\theta_{12} = 0.452^{+0.035}_{-0.033}$$

- (23) Sector: atmospheric and accelerator, L/E~500 km/GeV

$$^{\dagger\dagger}\left|\Delta m^2_{32}\right| = 2.32^{+0.12}_{-0.08} \times 10^{-3}\ \text{eV}^2 \qquad ^{*}\sin^2(2\theta_{23}) > 0.96\,(90\%\ \text{C.L.})$$

- (13) Sector mixing not yet observed

$$^{**}\sin^2(2\theta_{13}) < 0.15 - 0.16$$

†PRD 83.052002(2011)
††PRL 106. 181801(2011)
*SuperK Preliminary, Nu2010
** Eur.Phys. C27:331-374,2003

Why measure all these angles?

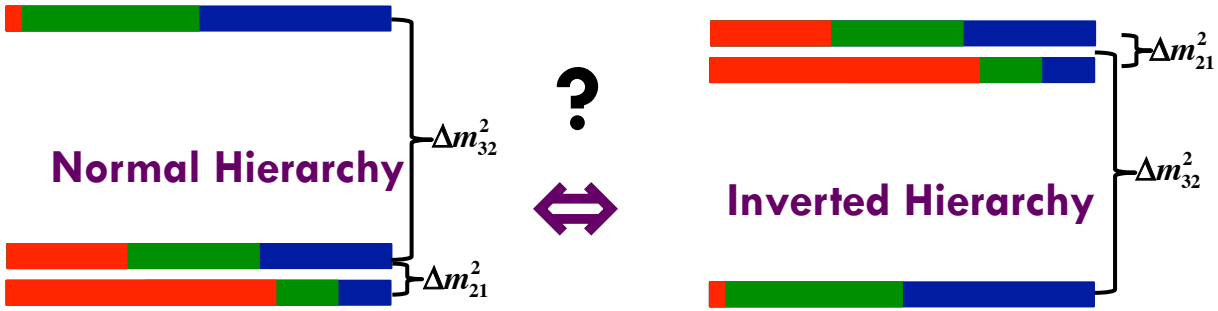
- Precision measurements provide a valuable check that neutrino oscillations are the solution to neutrino anomalies
- PMNS matrix analogous to CKM matrix
  - lepton sector mixing much larger than quark sector mixing
  - θ_{23} maximal, θ_{12} moderately large, θ_{13} small, zero? why?
  - Is there CP violation in the lepton sector?
  - Is it big enough to account for matter vs. antimatter asymmetry in the Universe?
- Small neutrino mass suggests a heavy partner (see-saw mechanism)—Neutrinos provide a window to physics at the GUT scale!

ν_e Appearance

- At L/E~400 km/GeV, dominant oscillation mode is $\nu_\mu \rightarrow \nu_\tau$
- A few percent of the missing ν_μ could change into ν_e

$$P(\nu_\mu \rightarrow \nu_e) = \left| \sqrt{P_{atm}}\, e^{-i\left(\frac{\Delta m^2_{32} L}{4E} + \delta_{cp}\right)} + \sqrt{P_{sol}} \right|^2$$

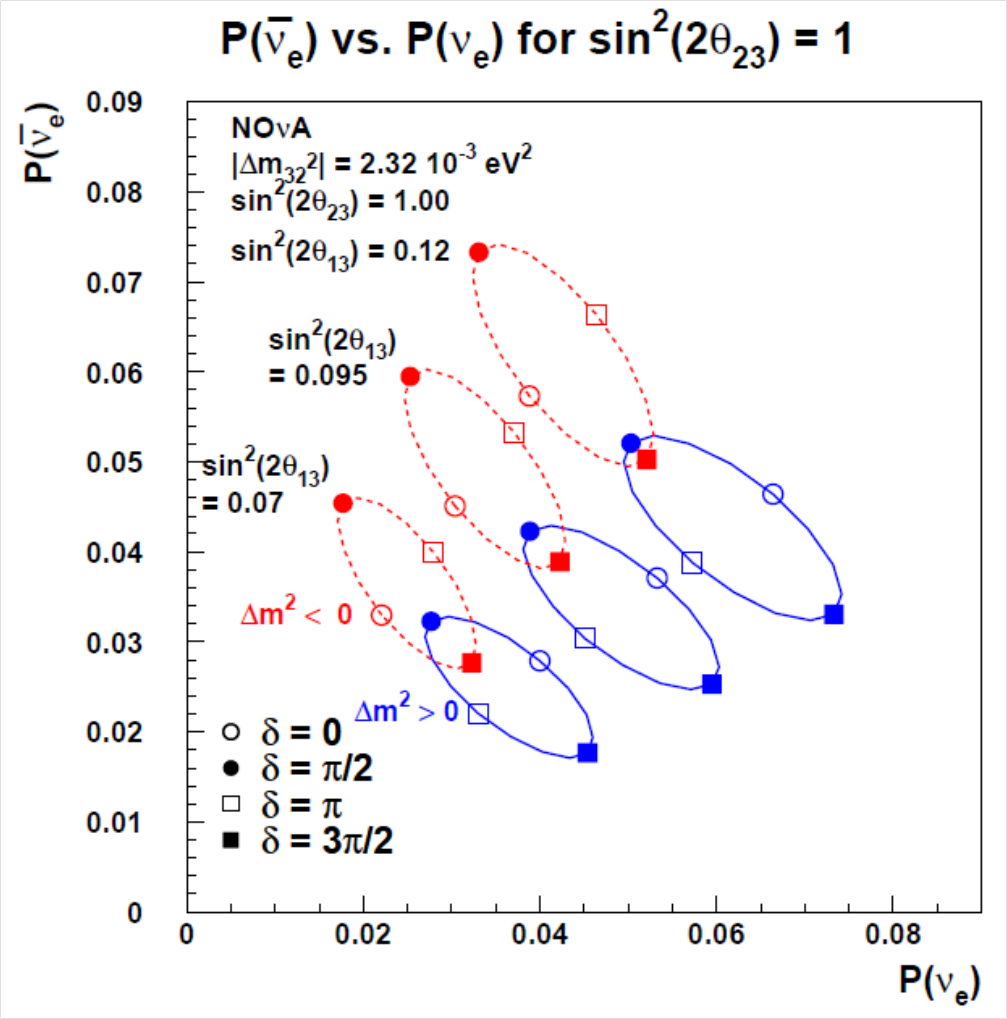
$$P_{atm} = \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{31} L}{4E} - aL\right) \left(\frac{\frac{\Delta m^2_{31} L}{4E}}{\left(\frac{\Delta m^2_{31} L}{4E} - aL\right)} \right)^2 \qquad P_{sol} \approx \cos^2\theta_{23} \sin^2 2\theta_{12} \sin^2(aL) \left(\frac{\frac{\Delta m^2_{21} L}{4E}}{aL} \right)^2$$



Oscillation probability depends on sign of Δm^2

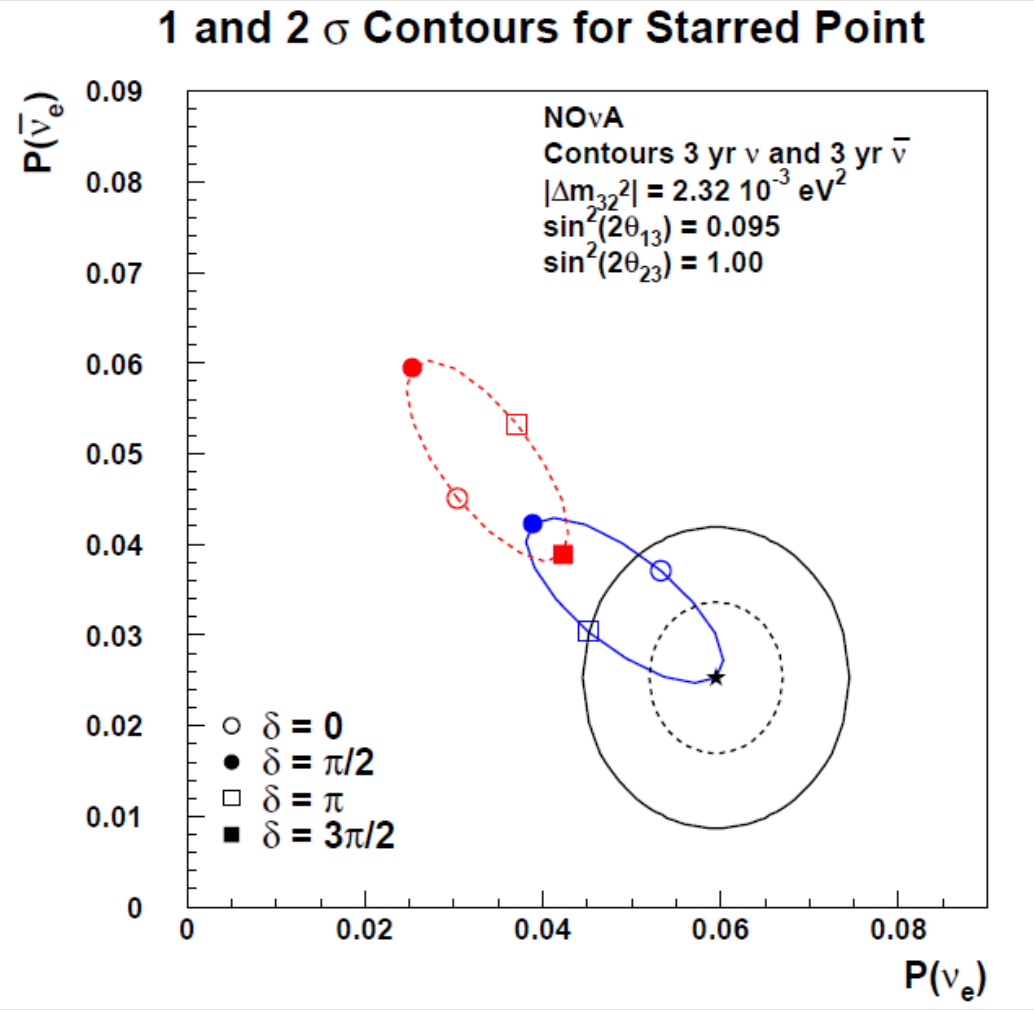
How its done

- Compare oscillation probability measured with neutrinos and antineutrinos



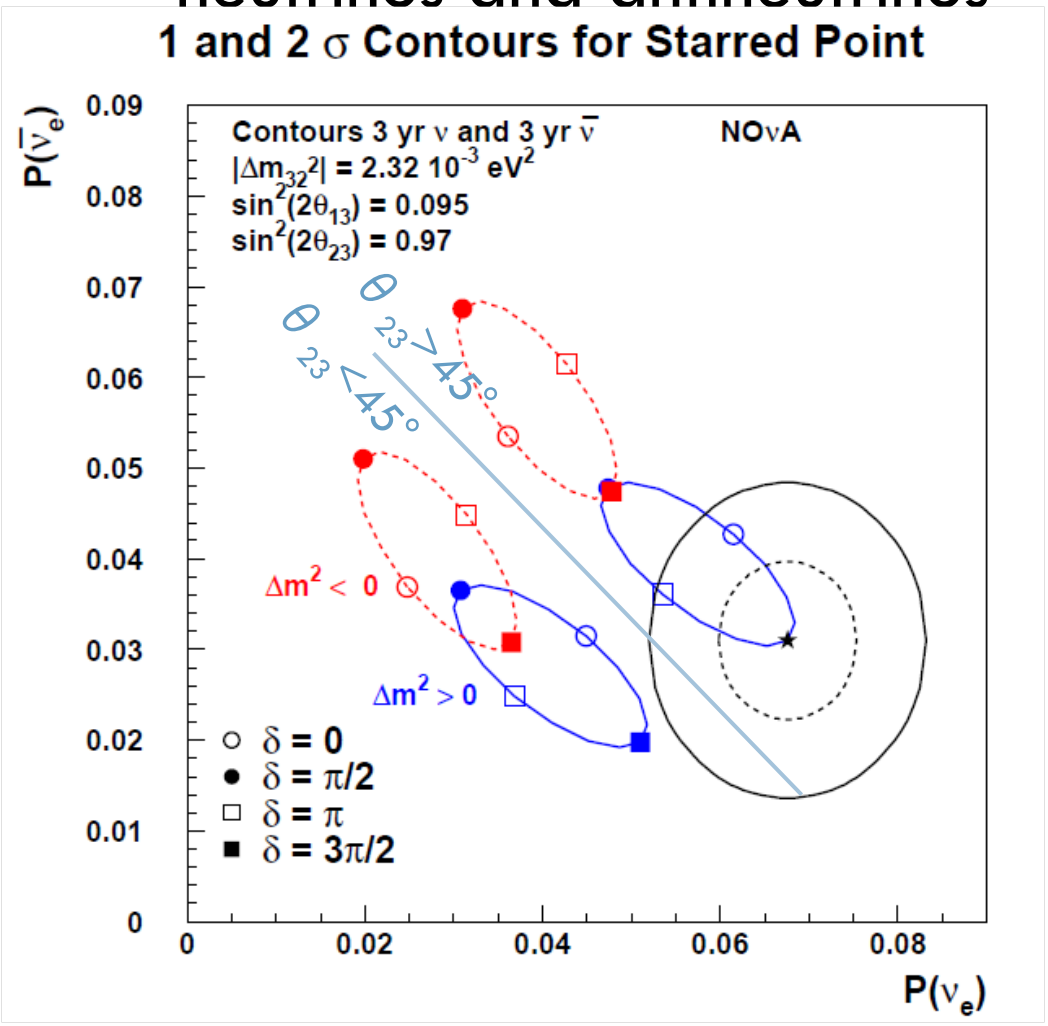
How its done

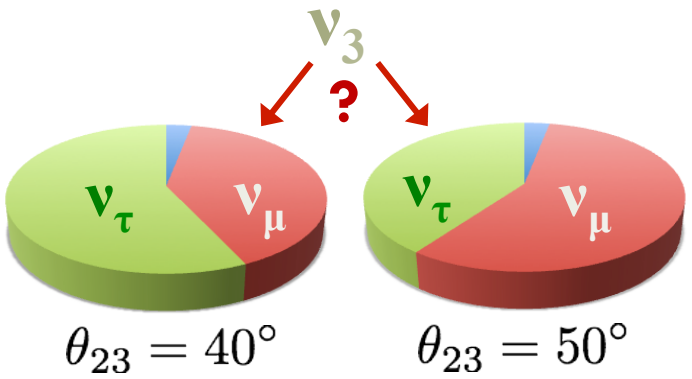
- Compare oscillation probability measured with neutrinos and antineutrinos



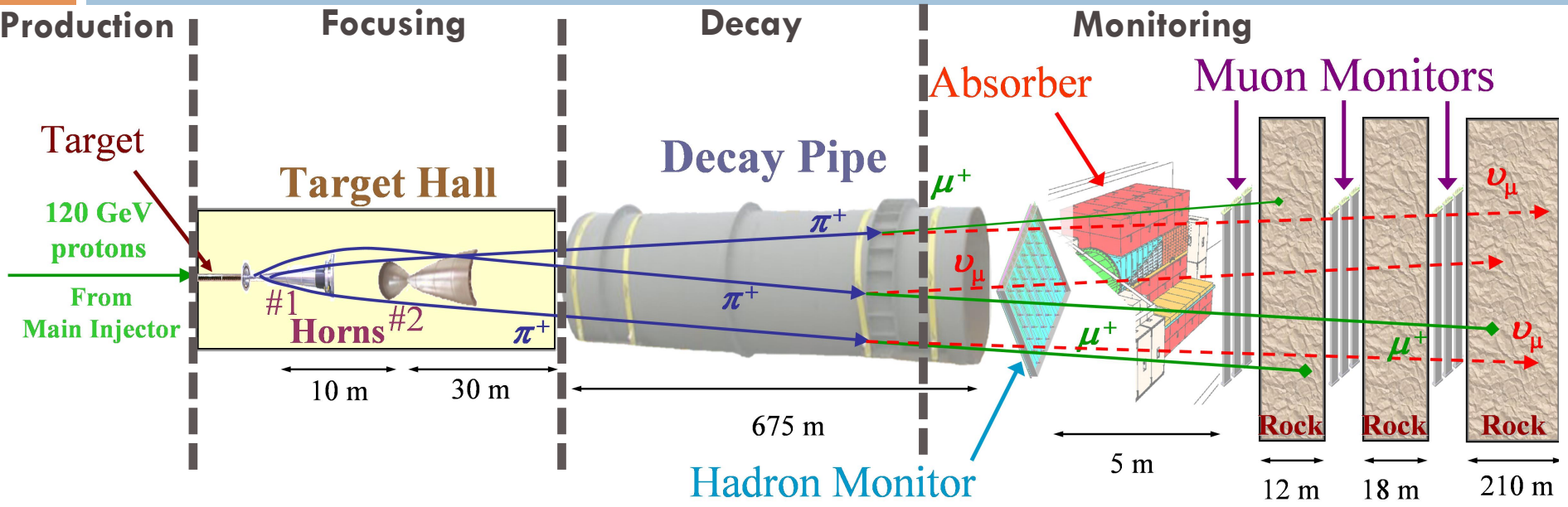
How its done

- Compare oscillation probability measured with neutrinos and antineutrinos



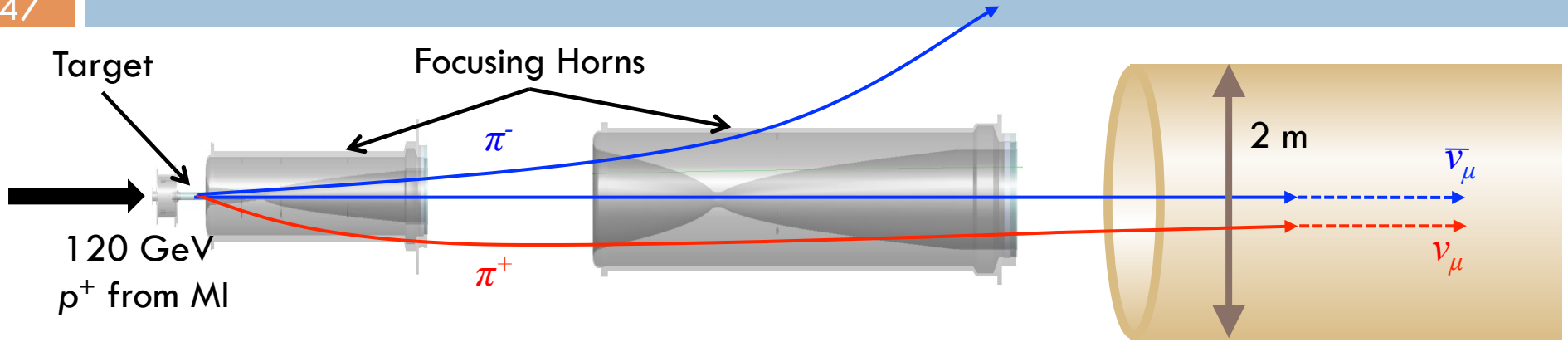


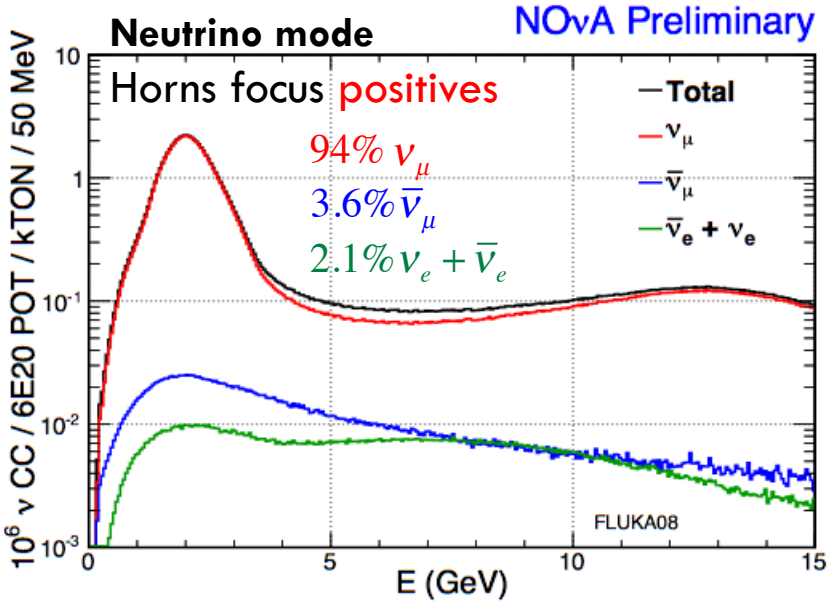
Making a Neutrino Beam

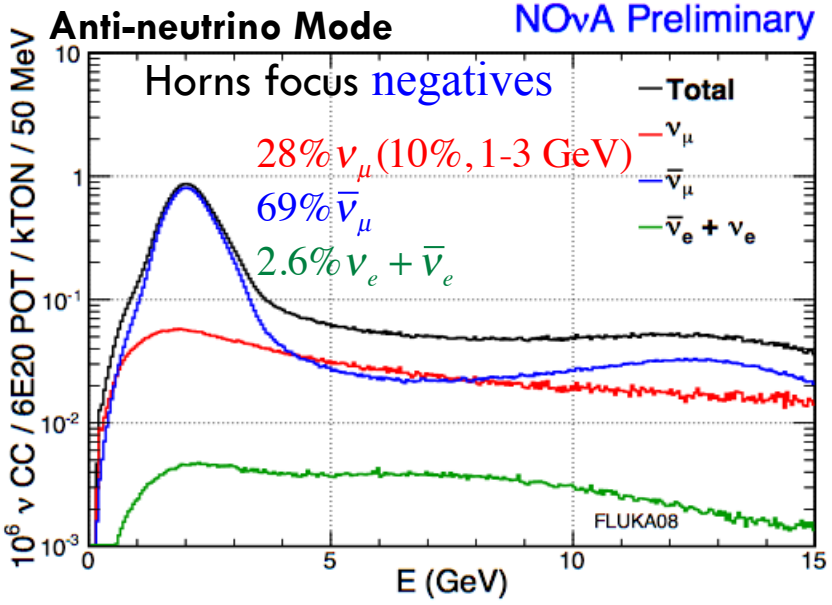


- **Enhanced 700kW NuMI beam line**
  - Cycle time from 2.2 s to 1.3 s using Recycler slip-stacking
  - Increased intensity: 12 Booster batches up from 11
  - New high power target
  - New horn, reconfigured for higher energy beam

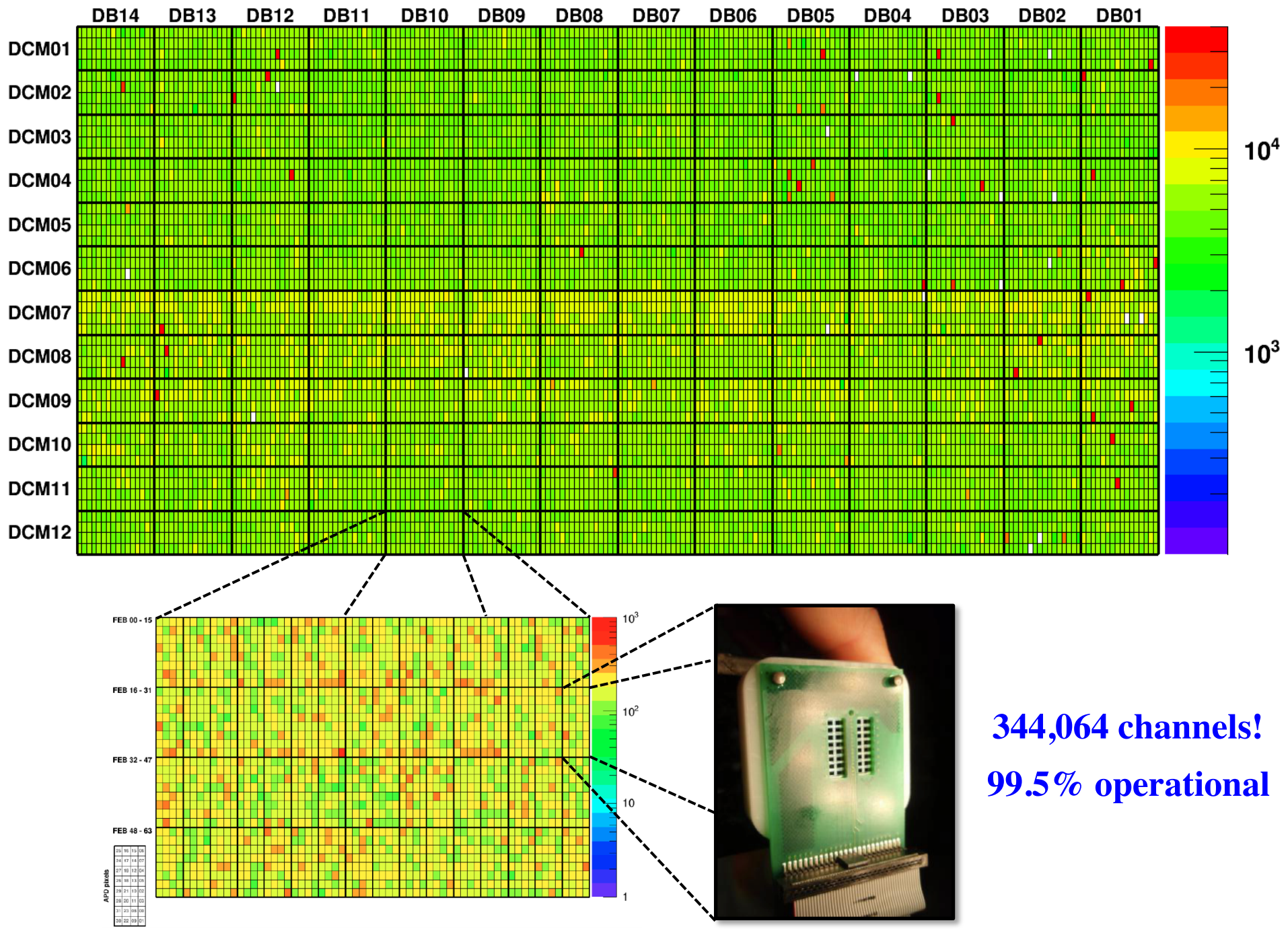
Making a Neutrino Beam





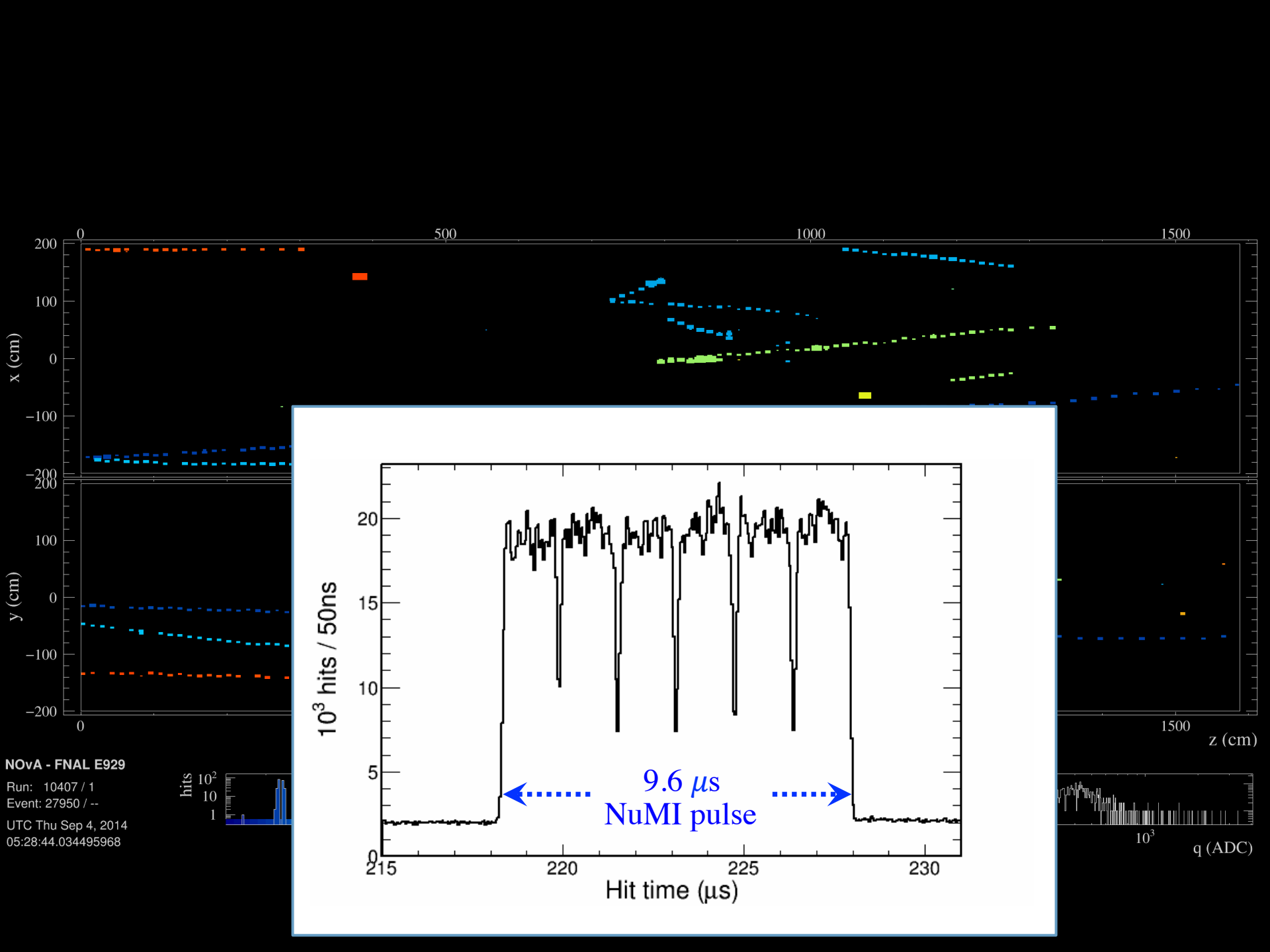



Empty Hall



344,064 channels!

99.5% operational

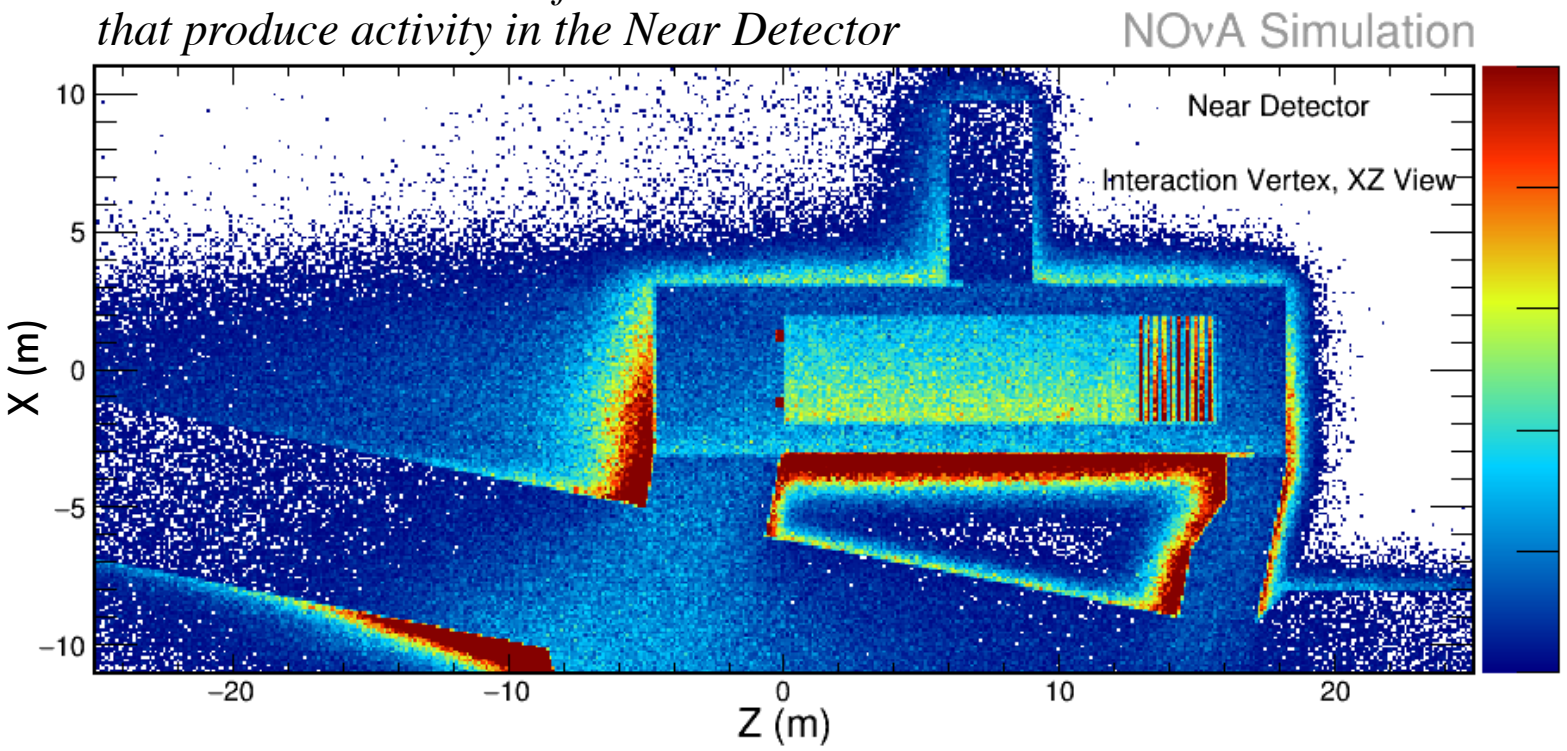

0
500
1000
1500
200
100
0
−100
−200
x (cm)
y (cm)
z (cm)
NOvA - FNAL E929
Run: 10407 / 1
Event: 27950 / --
UTC Thu Sep 4, 2014
05:28:44.034495968
hits
10^2
10
1
10^3
q (ADC)
10^3 hits / 50ns
20
15
10
5
0
215
220
225
230
Hit time (μs)
9.6 μs
NuMI pulse

Simulation

Highly detailed end-to-end simulation chain

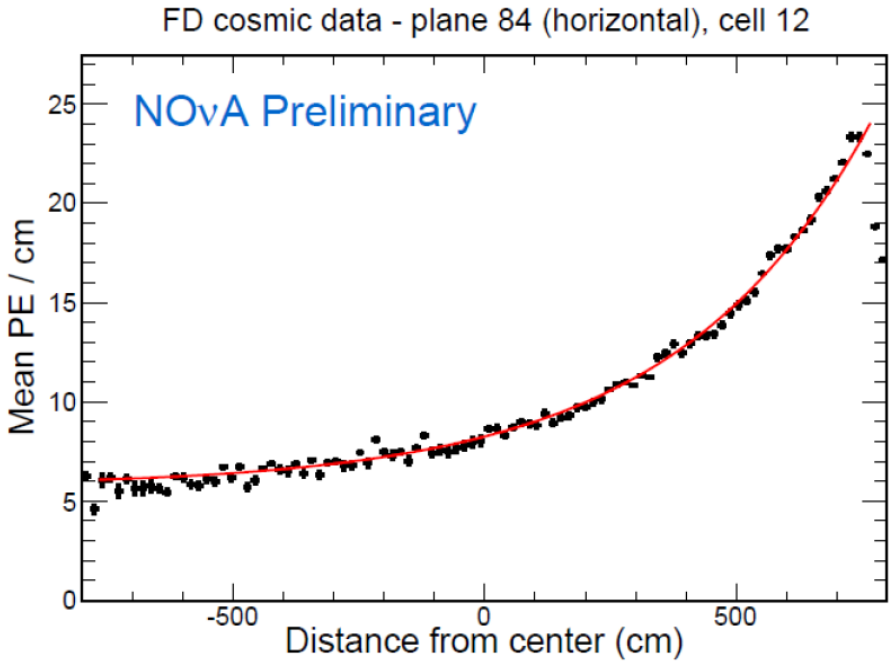
- Beam hadron production, propagation; neutrino flux: **FLUKA/FLUGG**
- Cosmic ray flux: **CRY**
- Neutrino interactions and FSI modeling: **GENIE**
- Detector simulation: **GEANT4**
- Readout electronics and DAQ: **Custom simulation routines**

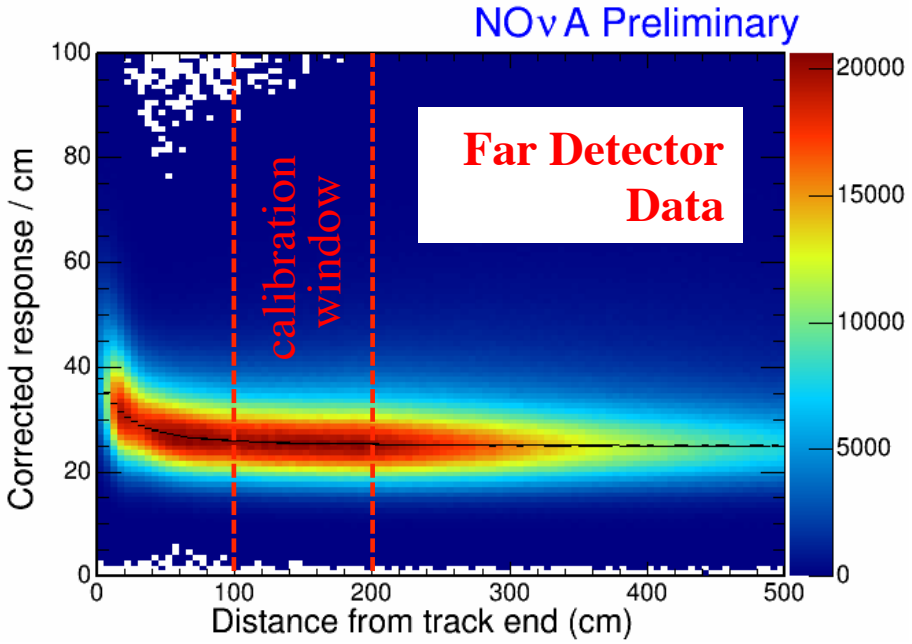
Simulation: Locations of neutrino interactions that produce activity in the Near Detector



Calibration

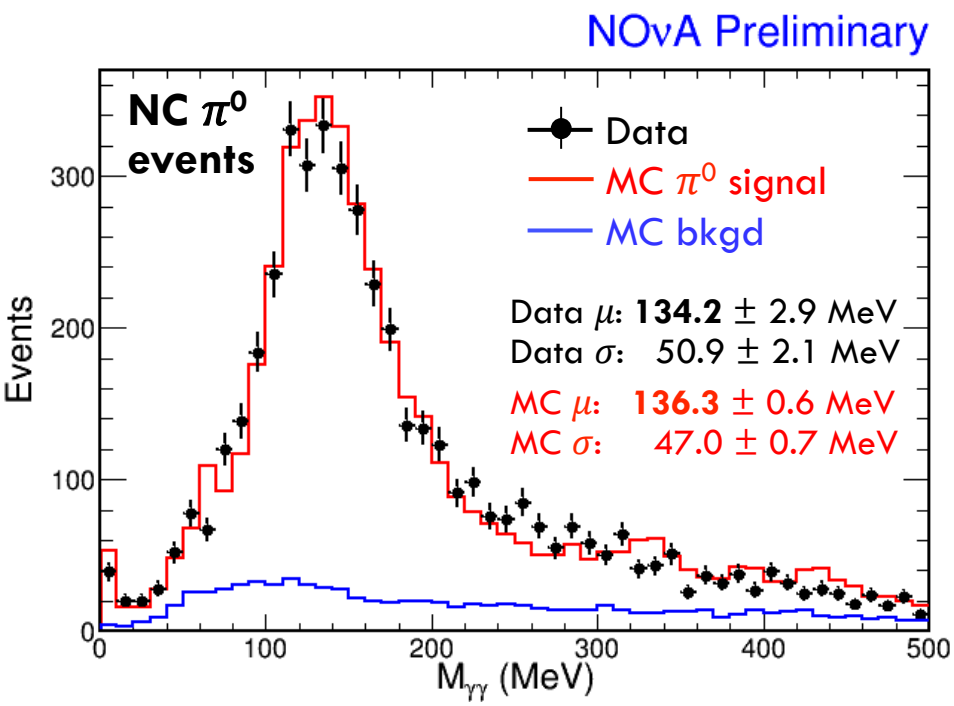
- Calibration achieved using cosmic rays
- Light levels drop by a factor of 8 across a FD cell
- Stopping muons provide a standard candle

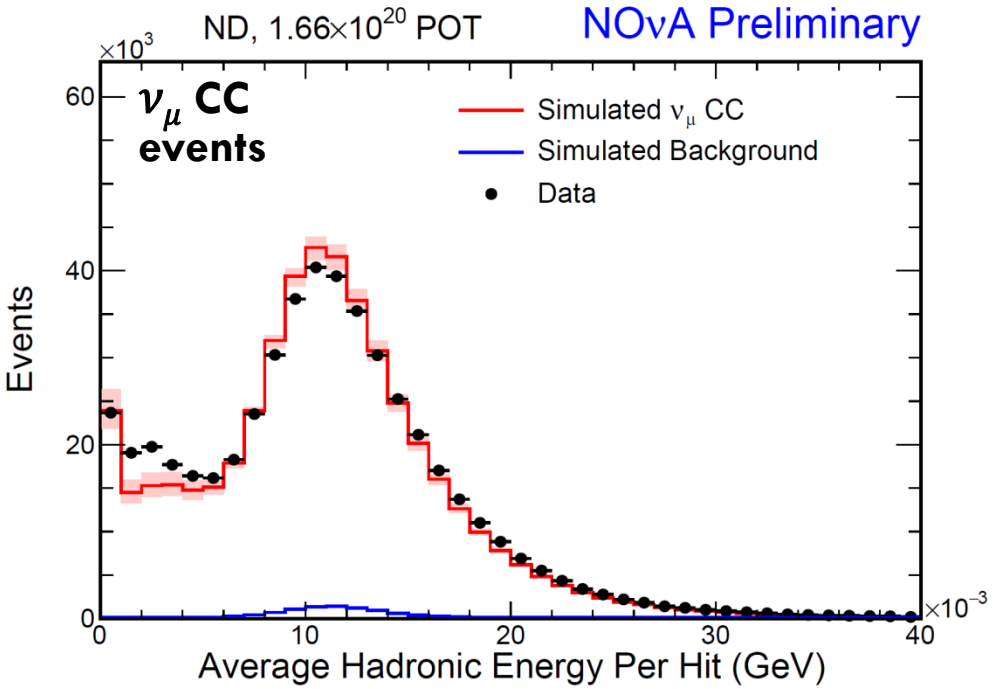




Energy Scale

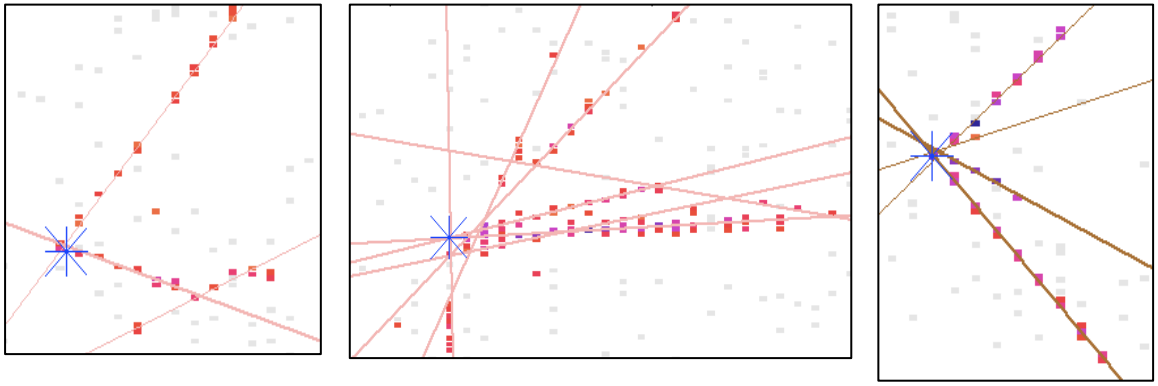
- Near Detector
  - cosmic μ dE/dx [~vertical]
  - beam μ dE/dx [~horizontal]
  - Michel e^- spectrum
  - π^0 mass
  - hadronic shower *E*-per-hit
- Far Detector
  - cosmic μ dE/dx [~vertical]
  - beam μ dE/dx [~horizontal]
  - Michel e^- spectrum
- All agree to 5%



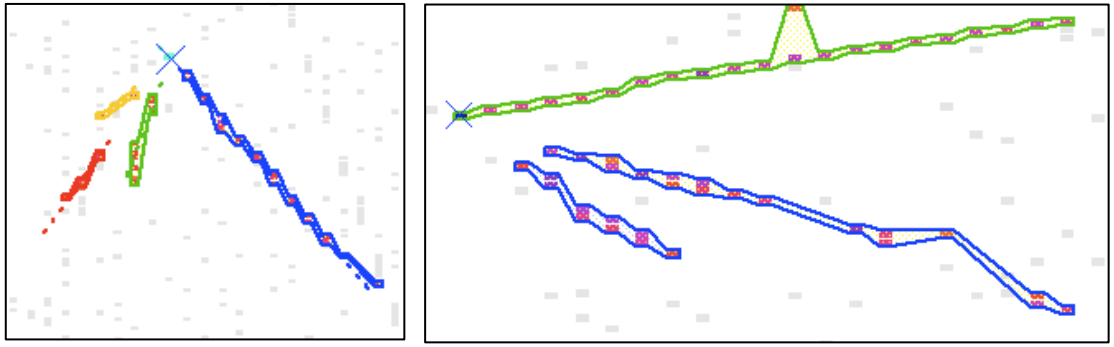


Reconstruction

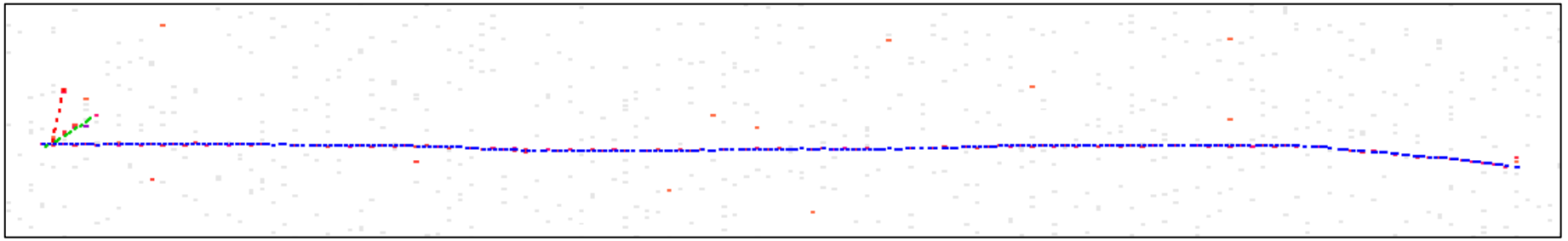
Vertexing: Find **lines of energy depositions** w/ Hough transform
CC events: 11 cm resolution



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

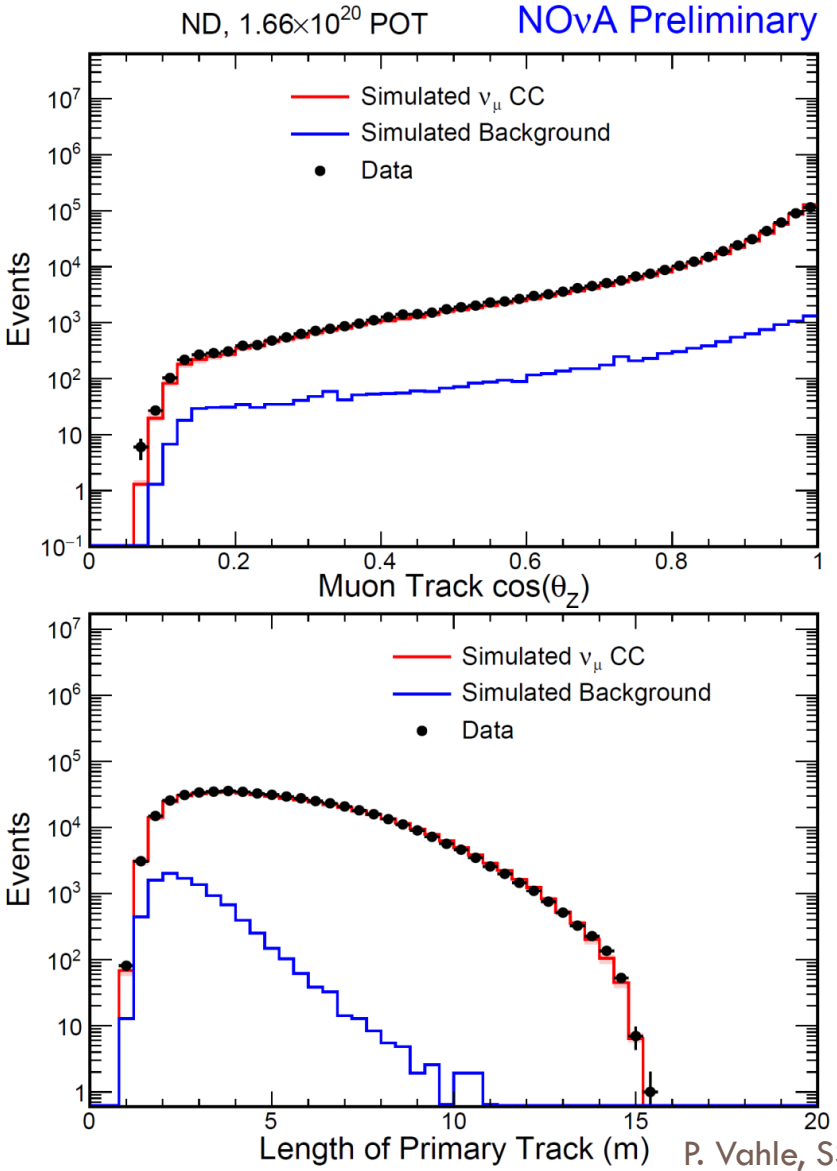


Tracking: Trace particle trajectories with **Kalman filter** tracker (below). Also have a **cosmic ray tracker**: lightweight, very fast, and useful for large calibration samples and online monitoring tools.



Selecting Muon Neutrinos

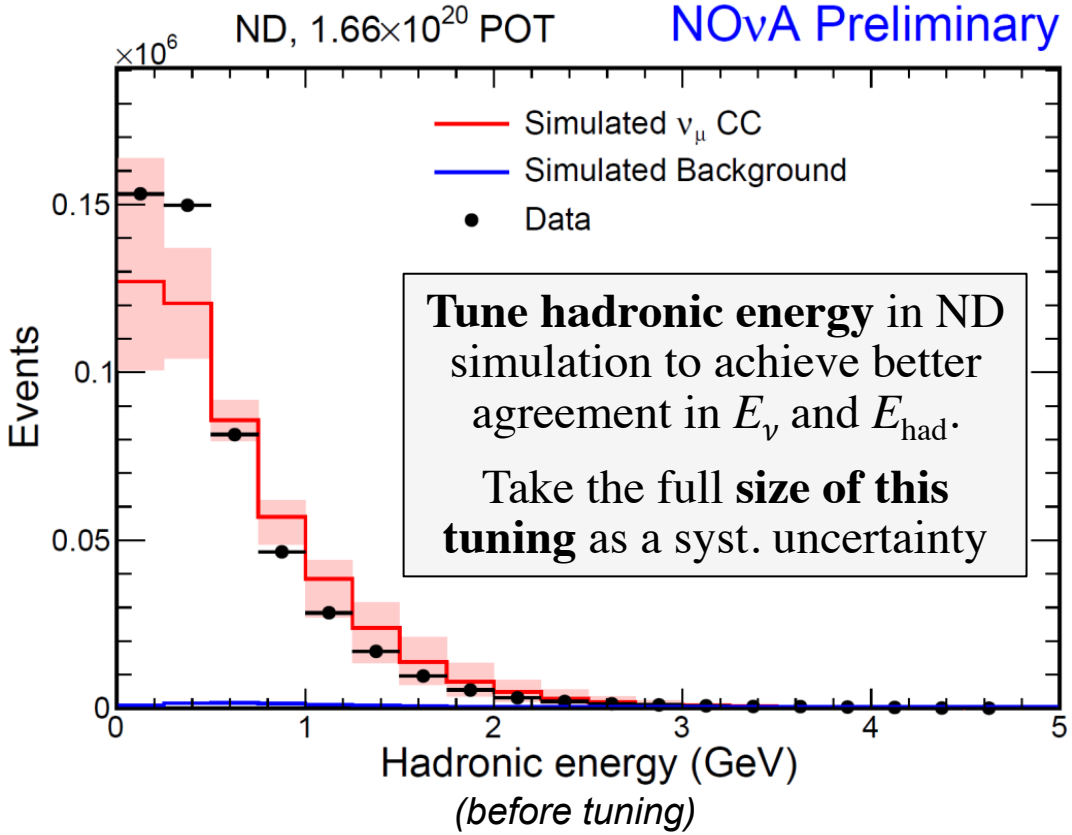
- Goal: Isolate a pure sample of ν_μCC events less than 5GeV
  - Select events with long tracks
  - Suppress NC and cosmic backgrounds
- Containment cuts require a buffer between walls and event
- 4-variable kNN used to identify muons
  - track length
  - dE/dx along track
  - scattering along track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



Systematics

Most of our systematic uncertainties have **relatively little influence** on the result

Hadronic modeling syst. is one with a noticeable effect
(impact reduced by ND-to-FD prediction procedure)



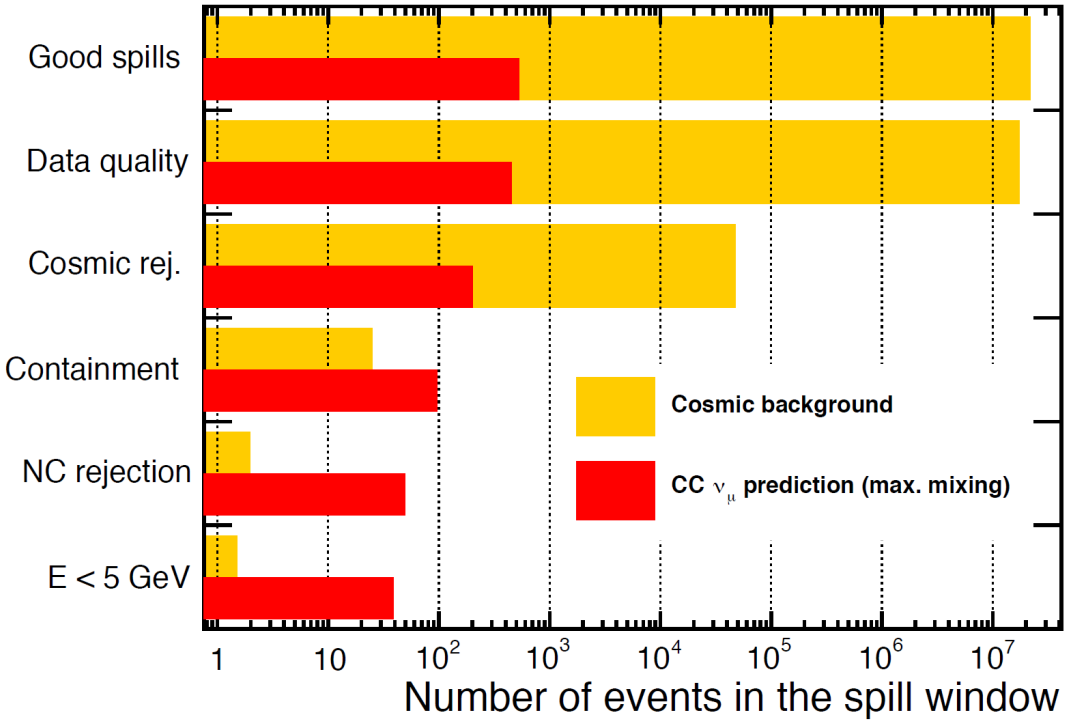
Uncertainties assessed

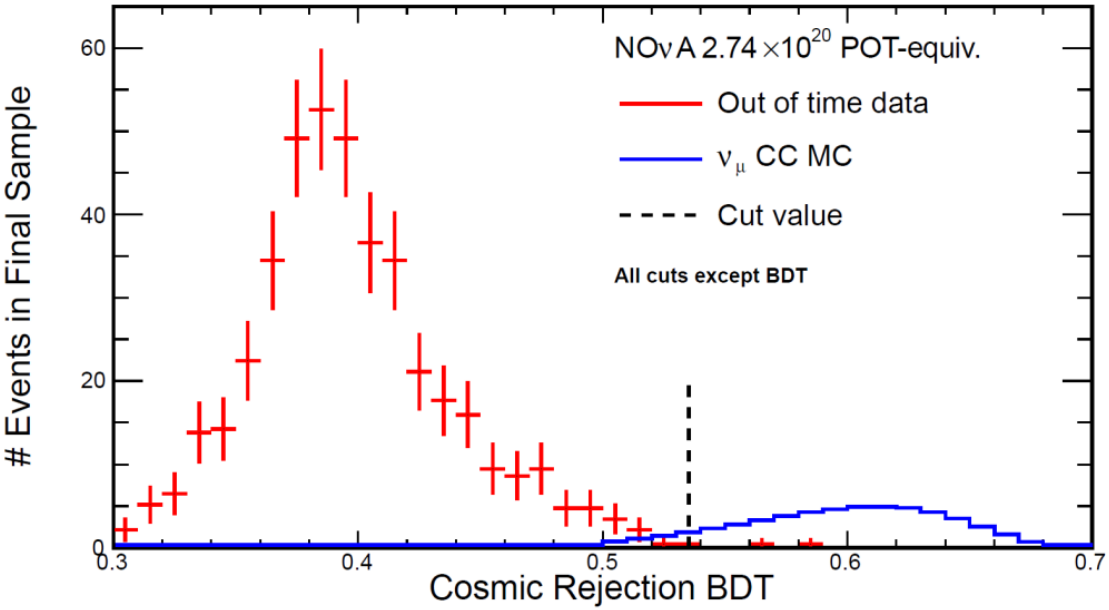
- Hadronic energy
  (21%, ~equiv. to 6% on E_ν)
- Neutrino flux
  (NA49 + beam transport model)
- Absolute, relative normalization
  (1%, 2%)
- Neutrino interactions
  (GENIE / Intranuke model)
- NC and ν_τ CC background rate
  (100% each)
- Multiple calibration and light-level systematics
  (Hit energy,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

Cosmic rejection

Rejection factor from
beam timing: **10^5**
event topology: **10^7 (!)**

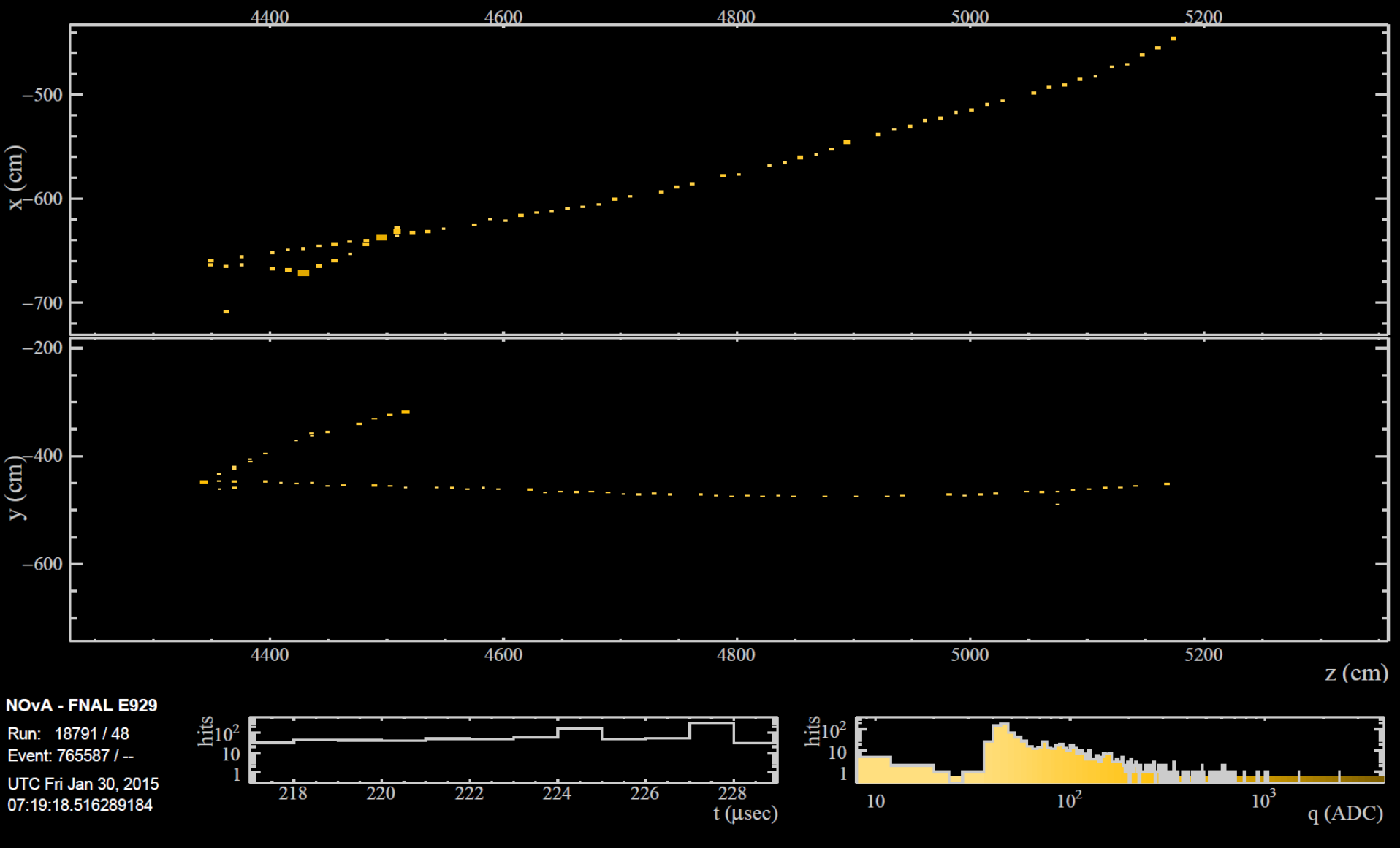
Final cosmic bkgnd rate **measured directly** with beam-off FD data.





← Output of **cosmic rejection decision tree** after all other cuts

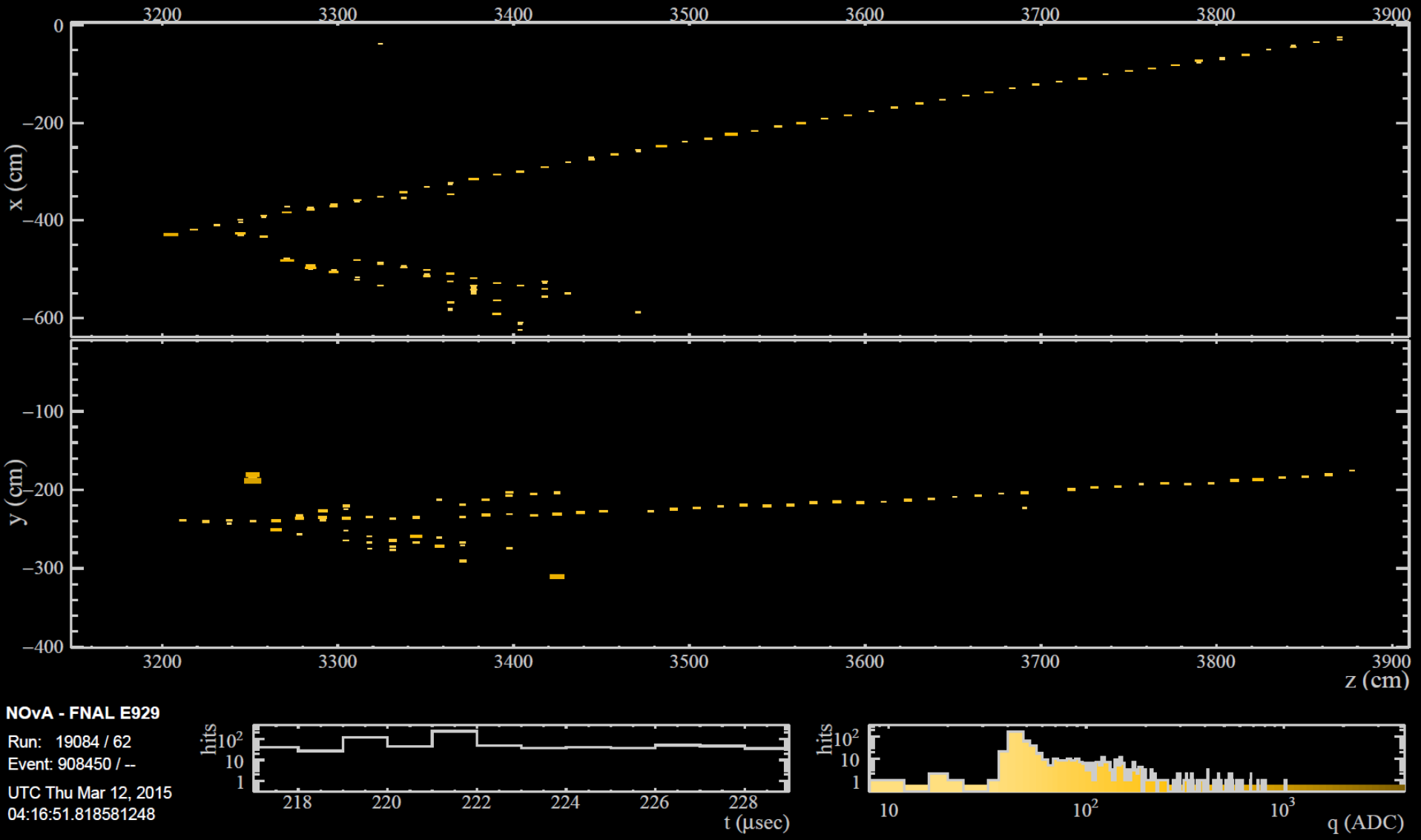
Based on reconstructed track direction, position, and length; and energy and number of hits in event

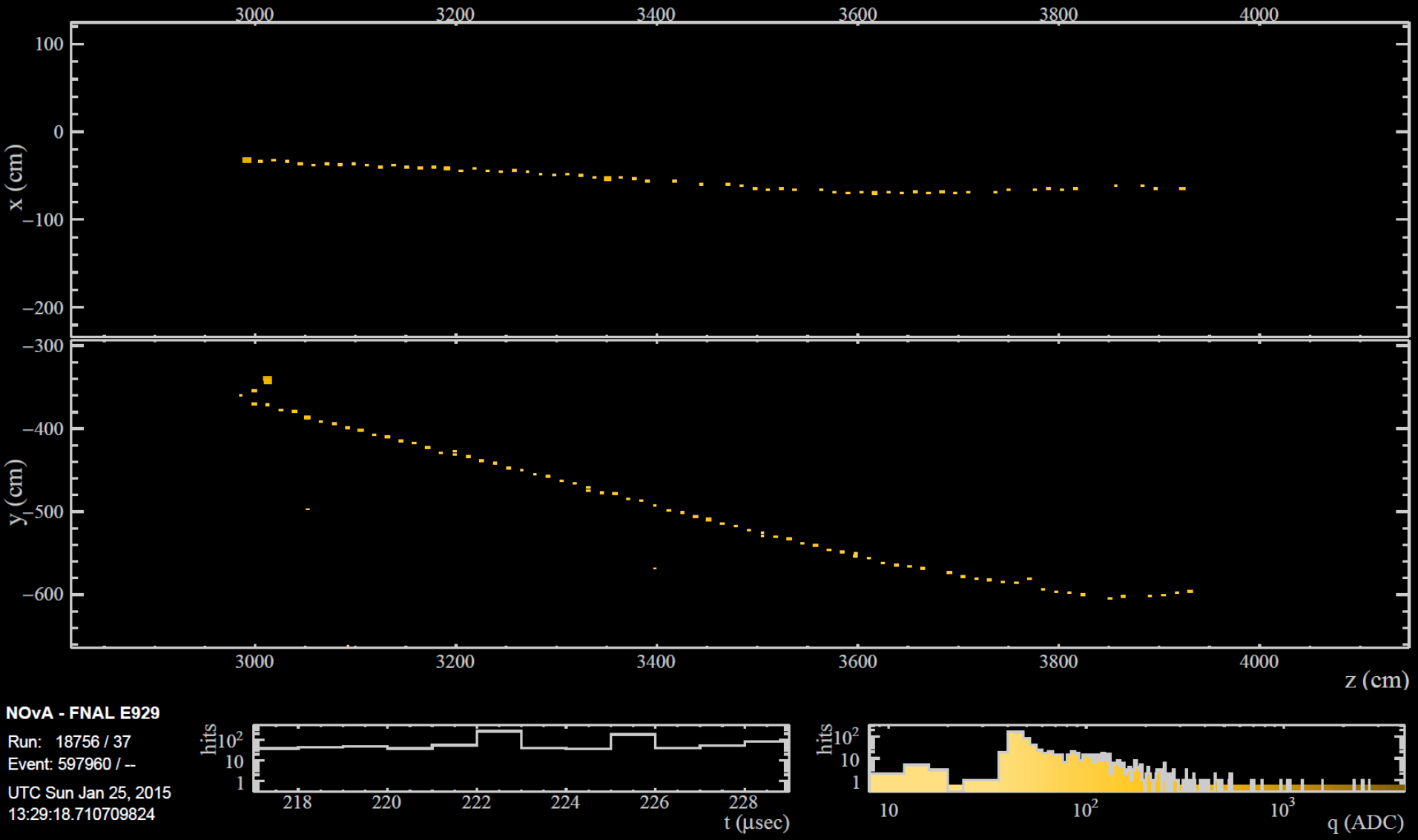


NOvA - FNAL E929

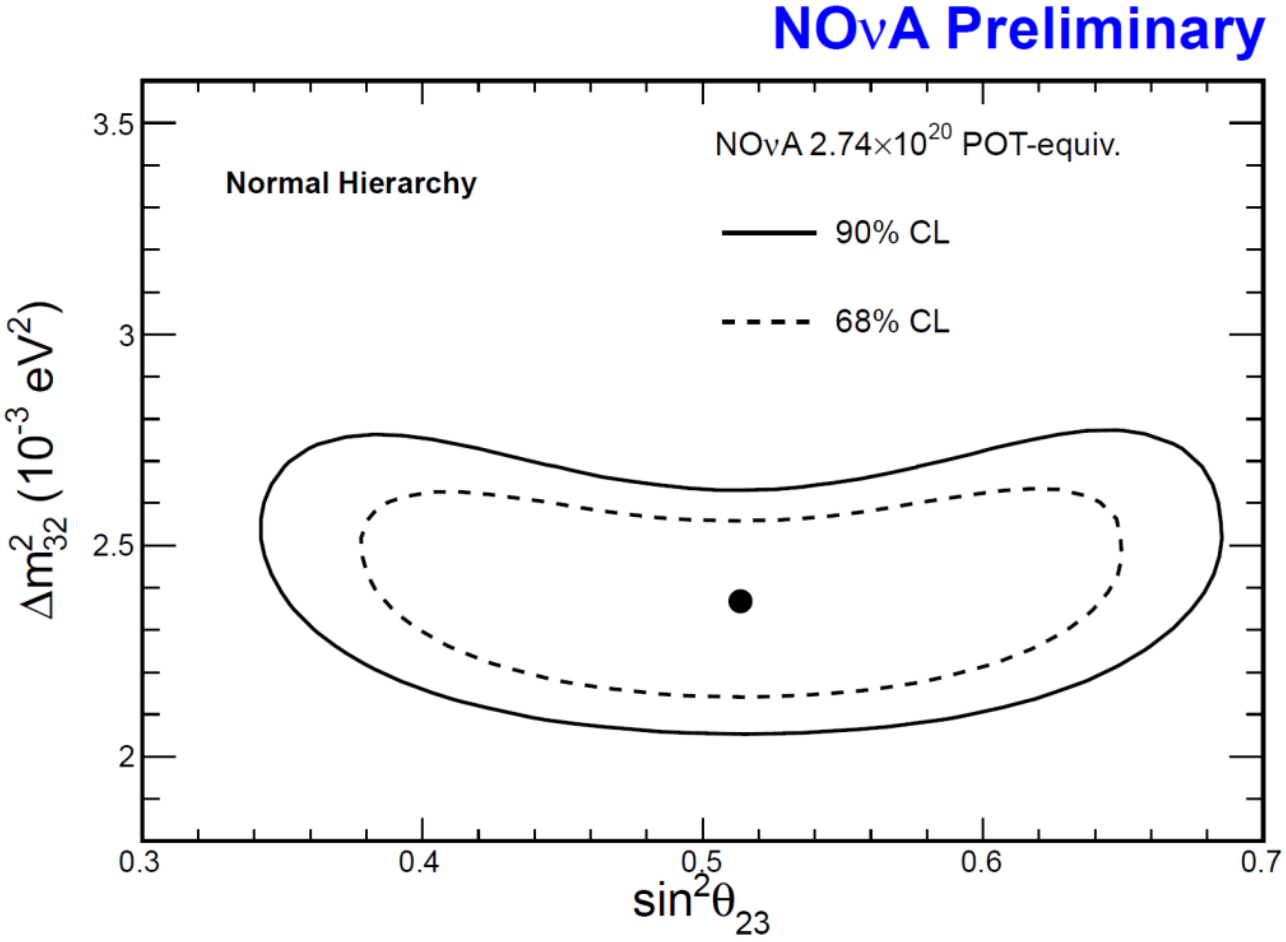
Run: 18791 / 48
Event: 765587 / --

UTC Fri Jan 30, 2015
07:19:18.516289184


3200
3300
3400
3500
3600
3700
3800
3900
0
−200
−400
−600
x (cm)
−100
−200
−300
−400
y (cm)
z (cm)
NOvA - FNAL E929
Run: 19084 / 62
Event: 908450 / --
UTC Thu Mar 12, 2015
04:16:51.818581248
hits
10^2
10
1
218
220
222
224
226
228
t (μsec)
hits
10^2
10
1
10
10^2
10^3
q (ADC)

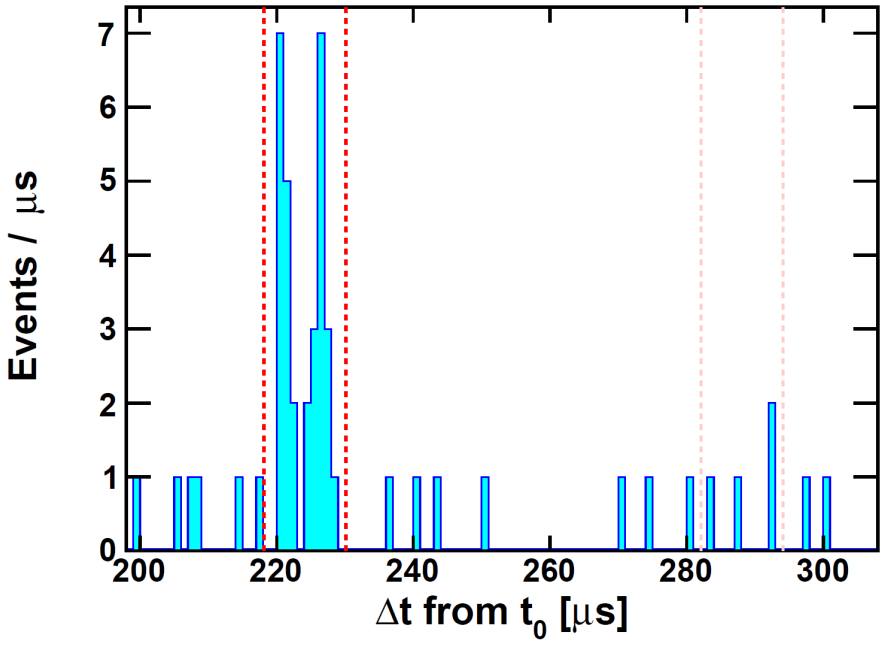

3000
3200
3400
3600
3800
4000
100
0
−100
−200
x (cm)
−300
−400
−500
−600
y (cm)
z (cm)
NOvA - FNAL E929
Run: 18756 / 37
Event: 597960 / --
UTC Sun Jan 25, 2015
13:29:18.710709824
hits
10^2
10
1
218
220
222
224
226
228
t (μsec)
10^3
q (ADC)

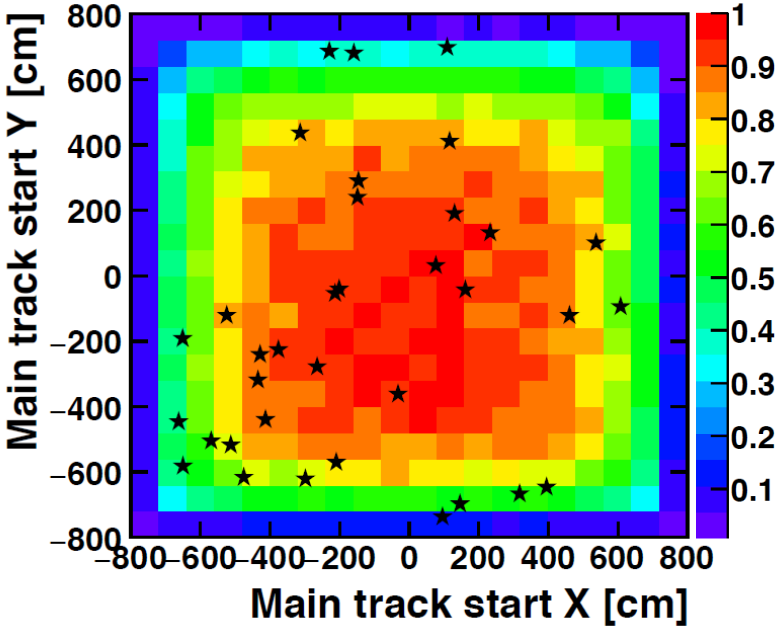
Muon Neutrino Disappearance

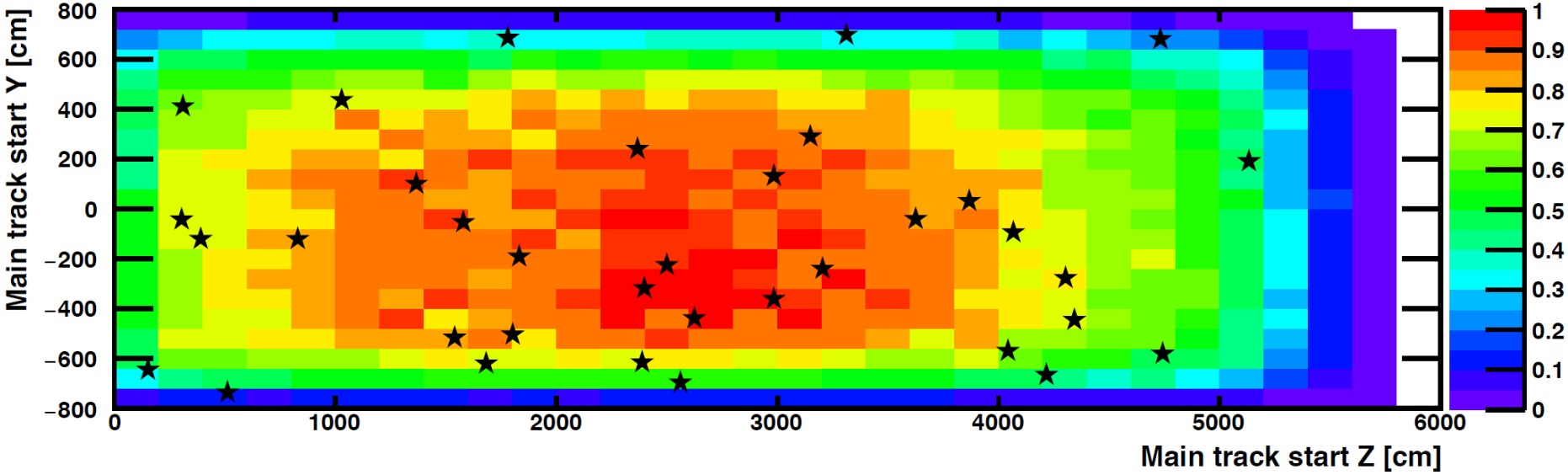


P. Vahle, SSI 2015

FD ν_μ CC candidates: when and where

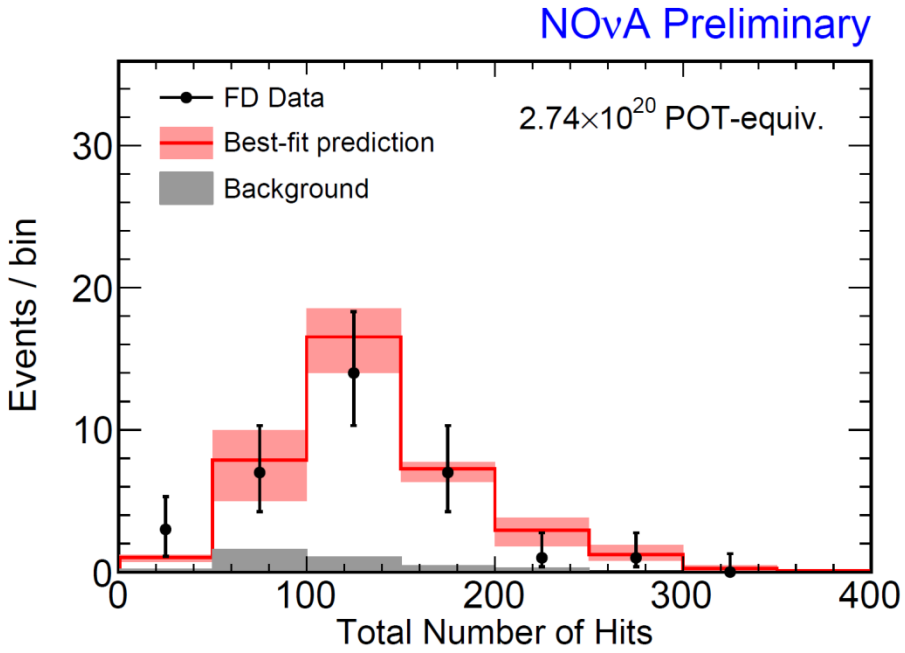


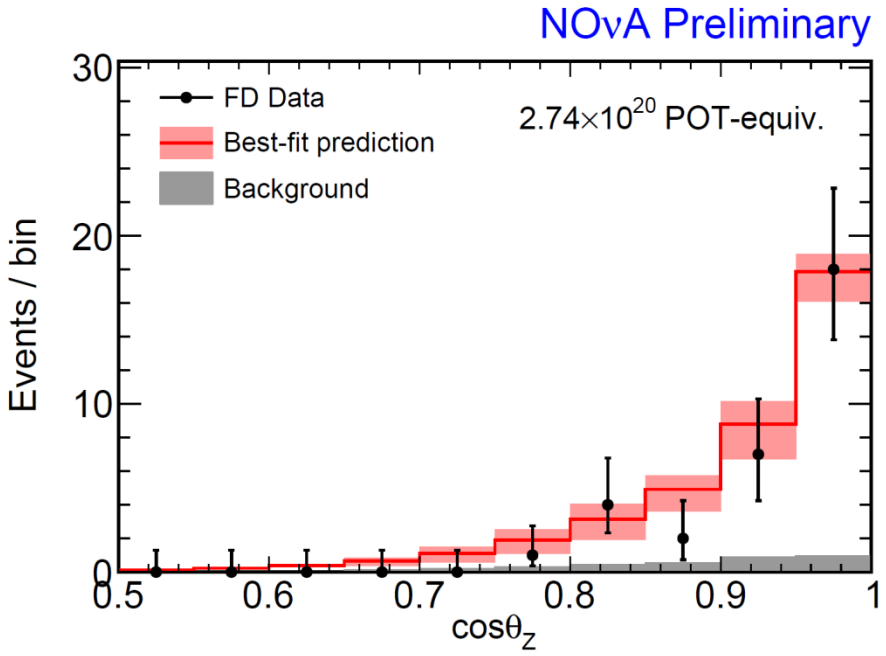


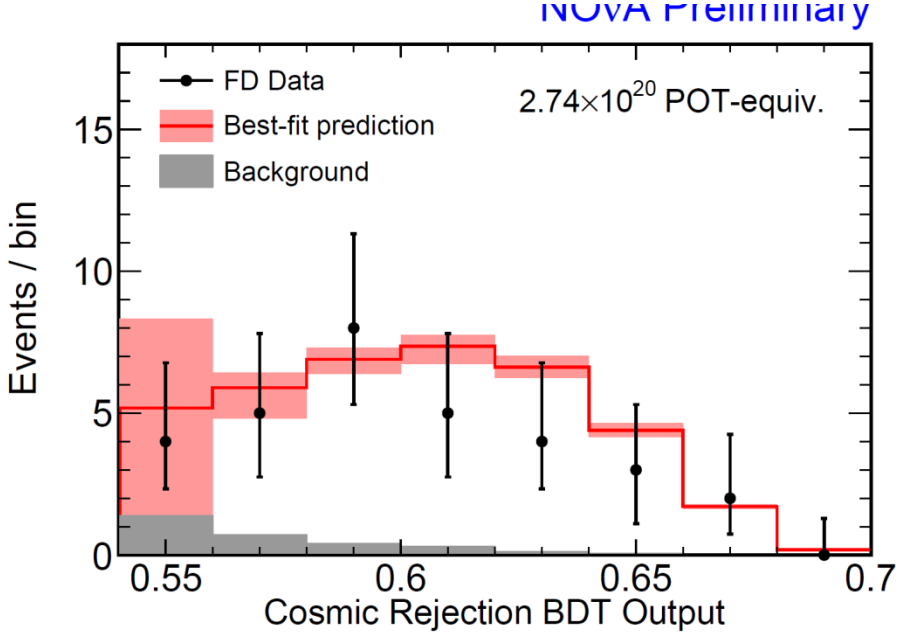


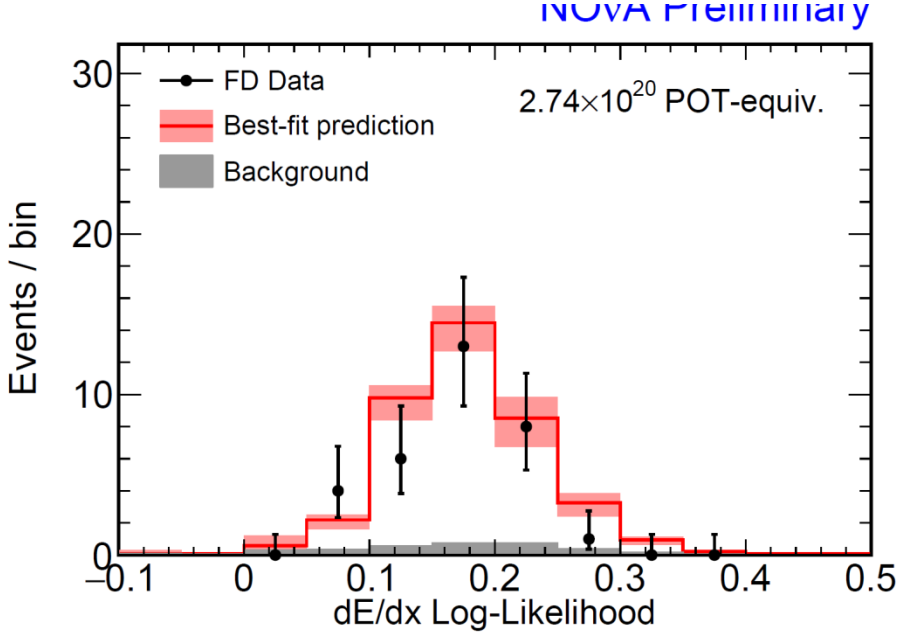
Note 1: Second timing window at +64 μs required for some of the early data
Note 2: Colors show relative efficiency. Not weighted by time variation in detector size.

FD ν_μ CC candidates: event distributions

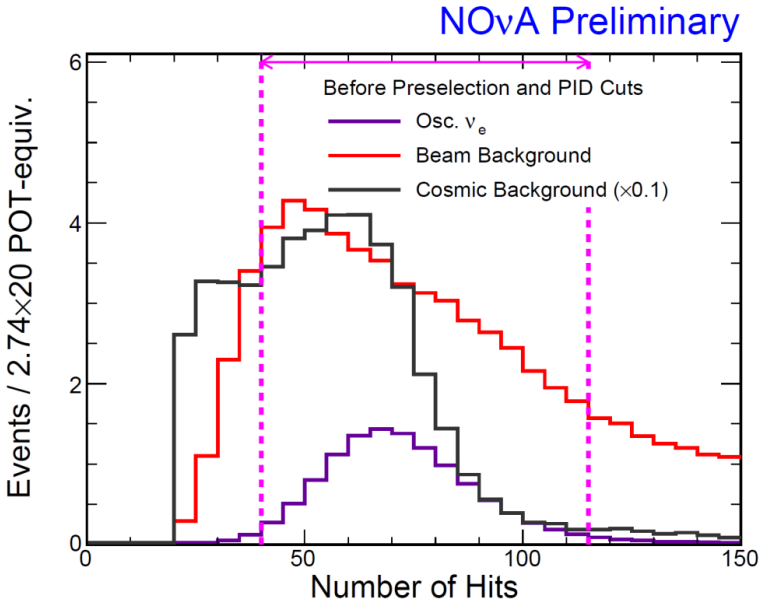


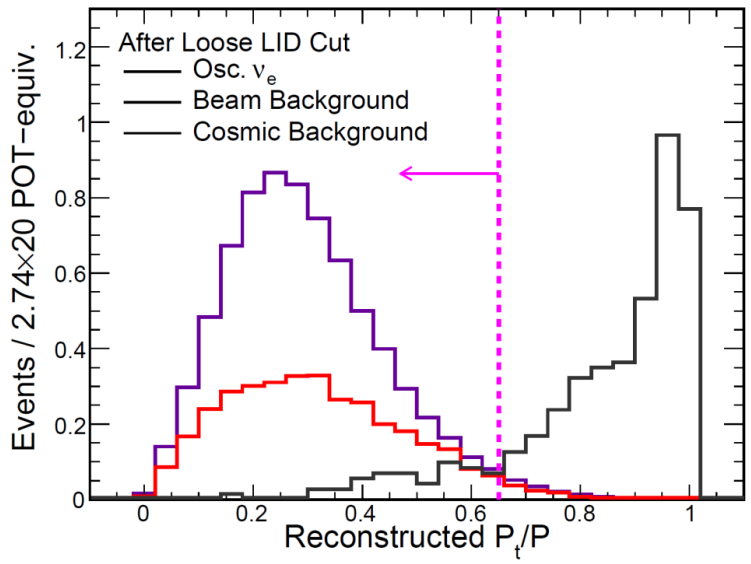






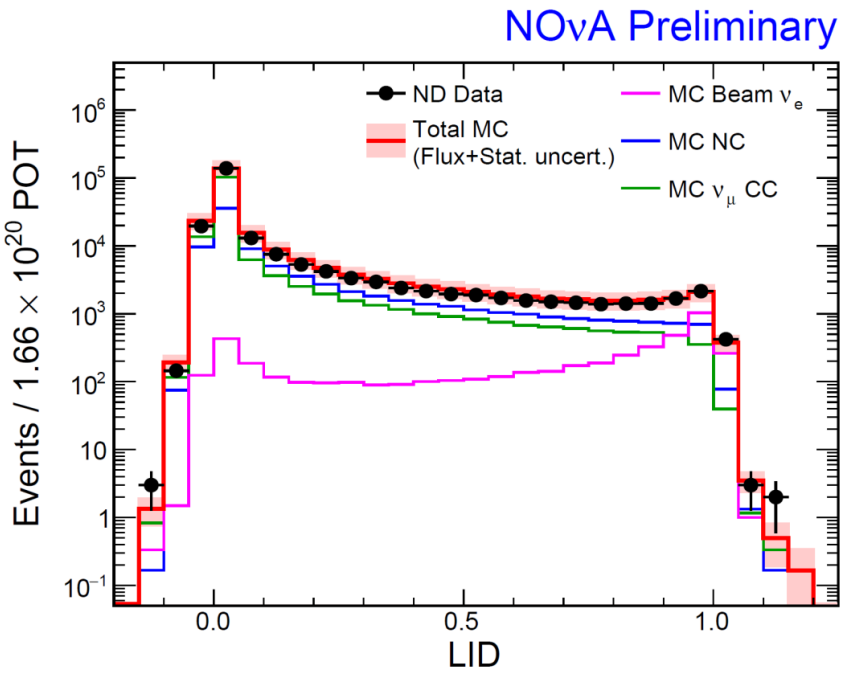
Selecting Electron Neutrinos

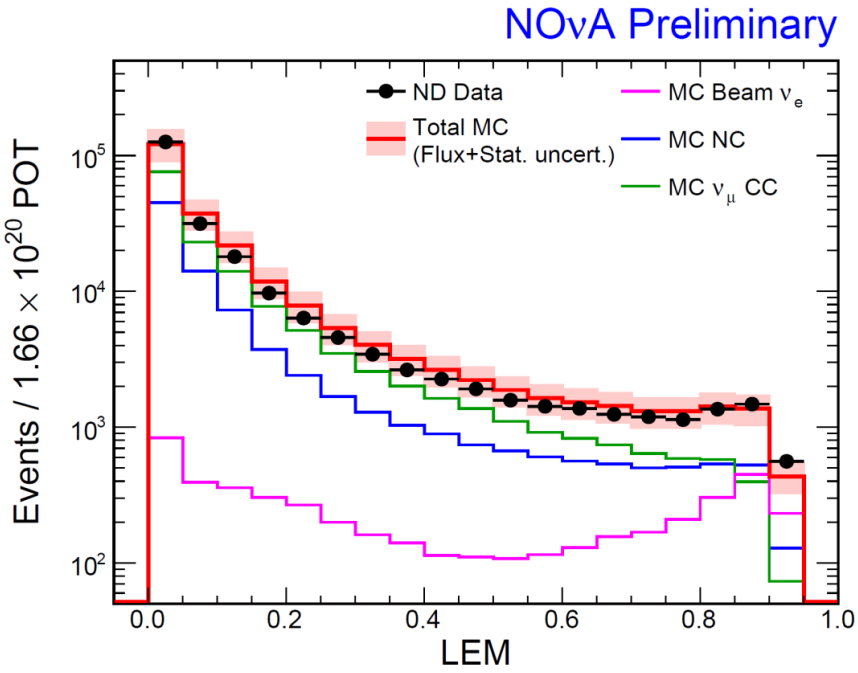




- Goal: Isolate a pure sample of ν_eCC events
  - Select events with electromagnetic showers
  - Suppress backgrounds from NC/ν_μCC/beam ν_e and cosmic events
- Basic cuts to remove obvious backgrounds:
  - Fiducial and Containment
  - Reconstructed p_T/p
    - remove very vertical events
  - Shower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

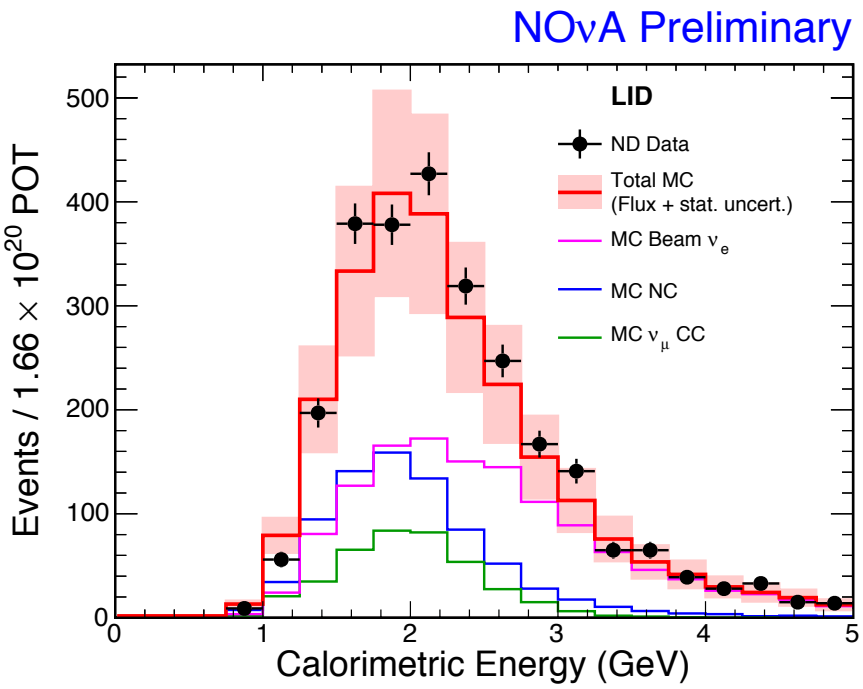
ND Data

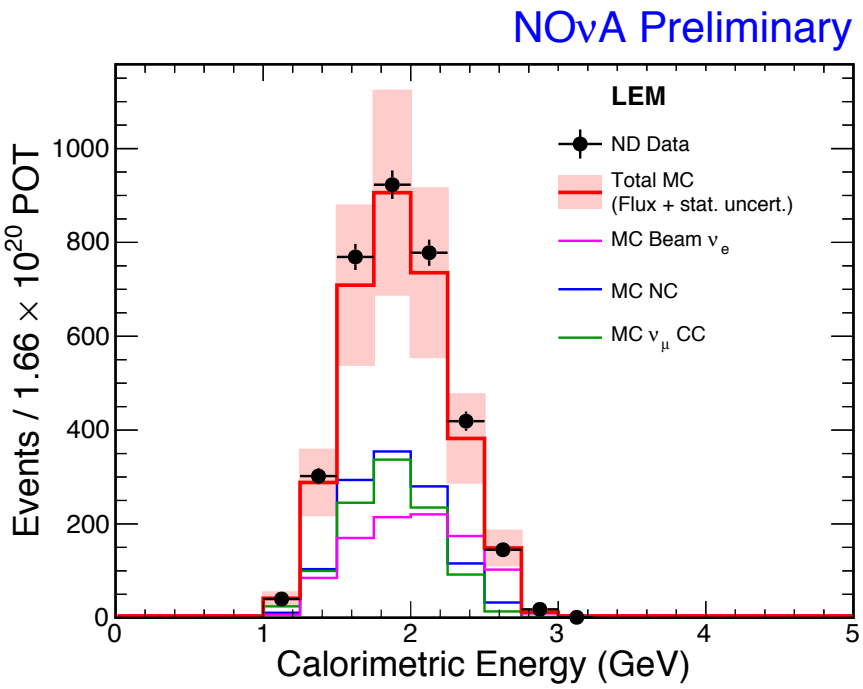




- ND data used to predict backgrounds in FD

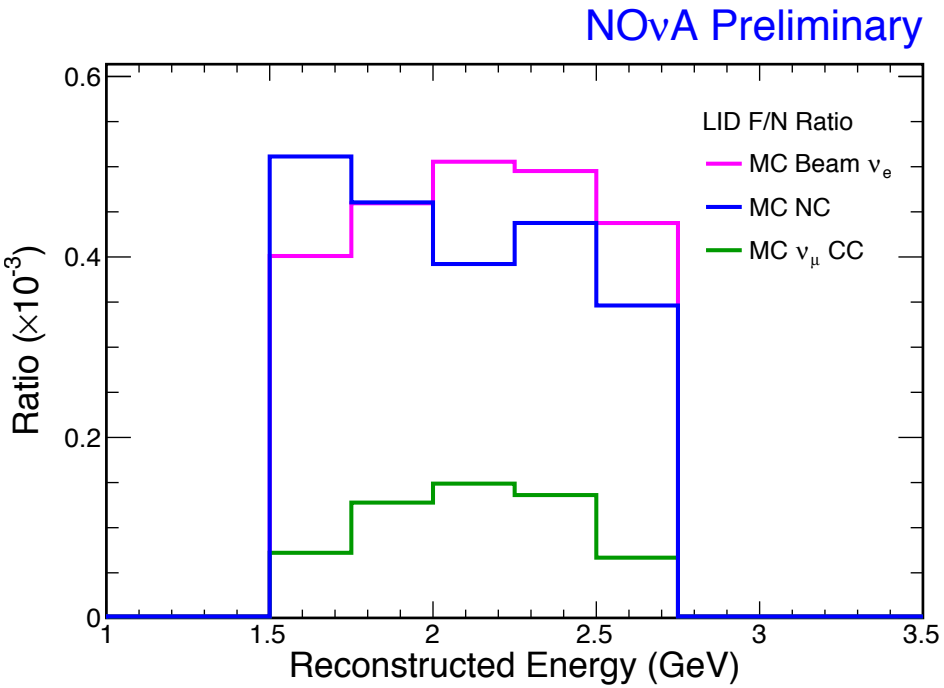
ND Data





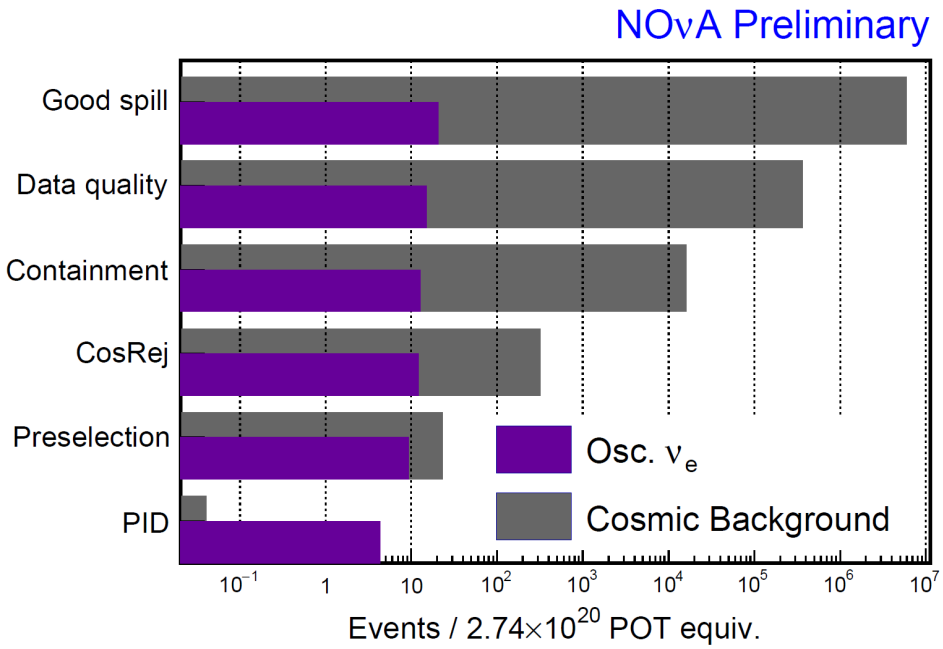
- Fairly good agreement after selection
- Data selects ~5% more events than simulation

F/N Ratio

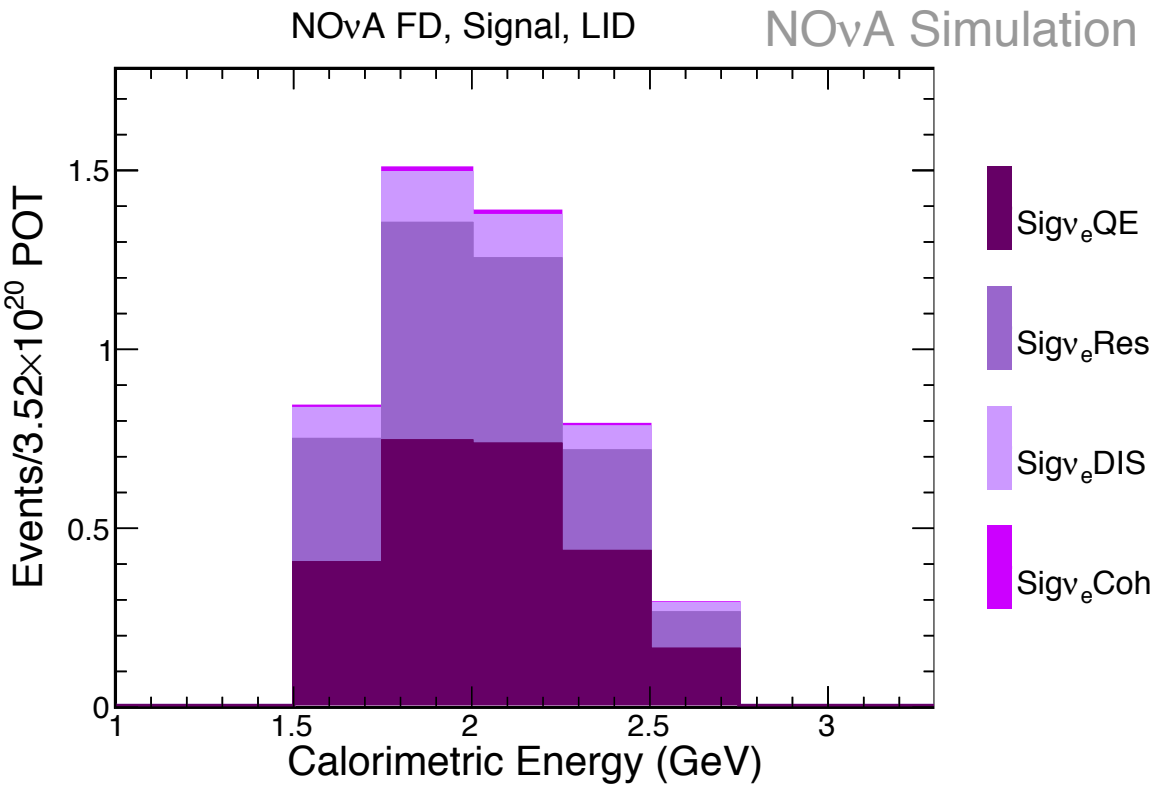

NOνA Preliminary
LID F/N Ratio
MC Beam ν_e
MC NC
MC ν_μ CC
Ratio ($\times 10^{-3}$)
0.6
0.4
0.2
0
1
1.5
2
2.5
3
3.5
Reconstructed Energy (GeV)

Cosmic Rejection

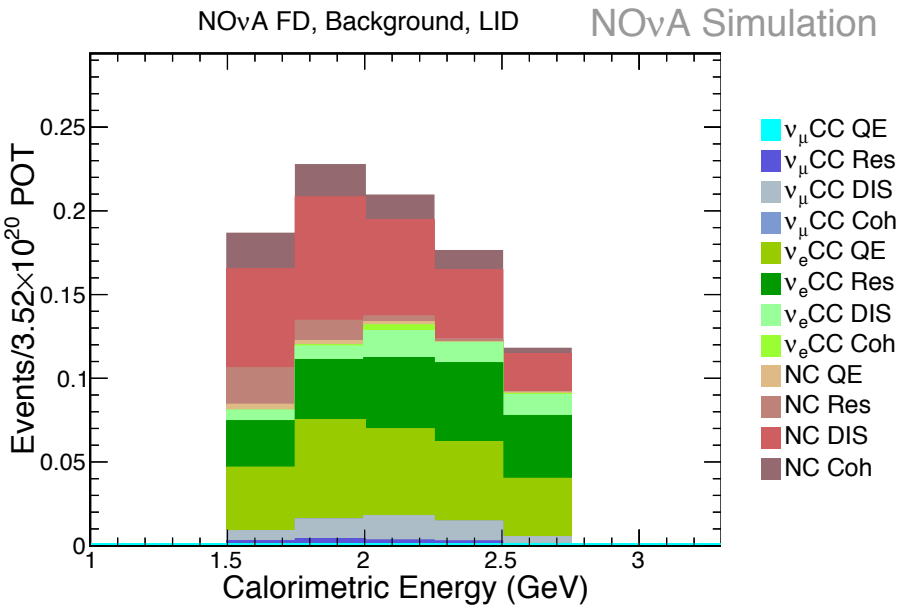
- We achieve better than 1 part in 10^8 rejection of cosmic ray interactions
- We measure this background using data collected outside of the beam spill
- We expect 0.06 cosmic events to pass our cuts



Signal characteristics

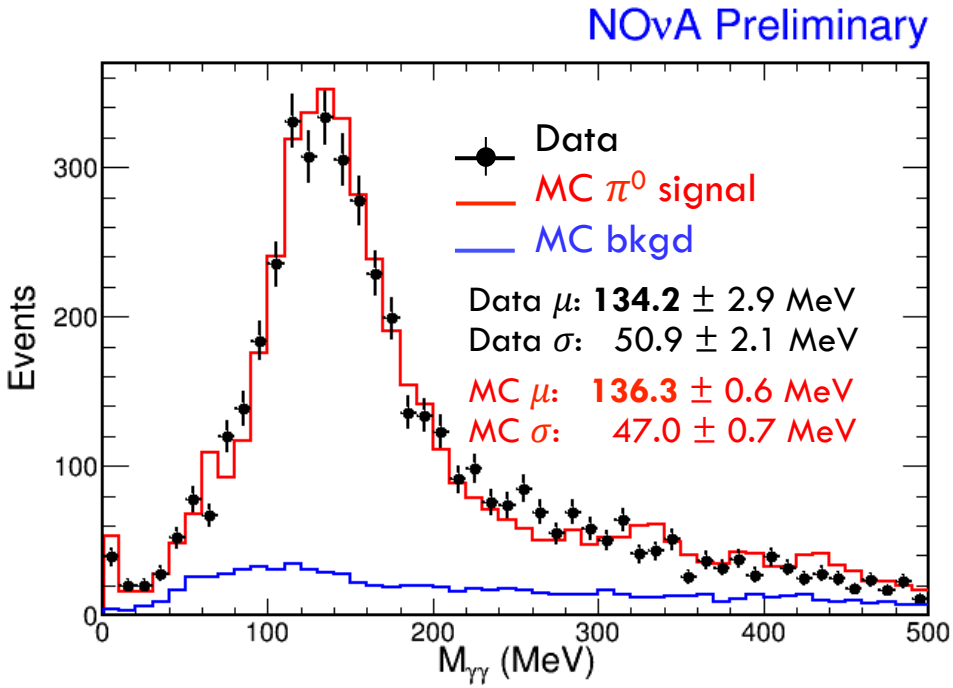


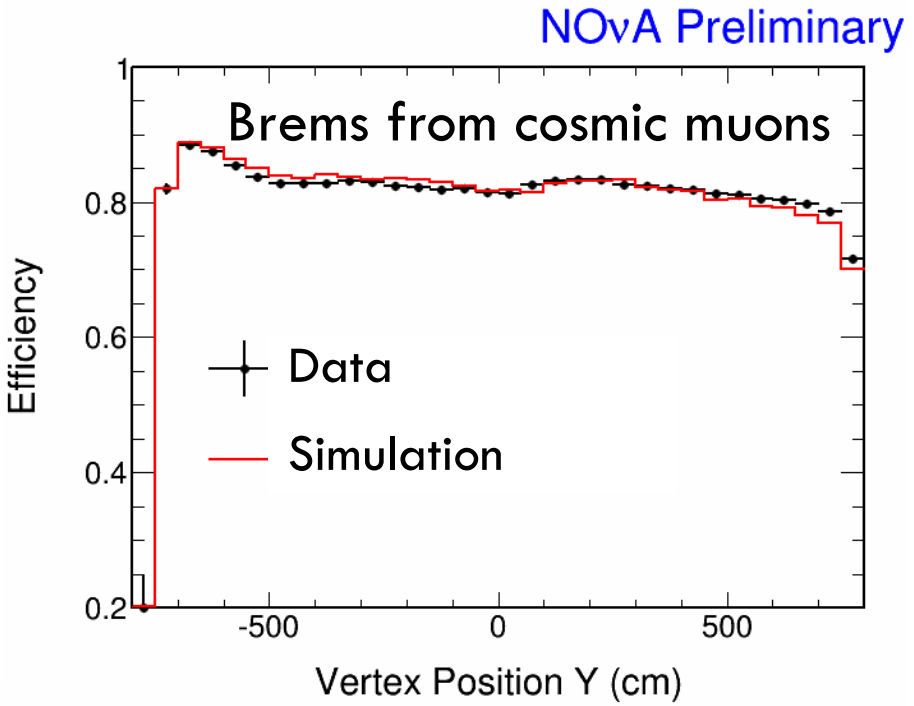
BG Characteristics



Signal Prediction

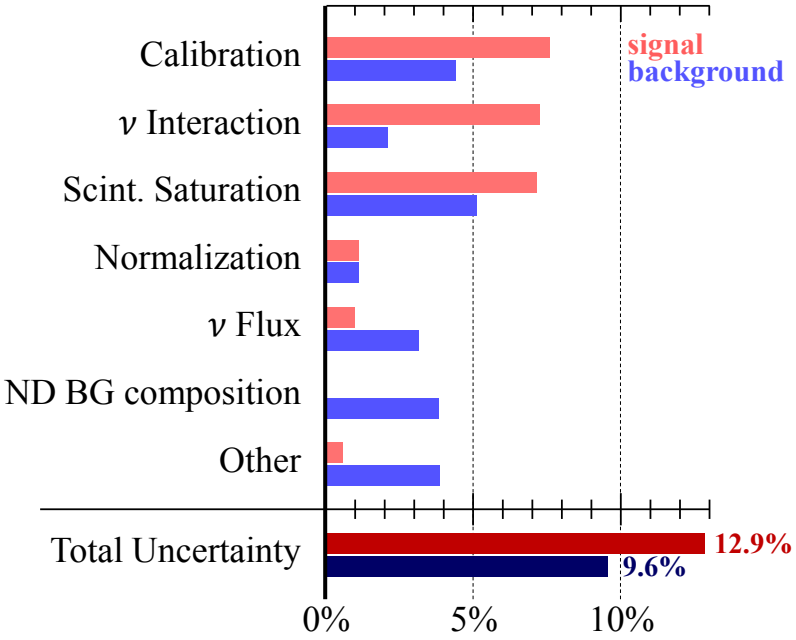
- Signal predictions based on ND ν_μCC energy spectrum
- No direct benchmark of simulation of signal events
- Independent EM samples show good data/MC agreement





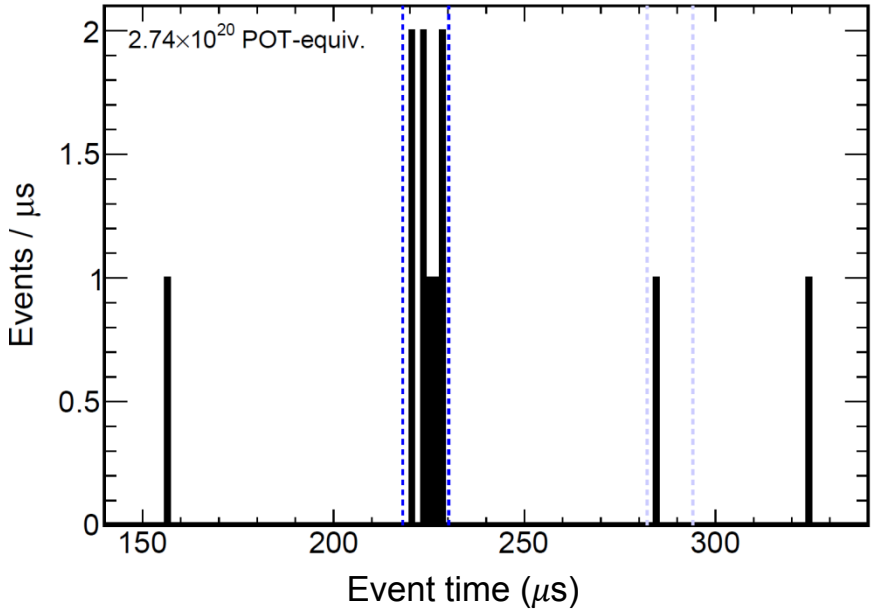
Systematic Uncertainties

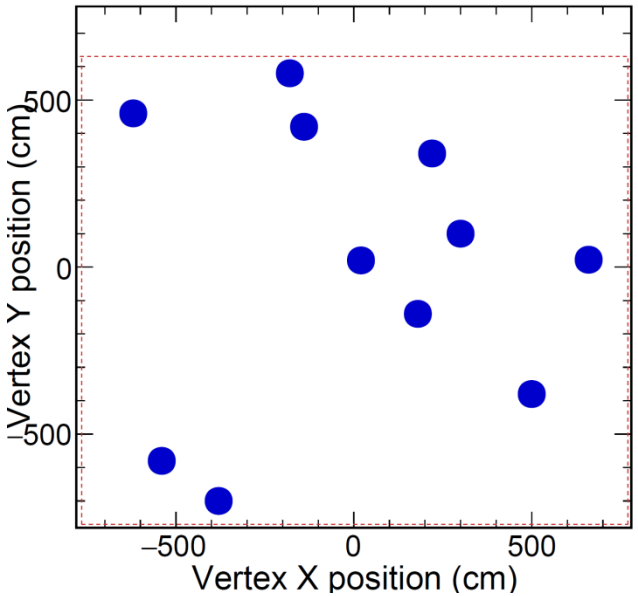
- Systematics assessed by modifying the simulation used in the extrapolation
- Variation in the BG and signal prediction taken as the size of the systematic

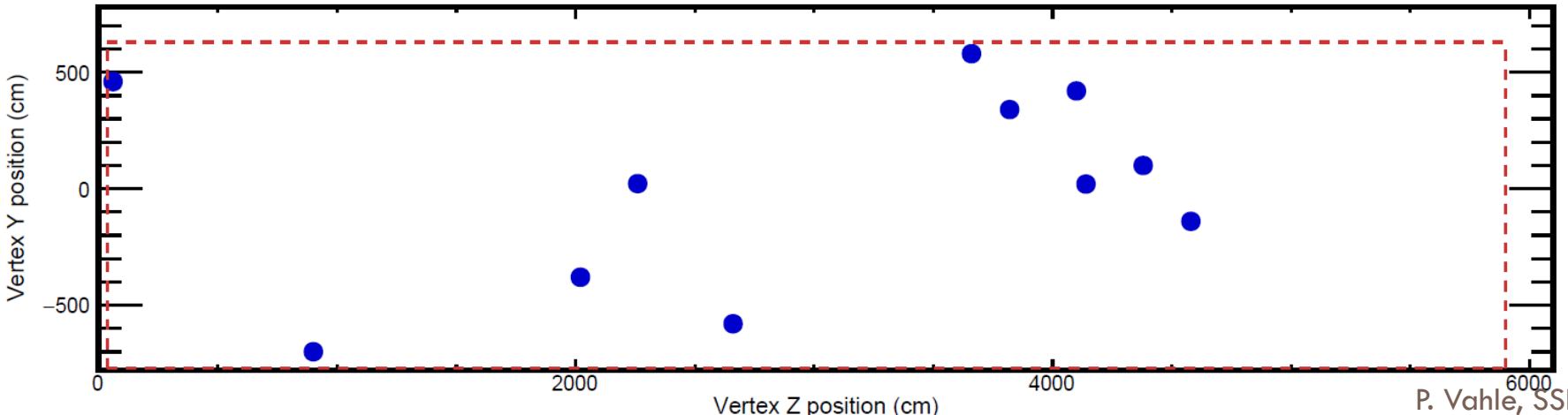


LEM has similar systematic uncertainties

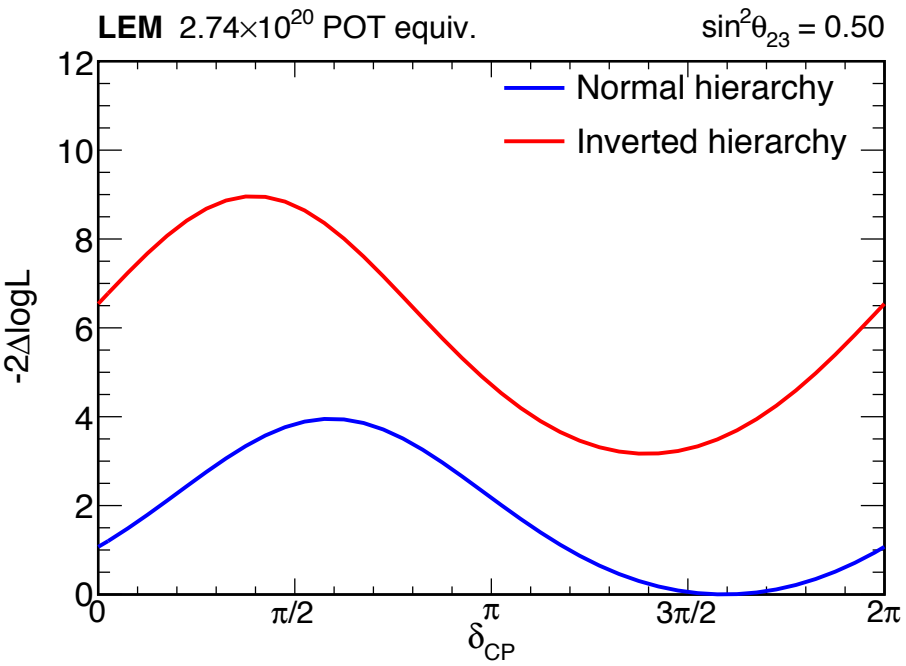
Vertex and Timing

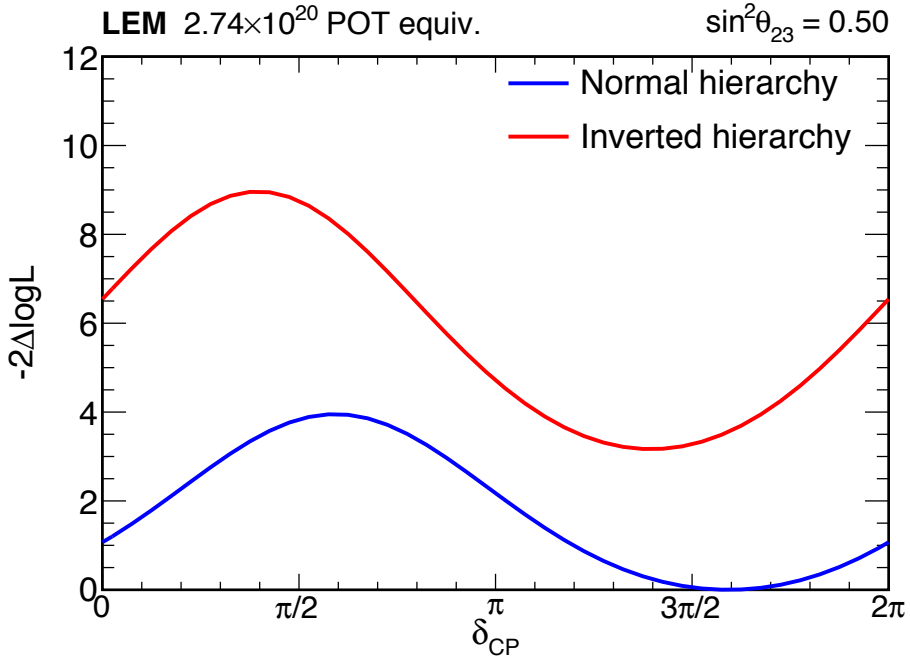




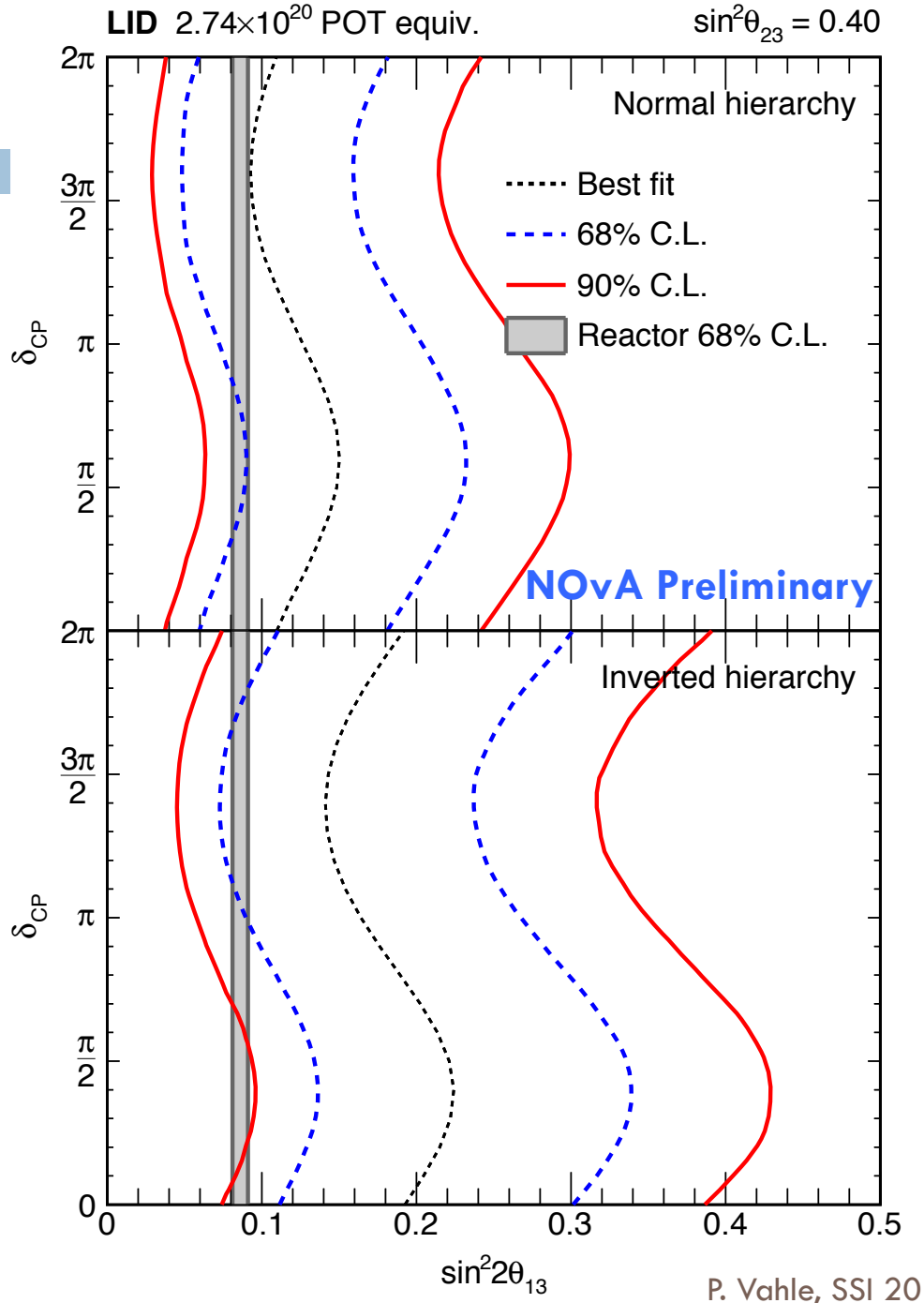


Chi2 vs Delta

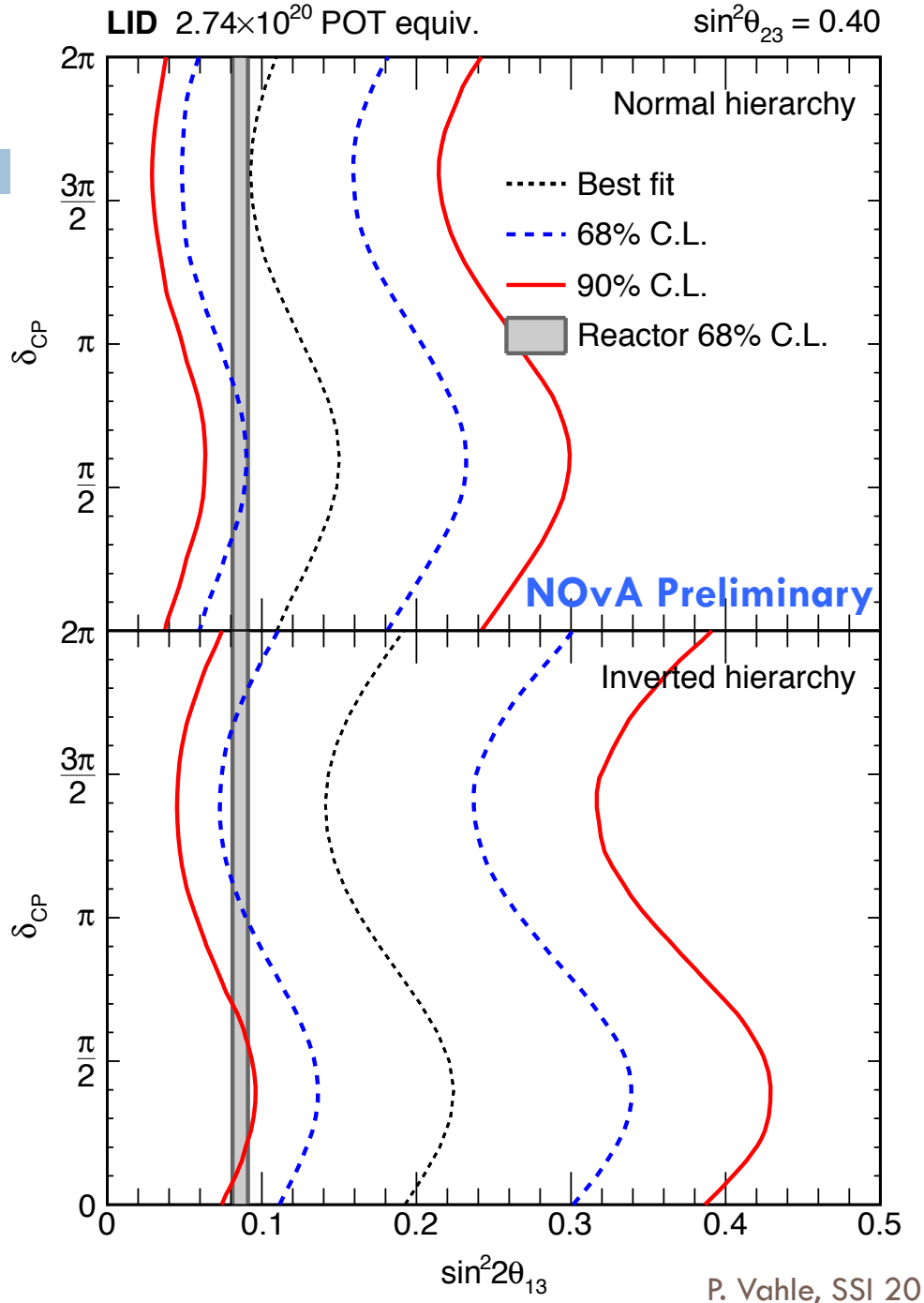




Results


LID 2.74×10^20 POT equiv.
sin²θ23 = 0.40
Normal hierarchy
Best fit
68% C.L.
90% C.L.
Reactor 68% C.L.
NOvA Preliminary
Inverted hierarchy
δCP
sin²2θ13
2π
3π/2
π
π/2
0
0.1
0.2
0.3
0.4
0.5

Results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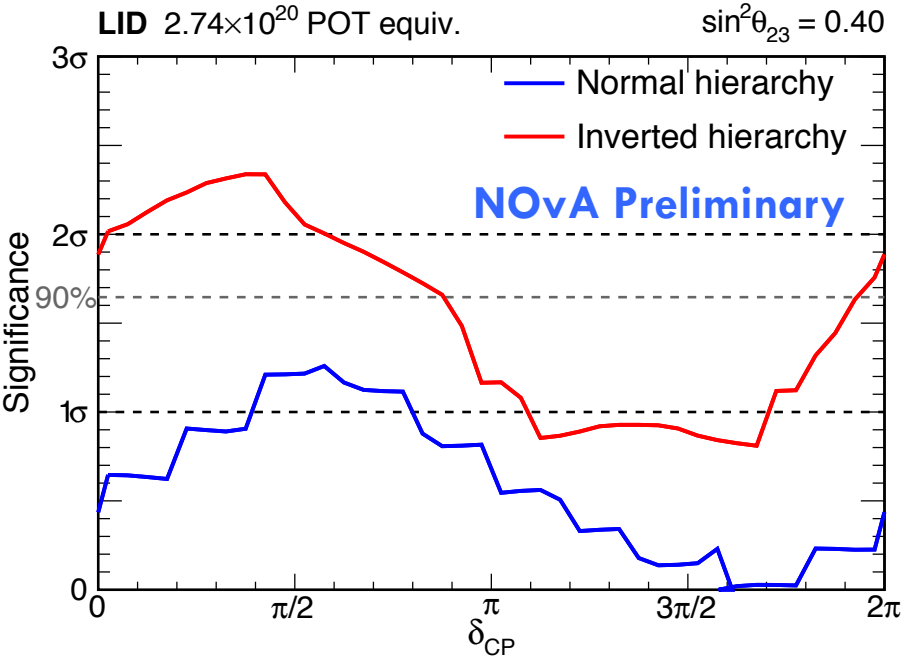
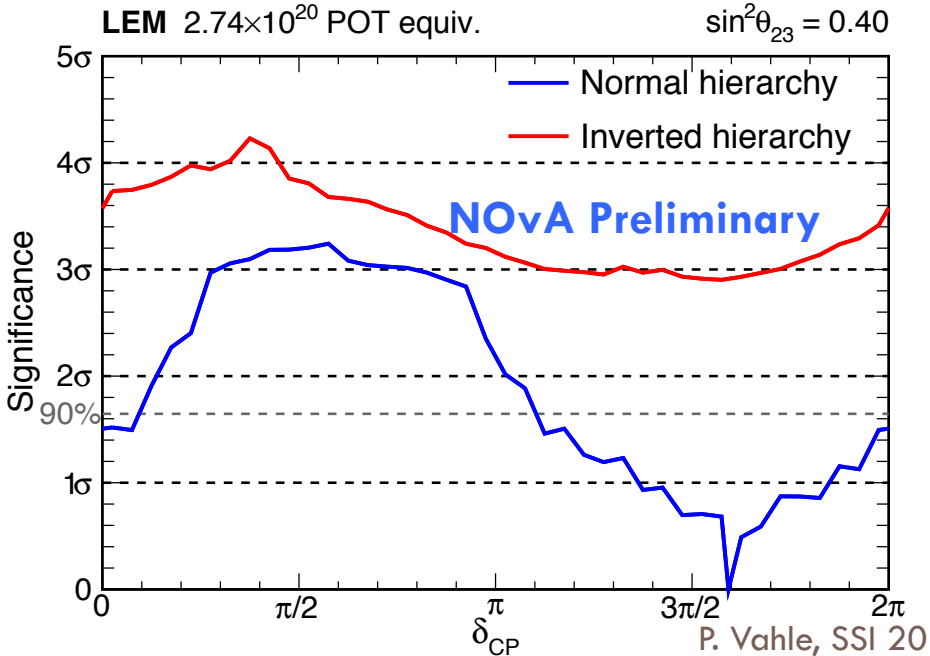
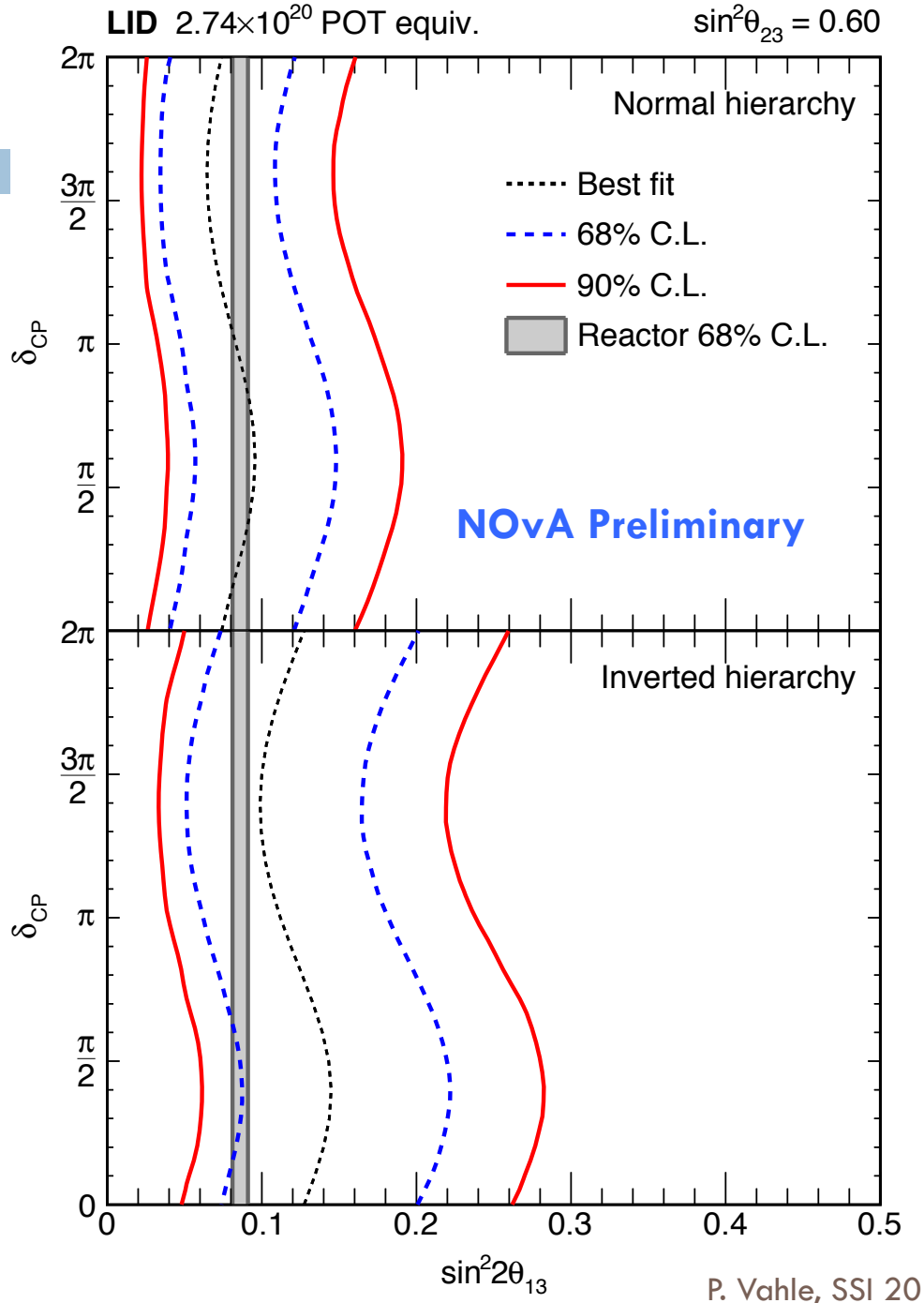
Inverted hierarchy
δCP
sin²2θ13
0
0.1
0.2
0.3
0.4
0.5
π/2
π
3π/2
2π

Results

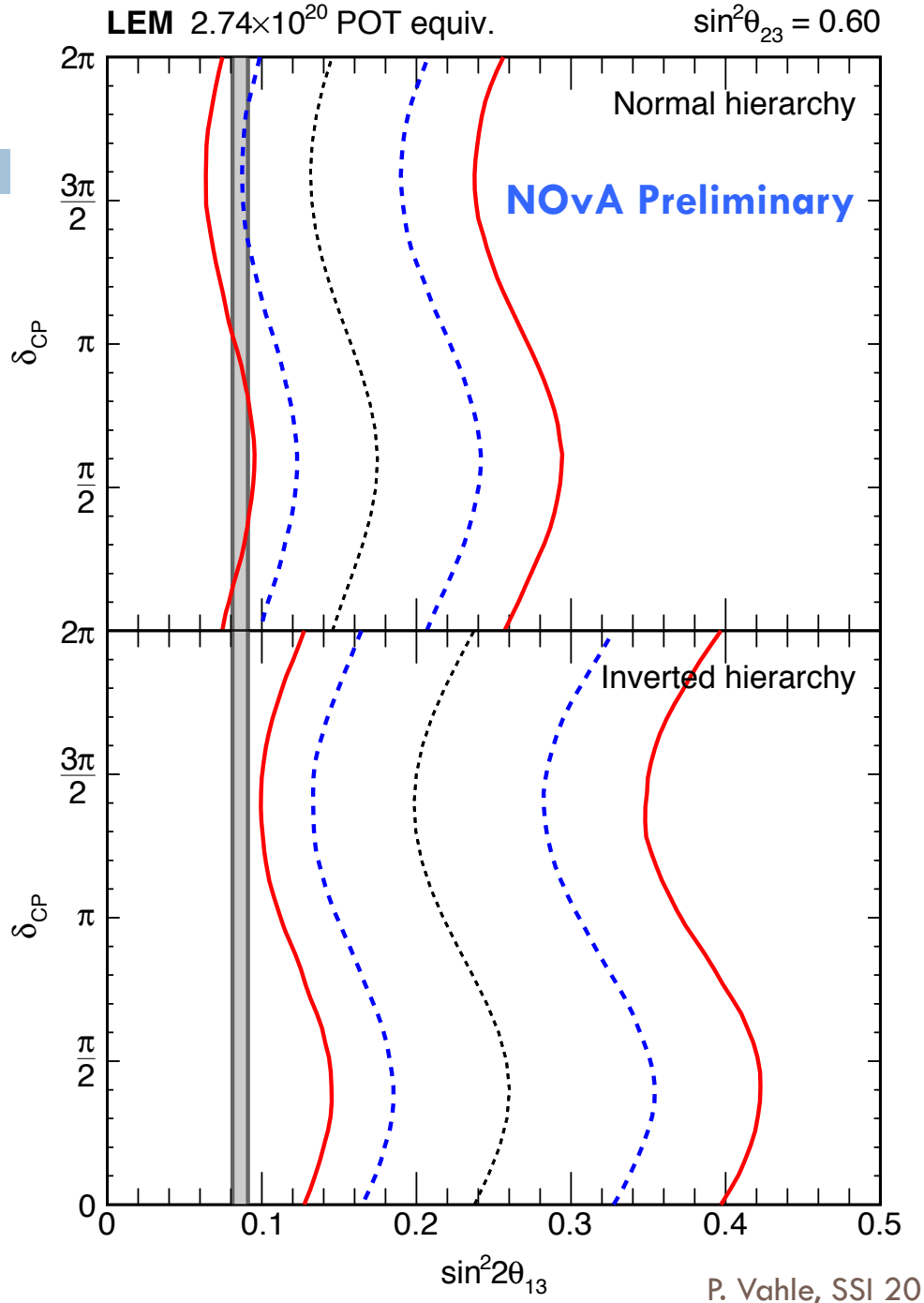

LID 2.74×10^20 POT equiv.
sin²θ23 = 0.40
Normal hierarchy
Inverted hierarchy
NOvA Preliminary
Significance
3σ
2σ
90%
1σ
0
0
π/2
π
3π/2
2π
δCP


LEM 2.74×10^20 POT equiv.
sin²θ23 = 0.40
Normal hierarchy
Inverted hierarchy
NOvA Preliminary
Significance
5σ
4σ
3σ
2σ
90%
1σ
0
0
π/2
π
3π/2
2π
δCP

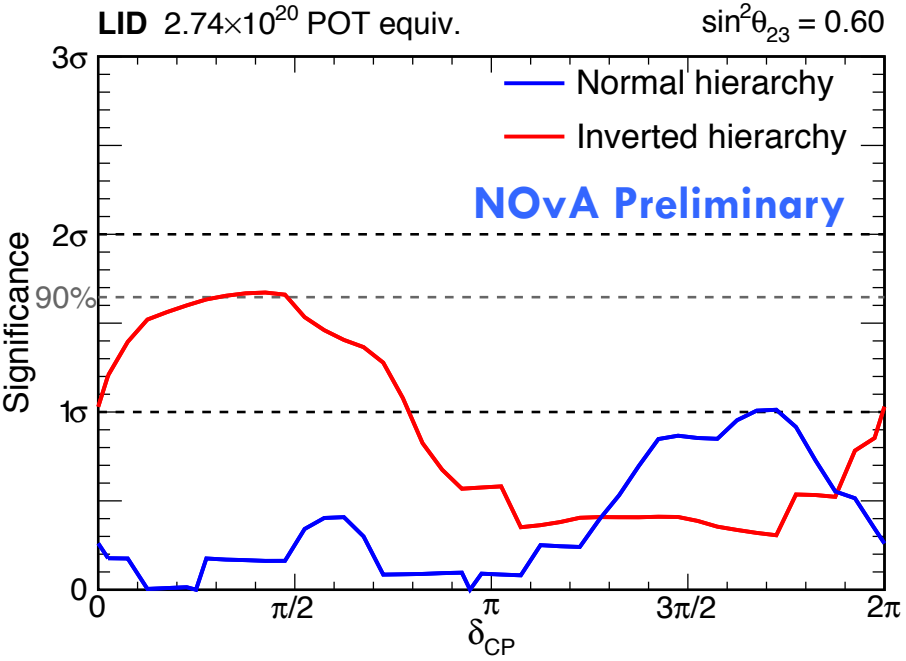
Results

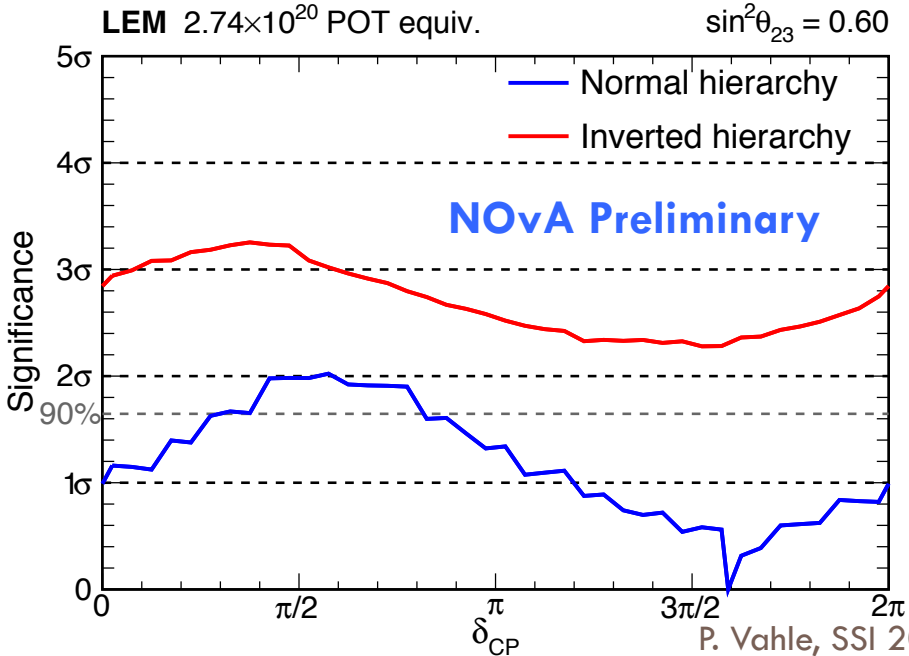

LID 2.74×10^20 POT equiv.
sin²θ23 = 0.60
Normal hierarchy
Best fit
68% C.L.
90% C.L.
Reactor 68% C.L.
NOvA Preliminary
Inverted hierarchy
δCP
2π
3π/2
π
π/2
0
0.1
0.2
0.3
0.4
0.5
sin²2θ13

Results

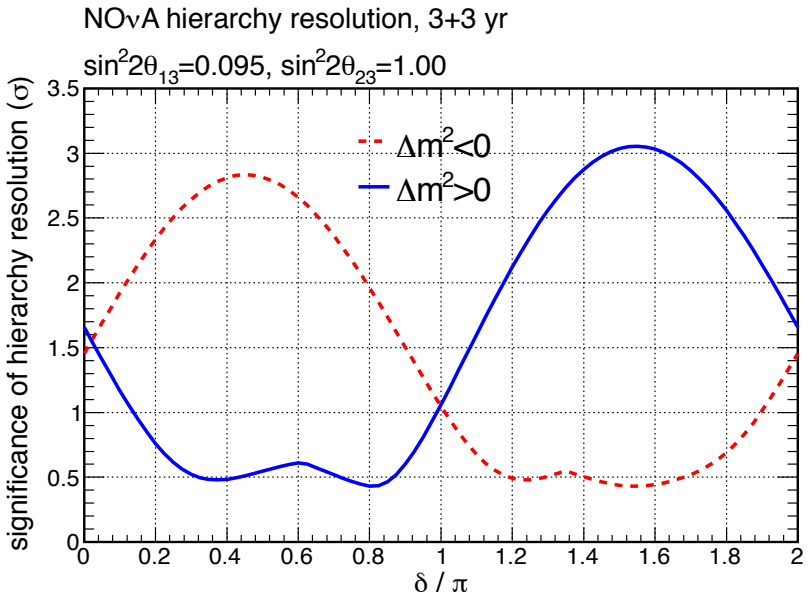

LEM 2.74×10^20 POT equiv.
sin²θ23 = 0.60
Normal hierarchy
NOvA Preliminary
Inverted hierarchy
δCP
2π
3π/2
π
π/2
0
0.1
0.2
0.3
0.4
0.5
sin²2θ13

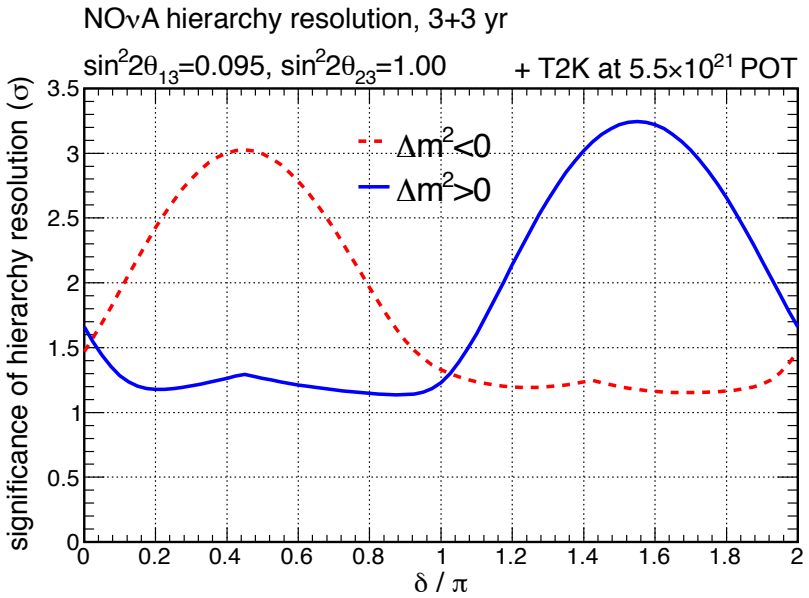
Results

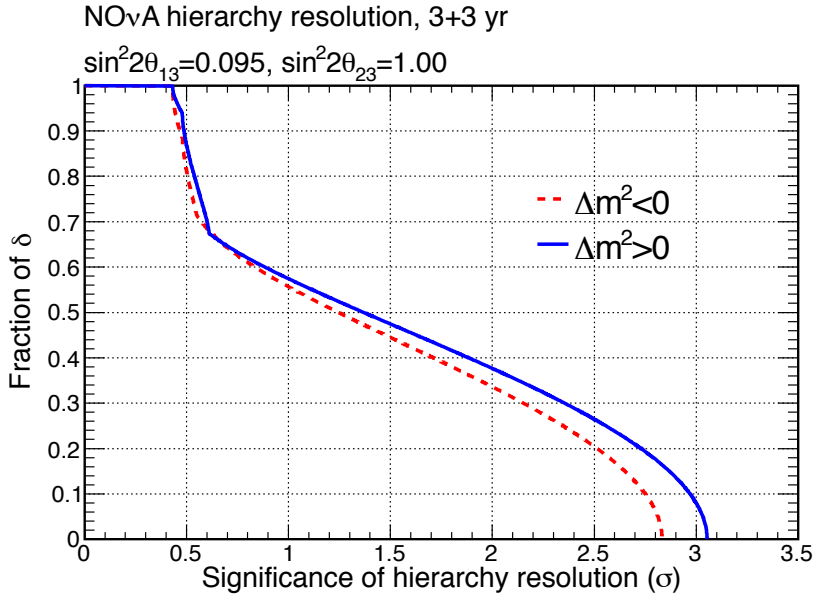

LID 2.74×10^20 POT equiv.
sin²θ23 = 0.60
Normal hierarchy
Inverted hierarchy
NOvA Preliminary
Significance
3σ
2σ
90%
1σ
0
0
π/2
π
3π/2
2π
δCP

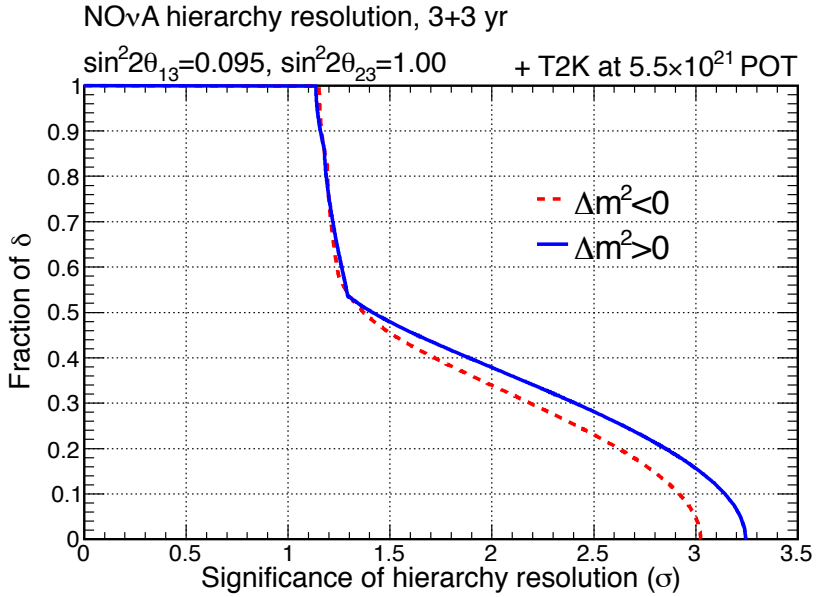

LEM 2.74×10^20 POT equiv.
sin²θ23 = 0.60
Normal hierarchy
Inverted hierarchy
NOvA Preliminary
Significance
5σ
4σ
3σ
2σ
90%
1σ
0
0
π/2
π
3π/2
2π
δCP

Mass Hierarchy Sensitivity



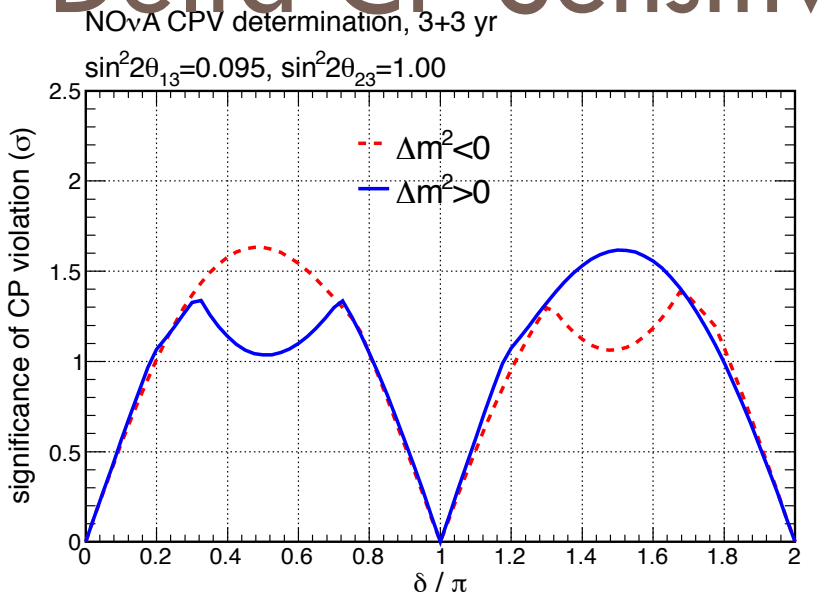


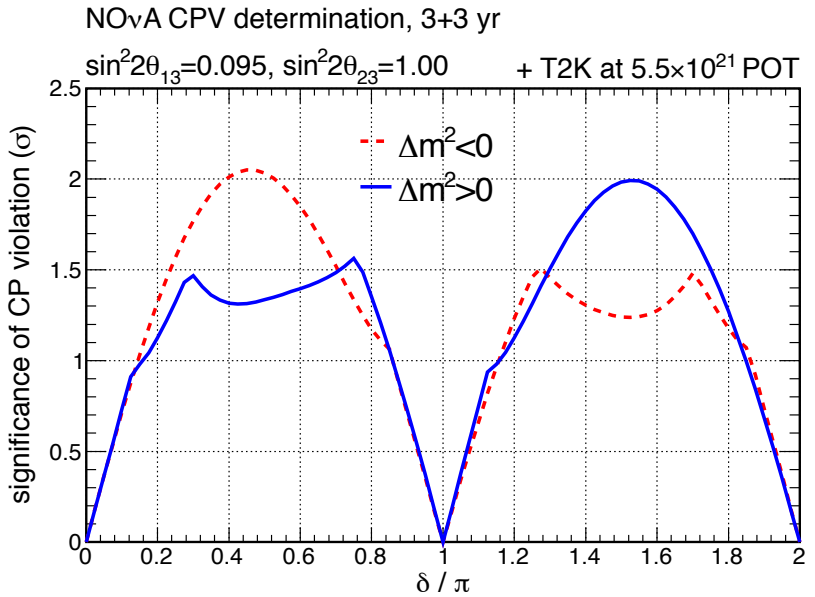


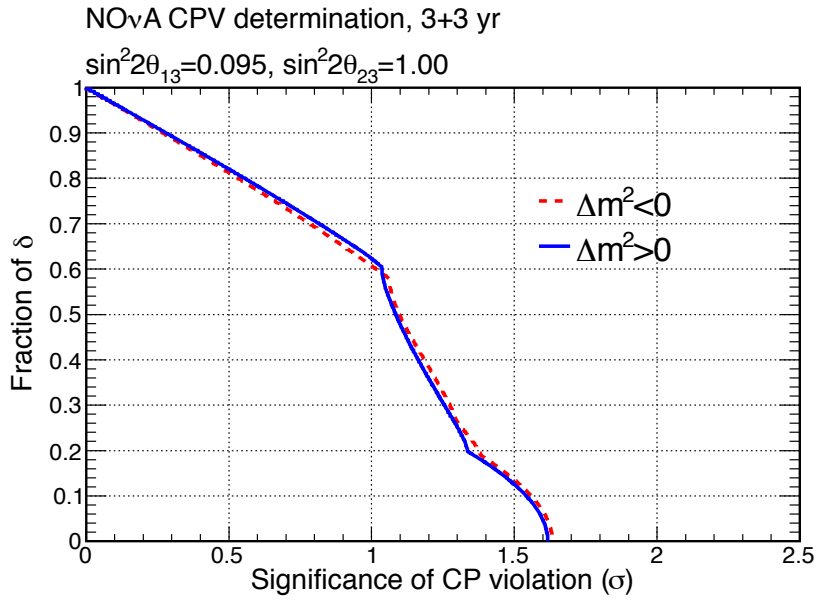


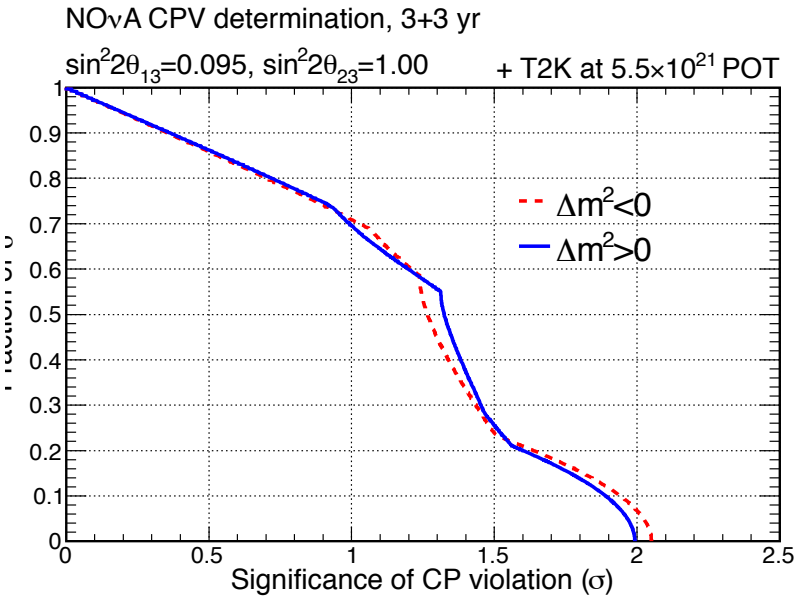
NOvA+T2K—shorter baseline helps when hierarchy/CP effects conspire

Delta CP Sensitivity

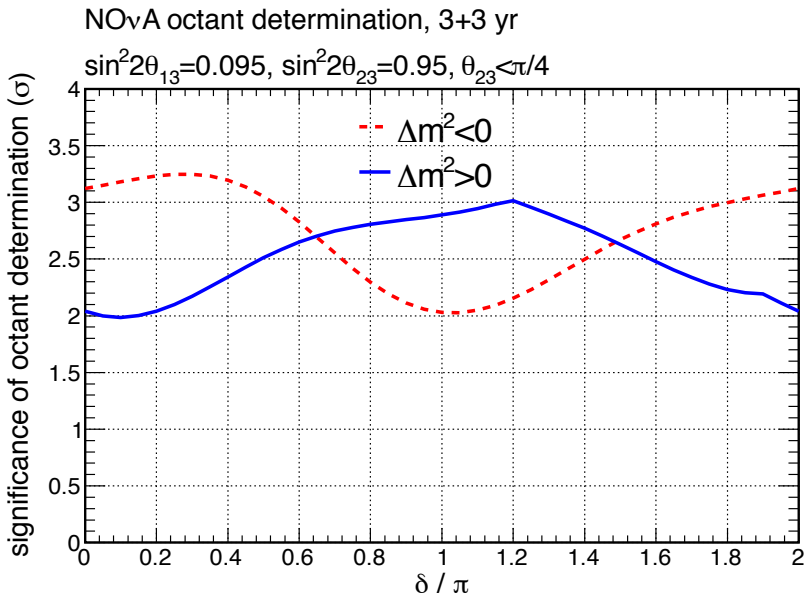


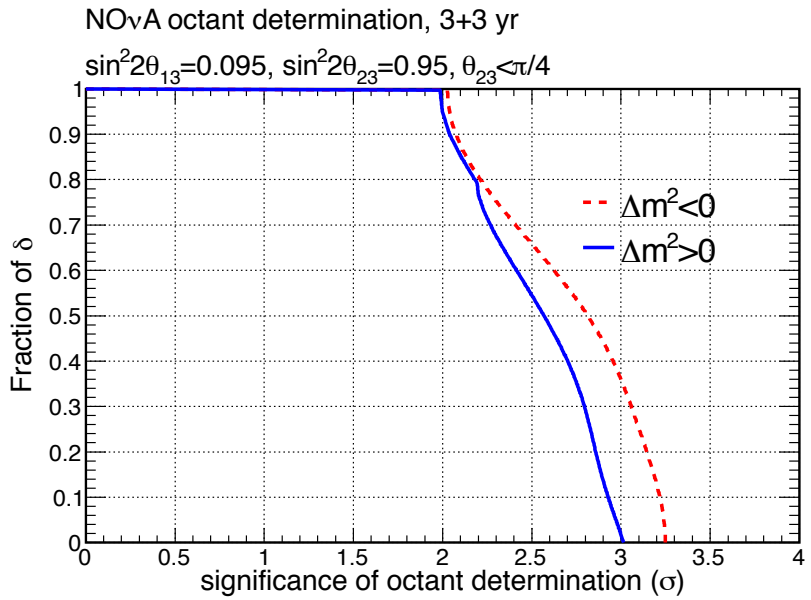






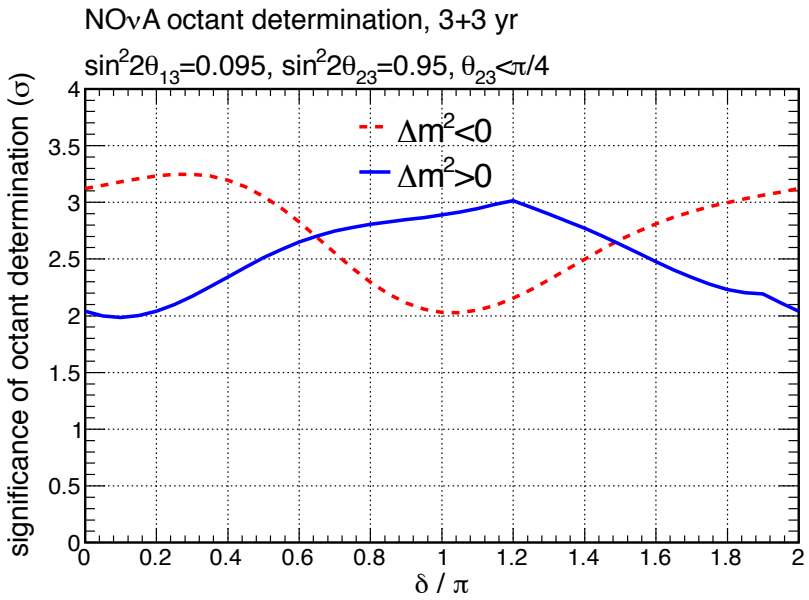
Octant Sensitivity

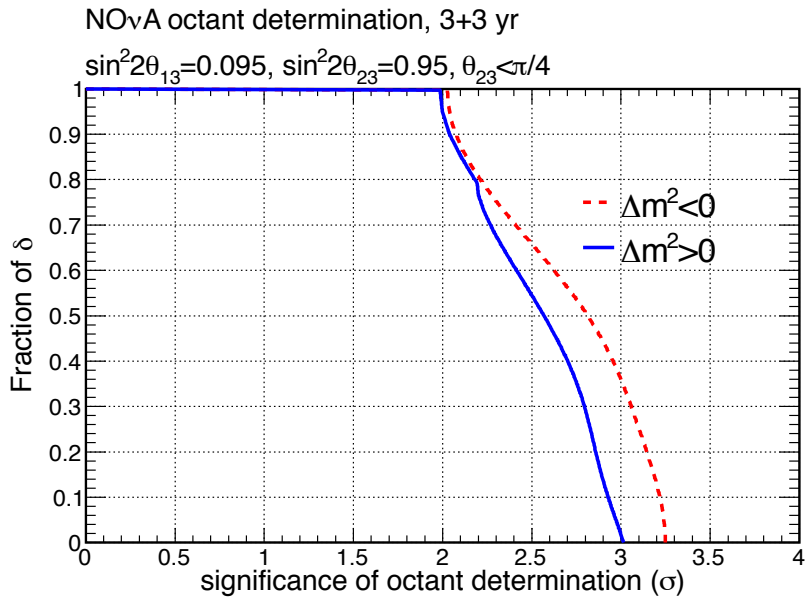




- Combines appearance and disappearance
- For lower octant
- Upper octant slightly better

Octant Sensitivity





- Combines appearance and disappearance
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