Latest Results from NOvA

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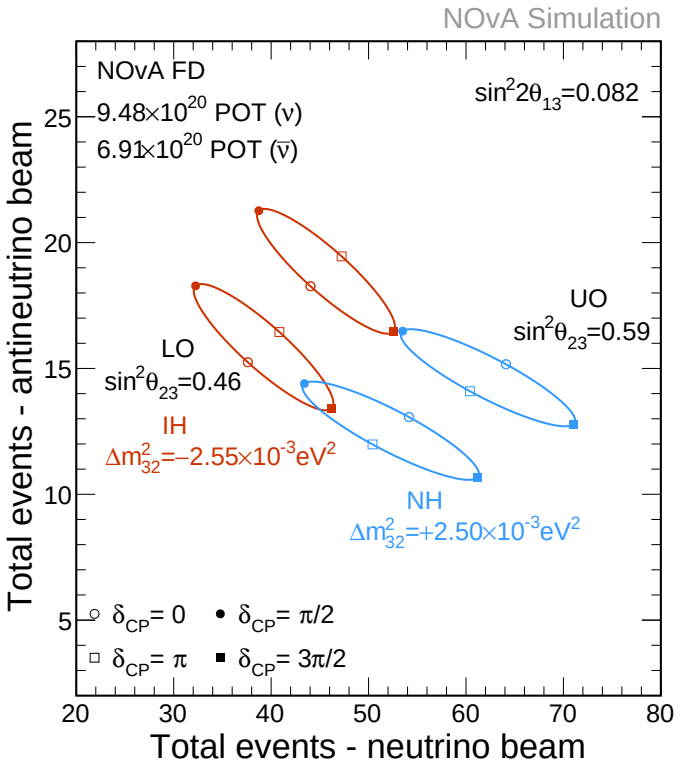
Outline

- Physics goals
- Experimental design
- Current status
- ν_e appearance and ν_μ disappearance analyses
- More topics — oscillation and otherwise
- Outlook

Physics Goals

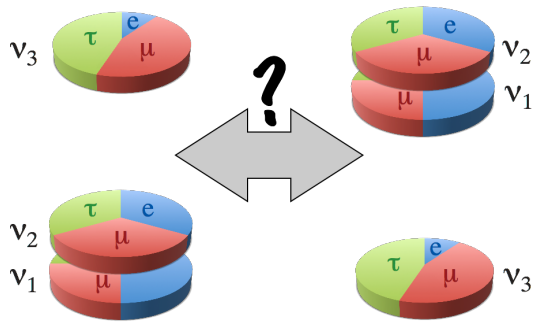


Matter effect enhances (suppresses) ν_e appearance for normal (inverted) ordering

- Observe:

$$\nu_\mu \to \nu_\mu \qquad \nu_\mu \to \nu_e$$
$$\bar{\nu}_\mu \to \bar{\nu}_\mu \qquad \bar{\nu}_\mu \to \bar{\nu}_e$$

- θ_{23} — is it maximal?
- Octant of θ_{23} if not maximal
- Sign of Δm^2_{32} — mass ordering (hierarchy)



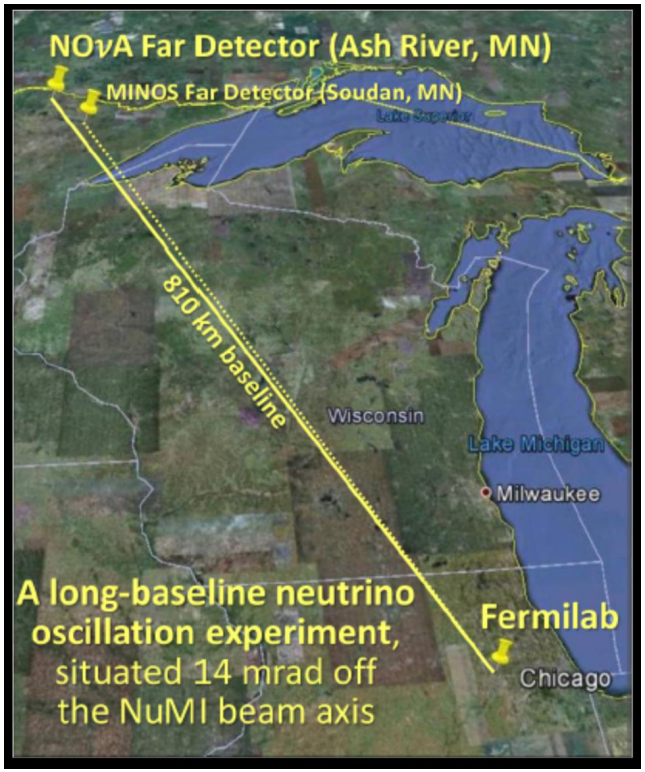
- Discover or constrain CP violation in neutrino sector

- Are there additional neutrinos?

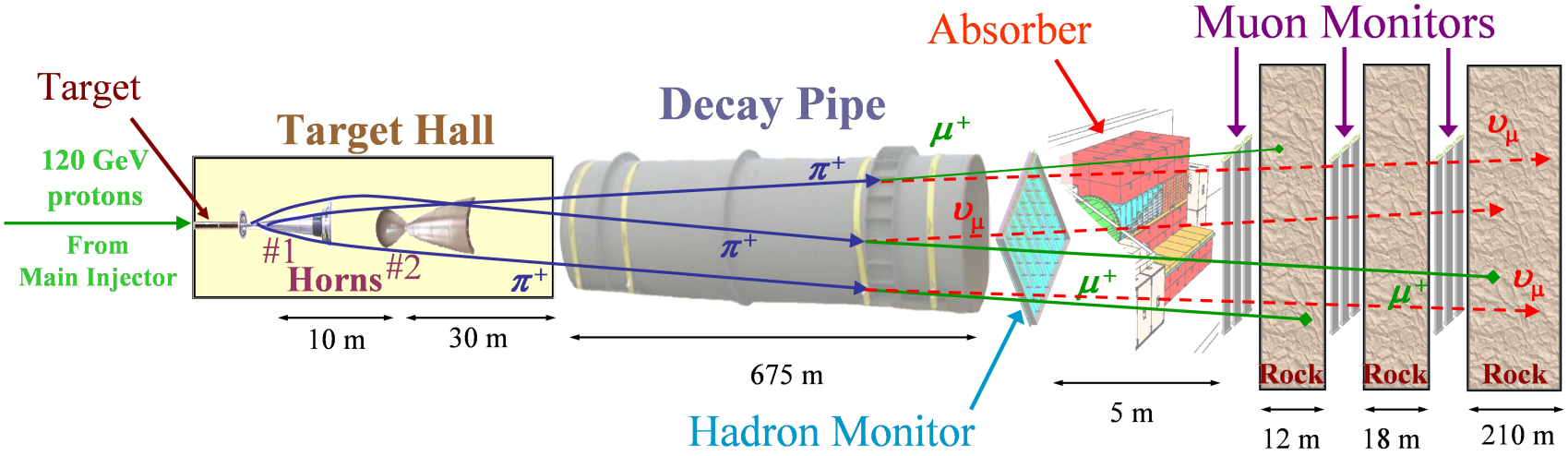
- Astrophysics

Design Overview

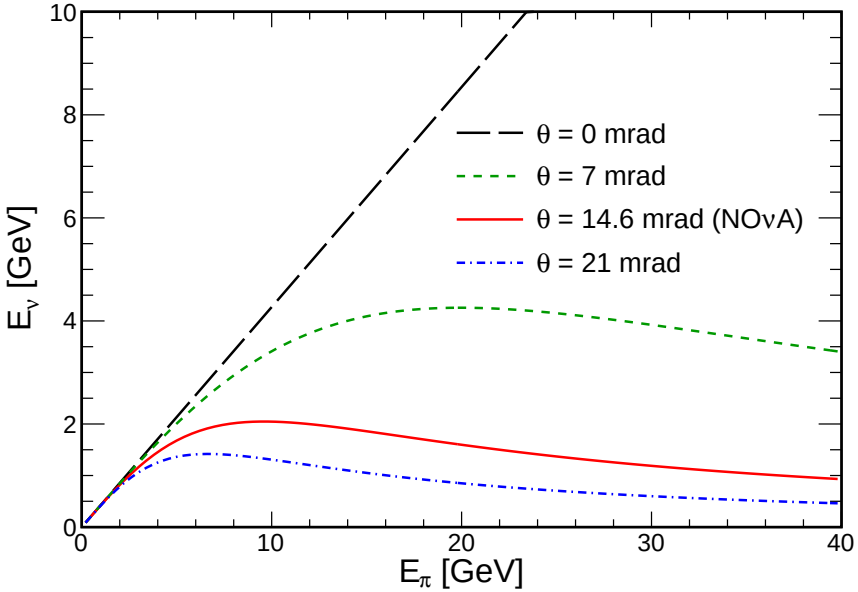
- NuMI beam
- Near detector
  - Measures unoscillated beam composition, energy spectrum
- Far detector
  - Observes oscillations

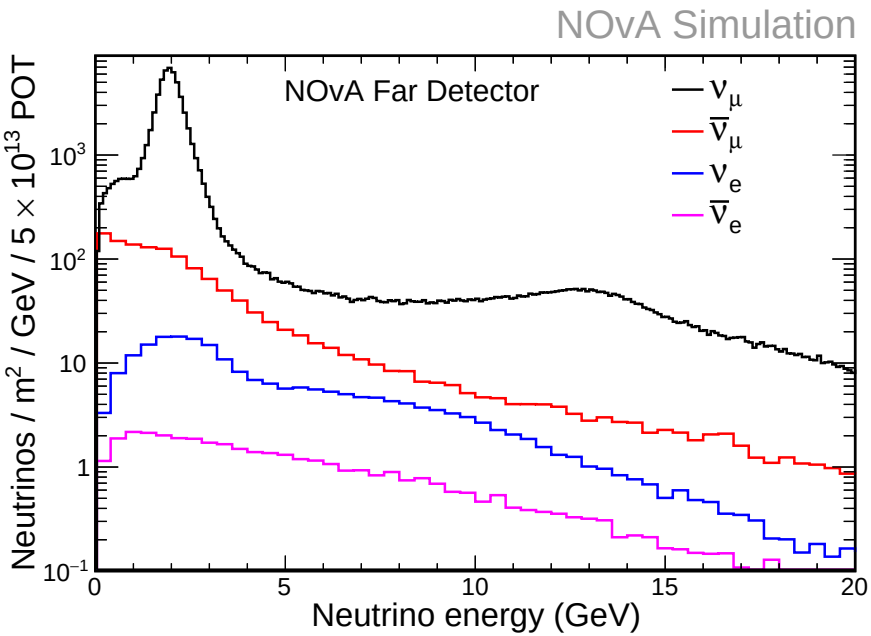


NuMI Beam



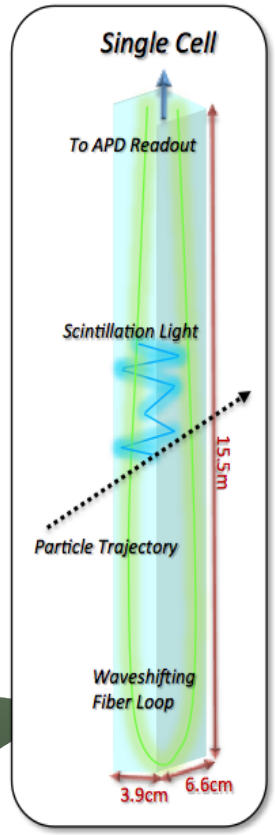
- Off-axis → narrow spectrum at 2 GeV, which is 1st oscillation maximum at 810 km

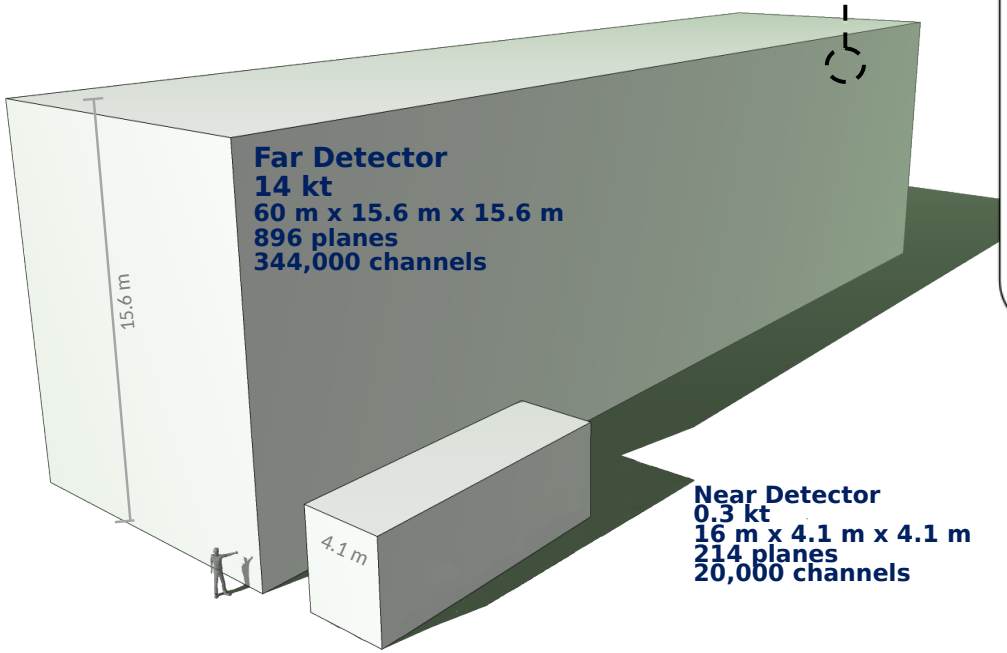




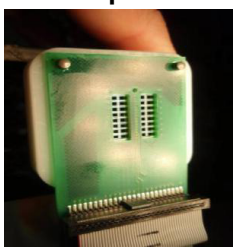
Detector Technology

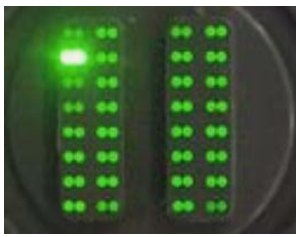
- Two functionally identical detectors
- Segmented plastic and scintillator sampling tracking calorimeter
- 63% active
- APD readout
- Near detector is 300 t, underground, 1 km from NuMI target
- Far detector is 14 kt, on the *surface*, 810 km north



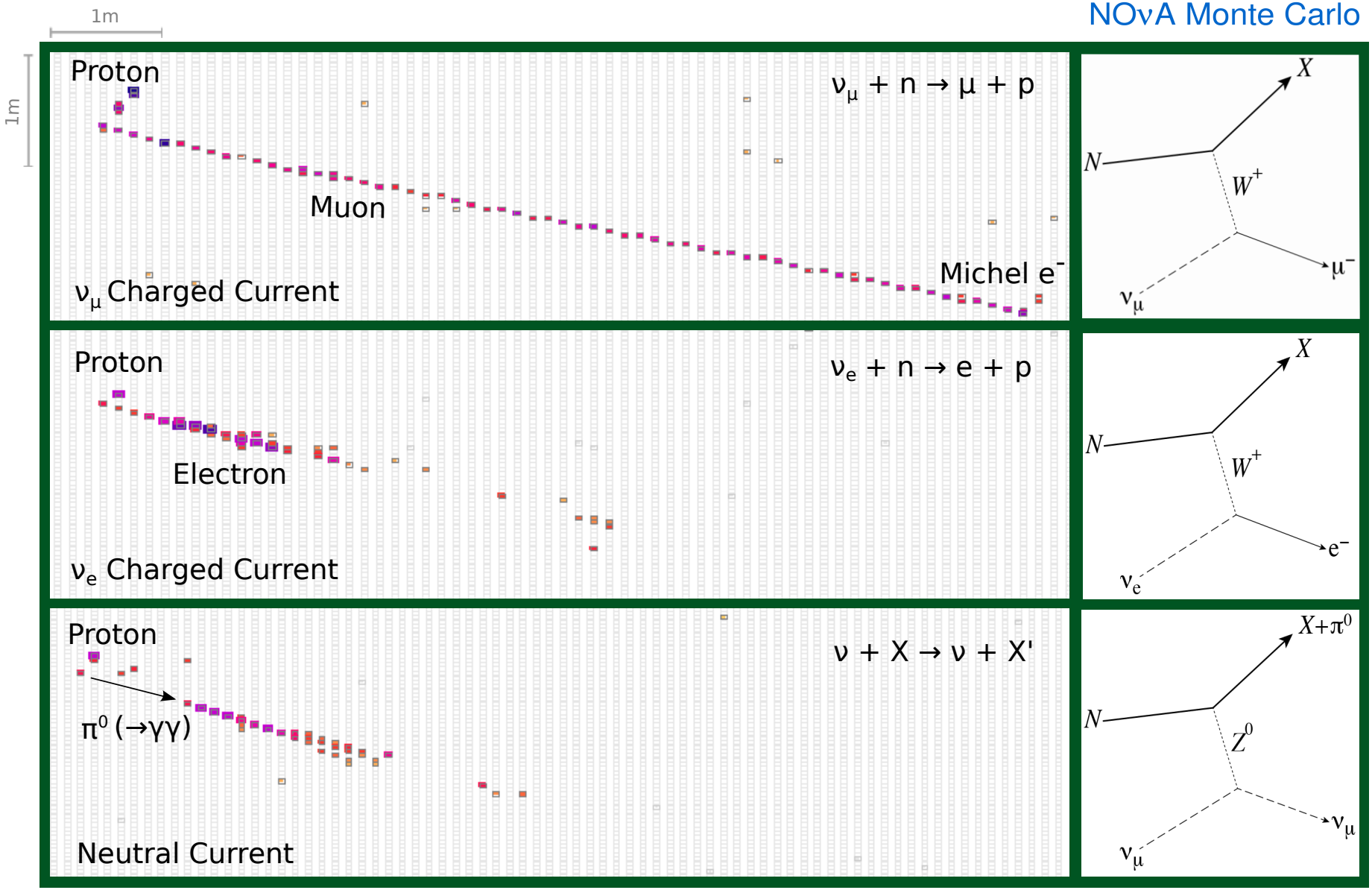


32 pixel APD sees fiber pairs from 32 cells



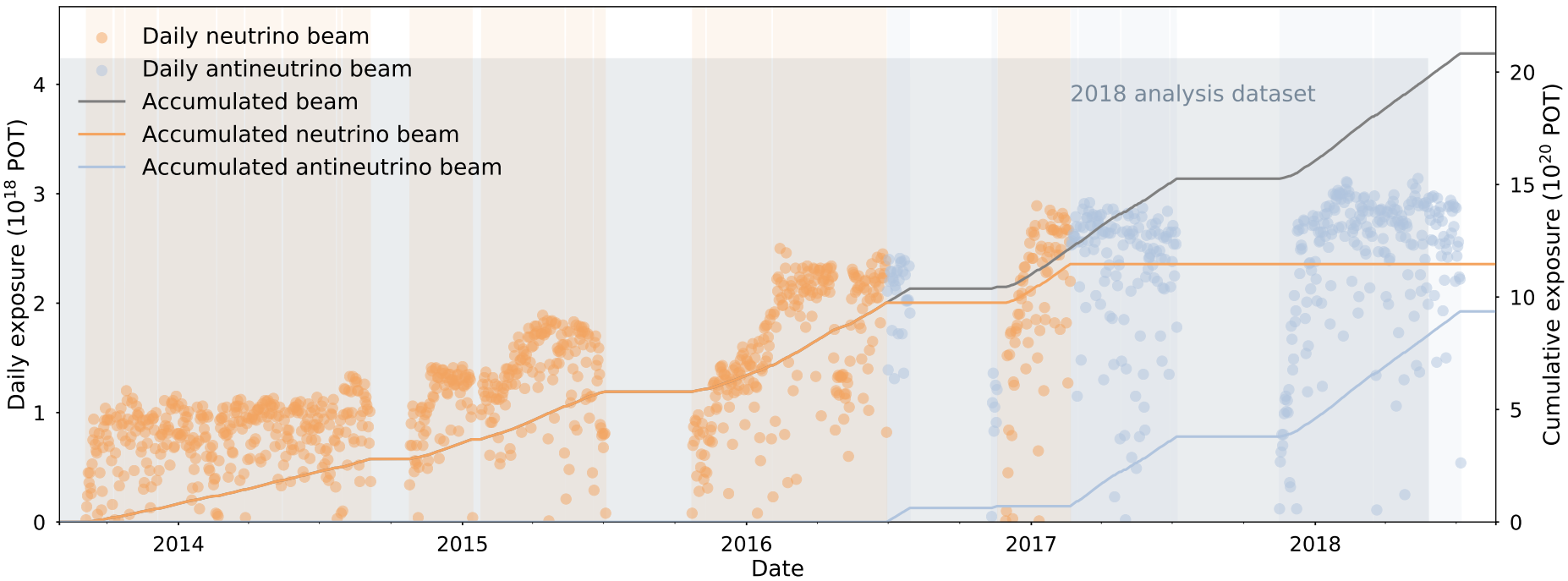


Event Topologies



Status

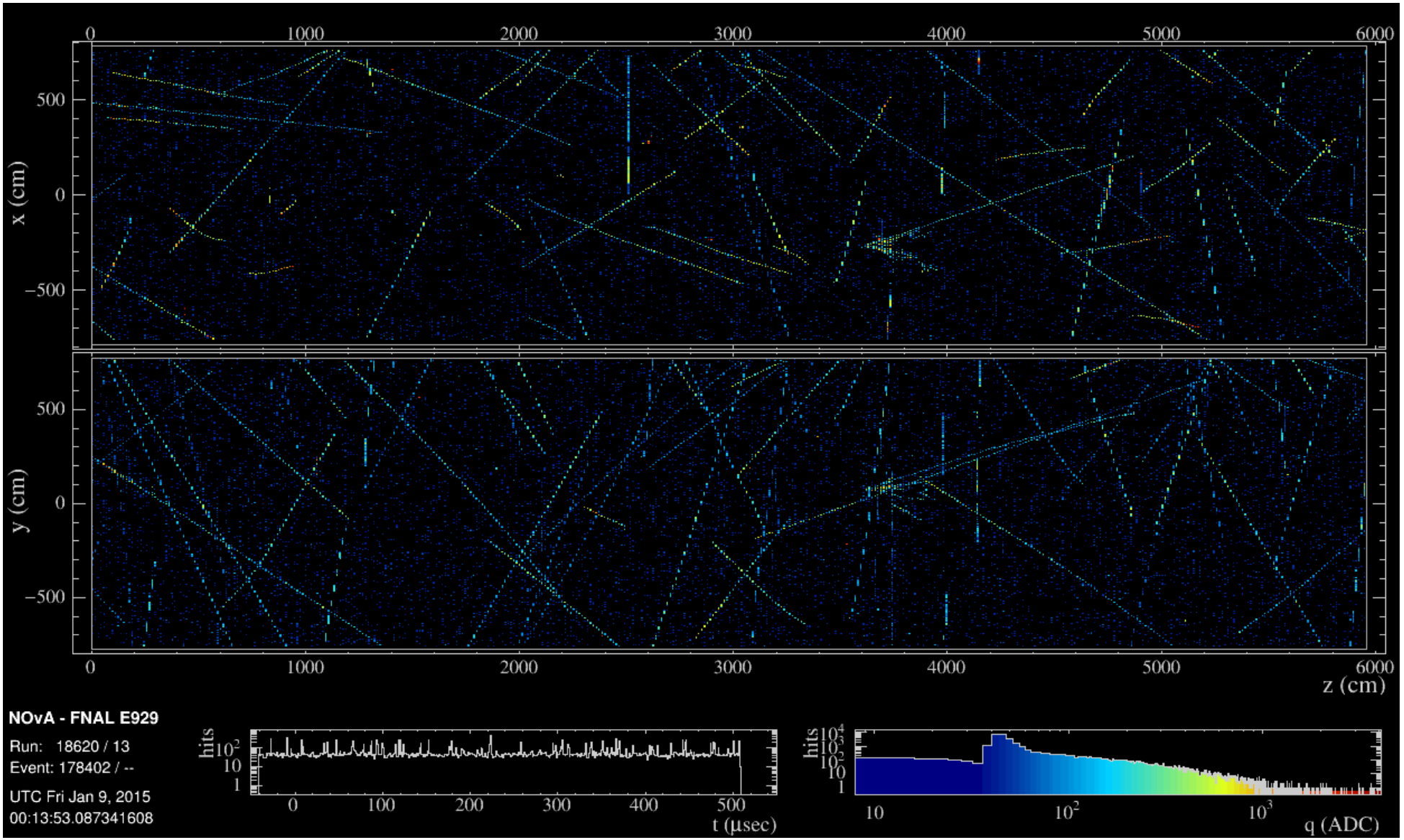
- This analysis:
  - 8.85×10^{20} POT-equivalent for 14 kt detector of **neutrino mode**
  - 6.91×10^{20} POT **anti-neutrino mode**
- NuMI now running typically at design power of 700 kW since January 2017
- Currently in summer shutdown
- Beam returns in the fall in anti-neutrino mode



Event Selection

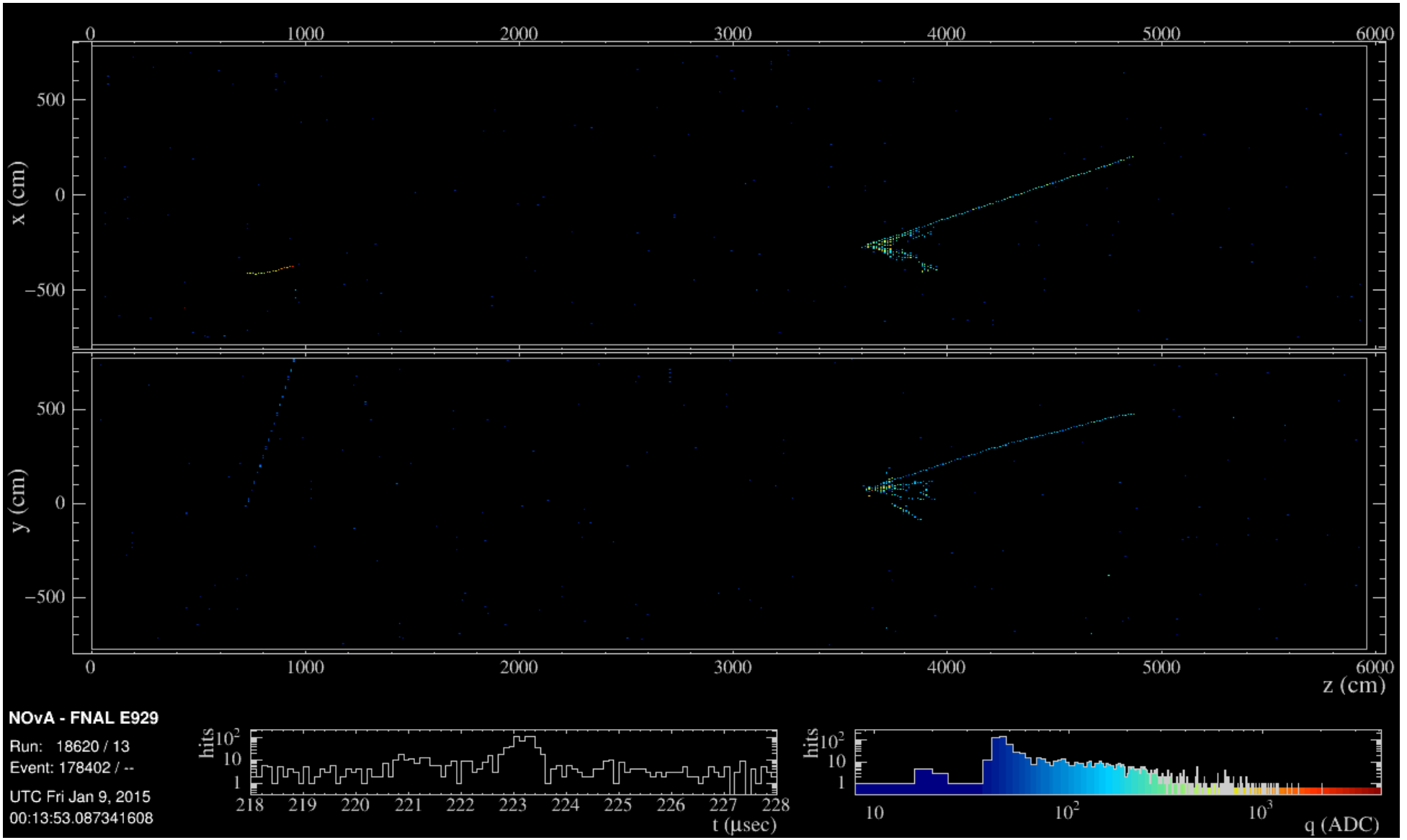
Cosmic Rejection

550 μs exposure of the Far Detector



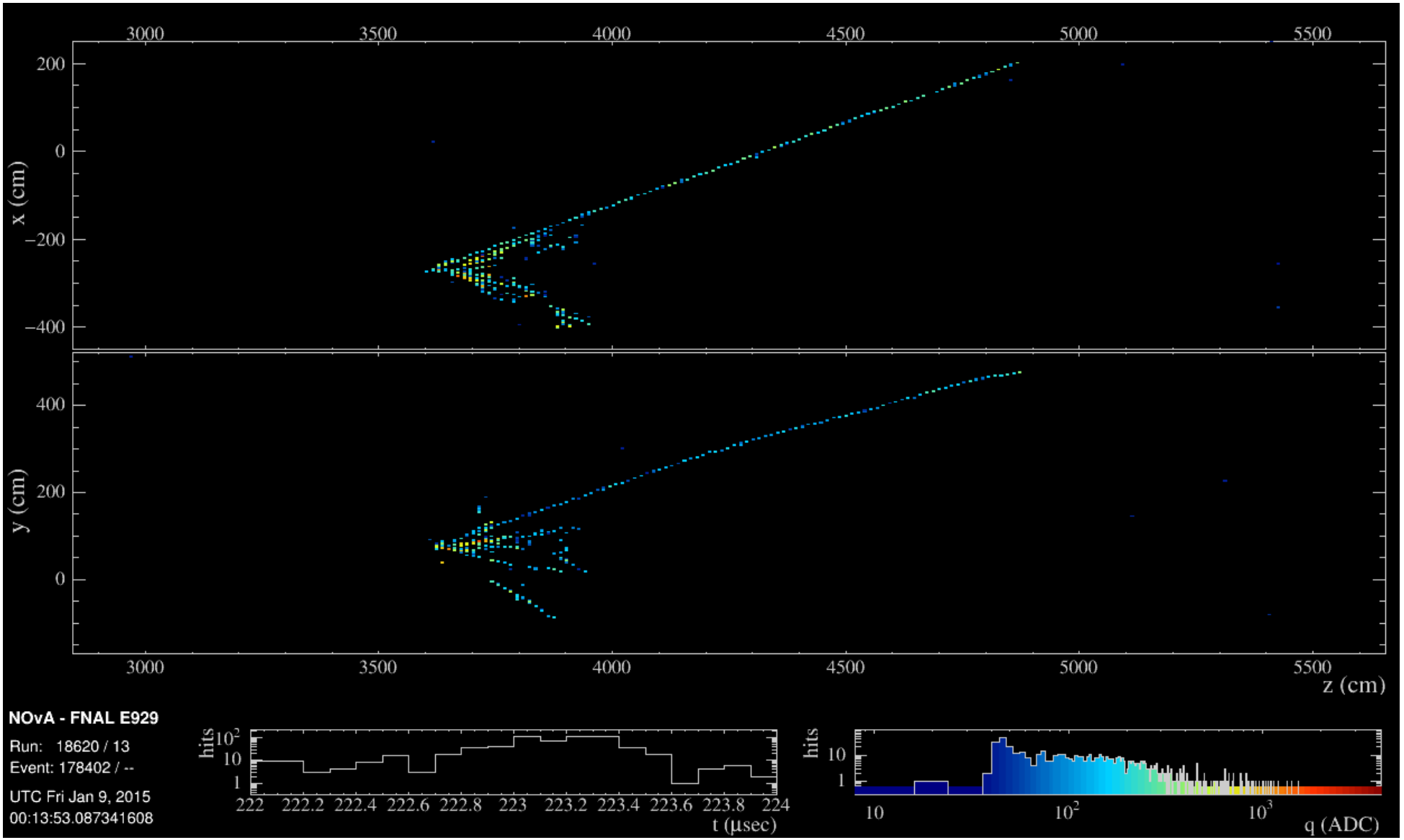
Cosmic Rejection

Zoomed into 10 μs NuMI beam pulse: 10^5 cosmic rejection



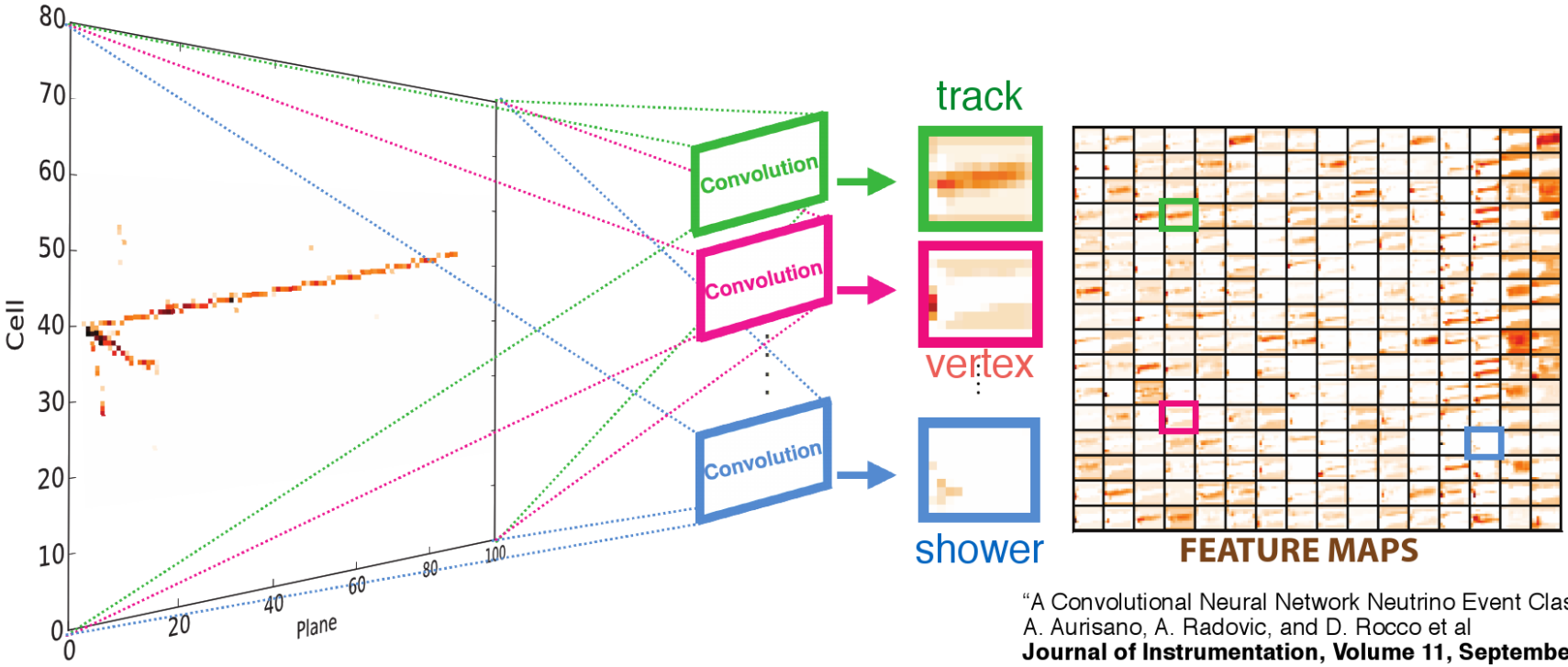
Cosmic Rejection

. . . and zoomed in spatially



Selection

- Additional factor of 10^7 cosmic rejection needed + must classify neutrino interactions. Single technique for both.
- Novel selection inspired by computer vision techniques: No explicit reconstruction
- Matrices of hit information are fed into a convolutional neural network (CNN)
- Abstract features extracted automatically
- Scores events on hypotheses of ν_e CC, ν_μ CC, NC and cosmic



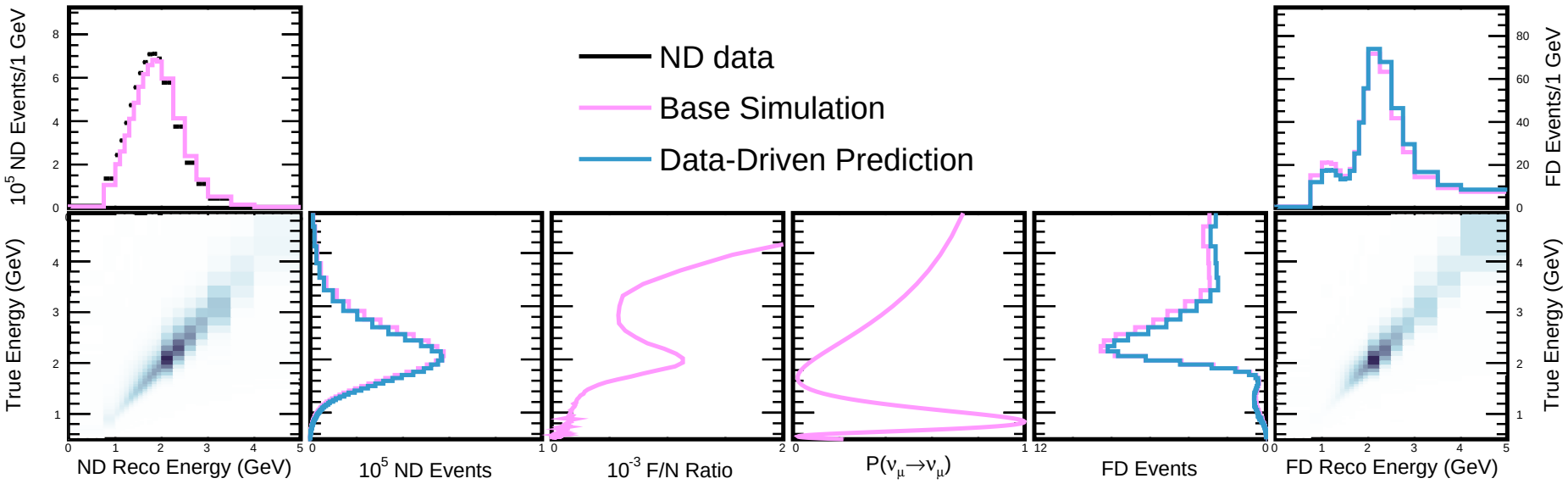
"A Convolutional Neural Network Neutrino Event Classifier"
A. Aurisano, A. Radovic, and D. Rocco et al
Journal of Instrumentation, Volume 11, September 2016

Predicting the Far Detector Spectrum

1. Near/Far technique
2. Cross section tuning
3. Wrong-sign background

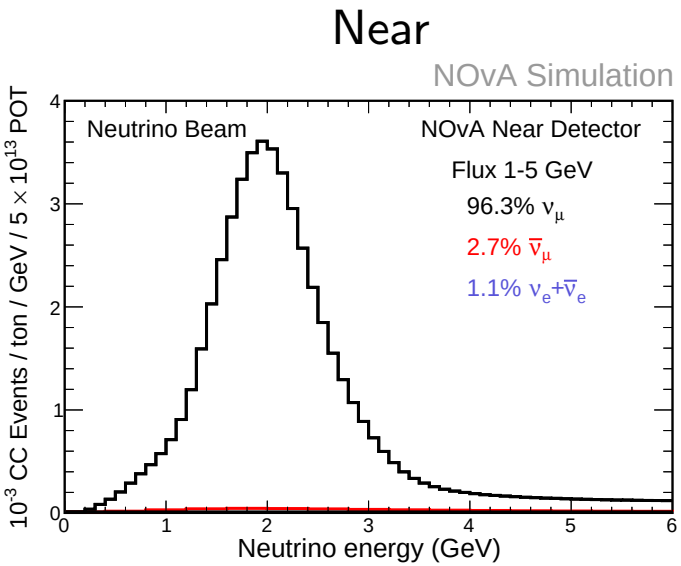
Predicting the Far Detector Spectrum

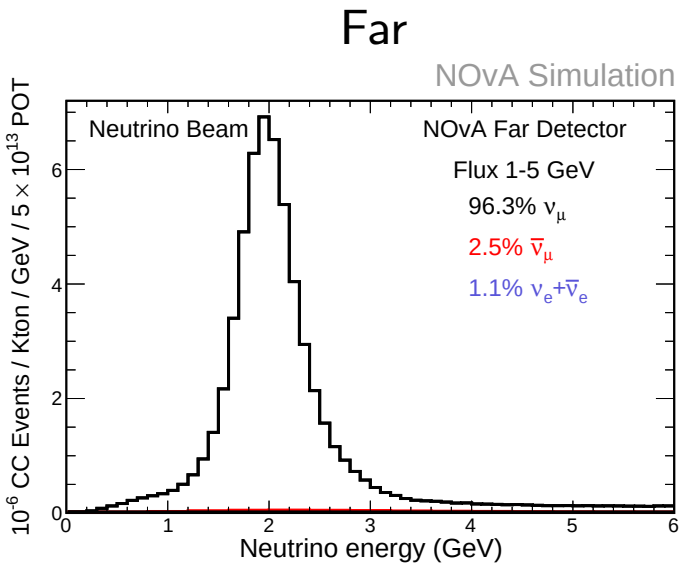
- Near Detector data used to predict Far Detector data given any oscillation parameters



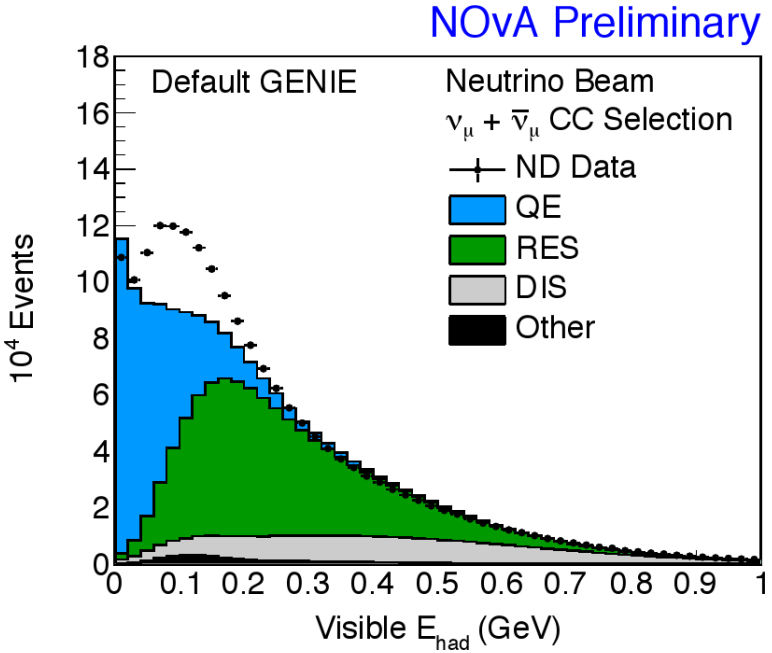
- Uncertainties in flux, cross section and efficiency largely cancel: similar detectors in same beam
- But at second order rely on simulation for reco-to-true matrices, Far/Near flux ratio, etc.

Near to Far Extrapolation





- GENIE out of the box does not describe Near Detector data well
- Differences believed to be mostly due to complex nuclear environment of neutrino interactions
- Use external information, then NOvA data, to produce a better tune and errors



Neutrino Interaction Tuning

- Compare ν_μ events in the ND

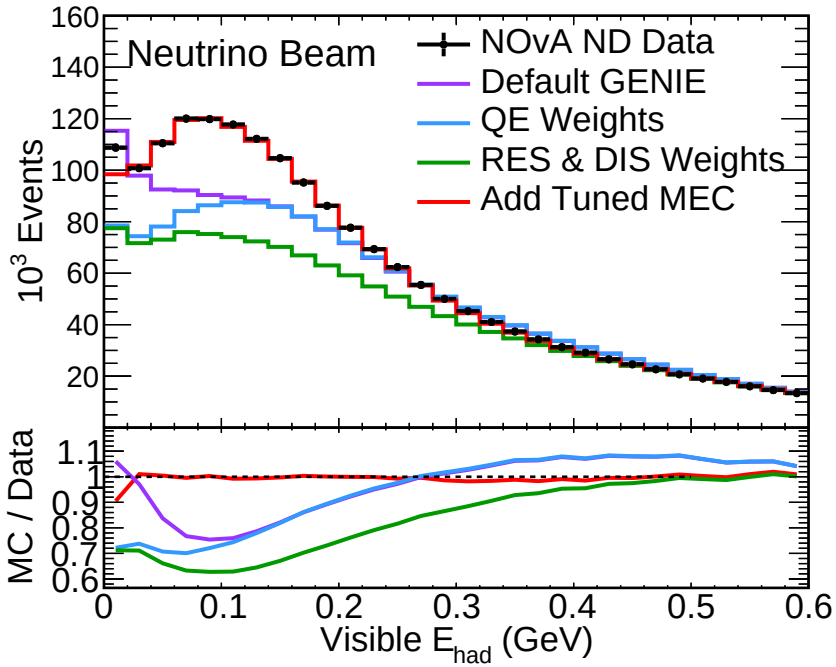
From external information:

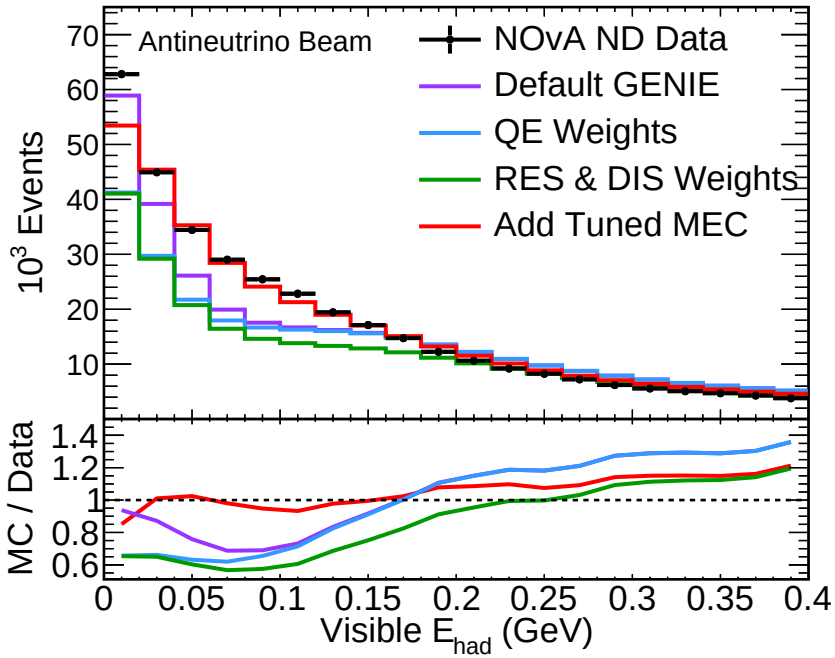
1. Reduce quasielastic component to account for RPA suppression
   - Long-range nuclear correlations
   - Using Valencia model, via work of R. Gran (MINERvA, arXiv:1705.02932)
2. Apply same reduction to resonant baryon production events

From NOvA data:

1. Increase deep inelastic scattering at high invariant mass ($W > 1.7$ GeV) 10%
2. Add tuned MEC (2p2h) model

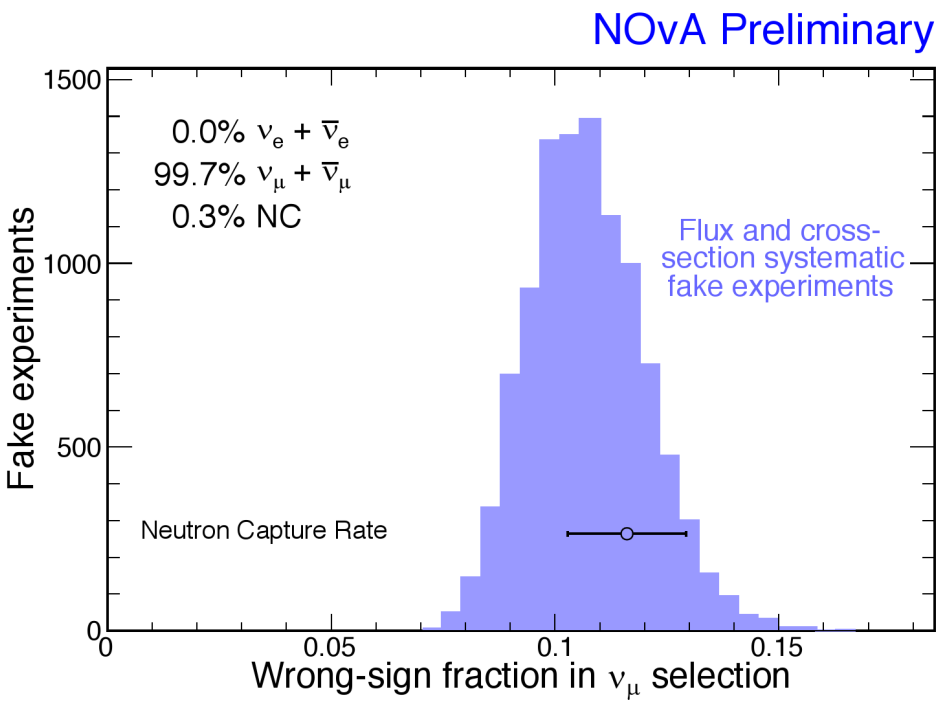
- Tuning done separately for neutrino and anti-neutrino beams



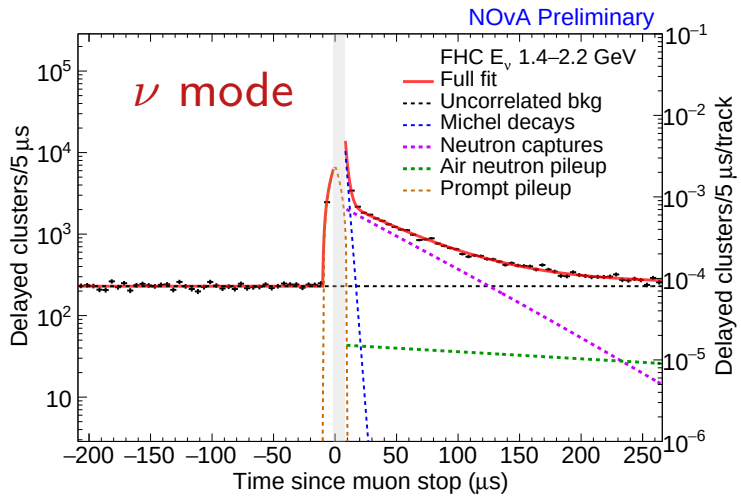


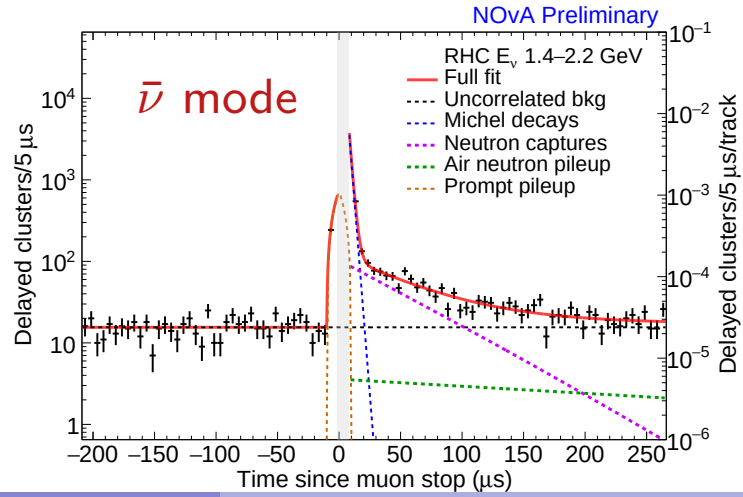
Wrong-sign Background

- ν_μ contamination in $\bar{\nu}_\mu$ beam oscillates to ν_e when $\bar{\nu}_e$ is of interest
- ND wrong-sign estimated to be:
  - 3% for ν mode,
  - 11% for $\bar{\nu}$ mode
- Anti-neutrino beam ν_μ content verified with data-driven study



- ^{35}Cl in NOvA plastic is a good neutron capture target
- Stopped μ^- (ν_μ) produce neutrons, μ^+ ($\bar{\nu}_\mu$) don't



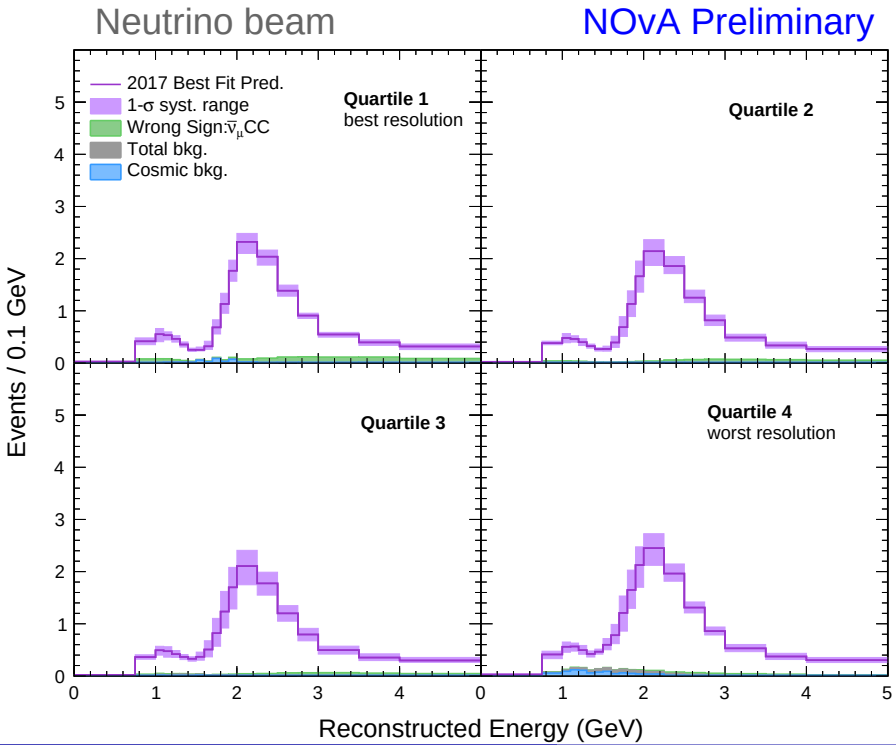


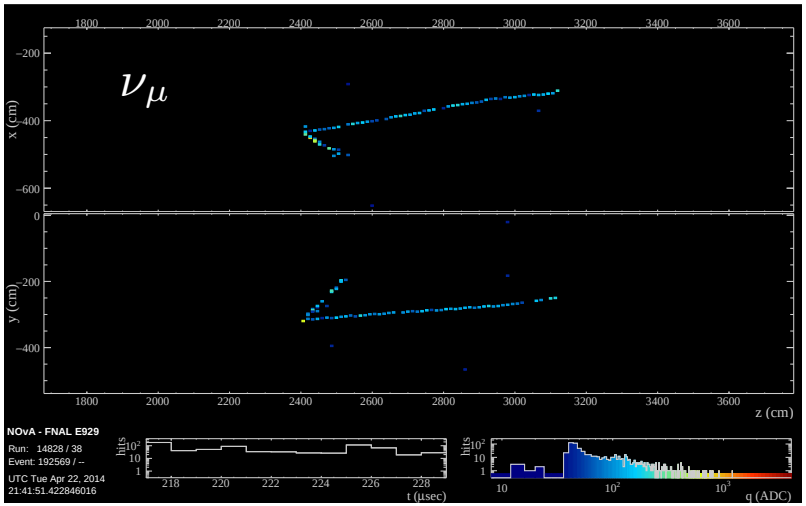
Muon Neutrino Disappearance Analysis

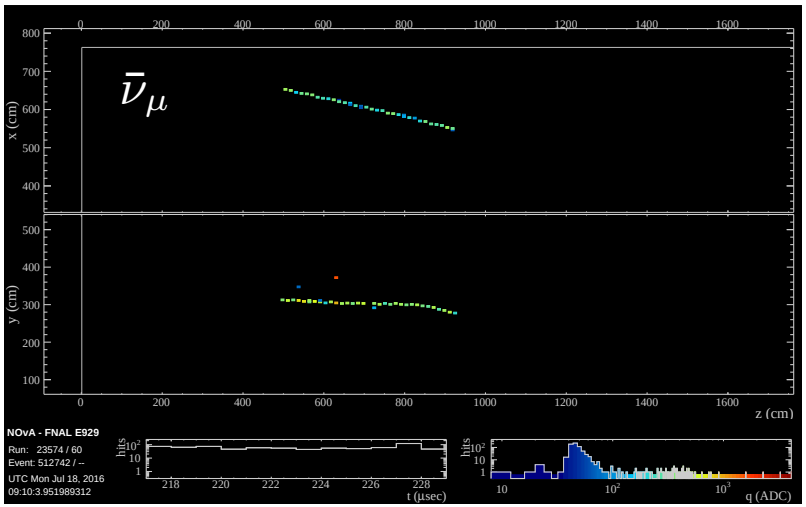
1. Binning scheme
2. Selected data
3. $sin^2\theta_{23}$ and Δm^2_{32} from disappearance alone

ν_μ Extrapolation

- Energy estimated from:
  - Muon track length (∼3% resolution)
  - Hadronic energy (∼30% resolution)
- Split in 4 quartiles of hadronic energy fraction
- Quartiles extrapolated independently Near to Far
  - Concentrates BG in one quartile
  - Further constrains systematics
  - Removes low-resolution events from osc. dip

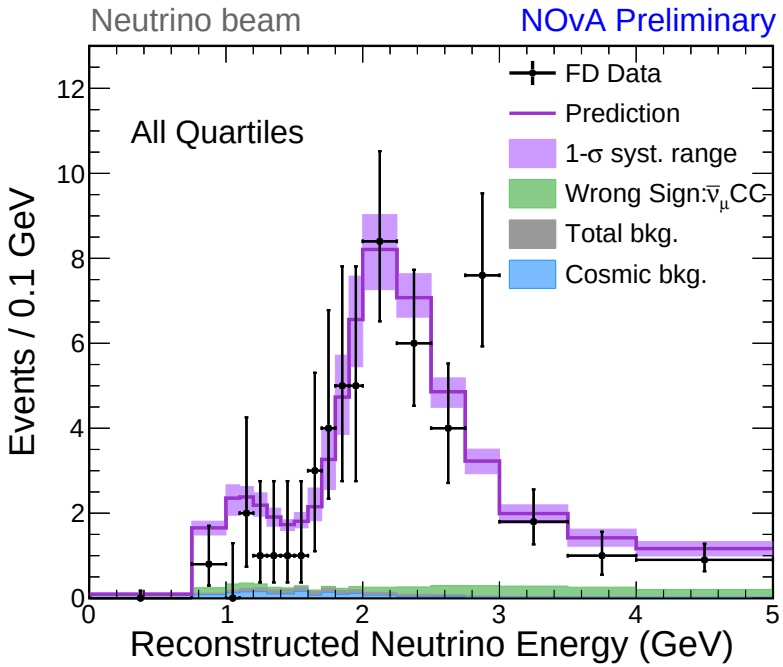




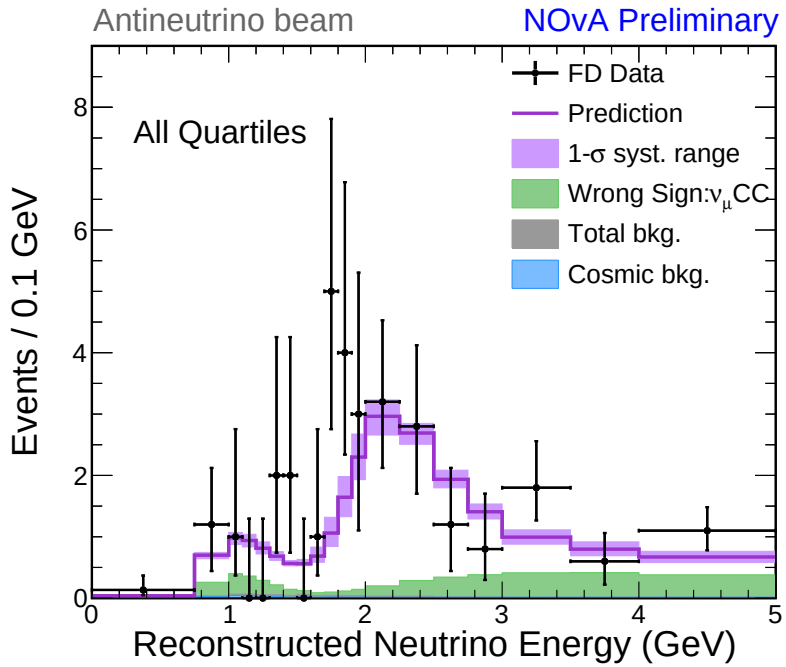


ν_μ Far Detector Data

- Neutrino mode: 730^{+38}_{-49}(syst.) without oscillations
- 113 events selected in Far Detector

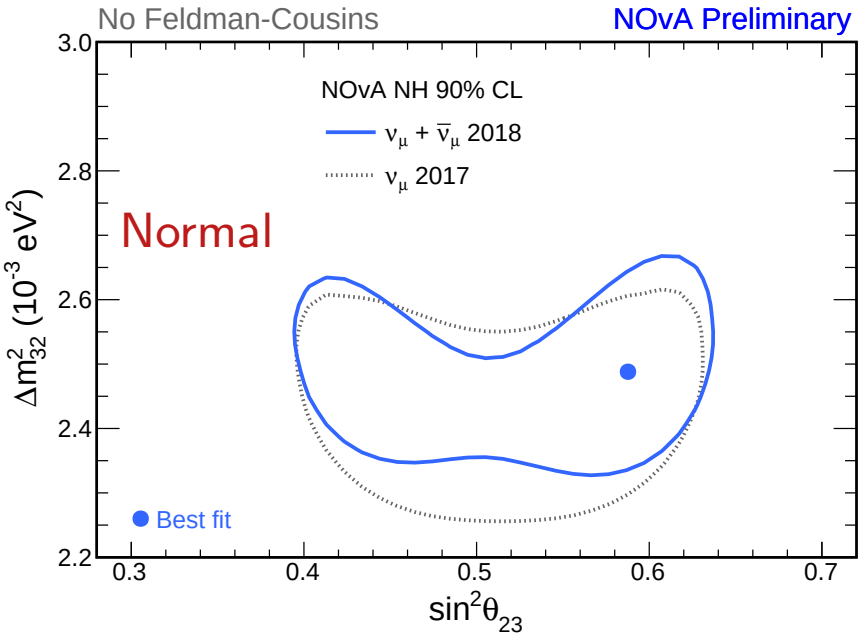


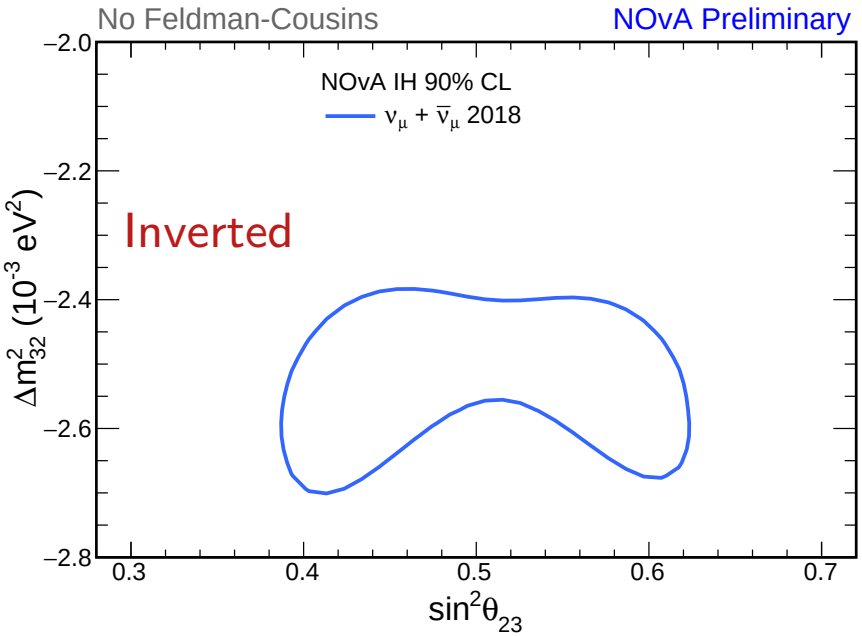
- Anti-neutrino mode: 266^{+12}_{-14}(syst.) without oscillations
- 65 selected



Results — ν_μ Only

- Neutrinos and anti-neutrinos are fit together assuming CPT
- If fit separately, antineutrino mode (the new data) prefers a more non-maximal solution than neutrino mode
- However, χ^2s are consistent with combined fit oscillation parameters with $p > 4\%$
- Also allowed region comparable to previous 2017 neutrino-only result





Electron Neutrino Appearance Analysis

1. FD background prediction
2. FD signal prediction
3. Selected events with $\bar{\nu}_e$ appearance

Near Detector Constraints on ν_e Backgrounds

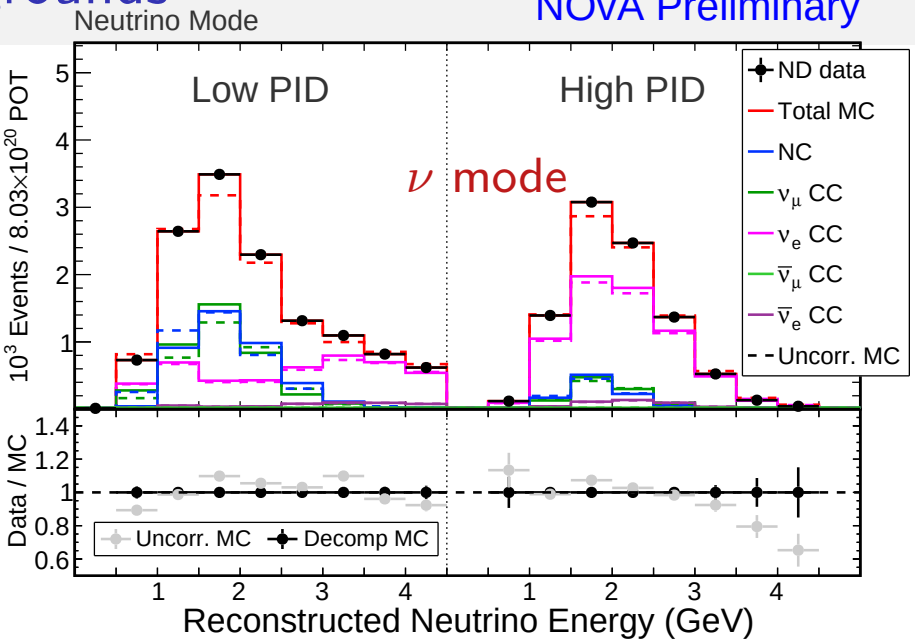
- ND ν_μ sample predicts FD ν_e signal
- ND ν_e-like sample predicts FD ν_e backgrounds
- Predicted FD backgrounds adjusted bin-by-bin with ND data

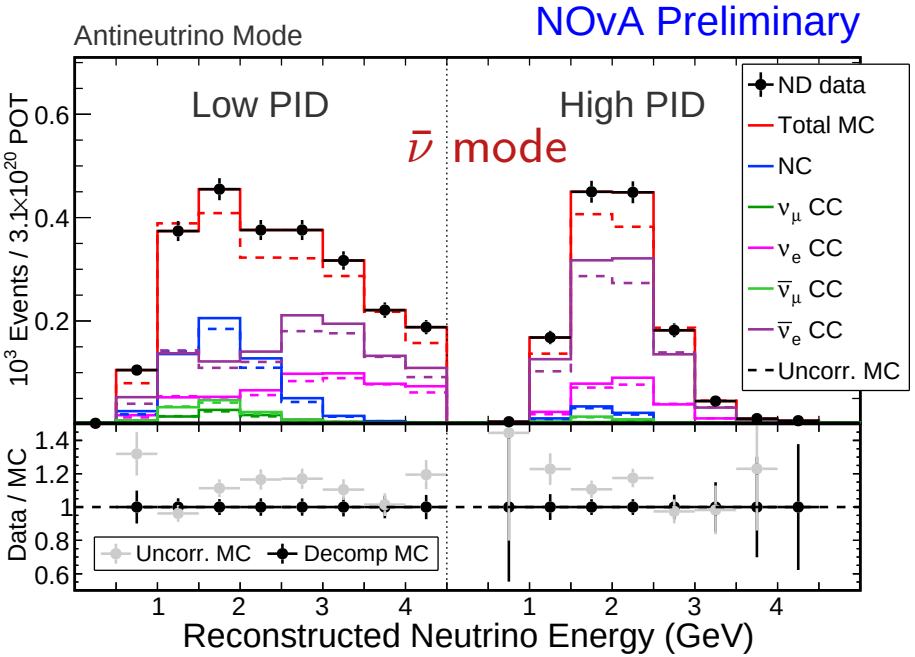
Neutrino beam:

- Intrinsic beam ν_e mostly from $\pi \to \mu$ (low E), kaons (high E). Adjust using ν_μ
- Remaining assigned to NC & ν_μ CC
  - Fraction of each (in each bin) determined by the number of Michel electrons seen

Antineutrino beam:

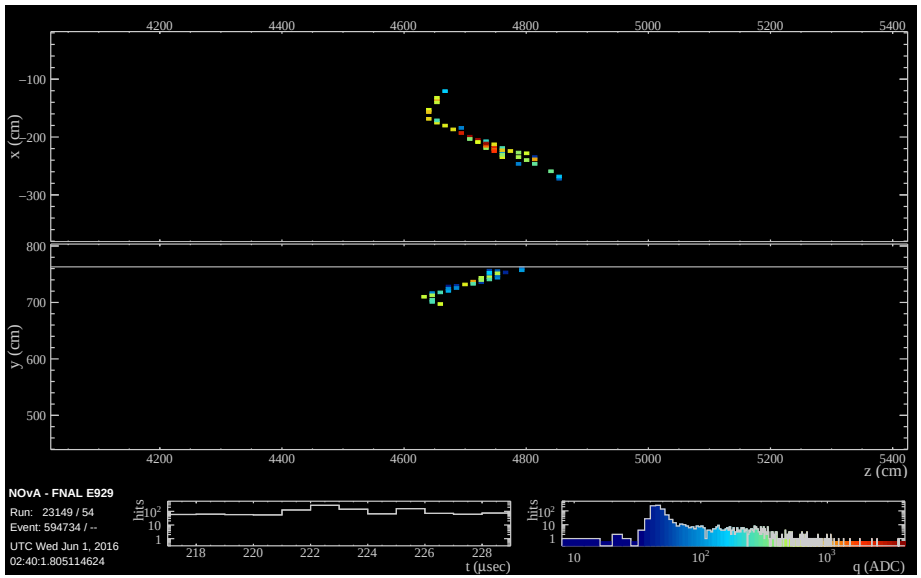
- Same procedure, but for now all components simply scaled evenly to match data

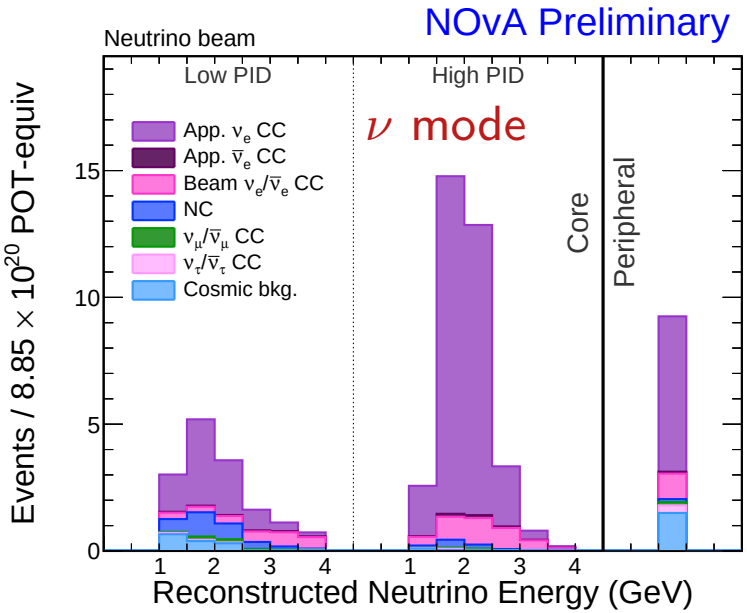


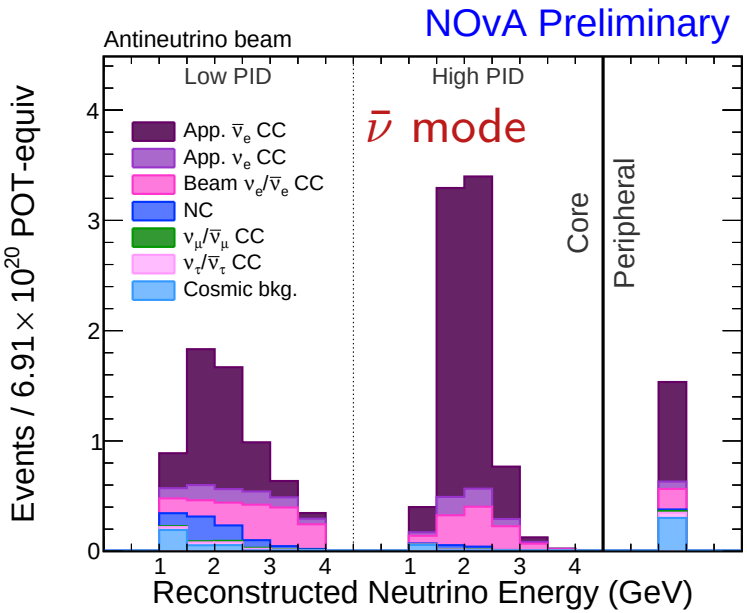


Far Detector ν_e Prediction

- Add one-bin "peripheral" signal sample
  - Events near the detector edge
  - Different cosmic rejection: BDT
  - High particle ID cut





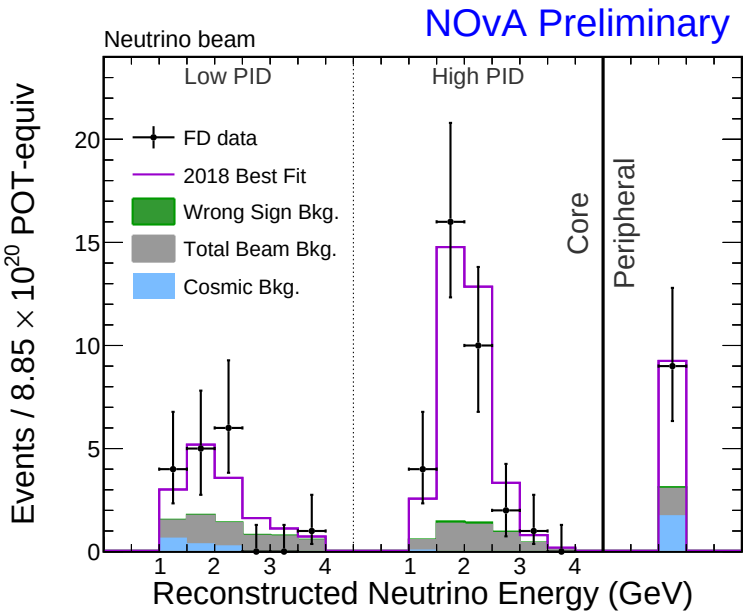


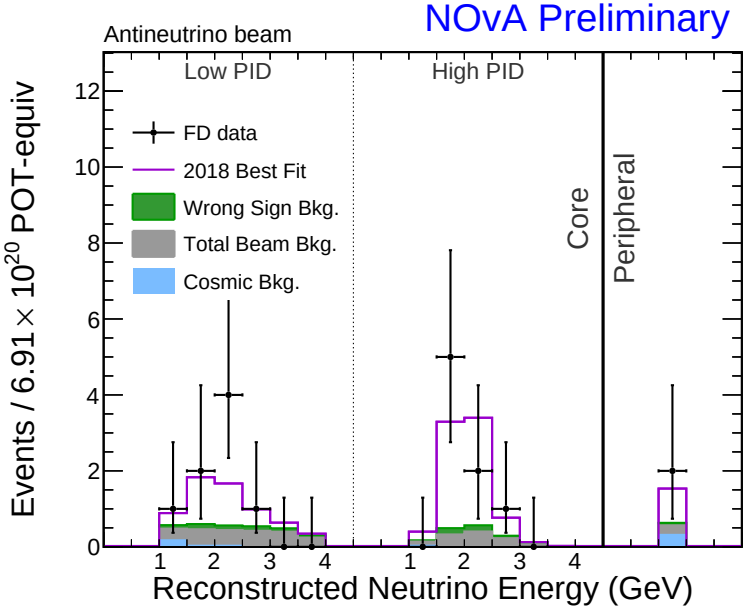
- Largest bg for both beams is real $\nu_e + \bar{\nu}_e$ intrinsic to beam
- Oscillated wrong sign component (ν_e) is small in comparison, even in $\bar{\nu}$ mode

Selected Events — ν_e

- Select 58 events in FD in ν mode
- Background: 15 events
  - 11 beam (intrinsic ν_e, ν_μ, ν_τ, neutral current)
  - 0.7 wrong-sign
  - 3 cosmic

- Select 18 in $\bar{\nu}$ mode
- Background: 5.3 events
  - 3.5 beam
  - 1.1 wrong-sign
  - 0.7 cosmic
- $> 4\sigma$ electron anti-neutrino appearance

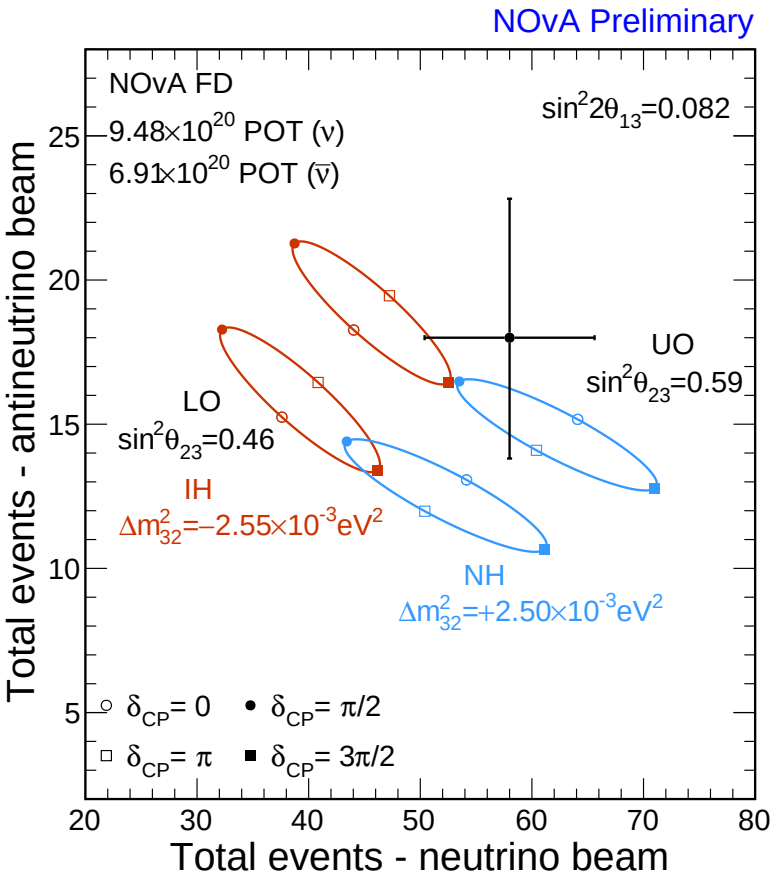


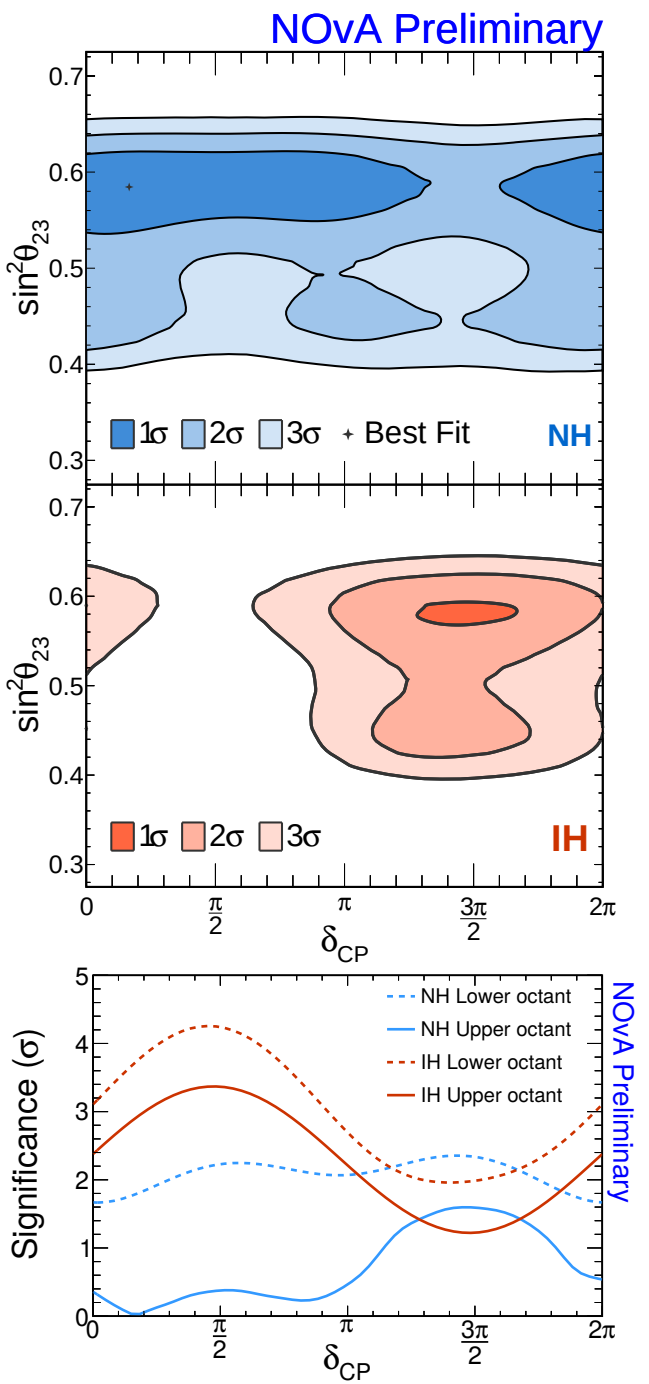


Parameter Extraction

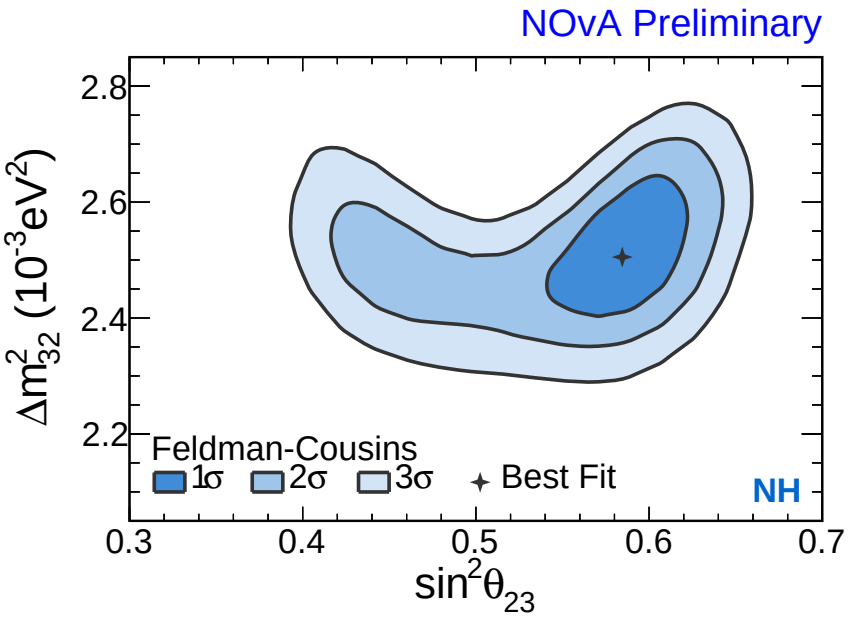
1. Hierarchy, Octant, δ
2. $\sin^2\theta_{23}$ and Δm^2_{32} with appearance and disappearance

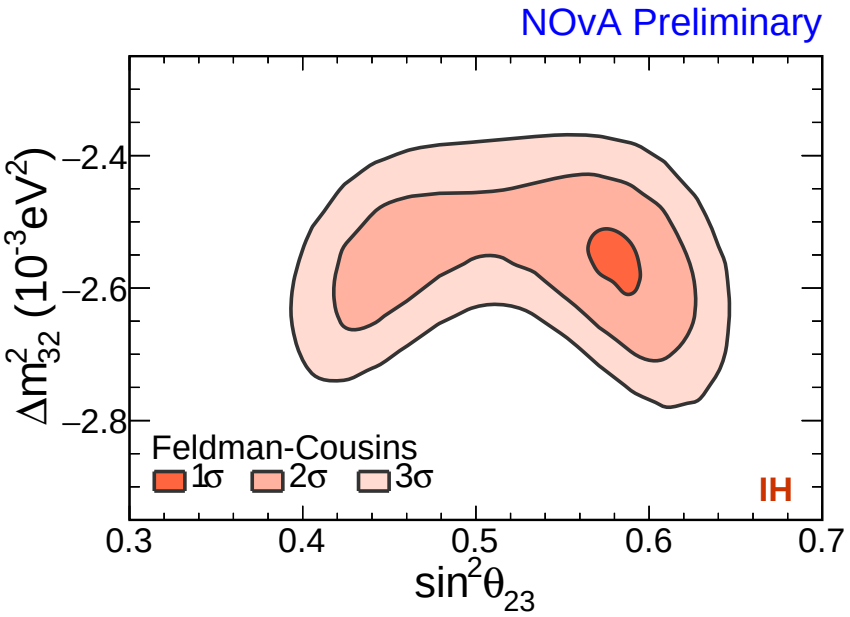
Combined Appearance/Disappearance Results



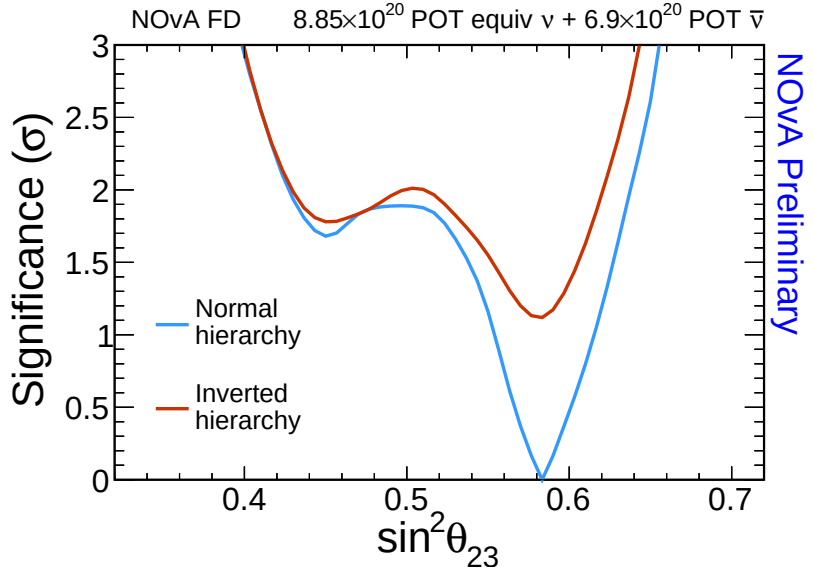


- Prefer normal hierarchy by 1.8σ
- Prefer **upper octant**
- Exclude $\delta = \pi/2$ in the IH at $> 3\sigma$
- Weakly prefer δ around $\pi/2$ in NH

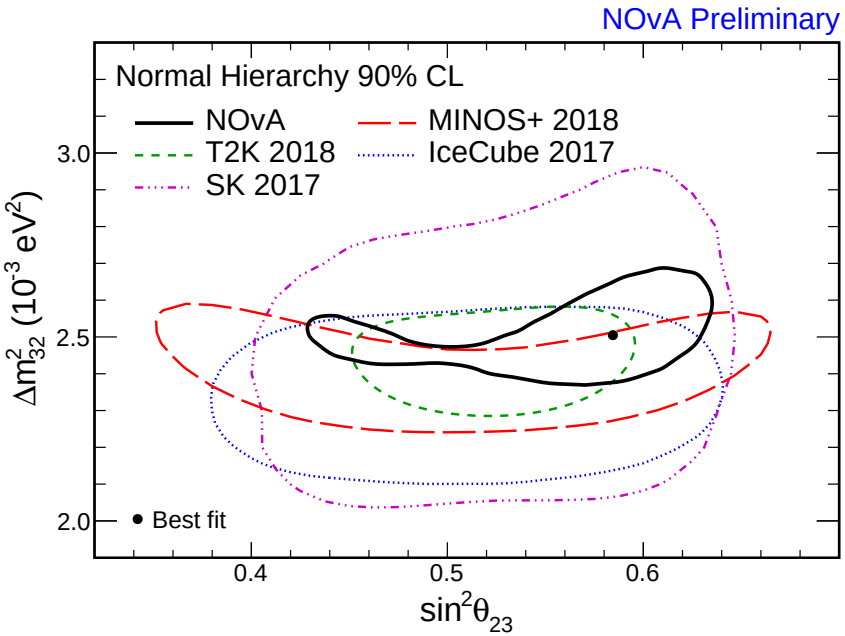




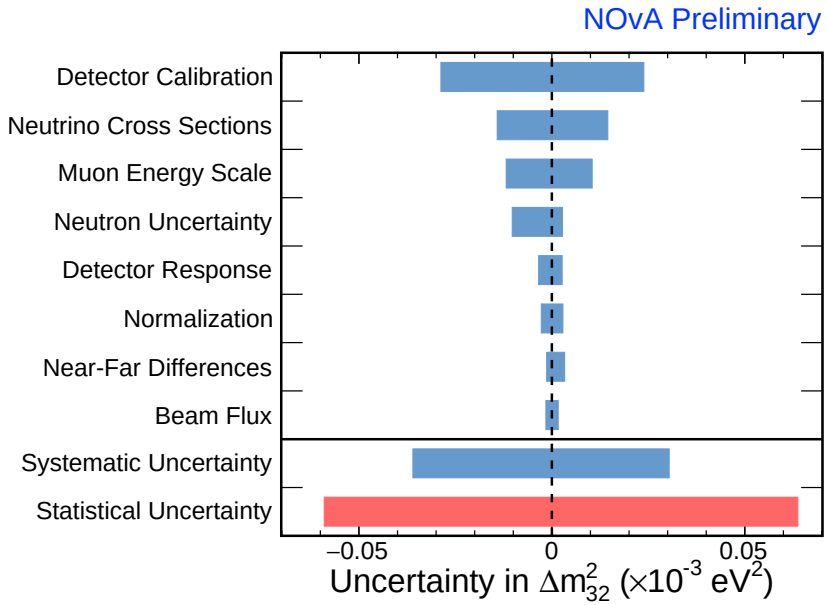
- $\Delta m^2_{32} = (2.51^{+0.12}_{-0.08}) \times 10^{-3}\,\mathrm{eV}^2$ (NH)

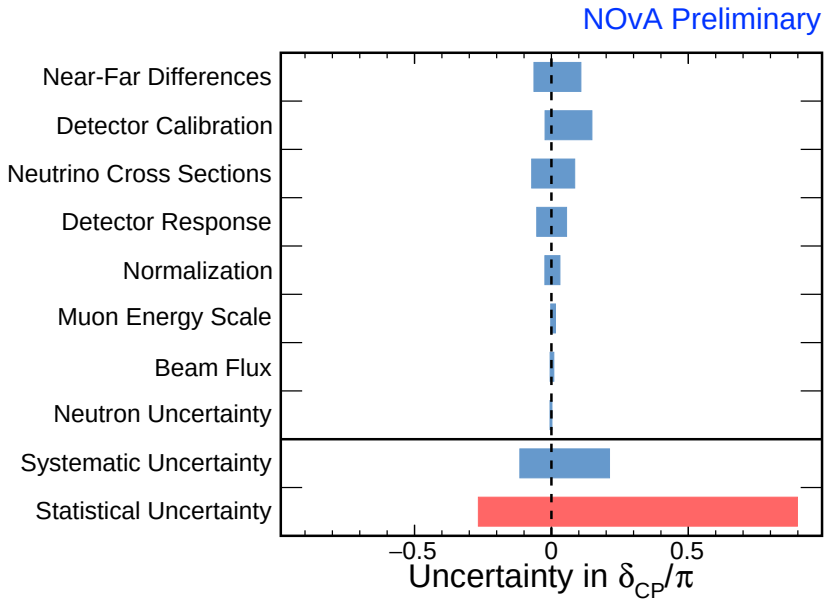


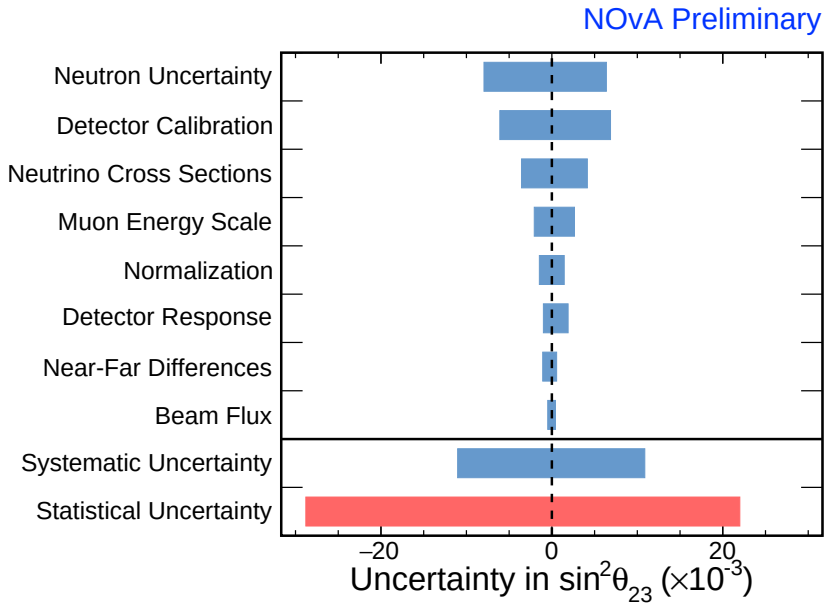
- $\sin^2\theta_{23} = 0.58 \pm 0.03$ (upper octant)
- Prefer non-maximal at 1.8σ



Systematics





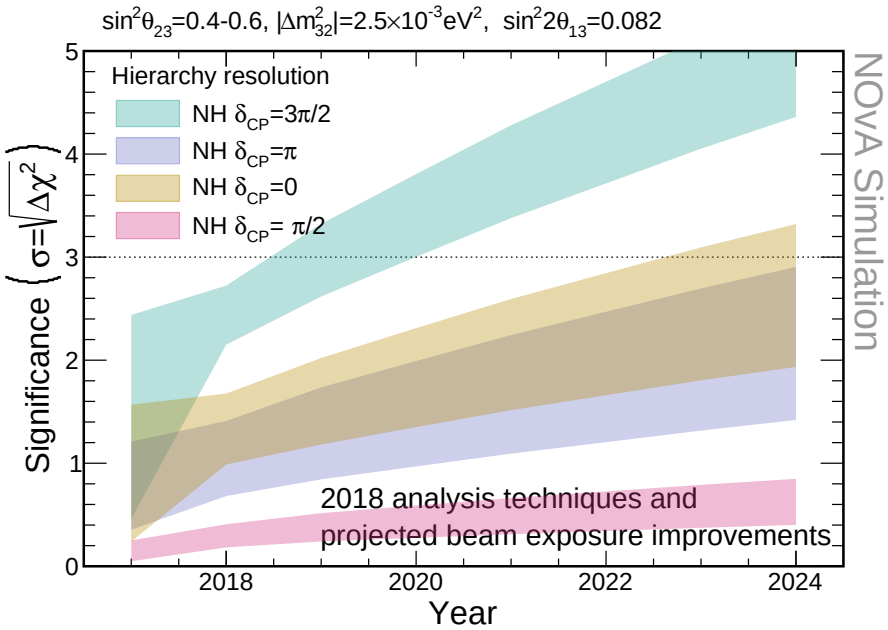


- Systematic uncertainties reduced since previous analysis
- Still statistics dominated
- Leading systematics:
  - Calibration — to be improved by 2019 test beam program
  - Cross sections — RPA, MEC
  - Neutron uncertainty — important for $\bar{\nu}$

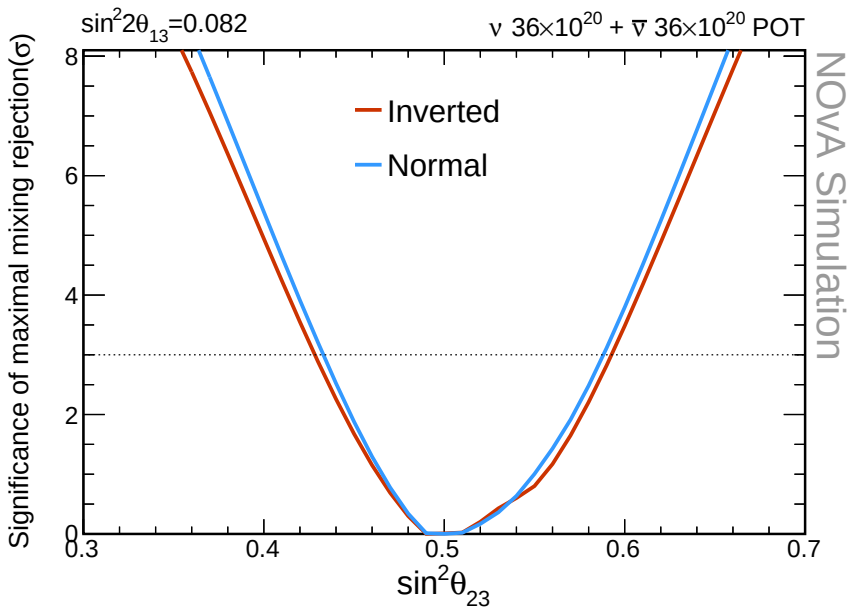
Outlook

Sensitivity assuming:

- 50% neutrino mode, 50% antineutrino mode; anti-neutrino for rest of 2018
- 36×10^{20} POT of each by 2024 given projected accelerator improvements
- Current analysis techniques (conservative), but modestly improved systematics



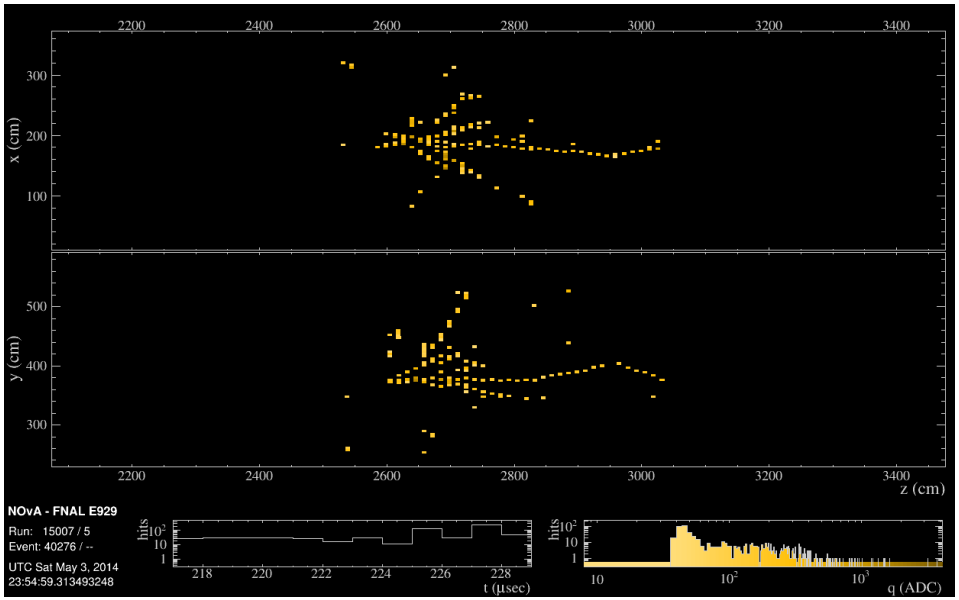
- For normal hierarchy, 3σ for $> 30\%$ of true δ values by 2024

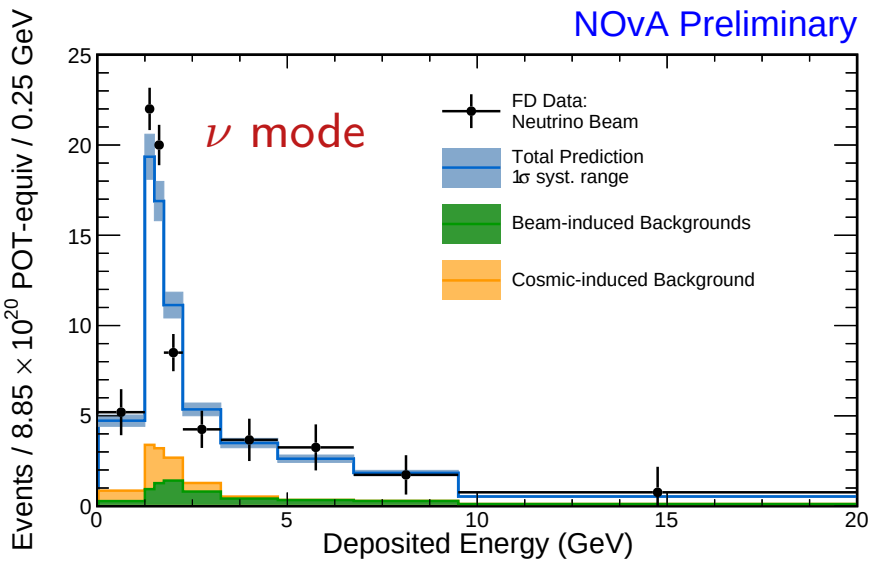


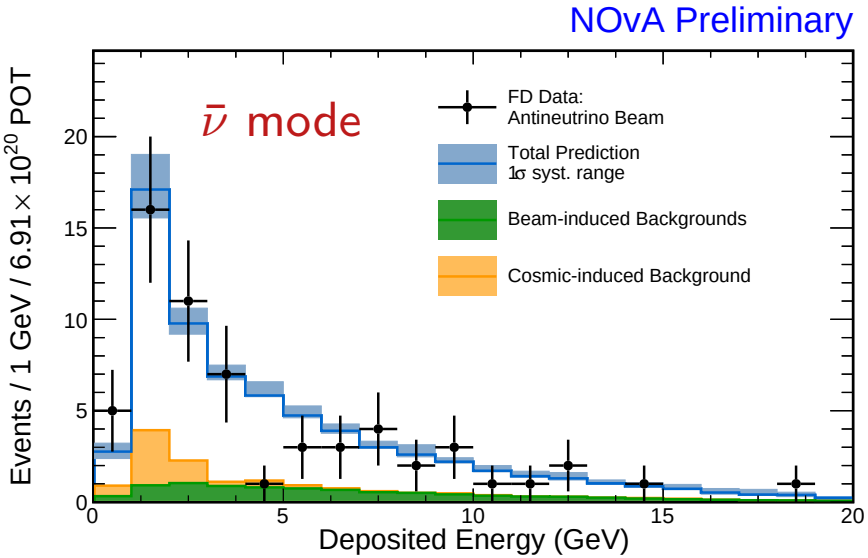
- 3σ rejection of maximal mixing if true $\sin^2\theta_{23} < 0.43$ or > 0.59

Search for Sterile Neutrinos

Neutral Current Disappearance





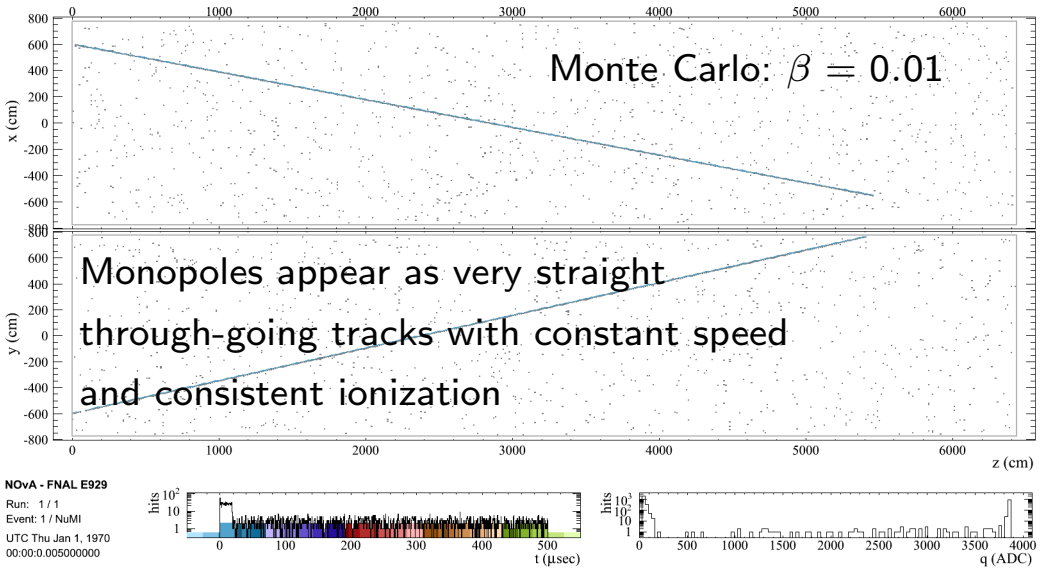


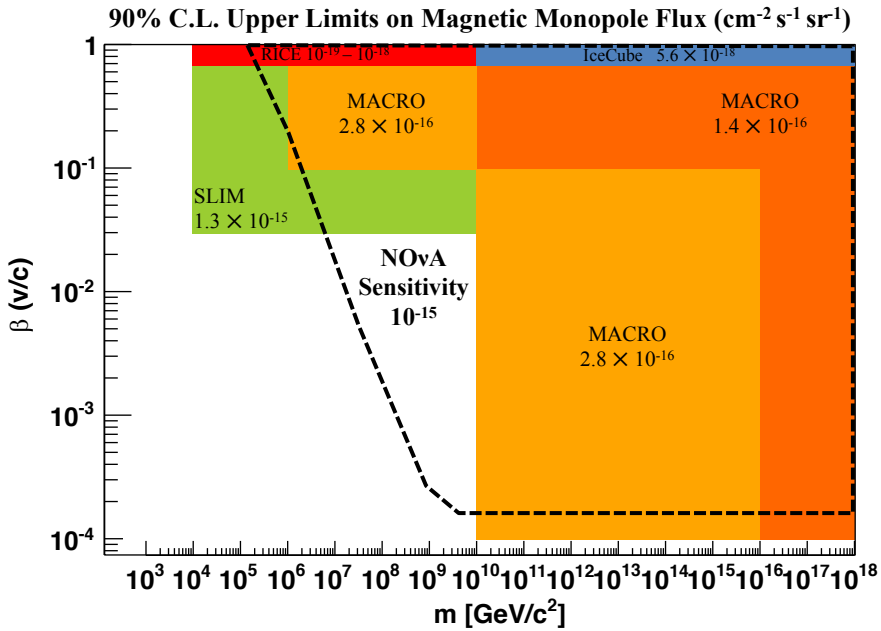
- Neutrino beam:
  - Predict 188 ± 13 (syst.) (38 bg)
  - Observe 201
- Antineutrino beam:
  - Predict 69 ± 8 (syst.) (16 bg)
  - Observe 61
- No significant suppression of neutral current interactions observed for neutrinos or antineutrinos

Non-oscillation physics

Astrophysics with NOvA — Magnetic Monopoles

- As a large fine-grained detector, NOvA supports a variety of astrophysical analyses
- Some, like monopoles, benefit from the Far Detector's location on the surface
- (Some can be done *in spite* of being on the surface)

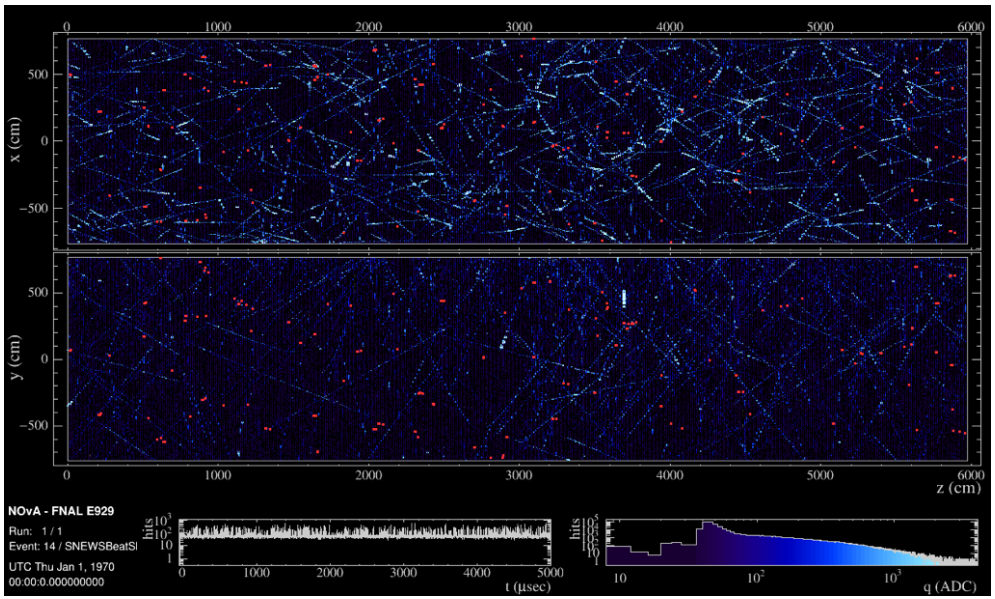




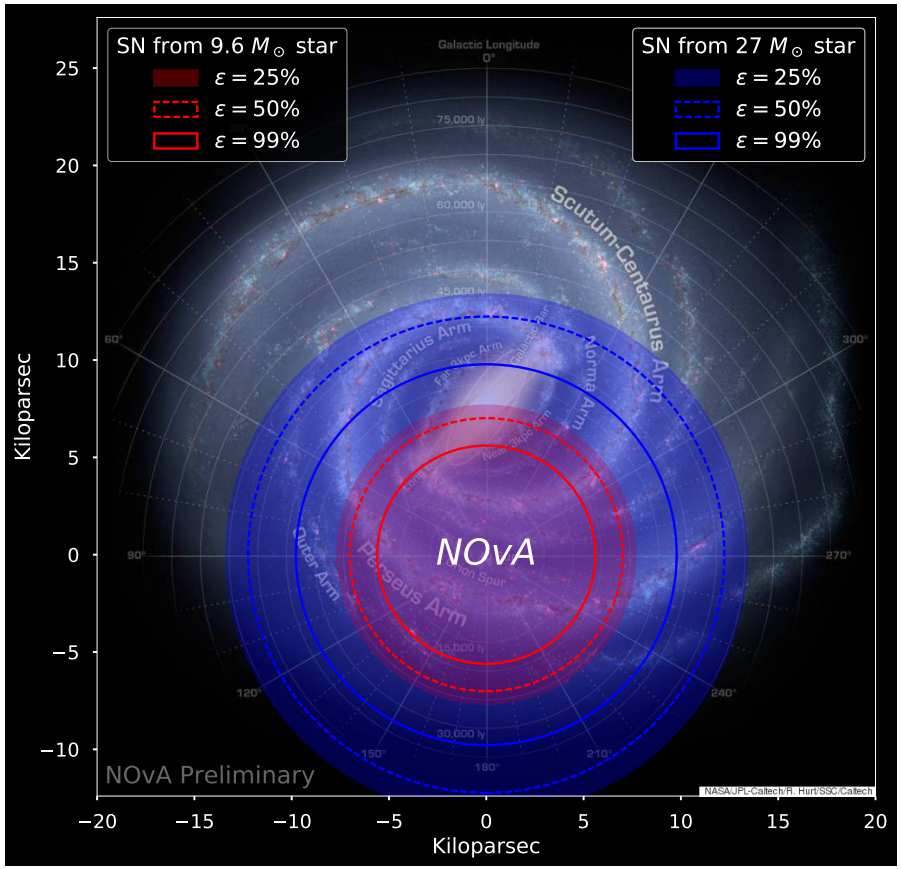
- First 120 live-days analyzed for $\beta < 0.01$ monopoles — paper in preparation
- 1000 more days on tape

Supernovae

- Sensitive to galactic core-collapse supernovae
- Primary channel is inverse beta decay: 10–50 MeV e^+
- Expect 2200 events for 10 kpc
- Trigger on excess of "noise" — burst of 2–4 hit clusters



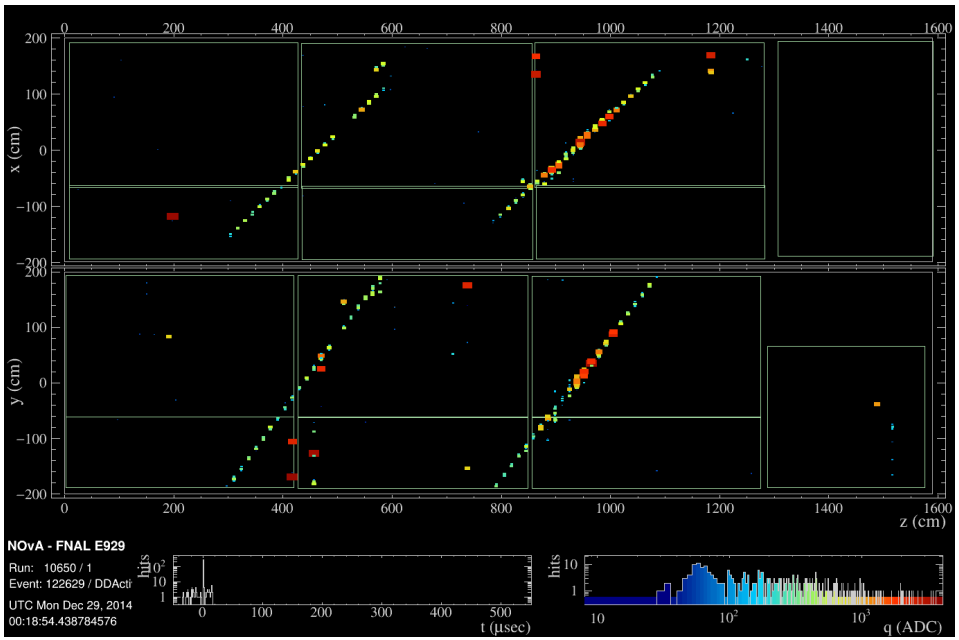
5 milliseconds, 10 kpc:
Data cosmics, simulated SN events (e^+ only)

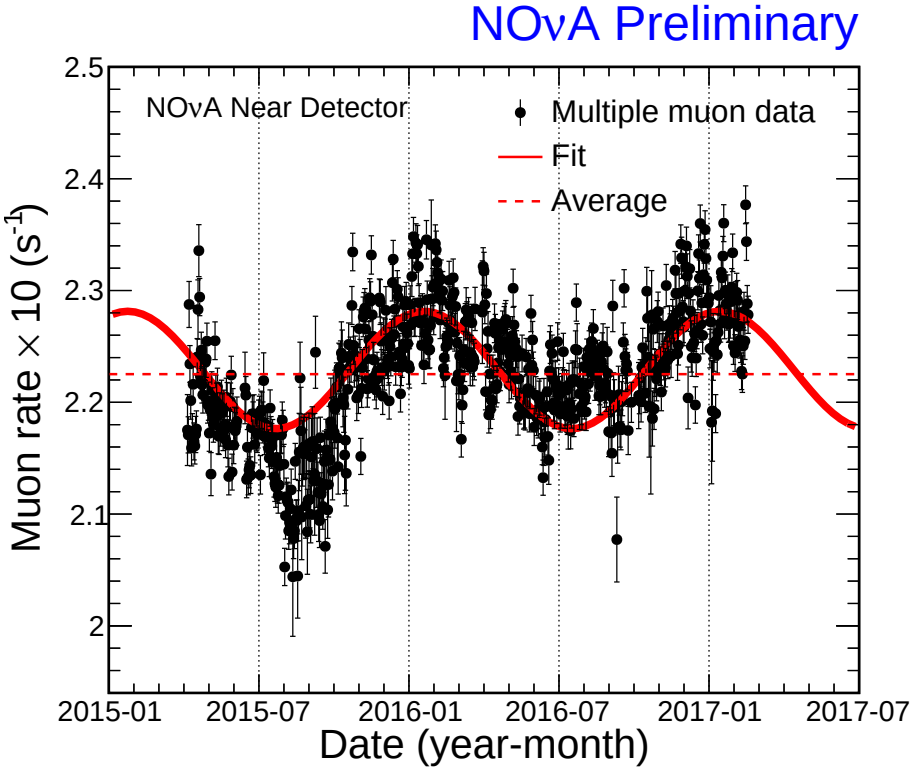


- Self-trigger if inside circled area
- Otherwise read out when alerted by SNEWS

Multi-muon Seasonal Effect

- Seasonal dependence of multi-muon cosmics in the Near Detector — underground
- Confirmed reversed seasonal dependence first seen by MINOS: winter maxima
- Paper in preparation





Plus dark matter searches, $n\bar{n}$ oscillation, and more. . .

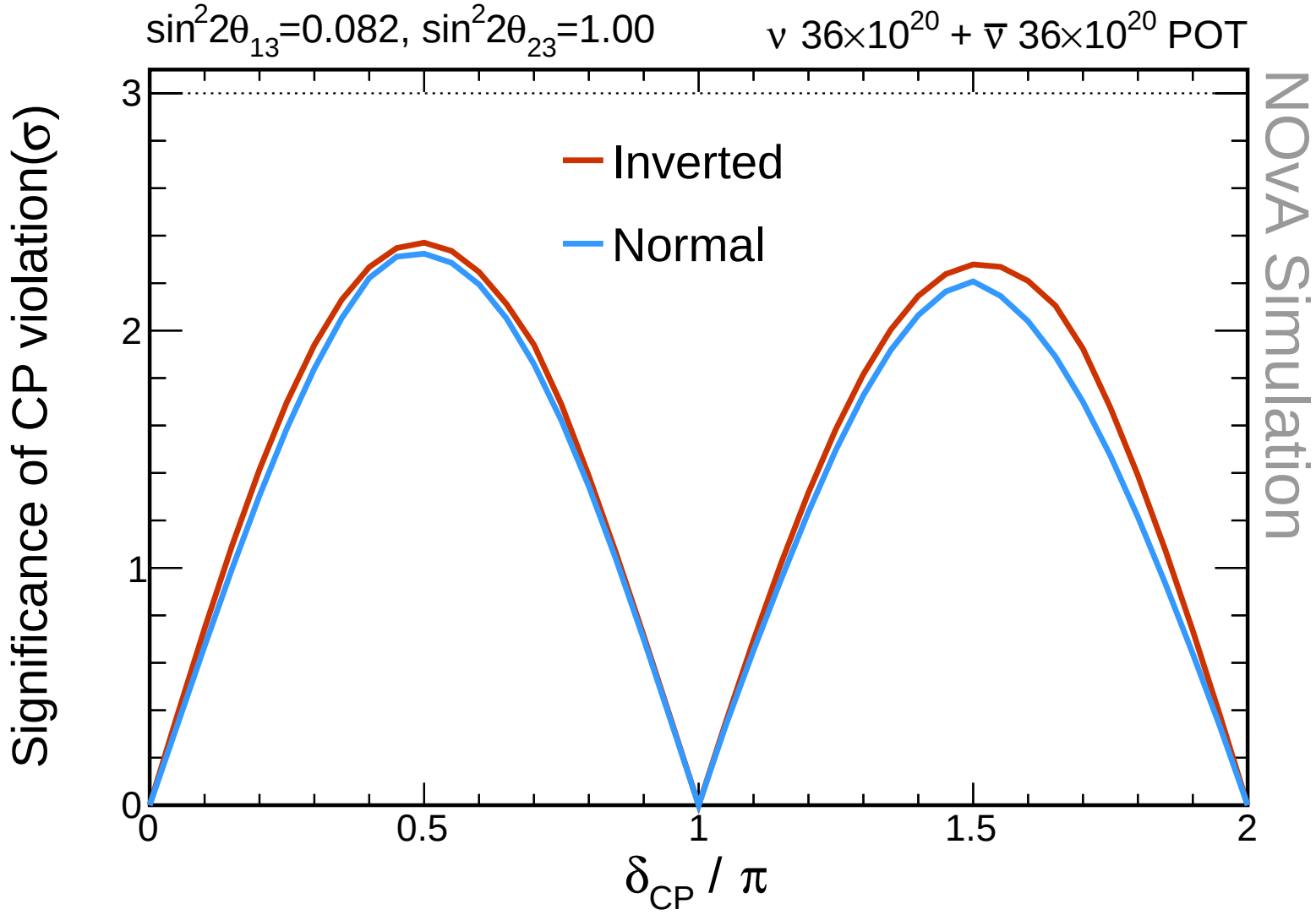
Conclusions

- First results with $\bar{\nu}$ beam.
- Observed appearance of $\bar{\nu}_e$ in a $\bar{\nu}_\mu$ beam at 4σ
- Joint $\nu_\mu + \nu_e$ analysis:
  - Favors normal hierarchy at 1.8σ
  - Inverted and $\delta = \pi/2$ excluded at 3σ
- No evidence of sterile neutrinos
- Suite of astrophysical results to come
- Plan to run until 2024
  - Potential 3σ reach for hierarchy

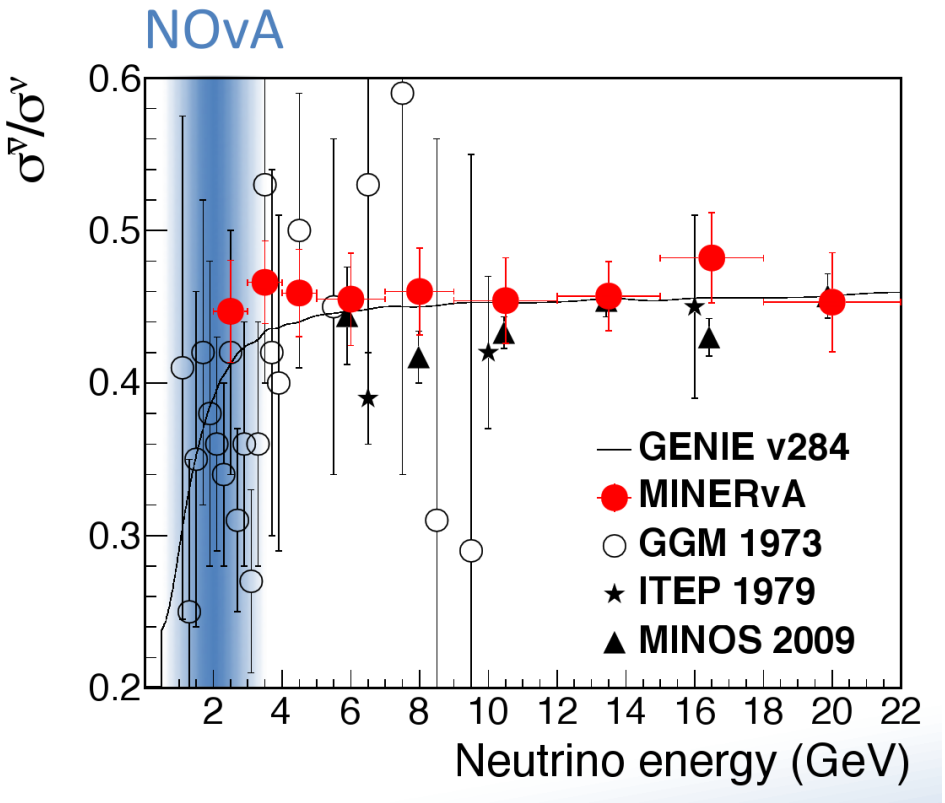
Backup

Backups

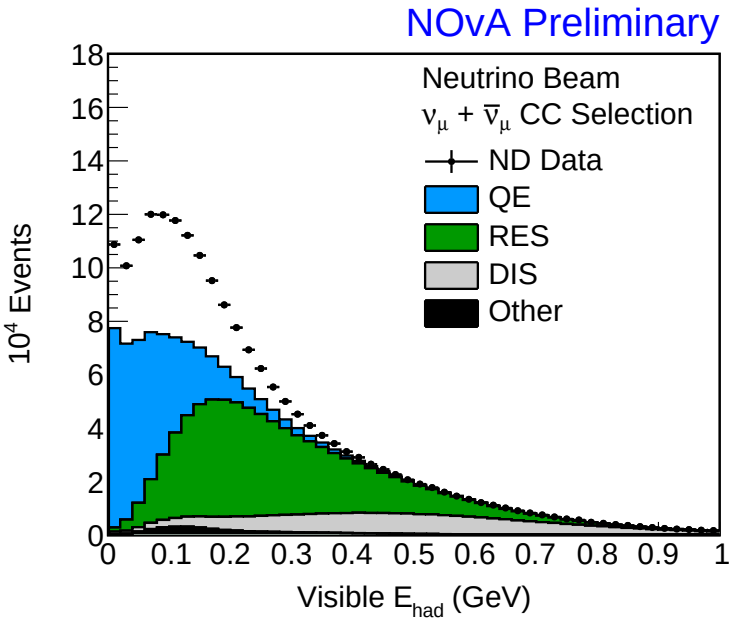
Delta sensitivity

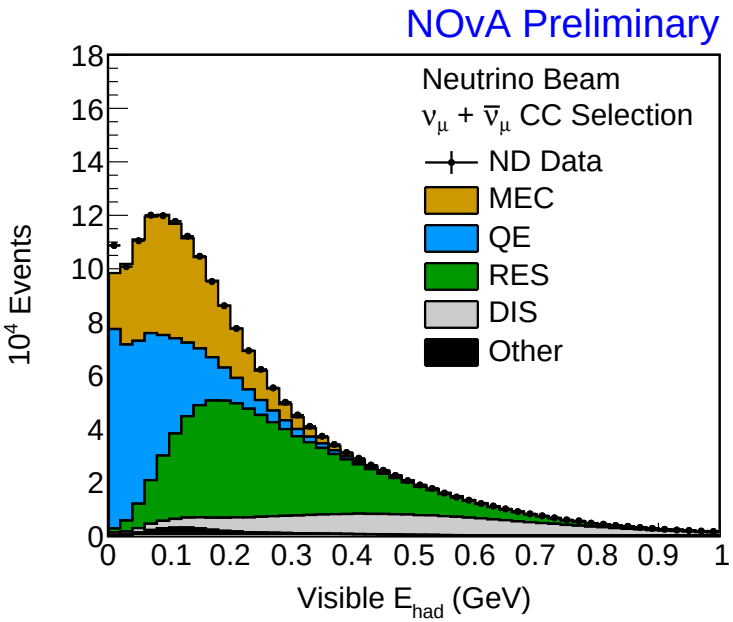


Wrong-sign cross section

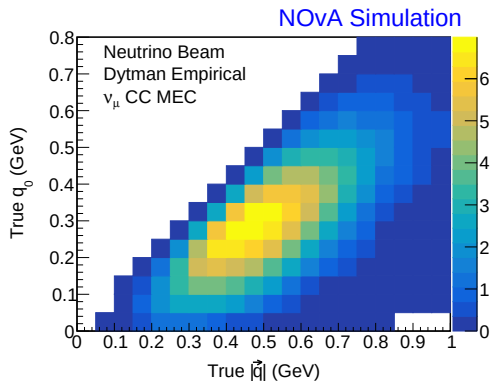


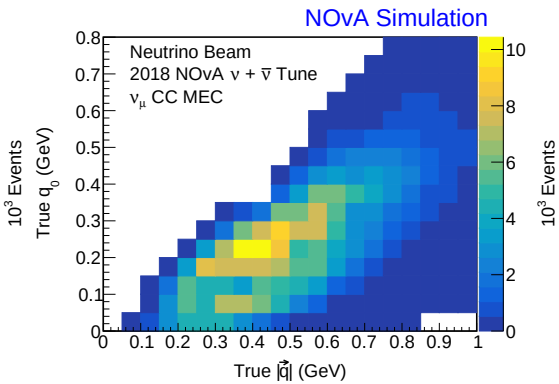
MEC Tuning





- We enable GENIE's empirical "meson exchange current" (MEC) model
- Accounts for interactions on correlated nucleon pairs leading to multi-nucleon knockout (two particle, two hole: 2p2h)
- All remaining ν_μ excess in data is used to scale MEC in 2D bins of $(q_0, |\vec{q}|)$

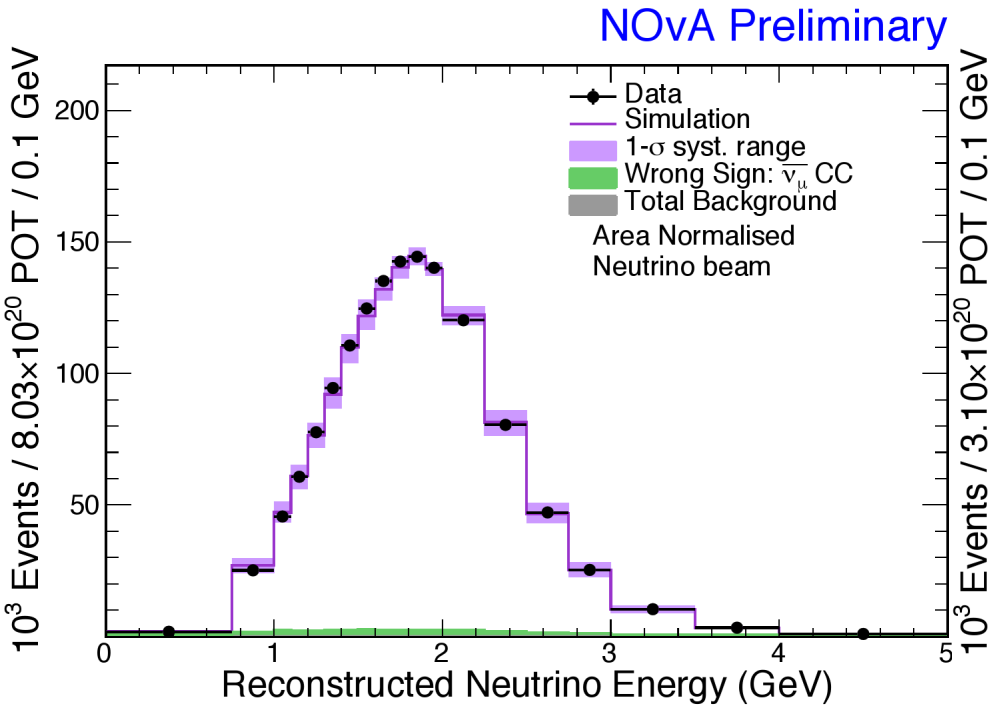


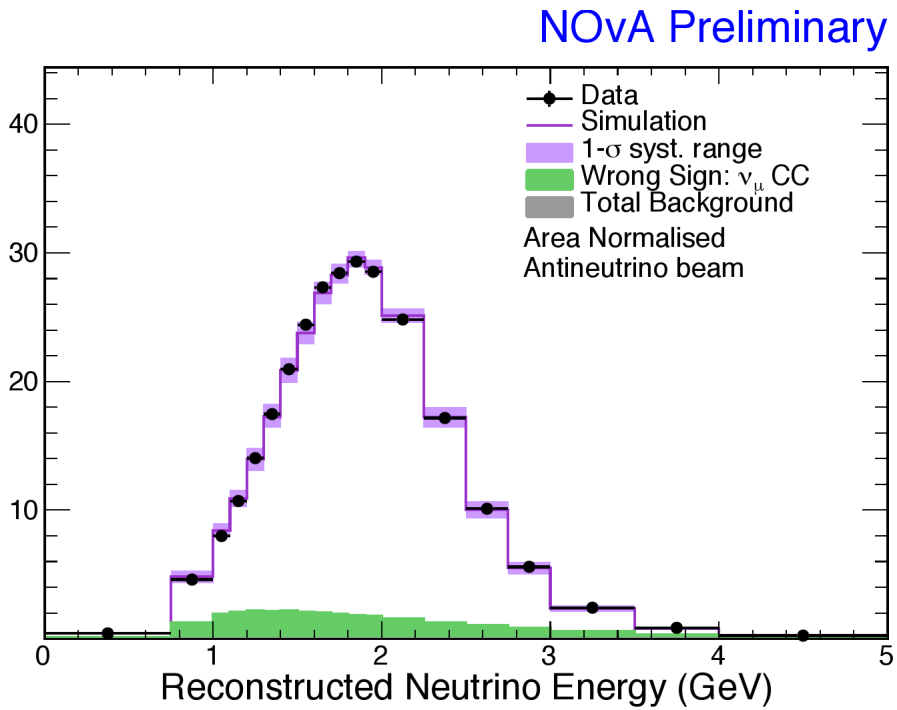


- By construction, tuned MC closely matches the data

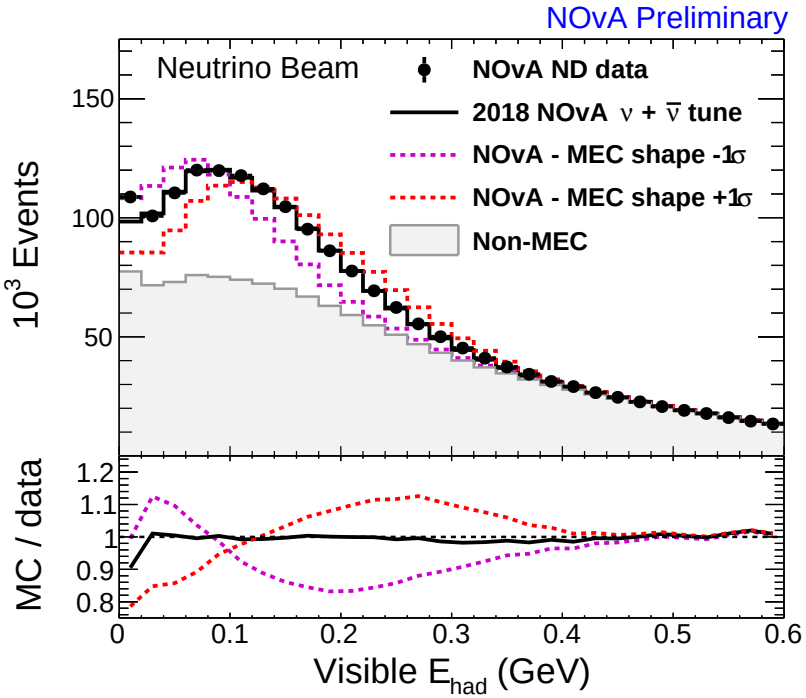
Near Detector Data/MC Agreement After Tune

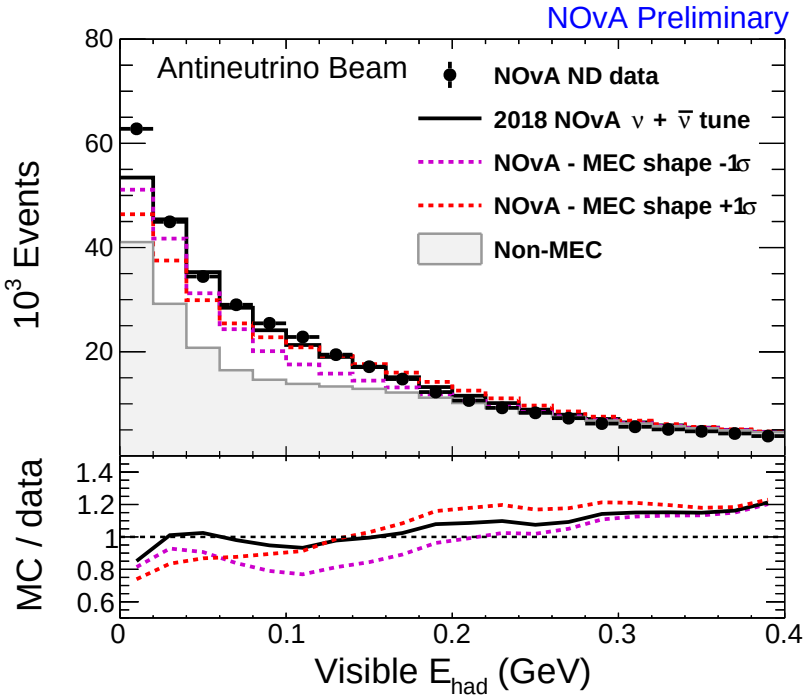
- After tune, data & MC agree up to 1.3% normalization difference for ν beam (0.5% for $\bar{\nu}$ beam)
- Shapes shown here — normalization difference removed for display





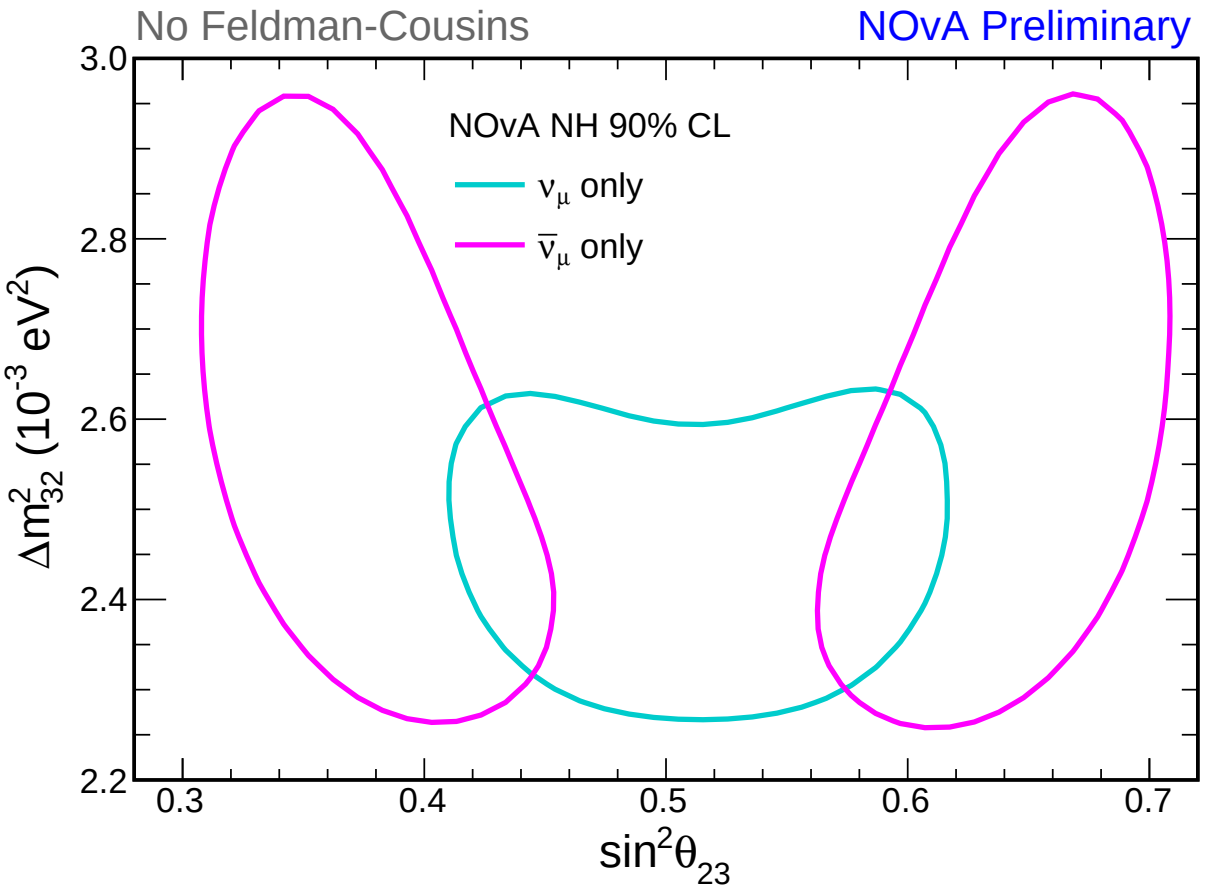
MEC Uncertainty





- Shift quasielastic and resonant events within their (correlated) errors and retune 2p2h to produce MEC error band

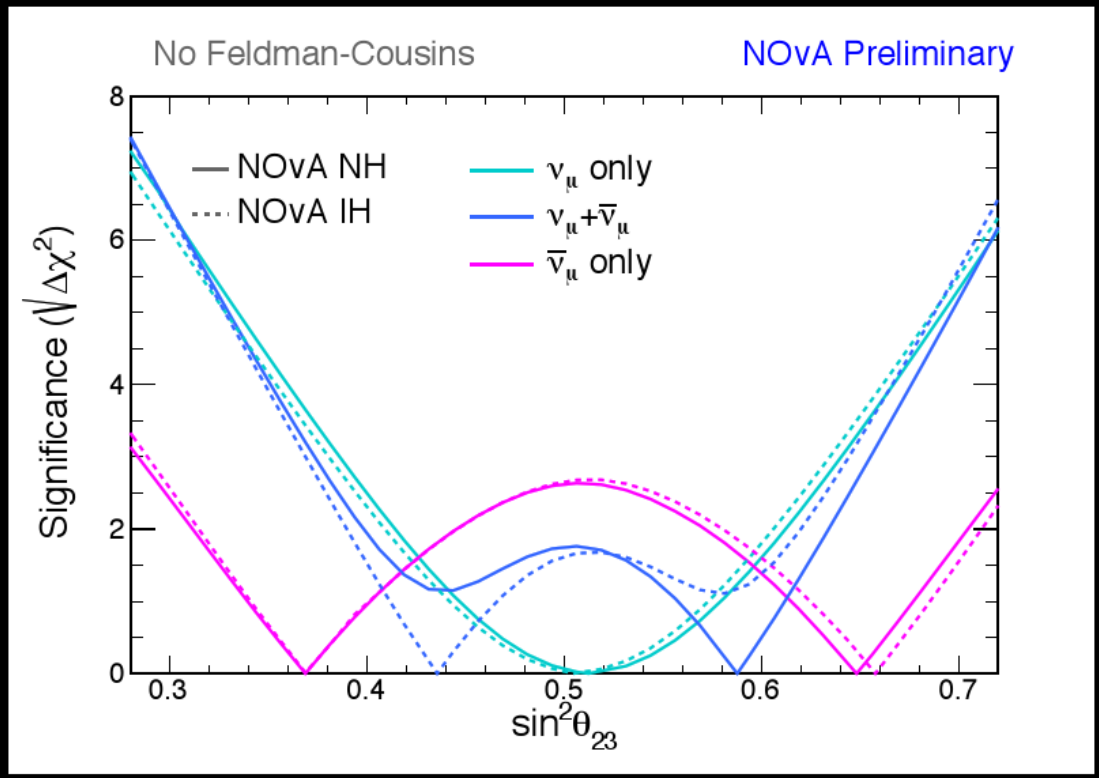
ν_μ Neutrinos and Antineutrinos fit separately



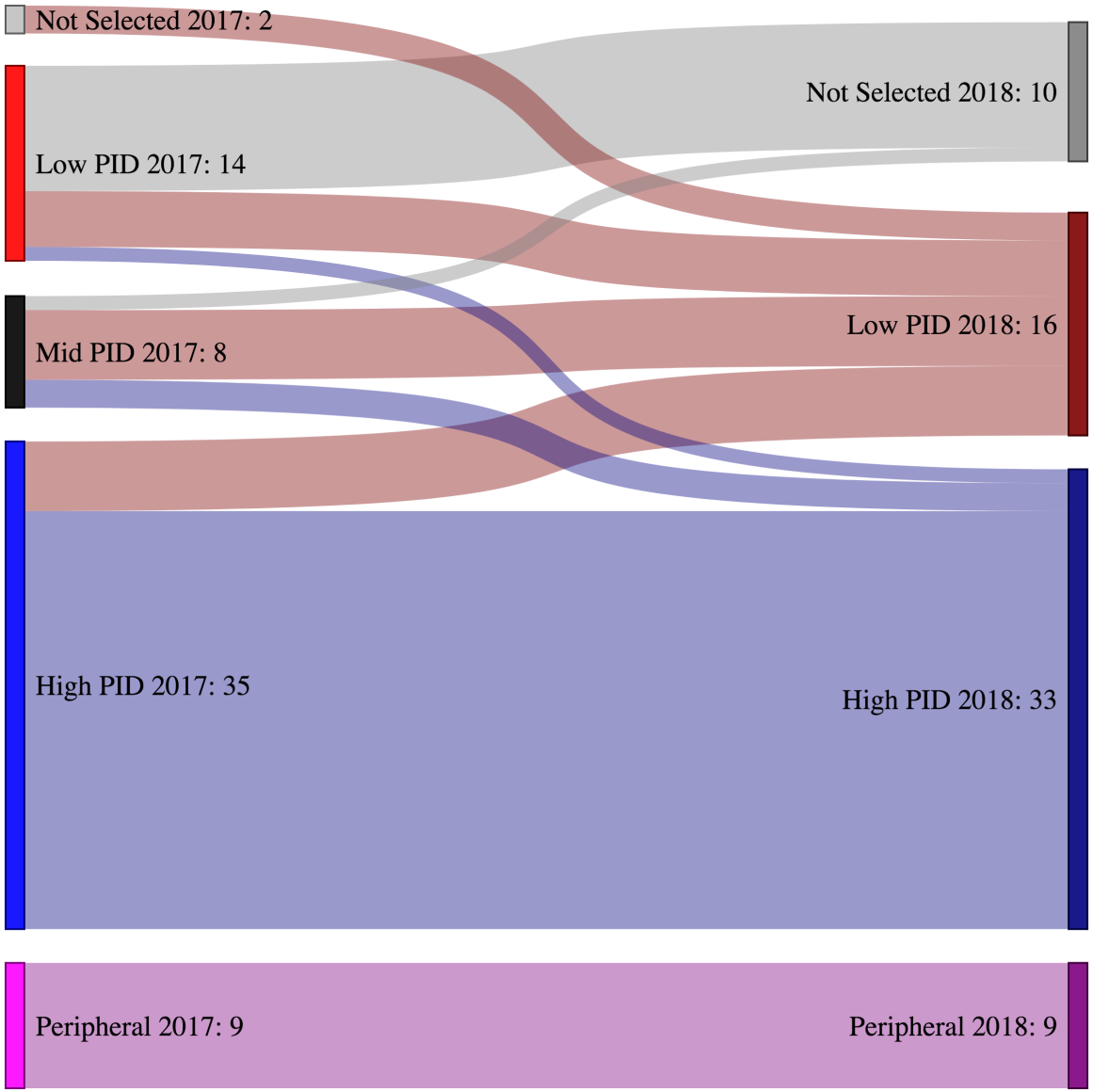
←

MUON NEUTRINO DISAPPEARANCE

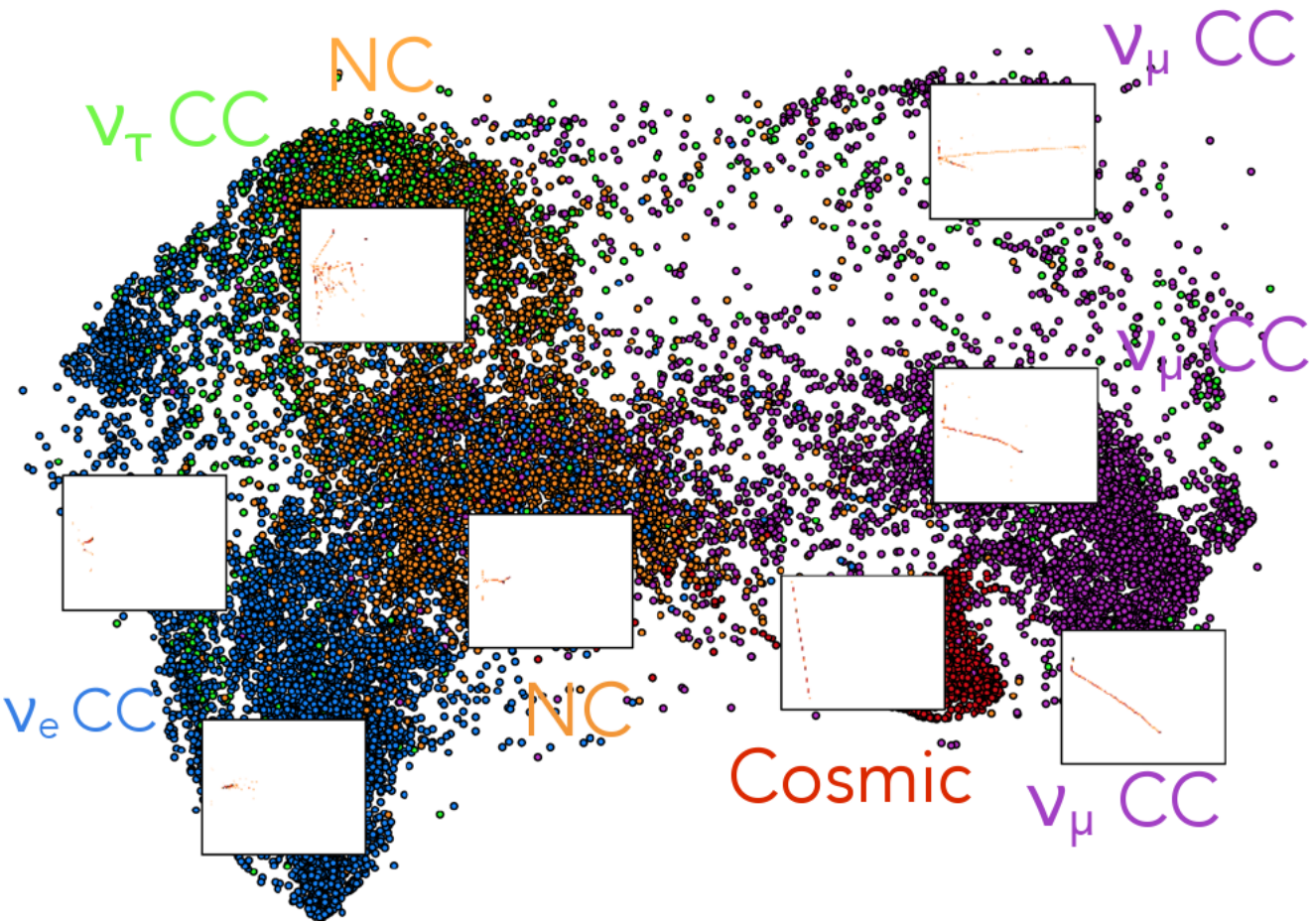
- The combined data of neutrino and antineutrino beams are fit assuming CPT invariance.
- We expect 126 at the best fit and observe 113 events in the neutrino beam mode and expect 52 at the best fit and observe 65 events in antineutrino beam mode.
- If fit separately, the antineutrino beam mode prefers a more non-maximal solution.
- Consistency with the combined fit oscillation parameters for the neutrino and antineutrino datasets is better than 4%. Combined result is consistent with previous result.



ν_e Event Flow 2017 to 2018



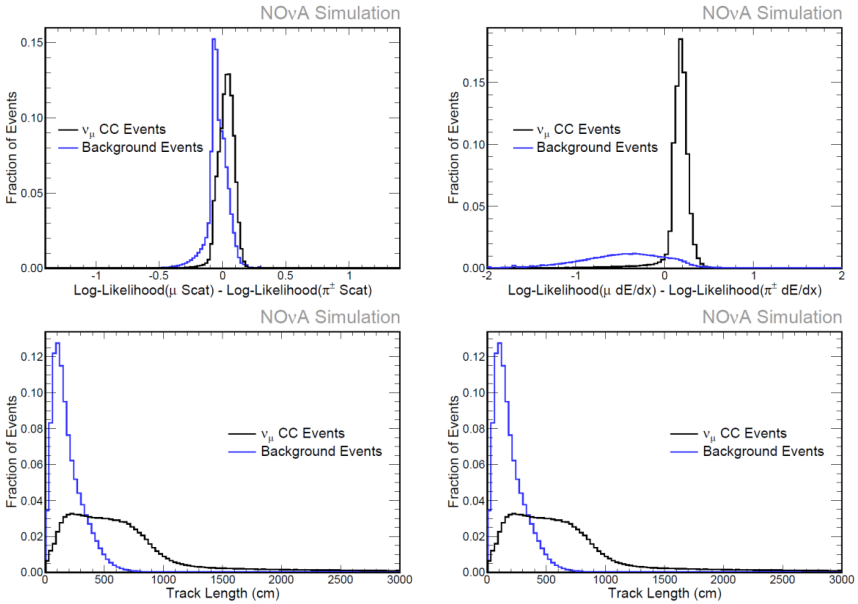
Updated Classifier for 2018

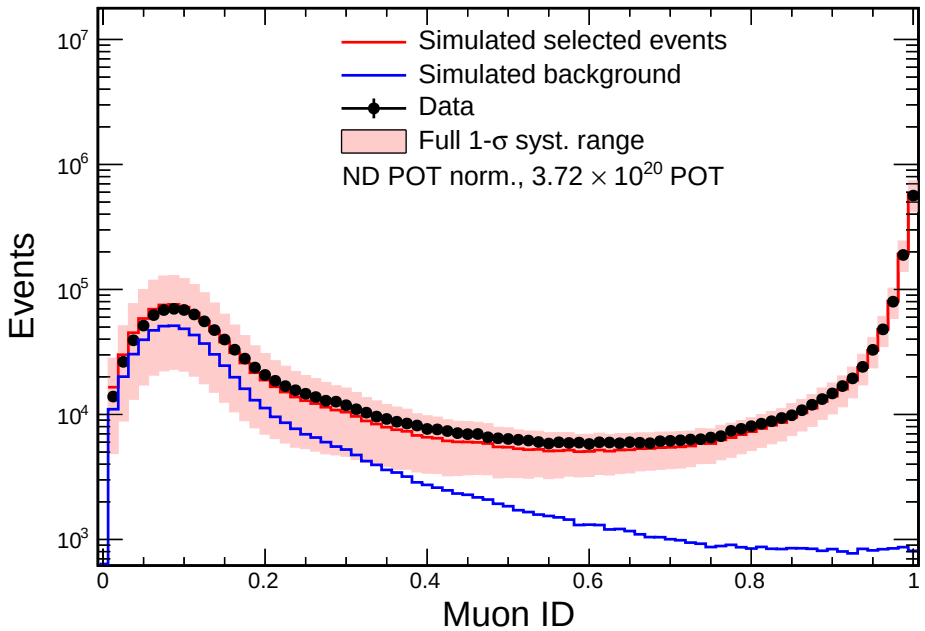


- Updated with improved tuning
- Optimized separately for neutrino and anti-neutrino beams
- Cosmic data included in training

Selection — ν_μ

- In selected ν_μ CC events, muon is selected using conventional kNN based on muon track length, scattering, fraction of planes with hadronic energy, $\mathrm{d}E/\mathrm{d}x$
- Events without a sufficiently muon-like track are rejected

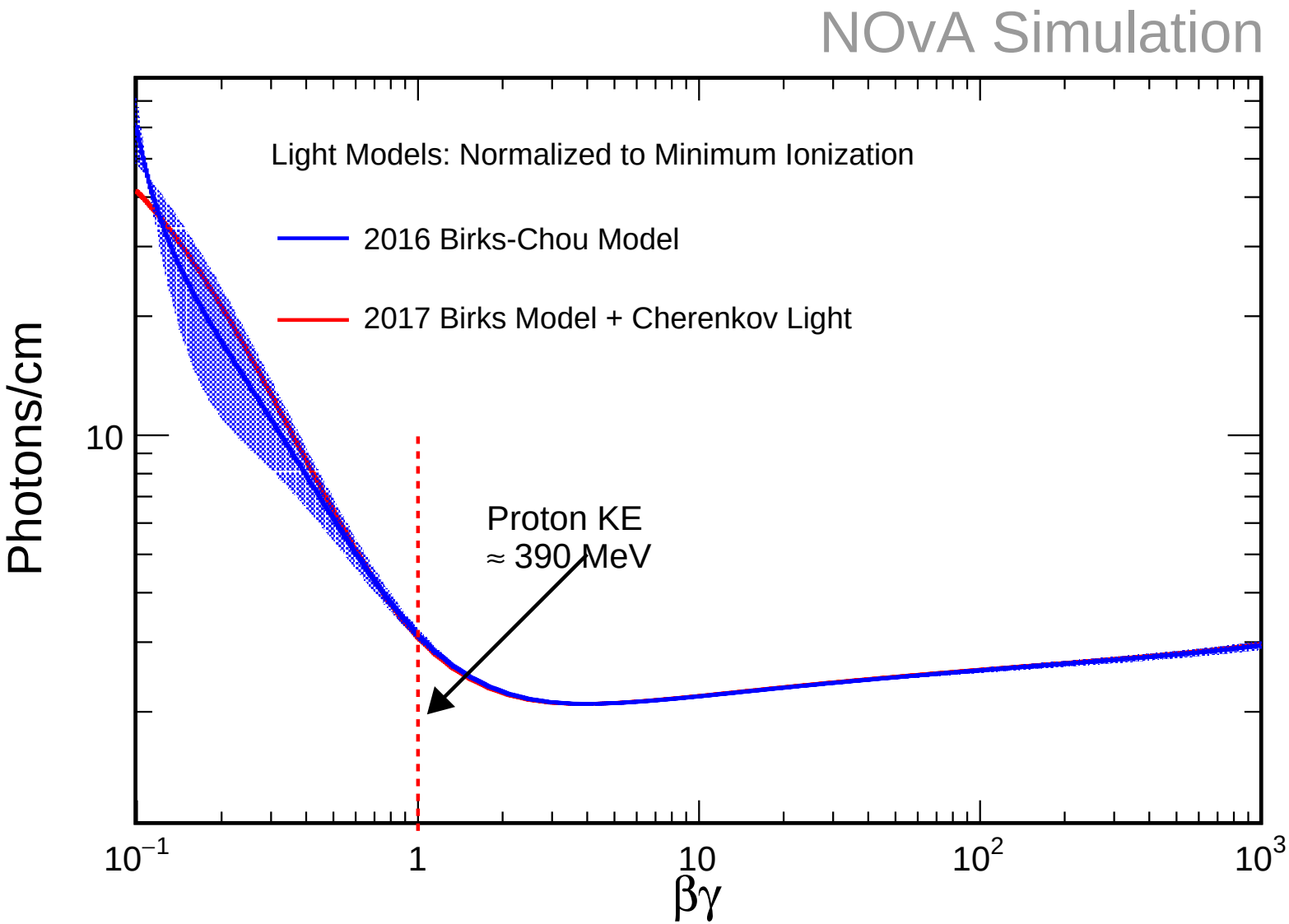




ν_e Selected events

Component	ν mode	$\bar{\nu}$ mode
Signal	43.97	10.59
Osc. Wrong Sign Bkg.	0.66	1.13
Total Beam Bkg.	11.07	3.48
Cosmic Bkg.	3.33	0.71
Total Prediction	59.04	15.90
Beam ν_e	6.85	2.57
NC	3.21	0.67
ν_μ	0.63	0.07
ν_τ	0.37	0.15
Rock	0.33	0.06

Birks, Cherenkov changes



Backup

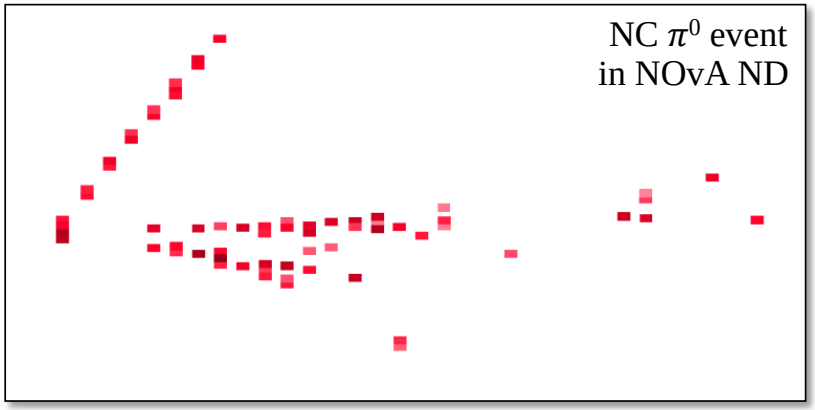
Checking energy scale

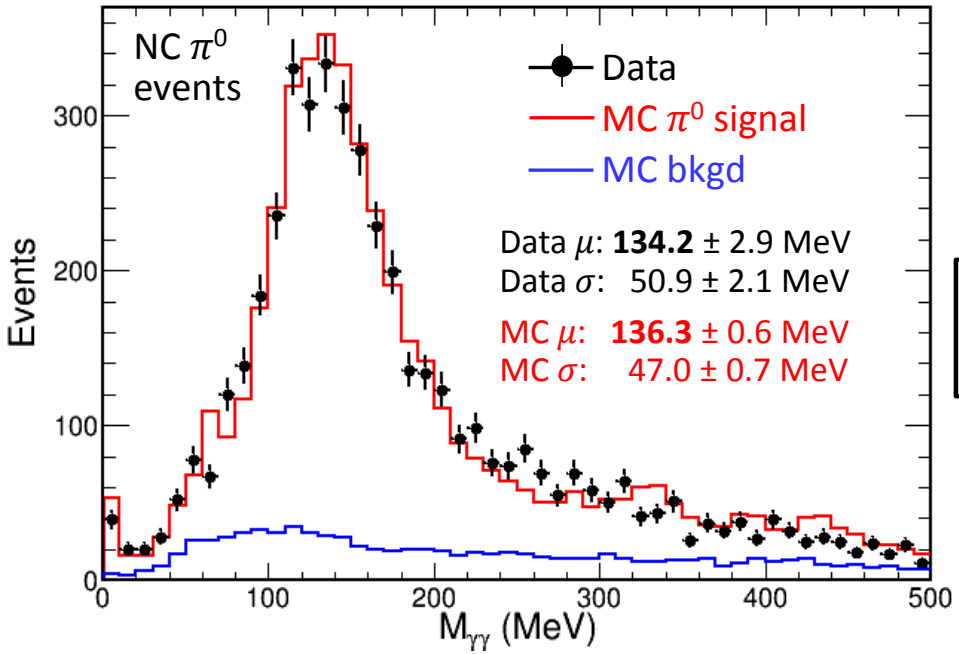
μ dE/dx , various positions/angles

Michel electron energy (μ decay)

bremsstrahlung energy

hadronic shower hits





π^0 invariant mass

All agree within ±5%

Backup

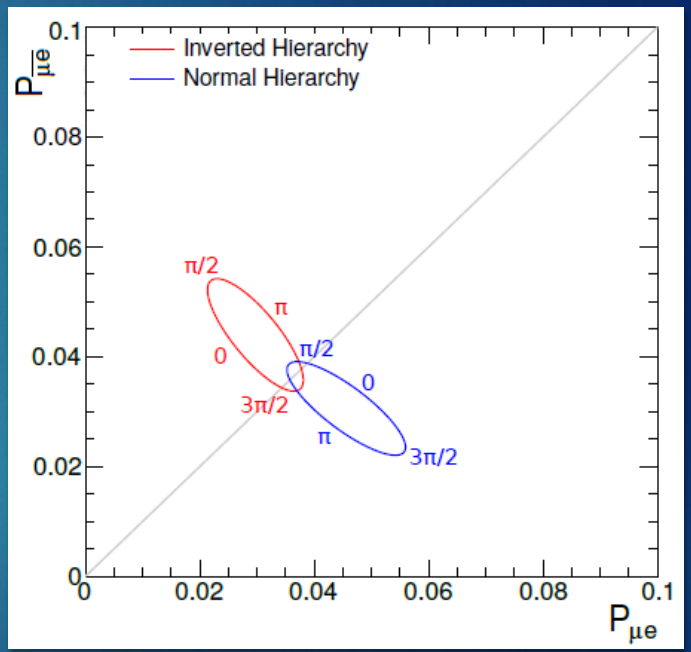
ν_e Appearance

$$P(\nu_\mu \to \nu_e) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2(\Delta_{31} - aL)}{(\Delta_{31} - aL)^2} \Delta_{31}^2$$
$$\alpha \sin 2\theta_{13} \cos\delta \frac{\sin(aL)}{(aL)} \frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)} \cos\Delta_{32} -$$
$$\alpha \sin 2\theta_{13} \sin\delta \frac{\sin(aL)}{(aL)} \frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)} \sin\Delta_{32}$$

$$\Delta_{ij} \equiv \frac{1.27\Delta m^2_{ij}[\mathrm{eV}^2]L[\mathrm{km}]}{E[\mathrm{GeV}]}$$
$$a = G_F N_e \sqrt{2} \simeq (4000\ \mathrm{km})^{-1}$$

- Depends simultaneously on θ_{13}, θ_{23}, δ_{CP}, $\mathrm{sign}(\Delta m^2_{31})$
- $sin^2 2\theta_{13}$=0.095 → most ν_μ go to ν_τ
- Look for deviations due to hierarchy (matter effects) and CP-violation

- NOvA measures $P(\nu_\mu \to \nu_e)$ and $P(\bar{\nu}_\mu \to \bar{\nu}_e)$ at 2GeV, different dependence on $sign(\Delta m^2_{32})$ and δ_{CP}



Backup

ν_e Appearance

16

$$P(\nu_\mu \to \nu_e) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2(\Delta_{31} - aL)}{(\Delta_{31} - aL)^2} \Delta_{31}^2$$
$$\alpha \sin 2\theta_{13} \cos\delta \frac{\sin(aL)}{(aL)} \frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)} \cos\Delta_{32} -$$
$$\alpha \sin 2\theta_{13} \sin\delta \frac{\sin(aL)}{(aL)} \frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)} \sin\Delta_{32}$$

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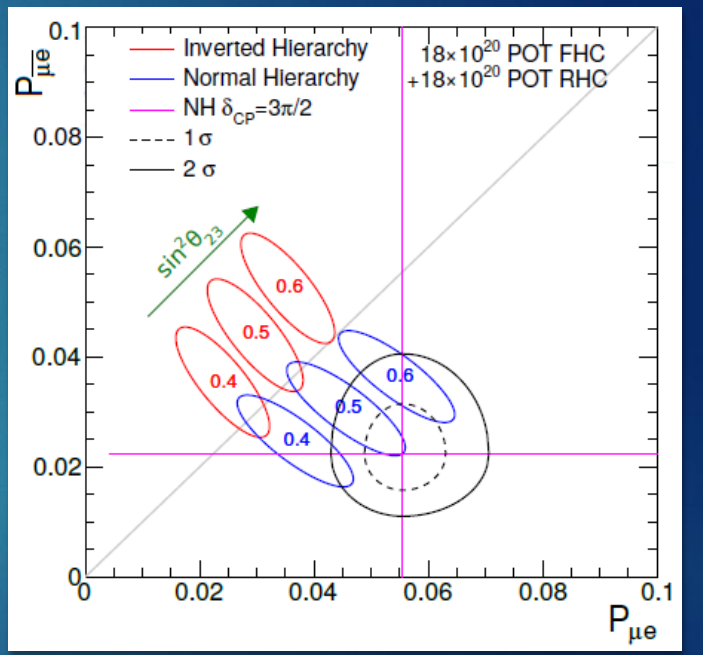
- NOvA measures $P(\nu_\mu \to \nu_e)$ and $P(\bar{\nu}_\mu \to \bar{\nu}_e)$ at 2GeV, different dependence on $sign(\Delta m^2_{32})$ and δ_{CP}
- $\mathbf{P} \propto sin^2\ \theta_{23}$
- Constrain a space region



Backup

NuMI beam

25

- Beam performance
- 14mrad Off-Axis:
  - Neutrino energy spectrum peaked at 2GeV, width~20%