Physics of fundamental Symmetries and Interactions - PSI2016

New Results from NOvA

Giulia Brunetti on behalf of the NOvA Collaboration

Fermilab

NOvA

Neutrinos

- Neutrino mix: flavors eigenstates are linear combinations of mass eigenstate

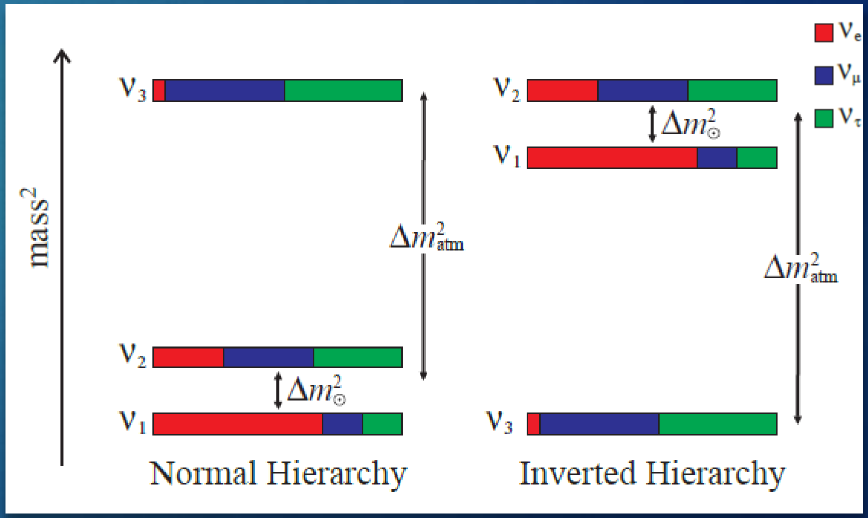
$$|\nu_\alpha\rangle = \sum_{k=1}^{n} U_{\alpha k} |\nu_k\rangle \quad (\alpha = e, \mu, \tau)$$

- Non-zero probability of detecting a different neutrino flavor than that produced at the source
  - depends on: squared mass difference, mixing angles, CP-violating phase, hierarchy….
- Mixing matrix for the three-flavor case:

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

$\theta_{23} \sim 45°$ $\theta_{13} = 8.5°$ $\theta_{12} = 33.5°$

$\Delta m^2_{23} \sim \pm 2.5 \times 10^{-3} eV^2$ δ_{CP}? $\Delta m^2_{21} = +7.5 \times 10^{-5} eV^2$



Neutrinos

- Open questions:
  - Maximal mixing in the atmospheric sector? (θ_{23})
  - CP-violation? (δ_{CP}, $P(\nu_\mu)$ vs $P(\bar{\nu}_\mu)$, matter/antimatter asymmetry in the universe)
  - Hierarchy? ($sign(\Delta m^2_{23})$, matter effects)
  - Majorana or Dirac? (IH & no $0\nu\beta\beta$ decays)
  - Absolute masses?

200+ collaborators
41 institutions
7 countries

- NOvA (NuMI Off-Axis ν_e Appearance) Experiment
  - designed to answer the next generation of ν questions: tuned for ν_e appearance in an almost pure ν_μ beam

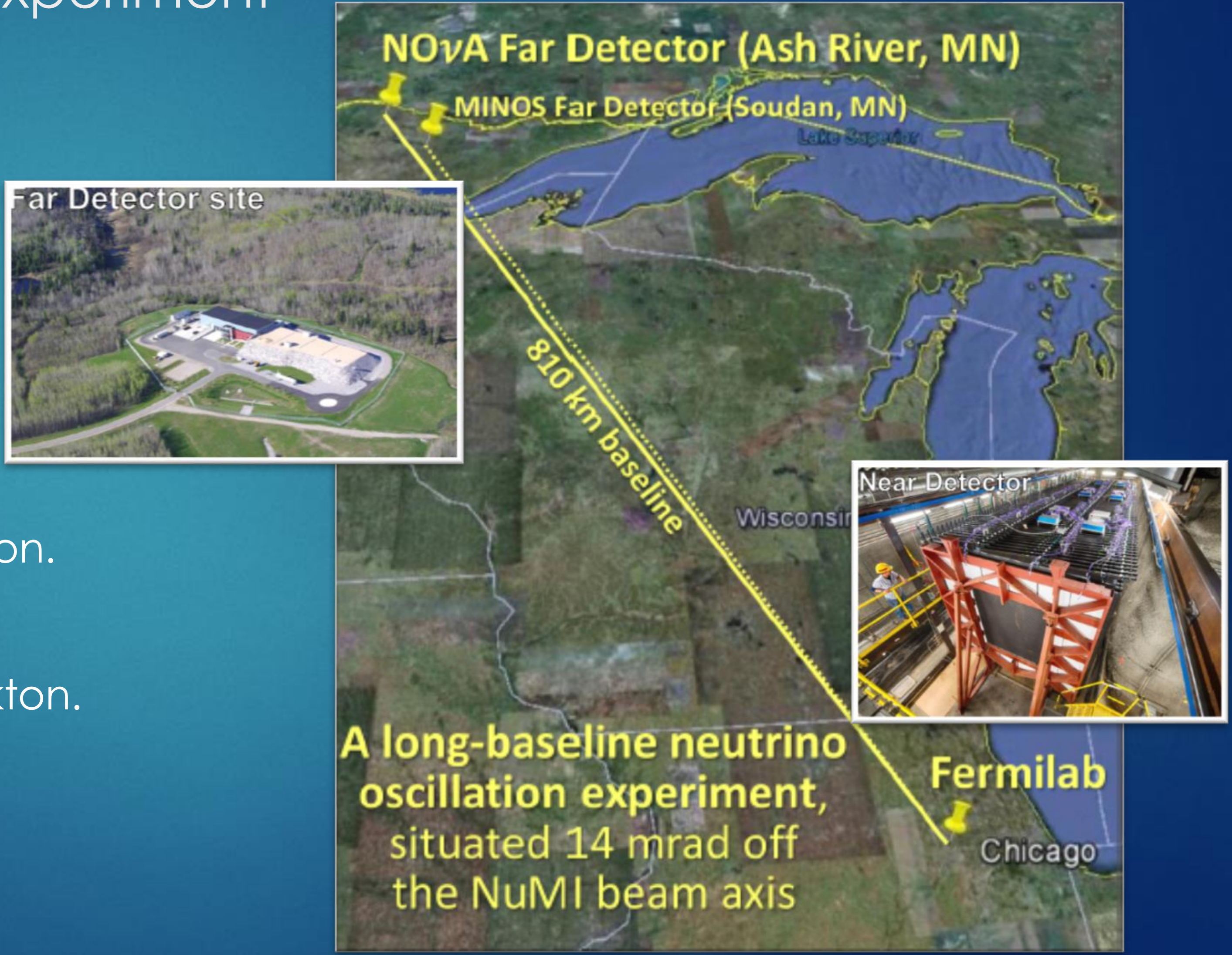
NOvA

NuMI Off-Axis ν_e Appearance Experiment

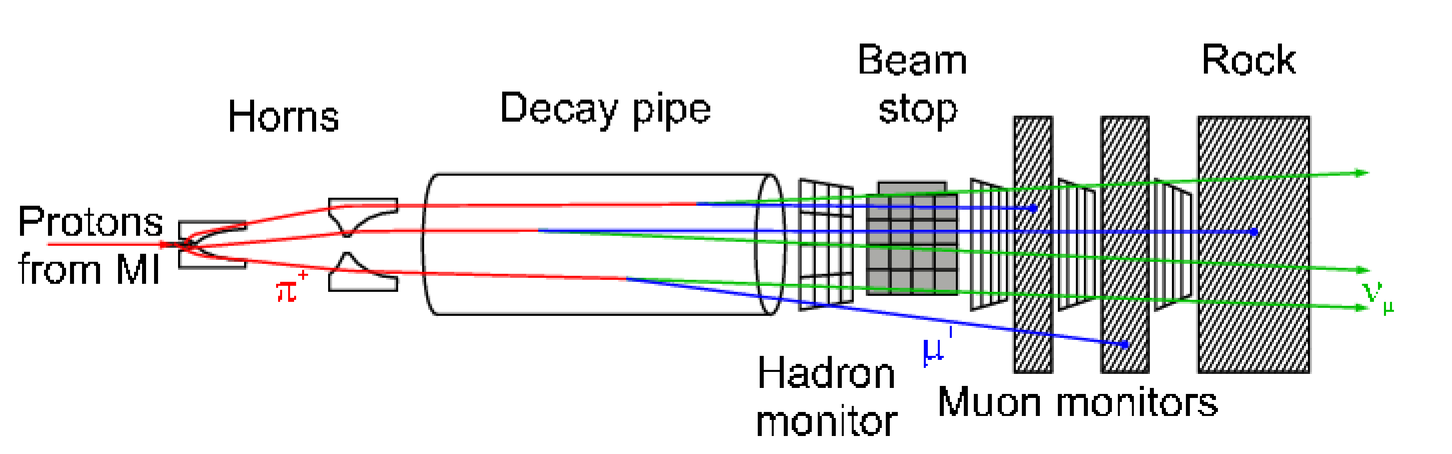
- NOvA is a long baseline (810 km), off-axis (14.6 mrad) neutrino oscillation experiment
- NuMI beam at Fermilab
- Energy peak @ 2 GeV
- 2 functionally identical detectors:
  - ND underground at Fermilab. 290-ton.

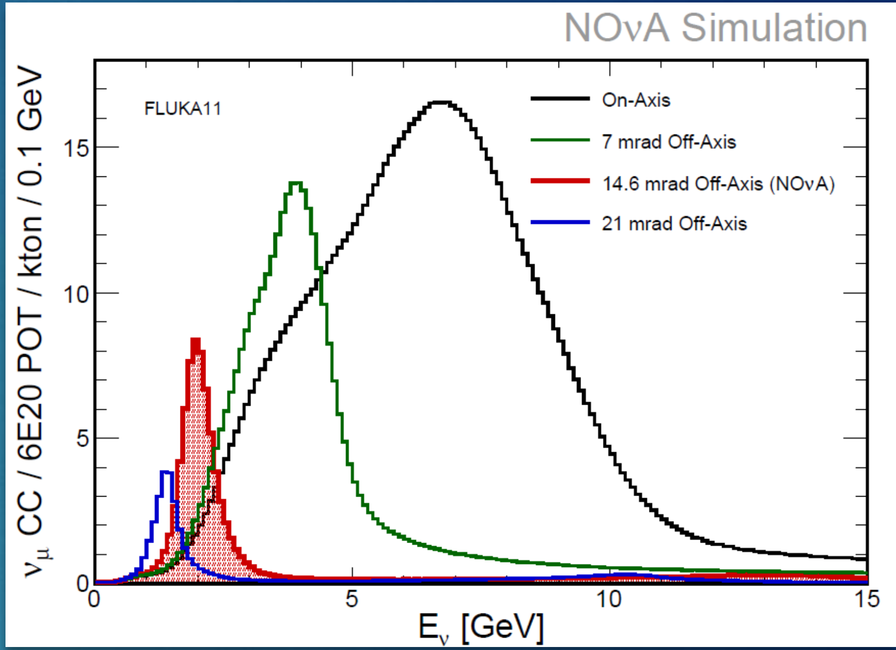
  Used to predict event rate at the FD
  - FD on surface in Ash River, MN. 14-kton.

  To look for oscillations



The NuMI beam

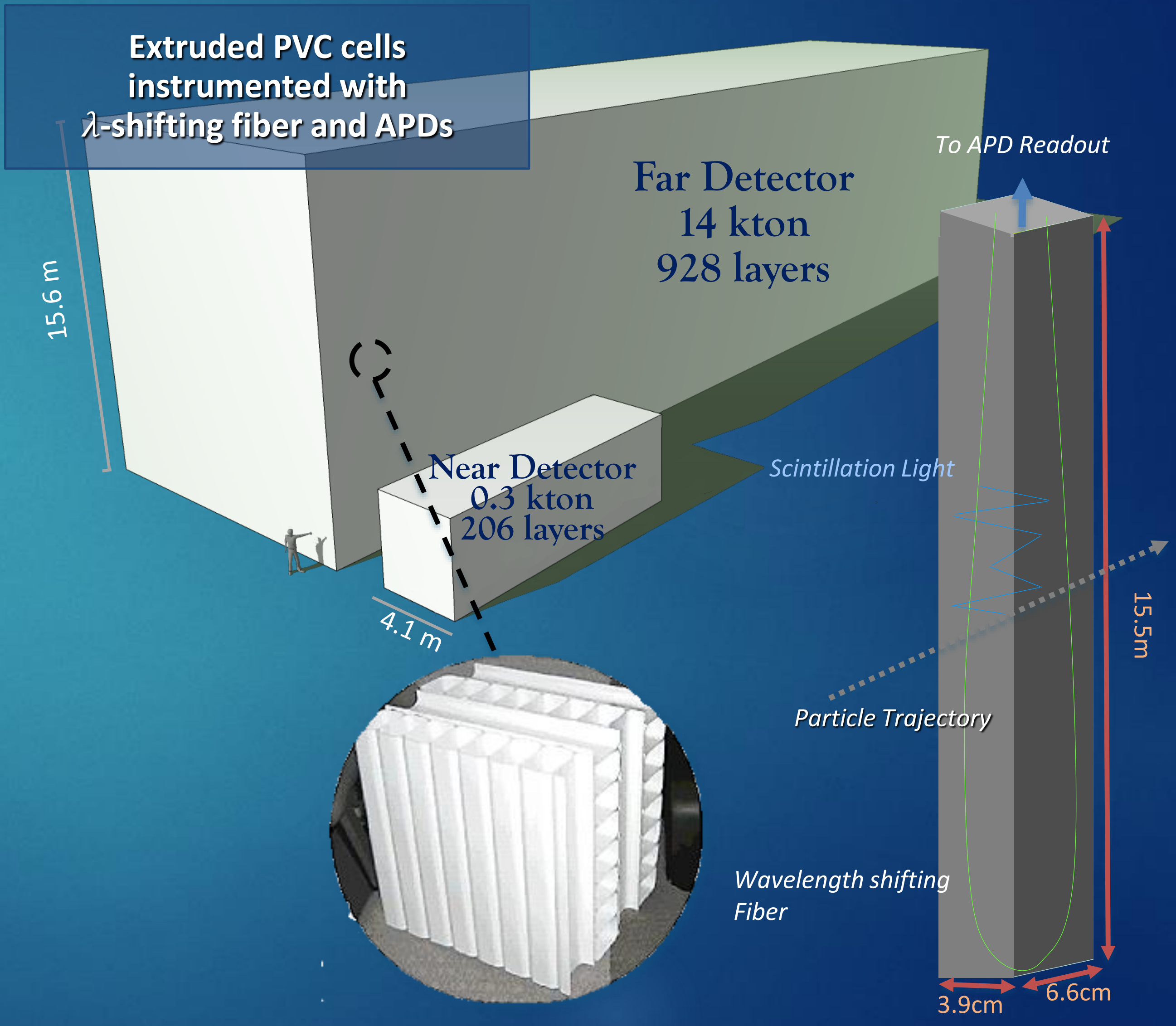




- 120 GeV protons onto a graphite target
- Secondary mesons charge-selected and focused by two magnets
- Pions decay into neutrinos/antineutrinos
- 6.05 10^{20} POT in 14 kton equivalent detector
- Currently running at 560 kW, achieved 700 kW design goal in tests on June13

NOvA Detectors

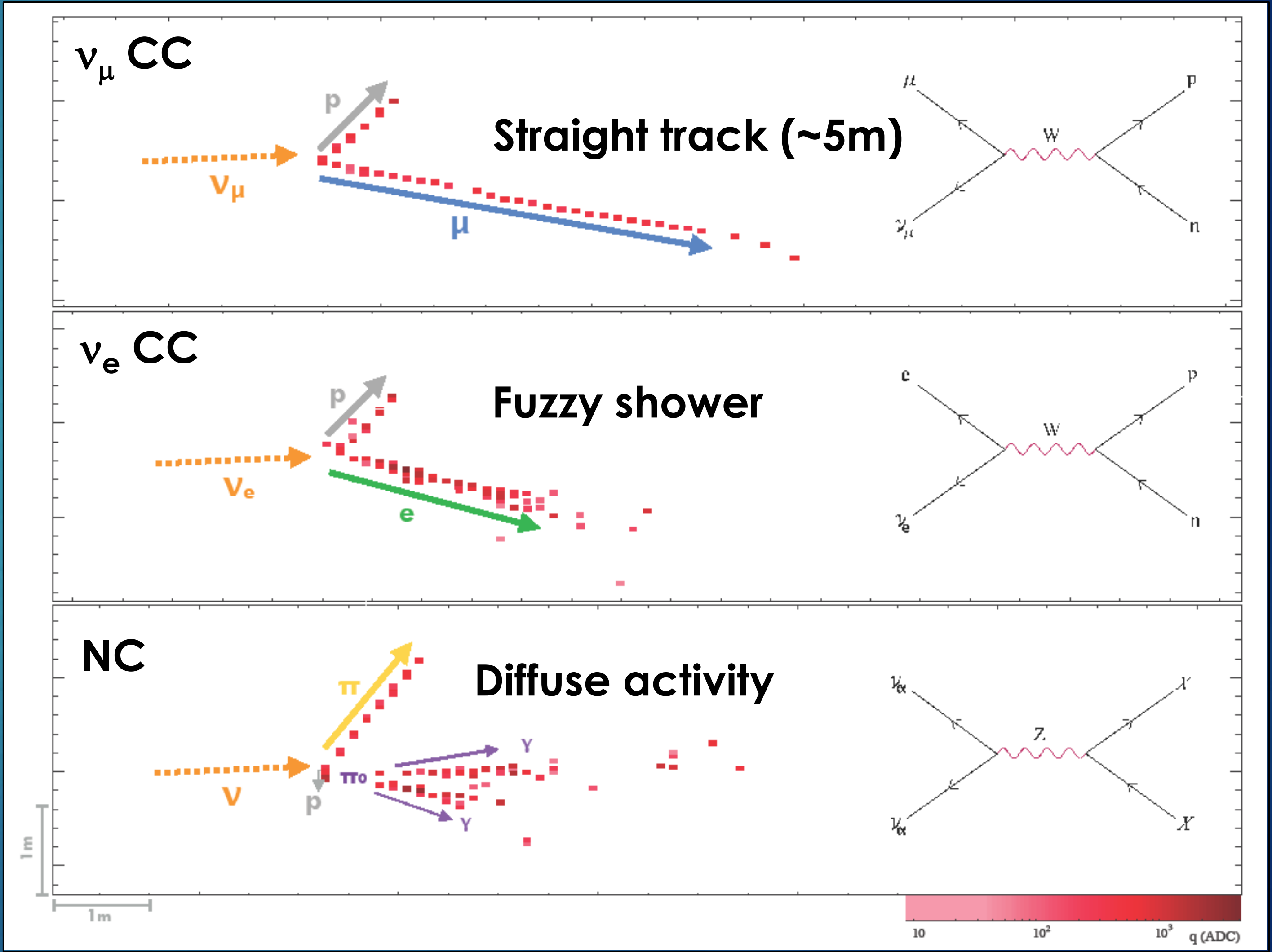
- Functionally identical, PVC cells filled with 10.2M Liters liquid scintillator
- Low-Z, 65% active volume, DAQ runs without deadtime (beam trigger, cosmic calibration samples, SNEWS, exotics)
- Read-out using WLS to APDs
- Cells organized in horizontal and vertical planes
- FD is 14 kton, ND is 0.3 kton



NOvA Physics

- **3-flavor oscillation analyses**
  - **DISAPPEARANCE: ν_μ ($\bar{\nu}_\mu$)→ ν_μ ($\bar{\nu}_\mu$)**
    - Δm^2_{23}, $\sin^2 2\theta_{23}$
  - **APPEARANCE: ν_μ ($\bar{\nu}_\mu$) → ν_e ($\bar{\nu}_e$)**
    - θ_{13}, θ_{23}, δ_{CP}, mass hierarchy
    - Matter effects over 810 km → ±30%

Event Topologies



- Good granularity
- X0 =38cm (6 cells depths, 10 cells widths)

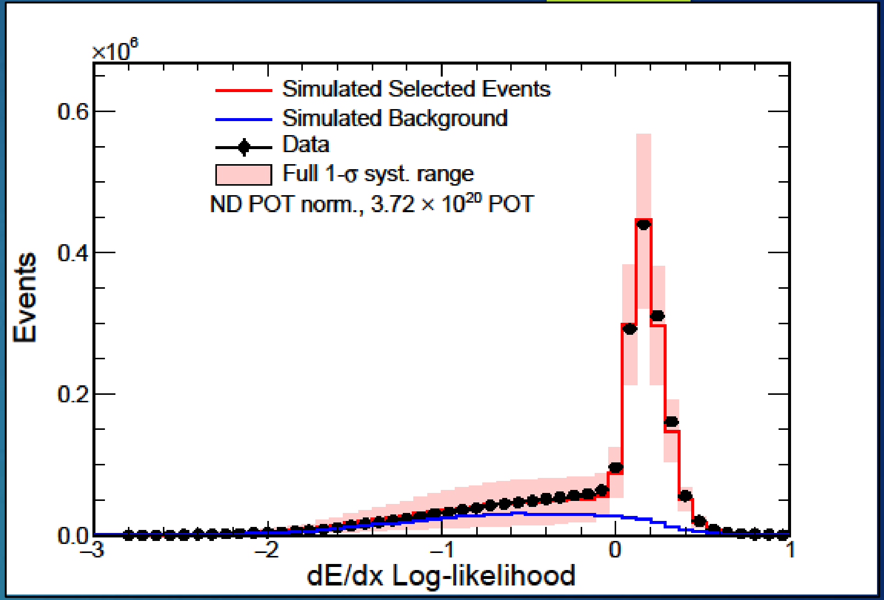
ν_μ Disappearance

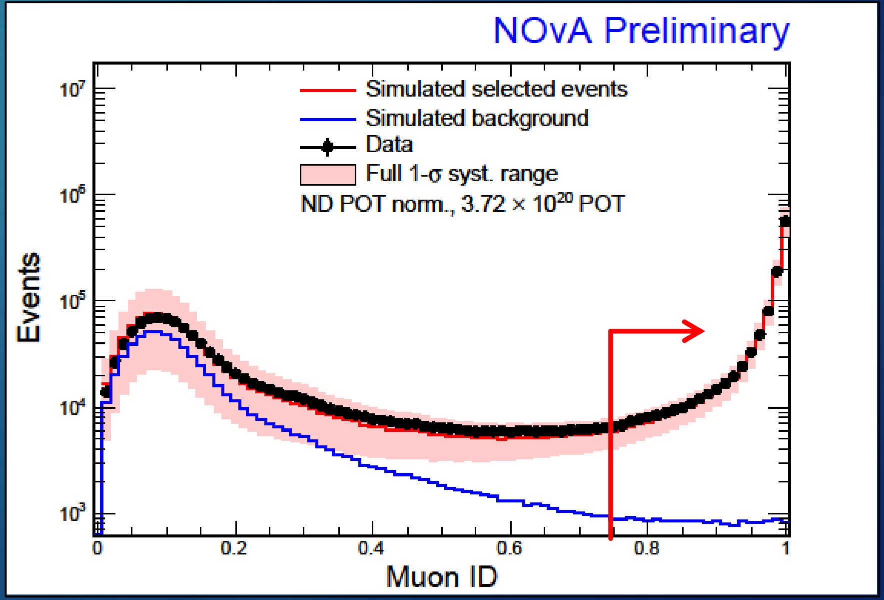
- The principle:
  - Select ν_μ CC sample: events with long tracks and distinctive dE/dx
  - Extrapolation of the ND spectrum to the FD and measurement of the deficit
  - 2-flavor oscillation approximation works well in this case:

$$P_{\mu\mu} \sim 1 - sin^2 2\boldsymbol{\theta_{23}} sin^2\left(\frac{\Delta m^2_{23} L}{4E}\right)$$

θ_{23} ~45°→ at the oscillation max almost all ν_μ disappear

- NC and cosmic background suppression, containment cuts to remove events with activity close to the detector walls
- ν_μ ID: Multivariate kNN classifier using 4 variables:
  - Track length
  - dE/dx
  - Scattering along the track
  - Track only fraction of planes
- 81% selection efficiency for signal with 95% purity

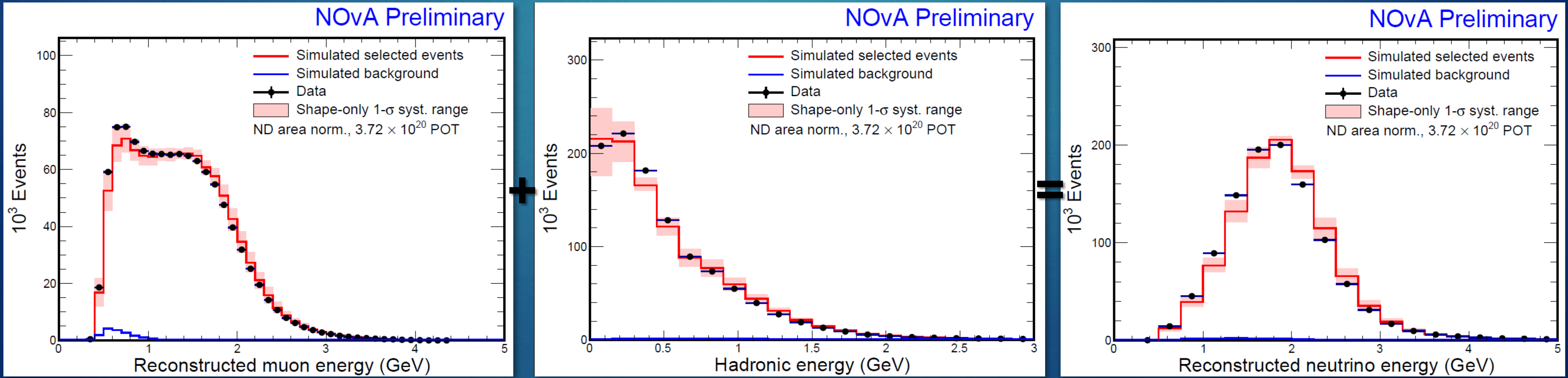




ν_μ Disappearance

- **ν_μ ND events**
  - Hadronic energy scale uncertainty from 14% to 5% with the addition of MEC events to the simulation (w.r.t. NOvA 2015 results)
  - ND reconstructed energy spectrum unfolded and extrapolated to FD using Far/Near true ratio for prediction

Eν = Eμ (L track) + E_{had} (7% res)

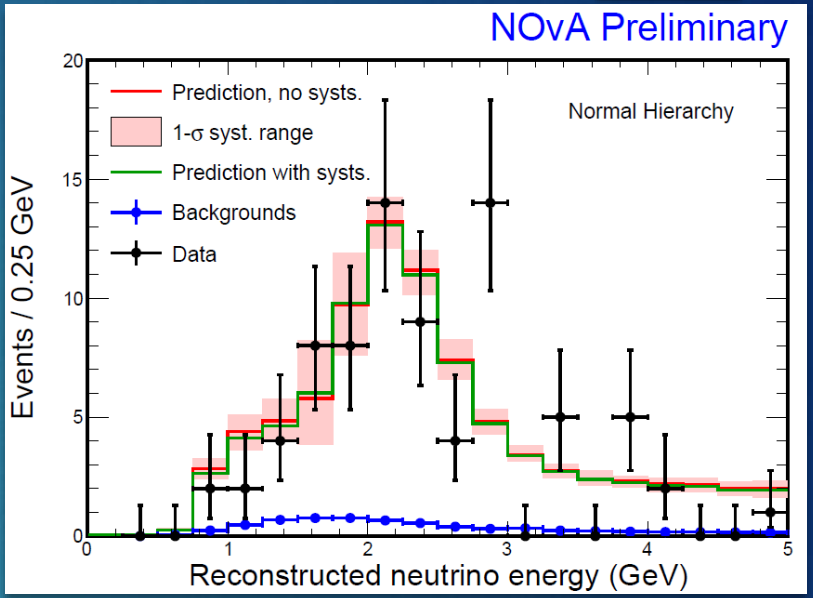


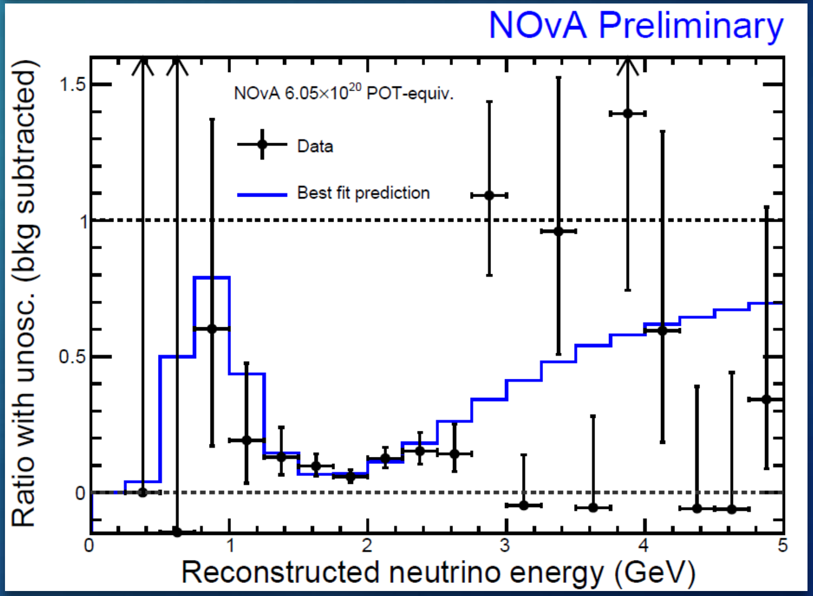
ν_μ Disappearance

- ν_μ FD events: **78** events observed
  - **No oscillation prediction: 473±30**
  - Best oscillation fit: 82 events
  - Beam BG: 3.7, Cosmics: 2.9

$\chi 2/NDF=41.6/17$

driven by fluctuations in the tail, no pull in oscillation fit





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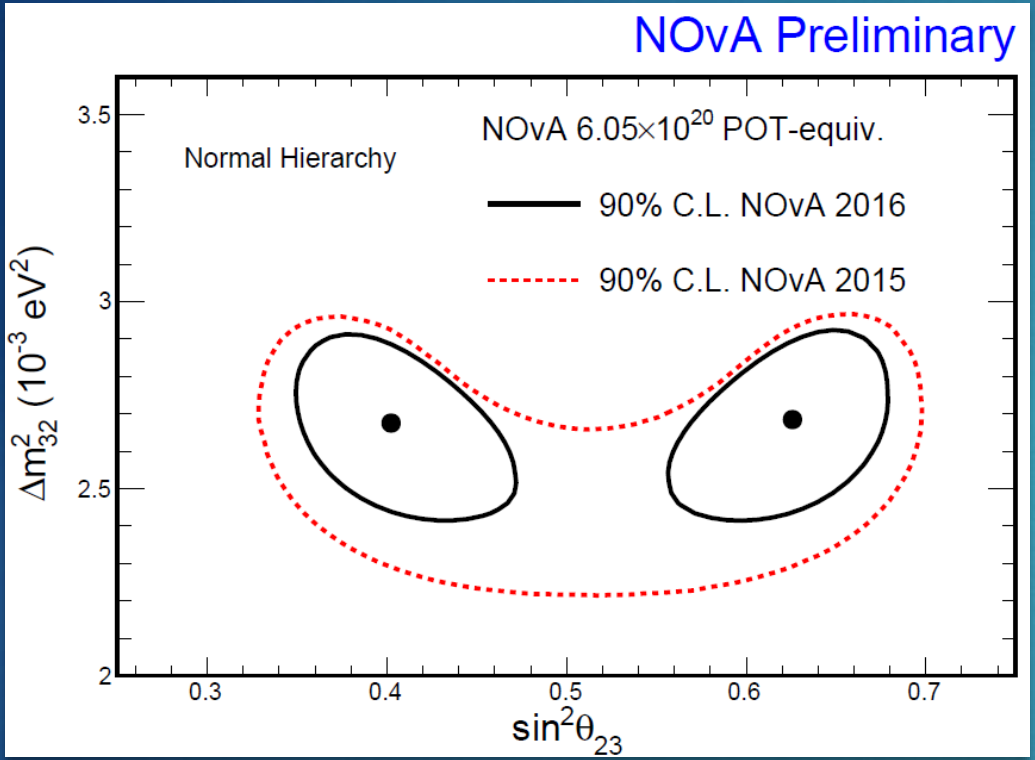


- Our best fit (in NH):

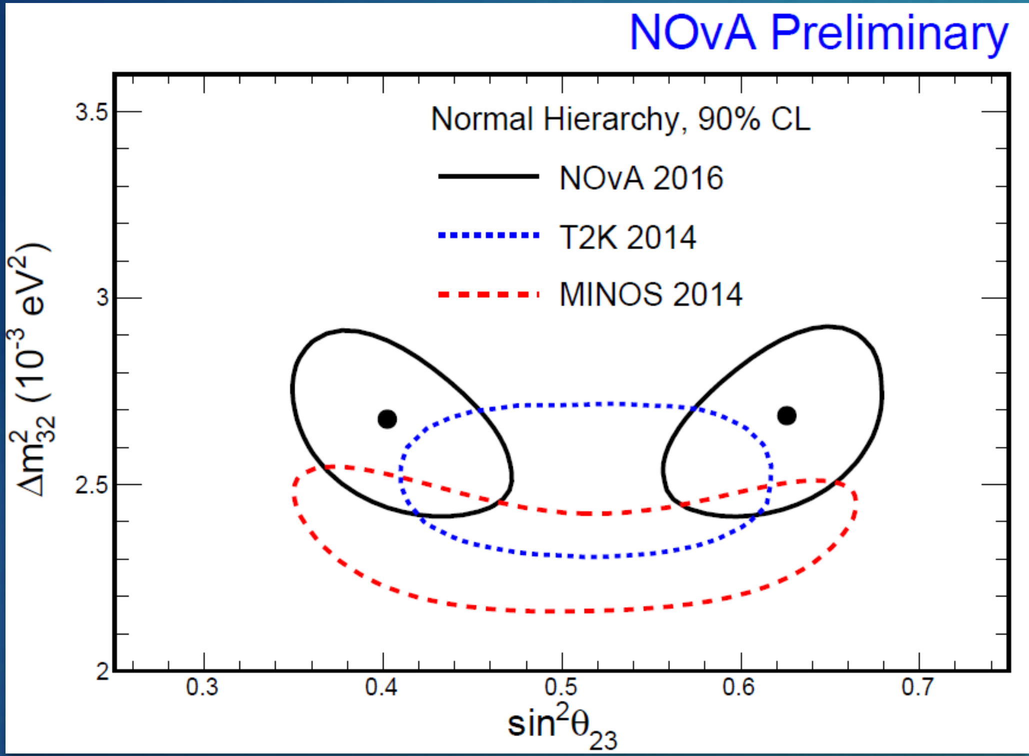
  $|\Delta m^2_{32}| = 2.67 \pm 0.12 \cdot 10^{-3}\ eV^2$

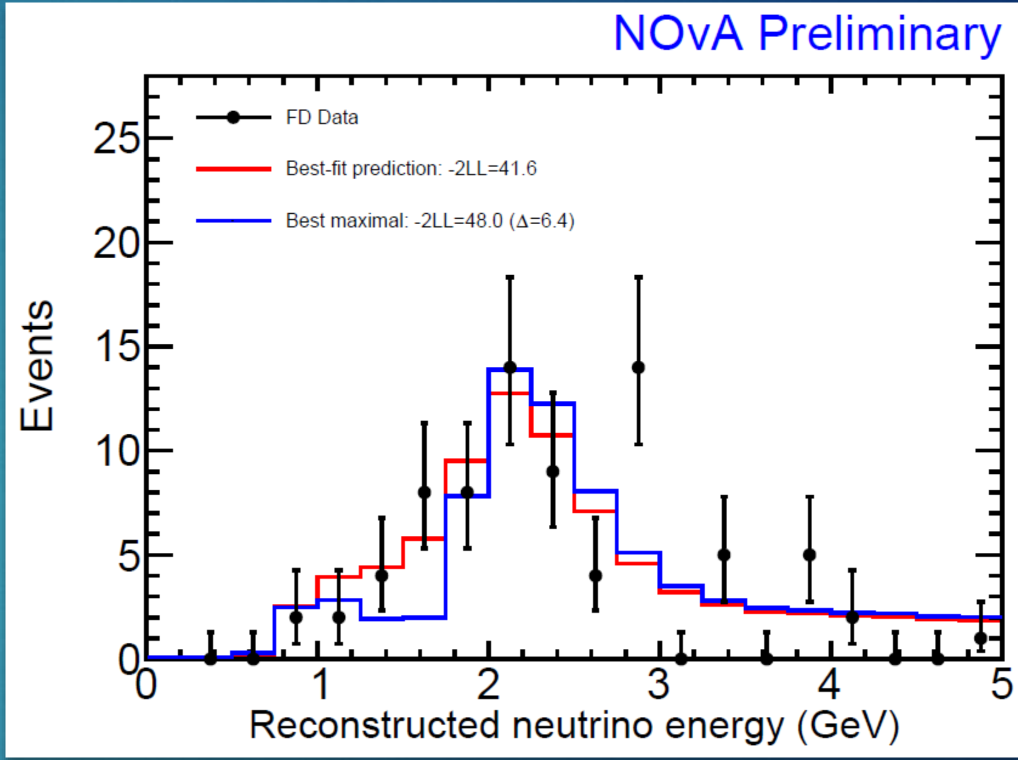
  $\sin^2\theta_{23} = 0.40^{+0.03}_{-0.02}\ (0.63^{+0.02}_{-0.03})$

- Fit for Δm^2 and $\sin^2\theta_{23}$
- Dominant systematic effects included in fit:
  - Normalization
  - NC background
  - Flux
  - Muon and hadronic energy scale
  - Cross section
  - Detector response and noise

Maximal mixing (θ_{23} =45°) excluded at 2.5σ

ν_μ Disappearance





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  $\sin^2\theta_{23} = 0.40^{+0.03}_{-0.02}\ (0.63^{+0.02}_{-0.03})$v

- Non-maximal fit is driven by bins in oscillation dip (1-2 GeV)
- Forcing maximal mixing gives:

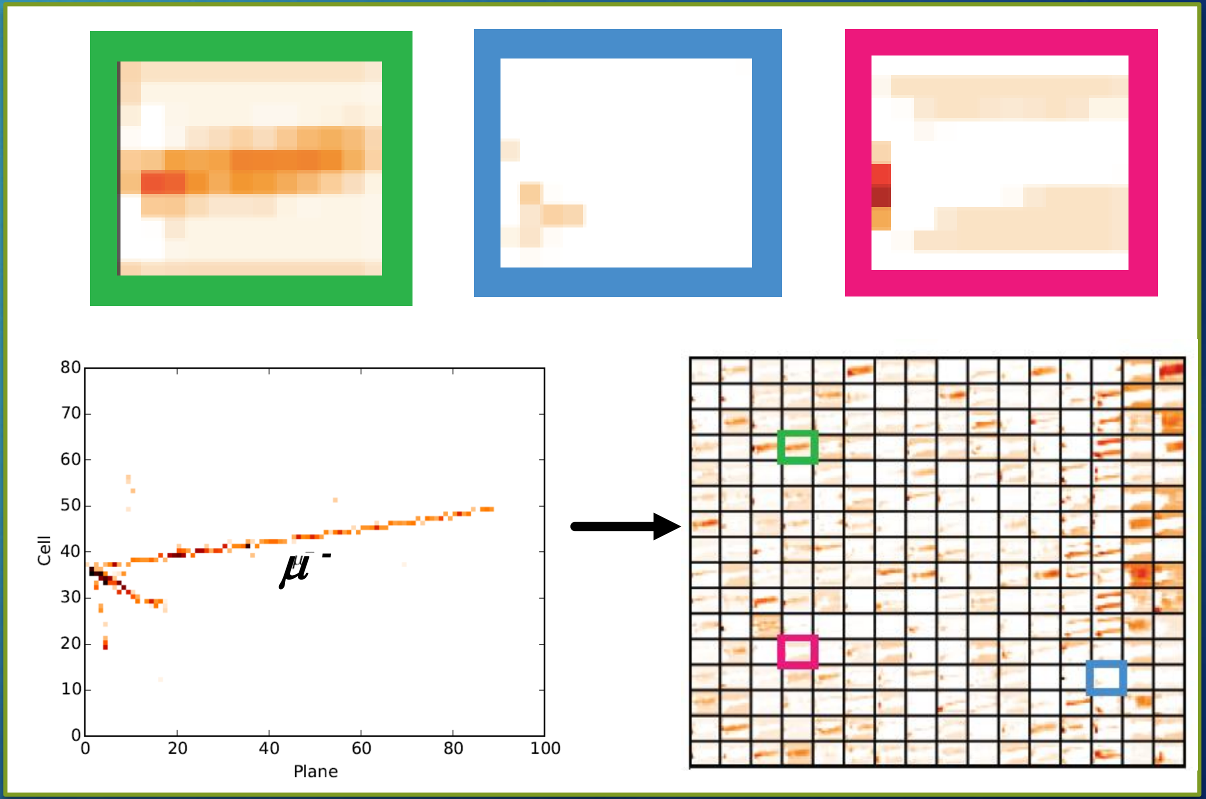
  $|\Delta m^2_{32}| = 2.46 \cdot 10^{-3}\ \mathrm{eV}^2$

Improved event selection

CVN – Convolutional Visual Network: new event selection technique based on ideas from computer vision and deep learning

- Calibrated hit maps are inputs to the CVN
- Series of image processing transformations applied to extract abstract features
- Extracted features used as inputs to a conventional neural network to classify the event

Improved sensitivity equivalent to 30% more exposure



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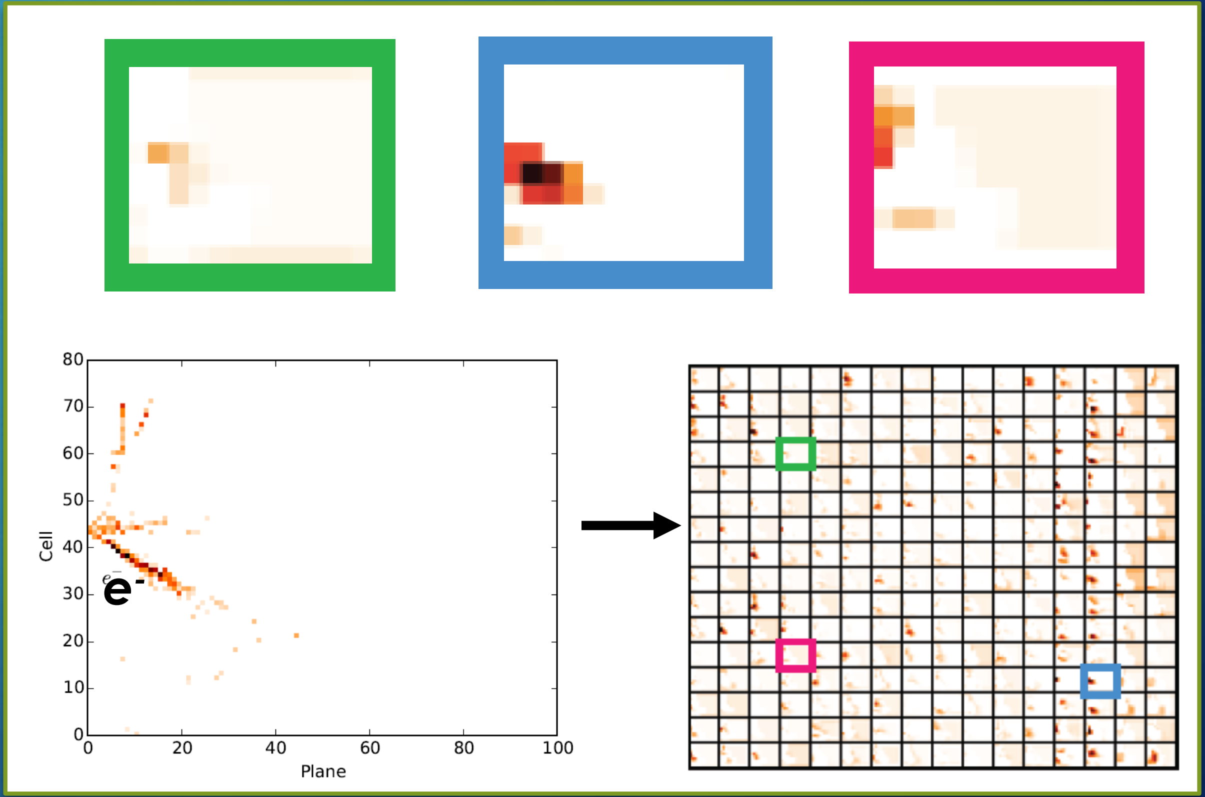


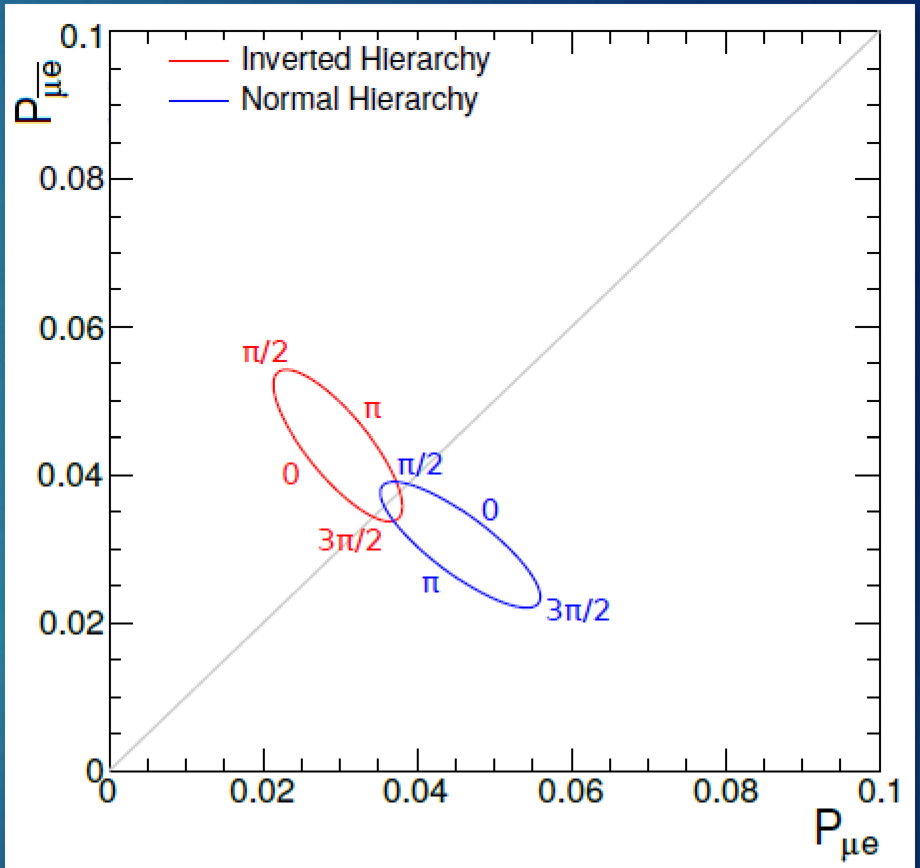
ν_e Appearance

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

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

- Depends simultaneously on θ_{13}, θ_{23}, δ_{CP}, sign(Δm^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}



ν_e Appearance

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

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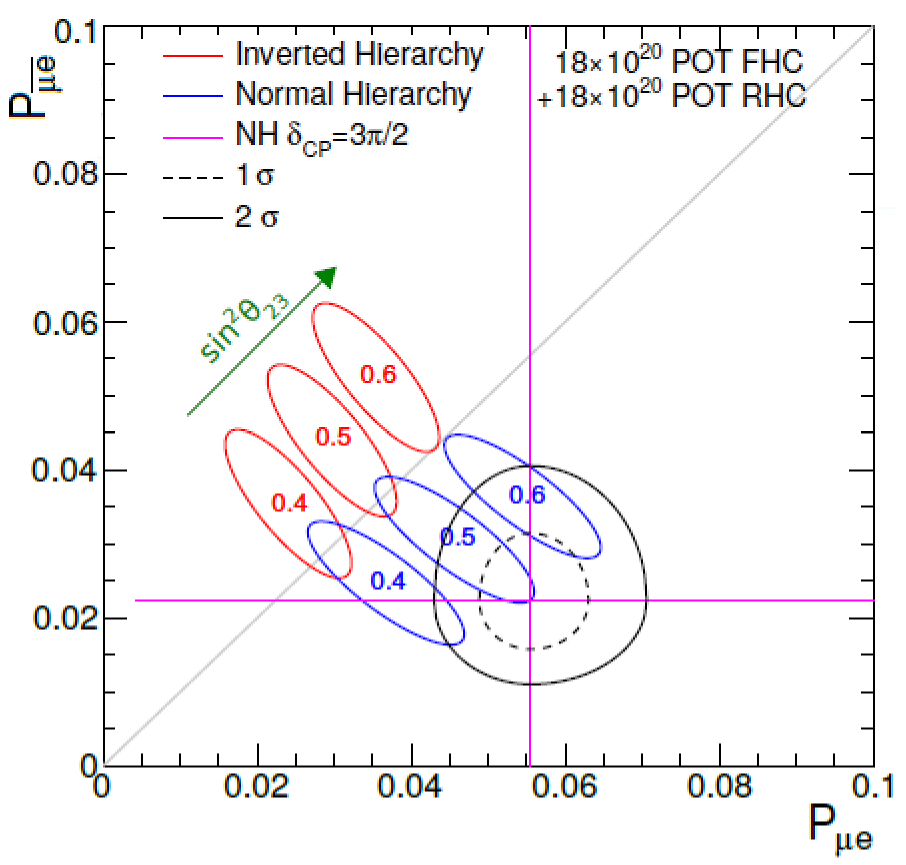
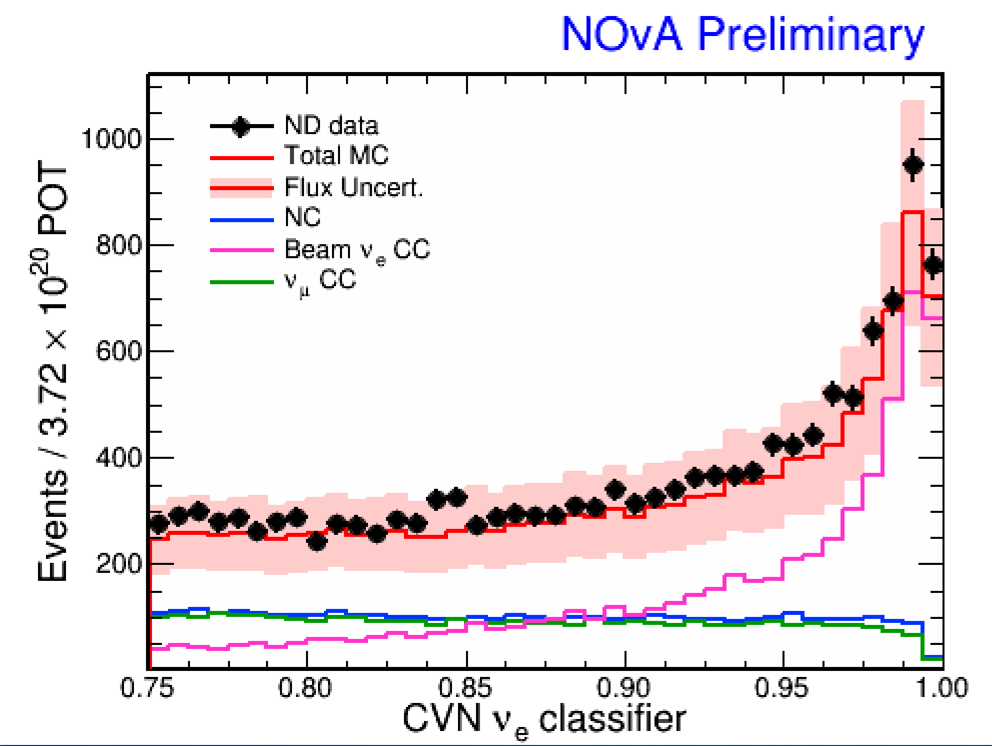
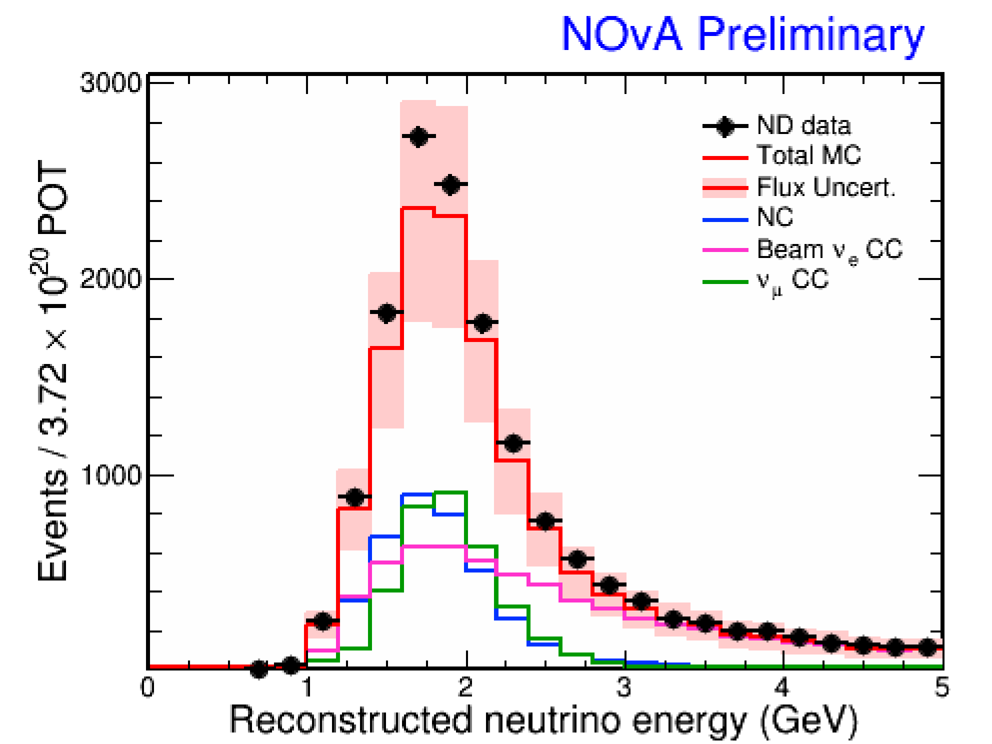
- $\mathbf{P} \propto sin^2\, \theta_{23}$
- Constrain a space region



ν_e Results

- CVN PID, loosen cut on Pid optimized to favor parameter measurement
- Separate ν_e CC interactions from backgrounds, backgrounds evaluated in ND:
  - intrinsic beam ν_e, Neutral Currents, ν_μ CC, each propagate differently
  - Use ND data to predict background in the FD
- Looking for an excess in the FD





ν_e Results

- Expected events depend on oscillation parameters:

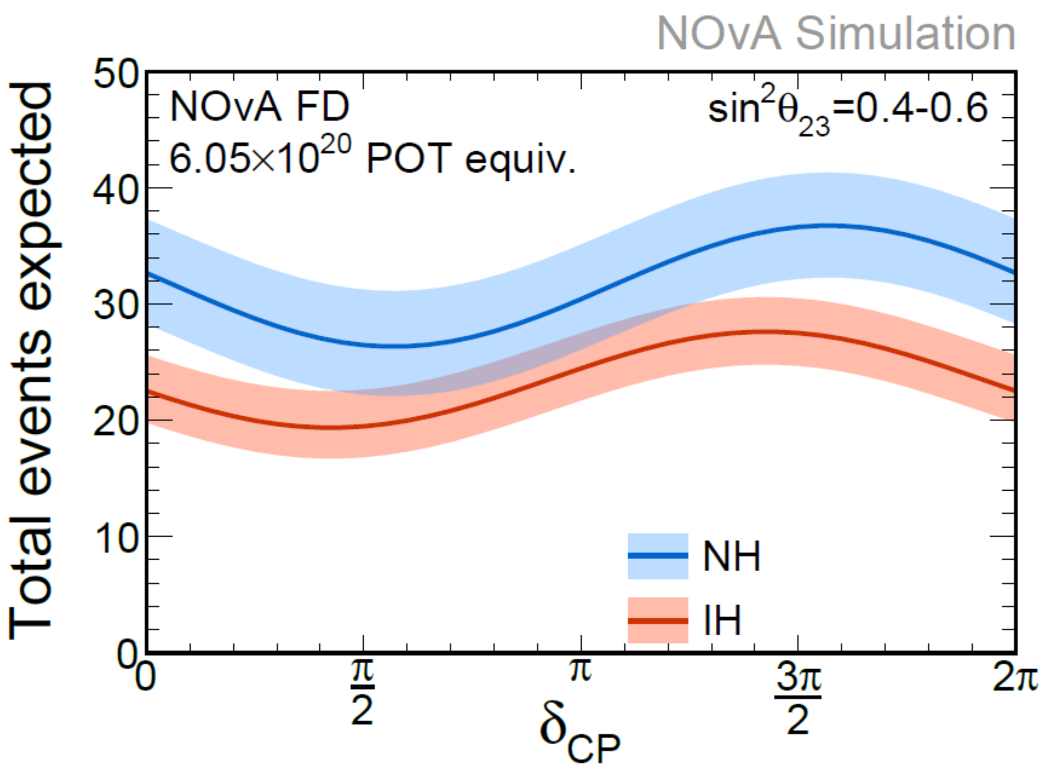
  $\sin^2\theta_{23} = 0.5$, $\pm 5\%$ syst.

  Total Prediction (signal+background):

NH, $3\pi/2$	IH, $\pi/2$
36.4	**19.4**

  Background components ($\pm 10\%$ syst):

Total BG	NC	Beam ν_e	ν_μ CC	ν_τ CC	Cosmics
8.2	3.7	3.1	0.7	0.1	0.5



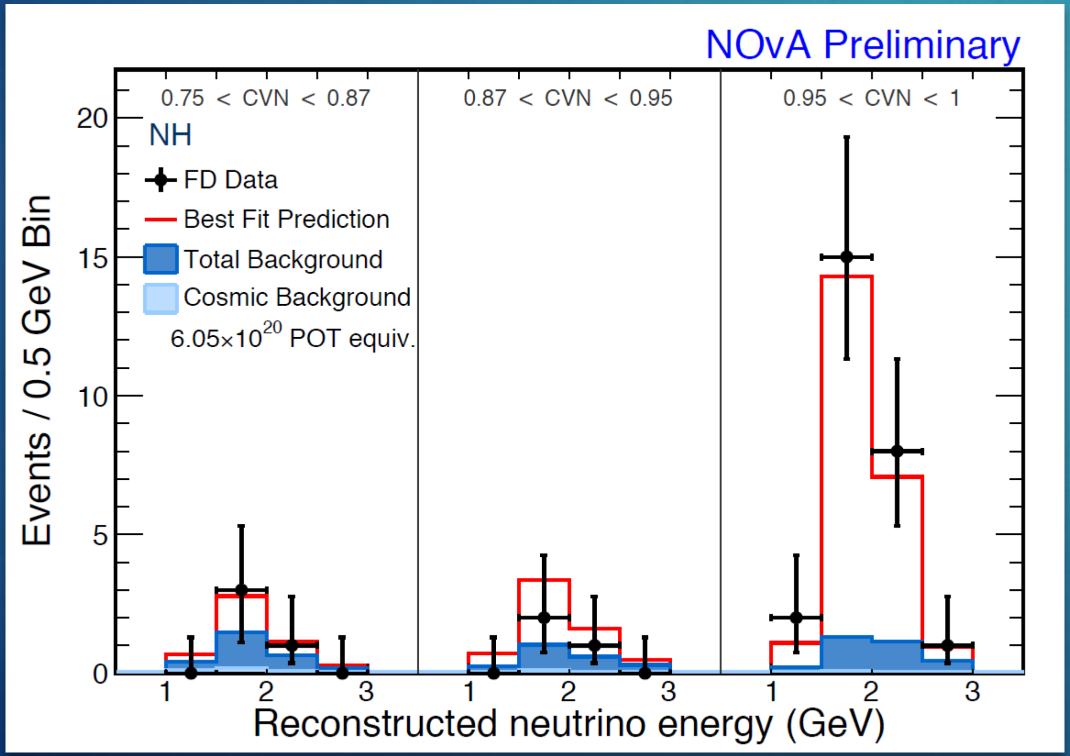
- Each component extrapolated in bins of energy and CVN output

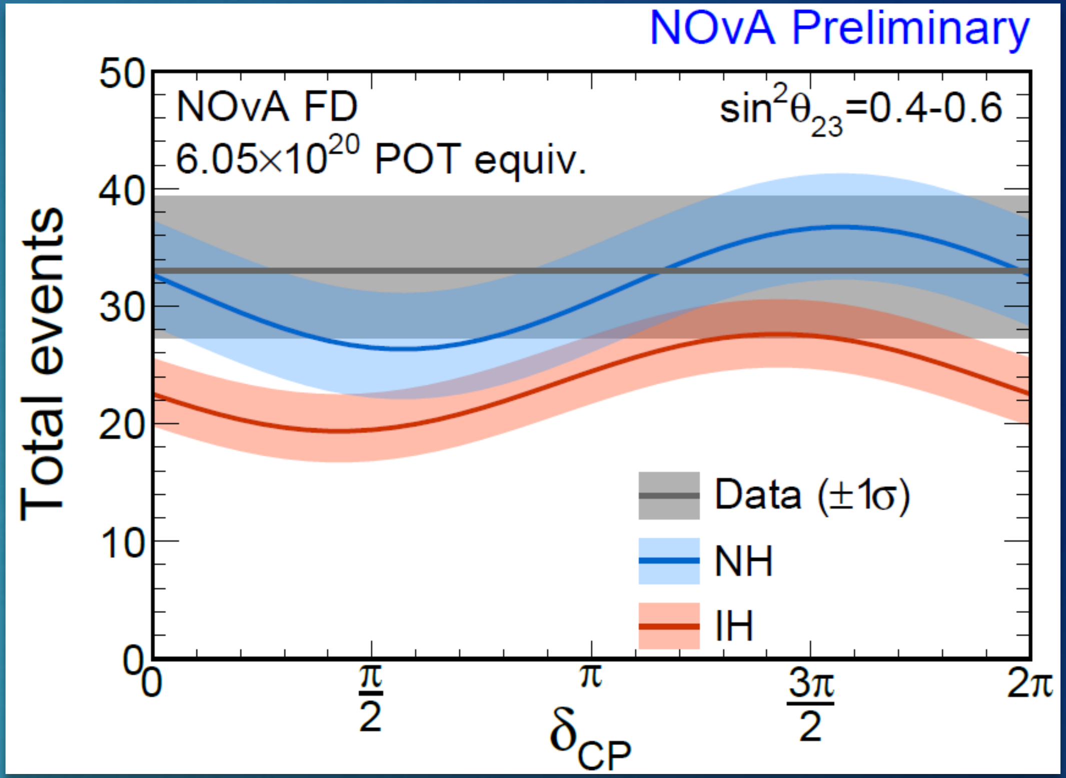
ν_e Results

- Total Prediction (signal+background):

NH, $3\pi/2$	IH, $\pi/2$
36.4	19.4

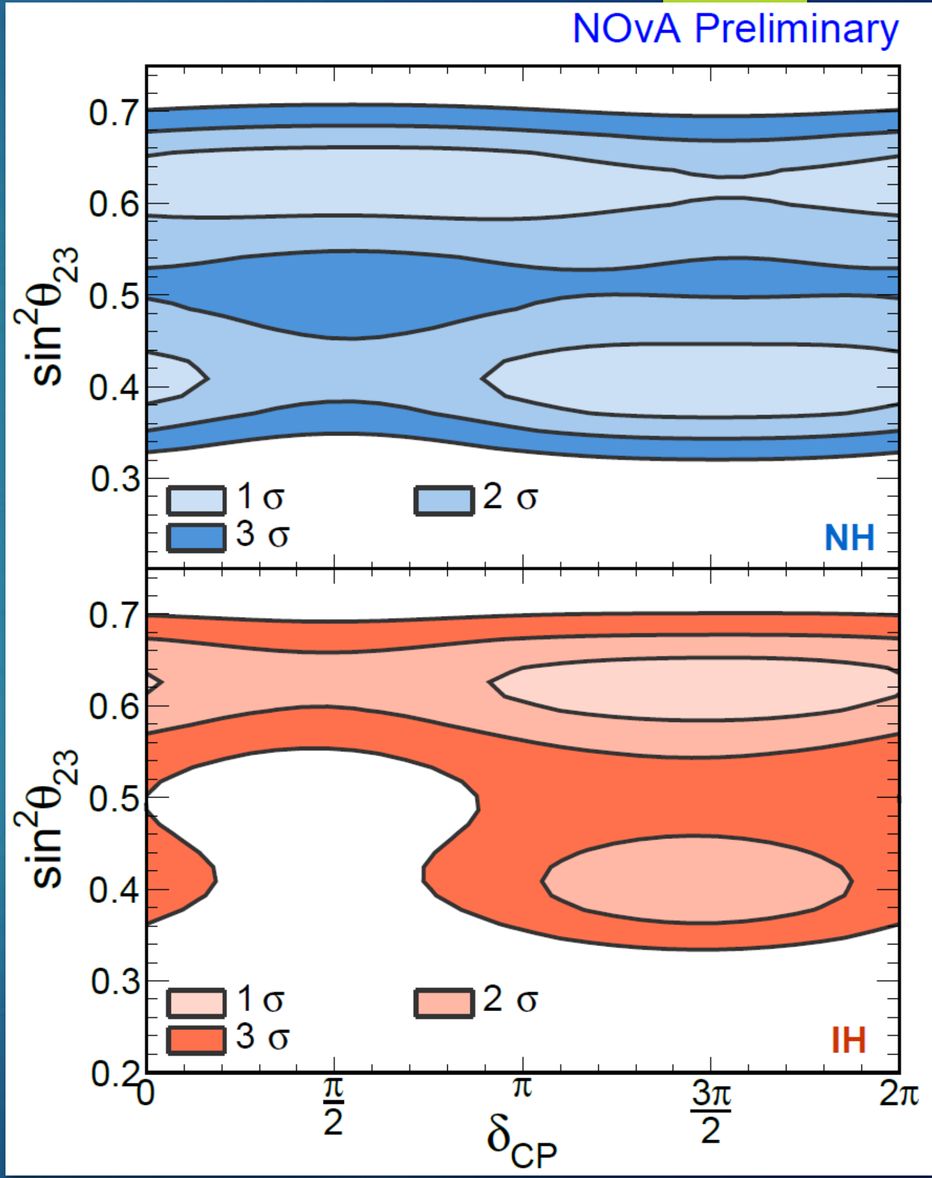
- **Observed events in FD: 33**





ν_e Results

- Fit for hierarchy, δ_{CP}, $\sin^2\theta_{23}$
  - Constrain $\sin^2(2\theta_{13})=0.085\pm0.05$ from reactor
  - Constrain Δm and $\sin\theta_{23}$ with NOvA disappearance results
  - Not a full joint fit, syst and other oscillation parameters not correlated
- Global best fit, preference for NH, $\Delta\chi^2=0.47$
  - δ_{CP} = 1.49π, $\sin^2(\theta_{23})$ = 0.40
  - Both octants and hierarchies allowed at 1σ
  - IH lower octant around δ_{CP} = π/2 excluded at 3σ



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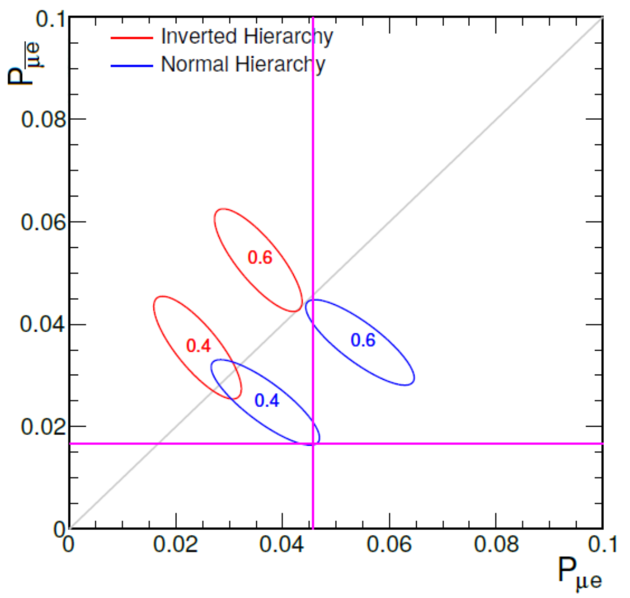
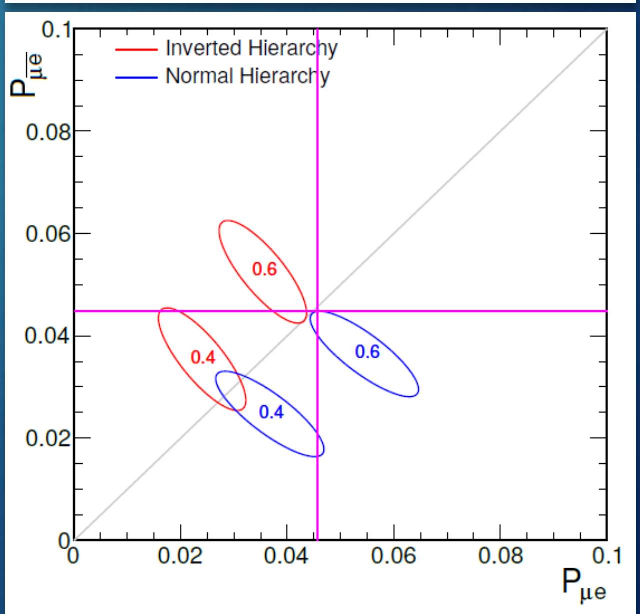
  - **Both octants and hierarchies allowed at 1σ**
  - **IH lower octant around δ_{CP} = π/2 excluded at 3σ**
- Antineutrino Run (planned for spring 2017) will help resolve degeneracies





Summary

- Early days for NOvA, our baseline program is six times our current exposure

  NOvA collected $6.05 \cdot 10^{20}$ POT, oscillation results:

  - ν_μ **disappear**, maximal mixing is excluded at 2.5σ
  - ν_e **appear**:
    - slight preference for NH
    - IH lower octant around $\delta_{CP} = \pi/2$ is exlcuded (>3 σ)
- Antineutrino run in spring 2017
- Many other interesting NOvA analyses!

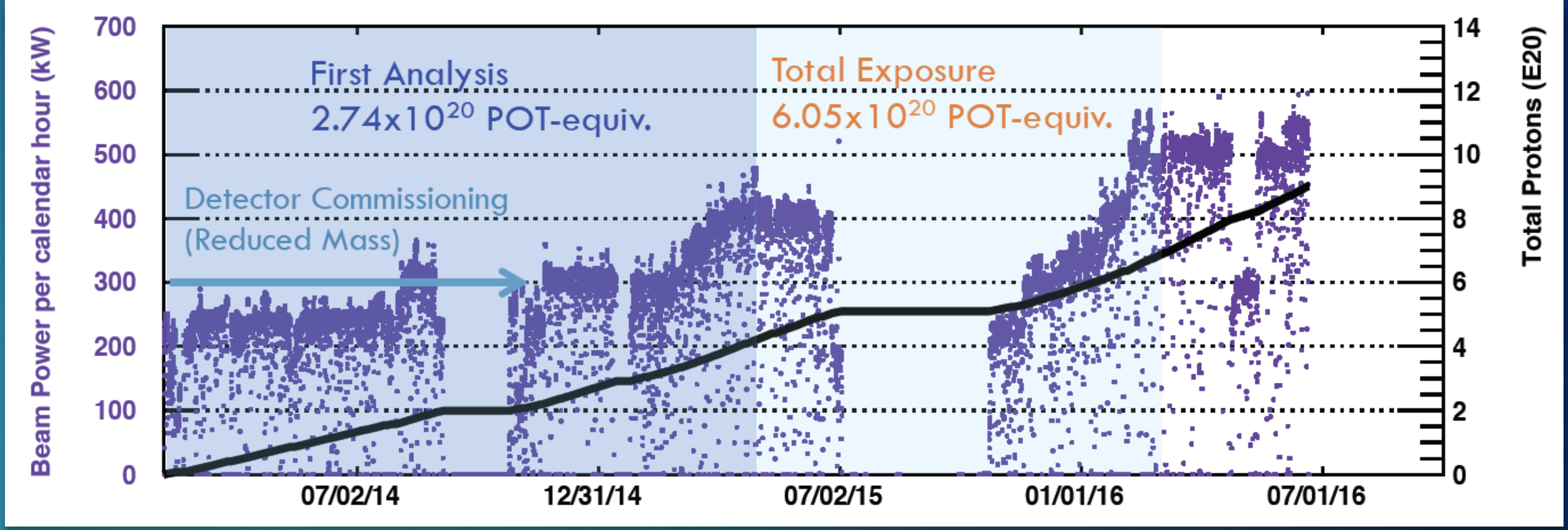
  sterile neutrinos, cross section measurements, supernovæ…

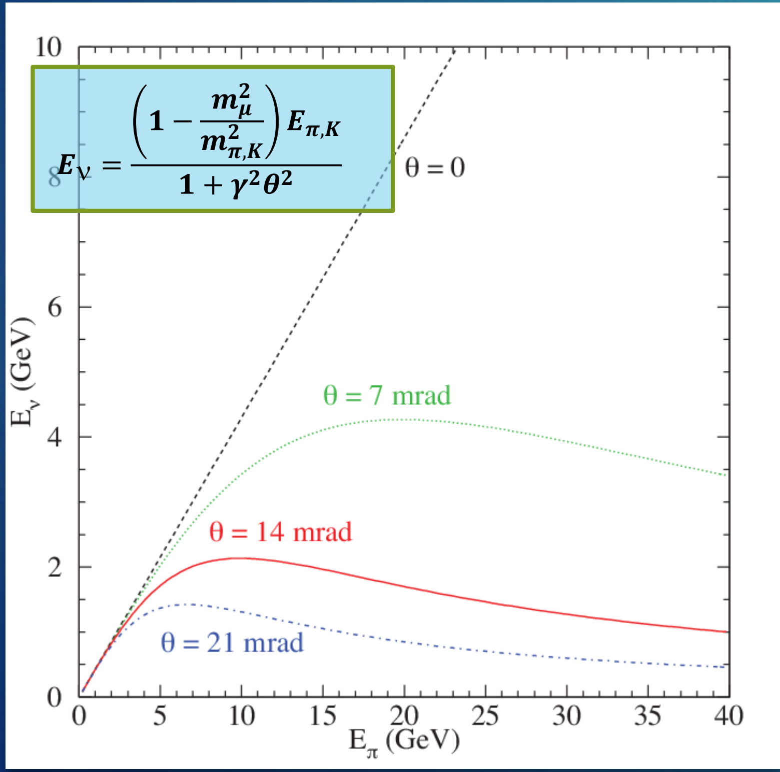
Argonne, Atlantico, Banaras Hindu, Caltech, CUSAT, Czech Academy of Sciences, Charles, Cincinnati, Colorado State, Czech Technical University, Delhi, Dubna, Fermilab, Goias, IIT-Guwahati, Harvard, IIT-Hyderabad, Hyderabad, Indiana, Iowa State, Jammu, Lebedev, Michigan State, Minnesota-Twin Cities, Minnesota-Duluth, INR Moscow, Panjab, SDMT, South Carolina, SMU, Stanford, Sussex, Tennessee, Texas-Austin, Tufts, UCL, Virginia, Wichita State, William and Mary, Winona State.

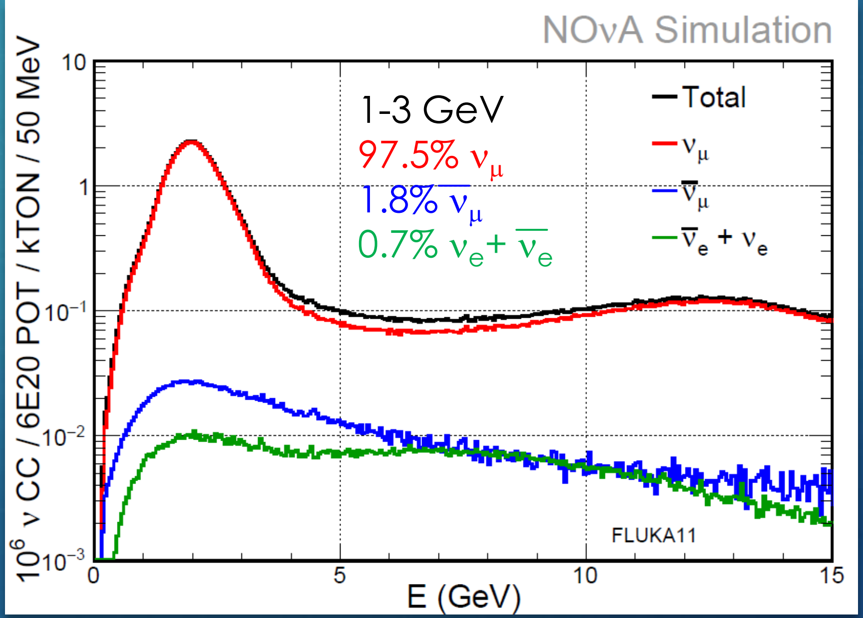
Back up

NuMI beam

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

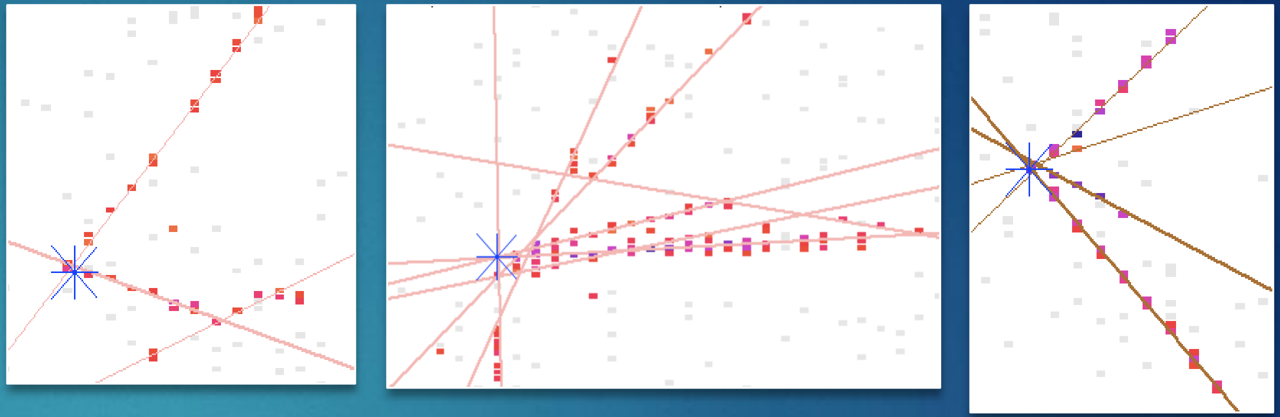




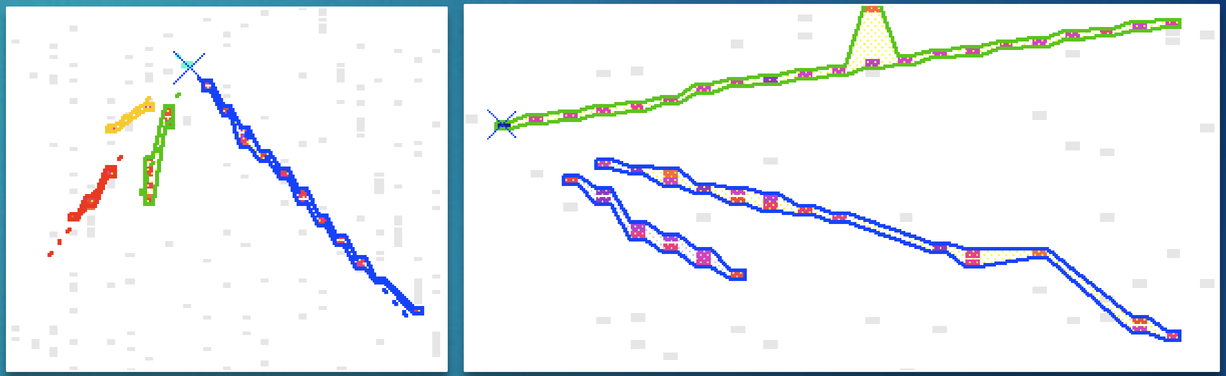


Reconstruction

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



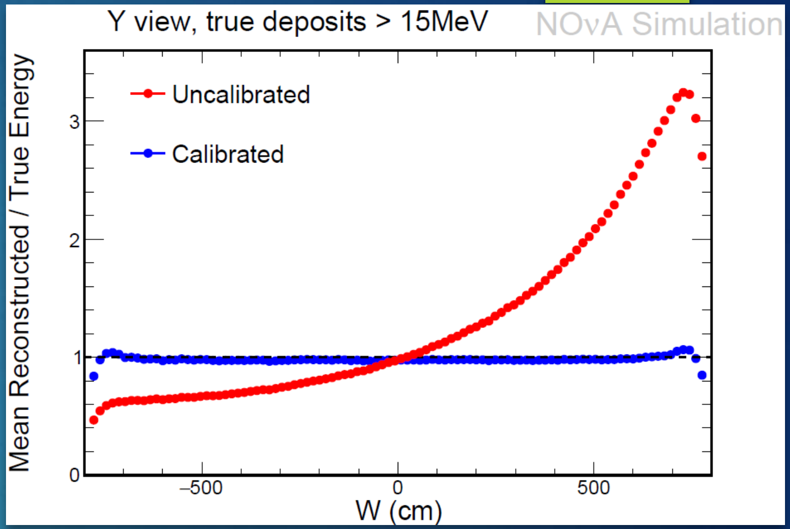
Clustering: Find **clusters in angular space** around vertex. **Merge views** via topology and prong dE/dx

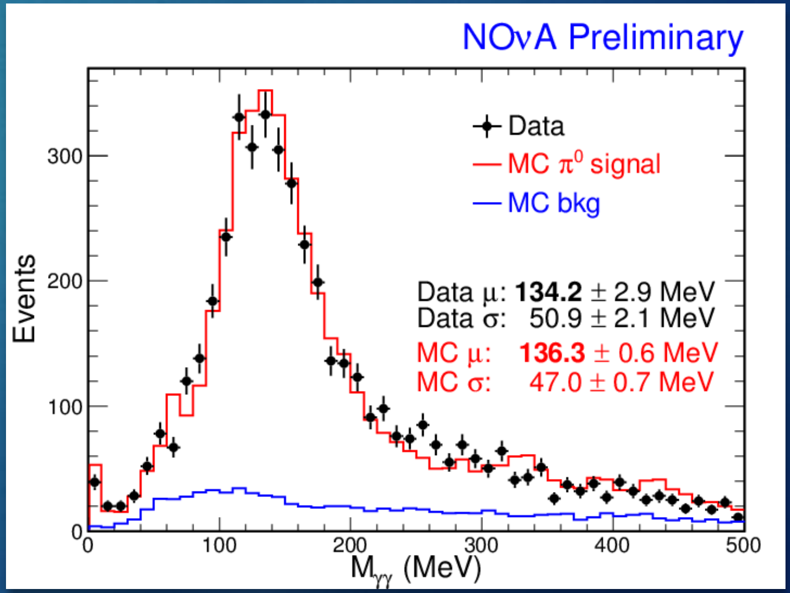


Tracking: Trace particle trajectories with **Kalman filter** tracker.
Also, **cosmic ray tracker**: lightweight, fast, and for large calibration samples, online monitoring.

ν_μ Disappearance

- Calibration and energy scale: Cosmic ray muons are the standard candle
- Cells individually corrected for
  - Llight attenuation along cell length
  - Shadowing due to detector bulk
  - Threshold effects far from readout
- Energy scale set by dE/dx near the end of stopping muons
  - Cross-check including π0 mass peak, Michel-e$^-$, beam muon dE/dx
  - Take 5% absolute and relative errors





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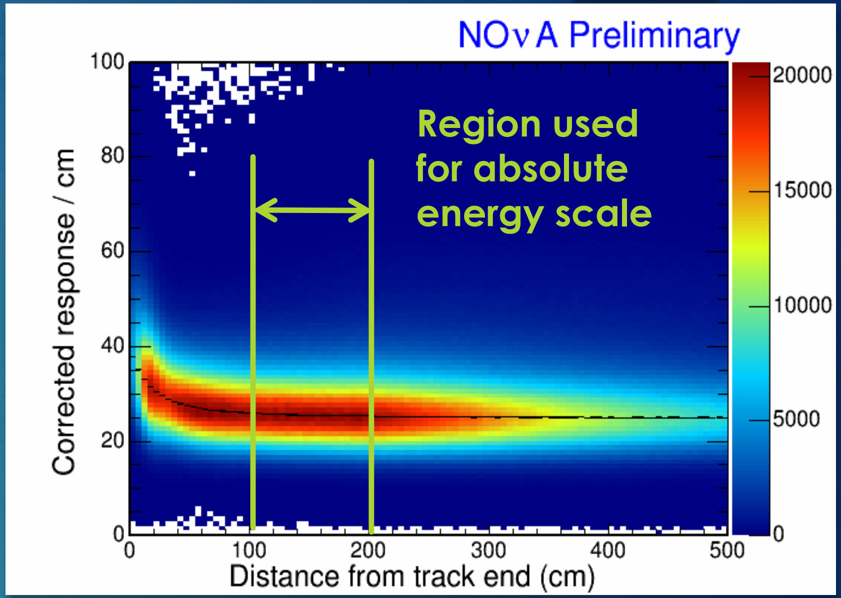
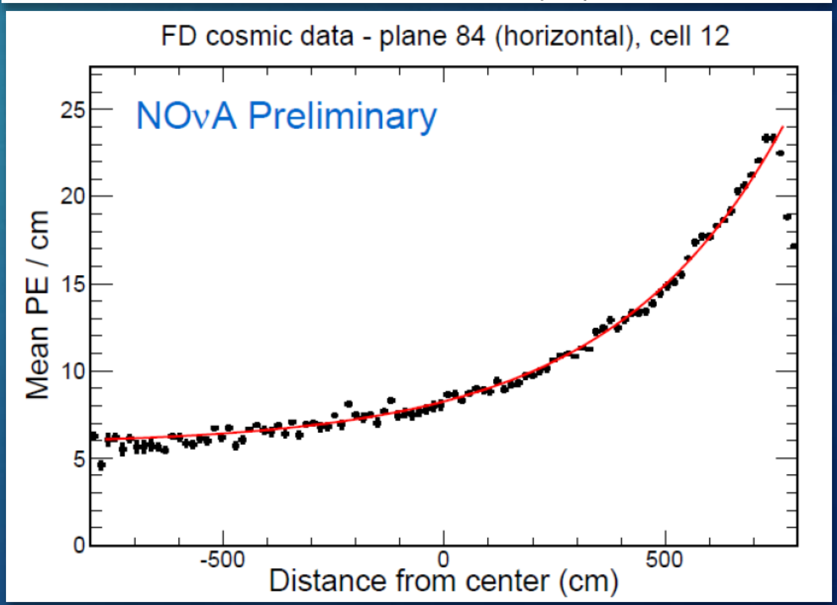
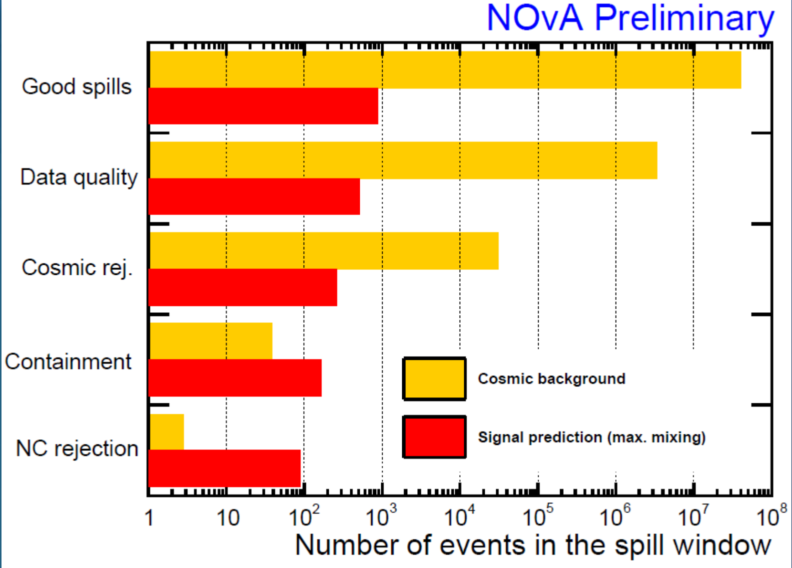


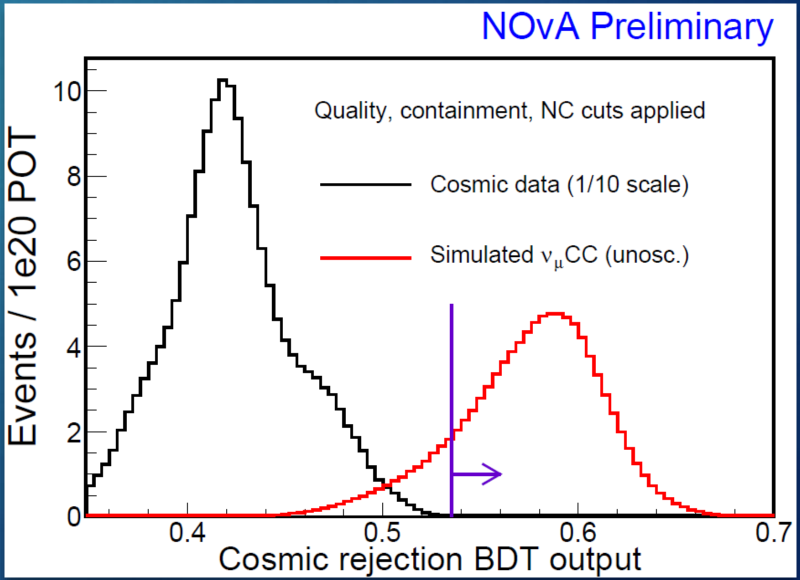


ν_μ Disappearance

Cosmic rejection

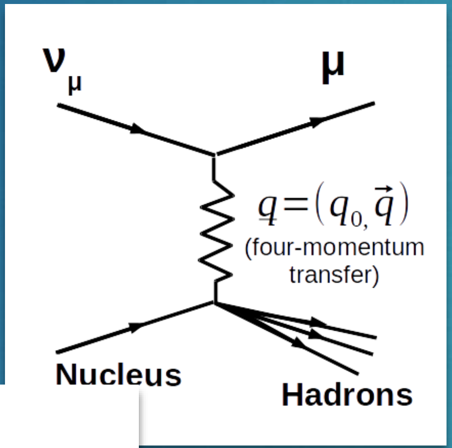
- 10μs spill window gives 10^5 rejection
- Cosmic ray data in data are measured in time window adjacent to the spill
- Event topology+BDT provide additional $O(10^7)$ reduction
  - BDT inputs: track direction, track start and end point, track length, energy, number of hits

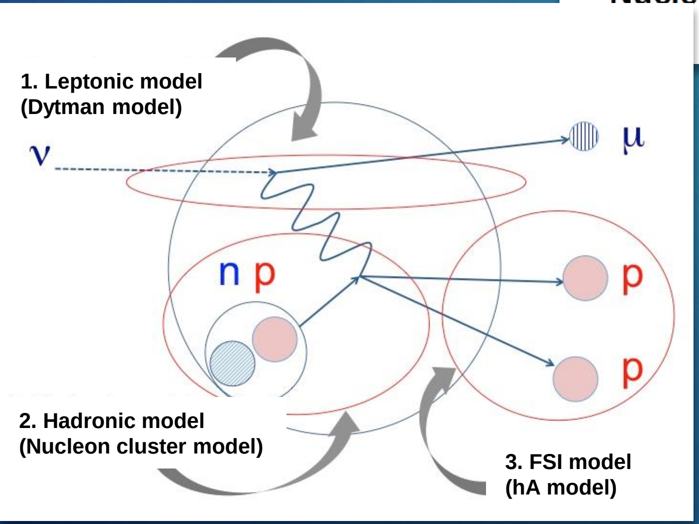


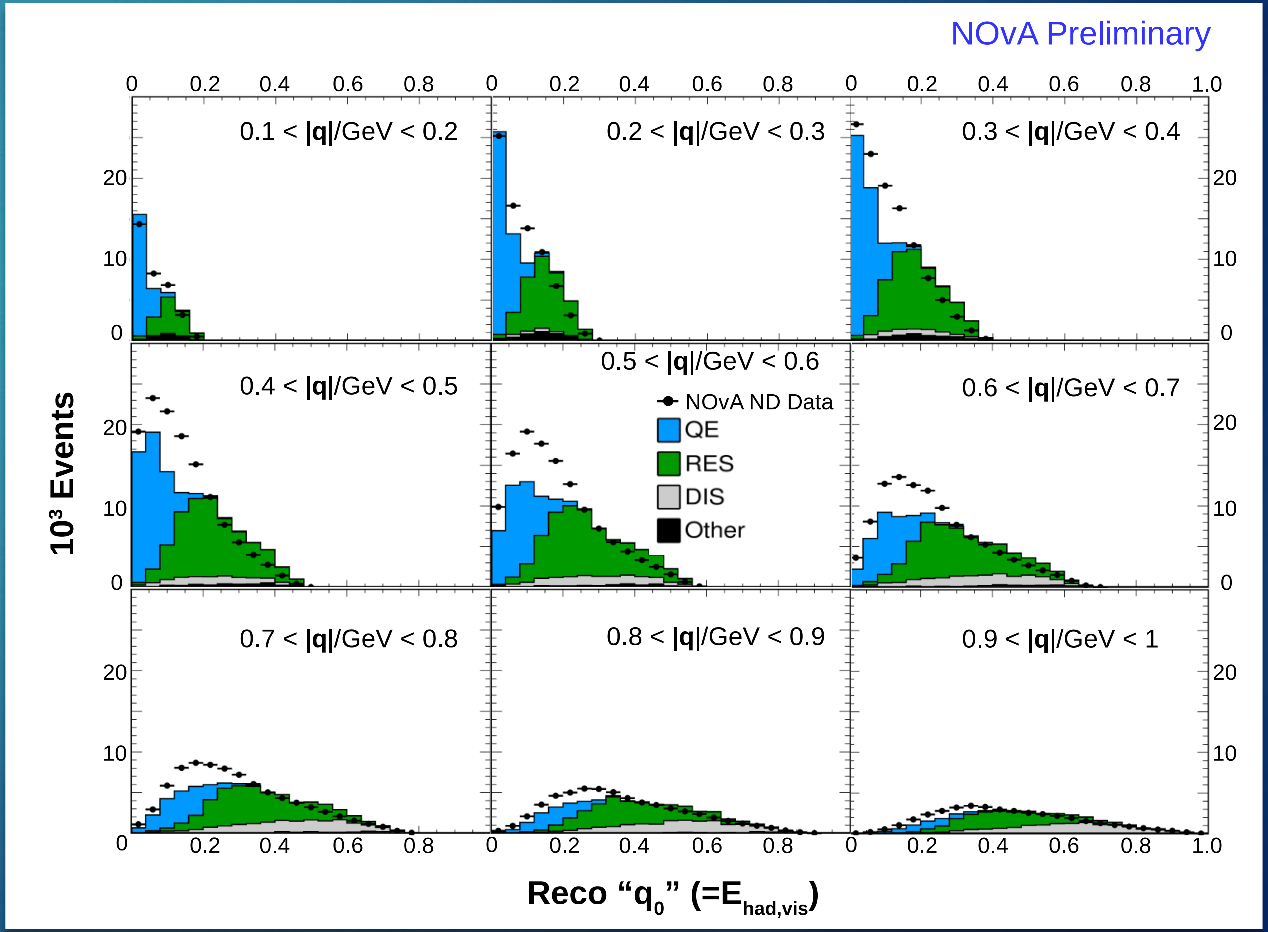


ν_μ Disappearance

ND data suggest unsimulated process between QE and Δ production (Minerva experiment reported similar excess)







ν_μ Disappearance

ND data suggest unsimulated process between QE and Δ production (Minerva experiment reported similar excess)

→enable GENIE empirical MEC
(50% systematic on MEC component)

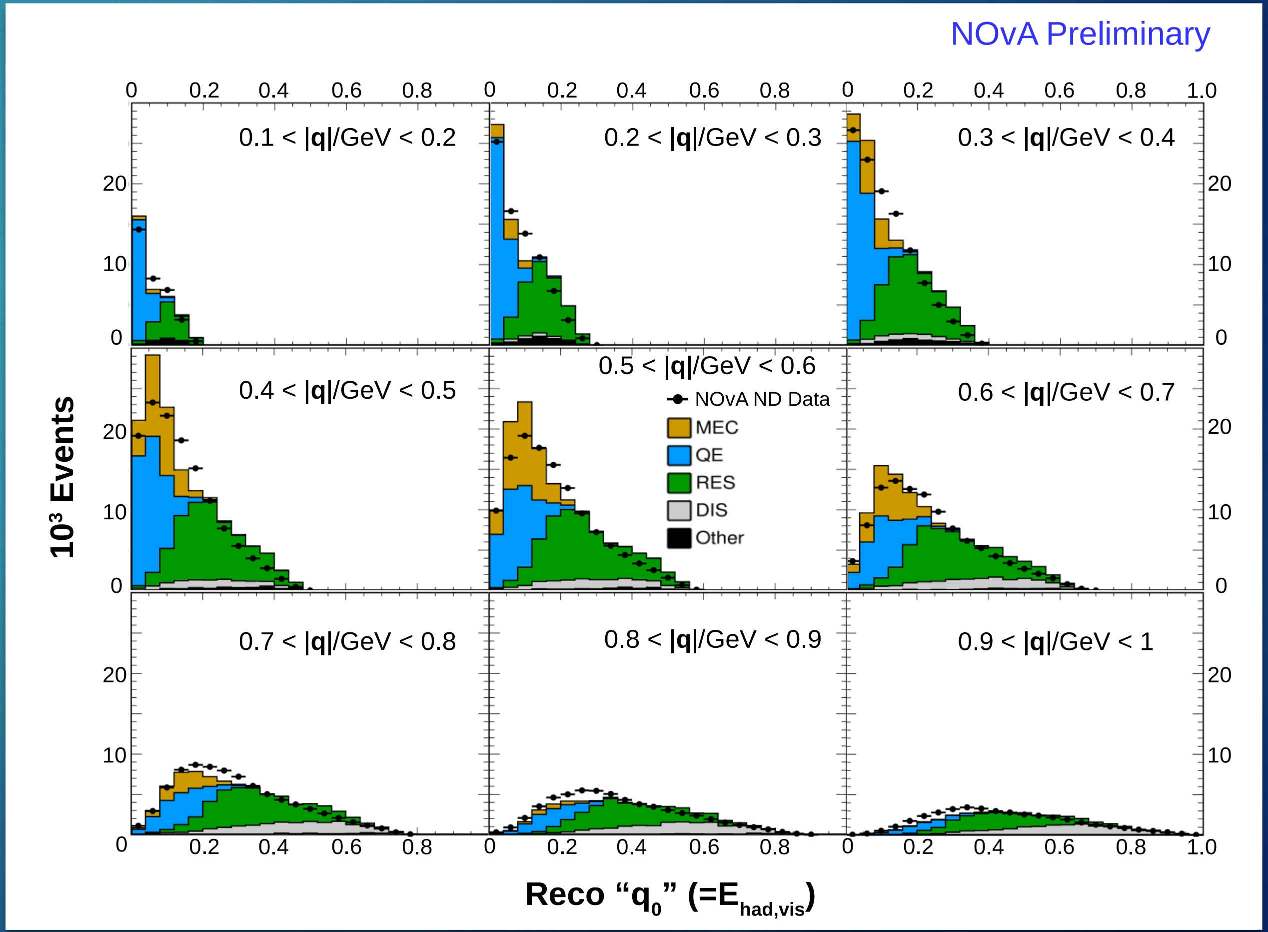
→reweight the model to match observation
as a function of $\vec{p}$ transfer

Reduction of largest systematics

-Hadronic energy scale

-QE cross section modeling

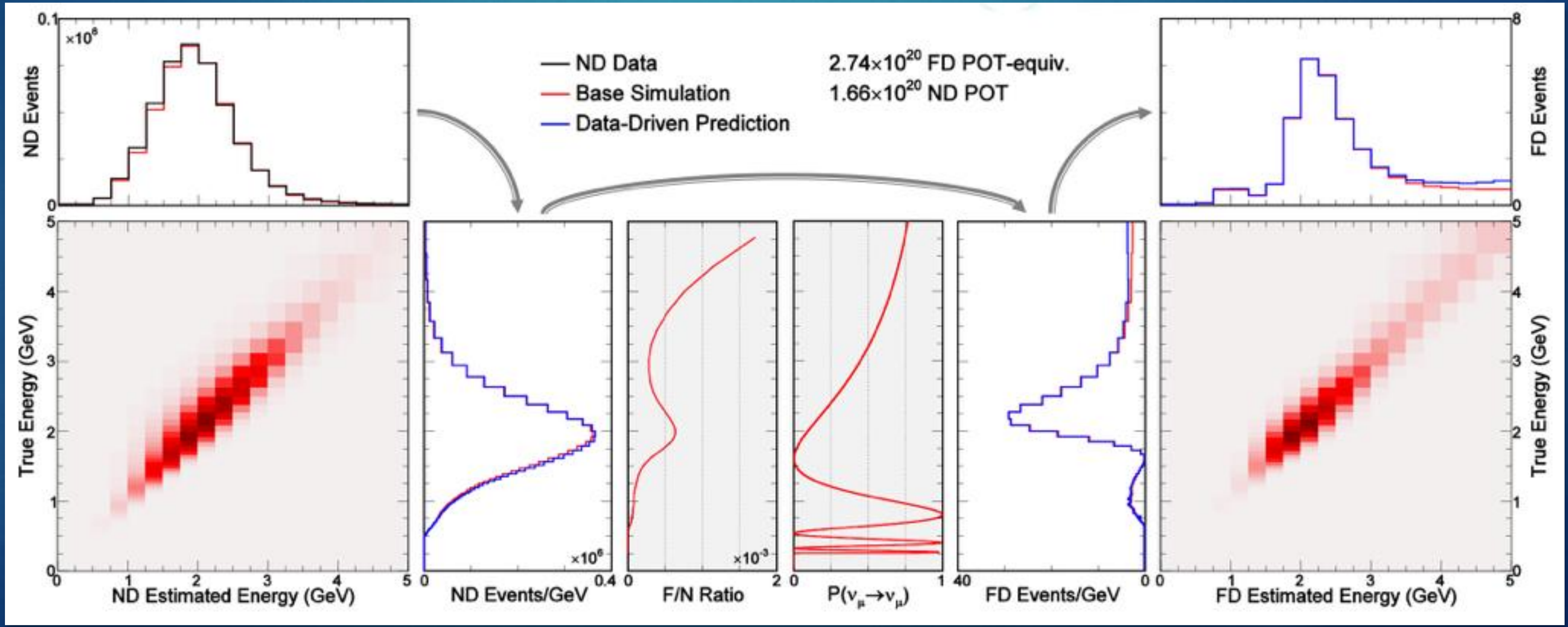
Reduction of single non-RES pion production by 50%



ν_μ Disappearance

Near-Far Extrapolation – 3 step process

1) Convert ND reconstructed energyto true energy
2) Use Near/Far ratio to convert to FD true energy spectrum
3) Translate back to reconstructed energy



ν_μ Disappearance

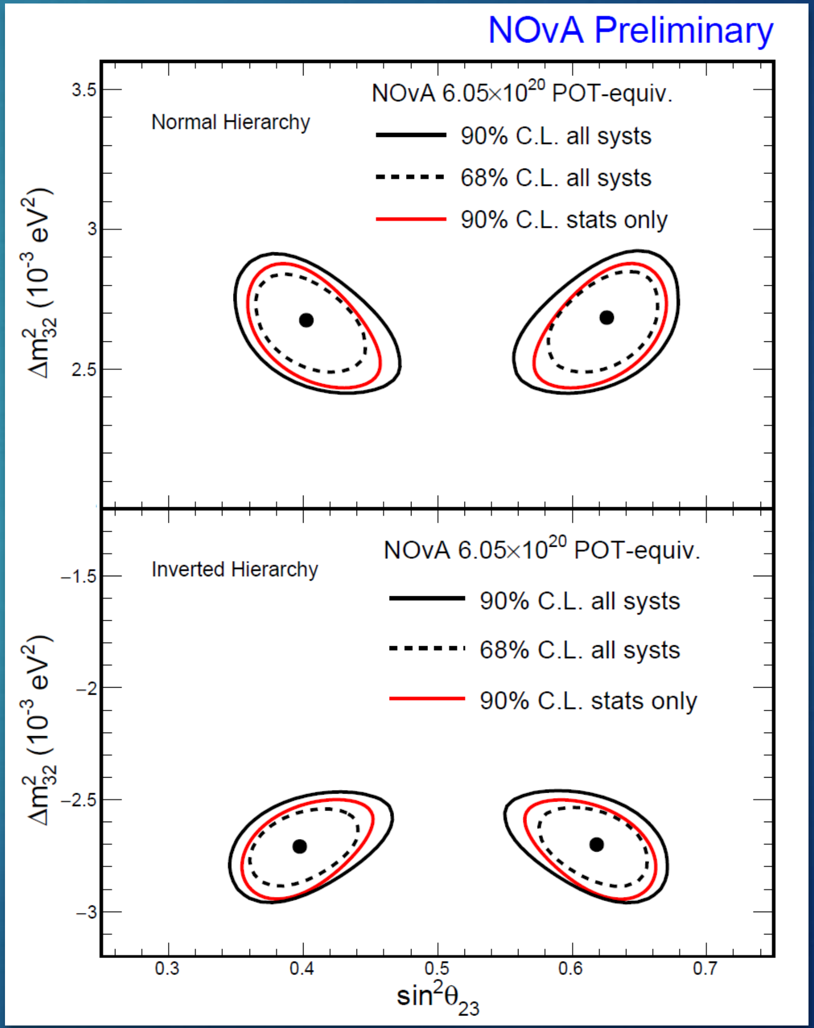
Systematic uncertainties

Systematic	Effect on $sin^2(\theta_{23})$	Effect on Δm^2_{32}
Normalisation	± 1.0%	± 0.2 %
Muon E scale	± 2.2%	± 0.8 %
Calibration	± 2.0 %	± 0.2 %
Relative E scale	± 2.0 %	± 0.9 %
Cross sections + FSI	± 0.6 %	± 0.5 %
Osc. parameters	± 0.7 %	± 1.5 %
Beam backgrounds	± 0.9 %	± 0.5 %
Scintillation model	± 0.7 %	± 0.1 %
All systematics	**± 3.4 %**	**± 2.4 %**
Stat. Uncertainty	**± 4.1 %**	**± 3.5 %**

In each case:

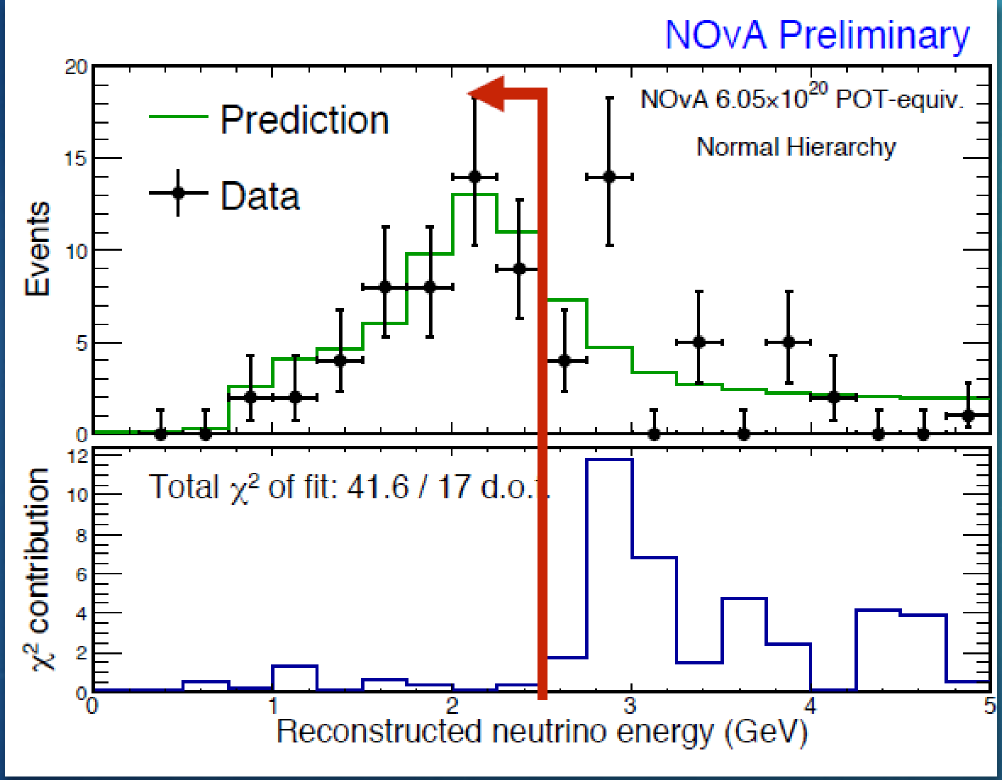
- The effect is propagated through the extrapolation
- We include those effects as pull terms in the fit
- The increase (in quadrature) of the parameter measurement error is recorded

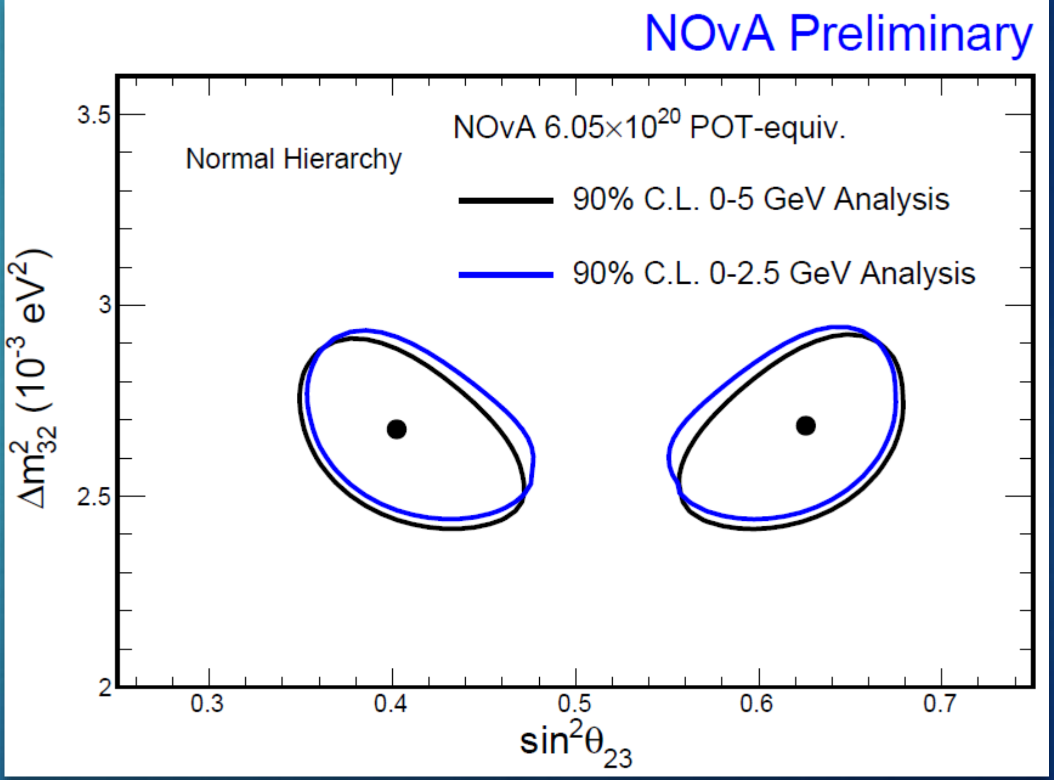
Inverted hierarchy contours



ν_μ Disappearance

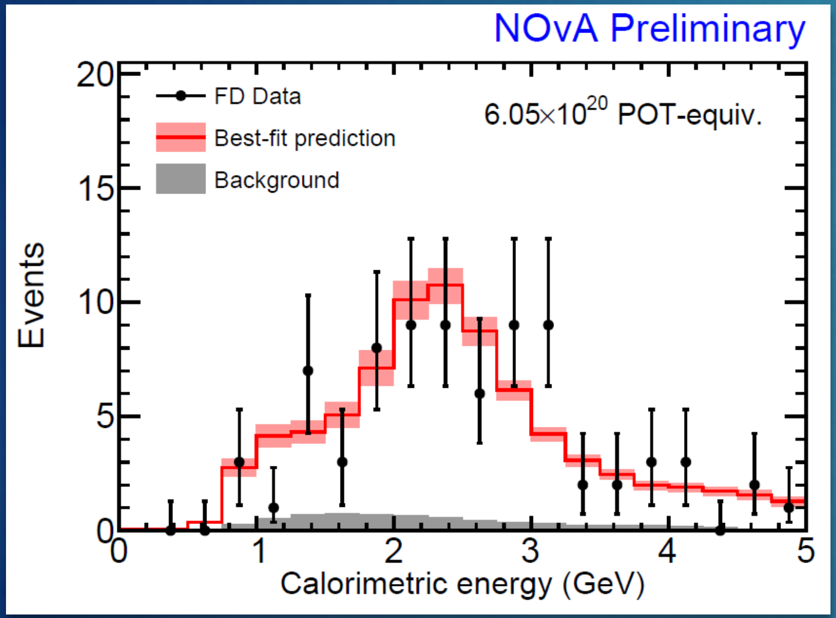
- Best Fit χ^2/DOF =41.5/17 is driven by the tail
- There is no significant pull in the oscillation fit from bins in the tail

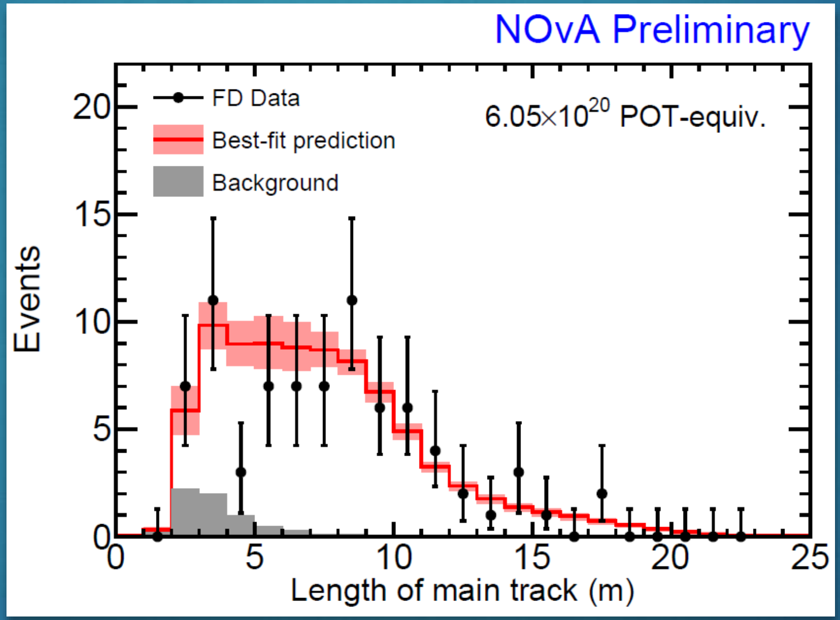


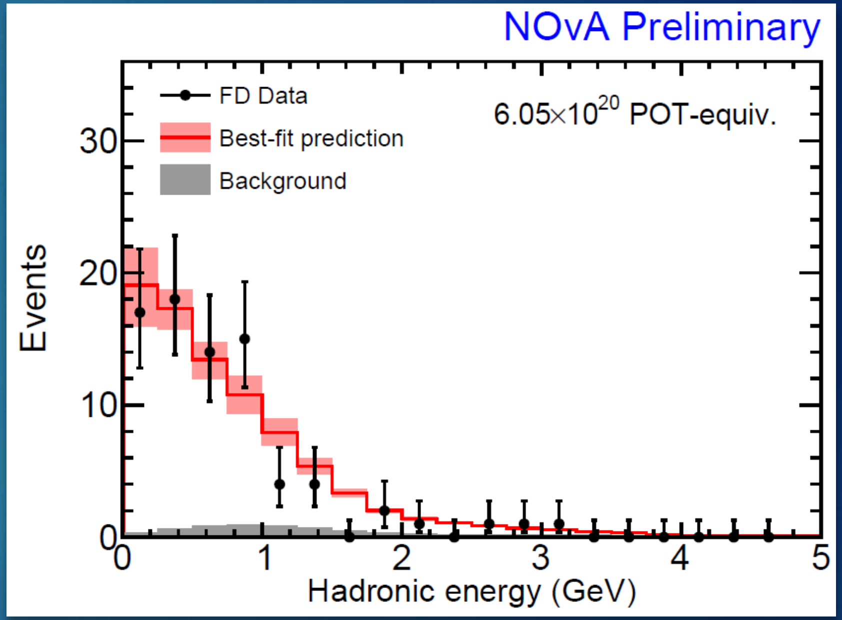


ν_μ Disappearance

- Fit-checks: best fit oscillation prediction matches other distributions well

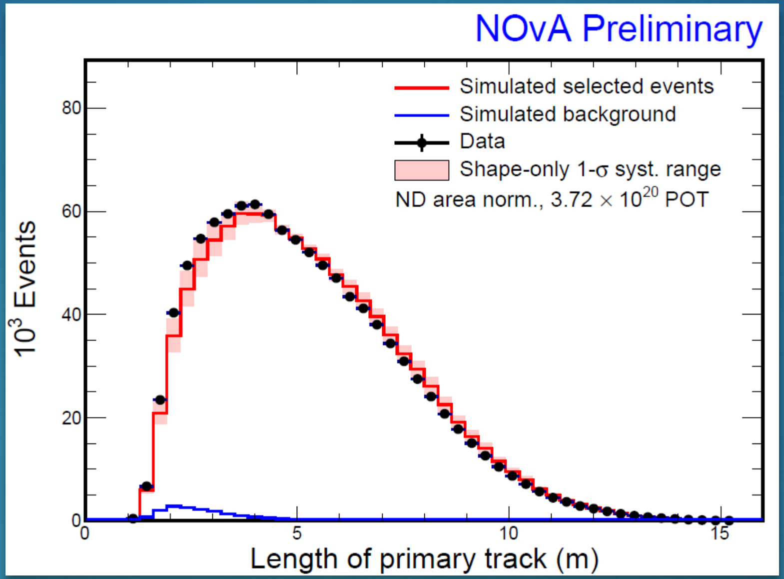


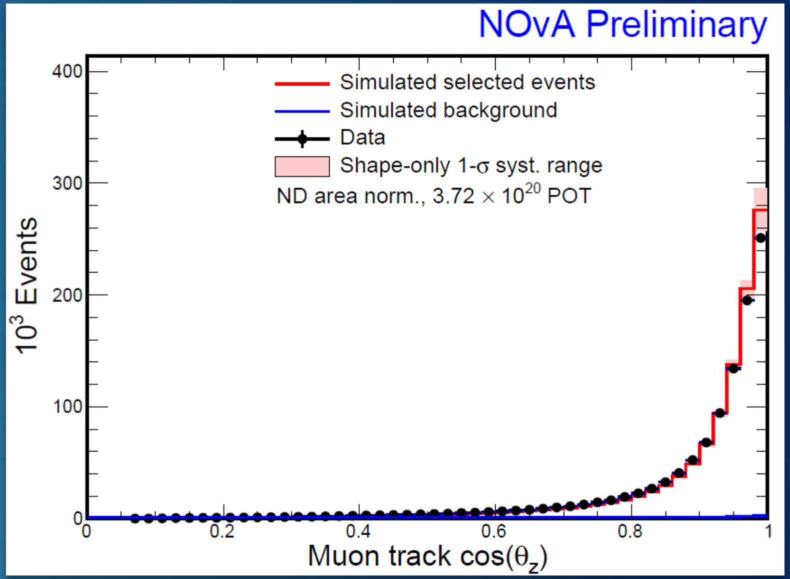




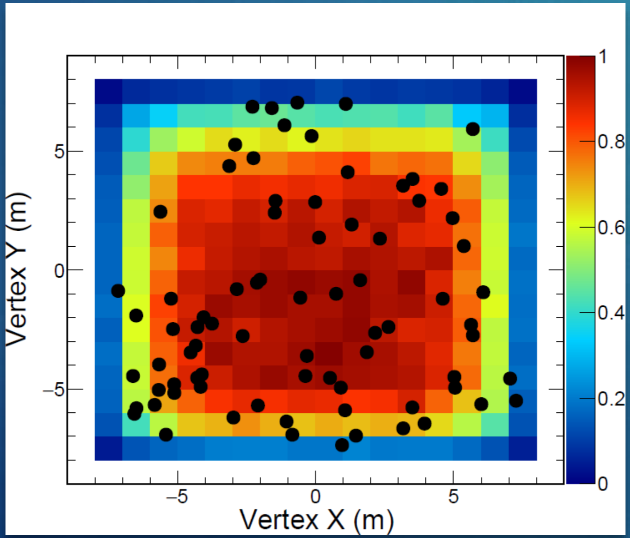
ν_μ Disappearance

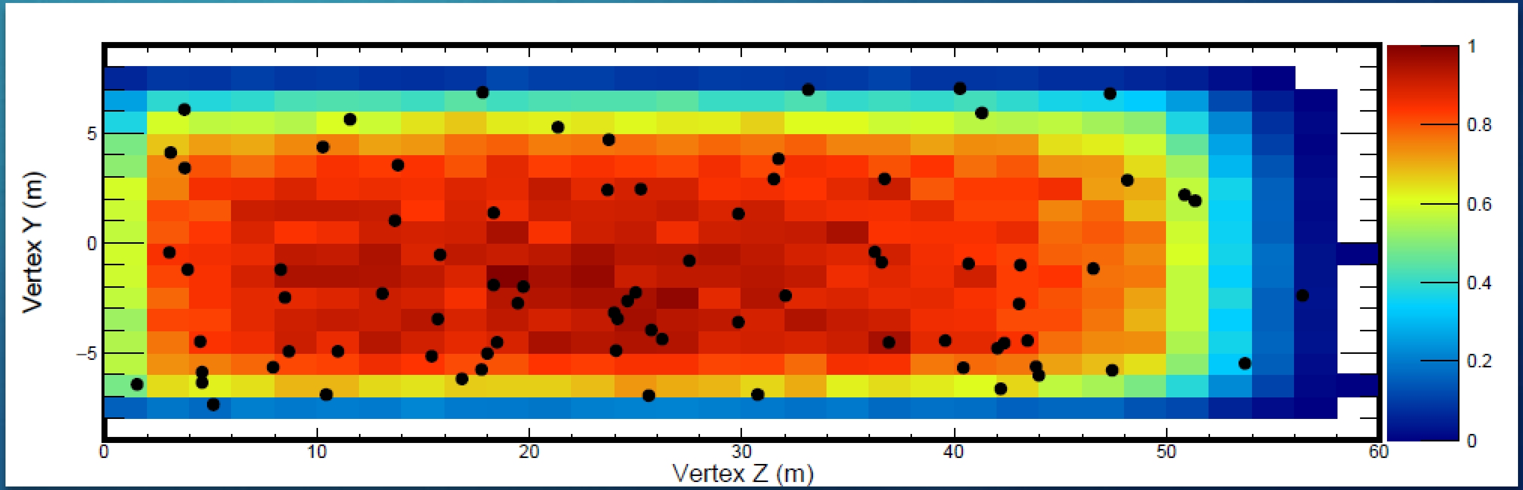
- Muon Selection





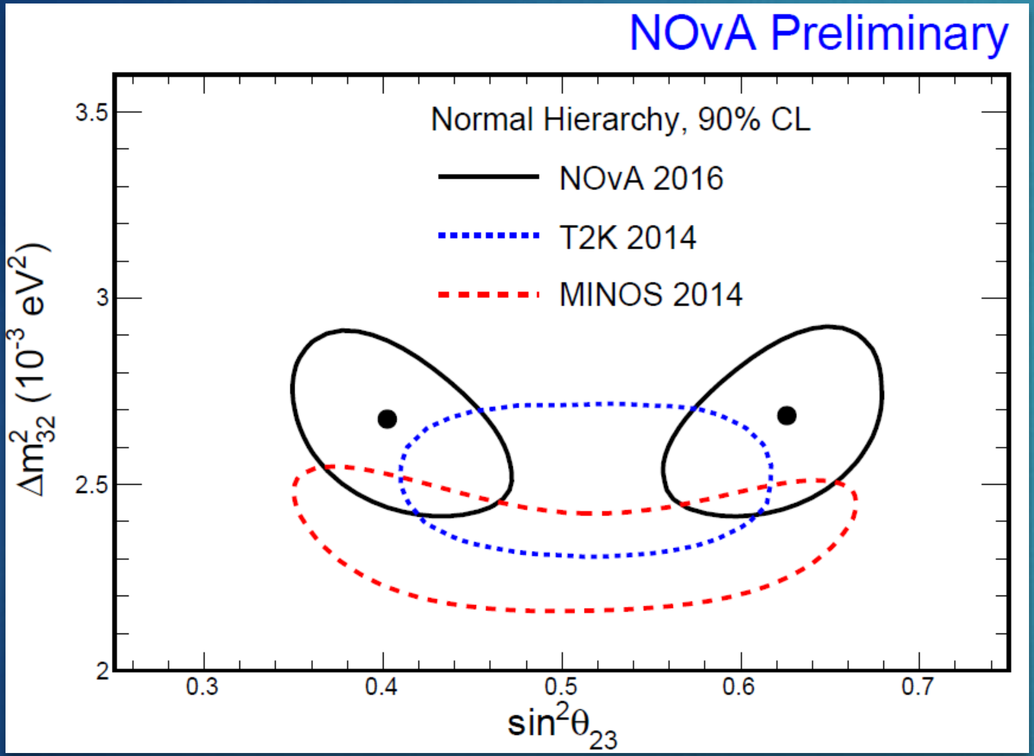
- Muon Neutrino FD data



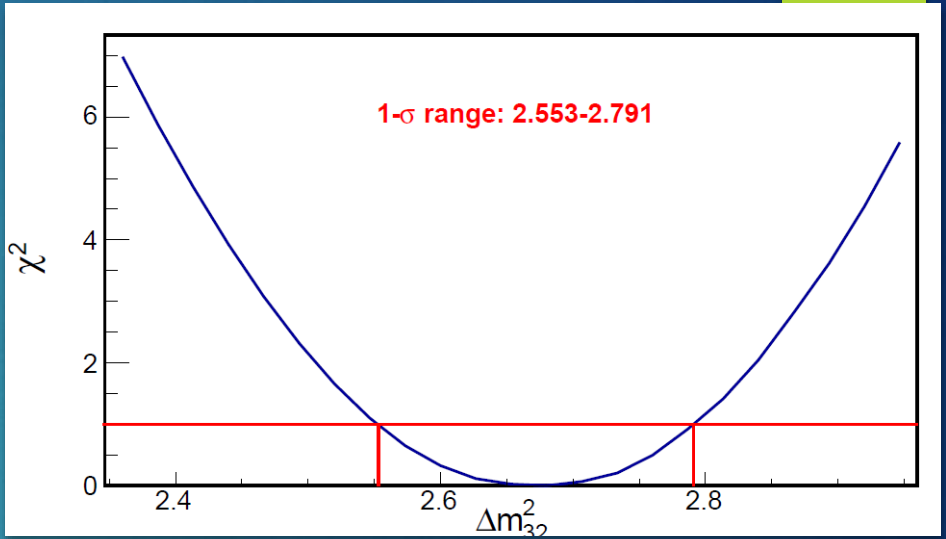


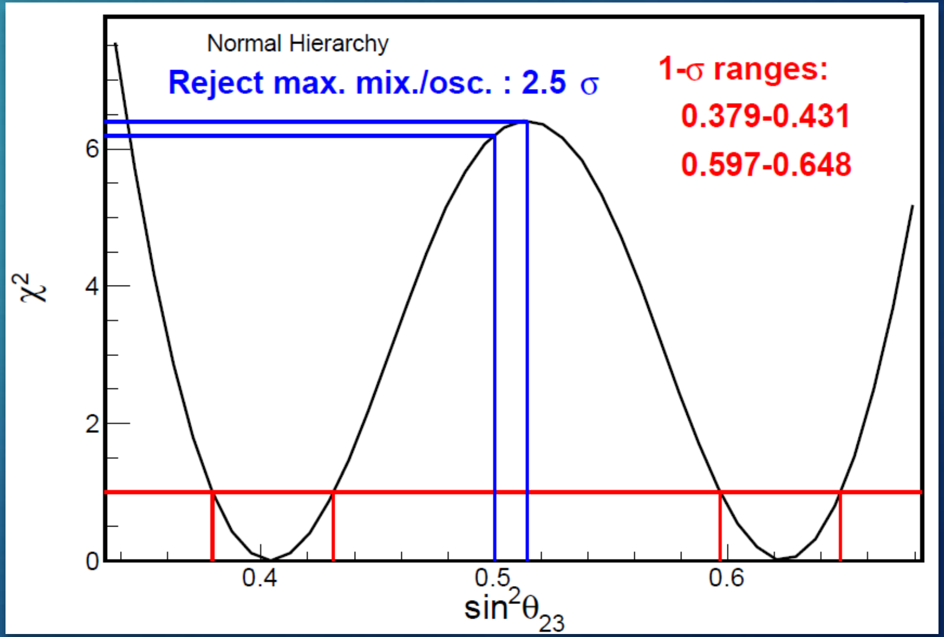
ν_μ Disappearance

- 1-D profiles



$$|\Delta m^2_{32}| = 2.67 \pm 0.12 \times 10^{-3}\mathrm{eV}^2$$
$$\sin^2\theta_{23} = 0.40^{+0.03}_{-0.02}(0.63^{+0.02}_{-0.03})$$

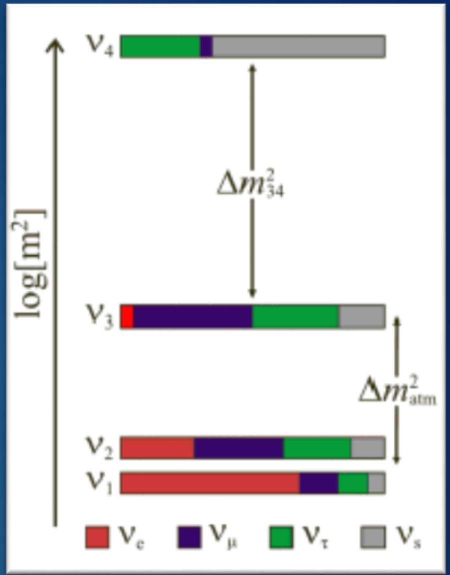


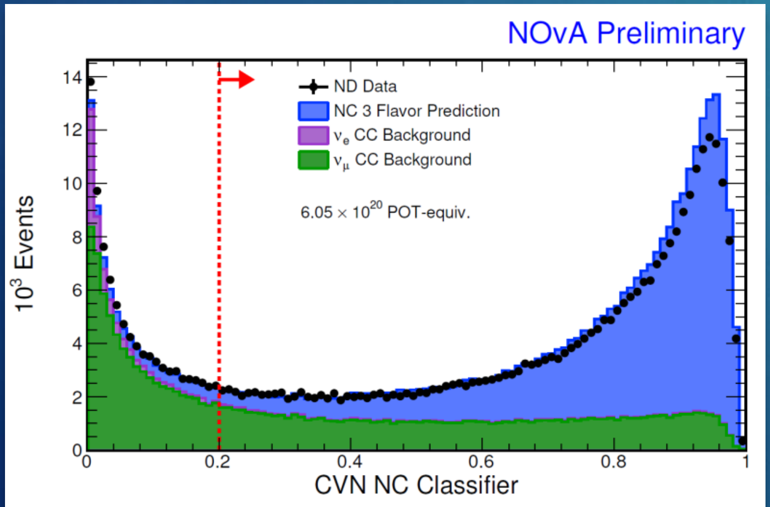


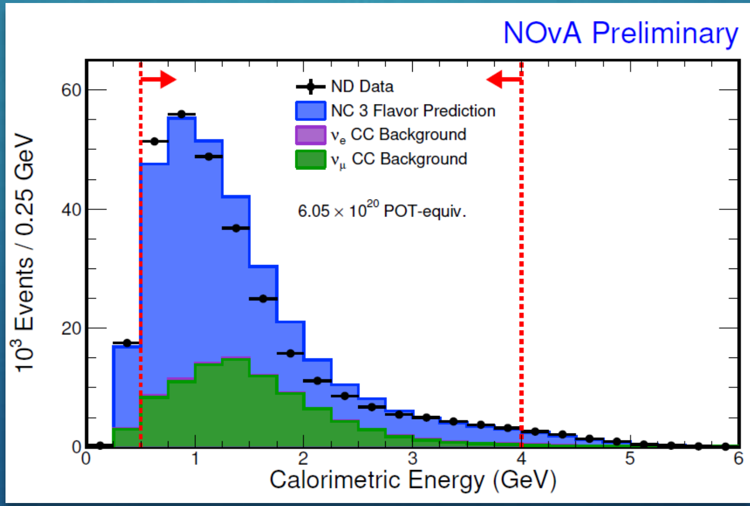
Neutral Current Results

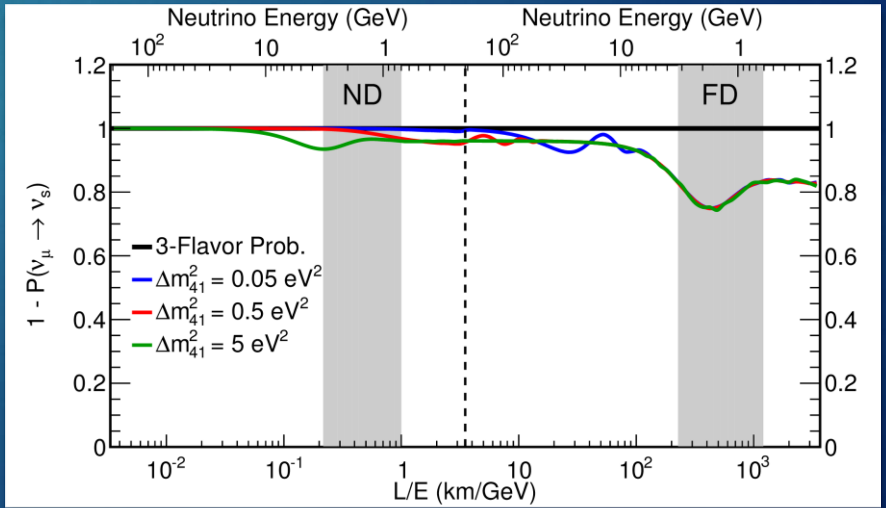
- NC events in the ND with CVN classification, extrapolate to the FD → prediction
- Count NC events in FD, compare to prediction
- For Δm^2_{41}=0.5 eV^2 rapid oscillations in FD, minimal in ND

- Normalization agrees well
- Data shifted to lower energy relative to MC
  - No MEC model for NC events
  - Large uncertainties on NC cross section









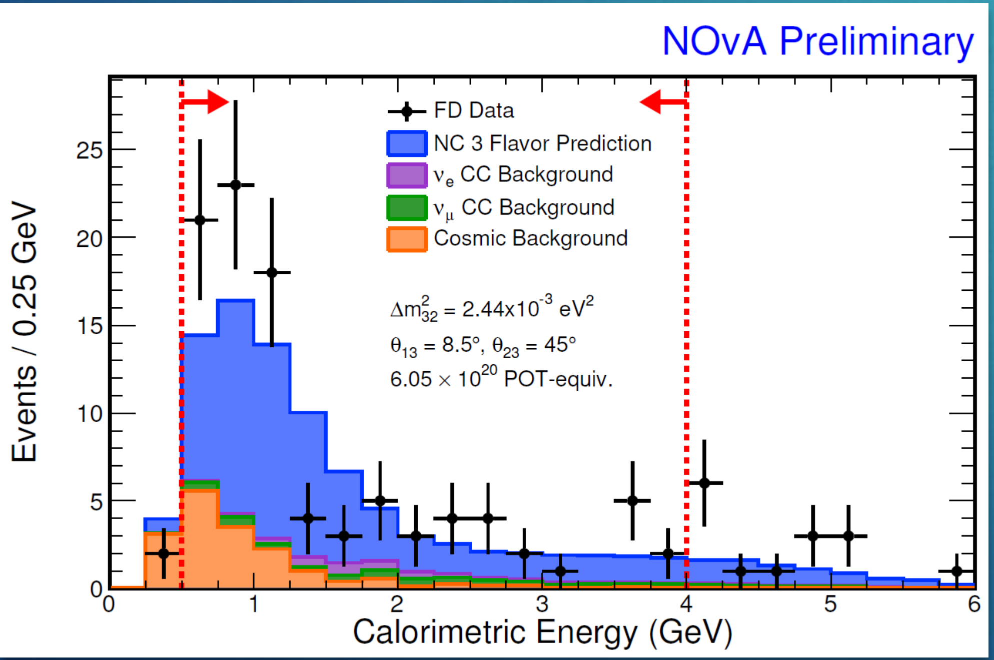
Neutral Current Results

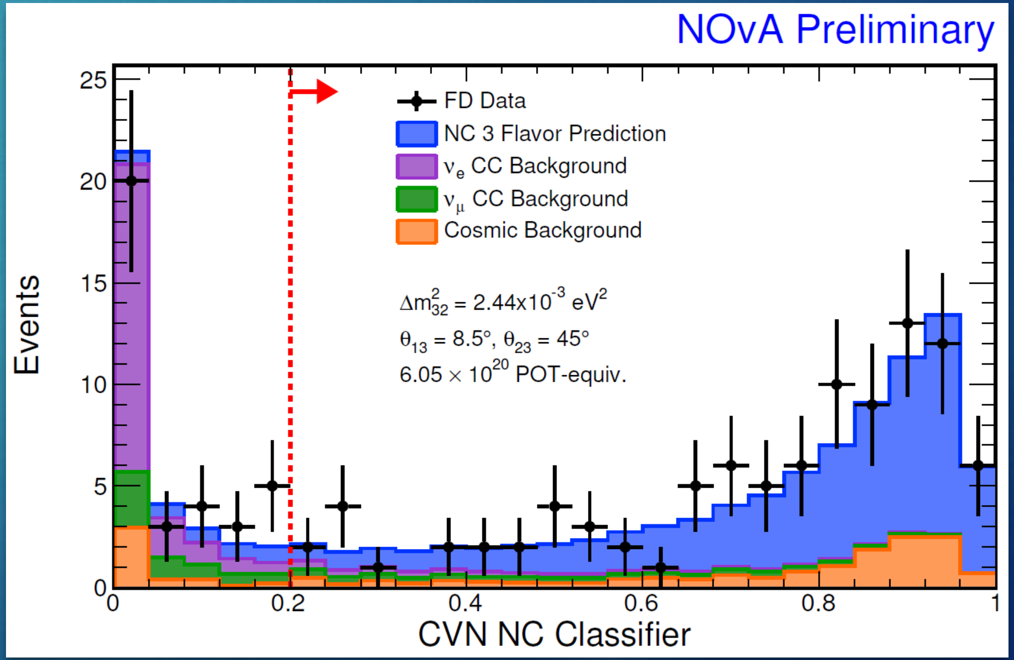
- Predicted events in the FD for 3-flavour mixing: **83.7** (60.6 NC, 4.8 ν_μ CC, 3.6 beam ν_e, 14.3 cosmics)
- Observed NC-like events in the FD: **95**

No evidence of oscillations involving steriles, consistent within 1σ

For 0.05 eV^2 < Δm^2_{41} < 0.5 eV^2 θ_{34} < 35° , θ_{24} < 21° (90% CL)

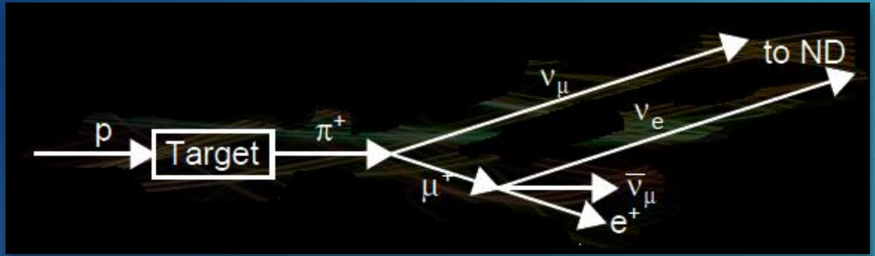
Excellent NC efficiency (50%) and purity (72%) promise strong future limits on θ_{34}





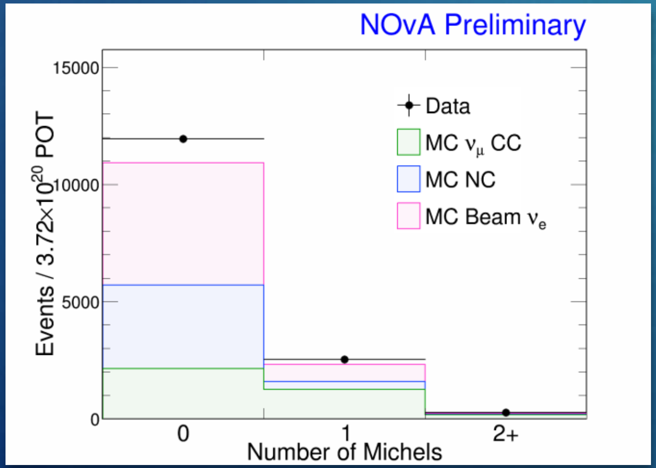
ν_e Results

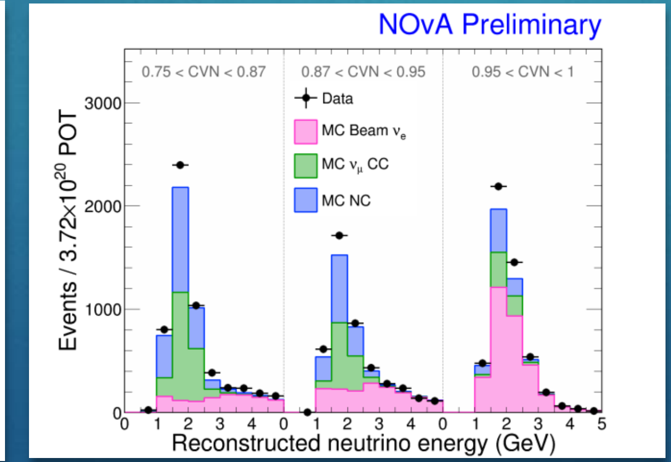
- CVN: 73% ν_e signal efficiency, 76% purity
- Use ND data to predict FD background, every component propagate differently:
  - Beam ν_e CC



- low-E ν_e and ν_μ trace back to the same π+ ancestor
- Use selected ν_μ CC events to constrain beam ν_e : reweight Kaon and Pion component to match the ν_μ CC energy spectrum in the data
- Overall effect is a 4% increase → Fix ν_e CC to flux-reweighted in the ND

  - ν_μ CC: use Michel-electron distribution to constrain





- Michel-e⁻ are produced also in ν_e CC and NC by pions but ν_μ has ~1more
- Fit observed N_{michel} in each bin
- Data excess assigned between NC(+10%) and ν_μ CC (+10%)

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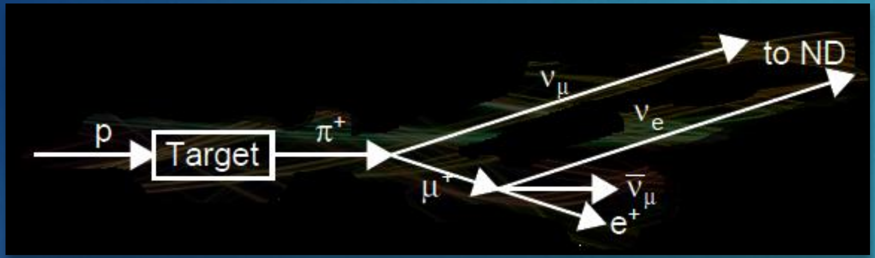

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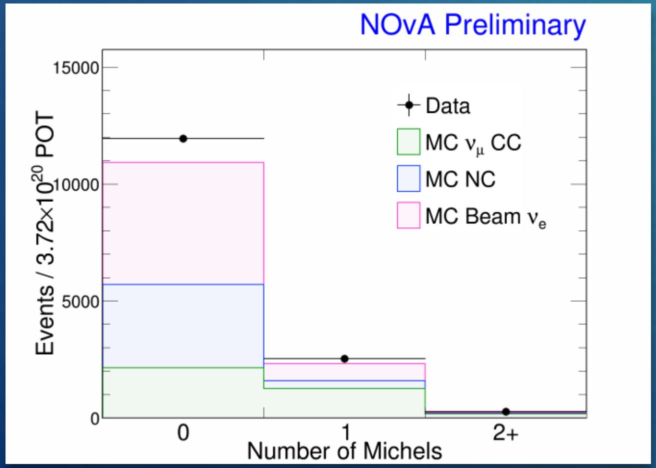

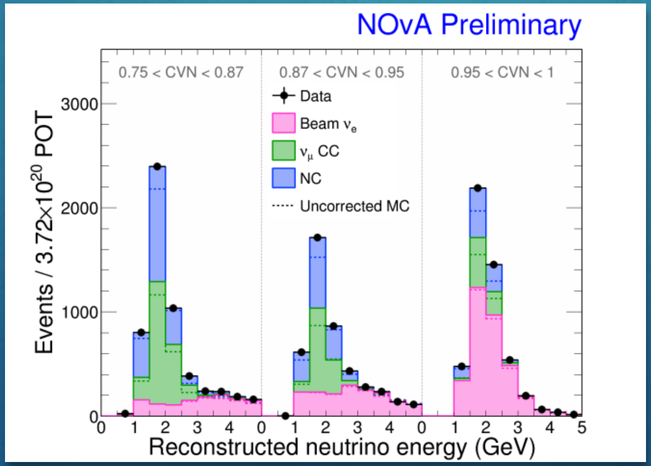

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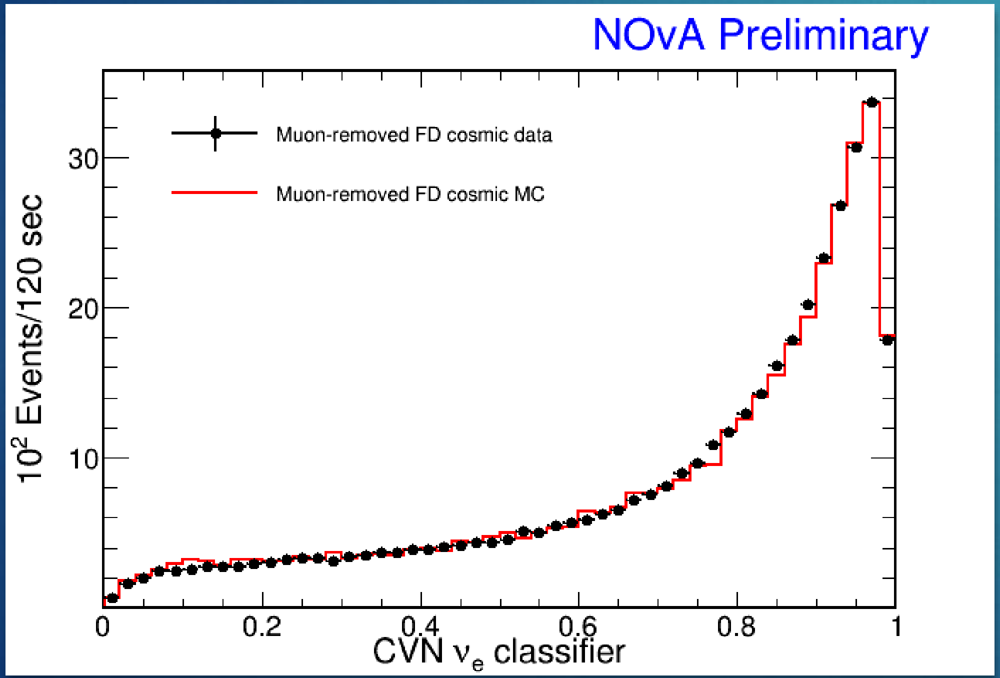
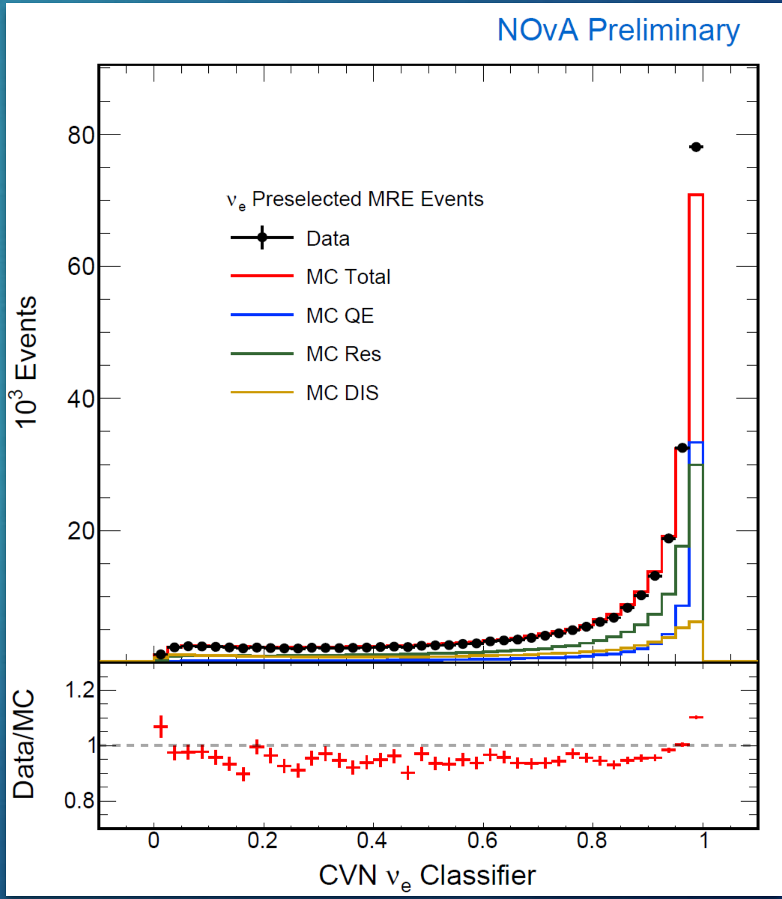
ν_e Results

Checking Signal Efficiency

- Far detector: Remove muon track in cosmic rays to select Brem. Showers → simulation of EM showers matches well

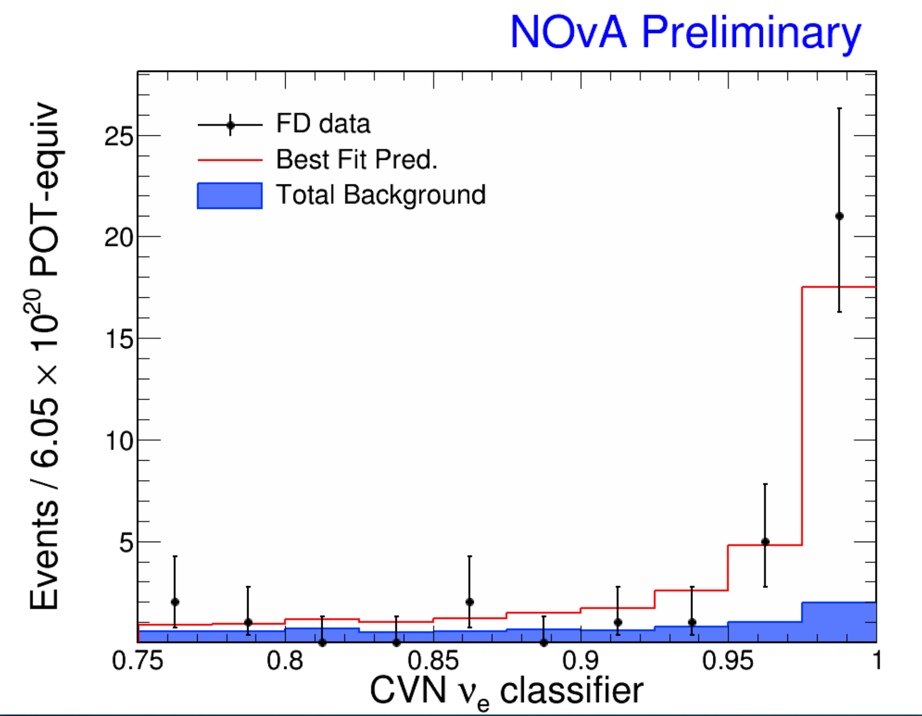


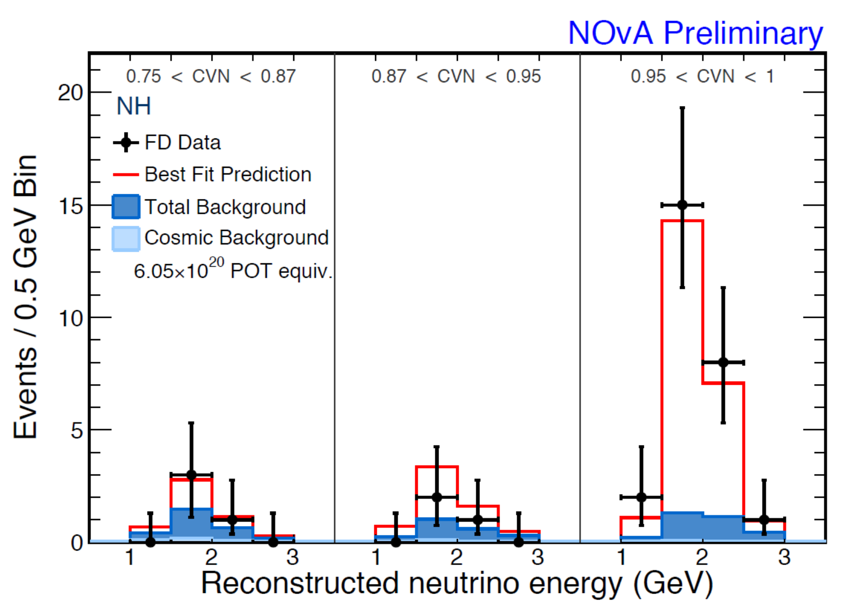
- Near Detector: replace muon tracks from ν_μ CC data with simulated electron showers → data/MC difference < 1%

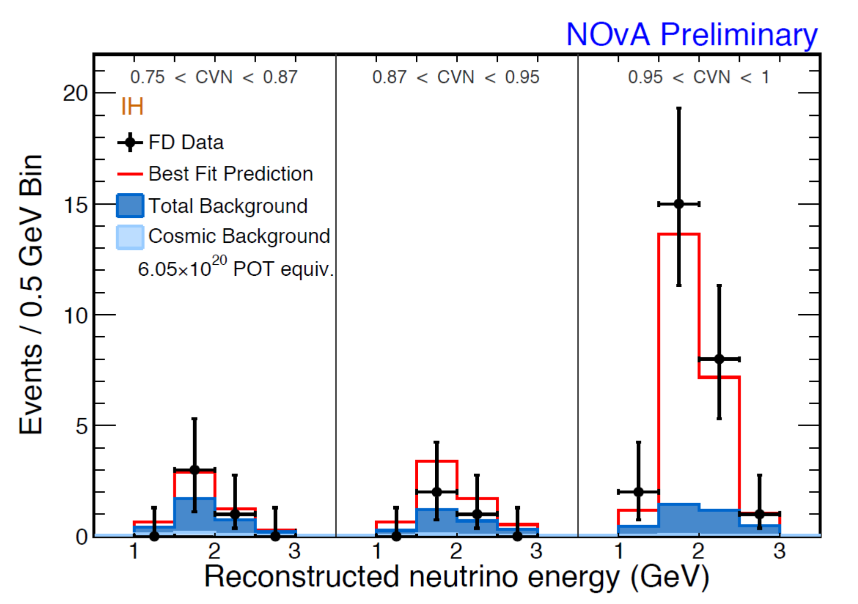


ν_e Results

FD data

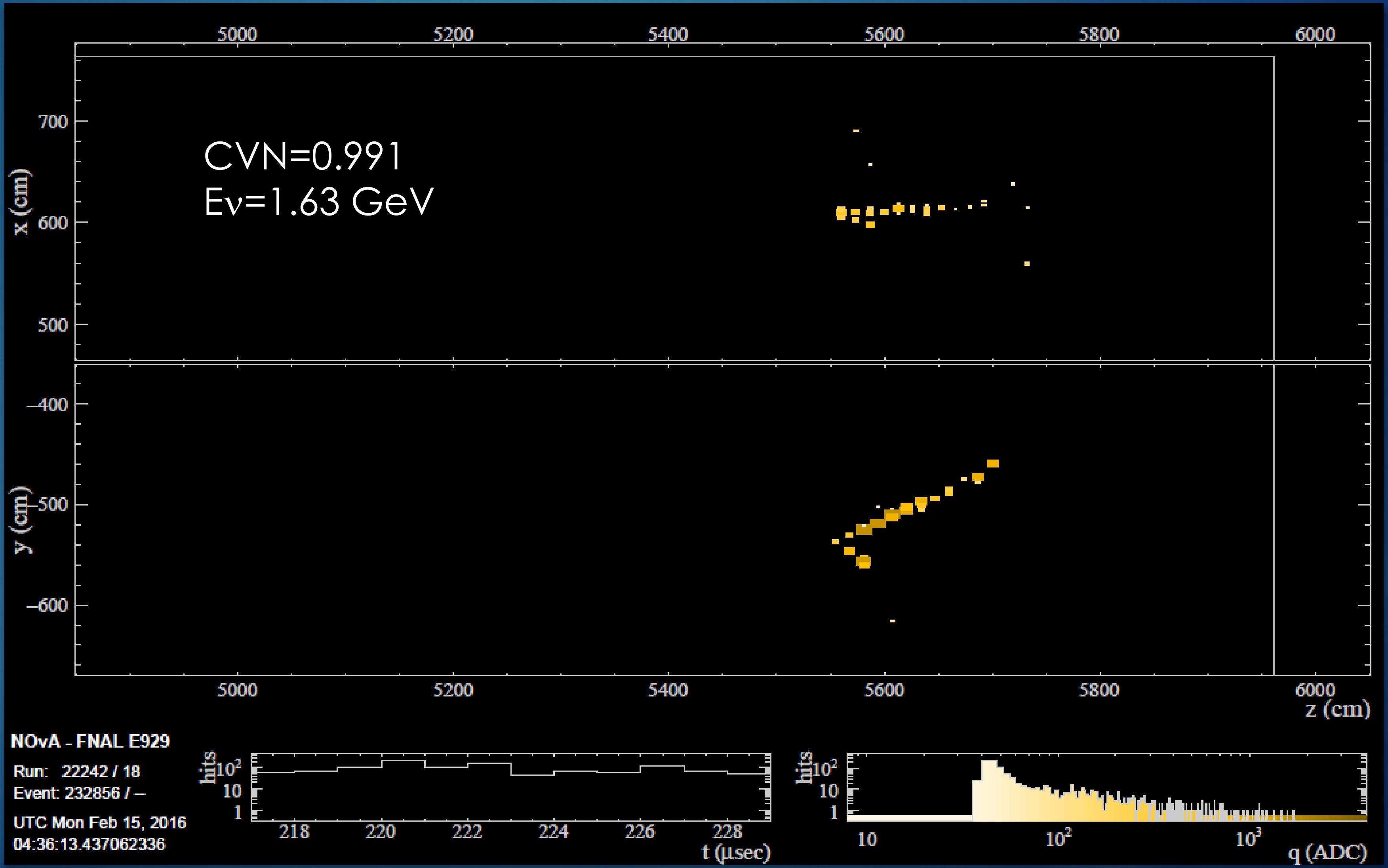






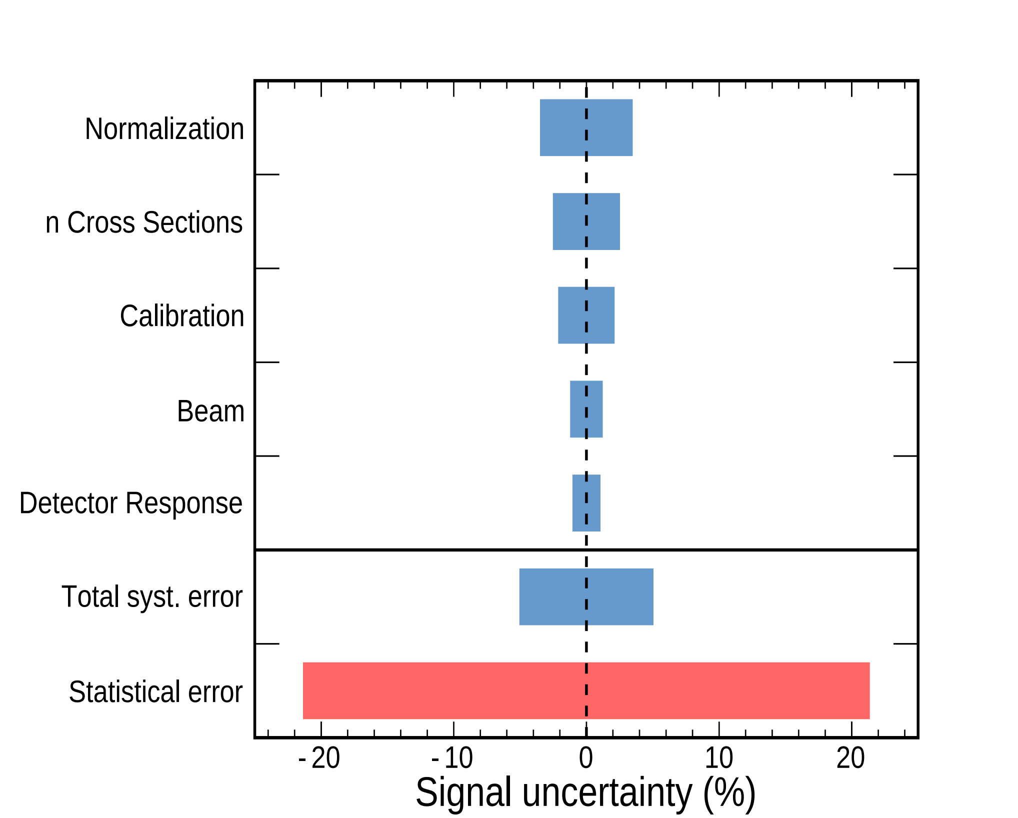
ν_e Results

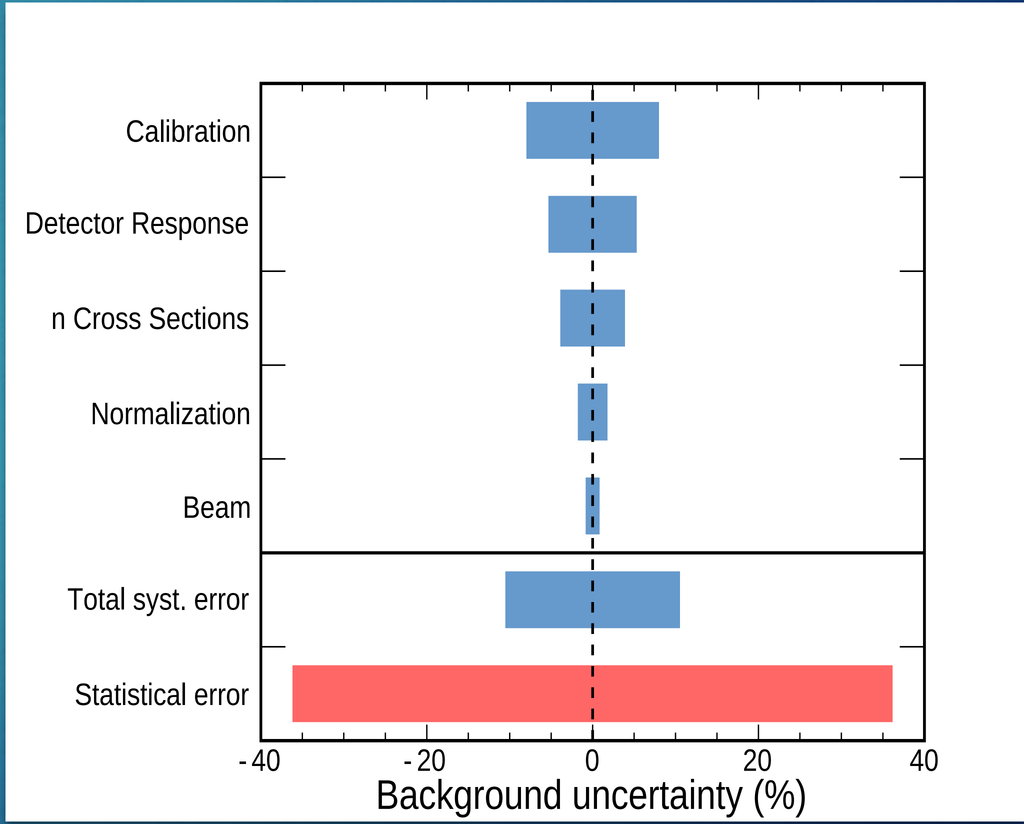
FD data



ν_e Results

Systematics





ν_e Results

Selection