The NOvA Experiment

Users Meeting 2017

Kanika Sachdev

Fermilab

June 08, 2017

Neutrinos Oscillate

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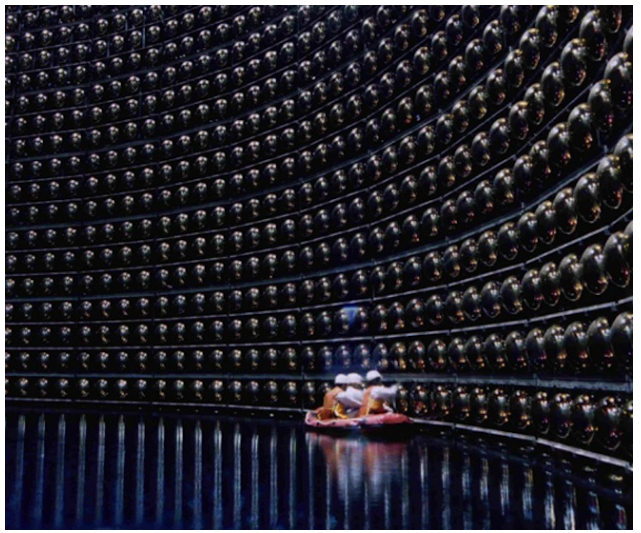
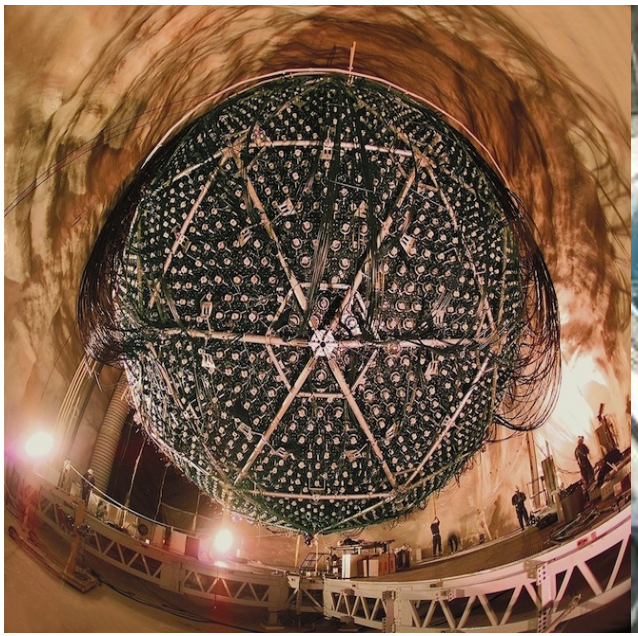
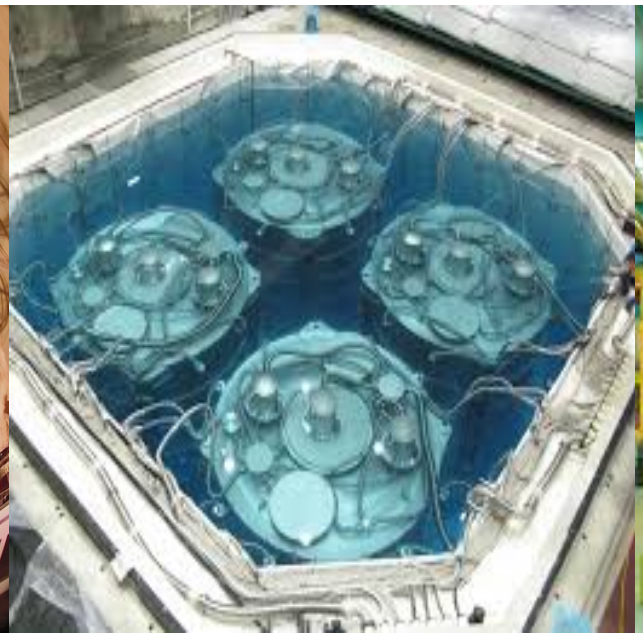
* Neutrino oscillation are a firmly established Beyond Standard Model phenomenon







Unanswered Questions in Neutrino Physics

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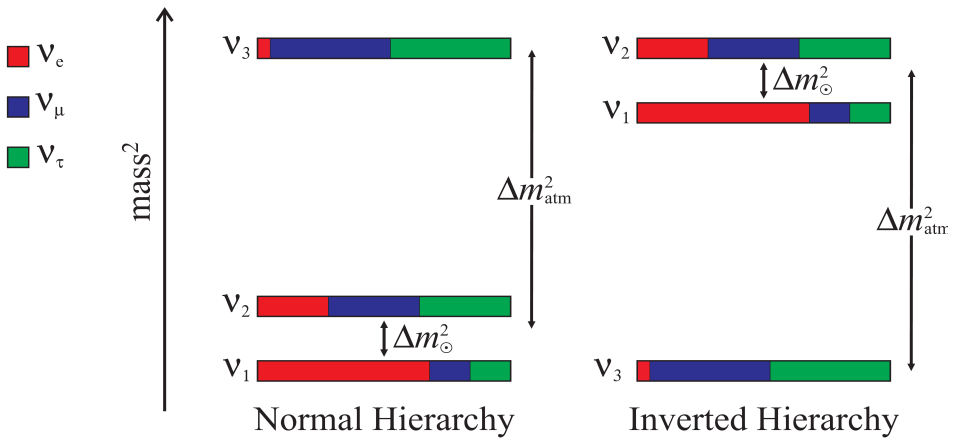
- Hierarchy of neutrino mass states :

  Normal or Inverted?

- Flavor content of ν_3: is θ_{23} maximal ie

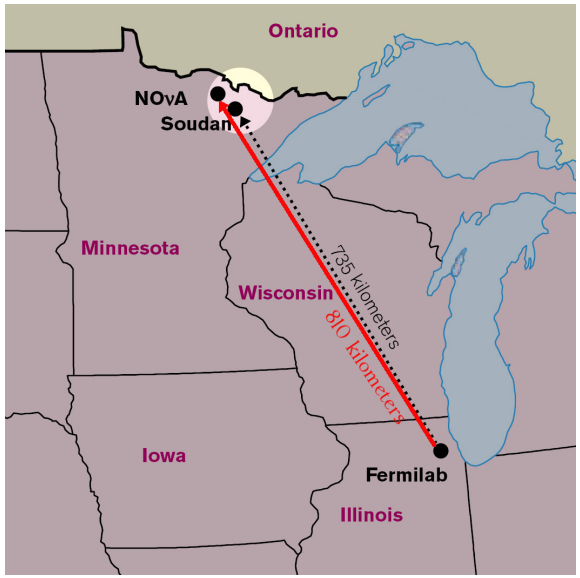
  $\pi/4$?

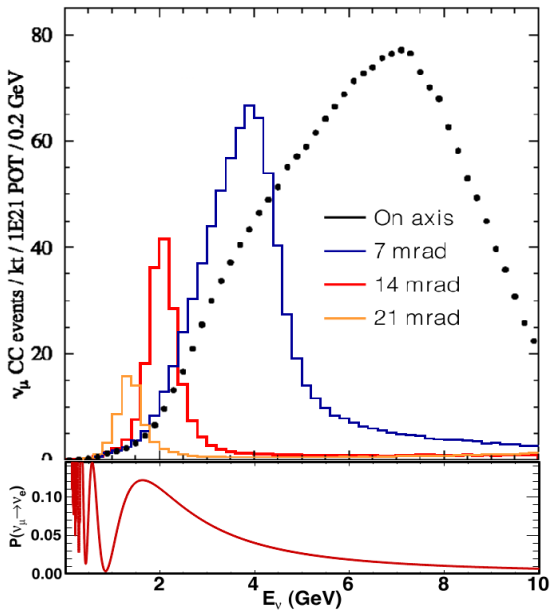
- Is CP violated by neutrinos: do neutrinos and anti-neutrinos oscillate differently?



The NOvA Experiment

- NOvA (NuMI Off-axis ν_e Appearance) is a neutrino oscillation experiment
  - Baseline of 810 km
  - NuMI, beam of mostly ν_μ
  - 14 mrad off-axis from the beam





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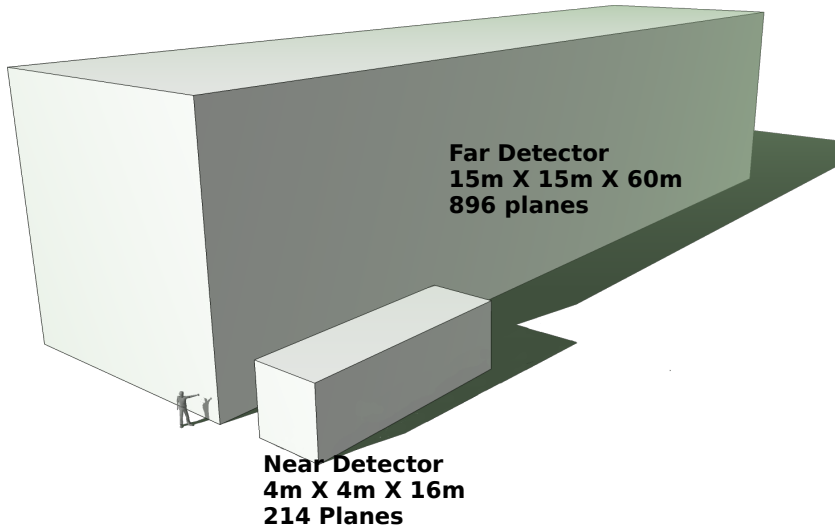

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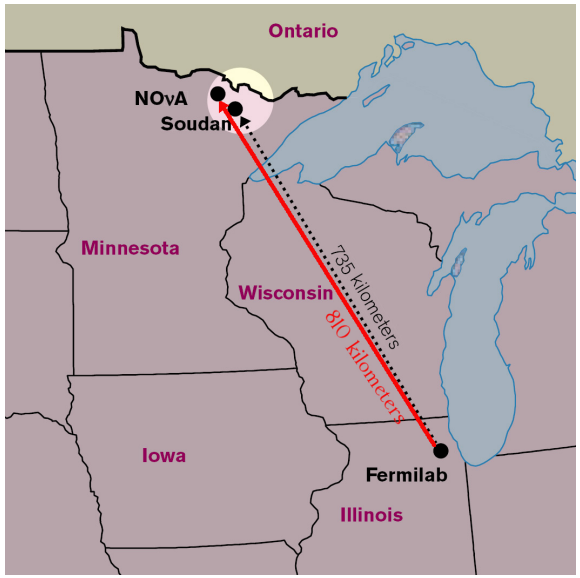
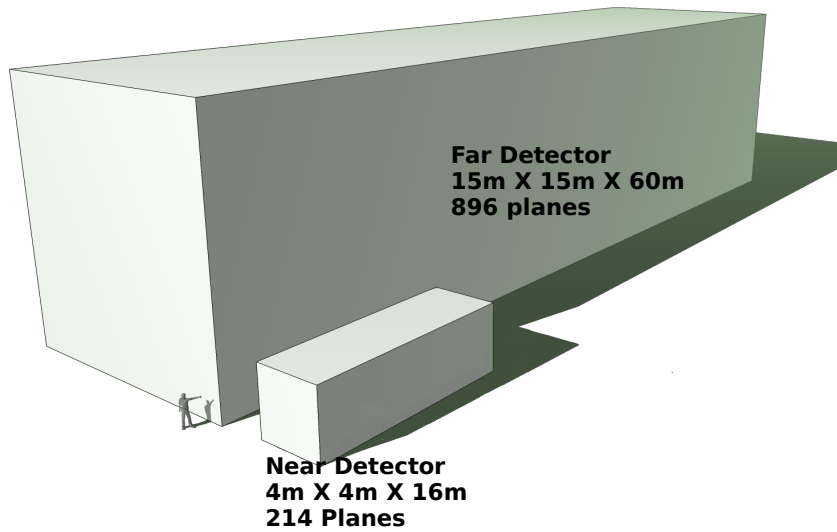
  - $\nu_\mu(\bar{\nu}_\mu)$ to $\nu_\mu(\bar{\nu}_\mu)$ (disappearance)
  - $\nu_\mu(\bar{\nu}_\mu)$ to $\nu_e(\bar{\nu}_e)$ (appearance)





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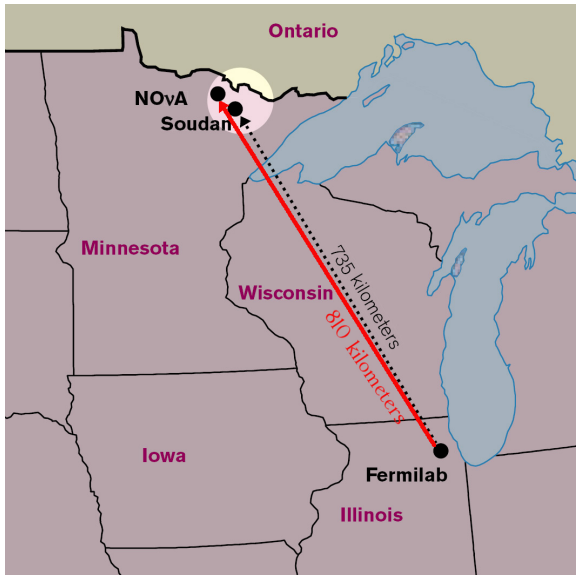
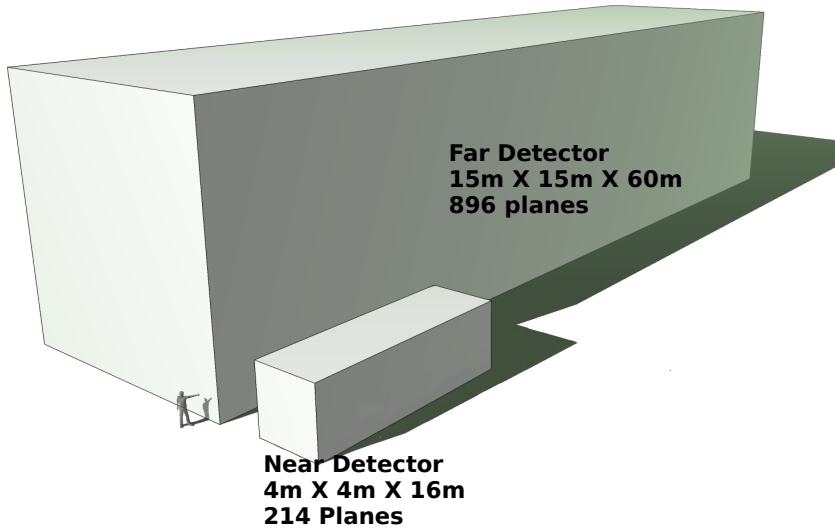
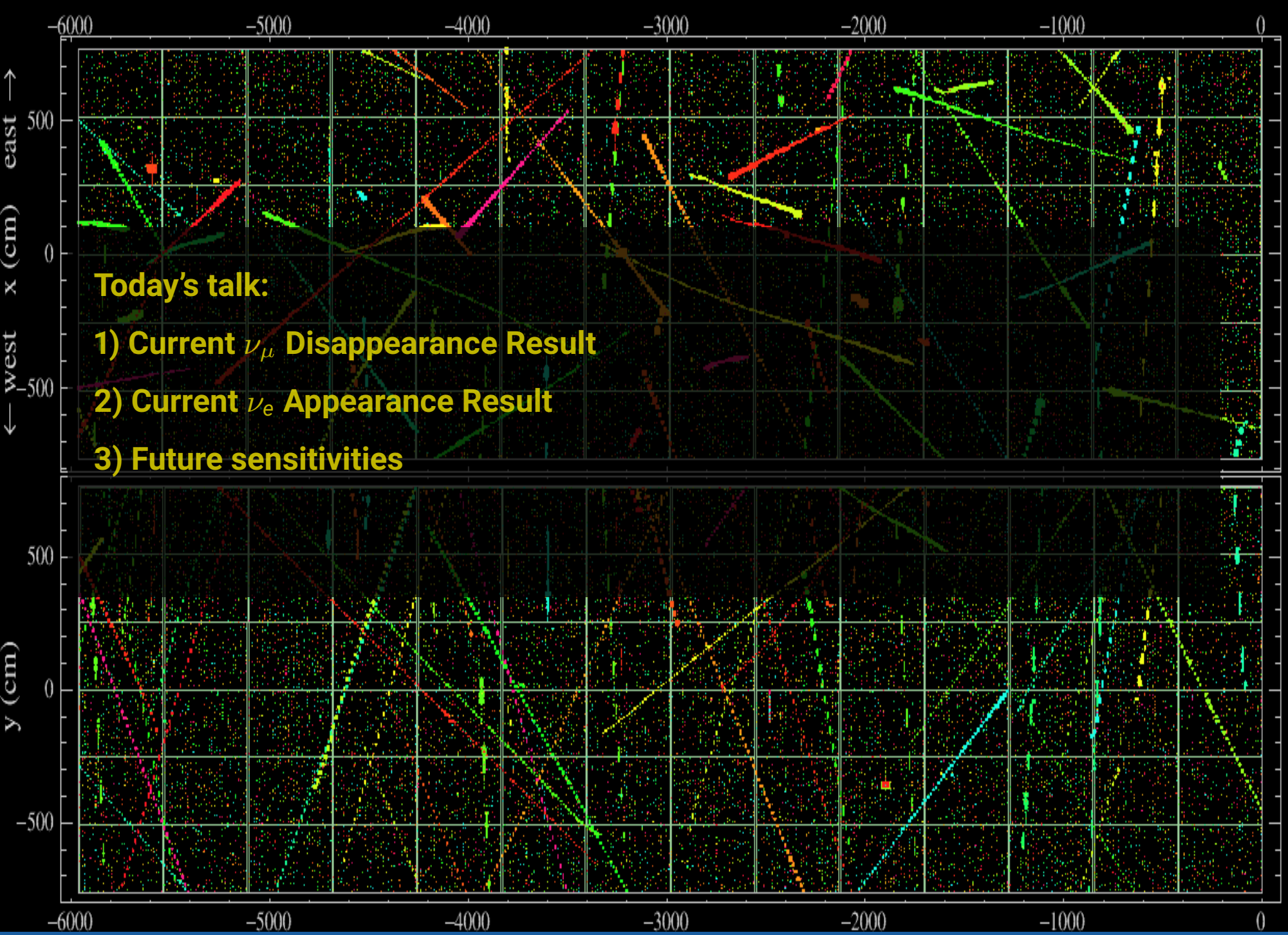
  - Sterile neutrino search
  - Cross-section measurements, supernovae, search for BSM phenomena etc






−6000
−5000
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−2000
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0
500
0
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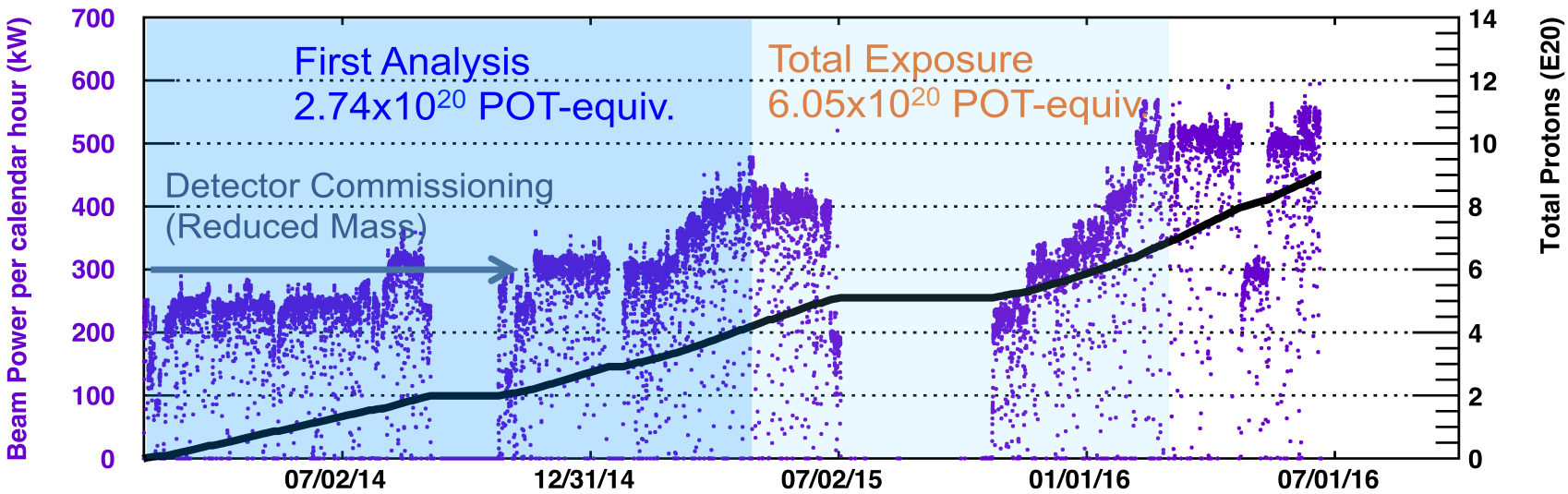
← west x (cm) east →
Today's talk:
1) Current ν_μ Disappearance Result
2) Current ν_e Appearance Result
3) Future sensitivities
500
0
−500
y (cm)
−6000
−5000
−4000
−3000
−2000
−1000
0

Data Used In Current Oscillation Analyses

Fermilab

- Full detector equivalent exposure: **6.05** $\times$ **10**^{20} POT
- More than double the exposure of the 2015 analyses
- Excellent beam!



- Hit 700 kW earlier this year, running routinely around 650 kW these days
- Currently running in anti-neutrino mode, since February 2017

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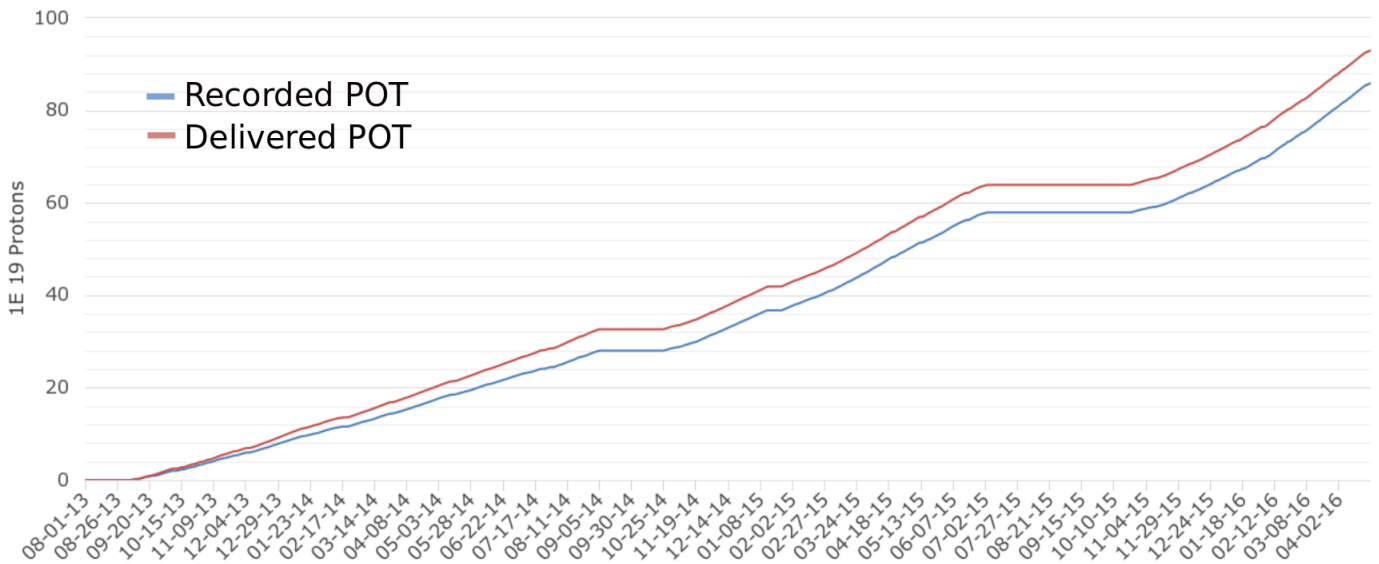
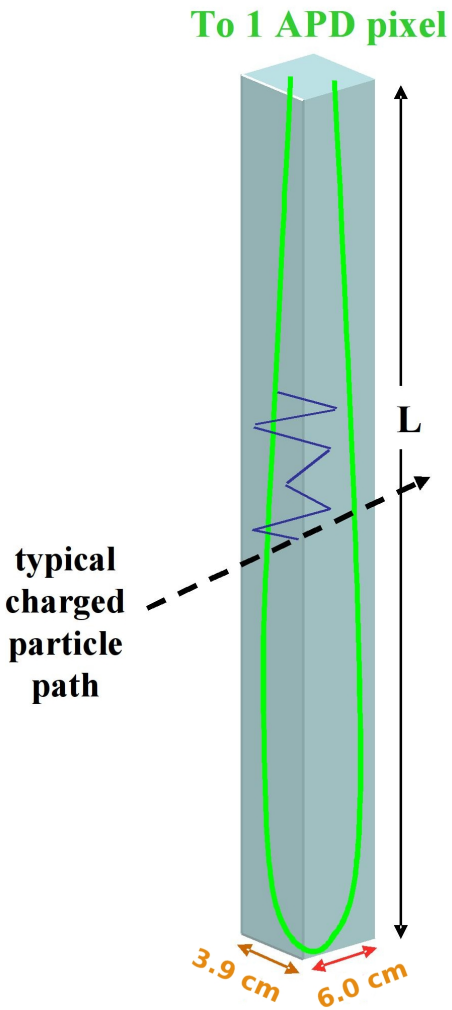
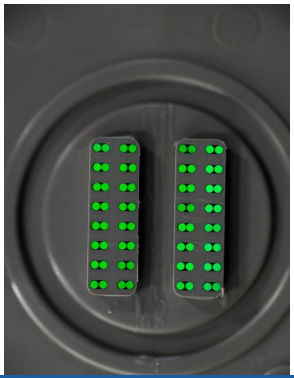
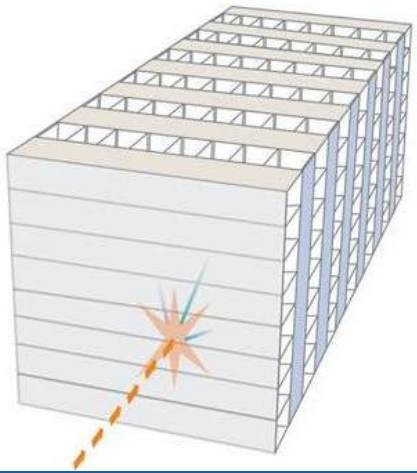


- FD has recorded 93% of the delivered POT over all time
- Currently operating at 98% efficiency



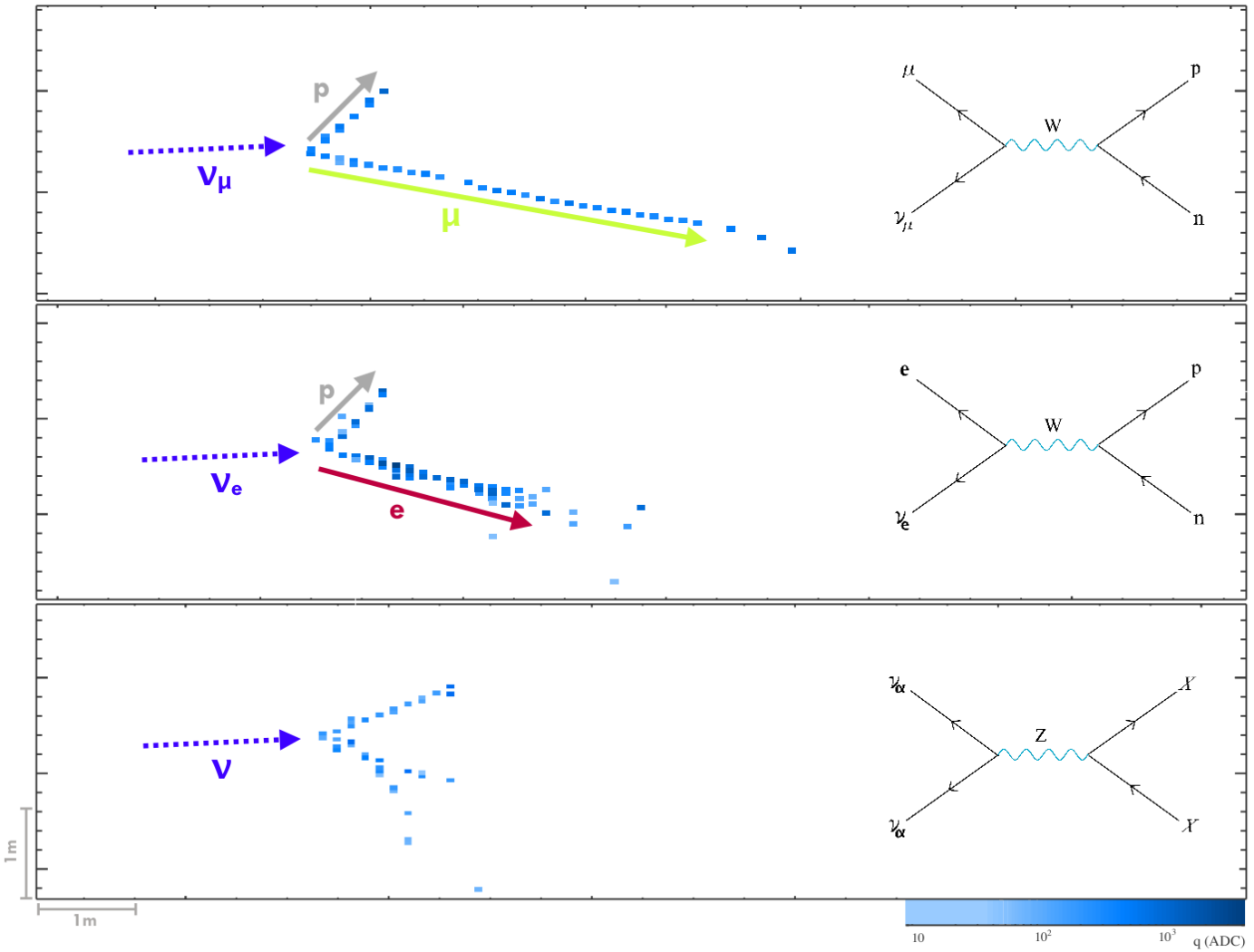
- Composed of PVC modules extruded to form long tube-like cells : 15 m long in FD, 4 m ND
- Each cell is filled with liquid scintillator
- Optical fiber loop carries scintillation light to a pixel on an Avalanche Photo Diode (APD)
- Cells arranged in planes, with alternating planes perpendicular in orientation
- Detectors are 65% active





Neutrino Events In NOvA

- Low-Z material, each plane samples ~ **0.18** radiation-lengths
- Molière radius is ~ **10** cm, 2.5 NOvA cells



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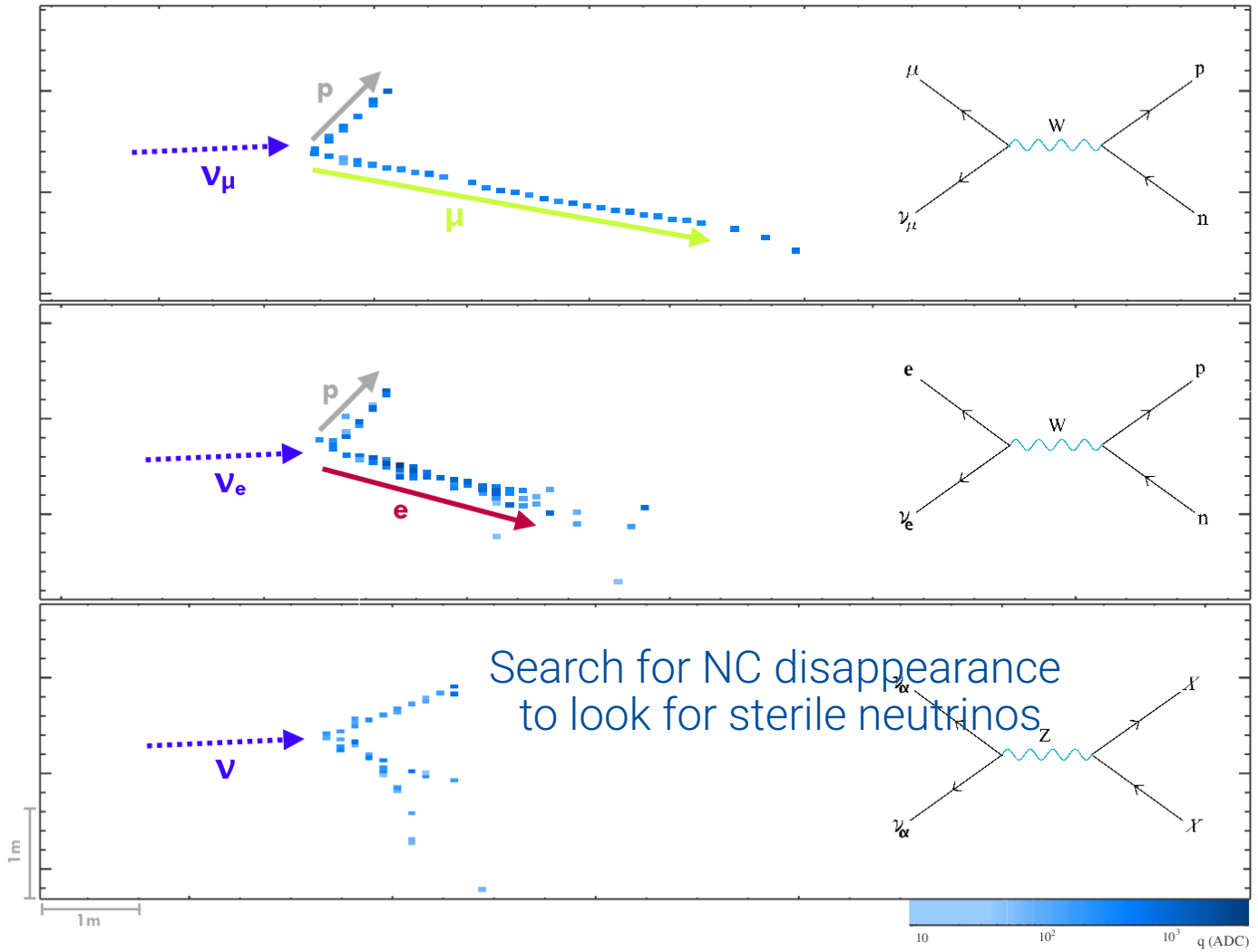
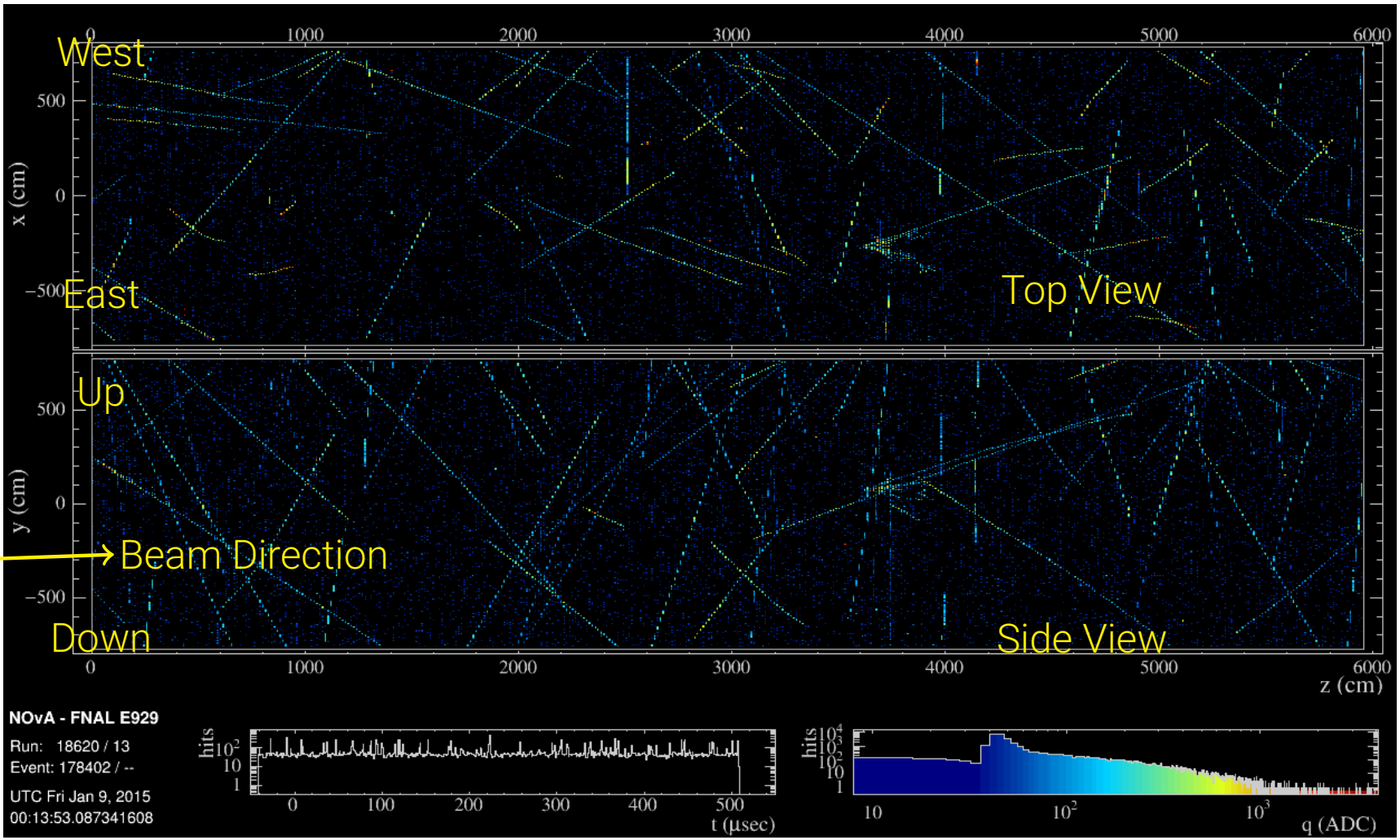


Far Detector Data

- FD is on the surface, 14 kT mass and has $>$ 344,000 channels
- Trigger window is 500 μs, neutrino spill only lasts 10 μs



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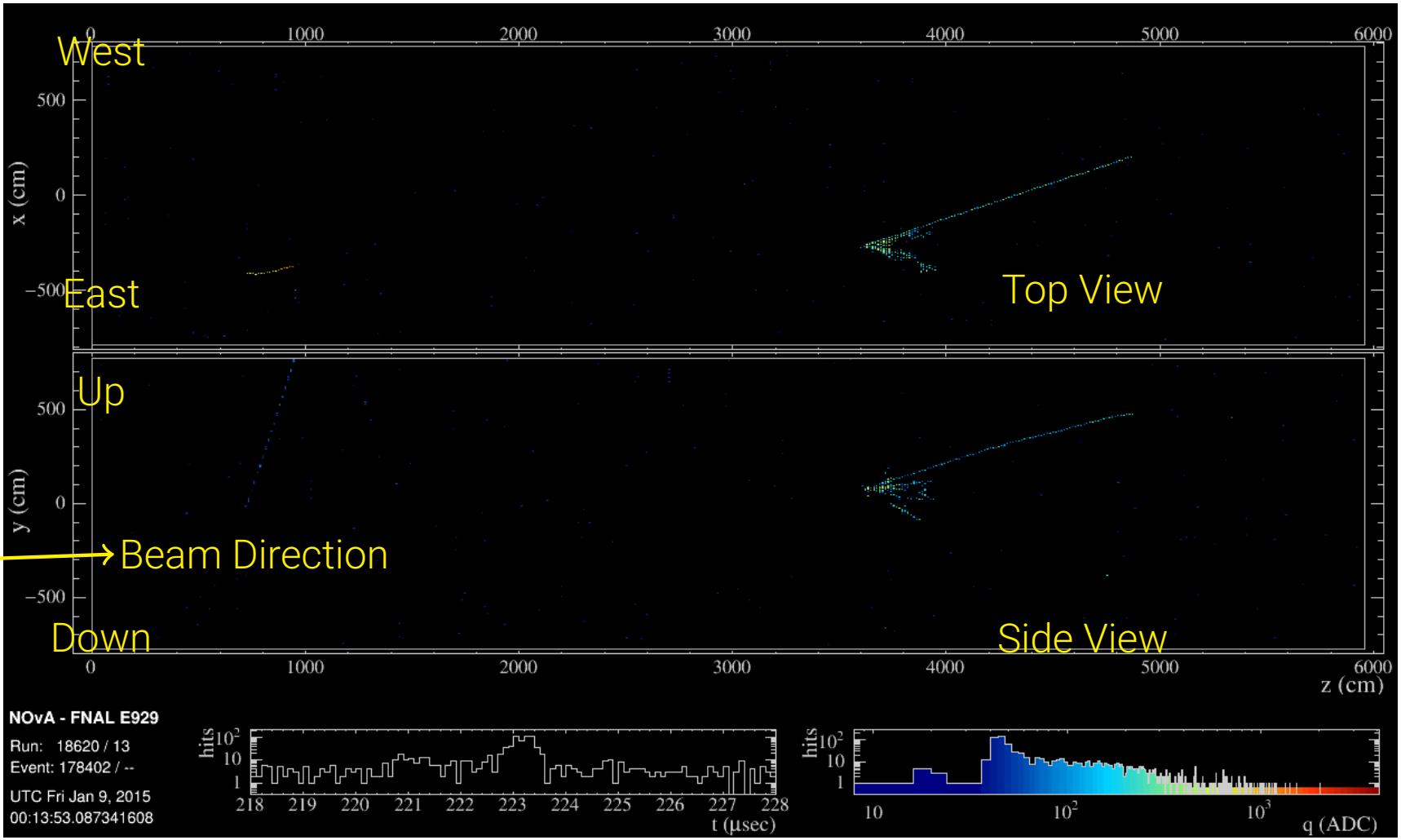

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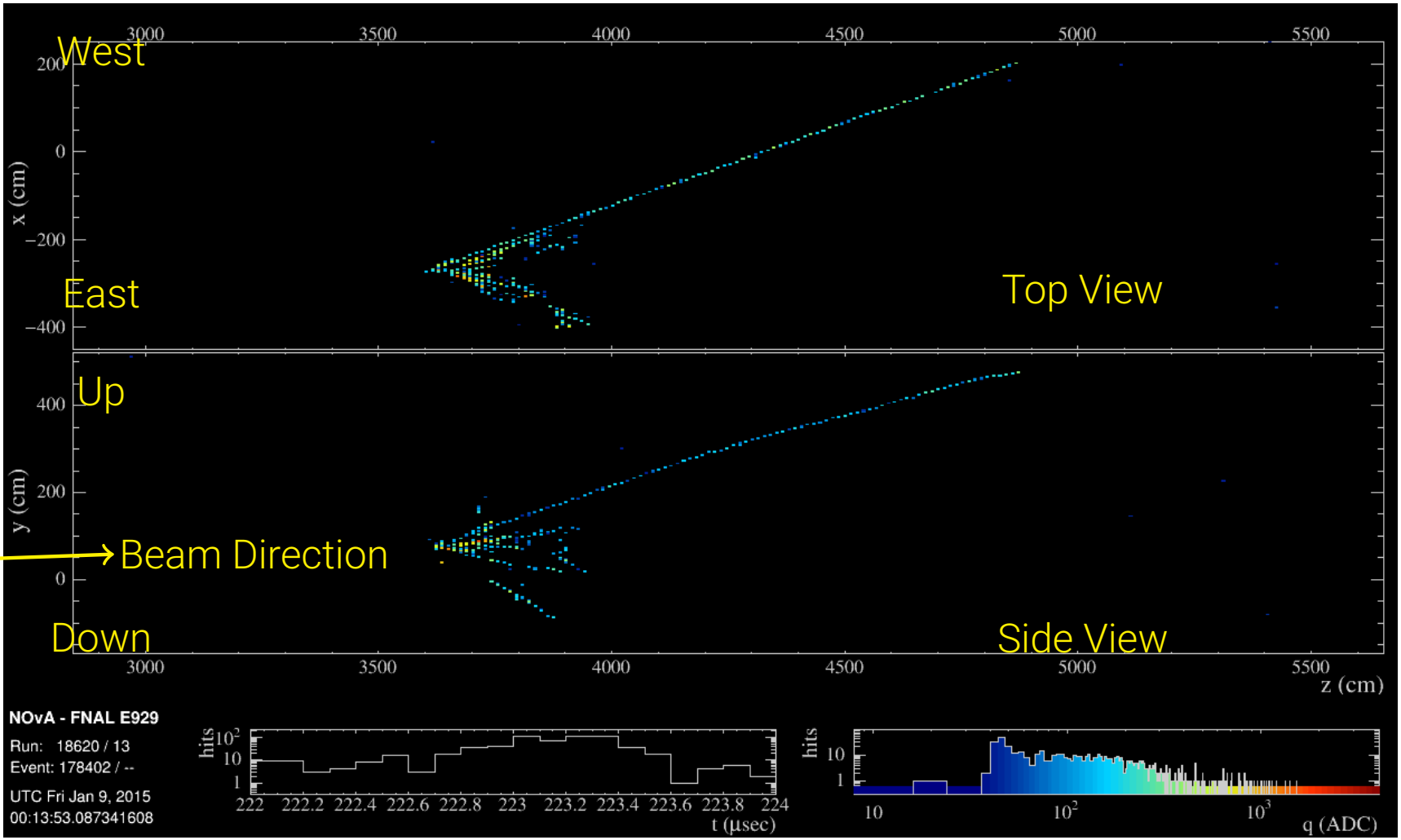

Near Detector Data

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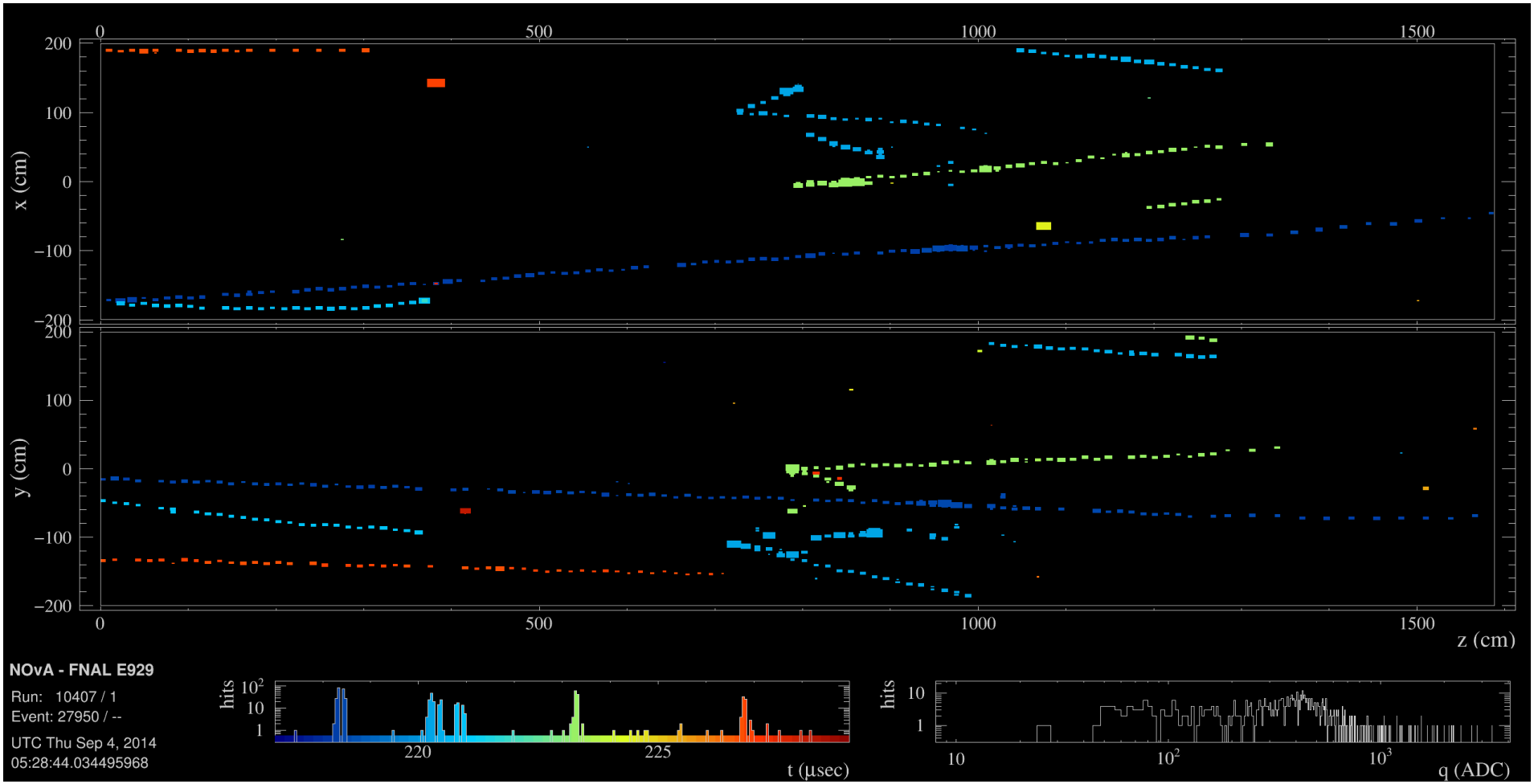
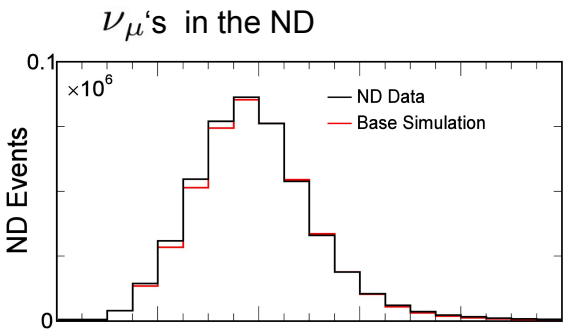
- ND is 100 m underground
- Has 0.3 kT mass and > 20,000 channels

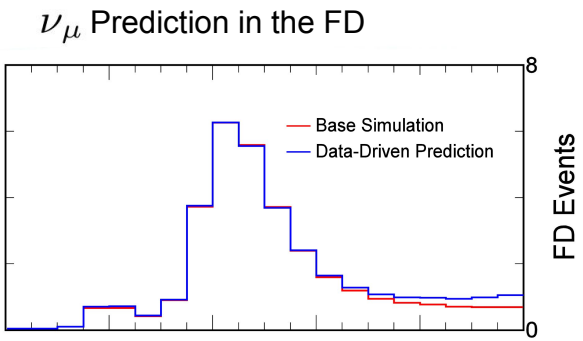


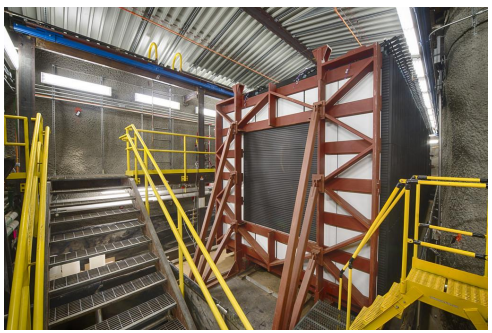
Oscillation Analyses

Two Detector Technique

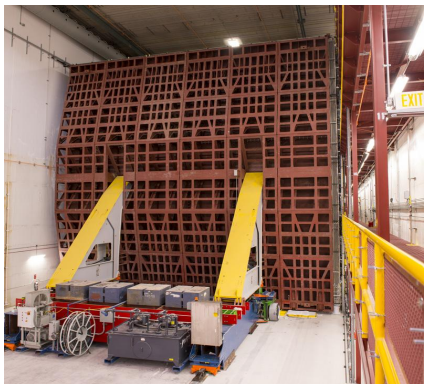
- We use ND data to predict the oscillated spectra in the FD
- Both disappearance ($\nu_\mu \rightarrow \nu_\mu$) and appearance ($\nu_\mu \rightarrow \nu_e$) analyses start with ν_μ's in ND







F/N X P ($\nu_\mu \longrightarrow \nu_\mu$)



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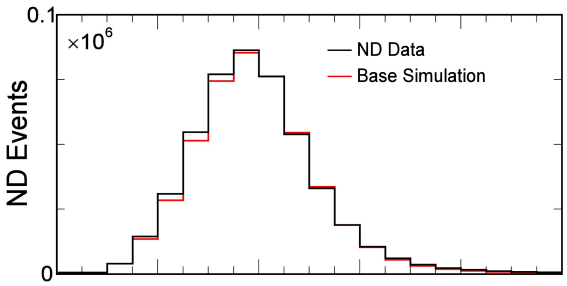
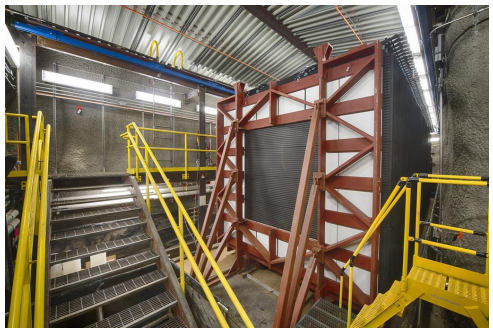
ν_μ's in the ND





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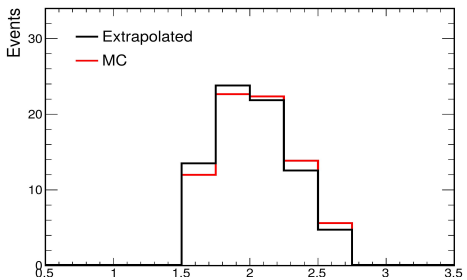
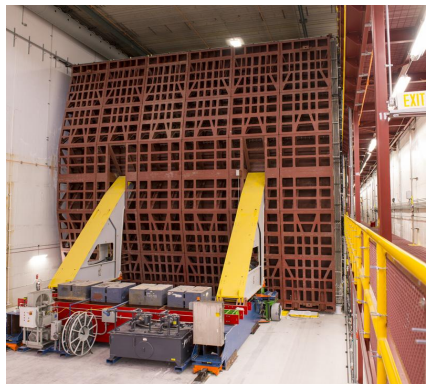
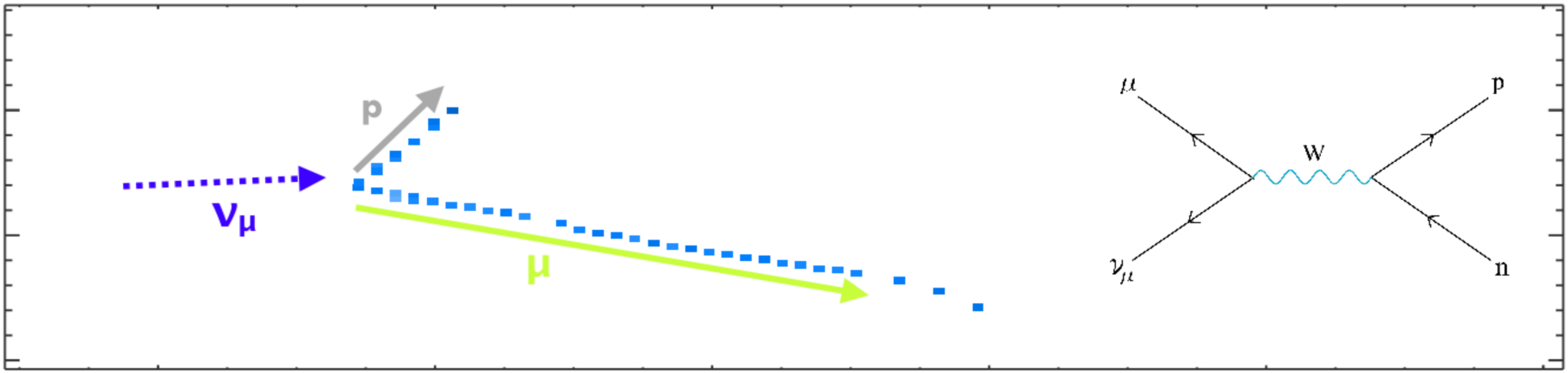
ν_e Prediction in the FD



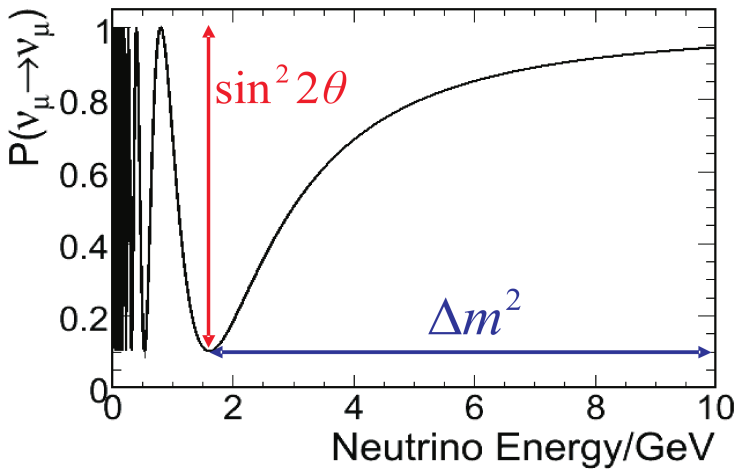


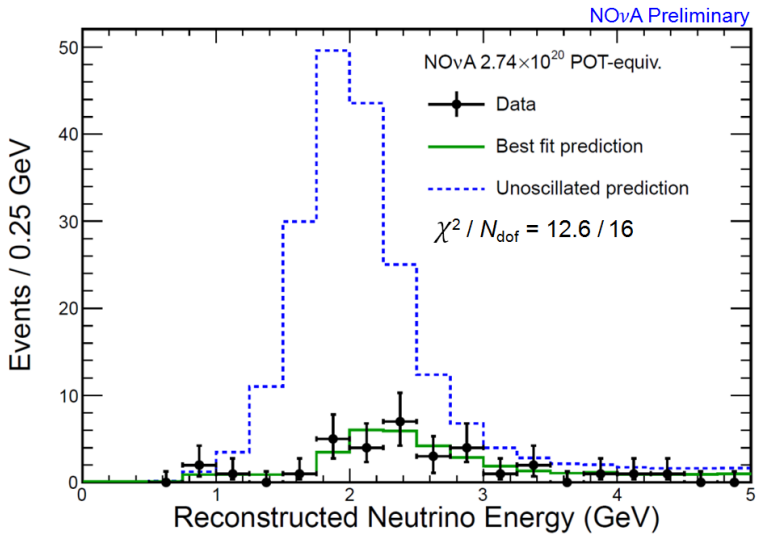
ν_μ Disappearance Analysis

- Requires identification of ν_μ



- Requires energy reconstruction

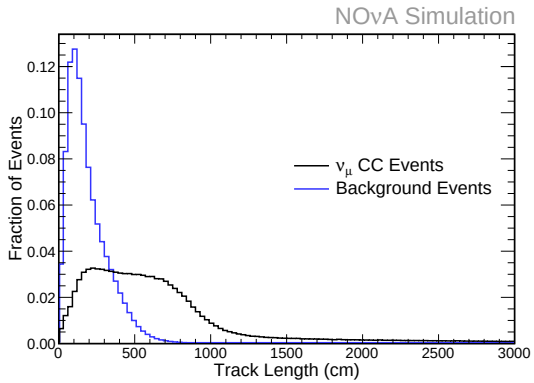


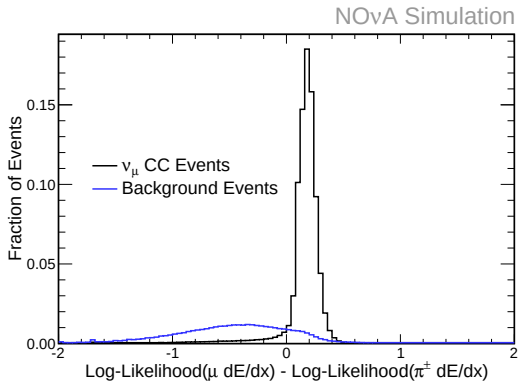


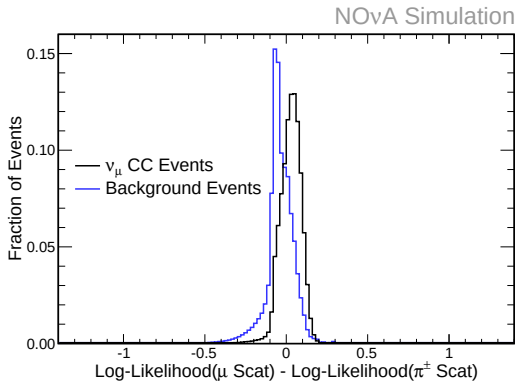
Selection of ν_μ CC

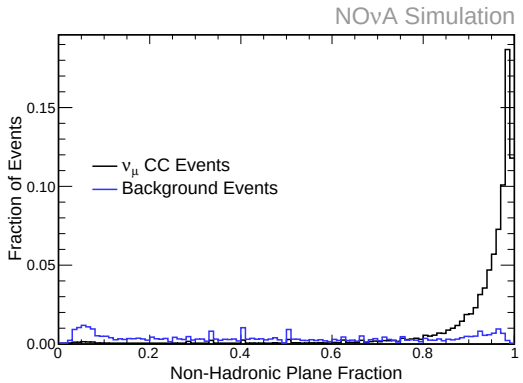
Fermilab

Combine input variables in a k-Nearest Neighbor algorithm
ν_μ selection purity of **95%** and efficiency of **81%**









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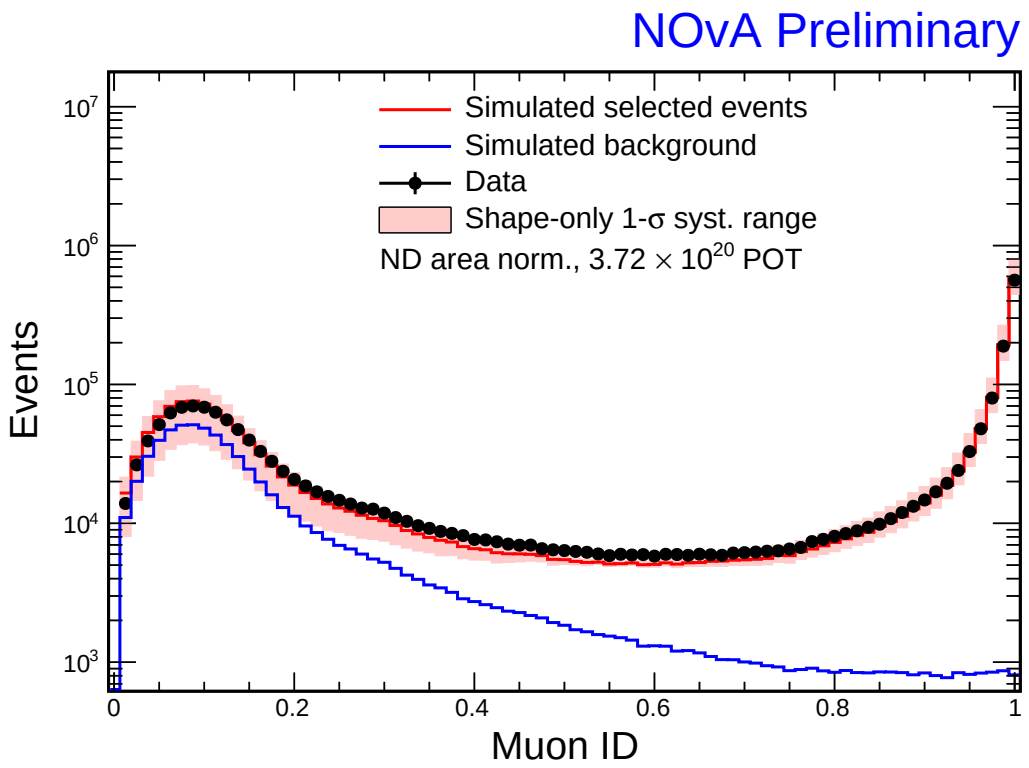
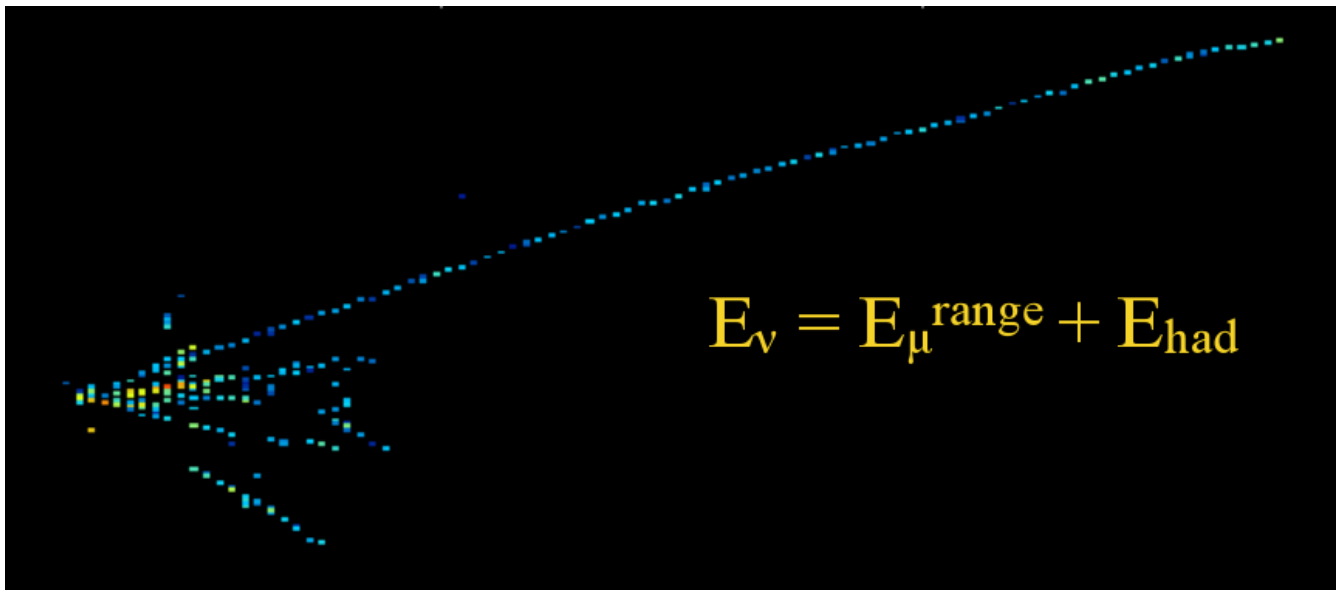


ν_μ Energy Reconstruction

Fermilab

- Muon energy reconstructed from range with resolution $\sim$ 3%
- Hadronic system: $\sum_{cell} E_{visible} \implies E_{had}$, resolution $\sim$ 20%
- Neutrino energy is the sum of the two
- Energy resolution $\sim$ **7%** at beam peak



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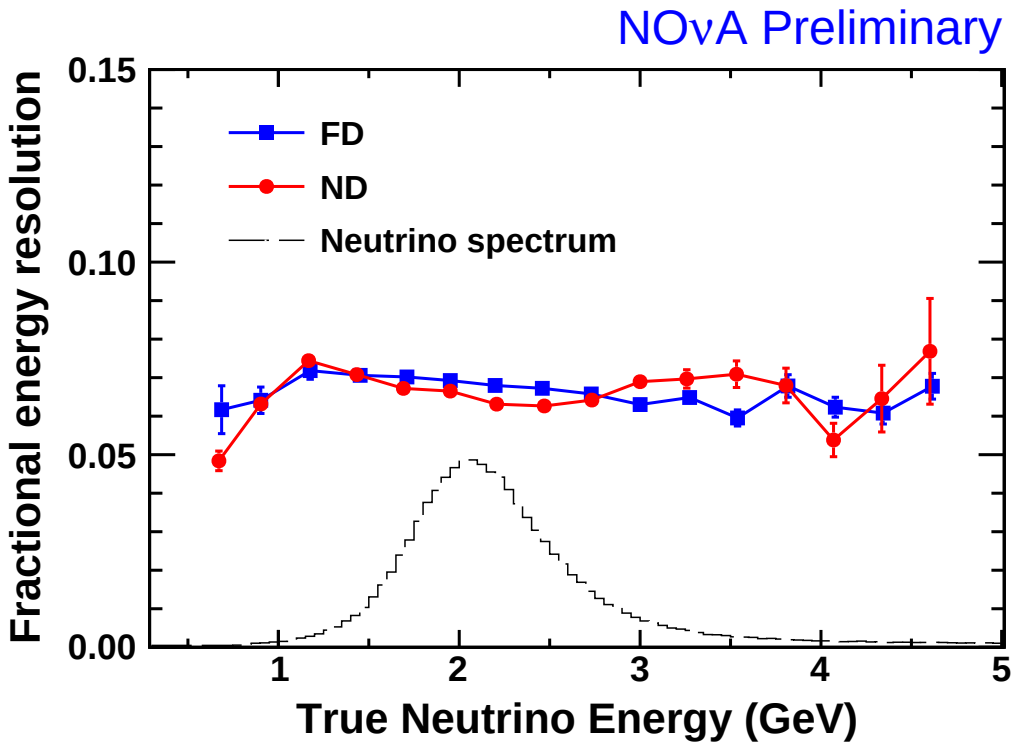
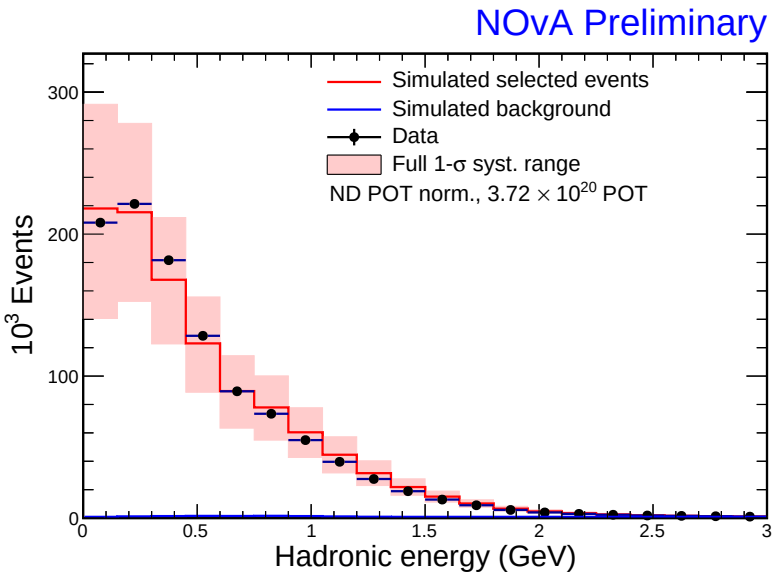
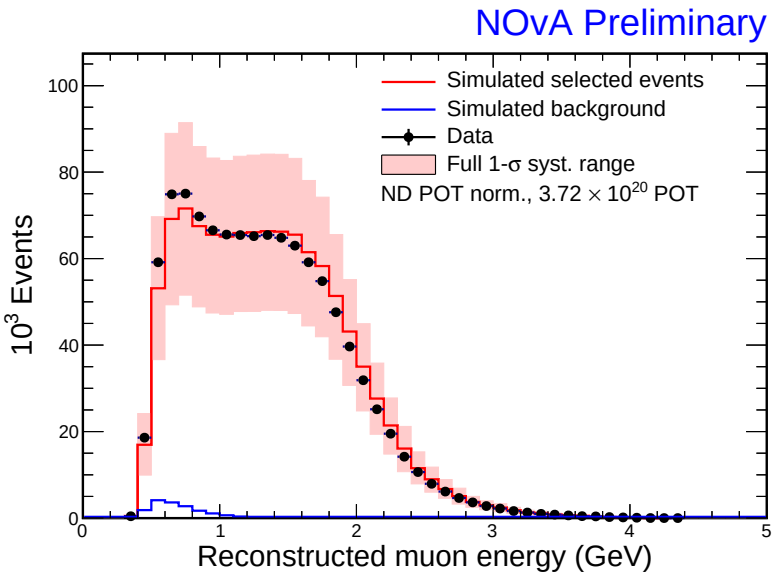
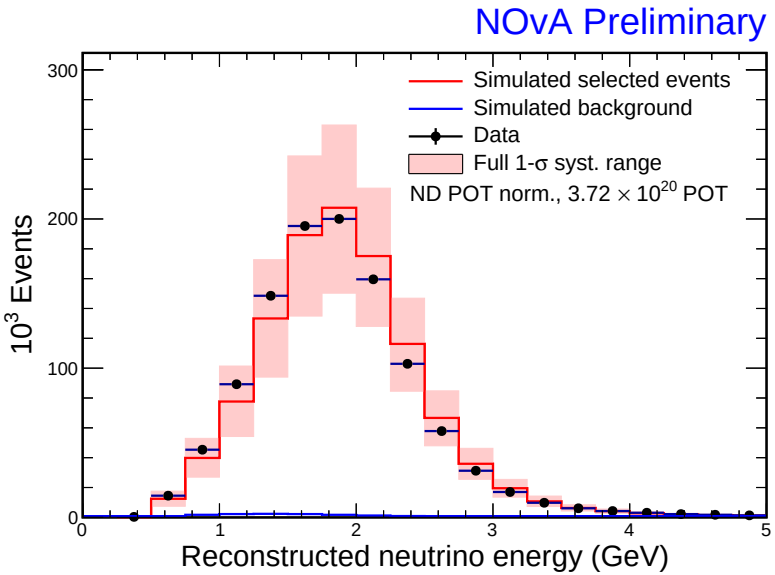


ν_μ Energy Spectra in ND

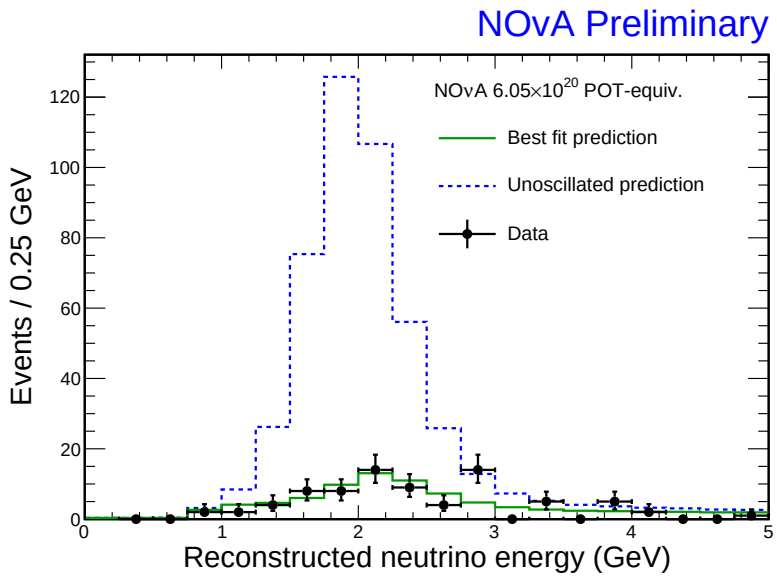


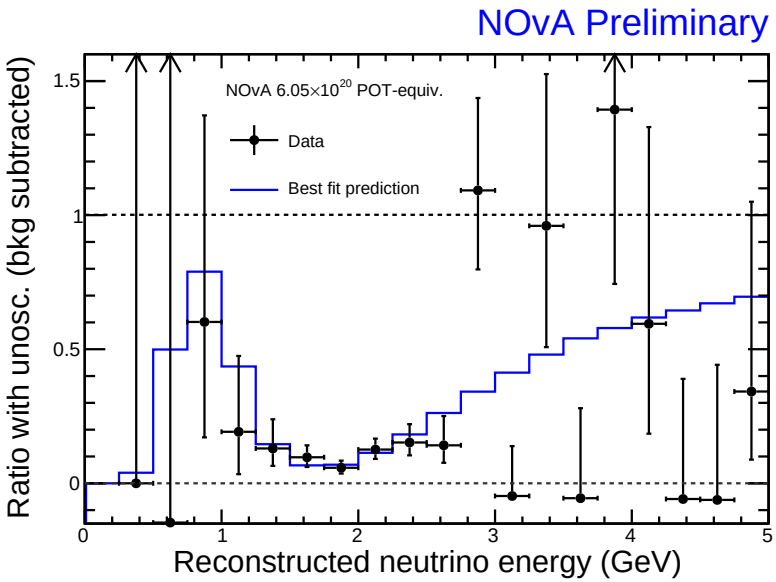


* Performance in the ND shows good data-MC agreement after simulation tuned to include nucleon-correlation effects, with input from our data and Minerva



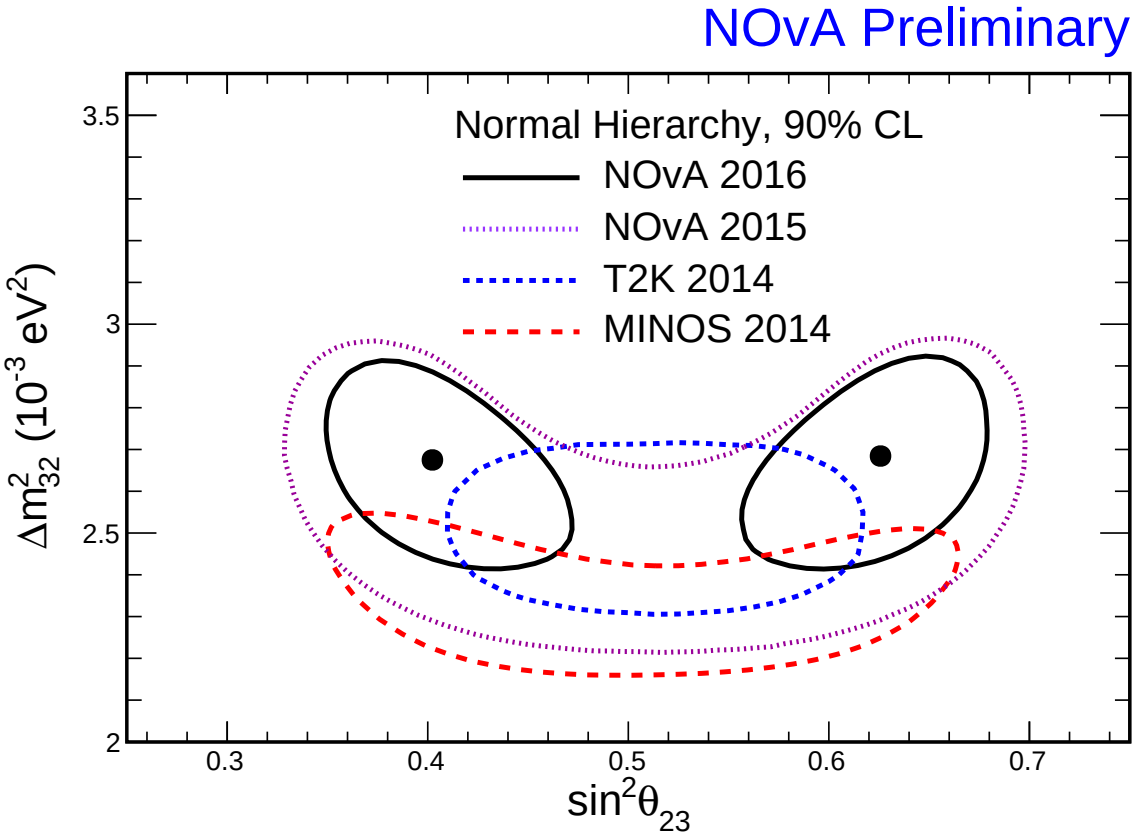
ν_μ Disappearance Result





- Expected 473 events, observe 78 events
- Estimated background of 3.7 events from beam and 2.9 from cosmics
- Fit for Δm^2_{32} and $\sin^2\theta_{23}$

ν_μ Disappearance Result



* Best fit at 68% CL (NH):

$$\Delta m^2_{32} = (2.67 \pm 0.11) \times 10^{-3}\ \mathrm{eV}^2$$

$$\sin^2\theta_{23} = 0.404^{+0.030}_{-0.022}$$

$$\textit{or}\ 0.624^{+0.022}_{-0.030}$$

* Fit $\chi^2 = 41.6/17$
* Rejection of maximal mixing at 2.6 σ

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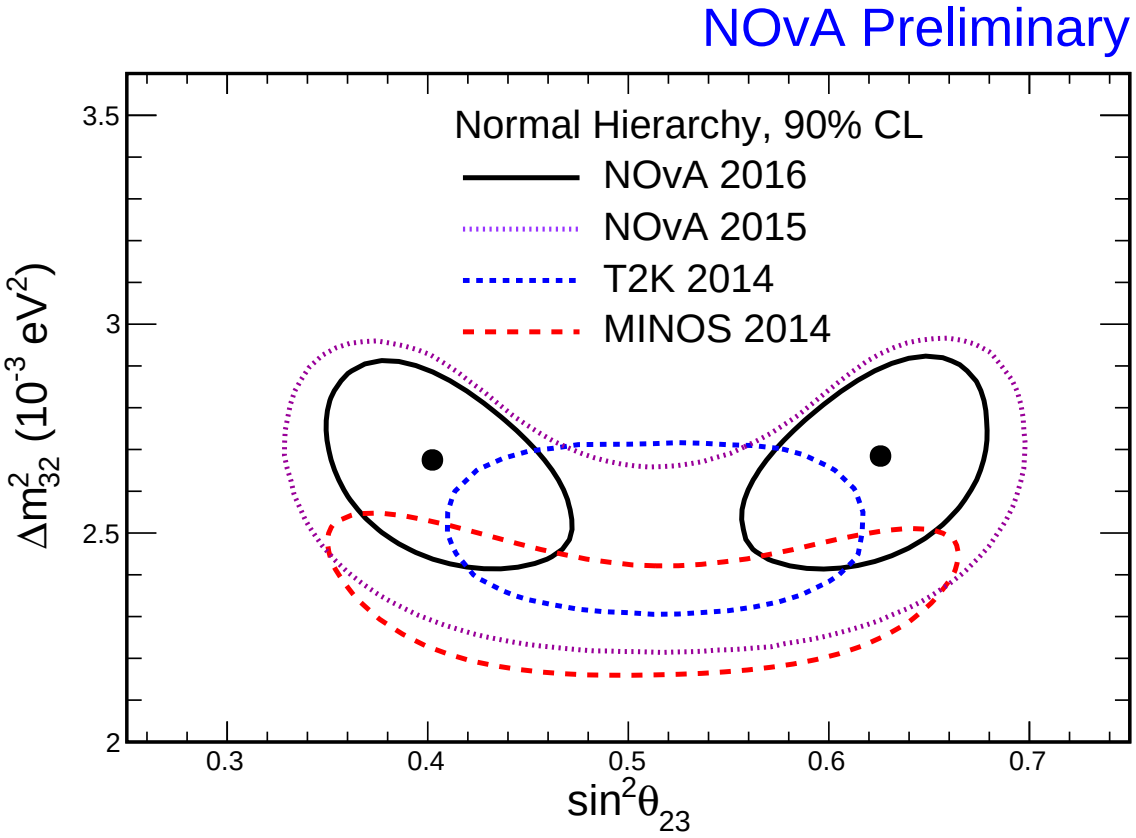

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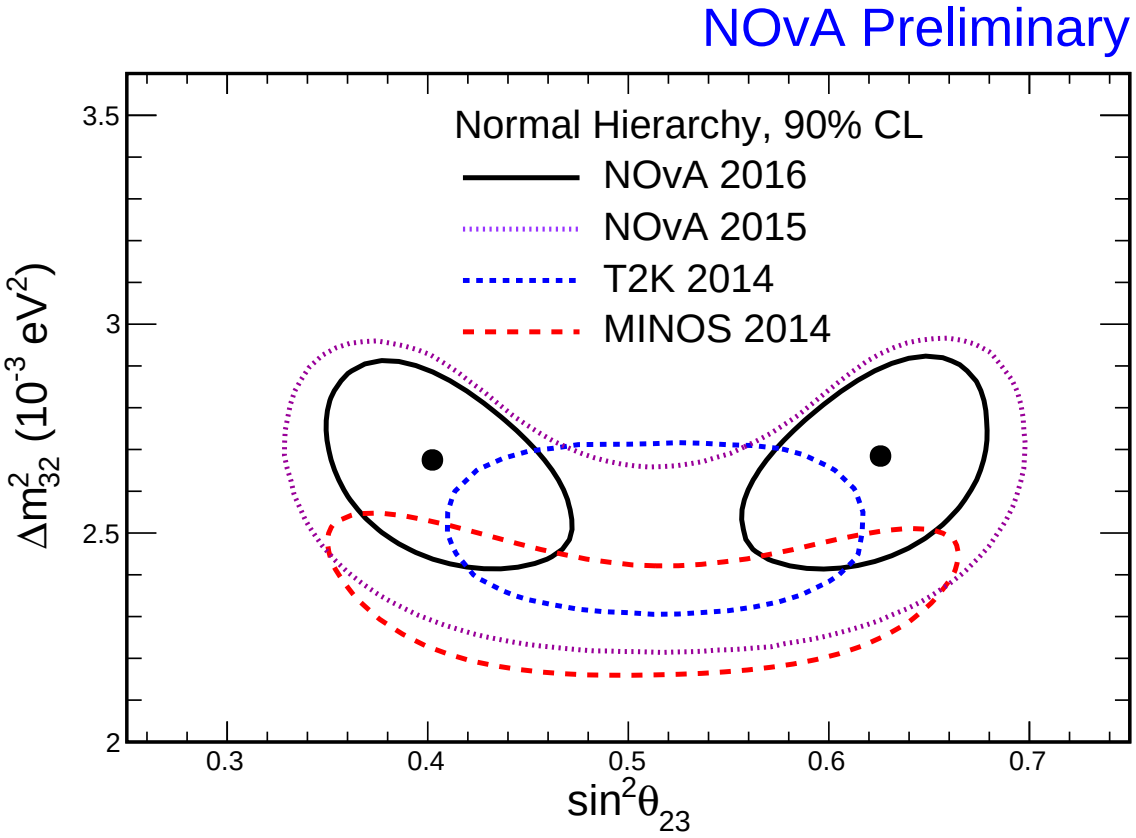
* Phys. Rev. Lett. 118, 151802 – Published 10 April 2017- Editors' Suggestion!

ν_μ Disappearance Result



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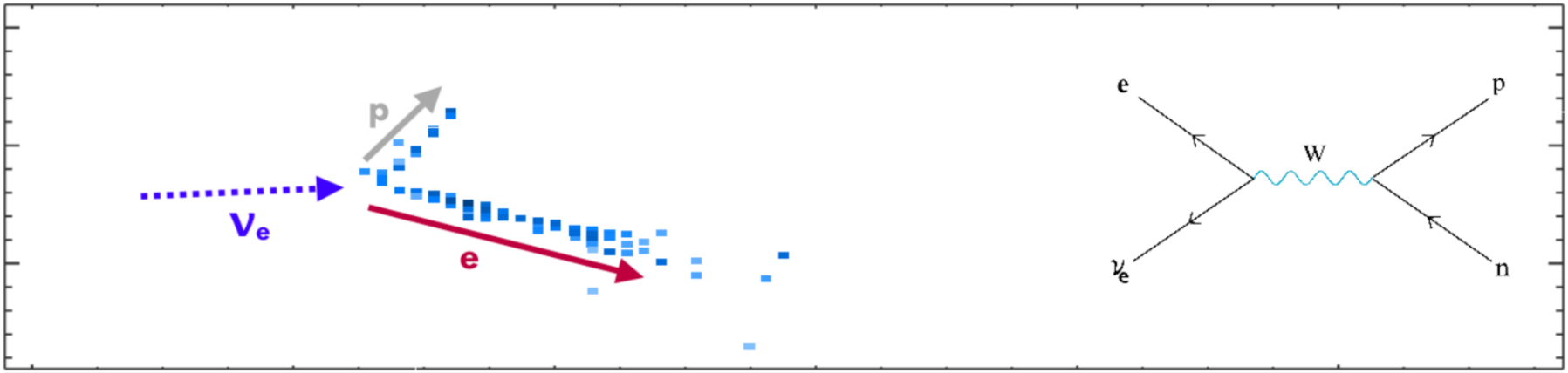
- Rejection of maximal mixing at 2.6 σ

- Phys. Rev. Lett. 118, 151802 – Published 10 April 2017- Editors' Suggestion!
- Higher statistic analysis with 50% more POT coming by Fall 2017

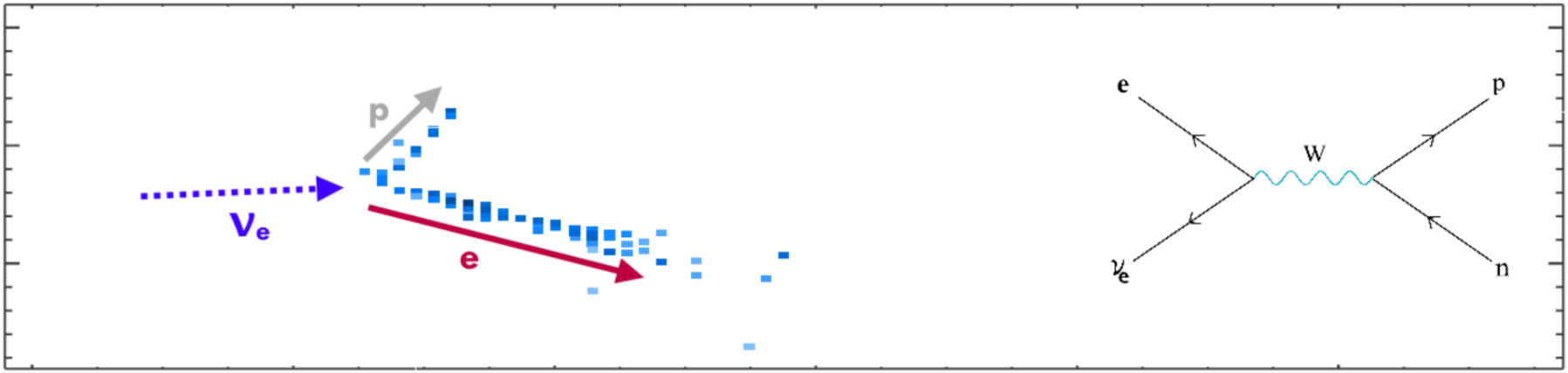
ν_e Appearance Analysis

ν_e Appearance Analysis



- Leading order term in $P(\nu_\mu \rightarrow \nu_e) \propto \sin^2 \theta_{23}$
- Other terms depend on δ_{CP} and mass hierarchy
- Cause enhancement or suppression in $P(\nu_\mu \rightarrow \nu_e)$ as large as 30%
- Hierarchy and CP have the opposite effects on ν and $\bar{\nu}$

ν_e Appearance Analysis

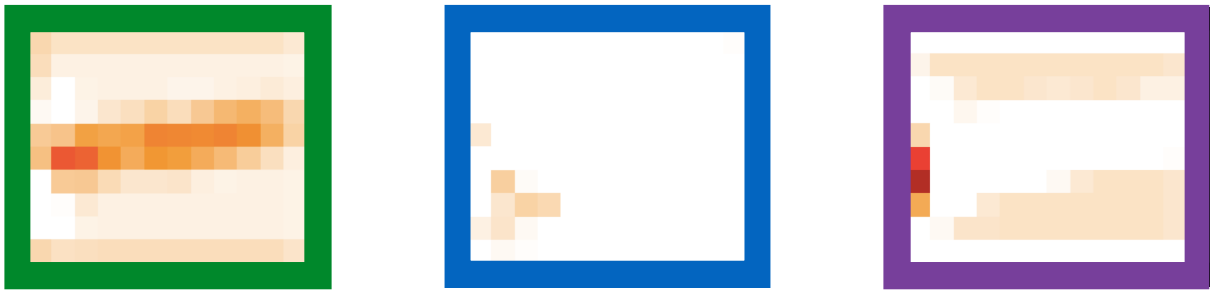


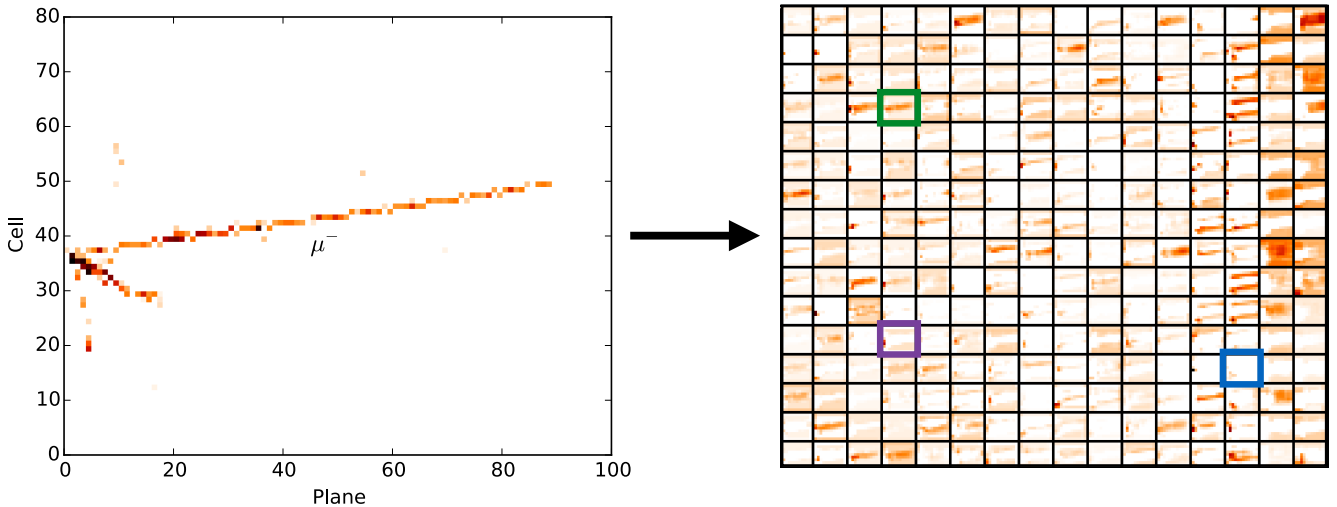
- Use ν_μ CC in ND to estimate ν_e appearance signal in FD
- Use ν_e PID in ND to estimate backgrounds (NC, beam ν_e CC and ν_μ CC)
- Extrapolate backgrounds to the FD for a complete prediction
- Fit the ν_e appearance spectrum to extract oscillation parameters

Identifying Electron Neutrinos: CVN

Fermilab

- CVN: Convolutional Visual Network, a deep neural netowork
- Input is the NOvA event display (pixel map)
- Each layer perform convolutions to extract abstract features





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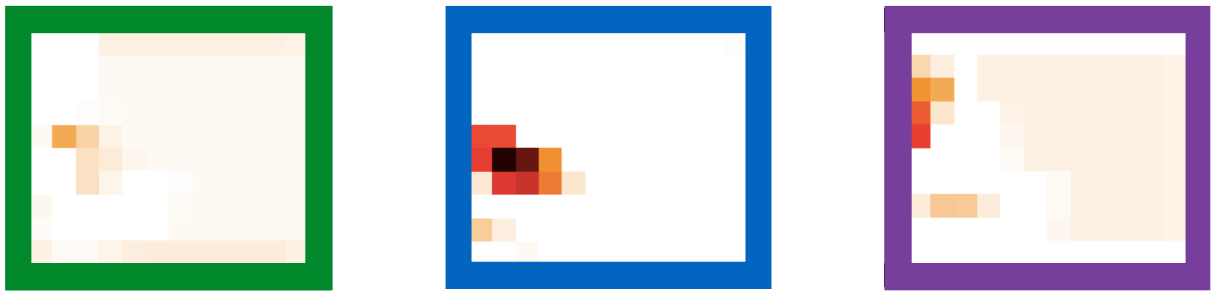
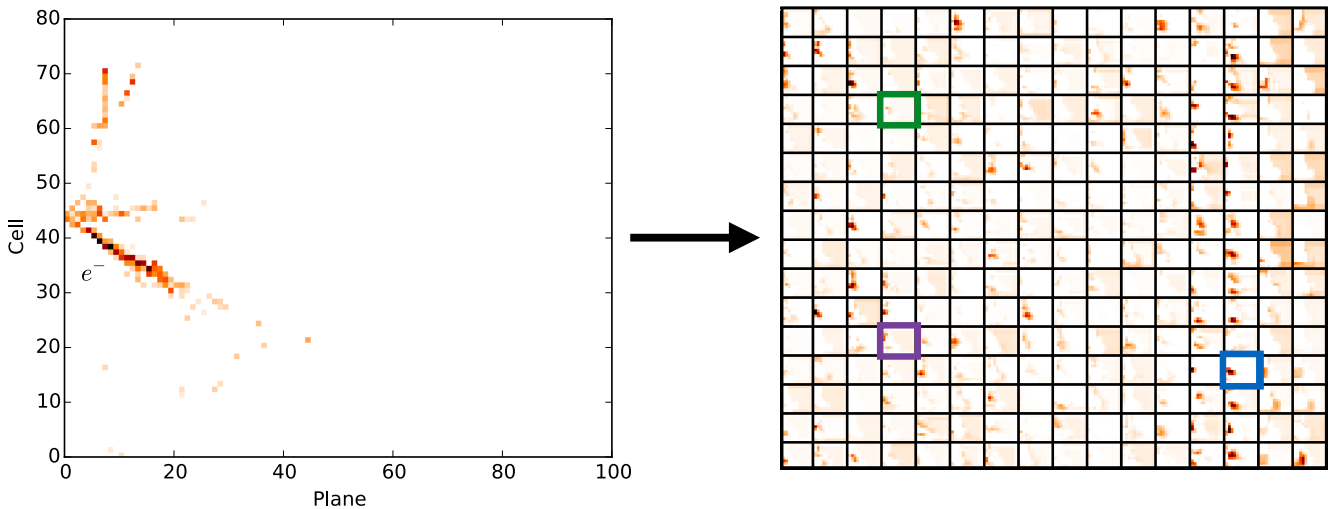
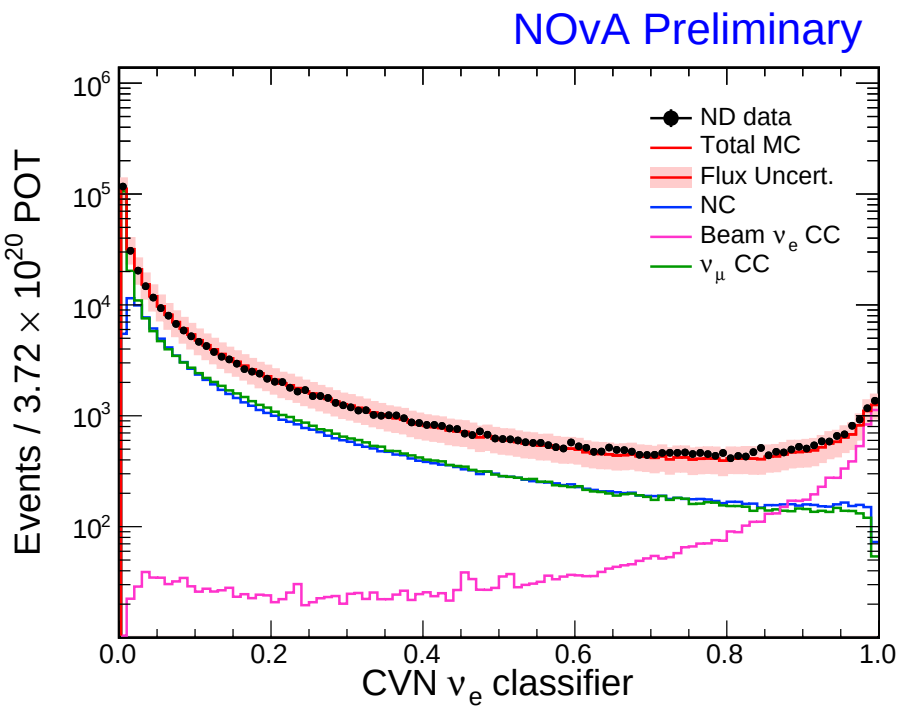




Performance of CVN

- Select ν_e CC interactions with 73% efficiency and 76% purity
- Most left over backgrounds have an energetic EM shower in them
- Equivalent to 30% increase in exposure compared to more conventional PIDs
- Presents good data-MC agreement in ND



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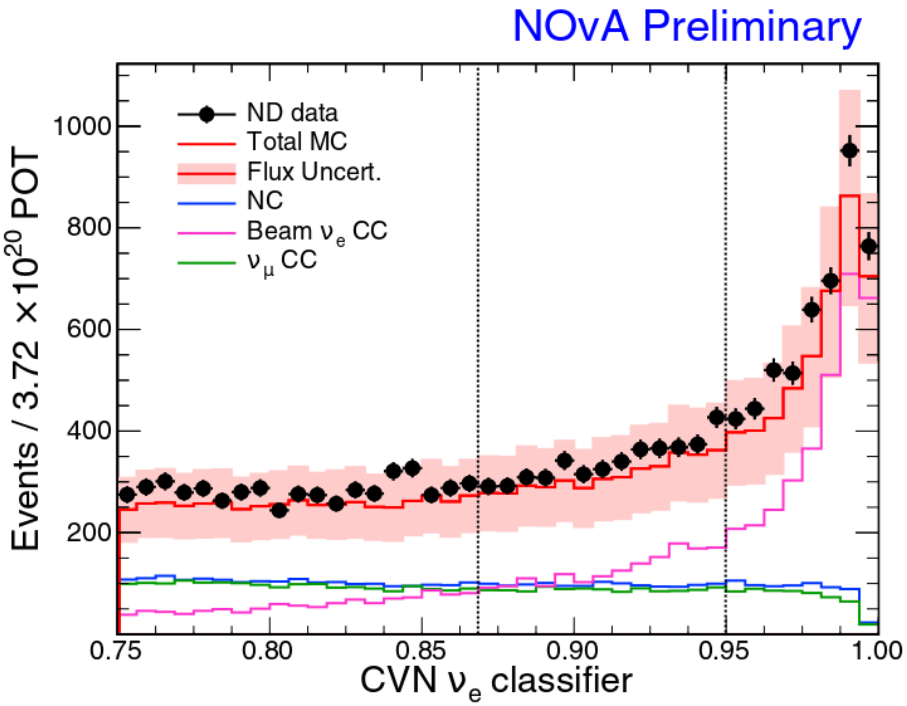
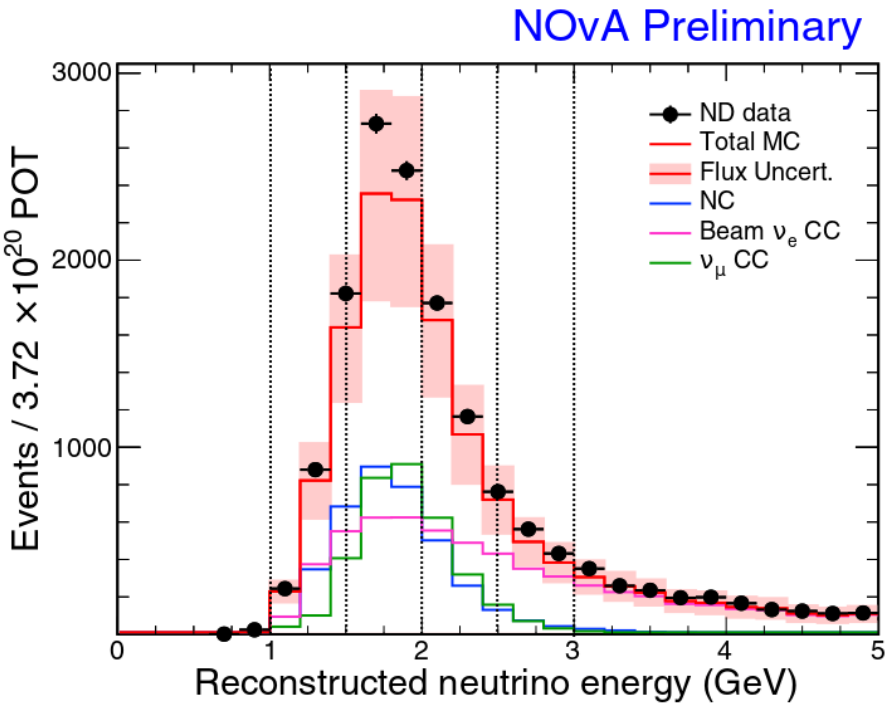
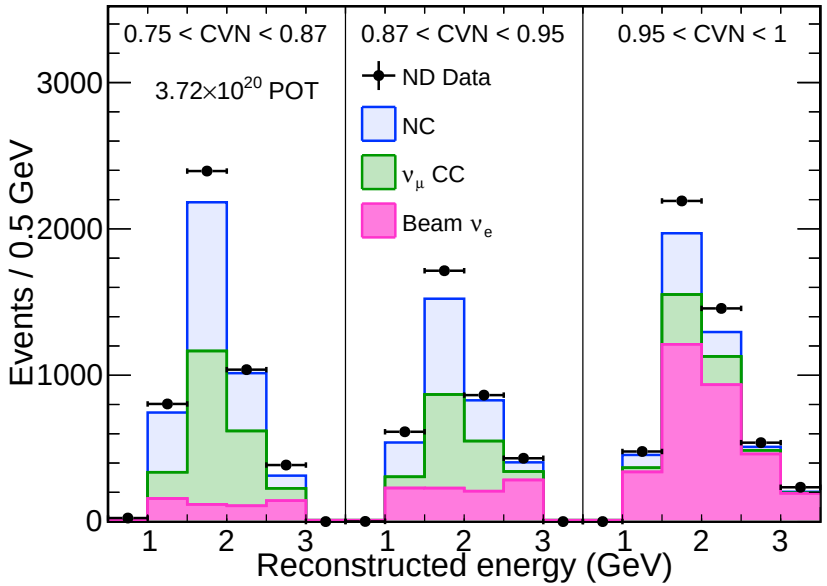
- Presents good data-MC agreement in ND
- Analysis done in 4 energy bins in each of 3 PID bins



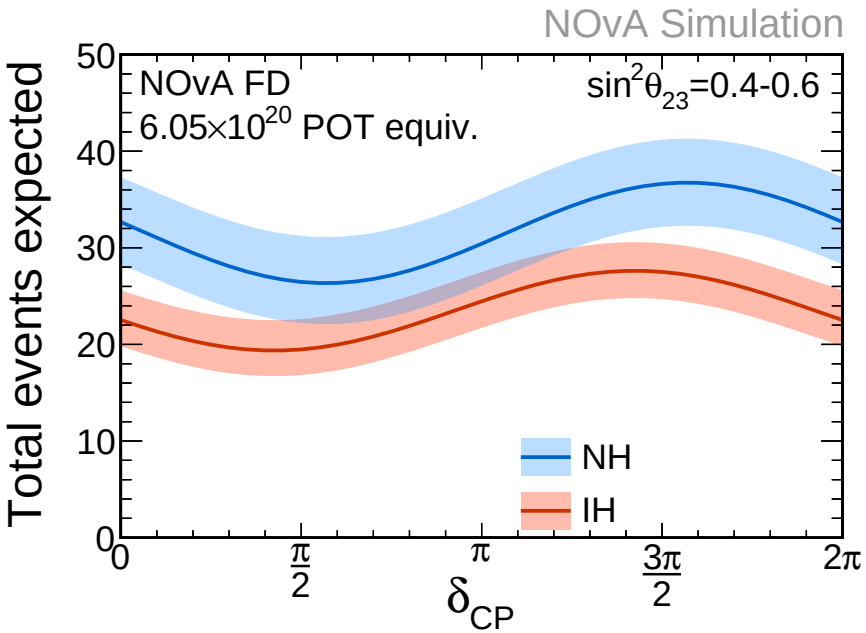


Background Estimate Using ND



- ν_e CC selection selects 10% more events in ND data than in simulation
- Use data driven methods to estimate what fraction in data is NC, beam ν_e CC and ν_μ CC
- Extrapolate these adjustments to the FD for more realistic background estimates

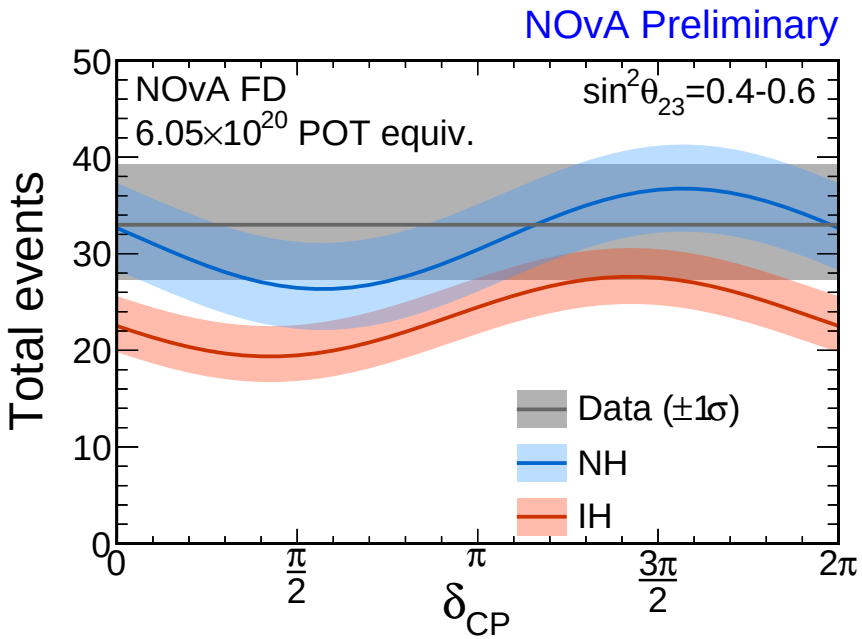
Final Prediction in FD

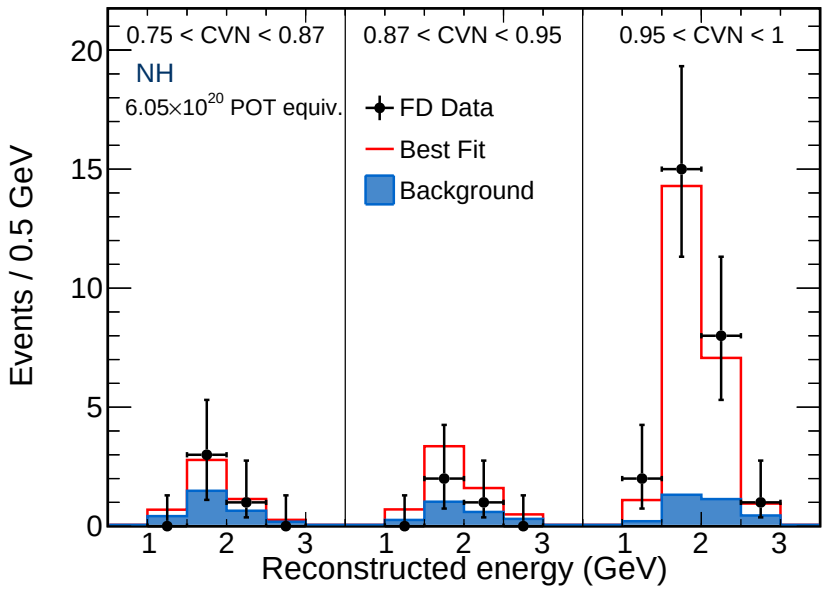


Background	Estimate
Total Bg	8.2
NC	3.7
Beam ν_e CC	3.1
ν_μ CC	0.7
ν_τ CC	0.1
Cosmic	0.5

Expect $\sim$ **19** and $\sim$ **36** events in total, in two most extreme oscillation scenarios (at maximal mixing)

Final Prediction in FD

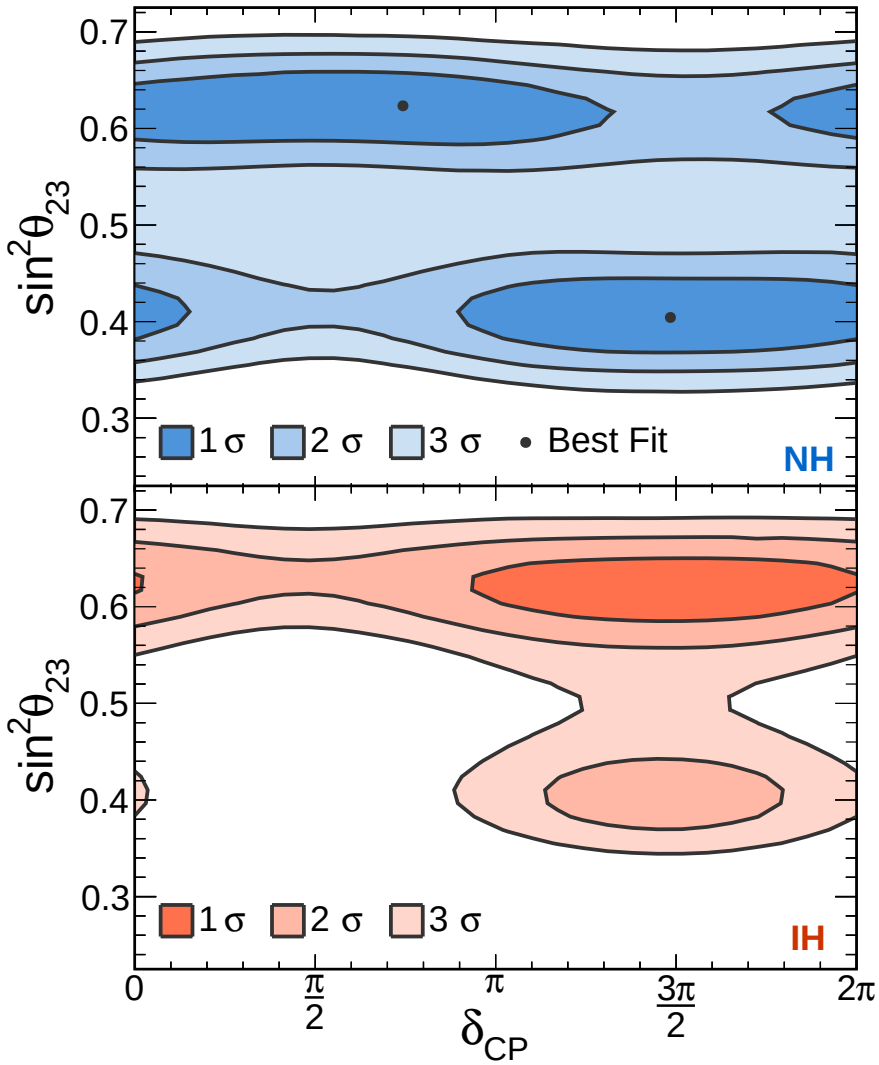




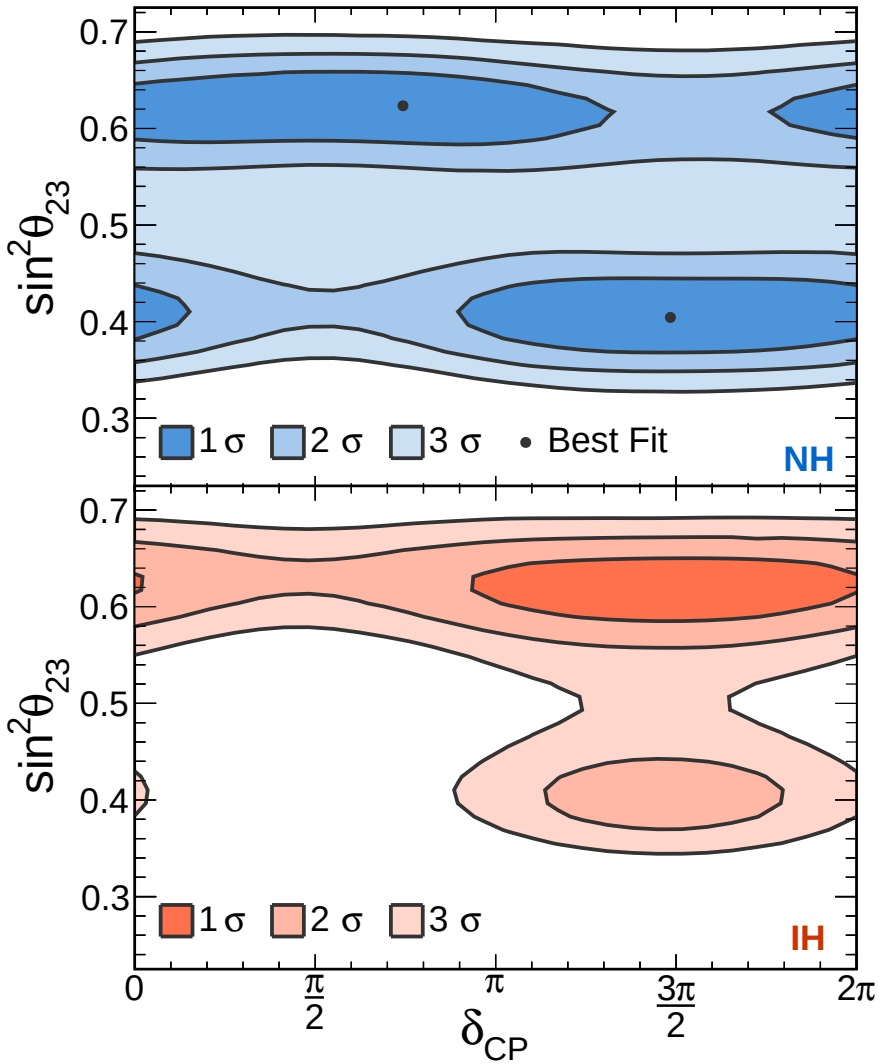
Observe 33 events

$> 8\sigma$ significance of ν_e appearance

ν_e Fit Result



- Joint fit of ν_e appearance data and ν_μ disappearance data from NOvA
- Constrain $\sin^2 2\theta_{13} = 0.085 \pm 0.005$, reactor average value
- Systematics included as nuisance parameters and correlated properly between ν_μ and ν_e in the fit
- Contours include Feldman-Cousins corrections



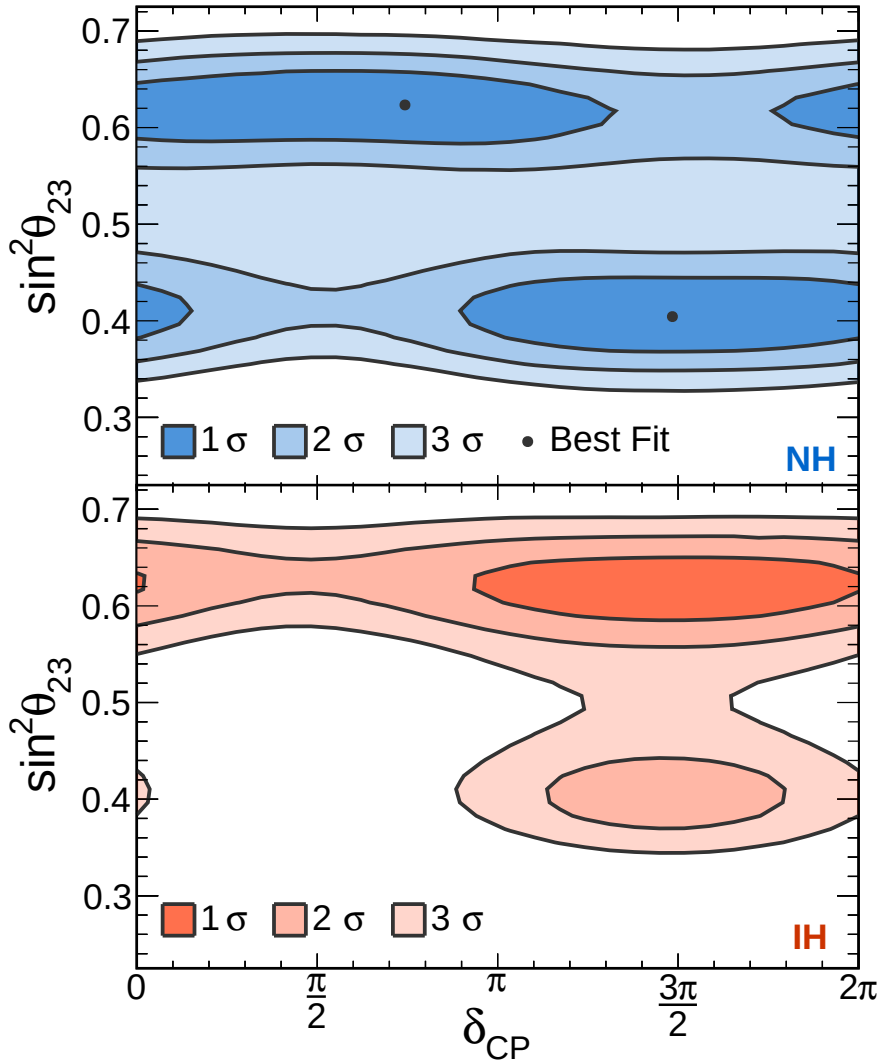
- Two statistically degenerate best fit points are in Normal Hierarchy

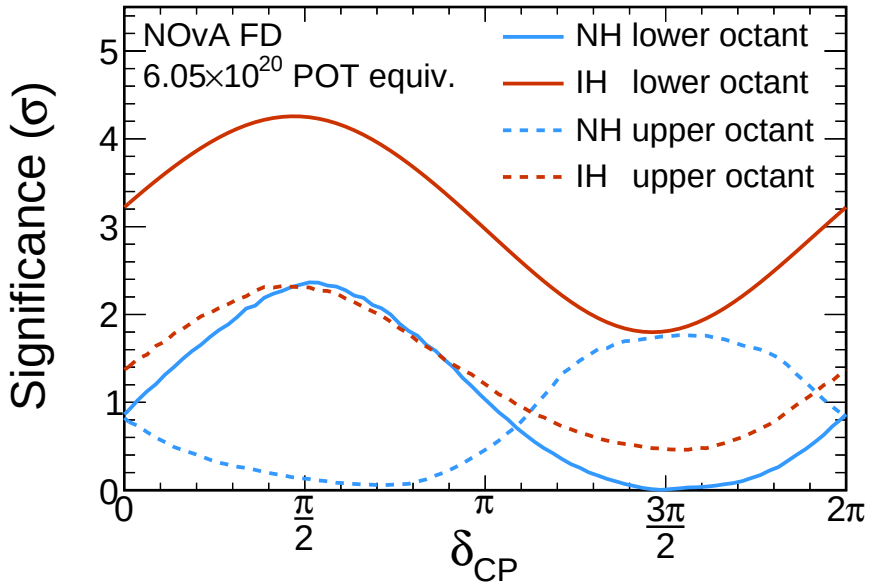
  $\sin^2\theta_{23} = 0.404, \delta_{CP} = 1.48\pi$, and

  $\sin^2\theta_{23} = 0.623, \delta_{CP} = 0.74\pi$

- The best-fit point in the Inverted Hierarchy near $\delta_{CP} = 3\pi/2$, 0.46 σ from the global best-fit points

ν_e Fit Result

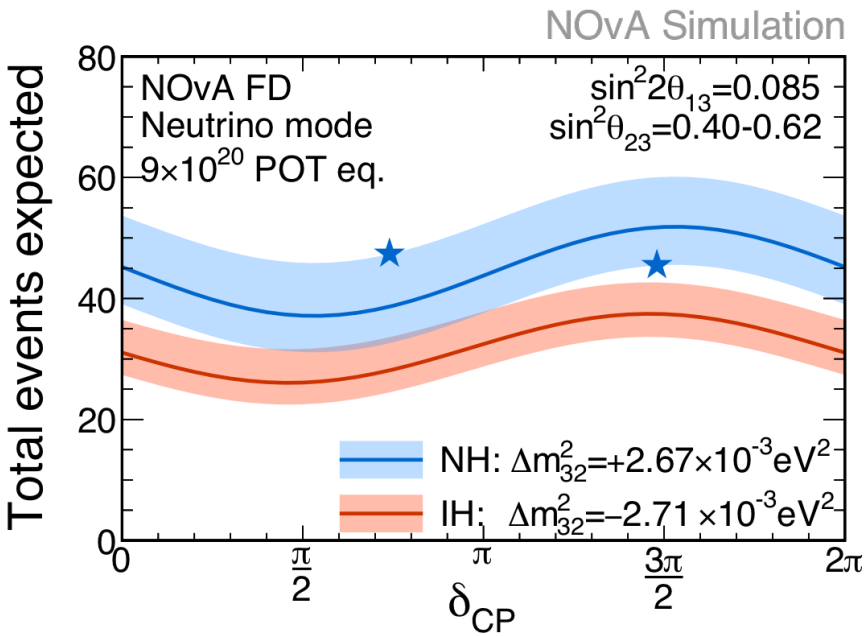




- Inverted Mass Hierarchy in the lower θ_{23} octant disfavored at $>$ 93% C.L. for all values of δ_{CP}
- Phys. Rev. Lett. 118, 231801 : Editors' Suggestion!

Future

Why Anti-neutrinos



- Hierarchy and CP have opposite effects on anti-neutrinos
- NuMI switched to anti-neutrino mode in February 2017
- Plan to collect ν and $\bar{\nu}$ data in 50-50 ratio
- Will help resolve some of the degeneracies

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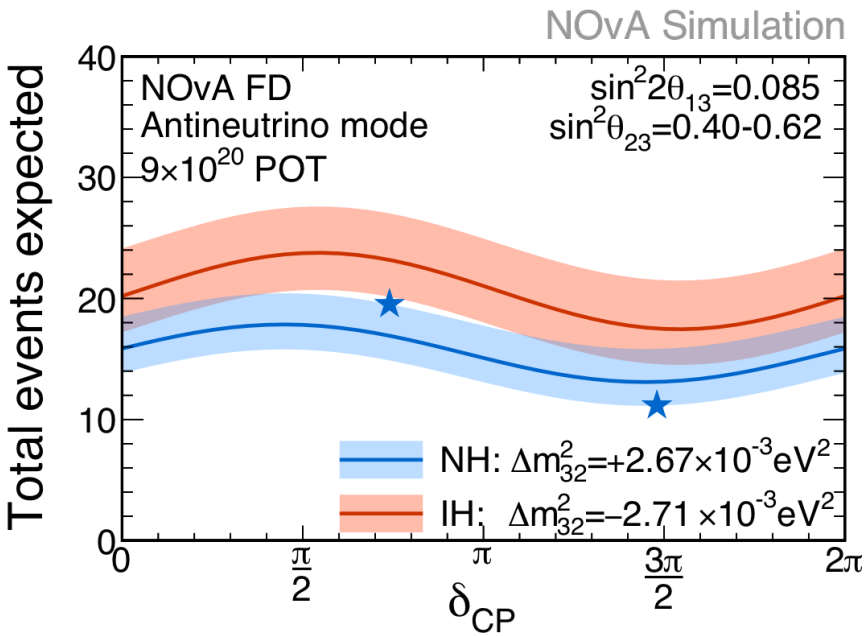

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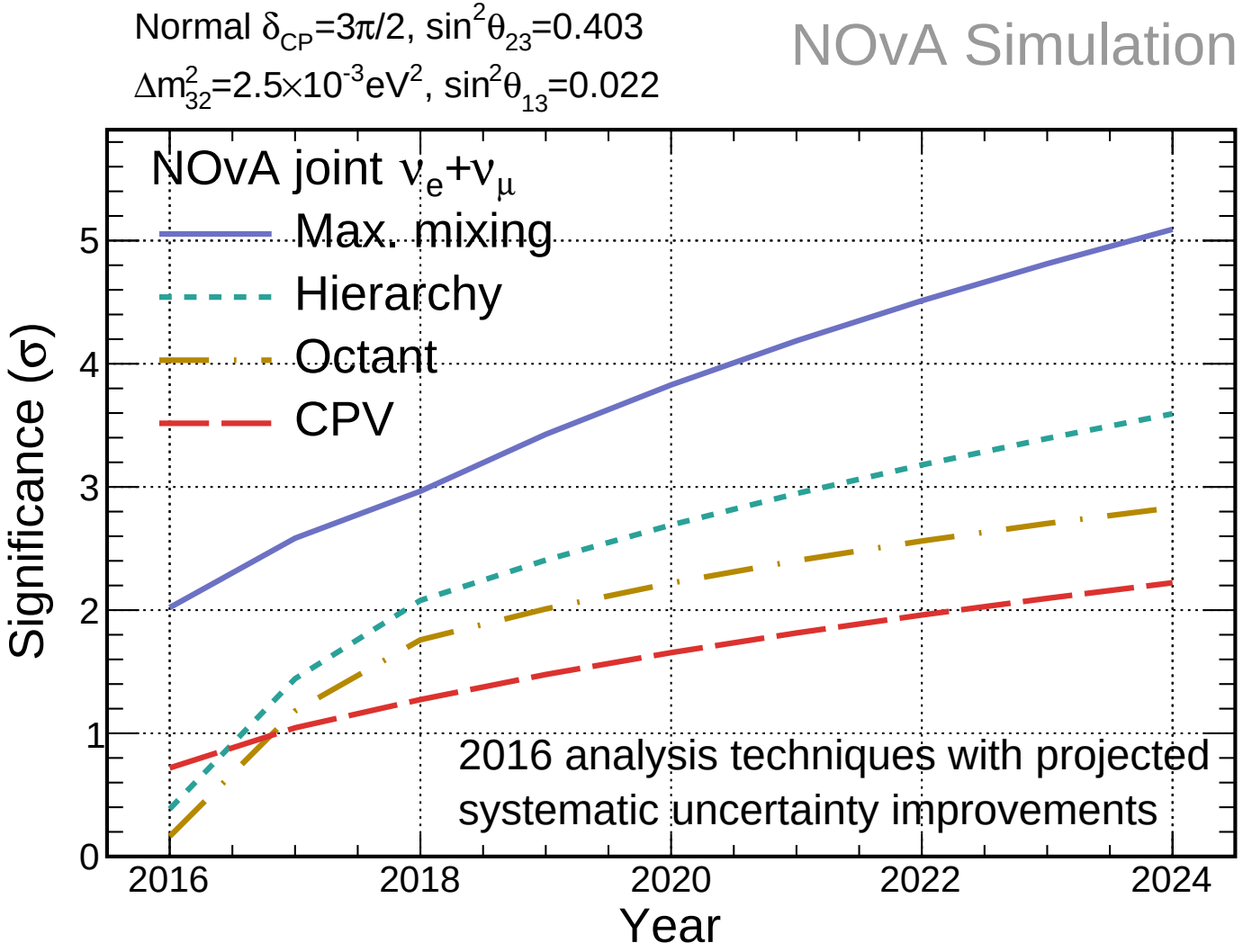
Future Sensitivity Projections

Fermilab

Projected significance of rejecting maximal mixing, wrong hierarchy, wrong octant and CP conservation



- Improvements in **suppressing systematics**
- 25% gain in exposure from **improved analysis**
- **40 weeks of beam** starting 2018
- **PIP 1+**: 800 kW in 2019, 900 kW in 2021 + target improvements

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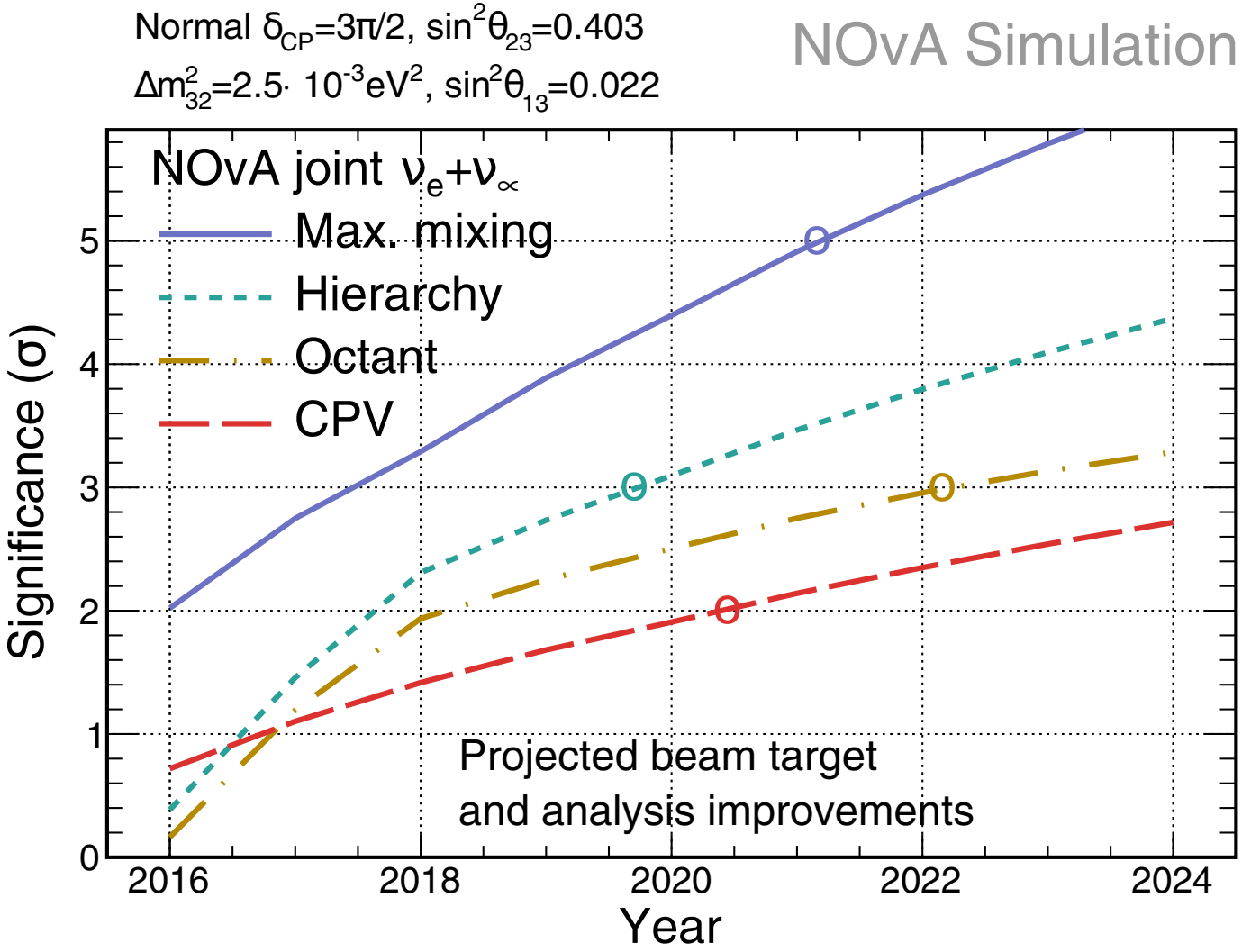

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Summary

Fermilab

- NOvA has analyzed $\mathbf{6.05 \times 10^{20}}$ POT worth of neutrino data
- The measurement of ν_μ disappearance at NOvA is **non-maximal at 2.6σ**
- A combined fit of appearance and disappearance channels **rejects Inverted Hierarchy with lower θ_{23} octant for all values of δ_{CP}** at $>$ 93% CL
- Here's what's coming soon:
  - Higher stats analysis of ν_μ **disappearance this Fall, improved precision of θ_{23}** measurement
  - Currently running in anti-neutrinos, should help break the degeneracy between upper and lower octant
  - **Combined $\nu - \bar{\nu}$** result scheduled for **Summer 2018**!

Summary: Looking Further Out

Fermilab

- With improvements across **analysis, detector operation and beam** we have an opportunity to hit **major milestones** in neutrino physics before 2024
- **5σ** rejection of **maximal mixing**
- **3σ** mass **hierarchy** determination
- **3σ octant** determination
- **2σ** sensitivity to **CP violation**

Thank you!

NOvA Posters at Users' Meeting 2017:

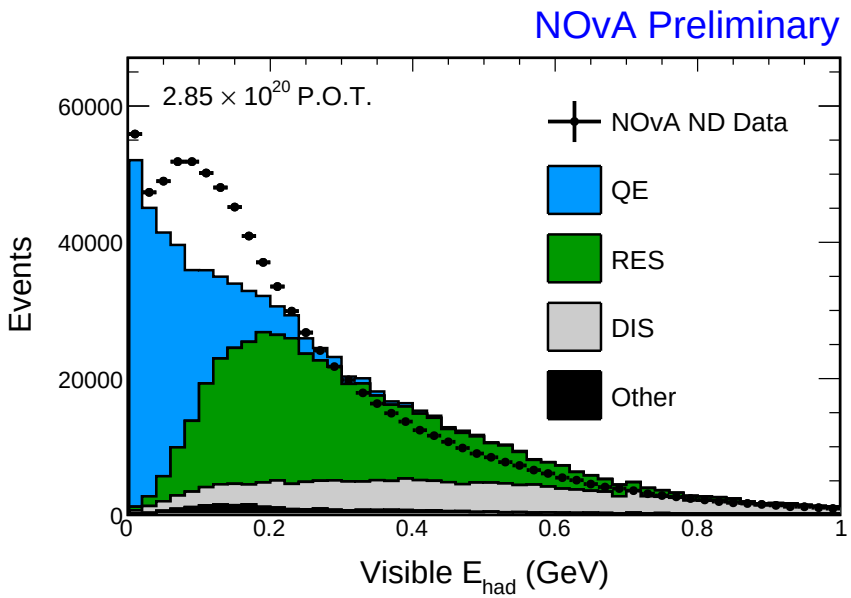
1. The **Physics Program** of NOvA - Alex Radovic and Gavin Davies
2. **Three-Flavor Oscillations** in NOvA - Erika Cantano-Mur and Kirk Bays
3. **Sterile neutrino** search through Neutral Current Disappearance in NOvA experiment - Shaokai Yang

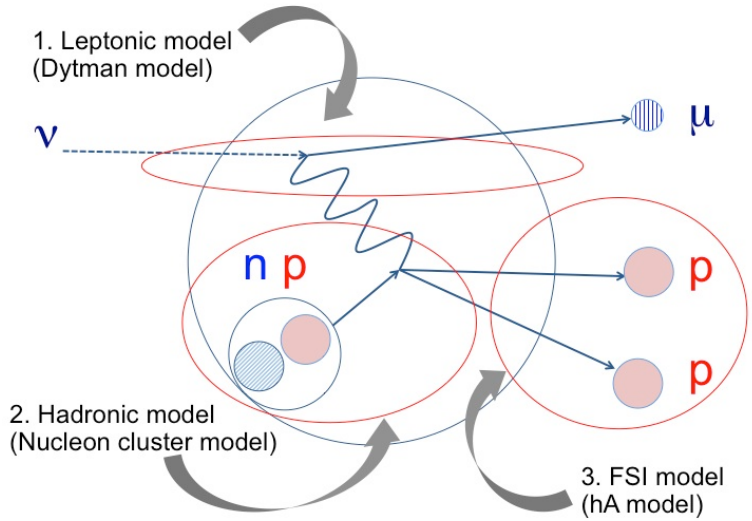
Backup

Scattering in a Nuclear Medium

Fermilab

- The hadornic energy spectrum in ND Data suggests missing interaction mode in simulation
- Supported by observations by Minerva experiment [a]
- Use GENIE's Meson Exchange Current to model these interactions of neutrinos scattering off correlated pair of nucleons [b]



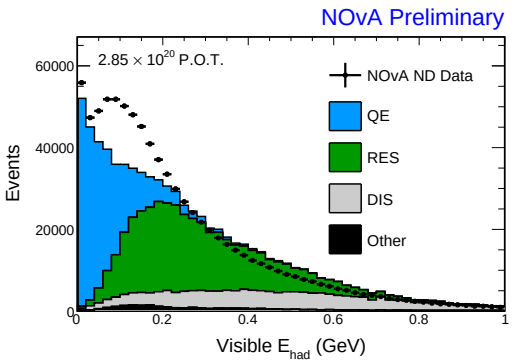


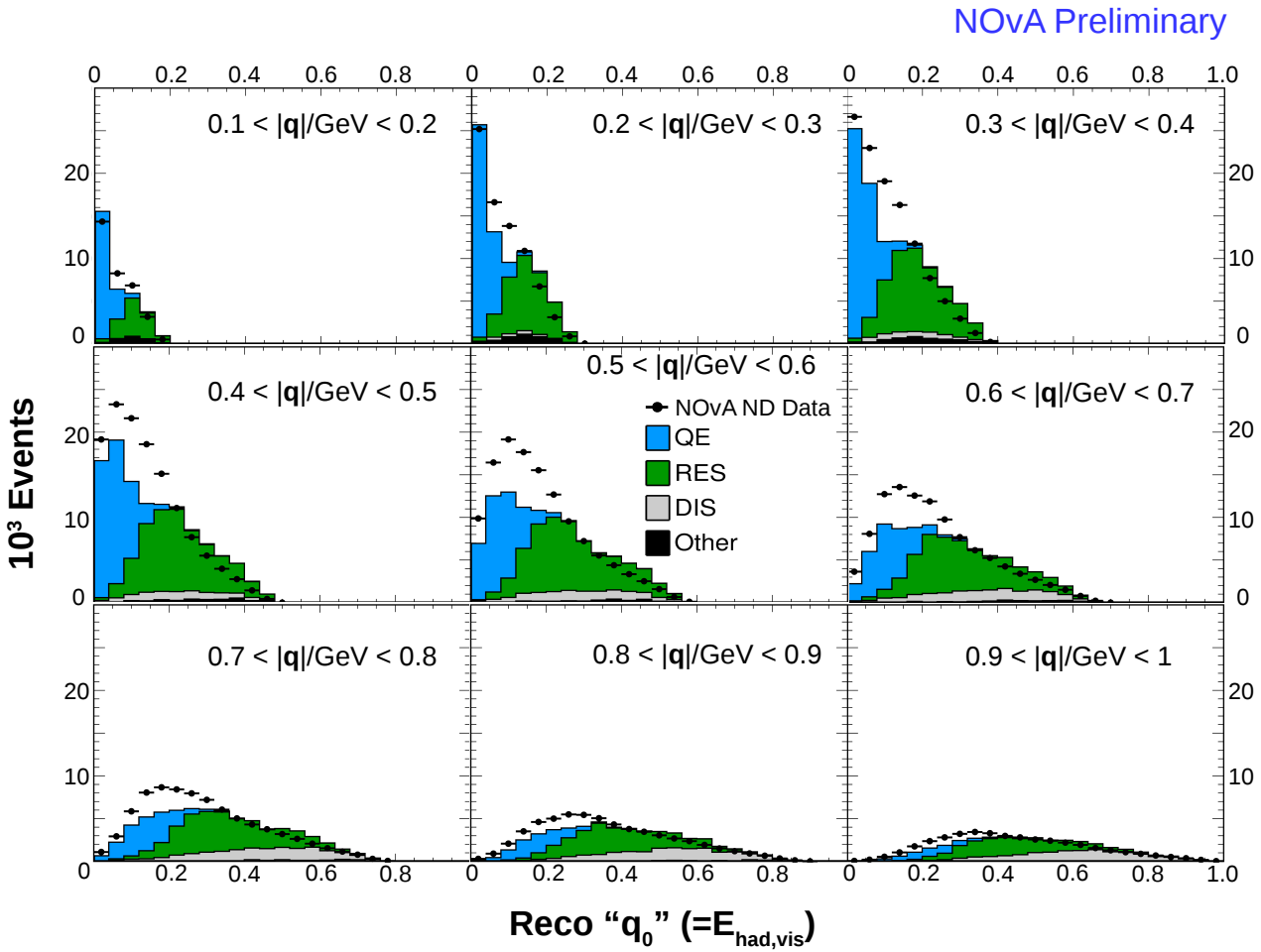
[a] P.A. Rodrigues et al. (MINERvA Collaboration) Phys. Rev. Lett. 116, 071802

[b] S. Dytman, based on J. W. Lightbody, J. S. OConnell, Comp. in Phys. 2 (1988) 57

Fermilab

- Tuned the default MEC model by fitting the data excess in bins of hadronic energy and momentum transfer





Scattering in a Nuclear Medium

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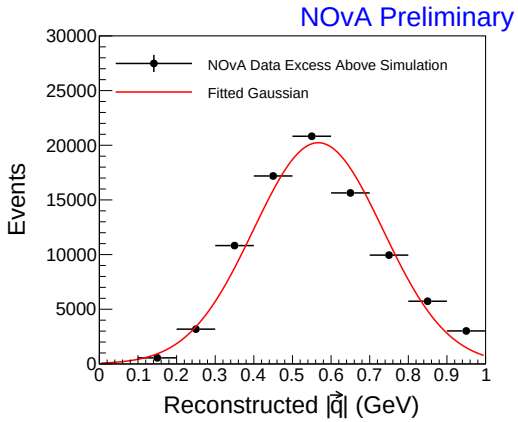

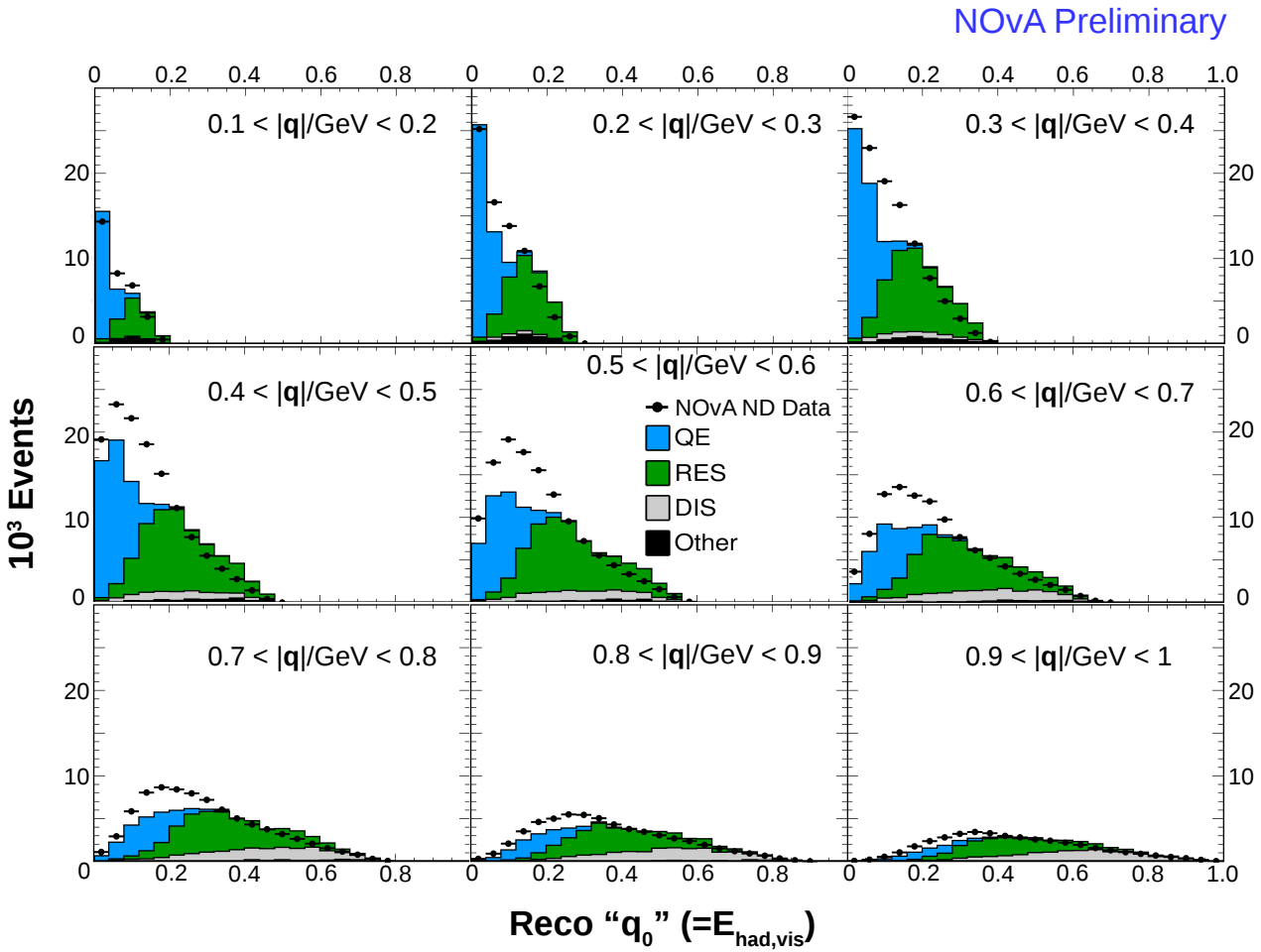

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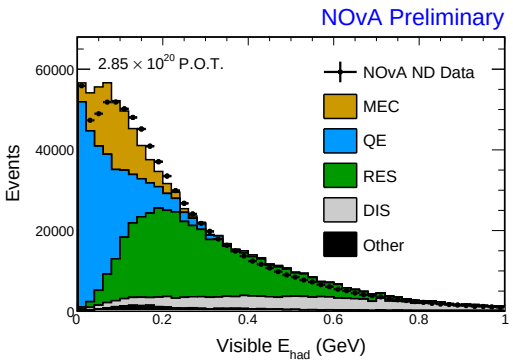
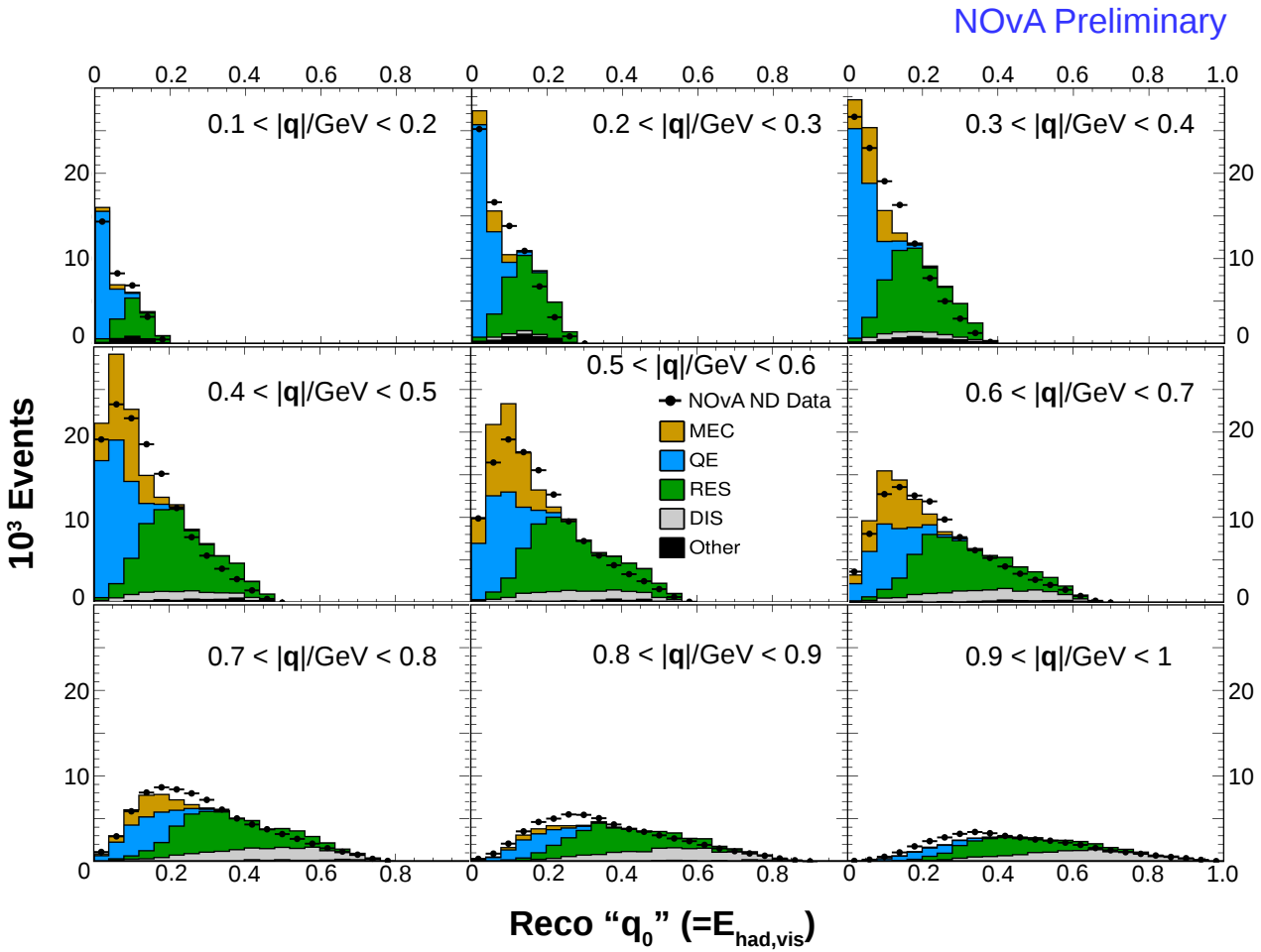
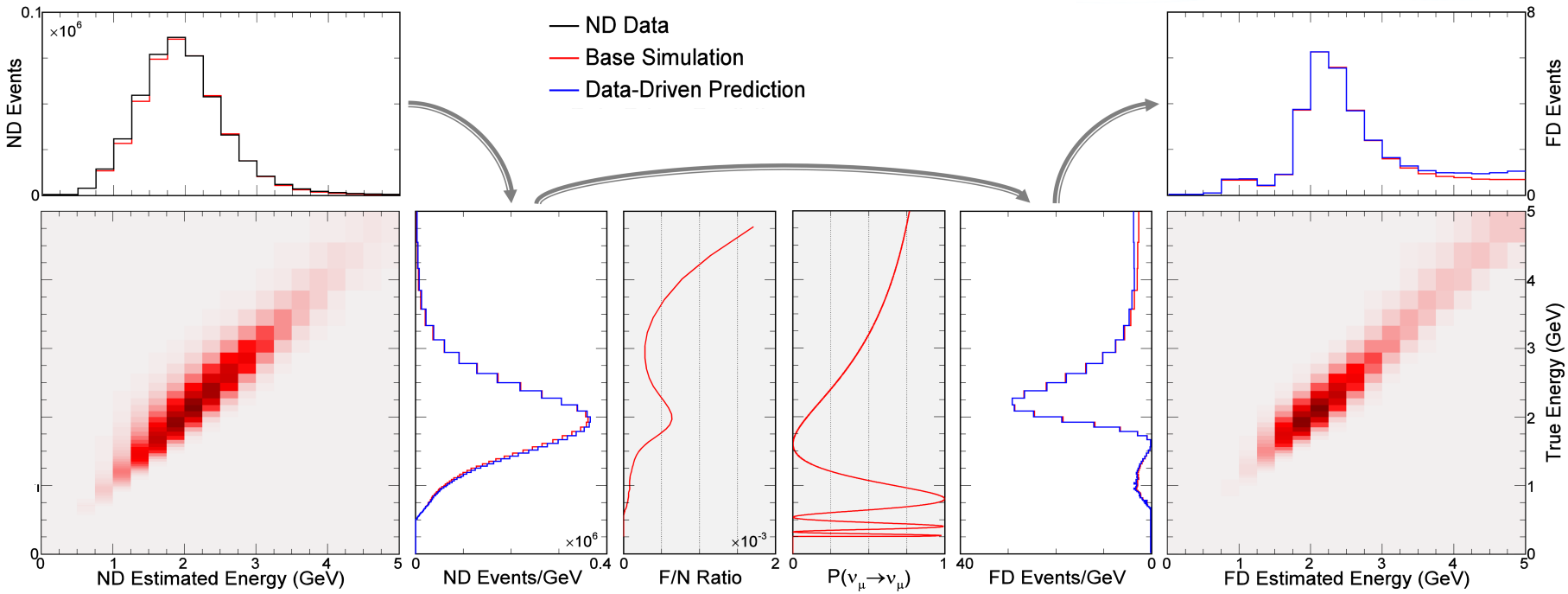




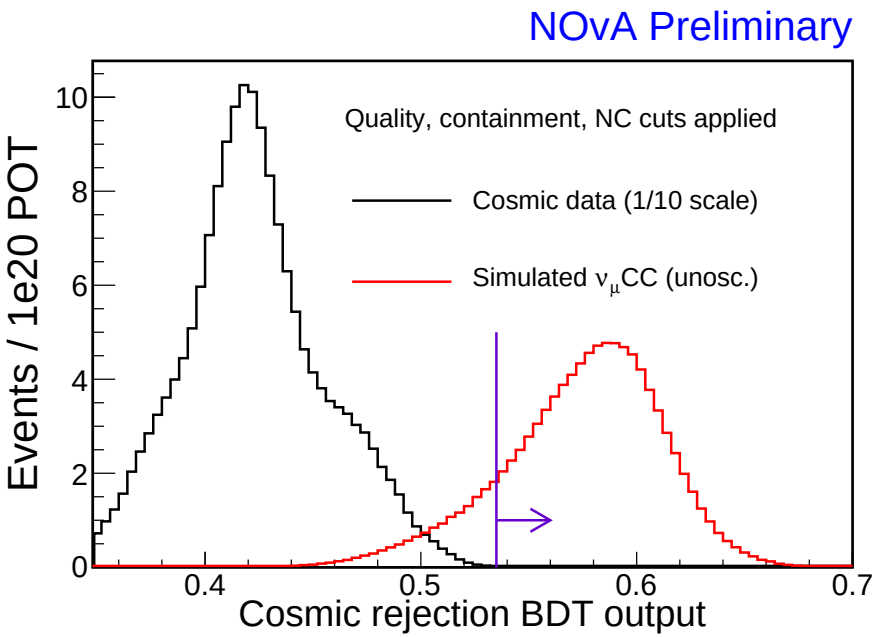
Two Detector Technique

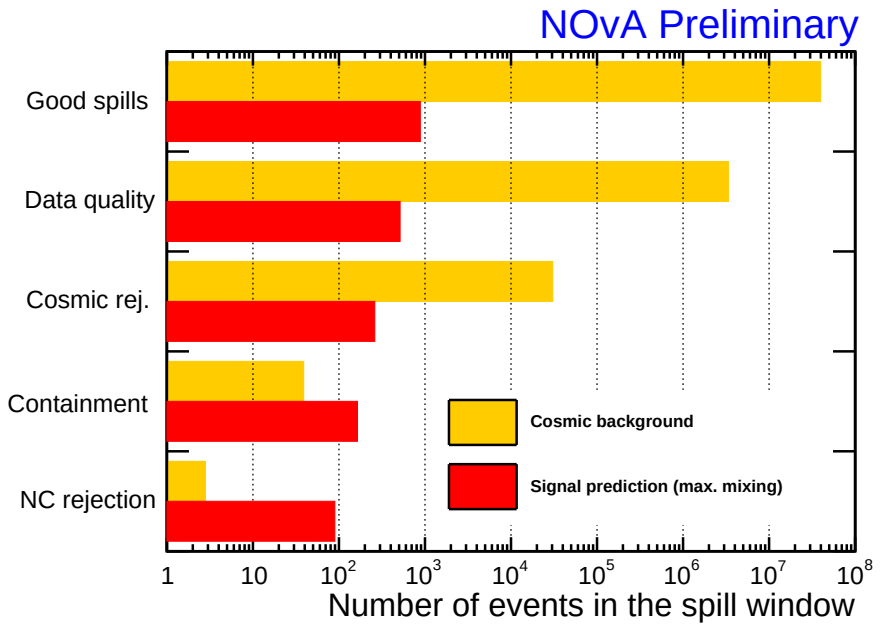
- To predict oscillated spectra in FD, both, appearance and disappearance analyses start with selecting ν_μ CC interactions in ND
- The reconstructed ND ν_μ CC energy spectrum is used to correct the FD simulated prediction



Cosmic Rejection

Cosmic rejection BDT based on muon direction, position, length, number of hits in slice and energy





Rejection factor of 10^7 achieved with event topology

Final background measured directly from beam-off FD data

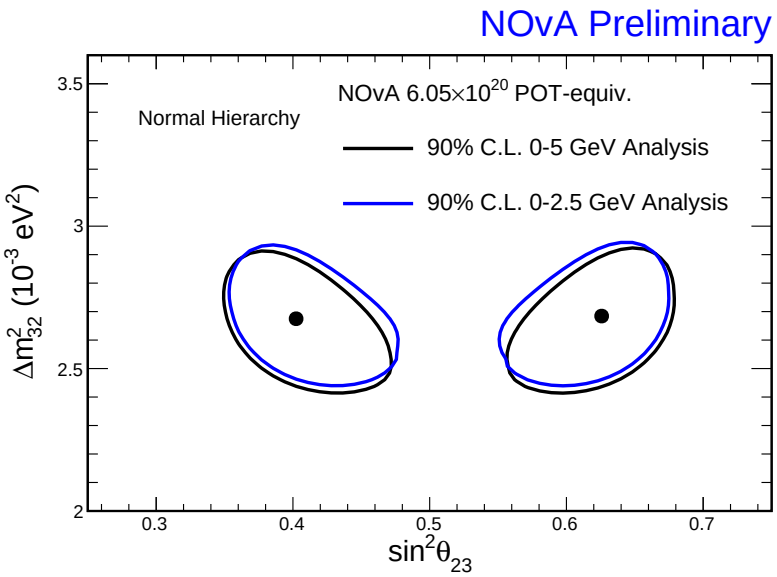
Systematics in Disappearance Analysis

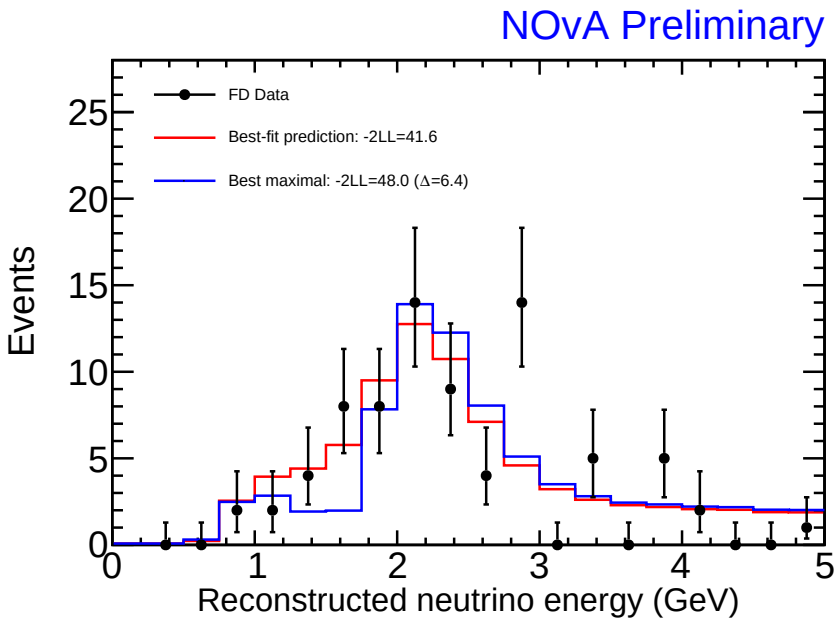
Fermilab

- Most systematics are negligible in F/N ratio
- Including MEC in simulation reduces hadronic energy systematic
- Systematics included as pull terms in the fit
- Table quotes increase in 68% contours relative to stat-only fit

Source of uncertainty	Uncertainty in $\sin^2\theta_{23}(\times 10^{-3})$	Uncertainty in Δm^2_{32} $(\times 10^{-6}$ eV$^2)$
Absolute muon energy scale [±2%]	+9 / -8	+3 / -10
Relative muon energy scale [±2%]	+9 / -9	+23 / -14
Absolute hadronic energy scale [±5%]	+5 / -5	+7 / -3
Relative hadronic energy scale [±5%]	+10 / -11	+29 / -19
Normalization [±5%]	+5 / -5	+4 / -8
Cross sections and final state interactions	+3 / -3	+12 / -15
Neutrino flux	+1 / -2	+4 / -7
Beam background normalization [±100%]	+3 / -6	+10 / -16
Scintillation model	+4 / -3	+2 / -5
δ_{CP} $[0-2\pi]$	+0.2 / -0.3	+10 / -9
Total systematic uncertainty	+17 / -19	+50 / -47
Statistical uncertainty	+21 / -23	+93 / -99

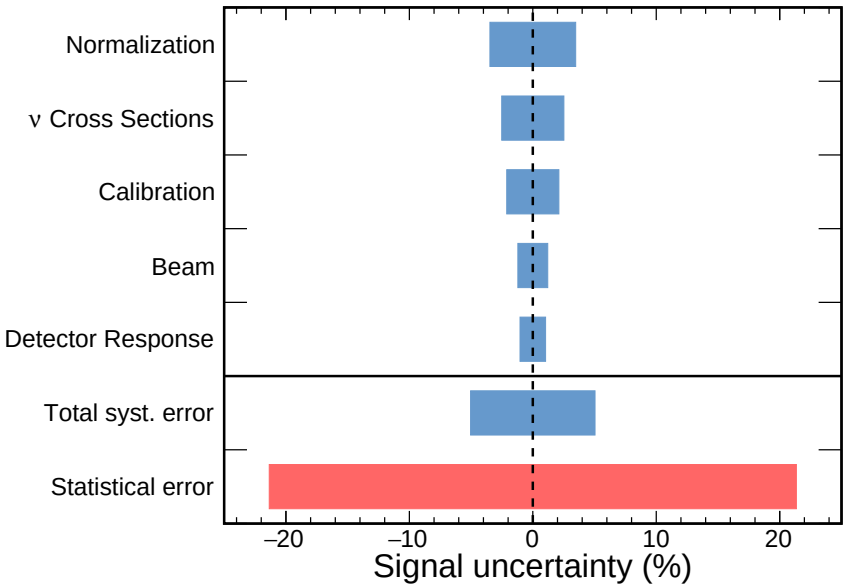
Disappearance Result

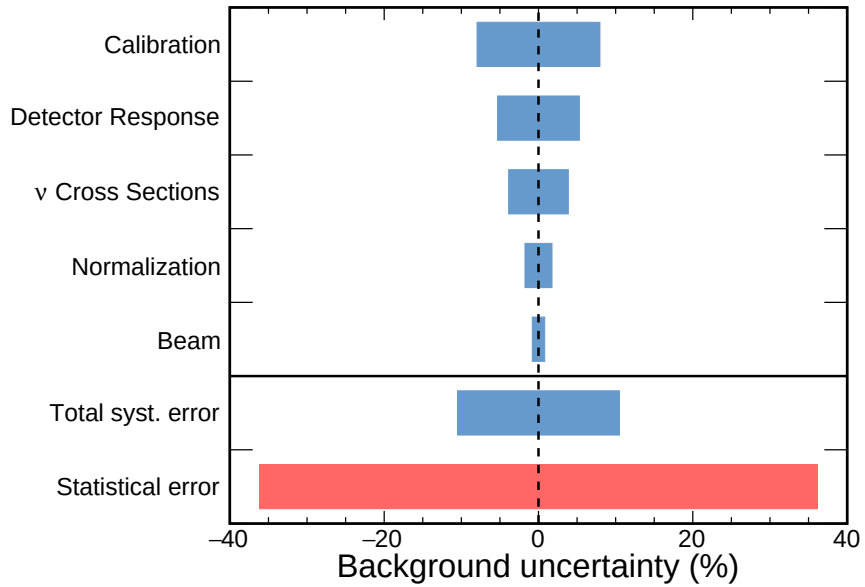




- $\chi^2 = 41.6/17$ driven by fluctuations in the tail
- Restricting the fit upto 2.5 GeV causes minimal change in the result

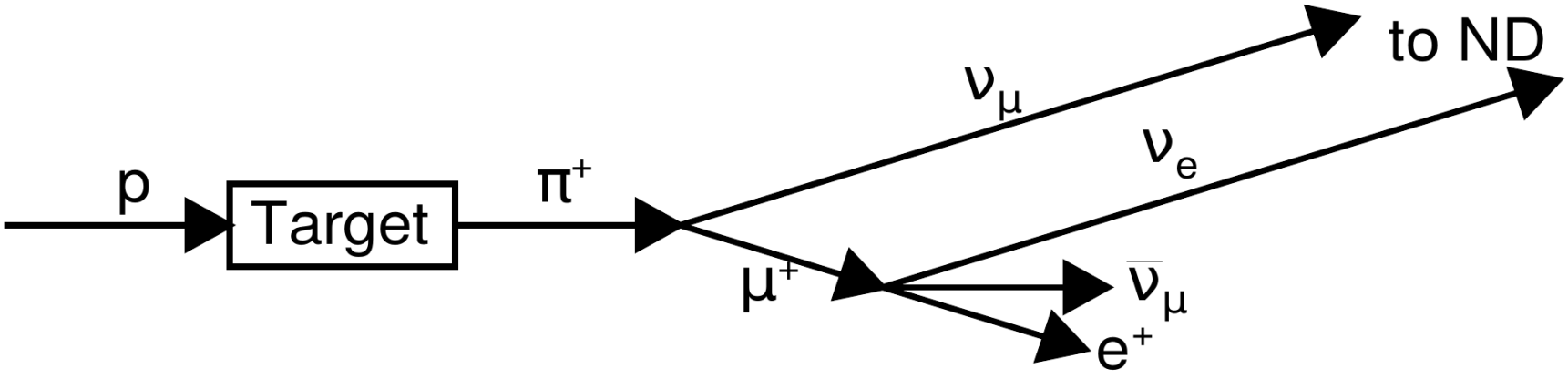
Systematic Error in ν_e Appearance





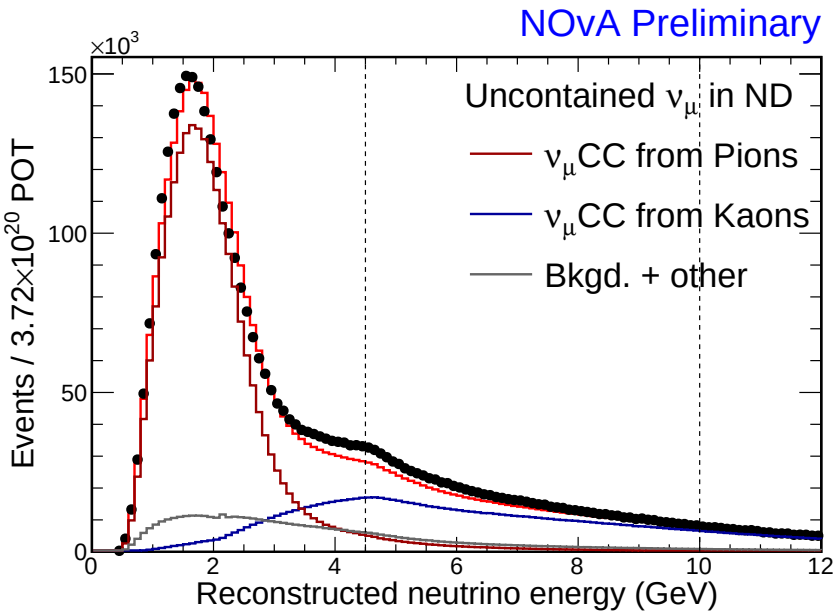
- Systematic error ∼5% on signal and ∼10% on background
- Systematic shifts to the PID × Energy spectrum included as nuisance parameters in the fit
- Dominated by statistical error

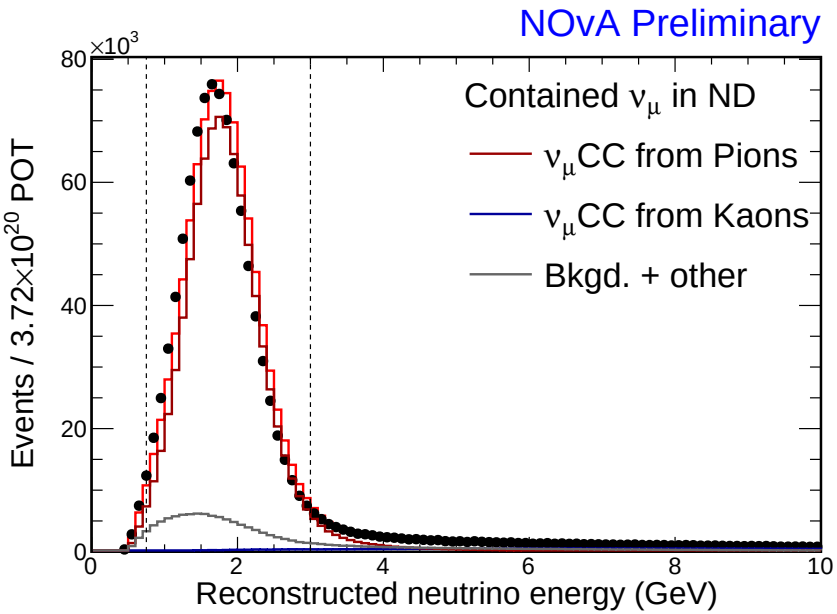
Beam ν_e Background Estimate



* Beam ν_e's at NOvA's location mostly arise from muon decay in beamline

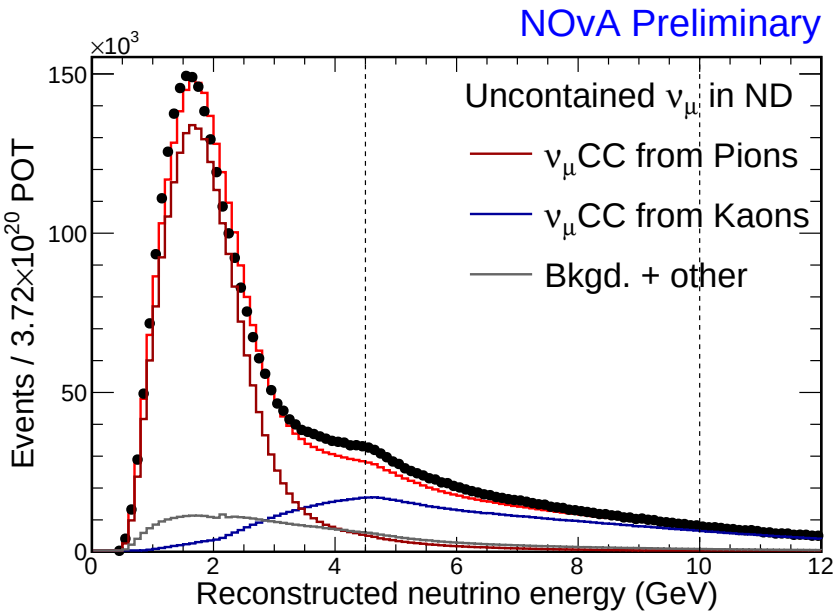
Beam ν_e Background Estimate

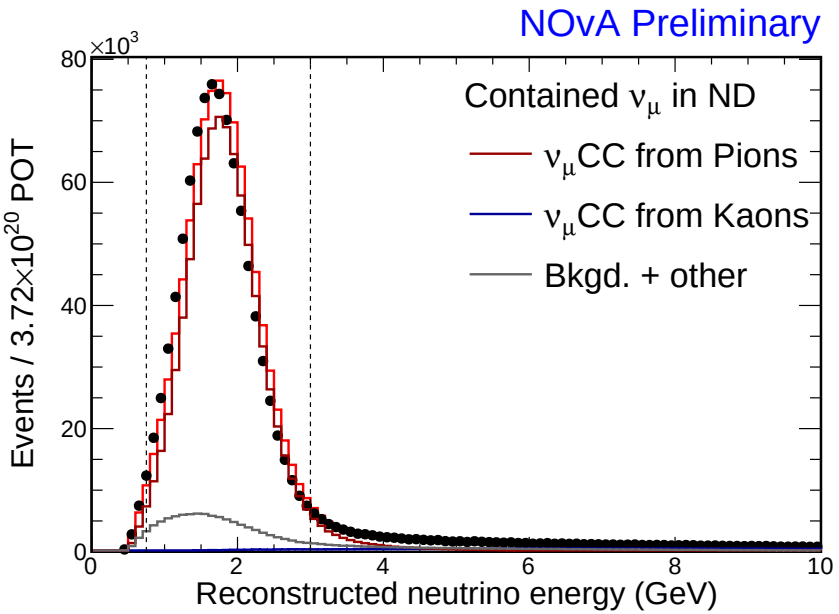




- Beam ν_e's at NOvA's location mostly arise from muon decay in beamline
- At low energy, ν_μ's and beam ν_e's come from common pion parents, at higher energy, the parents are Kaons
- Pion and Kaon yields are derived from the observed low and high energy ν_μ data

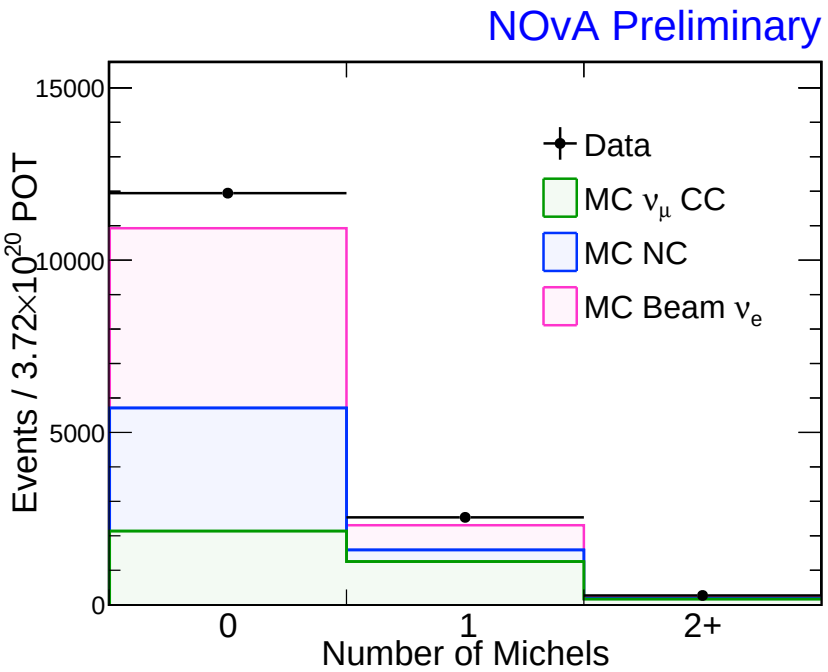
Beam ν_e Background Estimate





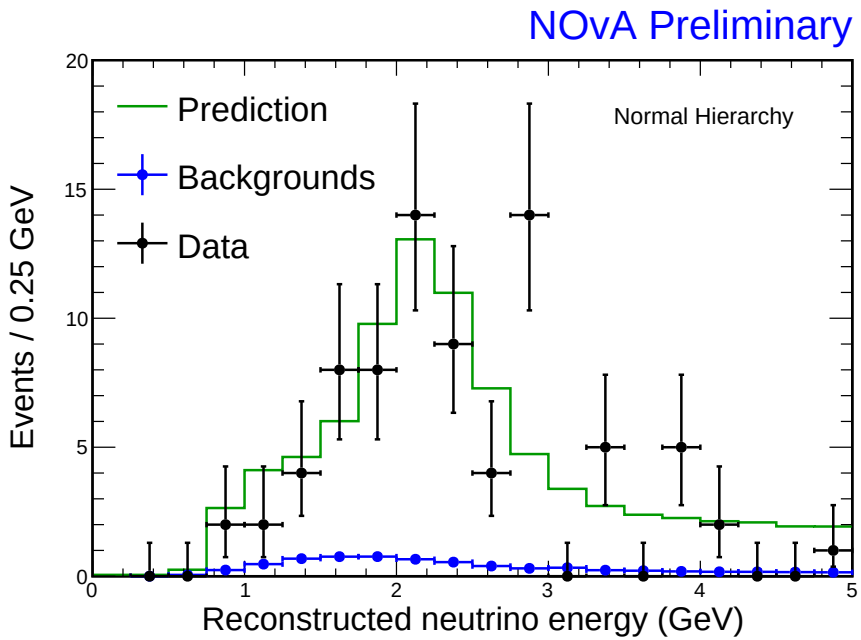
- Beam ν_e's at NOvA's location mostly arise from muon decay in beamline
- At low energy, ν_μ's and beam ν_e's come from common pion parents, at higher energy, the parents are Kaons
- Pion and Kaon yields are derived from the observed low and high energy ν_μ data
- Infer that Kaon yield is higher by 17% and Pion yield lower by 3%
- Leads to 1% increase in Beam ν_e background between 1-3 GeV in ND

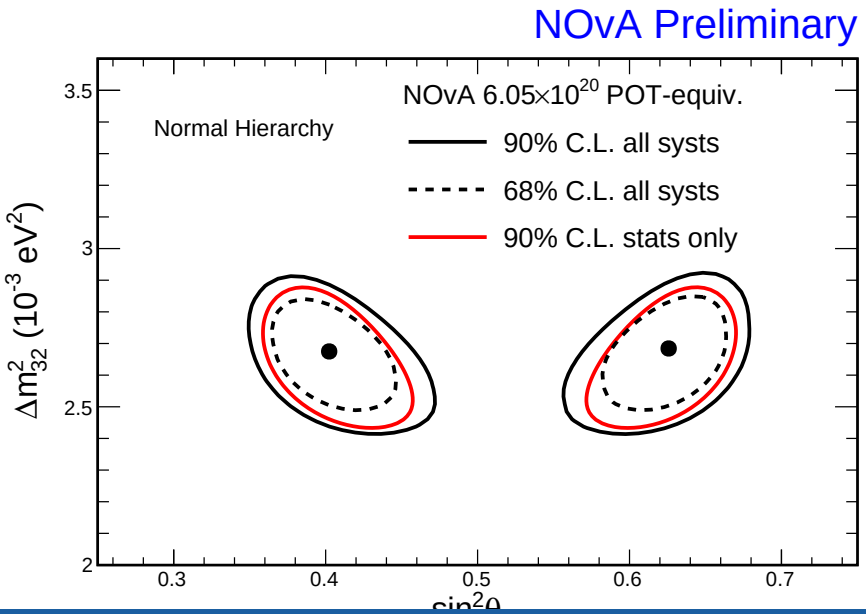
ν_μ CC Background Estimate

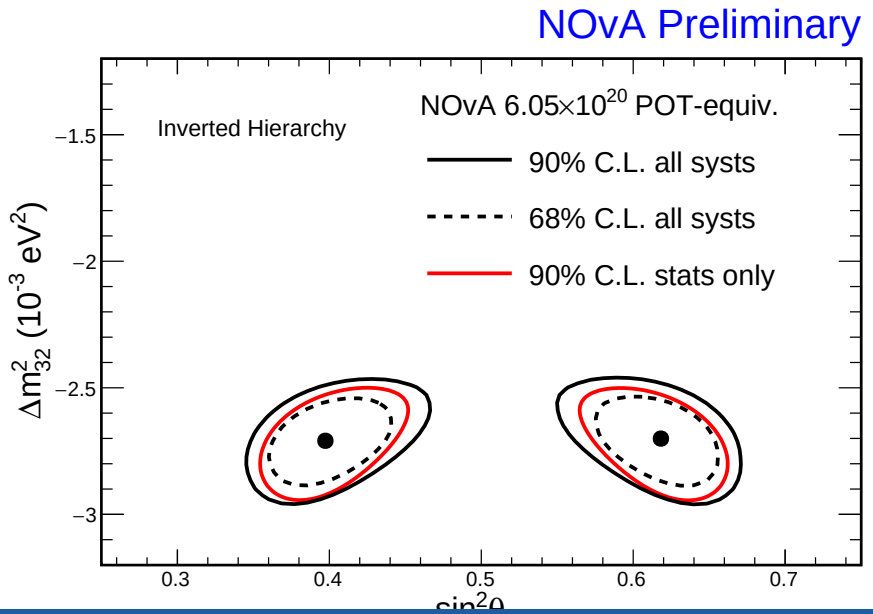


- Look for Michels electron associated with interactions selected with ν_e criteria
- ν_μ CC's should have 1 additional Michel electron than NC and ν_e CC's
- Fitting the number of Michels distribution suggests an integrated increase of 17.4% in ν_μ CC and 10.4% in NC backgrounds

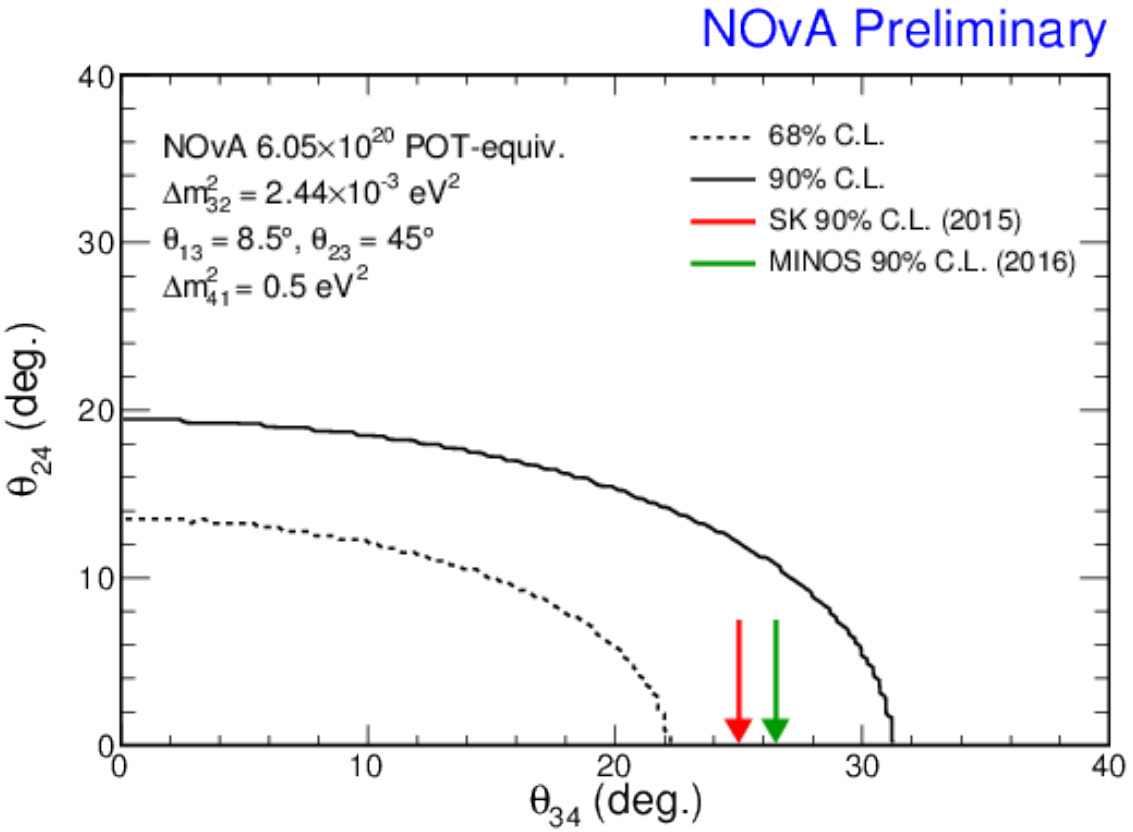
Disappearance Details



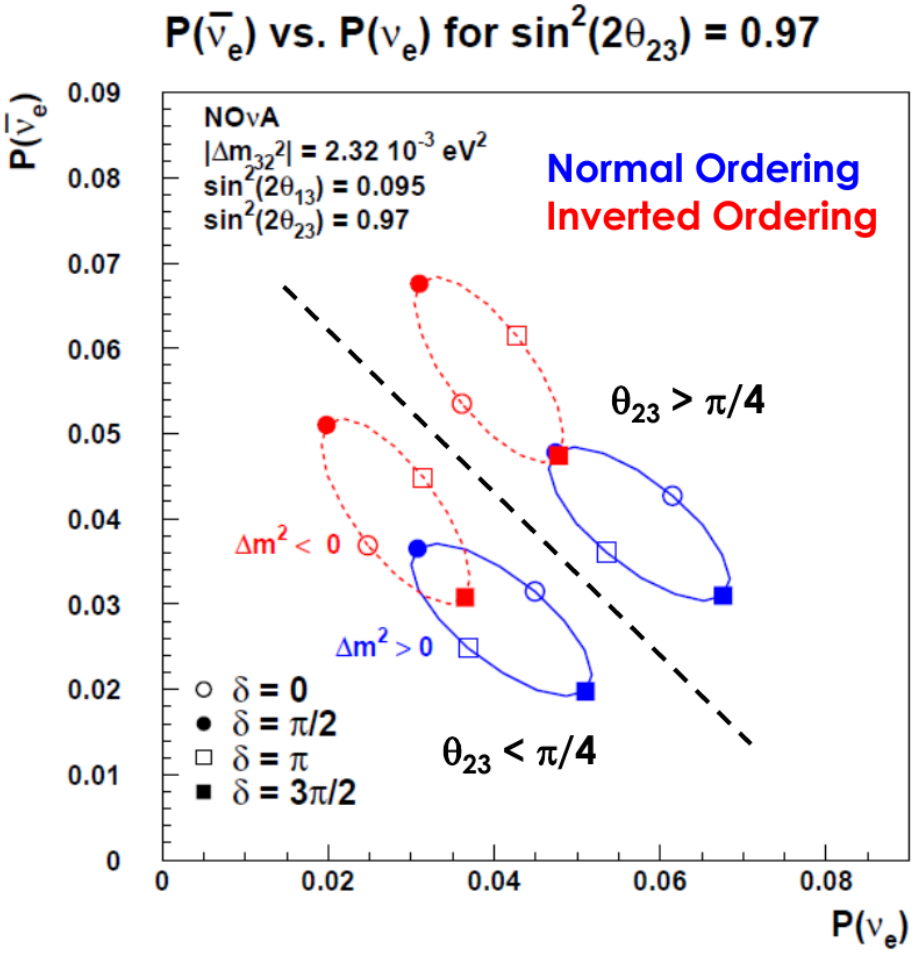




NC Disappearance Fit

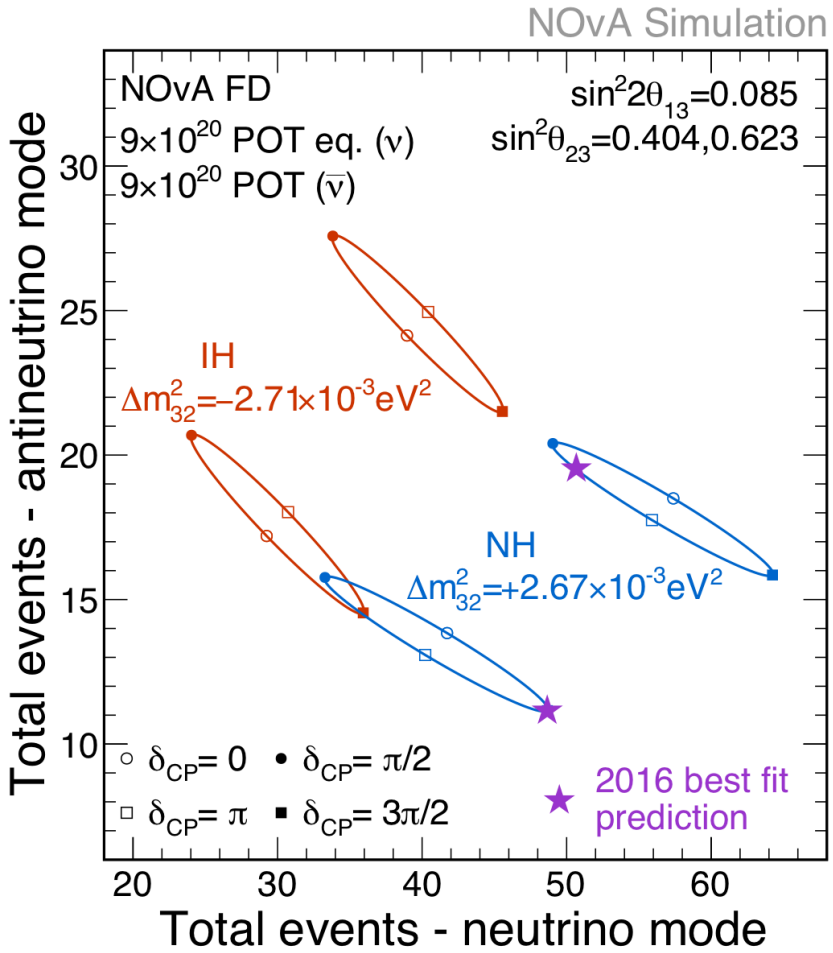


- Fitting a simple counting experiment
- $0.05\ \text{eV}^2 < \Delta m^2_{41} < 0.5\ \text{eV}^2$
- PDG2016 constraints on 3-flavor oscillation parameters
- 68% and 90% CL limits for 3+1 hypothesis



- Currently there is no information about the vertical axis
- NuMI switched to anti-neutrino mode in February 2017
- Plan to run 50% in neutrino and 50% in anti-neutrino mode in 2018
- Will help resolve some of the degeneracies

Why Anti-neutrinos



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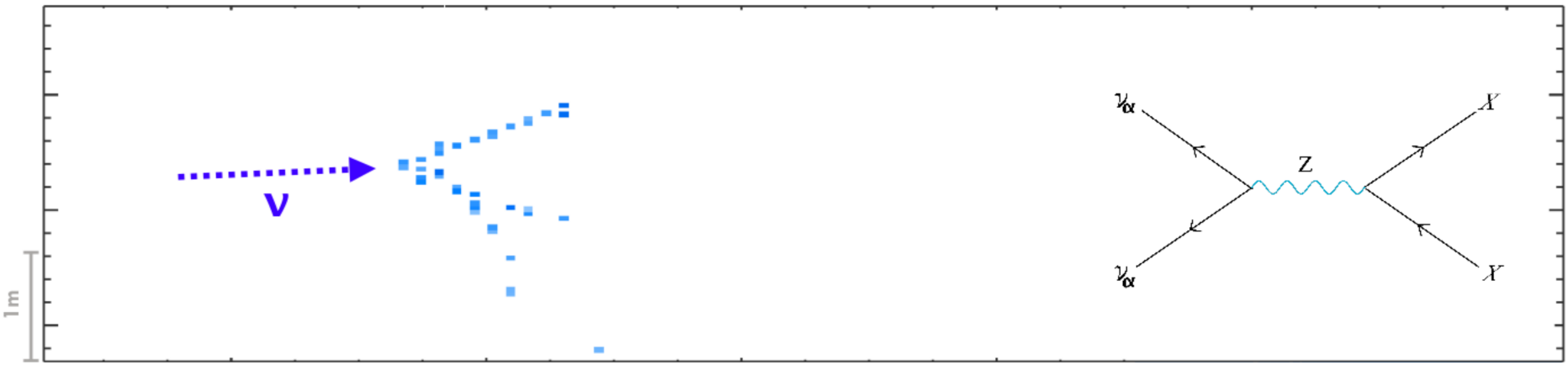
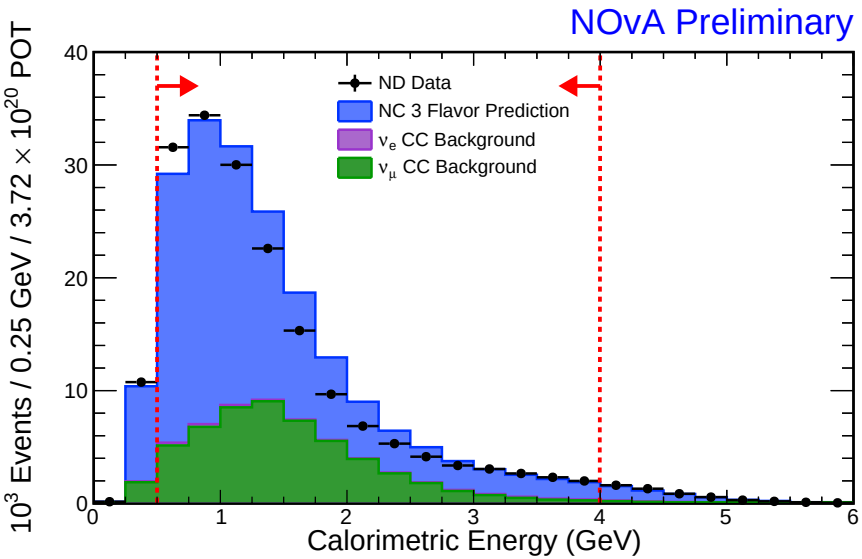
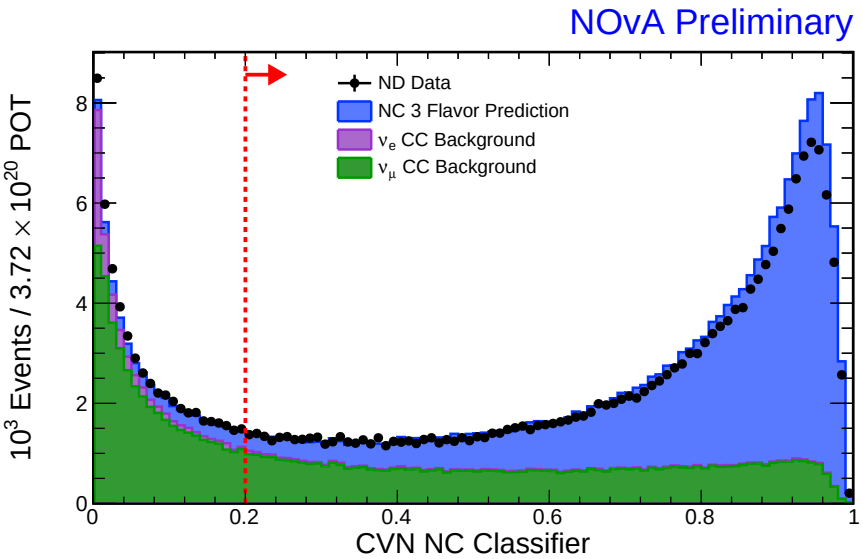
NC Disappearance Analysis



- Look for reduction in rate of NC, due to oscillation to sterile neutrinos
- Select NC interactions in ND
- Extrapolate to FD

NC Interactions in ND





- Using CVN to select NC
- Shows reasonable agreement between data and MC
- No NC MEC model available at the time led to large uncertainties

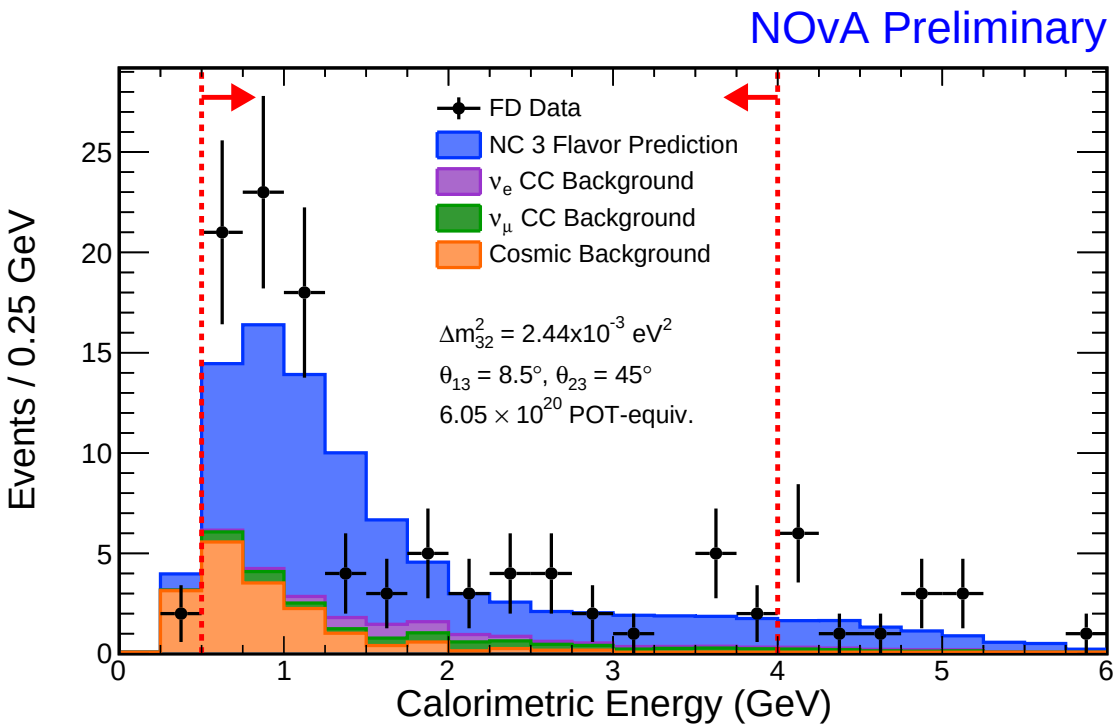
Prediction in FD

Fermilab

Event Type	Count
Total	83.5
NC	60.6
ν_μ CC	4.6
Beam ν_e CC	3.6
ν_τ CC	0.4
Cosmics	14.3

- Systematic uncertainties considered are similar to the ν_e appearance and ν_μ disappearance analyses
- 12.2% systematic error on signal and 15.3% on background
- Predicted event counts in table computed for maximal mixing

NC Disappearance Result



$$R = \frac{N_{data} - \sum N^{bg}_{pred}}{N^{NC}_{pred}}$$

- Observe 95 events on an expectation of 83
- The R statistic is $1.19 \pm 0.16(\text{stat.})^{0.10}_{0.14}(\text{syst.})$
- Measured value of R fully consistent with 3-flavor mixing