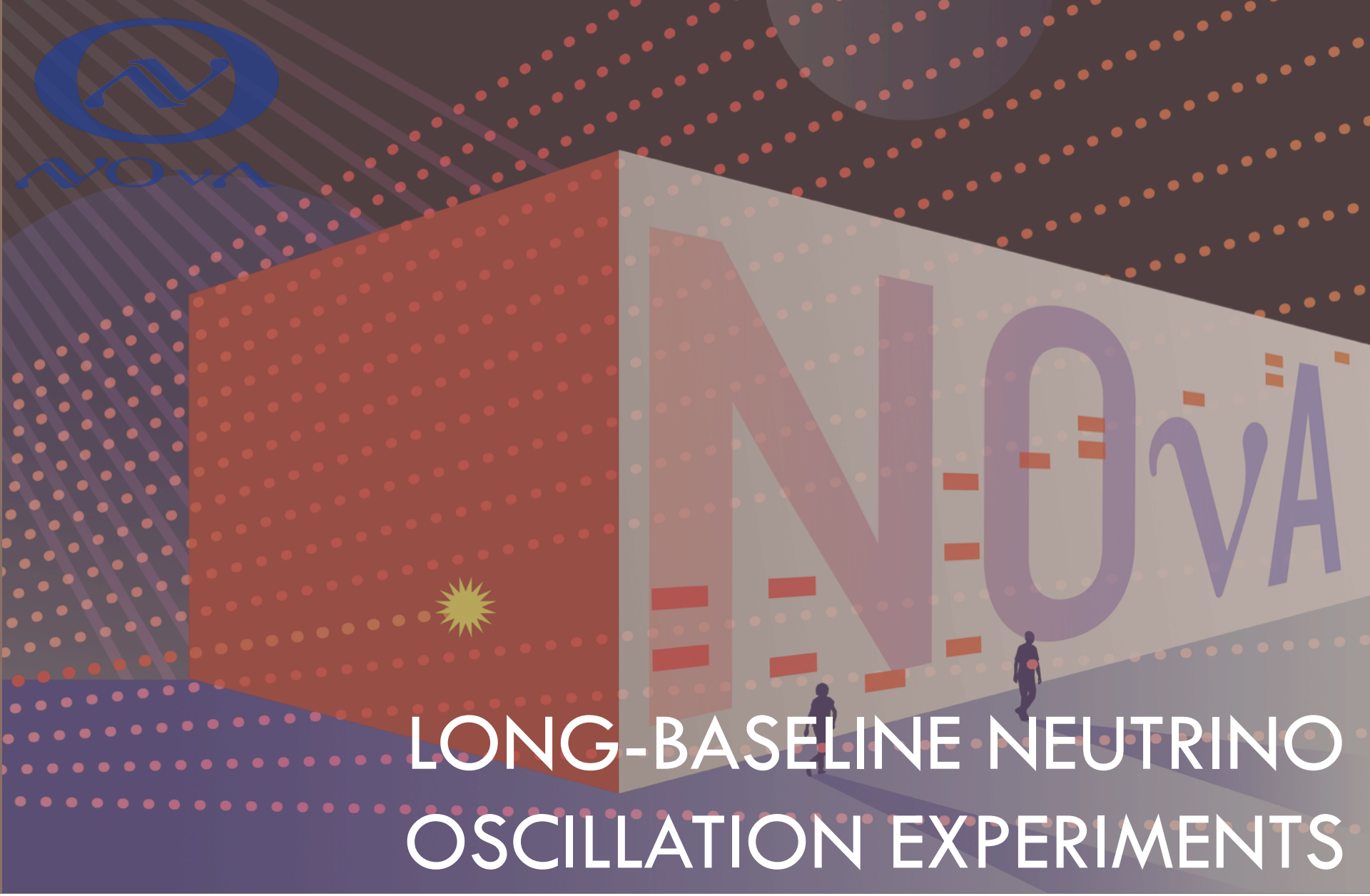
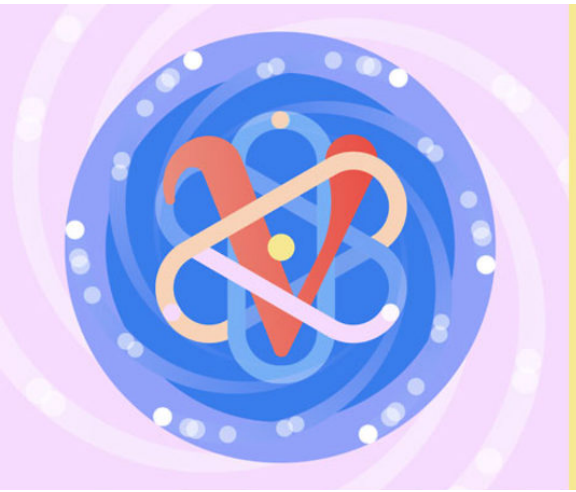


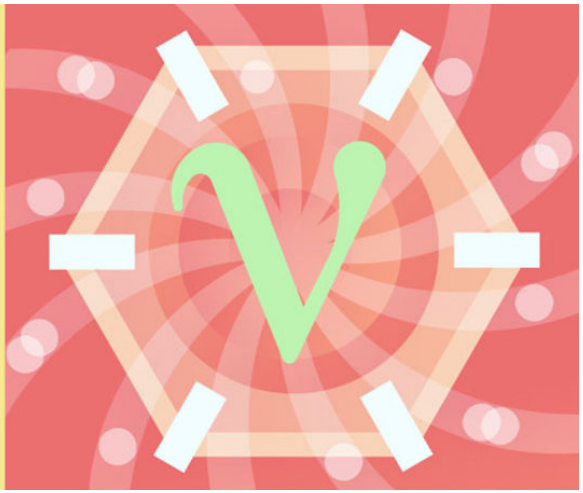
LONG-BASELINE NEUTRINO OSCILLATION EXPERIMENTS

Patricia Vahle
William and Mary

The Story of the Neutrino

- Reminder of the physics of neutrino oscillations
- The anatomy of an accelerator based long-baseline neutrino oscillation experiment—Case study: MINOS
- Recent results from NOvA and other neutrino experiments
- What's next?





Neutrinos Have Mass!

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

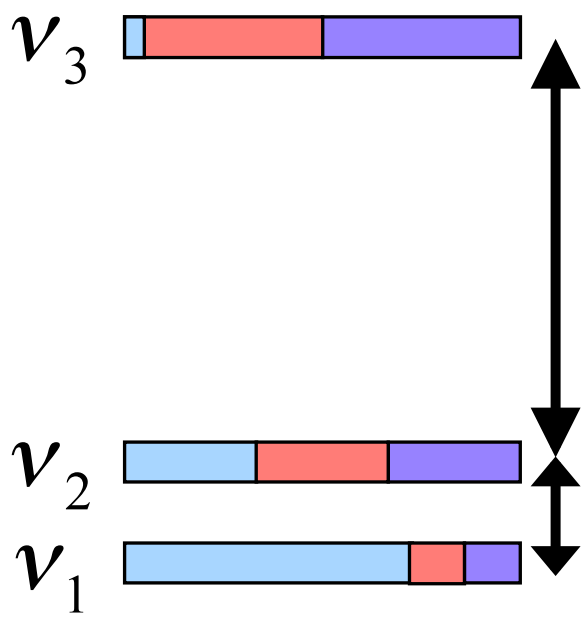
$$P(\nu_\alpha \rightarrow \nu_\beta) = \left| \sum_j U^*_{\beta j} e^{-i\frac{m_j^2 L}{2E}} U_{\alpha j} \right|^2$$

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

The PMNS Mixing Matrix

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

$$\theta_{23} \approx 45^\circ \qquad \theta_{13} \approx 9^\circ \qquad \theta_{12} \approx 34^\circ$$



What we know

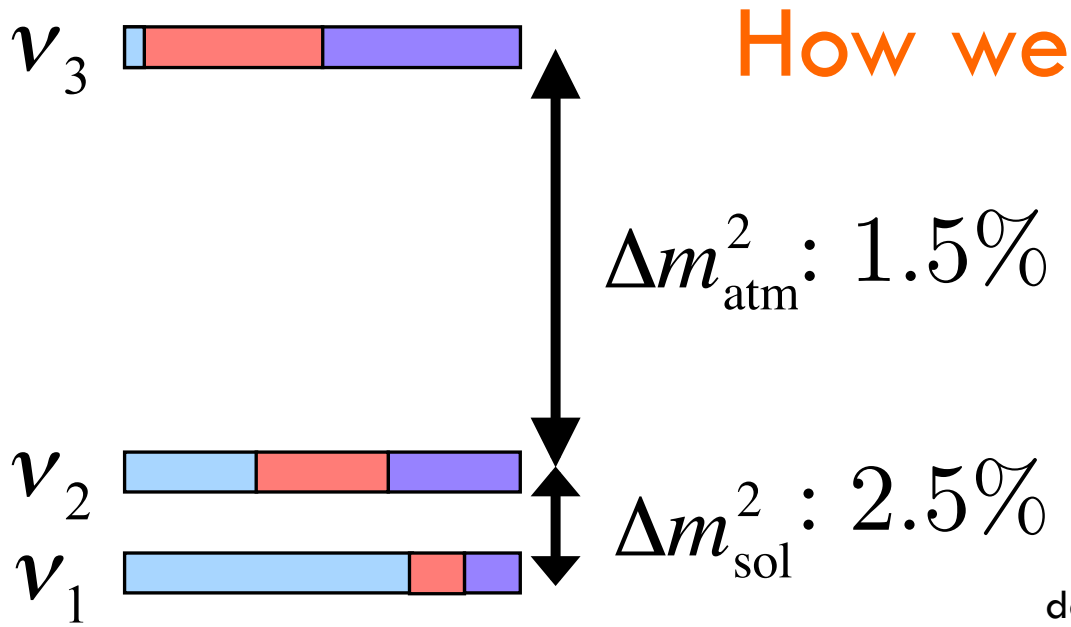
$$\Delta m^2_{\text{atm}} \approx 2 \times 10^{-3}\text{eV}^2$$

$$\Delta m^2_{\text{sol}} \approx 8 \times 10^{-5}\text{eV}^2$$

The PMNS Mixing Matrix

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

$\sin^2(\theta_{23}) : 5\%$ $\sin^2(\theta_{13}) : 3.5\%$ $\sin^2(\theta_{12}) : 5.5\%$



How well we know it

From M. Tortola, Neutrino2018 and deSalas et al, 1708.01186 (May 2018)

The PMNS Mixing Matrix

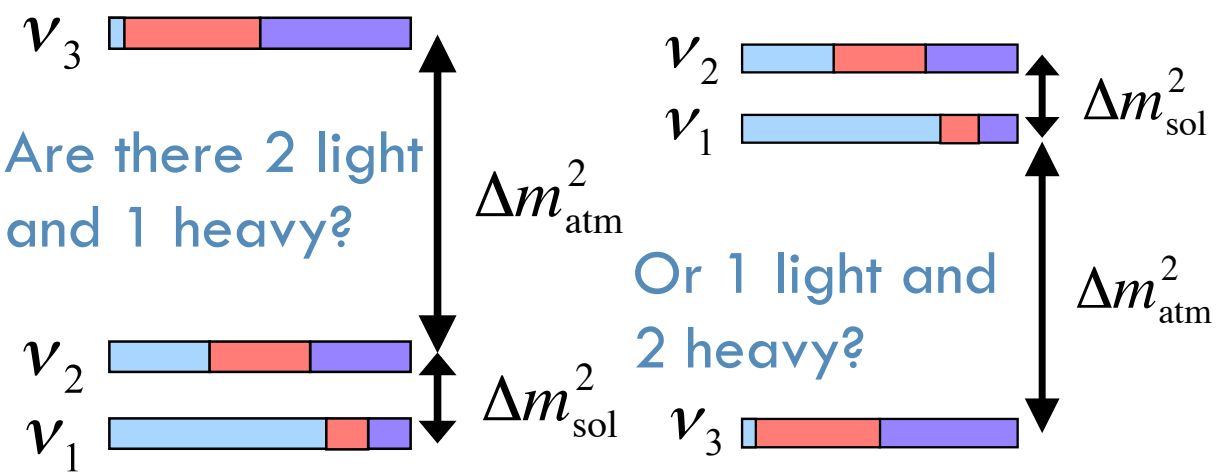
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12}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

Is it really 45°?

Is there CP violation?

What we don't know

The Mass Hierarchy



The PMNS Mixing Matrix

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

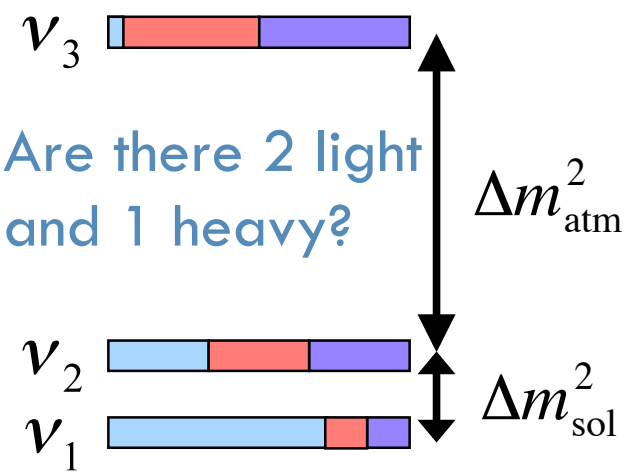
Is it really 45°?

Is there CP violation?

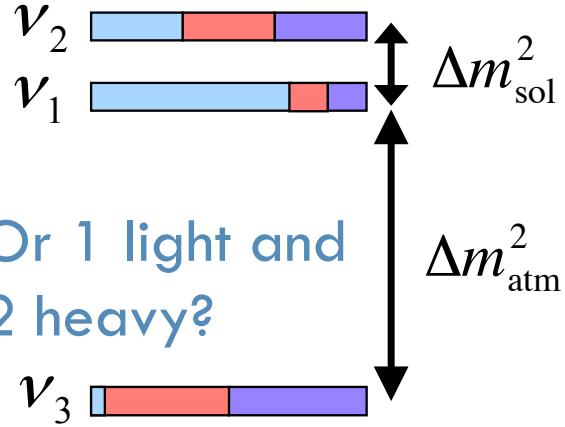
Why is the mixing bigger than in quarks?

What we don't know

The Mass Hierarchy



Are there 2 light and 1 heavy?



Or 1 light and 2 heavy?

Are there more than 3?

What is the absolute mass?

Are neutrinos their own antiparticles?

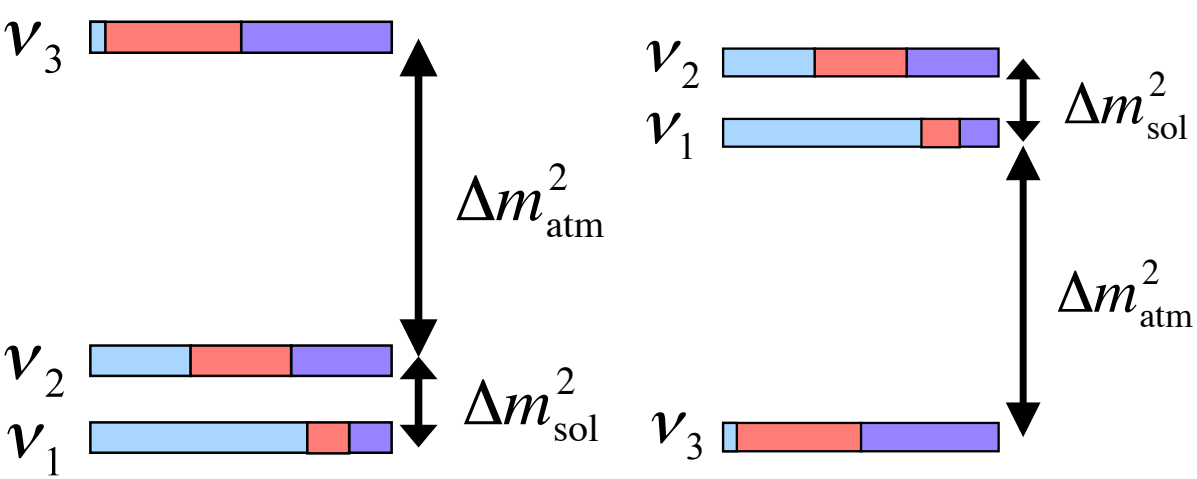
The PMNS Mixing Matrix

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

CP violation in neutrinos may help us understand the matter-antimatter asymmetry of the universe.

Why do we care?

The Mass Hierarchy



20 years on, we are still exploring how massive neutrinos fit into the Standard Model. Discrimination among models hinges on precision measurements and answers to these questions.

Long-baseline experiments

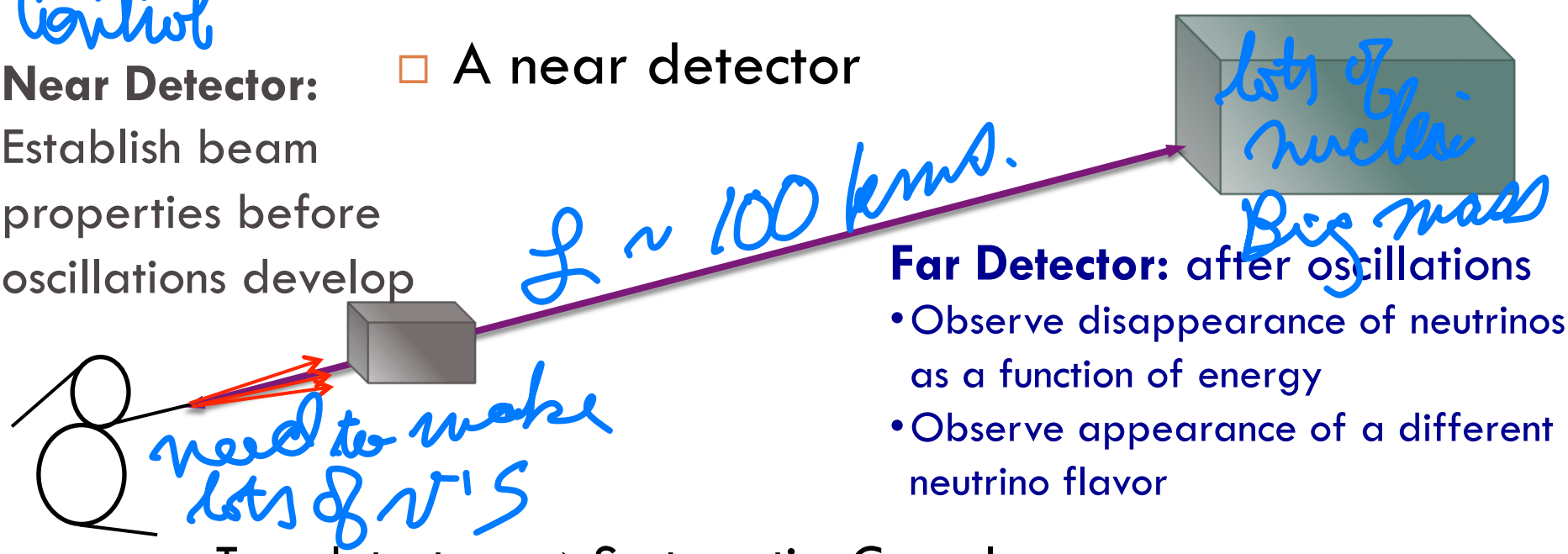
The long baseline recipe

- An intense neutrino beam
- A massive far detector
- A near detector

Flux ~ $\frac{1}{R^2}$

Control

Near Detector: Establish beam properties before oscillations develop



Far Detector: after oscillations

- Observe disappearance of neutrinos as a function of energy
- Observe appearance of a different neutrino flavor

Two detectors → Systematics Cancel

- Neutrino flux uncertainties
- Neutrino interaction uncertainties

Long-baseline experiments

*PRD 74 (2006) 072003

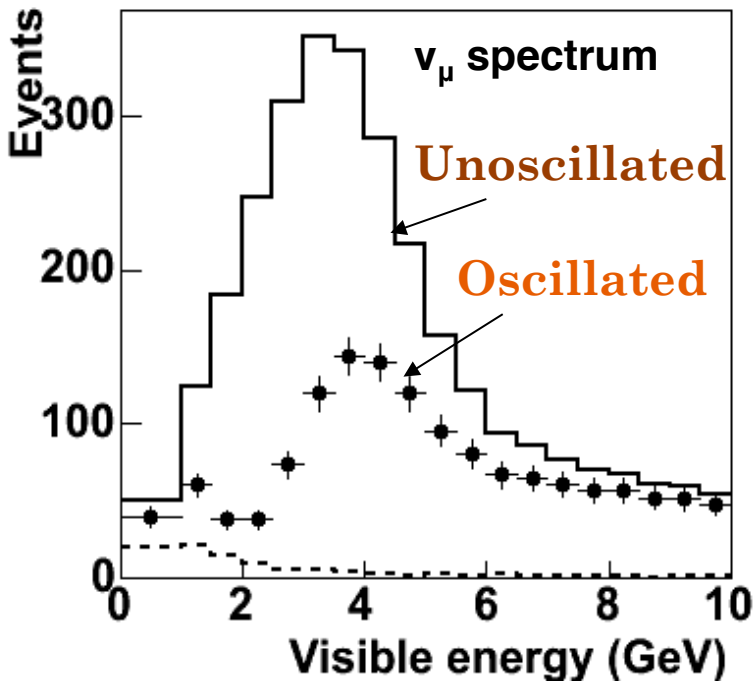
Long-baseline experiments

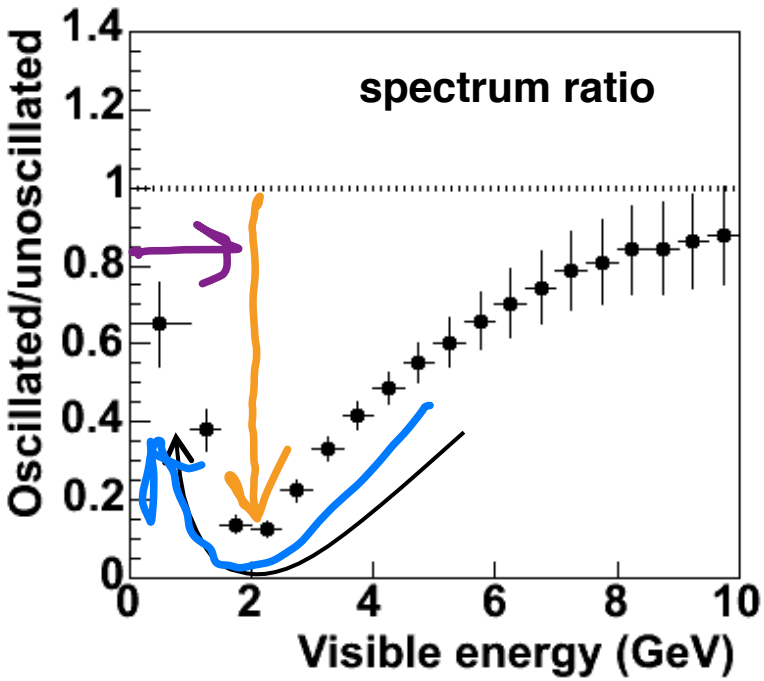
Study multiple oscillation modes, compare neutrino and antineutrino oscillation probabilities

- ν_μ disappearance $P(\nu_\mu \to \nu_\mu)$
  - clear suppression as a function of energy
  - $|\Delta m^2_{32}|$, $\sin^2(2\theta_{23})$
- ν_e appearance $P(\nu_\mu \to \nu_e)$
  - θ_{13}, θ_{23}, δ_{CP}, and mass hierarchy
  - may be different for neutrinos vs. antineutrinos
- ν_τ appearance $P(\nu_\mu \to \nu_\tau)$

Muon Neutrino Disappearance

$$P(\nu_\mu \to \nu_\mu) = 1 - \underbrace{\sin^2 2\theta}_{\text{amplitude}} \underbrace{\sin^2\left(1.27\,\frac{\Delta m^2 L}{E}\right)}_{\text{osc.}}$$





Monte Carlo

(Input parameters: $\sin^2 2\theta = 1.0$, $\Delta m^2 = 3.35\times10^{-3}\ \text{eV}^2$)

Extending to 3 Flavors

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta_{\mu\mu} \sin^2\left(1.27 \frac{\Delta m^2_{\mu\mu} L}{E}\right) + \underbrace{\mathcal{O}\left(\Delta m^2_{\mu\mu} \frac{L}{E}\right)^2}_{\text{Small.}}$$

where $\theta_{\mu\mu}$ & $\Delta m^2_{\mu\mu}$ are effective parameters

$$\sin^2\theta_{\mu\mu} = \sin^2\theta_{23}\cos^2\theta_{13}$$

$$\Delta m^2_{\mu\mu} = \Delta m^2_{32} + \frac{|U_{\mu 1}|^2}{1-|U_{\mu 3}|^2}\Delta m^2_{21}$$

$\cos^2\theta_{13} = .976$

$2 \times 10^{-5}\ eV^2$

ν_e Appearance

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

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

depends on octant!

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

amplitude depends on 2 mixing angles

osc, depends on Δm^2

"Atmospheric" Term

Depends on Δm^2 and θ_{13}

"Solar" Term

<1% for current accelerator experiments

ν_e Appearance

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

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

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

Interference Term

- for neutrinos

+ for antineutrinos

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

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

ν_e Appearance

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

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

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

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

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

whether you have ν's or $\bar{\nu}$'s

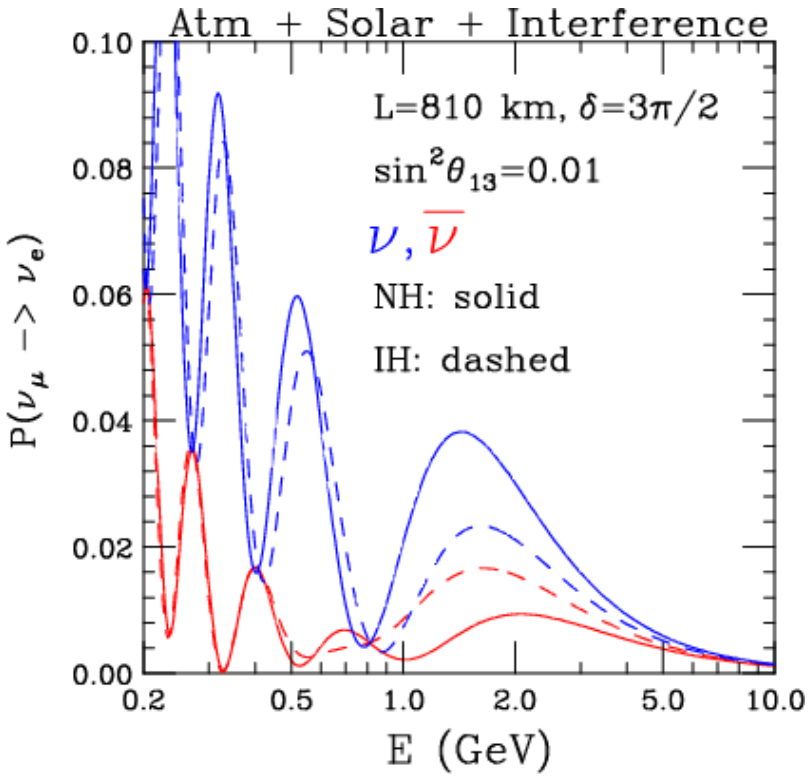
G_F - Fermi Constant

N_e - electron density

In matter, additional term in Hamiltonian from ν_e + e CC scattering modifies oscillation probability

ν_e Appearance

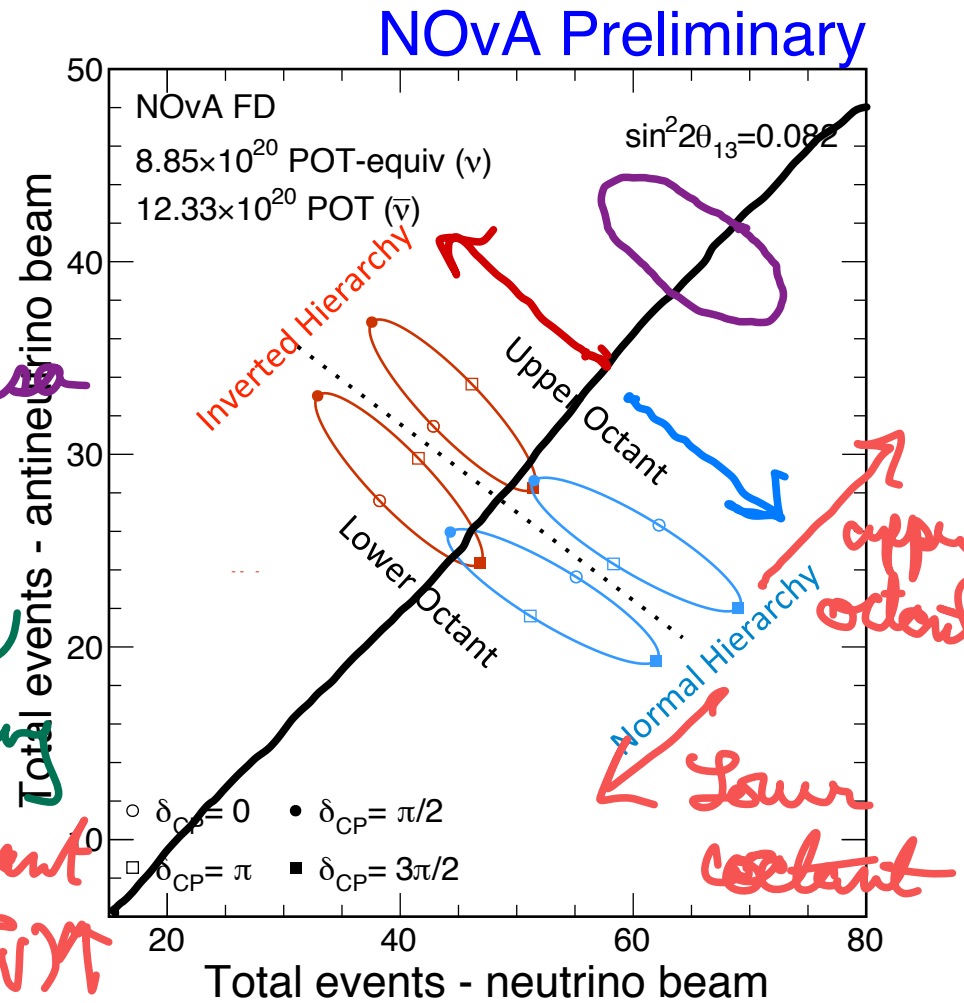
- At L/E~400 km/GeV, dominant oscillation mode is $\nu_\mu \rightarrow \nu_\tau$
- A few percent of the missing ν_μ could change into ν_e



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

ν_e Appearance

- Compare electron-neutrino appearance probability in neutrinos to antineutrinos
  - In vacuum, $\delta = 0$
    $P(\nu_\mu \to \nu_e) = P(\bar{\nu}_\mu \to \bar{\nu}_e)$
  - If $\delta_{CP} \neq 0$ or matter effects
    $P(\nu_\mu \to \nu_e) \uparrow$, $P(\bar{\nu}_\mu \to \bar{\nu}_e) \downarrow$
  - matter effects
    $P(\nu_\mu \to \nu_e) \uparrow$ $P(\bar{\nu}_\mu \to \bar{\nu}_e) \downarrow$
  - or mass hierarchy-dependent
  - If $\theta_{23} \neq 45°$, upper octant
    $P(\nu \to \nu) \uparrow$ $P(\bar{\nu} \to \bar{\nu}) \uparrow$



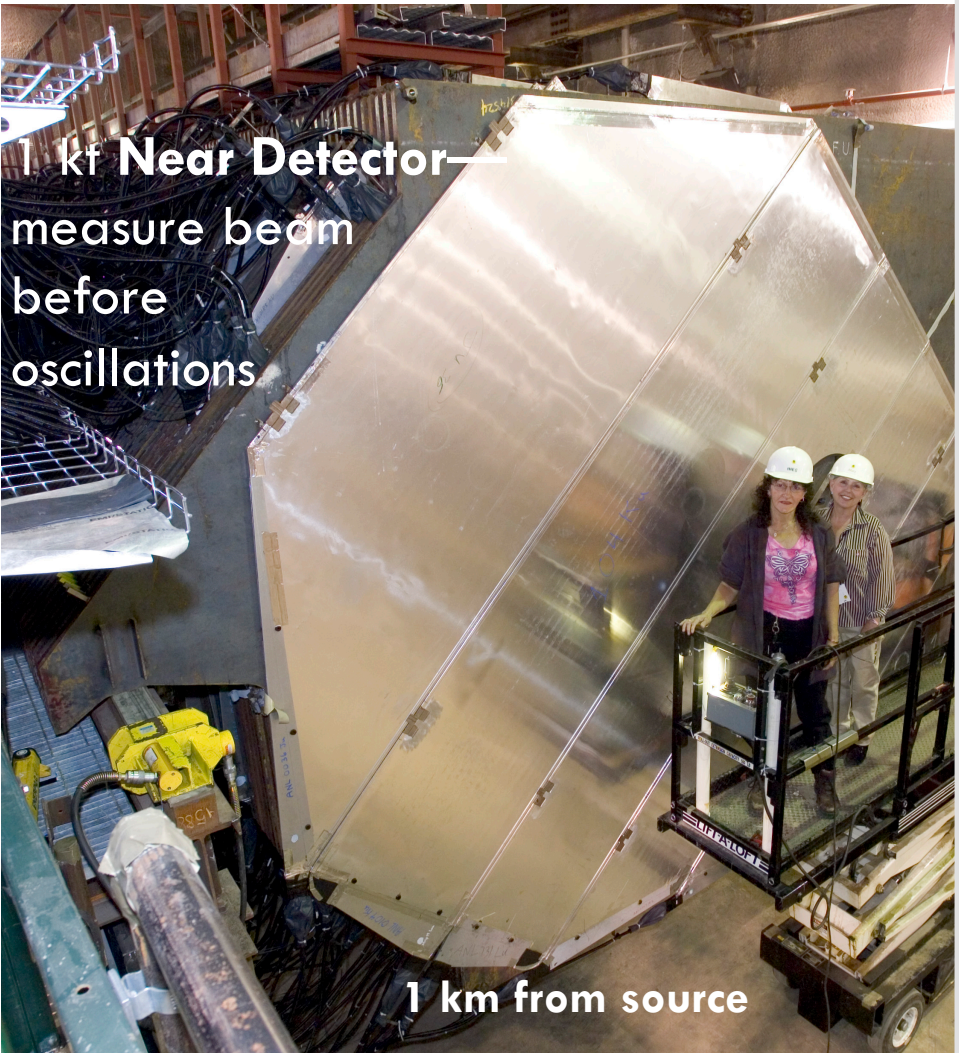
The MINOS Experiment

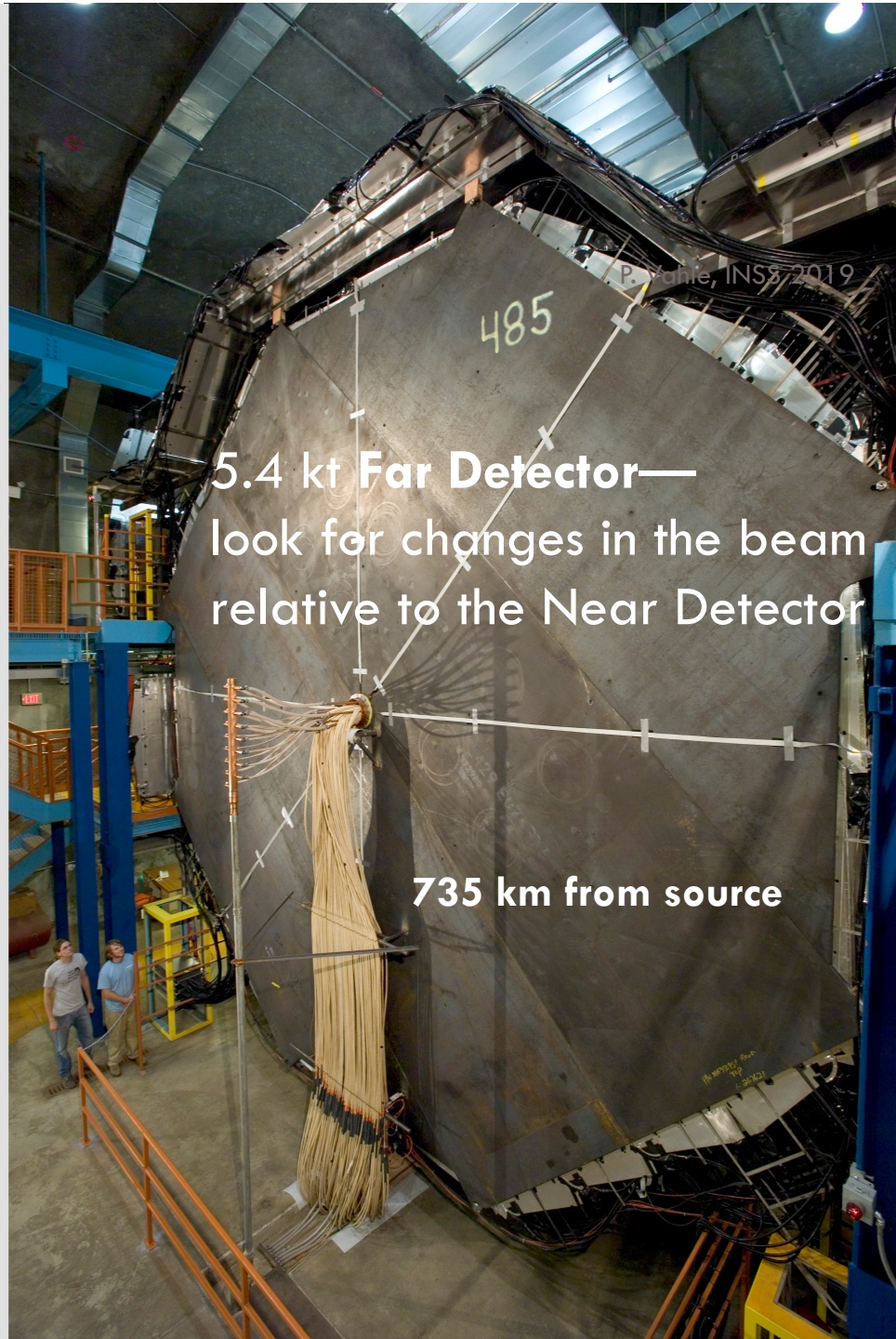
- Long-baseline neutrino oscillation experiment
- Neutrinos from NuMI beam line
- Designed for muon neutrino disappearance

- Two detectors mitigate systematic effects
  - beam flux mis-modeling
  - neutrino interaction uncertainties

The Detectors

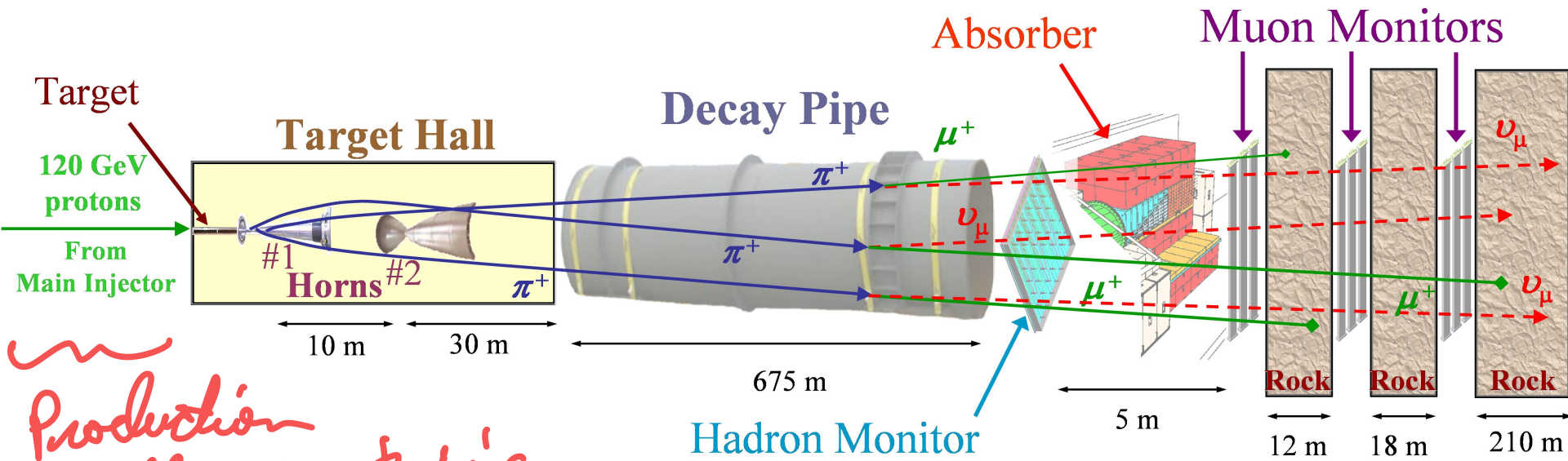
Magnetized, tracking calorimeters





NIM A806 (2016) 279-306

Making a Neutrino Beam



Production mostly π's & K's

Performance metric

Pot

Protons on Target

$$\text{Power} \approx \frac{\text{Energy}}{\text{time}}$$

$$= \frac{E(\text{joules})}{p^+} \cdot \frac{\text{pot/spill}}{\text{sec/spill}}$$

cycle time

minos Power 310 KW

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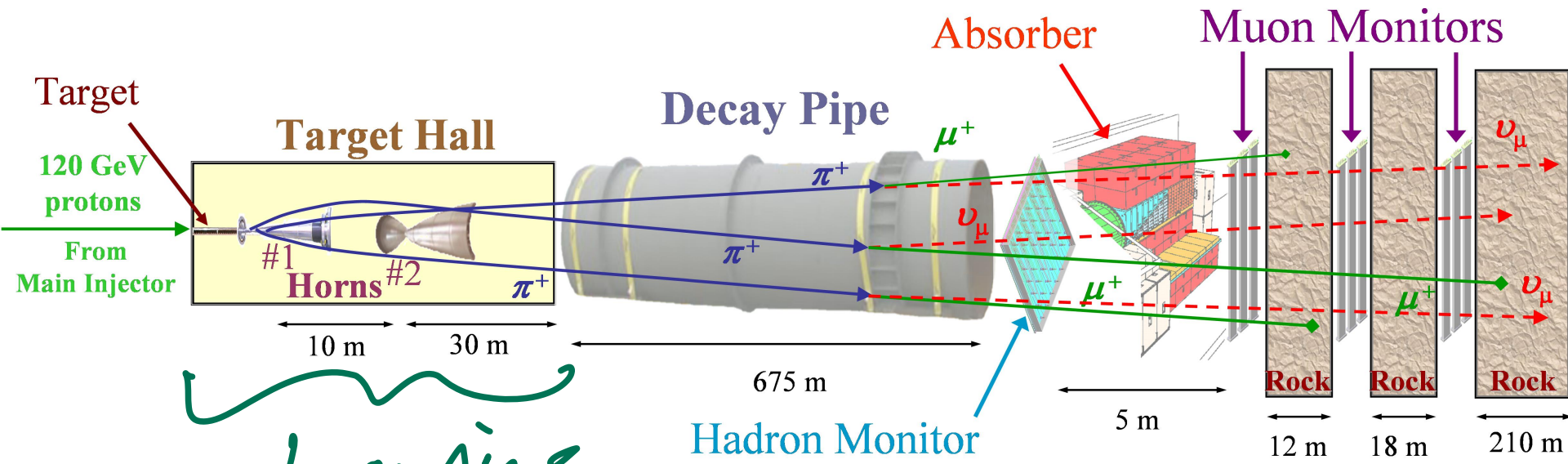
Making a Neutrino Beam



focusing

magnetic horns

Horns charge select → FHC - Forward Horn Current

$+ \rightarrow \nu$

→ RHC - Reverse - $\rightarrow \bar{\nu}$

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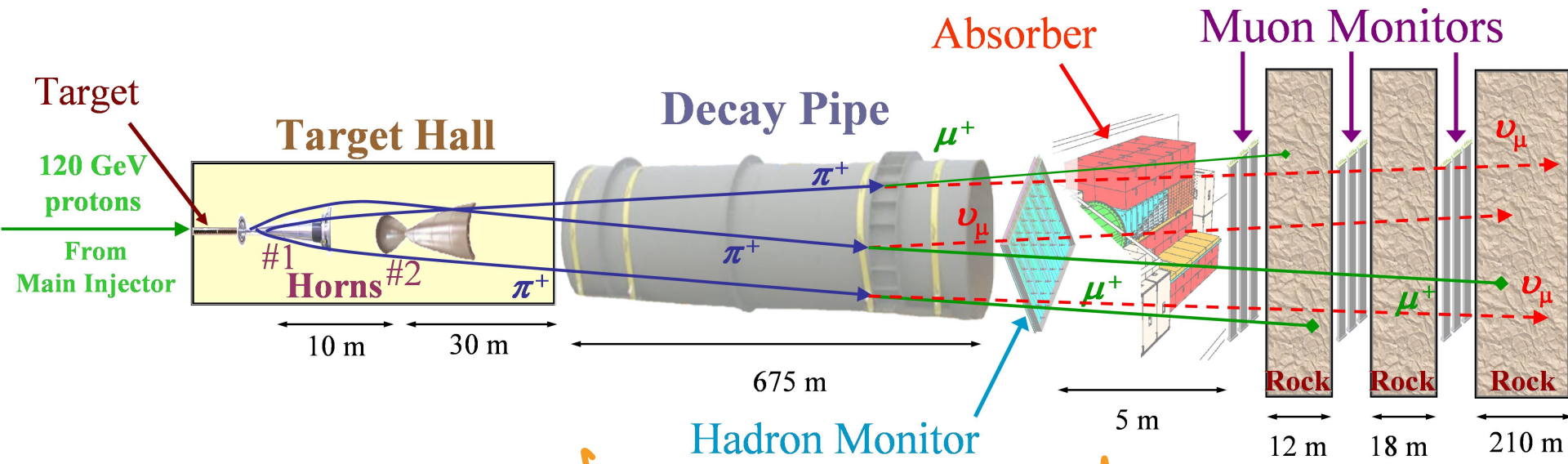
Making a Neutrino Beam



Decay

monitoring

$\pi \rightarrow \mu + \nu_\mu$

$K \rightarrow \mu + \nu_\mu$

Historical Interlude

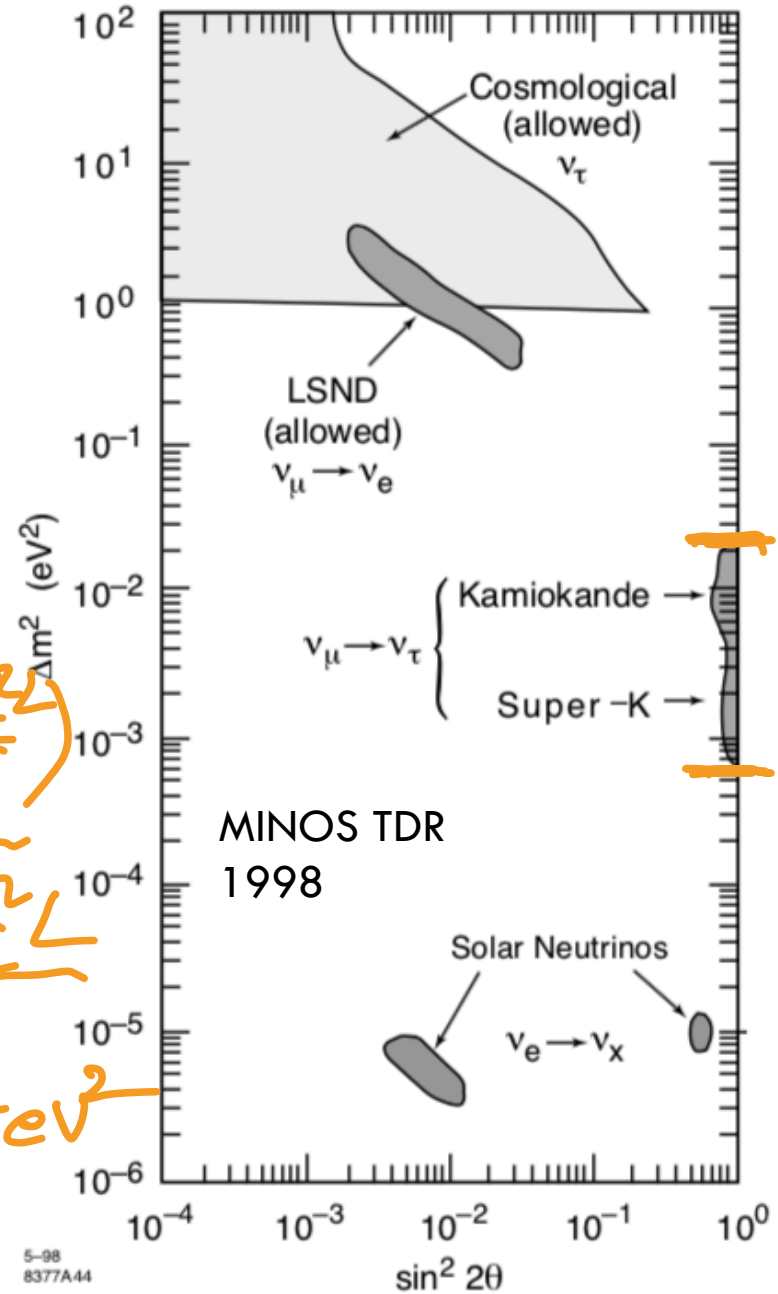
- The MINOS TDR describes "hints" of neutrino oscillations.
- What range of energy should MINOS span to cover Δm^2 range?

$$P(\nu_\mu \to \nu_\mu) \simeq 1 - \sin^2 2\theta \sin^2\left(1.27\frac{\Delta m^2 L}{E}\right)$$

$$1.27\frac{\Delta m^2 L}{E} \simeq \pi/2 \rightarrow E = \frac{2.54\,\Delta m^2 L}{\pi}$$

$L \simeq 735\,km$ $\quad \Delta m^2 \sim 5\times10^{-4} - 2\times10^{-2}\,eV^2$

$$E \sim .3 - 12\,GeV$$



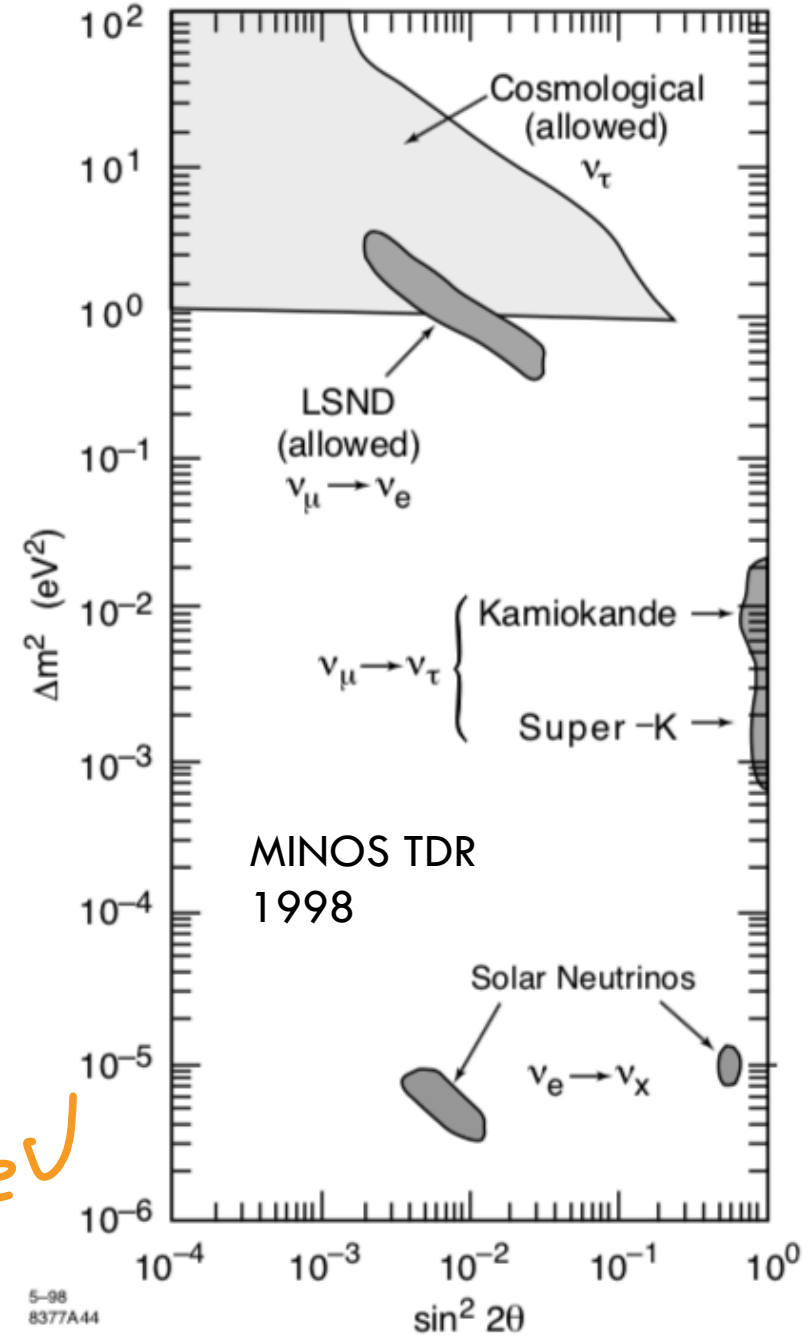
Historical Interlude

- By the time we started taking data in 2005, the central value was around $3 \times 10^{-3} eV^2$…

$E = 1.78 GeV$

- Would we see tau neutrino appearance?

$m_\tau = 1.78 GeV$ Pdmsh $= 3.5 GeV$



Planning ahead

- The MINOS beam could be reconfigured to access a wide range of energies
  - Horns could be moved
  - Target could be moved
  - Ultimately ran in LE config

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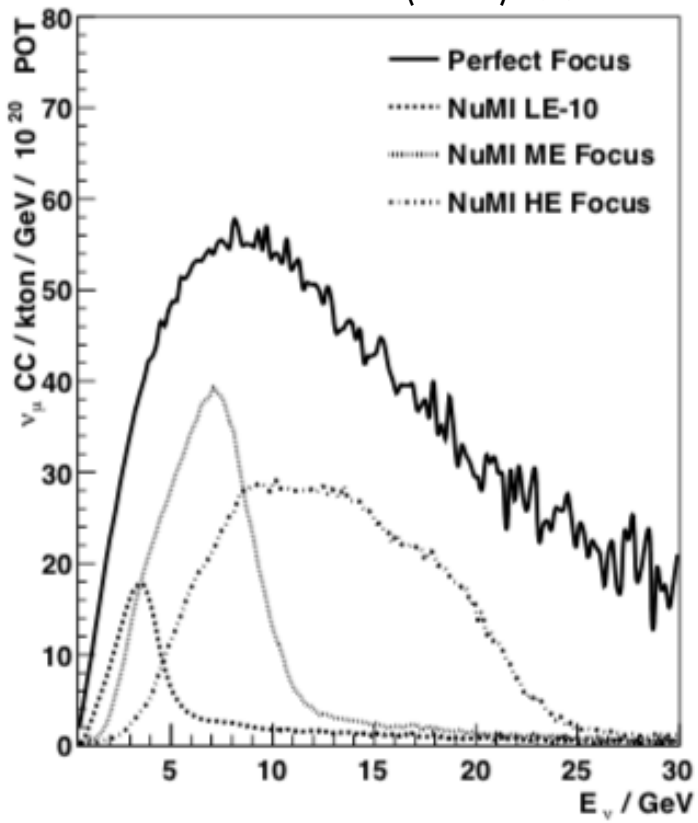
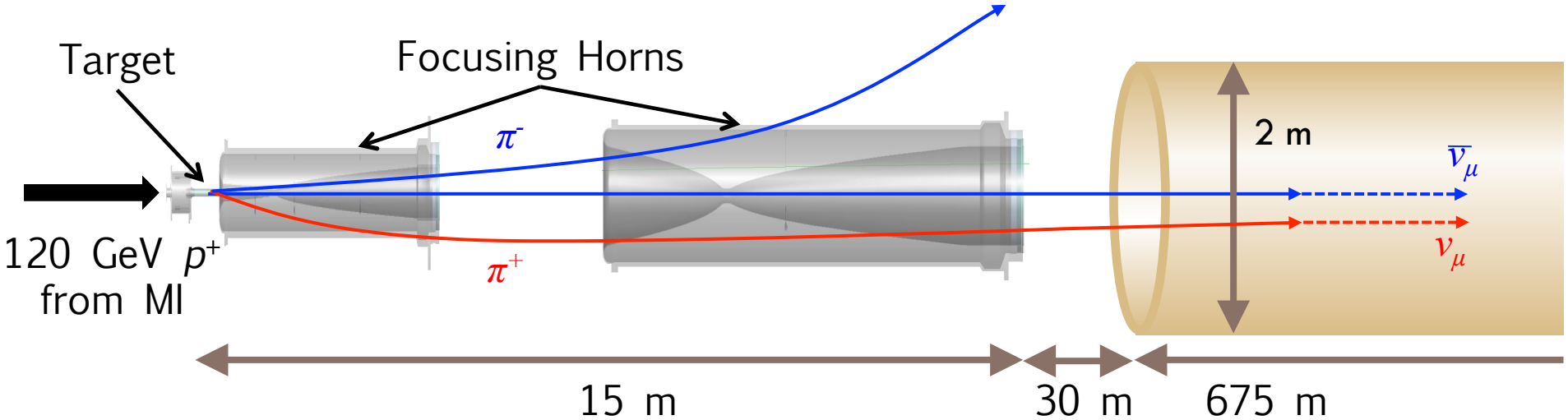
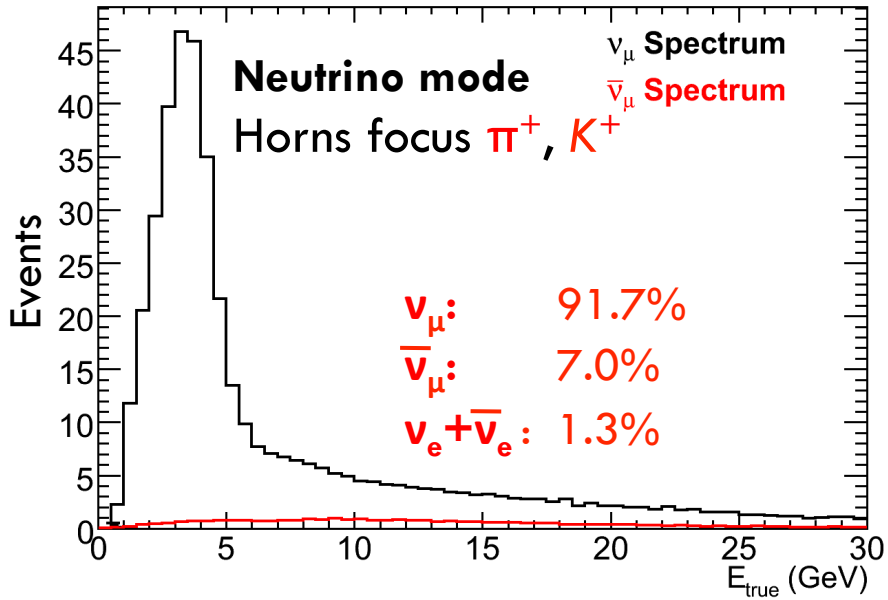
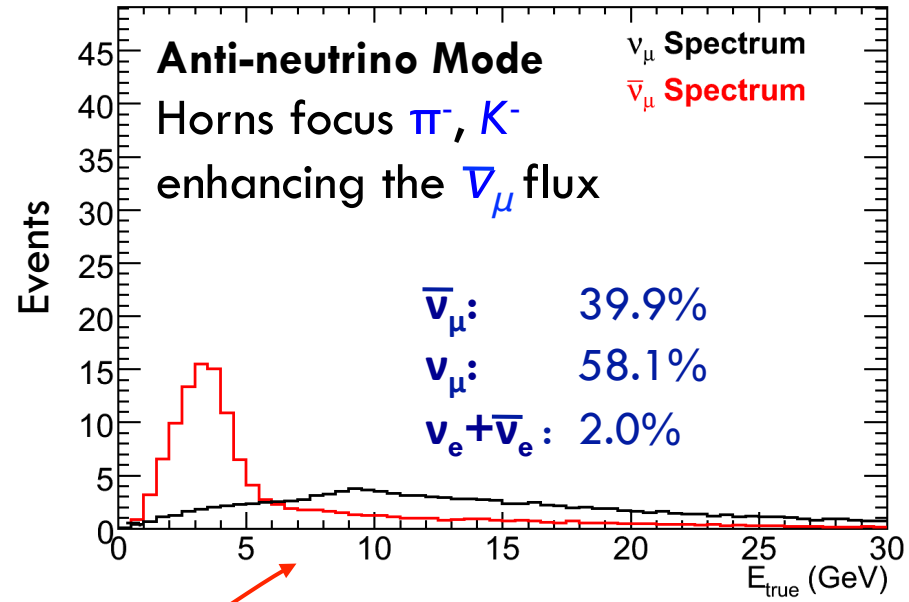
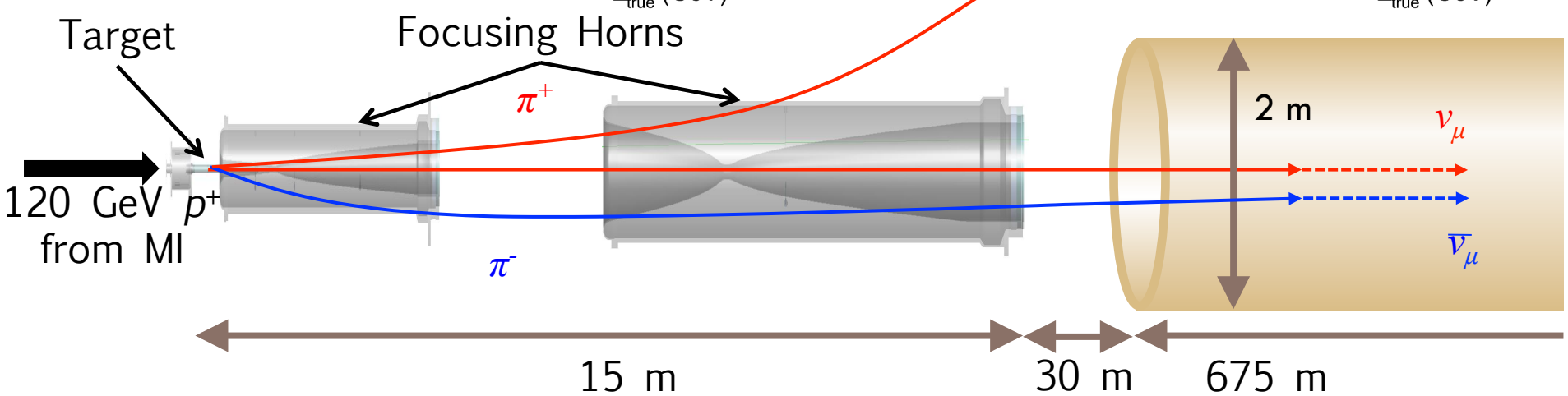




Making a Neutrino Beam

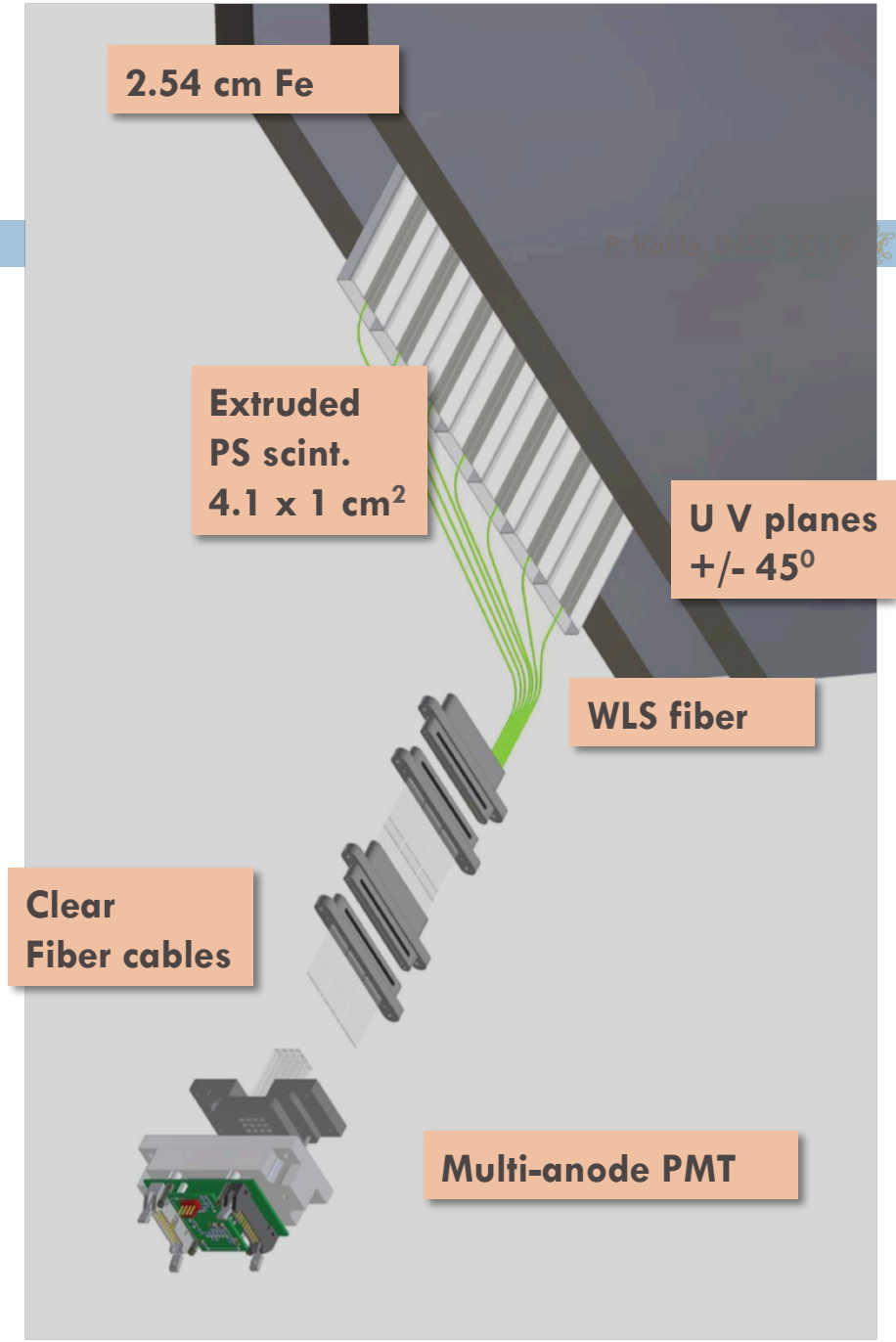




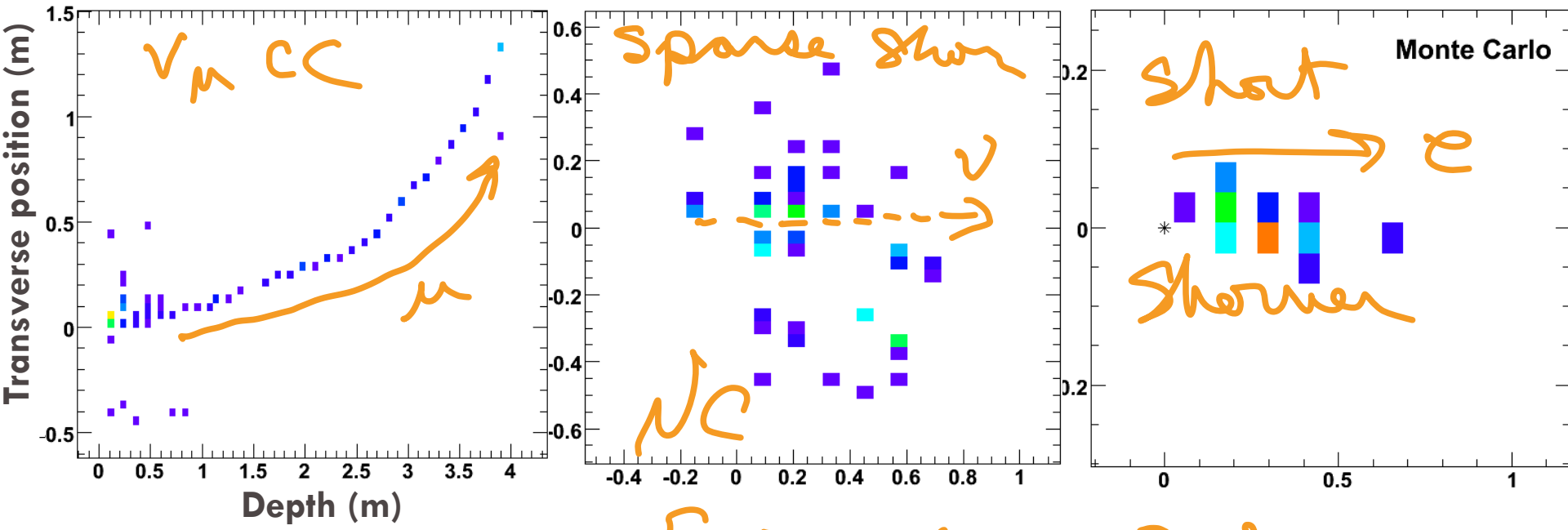


Detector Technology

- Tracking sampling calorimeters
  - steel absorber 2.54 cm thick (1.4 X_0)
  - scintillator strips 4.1 cm wide (1.1 Moliere radii)
  - 1 GeV muons penetrate 28 layers
- Magnetized
  - muon energy from range/curvature
  - distinguish μ^+ from μ^-
- Functionally equivalent
  - same segmentation
  - same materials
  - same mean B field (1.3 T)



Events in MINOS



$E_\nu = E_\mu + E_x$

range curvature

calorimetric response

E_{vis} - color.

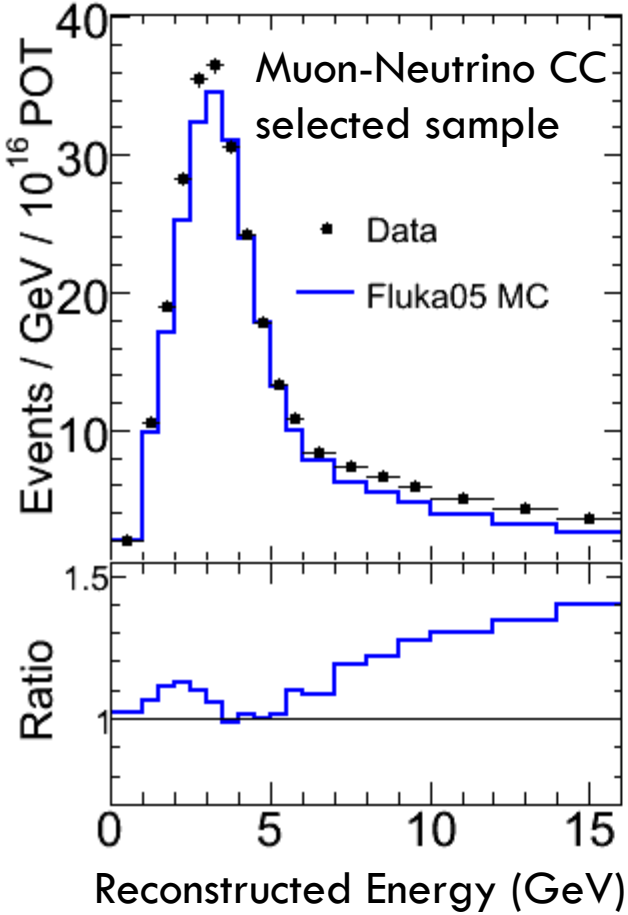
E_ν from color

To measure neutrino oscillations, you need to identify the neutrino flavor.

Can you name the neutrino events?

MINOS Near Detector

- Near Detectors are crucial in the control of potentially large systematic uncertainties facing oscillation experiments

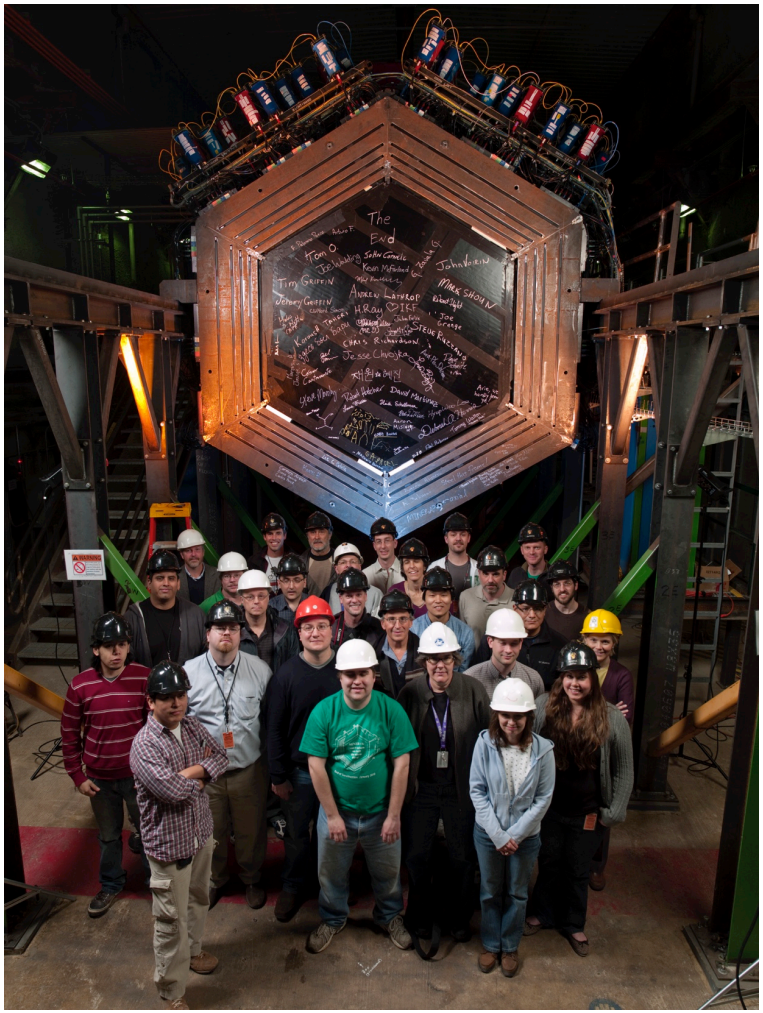


- Flux mis-modeling
- interaction uncertainties
- hadronization and final state interaction uncertainties

- Even in 2-detector experiments, good neutrino interaction and flux modeling makes for a more robust Far Detector prediction
  - Simulation used for acceptance and resolution corrections, help characterize impact of residual systematic uncertainties

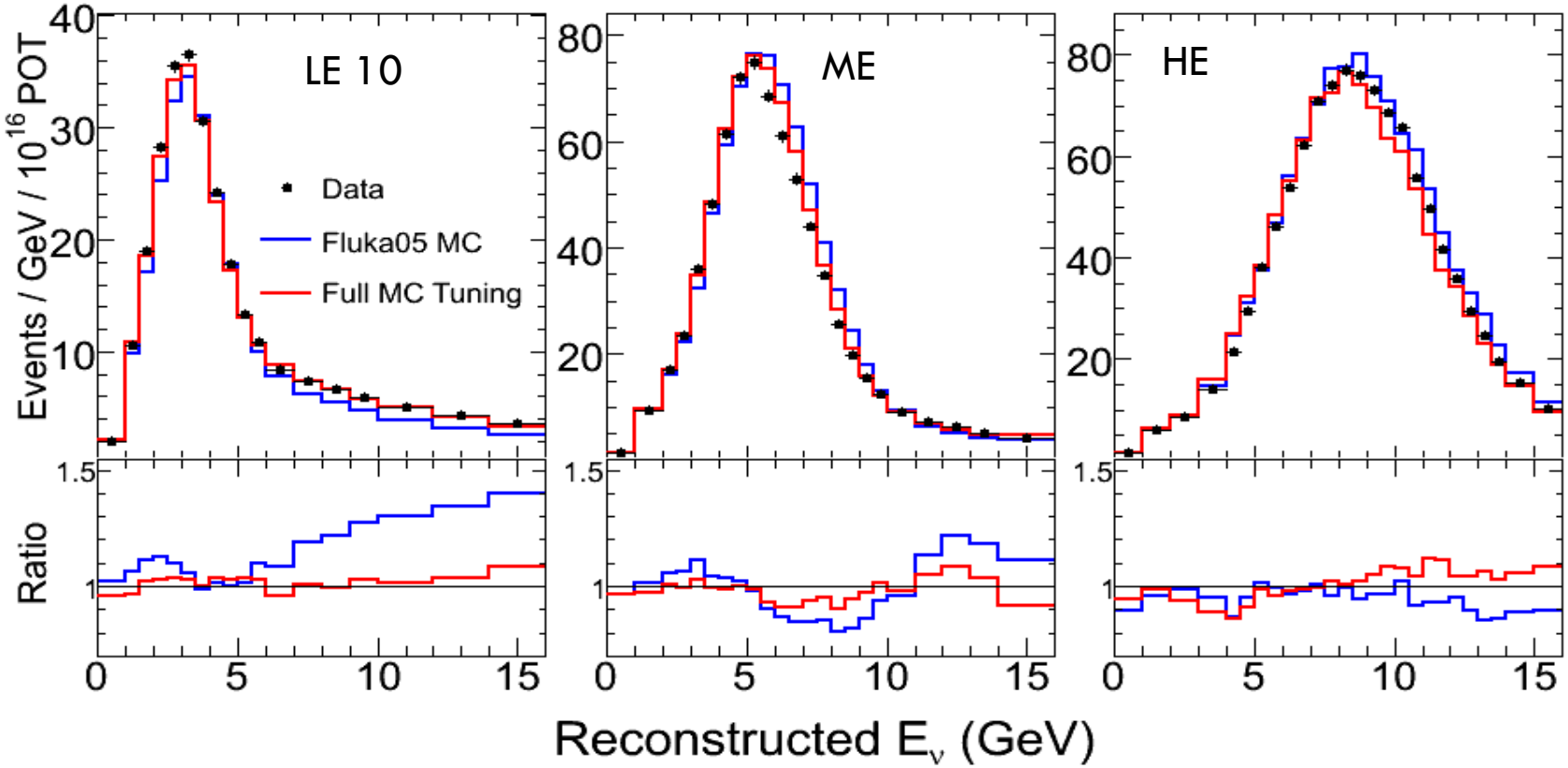
Cross section and hadron production experiments

- NOvA directly benefits from MINERvA measurements and experience
  - Flux from PPFX—package developed on MINERvA based on hadron production data (Phys. Rev. D 94, 092005. 2016)
  - neutrino interaction tuning guided by MINERvA experience (e.g. Eur. Phys. J. C76. 2016.)



Initial ND Data

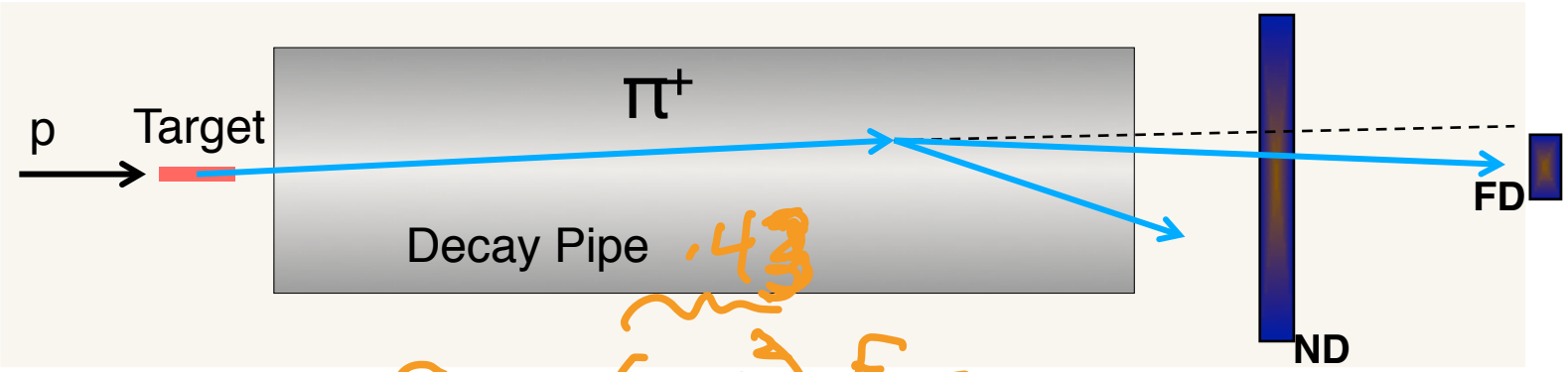
(Refs: Z. Pavlovich, UT Austin, 2008, Phys. Rev. D77 (2008) 072002)



- Discrepancy between Data/MC changes energy with different beam tunes, suggests production of Hadrons off the target is to blame.
- After adjusting hadron production, data/MC discrepancies ~5-10% level

Near to Far

Far spectrum without oscillations is similar, but not identical to the Near spectrum!

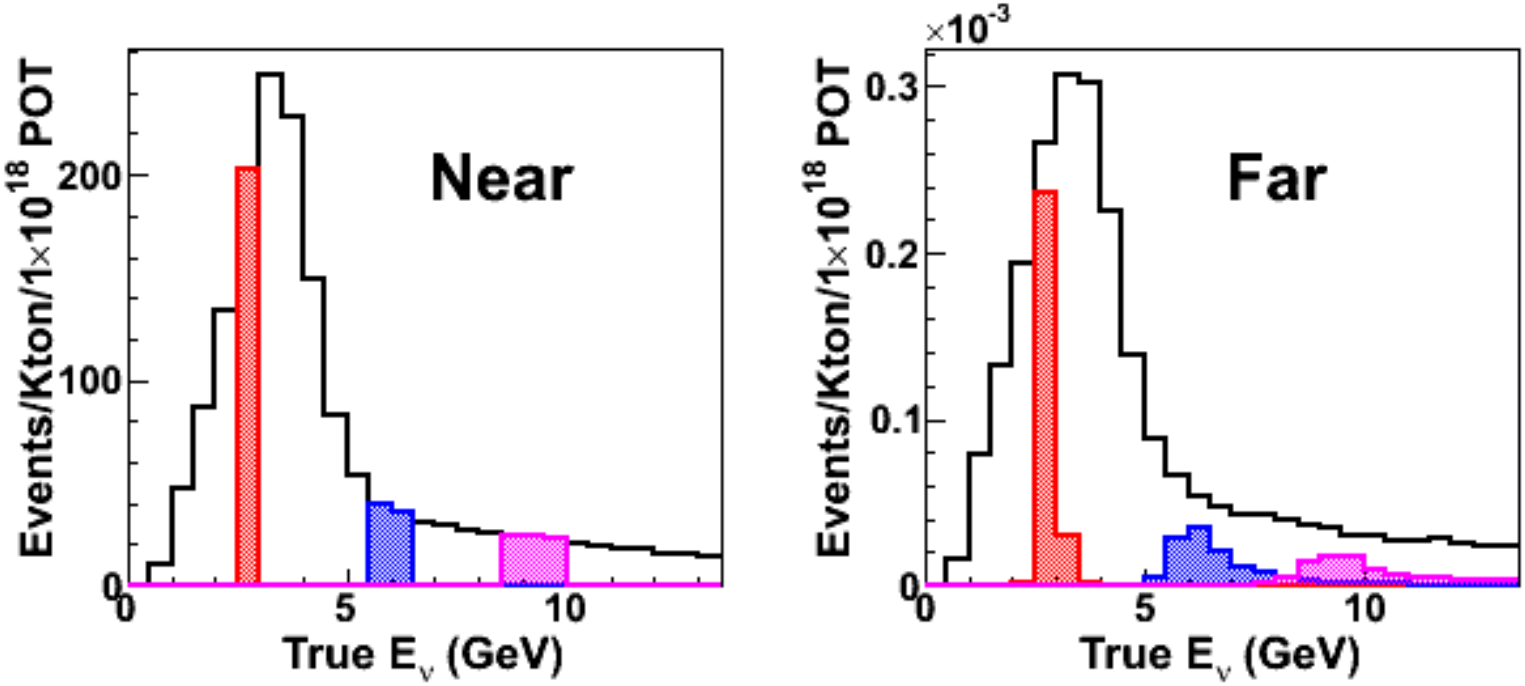


$$E_\nu = \left(1 - \frac{m_\mu^2}{m_\pi^2}\right) \frac{E_\pi}{1 + (\gamma\theta)^2}$$

- Neutrino energy depends on angle wrt original pion direction and parent energy
  - higher energy pions decay further along decay pipe
  - angular distributions different between Near and Far

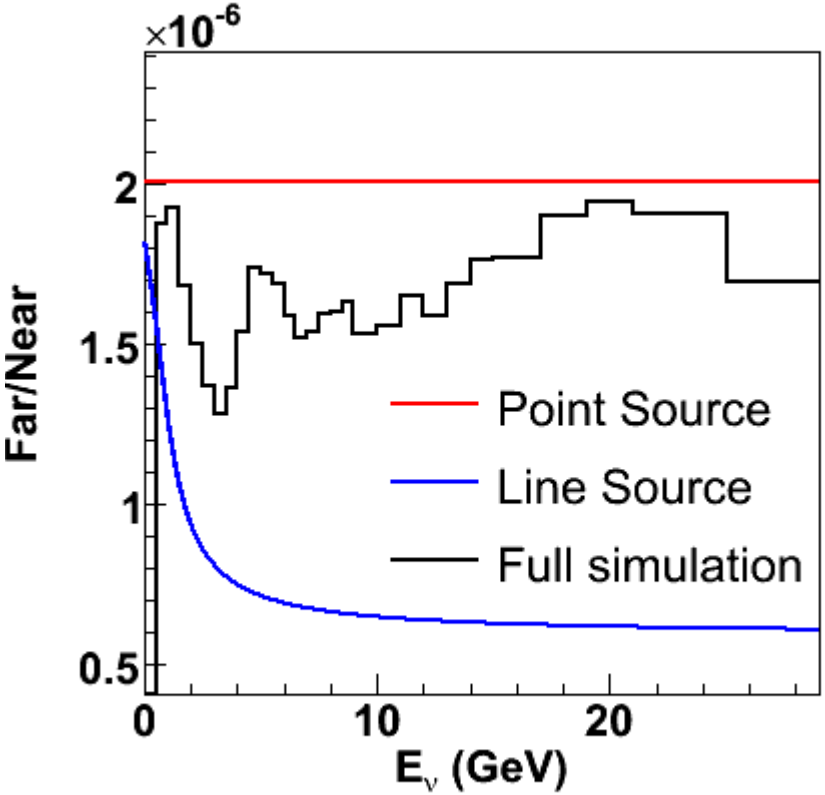
Near to Far

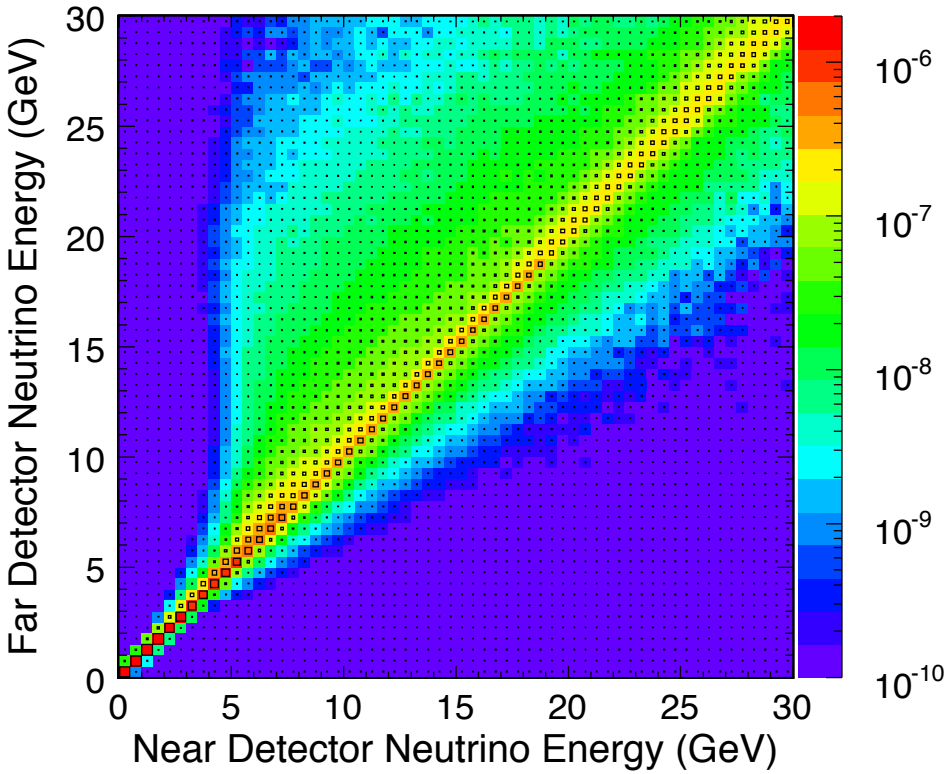
Far spectrum without oscillations is similar, but not identical to the Near spectrum!



Extrapolation

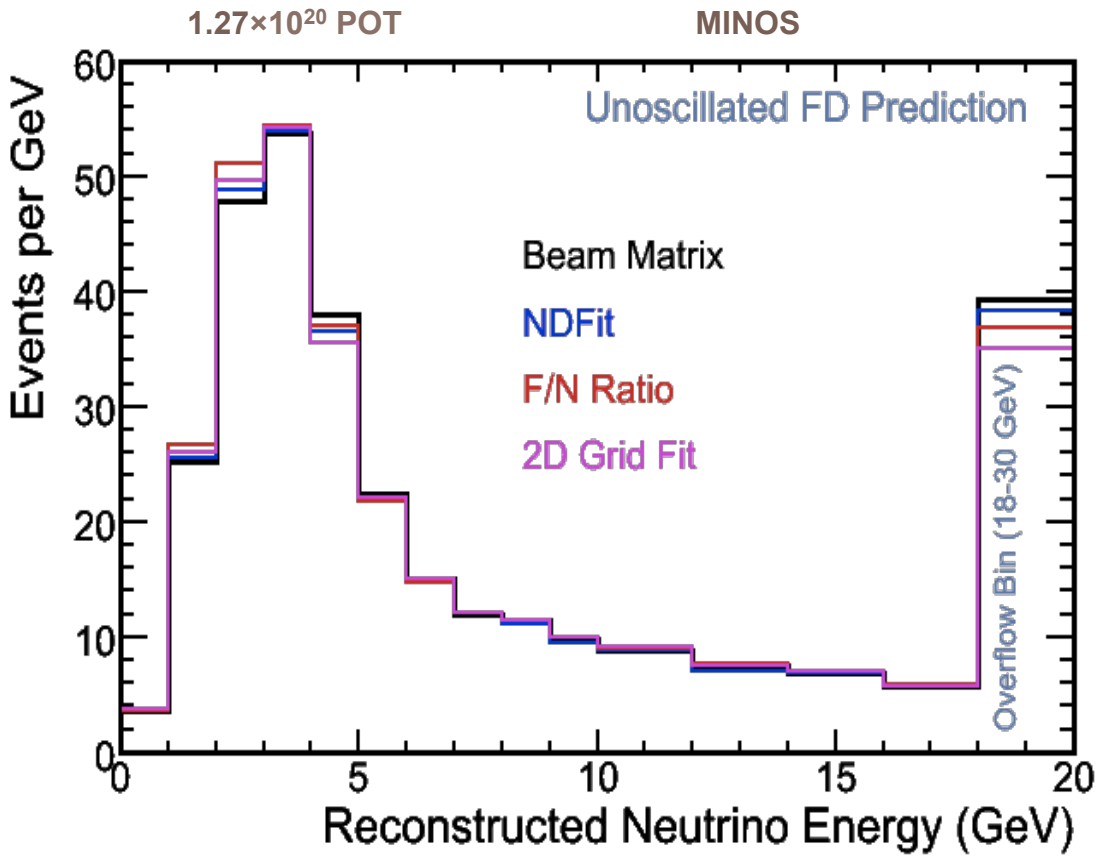
- How do you use the ND data to predict the FD?





Indirect Extrapolation

- Used additional extrapolation methods that described ND distributions by fitting physics quantities, predict FD spectrum from best fit (e.g., by reweighting MC)



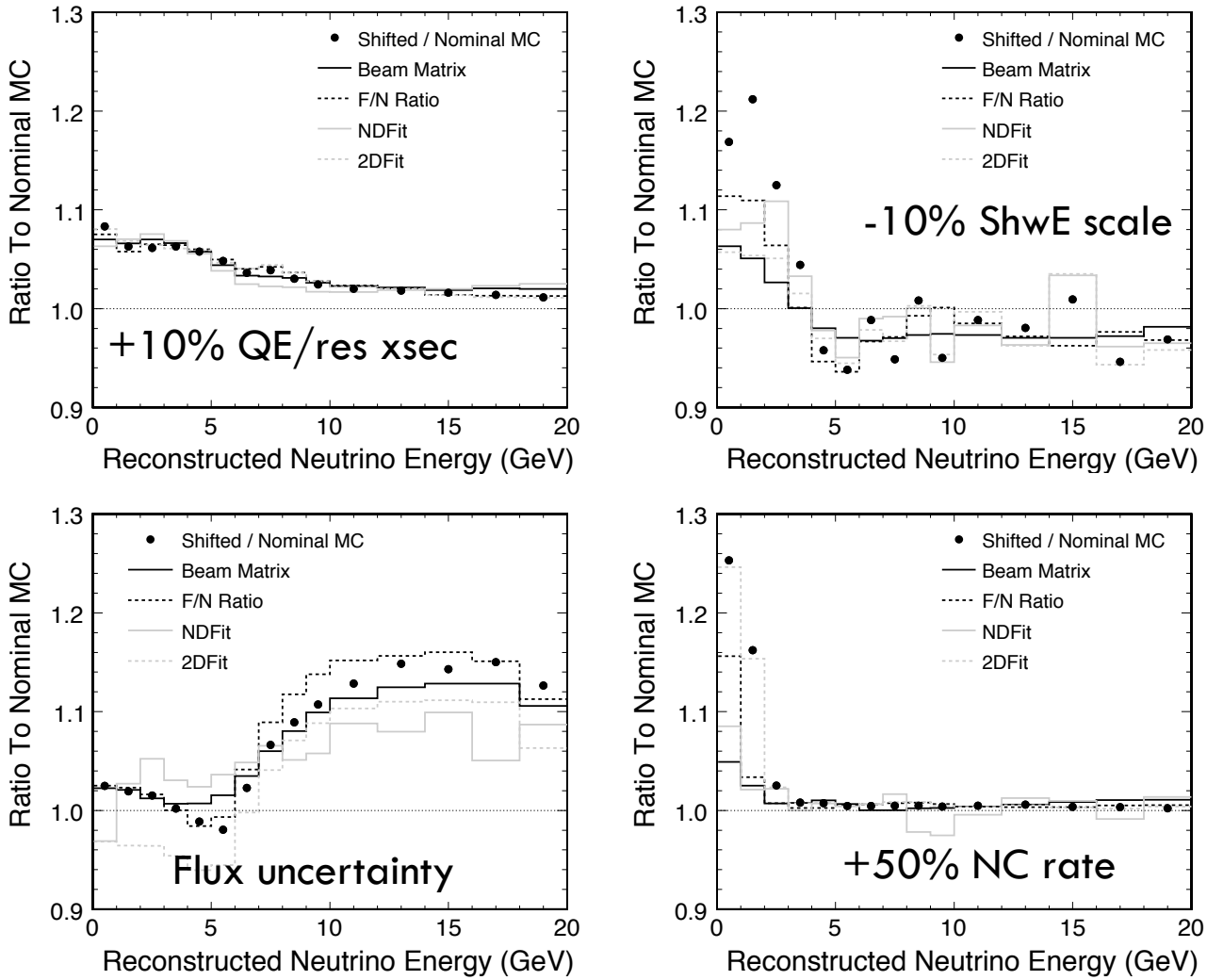
Prediction from all methods agreed to within ~ 5% bin-by-bin

Phys. Rev. D76 (2007) 072005

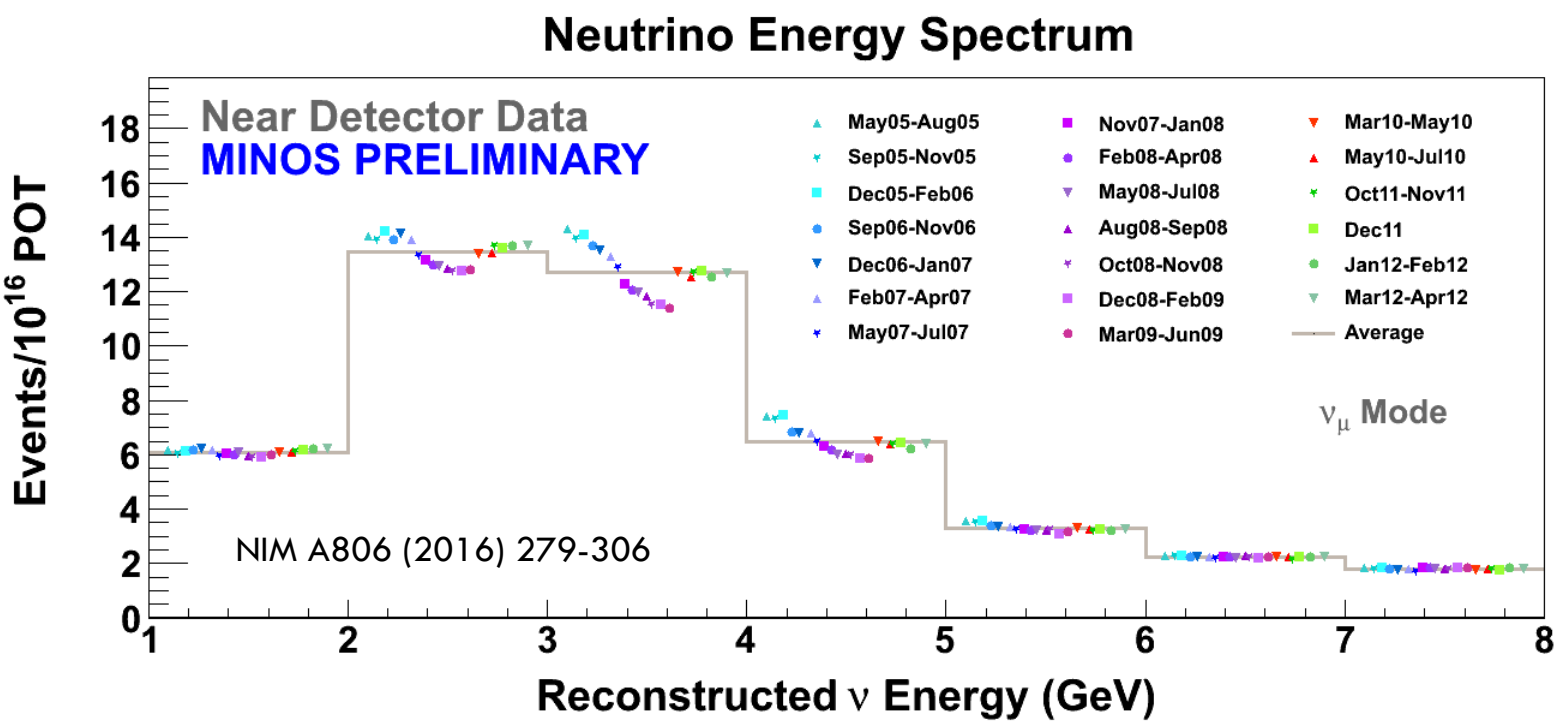
Phys. Rev. D77 (2008) 072002

Systematic Uncertainties

Extrapolation mitigates most systematic uncertainties



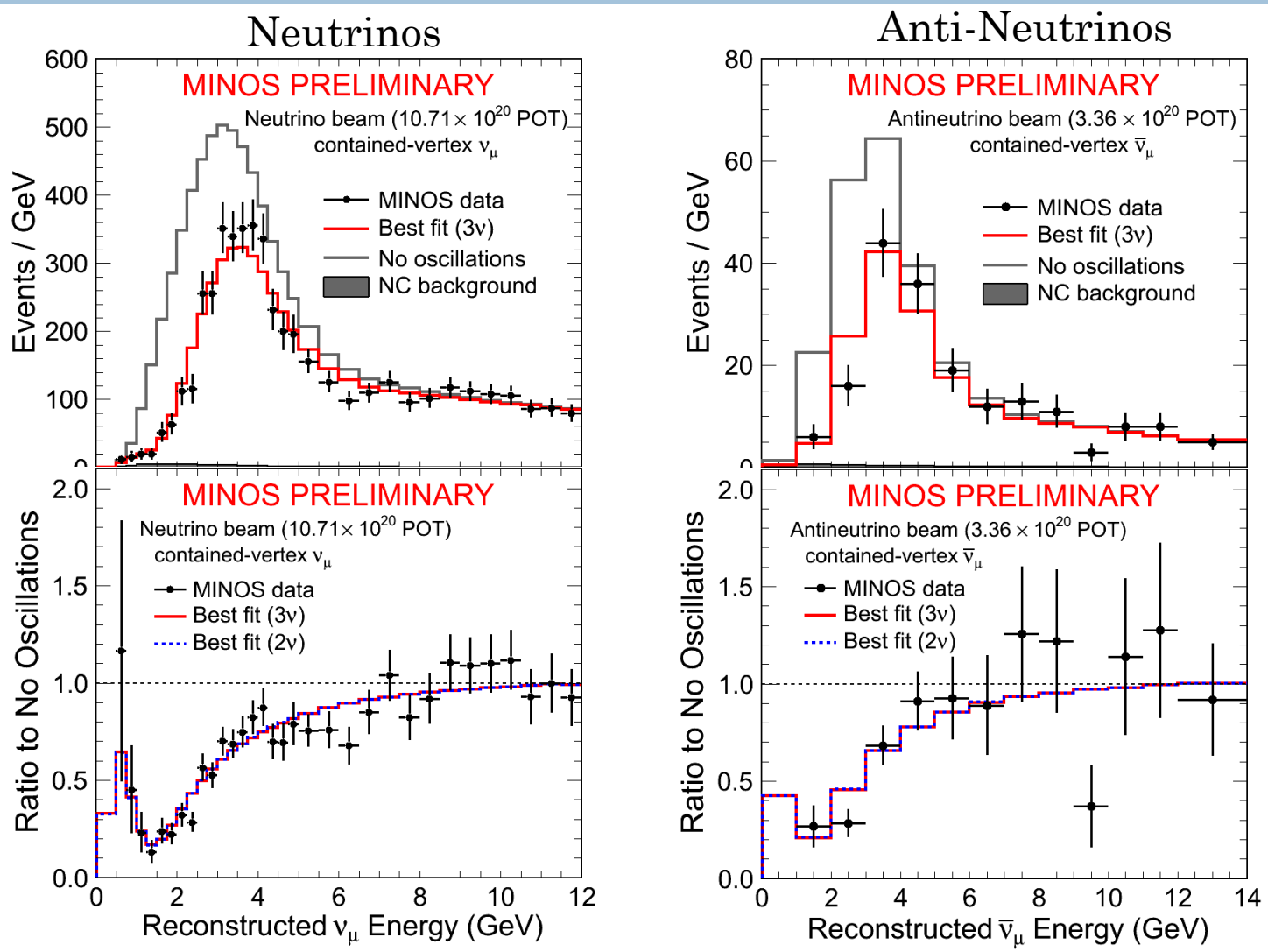
Beam Monitoring



- ND data naturally accounts for time variation of beam conditions and beam line hardware
  - Different targets, helium in decay pipe, target degradation

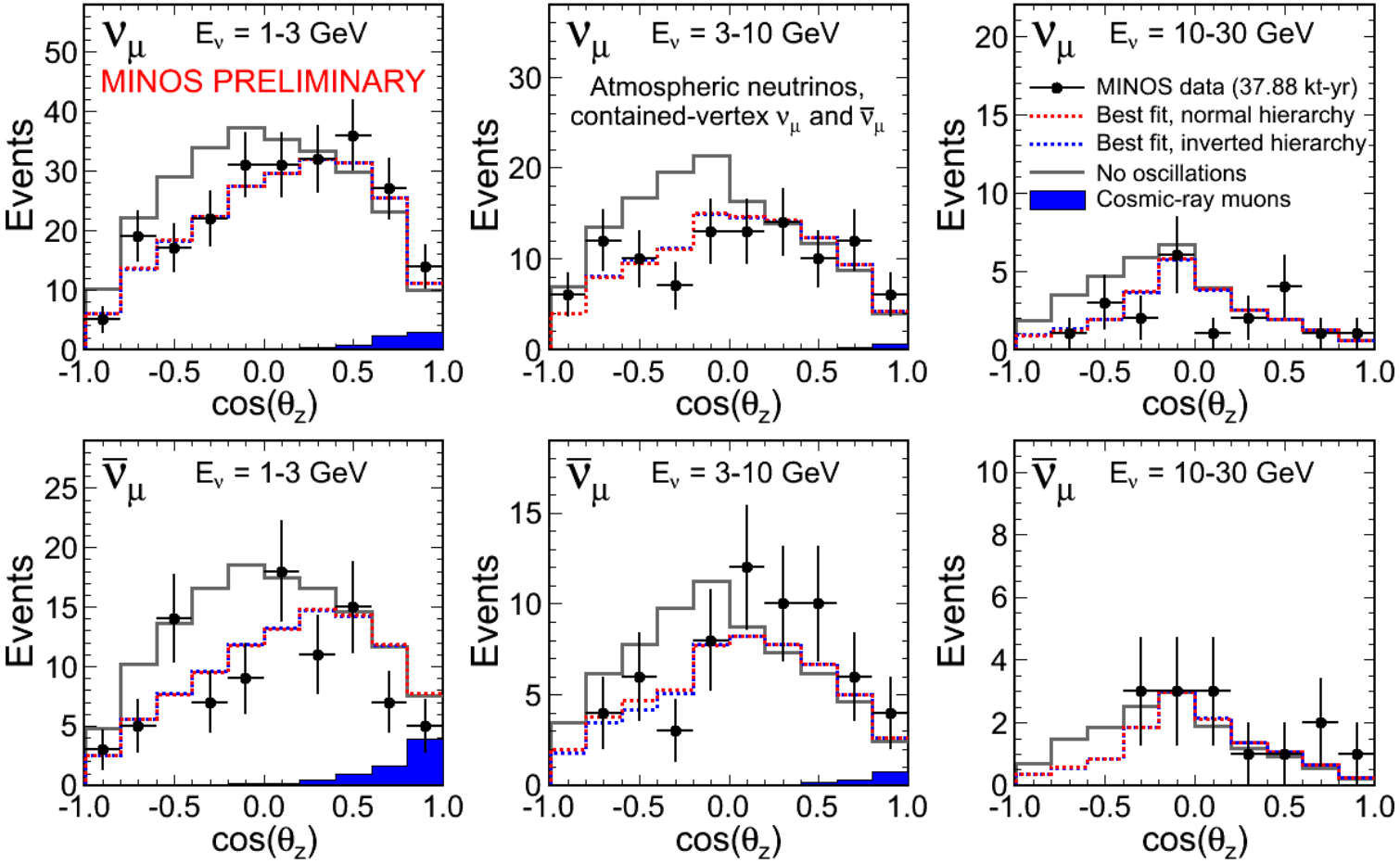
PRL 110 (2013) 251801

Far Detector Beam Samples



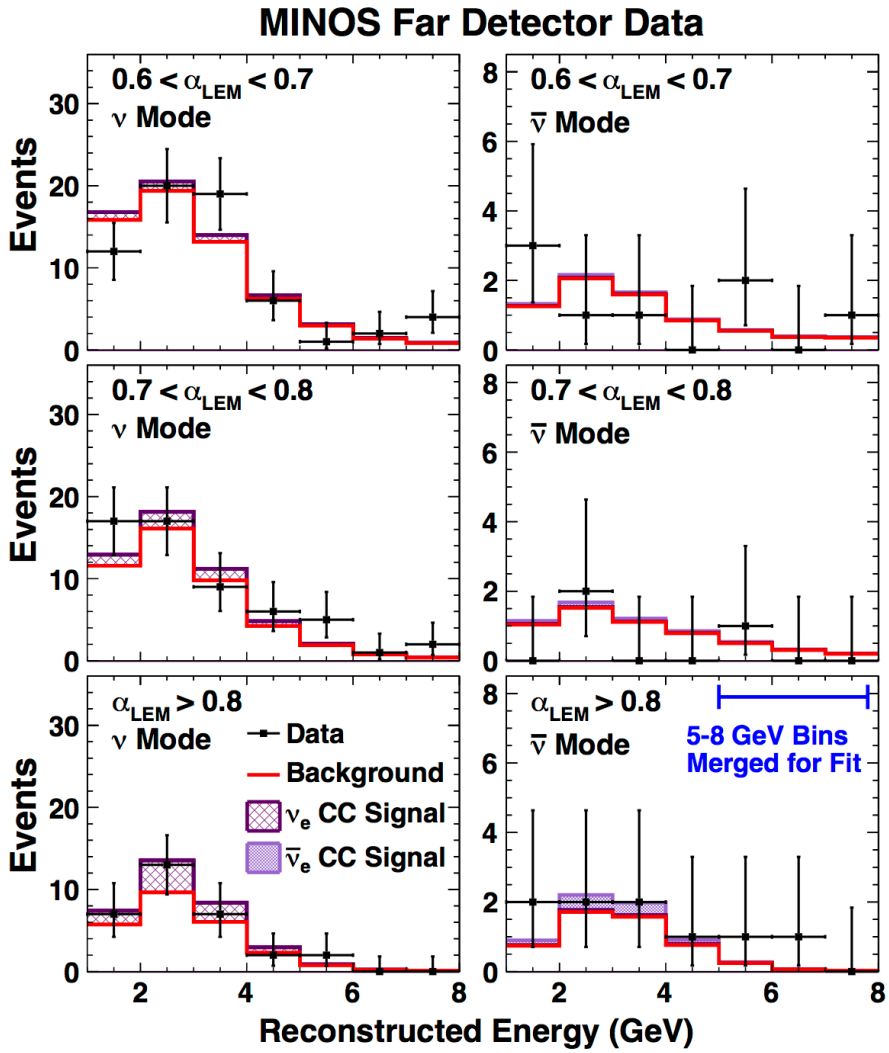
PRL 110 (2013) 251801

Far Detector Atmospheric Samples



- Contained muon neutrino events shown
- Partially contained and shower events also included in fit

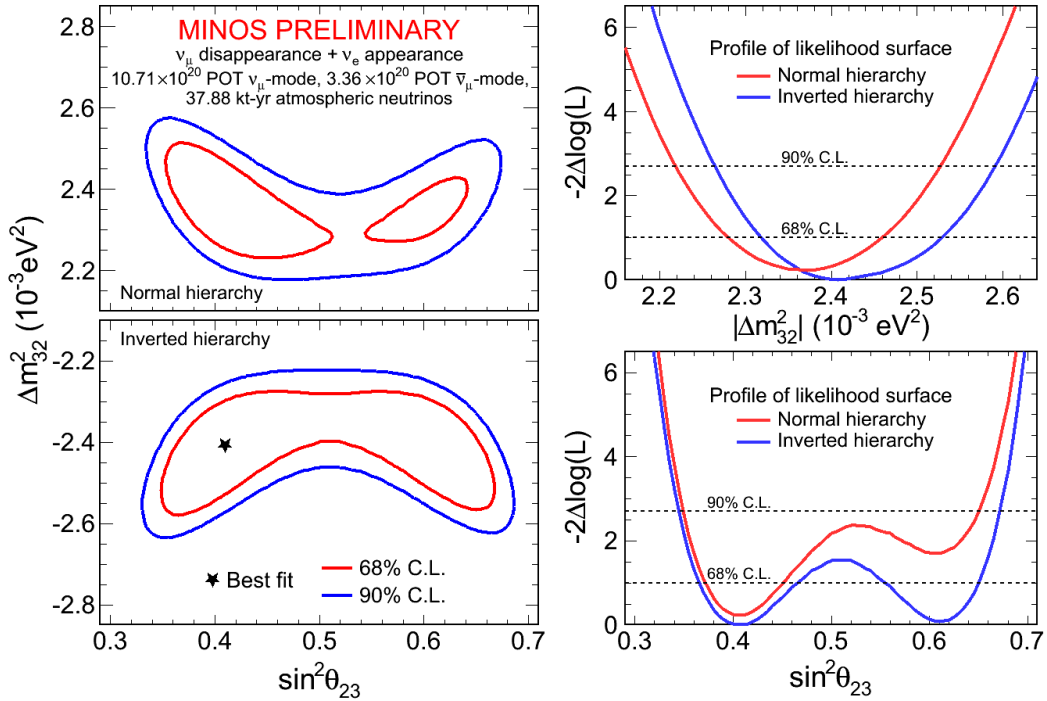
Electron Neutrino Appearance



PRL 110 (2013) 171801

PRL 112 (2014) 191801

Putting it all Together



- Solar mixing parameters fixed
- θ_{13} fit as nuisance parameter, constrained by reactor results
- δ_{CP}, θ_{23}, Δm^2 unconstrained
- major systematic uncertainties included as nuisance parameters

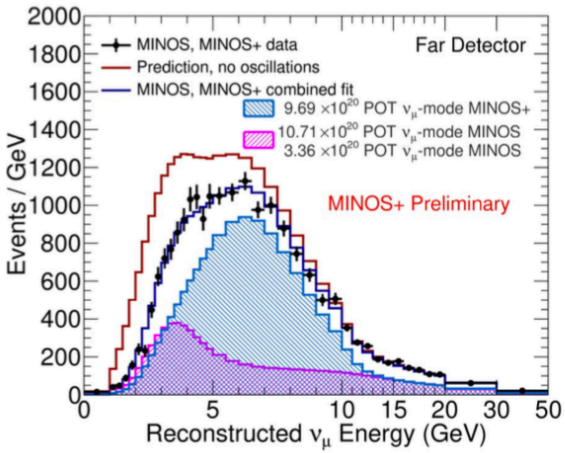
	Parameter	Best fit	Confidence limits
Normal hierarchy	$\lvert\Delta m^2_{32}\rvert/10^{-3}\text{eV}^2$	2.37	$2.28-2.46$ (68% C.L.)
	$\sin^2\theta_{23}$	0.41	$0.35-0.65$ (90% C.L.)
Inverted hierarchy	$\lvert\Delta m^2_{32}\rvert/10^{-3}\text{eV}^2$	2.41	$2.32-2.53$ (68% C.L.)
	$\sin^2\theta_{23}$	0.41	$0.34-0.67$ (90% C.L.)

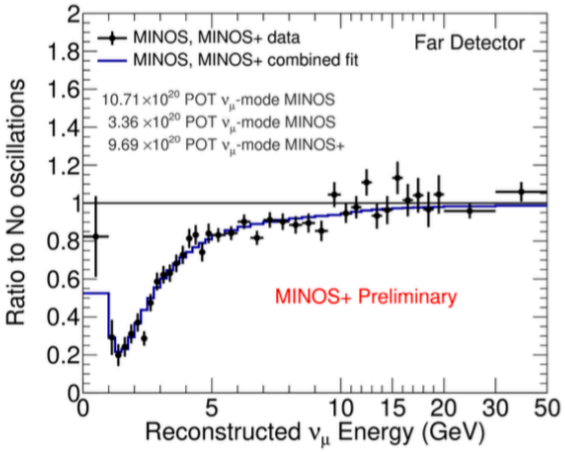
Preference for inverted hierarchy: $-2\Delta\log L = 0.23$

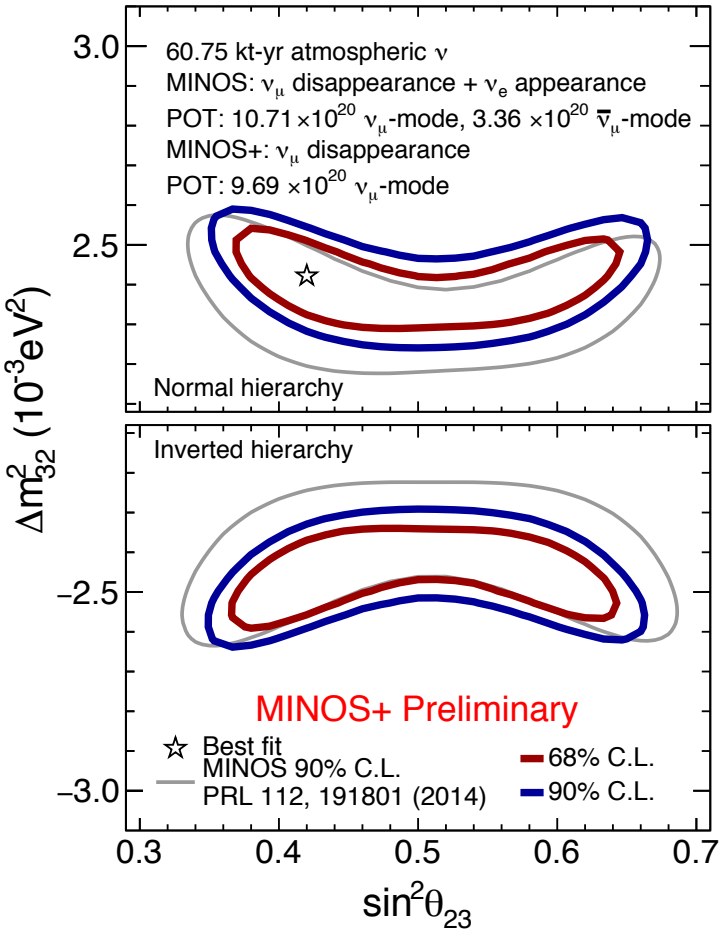
Preference for lower octant: $-2\Delta\log L = 0.09$

Preference for non-maximal mixing: $-2\Delta\log L = 1.54$ ($\Rightarrow$ 79% C.L.)

MINOS+







Best fit

$\Delta m^2_{32} = 2.42 \times 10^{-3}\ eV^2$

$\sin^2\theta_{23} = 0.42$

Exclusion of maximal mixing: 1.1σ

Preference for lower octant: 0.8σ

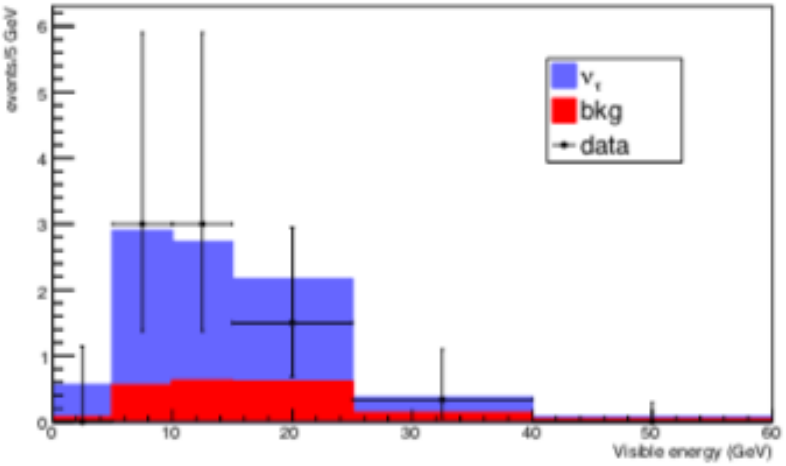
Preference for normal hierarchy: 0.2σ

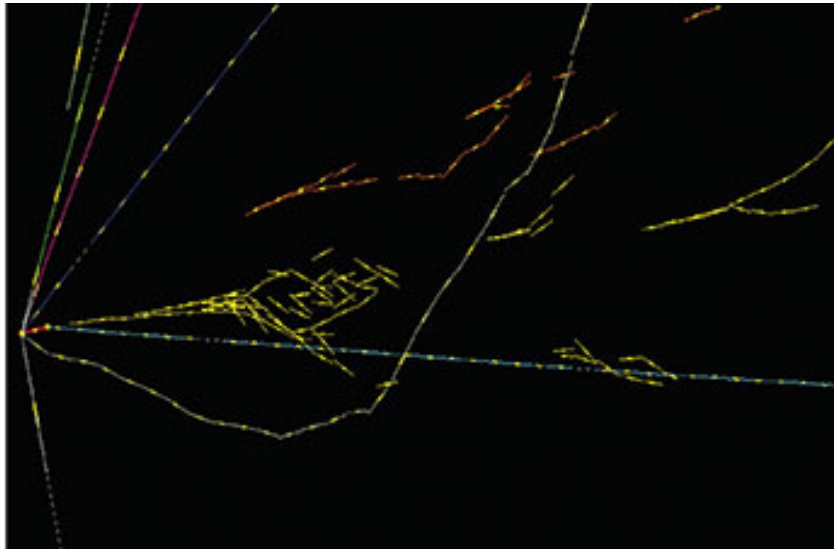
A. Aurisano, Neutrino 2018

What about tau appearance?

- Opera final results:
  - 10 tau neutrino candidates
  - 6.1sigma evidence of appearance
  - 20% measurement of mass splitting agrees with disappearance measurements

Phys. Rev. Lett. 120, 211801





Electron neutrino appearance

- MINOS electron neutrino appearance search is dominated by neutral current backgrounds. How can we do better?

1.

2.

3.

4.

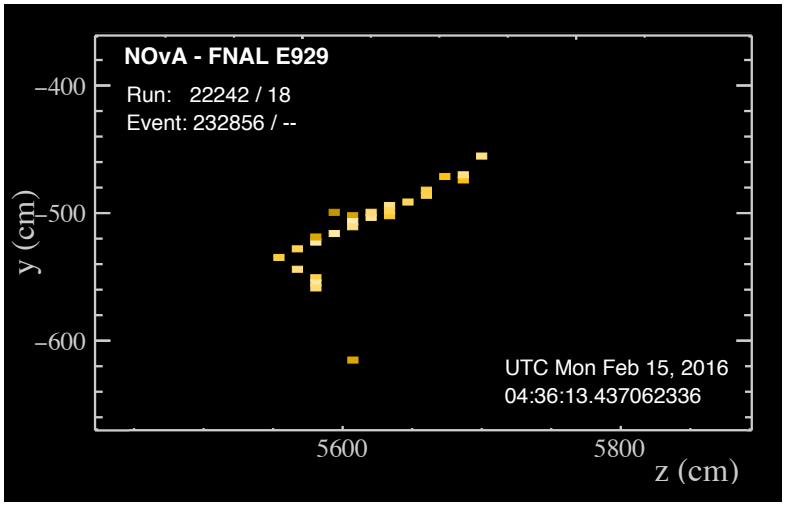
8 years of data collection

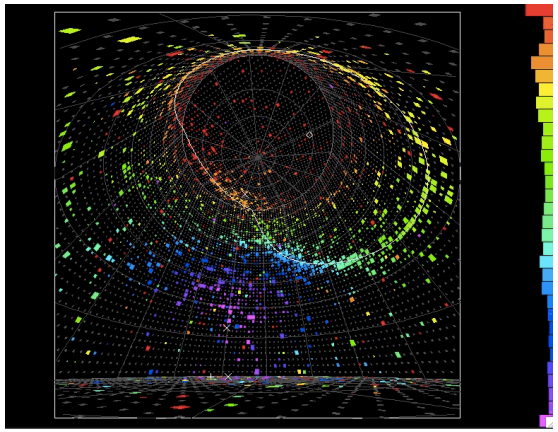
Event Type	ν beam mode	$\bar{\nu}$ beam mode
NC	89.4	13.9
ν_μ-CC and $\bar{\nu}_\mu$-CC	21.6	1.0
Intrinsic ν_e-CC and $\bar{\nu}_e$-CC	11.9	1.8
ν_τ-CC and $\bar{\nu}_\tau$-CC	4.8	0.8
$\nu_\mu \to \nu_e$-CC	33.0	0.7
$\bar{\nu}_\mu \to \bar{\nu}_e$-CC	0.7	3.2
Total	161.4	21.4
Data	152	20

TABLE II: Expected FD event yields for events with a value of $\alpha_{LEM} > 0.6$, assuming $\sin^2(2\theta_{13}) = 0.1$, $\delta = 0$, $\theta_{23} = \pi/4$, and a normal mass hierarchy.

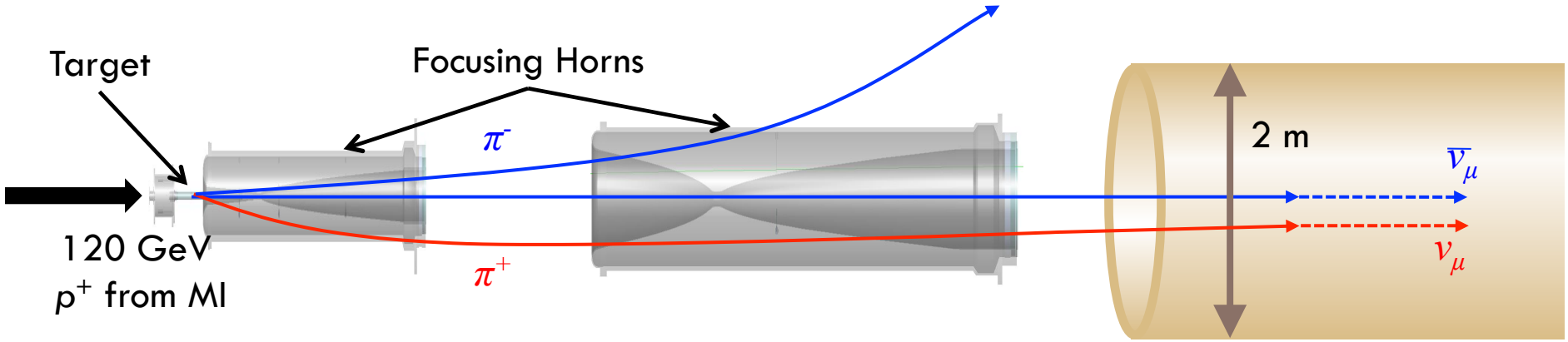
PRL 110 (2013) 171801

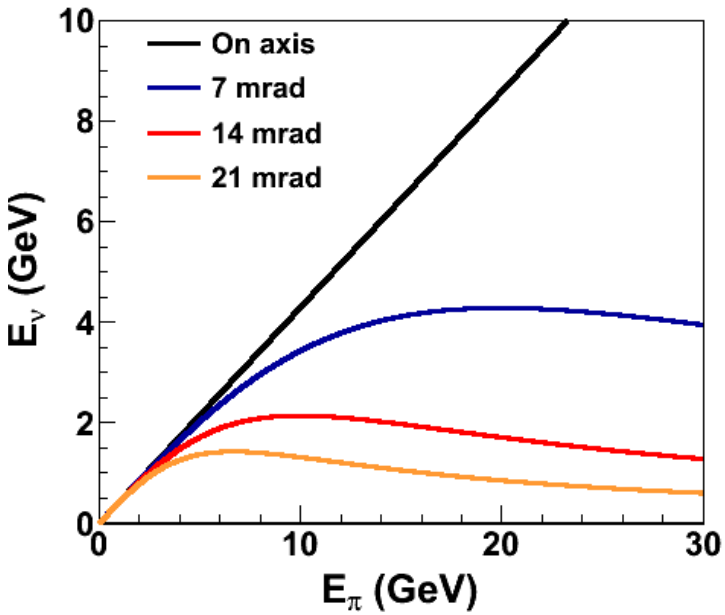
Next generation long-baseline experiments





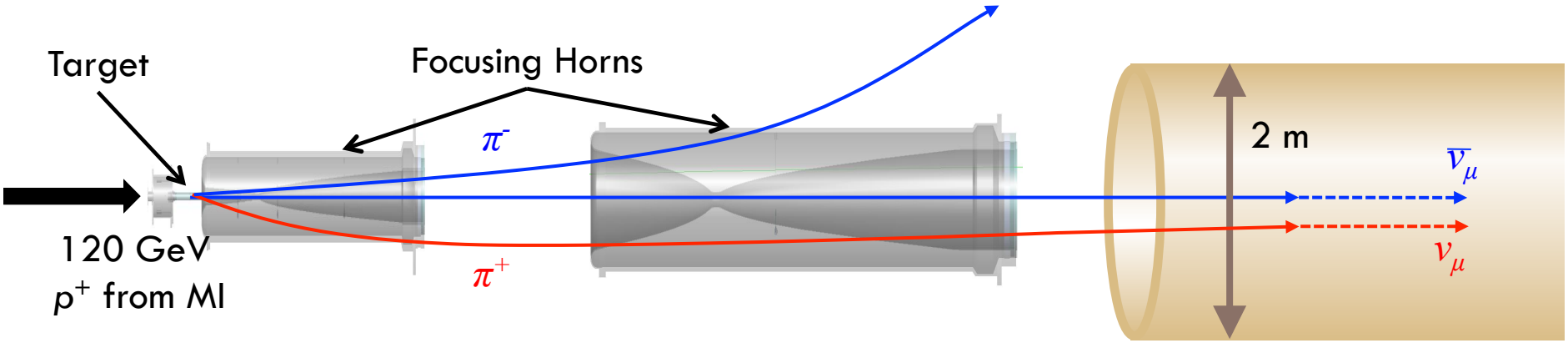
Making an off-axis neutrino beam

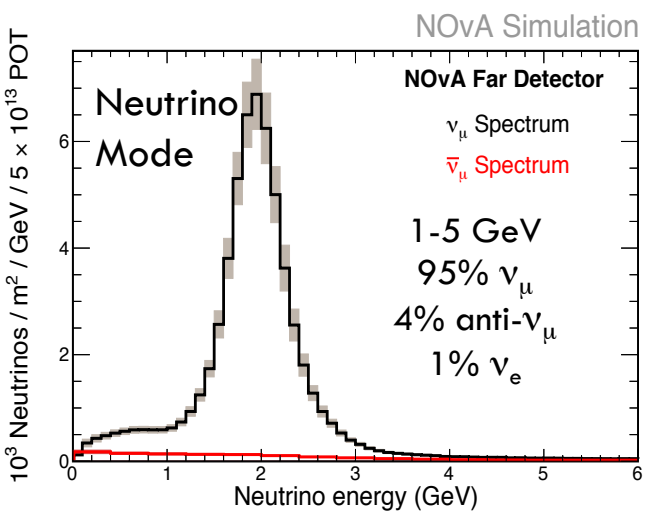


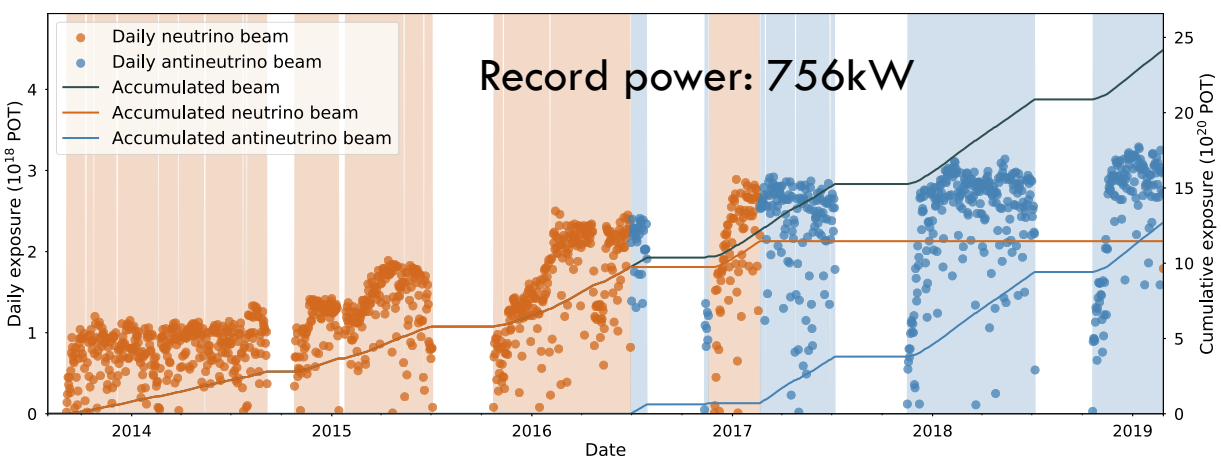


- NOvA is 14 mrad off-axis, sees a narrow band beam peaked at 2 GeV
  - Near (but slightly above) oscillation maximum
  - Few high energy NC background events

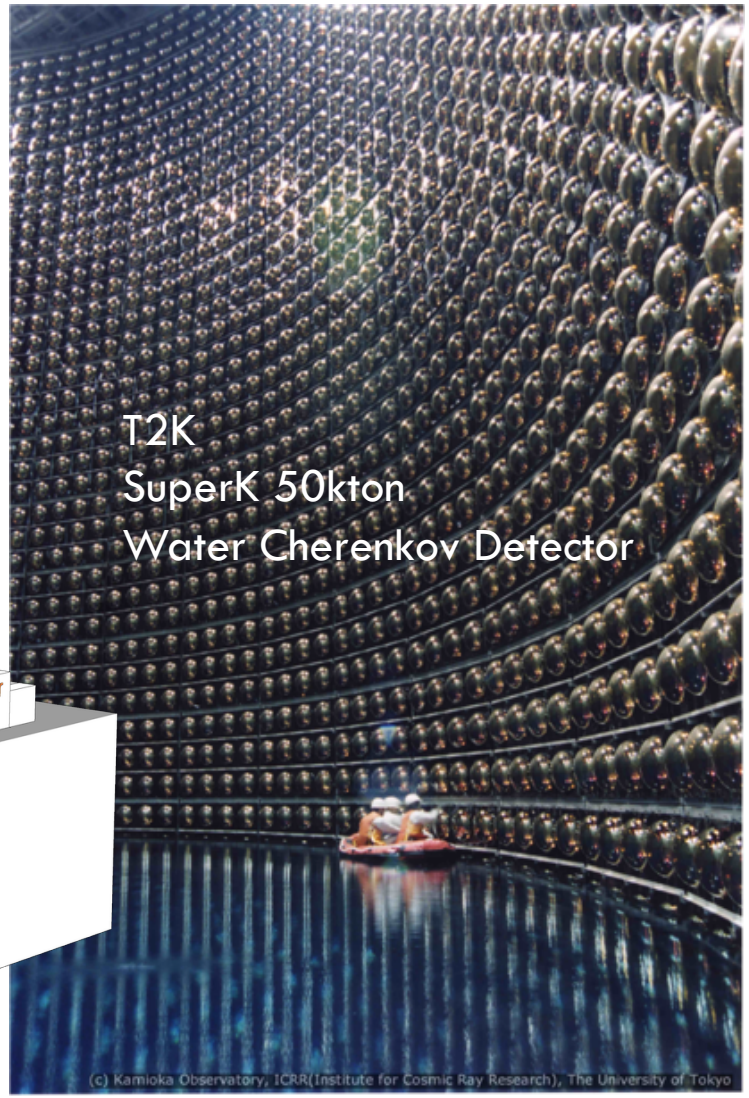
Making an off-axis neutrino beam

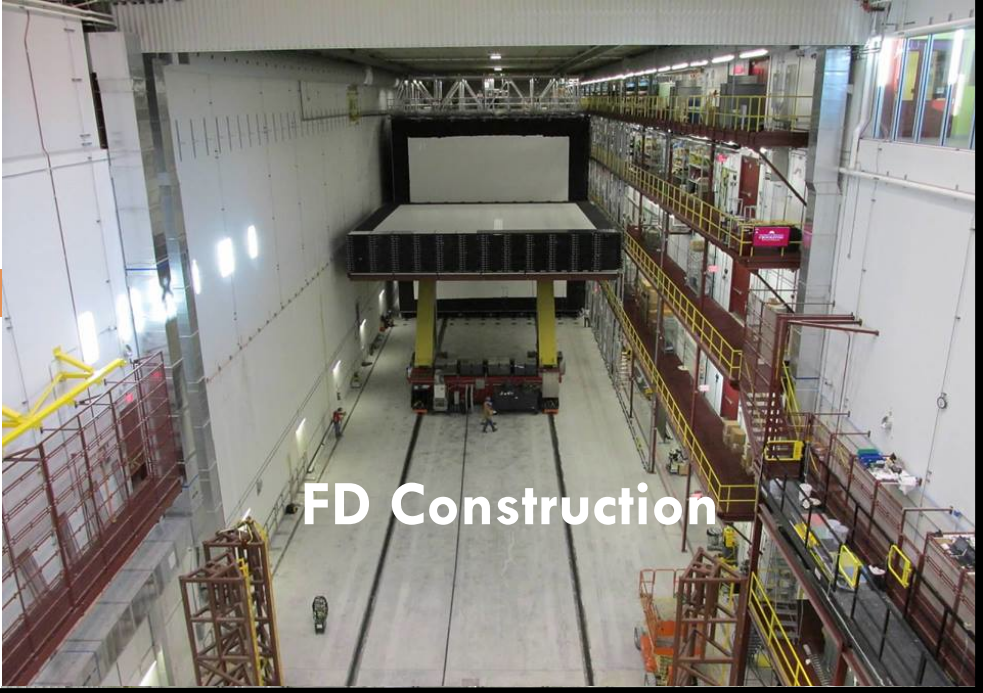




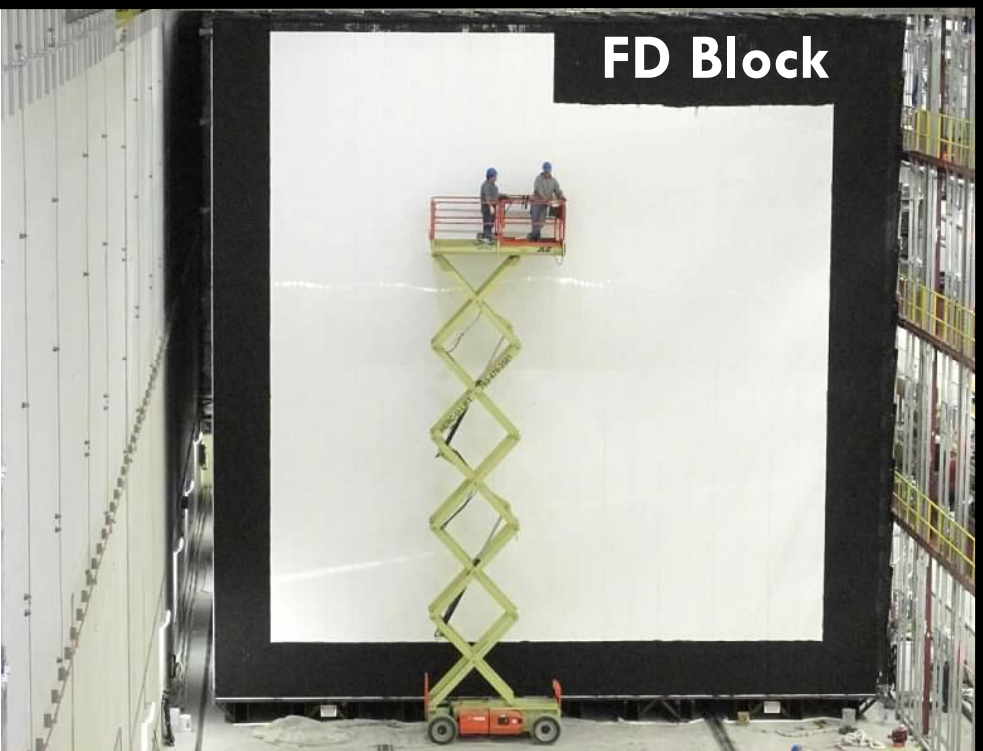


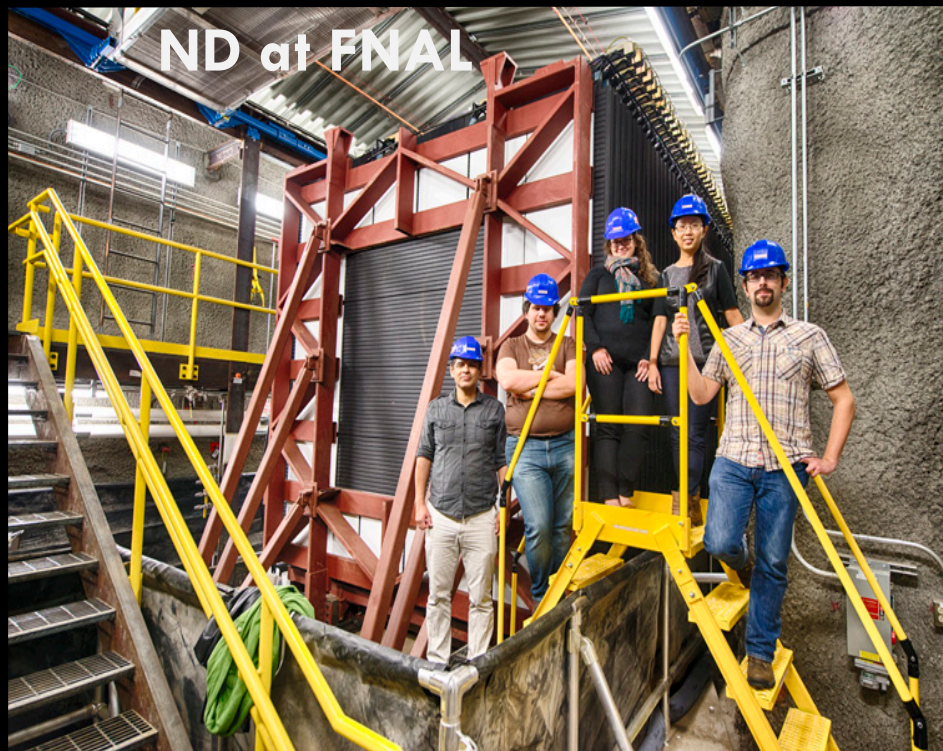
Big Detectors




FD Construction

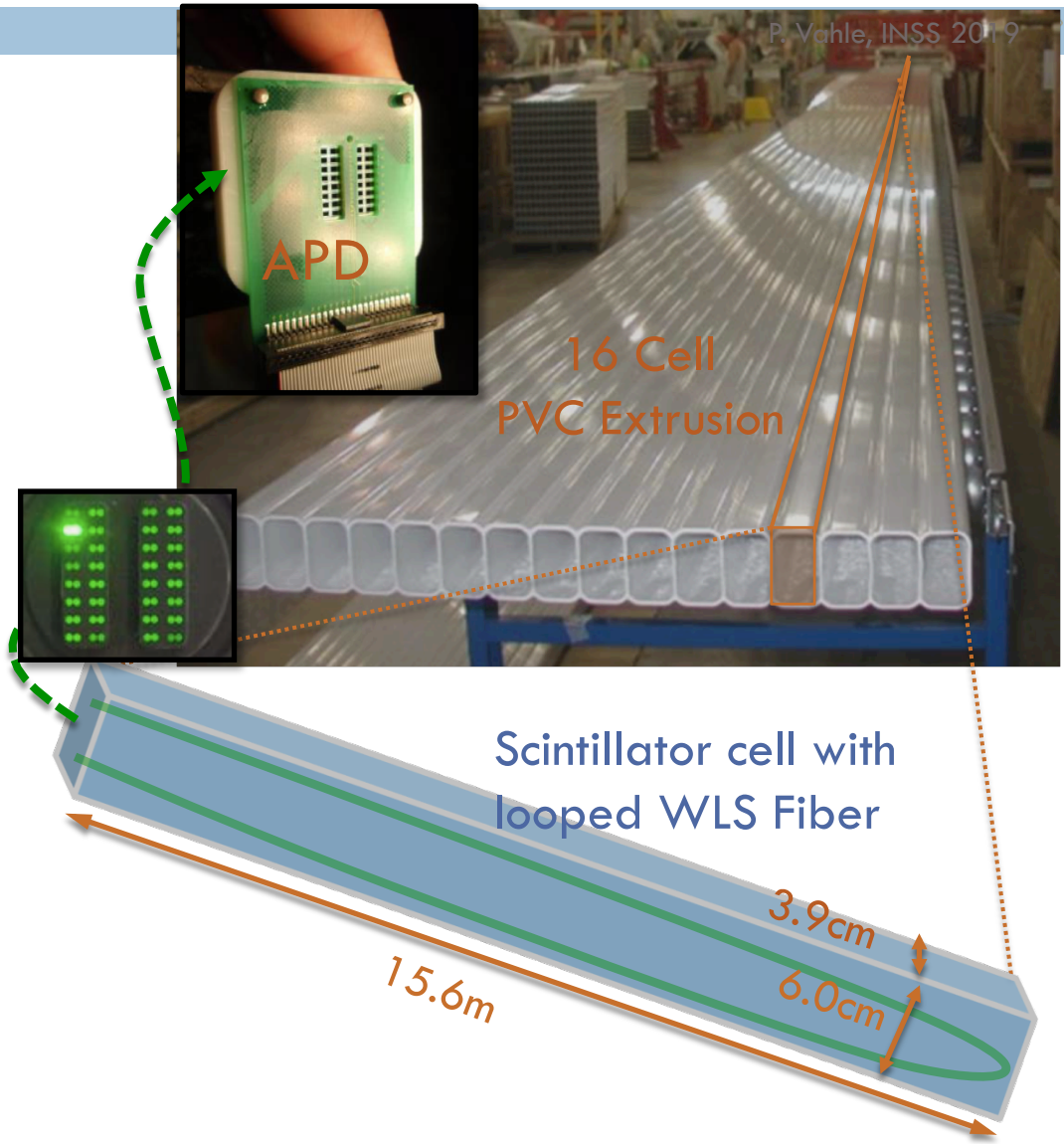
Outfitted FD

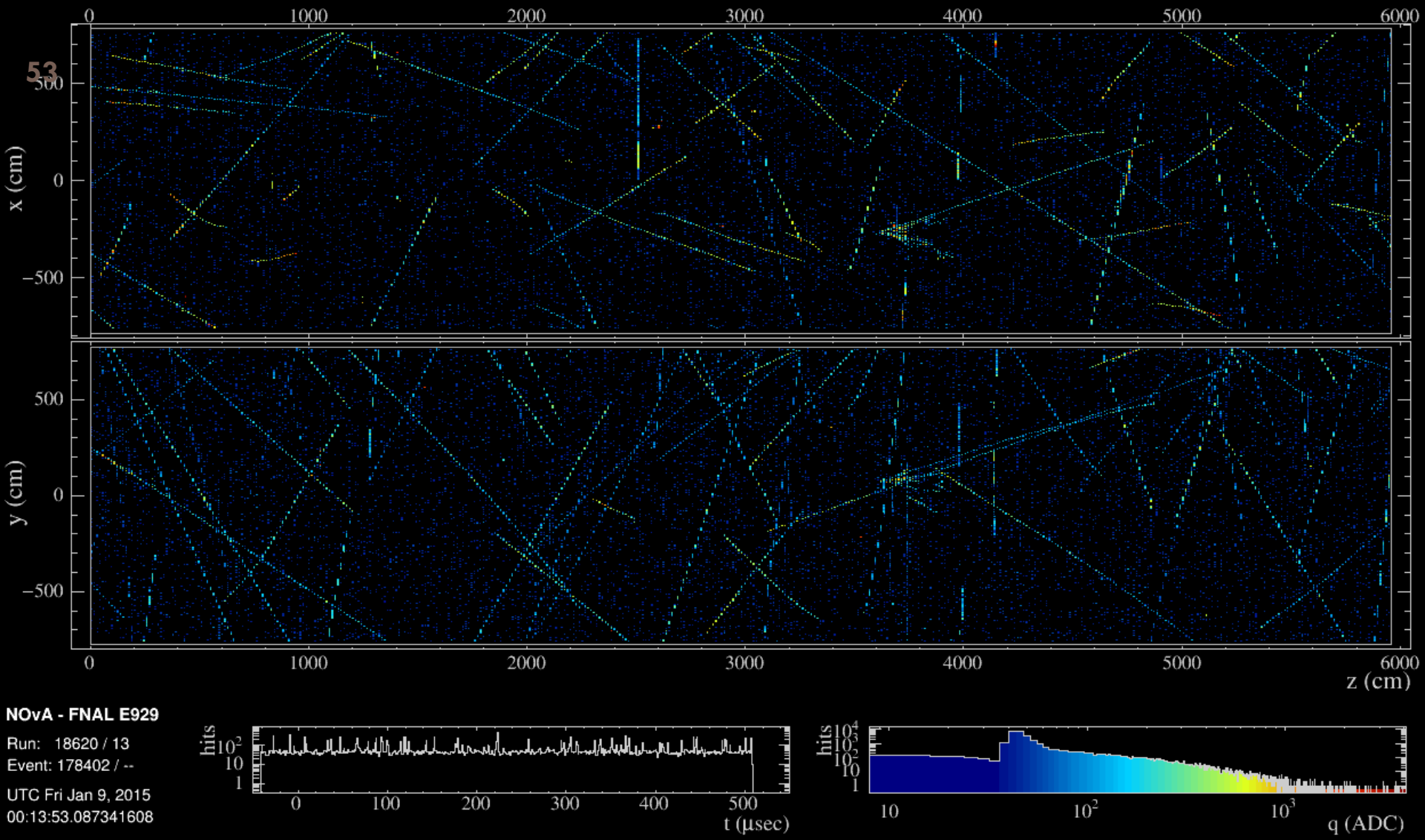

FD Block

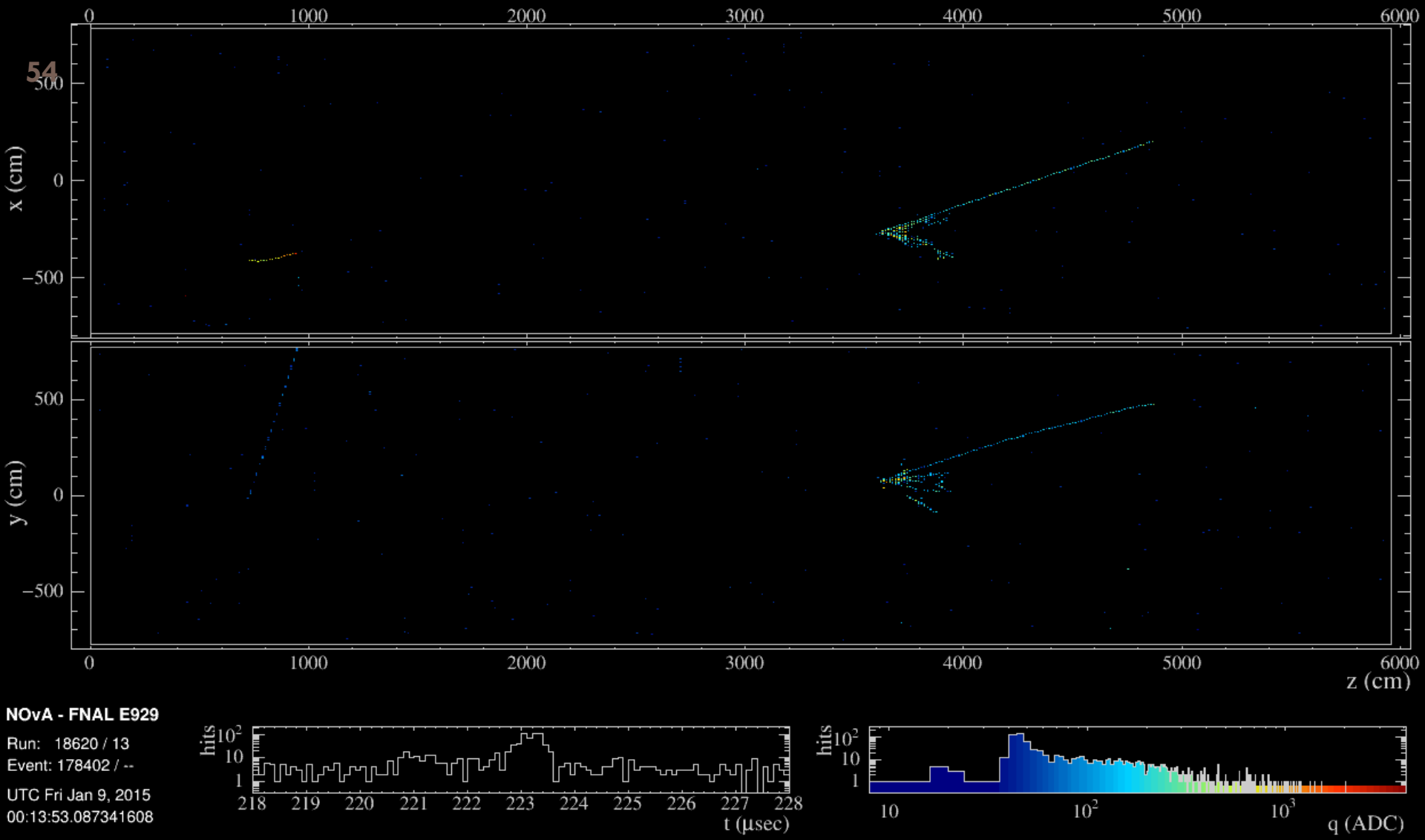

ND at FNAL

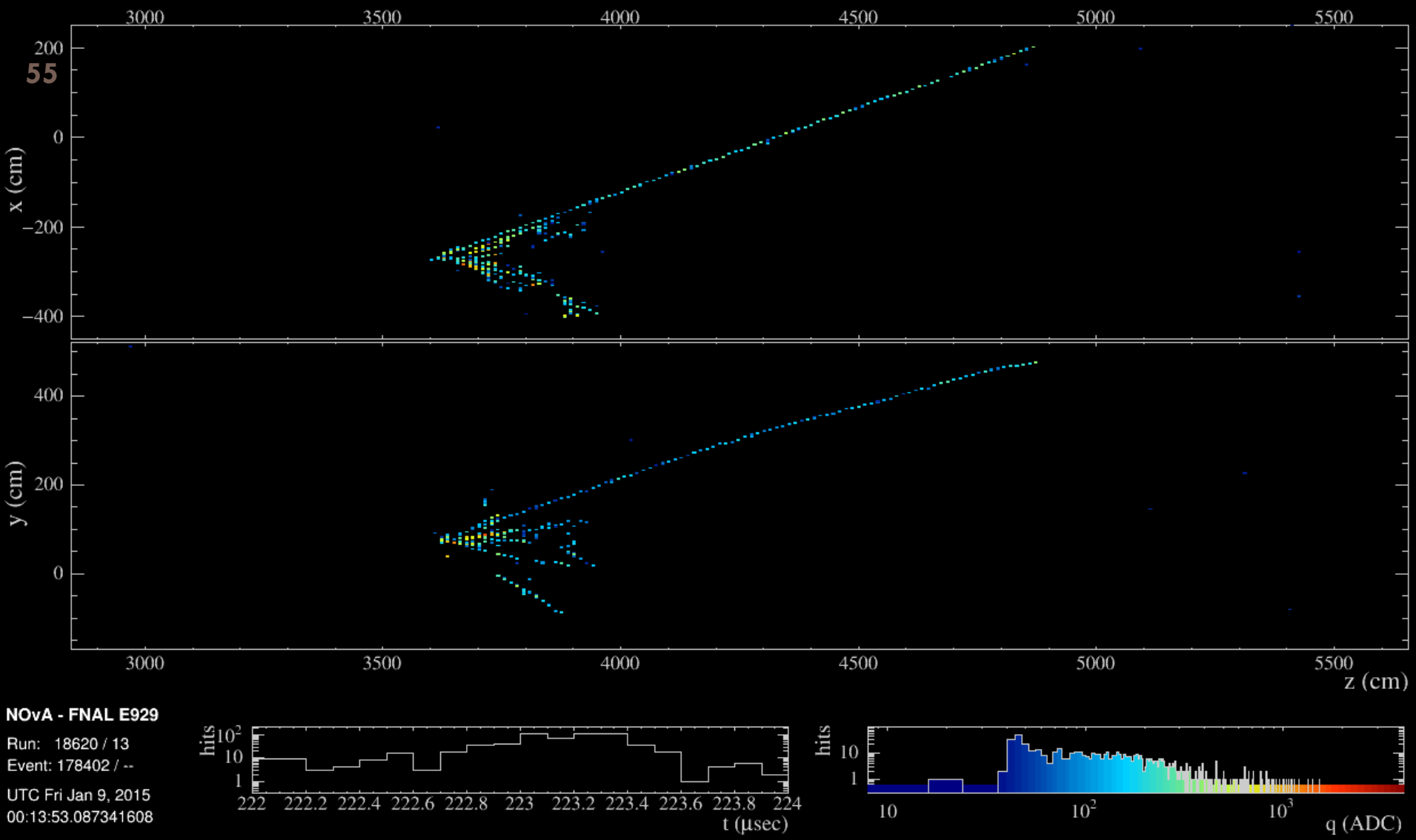
Detector Technology

- PVC+Liquid Scintillator
  - Mineral Oil
  - 5% pseudocumene
  - Read out via WLS fiber to APD
- Layered planes of orthogonal views
  - muon crossing far end ~40 PE
  - 0.17 X_0 per layer
- DAQ runs with zero deadtime
  - triggers for beam, SNEWS, cosmic ray calibration samples, exotic searches
  - 150kHz of cosmic induced events



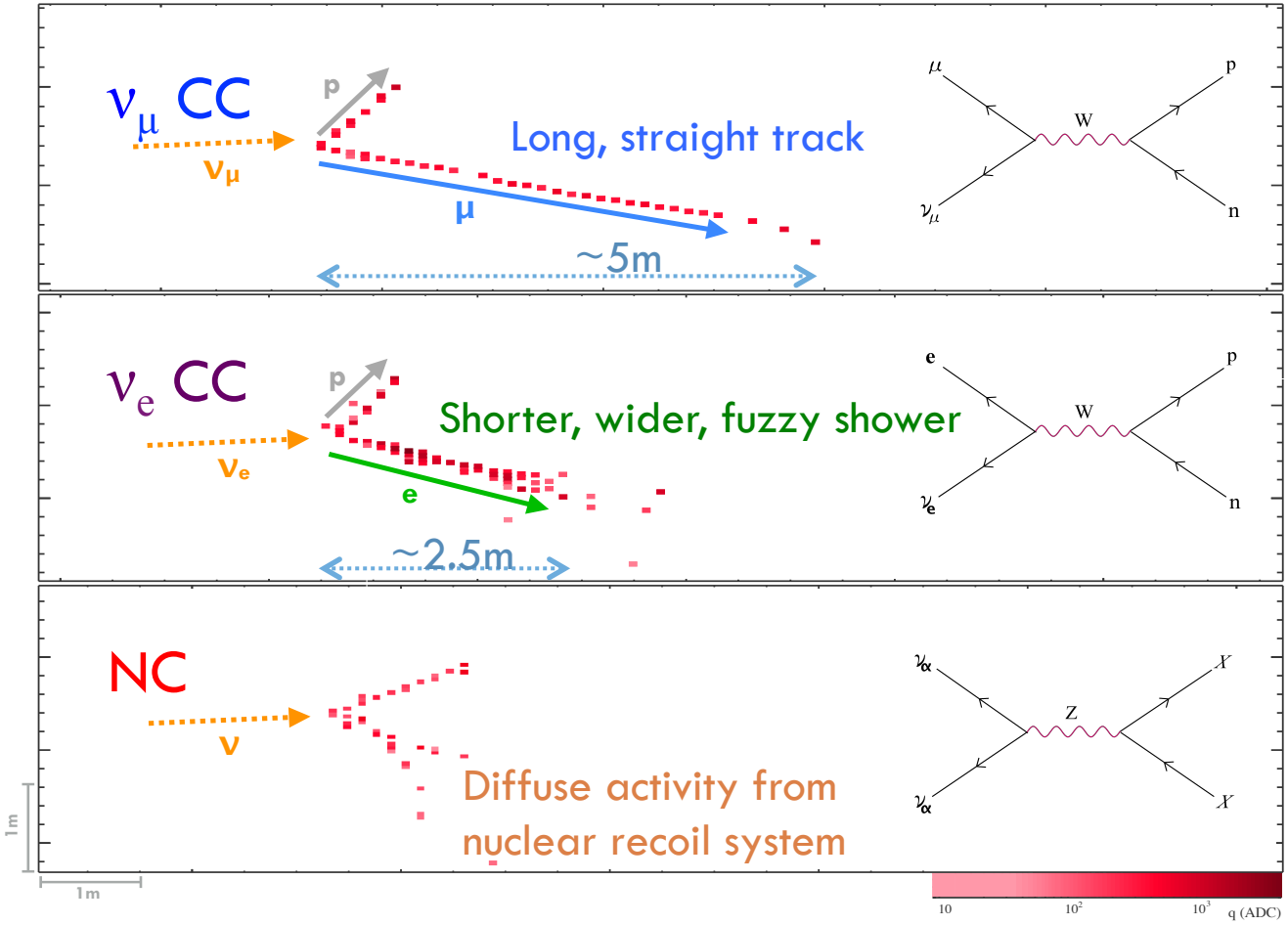

x (cm)
y (cm)
z (cm)
NOvA - FNAL E929
Run: 18620 / 13
Event: 178402 / --
UTC Fri Jan 9, 2015
00:13:53.087341608
hits
t (μsec)
q (ADC)


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


55
x (cm)
y (cm)
z (cm)
NOvA - FNAL E929
Run: 18620 / 13
Event: 178402 / --
UTC Fri Jan 9, 2015
00:13:53.087341608
hits
t (μsec)
q (ADC)

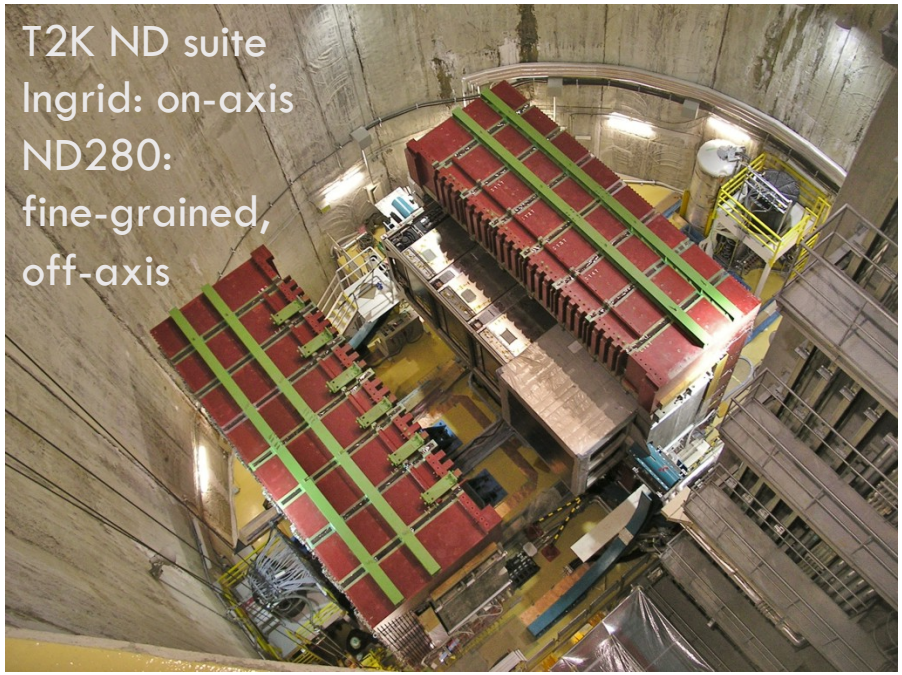
Event Selection

event classification technique based on ideas from computer vision and deep learning



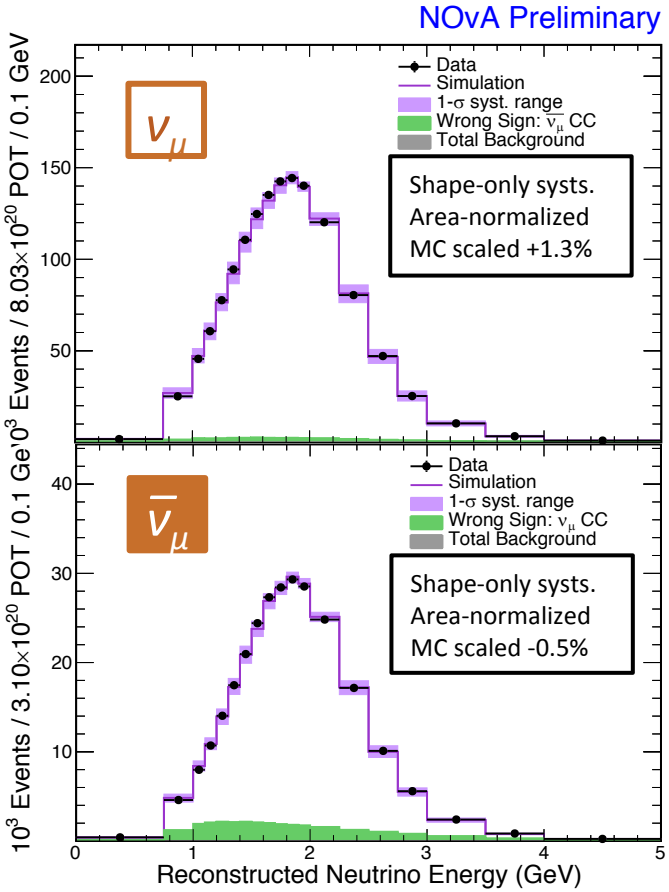
Two detector technique

- Near detectors used to predict far expectations and mitigate systematics

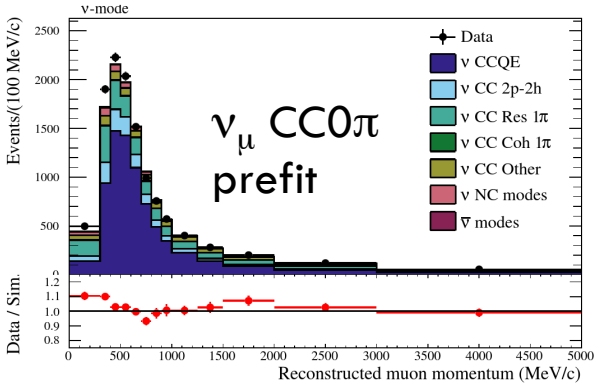


Two detector technique

- Near detectors used to predict far expectations and mitigate systematics

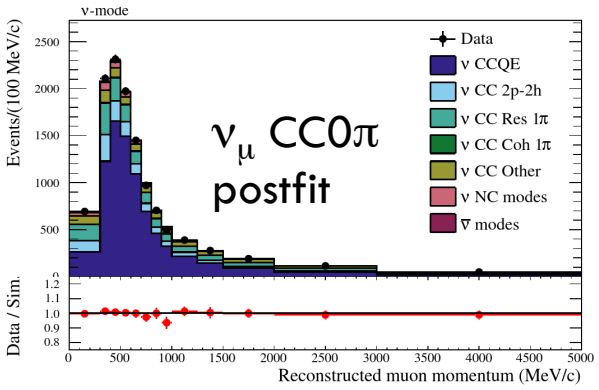


T2K:
Fit 14 different ND280 samples separated by muon charge and pion multiplicity with parameterized flux and cross section models



PRELIMINARY

NOvA:
Adjust flux and cross section models guided by external data, adjust empirical MEC model to match data, extrapolate remaining discrepancies in bins of energy resolution using F/N ratio



PRELIMINARY

M. Wascko, Neutrino2018

NOvA Appearance Results

New results announced at Users Meeting!

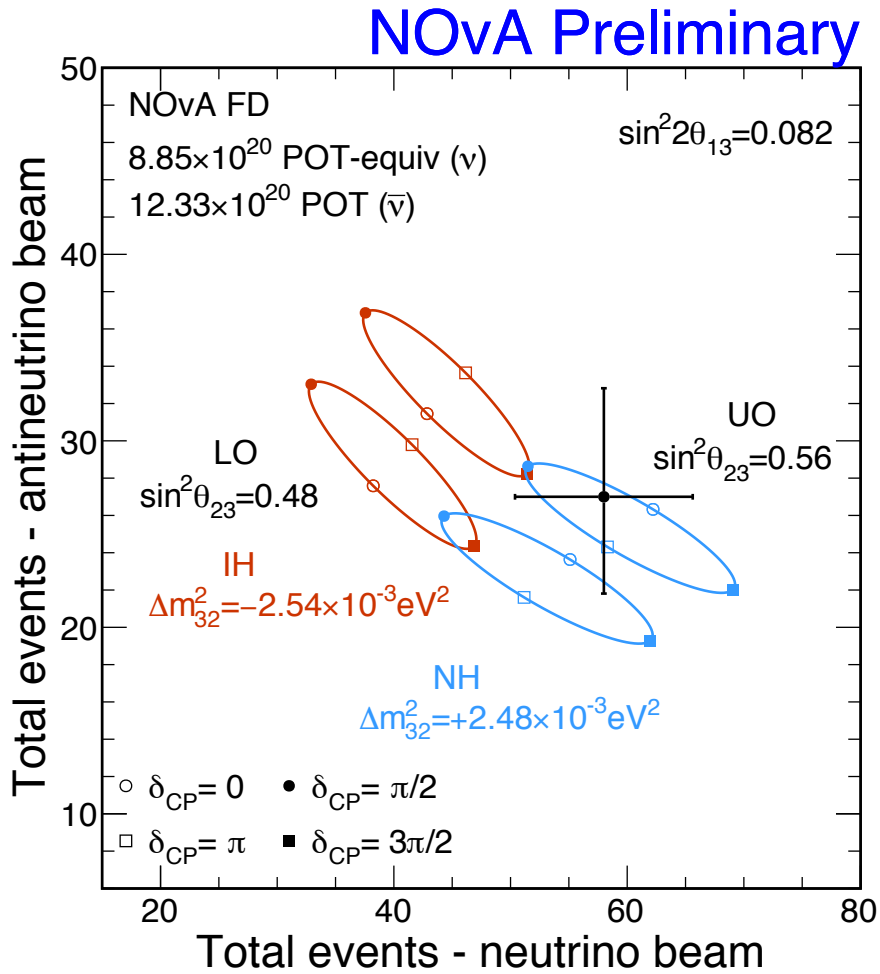
arXiv:1906.04907

- Neutrino mode
  - 58 events observed
  - 15 bkg expected
- Antineutrino mode
  - 27 events observed
  - 10 bkg expected

    (including 2 wrong sign)

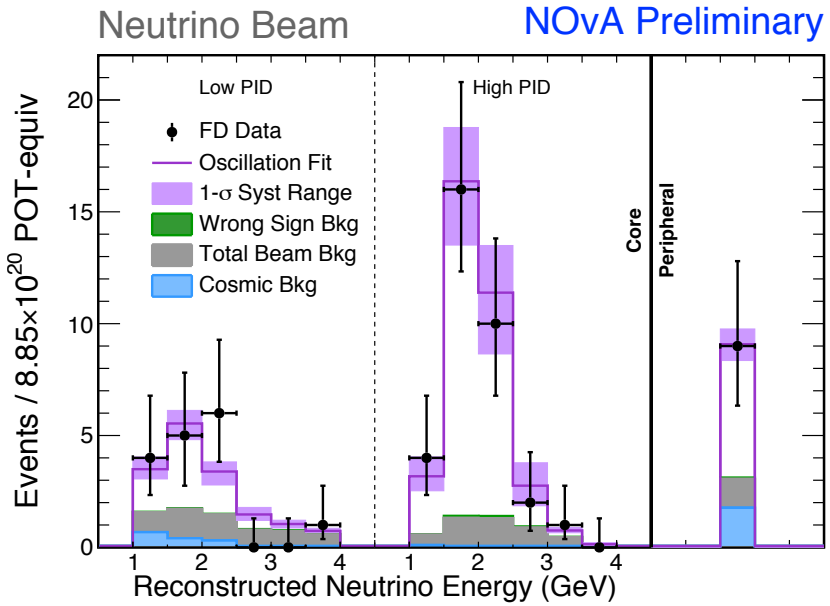
Strong (4.4 sigma) evidence of electron antineutrino appearance

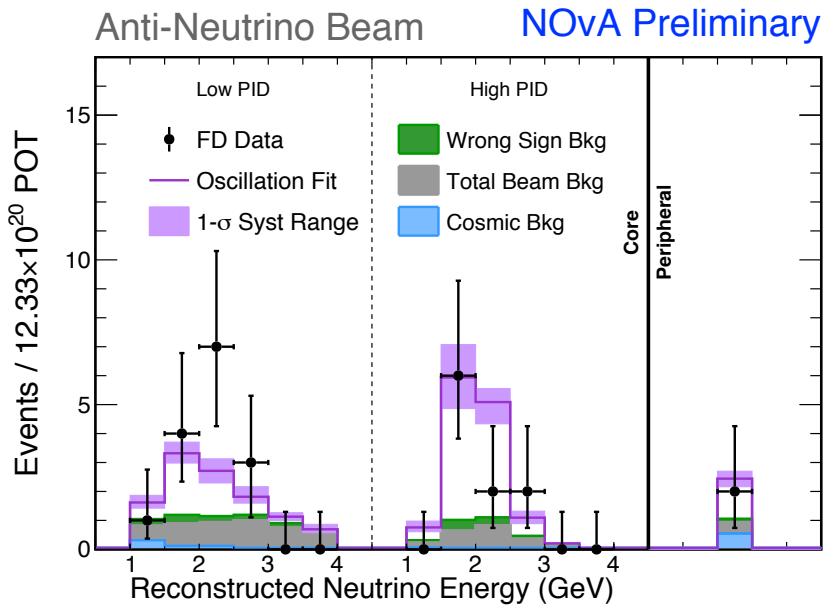
Full analysis power comes from joint fit to ν_e appearance and ν_μ disappearance spectra in both neutrino and antineutrinos



arXiv:1906.04907

Appearance Spectra





Neutrino Mode

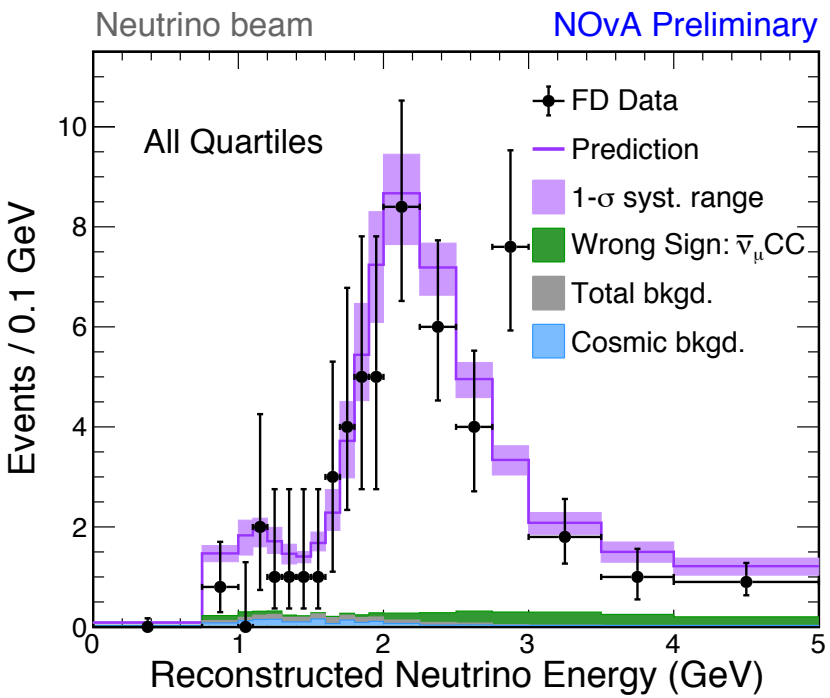
Total Observed	58
Total Prediction	59.3
Wrong-sign	0.6
Beam Bkgd.	11.7
Cosmic Bkgd.	3.3
Total Bkgd.	15.0

Antineutrino Mode

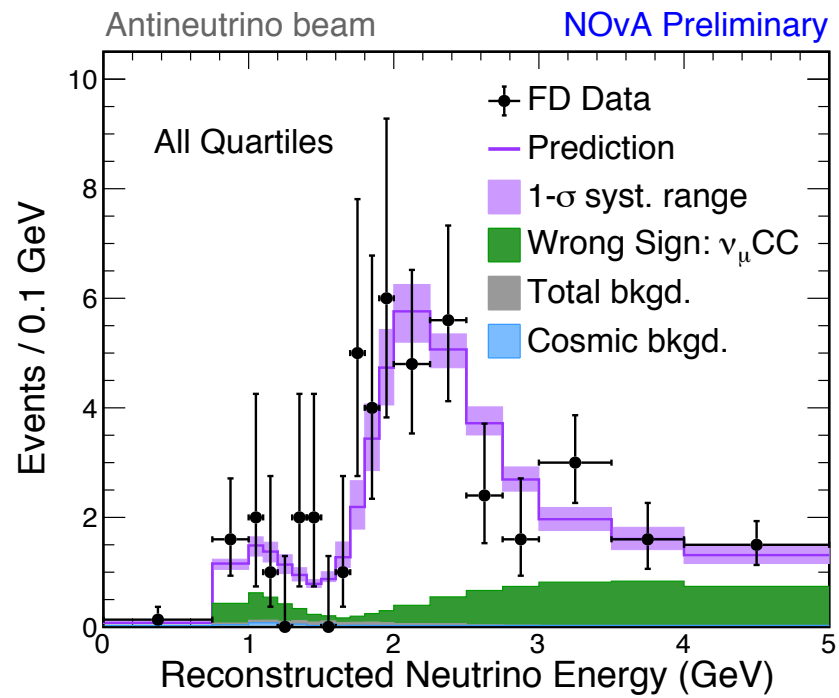
Total Observed	27
Total Prediction	26.8
Wrong-sign	2.2
Beam Bkgd.	9.2
Cosmic Bkgd.	1.1
Total Bkgd.	10.3

arXiv:1906.04907

Disappearance Spectra



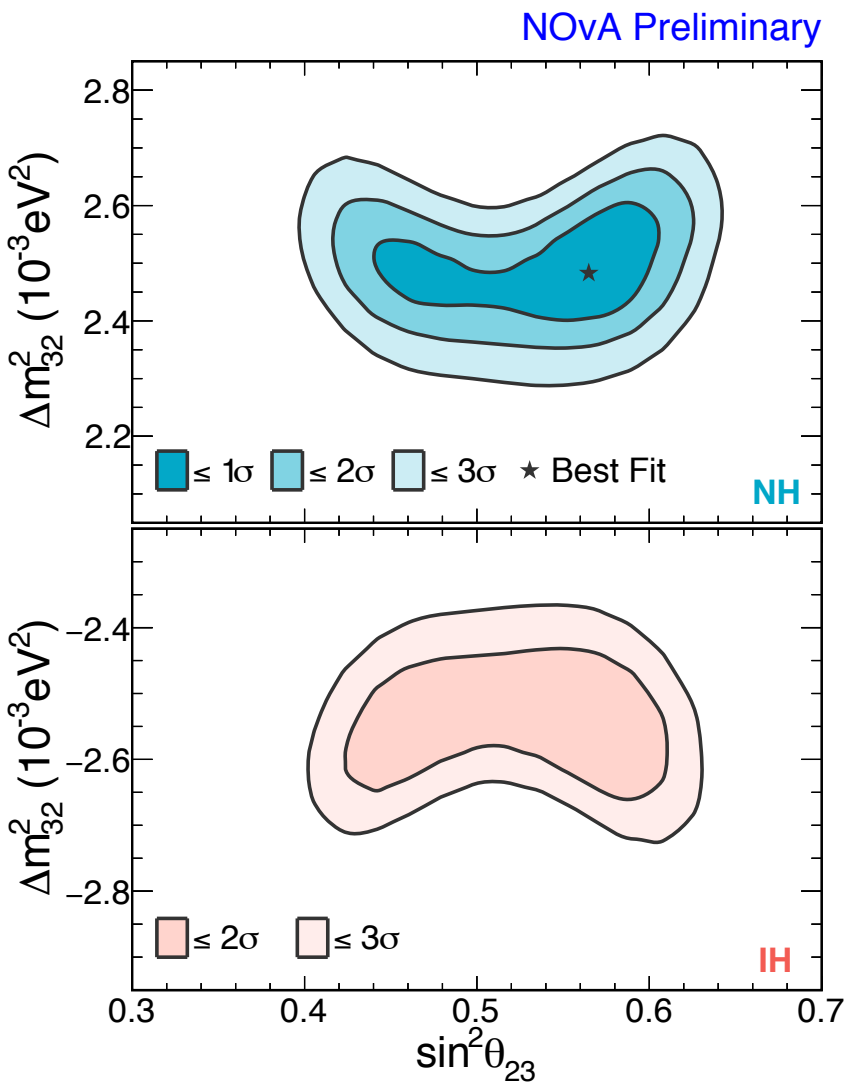
Total Observed	113
Best fit prediction	124
Cosmic Bkgd.	2.1
Beam Bkgd.	2.1
Unoscillated	730

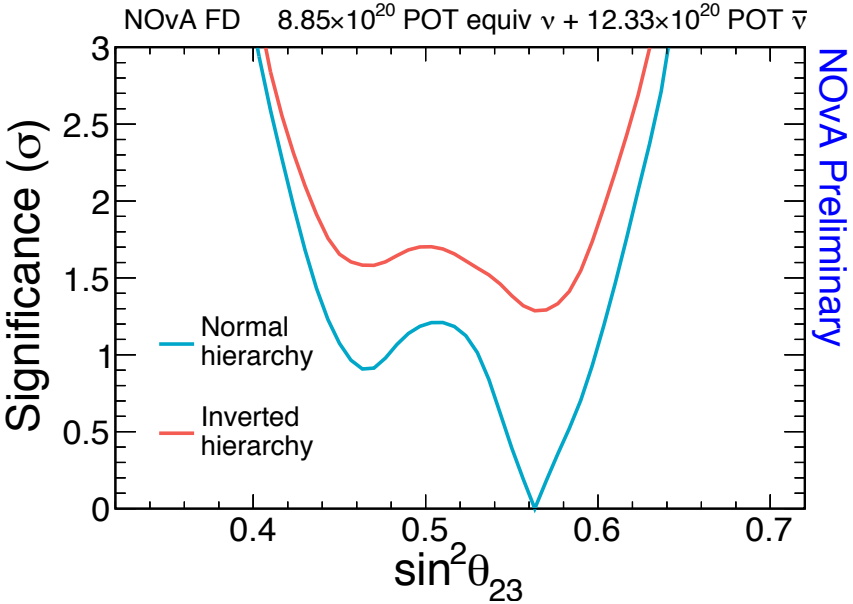


Total Observed	102
Best fit prediction	96.2
Cosmic Bkgd.	0.8
Beam Bkgd.	1.4
Unoscillated	476

arXiv:1906.04907

NOvA Fit Results: Mass splitting and mixing angle





Normal Hierarchy

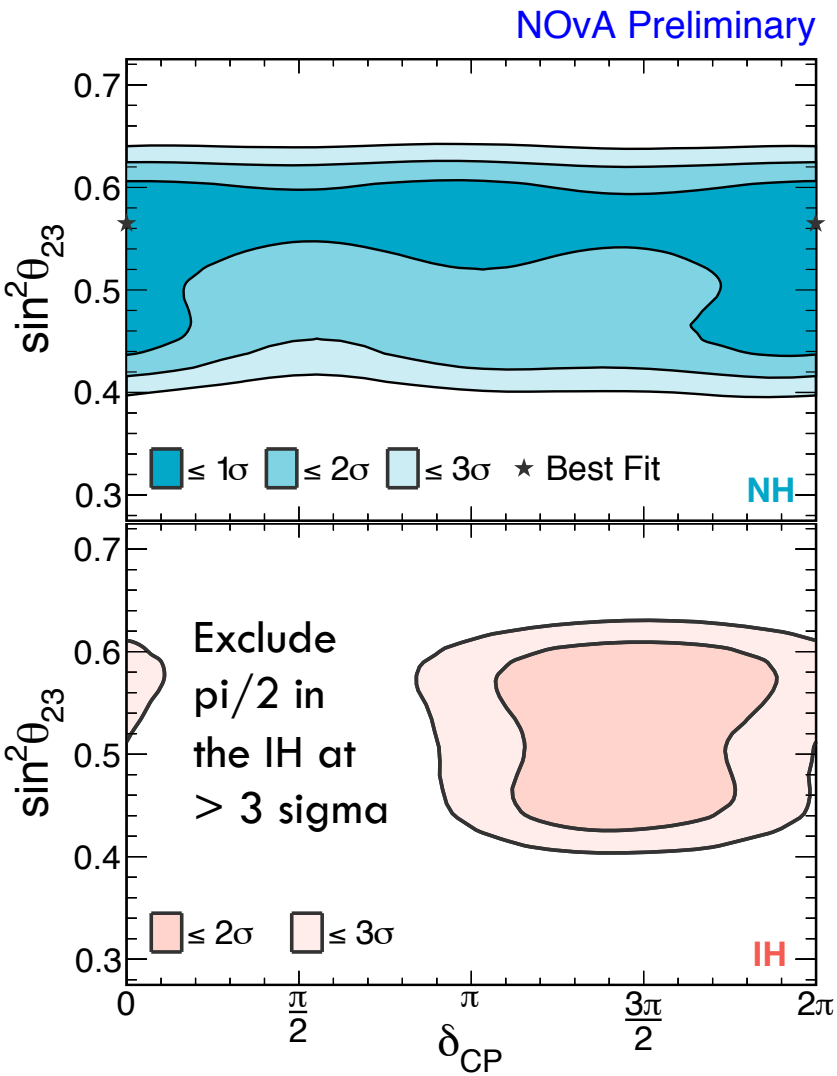
$$\Delta m^2_{32} = 2.48^{+0.11}_{-0.06} \times 10^{-3}\mathrm{eV}^2$$

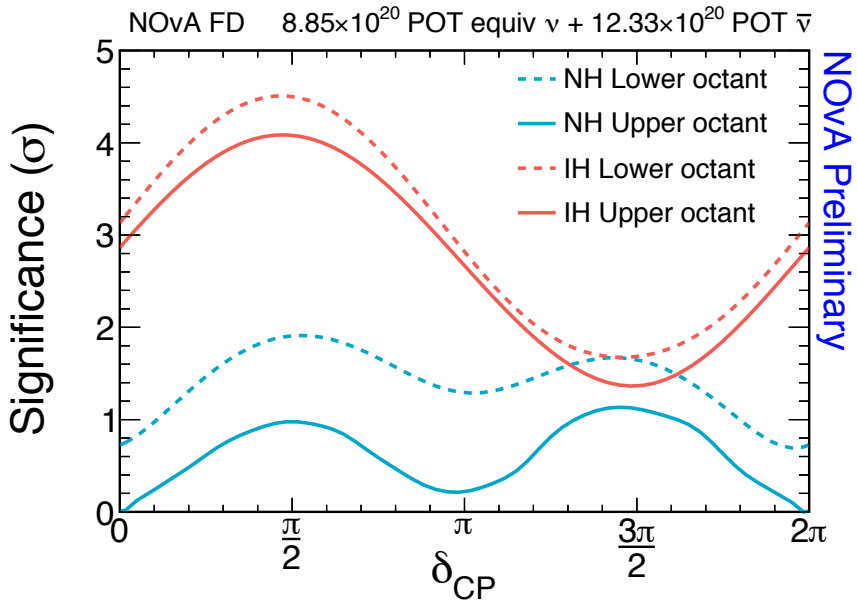
$$\sin^2\theta_{23} = 0.56^{+0.04}_{-0.03}$$

$$\delta_{CP} = 0.0\pi$$

NOvA Fit Results: Hierarchy and Delta CP

arXiv:1906.04907

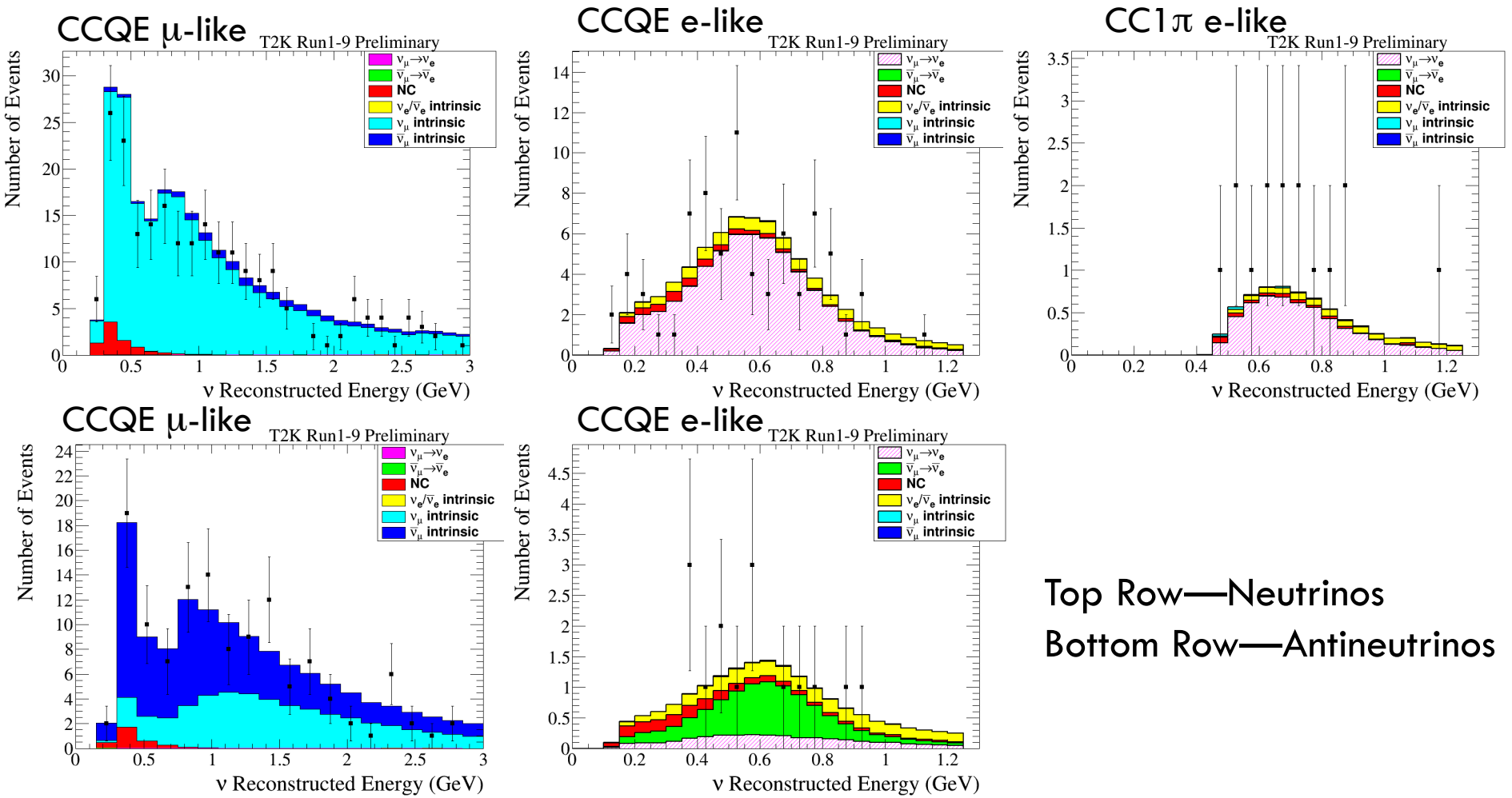




Normal Hierarchy preferred at 1.9 sigma
Upper Octant preferred at 1.6 sigma
All values of delta consistent at 1.1 sigma

Significances determined using Feldman-Cousins approach. Leveraged high performance computing at NERSC

SK Spectra



Top Row—Neutrinos

Bottom Row—Antineutrinos

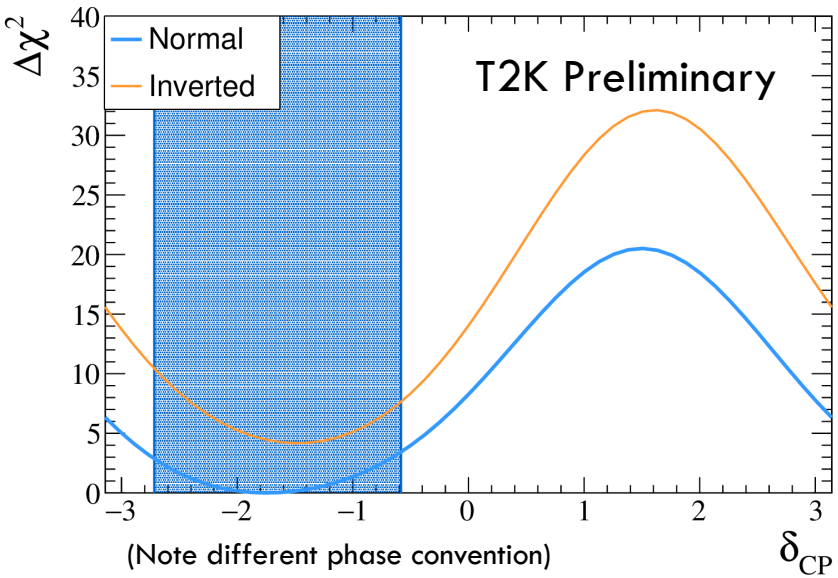
K. Porwit, NuTelescopes 2019

T2K Results: Delta CP

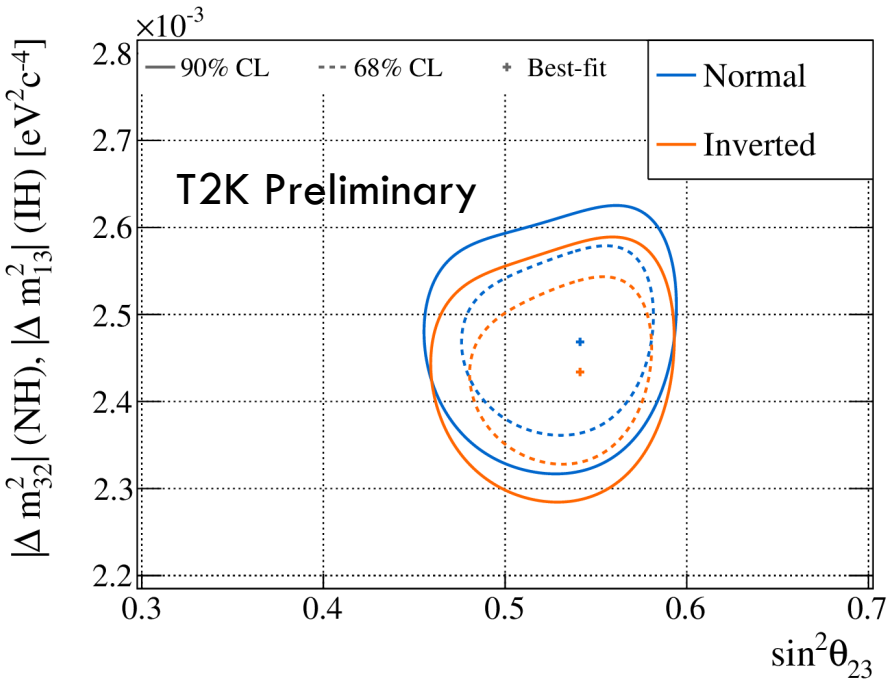
Gzarnecki, LaThuile 2019 Sample	Predicted				Observed	Systematic uncertainty for prediction
	$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = +\pi/2$	$\delta_{CP} = \pi$		
ν mode μ-like	272.4	272.0	272.4	272.8	243	5.1%
$\bar{\nu}$ mode μ-like	139.5	139.2	139.5	139.9	140	4.5%
ν mode e-like	74.4	62.2	50.6	62.7	75	8.8%
$\bar{\nu}$ mode e-like	17.1	19.4	21.7	19.3	15	7.1%
ν mode e-like + $1\pi^+$	7.0	6.1	4.9	5.9	15	18.4%

CP conserving values fall outside 2 sigma confidence interval!

Normal Hierarchy preferred at 89%



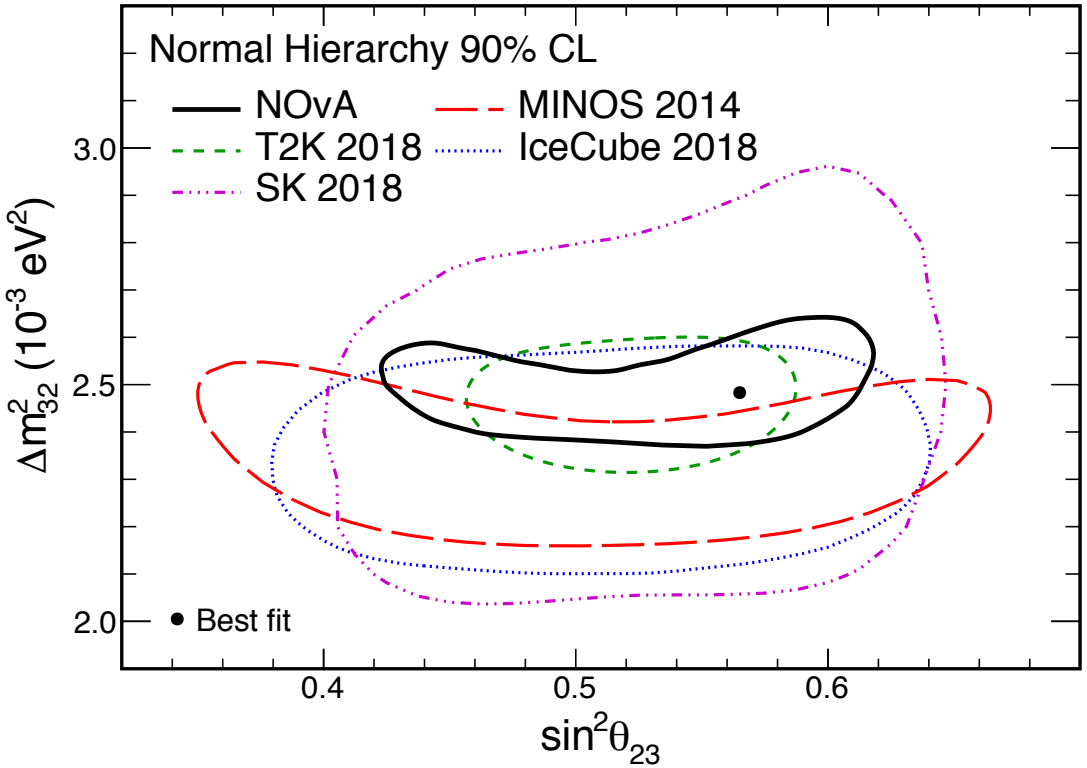
T2K Fit Results: Mass splitting and mixing angle



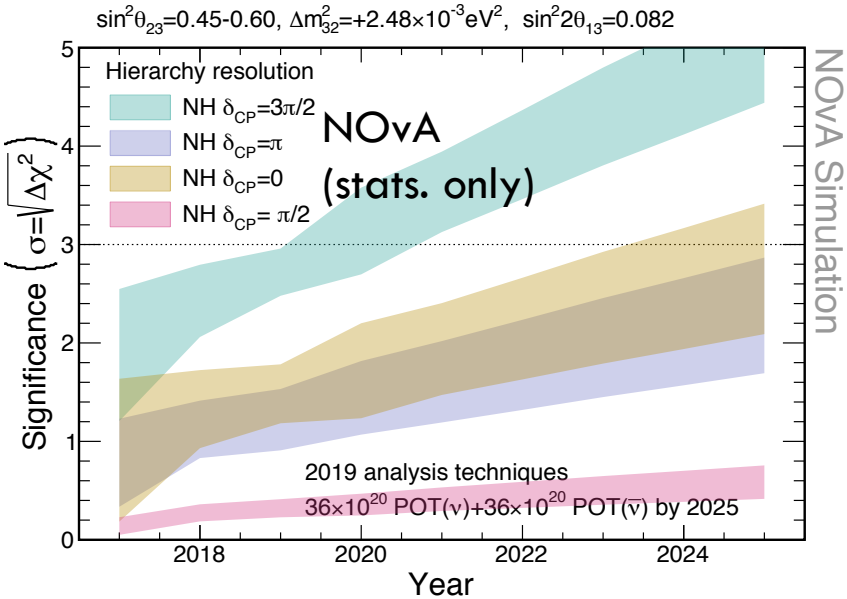
	Normal Hierarchy	Inverted Hierarchy
$sin^2(\theta_{23})$	$0.532^{+0.030}_{-0.037}$	$0.532^{+0.029}_{-0.035}$
$\lvert\Delta m^2_{32}\rvert \times 10^{-3} eV^2$	$2.452^{+0.070}_{-0.071}$	$2.432^{+0.069}_{-0.071}$

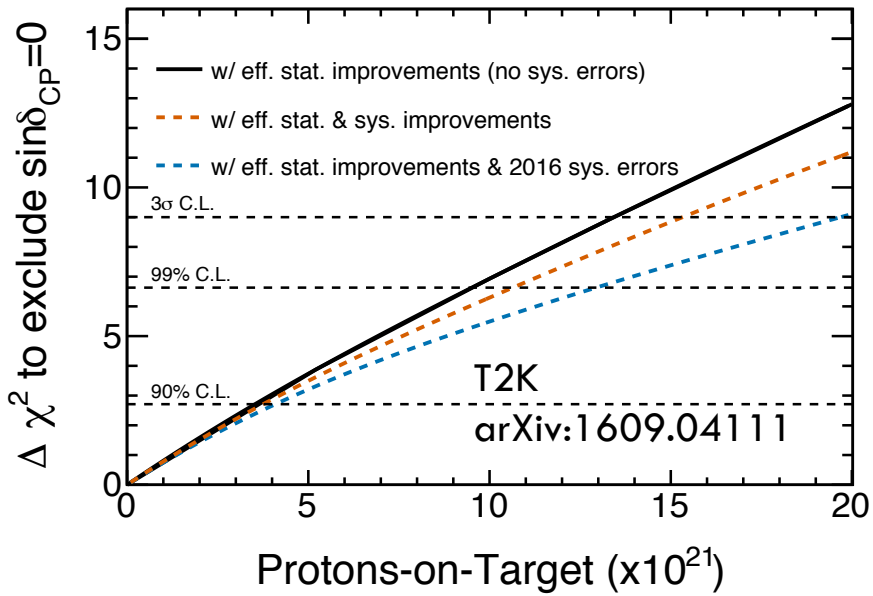
K. Porwit, NuTelescopes 2019

Comparisons



Outlook



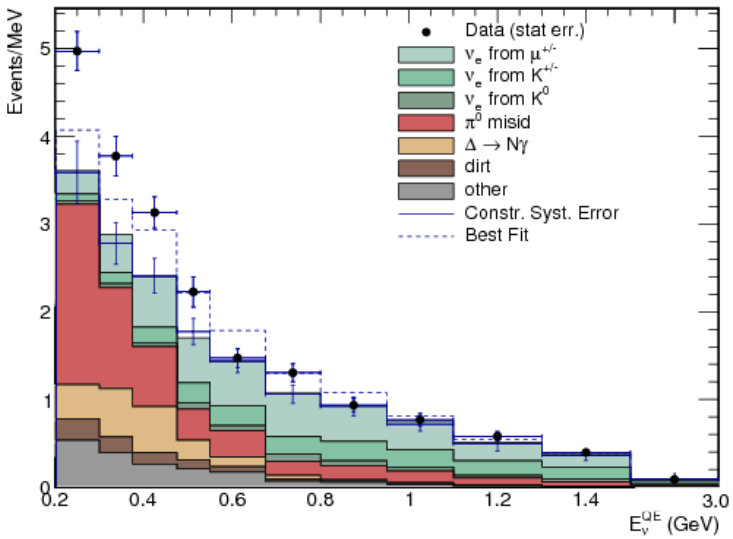


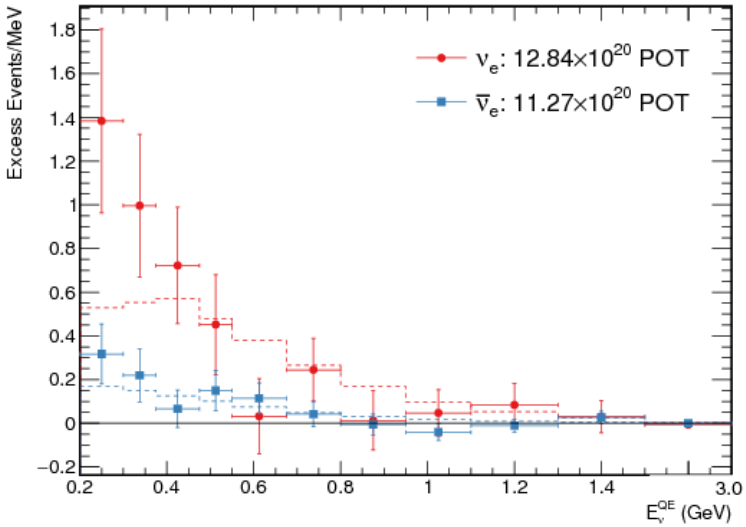
- For favorable parameters consistent with results, NOvA can achieve 3 sigma mass hierarchy sensitivity by 2020
  - 3 sigma sensitivity for 30-50% of delta CP range by 2025
  - >5 sigma in favorable cases by 2025
- T2K projects 3 sigma sensitivity to CP violation with 20x10^{21} POT, achievable by 2026

Beyond Three Flavor Oscillations

MiniBooNE

- Excess of electron neutrinos observed in MiniBooNE persists with double the neutrino data set

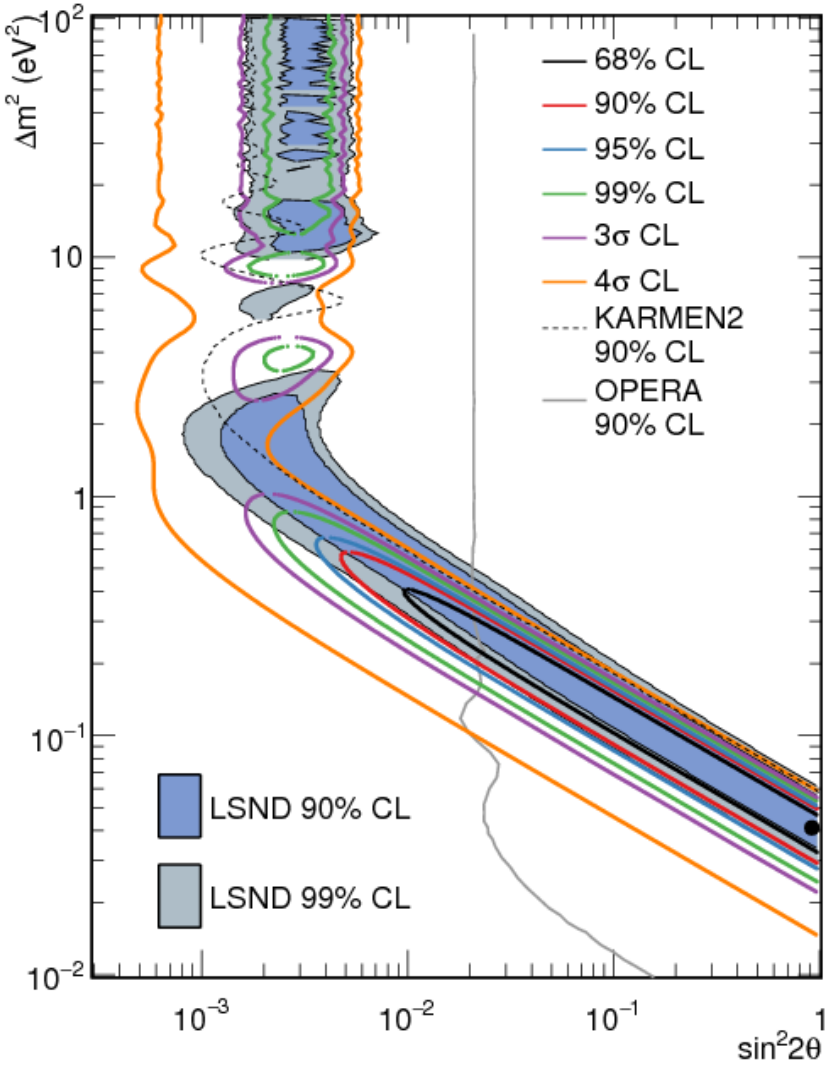




MiniBooNE excess in neutrino and antineutrino: 4.8 sigma
Combined with LSND: 6.1 sigma

PRL 121, 221801 (2018)

MiniBooNE



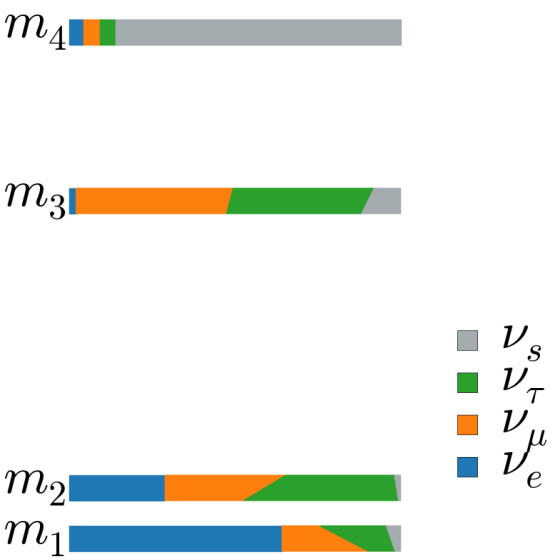
- Data fit using a 2-neutrino oscillation model
- Joint fit to neutrinos and antineutrinos shown

PRL 121, 221801 (2018)

3+1 Model

- To incorporate MiniBooNE excess into oscillation framework requires a new mass state and new sterile flavor
- Expand PMNS: 3x3->4x4
- 6 additional parameters
  - new mass splitting
  - three mixing angles
  - two CP-violating phases

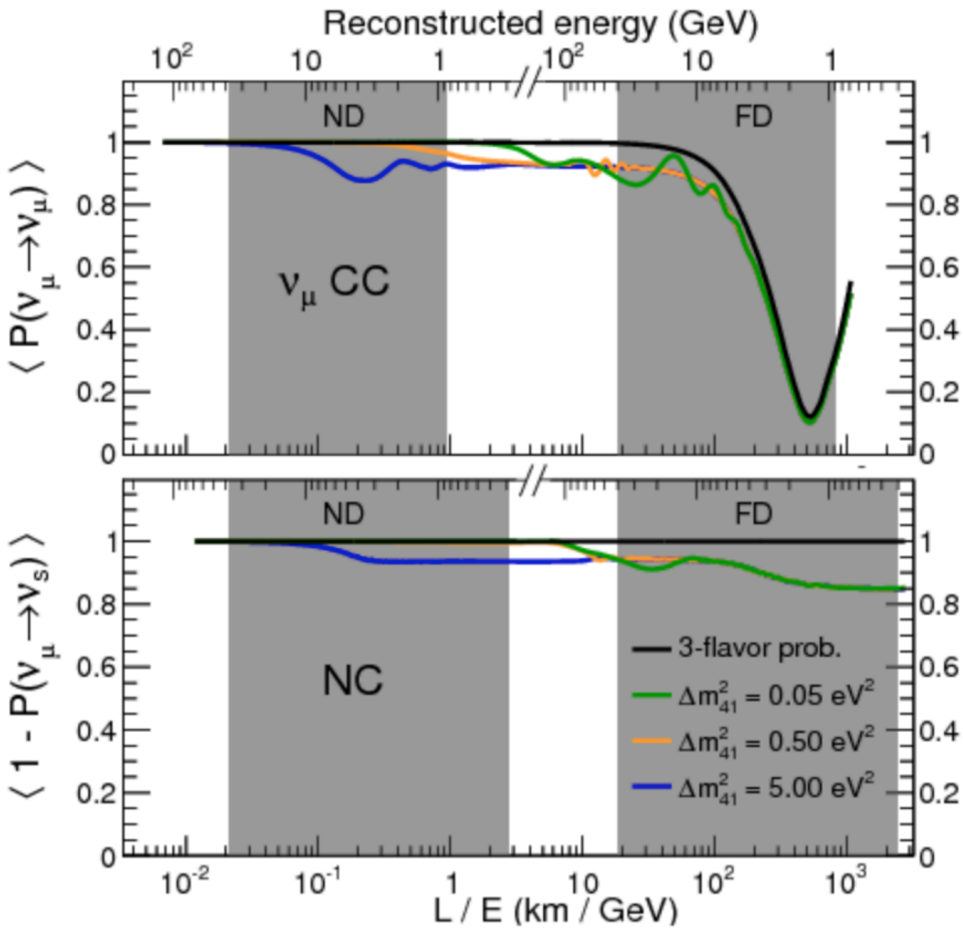
$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$



A. Aurisano,
Neutrino 2018

4 Flavor Oscillations at Long-baselines

- Small mass splitting
  - FD sees anomalous muon-neutrino disappearance at high energies and energy dependent suppression of neutral currents
  - ND sees no oscillations
- Large mass splitting
  - Rapid oscillations at FD at high energies average out
  - Large oscillation effects at the ND

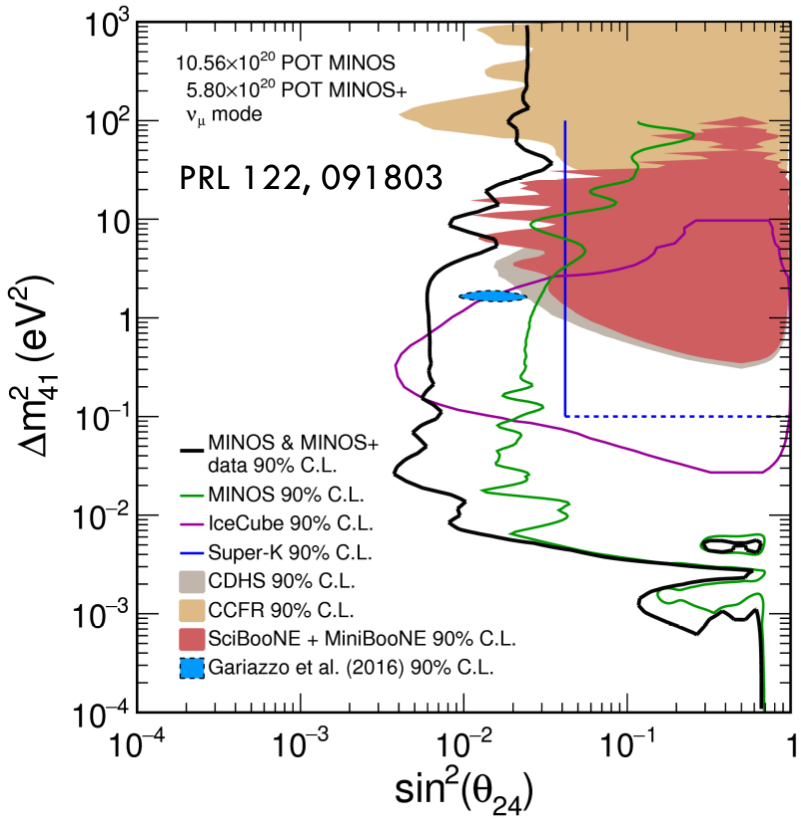


arXiv:1710.06488

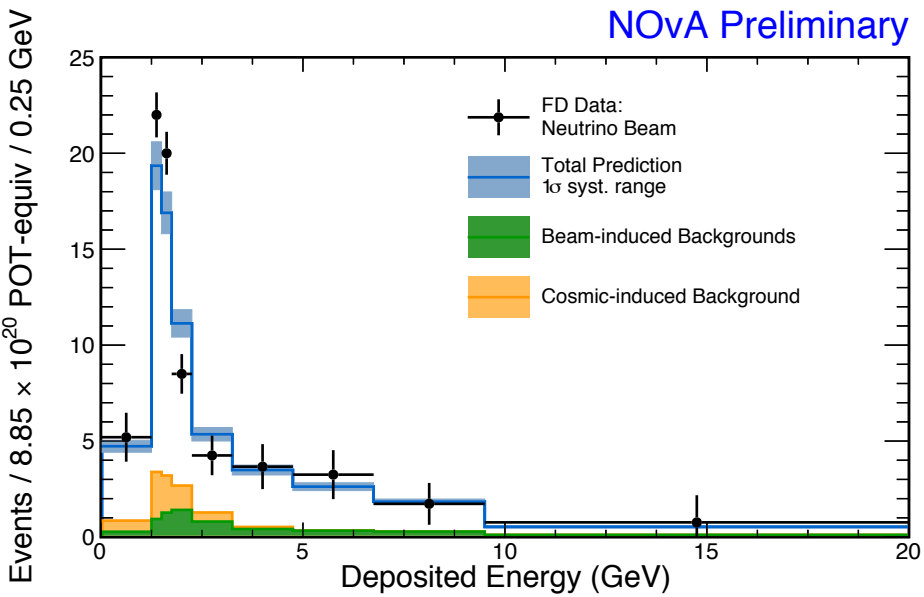
4 Flavor Oscillations at Long-baselines

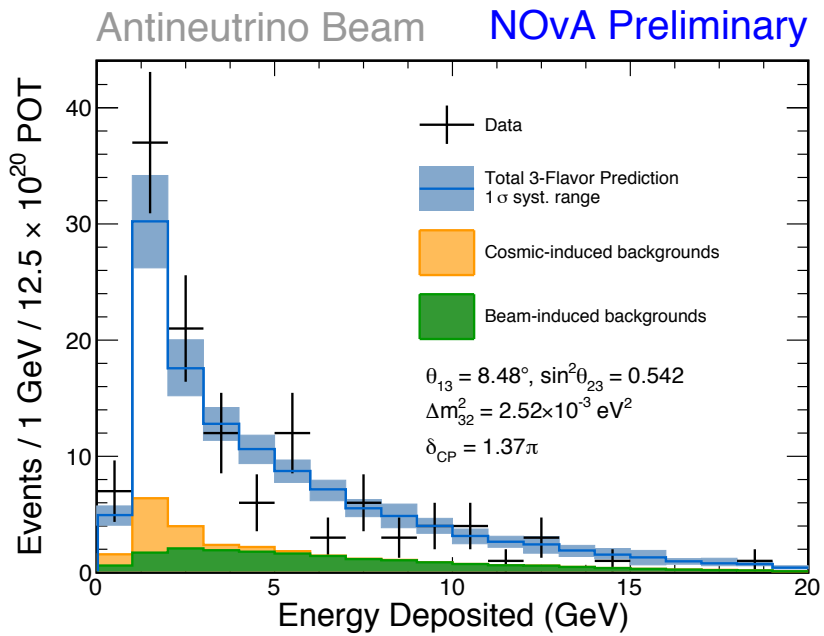
- 2 detector fit to MINOS and MINOS+ data provides limit on mixing angle over 7 orders of magnitude in Δm^2_{41}
- Combining LBL limits on θ_{24} with reactor limits on θ_{14} allows for comparison with MiniBooNE results

$$\sin^2(2\theta_{\mu e}) \sim \sin^2(2\theta_{14})\sin^2(\theta_{24})$$



NOvA NC Disappearance





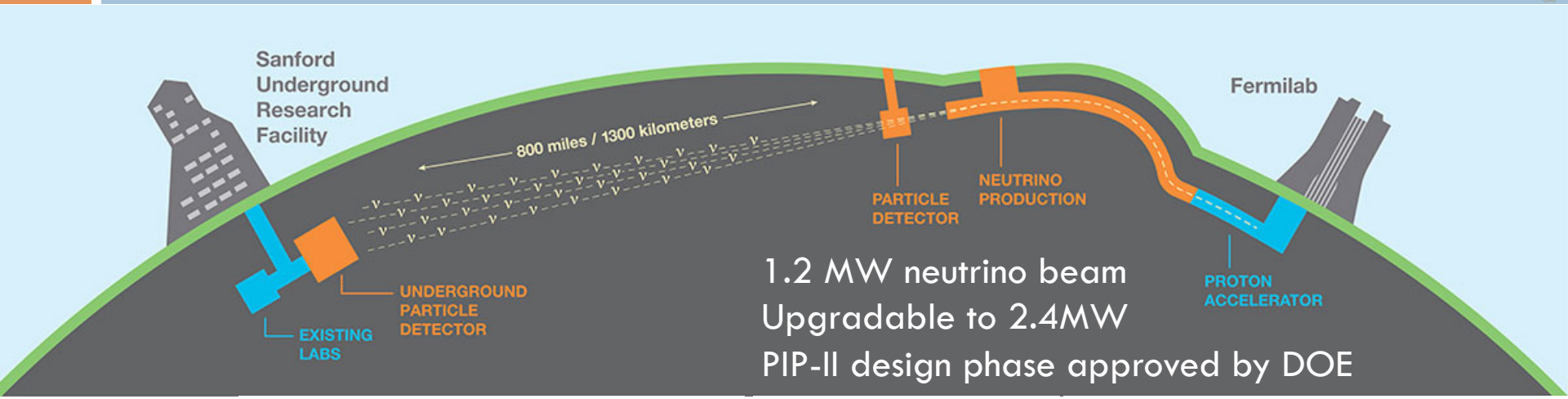
Neutrino mode:
expect 188+/-13 (syst.)
Observe 201 events

Antineutrino mode:
expect 122+/-18 (syst.)
Observe 121 events

No significant suppression of Neutral Current interactions in either neutrino or antineutrino mode

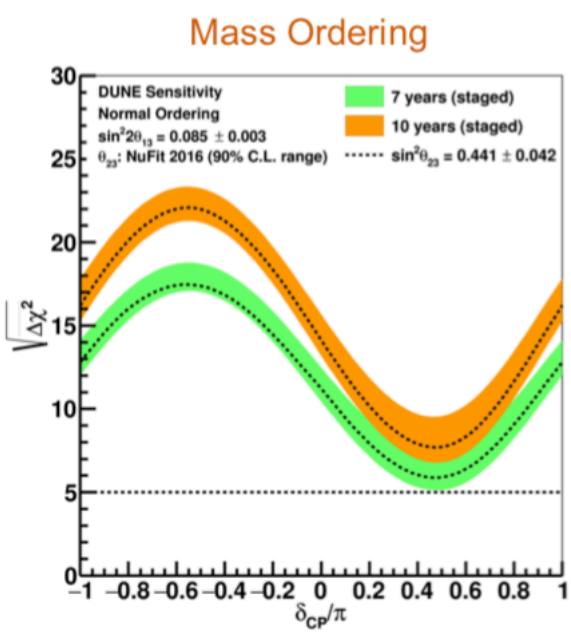
Beyond

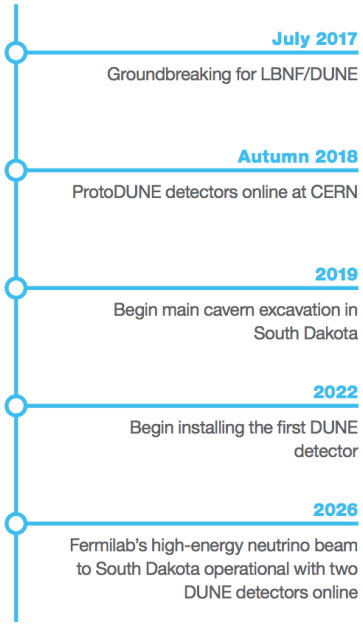
The Future of Long-baselines: DUNE

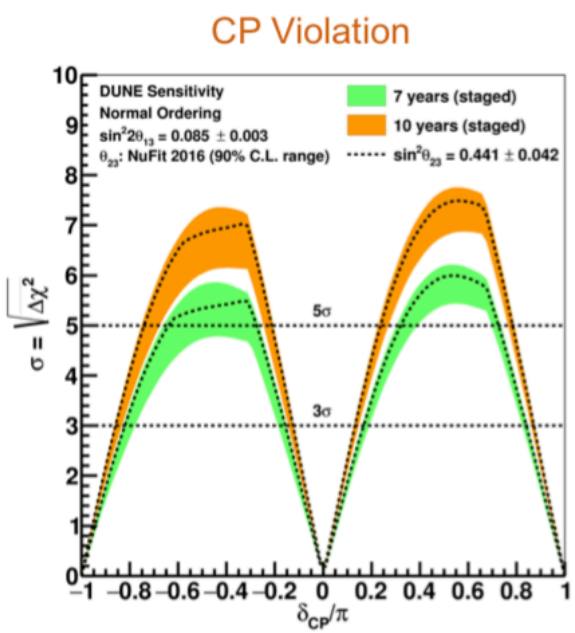


1.2 MW neutrino beam
Upgradable to 2.4MW
PIP-II design phase approved by DOE

E. Worchester, Neutrino 2018



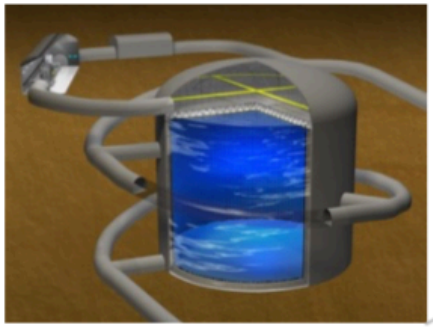




See:
S. Gollapinni, Thurs. Plen.
A. Chatterjee, Thurs WG1

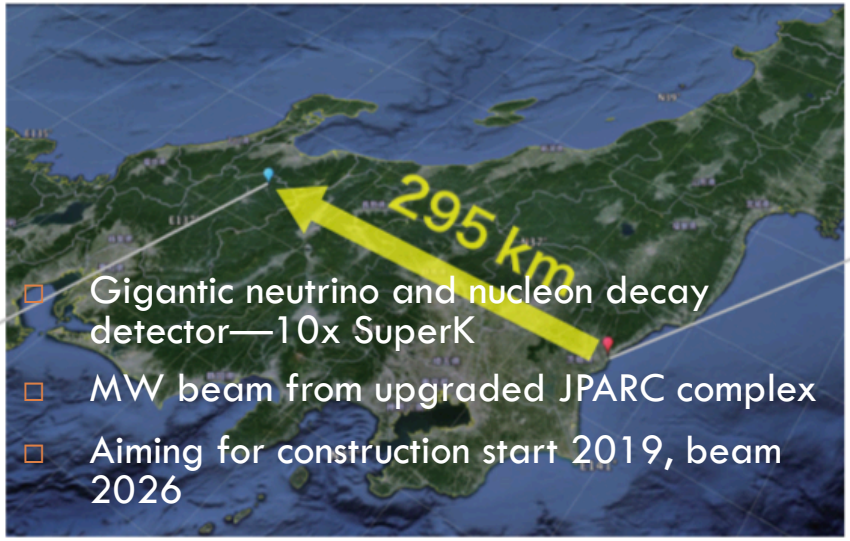
See: A. Blondel, Thurs. Plen., Thurs. WG1

The Future of Long-baselines: HyperK



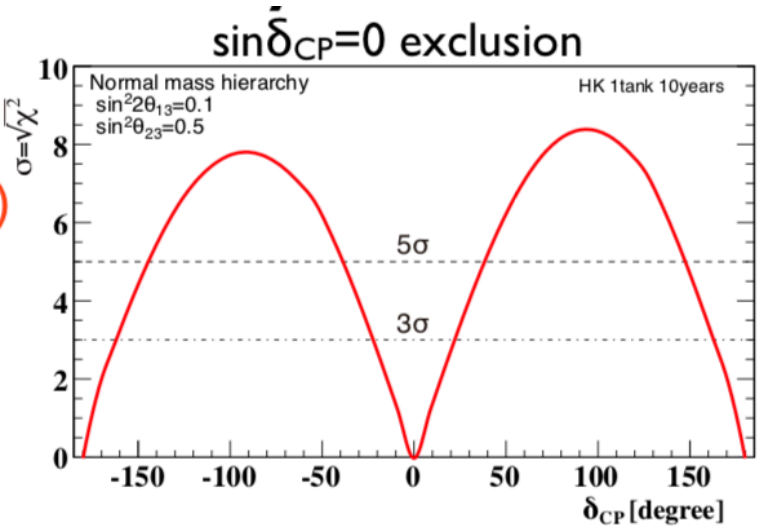
Hyper-K

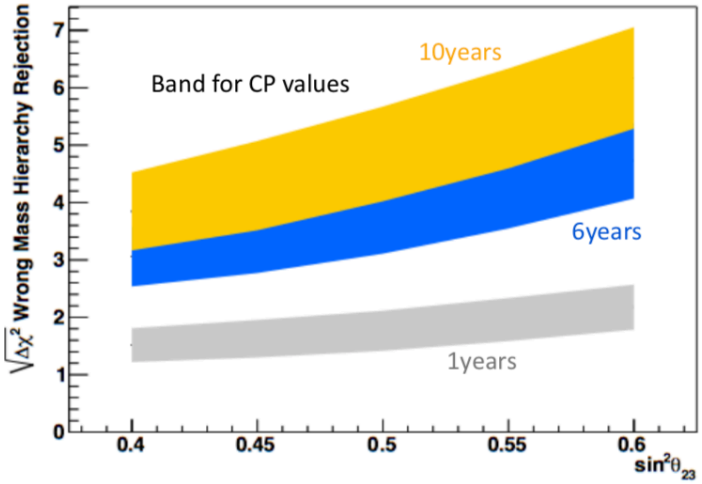
M. Shiozawa, Neutrino 2018



- Gigantic neutrino and nucleon decay detector—10x SuperK
- MW beam from upgraded JPARC complex
- Aiming for construction start 2019, beam 2026

J-PARC
Accelerator Complex





Design report released in May, arXiv:1805.04163

Summary

- 20 years from the discovery of neutrino mass and oscillations, we still have exciting discoveries to make.
- New results from accelerator experiments released this summer
  - NOvA has strong evidence of electron-antineutrino appearance
  - T2K favors non-CP conserving values of δ_{CP} at 2σ
- Future experiments should be in good stead to observe or constrain CP violation

Backup

Electron Neutrino Appearance

NOvA Collaboration

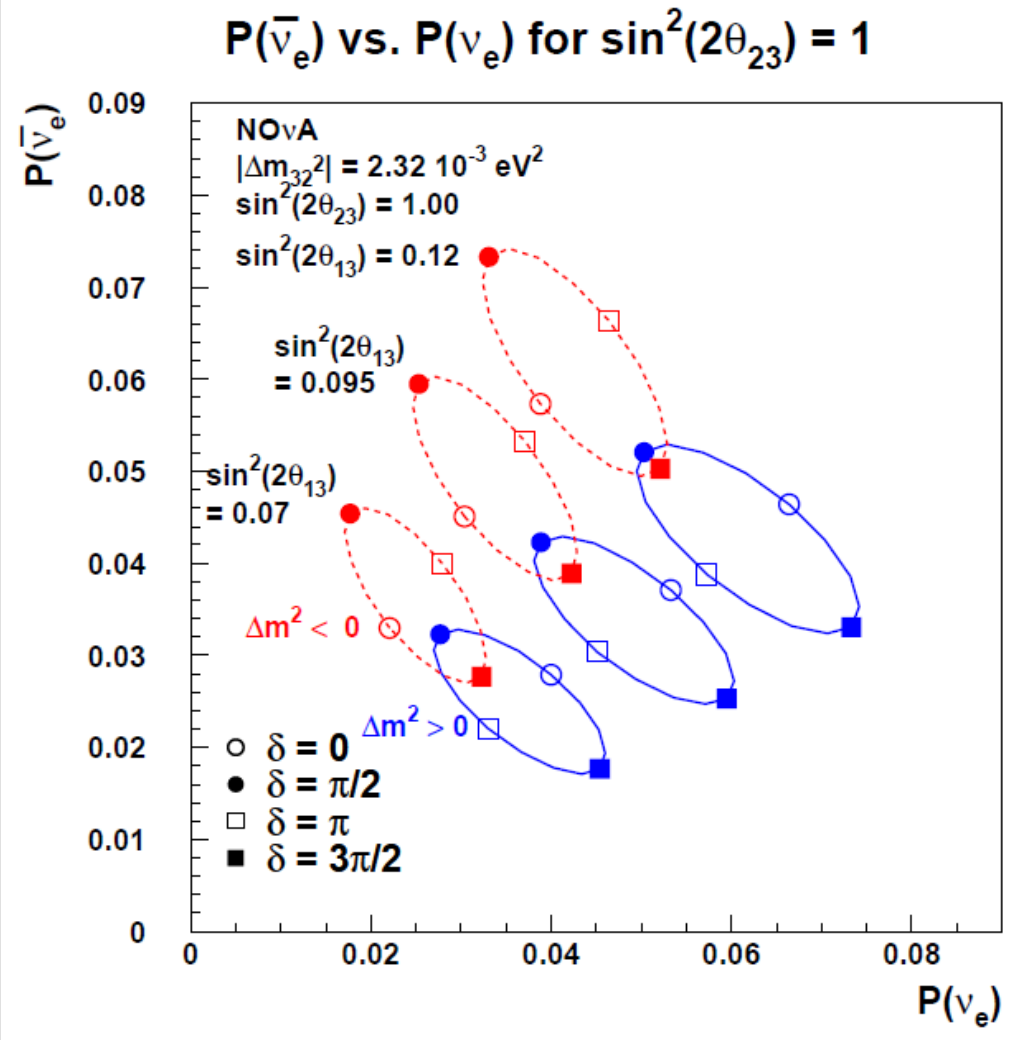
238 collaborators at 49 institutions across 7 countries

19 Remote Control Rooms across the globe

Publications and PhDs

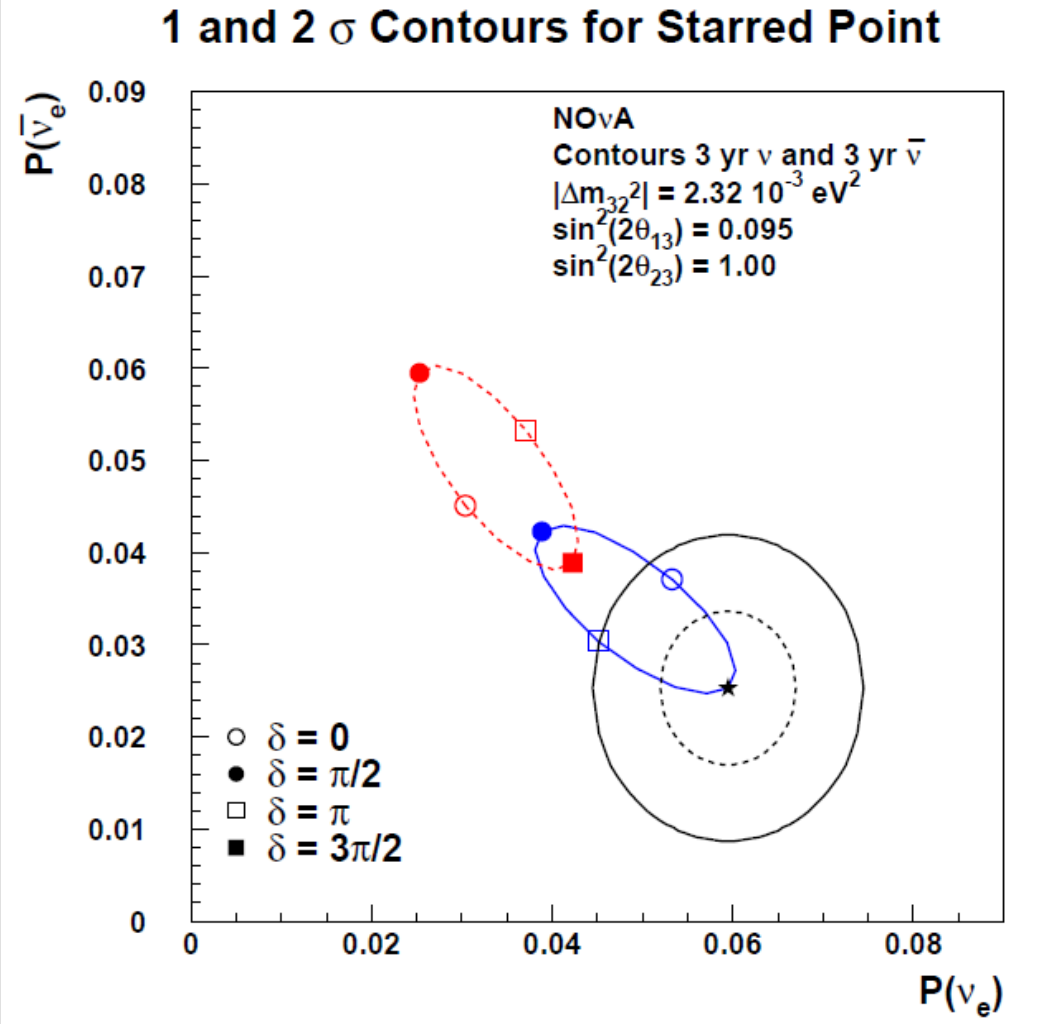
- 5 Publications + 1 submitted
  - arXiv:1806.0096 (2 cites)
  - Phys.Rev.D96 (2017) no. 7, 072006 (19 cites)
  - Phys.Rev.Lett. 118 (2017) no. 23, 231801 (83 cites)
  - Phys.Rev Lett. 118 (2017) no. 15, 151802 (83 cites)
  - Phys.Rev.D93 (2016) no. 5, 051104 (102 cites)
  - Phys.Rev. Lett.116 (2016) no. 15, 151806 (167 cites)
- 19 PhDs, 5 since last summer
  - Dan Pershey, CalTech
  - Stefano Tognini, Universidade Federal de Goias, Brazil
  - Fernanda Psihas, Indiana
  - Bio Wang, SMU
  - Luke Vinton, Sussex, UK

How its done



- Compare oscillation probability measured with neutrinos and antineutrinos

How its done



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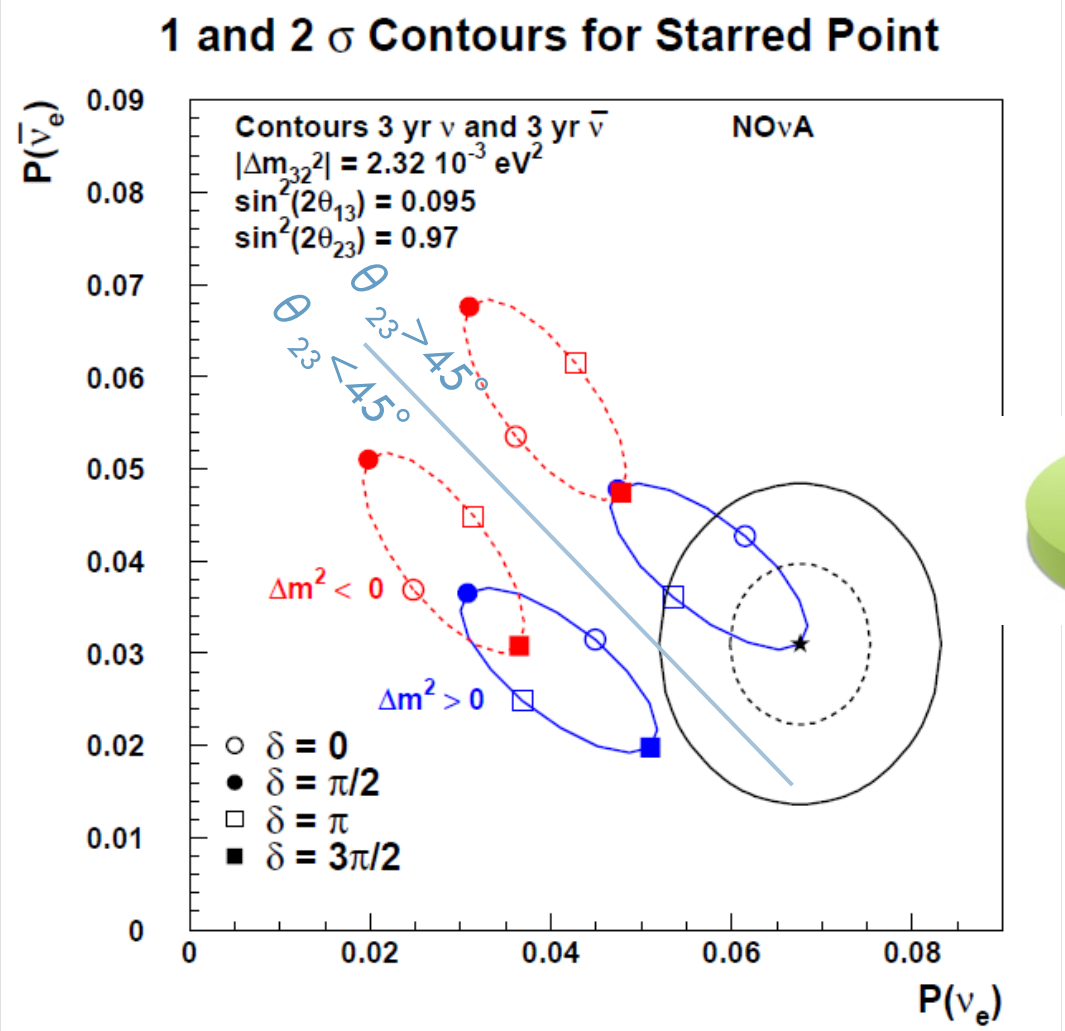
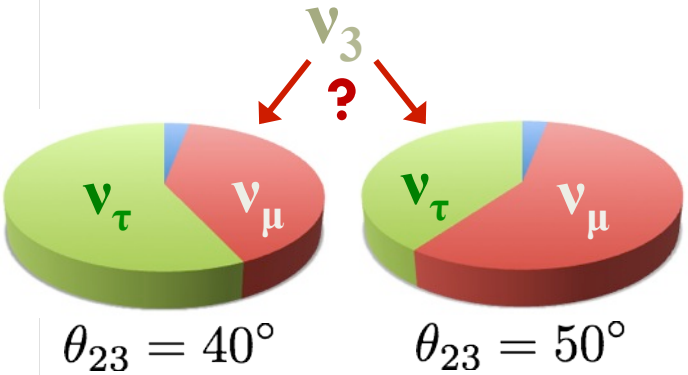
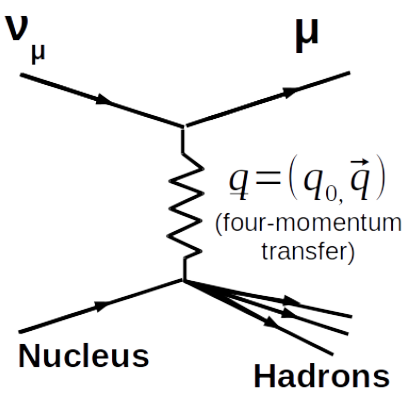
How its done

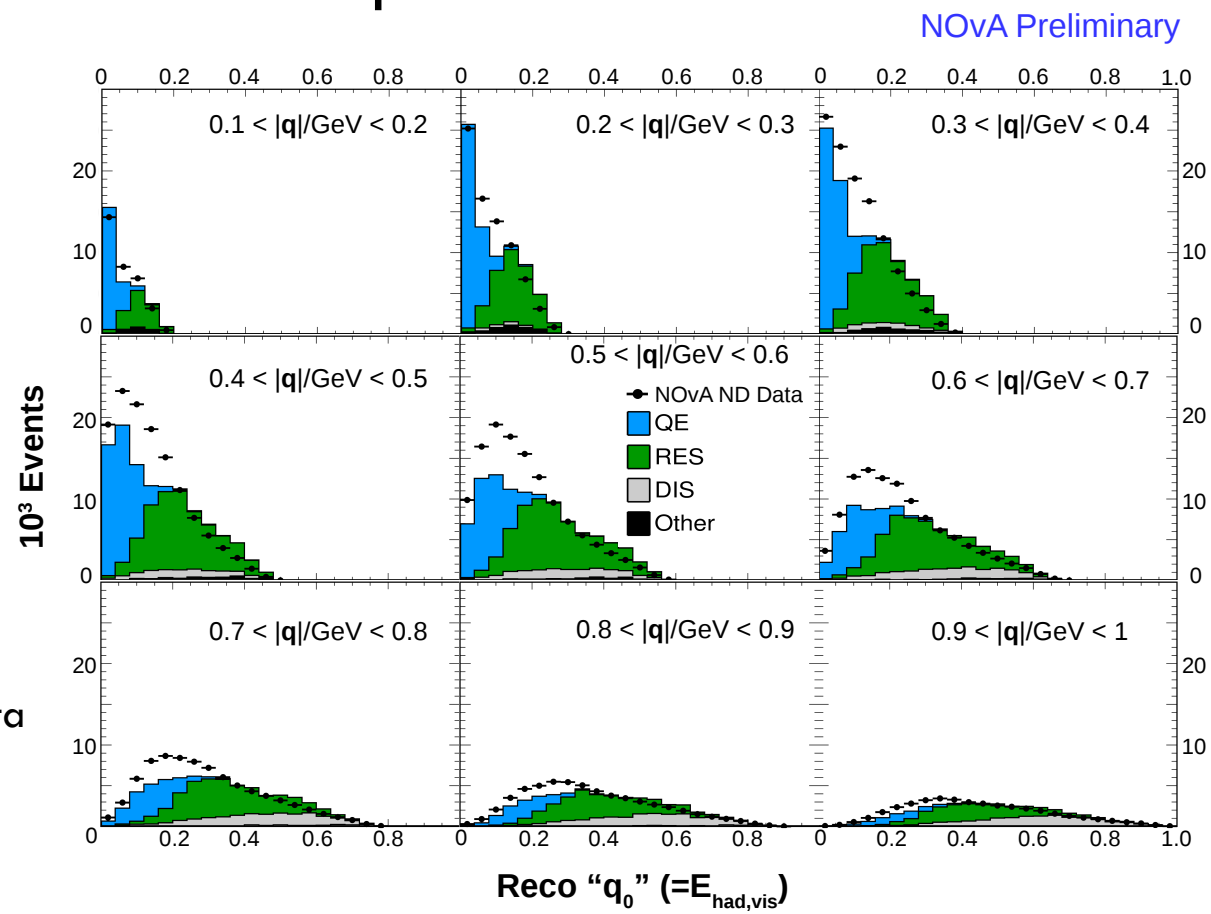

1 and 2 σ Contours for Starred Point
Contours 3 yr ν and 3 yr ν̄
NOνA
|Δm32²| = 2.32 10⁻³ eV²
sin²(2θ13) = 0.095
sin²(2θ23) = 0.97
θ23 > 45°
θ23 < 45°
Δm² < 0
Δm² > 0
δ = 0
δ = π/2
δ = π
δ = 3π/2
P(ν̄e)
P(νe)
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0.02
0.04
0.06
0.08


ν3
?
ντ
νμ
ντ
νμ
θ23 = 40°
θ23 = 50°

Scattering in a Nuclear Environment

- Near detector hadronic energy distribution suggests unsimulated process between quasi-elastic and delta production





Similar conclusions from MINERvA data reported in P.A. Rodrigues et al., PRL 116 (2016) 071802

Scattering in a Nuclear Environment

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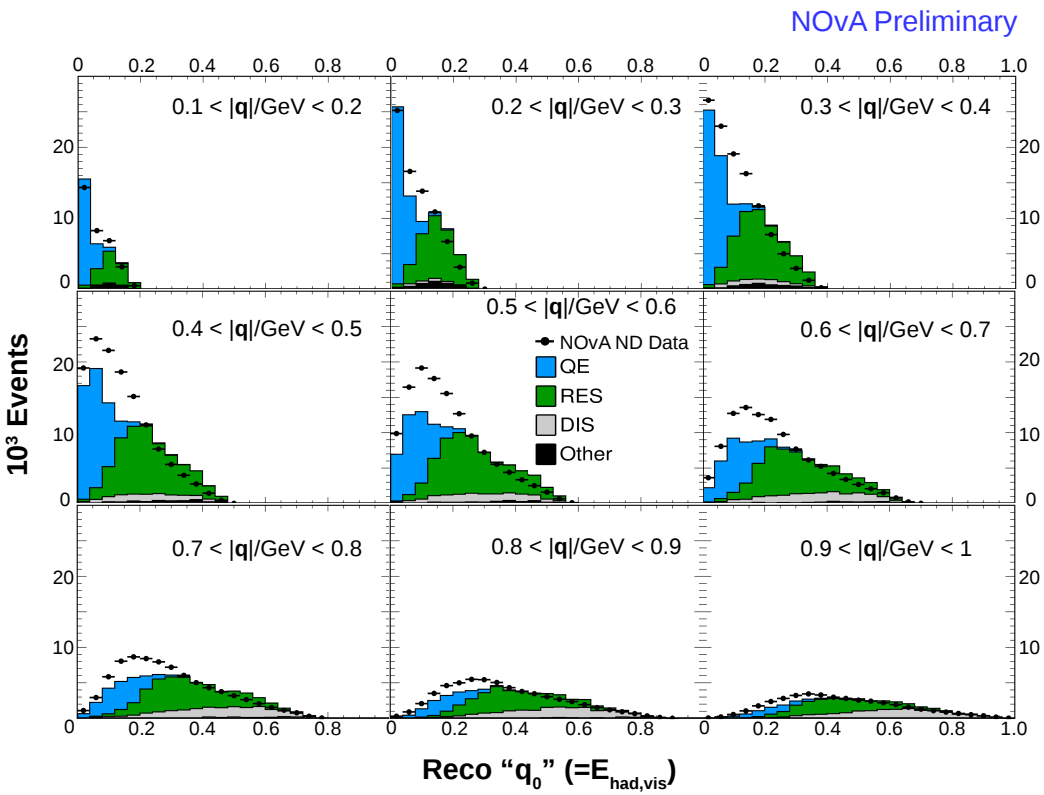
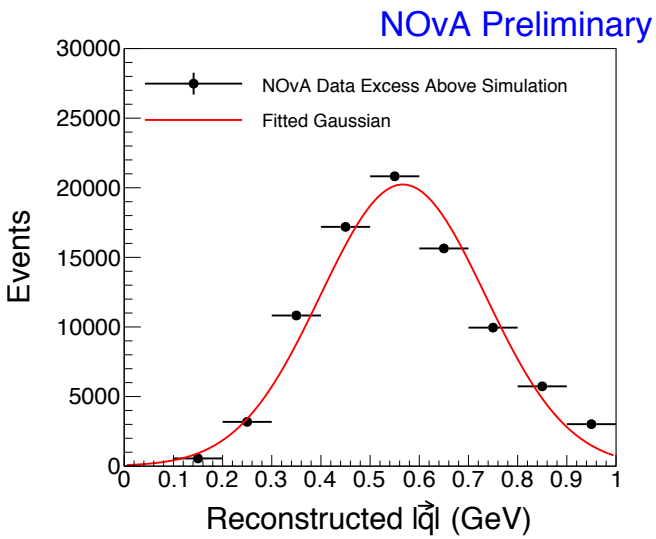
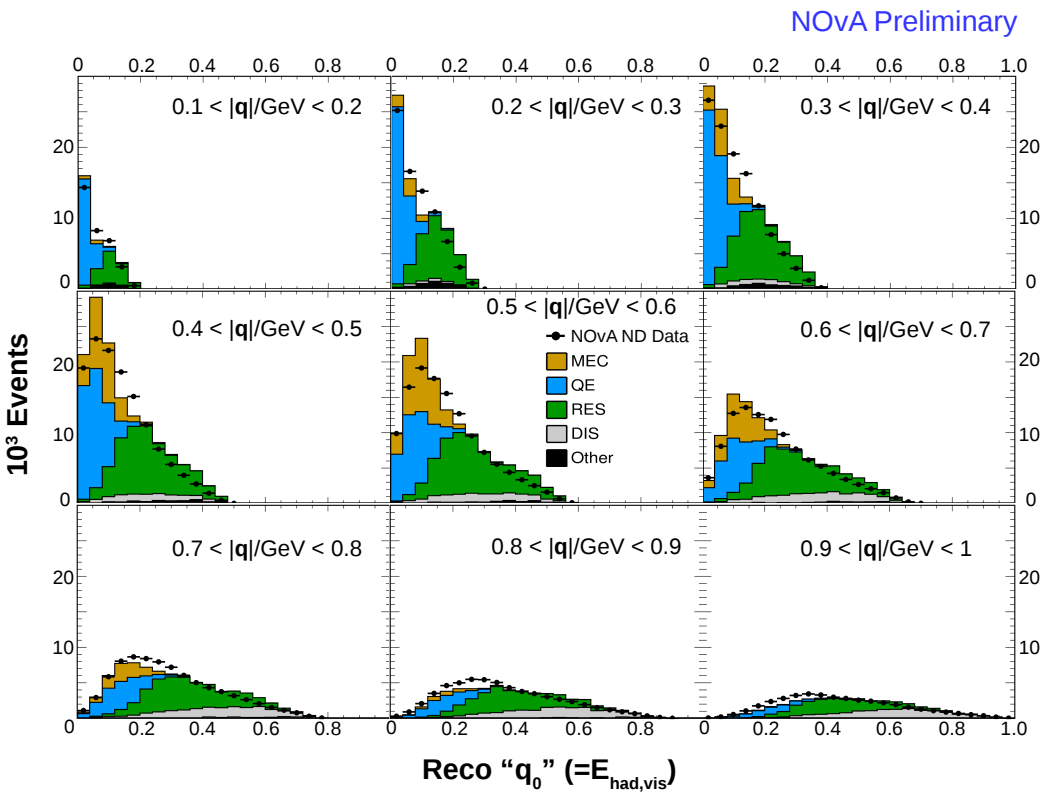




Similar conclusions from MINERvA data reported in P.A. Rodrigues et al., PRL 116 (2016) 071802

Scattering in a Nuclear Environment

- Enable GENIE empirical Meson Exchange Current Model
- Reweight model to match NOvA excess as a function of 3-momentum transfer

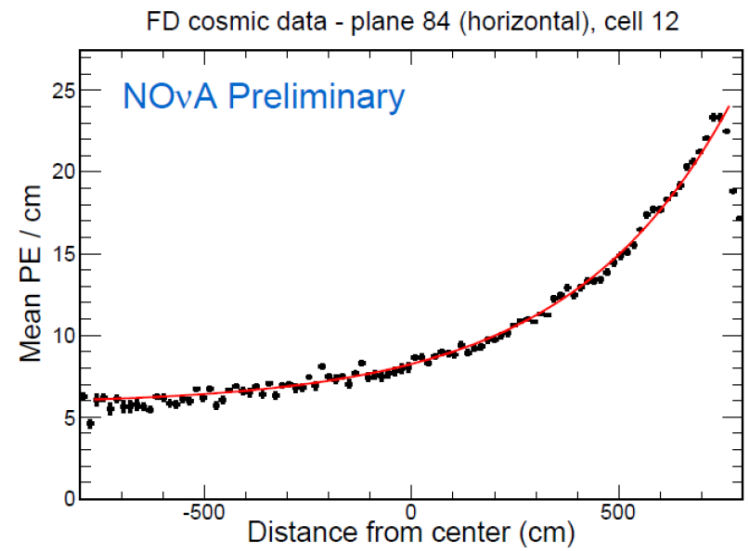


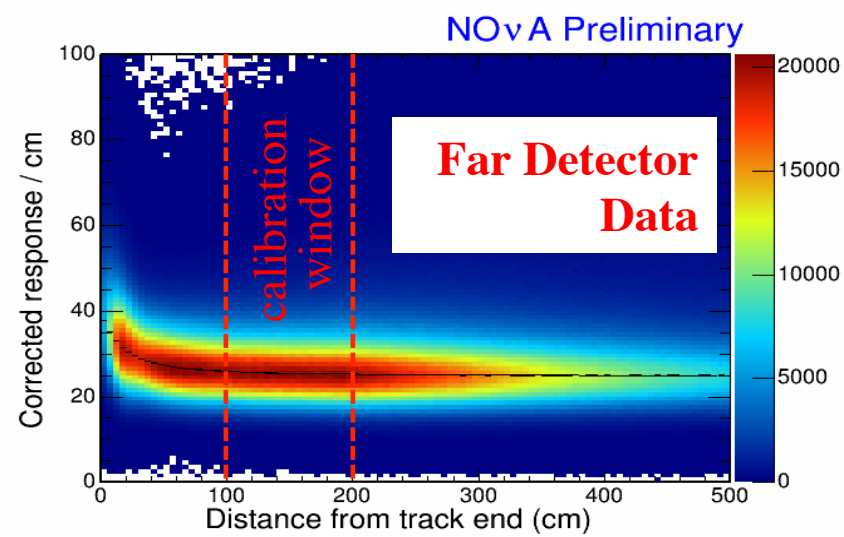
- Eliminate falloff of xsec with energy
- Fix final state nucleon composition
- Match MEC q_0 distribution to quasi-elastic distribution
- scale normalization in bins of 3-momentum transfer to match data/mc disagreement
- Include 50% systematic uncertainty on size of MEC component
- Additionally, reduce single non-resonant pion production by 50%

(P.A. Rodriques et al, arXiv:1601.01888.)

Calibration

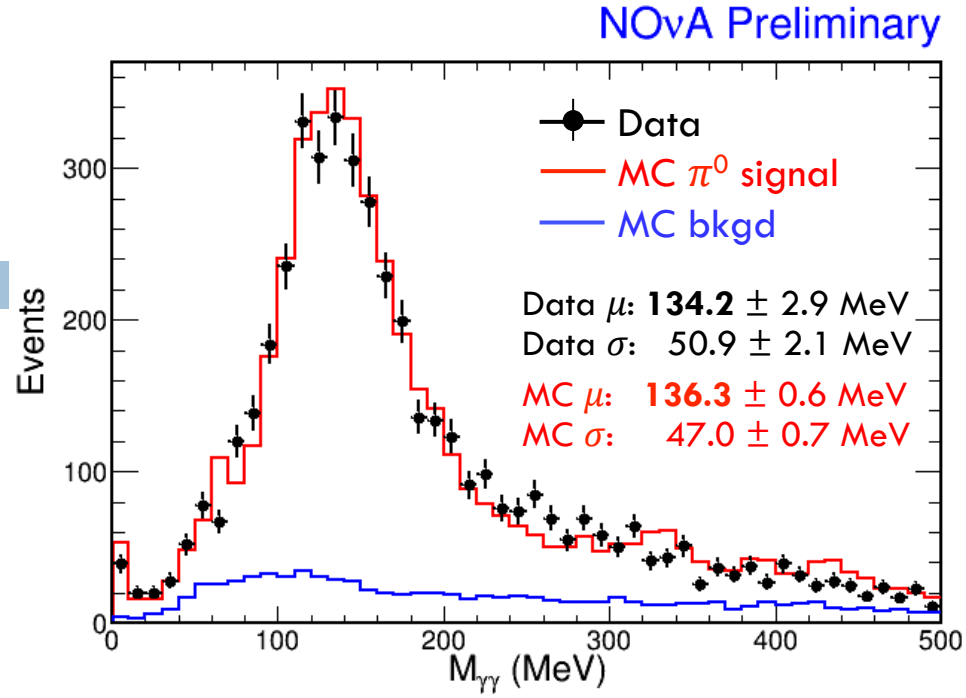
- Calibration achieved using cosmic rays
- Light levels drop by a factor of 8 across a FD cell
- Stopping muons provide a standard candle

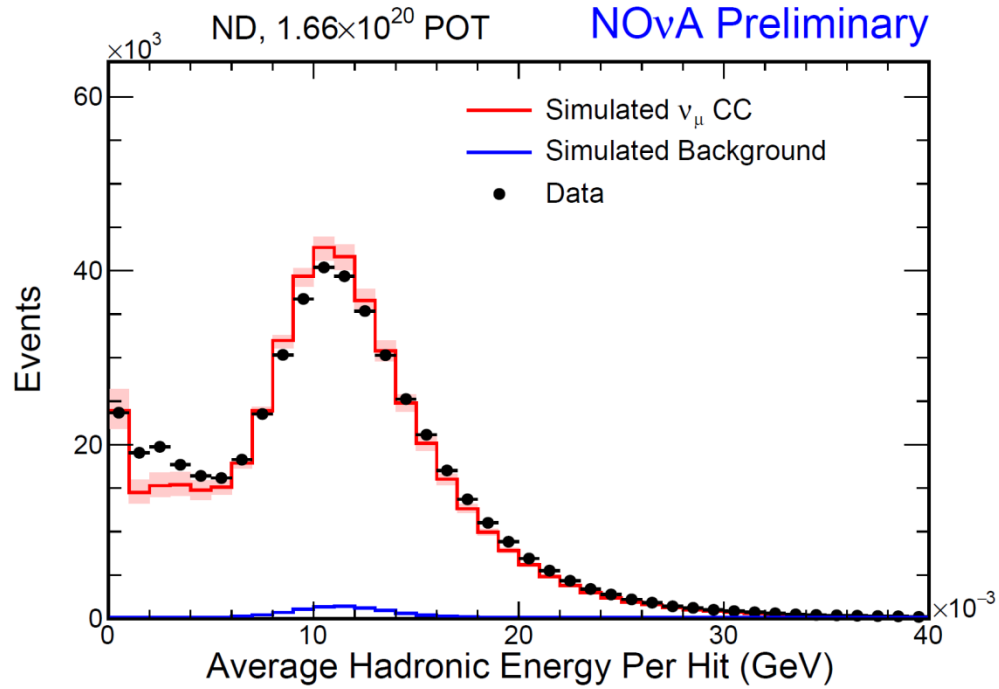




Energy Scale

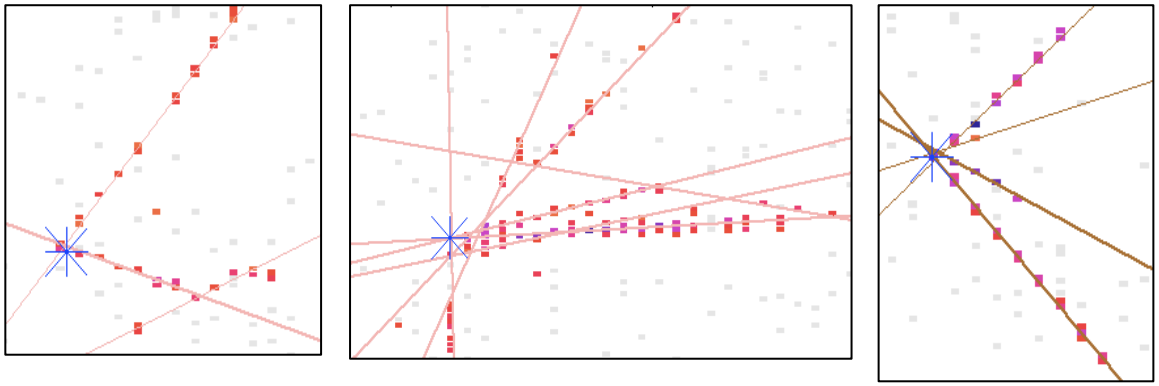
- Near Detector
  - cosmic μ dE/dx [~vertical]
  - beam μ dE/dx [~horizontal]
  - Michel e^- spectrum
  - π^0 mass
  - hadronic shower *E*-per-hit
- Far Detector
  - cosmic μ dE/dx [~vertical]
  - beam μ dE/dx [~horizontal]
  - Michel e^- spectrum
- All agree to 5%



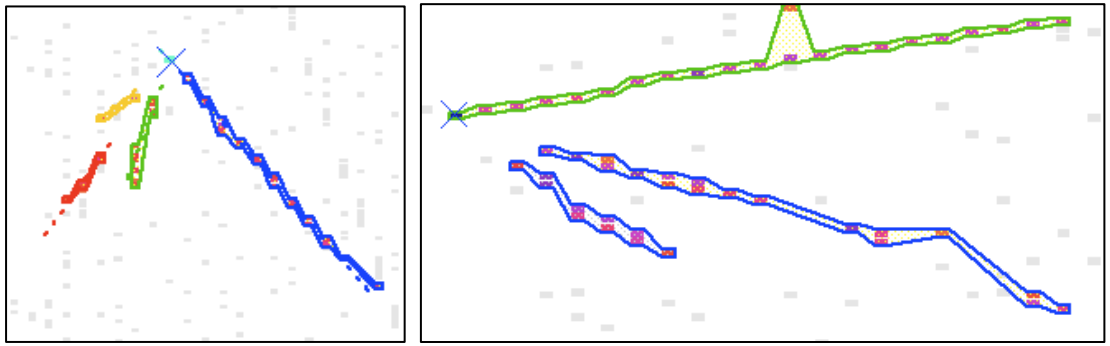


Reconstruction

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



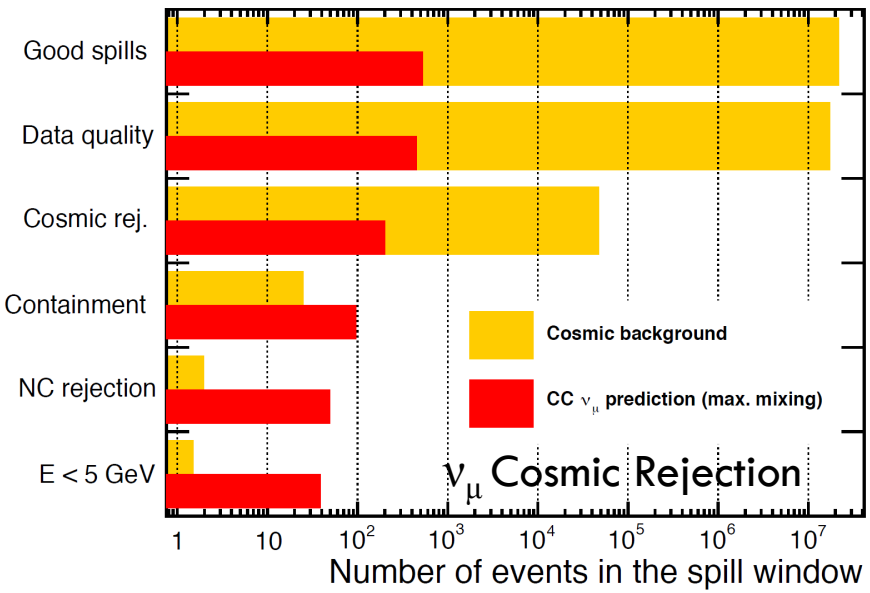
Clustering: Find **clusters in angular space** around vertex. **Merge views** via topology and prong dE/dx

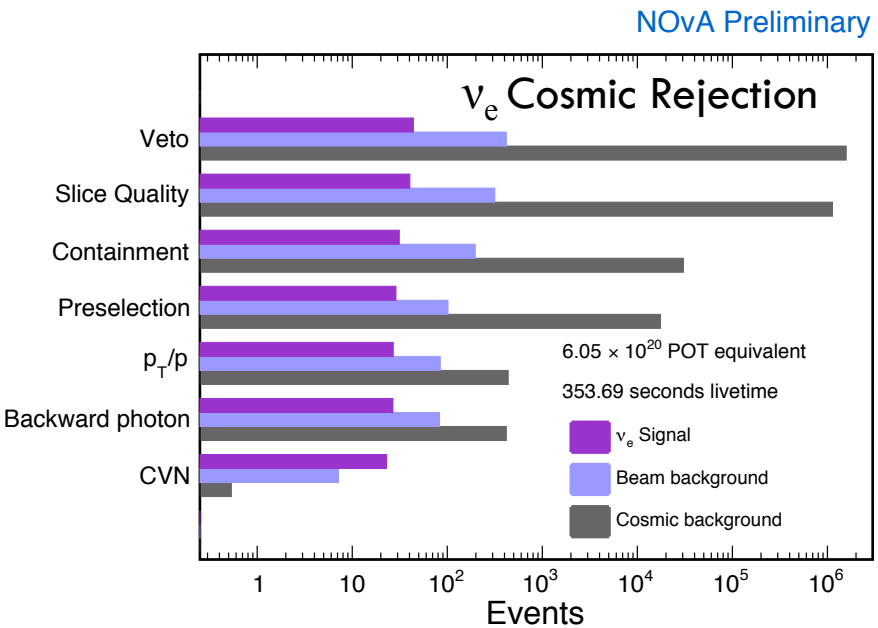


Tracking: Trace particle trajectories with **Kalman filter** tracker.
Also, **cosmic ray tracker**: lightweight, fast, and for large calibration samples, online monitoring.

Cosmic Rejection

- NOvA FD sees 150kHz of cosmic induced events
- Beam timing gives 10^5 rejection factor
- Combination of containment and event topology gives another ~10^7 in rejection



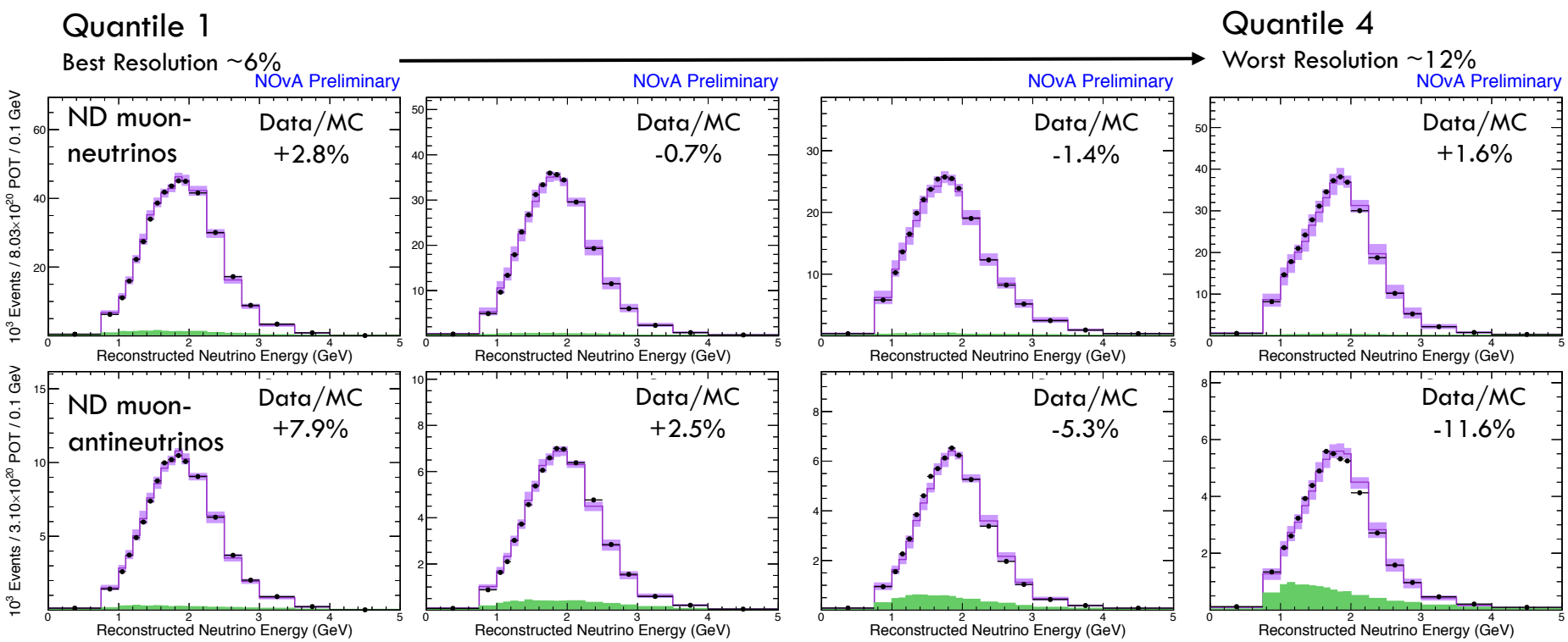


Backup—Disappearance Results

Analysis in more detail

Data
Area-normalized MC
Shape-only systematics
Wrong-sign

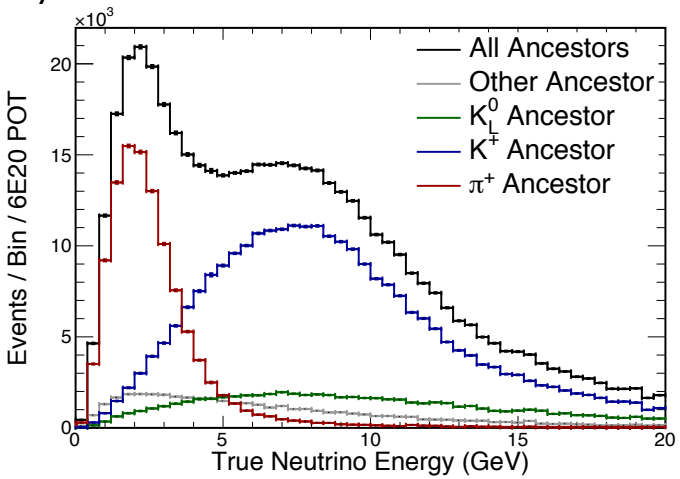
- Full power comes from joint fit to energy dependence of both disappearance and appearance in neutrinos and antineutrinos
  - Muon neutrino spectra further separated by energy resolution
  - Electron neutrino spectra further separated by event sample purity



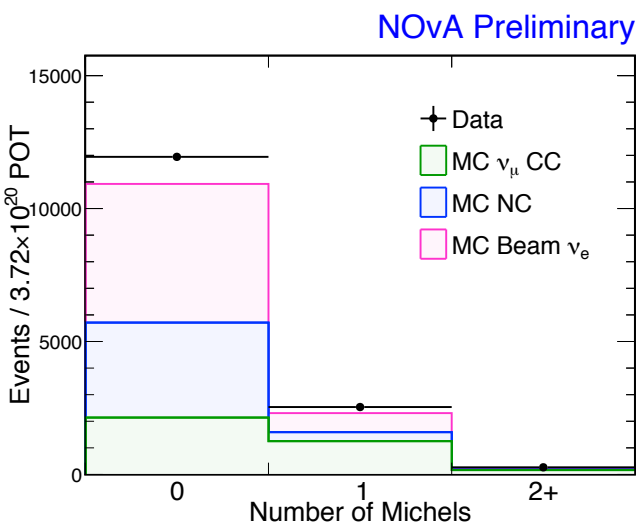
Backup—Appearance Results

Decomposition

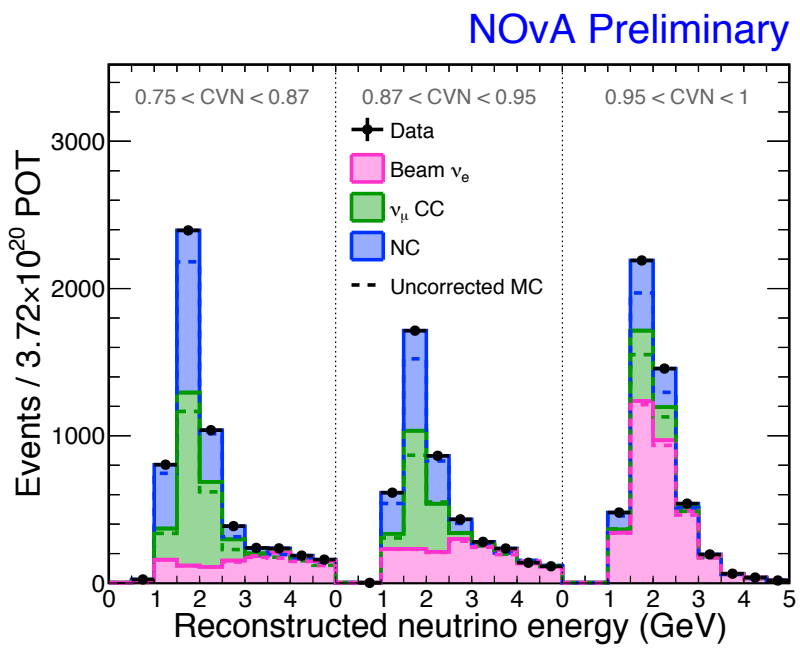
See Poster P1.030
by E. Catano-Mur



- Use ND data to predict FD background
- NC, CC, beam ν_e extrapolate differently
  - constrain beam ν_e using selected ν_μ CC spectrum
  - constrain CC with Michel Electron distribution

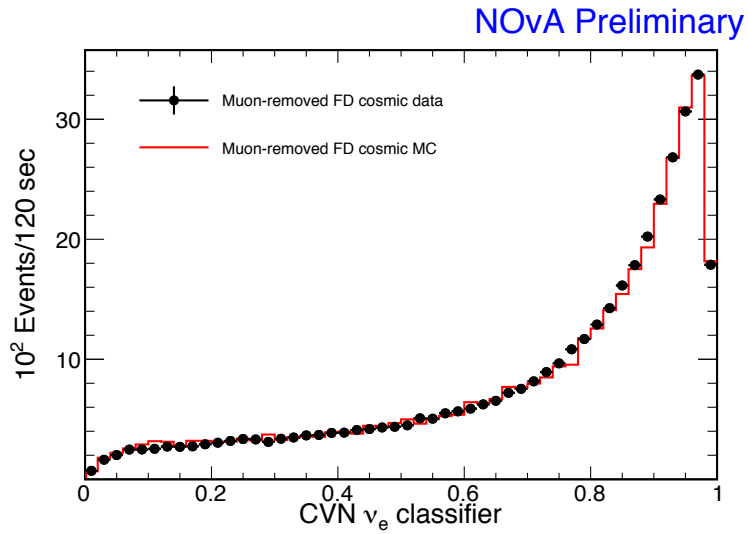


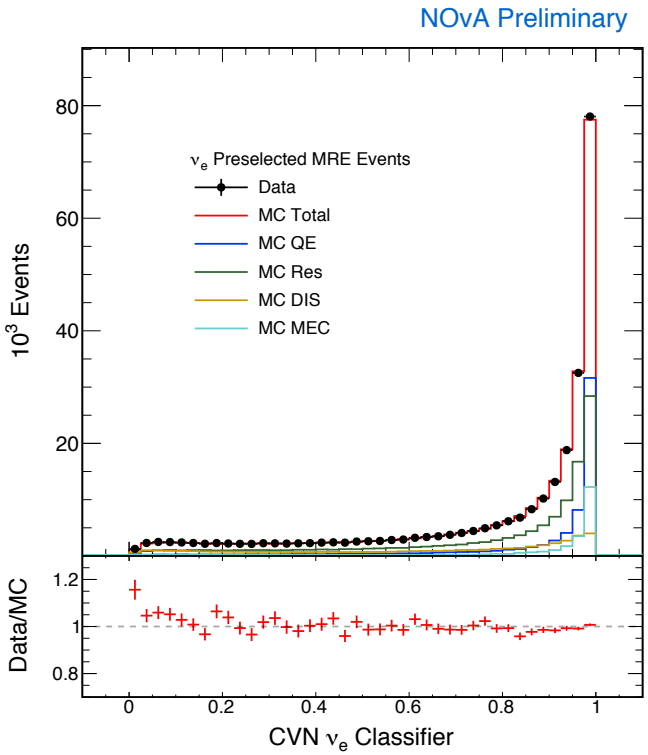
beam ν_e up by 4%
NC up by 10%
CC up by 17%



Checking the Signal Efficiency

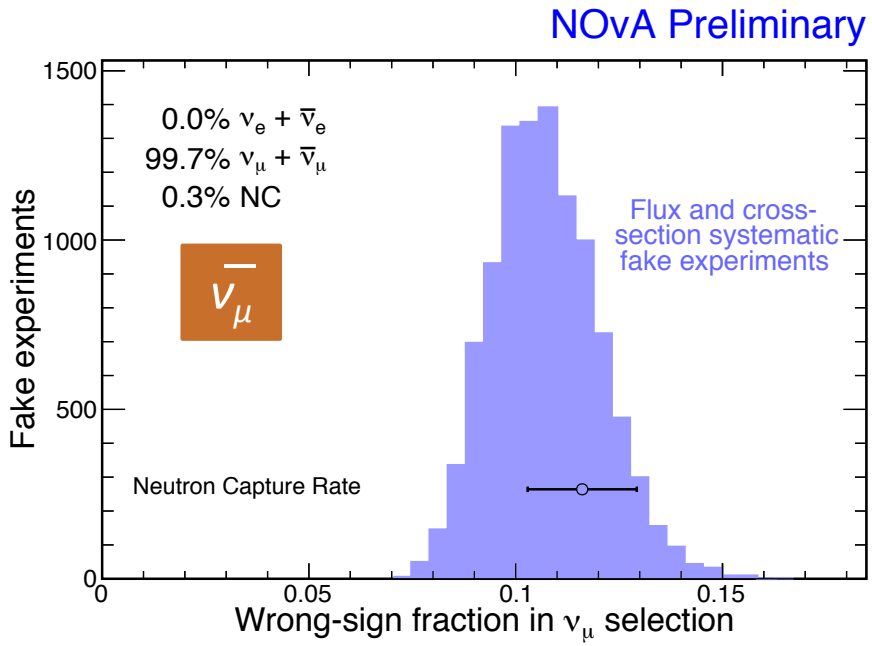
- Use bremstrahlung from cosmic ray muons to benchmark simulation of electron selection
  - event classifier distributions match well





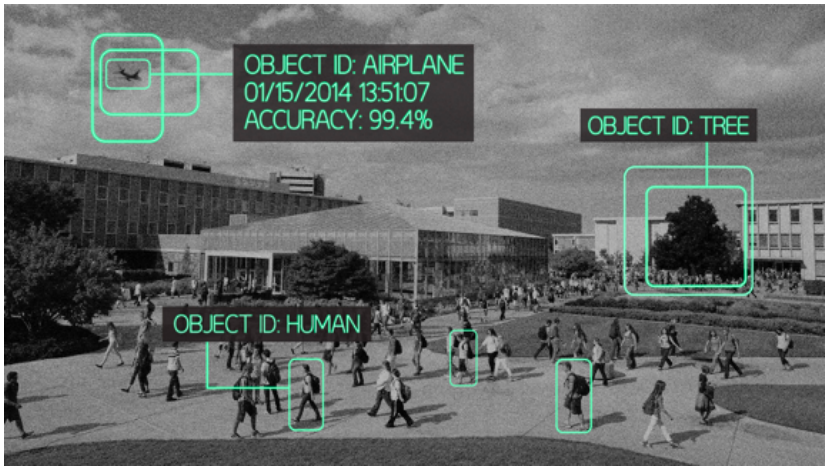
- Remove reconstructed muons from selected ν_μ events, replace with simulated electron (MRE)
  - better than 1% agreement between efficiency for selecting data MRE events and efficiency for selecting MC MRE events

Wrong-sign Background



- The 11% wrong-sign fraction of the $\bar{\nu}_\mu$ **events** is important since it becomes the WS background in the $\bar{\nu}_e$ **appearance analysis**.
- ~10% systematic uncertainty on wrong-sign from flux and cross section
  - Does not include uncertainties from detector effects.
- Confirmed using data-driven cross-check of the wrong-sign contamination
  - 11% wrong-sign in the $\bar{\nu}_\mu$ sample checked using neutron captures in the neutrino and antineutrino beams.

Computer Vision based event selection

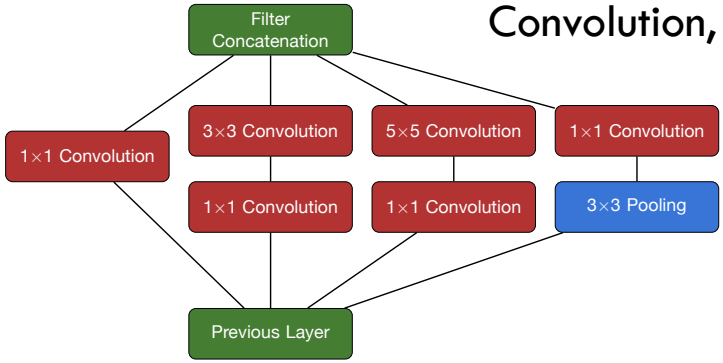


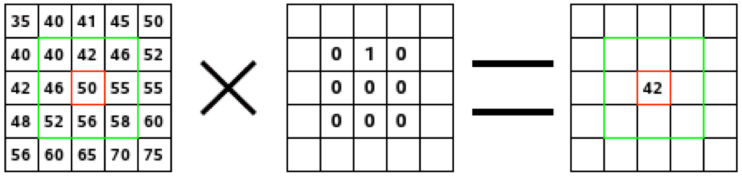
- Advances in machine learning/computer vision achieve near-human performance on image classification
- Use the same techniques to classify event displays

A. Aurisano et al., arXiv:1604.01444

CVN Architecture

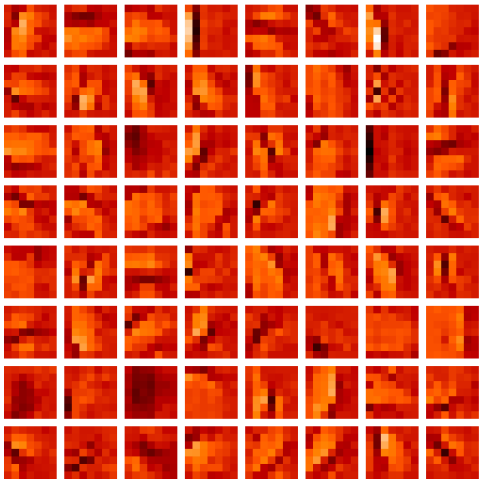
GoogLeNet
Inception Module
C. Szegedy et al.,
arXiv:1409.4842





Example image processing transformation
Convolution, or kernel map

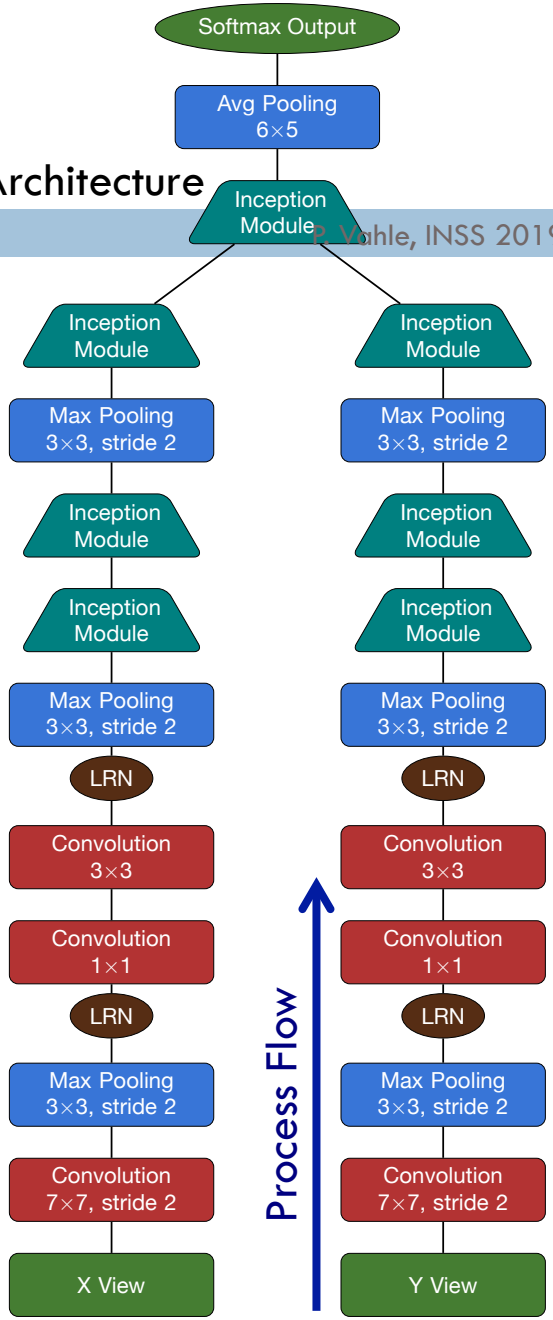
Example Convolutional
Filter Layer



Network implemented and trained
in the Caffe Framework
(Y. Jia et al., arXiv:1408.5093)

Trained over 4.7M simulated events,
Trained on FNAL GPU farm

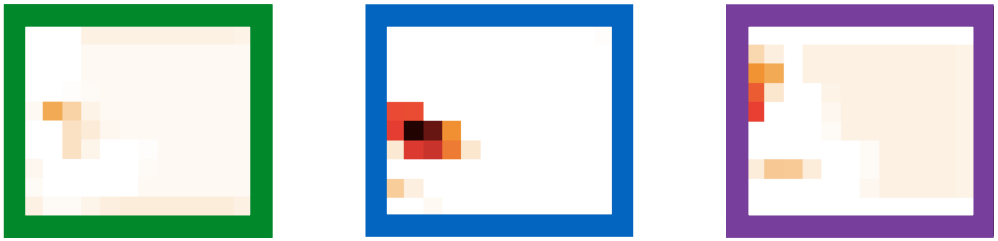
CVN Architecture

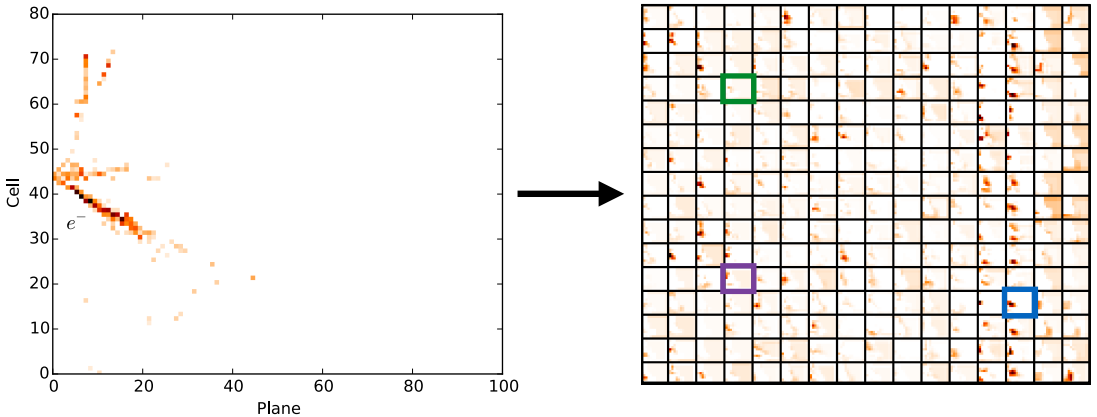


Improved Event Selection

- This analysis features a new event selection technique based on ideas from computer vision and deep learning

- Calibrated hit maps are inputs to Convolutional Visual Network (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





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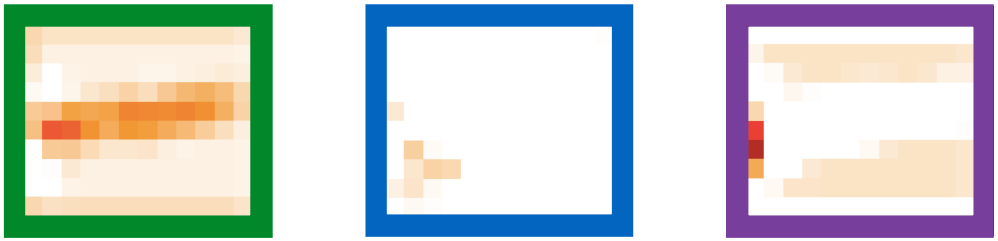

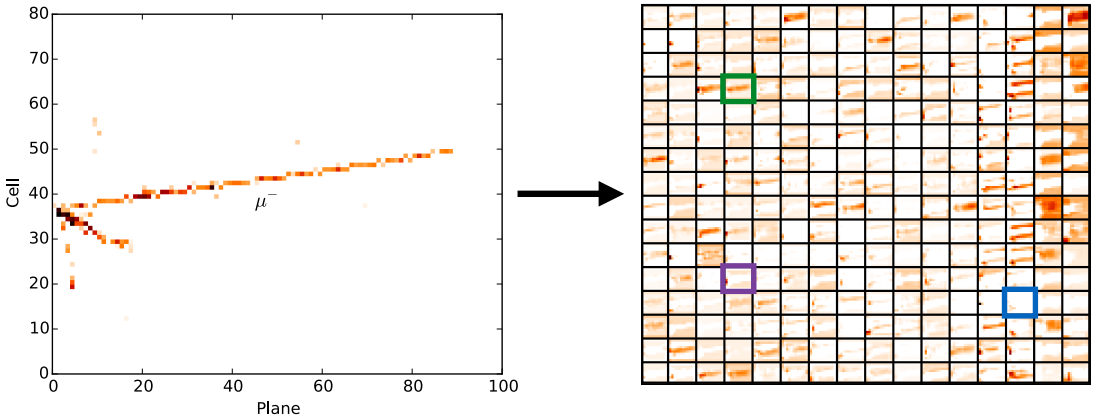

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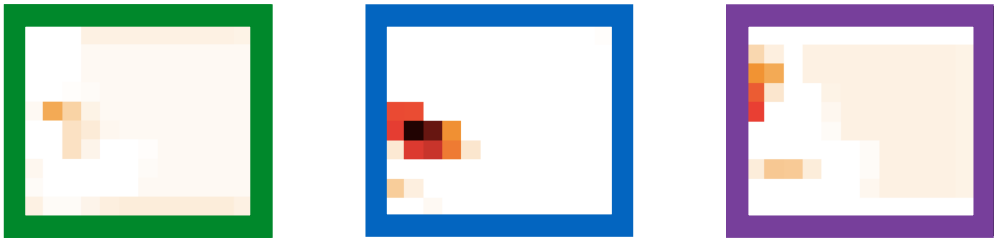
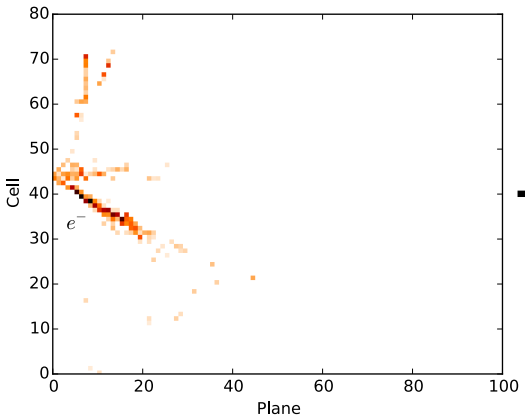
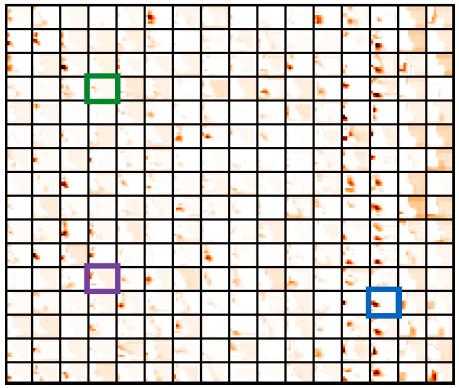


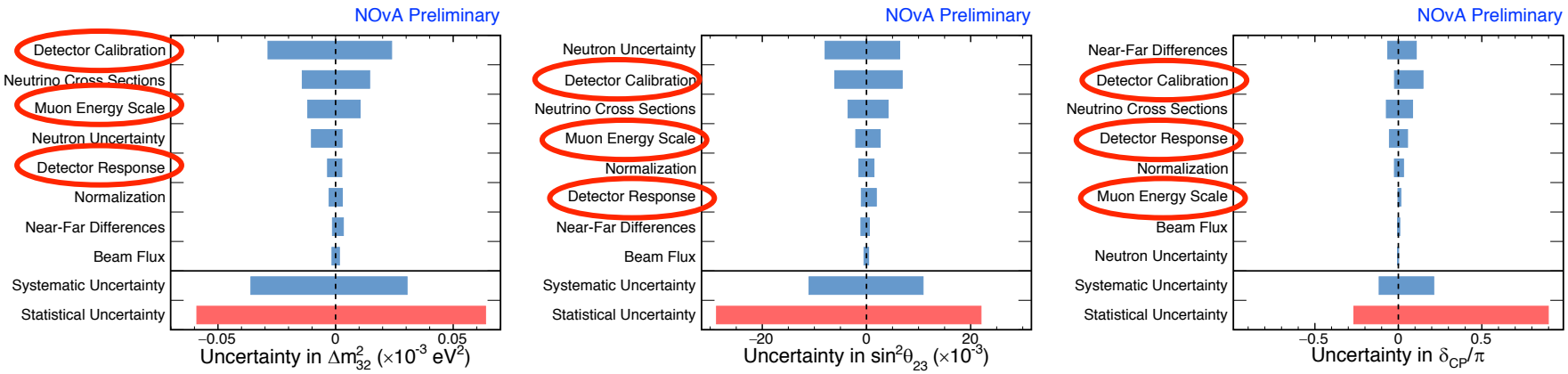


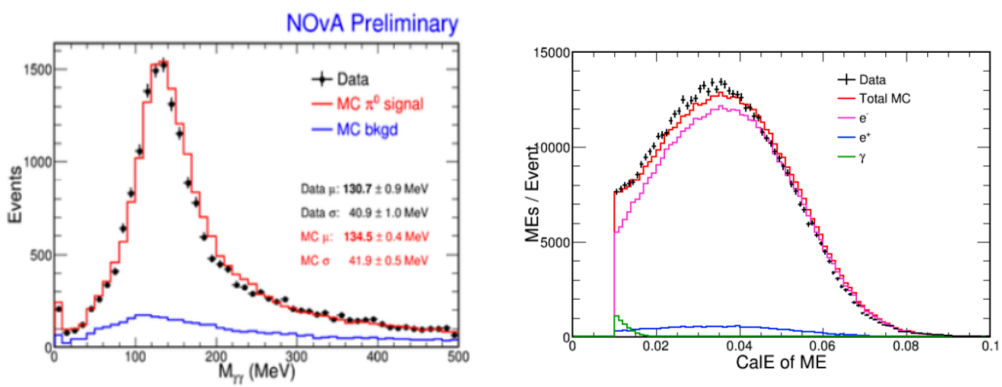


Improvement in sensitivity from CVN equivalent to 30% more exposure

Backup—TestBeam

Systematics and Testbeam Motivation



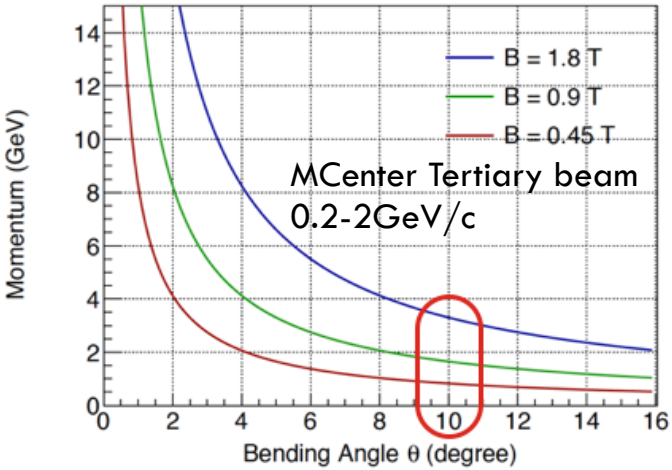


- Estimate of energy/calibration uncertainty comes from ~5% difference in data vs. MC when comparing pi0 mass and Michel e distributions
- Testbeam data decouples detector response from hadronic final state, neutrino cross section, flux uncertainties

- Testbeam effort affords detailed understanding of detectors energy scale (muon, electromagnetic, and hadronic)
- Allows study of light model, scintillator quenching
- Provides real data for study of particle identification techniques

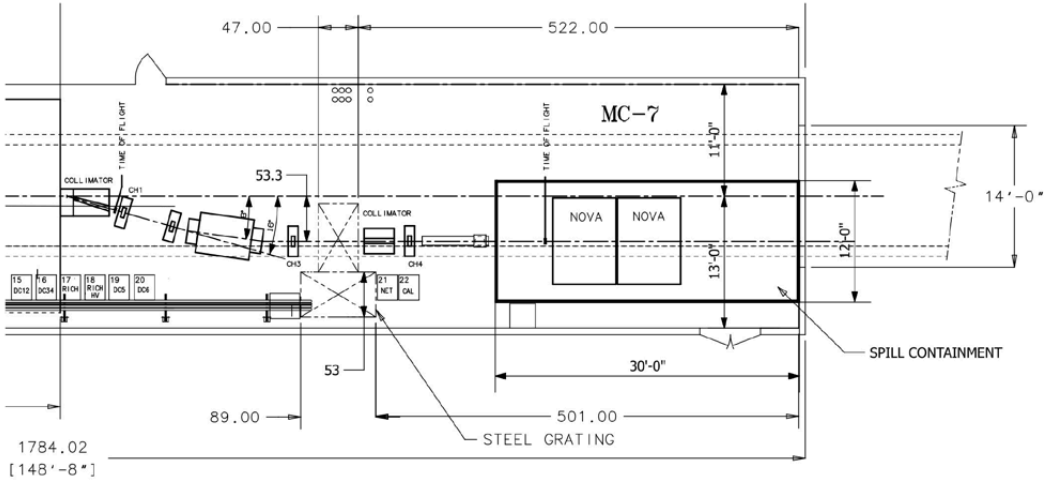
Testbeam

- Testbeam program addresses dominant NOvA systematic errors
  - energy scale for muons, hadrons, EM showers
  - relative calibration
  - light/scintillator response model
- Provides real (tagged) data for sophisticated machine learning particle ID algorithms
- Installation begins this summer
  - Data collection starts end of the calendar year

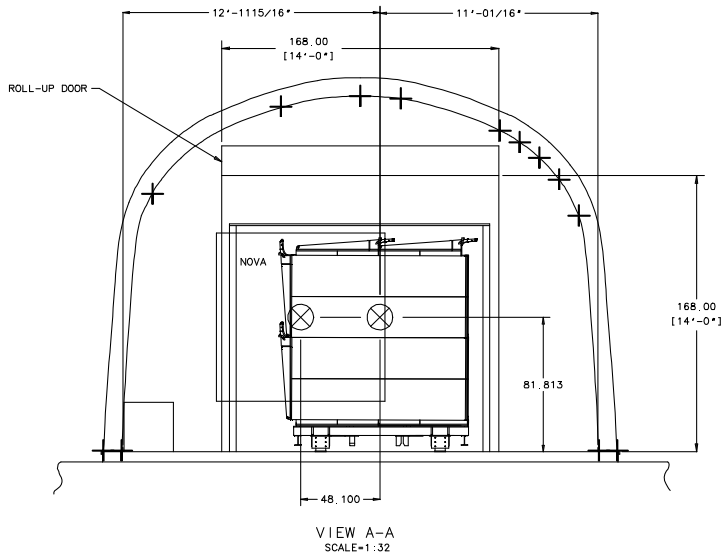


Testbeam

- Installed in the MCenter Beamline
  - MC7
  - Space formerly used by MIPP
  - Downstream of Lariat
- Tertiary beam
  - e, mu, pi, p, K
  - momentum 0.2-2GeV/C



Testbeam



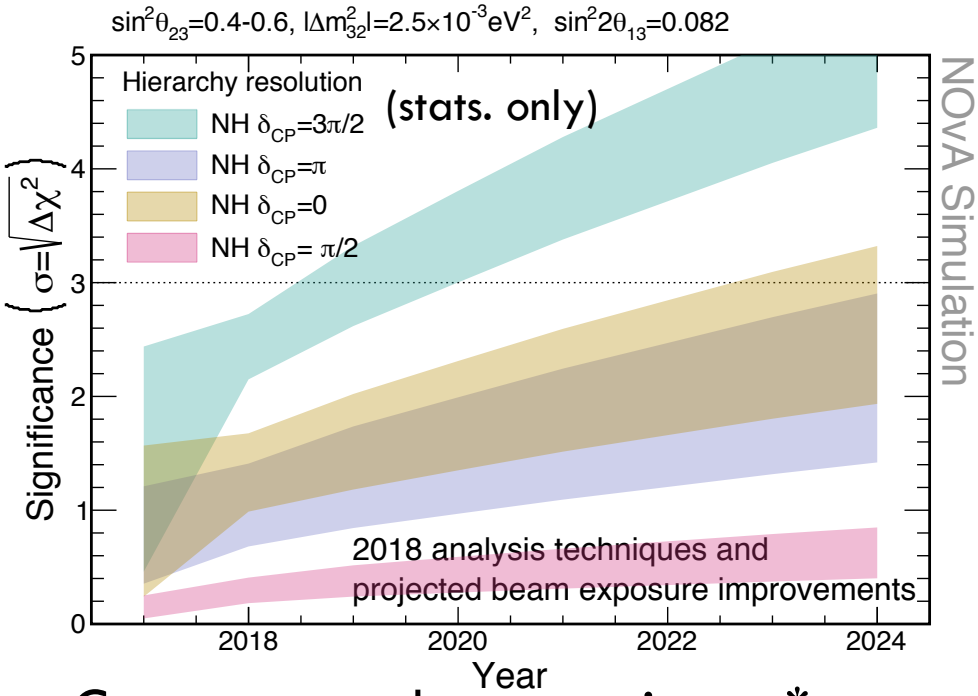
Detector Configuration	Two 2×2 31-plane blocks + One horiz. plane
Dimensions W(m)× H(m)× L(m)	2.6×2.6×4.1
Scintillator/plane (gallons)	86
Total Scintillator Volume (gallons)	5418
PVC Mass/plane (kg)	171.2
Adhesive Mass/plane (kg)	3.1
Total Empty Mass (kg)	10981
Total Scintillator Mass (kg)	17608
Total Detector Mass (kg)	28582
#APDs = #FEBs	126 (118 FEB 4.1 + 8 FEB 5.2)
#DCMs	3

Backup—Sensitivity

Proposed Accelerator Improvement Projects

- 2 accelerator improvement projects have the potential to boost NuMI power beyond 700kW (up to 900kW-1MW)
  - Target System
    - New target design rated for 1MW
    - Improved horn stripline cooling
    - Radioactive water system upgrade
    - Target chase chiller and air handling upgrade
  - Intensity
    - Assorted projects to lower Booster losses
- Projects not only enable higher power, but improve reliability, mitigate risk
  - Lifetime extension to 2024
  - Support plan to run 40+ weeks/year (recent experience is 34-40)
- In our projections, we assume:
  - Power at 800 kW in FY19, 900kW in FY20-21, 1MW beyond
  - 40 weeks of running a year with uptime comparable to current running

Future Sensitivity

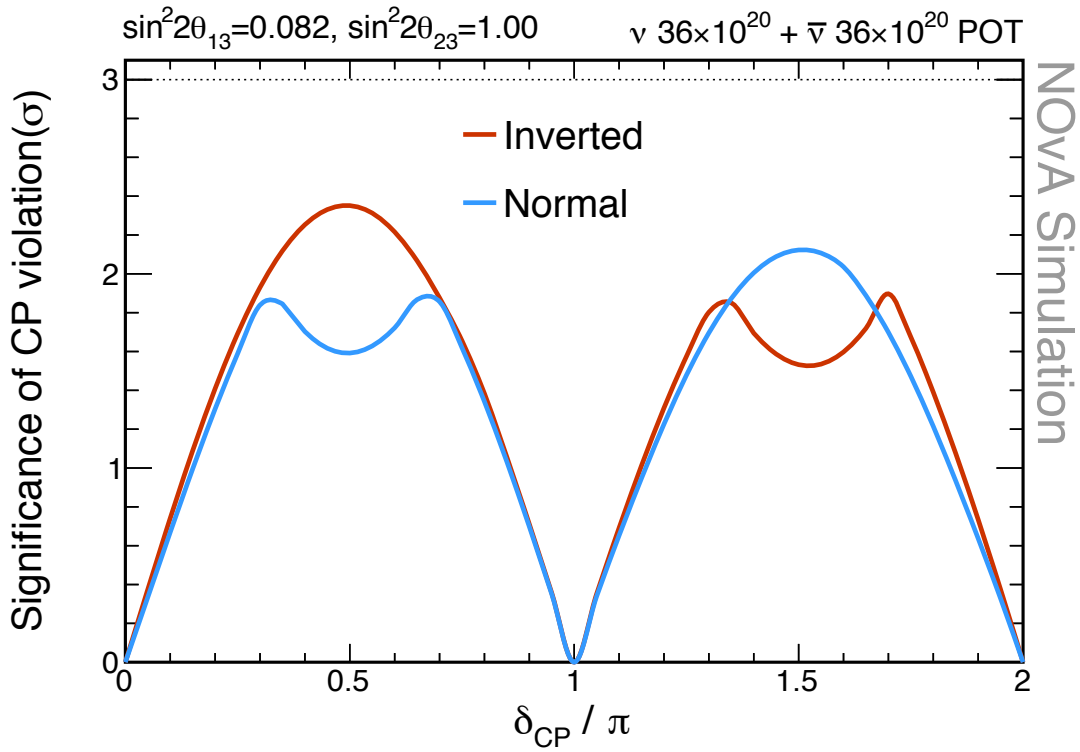


- Sensitivity dependent on true values in nature
- For favorable parameters consistent with results, we can achieve 3 sigma mass hierarchy sensitivity by 2020
  - 3 sigma sensitivity for 30-50% of delta CP range by 2024
  - >5 sigma in favorable cases by 2024, possible only with POT boosts from AIP work

- Compare to other experiments*:
  - T2K reports Bayes factor NH/IH=7.9 (NH preferred at ~89%)
  - SK prefers NH at at 80.6% to 96.7% (depending on θ_{23})
  - Juno 3-4 sigma sensitivity 6 years after start in 2021(depending on error on $\Delta m^2_{\mu\mu}$)
  - KM3Net/Orca 5 sigma in 2024/2025 (depending on θ_{23})

*Taken from Neutrino2018 talks by M. Wascko, Y. Hayuto, B. Wonsak, U. Katz

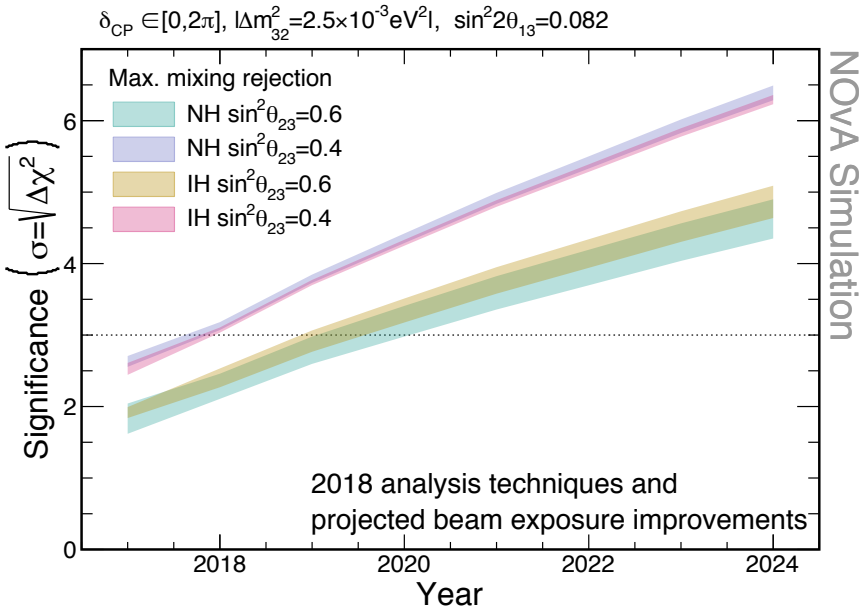
CP Violation Sensitivity



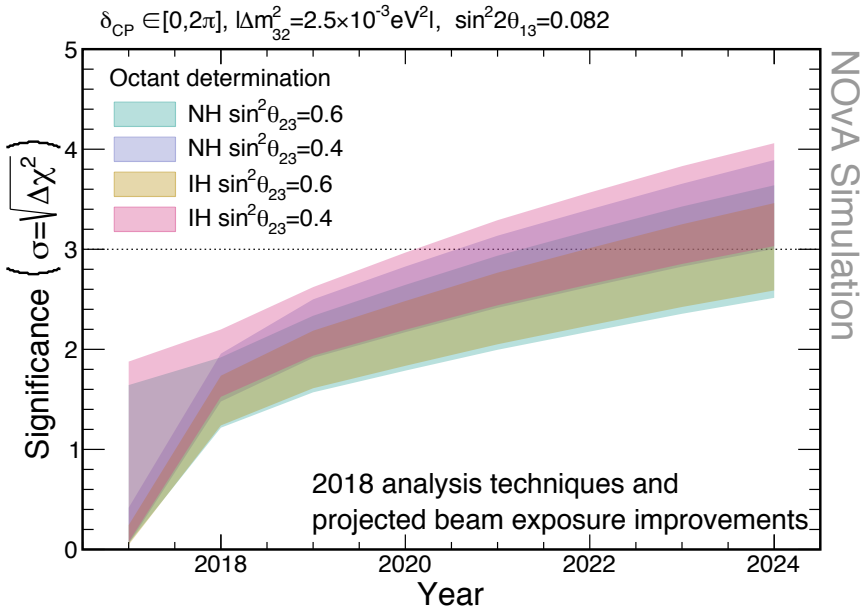
2+ σ sensitivity for CP violation in both hierarchies at $\delta_{CP}=3\pi/2$ or $\delta_{CP}=\pi/2$ (assuming unknown hierarchy) by 2024

Future Sensitivity

Max mixing rejection



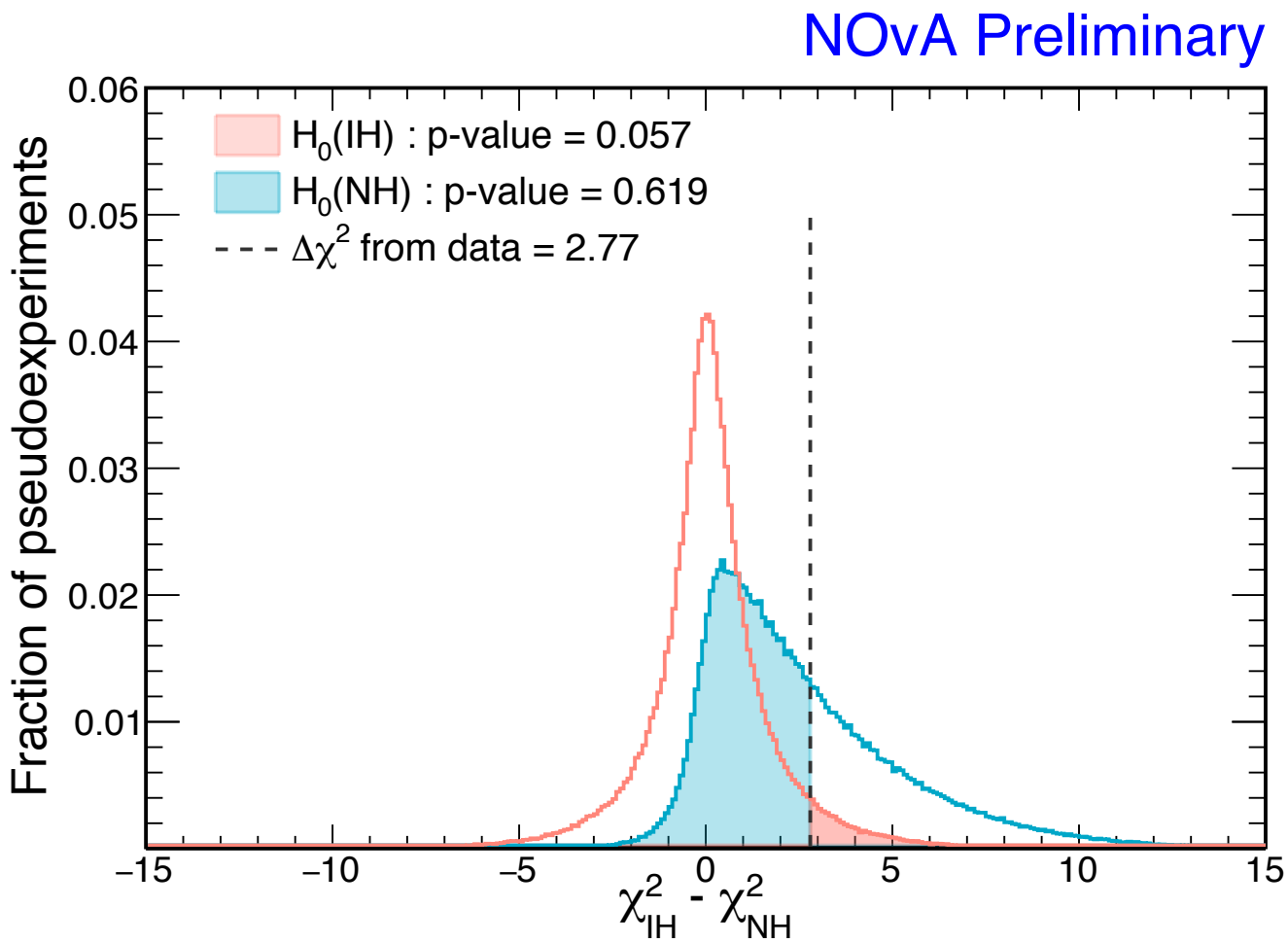
Octant



Other Experiments

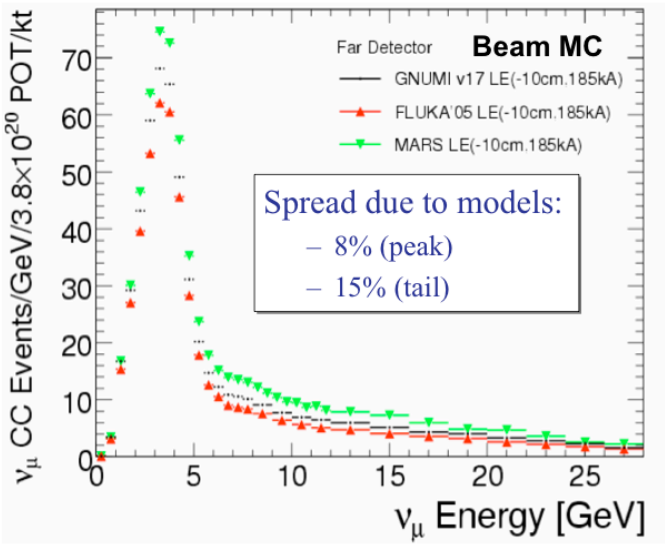
- T2K
  - M. Wascko—Nu2018
  - Bayes factor for NH/IH=7.9->NH prefered at 89%
- SuperK
  - Y. Hayuto—Nu2018
  - NH favored at 80.6 to 96.7% depending on theta_23
  - Expanding the fiducial volume
- Juno
  - Bjorn Wonsak—Nu2018
  - Start datataking in 2021
  - after 6 years, 3sigma or 4sigma MH resolution depending on constraint on dm_mumu
- KM3Net/Orca
  - U. Katz—Nu2018
  - 5sigma by 2024 at nova favored theta_23

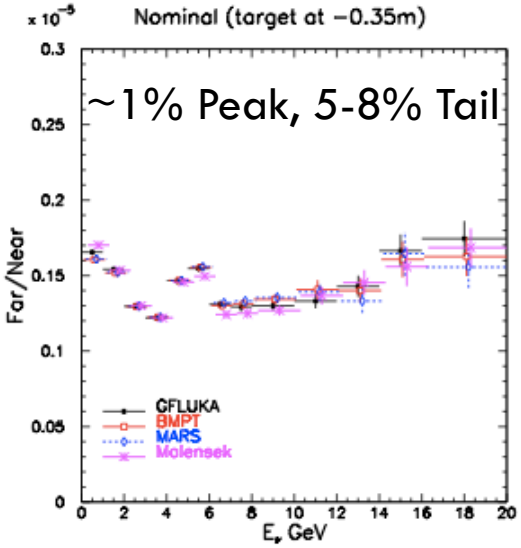
Hierarchy Significance



Predicting the Flux

Hadron Production Uncertainty



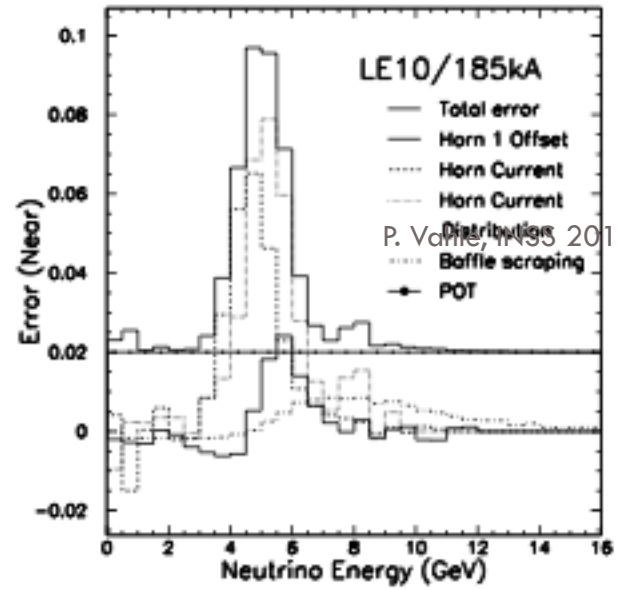


- Flux an extrapolation of (sparse) external data to MINOS beam energy, target thickness, target material
- Systematics originally evaluated using model spread, with additional systematics from focusing system alignment, horn current calibration, skin depth, etc

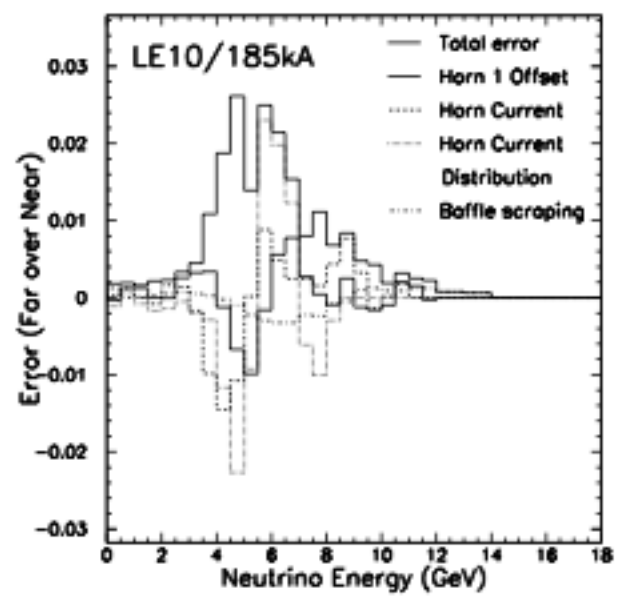
Uncertainties in the neutrino flux cause large uncertainties in the ND simulated spectrum, but the errors largely cancel in the Far to Near Comparison

Beam Systematics

- Additional flux uncertainties arise from focusing and alignment uncertainties
- Errors in flux estimated using comparisons between nominal (pbeam) simulation and systematically offset simulation sets
- Offsets determined from beam survey measurements, target scans, hadron/muon monitoring, etc. (Documented in R. Zwaska thesis, UT Austin, 2005)



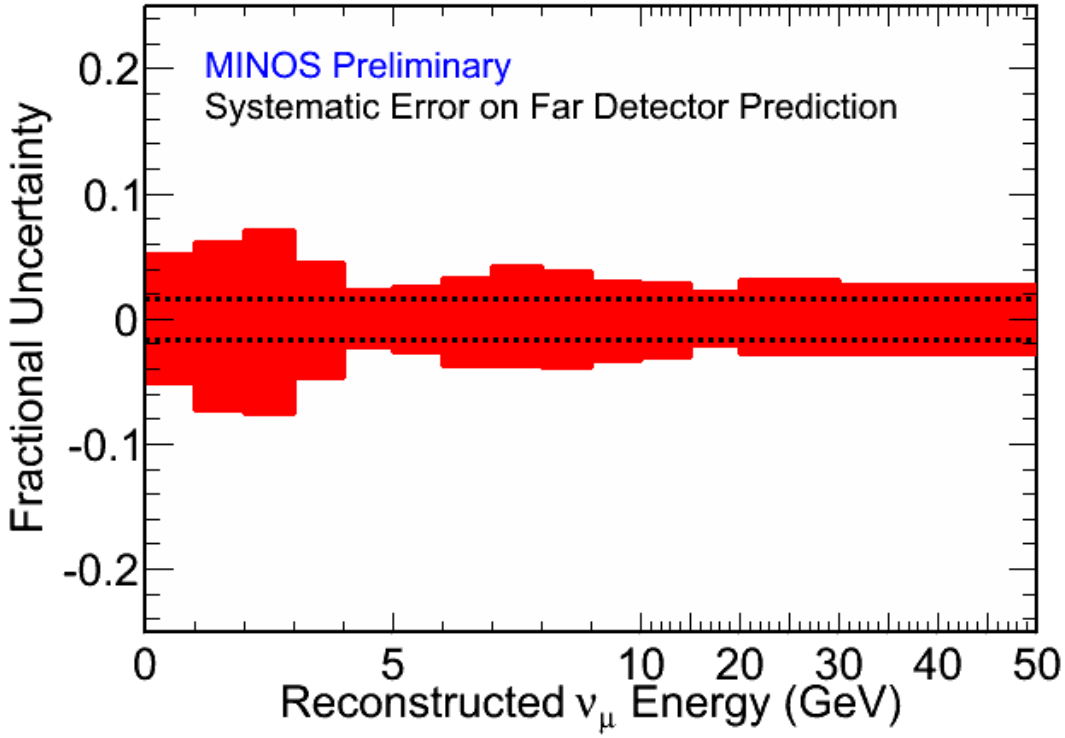
(a)



(b)

(Horn angles, horn 2 offset errors also evaluated, small, not shown on plots)

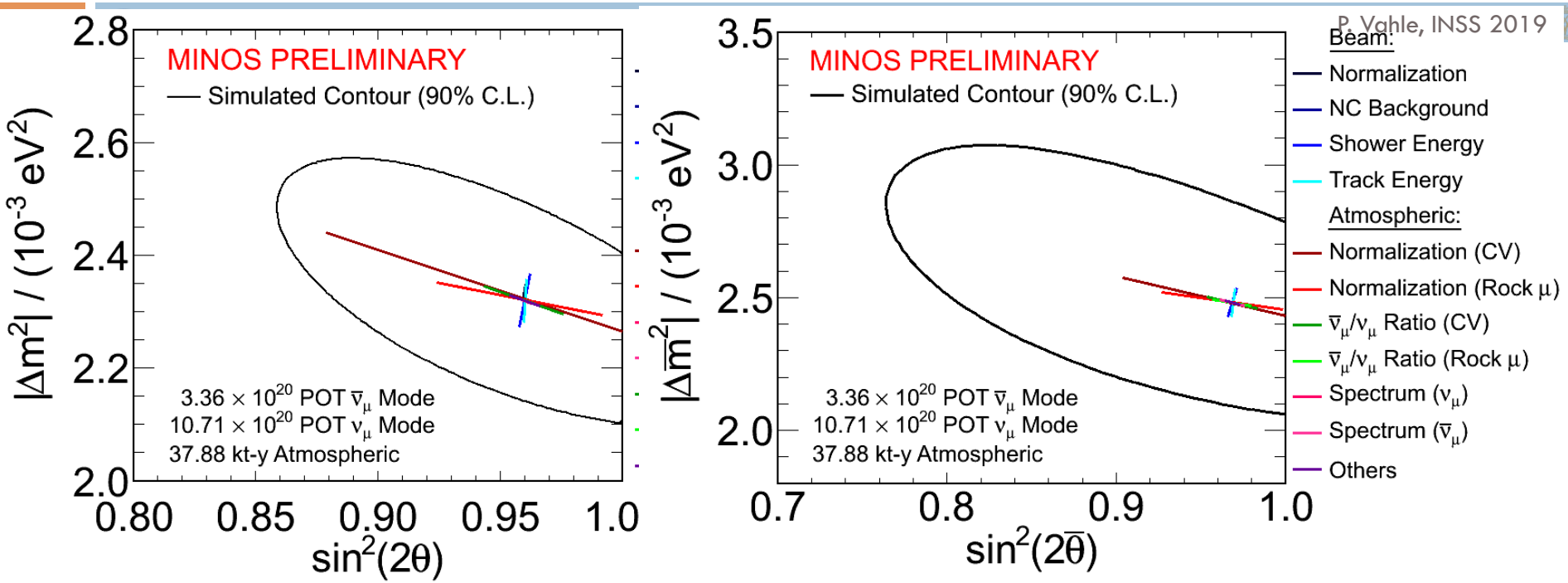
Systematic Error



- Dominant systematics:
  - hadronic energy calibration: energy dependent, ~7% below 3GeV
  - track energy calibration: 2% if by range, 3% if by curvature
  - NC background: 20% normalization
  - relative Near to Far normalization (uptime, Fid. Mass): 1.6%

Current Day Systematic Uncertainties

P. Vahle, INSS 2019



- MINOS now combines beam and atmospheric data
- Dominant systematic uncertainties included in fit as nuisance parameters
- Effects even smaller in final quoted parameter errors

Soudan Fire

- March 17, smoke detected in FD hall due to a fire in the shaft
- Power to the lab shut off automatically
- Foam pumped in to extinguish the fire
- No damage to the MINOS detector
- Detector returned to full operations May 19

PRD 74 (2006) 072003

K2K

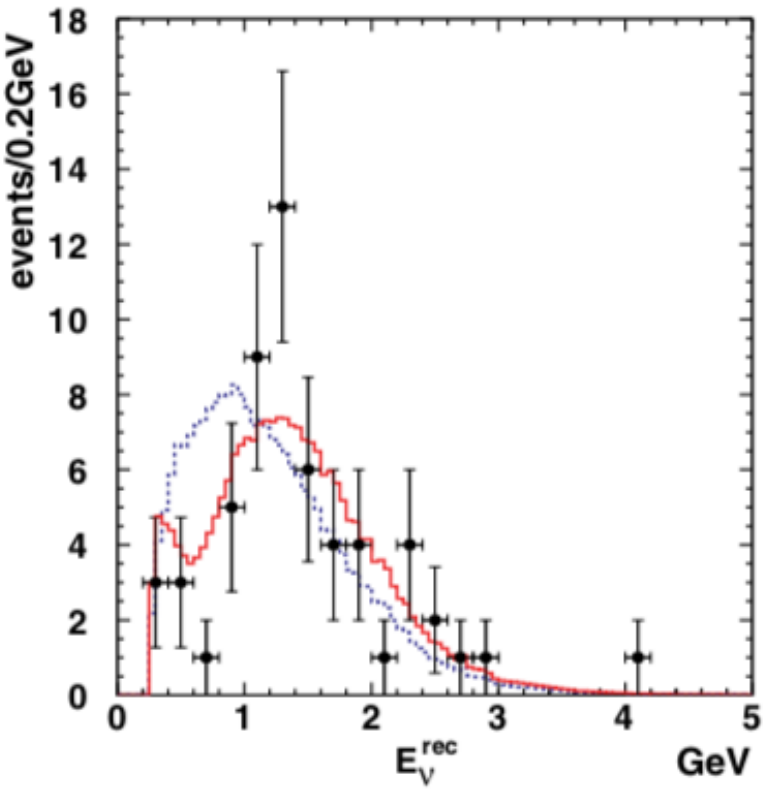


FIG. 43 (color online). The reconstructed E_ν distribution for the one-ring μ-like sample. Points with error bars are data. The solid line is the best-fit spectrum with neutrino oscillation and the dashed line is the expectation without oscillation. These histograms are normalized by the number of events observed (58).

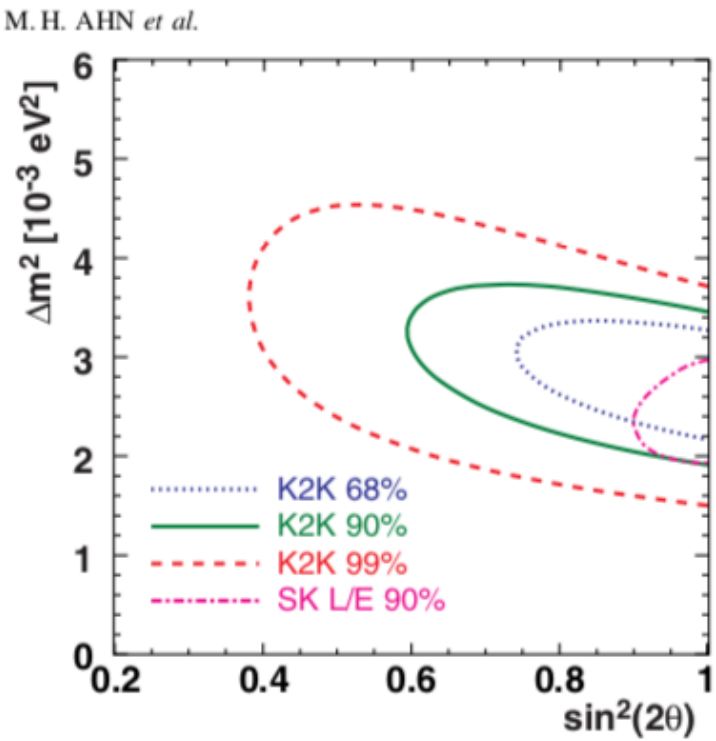
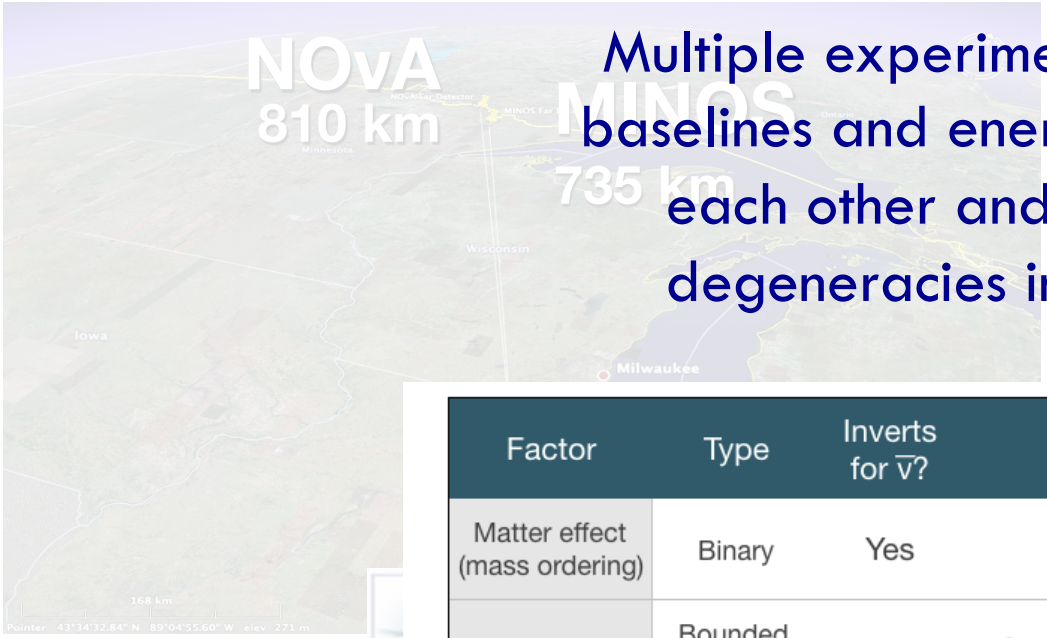


FIG. 48 (color online). Comparison of K2K results with the SK atmospheric neutrino measurement [2]. Dotted, solid, dashed, and dash-dotted lines represent 68%, 90%, 99% C.L. allowed regions of K2K and 90% C.L. allowed region from SK atmospheric neutrino, respectively.

Joint Analysis

- Four joint meetings since 2016
  - laying groundwork for joint fit, meet every 6-9 months.
  - identifying important correlations in systematics
- Targeting first joint fits in 2021, with scope to be clarified summer 2020.

Long-baseline experiments



Multiple experiments at different baselines and energies compliment each other and help resolve degeneracies in parameters

Factor	Type	Inverts for $\bar{\nu}$?	NOvA	T2K
Matter effect (mass ordering)	Binary	Yes	±19%	±10%
CP violation	Bounded, continuous	Yes	[-22…+22]%	[-29…+29]%
θ_{23} octant	Unbounded, continuous	No	[-22…+22]%	[-22…+22]%

Nota bene:

- Calculations are for rate only; there is some additional information in the energy spectrum
- These estimates neglect non-linearities in combining different effects
- In the calculation of the matter effect and CP violation effects the calculated values account for the fact that T2K runs at an energy on the first oscillation maximum while NOvA runs at an energy slightly above the oscillation maximum
- θ_{23} was varied inside the $\pm 2\sigma$ range found by a recent global fit (PRD 90, 093006)

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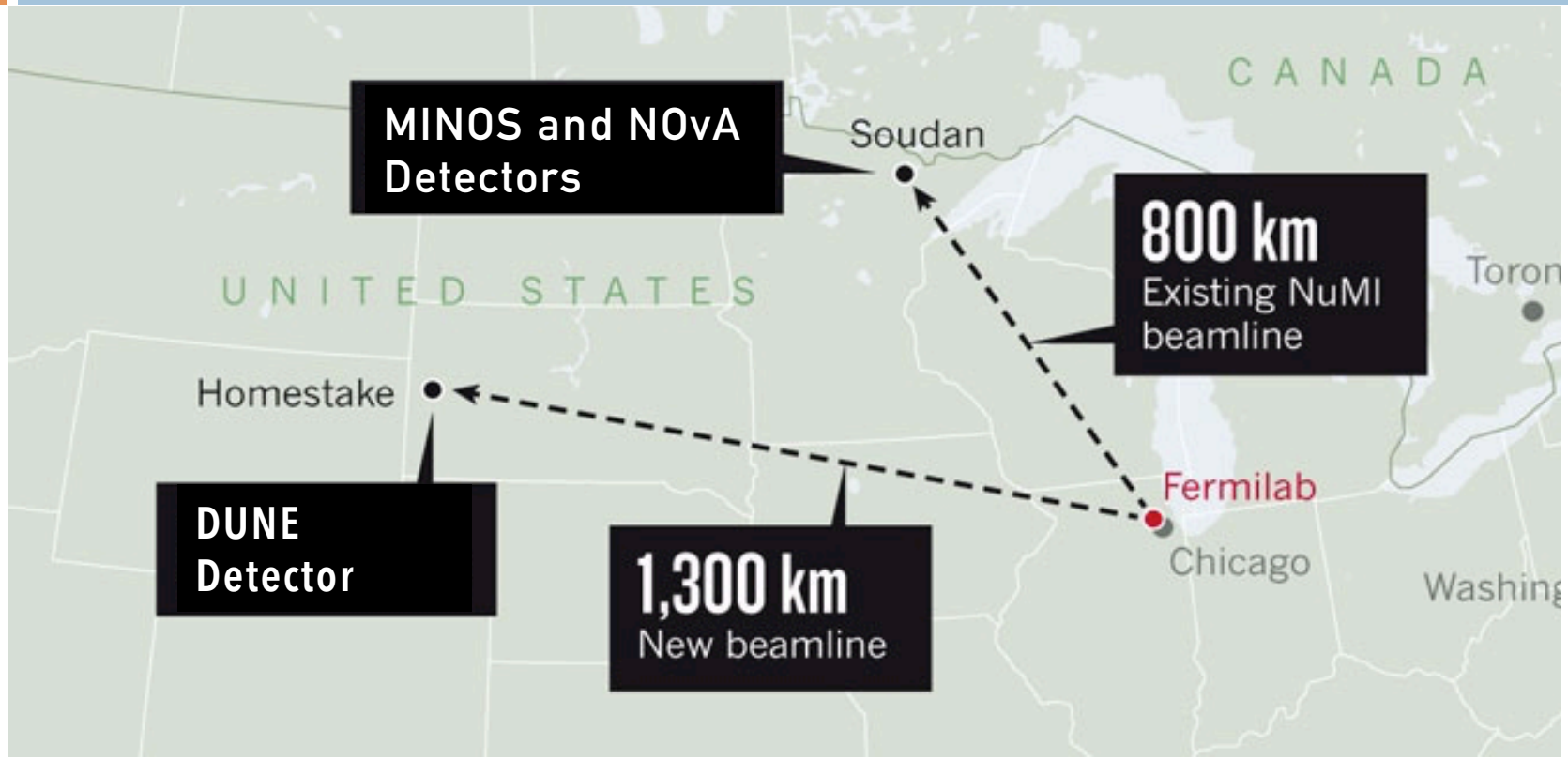
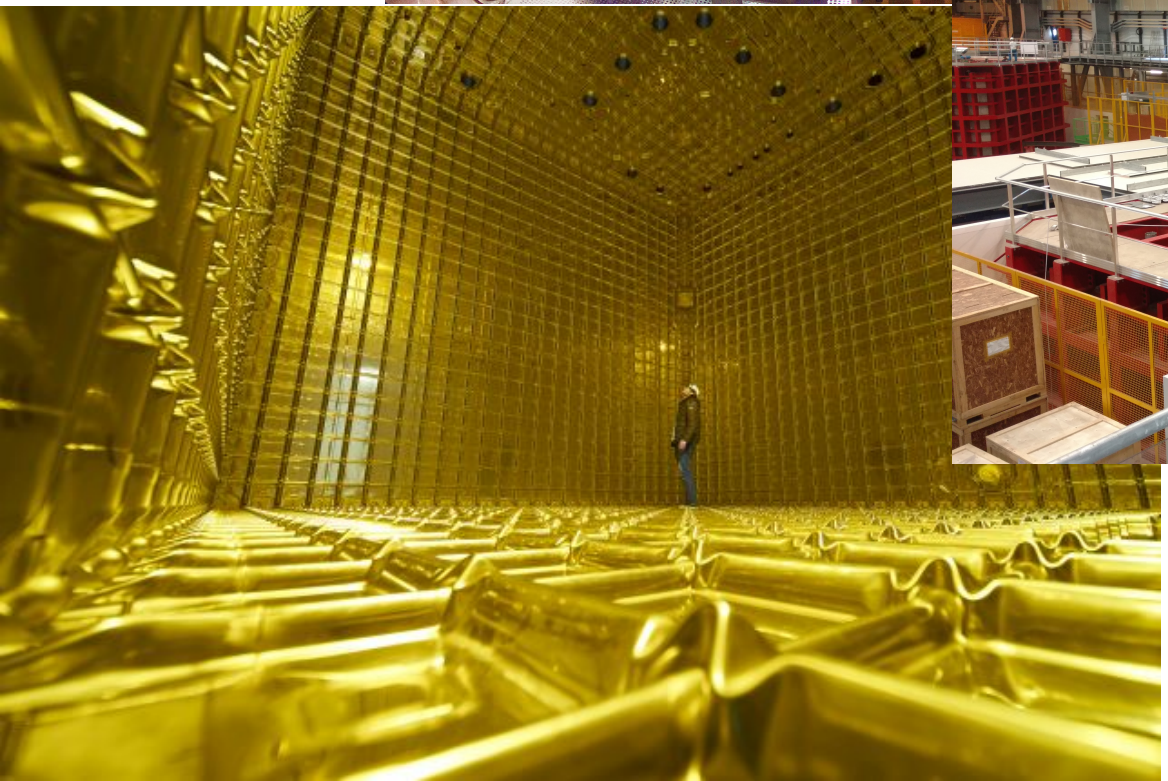
Table courtesy M. Messier

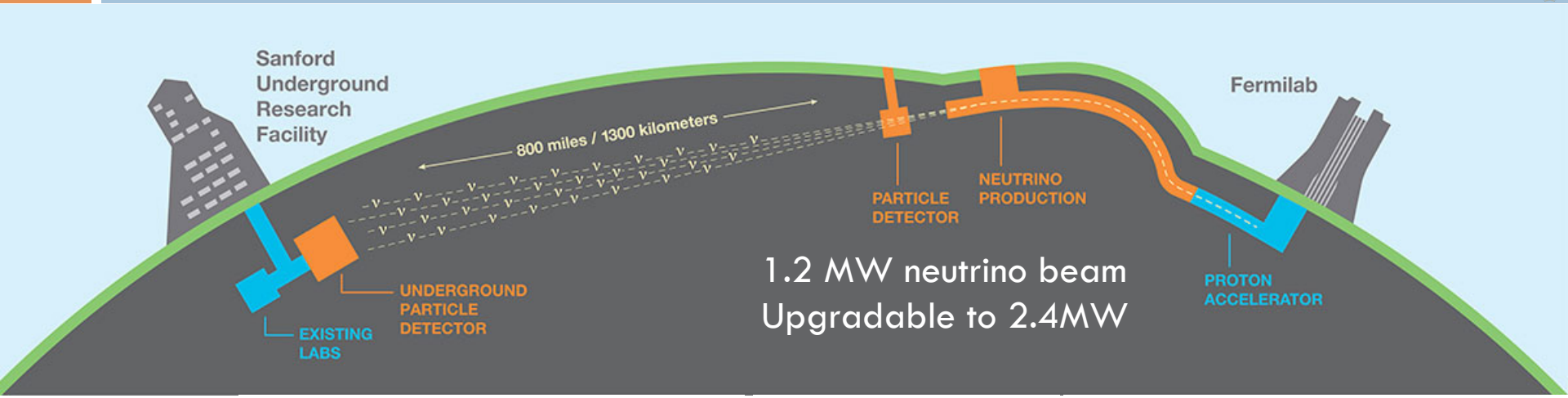
DEEP UNDERGROUND NEUTRINO EXPERIMENT



- 40 kT liquid argon Time Projection Chamber (TPC)
- New beam line with higher power at a longer baseline (LBNF)
- Should start collecting data sometime in middle of next decade

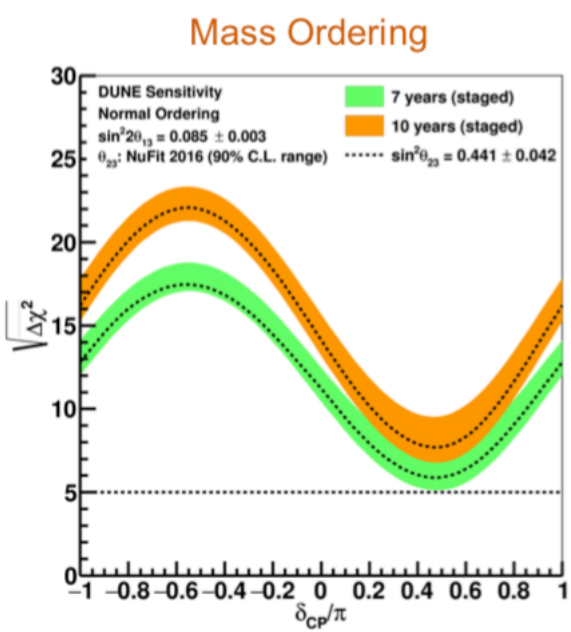


The Future of Long-baselines: DUNE



1.2 MW neutrino beam
Upgradable to 2.4MW

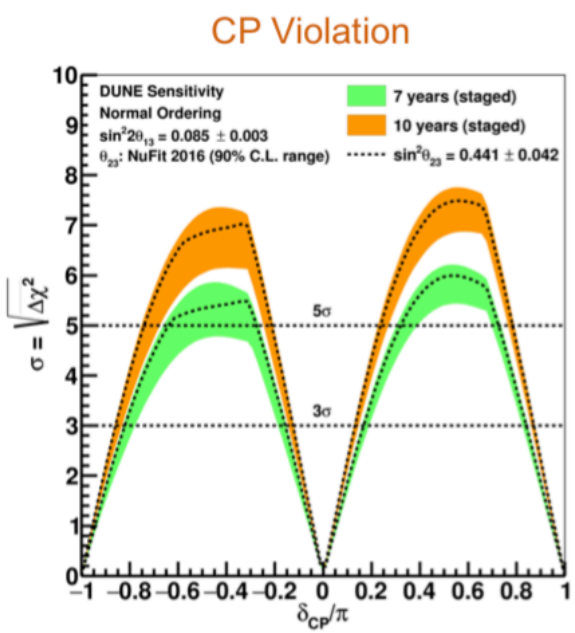
E. Worchester, Neutrino 2018



July 2017
Groundbreaking for LBNF/DUNE

Autumn 2018
ProtoDUNE detectors online at CERN

2019
Begin main cavern excavation in South Dakota

2022
Begin installing the first DUNE detector

2026
Fermilab's high-energy neutrino beam to South Dakota operational with two DUNE detectors online