Long-Baseline Program at Fermilab: Current Results and Future Expectations

International Workshop on Frontiers in Electroweak Interactions of Leptons and Hadrons, AMU, 2-6 Nov., 2016

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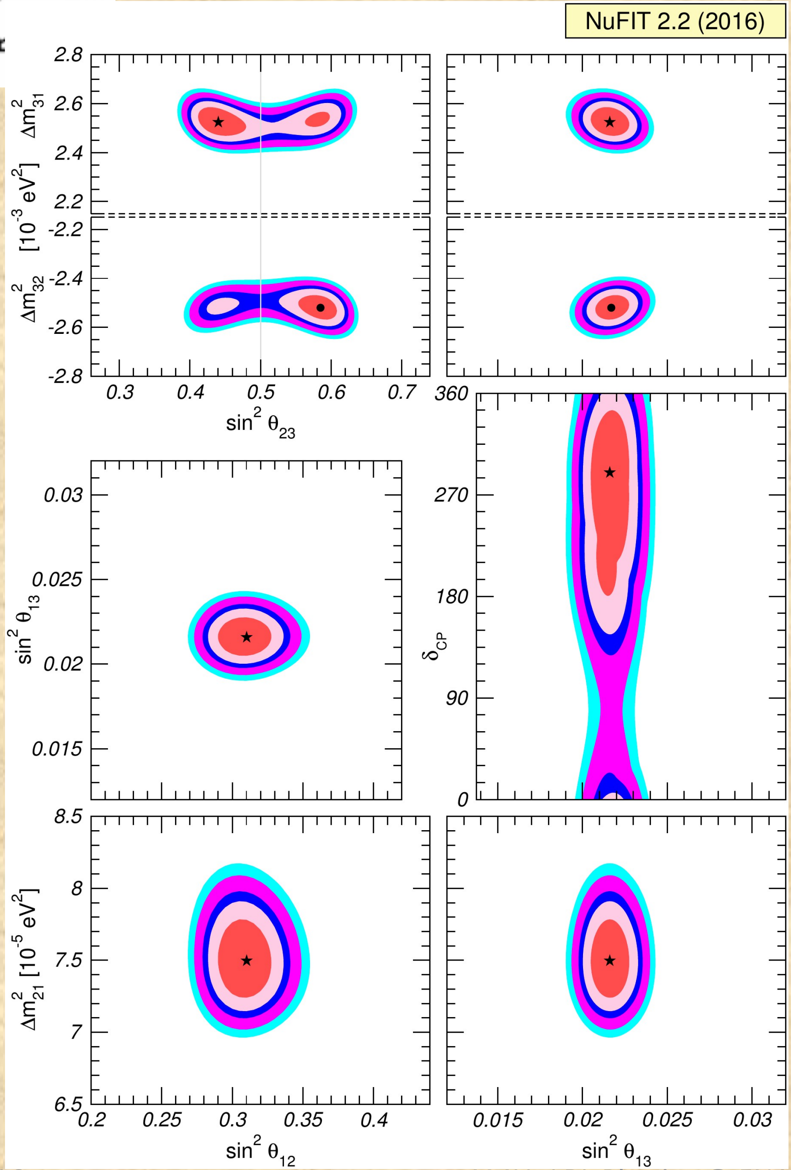
What do we know about the Neutrinos?

There are three generations of light neutrinos, they have mass, hence they mix and it has been confirmed by the Nobel Committee in 2015.

Post ν2016 Status

Gonzalez-Garcia, Maltoni, Salvado, Schwetz

JHEP 11 (2014) 052, arXiv:1409.5439v



1σ, 90%, 2σ, 99% & 3σ CL (2 dof).

Normalization of reactor fluxes is left free and data from SBL reactor experiments are included.

Atmospheric mass-squared splitting
Δm^2_{31} for NO
Δm^2_{32} for IO

Post ν2016 Status

JHEP 11 (2014) 052, arXiv:1409.5439v

NuFIT 2.2 (2016)

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 0.56$)		Any Ordering
	bfp $\pm1\sigma$	3σ range	bfp $\pm1\sigma$	3σ range	3σ range
$\sin^2\theta_{12}$	$0.308^{+0.013}_{-0.012}$	$0.273 \to 0.348$	$0.308^{+0.013}_{-0.012}$	$0.273 \to 0.349$	$0.273 \to 0.348$
$\theta_{12}/^\circ$	$33.72^{+0.79}_{-0.76}$	$31.52 \to 36.18$	$33.72^{+0.79}_{-0.76}$	$31.52 \to 36.18$	$31.52 \to 36.18$
$\sin^2\theta_{23}$	$0.440^{+0.023}_{-0.019}$	$0.388 \to 0.630$	$0.584^{+0.018}_{-0.022}$	$0.398 \to 0.634$	$0.388 \to 0.632$
$\theta_{23}/^\circ$	$41.5^{+1.3}_{-1.1}$	$38.6 \to 52.5$	$49.9^{+1.1}_{-1.3}$	$39.1 \to 52.8$	$38.6 \to 52.7$
$\sin^2\theta_{13}$	$0.02163^{+0.00074}_{-0.00074}$	$0.01938 \to 0.02388$	$0.02175^{+0.00075}_{-0.00074}$	$0.01950 \to 0.02403$	$0.01938 \to 0.02396$
$\theta_{13}/^\circ$	$8.46^{+0.14}_{-0.15}$	$8.00 \to 8.89$	$8.48^{+0.15}_{-0.15}$	$8.03 \to 8.92$	$8.00 \to 8.90$
$\delta_{CP}/^\circ$	289^{+38}_{-51}	$0 \to 360$	269^{+39}_{-45}	$146 \to 377$	$0 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.49^{+0.19}_{-0.17}$	$7.02 \to 8.08$	$7.49^{+0.19}_{-0.17}$	$7.02 \to 8.08$	$7.02 \to 8.08$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.526^{+0.039}_{-0.037}$	$+2.413 \to +2.645$	$-2.518^{+0.038}_{-0.037}$	$-2.634 \to -2.406$	$\begin{bmatrix}+2.413 \to +2.645\\ -2.630 \to -2.409\end{bmatrix}$

Total 3σ relative precision on parameters: θ_{12}~14%, θ_{23}~32%, θ_{13}~15%, Δm^2_{21}~ 14%, $|\Delta m^2_{31}|$ ~ 11%.
Divide by 2 for getting ±3σ error.

Gonzales-Garcia, Maltoni, Salvado, Schwetz

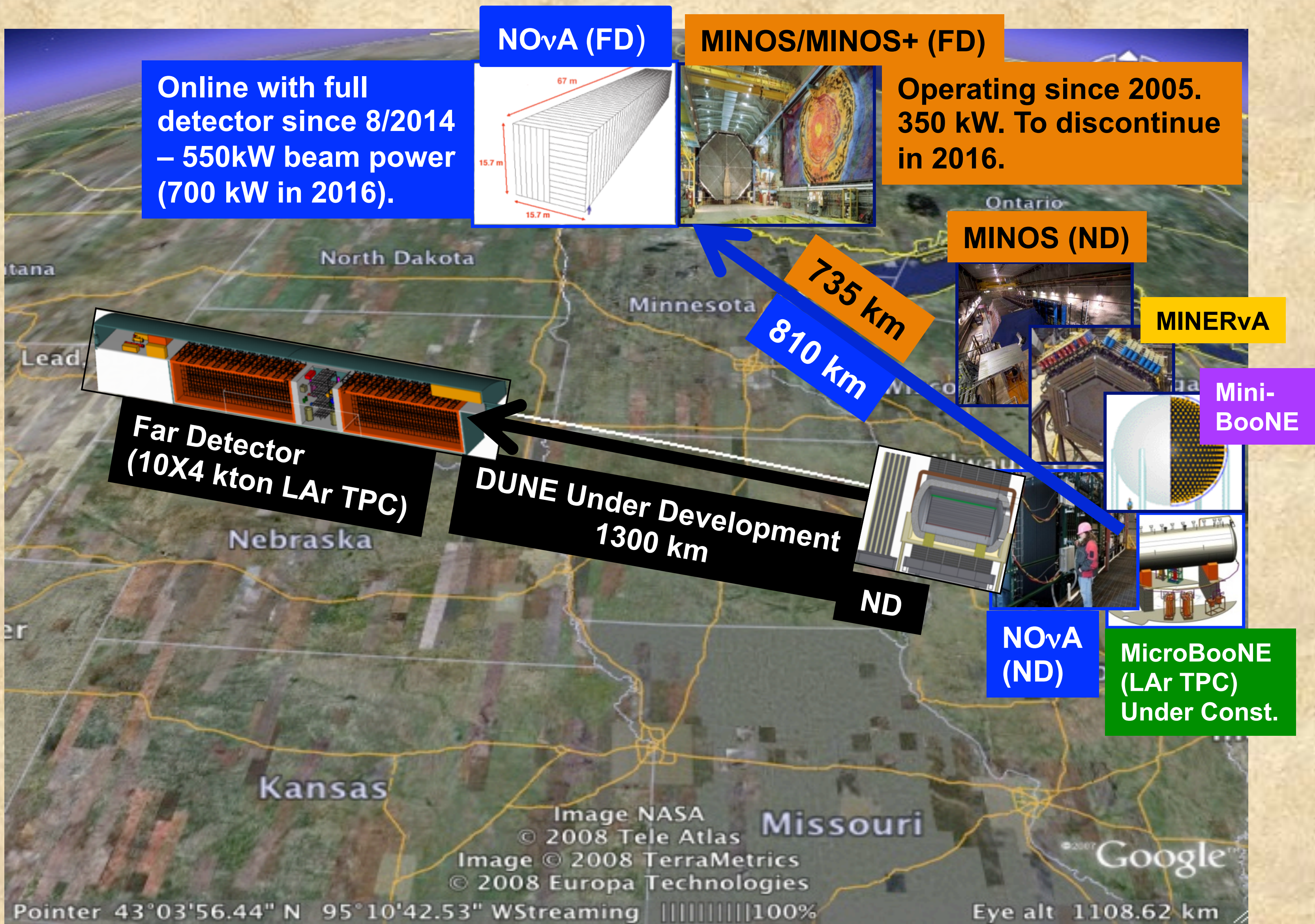
Long- and Short-Baseline Science Goals

- ***CP Violation in Neutrino Sector***
  - *Violation of a fundamental symmetry of nature; viability of leptogenesis models -> matter/antimatter*
- ***Neutrino Mass Ordering (or Hierarchy)***
  - *GUTs, Dirac vs. Majorana nature and feasibility of $0\nu\beta\beta$ decay*
- ***Testing the Three-Flavor Paradigm***
  - *Precision measurements of known fundamental mixing parameters for neutrinos and anti-neutrinos*
  - *New physics -> non-standard interactions, sterile neutrinos… (beam + atmospheric ν sources)*
  - *Precision neutrino interactions studies (near detector)*
- ***Nucleon Decay***
- ***Astrophysics:*** *Supernova ν burst*

Open Questions in ν-Physics with emphasis to Long-Baseline + Atmospheric Physics

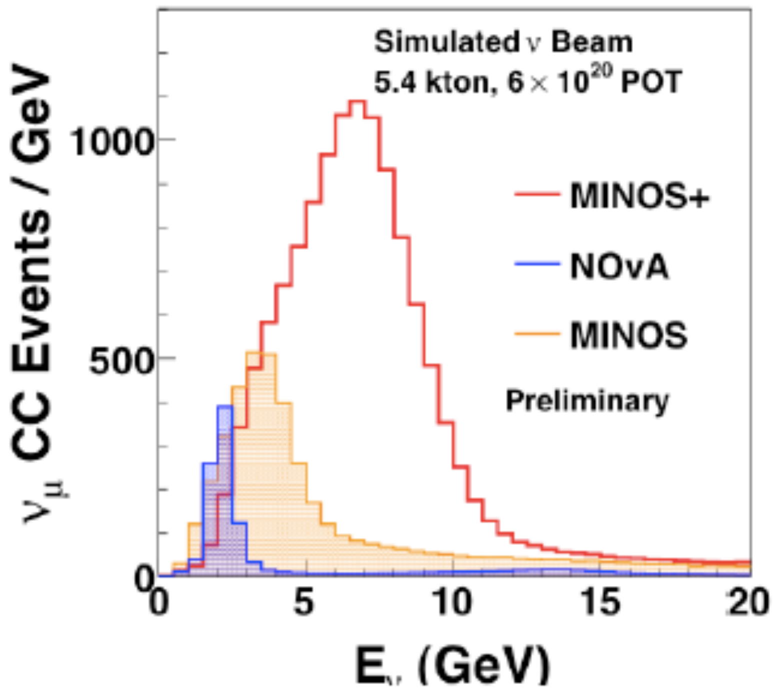
1. ***MH*** *– NOvA+T2K, JUNO/RENO-50, PINGU/ORCA/INO, HK, DUNE (Beam and Atmospheric independently)*
2. ***CPV –*** *NOvA+T2K, DUNE, T2HK*
3. ***Precision on oscillation parameter*** *– θ_{23} octant*
4. ***Number of Neutrinos*** *– 3+n-Sterile – SBL, LBL-ND*
5. ***Proton Decay*** *– DUNE, Super-K/HK*
6. ***Supernova Neutrinos*** *– DUNE, Super-K/HK, JUNO*
7. ***Etc. etc.***

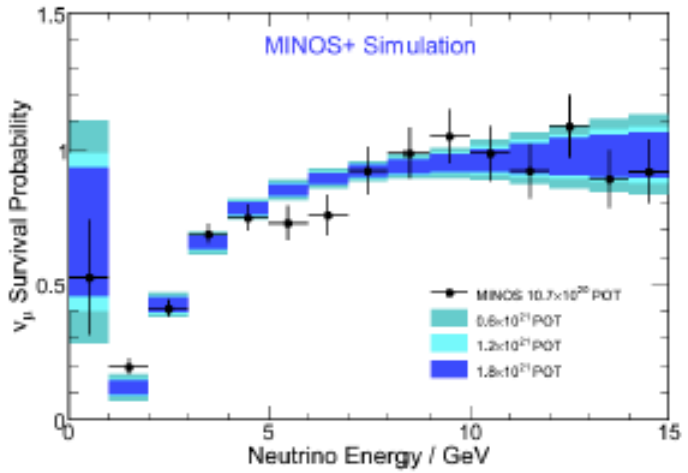
Fermilab Neutrino Program



Fermilab Accelerator Complex

MINOS+ Goals

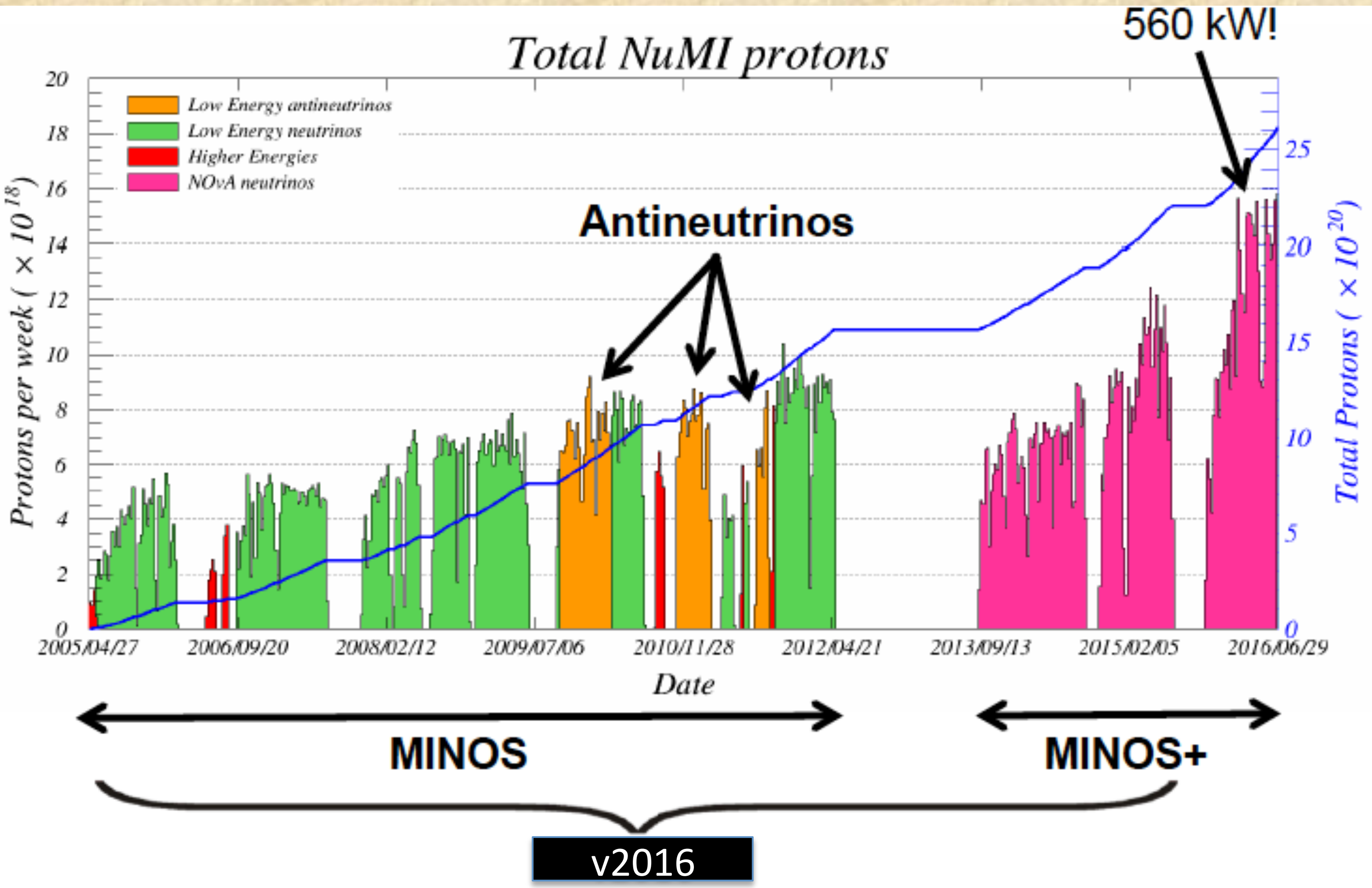




- MINOS+ (E-1016, proposed in 2012) for continued exploitation of the NuMI beam and MINOS detectors (MINOS (E-875), proposed in 1995)
  - ✓ improve measurements of "atmospheric" oscillations (by probing the multi-GeV energy region)
  - ✓ search for light sterile neutrinos
  - ✓ search for NSI and other "exotic" transitions (e.g., large extra dimensions)
  - ✓ continue cosmic rays data acquisition & analysis
- Requested in the proposal:
  - ✓ 3 years of running (2013-2016)
  - ✓ 18 x 10^{20} POT
  - ✓ Collect ~3000 ν_μ CC events/year

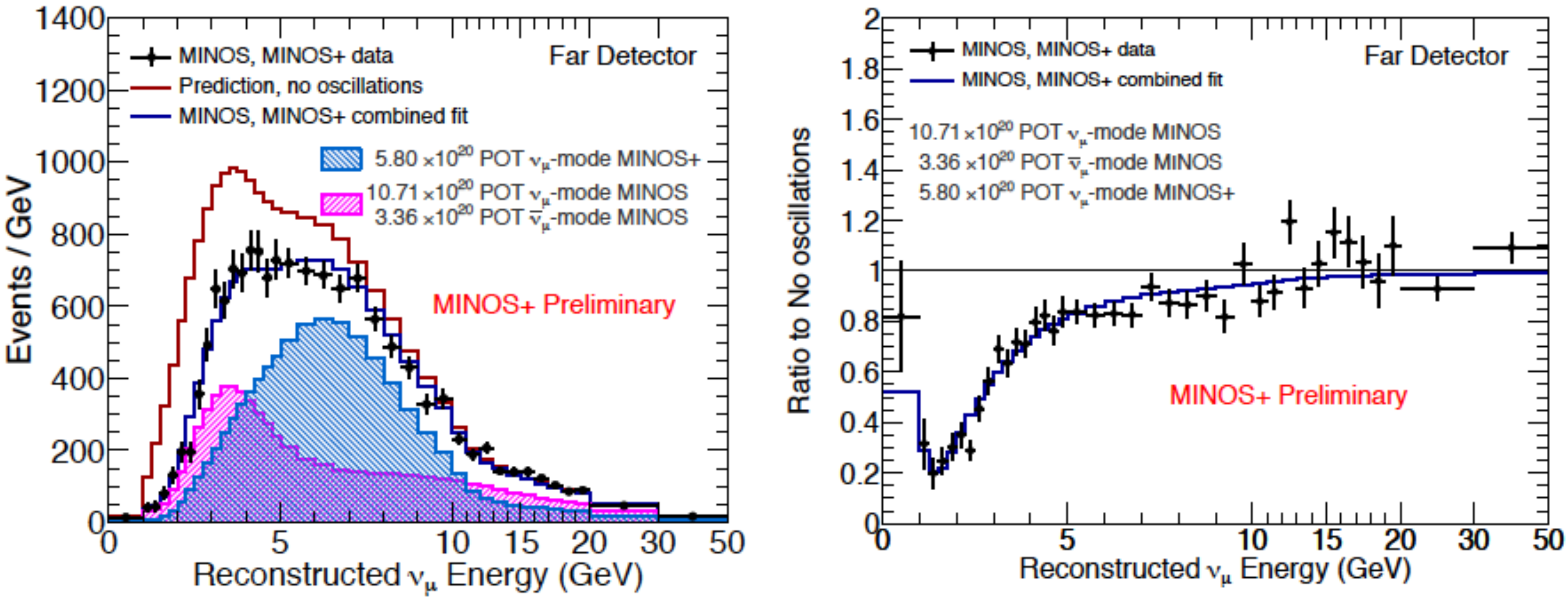
Karol Lang, Fermilab PAC, 20 Jan 2016

MINOS and MINOS+



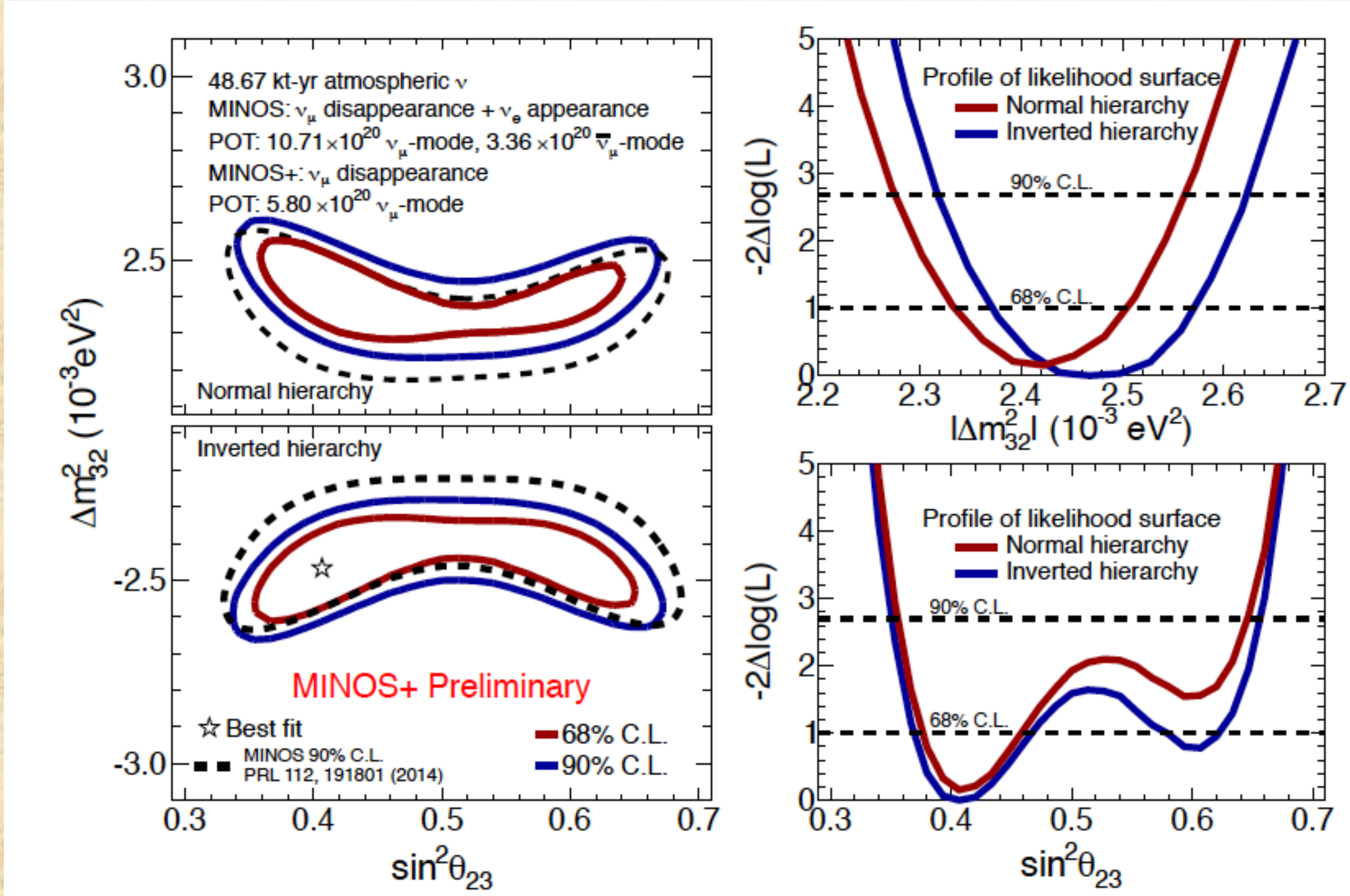
10.56×10^{20} PoT MINOS neutrino-mode
5.80×10^{20} PoT MINOS+ neutrino-mode
3.36×10^{20} PoT MINOS antineutrino-mode

MINOS + MINOS+ Analysis

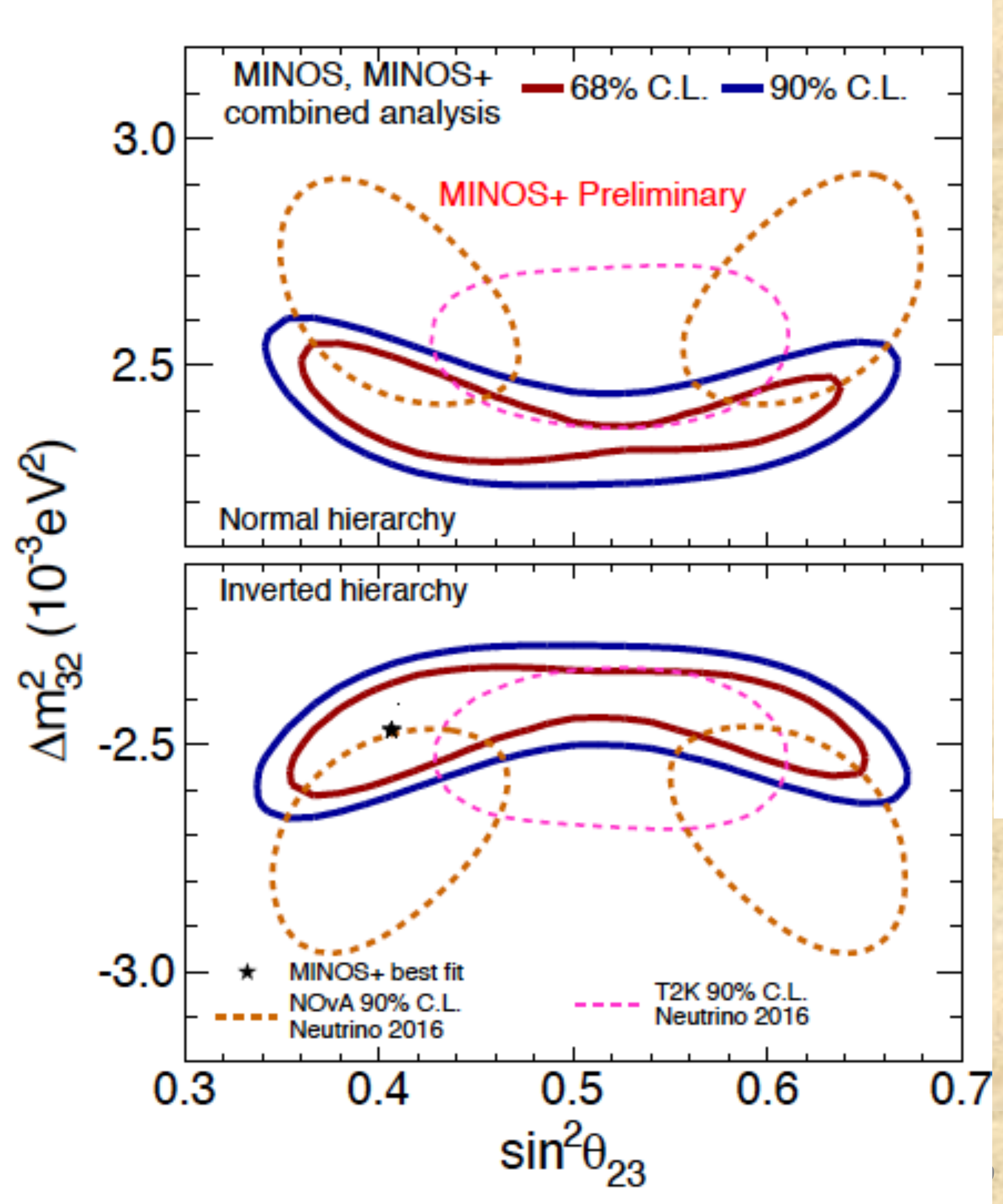


1. ***Combine spectrum of MINOS & MINOS+ disappearance data.***
2. ***Can test the "rising edge" of the spectral ratio (survival Probability)***
3. ***A combined fit performed***
4. ***MINOS+ spectrum consistent with MINOS spectrum***

MINOS/MINOS+ - Oscillations



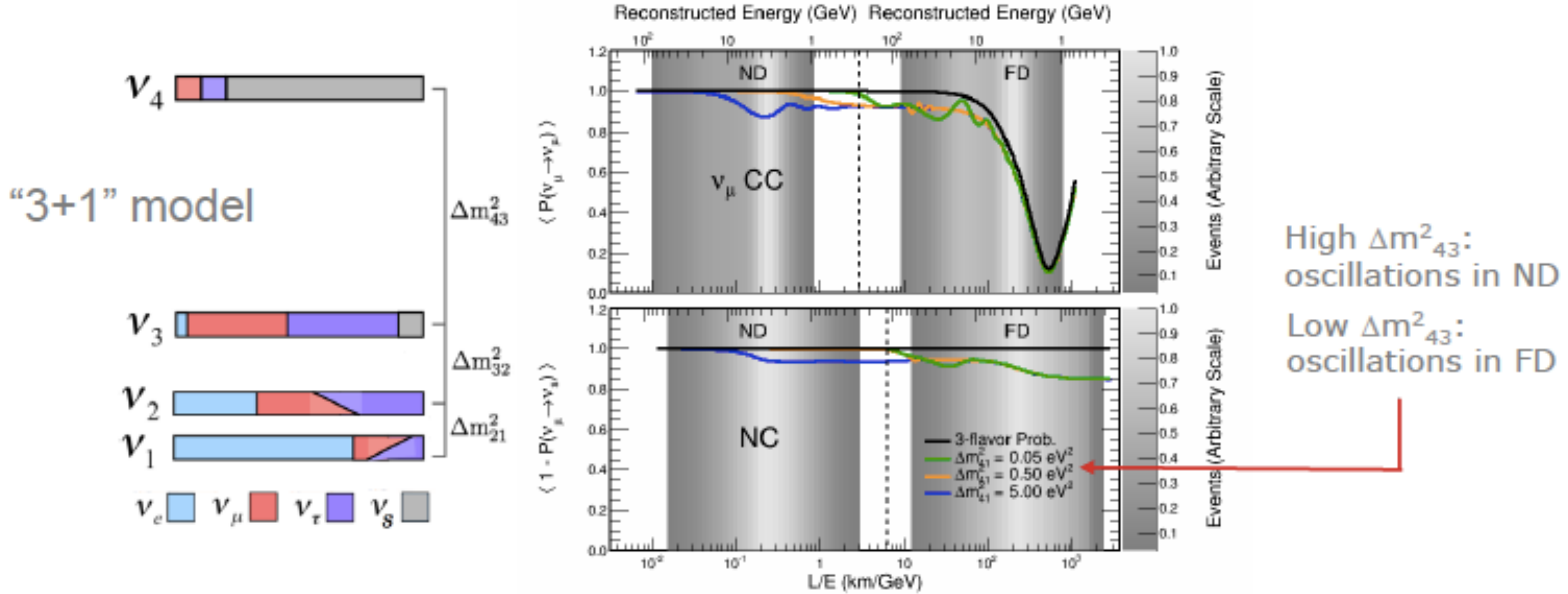
MINOS/MINOS+ - Oscillations



$$\Delta m^2_{32} = \begin{cases} 2.42 \pm 0.09 \times 10^{-3}\,\mathrm{eV}^2 & \text{Normal} \\ -2.48^{+0.09}_{-0.11} \times 10^{-3}\,\mathrm{eV}^2 & \text{Inverted} \end{cases}$$

$$\sin^2(\theta_{23}) = \begin{cases} 0.35\text{–}0.65\ (90\%\ \text{C.L.}) & \text{Normal} \\ 0.35\text{–}0.66\ (90\%\ \text{C.L.}) & \text{Inverted} \end{cases}$$

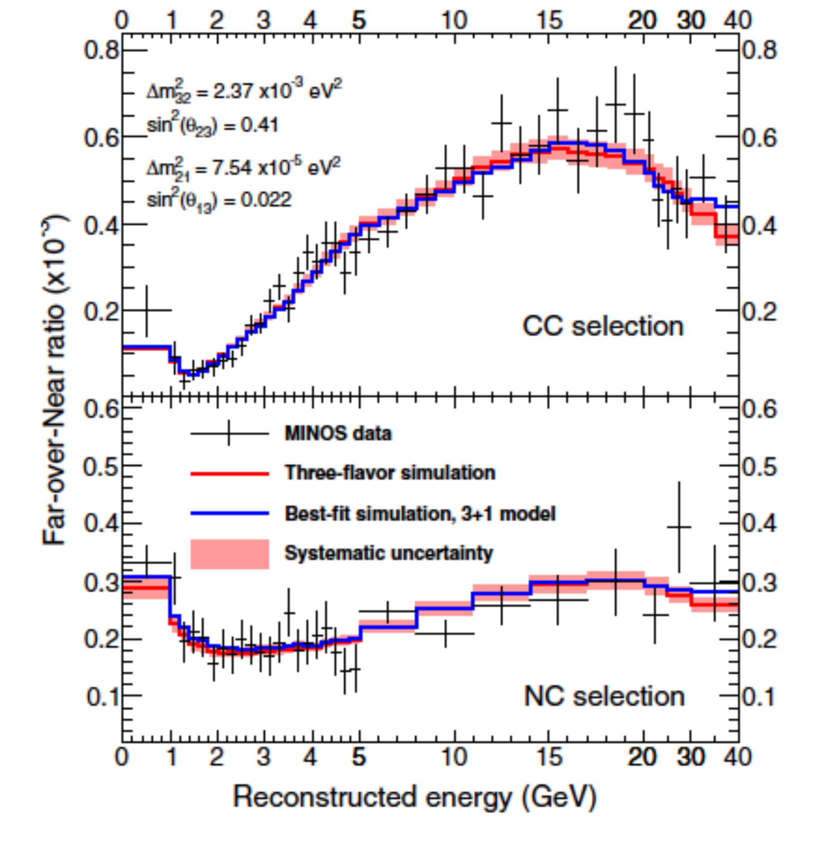
Sterile Neutrinos in MINOS+

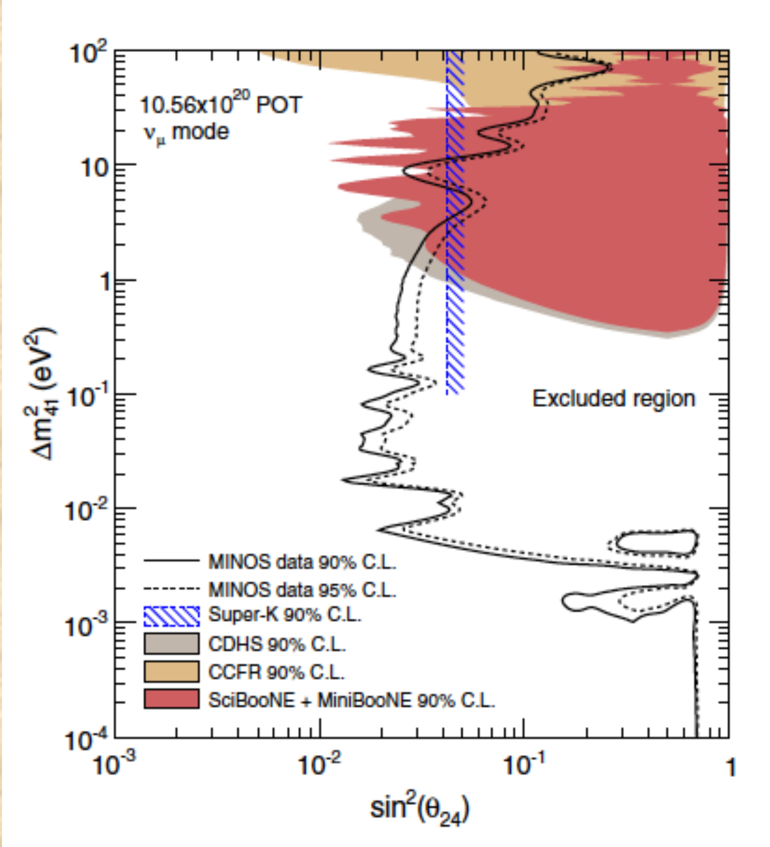


- ✓ ***Main signatures***
  - ❖ ***ν_μ CC spectrum – distortion from standard oscillation due to extra splitting***
  - ❖ ***NC spectrum will show deficit because of $\nu_\mu \rightarrow \nu_s$ oscillation***
- ✓ ***Can happen in either ND or FD***
- ✓ ***Increased sensitivity due to higher energy spectrum in MINOS+***

PRL 117, 151803 (2016)

Sterile Neutrino Analysis in MINOS





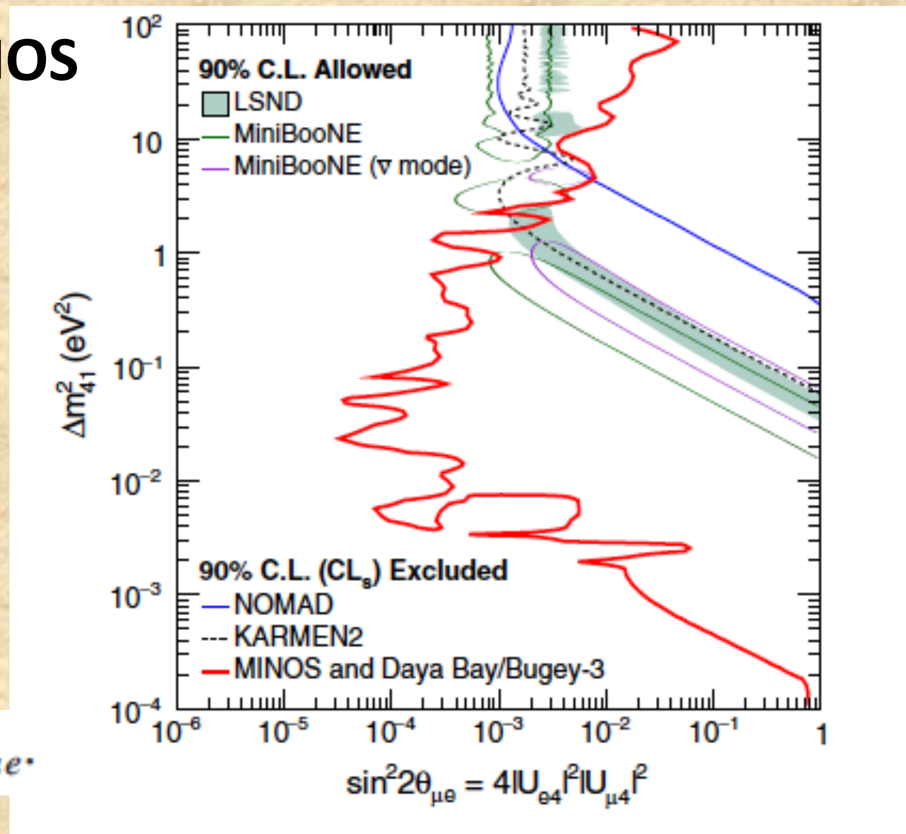
- ***Distortion in ND analysis requires fundamental change in MINOS analysis***
- ***Look for deviation in FD/ND energy spectrum from standard oscillation***
  - ***Simultaneous fit to νμ CC and NC data***
- ***CC and NC samples provide sensitivity to different components of sterile mixing***
- ***Best constraint till date on $\nu_\mu \rightarrow \nu_s$ disappearance for sterile neutrino mass splitting below 1 eV^2***

PRL 117, 151803 (2016)

Sterile Neutrino Analysis MINOS + Bugey + Daya Bay

- ✓ Use best fit to NC and ν_μ CC MINOS disappearance
- ✓ Combine MINOS with the ν_e disappearance from Bugey and Daya Bay
  - ✓ MINOS: 90% CL on θ_{24}
  - ✓ Bugey: 90% CL on θ_{14}
  - ✓ Daya bay: 90% CL on θ_{14}
- ✓ Construct combined limit on:

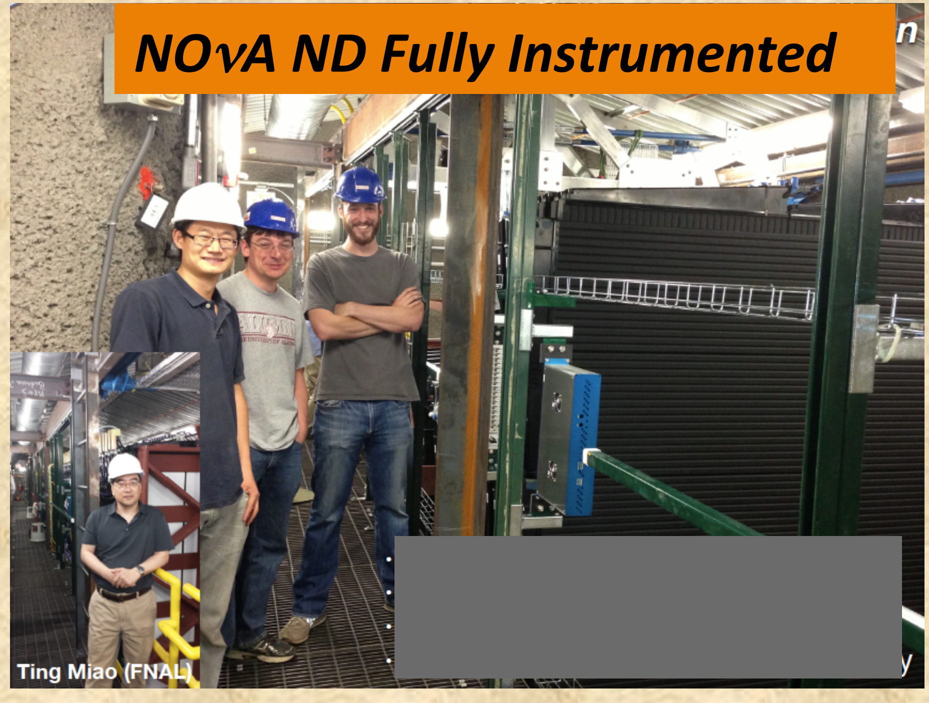
$$4|U_{e4}|^2|U_{\mu4}|^2 = \sin^2 2\theta_{14}\sin^2\theta_{24} \equiv \sin^2 2\theta_{\mu e}.$$



- ✓ Combined limit can be compared to LSND, MiniBooNE, NOMAD, KARMEN
- ✓ **Rules out Δm^2_{41} < 0.8 eV^2 at 95% CL**

PRL 117, 151801 (2016)

NOνA Experiment



- **The long-baseline off-axis (14 mrad) neutrino oscillation experiment with functionally identical Near and Far Detectors.**
- **Data taking with complete detectors started in November 2014.**
- **First Results Announced on August 6, 2015.**
- **New Results Announced on July 4, 2016.**
- **Low-Z tracking calorimeters**
- **High power NuMI beam - upgraded for NOvA to take the power from 350 to 700 kW.**
- **This result based on: 6.05 x 10^{20} POT, 700 kW peak intensity, average = 550kW.**

NOνA Collaboration

Argonne, Atlantico, Banaras Hindu University, Caltech, Cochin, Institute of Physics and Computer science of the Czech Academy of Sciences, Charles University, Cincinnati, Colorado State, Czech Technical University, Delhi, JINR, Fermilab, Goiás, IIT Guwahati, Harvard, IIT Hyderabad, U. Hyderabad, Indiana, Iowa State, Jammu, Lebedev, Michigan State, Minnesota-Twin Cities, Minnesota-Duluth, INR Moscow, Panjab, South Carolina, SD School of Mines, SMU, Stanford, Sussex, Tennessee, Texas-Austin, Tufts, UCL,Virginia, Wichita State, William and Mary, Winona State

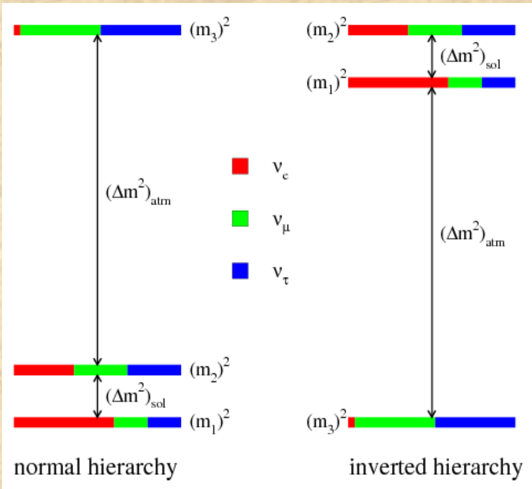
7 Countries, 41 Institutions, 234 Collaborators

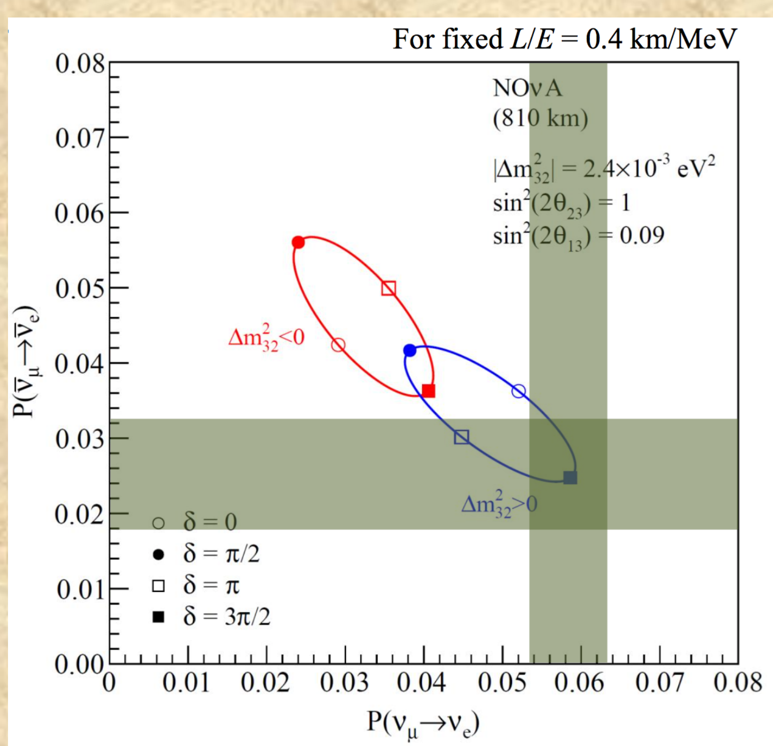
Goals of NOνA Experiment

- Measure the oscillation probabilities of
  a) Appearance channels: $\nu_\mu \rightarrow \nu_e$ and $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$
  b) Disappearance channels: $\nu_\mu \rightarrow \nu_\mu$ and $\overline{\nu}_\mu \rightarrow \overline{\nu}_\mu$

$$P(\nu_\alpha \rightarrow \nu_\beta) \neq P(\overline{\nu}_\alpha \rightarrow \overline{\nu}_\beta)\ ?$$

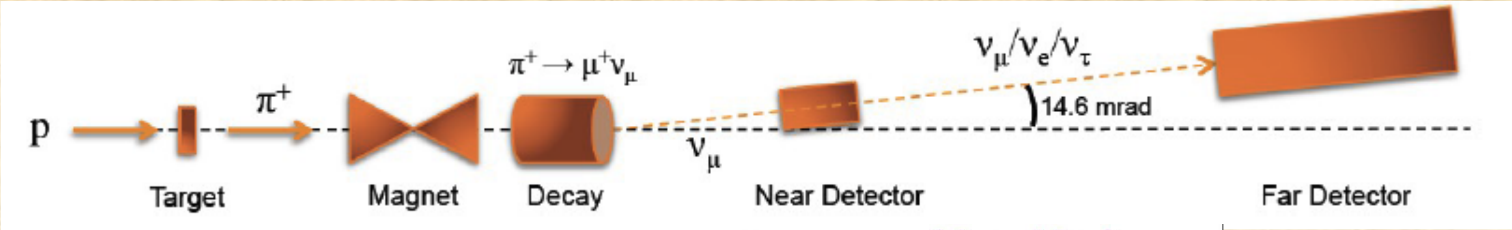
- Precision measurements of θ_{13}, Δm^2_{32}, θ_{23}
- Probe the Mass Hierarchy
- Study the CP violation parameter δ

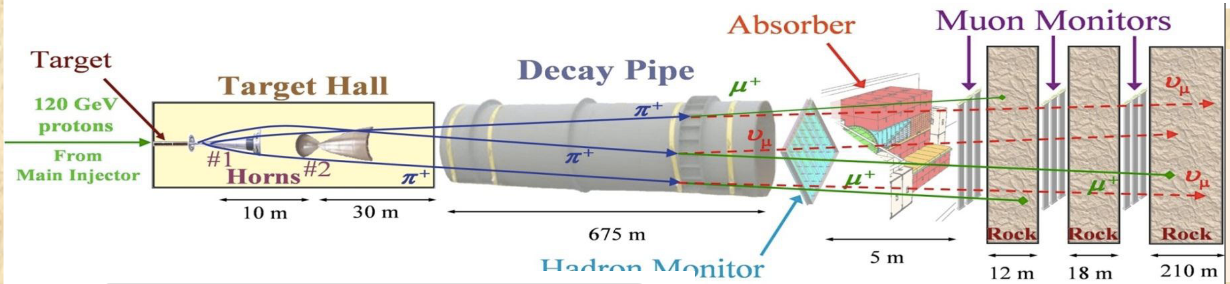




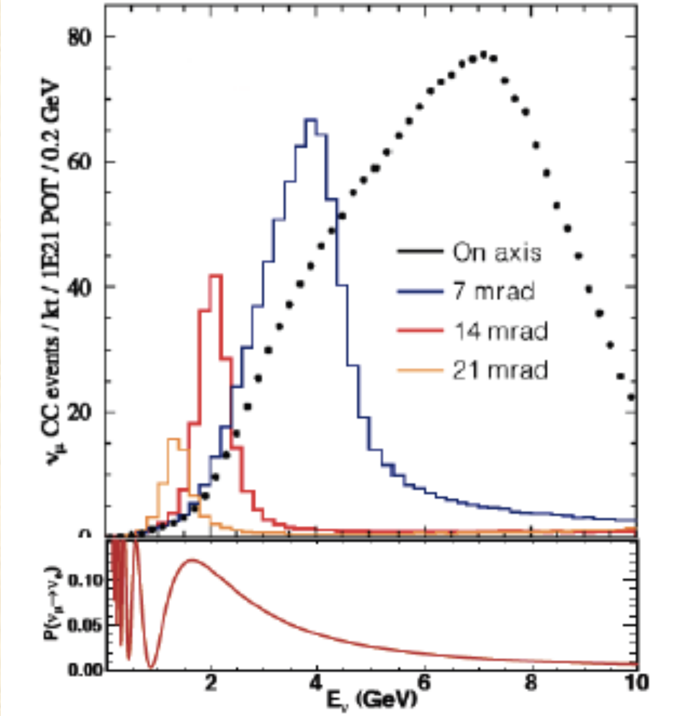
- Additional Physics Goals:
  -Neutrino cross-sections and interaction physics
  -Sterile Neutrinos
  -Supernovae and Exotic Searches

NOνA Off-Axis Beam





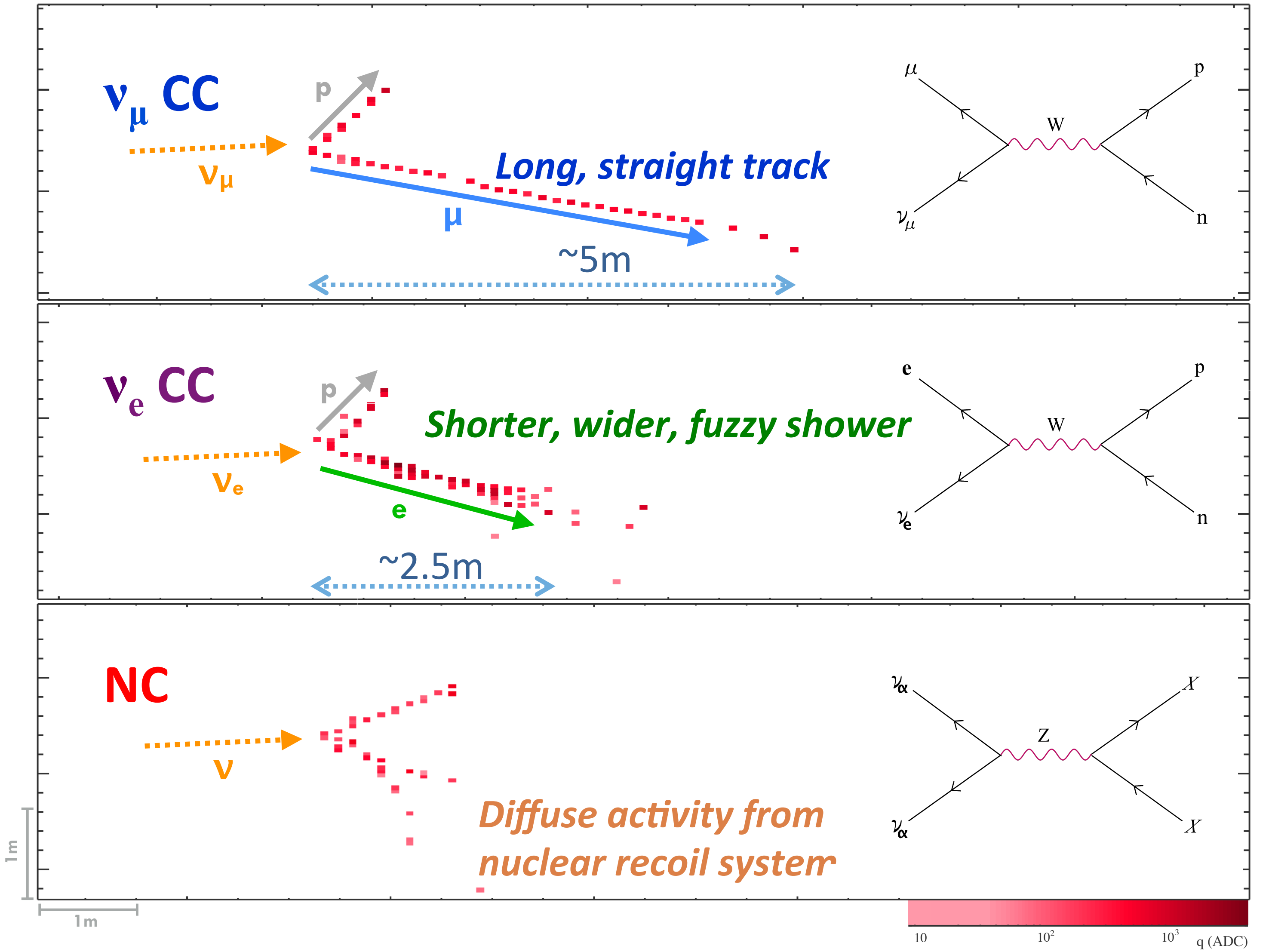
- ➢ *NuMI beam operated up to 700 kW*
- ➢ *2016–expect 700kW*



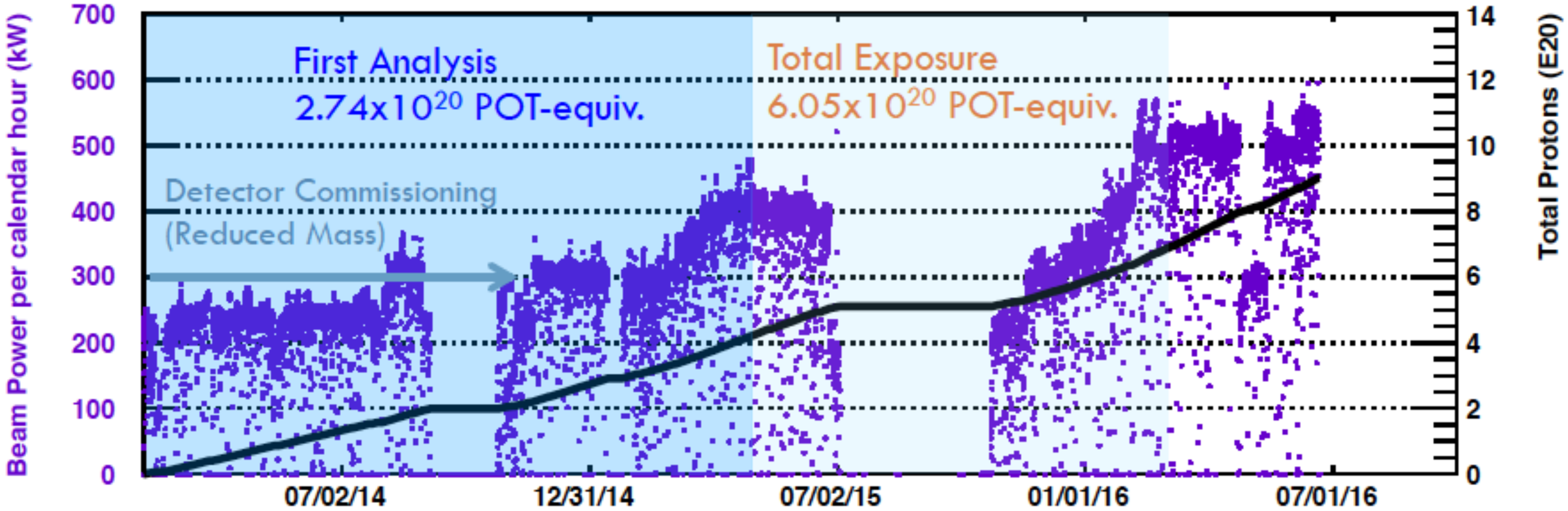
Detectors placed at 14.6 mrad off-axis from the beam direction

- ✓ *This leads to a narrow band beam peaked at ~2GeV energy*
- ✓ *This happens near the maximum oscillation*
- ✓ *Leads to reduced high energy Neutral Current (NC) events*

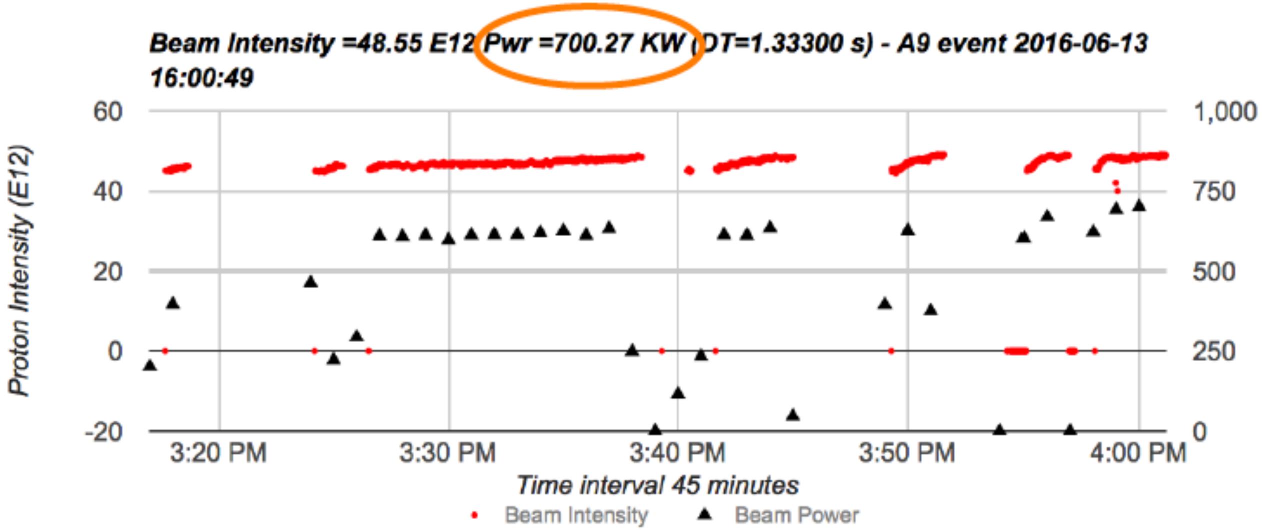
NOνA Event Topologies



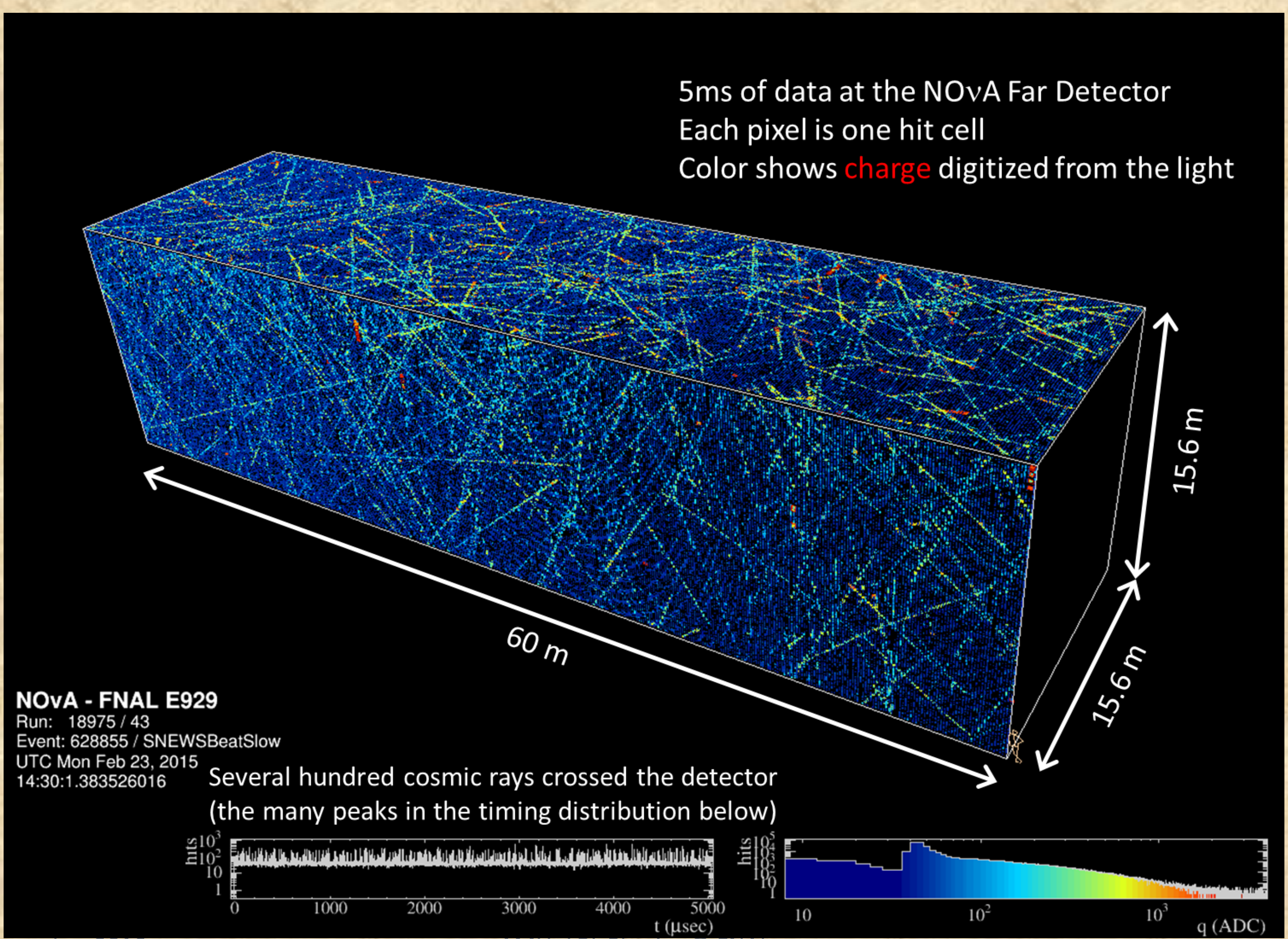
NOνA FD Exposure



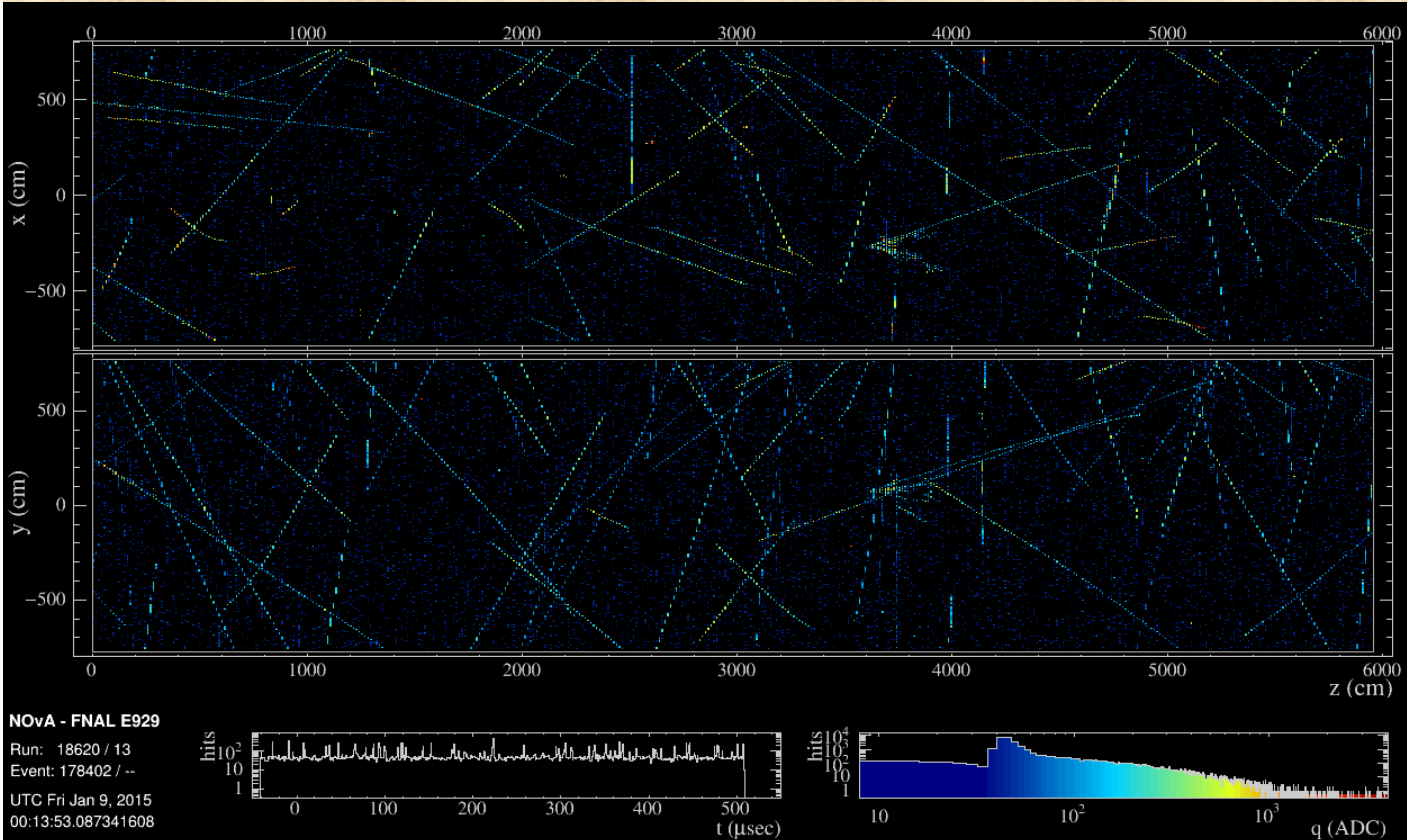
Achieved design power 700kW!



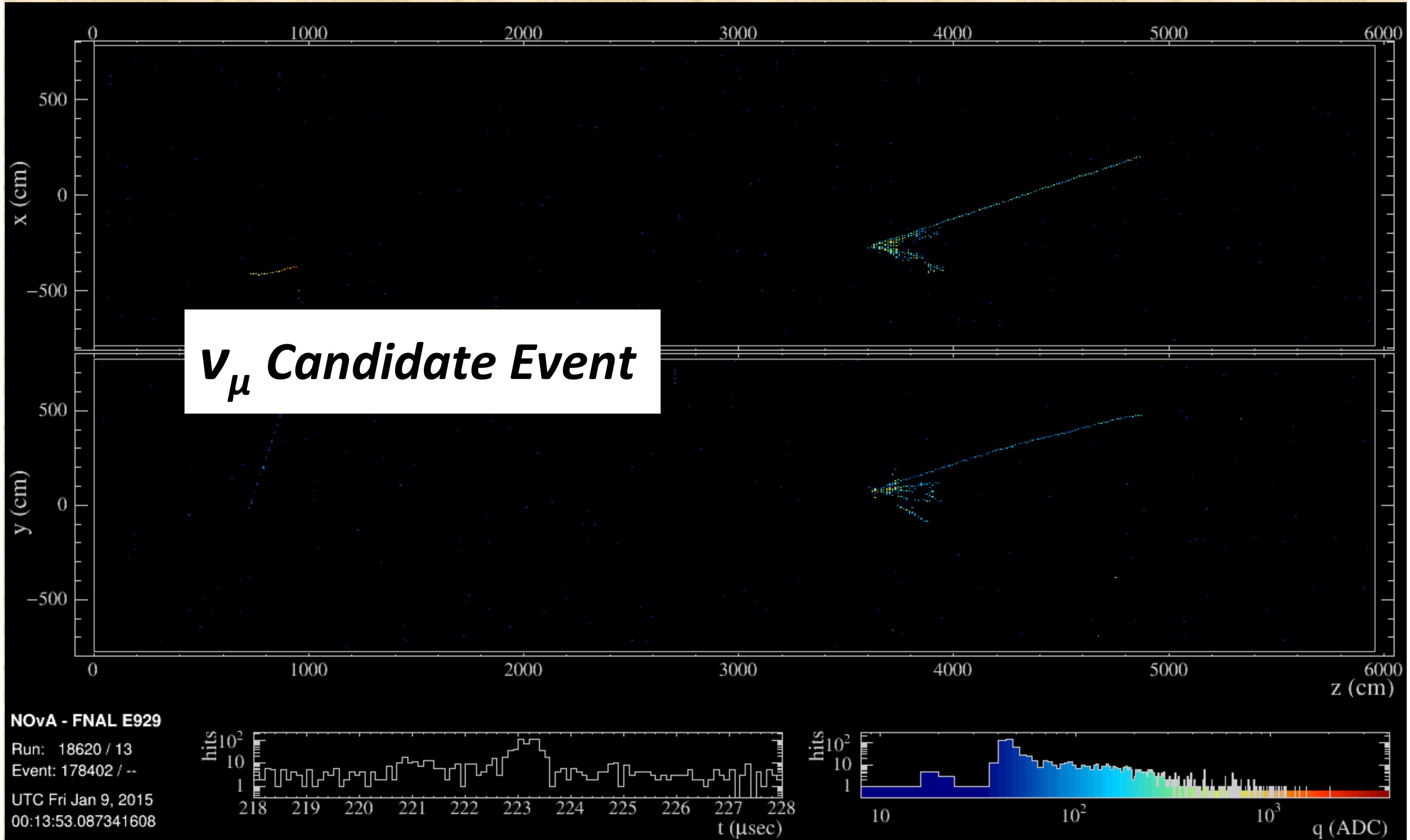
NOνA FD ~ 5 ms Block



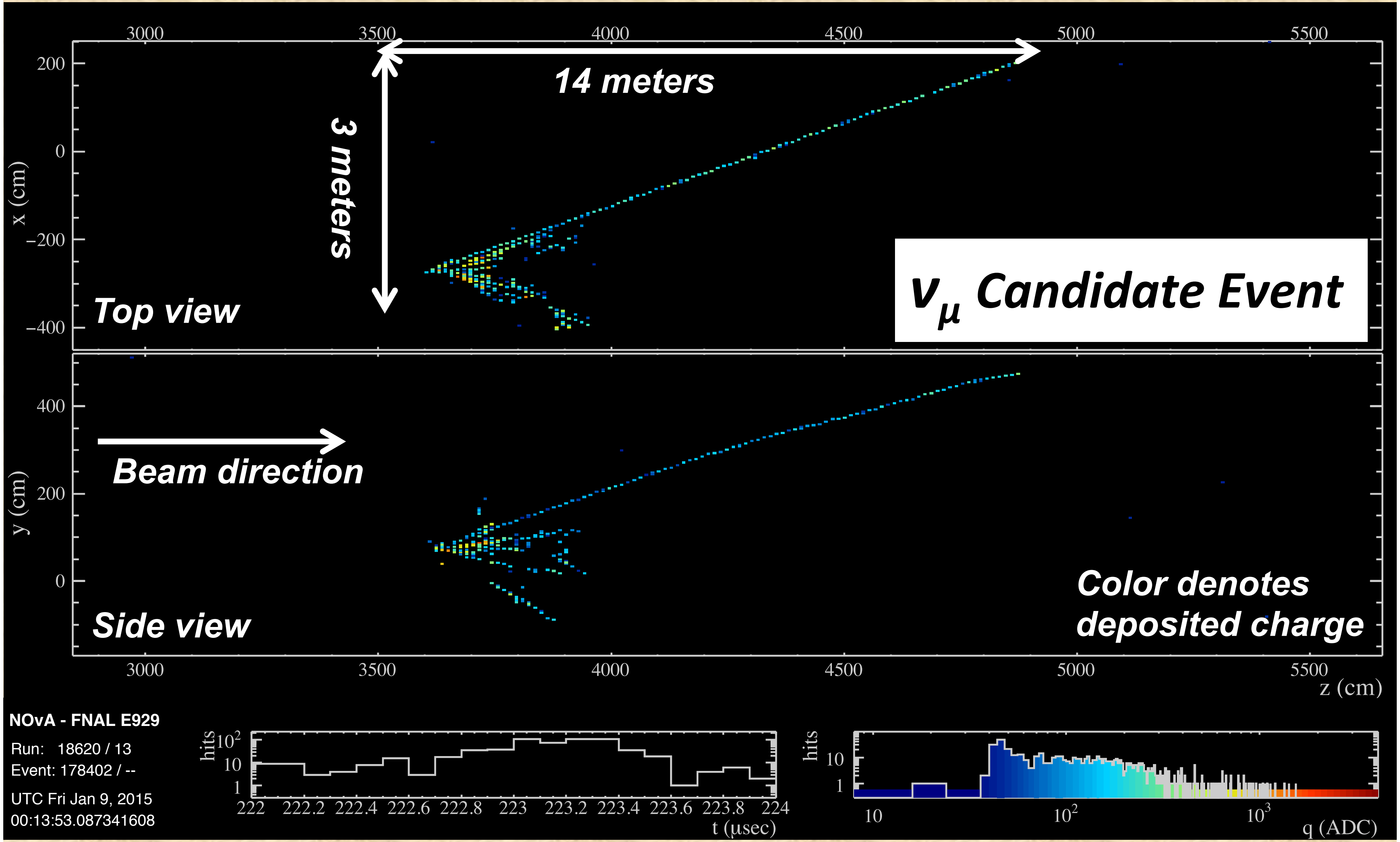
NOνA FD ~ 500 μs around a NuMI Spill



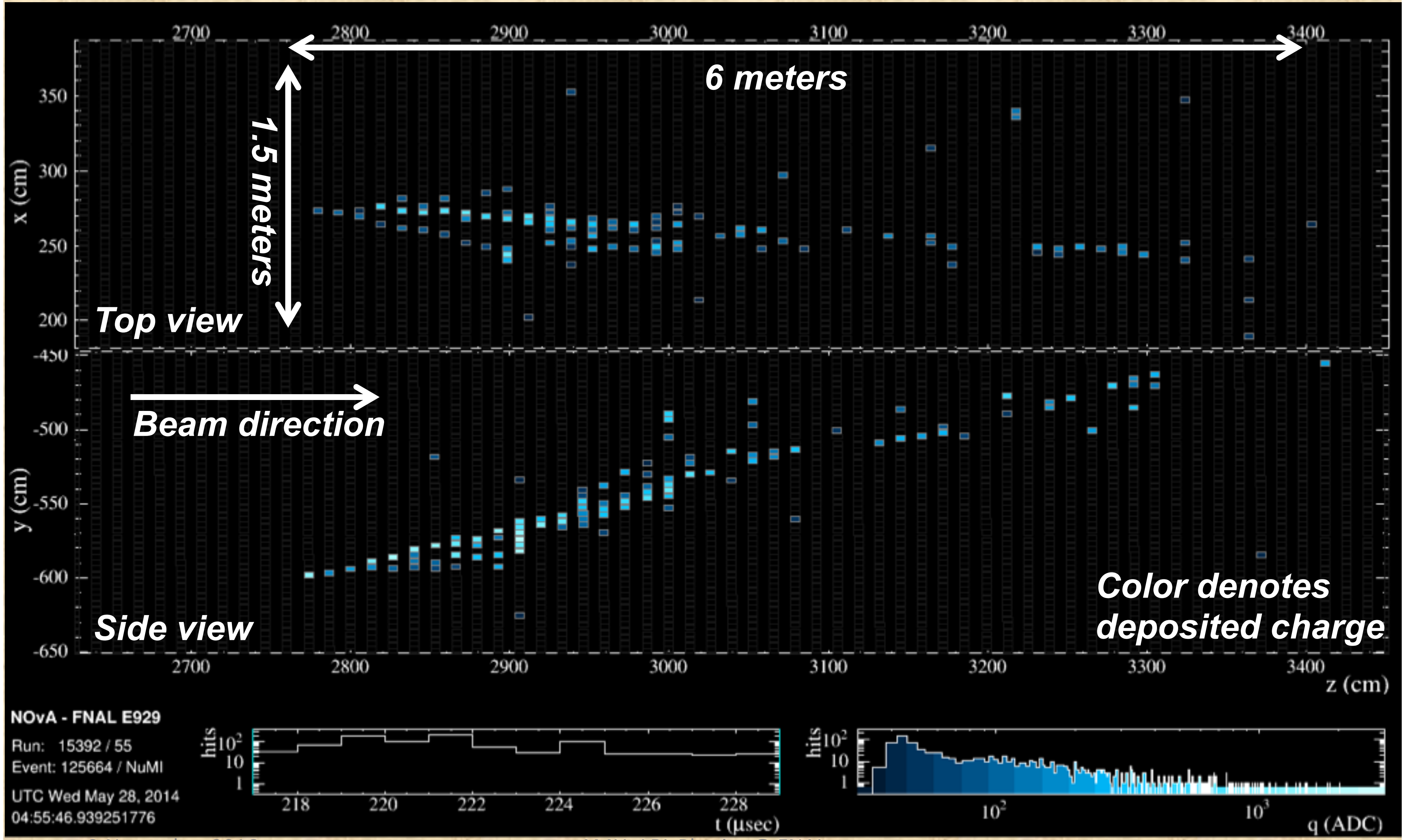
NOνA FD ~ 12 μs Beam Window



NOνA FD - ν_μ Candidate Event



NOνA FD - ν_e Candidate Event



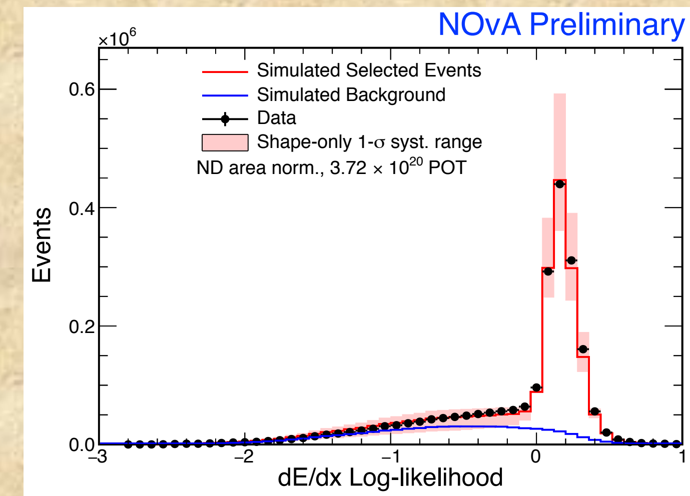
ν_μ Analysis

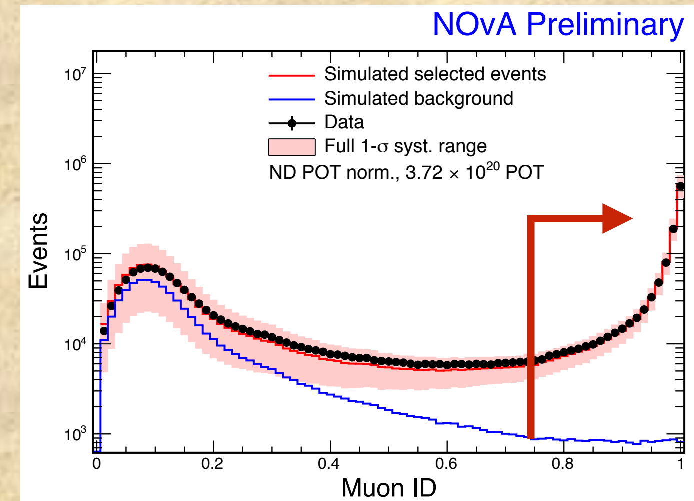
ν_μ Disappearance Search

- Identify contained ν_μ CC events in both Near and Far Detector
- Measure Energy
- Extract oscillation information from differences between the FD and ND energy spectra

ν_μ Event Selection

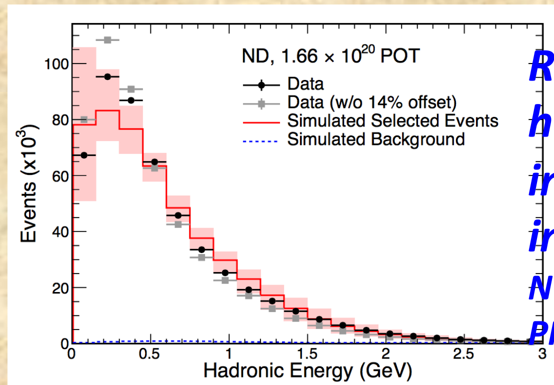
- Isolate a pure sample of ν_μ CC events less than 5GeV
  - Select events with long tracks
  - Suppress NC and cosmic backgrounds
- 4-variable kNN used to identify muon based on
  - track length
  - dE/dx along track
  - scattering along the track
  - track-only plane fraction
- ND data matches simulation well for muon variables





Energy Measurement

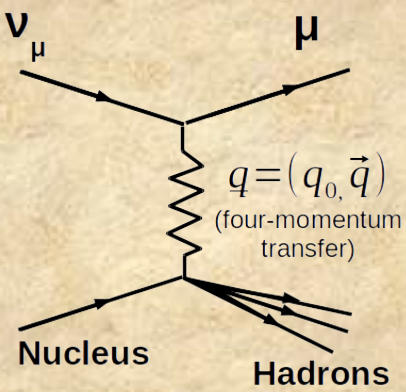
- The reconstructed neutrino energy E_ν of a contained ν_μ CC event is given by $E_\nu = E_\mu + E_{had}$

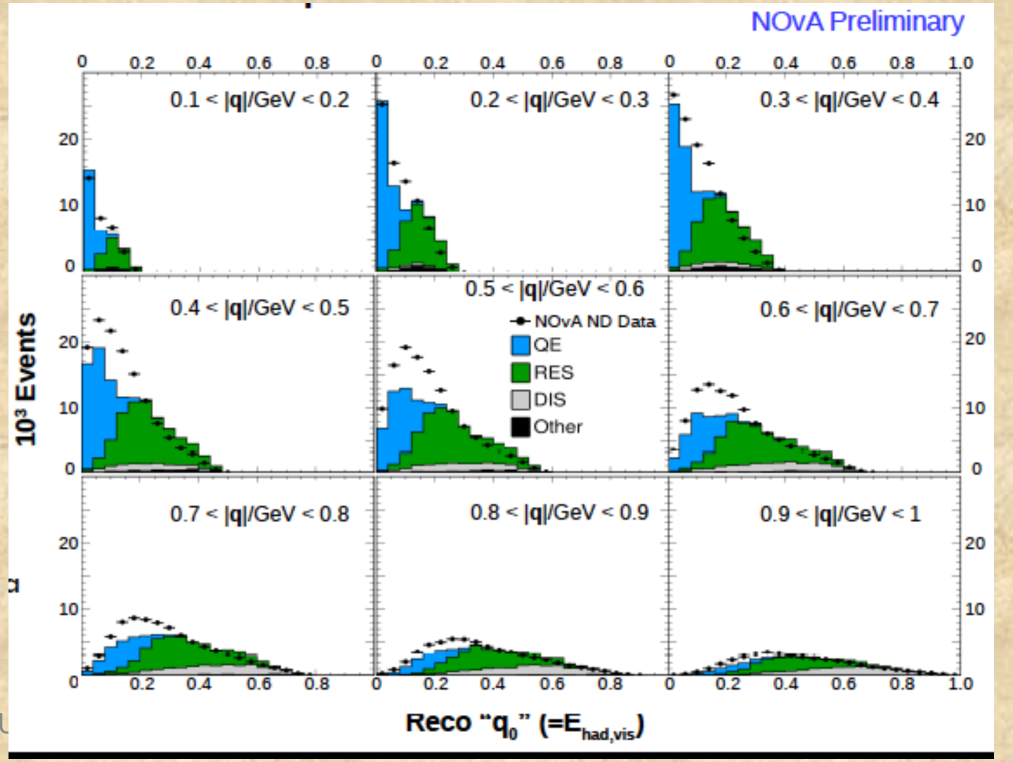


Reconstructed hadronic energy in ND ν_μ CC interactions

NOvA 1st ν_μ result: PRD 93 (2016) 051104

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



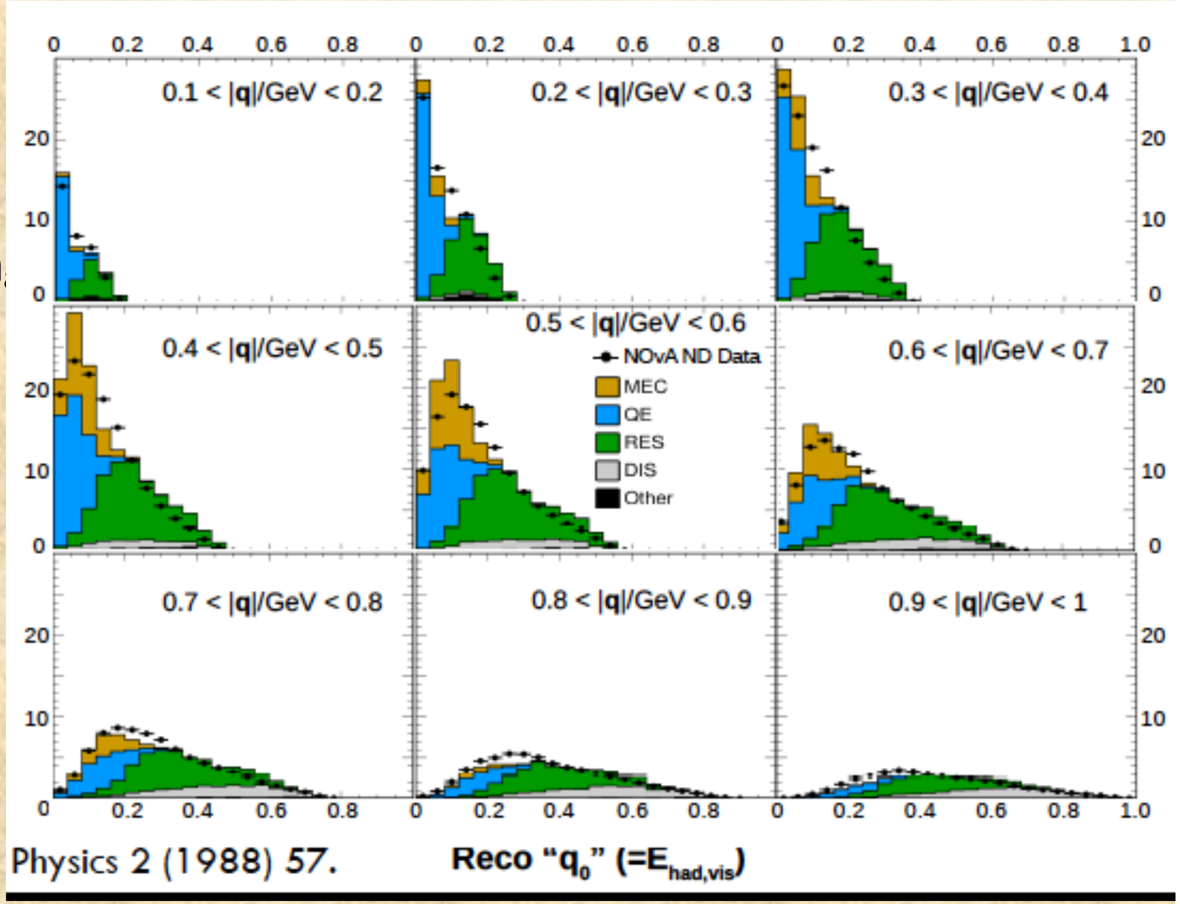


Similar conclusions from MINERvA data reported in P.A. Rodrigues et al., PRL 116 (2016) 071802

Scattering in a Nuclear Environment

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

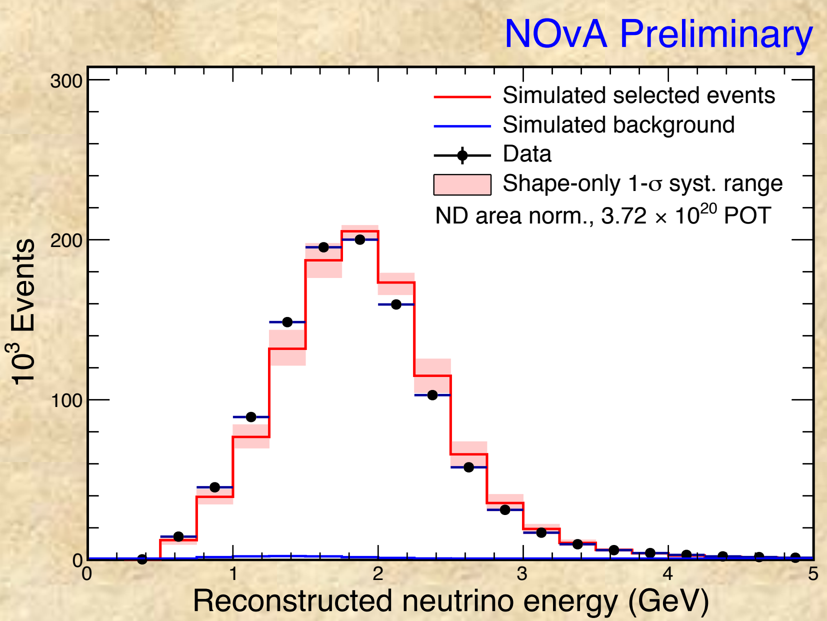
- **50% systematic uncertainty on MEC component**
- **Reduces largest systematics**
  - **hadronic energy scale**
  - **QE cross section modelin**
- **Reduce single non-resonant pion production by 50% (P.A. Rodrigues et al, arXiv:1601.01888.)**

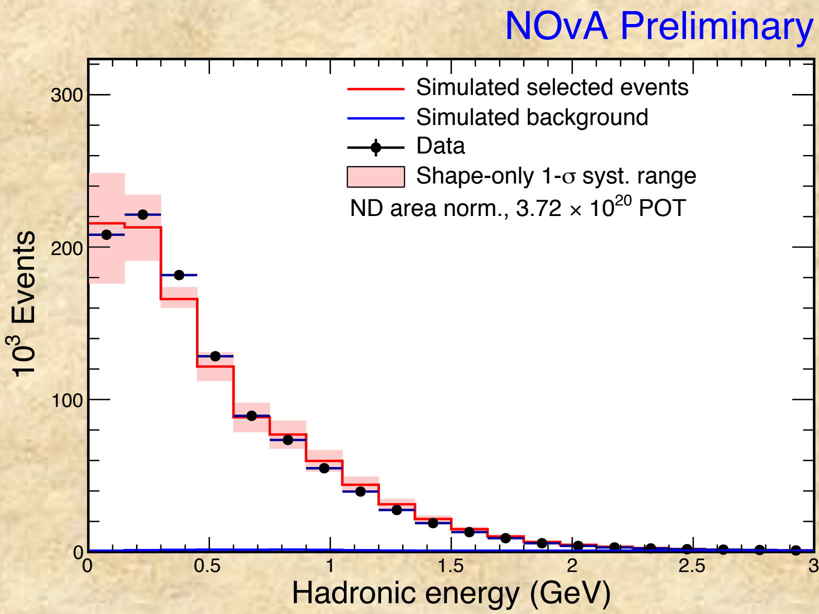


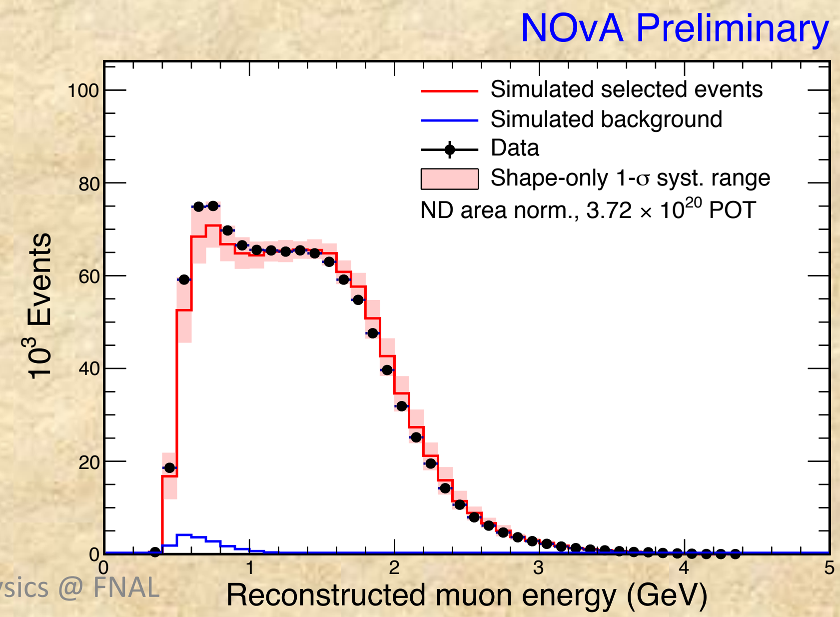
MEC model by S. Dytman, inspired by J. W. Lightbody, J. S. O'Connell, Computers in Physics 2 (1988) 57.

NOvA ν_μ Disappearance Search

- **Addition of MEC events substantially improves simulated hadronic energy distribution**
  - **hadronic energy scale uncertainty reduced from 14% to 5%**





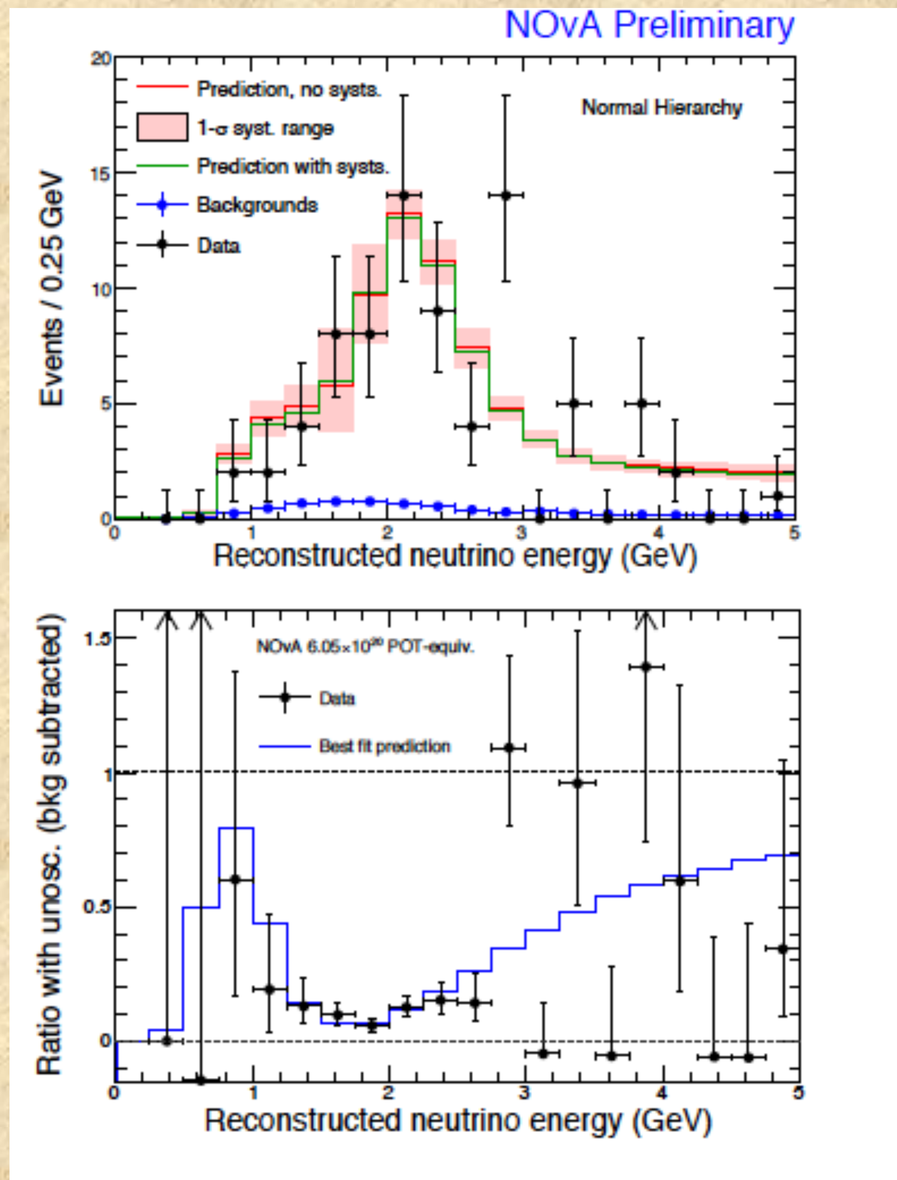


- ***Reconstructed neutrino energy unfolded, true Far/Near ratio used to extrapolate ND data for a FD prediction***

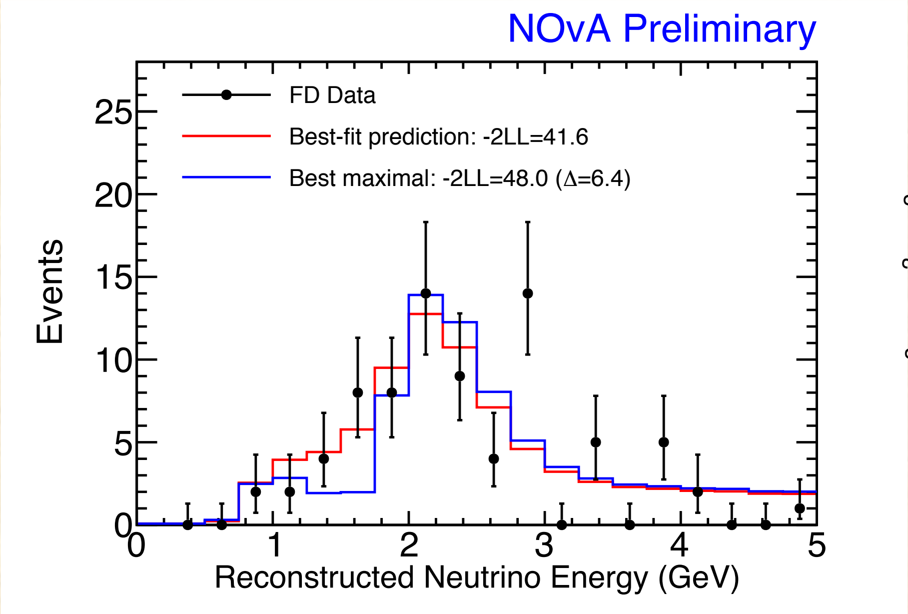
Muon Neutrino FD Data

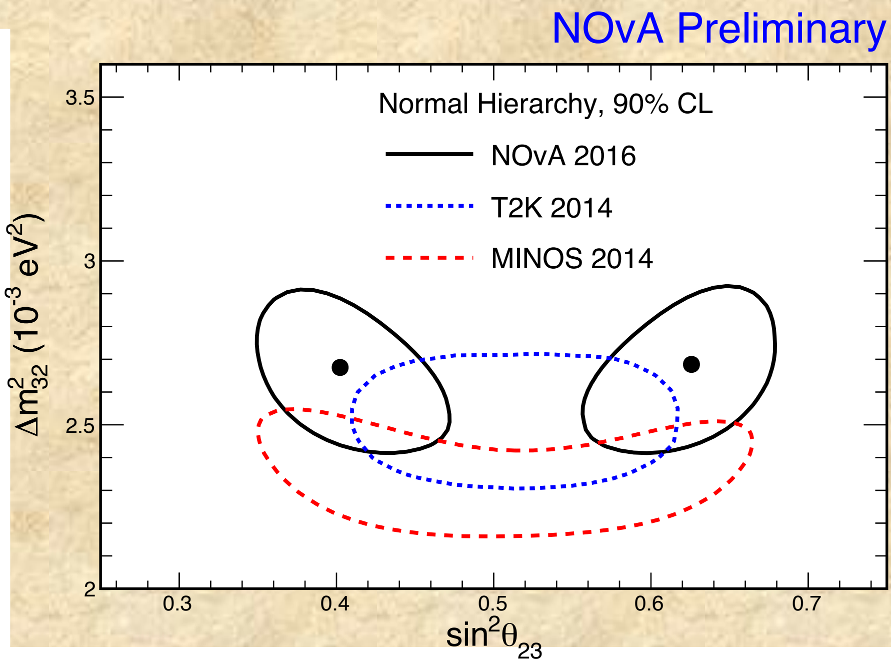
78 Events Observed in FD
473 ± 30 with no Oscillation
82 expected at Best Fit
3.7 Beam bkg + 2.7 Cosmics

χ^2/NDF=41.6/17
Driven by fluctuations in tail,
no pull in oscillation fit



NuMu Disappearance Results. POT = 6.05E20





Dominant systematics included in the fit:

- ✓ Normalization
- ✓ NC Background
- ✓ Flux
- ✓ Muon and hadronic energy scales
- ✓ X-section
- ✓ Detector response and noise

Best Fit (in NH):

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

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

Maximal Mixing excluded at 2.5σ

ν_e Analysis

ν_e Appearance Search

- *Identify contained ν_e CC events in both Near and Far Detector*
- *Use Near Detector Data/MC to predict beam backgrounds in the Far Detector*
- *Extract oscillation information from Far Detector excess over predicted backgrounds*

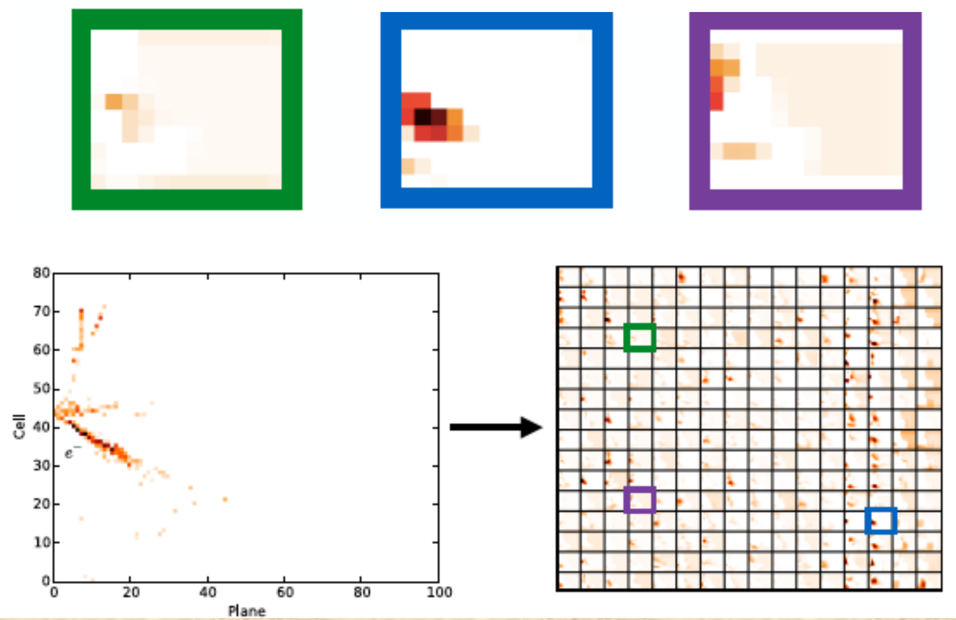
Ist Analysis Published in PRL

✓ Improved Event Selection

A new particle ID techniques used to identify ν_e candidates: A convolutional neural network neutrino event classifier (CVN)

- *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*

Technique published in JINST 11 (2016) no.09, P09001



Improvement in sensitivity from CVN equivalent to 30% more exposure

ν_e Appearance Search

- *Identify contained ν_e CC events in both Near and Far Detector*
- *Use Near Detector Data/MC to predict beam backgrounds in the Far Detector*
- *Extract oscillation information from Far Detector excess over predicted backgrounds*

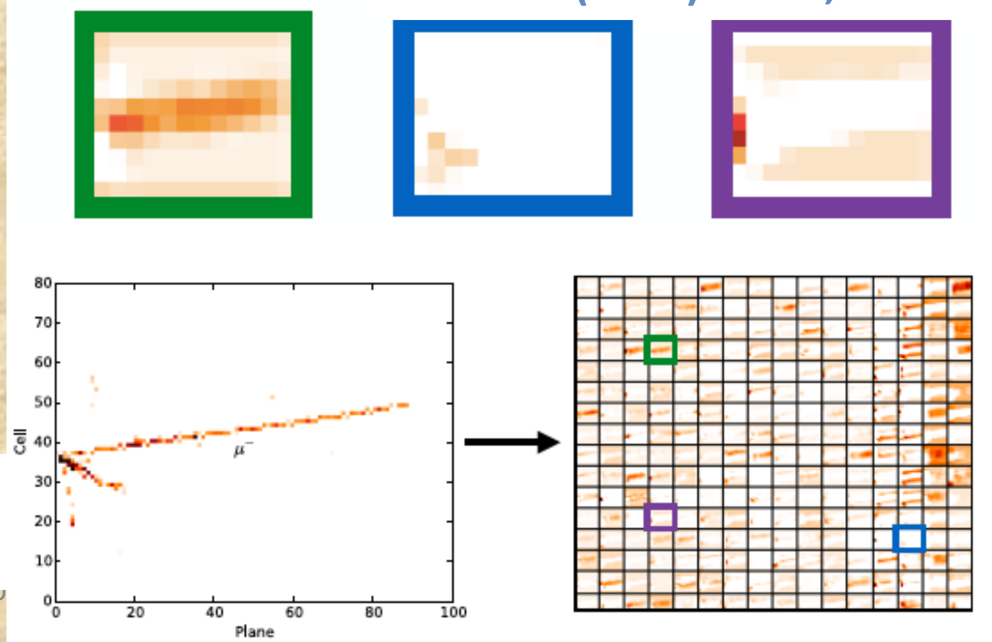
Ist Analysis Published in PRL

✓ Improved Event Selection

A new particle ID techniques used to identify ν_e candidates: A convolutional neural network neutrino event classifier (CVN)

- *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*

Technique published in JINST 11 (2016) no.09, P09001

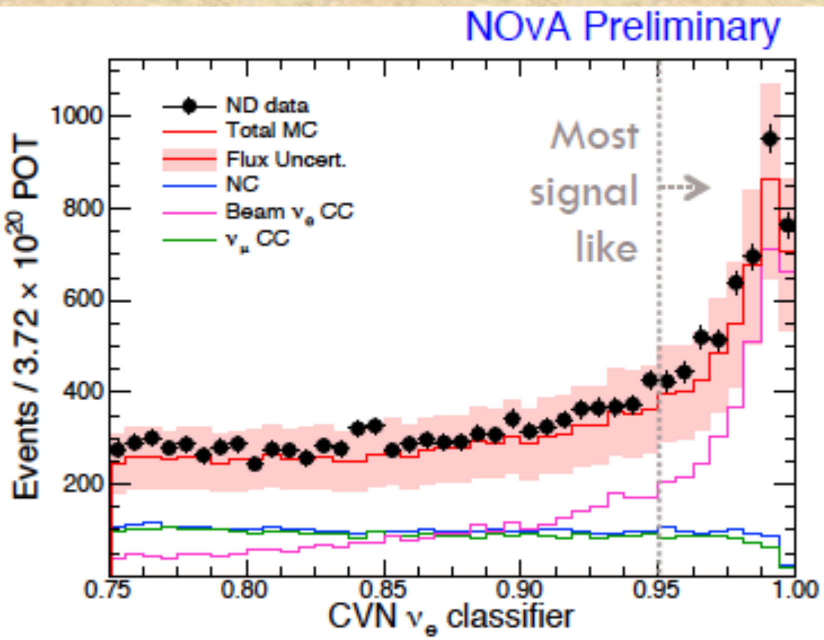


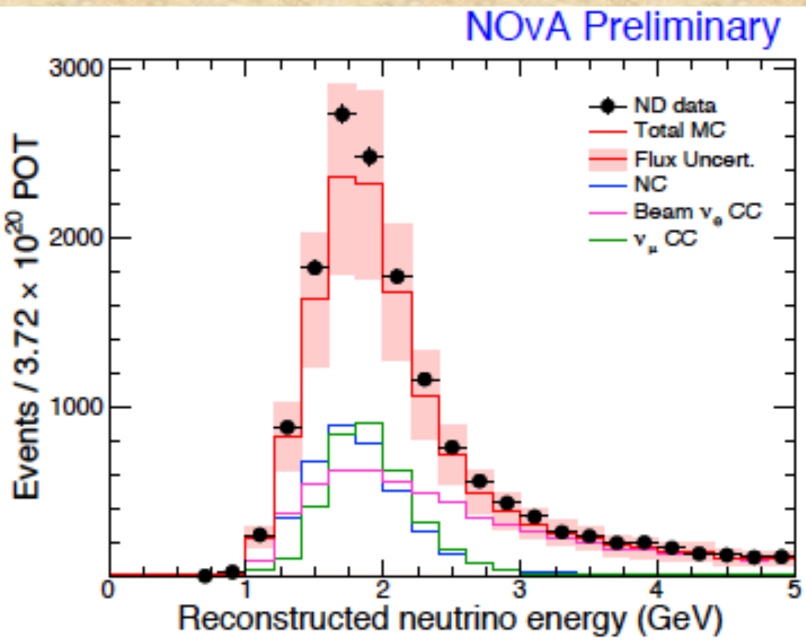
Improvement in sensitivity from CVN equivalent to 30% more exposure

ν_e ND Data

- *Selection optimized to favor parameter measurement*
  - *both cosmic rejection and classifier cut*
  - *increased signal efficiency, including lower purity bins*
- *Used ND data to predict background in FD*
  - *NC, CC, beam ν_e each propagate differently*
  - *constrain beam ν_e using selected ν_μ CC spectrum*
  - *constrain ν_μ CC using Michel Electron distribution*

Beam ν_e up by 4%
NC up by 10%
ν_μ CC up by 17%

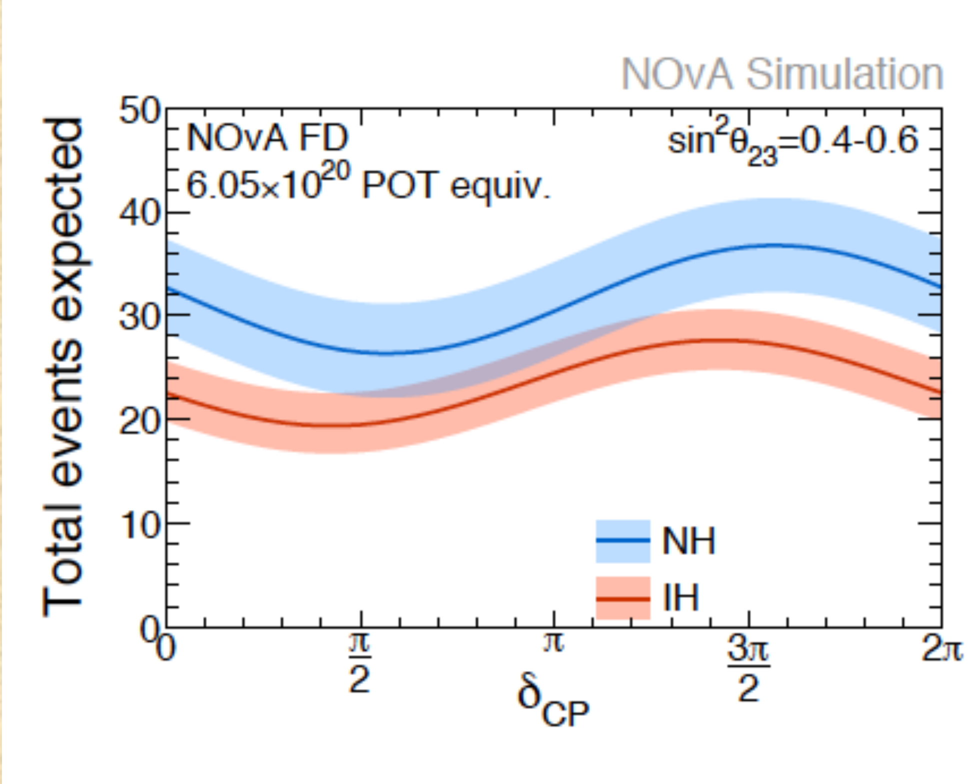




Far Detector ν_e Signal Prediction

- ***Extrapolate each background component in bins of energy and CVN output***
- ***Expected event counts depend on oscillation parameters***
- ***Signal event with ±5% systematics***

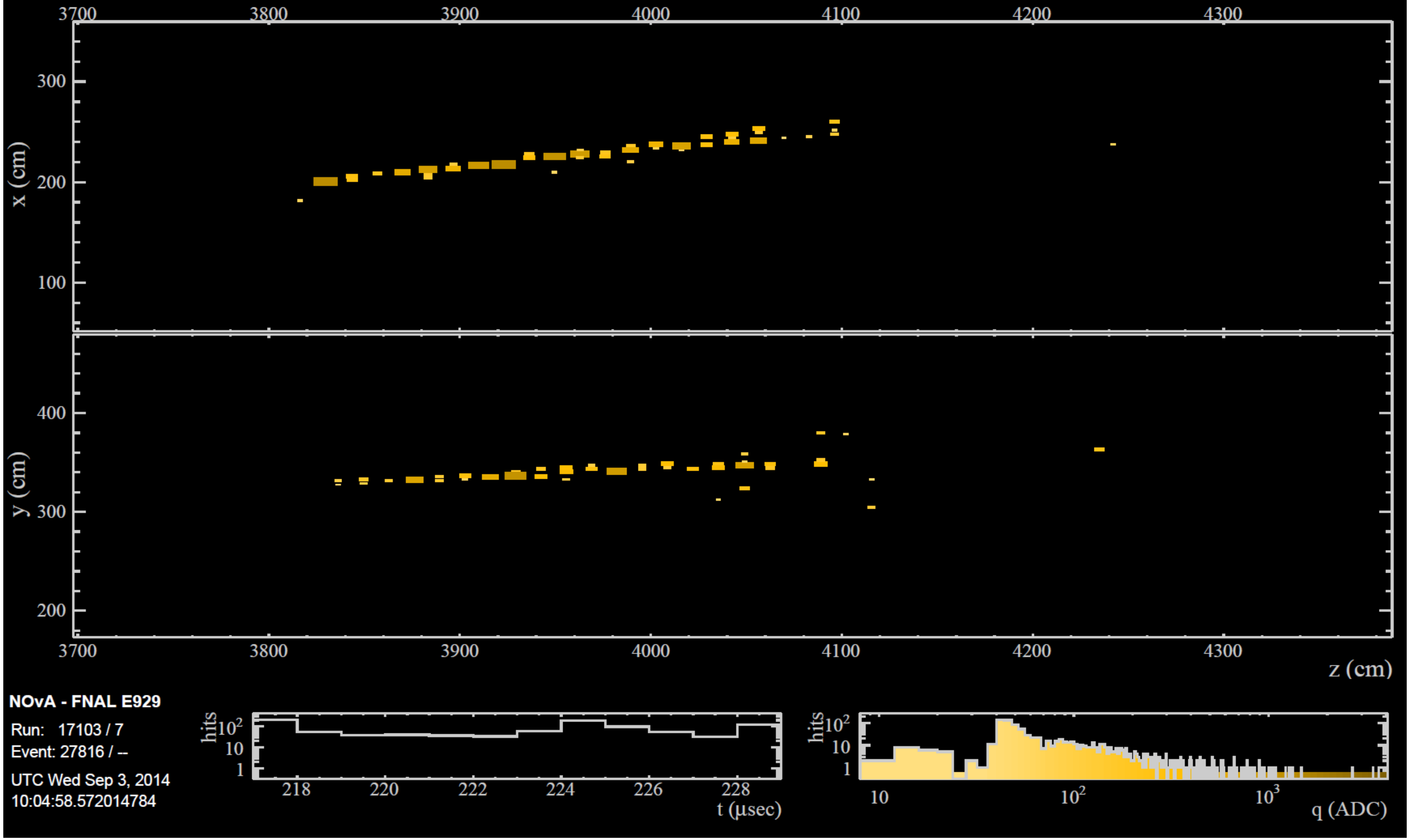
NH, 3π/2,	IH, π/2,
28.2	11.2



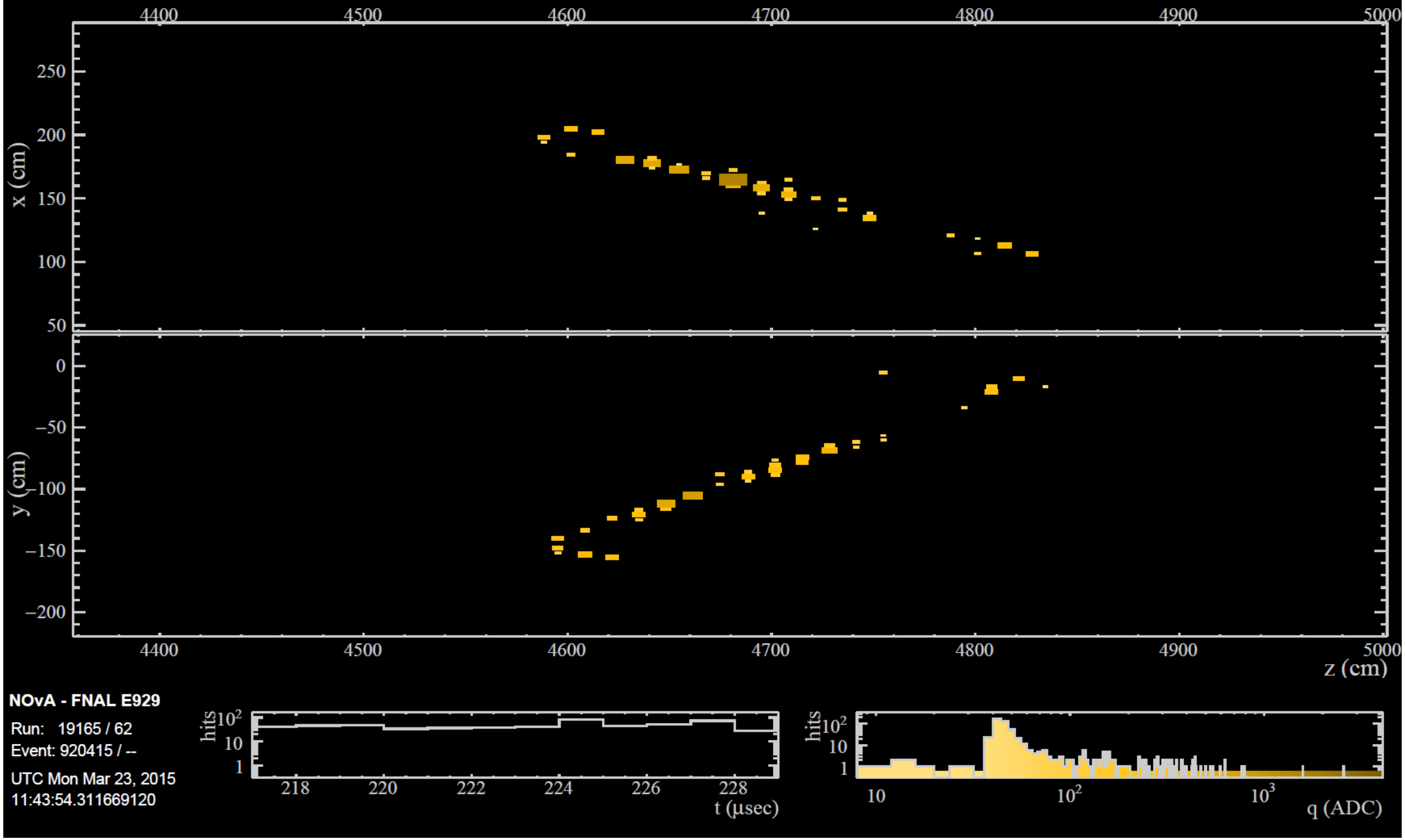
- ***Background by component (±10% systematics)***

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

Far Detector selected ν_e CC candidate

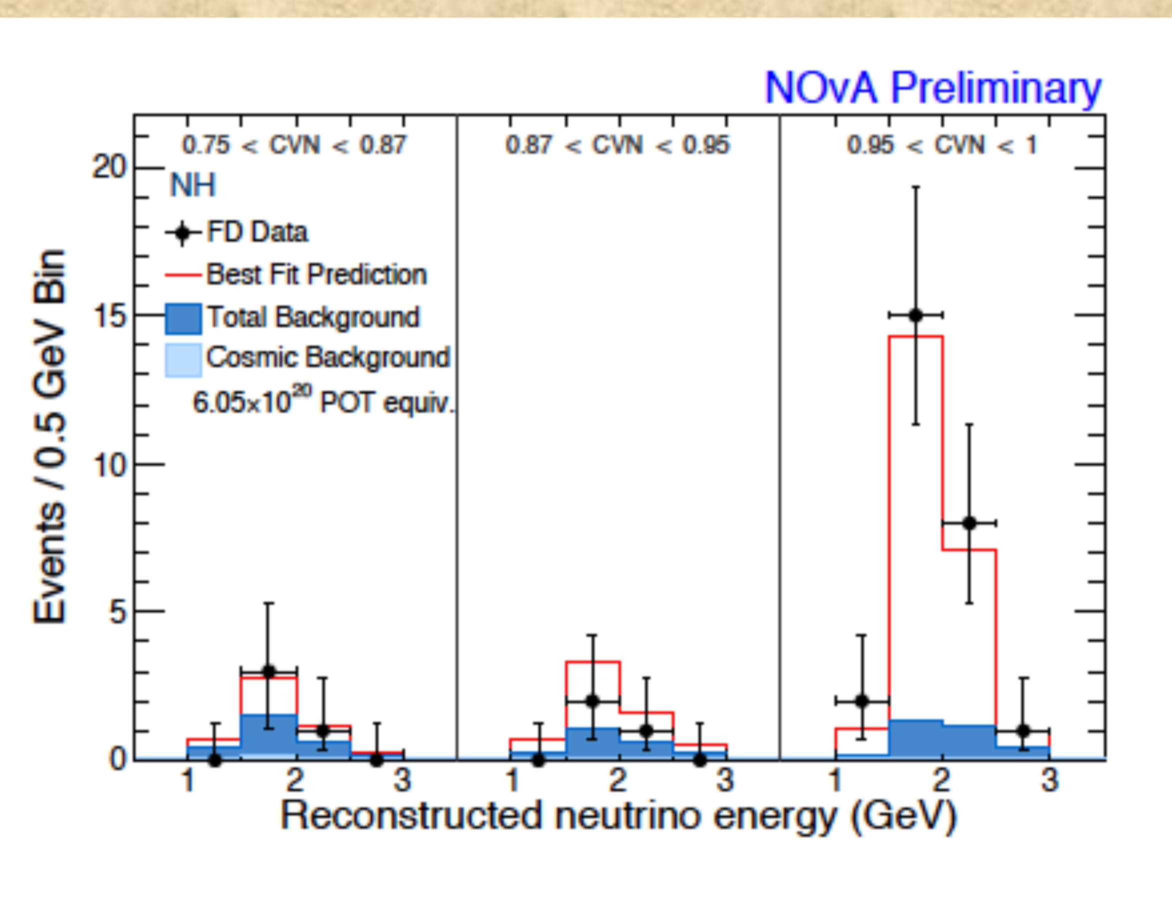


Far Detector selected ν_e CC candidate



Far Detector ν_e Data vs Prediction

>8σ electron neutrino appearance signal

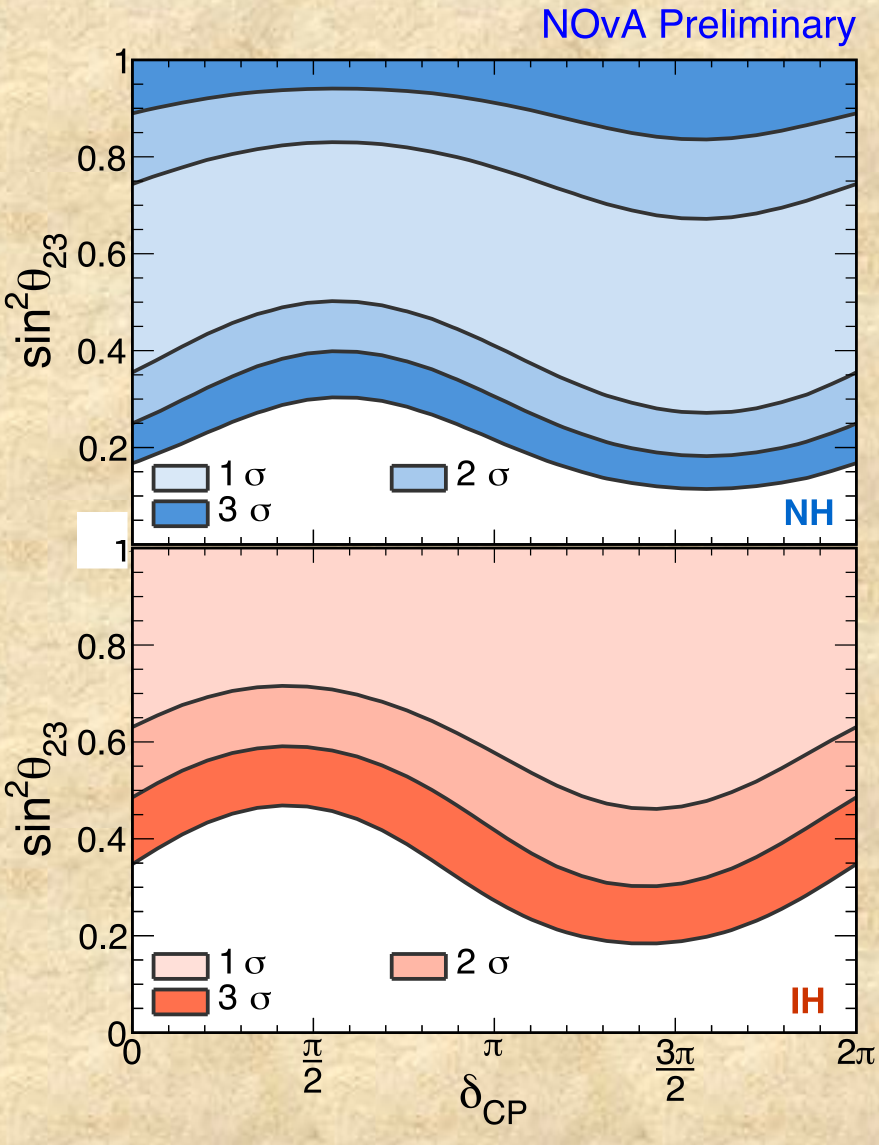


- ***Observed In FD: 33 events***
- ***Background estimate: 8.2 ± 0.8***

Alternate PID selection based on 2015 analysis show consistent results
- ***LID: 34 events, 12.2±1.2 BG expected***
- ***LEM: 33 events, 10.3±1.0 BG expected***

NovA ν_e Appearance Results

- *Fit for hierarchy, δ_{CP}, $\sin^2\vartheta_{23}$*
- *Inputs:*
  - $\sin^2(2\vartheta_{13}) = 0.085 \pm 0.05$
  - $\Delta m^2 = 2.44 \pm 0.06 \times 10^{-3}\ eV^2$, NH
  - $\Delta m^2 = -2.49 \pm 0.06 \times 10^{-3}\ eV^2$, IH
  - *Systematic effects included as nuisance parameters (normalization, flux, calibration, cross-section, and detector response effects)*

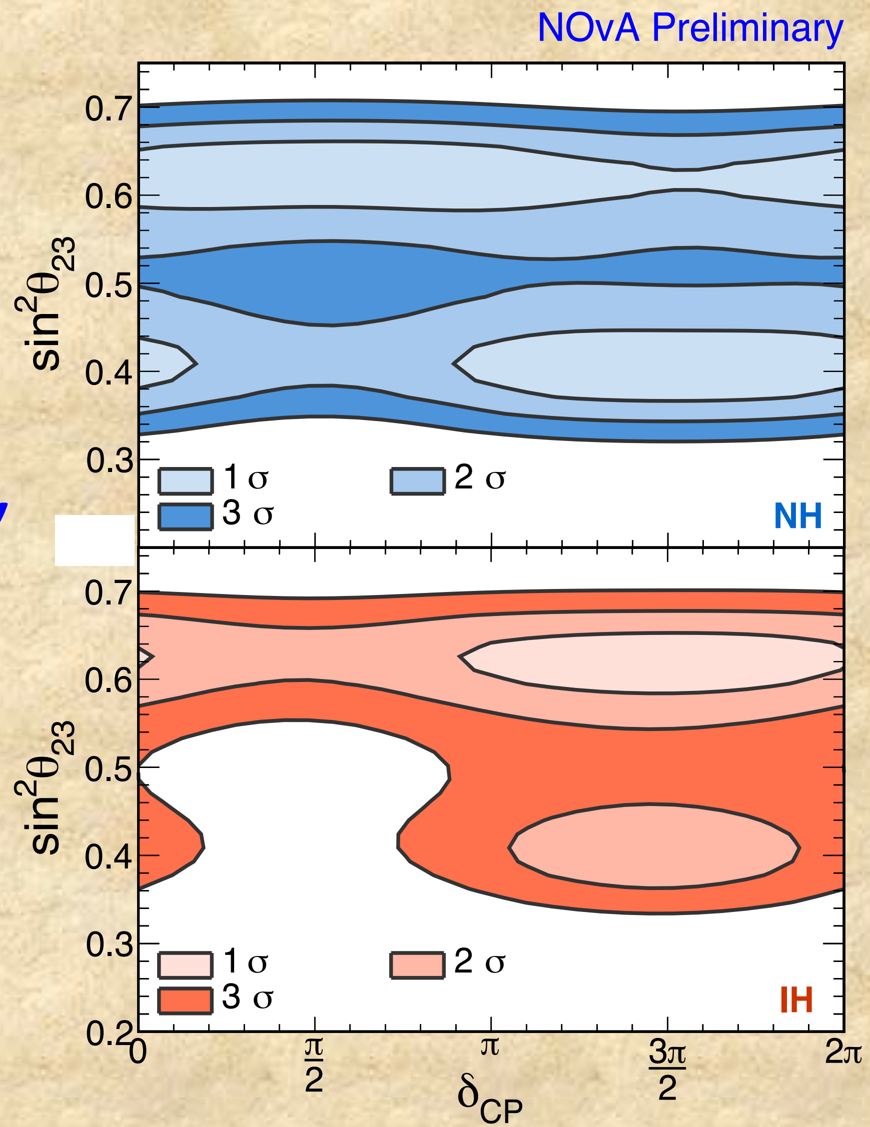


NovA ν_e Appearance Results

- *Fit for hierarchy, δ_{CP}, $\sin^2\vartheta_{23}$*
  - *Constrain Δm^2 and $\sin^2\vartheta_{23}$ with NOvA disappearance results*
  - *Not a full joint fit, systematics and other oscillation parameters not correlated between two samples*
- *Global best fit Normal Hierarchy*

$\delta_{CP} = 1.49\pi$
$\sin^2(\theta_{23}) = 0.40$

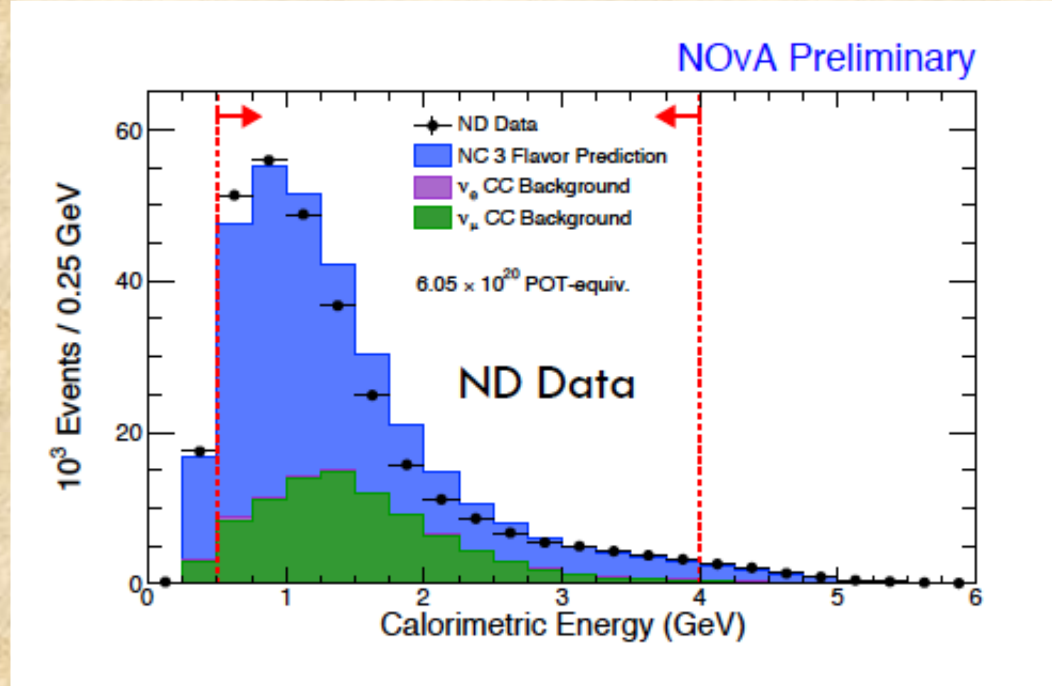
  - *best fit IH-NH, $\Delta\chi^2$=0.47*
  - *both octants and hierarchies allowed at 1σ*
  - *3σ exclusion in IH, lower octant around δ_{CP}=π/2*



ν_s Analysis

Neutral Current ND Data

- ✓ ***Events classified using CVN***
- ✓ ***Normalization agrees well***
- ✓ ***Data shifted to lower energy compared to MC***
  - ✓ ***No MEC model for the NC events***
  - ✓ ***Large uncertainties on the NC X-section***

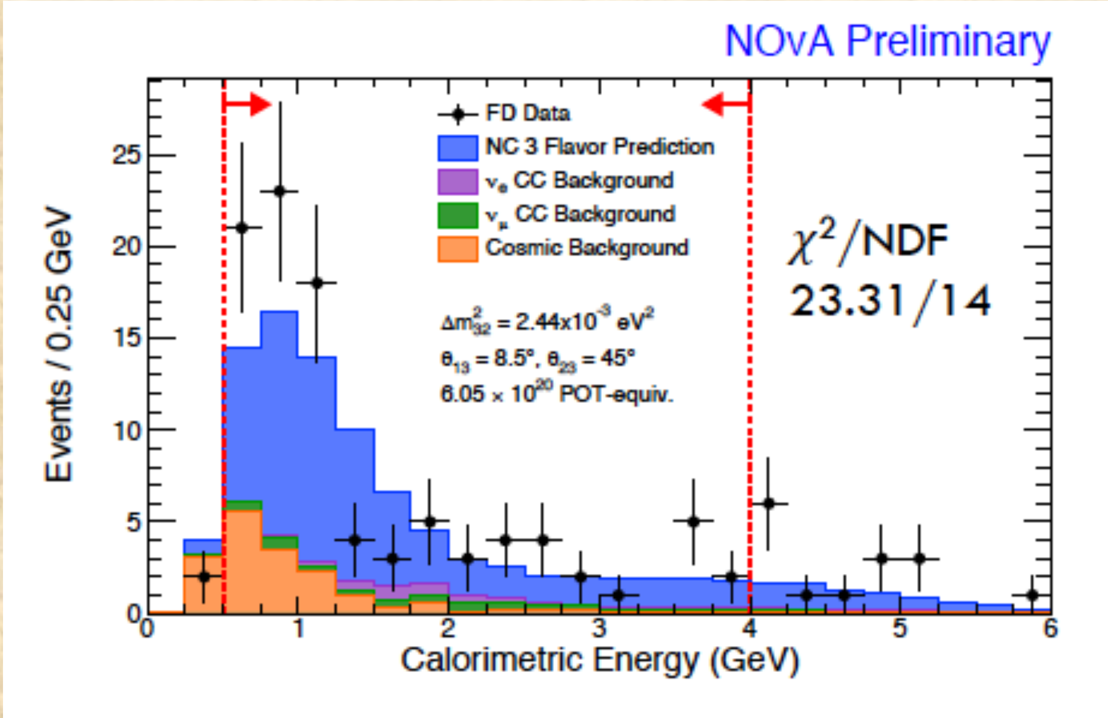


Extrapolation of ND data using F/N in reconstructed energy gives a prediction:

Total	NC	ν_μ CC	Beam ν_e	Cosmics
83.7±8.3	60.6	4.8	3.6	14.3

Neutral Current FD Data

- *Observed 95 events*
- *No oscillation observed in NC Data*

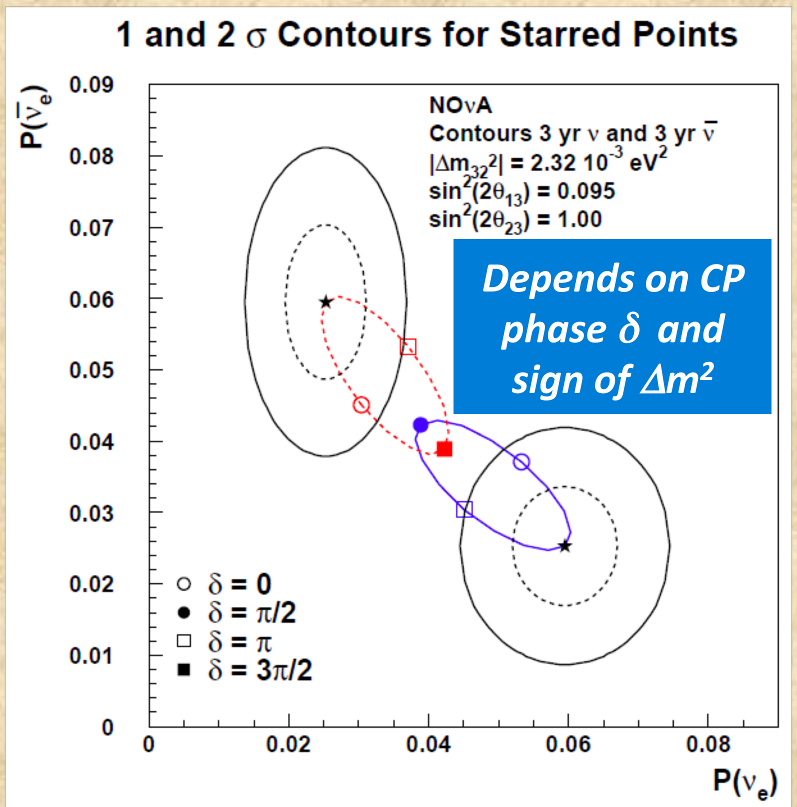


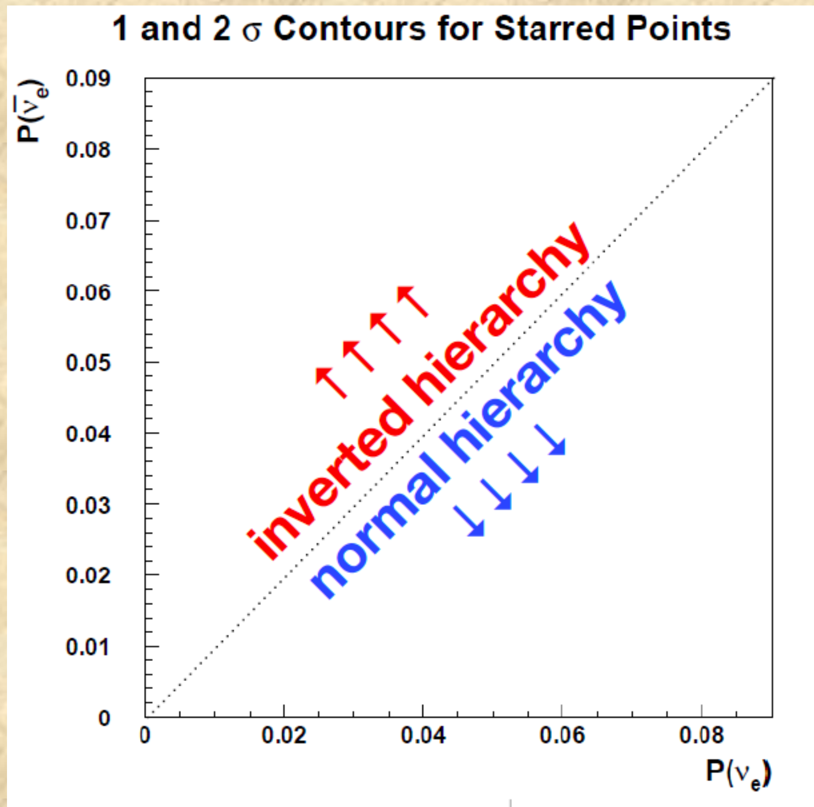
$$\text{For } 0.05\ \text{eV}^2 < \Delta m^2_{41} < 0.5\ \text{eV}^2$$

$$\theta_{34} < 35°,\ \theta_{24} < 21°\ (90\%\text{C.L.})$$

NC efficiency = 50%, Purity = 72%.

NOνA Physics – MH

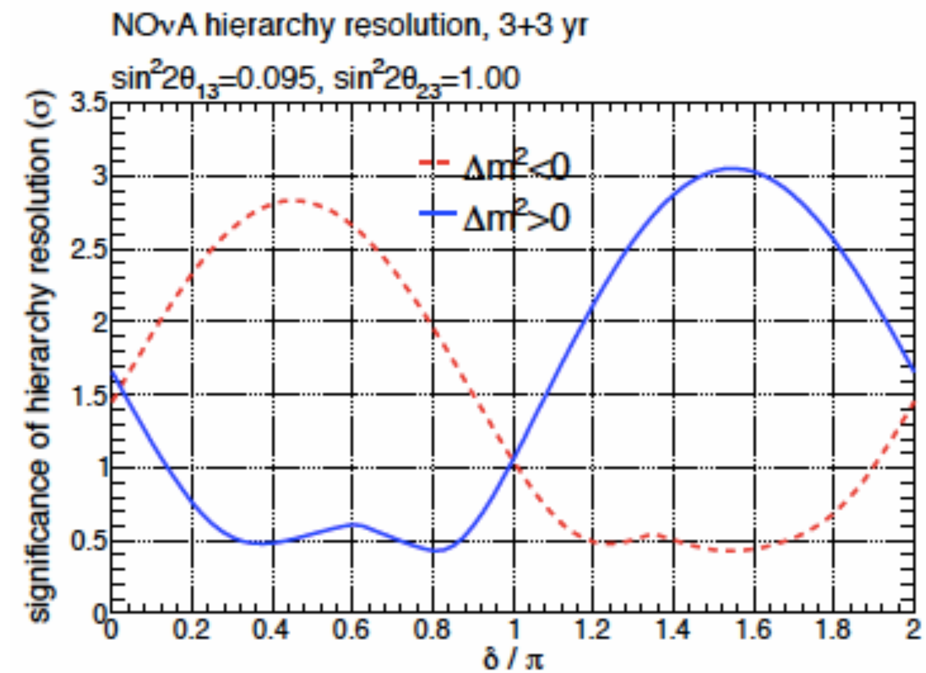




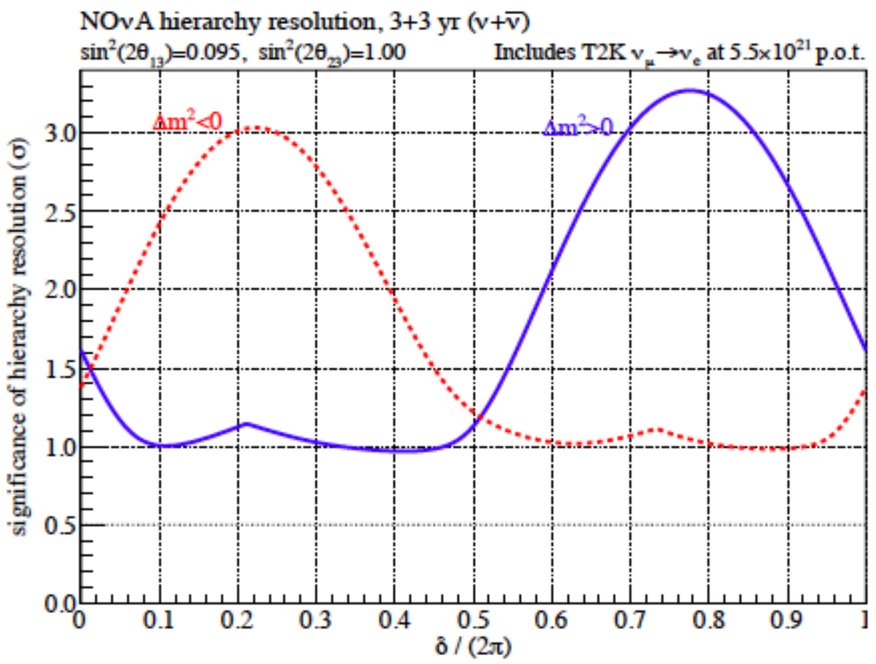
NOνA will measure $P(\nu_\mu \rightarrow \nu_e)$ & $P(\nu bar_\mu \rightarrow \nu bar_e)$ at 2 GeV

Large θ_{13} is better for NOνA. It reduces the overlap between these bi-polarity ellipses, reducing the likelihood of degeneracy

NOνA Physics – MH

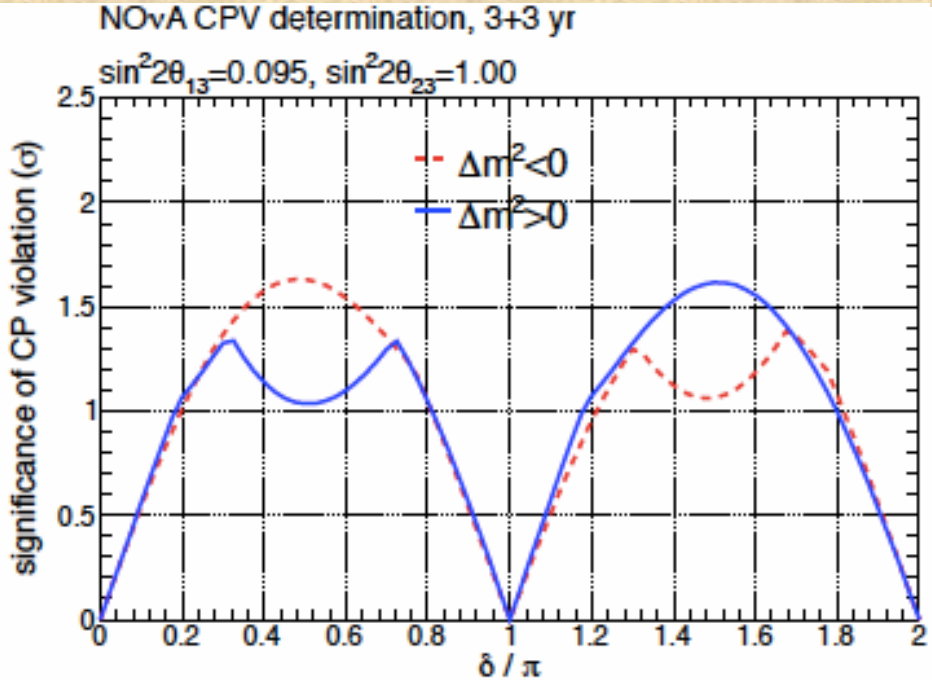


Significance of MH vs δ_{CP}

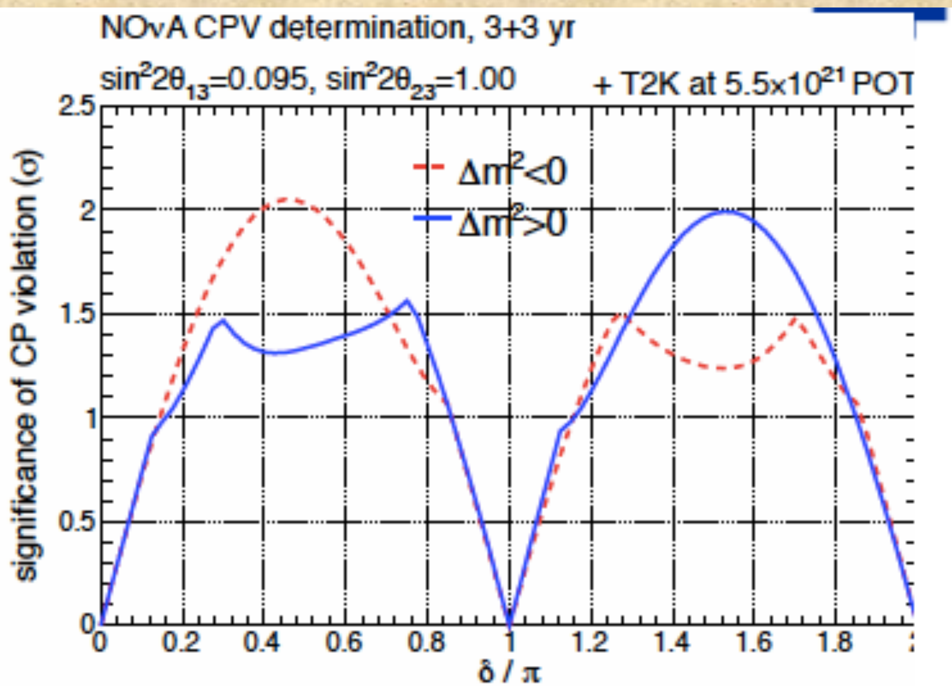


- *3 + 3 years of running in neutrino and anti-neutrino mode.*
- *NOVA data will yield regions in P(ν_e) vs. P(νbar_e) space.*
- *A measurement of the probabilities might allow resolving the MH and provide information on δ_{CP}*
- *Additional sensitivity from T2K.*

NOvA Physics – CPV



Significance of CP violation vs δ_{CP}



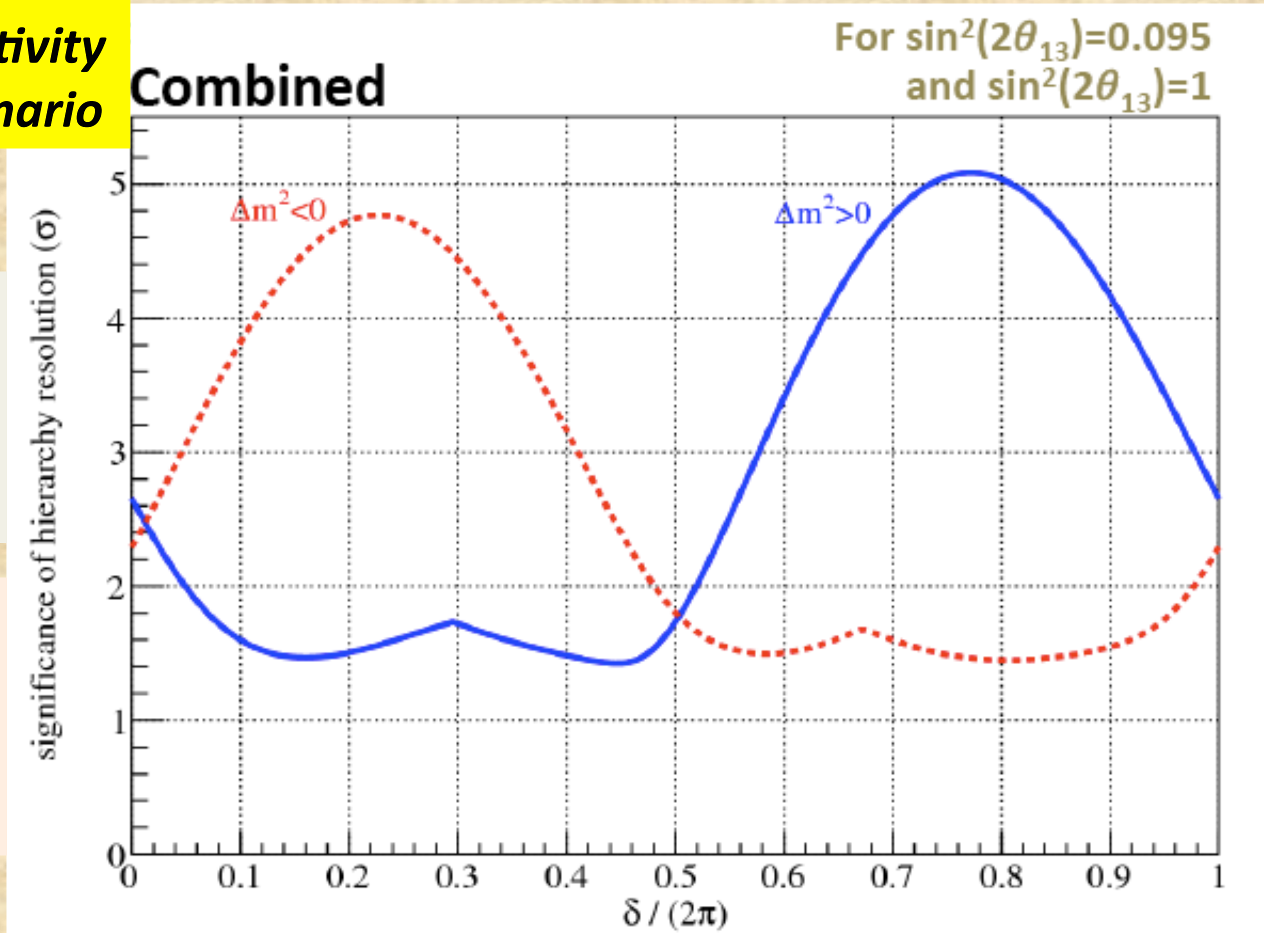
Significance of CP violation vs δ_{CP}

- ***3 + 3 years of running in neutrino and anti-neutrino mode.***
- ***NOVA data will yield regions in P(ν_e) vs. P(νbar_e) space.***
- ***NOvA has limited sensitivity to CP measurement.***
- ***Marginal sensitivity from T2K.***

NOνA in the Long Run?

- ✓ *If NOvA and T2K ran for 12 years each – up to 2025-26*
- ✓ *If NOvA achieves a further 20% and T2K achieves a further 10% gain in sensitivity through analysis improvements*

Raw Hierarchy Sensitivity
Maximal mixing Scenario



Best Sensitivity: 5.1σ

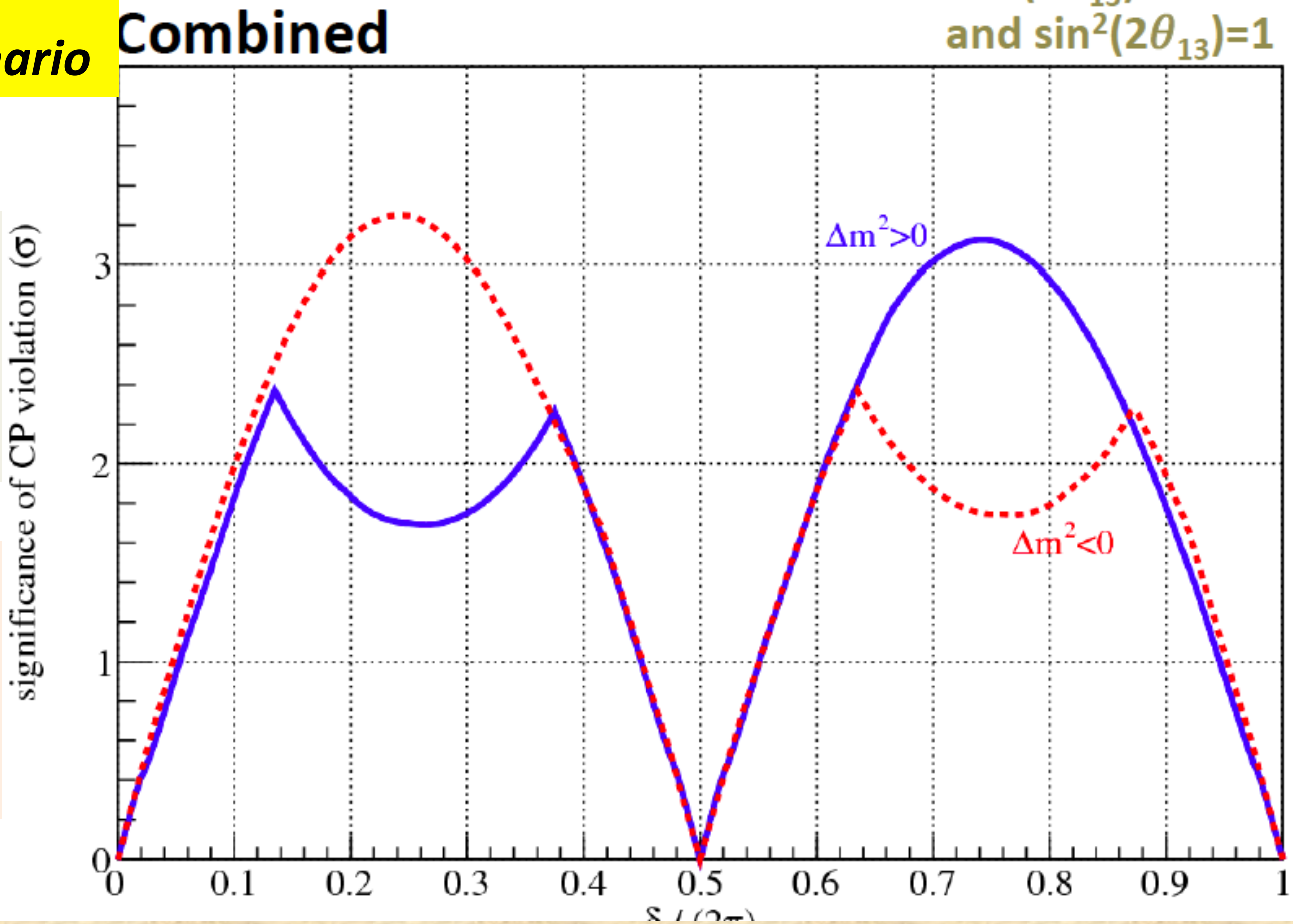
53% of δ range: > 2σ
40% of δ range: > 3σ

For illustration & discussion only:
From Jeff Hartnell's talk: NuFact 2012
Figure Credit: Ryan Patterson

NOνA in the Long Run?

- ✓ *If NOvA and T2K ran for 12 years each – up to 2025-26*
- ✓ *If NOvA achieves a further 20% and T2K achieves a further 10% gain in sensitivity through analysis improvements*

Raw CPV Sensitivity
Maximal mixing Scenario



Best Sensitivity: 3.2σ

50% of δ range: > 2σ
10% of δ range: > 3σ

For illustration & discussion only:
From Jeff Hartnell's talk: NuFact 2012
Figure Credit: Ryan Patterson

NovA Summary and Prospects

- ***NOvA results with 6.05 x 10^{20} POT exposure***
- ***ν_μ Disappearance result***
  -Best fit is non-maximal: Maximal mixing excluded at 2.5σ
- ***ν_e Appearance result***
  -Electron neutrinos appear at > 8σ
  -Data prefers NH at low significance
  -Region in IH, lower octant around $\delta_{CP} = \pi/2$ is excluded
- ***Neutral current event rate shows no evidence of sterile neutrinos***
  -With more data, expect strong limits on ϑ_{34}
- ***NOvA to take anti-neutrino data***
  -Short anti-neutrino run taken in Summer 2016
  -Long anti-neutrino run anticipated to start in Spring 2017

LBNF/DUNE

Long-Baseline Neutrino Facility

Deep Underground Neutrino Experiment

LBNF – DUNE Science Goals

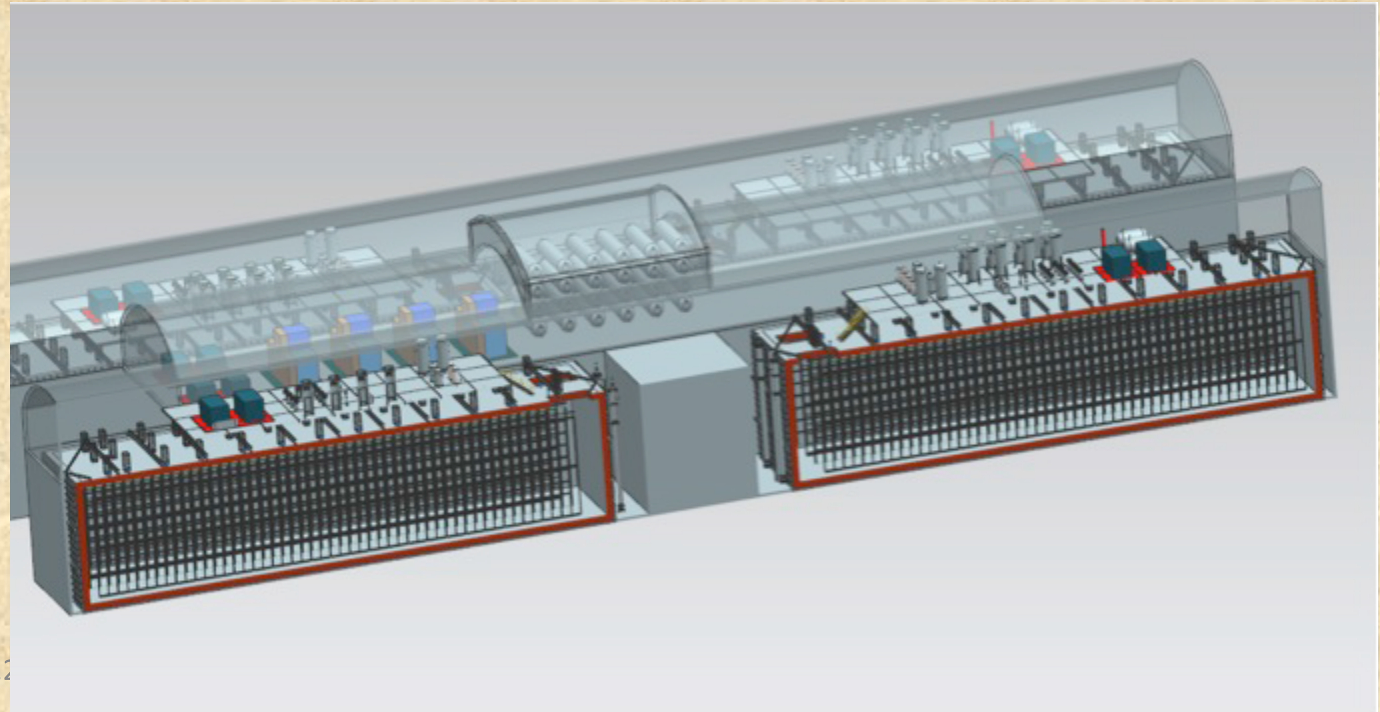
- ***CP Violation in the Neutrino Sector***
- ***Neutrino Mass Hierarchy***
- ***Testing the Three-Flavor Paradigm***
- ***Nucleon Decay***
- ***Astrophysics: Supernova ν burst and Low energy Neutrinos***

A Global Collaboration of 856 collaborators from 149 institutions and 29 countries – several institutions from India too.

DUNE – Far Detectors – 40kt LAr TPC Modules

Cavern layout at the Stanford Underground Research Facility (SURF):

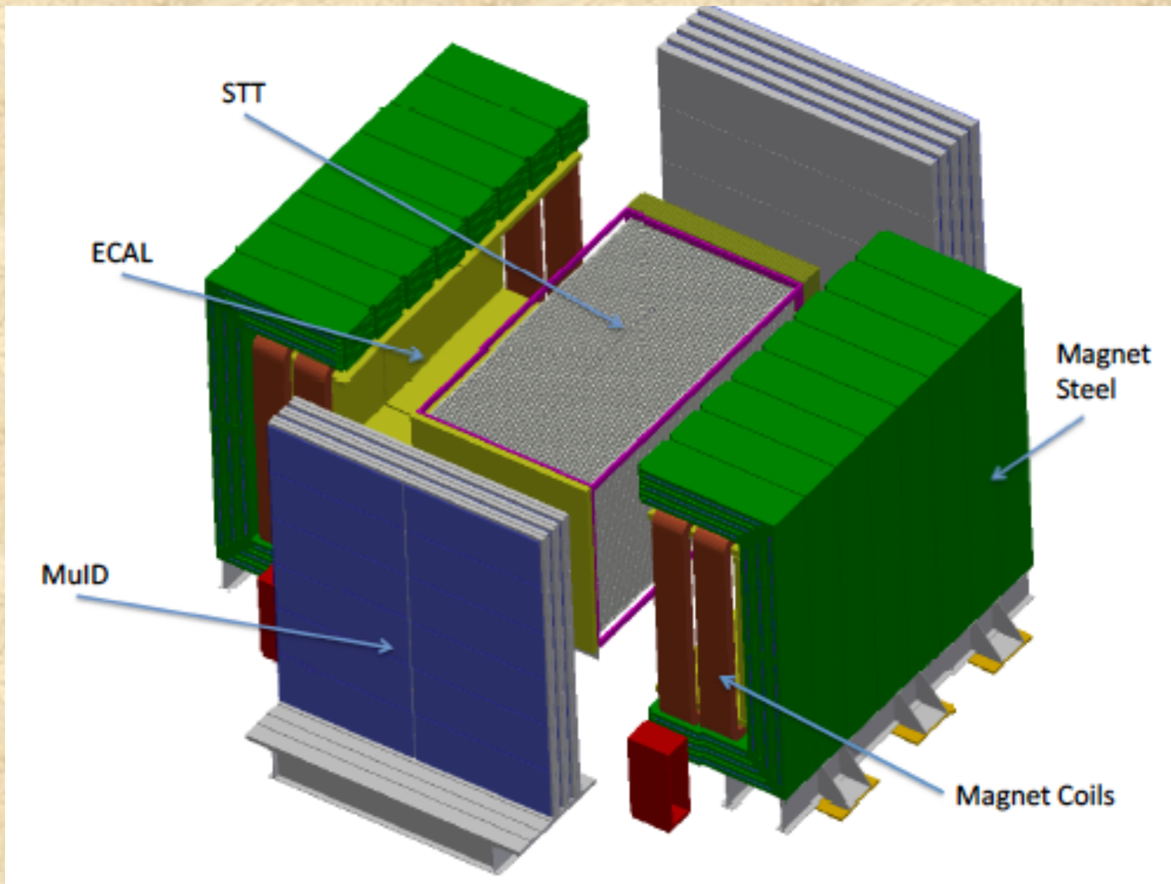
- ✓ **Four chambers hosting four independent 10kT FD modules**
  - ❖ **Gives flexibility for staging & evolution of LAr-TPC technology design**
    - ➢ **Assume four identical cryostats: 15.1 (W) X 14.0 (H) X 62 (L) m^3**
    - ➢ **The four 10kT modules will be similar but may not be identical**



DUNE – Far Detectors – Development

- ✓ **Single-phase LAr-TPC (APA Readout)**
  - ➢ **Evolution from ICARUS – design well advanced**
  - ➢ **Supported by strong program at Fermilab**
    - ❖ **35-t prototype (run ended 01/2016)**
    - ❖ **Micro-BooNE (operational since 2015)**
    - ❖ **SBND (aiming for operation in 2018)**
- ✓ **Dual-phase LAr-TPC (CRP Readout)**
  - ➢ **Demonstrated at 200-*l* scale**
  - ➢ **Large scale demonstration at CERN**
  - ➢ **WA105 1X1X3 m^3 prototype at CERN**
- ➢ **Proto-DUNE at CERN NP**
  - ➢ **Large scale (~6X6X6 m^3) engineering prototypes**
  - ➢ **Formed from full-scale detector elements**
  - ➢ **6 full-sized APAs c.f. 150 APAs in 10-kT FD modules**

DUNE ND – High Resolution FGT

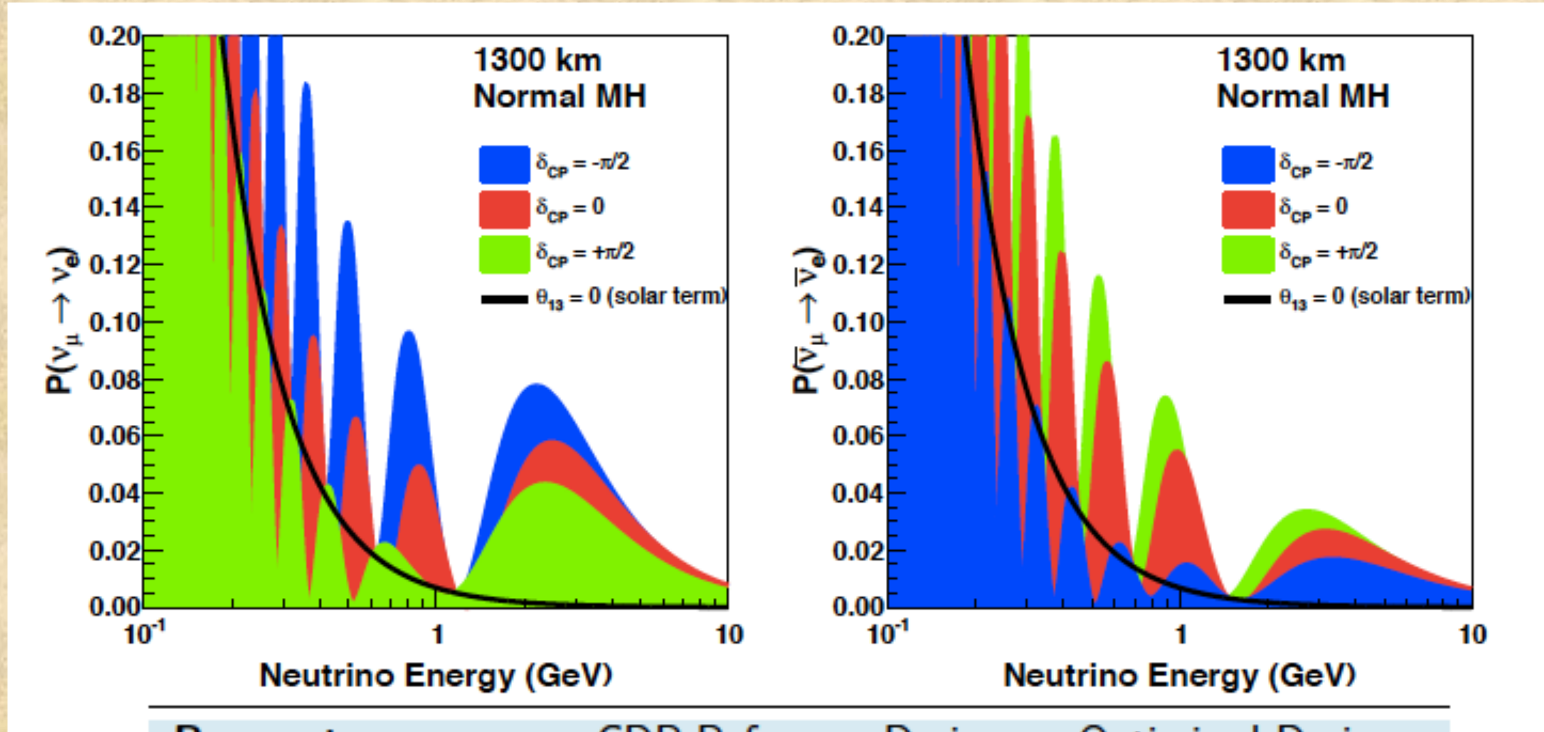


Precisely measure neutrino beam spectra and flavor
Constraint systematics
Neutrino Interaction Physics
New Searches

- ~3.5m x 3.5m x 7m STT ($\rho \simeq 0.1 gm/cm^3$)
- 4π-ECAL in a Dipole-B-Field (0.4T)
- 4π-μ-Detector (RPC) in Dipole and Downstream
- Pressurized Ar-target (≃x5 FD-Stat) ⇛ LAr-FD

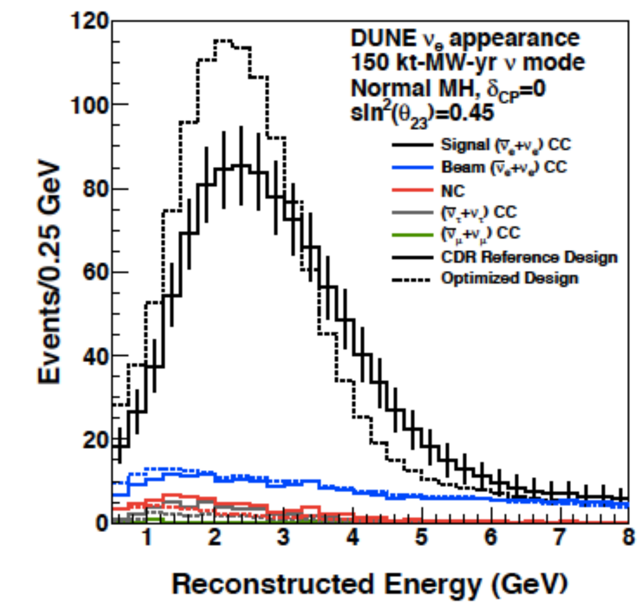
Transition Radiation ↠ $e^{+/-}$ ID ⇒ γ
dE/dx ↠ Proton, $\pi^{+/-}$, $K^{+/-}$
Magnet/Muon Detector ↠ $\mu^{+/-}$ $e^{+/-}$
(⇛ *Absolute Flux measurement*)

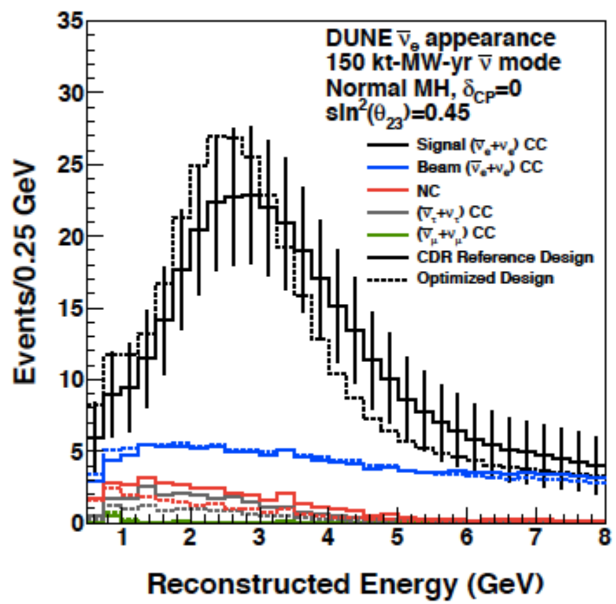
DUNE Beam Design Optimization

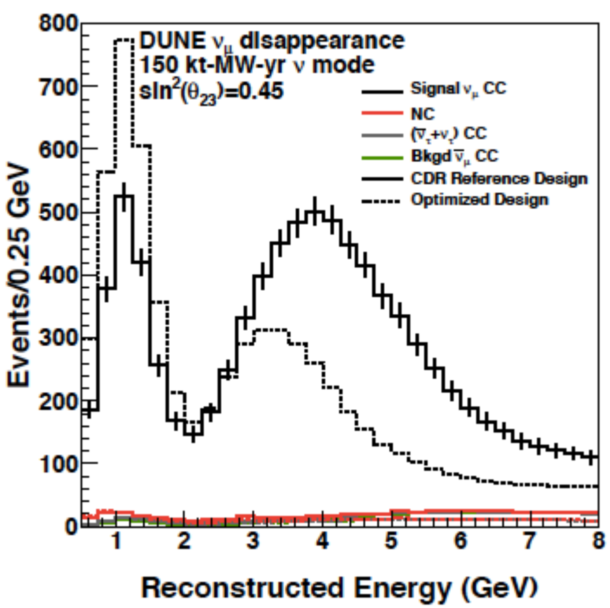


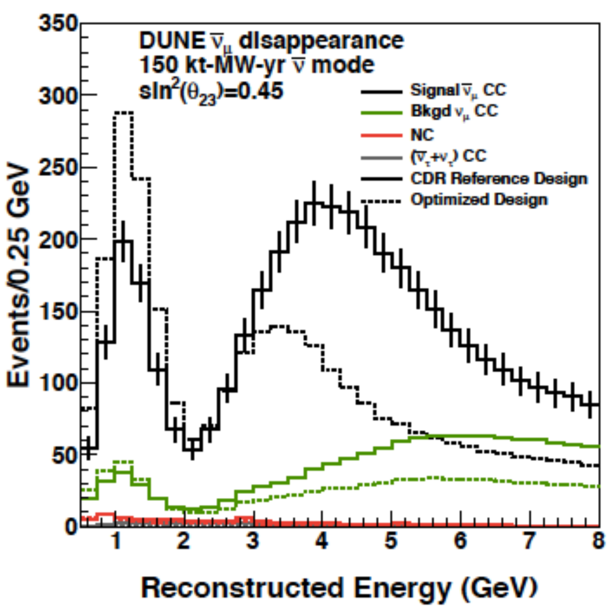
Parameter	CDR Reference Design	Optimized Design
Proton Beam Energy	80 GeV	80 GeV
Proton Beam Power	1.07 MW	1.07 MW
Target	Graphite	Graphite
Horn Current	230 kA	297 kA
Horn Design	NuMI-style	Genetic Optimization
Decay Pipe Length	204 m	241 m
Decay Pipe Diameter	4 m	4 m

DUNE – Appearance Spectra

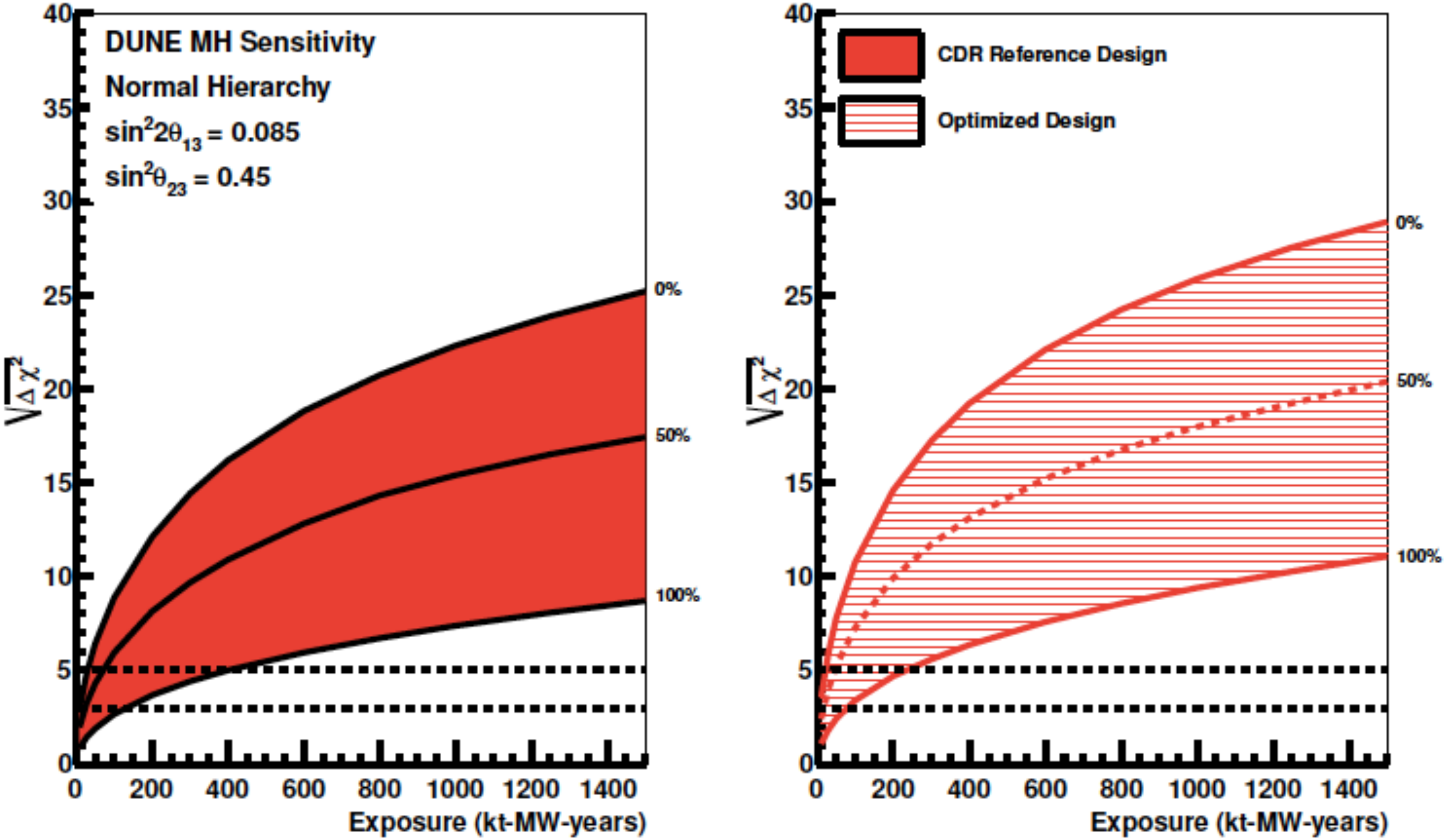




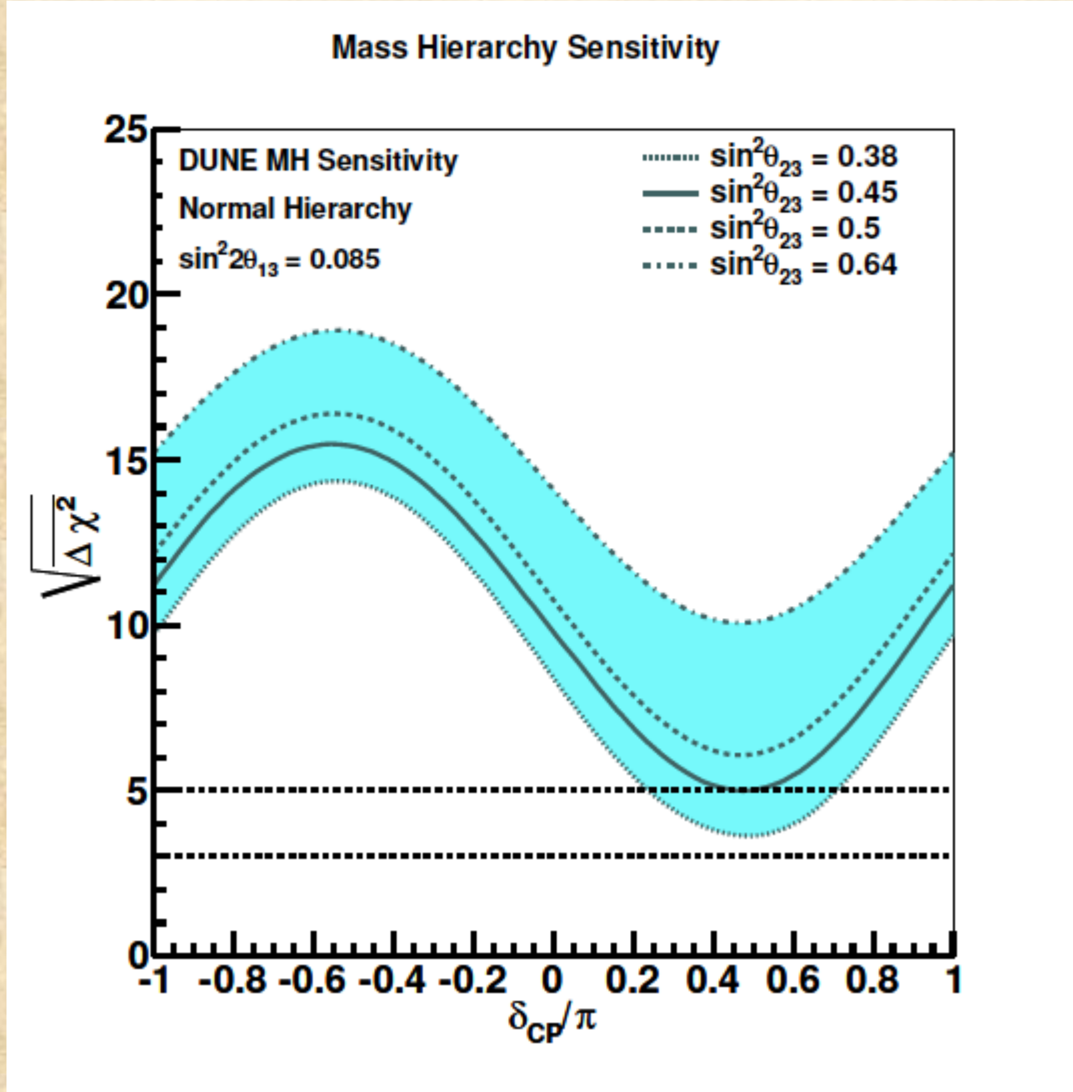




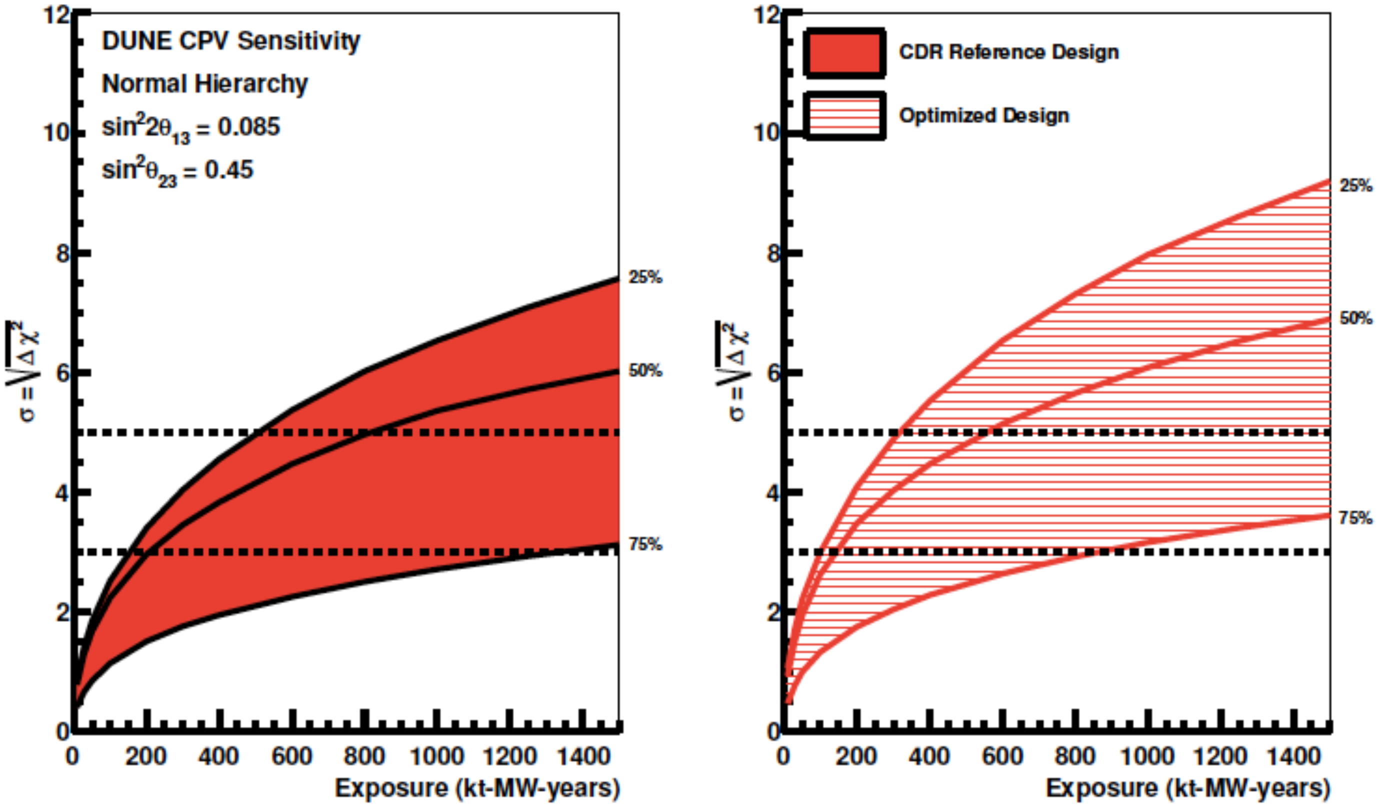
DUNE Sensitivity to MH



DUNE Sensitivity to MH

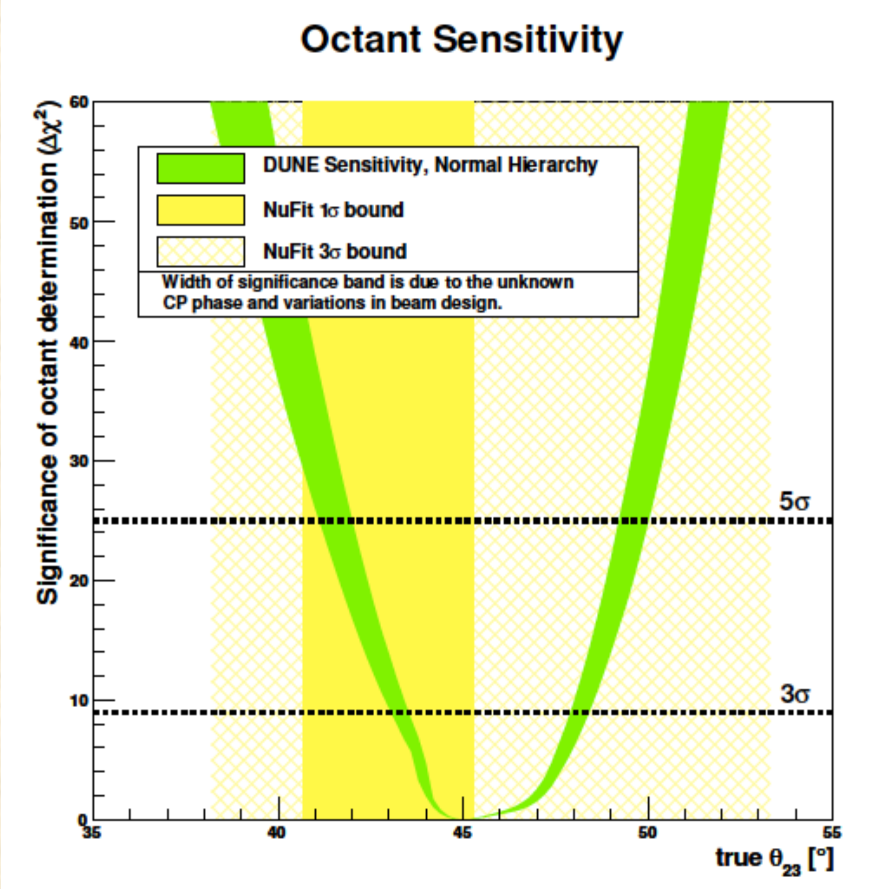


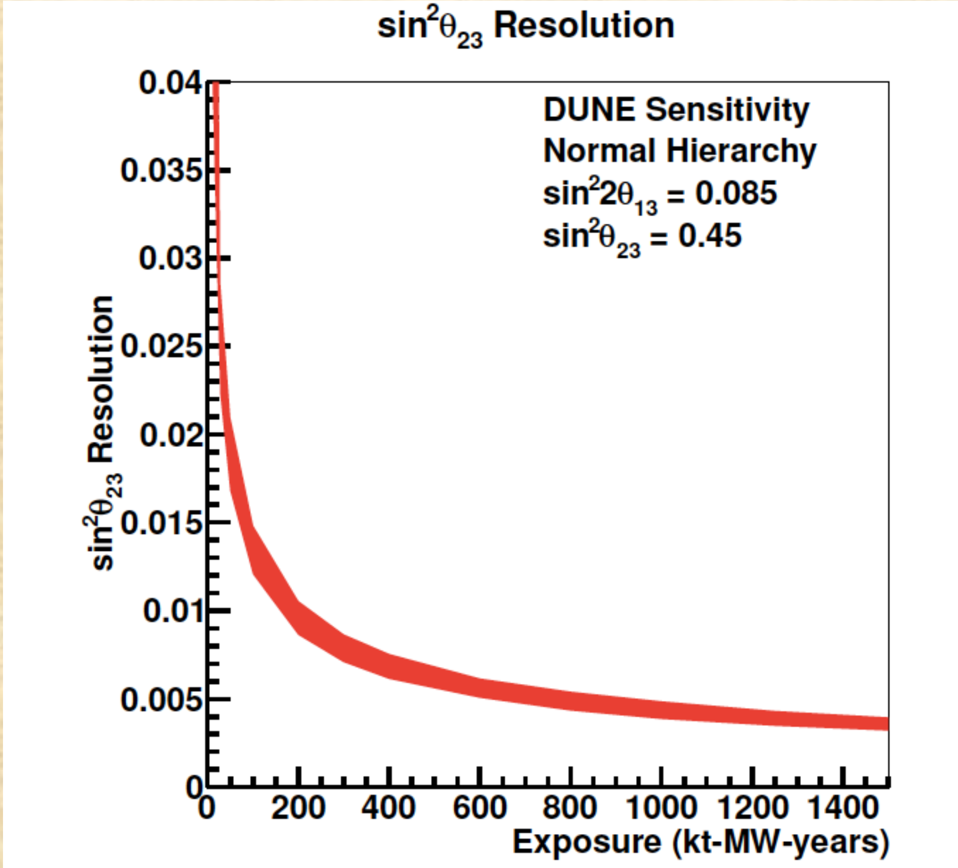
DUNE Sensitivity to CPV



Significance	CDR Reference Design	Optimized Design
3σ for 75% of δ_{CP} values	1320 kt · MW · year	850 kt · MW · year
5σ for 50% of δ_{CP} values	810 kt · MW · year	550 kt · MW · year

DUNE - Octant Sensitivity & $Sin^2\vartheta_{23}$ Resolution

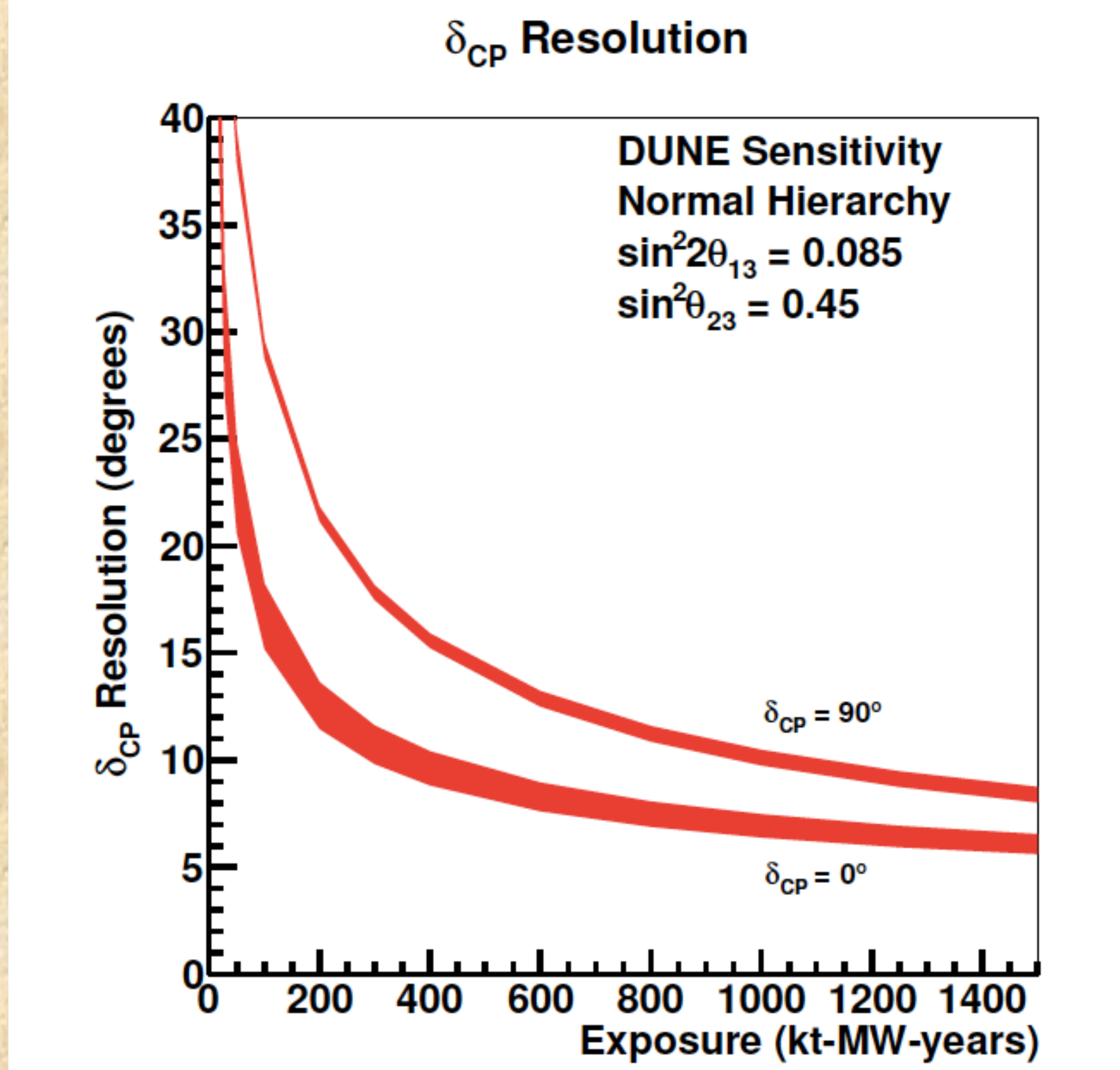




1320 kt-MW-yr – Reference Beam
850 kt-MW-yr – Optimized Beam, for 3σ significance.
Band in green shaded – due to beam design and true value of δ_{CP}

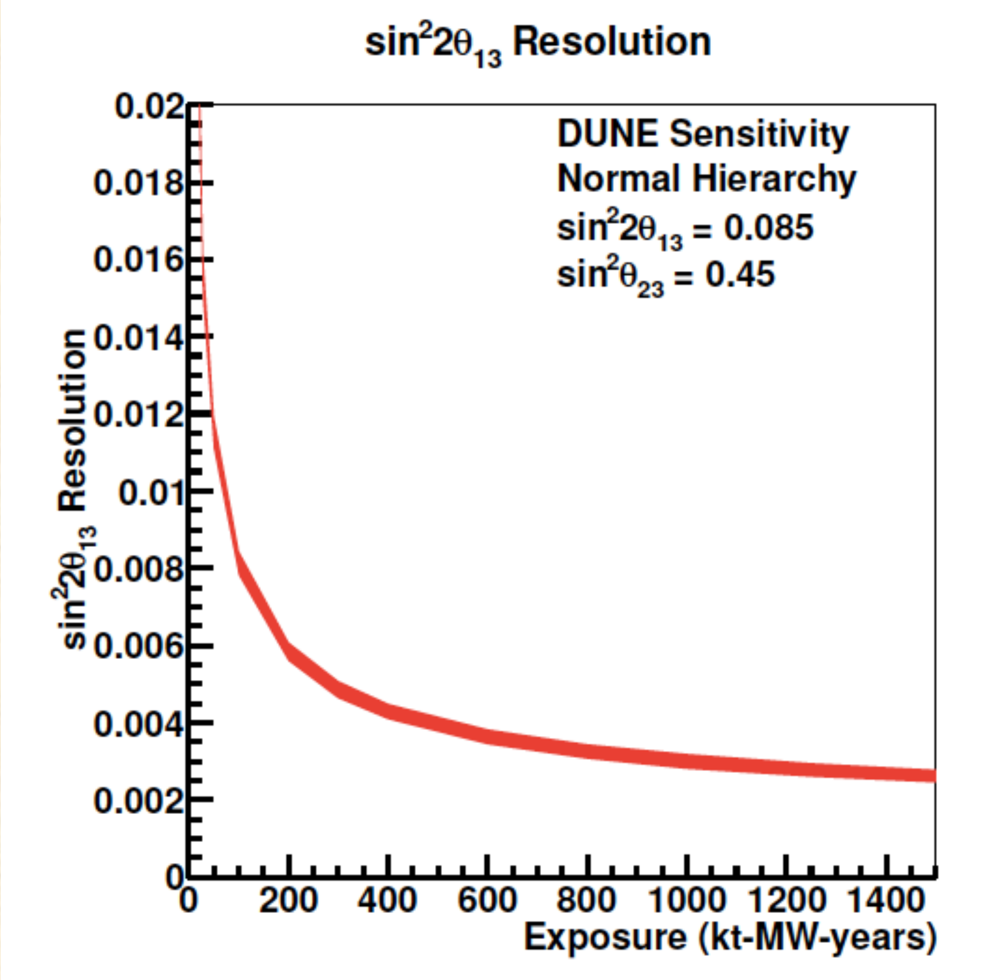
The shaded region represents the range in sensitivity due to potential variation in beam design

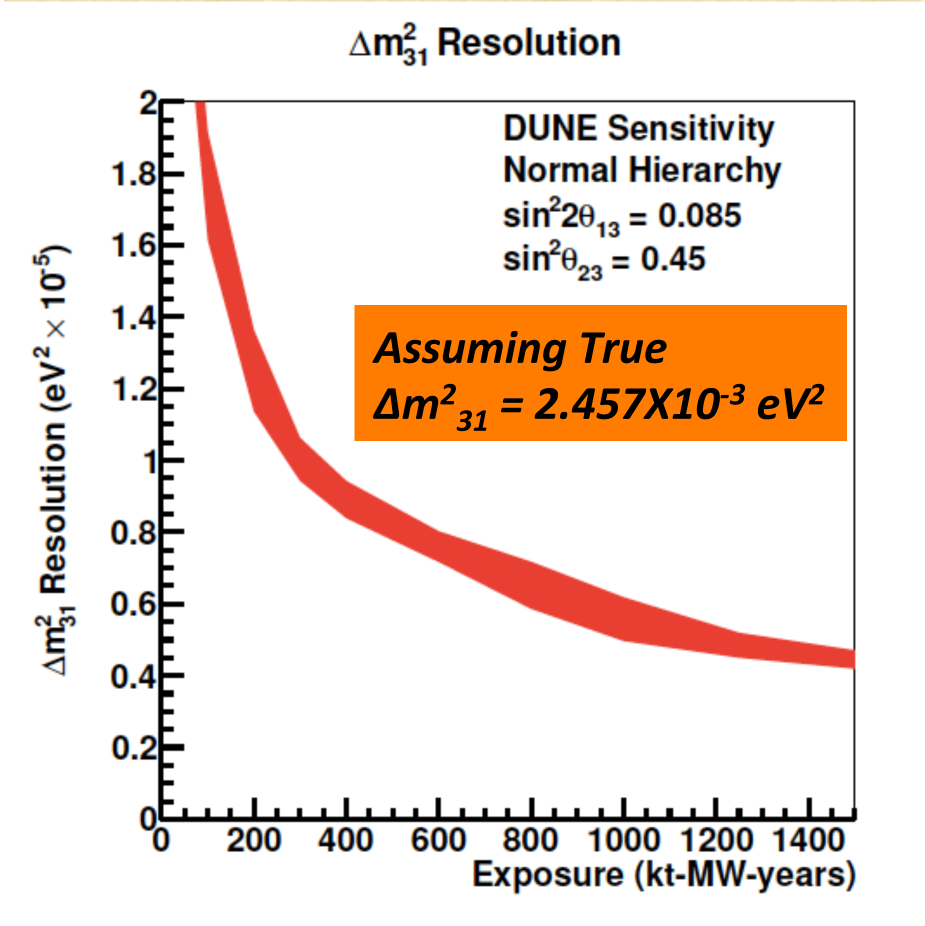
DUNE – δ_{CP} Resolution



The shaded region represents the range in sensitivity due to potential variation in beam design.

DUNE – $Sin^2 2\vartheta_{13}$ and Δm^2_{31} Resolution





The shaded region represents the range in sensitivity due to potential variation in beam design.

Physics Milestones – Early Physics Possible

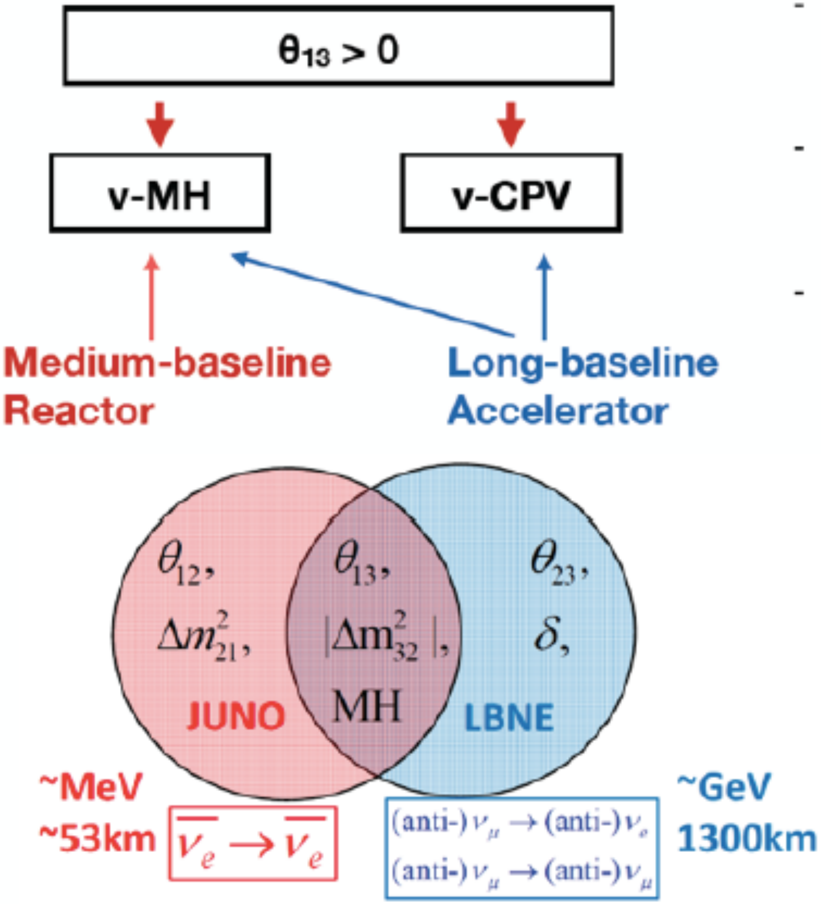
Physics milestone	Exposure kt · MW · year (reference beam)	Exposure kt · MW · year (optimized beam)
$1°$ θ_{23} resolution ($\theta_{23} = 42°$)	70	45
CPV at 3σ ($\delta_{\rm CP} = +\pi/2$)	70	60
CPV at 3σ ($\delta_{\rm CP} = -\pi/2$)	160	100
CPV at 5σ ($\delta_{\rm CP} = +\pi/2$)	280	210
MH at 5σ (worst point)	400	230
$10°$ resolution ($\delta_{\rm CP} = 0$)	450	290
CPV at 5σ ($\delta_{\rm CP} = -\pi/2$)	525	320
CPV at 5σ 50% of $\delta_{\rm CP}$	810	550
Reactor θ_{13} resolution ($\sin^2 2\theta_{13} = 0.084 \pm 0.003$)	1200	850
CPV at 3σ 75% of $\delta_{\rm CP}$	1320	850

Best Case Scenario:

CPV (δ_{CP} = +π/2) – 60-70 kt.MW.yr for 3σ sensitivity

MH – 20-30 kt.MW.yr for 5σ sensitivity

Precision measurements of U_{PMNS} with laboratory experiments.



- Why is leptonic mixing angles large compared to quark mixing in CKM?
- Is there any pattern in U_{PMNS} that guide us to the theory of flavor
- Is U_{PMNS} unitary?

The journey of PMNS unitarity test in the precision neutrino physics era just began!

X.Qian, C.Zhang, P.Vogel, M.Diwan arXiv: 1308.5700

And, huge opportunities for underground science! proton decay, supernova… etc

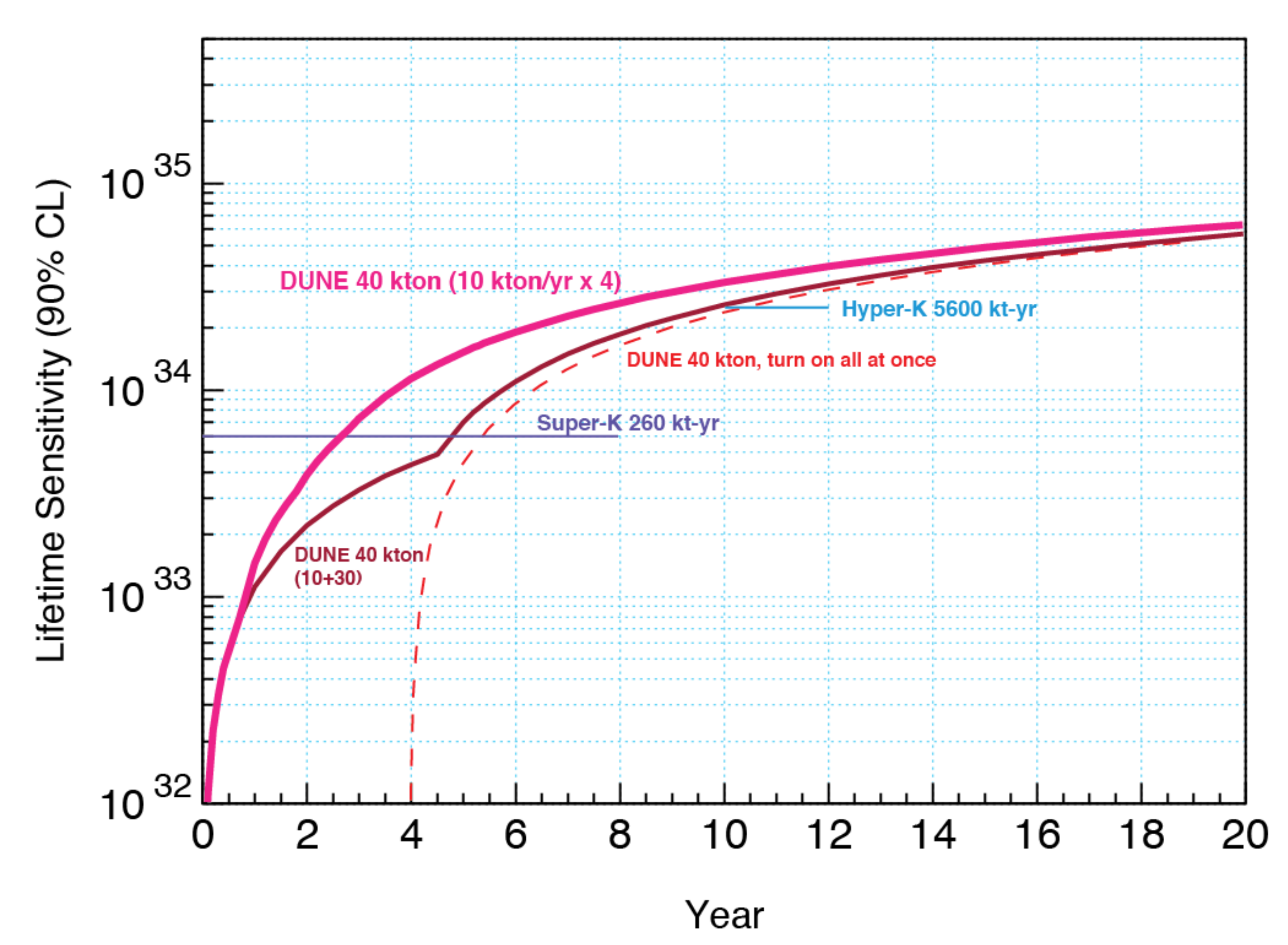
	JUNO	LBNE
$\sin^2 2\theta_{12}$	0.7%	
Δm^2_{21}	0.6%	
$\lvert\Delta m^2_{32}\rvert$	0.5%	0.3%
MH	3-4σ*	>5σ
$\sin^2 2\theta_{13}$	14%**	3%
$\sin^2\theta_{23}$		3%
δ_{CP}		10°

* 4σ requires 1% $\lvert\Delta m^2_{\mu\mu}\rvert$ ** Daya Bay reaches 3%

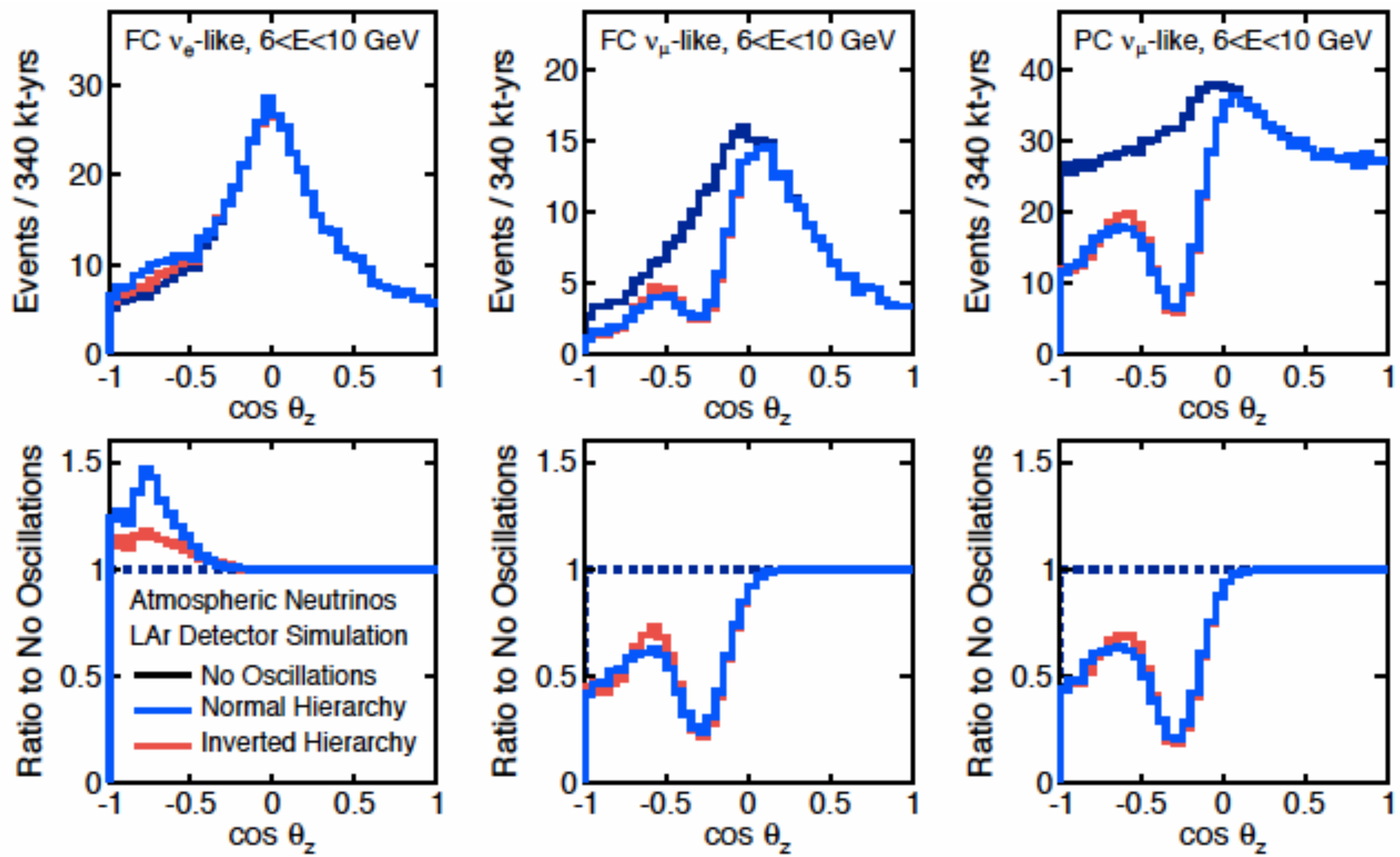
From Milind Diwan's Talk at KITP

LBNE is a comprehensive experiment. When combined with a reactor effort we characterize the whole matrix redundantly.

Proton Decay Sensitivity $p \rightarrow K^+\nu$ – 20 Yr Lifetime

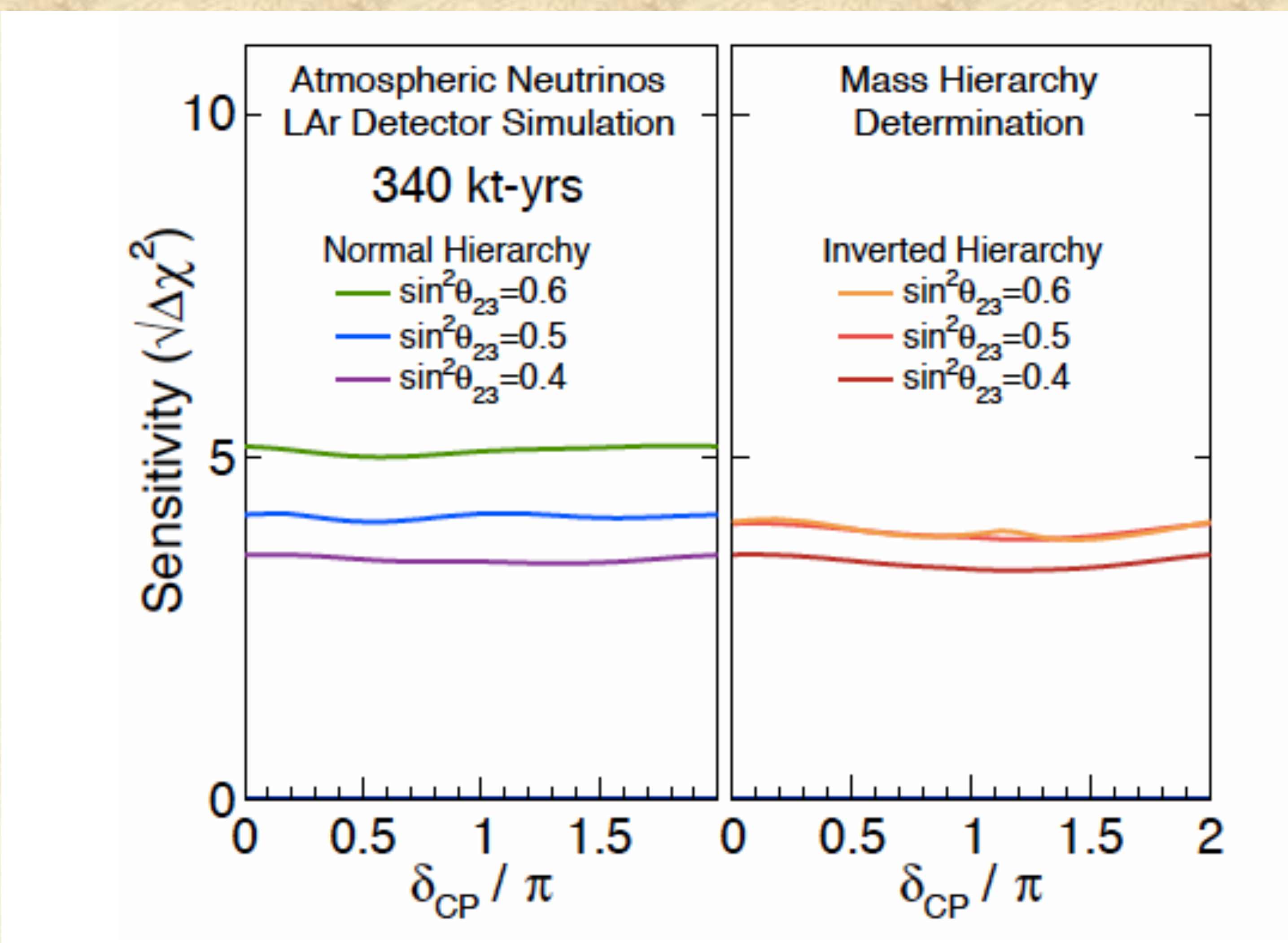


Atmospheric Neutrinos – MH Sensitivity



Zenith angle distributiosns for events w/E 6-10 GeV. Comparison of NH vs MH.

Atmospheric Neutrinos – MH Results

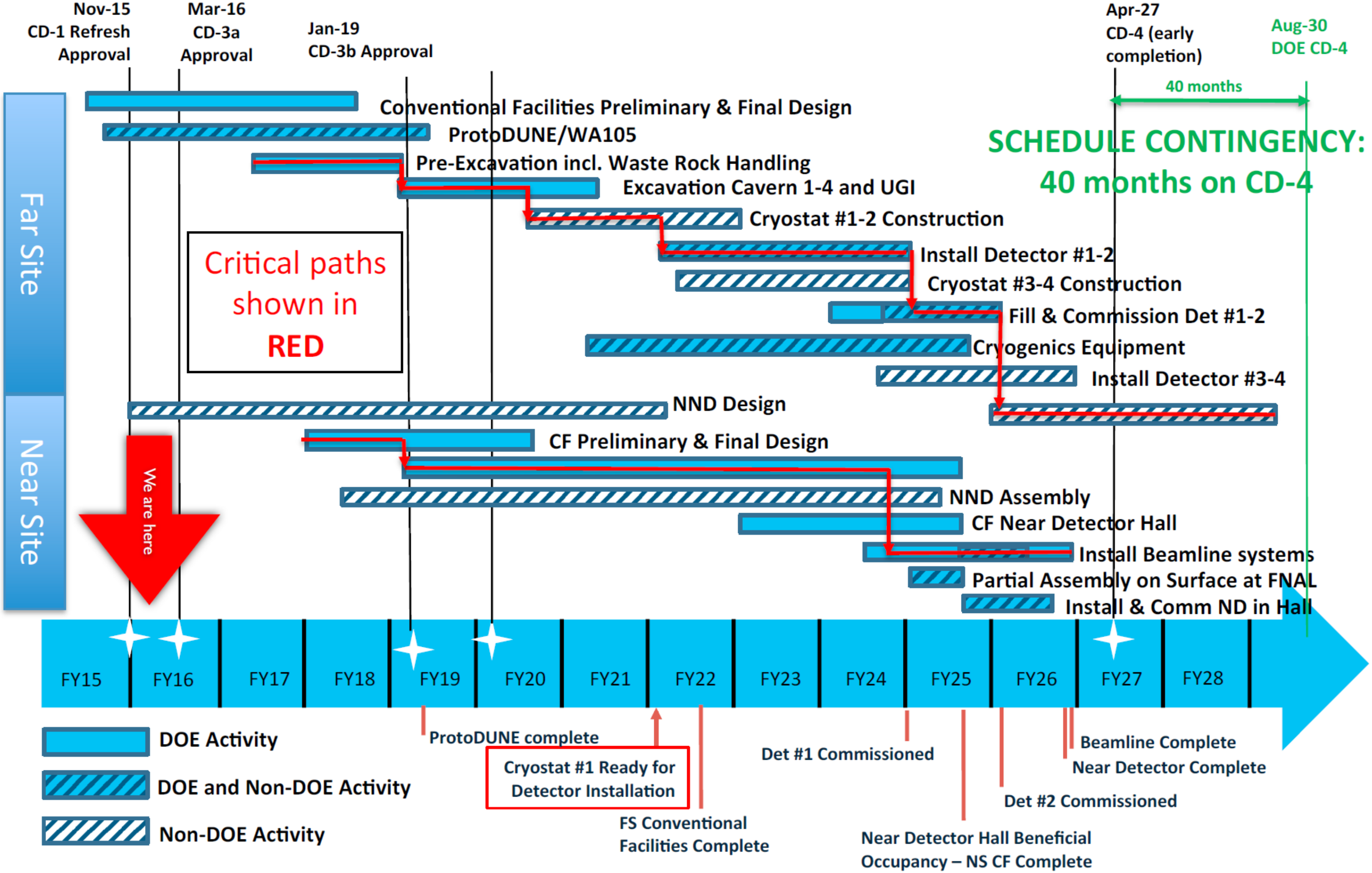


MH sensitivity is roughly independent of CP Phase

DUNE- Other Topics

- ✓ ***Neutrino Interaction Physics***
- ✓ ***Indirect Dark Matter Searches***
- ✓ ***Cosmic Ray Physics***
- ✓ ***Lorentz and CPT violations***
- ✓ ***Extra Dimensions***
- ✓ ***NSI***
- ✓ ***Sterile Neutrinos***
- ✓ ***Exploring potential of lower energy neutrino studies:***
  - ◆ ***Solar neutrinos***
  - ◆ ***Diffuse Supernova neutrino background***

LBNF/DUNE Schedule



Summary & Outlook

- ***LBNF/DUNE will be a game-changing program in neutrino physics and astro-particle physics***
  - *Definitive 5σ determination of MH*
  - *Broad exploration of leptonic CPV with significant prospects for discovery*
  - *Precisely test 3-flavor oscillation paradigm*
  - *Extend sensitivity to nucleon decay*
  - *Unique measurements of supernova neutrinos (if one should occur in the lifetime of the experiment)*
  - *Generational advance in precision neutrino physics at the near site*
- ***A strong world-wide collaboration has formed to build the experiment***
  - *LAr TPC Far Detector,*
  - *Task force looking into various designs of ND –*
    - *Fine-Grained Tracker Near Detector a possibility*
  - *MW-class Neutrino Beam*
- ***The LBNF/DUNE Project is moving ahead.***

Thank You