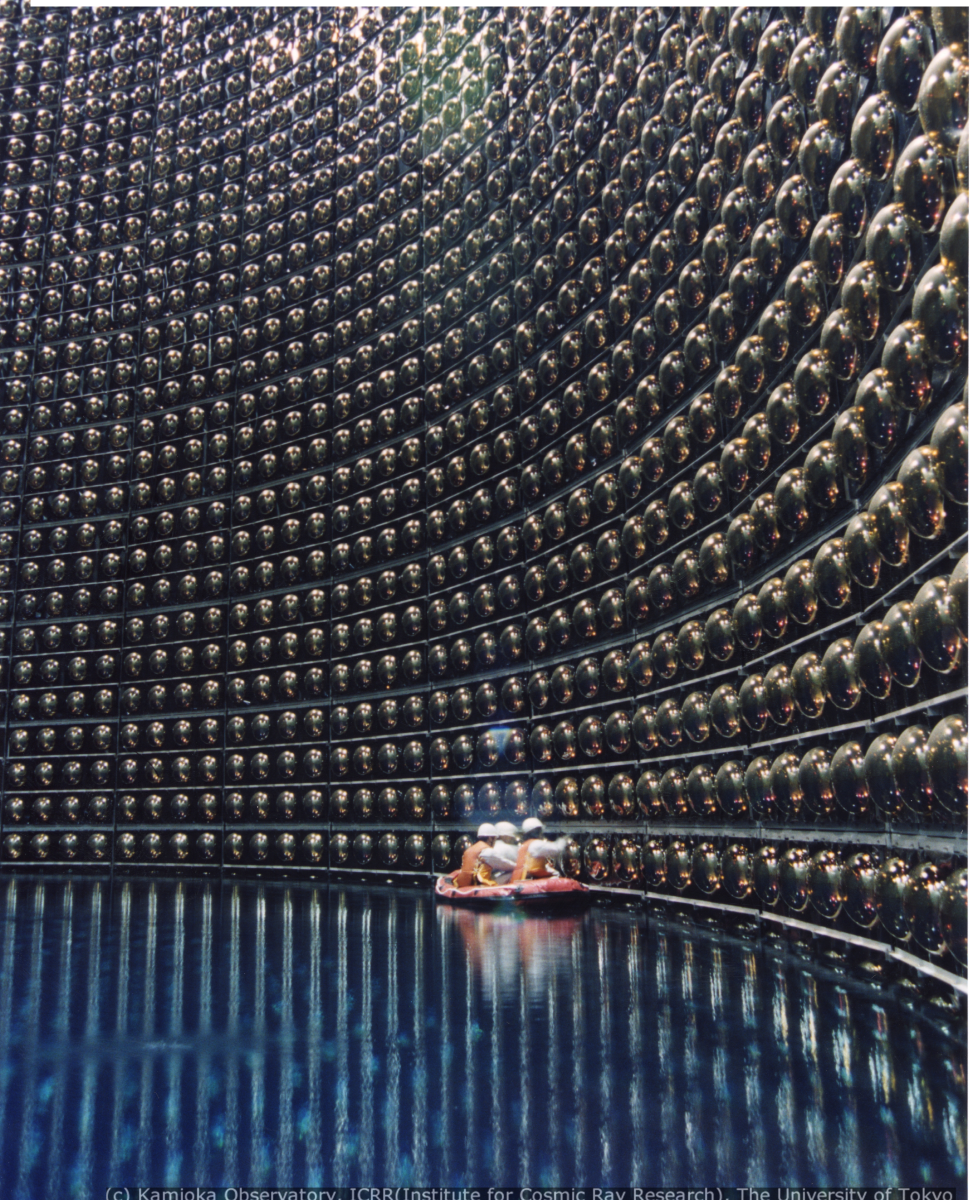
ACCELERATOR NEUTRINO EXPERIMENTS

Louise Suter, Argonne National Laboratory

9th June 2016

Flavor Physics and CP Violation, Pasadena, CA

2015 noble prize in physics for *“ the discovery of neutrino oscillations, which shows that neutrinos have mass”*



- Takaaki Kajita for the first measurement of ν_μ disappearance looking at atmosphere ν using Super-Kamiokande

- Arthur McDonald for leading the SNO collaboration who demonstrated that solar ν were not disappearing on their way to Earth, instead they arrived at SNO with a different ν flavor

Proved that neutrinos must have mass

New York Times, June 5th 1998

Mass Found in Elusive Particle; Universe May Never Be the Same

Discovery on Neutrino Rattles Basic Theory About All Matter

By MALCOLM W. BROWNE

Mass mixing matrix factorizes into three terms

$$\begin{vmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{vmatrix}\Big\rangle = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix} \begin{vmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{vmatrix}\Big\rangle$$

$$\Delta m^2_{32} \simeq 2 \times 10^{-3} \mathrm{eV}^2 \quad L/E = 500 \ \mathrm{km/GeV}$$

$$\Delta m^2_{31} \approx \Delta m^2_{32}$$

$$\Delta m^2_{21} \simeq 8 \times 10^{-5} \mathrm{eV}^2 \quad L/E = 15,000 \ \mathrm{km/GeV}$$

$\nu_\mu \to \nu_\mu$
$\nu_\mu \to \nu_\tau$
atmospheric and long baseline

$\nu_e \to \nu_e$
$\nu_\mu \to \nu_e$
reactor and long baseline

$\nu_e \to \nu_e$
$\nu_e \to \nu_\mu + \nu_\tau$
solar and reactor

$c_{\alpha\beta} = \cos_{\alpha\beta} \quad s_{\alpha\beta} = \sin_{\alpha\beta}$

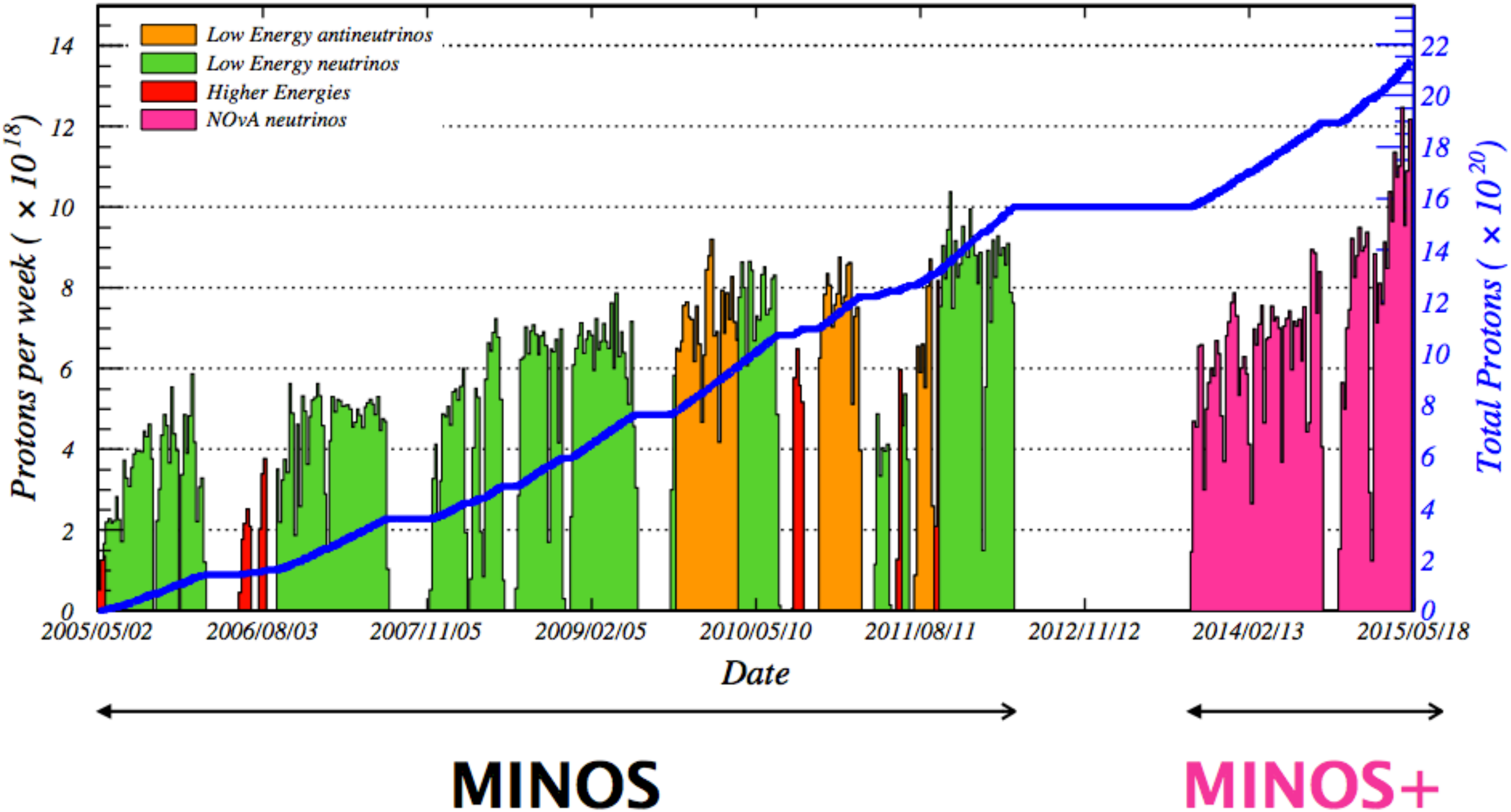
The ongoing and future accelerator neutrino program aims to answer some of the remaining big questions

- Mass ordering?
- Nature of ν_3 i.e. θ_{23} octant ?
- Is CP violated in the neutrino sector?
- Are the sterile neutrinos?

MINOS/MINOS+

- Two detector long baseline neutrino oscillation experiment
- Near:
  - 23.7 ton fiducial mass
  - 1.04 km downstream from target
- Far:
  - 4.2 kiloton fiducial mass
  - Veto shield for cosmic suppression
  - 705m underground
- Both detectors are magnetized tracking/ sampling calorimeters, segmented into planes composed of 2.54 cm-thick steel planes and 1 cm-thick scintillator strips

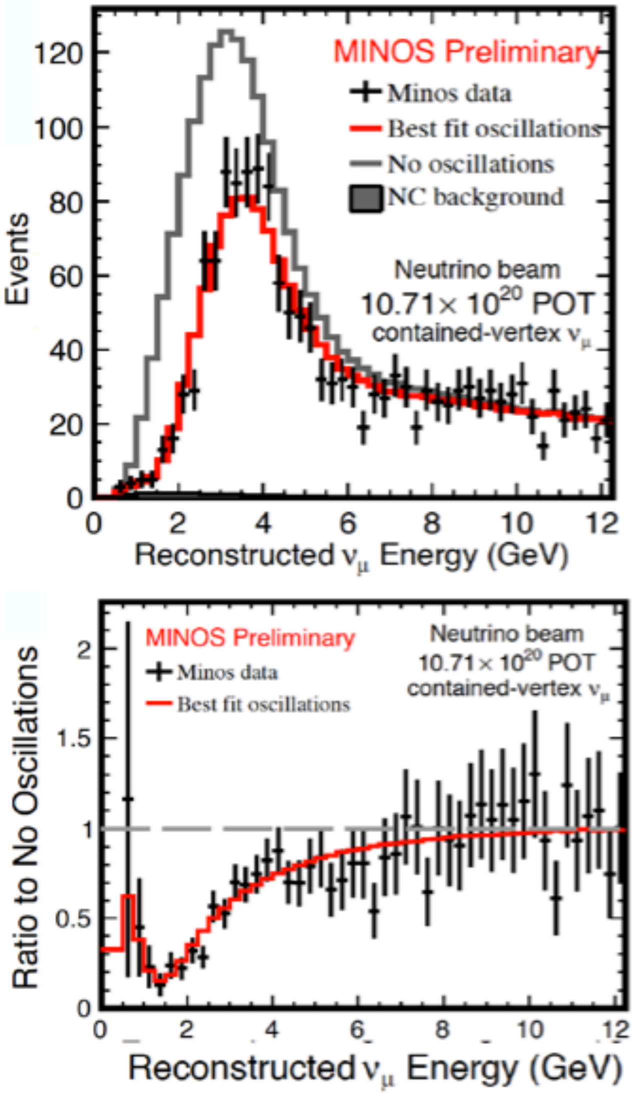
MINOS/MINOS+



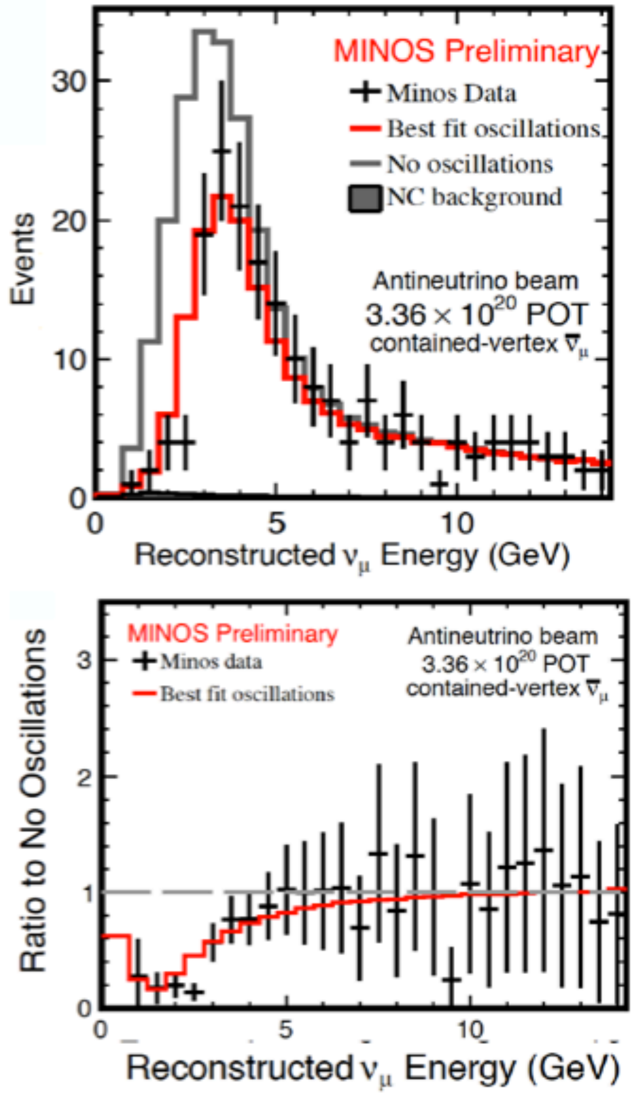
Low energy beam
data 2003 to 2011

High energy beam
data 2013 to 2016

Neutrinos



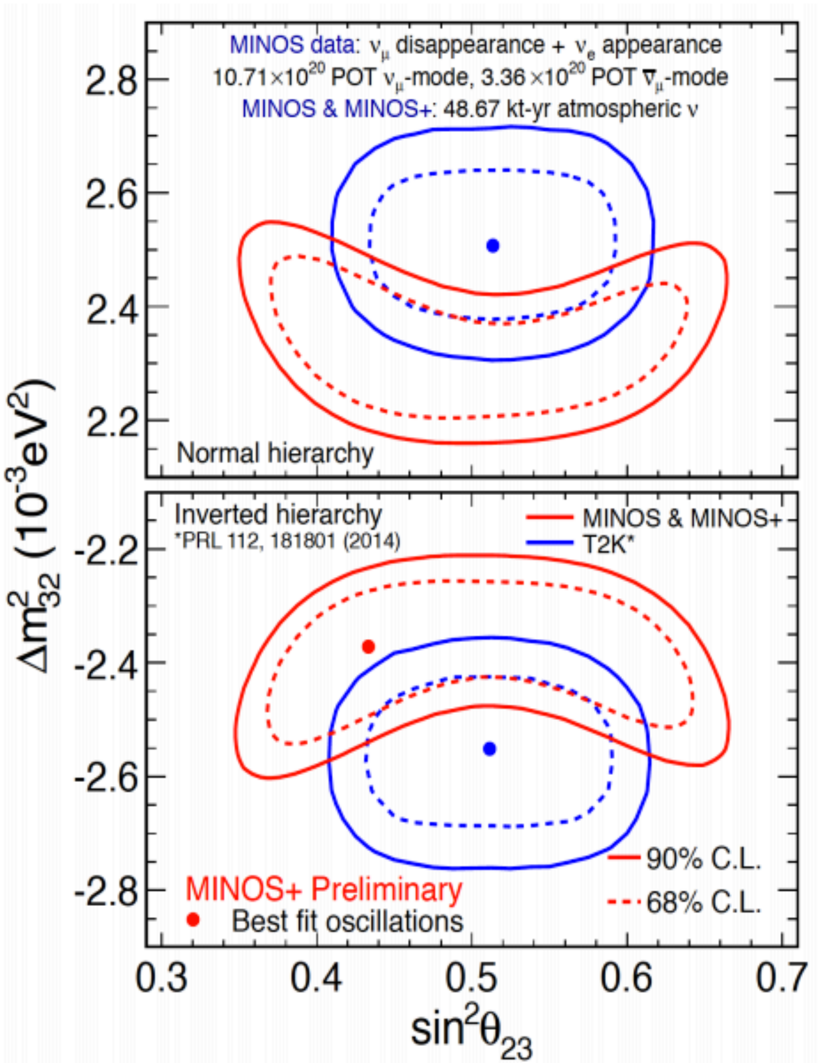
Antineutrinos



backgrounds	69.1	10.5
“nominal” signal at θ	+26.0	+3.1
total:	**95.1**	**13.6**
Observed	**88**	**12**

courtesy of M. Messier

Muon-Neutrino Disappearance



Inverted Hierarchy

$|\Delta m^2_{32}| = 2.37^{+0.11}_{-0.07} \times 10^{-3}\text{eV}^2$

$\sin^2\theta_{23} = 0.43^{+0.19}_{-0.05}$

$0.36 < \sin^2\theta_{23} < 0.65$ (90% C.L.)

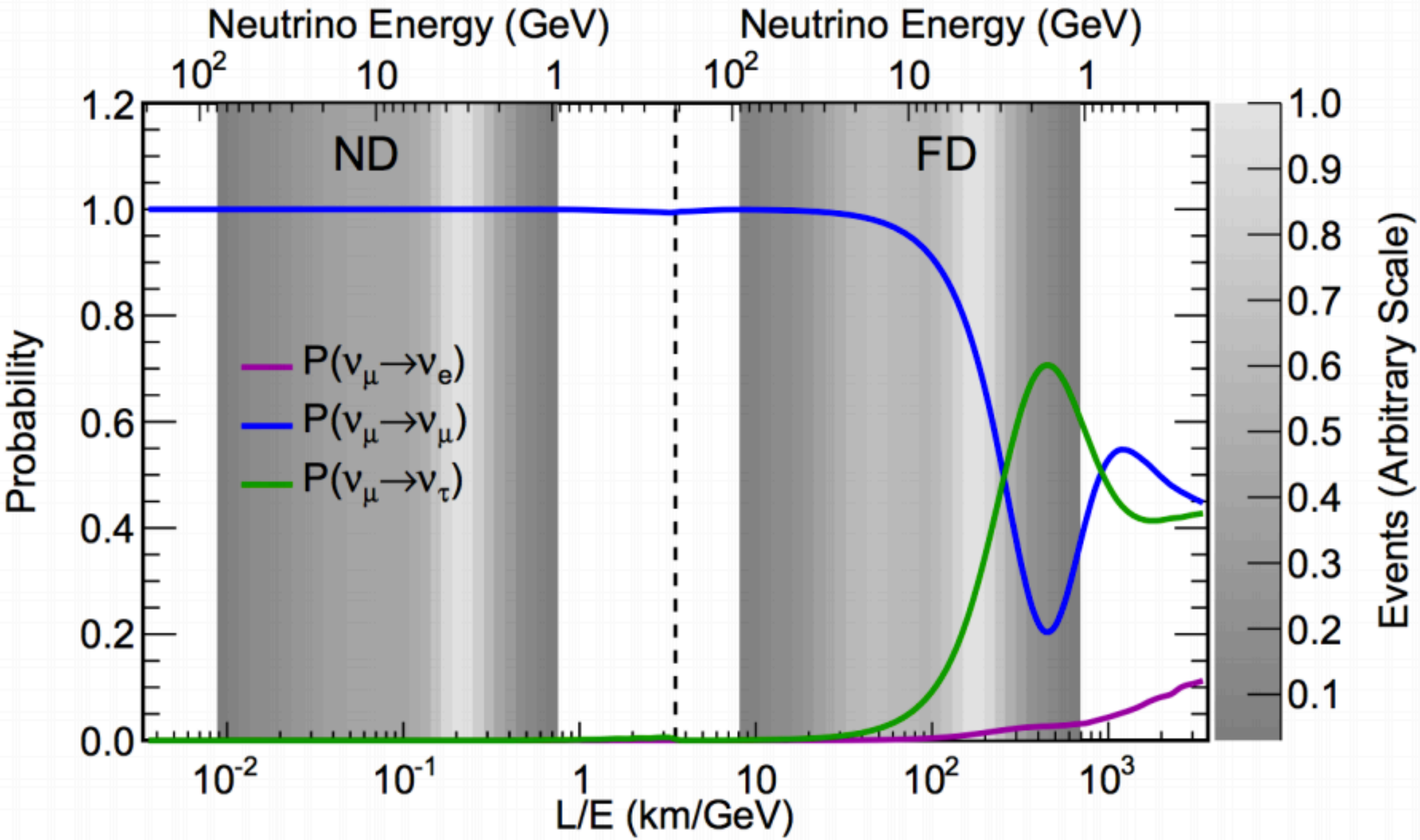
Normal Hierarchy

$|\Delta m^2_{32}| = 2.34^{+0.09}_{-0.09} \times 10^{-3}\text{eV}^2$

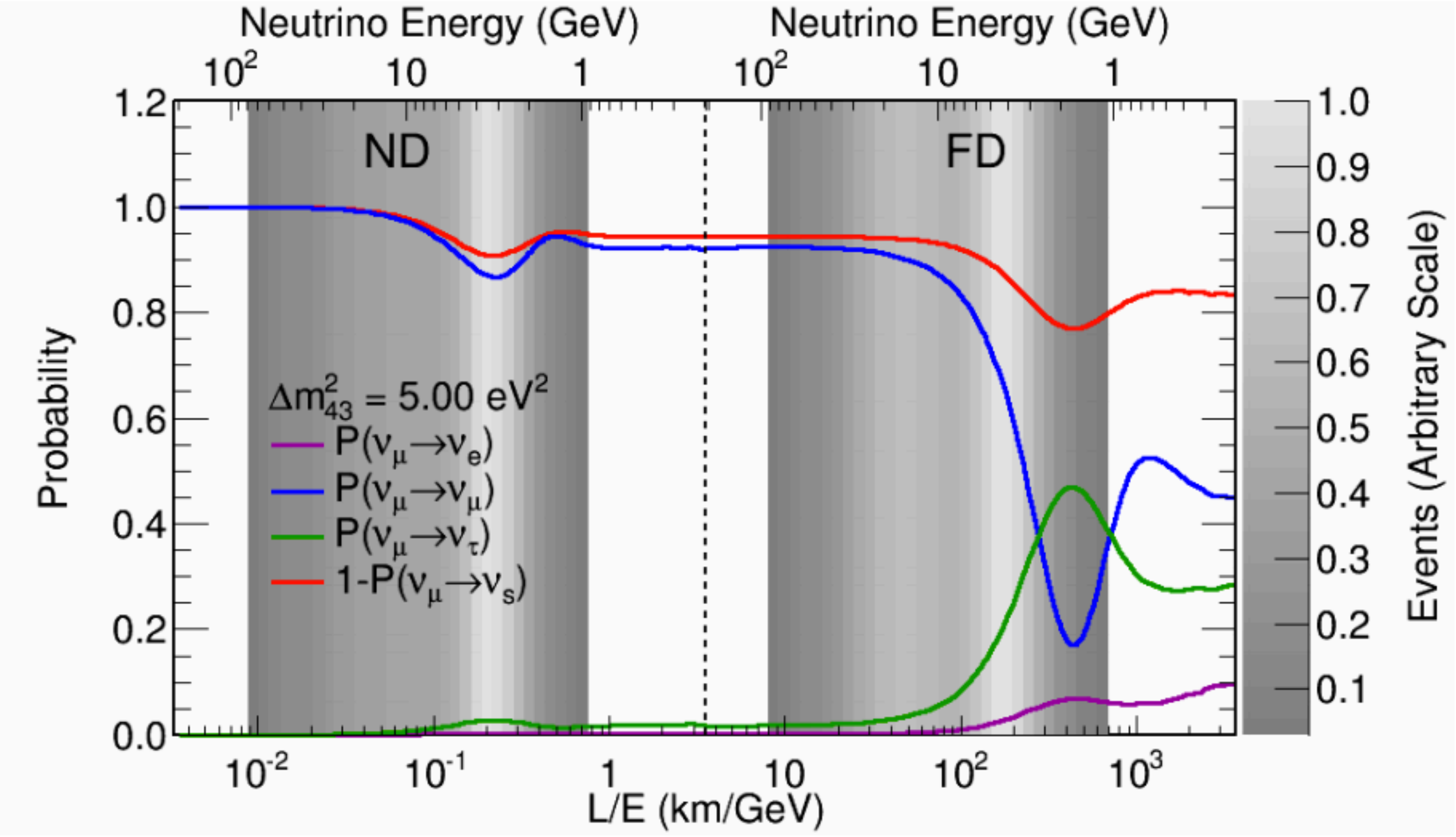
$\sin^2\theta_{23} = 0.43^{+0.16}_{-0.04}$

$0.37 < \sin^2\theta_{23} < 0.64$ (90% C.L.)

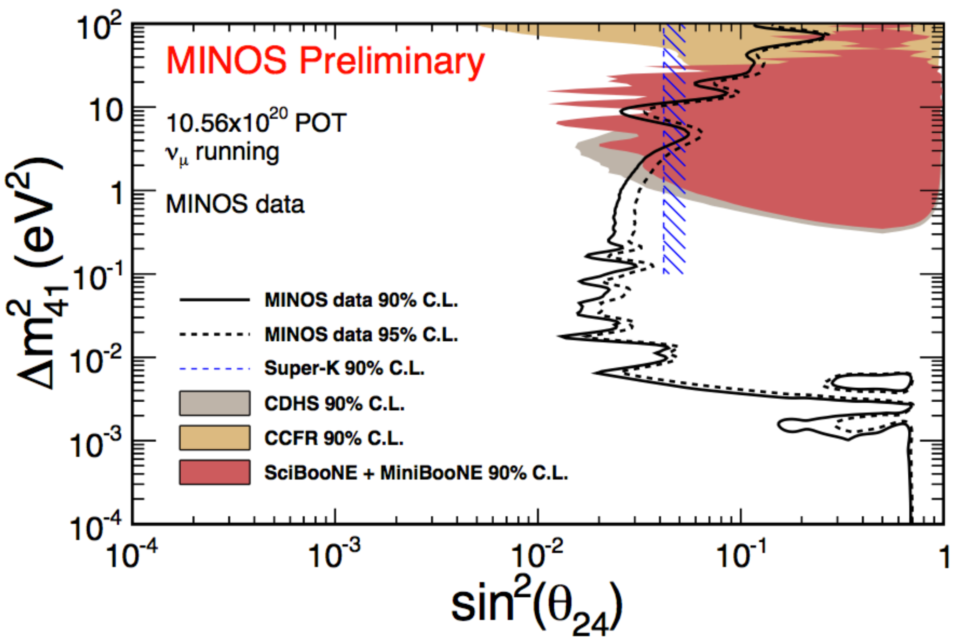
Sterile Neutrinos at MINOS

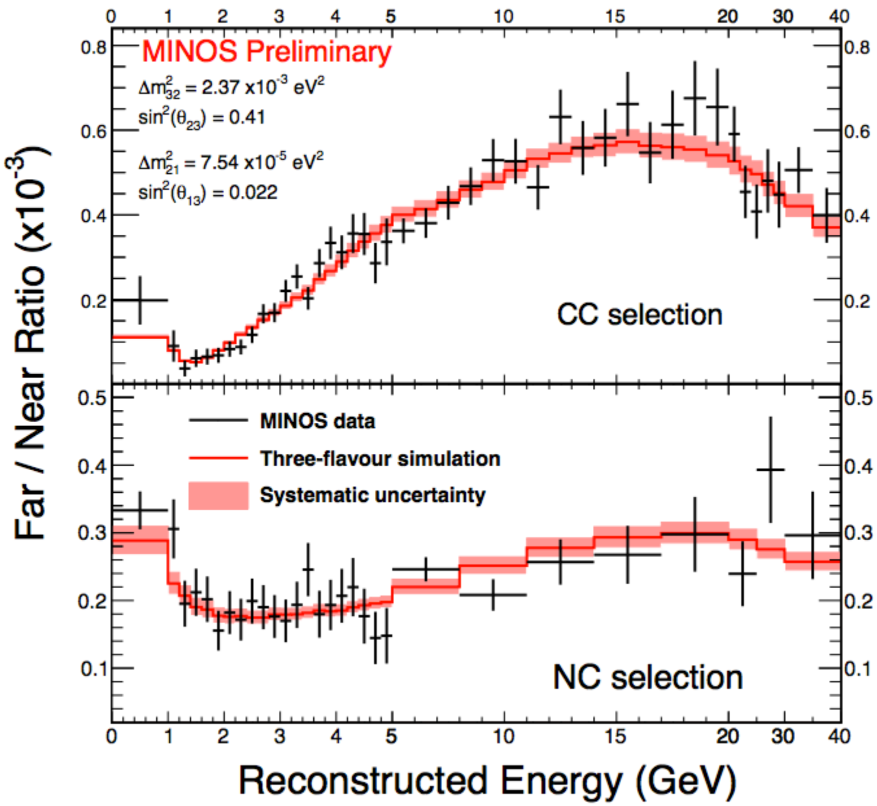


Sterile Neutrinos at MINOS



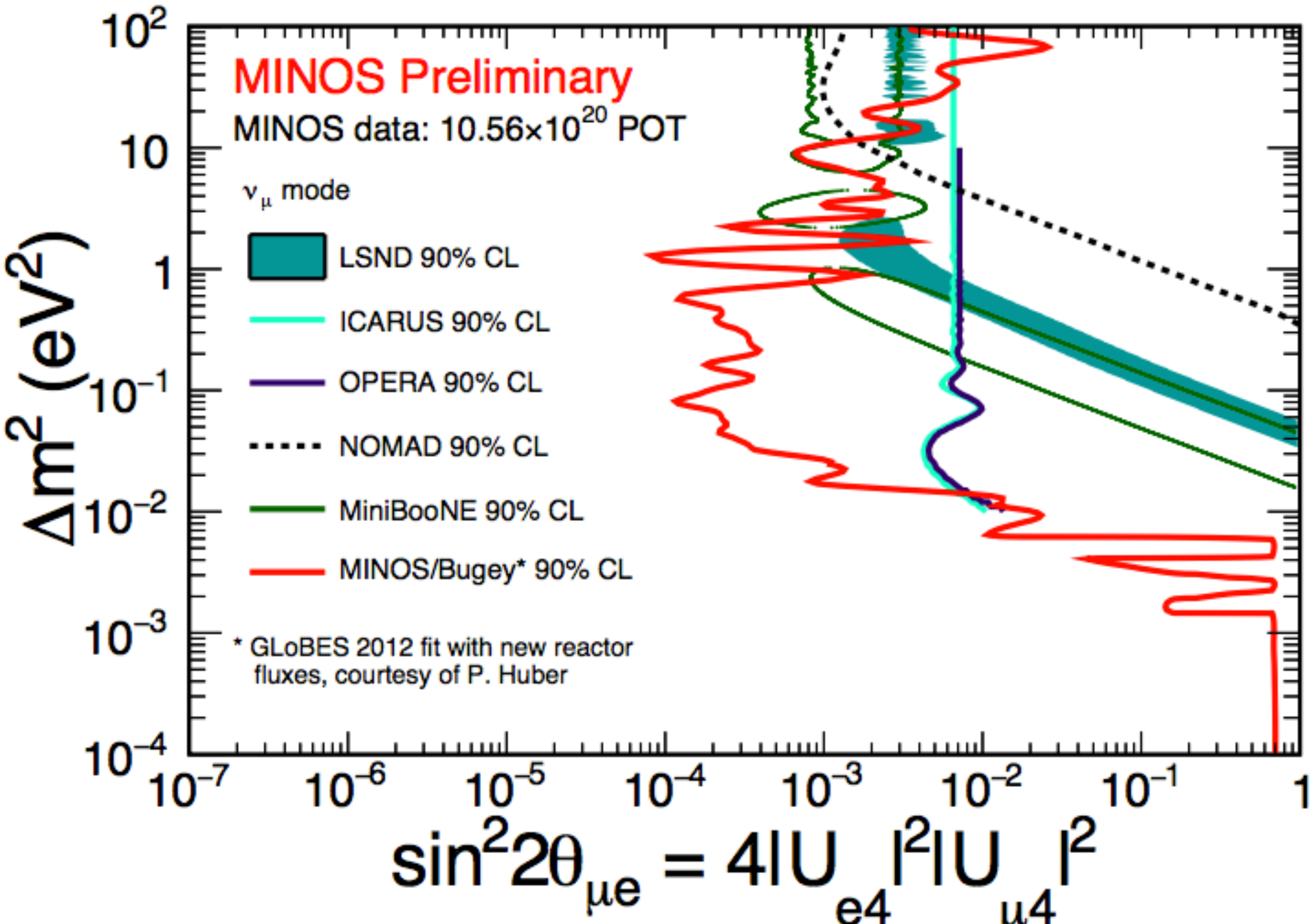
Direct fit to F/N ratio for CC and NC events
Set δ_{13}, δ_{14}, δ_{24} and θ_{14} to zero
Parameters fit are: Δm^2_{32}, Δm^2_{41}, θ_{24}, θ_{23}, and θ_{34}





Exclude large previously unexplored region of Δm^2_{41}

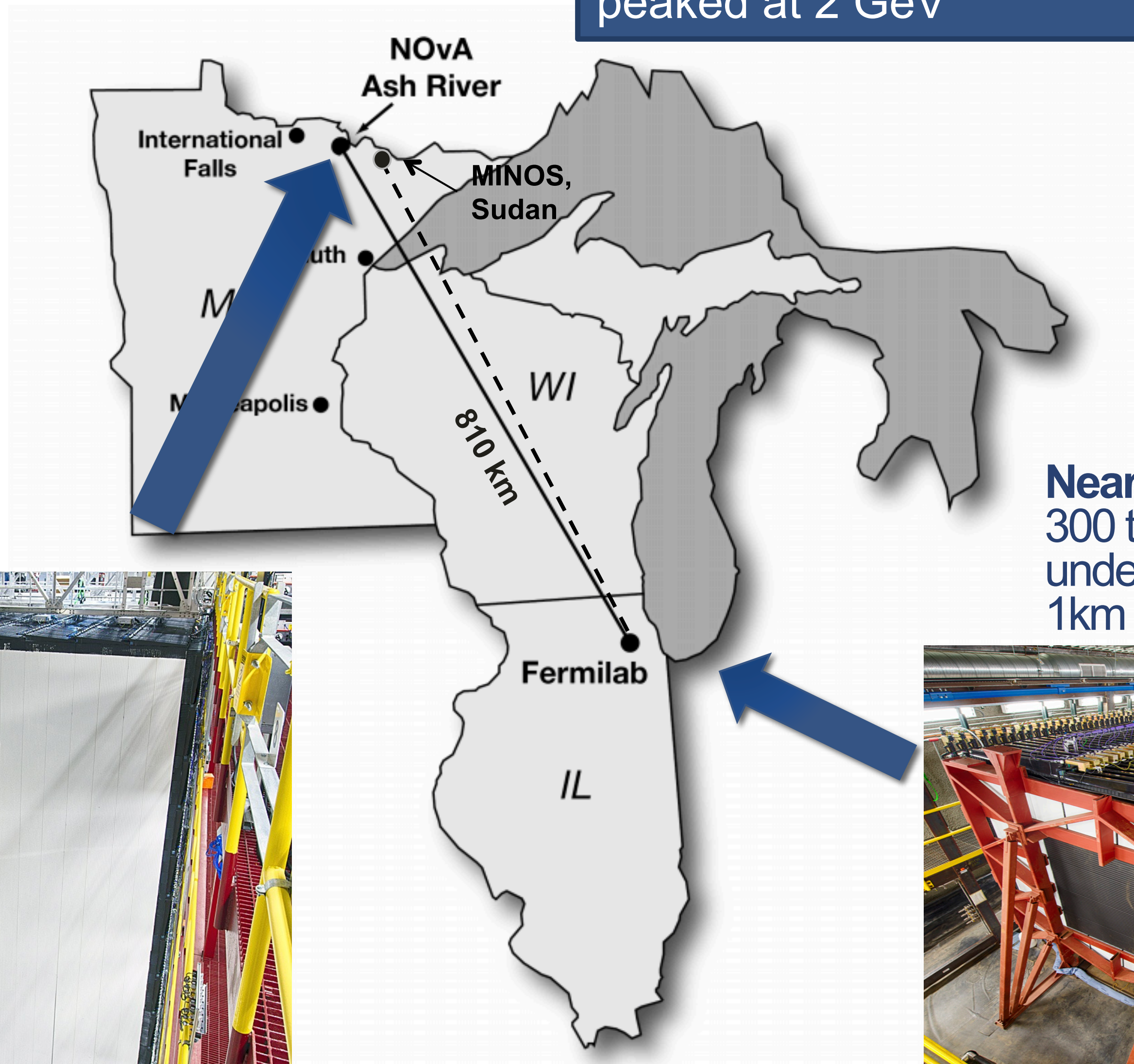
Combine with Bugey to produce $\sin^2 2\theta_{\mu e}$ $\Delta m^2(eV^2)$ limits



Combined MINOS & Bugey exclude most of the region allowed by LSND & MiniBooNE

NOvA

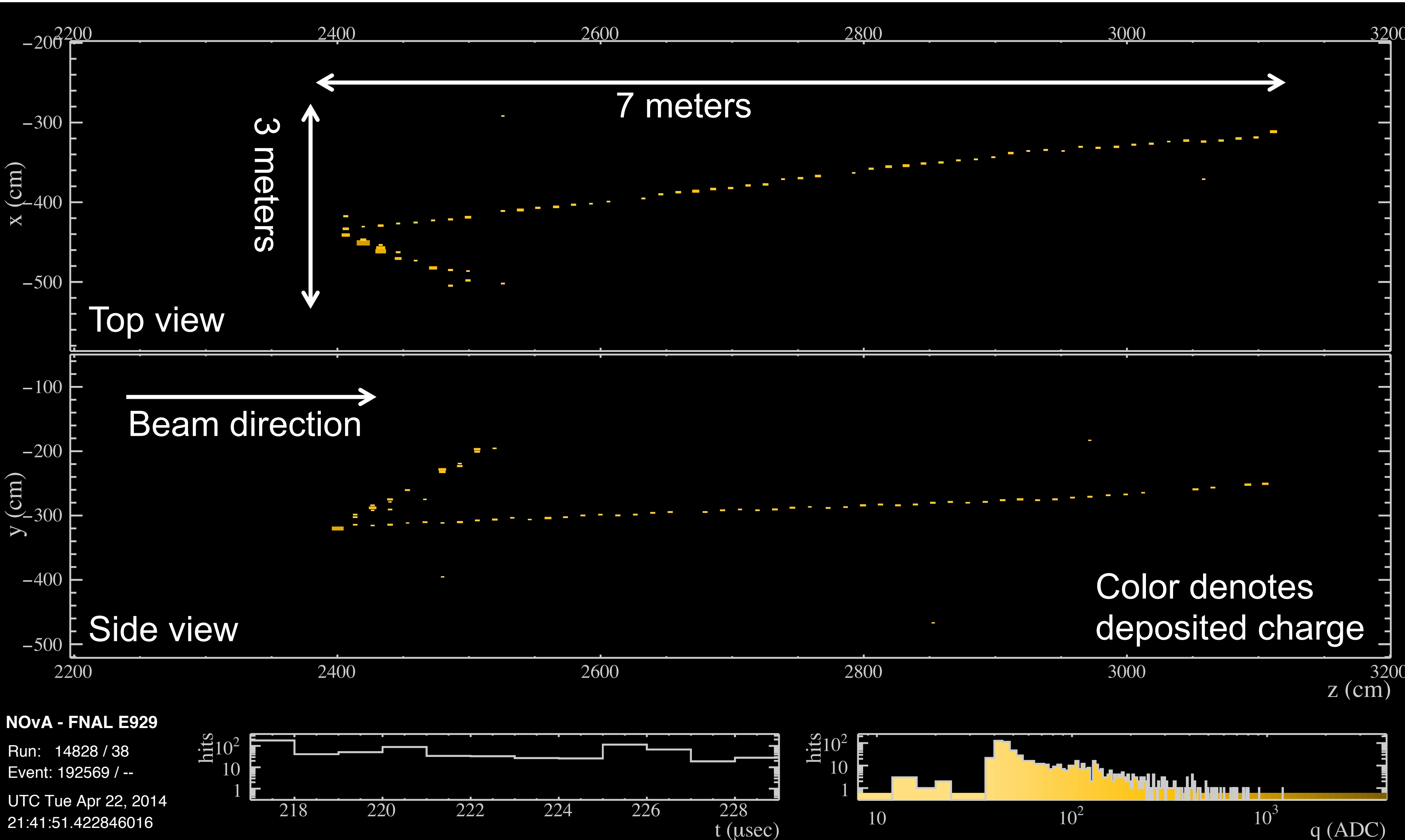
Almost totally active tracking calorimeter
14.6 mrad off axis, narrow band beam peaked at 2 GeV



Far Detector
14 kton
810 km from target

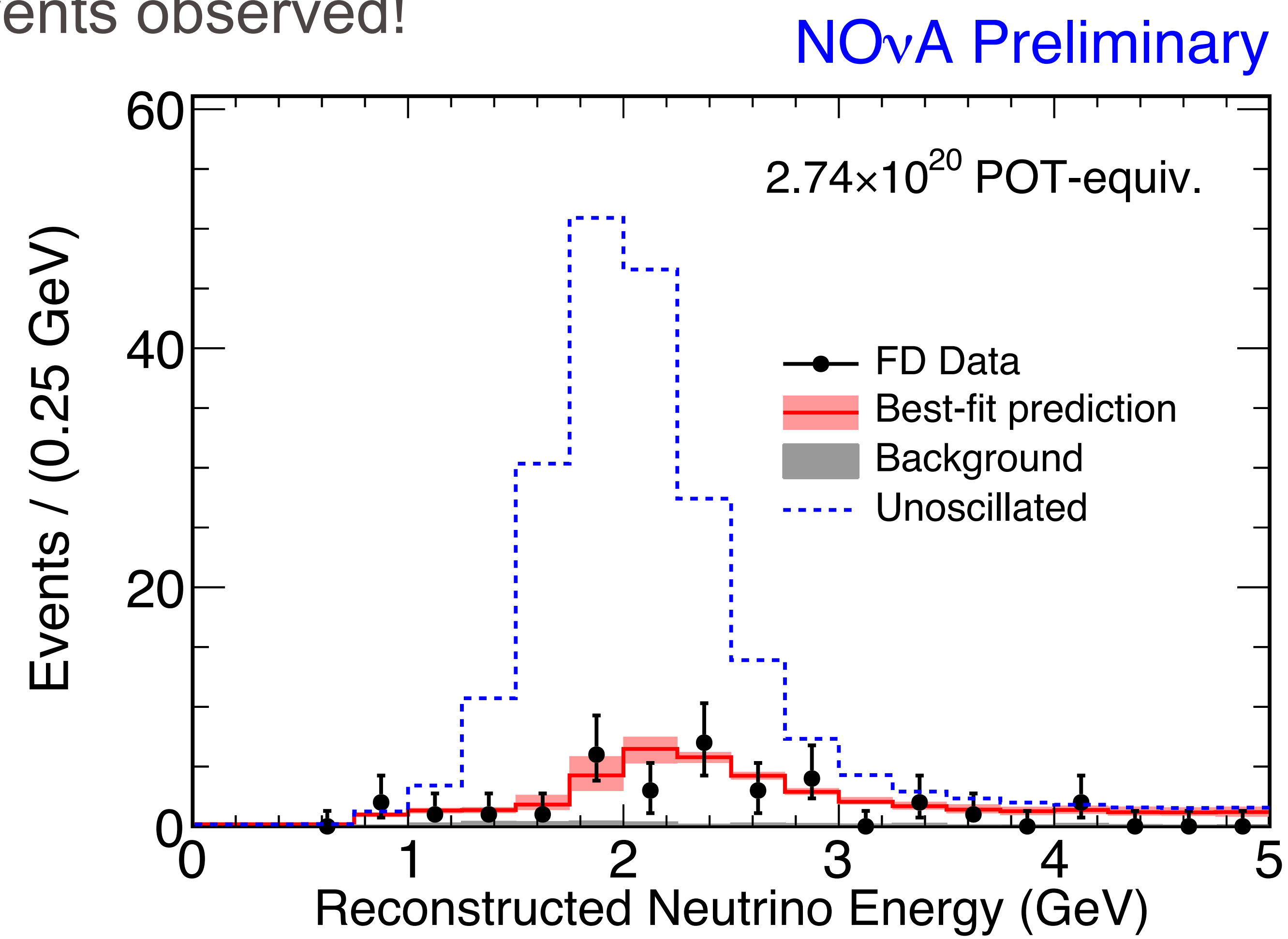
Near Detector
300 tons, 100 meters underground
1km from target

Selected ν_μ event



ν_μ Disappearance Results

- 211.8 ± 12.5 events predicted without oscillations
  - Including 2 ± 2 beam background and 1.4 ± 0.2 cosmic events
- 33 events observed!



ν_μ oscillation probability

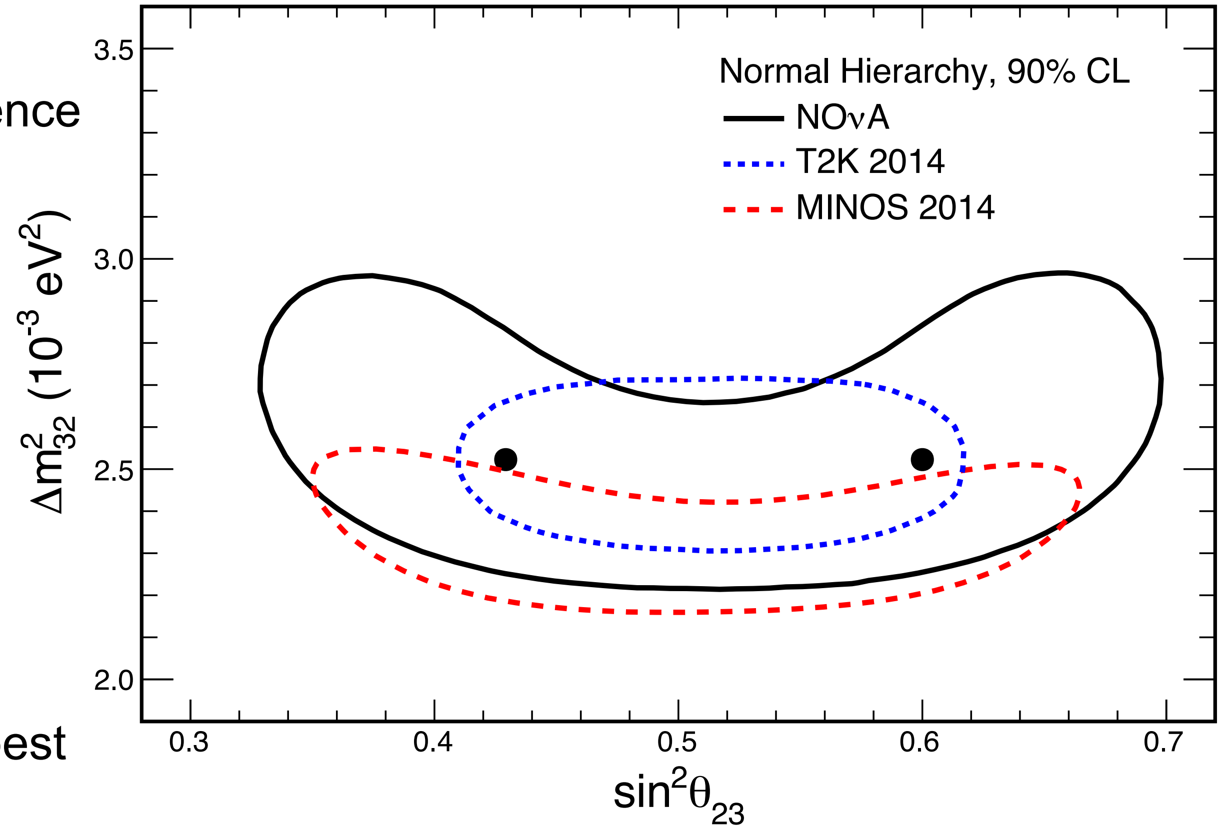
$$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \sin^2(\Delta m^2_{32} L/4E)$$

Two solutions due to dependence on hierarchy

$$\Delta m^2 = \begin{cases} +2.52^{+0.20}_{-0.18} \\ -2.56^{+0.19}_{-0.19} \end{cases} \times 10^{-3}\ \mathrm{eV}^2$$

$$\sin^2\theta = \begin{cases} 0.43 \text{ and } 0.60 \\ 0.44 \text{ and } 0.59 \end{cases}$$

Two statistically-degenerate best fit points



- Good compatibility with both MINOS and T2K
- With **less than 10% of the nominal final statistics** NOνA is already competitive with the world limits

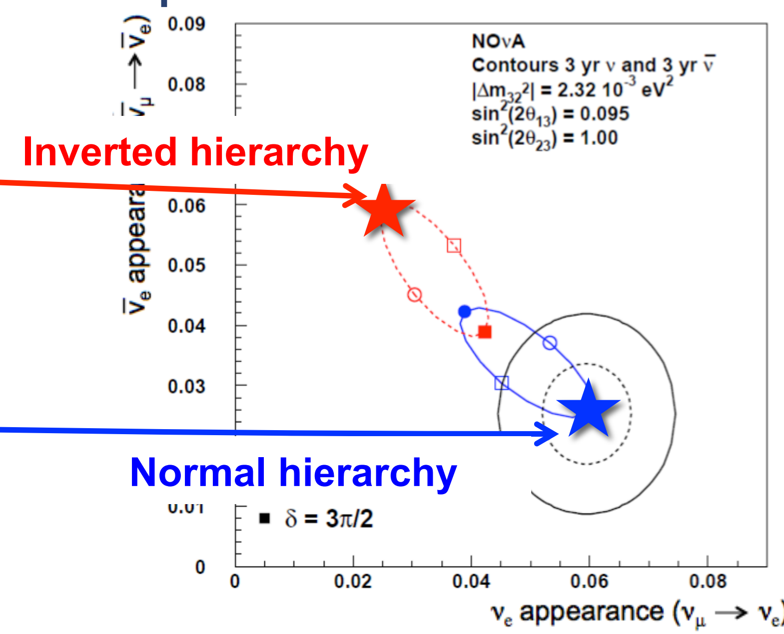
Electron-neutrino Appearance

Two separate electron-neutrino selection algorithms, LID and LEM
Predicted 2 – 5 signal events on background of 1

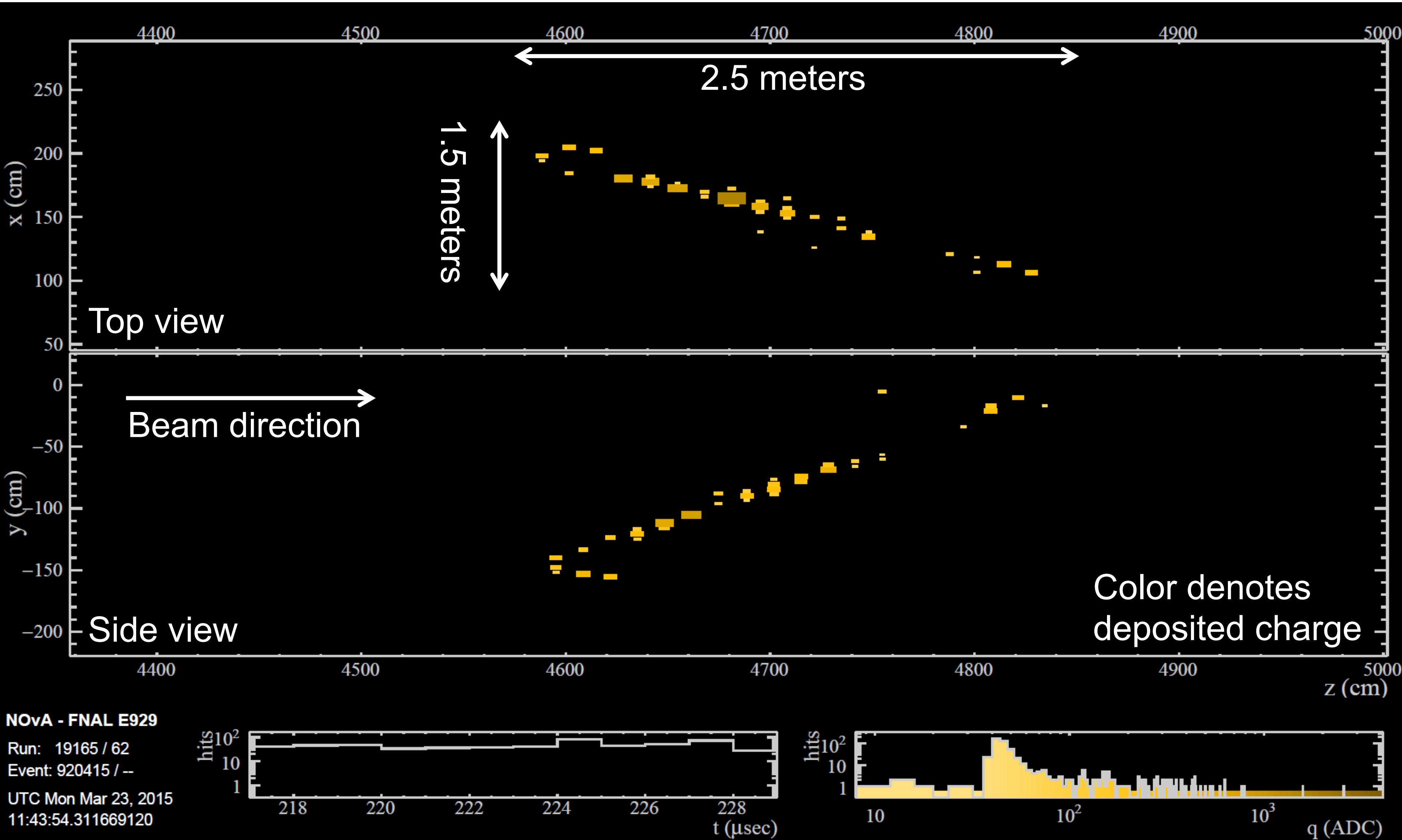
	Total Bkg	Beam ν_e	NC	ν_μ CC	ν_τ CC	Cosmic
LID	0.94 ± 0.09	0.47	0.36	0.05	0.02	0.06
LEM	1.00 ± 0.11	0.46	0.40	0.07	0.02	0.06

Signal prediction depends on oscillation parameters

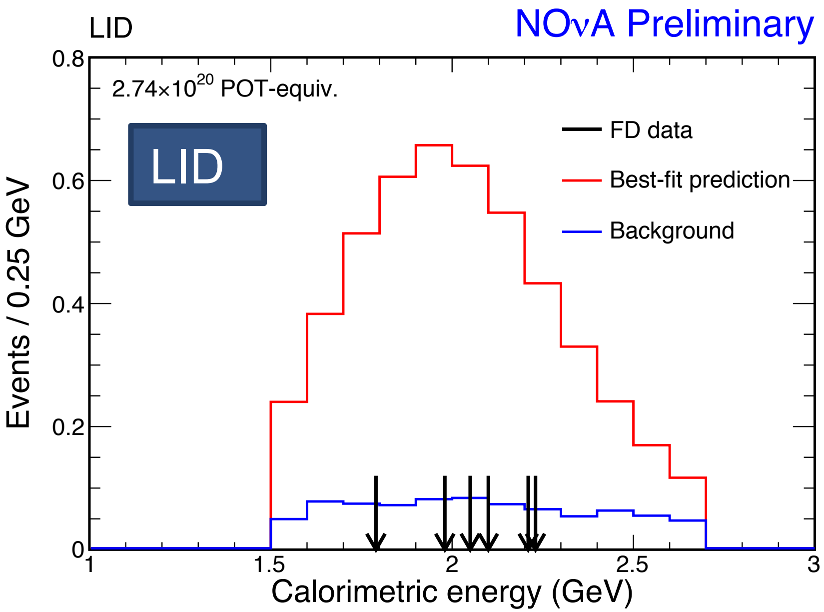
Signal	Most	Least
	NH $\delta_{CP}=3\pi/2$	IH $\delta_{CP}=\pi/2$
LID	5.62 ± 0.72	2.24 ± 0.29
LEM	5.91 ± 0.59	2.34 ± 0.23

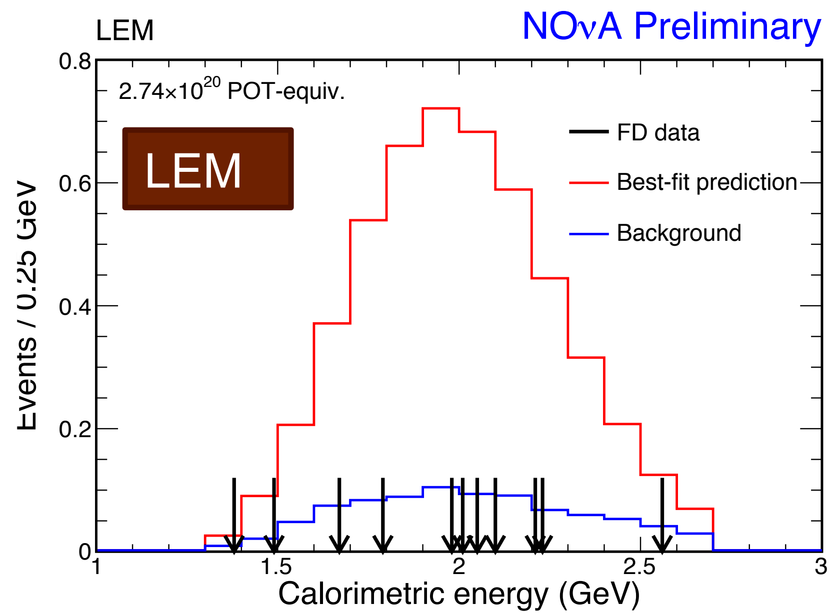


Selected ν_e event



ν_e Appearance Results





LID: Selected 6 events
3.3σ significance for ν_e appearance

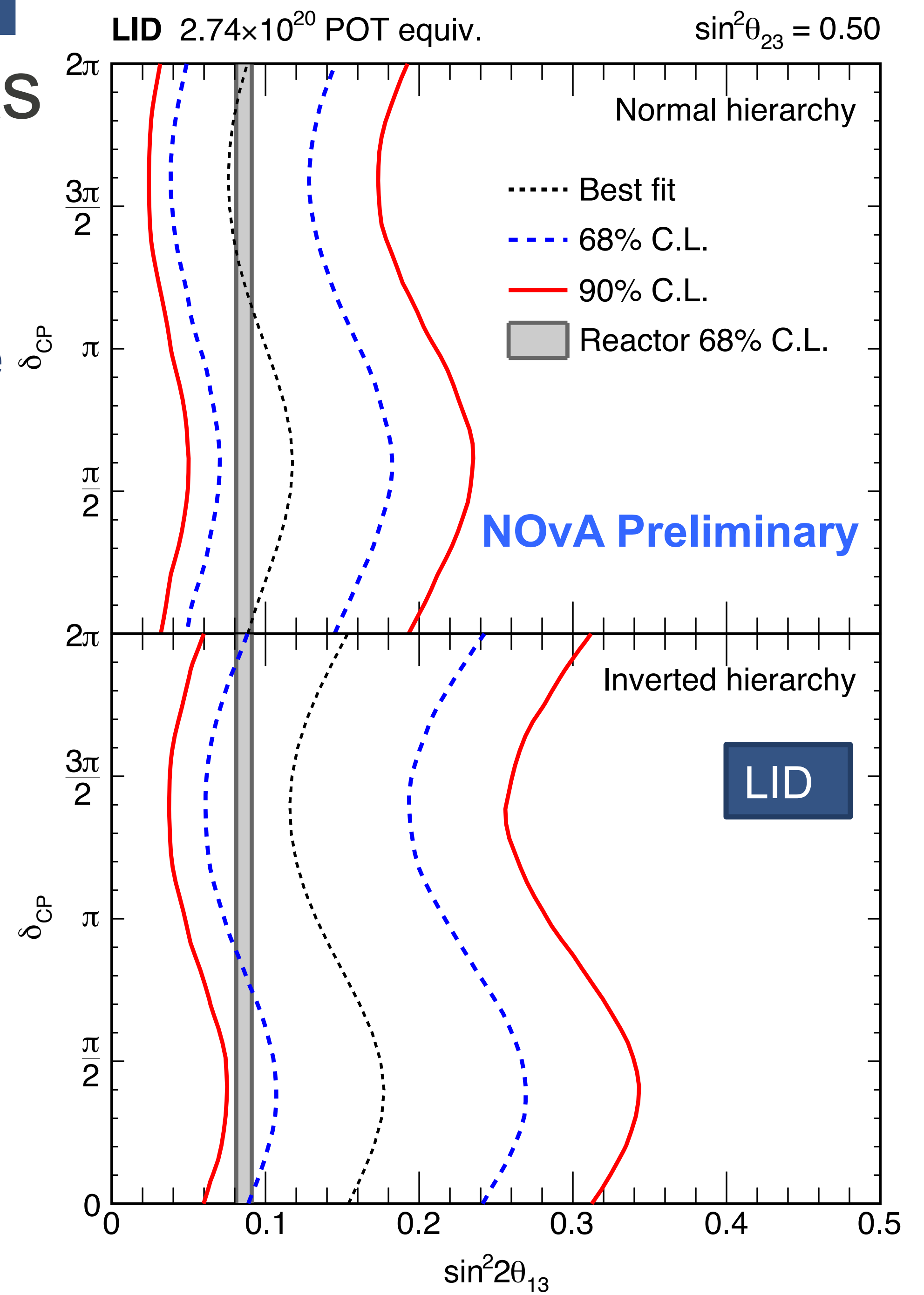
LEM: Select 11 events
5.5σ significance for ν_e appearance

- All 6 LID events selected by LEM
- Trinomial probability of selecting this combination (11:6/5/0) is 9.2%

ν_e Appearance Results
LID

- Contours determined using Feldman-Cousins procedure
  - Include uncertainties on solar parameters
  - Atmospheric Δm^2 varied within new NOvA uncertainties
  - $\sin^2\theta_{23}$ held fixed at 0.5
- LID results in good agreement with reactor measurements

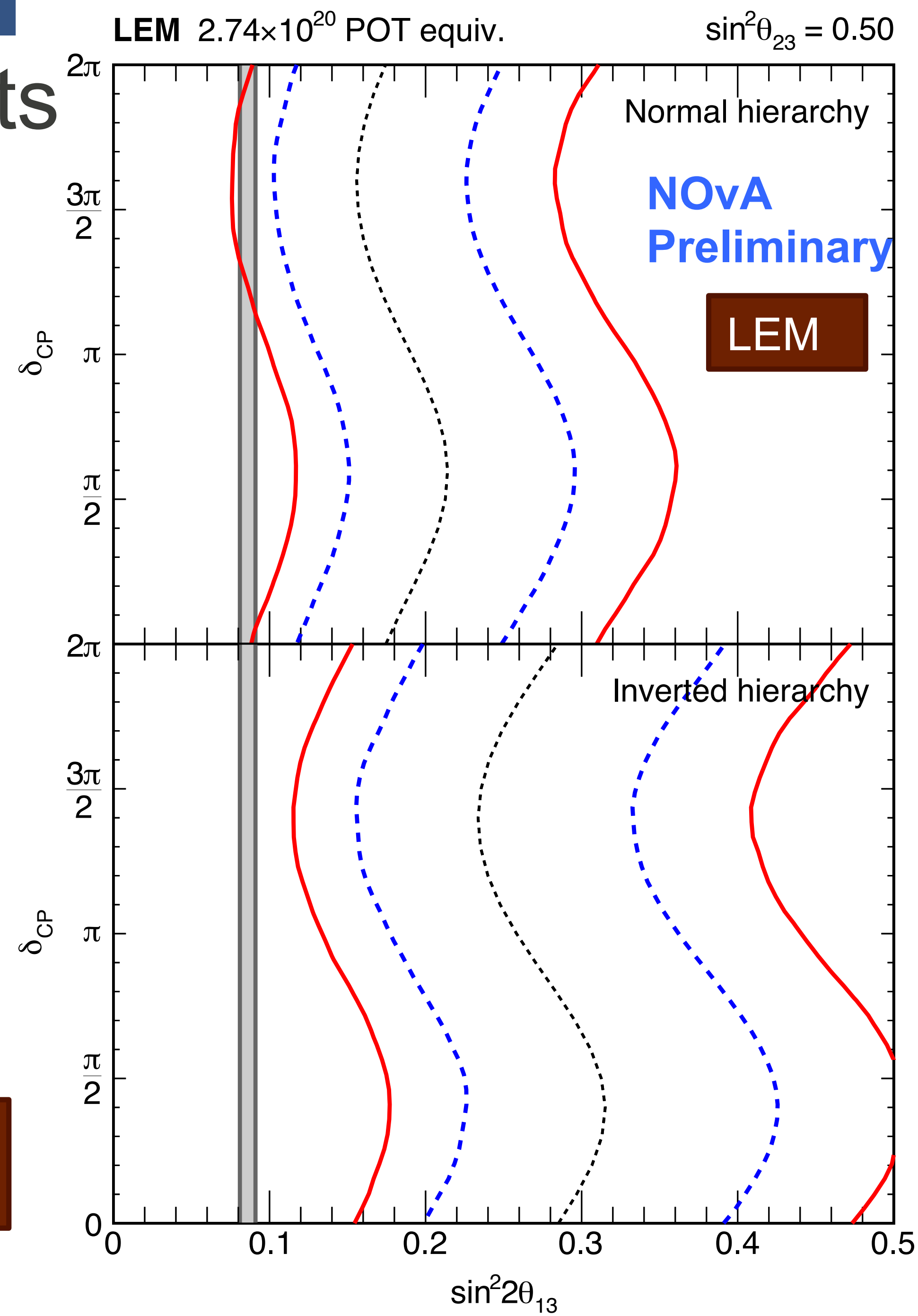
LID: Selected 6 events
3.3σ significance for ν_e appearance



ν_e Appearance Results

LEM

- LEM curves shift to the right
- Some tension with reactor results, particularly in IH

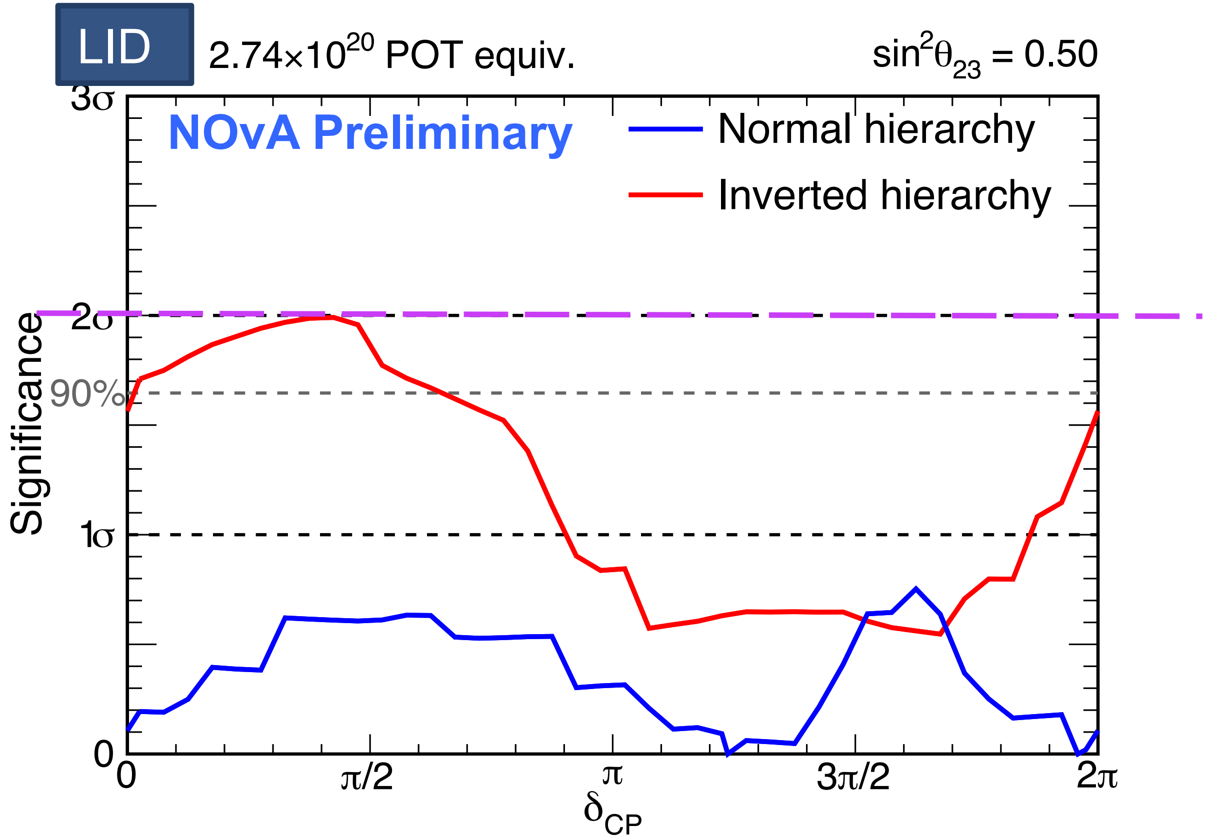


LEM: Select 11 events
5.5σ significance for ν_e appearance

ν_e Appearance Results

Statements holds for $0.4 < \sin^2\theta_{23} < 0.6$

- LID shows mild tension with IH, $0 < \delta_{CP} < 0.8\pi$
- LEM disfavors IH at greater than 2σ for all δ_{CP}



Jagged structure due to discrete nature of counting experiment

ν_e Appearance Results

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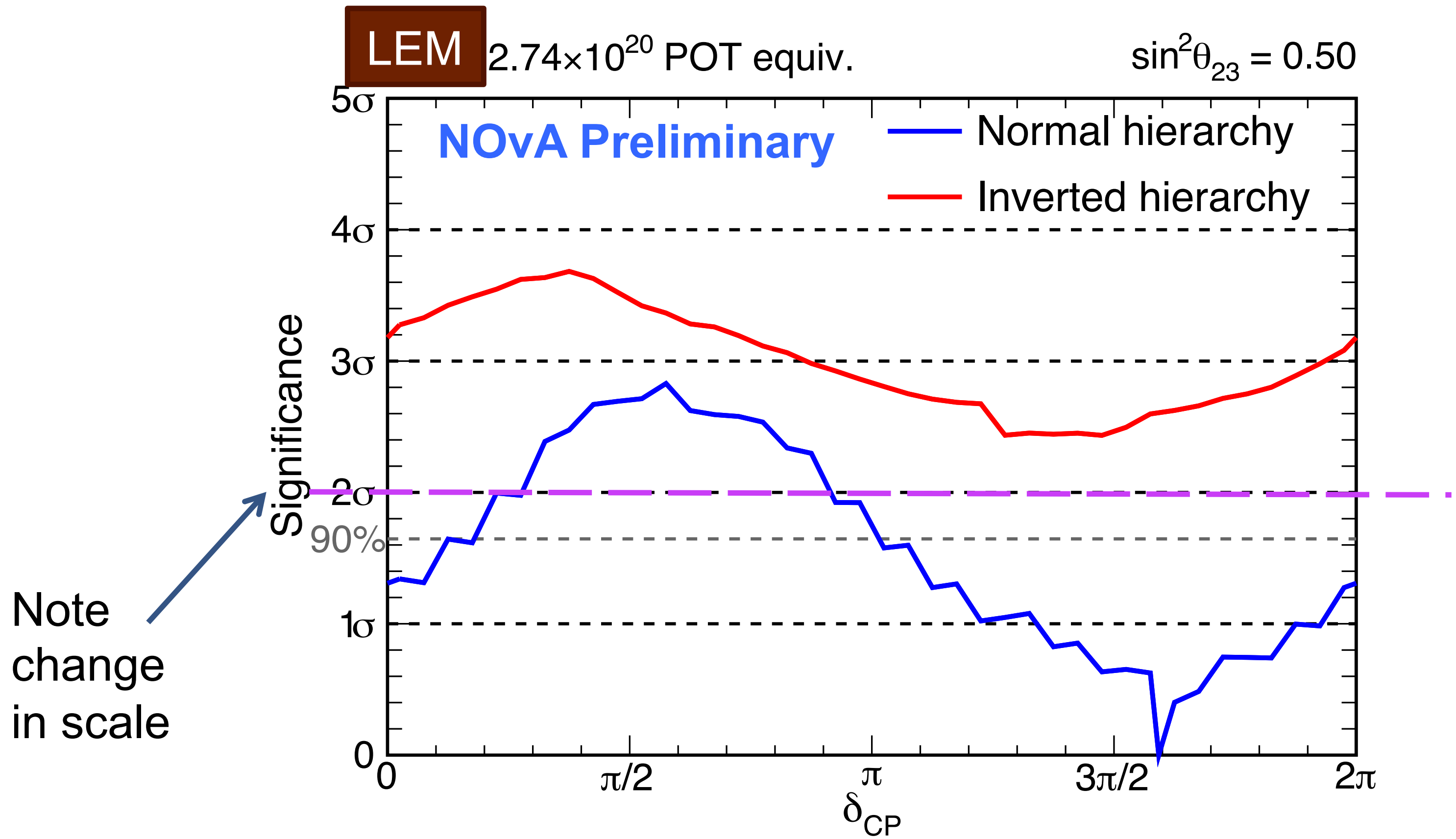
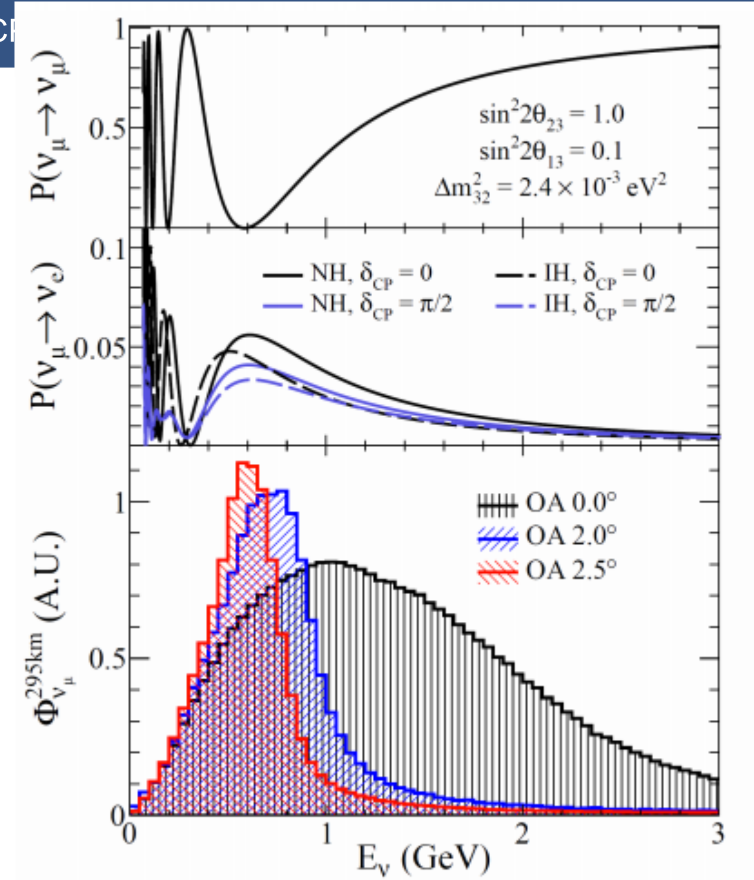


Jagged structure due to discrete nature of counting experiment

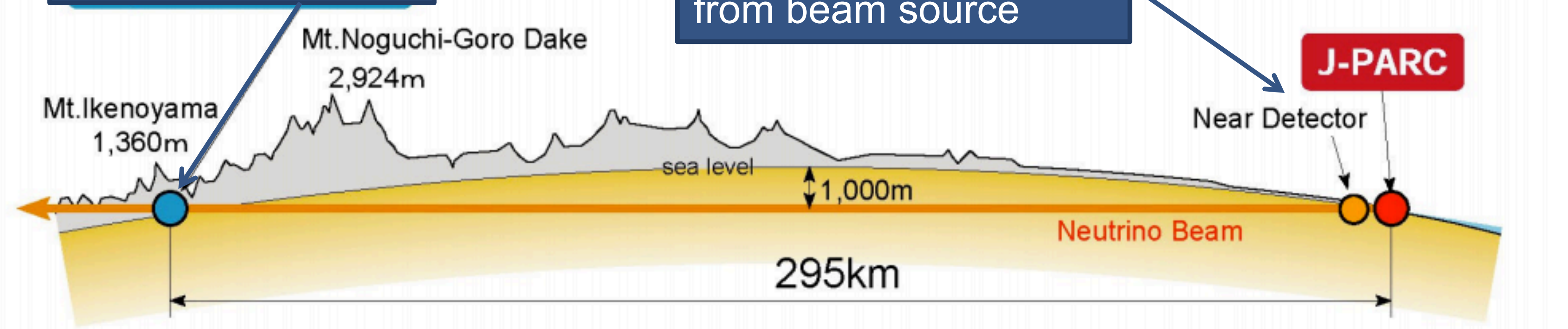
T2K

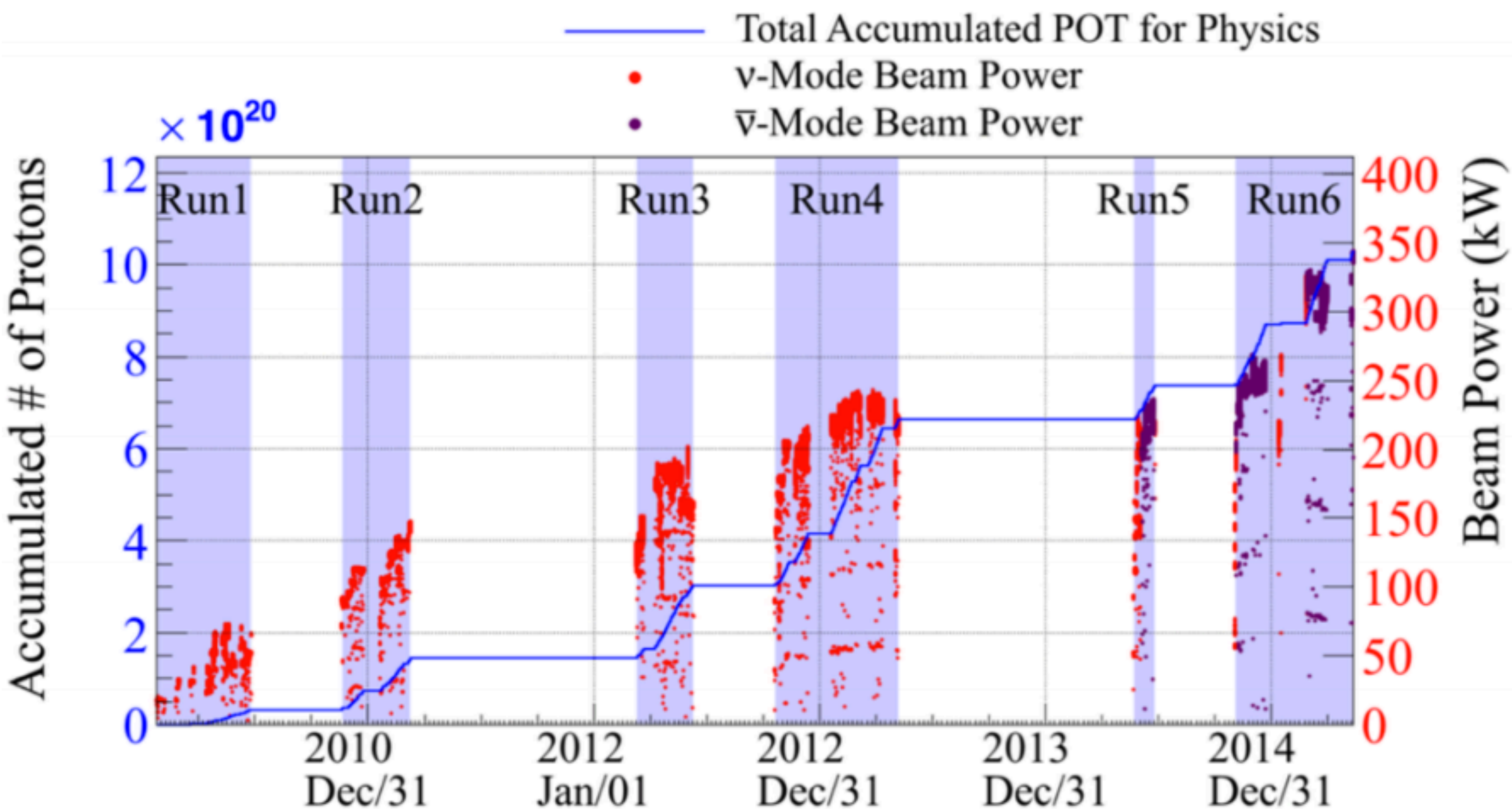
- T2K is a long-baseline neutrino experiment with a 600 MeV narrow band muon neutrino beam
- Detectors 2.5° off axis from neutrino beam
- Neutrino energy spectrum tuned to hit oscillation maximum at far detector



Far detector, Super-Kamiokande 295 km from source

Near detector at 280 m from beam source





neutrinos: 6.9×10^{20} POT

anti-neutrinos: 4.0×10^{20} POT

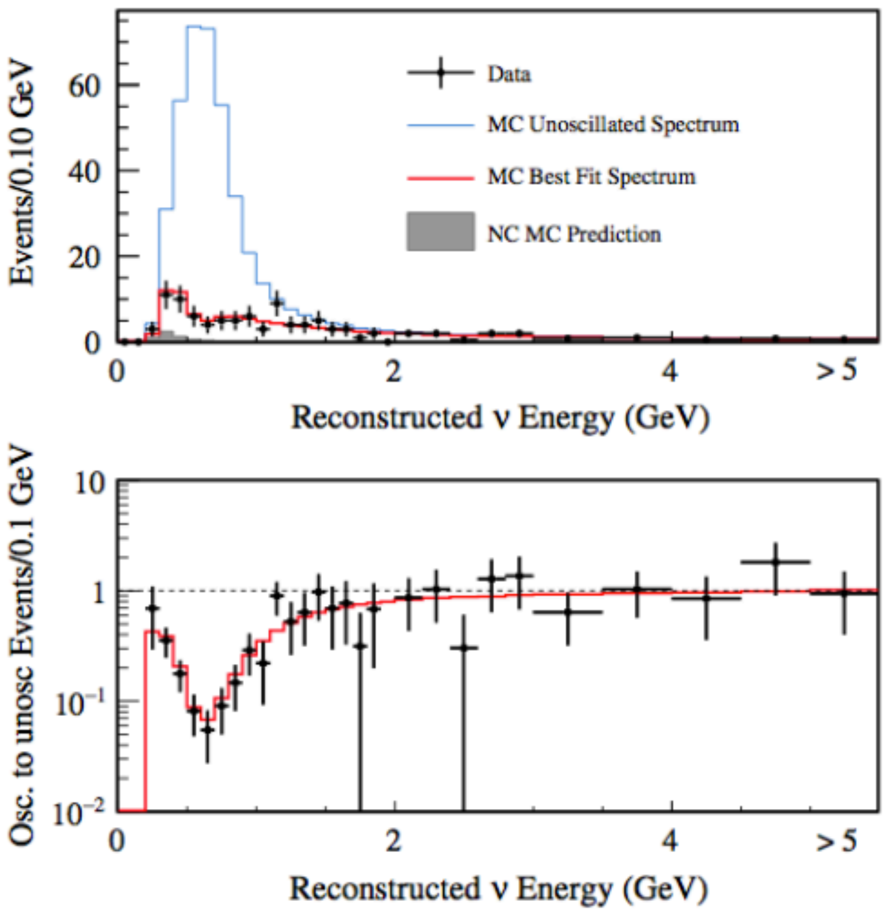
Total: 10.9×10^{20} POT

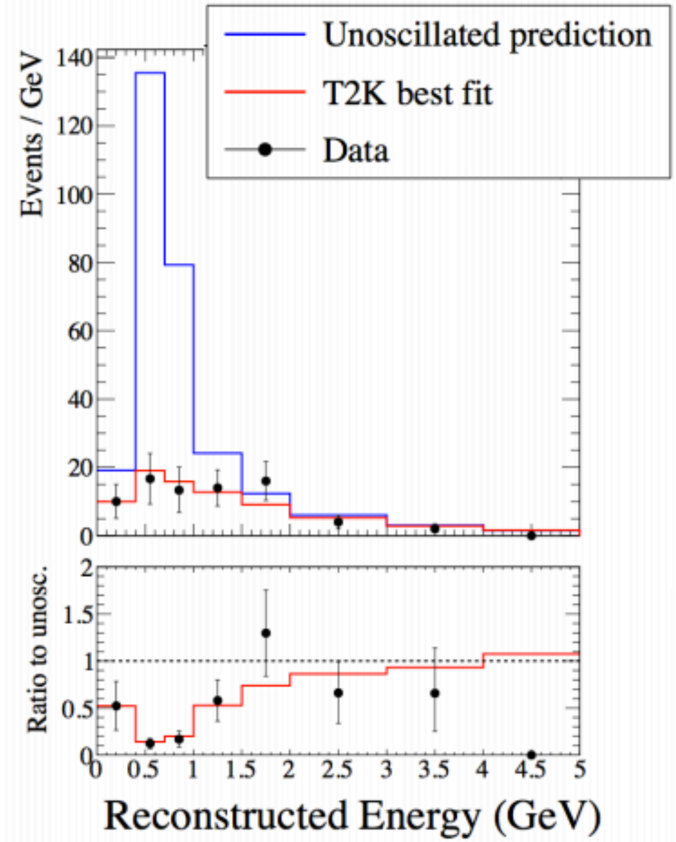
Been running in anti-neutrino mode since 2014

6.6e20 POT neutrino mode
120 μ-like events seen
Clear evidence of oscillation

Neutrino Mode

Phys. Rev. D 91, 072010



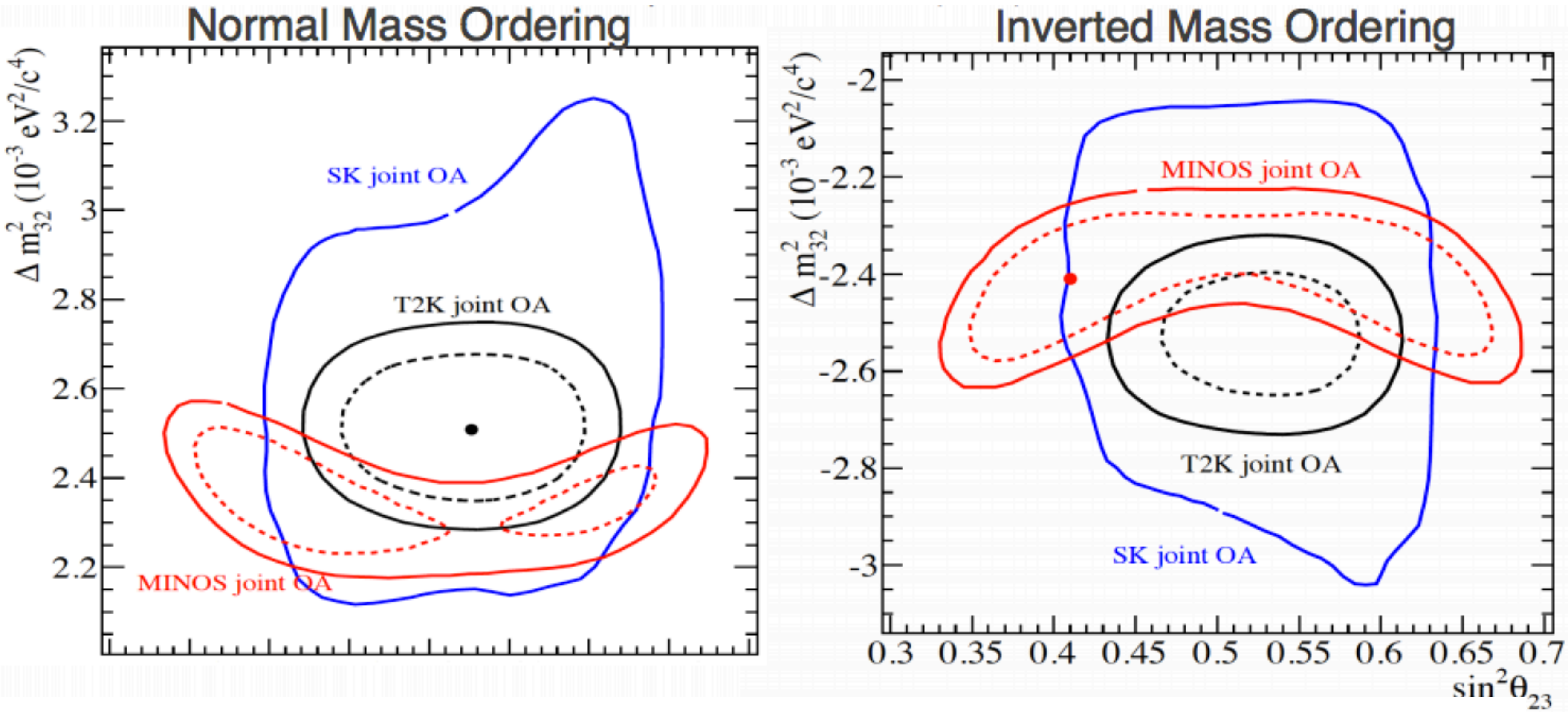


Anti-neutrino mode

M. Salzgeber
EPS, Vienna, July 23, 2015

4e20 POT in antineutrino mode
34 μ-like events seen
Clear evidence of oscillation

Joint ν_μ Disappearance/ν_e Appearance Result



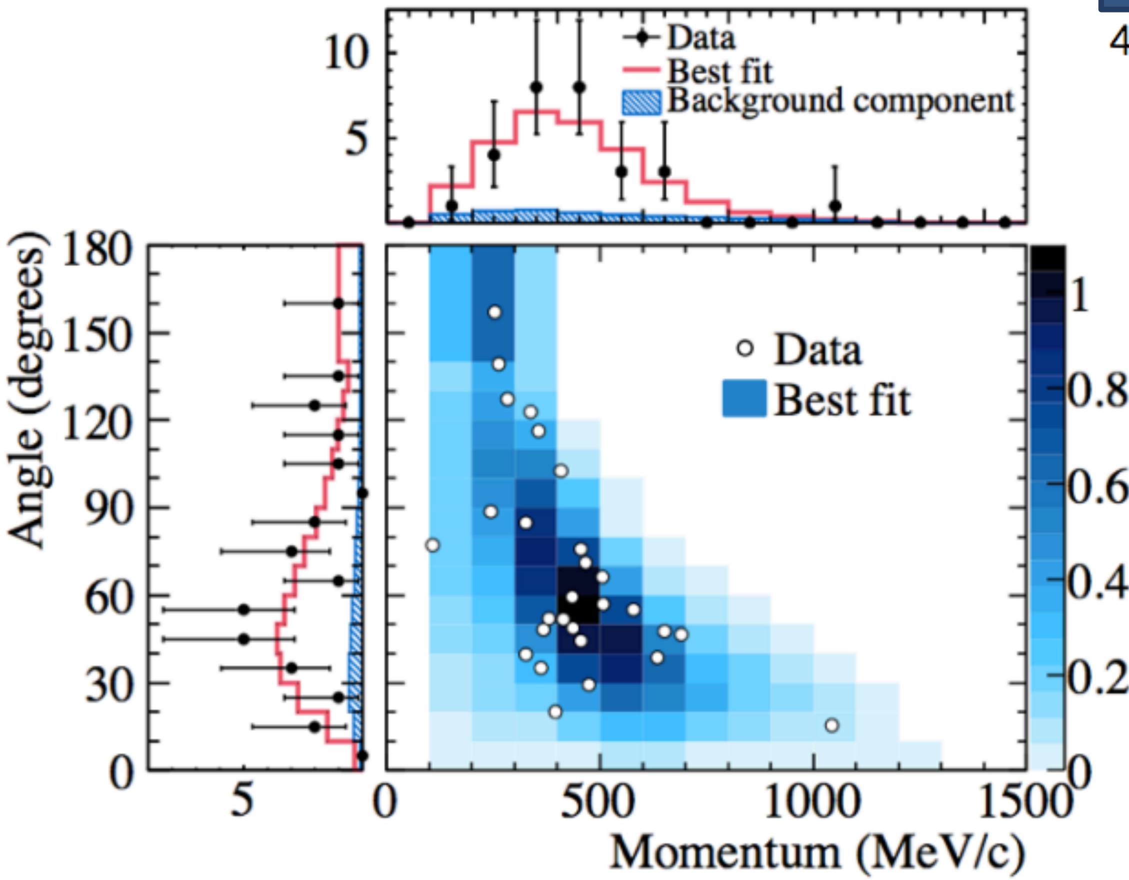
- T2K best fits: slight (<1σ) preference for **Normal Ordering**, $\sin^2\theta_{23}$=consistent with maximal
- MINOS best fits: slight preference for **Inverted Ordering**. Negligible preference for lower θ_{23} octant

Without reactor constraints:

Normal hierarchy: $\sin^2\theta_{23} = 0.514^{+0.055}_{-0.056}$

Inverted hierarchy: $\sin^2\theta_{23} = 0.511 \pm 0.055$

Electron-Neutrino and Anti-Neutrino Appearance



Electron-neutrinos

4.92 ± 0.55 background

28 events observed

7.3σ observation

21.6 events expected

$\sin^2 2\theta_{13}=0.1$

$\delta_{CP} = 0$

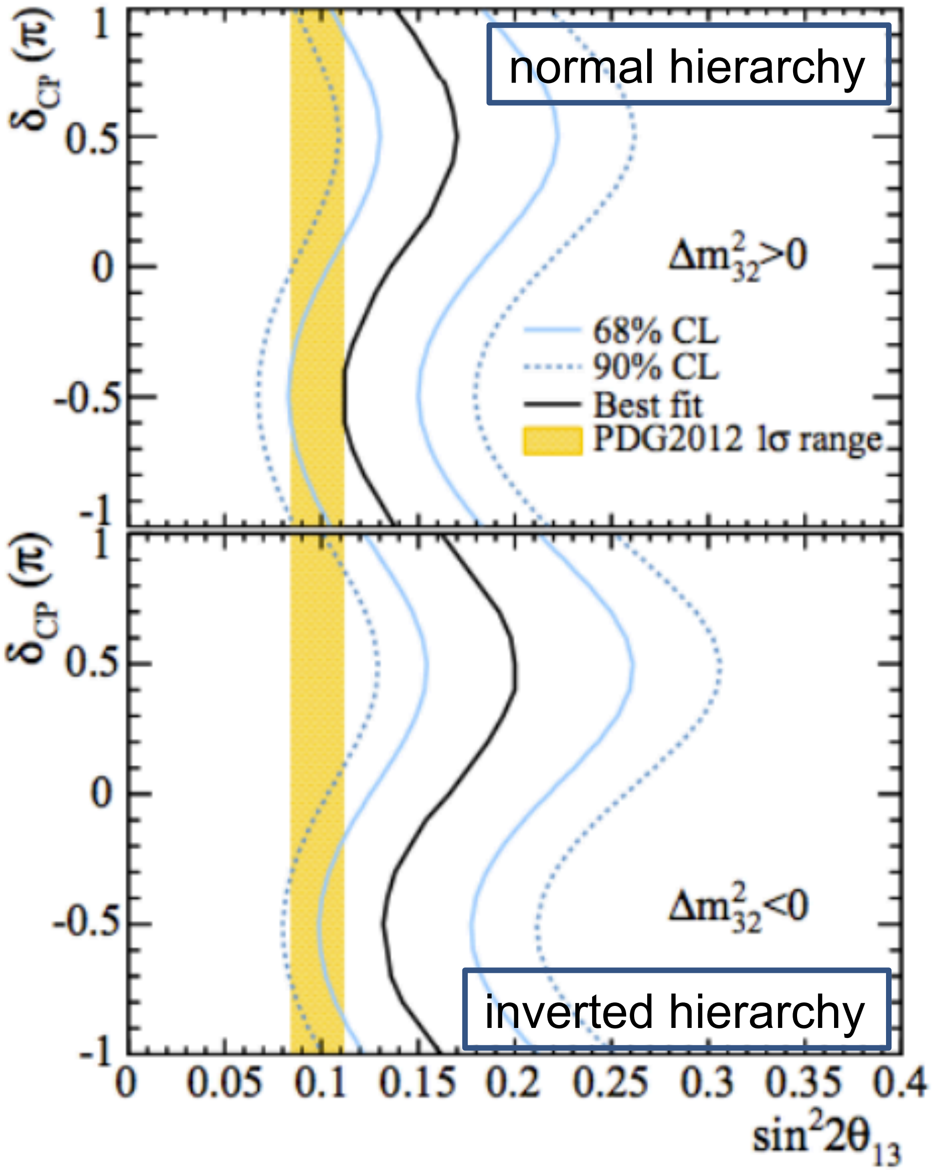
$\sin^2\theta_{23} = 0.5$

Anti-Neutrino: 3 events on a background of 1.8 seen
Update expected this summer

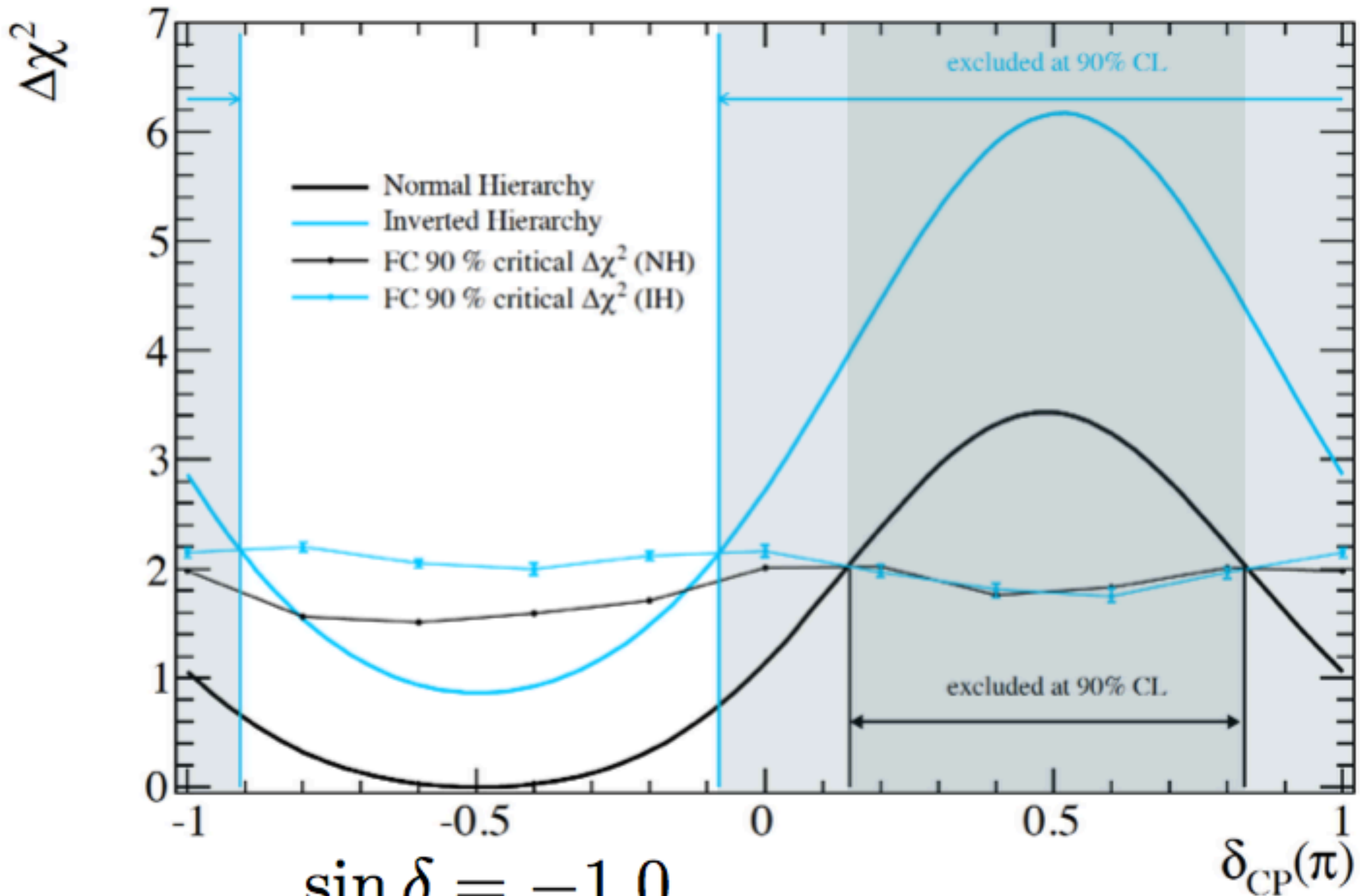
courtesy of M. Messier

Electron-Neutrino Appearance

- T2K $\sin^2 2\theta_{13}$ result computed assuming $\sin^2\theta_{23}$=0.5
- Consistent at 90% CL (1.6σ)
- Excess seen by T2K nudges all remaining unknowns in direction to increase rates
  - normal hierarchy
  - $\theta_{23} > 45^o$
  - δ_{CP}= -π/2 (aka 3π/2)



courtesy of M. Messier



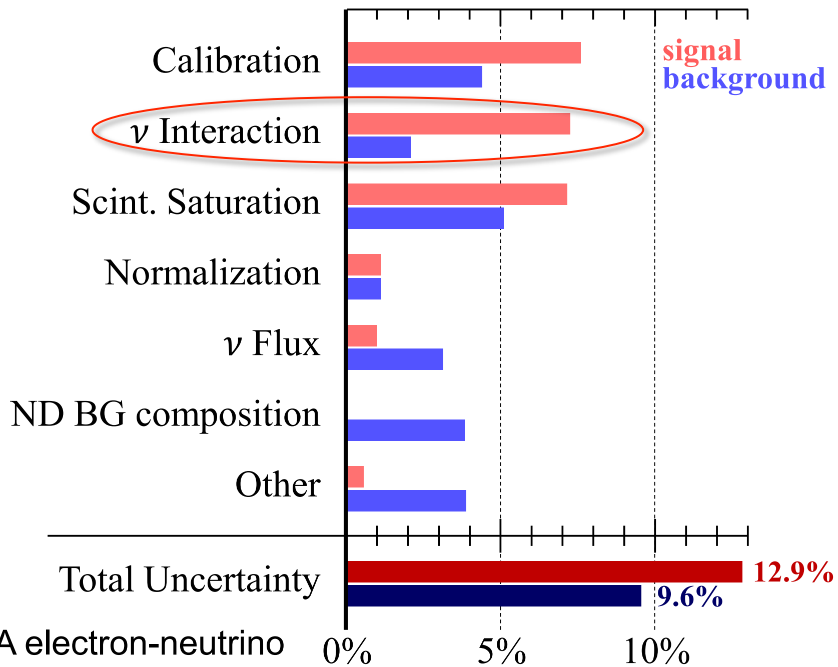
$\sin\delta = -1.0$

The tension with reactors gives some early sensitivity to δ_{CP}
T2K data prefers the normal hierarchy with $\delta_{CP}<0$ at ~90% C.L.

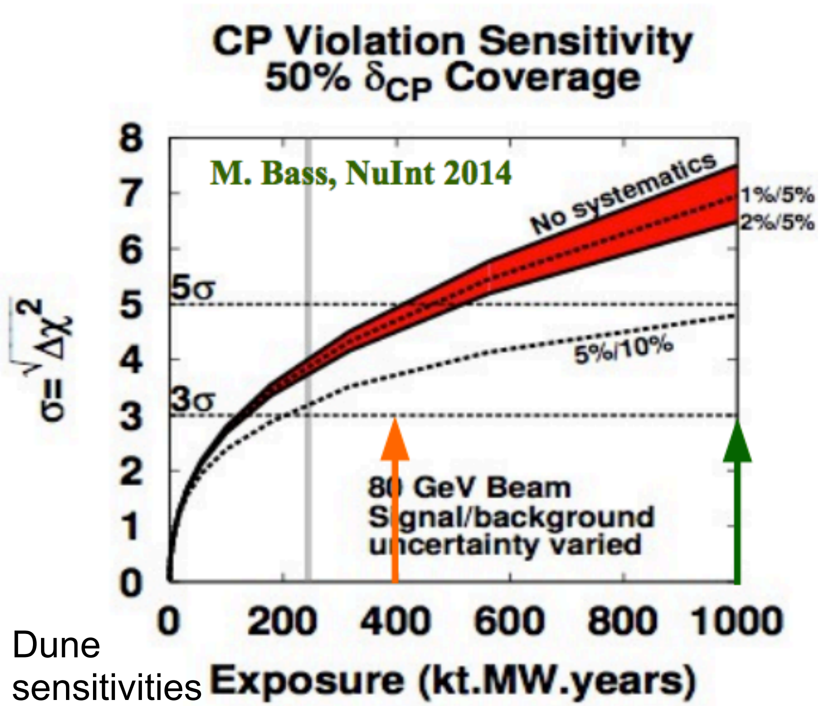
courtesy of M. Messier

MINERvA

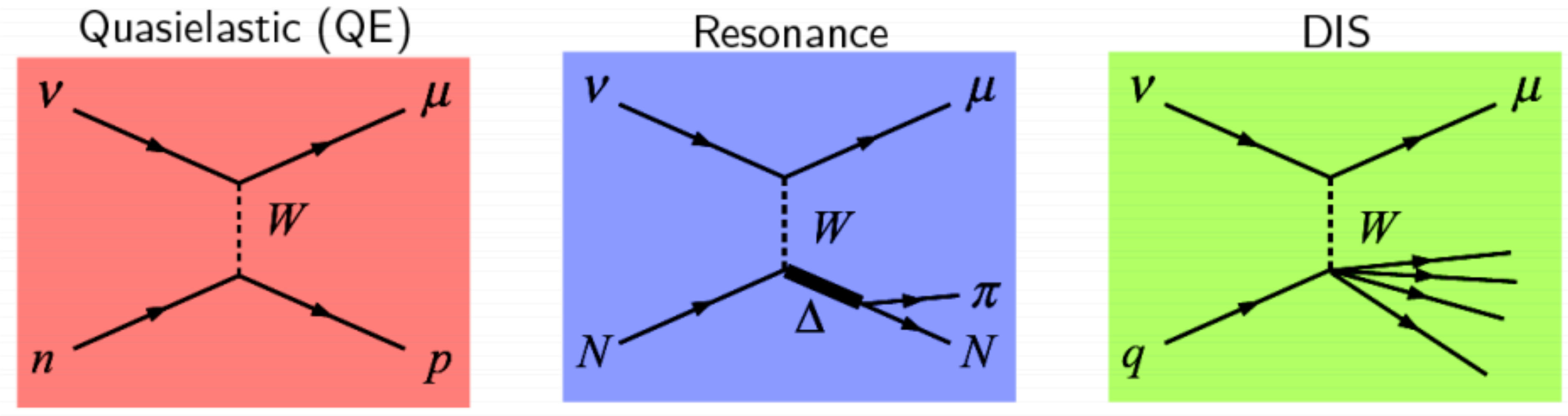
- Study neutrino-nucleus scattering at a few GeV, using Fermilabs NuMI 120 GeV beam
- Measure the effects of the nuclear environment on neutrino scattering
- Improve understanding of neutrino-nucleus cross section model by working with generators
- Benefits current and future neutrino oscillation experiments



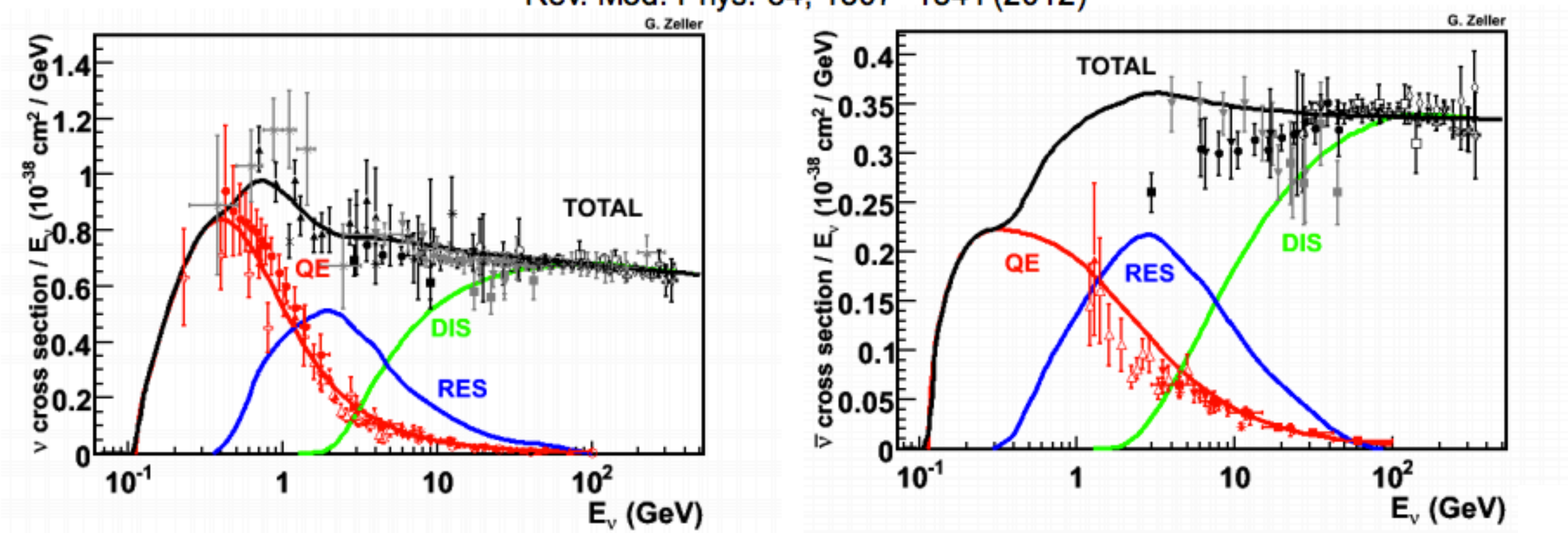
NOvA electron-neutrino appearance systematics



Dune sensitivities



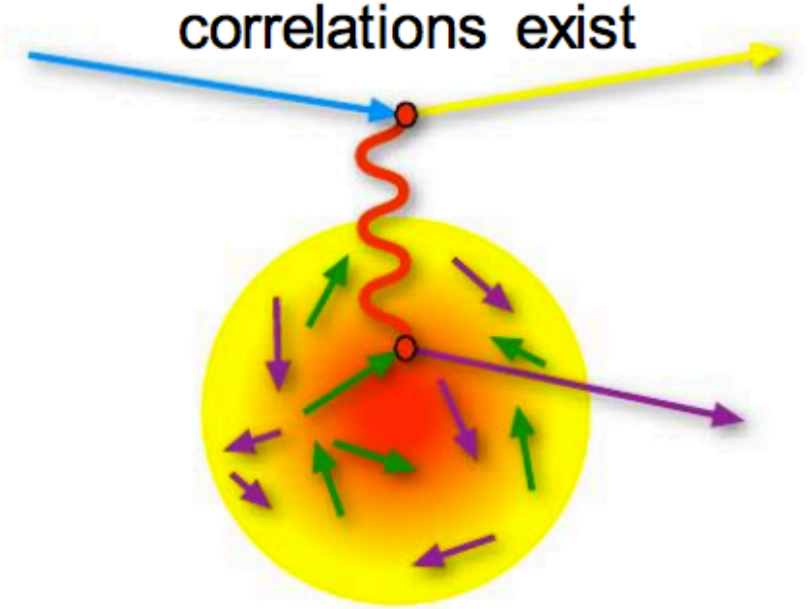
Rev. Mod. Phys. 84, 1307–1341 (2012)



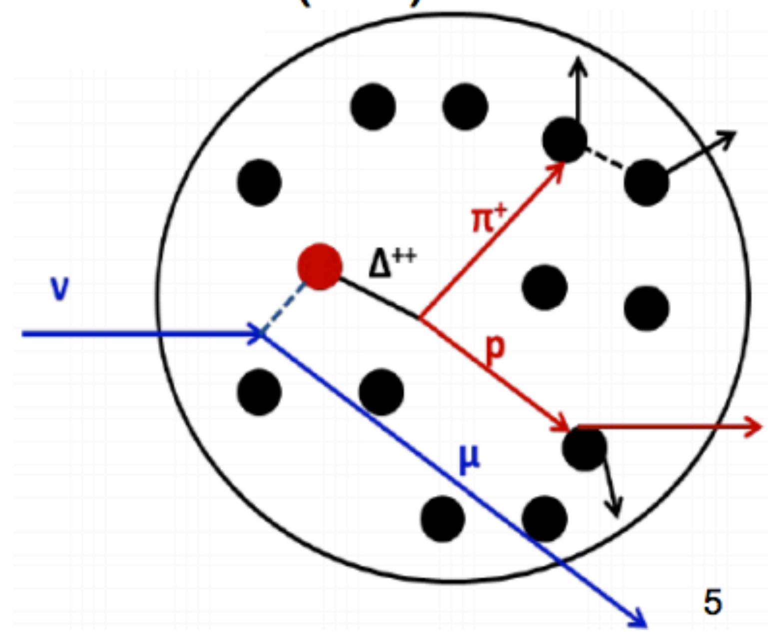
courtesy of D Ruterbories

Detector built with heavy nuclei for high interaction rate but introduces complications

Struck nucleon is not isolated short and long range correlations exist



Particles created have to propagate out of the nucleus. So called final state interactions (FSI)



courtesy of D Ruterbories

MINERvA ongoing analyses

Not-yet-published MINERvA analyses in Low Energy Beam

- Nuclear effects at low-momentum transfer (arXiv: 1511.05944)
- Electron neutrino charged-current quasi-elastic scattering (arXiv:1509.05729)
- DIS on nuclear target (Carbon, Iron and Lead)
- Neutral current diffractive pio production
- Neutrino-electron scattering
- Measurements of muon kinematics in neutrino induced charged pion production and antineutrino induced neutral pion production
- Double differential muon neutrino and antineutrino quasi-elastic scattering
- Neutrino and antineutrino flux and inclusive cross sections using the "low-nu" technique
- 3 Kaon production analyses (charged current, neutral current and coherent)
- neutrino charged current neutral pion production
- Antineutrino charged-current inclusive scattering on Carbon, Iron and Lead
- Neutrino charged-current inclusive scattering on Helium

Highest Priority Medium Energy Beam analyses

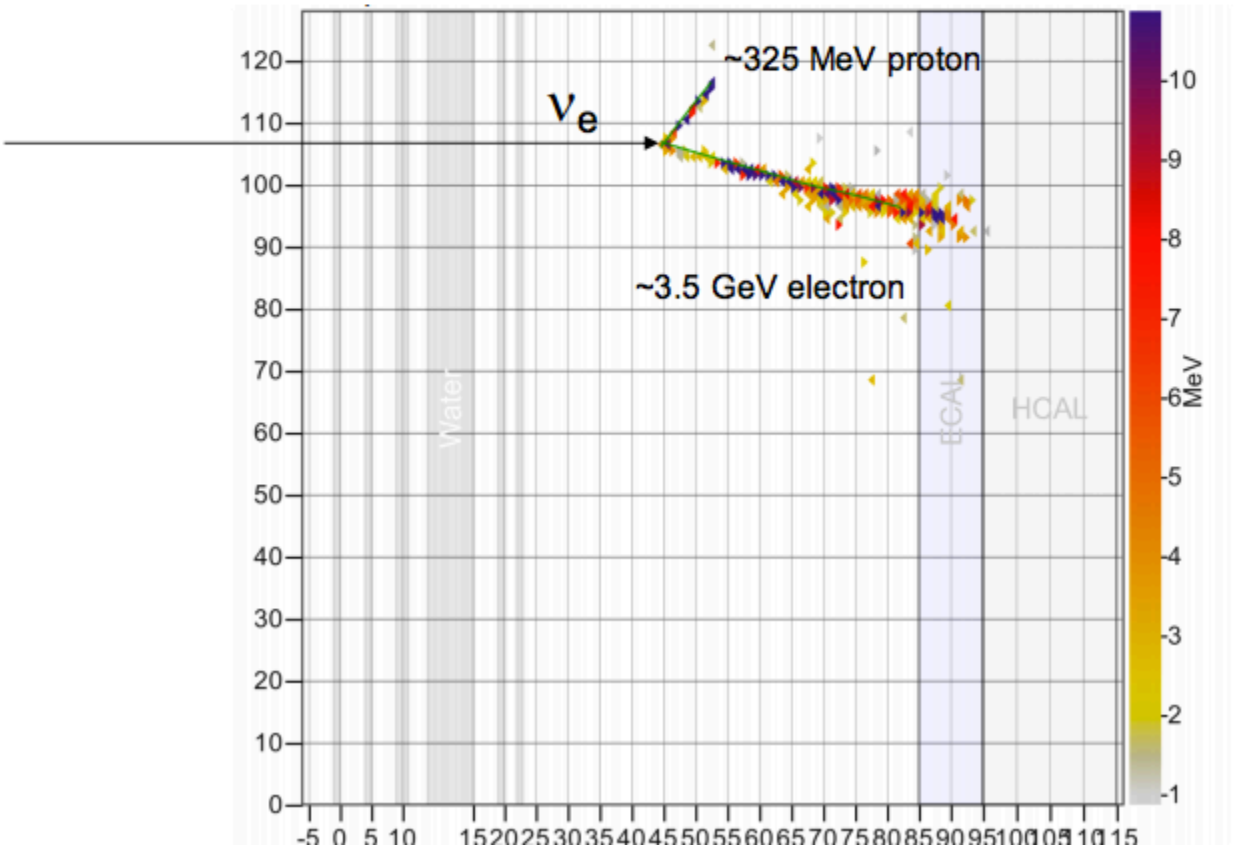
- Neutrino electron scattering on scintillator
- Neutrino DIS on scintillator, iron, carbon & lead
- CCQE on scintillator, iron, carbon & lead
- Pion production on scintillator, iron, carbon & lead
- Coherent pion production on scintillator, iron, carbon & lead
- Nuclear structure functions

Keep them coming.....

From Laura Fields

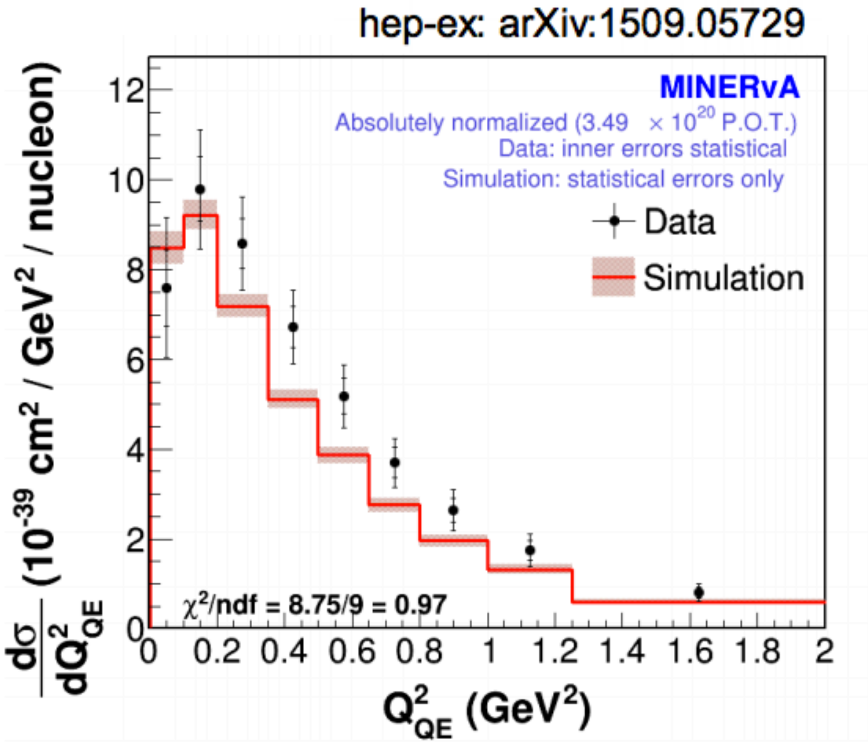
CC QE via ν_e– nucleus scattering

Dominant neutrino oscillation ν_e-appearance signal process

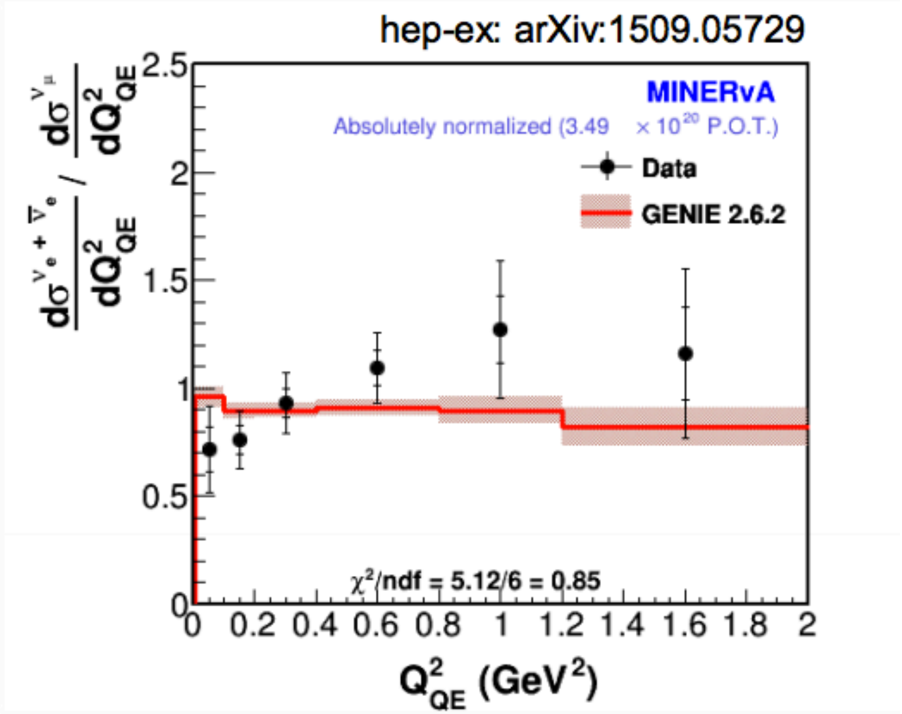


courtesy of D Ruterbories

ν_e CC QE differential cross section



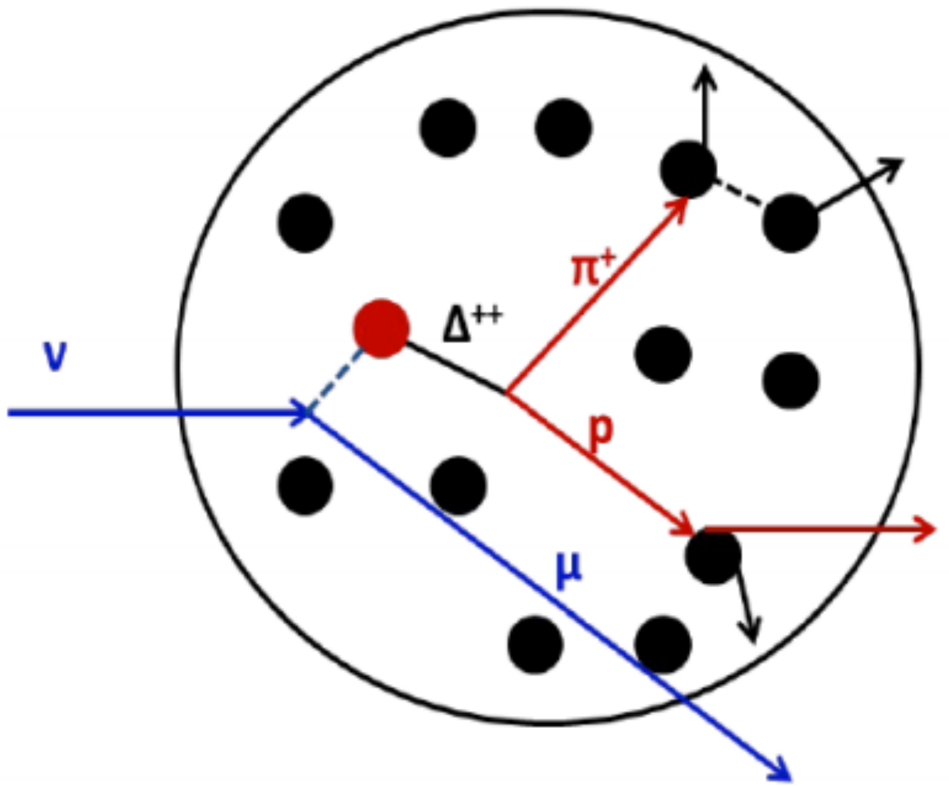
ν_e to ν_μ differential cross section ratio



- Ratio is consistent with 1.0, but shape is not significant
- Large correlated errors

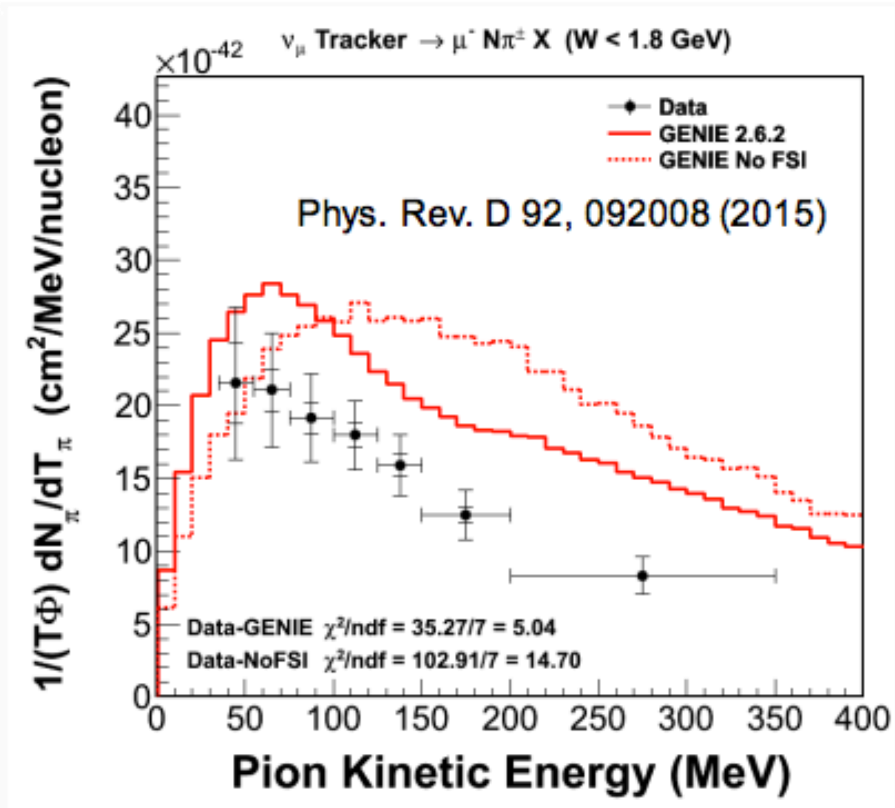
Charged and neutral pion production

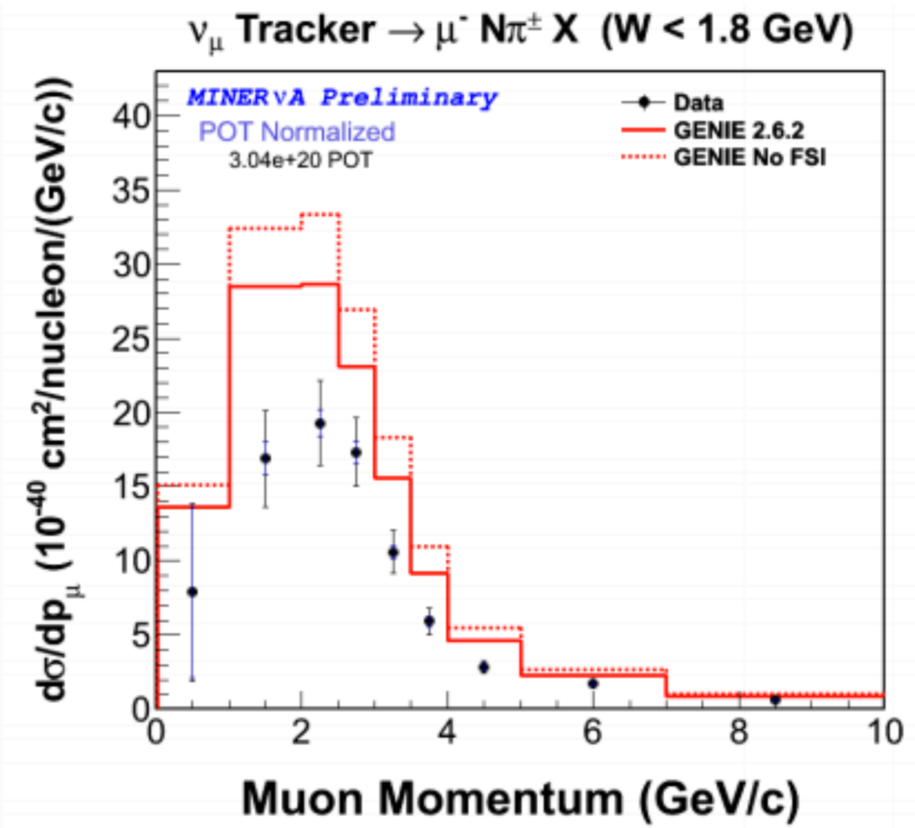
- Can investigate final state interactions by measuring the pion spectra
- Can investigate nuclear modifications by measuring Q^2 which is insensitive to pion FSI since you measure via the outgoing lepton



courtesy D Ruterbories

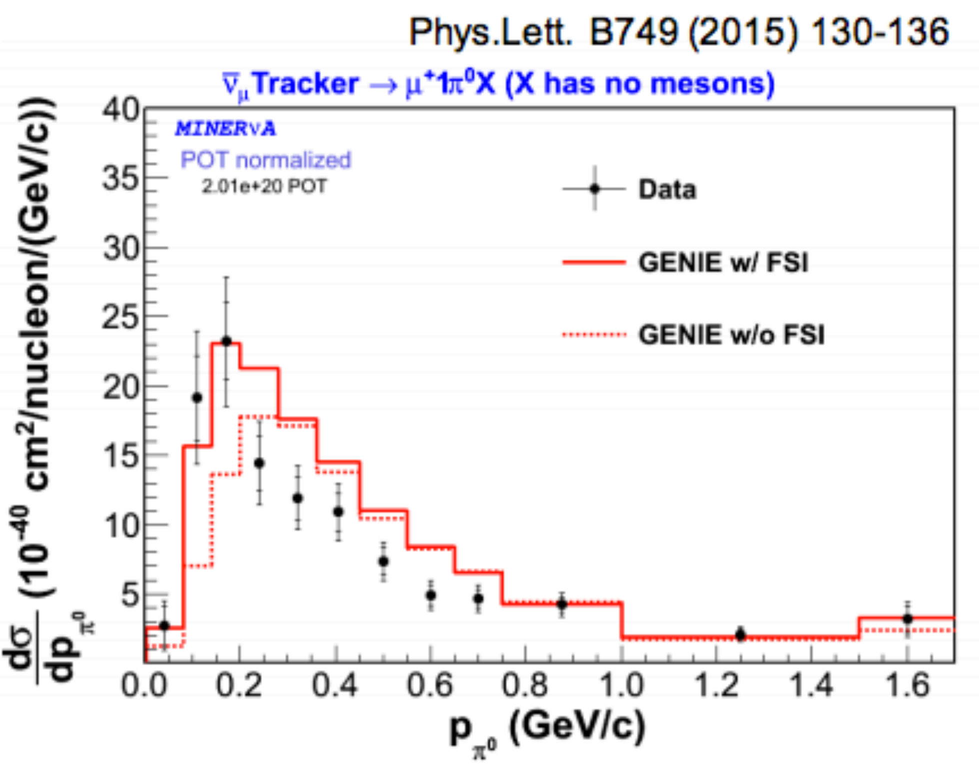
Charged Pion Production

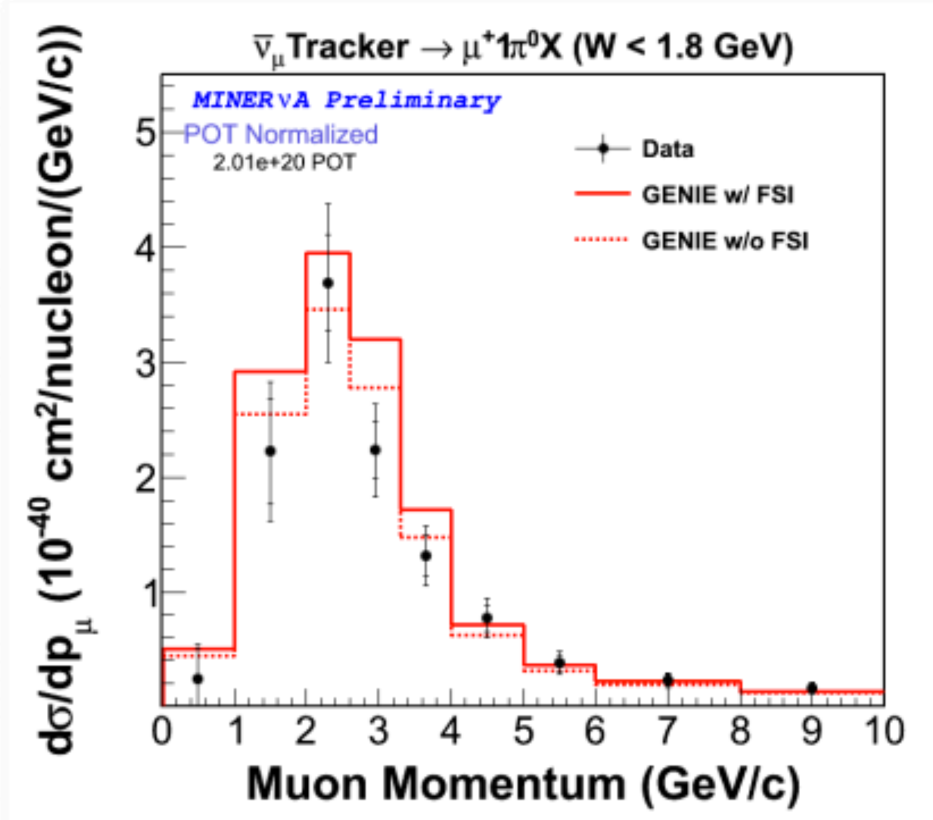




- Shape agrees, but cross section is over predicted
- FSI reduces the cross section due to pion absorption

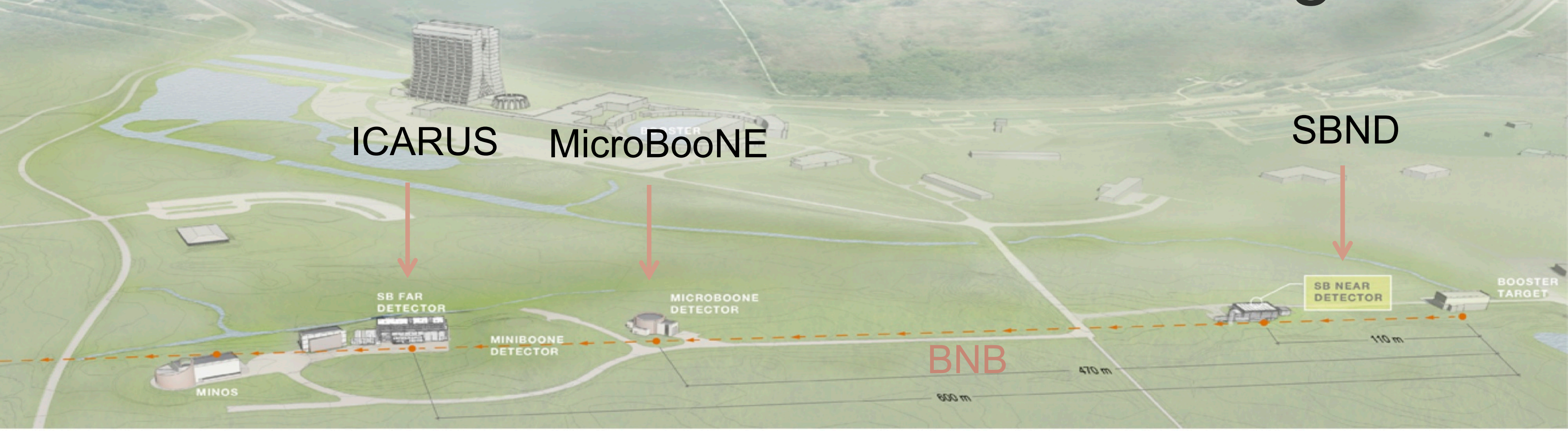
Neutral pion production





- Shape agrees
- FSI increases the cross section due to charge exchange

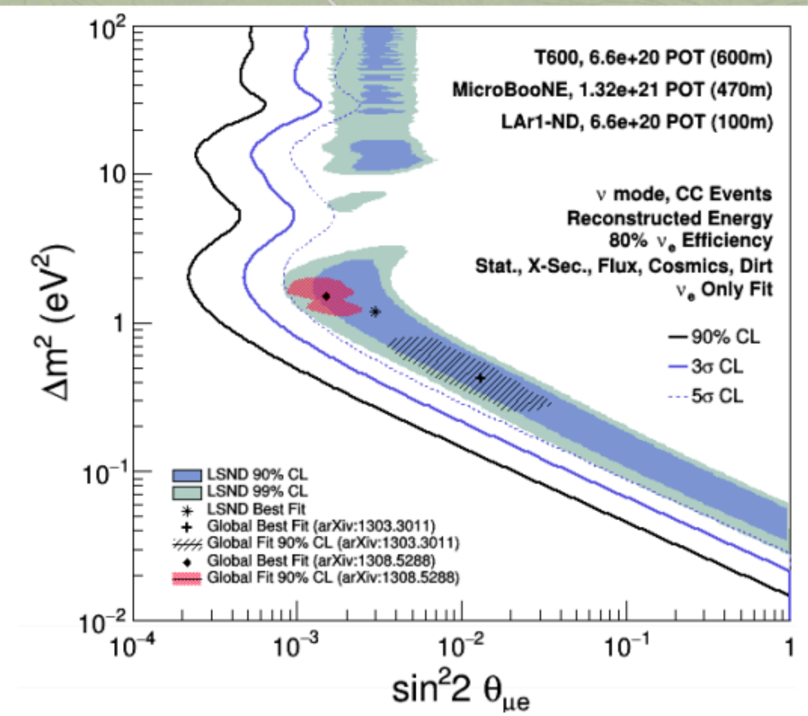
Fermilab's Short-Baseline Neutrino Program



Three LArTPC detector program

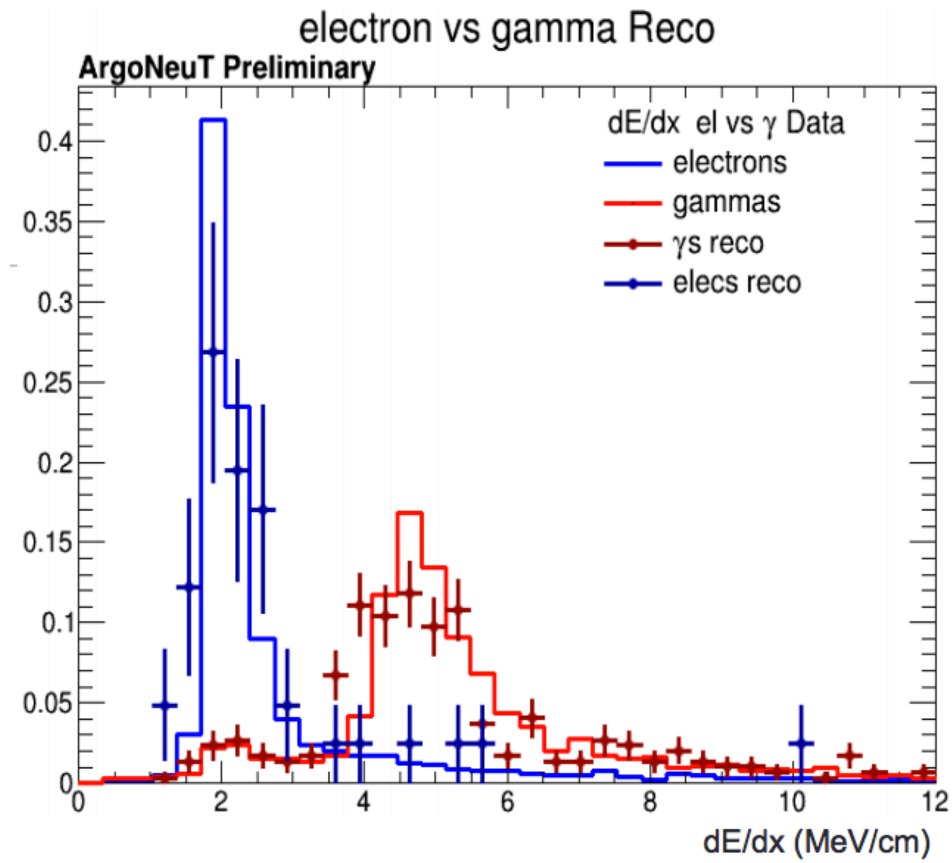
1) MicroBooNE: currently taking data
2) Near Detector SBND: Construction to start ~now, first data in 2018
3) Far Detector ICARUS@FNAL: Construction started 2015, first data in 2018

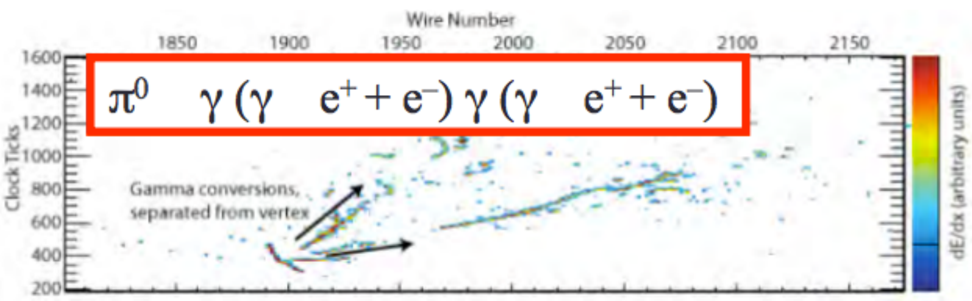
Designed to answer the question of sterile neutrinos and test bed for LArTPC technology

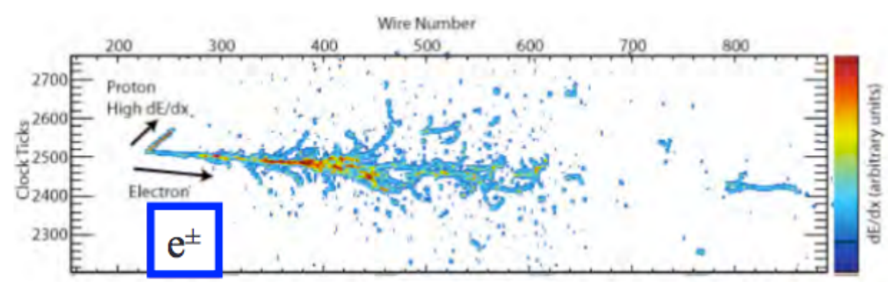


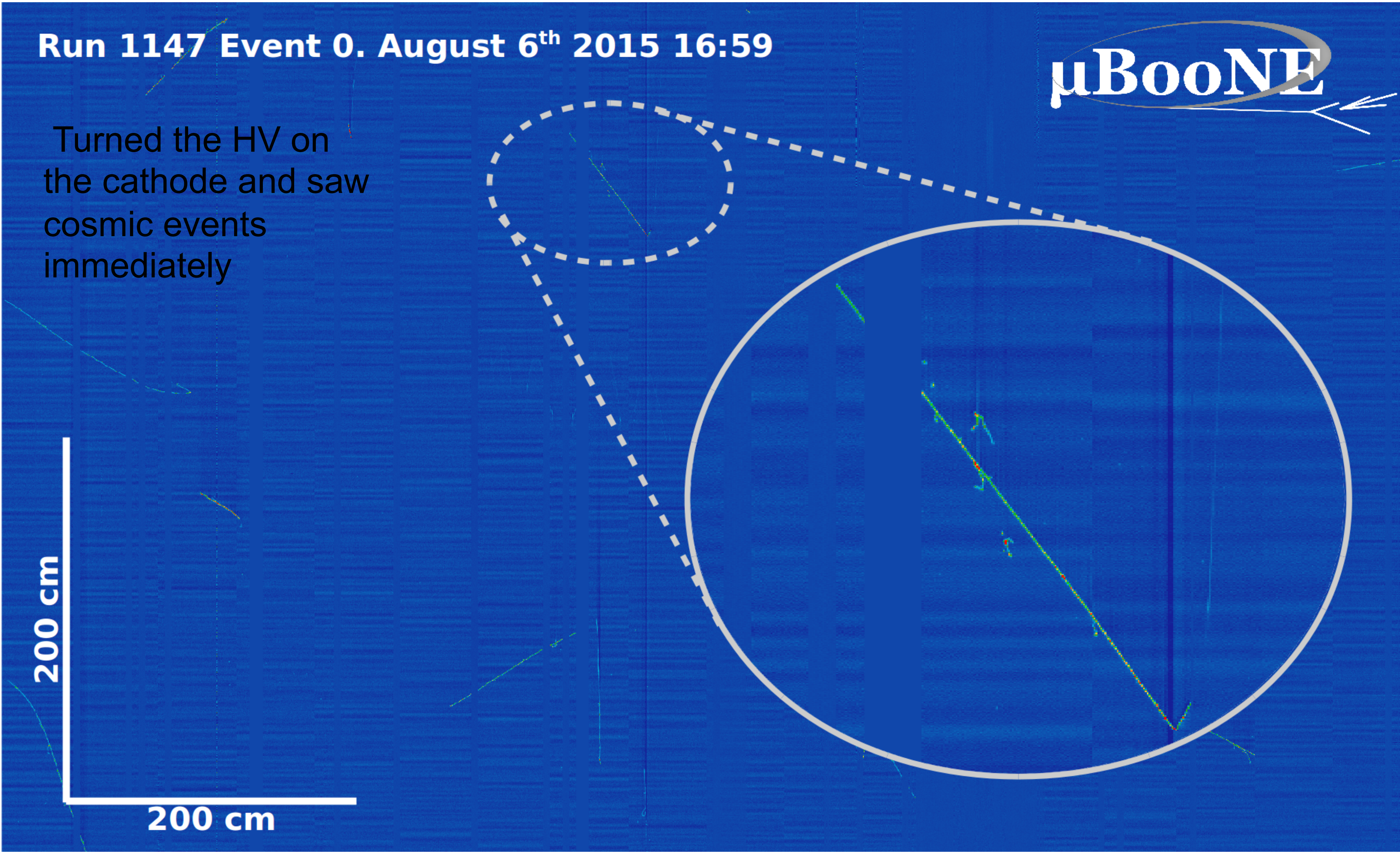
MircoBooNE

- LArTPC allow for precision electron-photon separation
- MicroBooNE aims to answer question of whether excess seen by MiniBooNE is electrons or photons
- Expect millions of events per year, active cross sections group

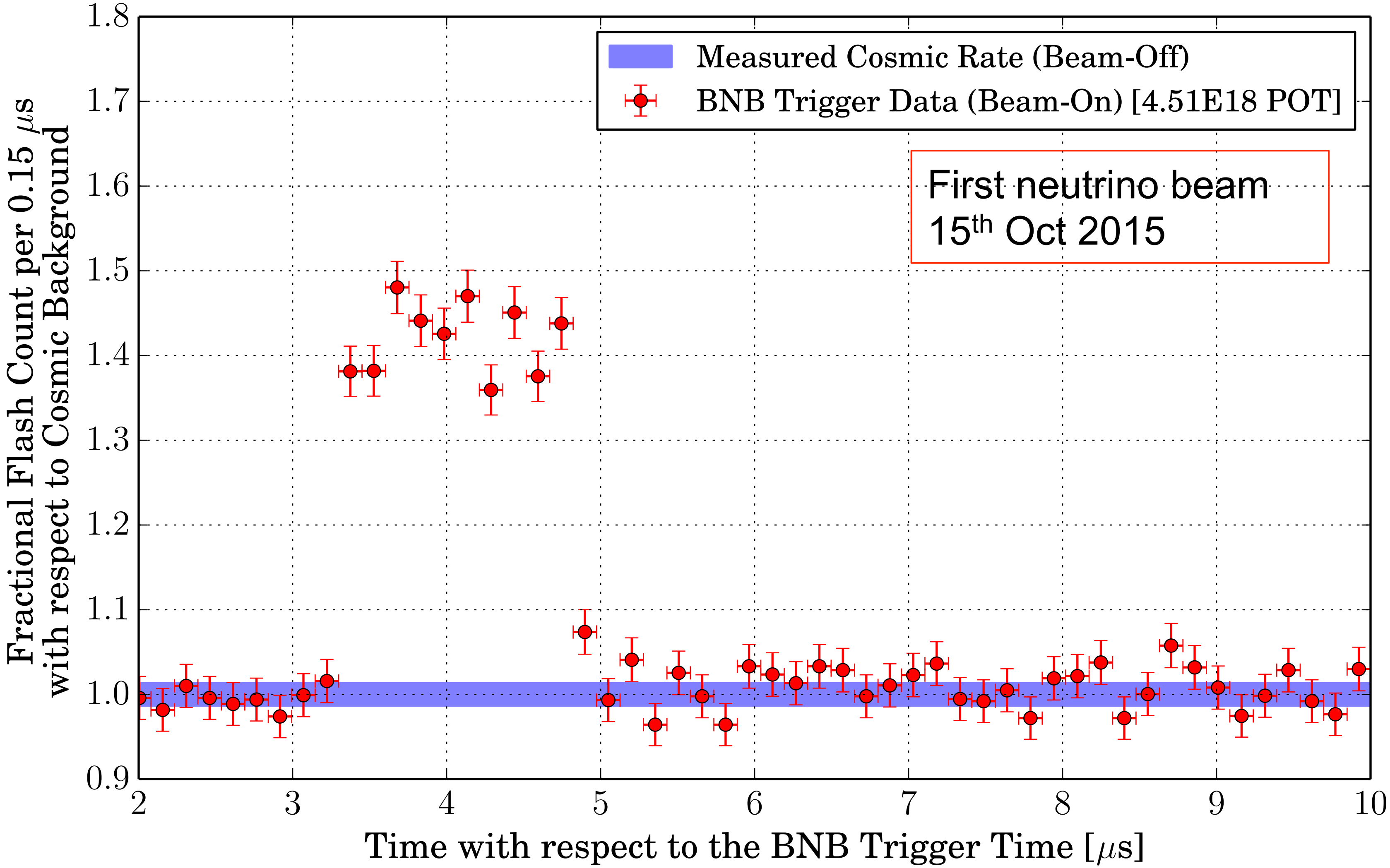






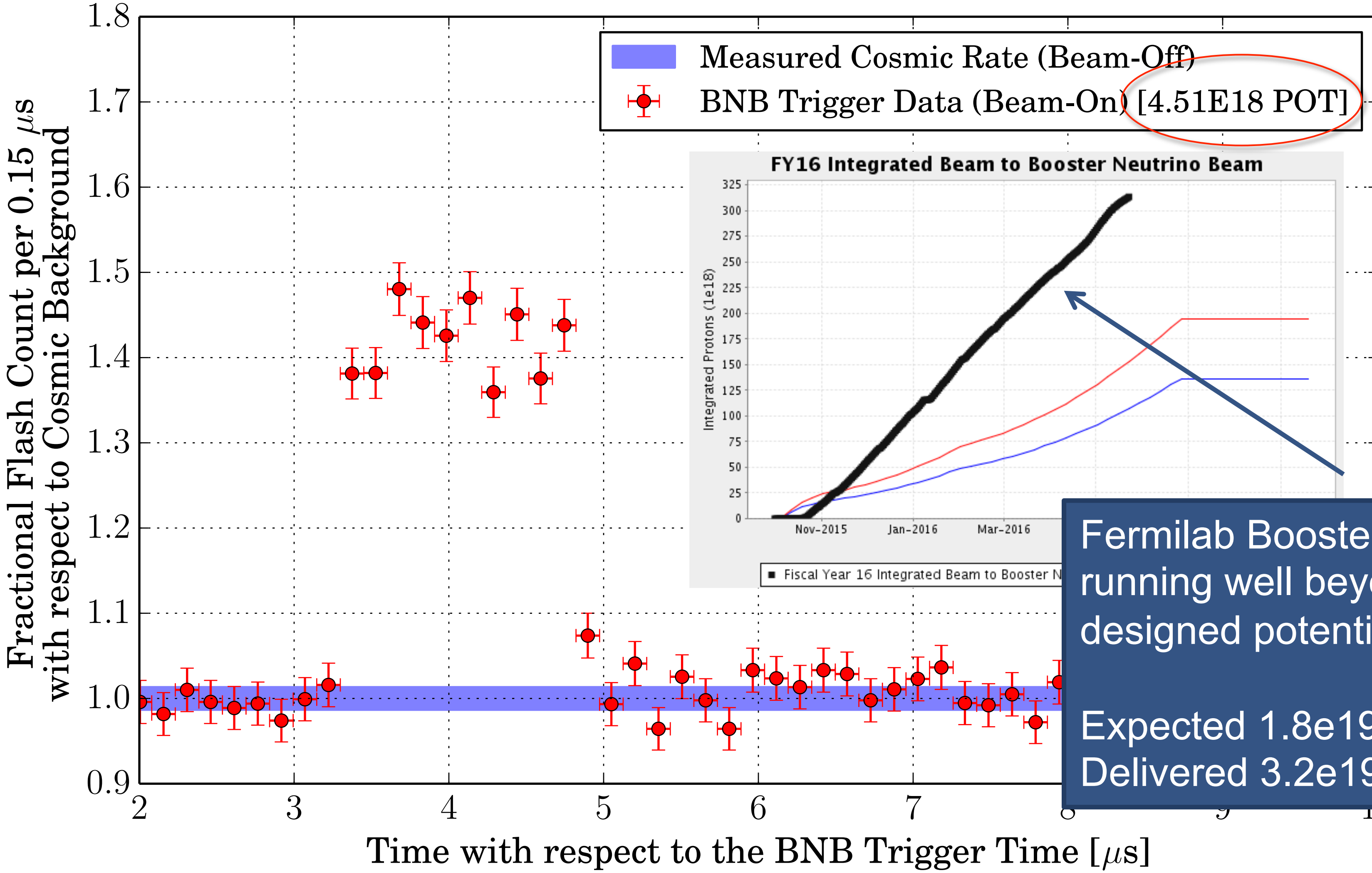


Turned the HV on the cathode and saw cosmic events immediately



Detector on surface large cosmic ray background

Events identified using reconstruction from both the wire readout and the light collection system

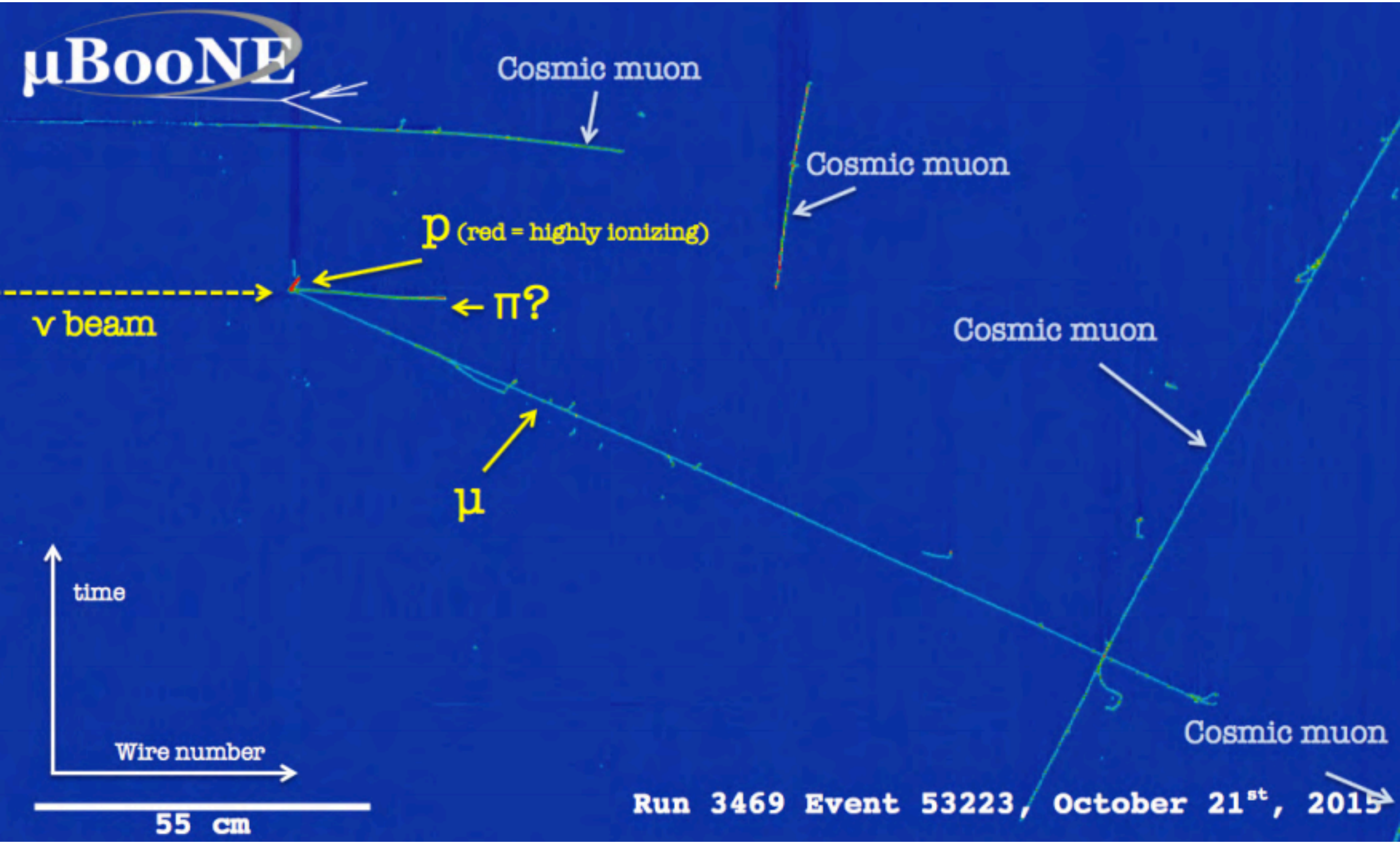


Fermilab Booster beam running well beyond the designed potential

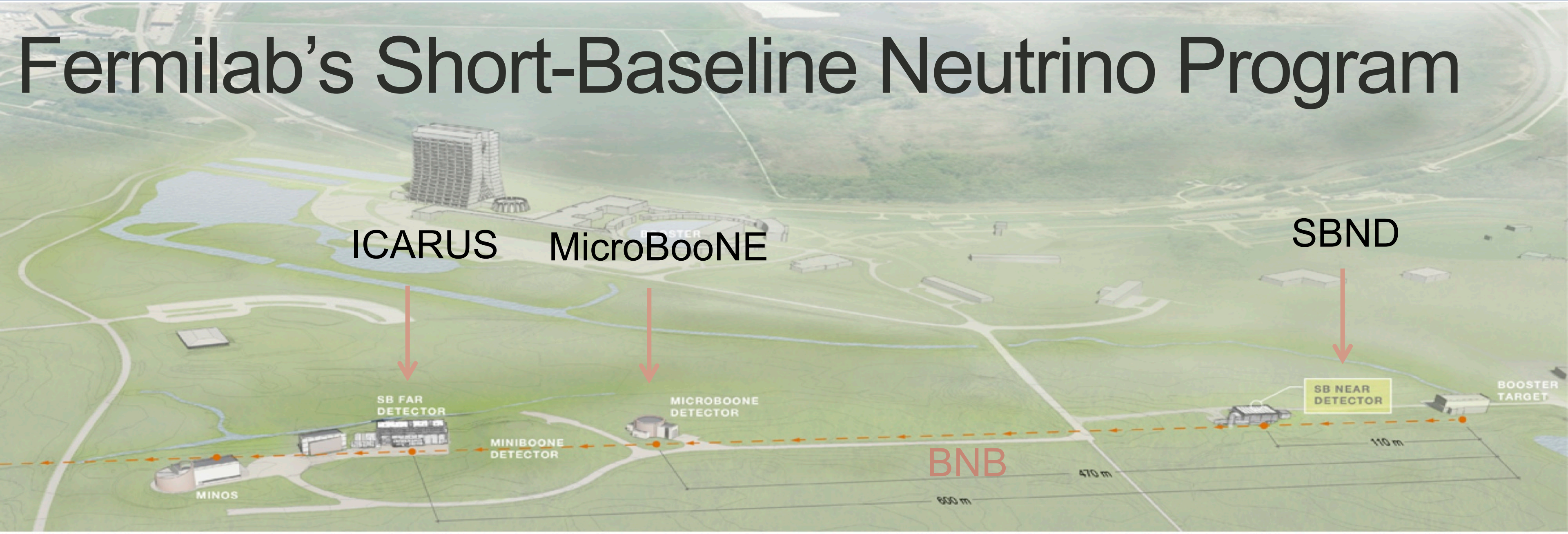
Expected 1.8e19 POT
Delivered 3.2e19 POT

Detector on surface large cosmic ray background

Events identified using reconstruction from both the wire readout and the light collection system


μBooNE
Cosmic muon
Cosmic muon
p (red = highly ionizing)
ν beam
← π?
Cosmic muon
μ
time
Wire number
Cosmic muon
55 cm
Run 3469 Event 53223, October 21st, 2015

Fermilab's Short-Baseline Neutrino Program



Three LArTPC detector program

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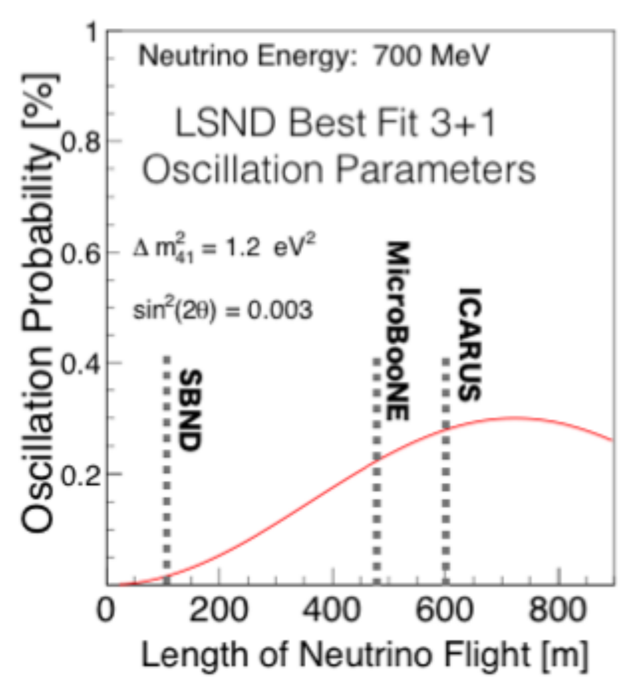
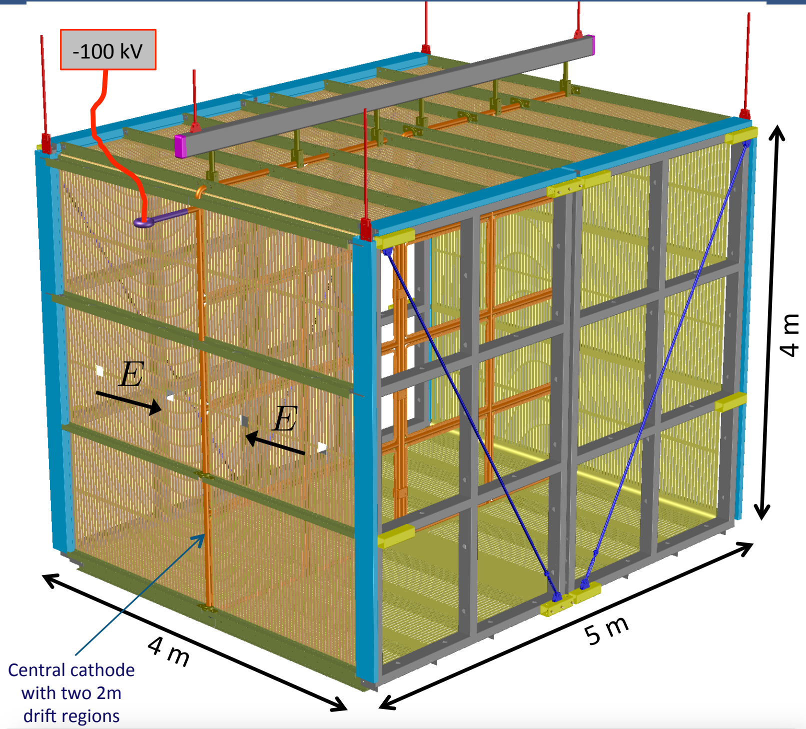
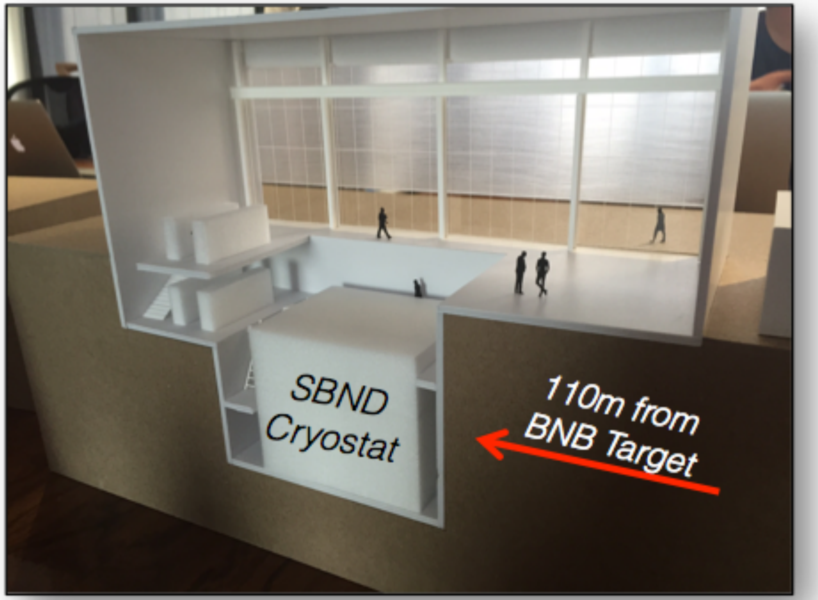


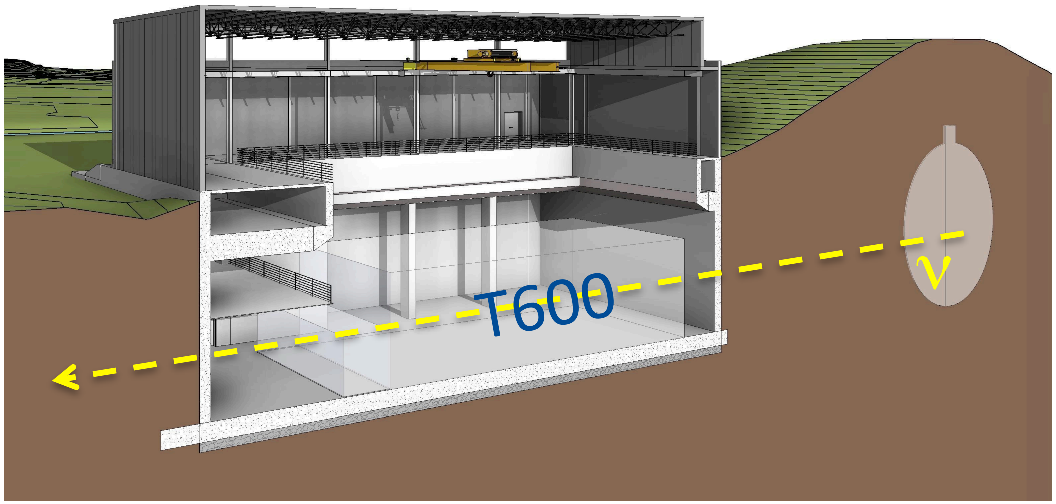
Short Baseline Near Detector

- Short baseline program with long baseline design
  - Near detector to provide a detailed characterization of the beam before oscillation
  - Allows for the cancelation of many of the dominant systematics
- Expects > 1.5 million neutrino events per year to able to perform high precision cross section measurements
- **First data 2018**





ICURAS @ FNAL



- SBN Far Detector uses the largest LArTPC in the world
  - 6x larger than MicroBooNE
- Been running at Gran Sasso since 2010, was moved to CERN in 2014 to be refurbished
- Will be moved to FNAL 2017
- **First data 2018**

Conclusions

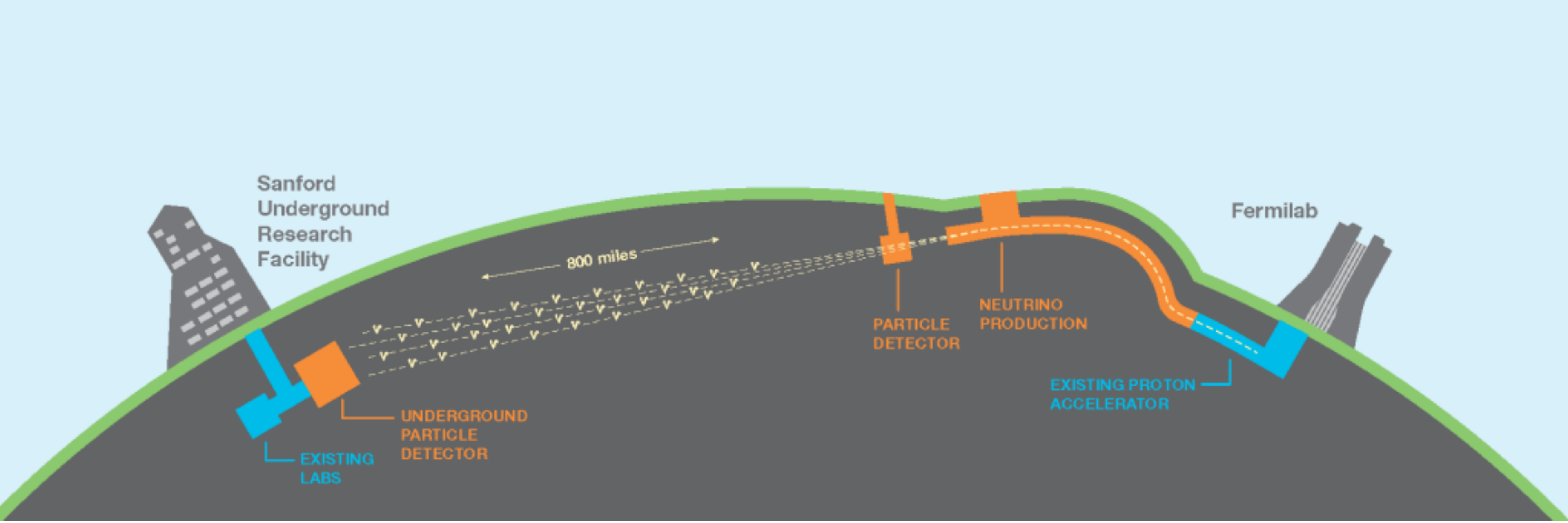
- Measurements using atmospheric neutrinos, reactor neutrinos and long-baseline neutrinos form a consistent picture
  - Large θ_{23} ($0.4 < \sin^2\theta_{23} < 0.6$)
  - Precisely known $\theta_{13} = 8.4^o$
- Consistent hints favoring
  - $\pi<\delta_{CP}<2\pi$
  - Normal mass ordering
- First data from NOvA strengthens this picture

- New results from NOvA, T2k, and MINOS+ this summer, will be very exciting times
- New results from MINERvA and MircoBooNE will strengthen our understanding of neutrino interactions and our other measurements

Backup

DUNE

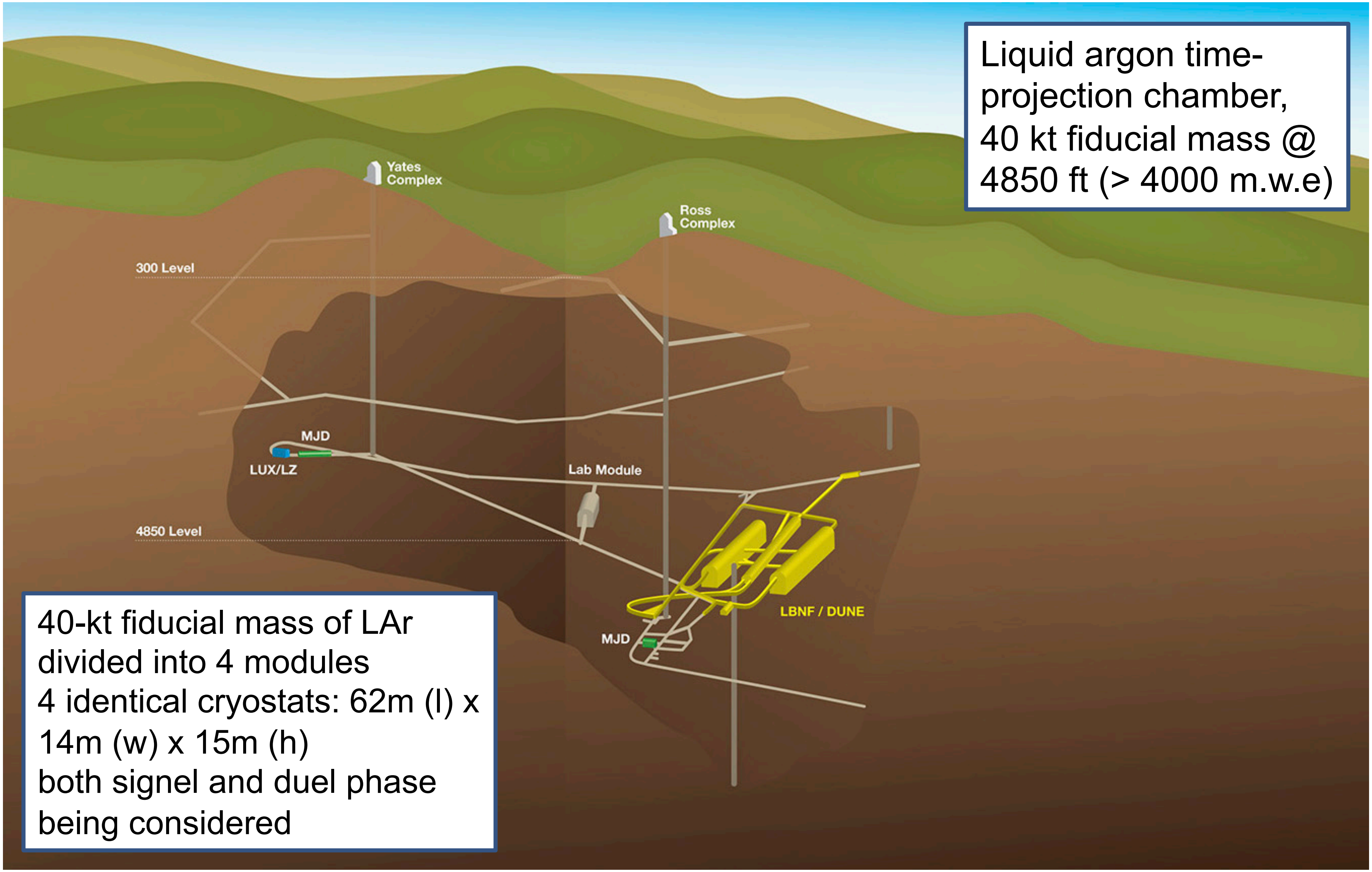
Wide-band on-axis neutrino beam produced by the primary 60-120 GeV proton beam. Initial power 1.2 MW, upgradable to 2.4 MW



1300 km (800 mile) baseline, 1 st (2nd) oscillation max. @ ~2.4 (0.8) GeV

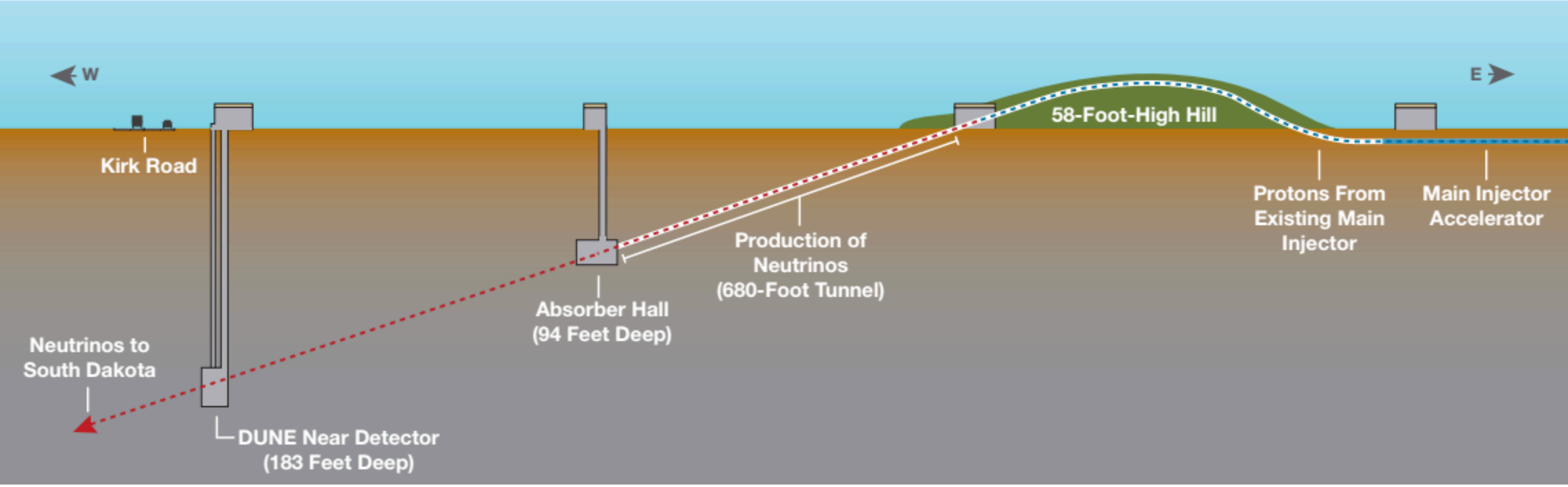
First data 2024, first beam 2026

Fine-grained near detector complex, enabling unprecedented studies of neutrino interactions

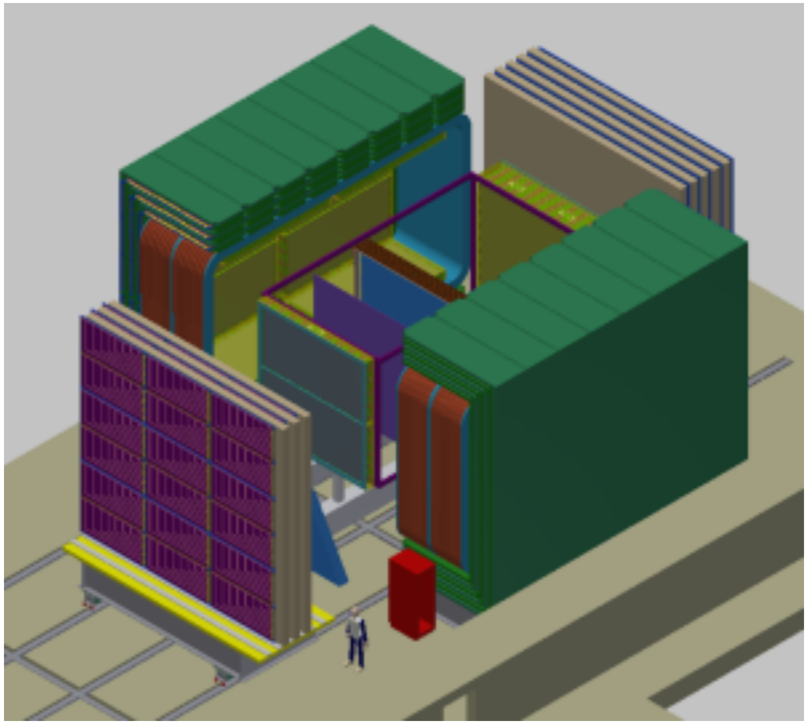


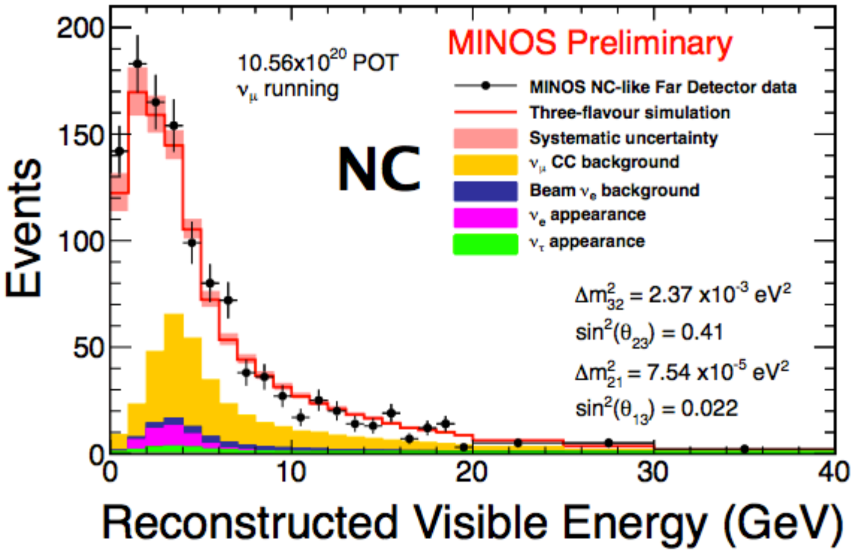
Liquid argon time-projection chamber,
40 kt fiducial mass @ 4850 ft (> 4000 m.w.e)

40-kt fiducial mass of LAr divided into 4 modules
4 identical cryostats: 62m (l) x 14m (w) x 15m (h)
both signel and duel phase being considered

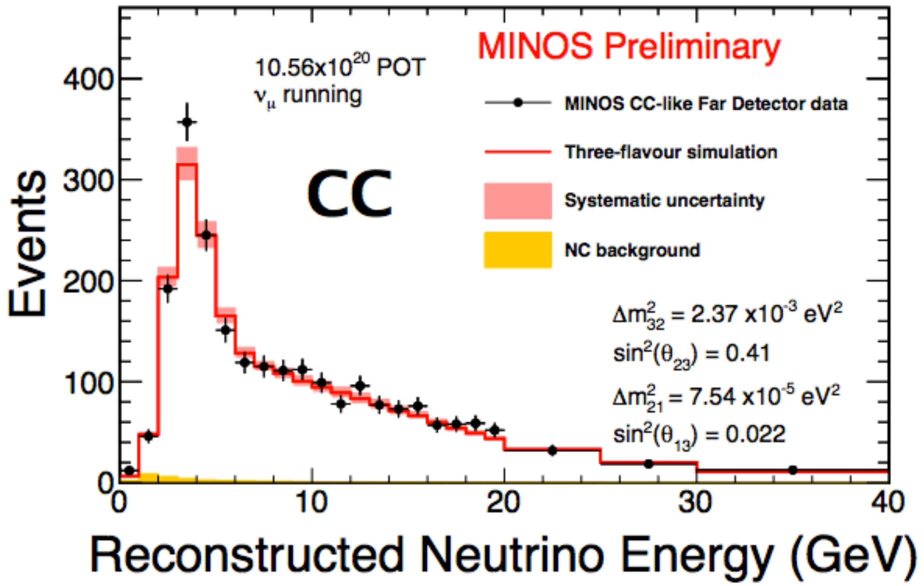


central straw-tube tracking (STT) system with embedded nuclear targets (CH, C, Ar, ...)
4π electromagnetic calorimeters (ECAL)
dipole 0.4-T magnet surrounding STT and ECAL
4π muon identifiers
Additional detectors under study: magnetized LAr TPC and high-pressure gas TPC > 100 million events per year for a wide range of energies





1211 NC-like events



2563 CC-like events

FD spectra three-flavor oscillated with MINOS 2012 CC-analysis fit values

$$R = \frac{N_{data} - \sum B_{CC}}{S_{NC}}$$

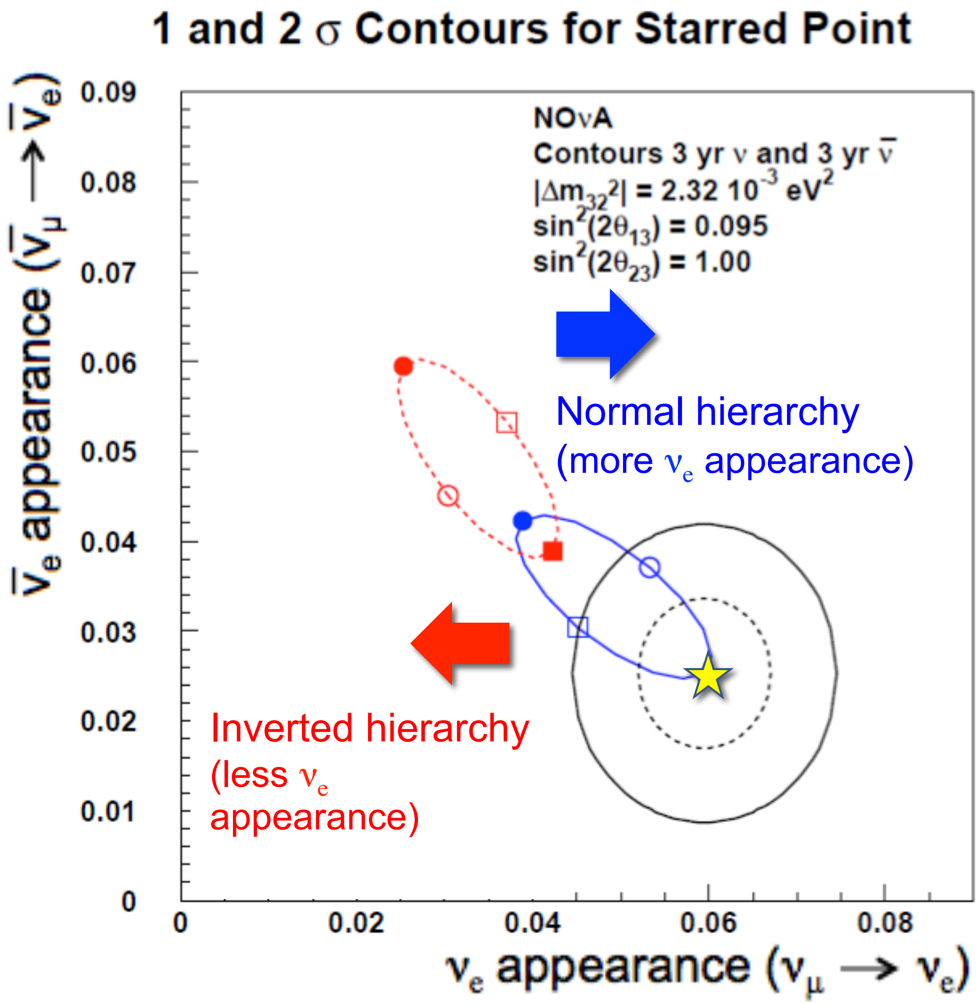
$\sum B_{CC}$: Predicted CC background from all flavors

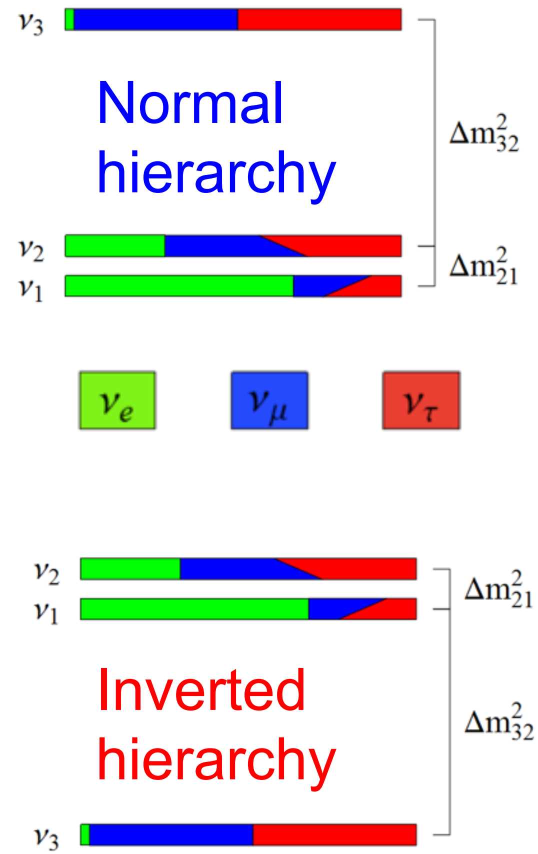
S_{NC}: Predicted NC interaction signal

R [0–3 GeV] = 1.10 +/– 0.06 +/– 0.07

R [0–40 GeV] = 1.05 +/– 0.04 +/– 0.10

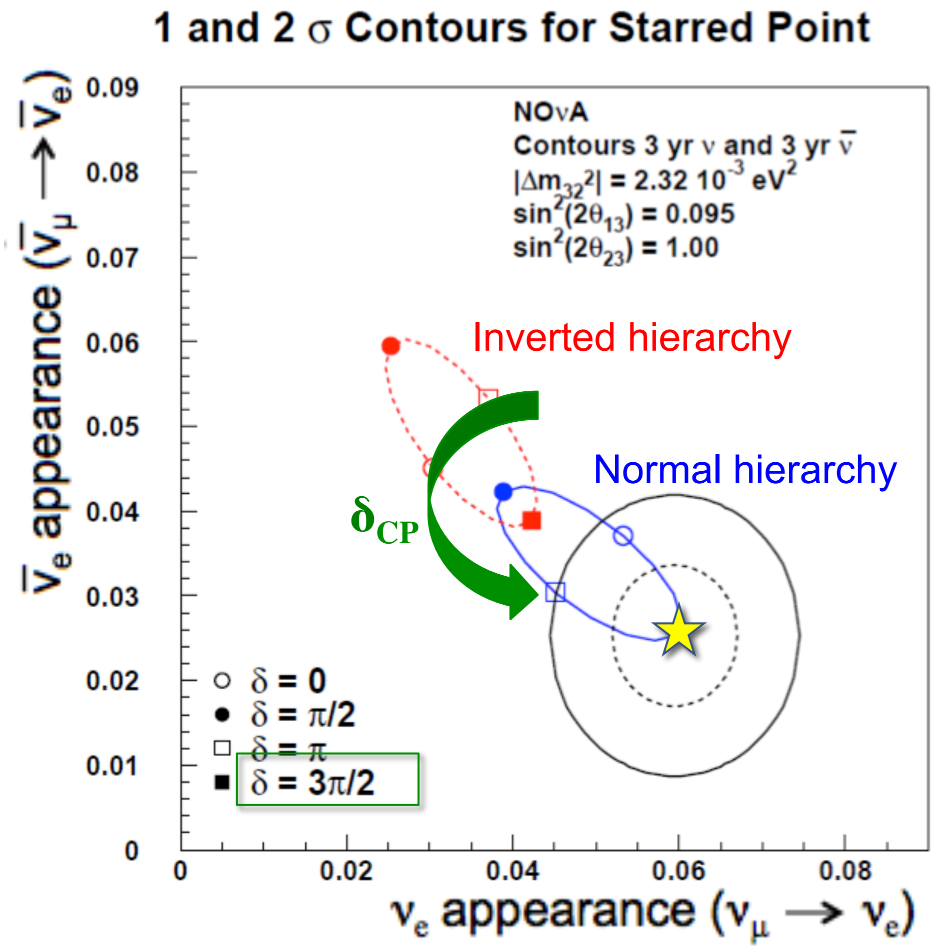
Mass hierarchy: Electron-neutrino appearance





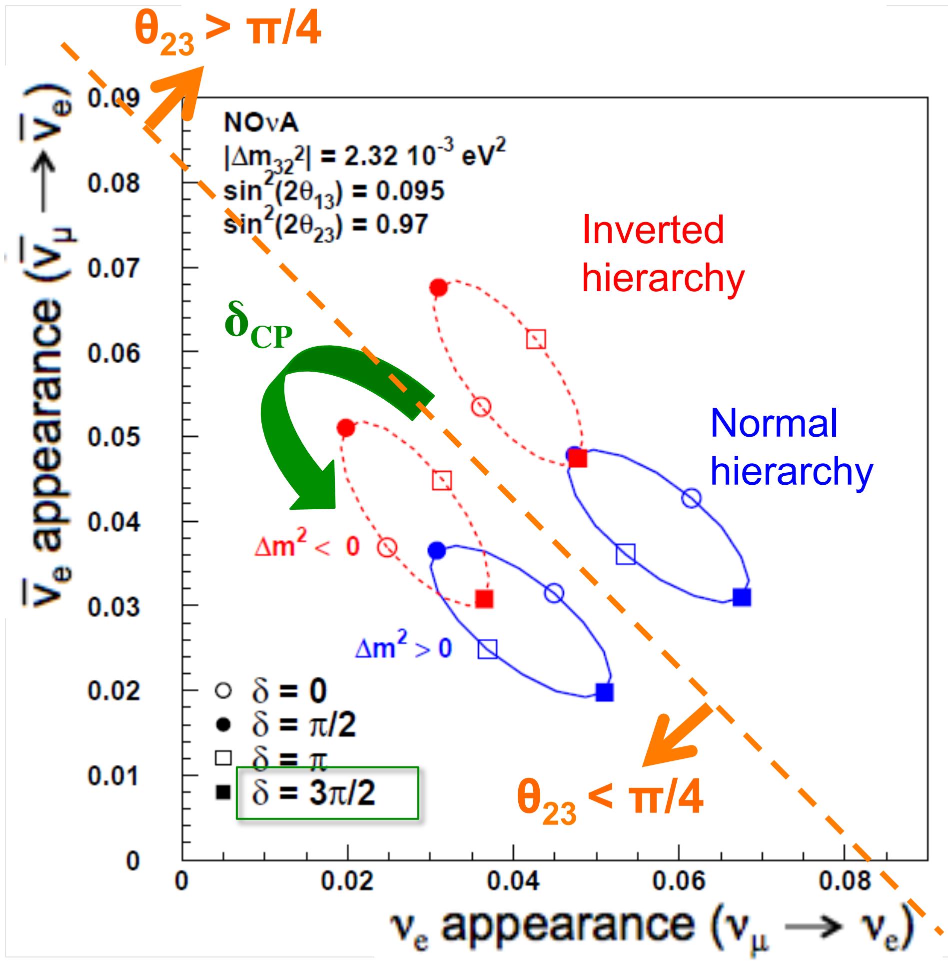
Number of electron neutrinos appearing depends on **ordering of the mass states**

CP violation: Electron-neutrino appearance



Number of electron neutrinos appearing depends on **amount of CP violation in neutrino sector**

θ_{23} octant : Electron-neutrino appearance



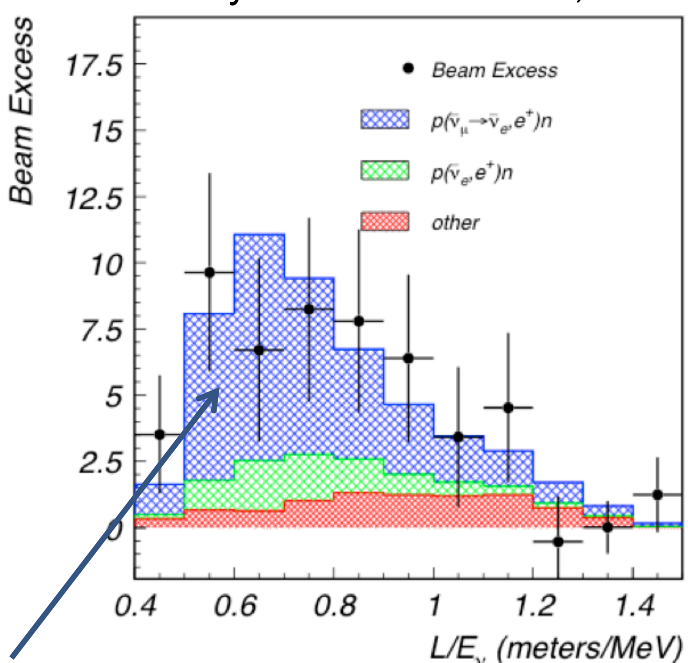
Number of electron neutrinos appearing depends on **θ_{23} octant**

Sterile Neutrinos Hints

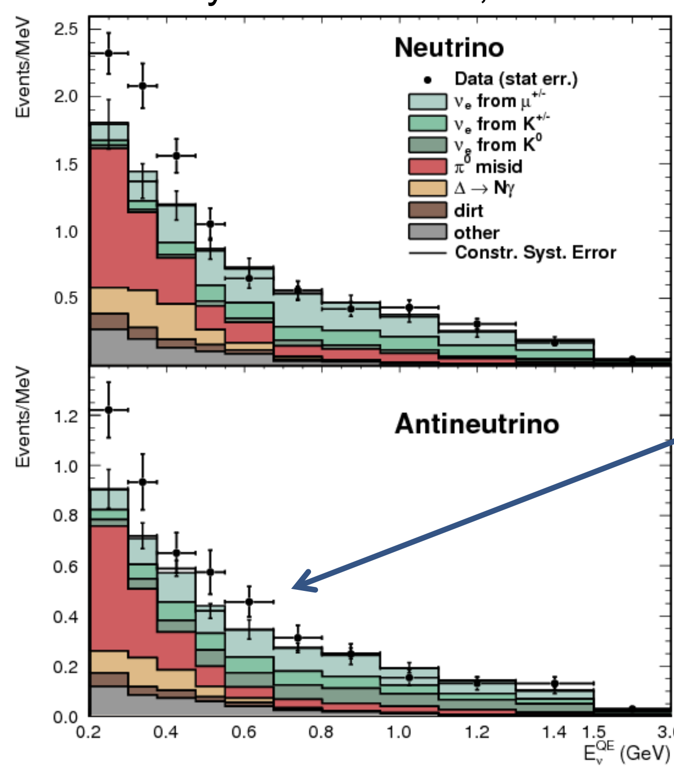
LSND and MiniBooNE have experimental results which could be interpreted as due to a new neutrino with a mass ~1 eV

Appearance of ν_e ($\bar{\nu}_e$) in ν_μ ($\bar{\nu}_\mu$) beam

Phys.Rev.D64:112007,2001



Phys.Rev.Lett.110, 161801

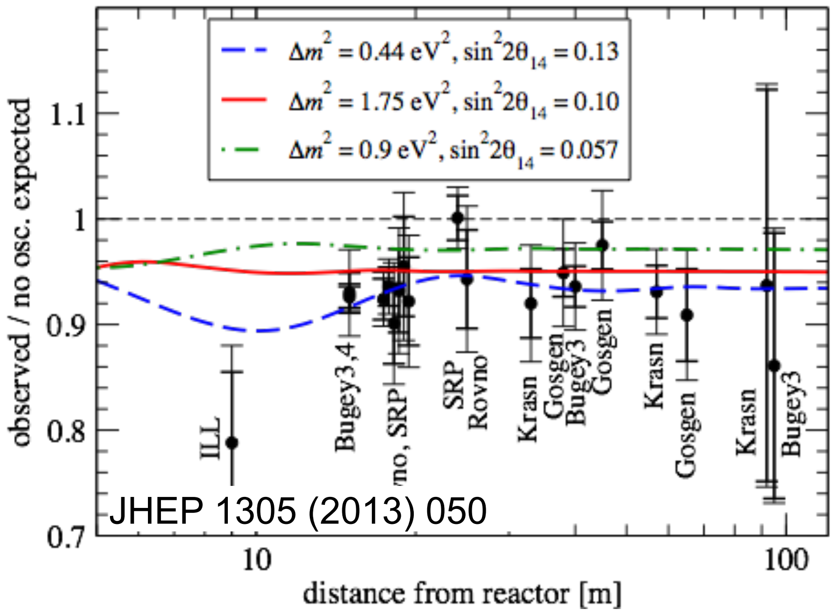


Blue sample is fitted ν_e appearance

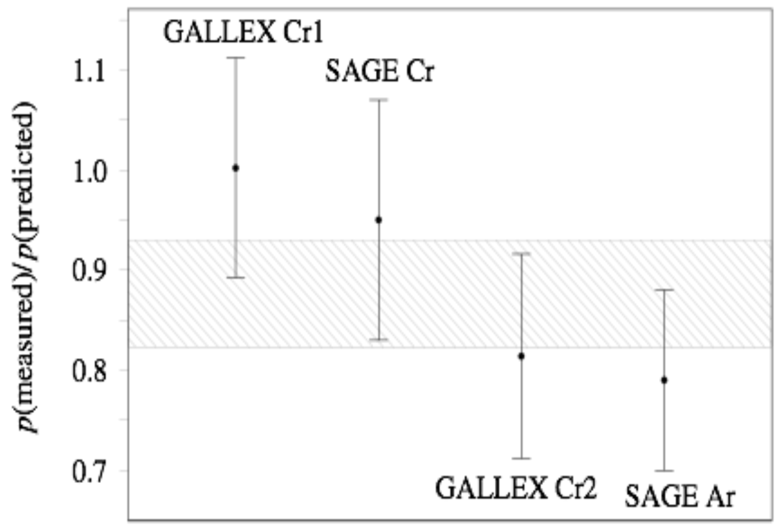
Low energy excess

Sterile Neutrinos Hints

Anomalies from rector neutrino experiments and rate measurements of radioactive sources on Gallium could also be interpreted in this context



JHEP 1305 (2013) 050



SAGE Collab. Phys.Rev. C73 (2006) 045805

Experiment	Type	Channel	Significance
LSND	DAR	$\bar{\nu}_\mu \to \bar{\nu}_e$ CC	3.8σ
MiniBooNE	SBL accelerator	$\nu_\mu \to \nu_e$ CC	3.4σ
MiniBooNE	SBL accelerator	$\bar{\nu}_\mu \to \bar{\nu}_e$ CC	2.8σ
GALLEX/SAGE	Source - e capture	ν_e disappearance	2.8σ
Reactors	Beta-decay	$\bar{\nu}_e$ disappearance	3.0σ

K. N. Abazajian et al. (arXiv:1204.5379 [hep-ph])