Nu Landscapes

Stephen Parke, Fermilab

NuSM

Beyond NuSM

SM Nu physics
(+Technology)

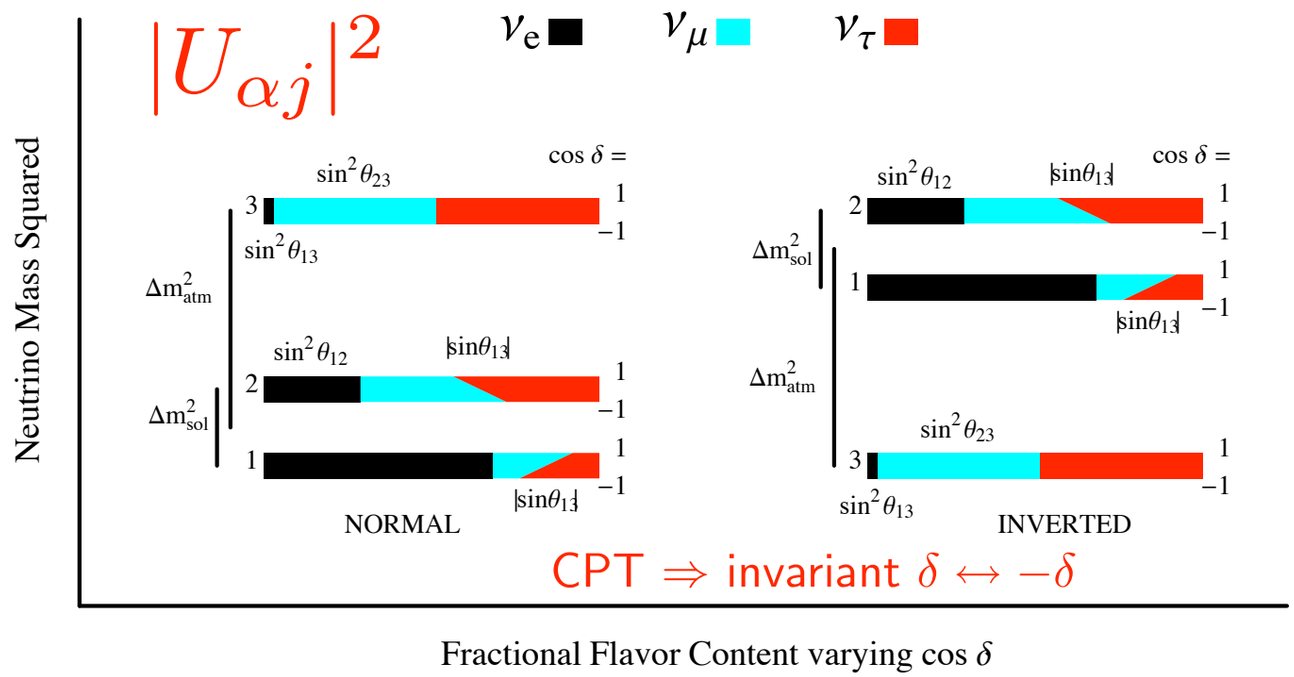
Nu Astro

Fermilab Exp:
Booster: miniBooNE, SciBooNE, microBooNE
NuMI: MINOS, ArgoNeut, NOvA
New: LBNE

Elsewhere:
KamLand, SuperK, T2K, T2?
DChooz, Daya Bay, RENO
Opera, Icarus, Borexino
ICECUBE, Antares .....
Double Beta Decay, Mass Exp

Neutrino Masses & Mixings:

$$\sin^2\theta_{13} \equiv |U_{e3}|^2, \quad \sin^2\theta_{12} \equiv \frac{|U_{e2}|^2}{(1-|U_{e3}|^2)}, \quad \sin^2\theta_{23} \equiv \frac{|U_{\mu 3}|^2}{(1-|U_{e3}|^2)}$$



$$\delta m^2_{sol} = +7.6 \times 10^{-5}\ eV^2$$

$$|\delta m^2_{atm}| = 2.4 \times 10^{-3}\ eV^2$$

$$|\delta m^2_{sol}|/|\delta m^2_{atm}| \approx 0.03$$

$$\sqrt{\delta m^2_{atm}} = 0.05\ eV < \sum m_{\nu_i} < 0.5\ eV = 10^{-6} * m_e$$

$$\sin^2\theta_{12} \sim 1/3$$

$$\sin^2\theta_{23} \sim 1/2$$

$$\sin^2\theta_{13} < 3\%$$

$$0 \leq \delta < 2\pi$$

Chooz
Minos

- $\theta_{13} \neq 0$ allows ν_e to oscillate at the Atmospheric scale 500km/GeV !!!
  (as well as the Solar scale 15,000km/GeV)
- CPV and Mass Hierarchy

At 2σ we have the following limits:

$$\sin^2\theta_{13} < 0.04$$

$$|\sin^2\theta_{12} - \frac{1}{3}| < 0.04$$

$$|\sin^2\theta_{23} - \frac{1}{2}| < 0.12$$

At 2σ we have the following limits:

$$\sin^2\theta_{13} \quad < \quad 0.04 \quad \approx \left(\frac{\delta m^2_{21}}{\delta m^2_{31}}\right)^1$$

$$|\sin^2\theta_{12} - \frac{1}{3}| \quad < \quad 0.04 \quad \approx \left(\frac{\delta m^2_{21}}{\delta m^2_{31}}\right)^1$$

$$|\sin^2\theta_{23} - \frac{1}{2}| \quad < \quad 0.12 \quad \approx \left(\frac{\delta m^2_{21}}{\delta m^2_{31}}\right)^{0.6}$$

Close to Tri-Bi-Maximal: Accident or Symmetry ?

$$U_{\rm TBM} = \begin{pmatrix} \sqrt{\frac{2}{3}} & \sqrt{\frac{1}{3}} & 0 \\ -\sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & \sqrt{\frac{1}{2}} \\ \sqrt{\frac{1}{6}} & -\sqrt{\frac{1}{3}} & \sqrt{\frac{1}{2}} \end{pmatrix}$$

Near term goal to push to $\Longrightarrow \left(\frac{\delta m^2_{21}}{\delta m^2_{31}}\right)^2 \sim 0.001$

and eventually smaller to $\Longrightarrow \left(\frac{\delta m^2_{21}}{\delta m^2_{31}}\right)^3 \sim 3 \times 10^{-5}$ and beyond !

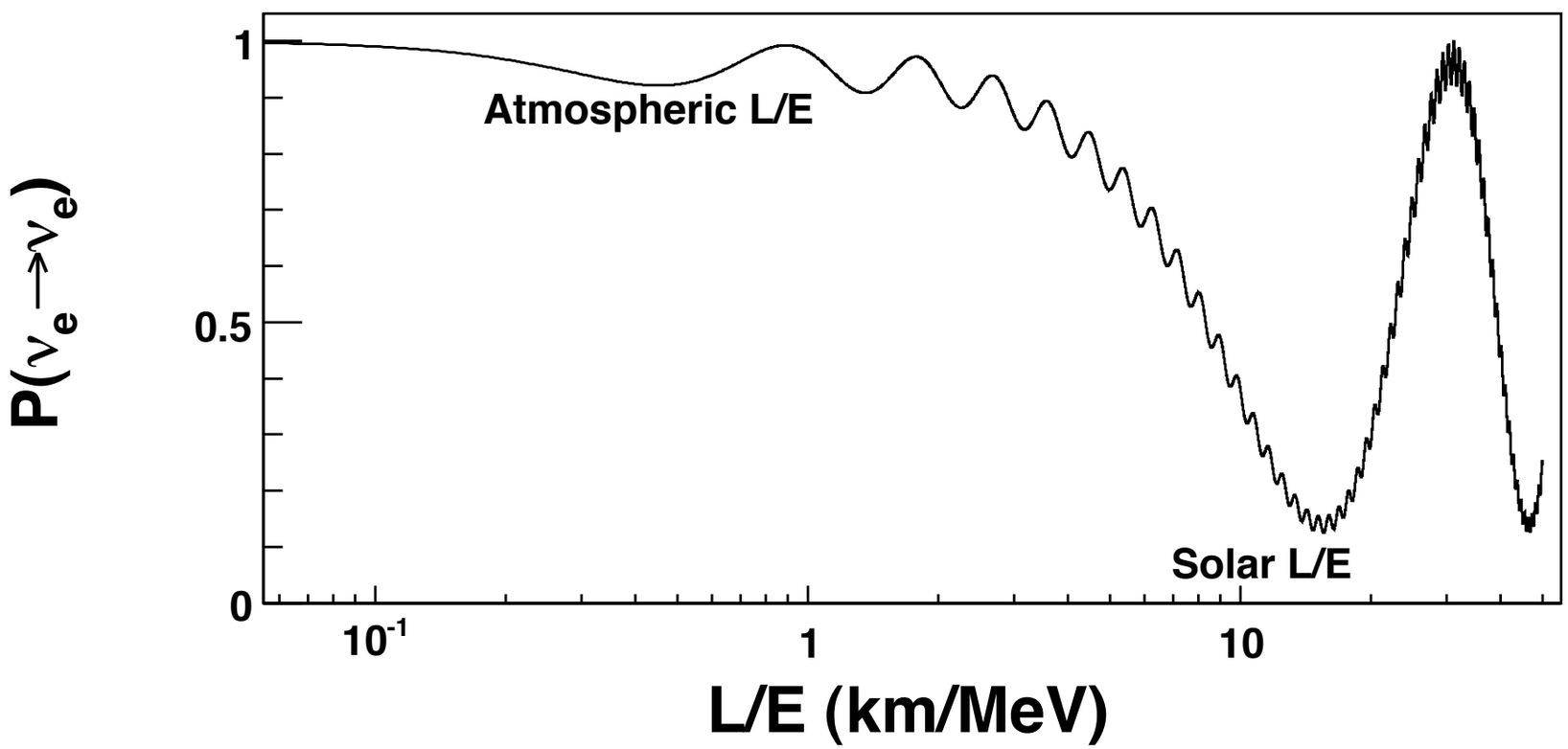
θ_{13} from Reactor Disappearance

kinematic phase:
$\Delta_{ij} \equiv \frac{\delta m^2_{ij} L}{4E}$

$$P(\bar{\nu}_e \to \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\delta m^2_{ee} L}{4E}\right) - \mathcal{O}(\Delta_{21})^2$$

where $\delta m^2_{ee} = \cos^2\theta_{12}|\delta m^2_{31}| + \sin^2\theta_{12}|\delta m^2_{32}|$

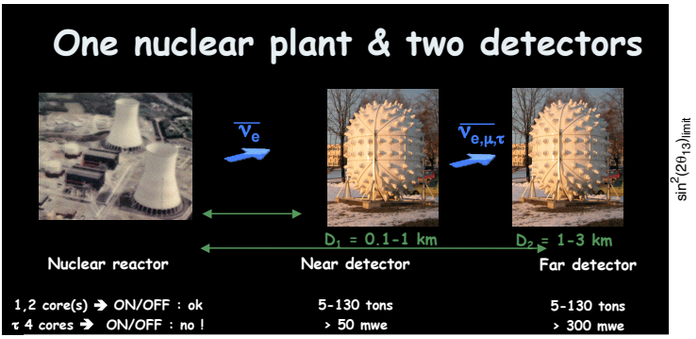
ν_e weight average of $|\delta m^2_{31}|$ and $|\delta m^2_{32}|$

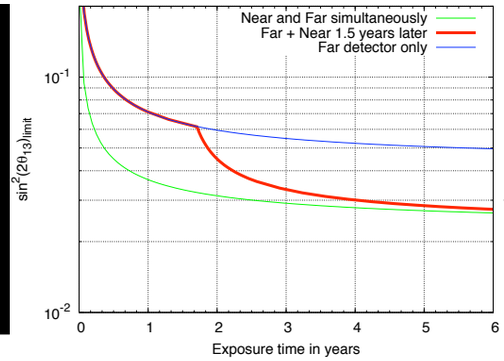


Pure measurement of $\sin^2\theta_{13}$!!!

the ν_e component of ν_3

Double Chooz:

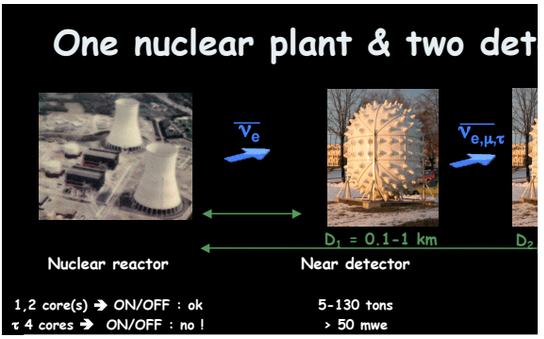




.03

Figure 18: $\sin^2(2\theta_{13})$ sensitivity limit for the detectors installation scheduled scenario

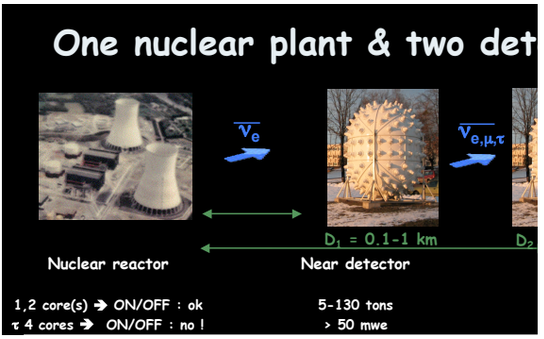
Double Chooz:



Daya Bay

push the limit on
$\sin^2 2\theta_{13} < 0.01$

Double Chooz:



Daya Bay

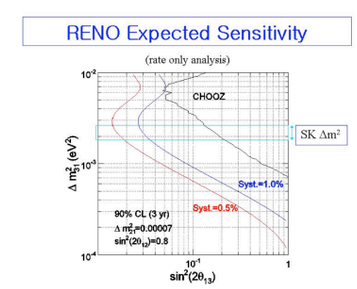
push the limi

$$\sin^2 2\theta_{13} < 0$$

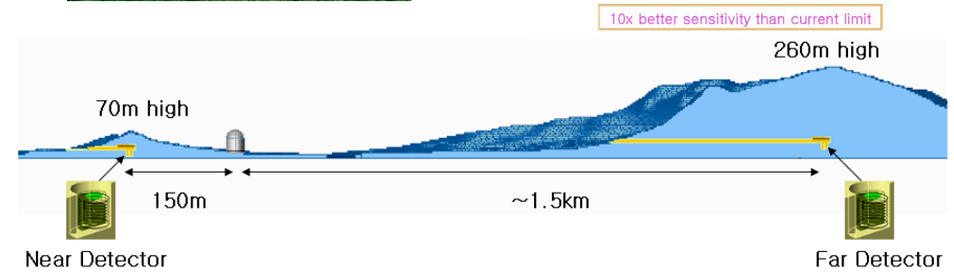
RENO

ν θ_{13}

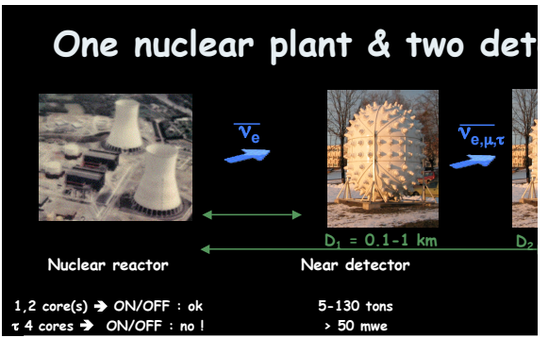
(Reactor Experiment for Neutrino Oscillation)



10x better sensitivity than current limit



Double Chooz:



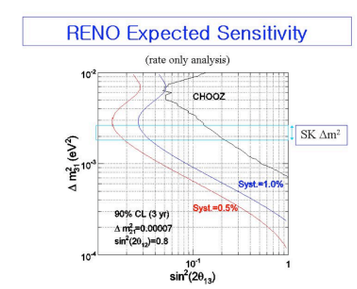
Daya Bay

RENO

(Reactor Experiment for Neutrino Oscillation)

push the limi

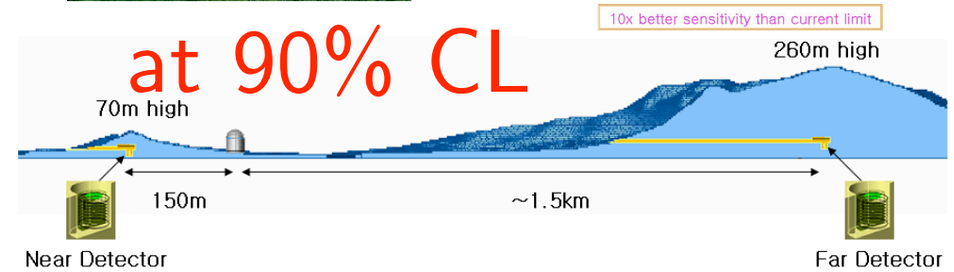
$\sin^2 2\theta_{13} < 0$



10x better sensitivity than current limit

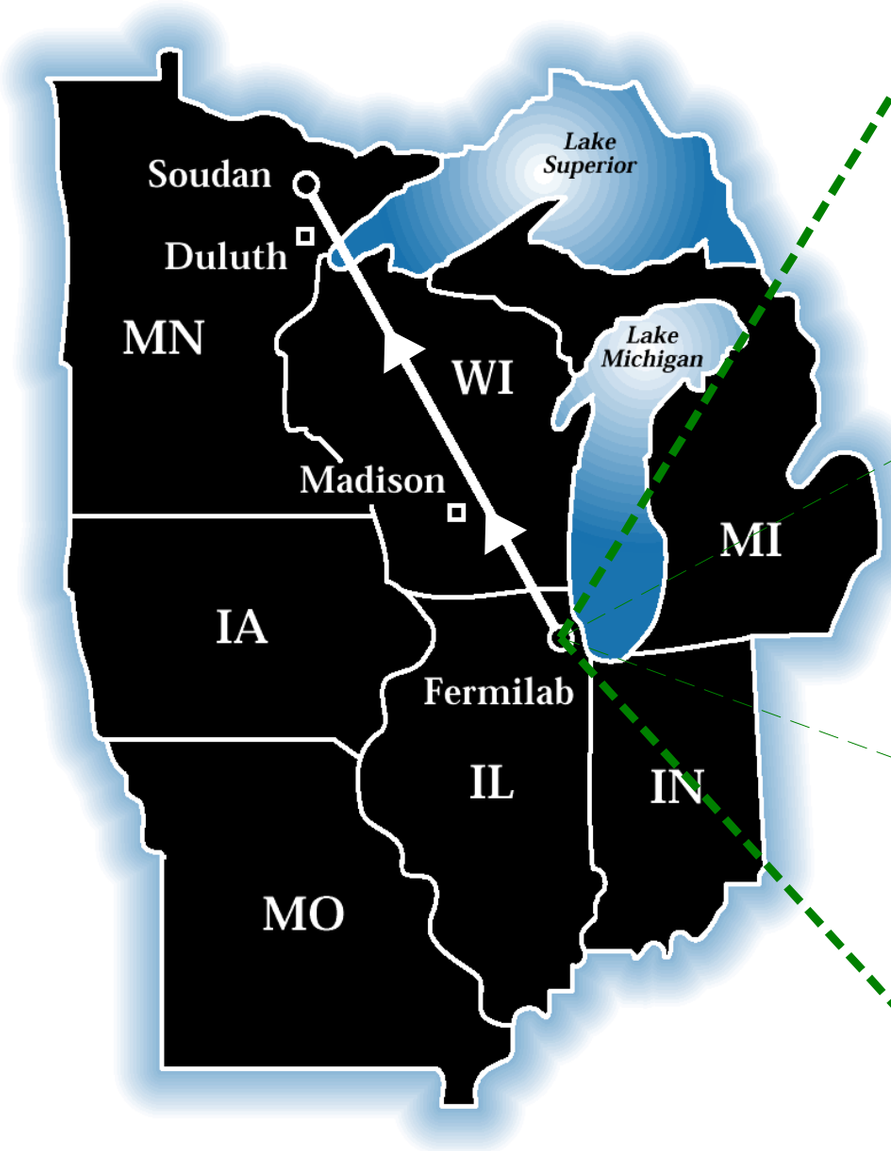
$$1 - \langle P(\nu_e \to \nu_e) \rangle \sim 1.0 - 3.0\%$$

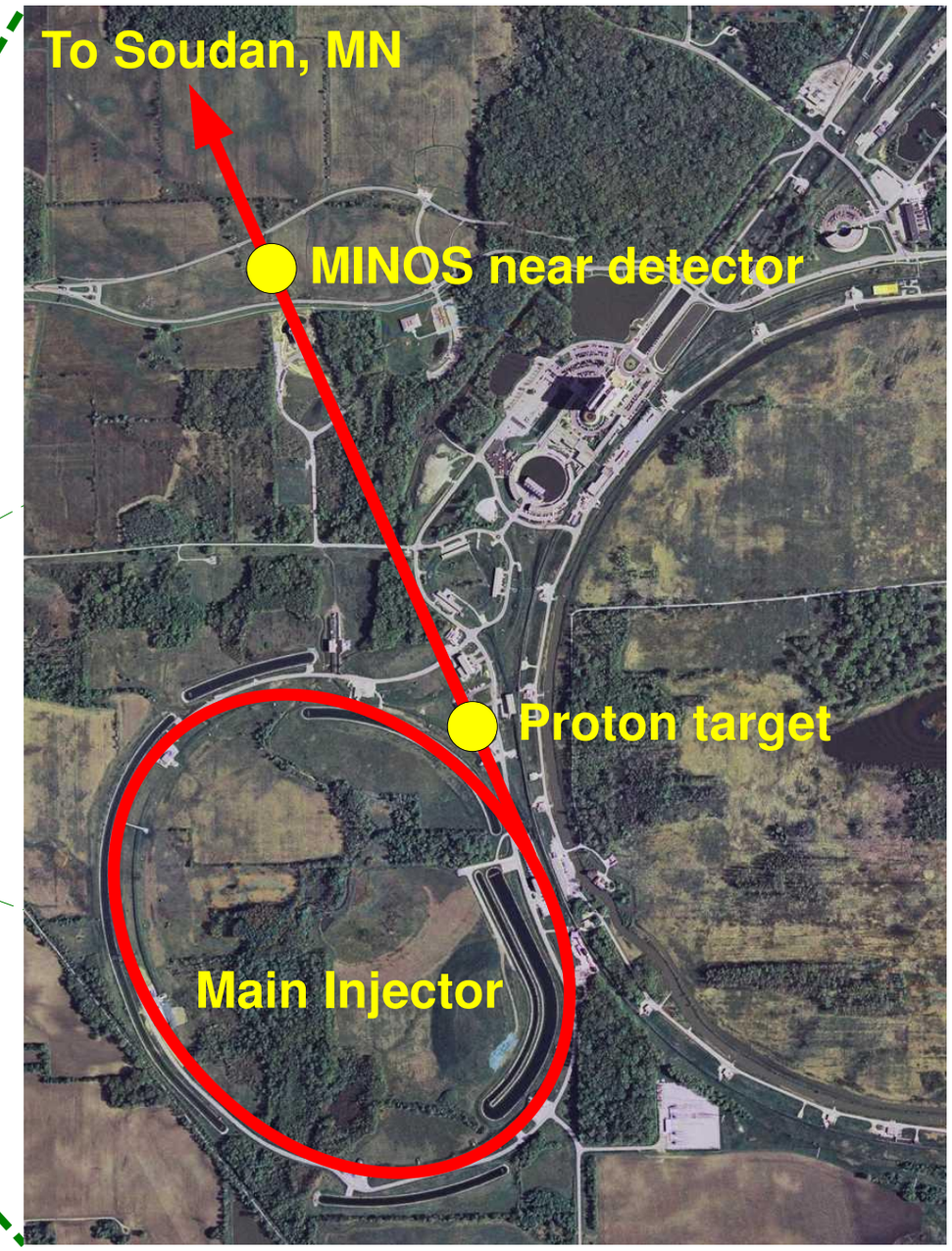
at 90% CL



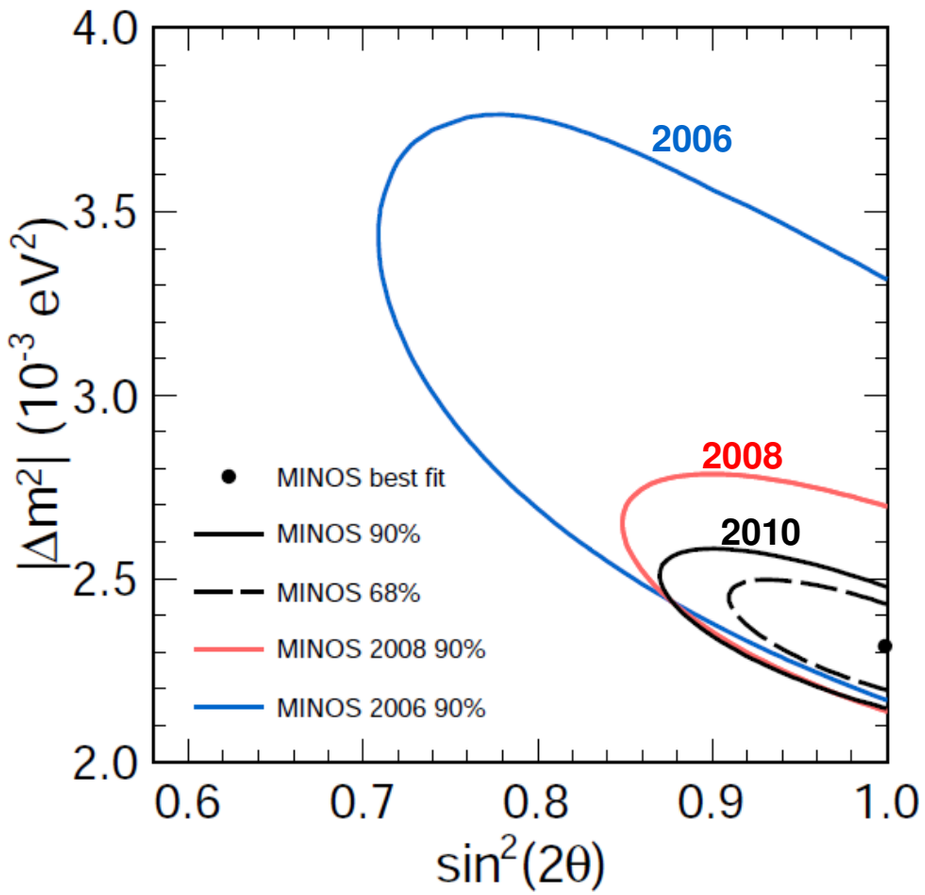
Main Injector Neutrino Oscillation Search (MINOS)

735 km to the far detector





MINOS:



Oscillation interpretation:

- Parameter space shown at left.
- Most precise $\Delta m^2_{\rm atm}$ measurement:

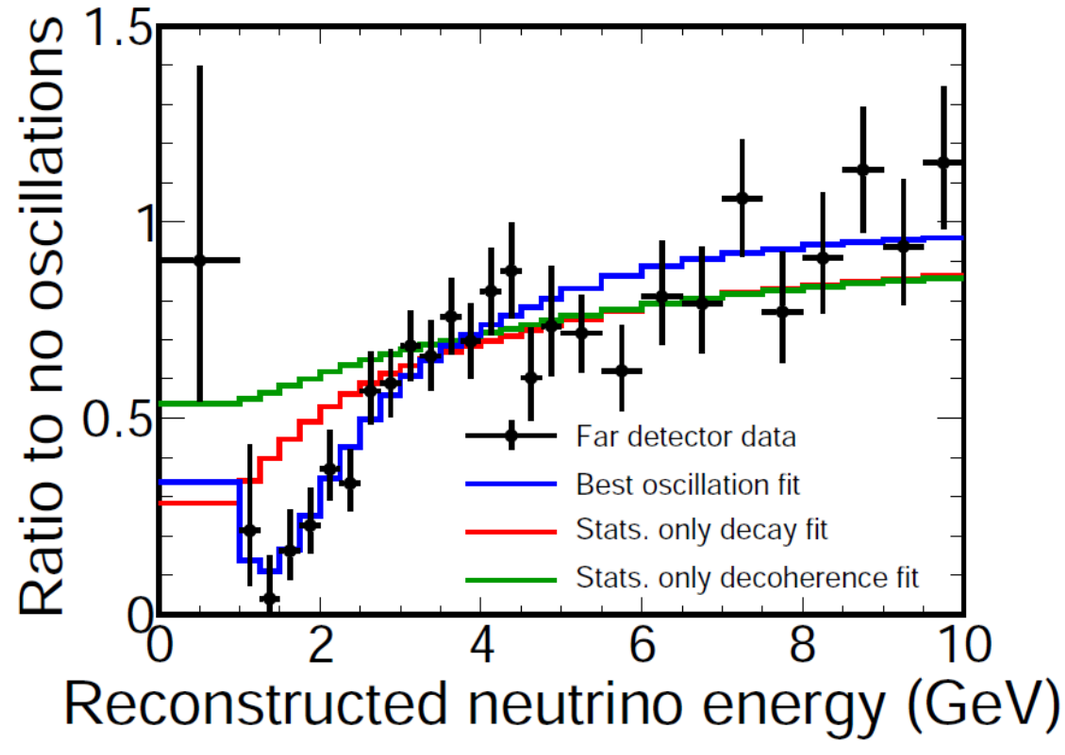
$$\Delta m^2_{\rm atm} = (2.32^{+0.12}_{-0.08}) \times 10^{-3}\ {\rm eV}^2$$

MINOS, PRL **106**, 181801 (2011)

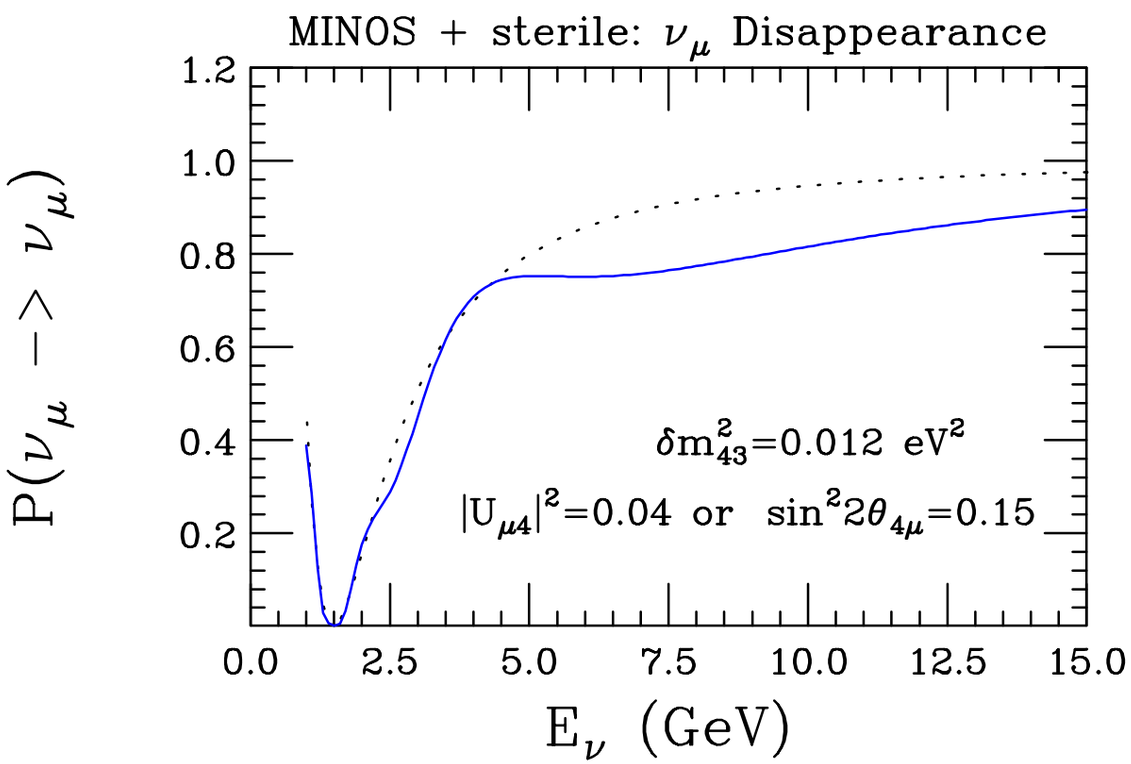
Strongly disfavored alternative interpretations:

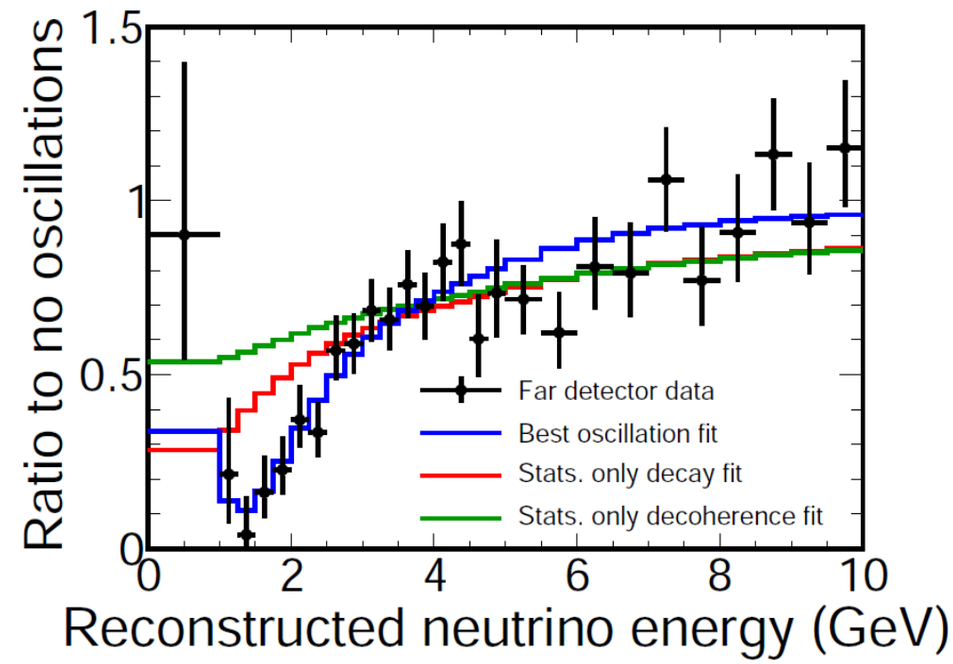
Neutrino decay: $>7\sigma$

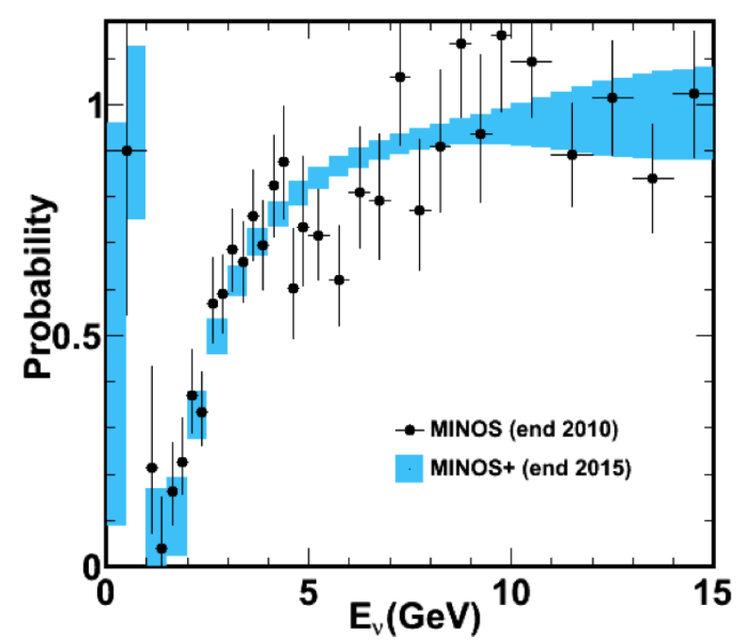
Decoherence: $>9\sigma$



MINOS + Sterile:

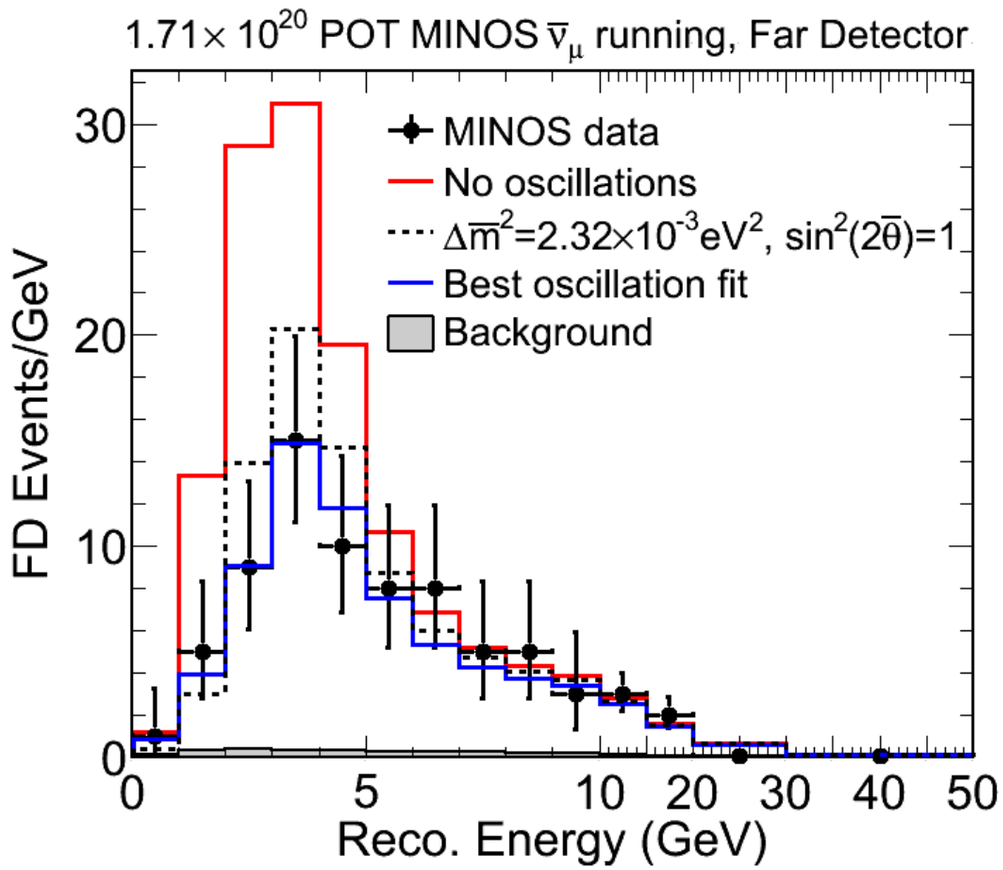


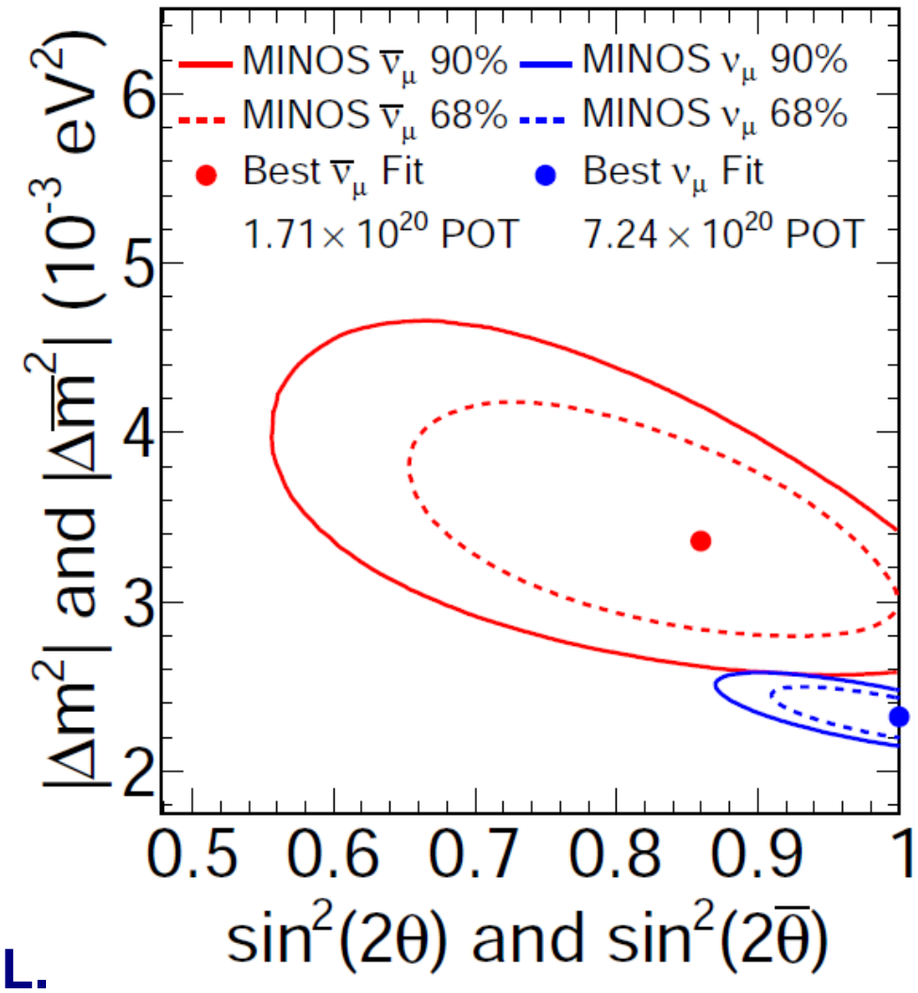




MINOS:

$\bar{\nu}_\mu$ observed in the Far Detector





- $\bar{\nu}_\mu$ **disappearance** observed at **6.3σ C.L.**
- Well described by **flavor oscillations:**

stat. errors dominate

$$\Delta\overline{m}^2_{\rm atm} = (3.36^{+0.46}_{-0.40})\times 10^{-3}\ {\rm eV}^2$$
$$\sin^2(2\overline{\theta}) = 0.86^{+0.11}_{-0.12}$$

MINOS, arXiv:1104.0344 (2011)

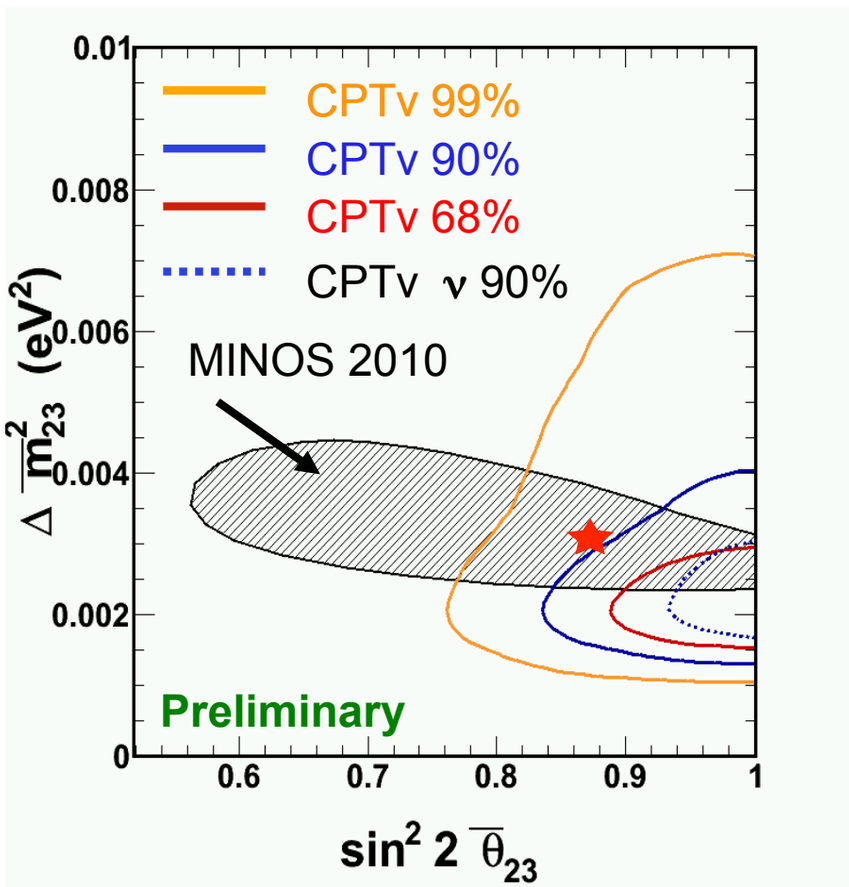
$\nu/\bar{\nu}$ compatibility at only 2% C.L.

NOvA (T2K ?) will address this !!!

Antineutrino Oscillations : CPT violation

- CPT theorem: $P(\nu \Diamond \nu)$ and $P(\bar{\nu} \Diamond \bar{\nu})$ should be the same.
- Test ν oscillation or $\bar{\nu}$ oscillation separately.

in vacuum!!!



SK 2806 Days

n	Best Fit
Δm^2	2.1×10^{-3} eV^2
$\sin^2 2\theta$	1.0

n	Best Fit
Δm^2	2.0×10^{-3} eV^2
$\sin^2 2\theta$	1.0
χ^2	468.8 / 416 D.O.F

Equal neutrino and antineutrino mixing favored by the data

» No evidence for CPT violation in SK atmospheric data

» Field theories are still safe...

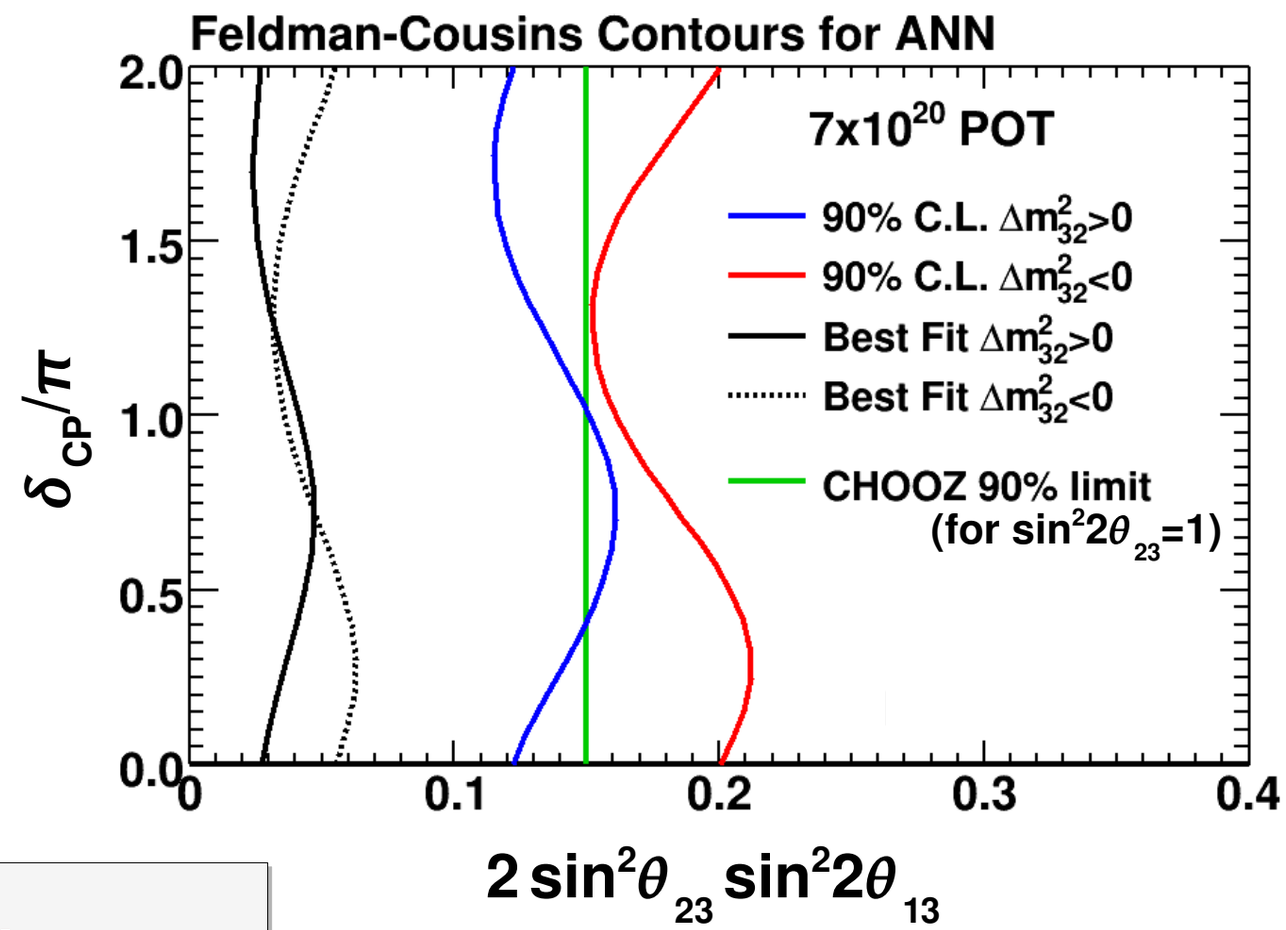
13

MINOS:

Oscillation interpretation of the data (2010)

$\sin^2(2\theta_{13})$ allowed range depends on **CP-phase δ** and **mass hierarchy** [sign(Δm^2)]

90% C.L. allowed ranges →



MINOS, PRD **82**, 051102 (2010)

Representative 90% C.L. limits:

→ *put* $\delta_{CP}=0$, $\theta_{23}=\pi/4$

normal hier. ⇒ $\sin^2 2\theta_{13} < 0.12$

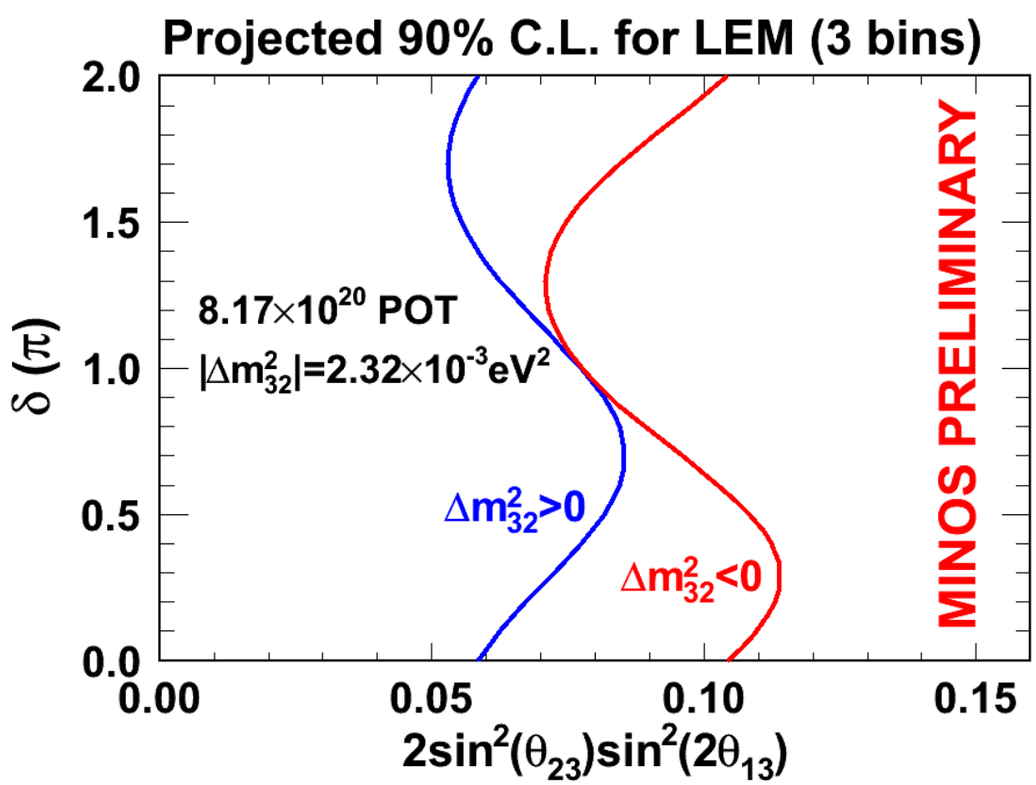
inverted hier. ⇒ $\sin^2 2\theta_{13} < 0.20$

(other oscillation parameters' uncertainties taken into account)

MINOS:

New for 2011 analysis

- **30% improvement** in $\sin^2(2\theta_{13})$ sensitivity over 2010 result
- 24% improvement from the **analysis upgrades** alone
  (roughly half from new selector, half from fitting)
- ***Below:*** **preliminary 90% C.L. sensitivity** for 8.17×10^{20} p.o.t. analysis



Look for a new θ_{13} result this summer.

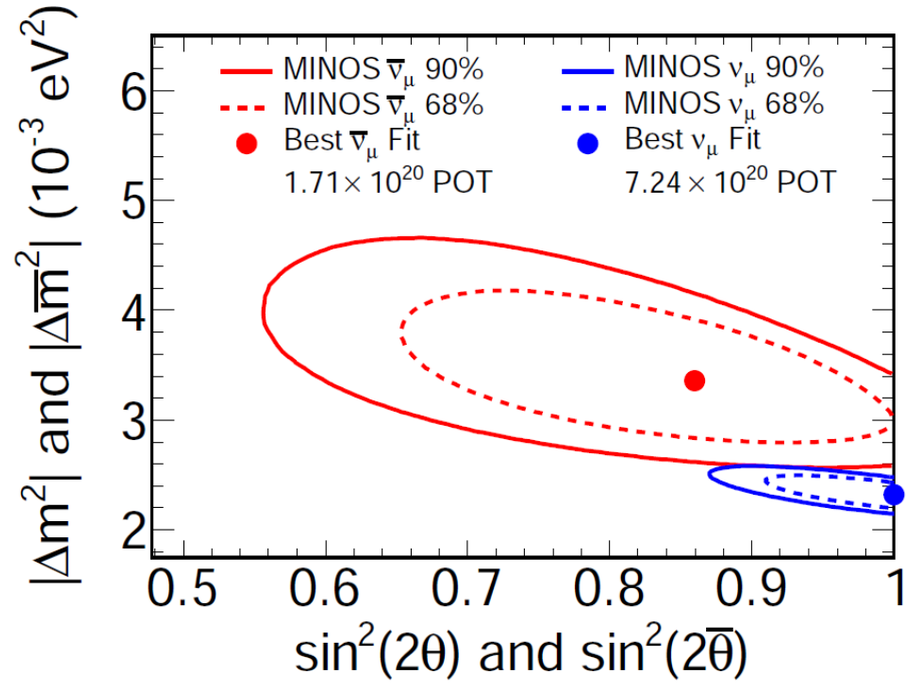
"Tomorrow"

MINOS Summary

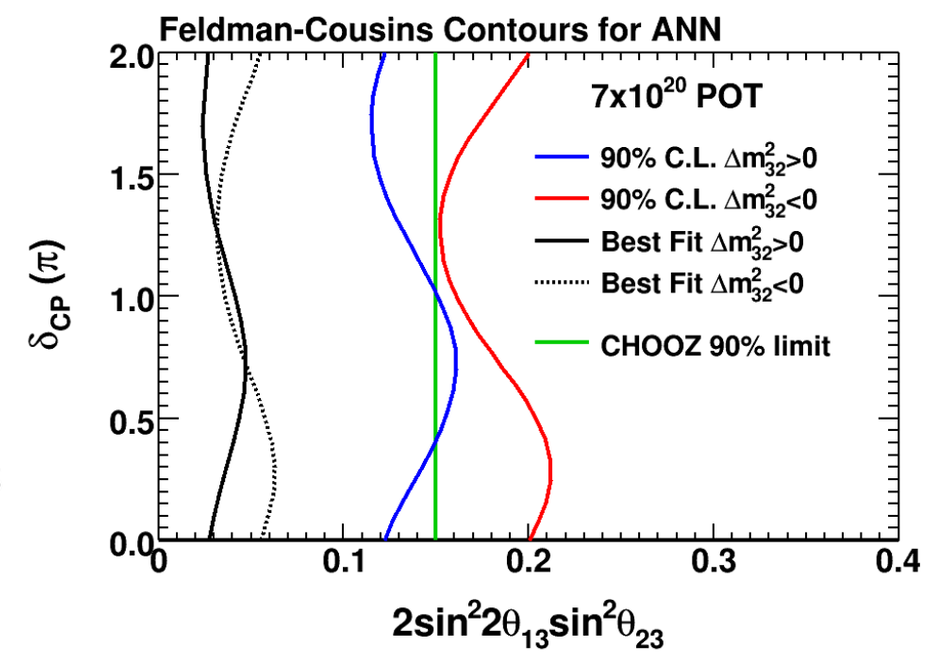
- **New ν_μ disappearance result**
  - ➡ *precision mass-splitting measurement:*

    $$\Delta m^2_{\rm atm} = (2.32^{+0.12}_{-0.08})\times 10^{-3}\ {\rm eV}^2$$

- **High-purity $\bar{\nu}_\mu$ measurement** →
  - ➡ *some tension (2% C.L. agreement w/ ν_μ)*
  - ➡ *updated result this summer*



- **New $\sin^2(\theta_{13})$ limits** →
  - ➡ *improved sensitivity this summer*



- **No evidence for sterile mixing:**
  - ➡ $f_s < 0.22$ (90% C.L.; θ_{13}=0)

- ***Did not cover...***
  - physics with atmo. neutrinos, cosmic rays
  - neutrino/antineutrino cross sections
  - other BSM physics searches

- **MINOS+ proposed** to collect large sample of 4–10 GeV ν and anti-ν interactions parasitically during NOνA running

Vacuum LBL: $\nu_\mu \longrightarrow \nu_e$

$$P_{\mu\to e} \approx \left| \sqrt{P_{atm}} e^{-i(\Delta_{32} \pm \delta)} + \sqrt{P_{sol}} \right|^2$$

CP violation !!!

$$\Delta_{ij} = \delta m^2_{ij} L/4E$$

where $\sqrt{P_{atm}} = \sin\theta_{23} \sin 2\theta_{13} \ \sin\Delta_{31}$

and $\sqrt{P_{sol}} = \cos\theta_{23} \sin 2\theta_{12} \ \sin\Delta_{21}$

Vacuum LBL: $\nu_\mu \longrightarrow \nu_e$

$$P_{\mu\to e} \approx \left| \sqrt{P_{atm}} e^{-i(\Delta_{32} \pm \delta)} + \sqrt{P_{sol}} \right|^2$$

CP violation !!!

$$\Delta_{ij} = \delta m^2_{ij} L/4E$$

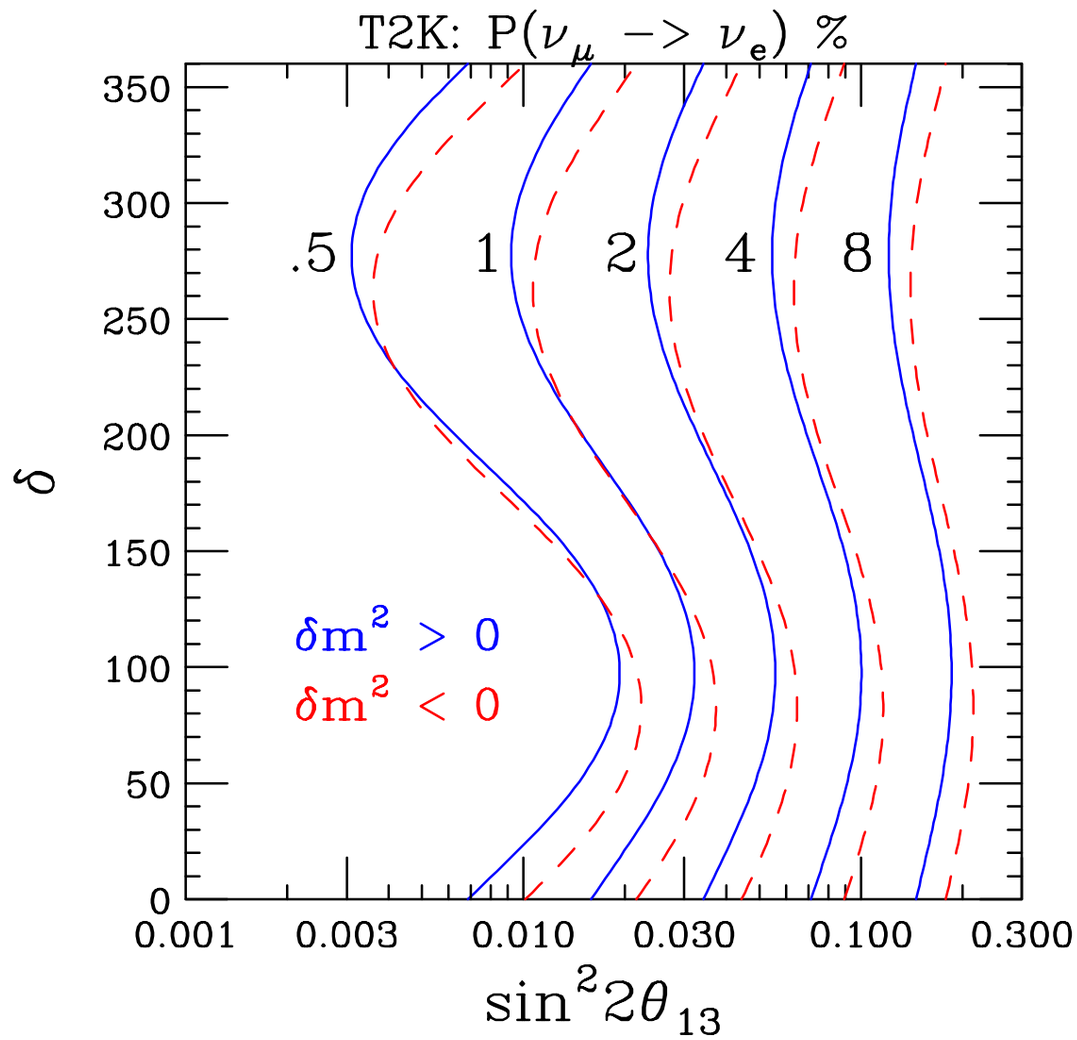
where $\sqrt{P_{atm}} = \sin\theta_{23} \sin 2\theta_{13} \ \sin\Delta_{31}$

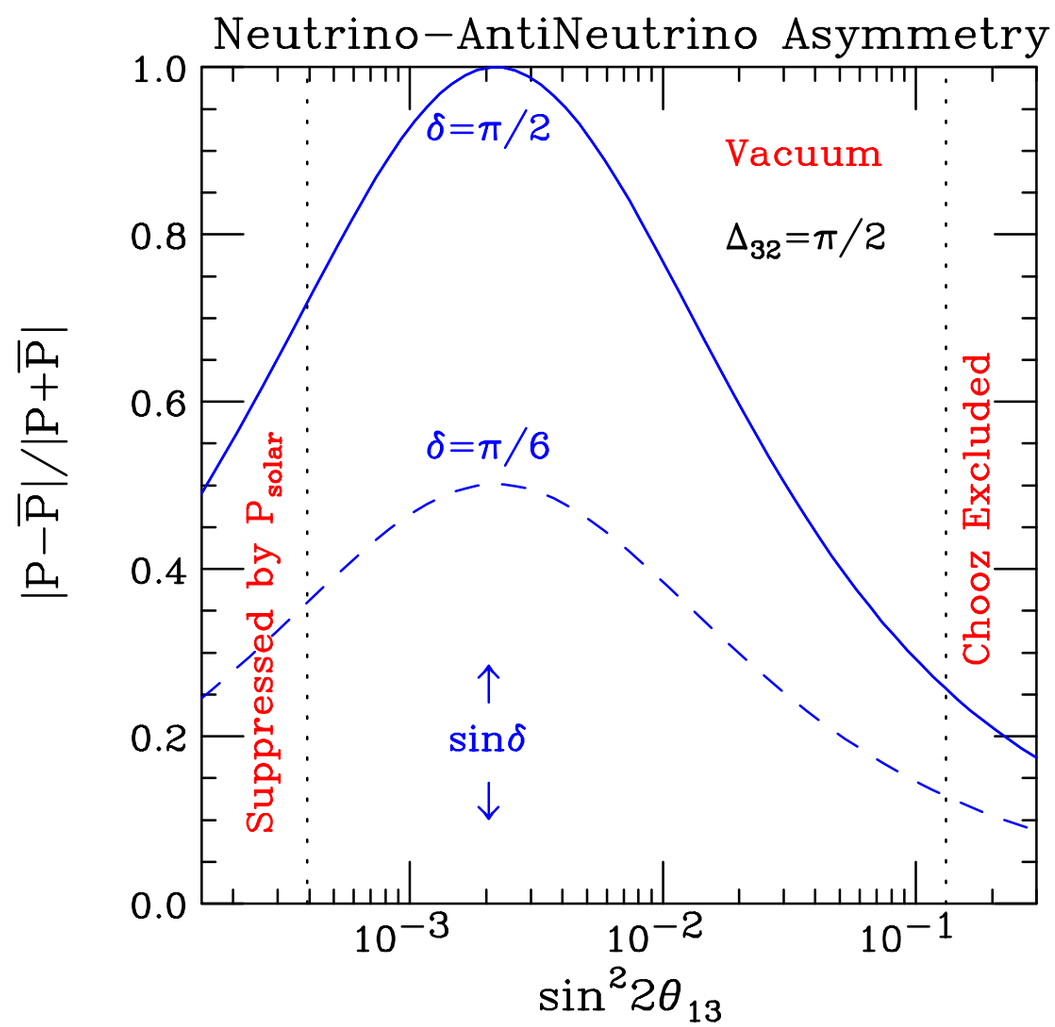
and $\sqrt{P_{sol}} = \cos\theta_{23} \sin 2\theta_{12} \ \sin\Delta_{21}$

$$\boxed{P_{\mu\to e} \approx P_{atm} + 2\sqrt{P_{atm} P_{sol}} \cos(\Delta_{32} \pm \delta) + P_{sol}}$$

only CPV

$$\cos(\Delta_{32} \pm \delta) = \cos\Delta_{32} \cos\delta \mp \sin\Delta_{32} \sin\delta$$


T2K: P(ν_μ -> ν_e) %
.5
1
2
4
8
$\delta m^2 > 0$
$\delta m^2 < 0$
δ
$\sin^2 2\theta_{13}$


Neutrino−AntiNeutrino Asymmetry
$\delta=\pi/2$
Vacuum
$\Delta_{32}=\pi/2$
$\delta=\pi/6$
$\sin\delta$
Suppressed by P_{solar}
Chooz Excluded
$|P-\bar{P}|/|P+\bar{P}|$
$\sin^2 2\theta_{13}$

with MATTER

where $\sqrt{P_{atm}} = \sin\theta_{23}\sin 2\theta_{13}\frac{\sin(\Delta_{31}\mp aL)}{(\Delta_{31}\mp aL)}\Delta_{31}$

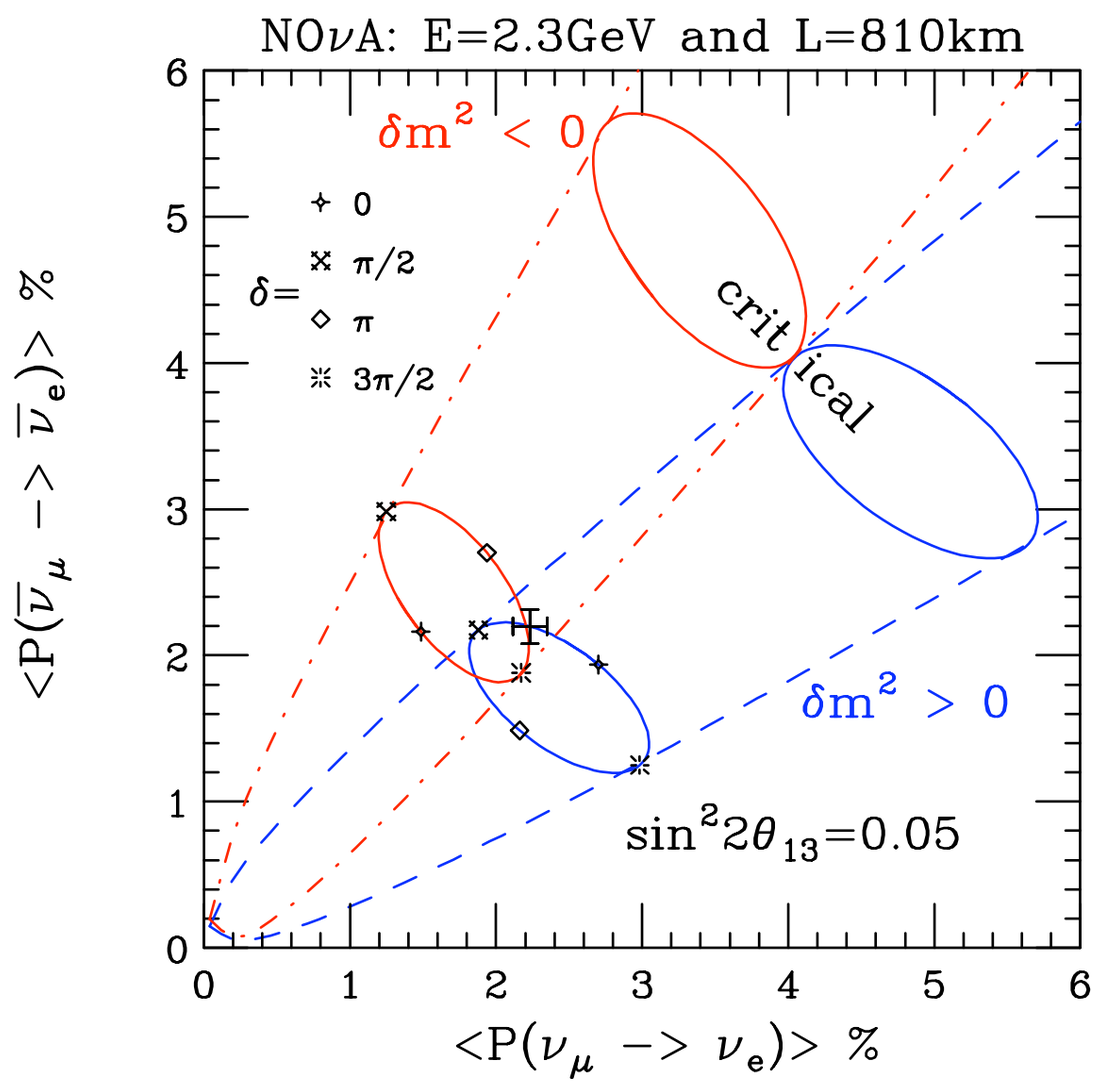
in vac $\sin\Delta_{31}$

and $\sqrt{P_{sol}} = \cos\theta_{23}\sin 2\theta_{12}\frac{\sin(aL)}{(aL)}\Delta_{21}$

in vac $\sin\Delta_{21}$

$$a = G_F N_e/\sqrt{2} = (4000\ km)^{-1},$$

$$\pm = sign(\delta m^2_{31}) \quad \Delta_{ij} = |\delta m^2_{ij}|L/4E$$



Report on T2K Result:

http://jnusrv01.kek.jp/public/t2k/index.php

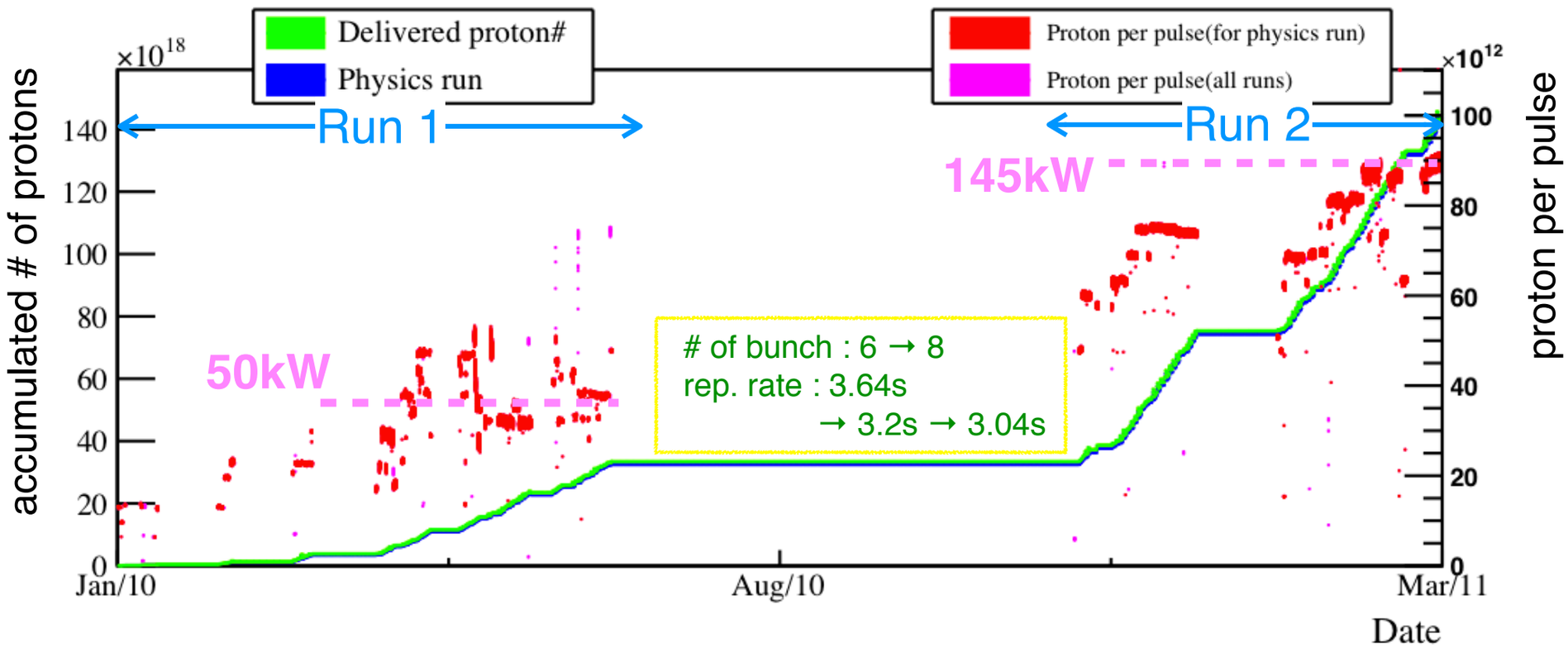
Paper: http://arxiv.org/abs/1106.1238
Talk: http://jnusrv01.kek.jp/public/t2k/sites/default/files/t2k-nue1st.pdf
Press: http://www.kek.jp/intra-e/press/2011/J-PARC_T2Kneutrino.html

T2K Main Goals:

★ Discovery of $\nu_\mu \rightarrow \nu_e$ oscillation (ν_e appearance)

★ Precision measurement of ν_μ disappearance

Total # of protons used for analysis



Run 1 (Jan. '10 - June '10)

- 3.23 x 10^{19} p.o.t. for analysis
- 50kW stable beam operation

Run 2 (Nov. '10 - Mar. '11)

- 11.08 x 10^{19} p.o.t. for analysis
- ~145kW beam operation

Total # of protons used for this analysis is 1.43 x 10^{20} pot

2% of T2K's final goal and ~5 times exposure of the previous report

The expected number of events for $\sin^2 2\theta_{13}=0$

The expected number of events with 1.43 x 10^{20} p.o.t.

$N^{exp}_{SK\ tot.} = 1.5$ events

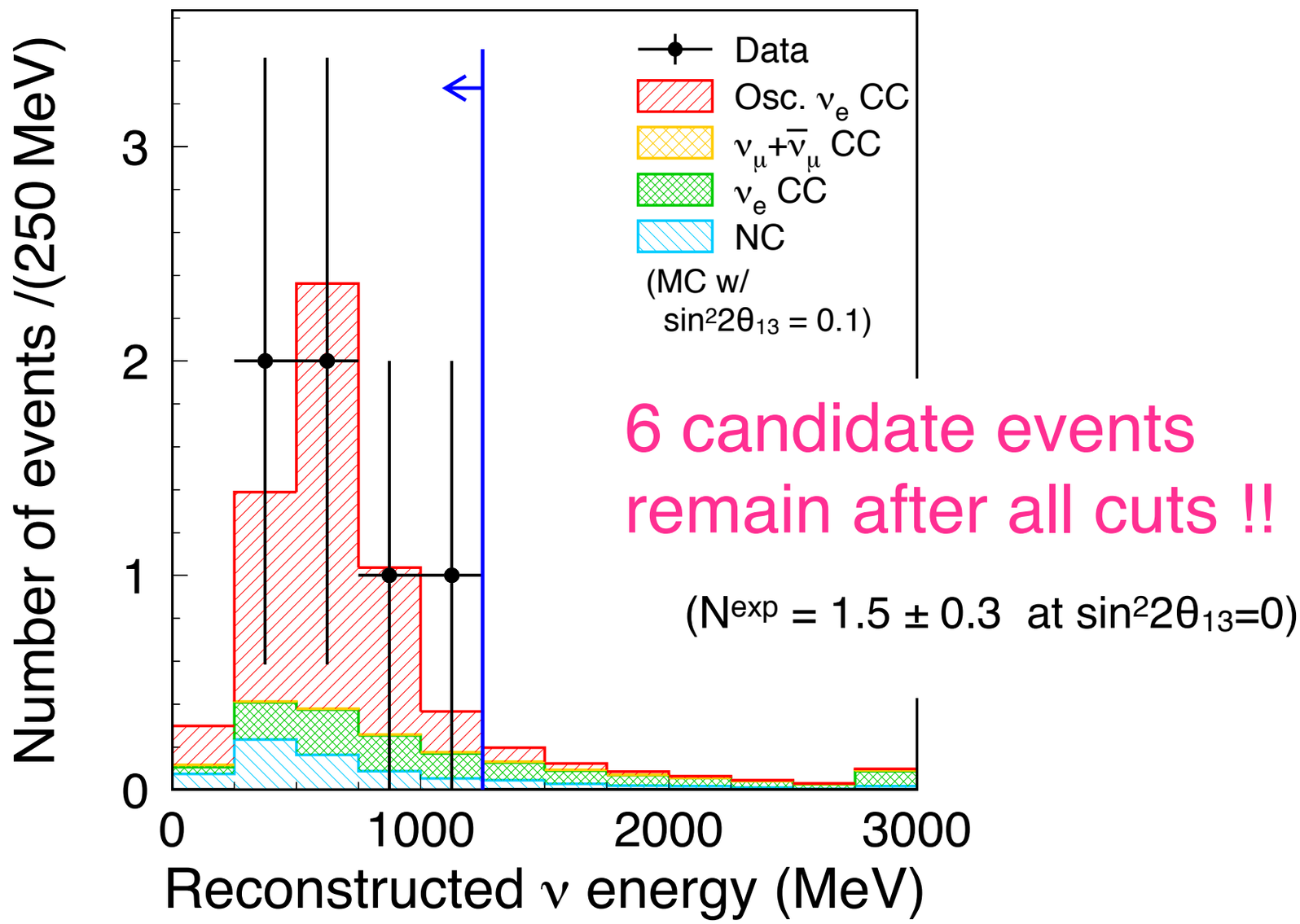
	Beam ν_e background	NC background	Oscillated $\nu_\mu \rightarrow \nu_e$ (solar term)	Total
The expected # of events at SK	0.8	0.6	0.1	1.5

comparable

Psol ~ 0.0010 at first oscillation max.

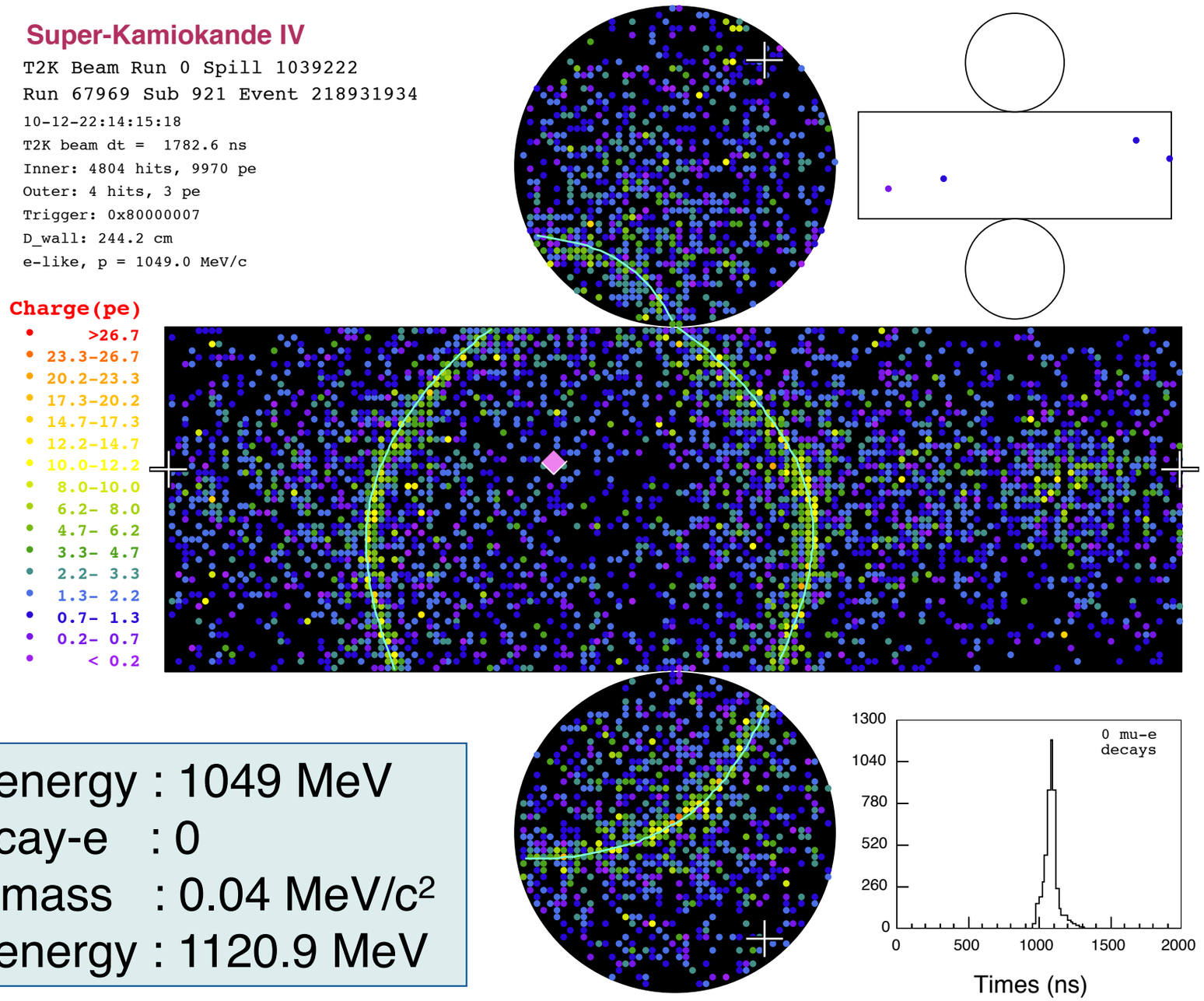
Results for ν_e appearance search with 1.43×10^{20} p.o.t.

Reconstructed ν energy cut (E_{rec} < 1250 MeV) : *Final cut*



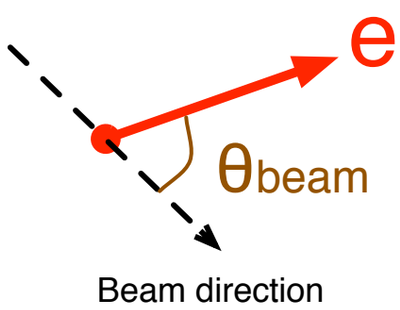
Under the θ_{13}=0 hypothesis, the probability to observe six or more candidate events is 0.007 (equivalent to 2.5σ significance)

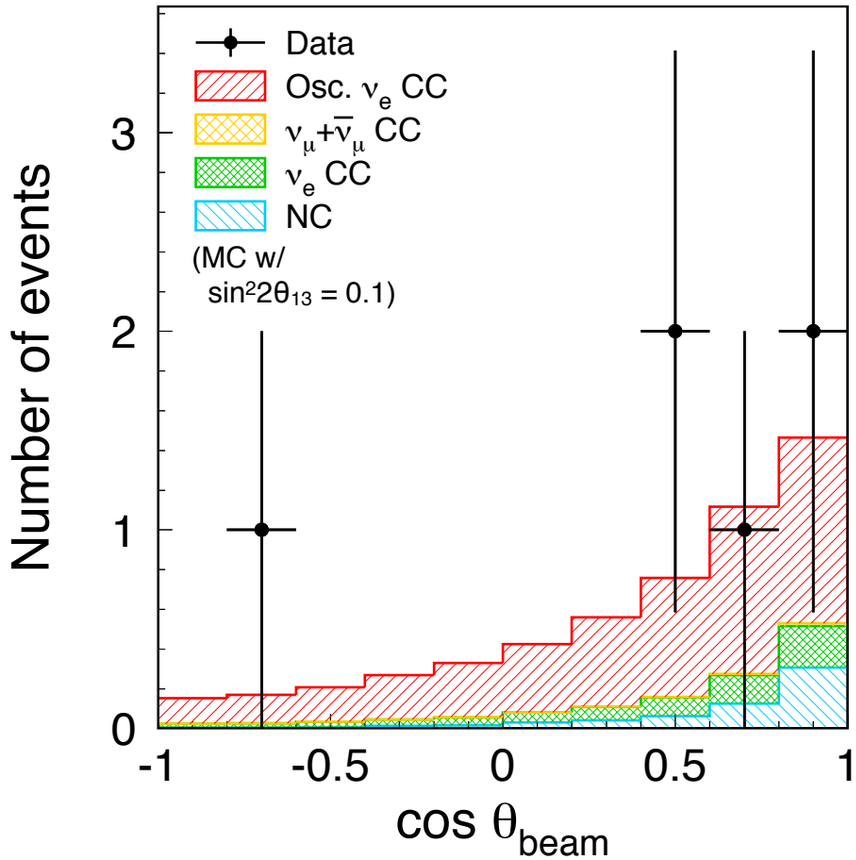
ν_e candidate event



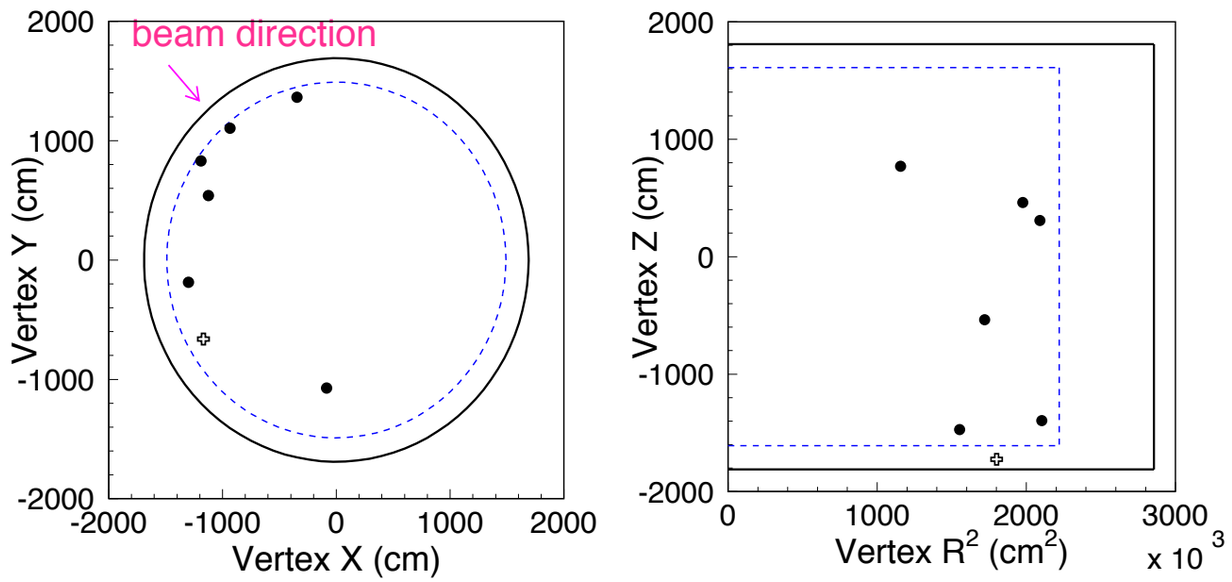
visible energy : 1049 MeV
# of decay-e : 0
2γ Inv. mass : 0.04 MeV/c^2
recon. energy : 1120.9 MeV

Check several distribution of ν_e candidate events





Vertex distribution of ν_e candidate events

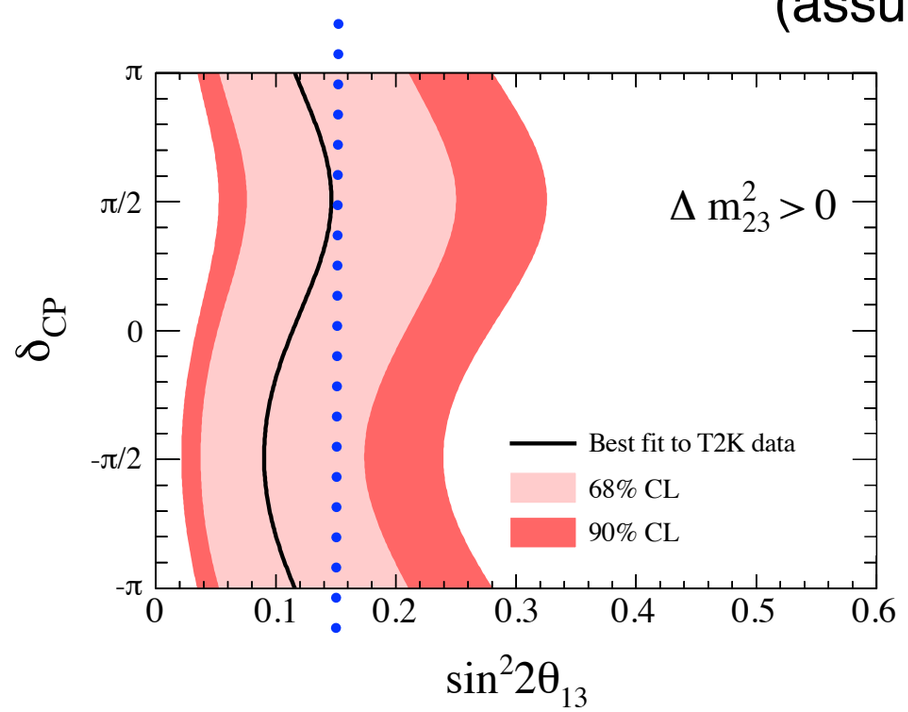


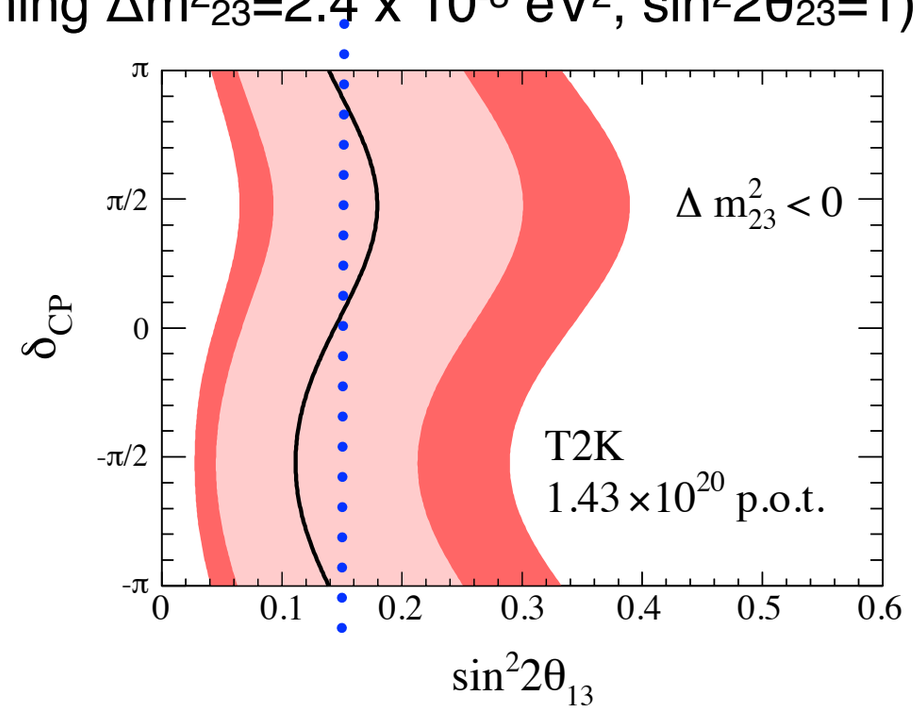
These events are clustered at large R
→ Perform several checks. for example

* Check distribution of events outside FV → no indication of BG contamination
* Check distribution of OD events → no indication of BG contamination
* K.S. test on the R^2 distribution yields a p-value of 0.03

Allowed region of $\sin^2 2\theta_{13}$ as a function of δ_{CP}

(assuming $\Delta m^2_{23}=2.4 \times 10^{-3}$ eV^2, $\sin^2 2\theta_{23}=1$)





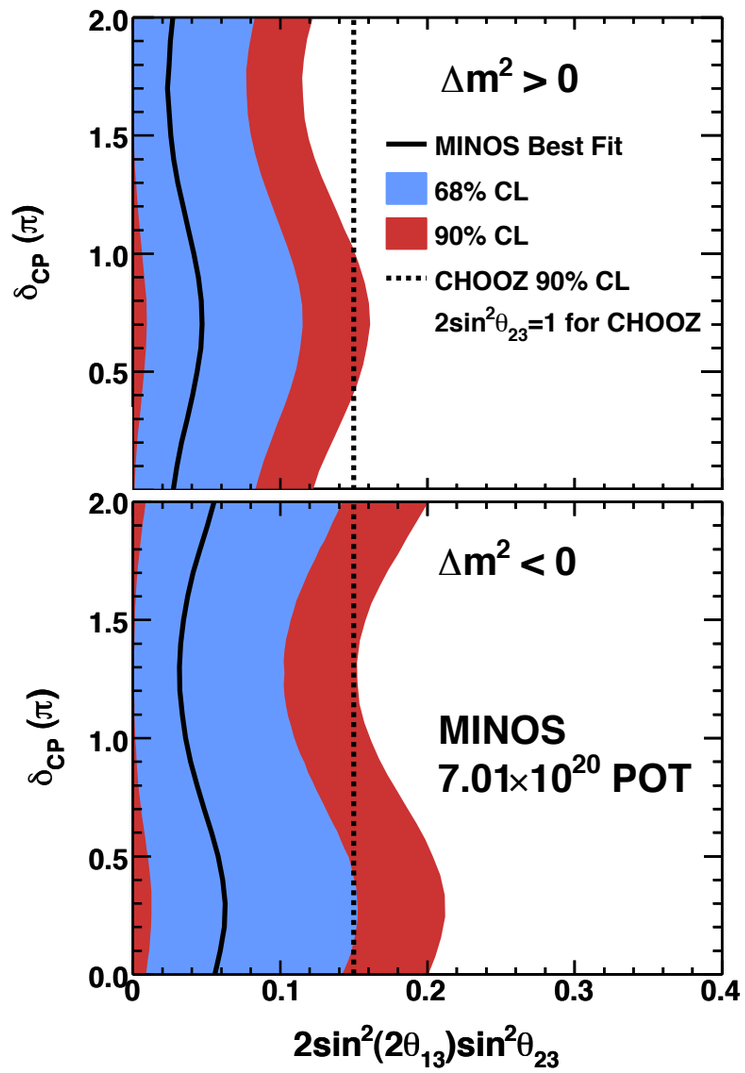
90% C.L. interval & Best fit point (assuming $\Delta m^2_{23}=2.4 \times 10^{-3}$ eV^2, $\sin^2 2\theta_{23}=1$, $\delta_{CP}=0$)

$0.03 < \sin^2 2\theta_{13} < 0.28$ | **$0.04 < \sin^2 2\theta_{13} < 0.34$**

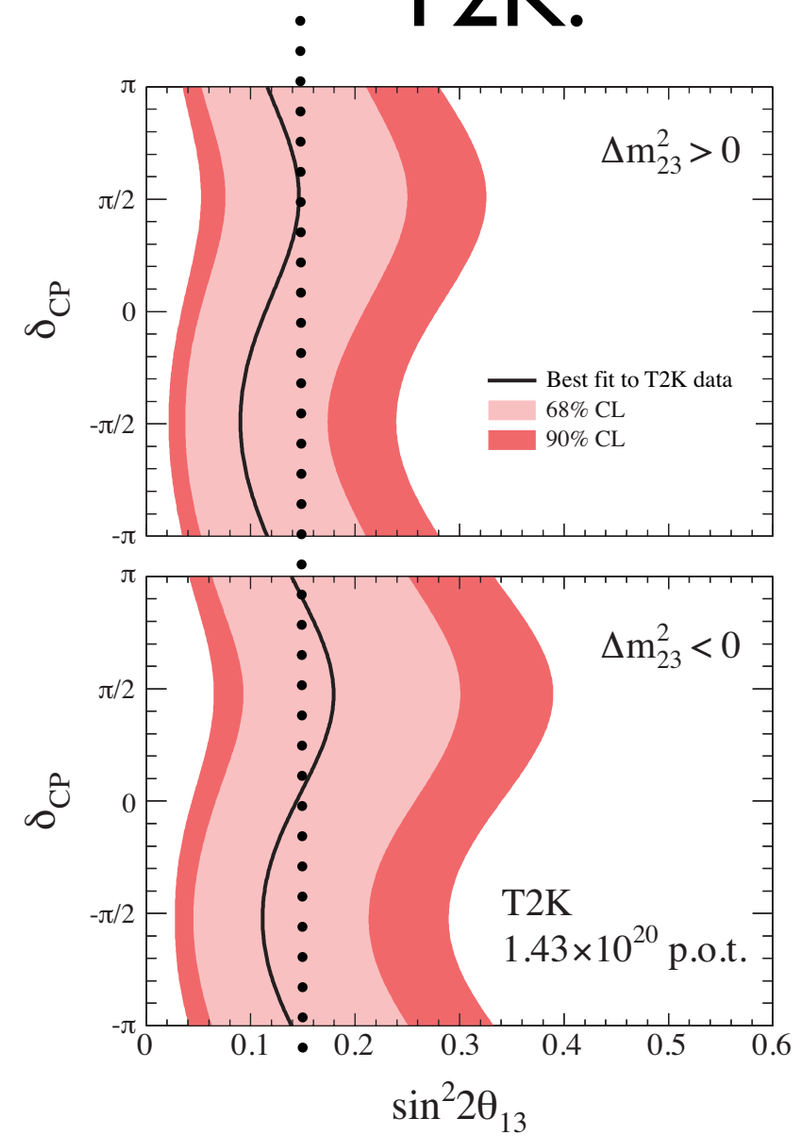
$\sin^2 2\theta_{13} = 0.11$ | **$\sin^2 2\theta_{13} = 0.14$**

Chooz bound assuming $\sin^2\theta_{23} = \frac{1}{2}$

MINOS:

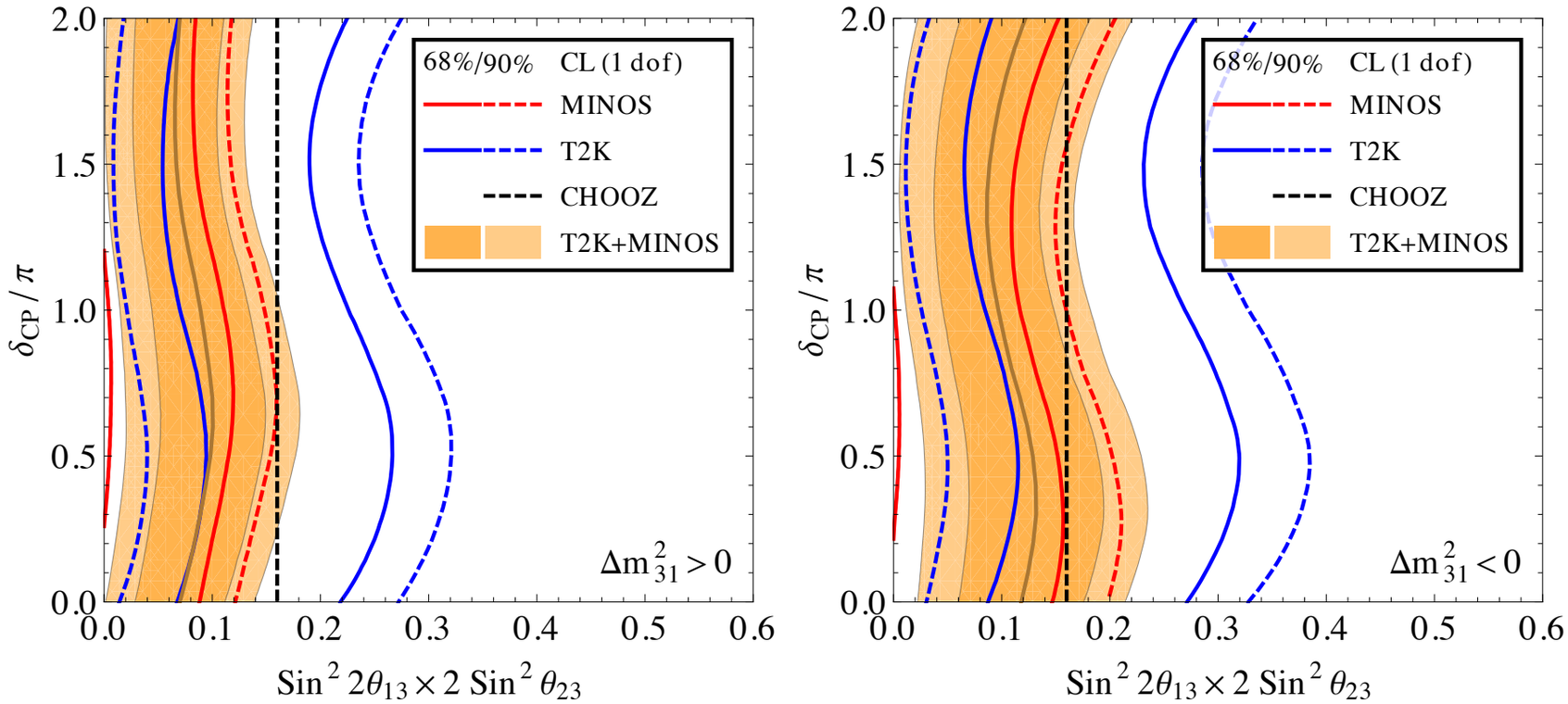


T2K:



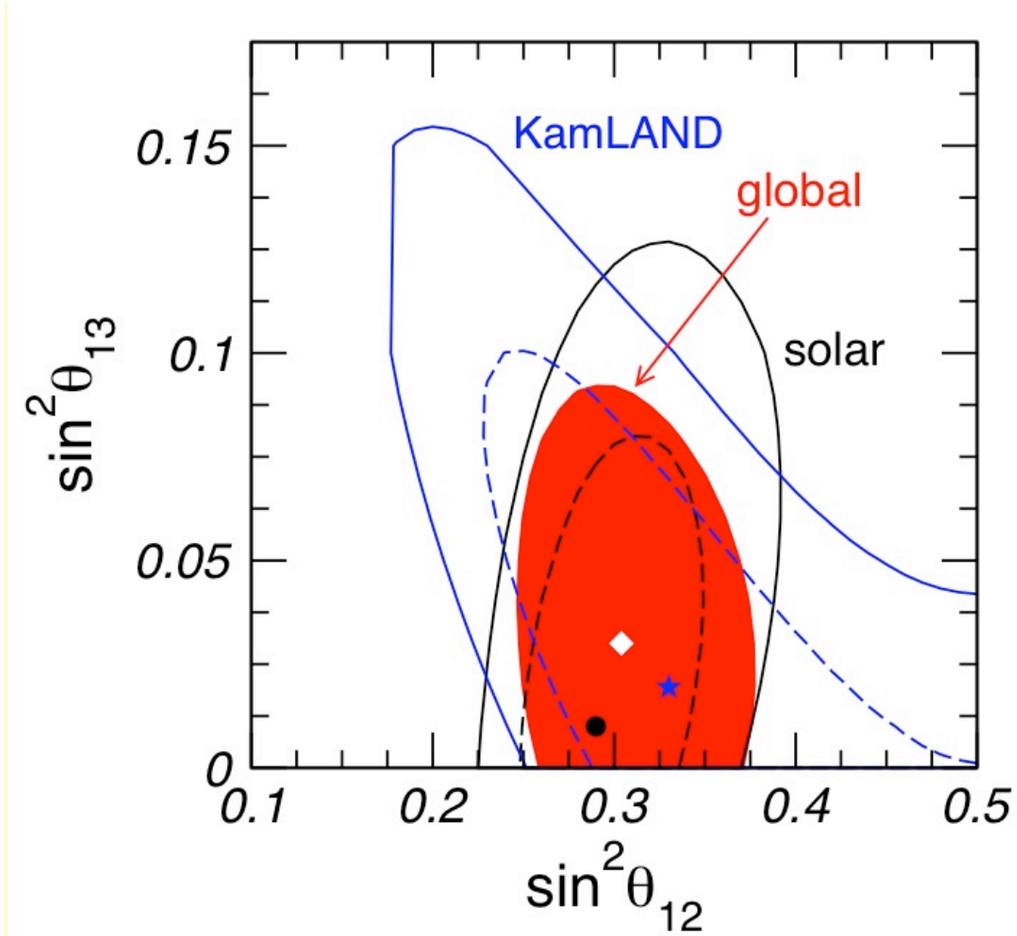
Chooz bound assuming $\sin^2\theta_{23} = \frac{1}{2}$

Cmbining MINOS and T2K results



- Upper limit on θ_{13} dominated by MINOS
- Lower limit dominated by T2K
- Significance of $\theta_{13} \neq 0$ reduced in combination
- *Method not accurate enough for quantitative statements!*

Other:

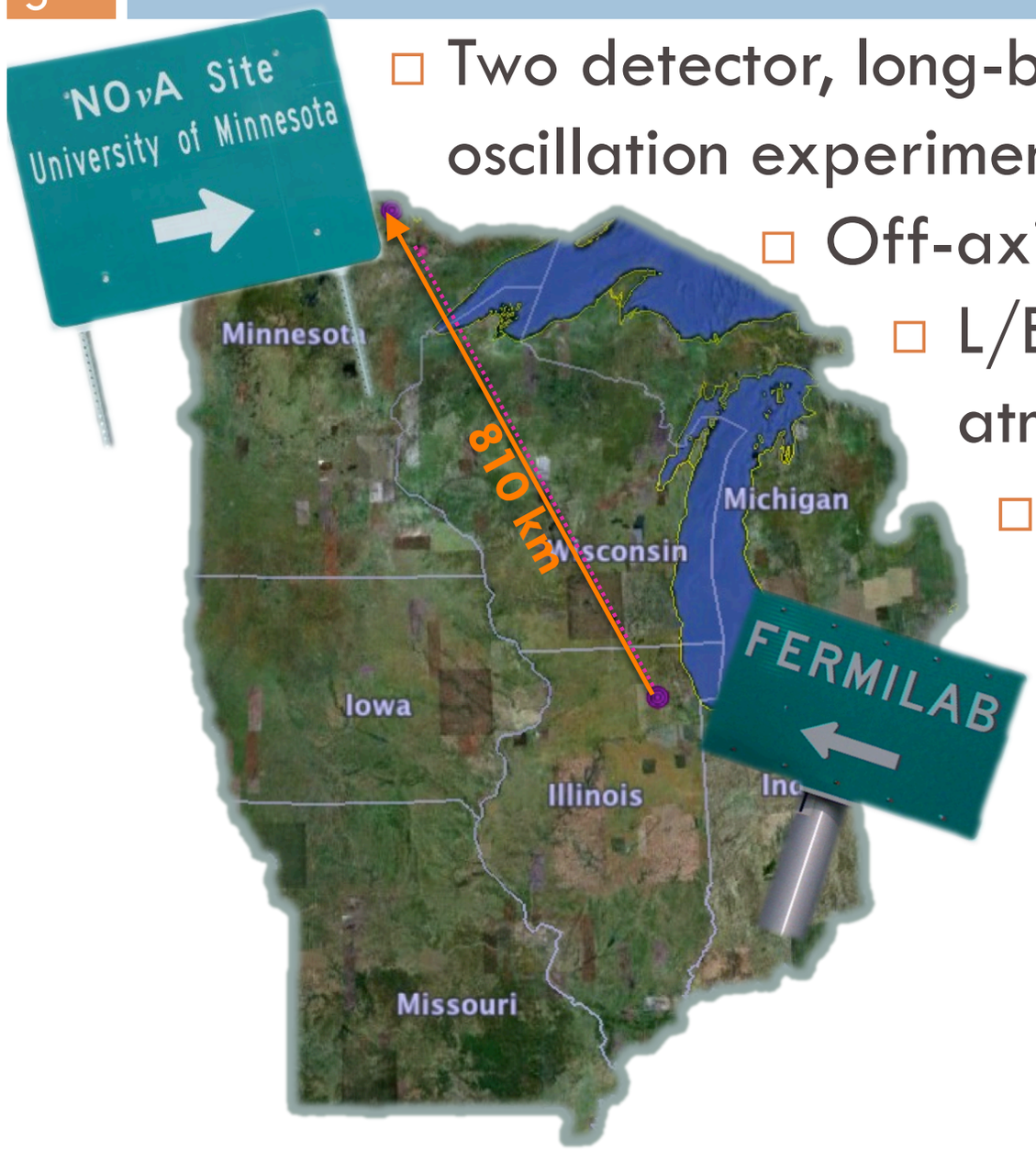


From Schwetz, Tortola, Valle
New J.Phys.10:113011,2008
(arXiv:0808.2016)

$\sin^2\theta_{13} \sim 0.02 \pm 0.01$

namely, an overall indication at ~ 2 sigma (95% CL)

The NOvA Experiment



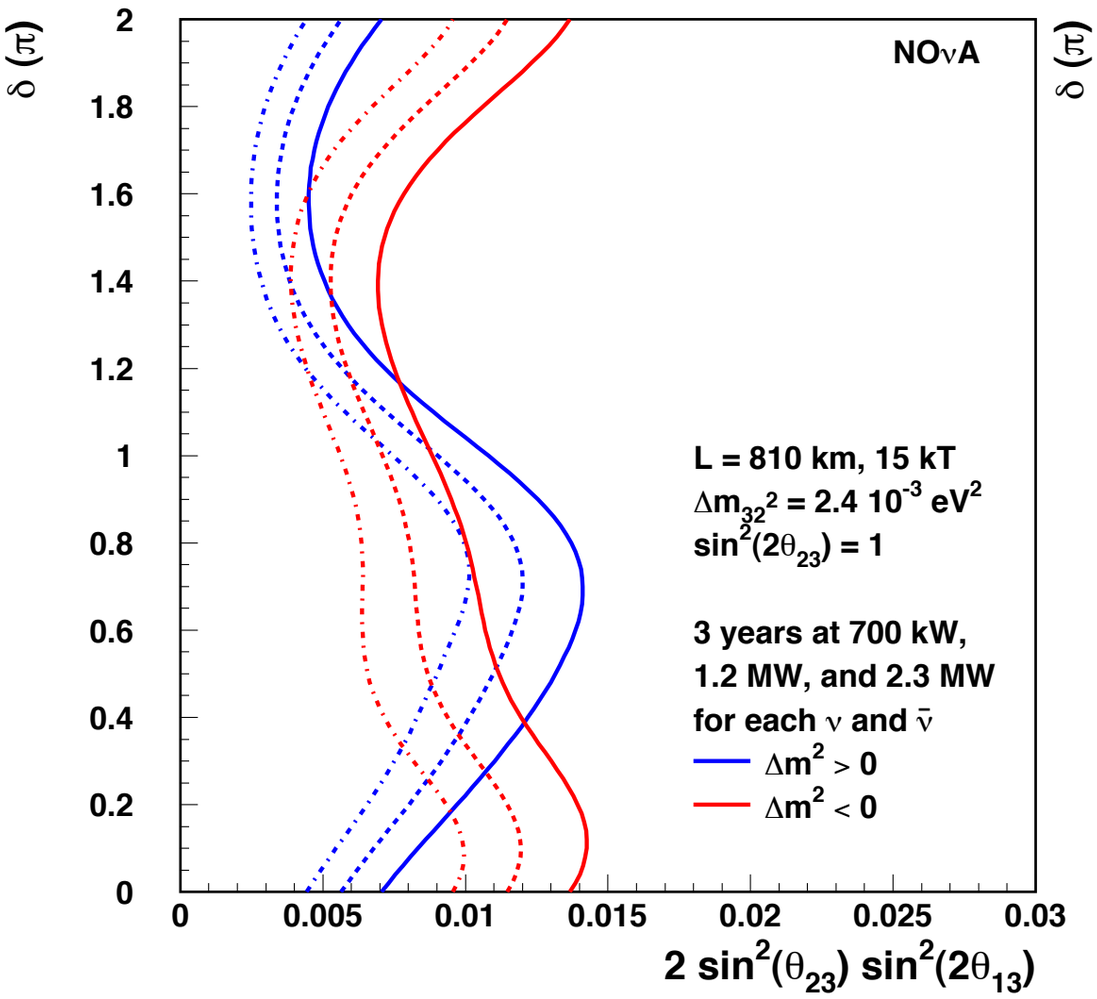
- Two detector, long-baseline neutrino oscillation experiment
  - Off-axis neutrinos from NuMI beam
    - L/E~400 km/GeV, atmospheric Δm^2
      - Physics goals:
        - Search for $\nu_\mu \rightarrow \nu_e$ transitions (with both neutrinos and antineutrinos)
        - measure/limit θ_{13}
        - determine mass hierarchy
        - constrain CP violating phase
        - precision measurements of Δm^2, θ_{23}

P. Vahle, FNAL 2011

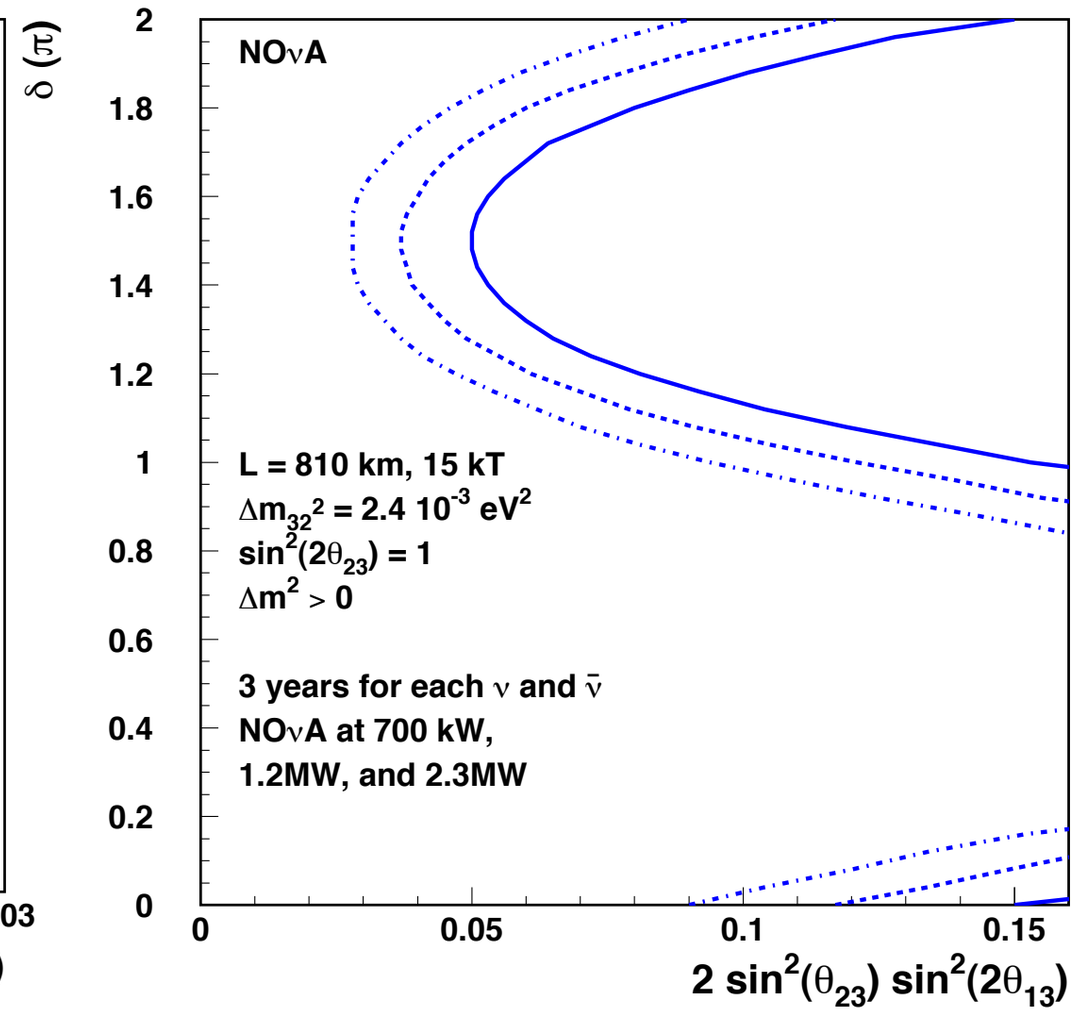
Long Baseline + Nu and AntiNu running

Sensitivity

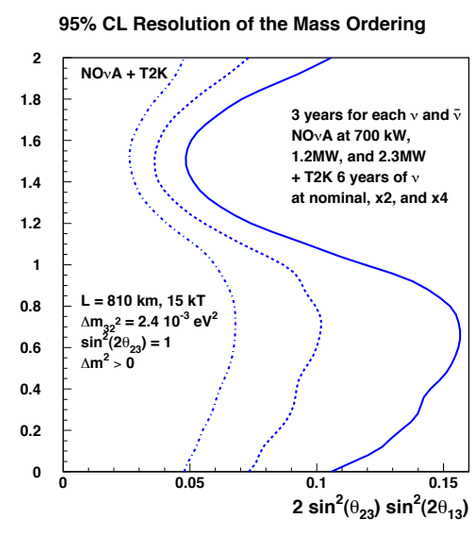
90% CL Sensitivity to $\sin^2(2\theta_{13}) \neq 0$



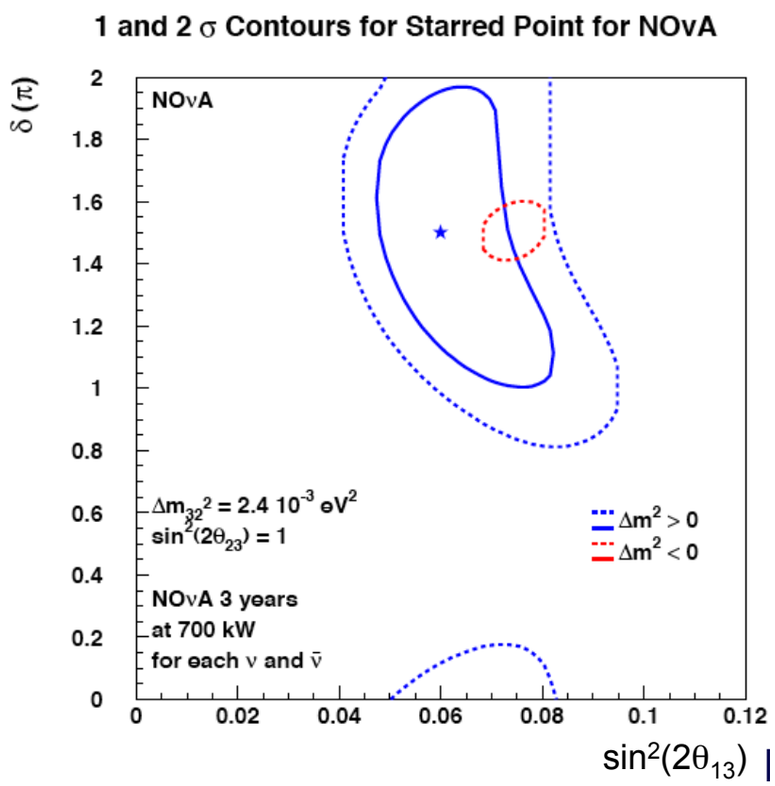
95% CL Resolution of the Mass Ordering

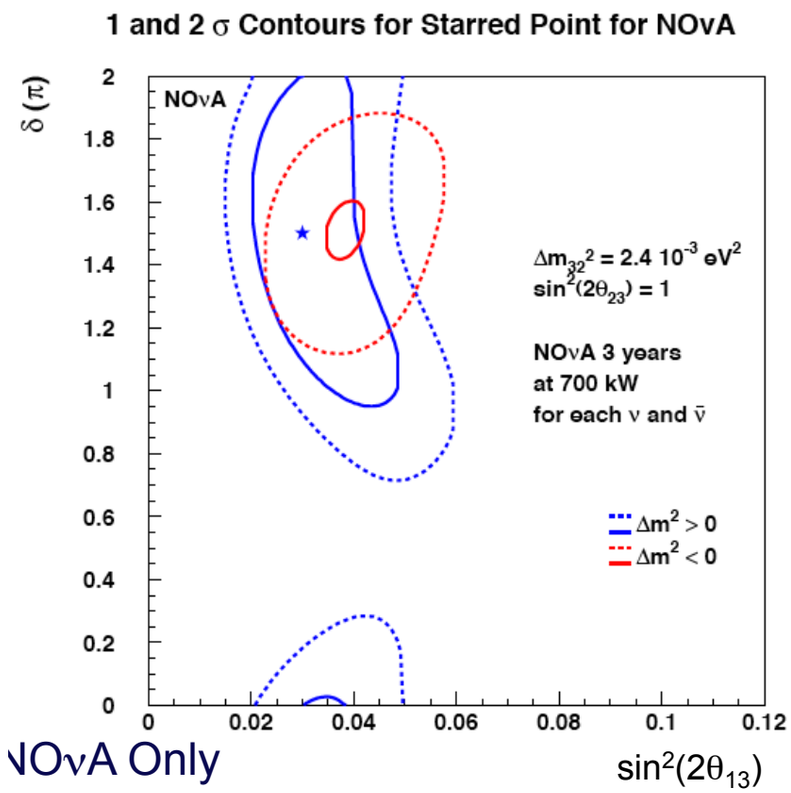


- Sensitivity to $\sin^2(2\theta_{13})$ after 3 years each of neutrino beam and antineutrino beam
- Sensitivity to mass hierarchy



P. Vahle, FNAL 2011


1 and 2 σ Contours for Starred Point for NOνA
δ (π)
NOνA
$\Delta m_{32}^2 = 2.4\ 10^{-3}\ eV^2$
$\sin^2(2\theta_{23}) = 1$
NOνA 3 years
at 700 kW
for each ν and ν̄
$\Delta m^2 > 0$
$\Delta m^2 < 0$
$\sin^2(2\theta_{13})$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NOνA 3 years
at 700 kW
for each ν and ν̄
$\Delta m^2 > 0$
$\Delta m^2 < 0$
$\sin^2(2\theta_{13})$

NOνA Only

$\nu_\mu \longrightarrow \nu_e$ and $\bar{\nu}_\mu \longrightarrow \bar{\nu}_e$

At Vac. Osc. Max. ($\Delta_{31} = \frac{\pi}{2}$)

$$P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e) \approx 2\sin^2\theta_{23}\sin^2 2\theta_{13} \quad + \quad \mathcal{O}[(aL)\sin\delta]$$

directly comparable to reactor

$$1 - P(\bar{\nu}_e \to \bar{\nu}_e) = \sin^2 2\theta_{13}$$

$\nu_\mu \longrightarrow \nu_e$ and $\bar{\nu}_\mu \longrightarrow \bar{\nu}_e$

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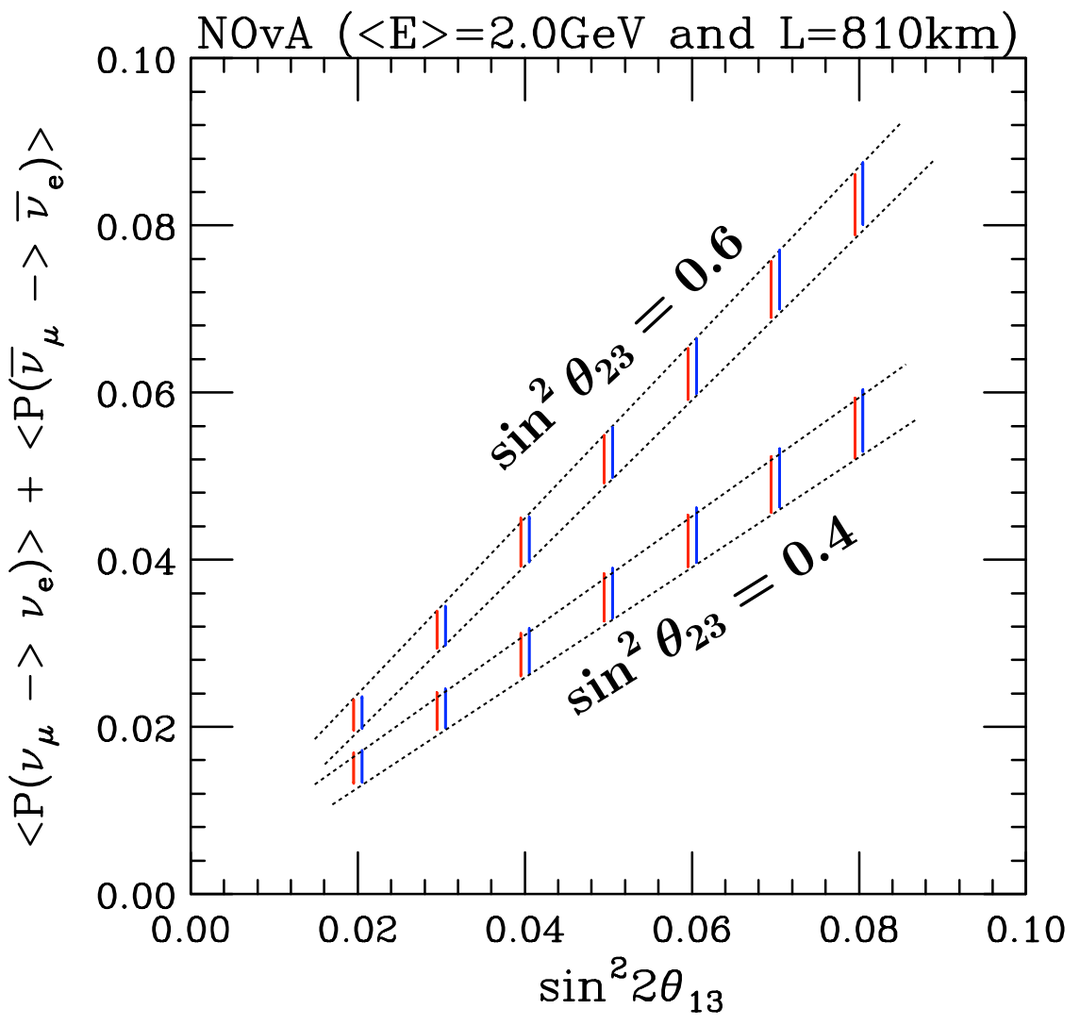
NOvA



For $\sin^2 2\theta_{23} = 0.96$
thus $\sin^2\theta_{23} = 0.4$ or 0.6

(4*0.4*0.6=0.96)

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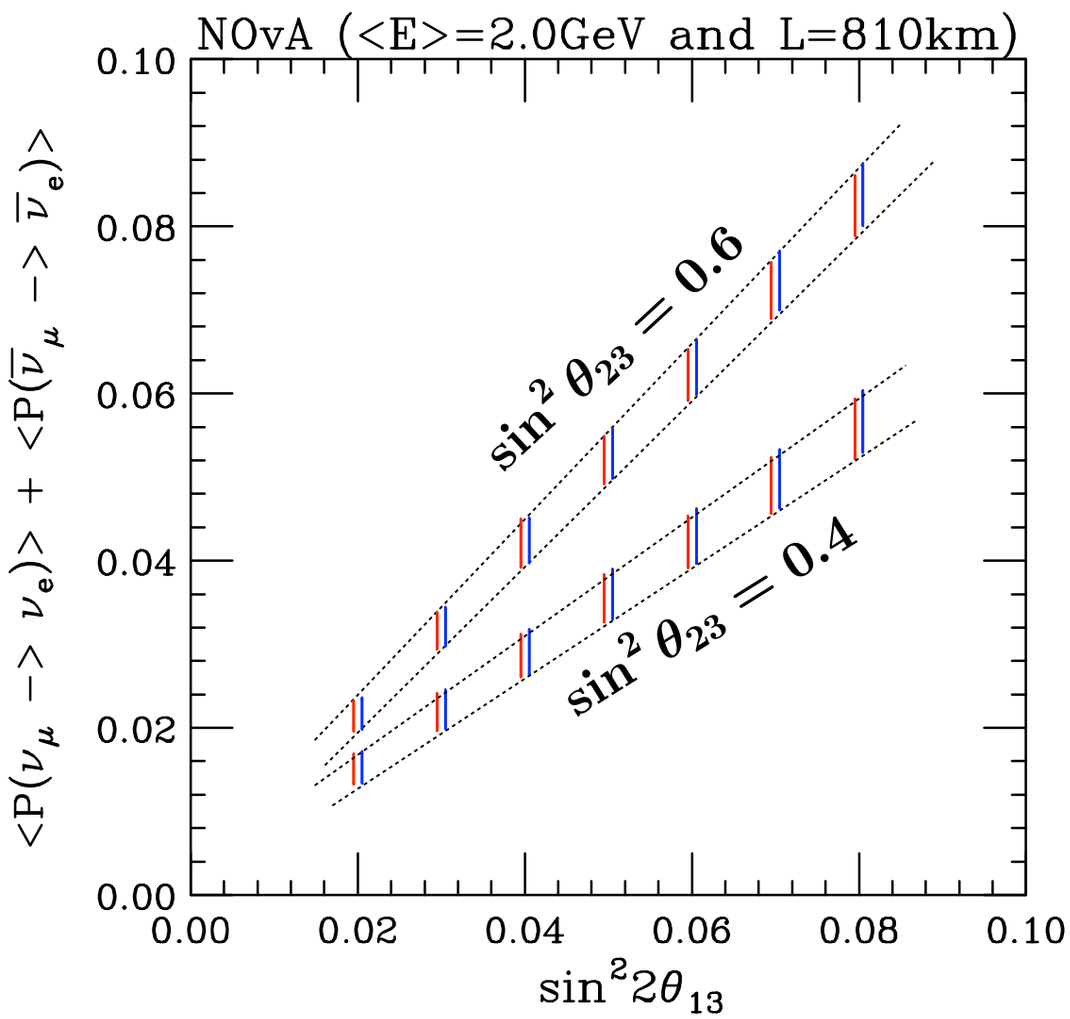
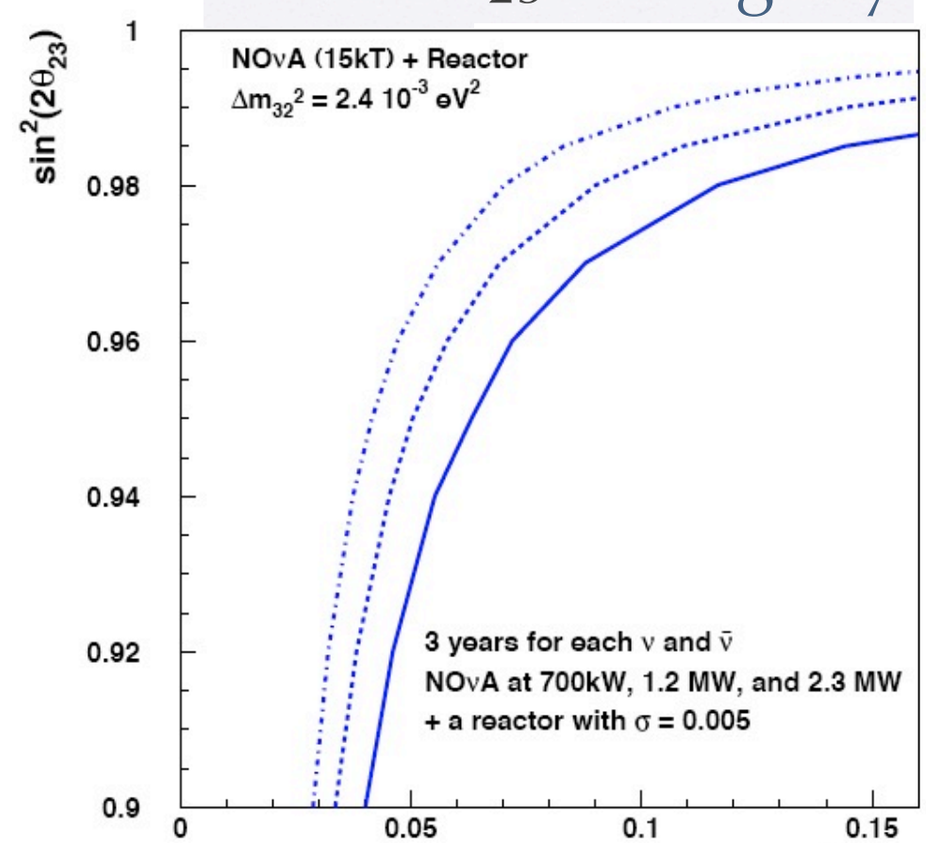
NOvA



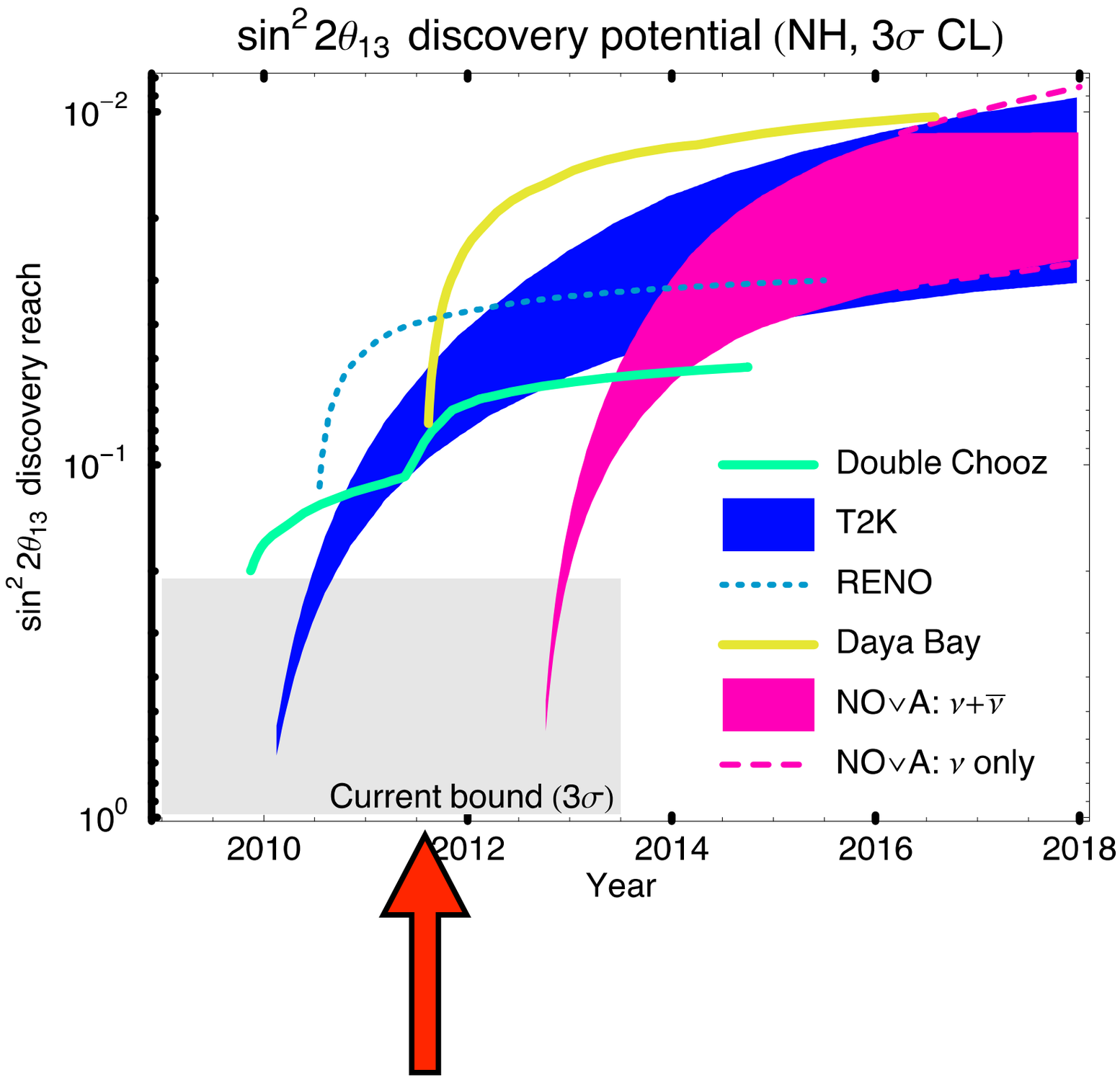
For $\sin^2 2\theta_{23} = 0.96$
thus $\sin^2\theta_{23} = 0.4$ or 0.6

(4*0.4*0.6=0.96)

95% CL Resolution of the θ_{23} ambiguity

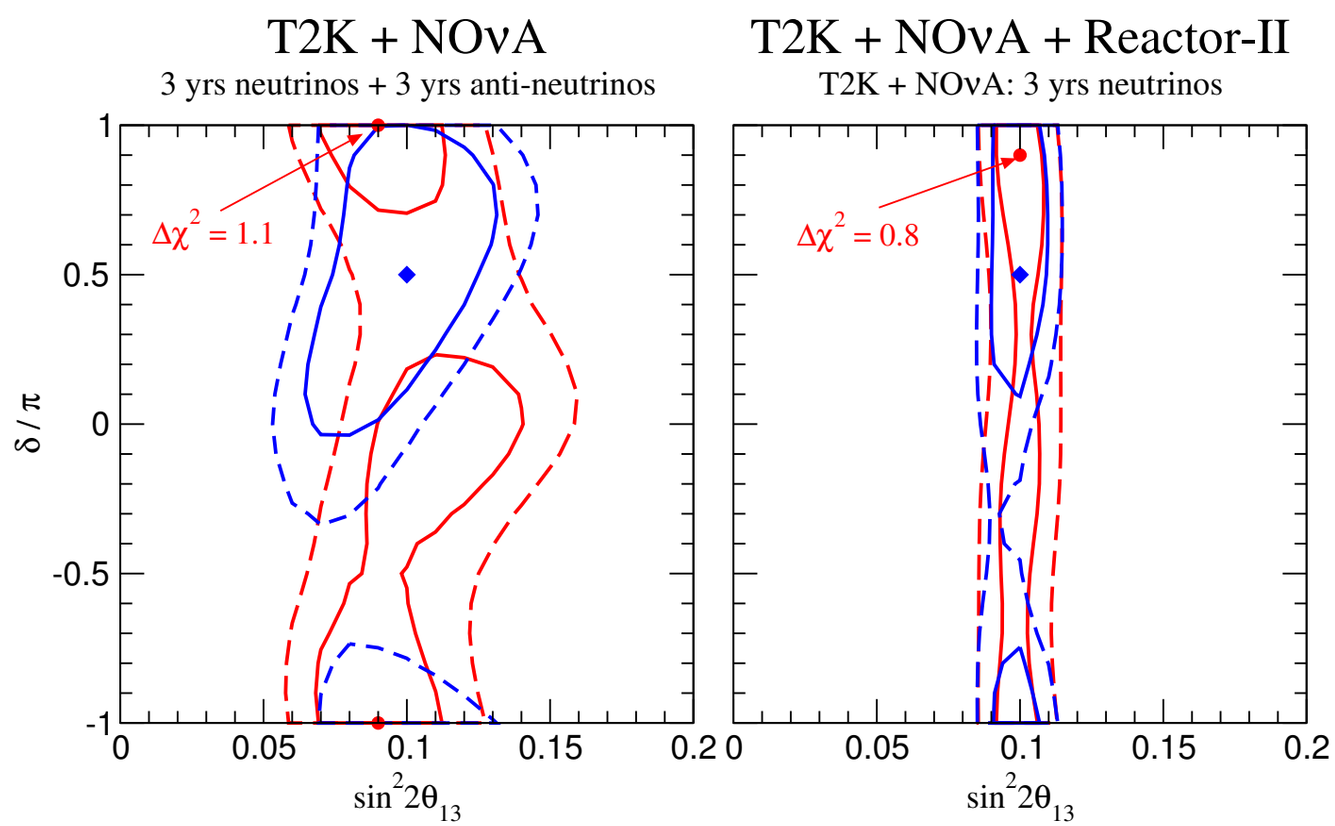


T2K could also do this, if they ran $\bar{\nu}_\mu$


$\sin^2 2\theta_{13}$ discovery potential (NH, 3σ CL)
$\sin^2 2\theta_{13}$ discovery reach
10^{-2}
10^{-1}
10^{0}
2010
2012
2014
2016
2018
Year
Current bound (3σ)
Double Chooz
T2K
RENO
Daya Bay
NOνA: $\nu+\bar{\nu}$
NOνA: ν only

Implications of $\theta_{13} \neq 0$ for future experiments

- Can expect constraints on δ_{CP} from T2K, NOνA, reactors
- Need anti-neutrino runs

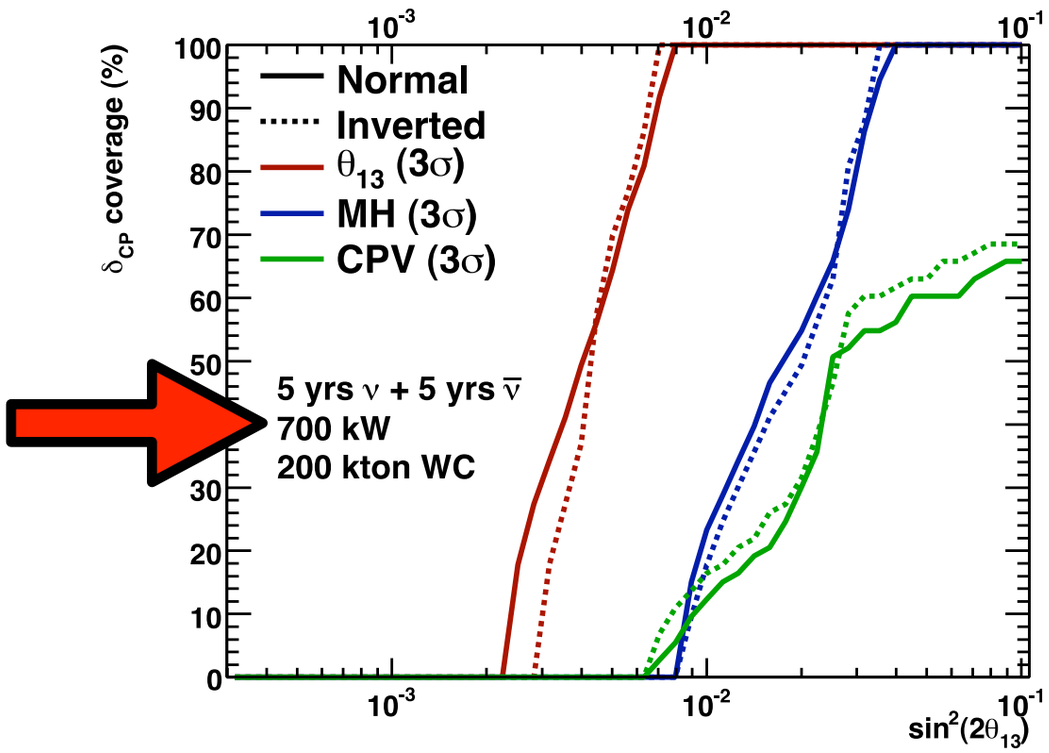


Contours: 90%, 3σ; blue: NH, red: IH

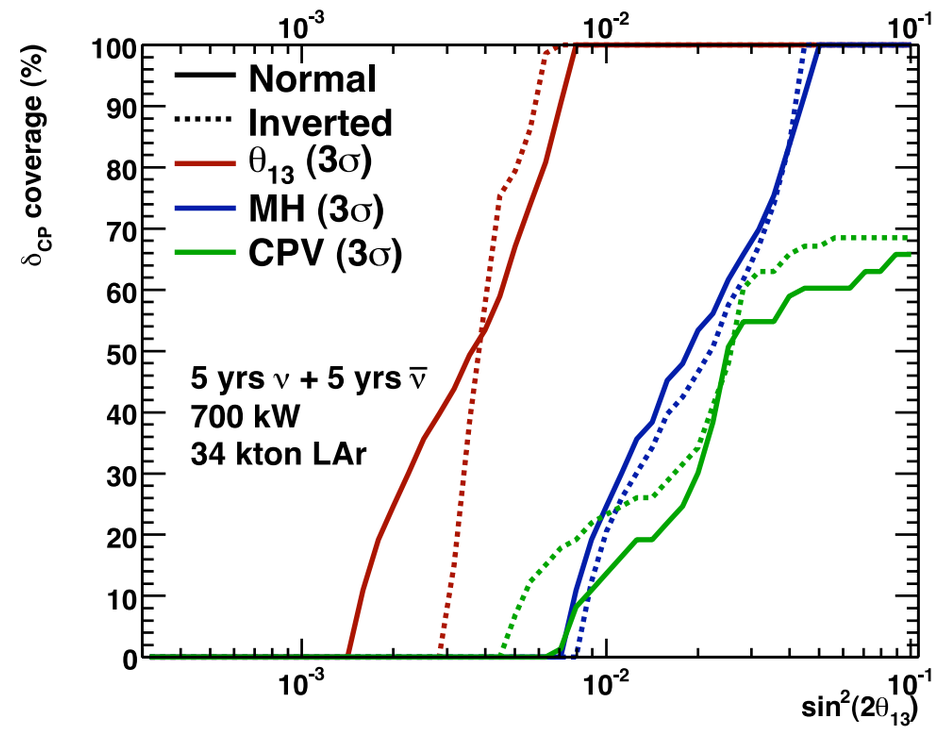
Huber Lindner Rolinec Schwetz Winter, hep-ph/0412133

Performance of LBNE:
Long-Baseline $\nu_\mu \rightarrow \nu_e$ Oscillations

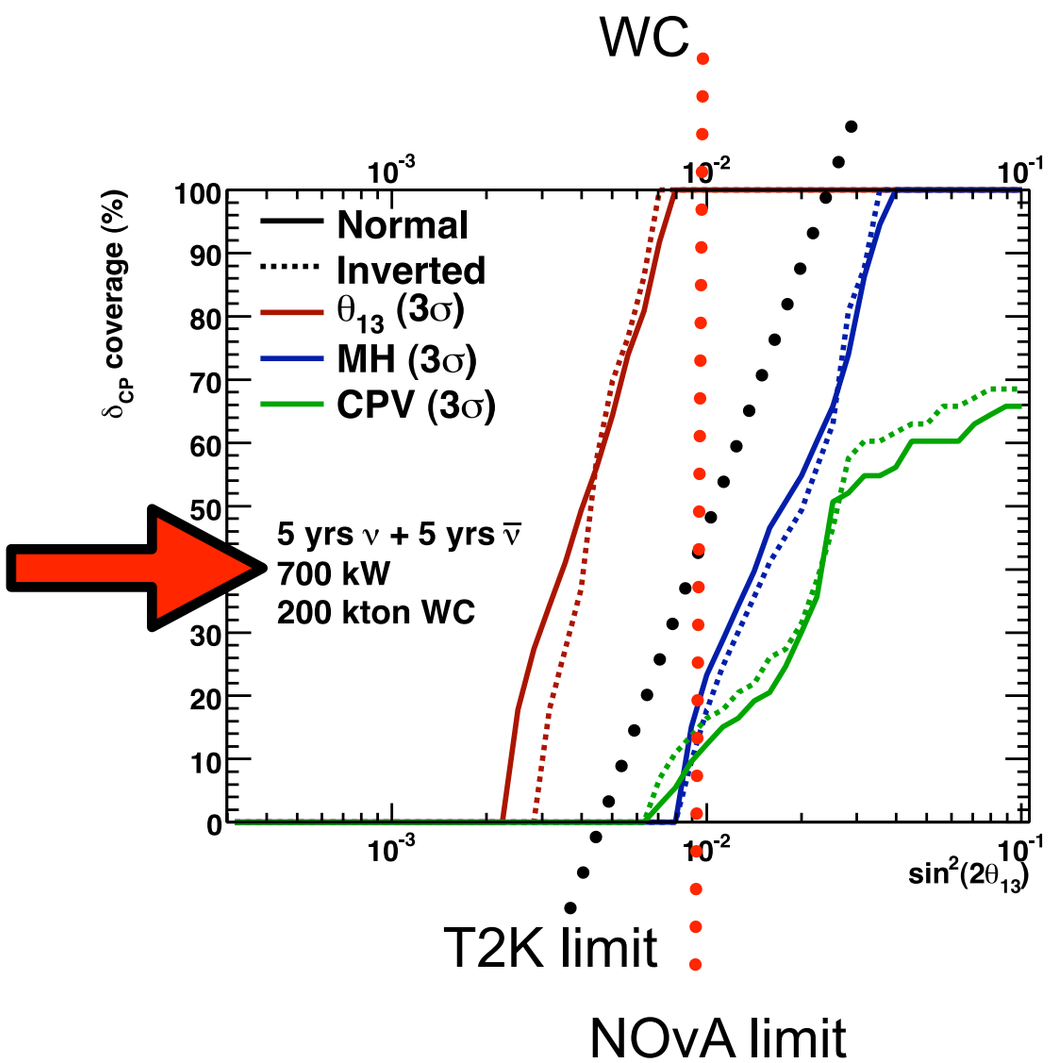
WC

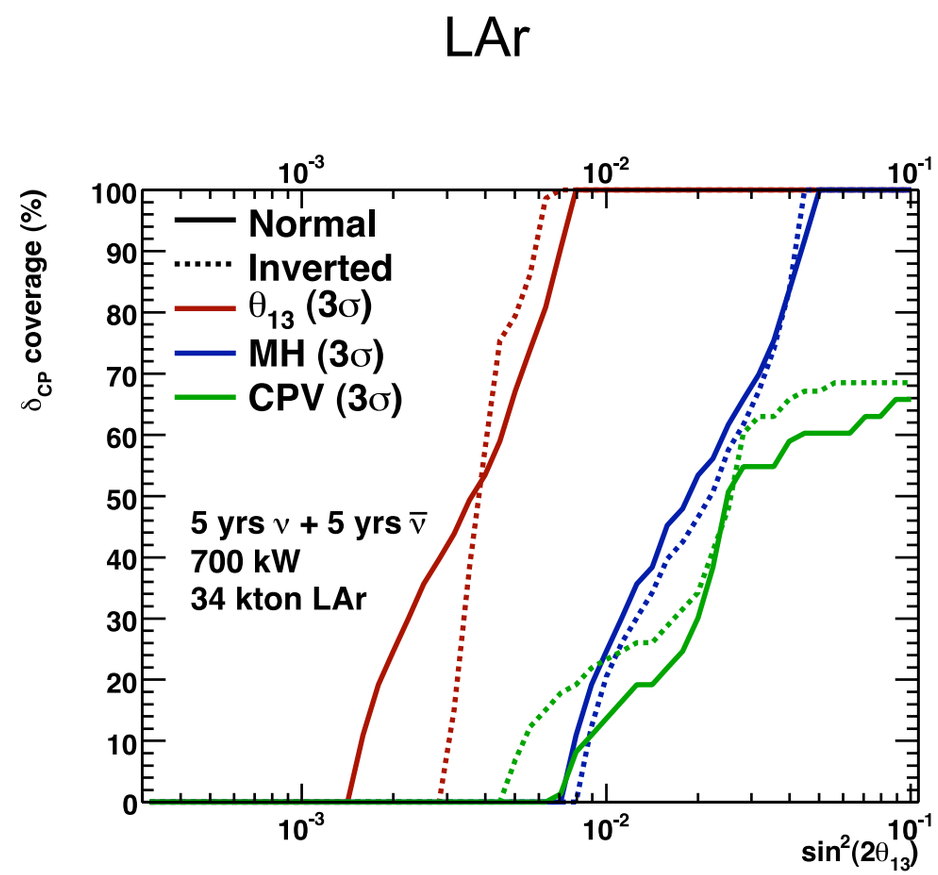


LAr



Performance of LBNE:
Long-Baseline $\nu_\mu \rightarrow \nu_e$ Oscillations





Beyond NuSM + Cross Sections Exp.

miniBooNE
microBooNE
ArgoNeut
SciBooNE
MINERVA

MiniBooNE Physics Goals and Recent Publications

20 publications (8 in 2010-2011)

- ν_e and $\overline{\nu}_e$ appearance
  - "Event Excess in the MiniBooNE Search for $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ Oscillations," Phys. Rev. Lett. 105,181801 (2010)
- ν_μ and $\overline{\nu}_\mu$ disappearance
- ν_μ and $\overline{\nu}_\mu$ cross section measurements
  - "Measurement of neutrino-induced charged-current charged pion production cross sections on mineral oil at E_ν ~1 GeV," Phys. Rev. D83, 052007 (2011)
  - "Measurement of ν_μ-induced charged-current neutral pion production cross sections on mineral oil at E_ν from 0.5-2.0 GeV," Phys. Rev. D83, 052009 (2011)
  - "Measurement of the neutrino neutral-current elastic differential cross section," Phys. Rev. D82, 092005 (2010)
  - "First measurement of the muon neutrino charged current quasielastic double differential cross section," Phys. Rev. D81, 092005 (2010)
  - "Measurement of ν_μ and $\overline{\nu}_\mu$-induced neutral current single π^0 production cross sections on mineral oil at $E\nu$ ~1 GeV," Phys. Rev. D81, 013005 (2010)

BNB Oscillation Summary

	SciBooNE	MiniBooNE
ν mode	0.99×10^{20} POT	6.5×10^{20} POT
$\bar{\nu}$ mode	1.53×10^{20} POT	8.7×10^{20} POT

Low energy excess (below 475 MeV)

- MB: 3σ ν_e-like excess in neutrino mode (128 ± 43 events)
  - Does not fit simple 2ν oscillation hypothesis
- MB: Negligible excess in anti-neutrino mode (18 ± 14 events)
  - Rules out some explanations of neutrino-mode excess

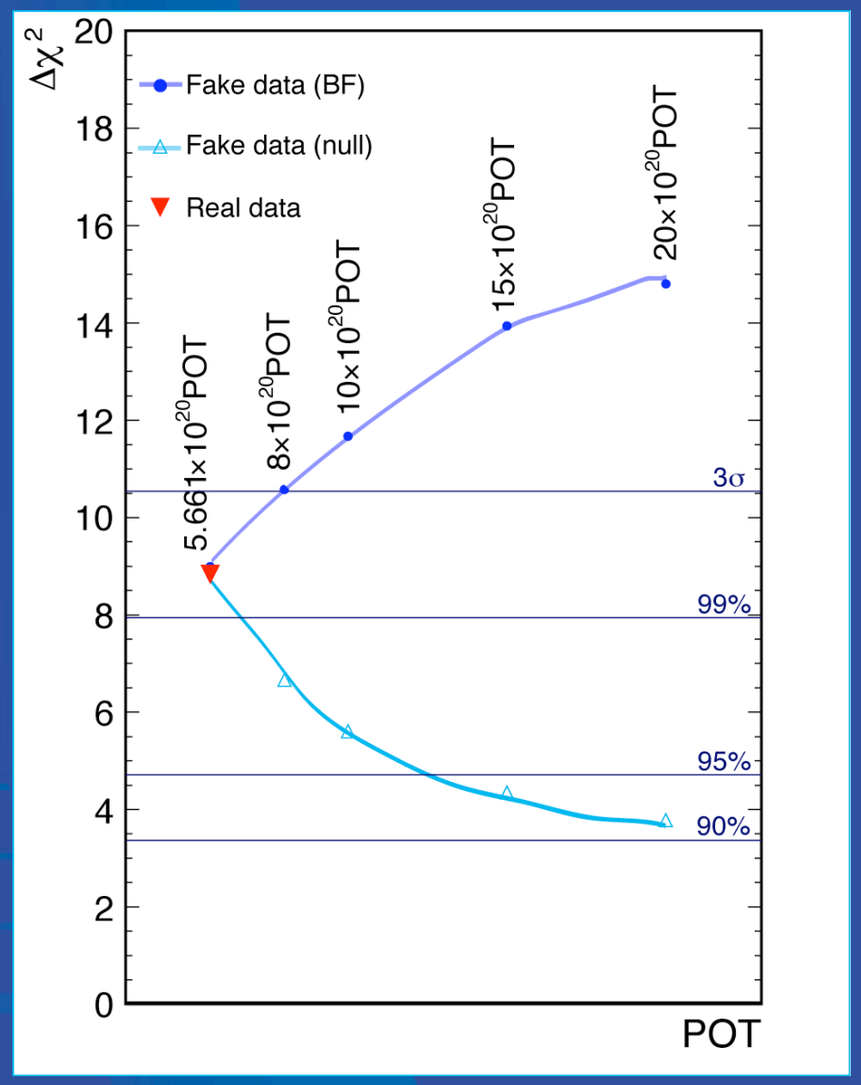
LSND-like signal (above 475 MeV)

- MB: No evidence of ν_e excess in neutrino mode
- MB: 2.7σ excess in anti-neutrino mode
  - Null hypothesis 0.5% probable, 2ν fit prefers LSND-like signal at 99.4% CL

ν_μ and $\bar{\nu}_\mu$ disappearance

- MB: No evidence in neutrino or anti-neutrino mode
- MB + SB: No evidence in neutrino mode
  - More precise anti-neutrino joint analysis underway

MiniBooNE: Expected sensitivity with additional $\bar{\nu}$ data

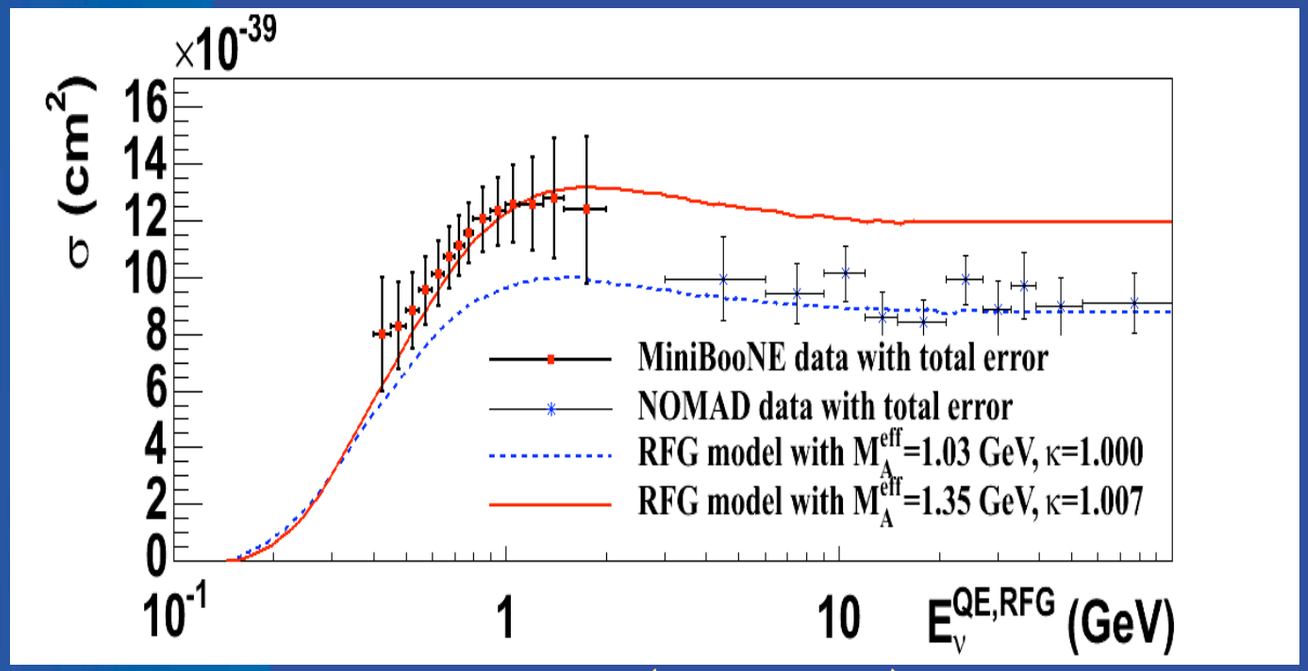


With 15 x 10^{20} POT $\bar{\nu}$ significance could grow to 3.7σ, or fall back to include null at 95% CL.

Analysis of 8.5 x 10^{20} POT will be released this summer.

MiniBooNE Cross Sections

Neutrino cross sections are not well-known below ~2 GeV



MiniBooNE CC quasi-elastic cross section ~30% higher than "standard" QE prediction

MINERνA, MINOS, ArgoNeuT

If discrepancy is due to extra nucleons, MINERνA, MINOS, and ArgoNeuT are all capable of detecting them, and they cover the gap between MiniBooNE and NOMAD data!

SciBooNE Physics Goals and Recent Publications

5 publications (3 in 2010-2011)

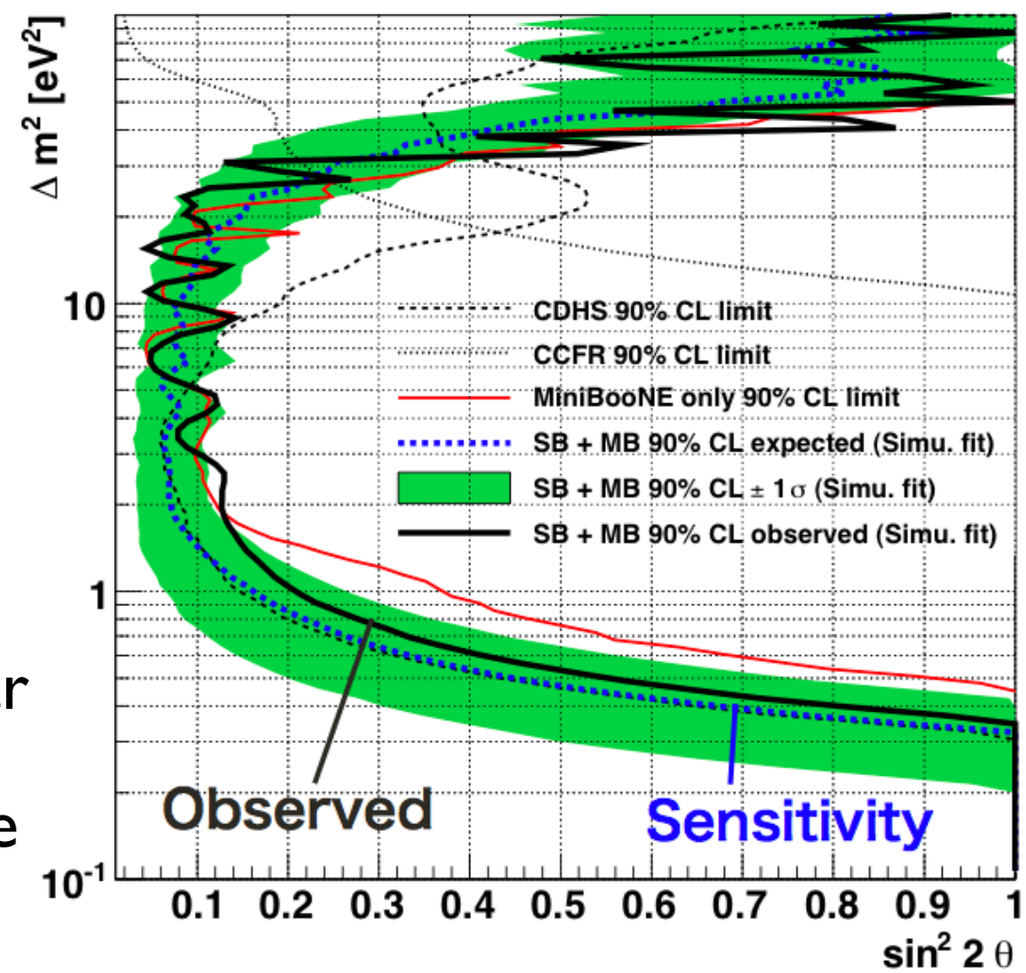
- ν_μ and $\bar{\nu}_\mu$ cross section measurements
  - "Measurement of K^+ production cross section by 8 GeV protons using high energy neutrino interactions in the SciBooNE detector," arXiv:1105.2871, submitted to Phys. Rev. D (2011)
  - "Measurement of inclusive charged current interactions on carbon in a few-GeV neutrino beam," Phys. Rev. D83, 012005 (2011)
  - "Improved measurement of neutral current coherent π^0 production on carbon in a few-GeV neutrino beam," Phys. Rev. D81, 111102(R) (2010)
- Measure background processes for oscillation experiments (T2K)
- Act as MiniBooNE near detector

Joint MiniBooNE-SciBooNE ν_μ Disappearance Analysis

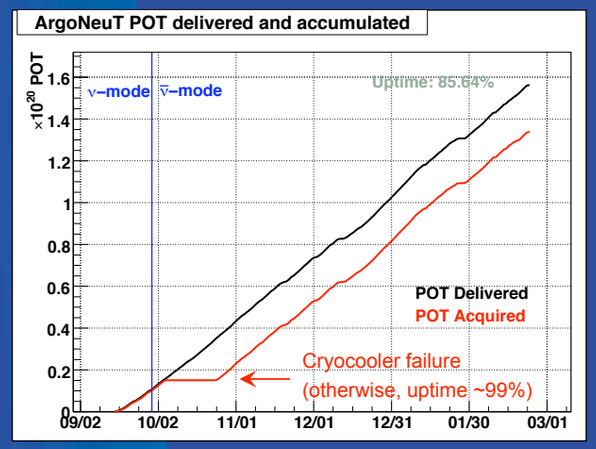
Joe Grange 44th Fermilab User's Meeting 2nd June 2011

- By comparing rate and shape information in ν_μ CC interactions between the two detectors, set limits for ν_μ disappearance
  - world's strongest limit at $10 < \Delta m^2\ (eV^2) < 30$
- Constrains $\nu_\mu \rightarrow \nu_e$ oscillations as well as other, more exotic models
  - extra dimensions, ~~CPT~~
- See Y. Nakajima's 4/29/11 FNAL Wine & Cheese seminar

  Paper in draft
- Forthcoming $\bar{\nu}_\mu$ disappearance analysis



ArgoNeuT in the NuMI Beamline



ArgoNeuT in the MINOS hall

175 liter liquid argon TPC

Physics run: Sept. 2009 – Feb. 2010

Data collected: ~1.35 x 10^{20} P.O.T.

0.1 x 10^{20} ν-mode, 1.25 x 10^{20} ν̄-mode

Coming this summer…

DRAFT Analysis of a Large Sample of Muons with the ArgoNeuT Detector

M. Antonelllo[a], B. Baller[b], C. Bromberg[c], F. Cavanna[e], D. Edmunds[c], B. Fleming[f], C. James[b], K. Lang[g], P. Laurens[c], S. Linden[f], R. Mehdiyev[g], B. Page[c], O. Palamara[a], K. Partyka[f], G. Rameika[b], B. Rebel[b], M. Soderberg[b,d], J. Spitz[f], T. Wongjirad[f]

[a]*Gran Sasso National Laboratory*
[b]*Fermi National Accelerator Laboratory, Chicago, Illinois*
[c]*Michigan State University, East Lansing, Michigan 48824*
[d]*Syracuse University, Syracuse, New York 13039*
[e]*University of L'Aquila, L'Aquila, Italy*
[f]*Yale University, New Haven, Connecticut, USA*
[g]*The University of Texas at Austin, Austin, Texas 78712*

Abstract

ArgoNeuT has recently collected thousands of neutrino and anti-neutrino events in the NuMI beamline at Fermilab. The main physics thrust of the experiment is to measure neutrino cross sections in the 0.1-10 GeV energy range. Fully reconstructing the muon is imperative to measuring muon-neutrino charged current cross sections. This paper focuses on the complete kinematic reconstruction and identification of muons and line-like tracks in general with ArgoNeuT's automated reconstruction software. The various pattern recognition and characterization algorithms implemented in the software are described in detail with a focus on reconstructing neutrino-induced through-going muons, rather than neutrino events themselves. Along with being imperative to detector calibration, a high statistics sample of minimum ionizing, line-like tracks provides a means of measuring the electron drift velocity and lifetime in the liquid argon.

Keywords:

1. Introduction

Liquid Argon Time Projection Chambers (LArTPCs) are well suited for the study of neutrino interactions thanks to their unique combination of scalability, fine-grained tracking, and calorimetry. LArTPCs were proposed in the 1970s and have a long history of development in Europe [1, 2]. Until recently, only one LArTPC has ever been exposed to a neutrino beam [3]. There is considerable interest in developing this detector technology, with the goal of deploying a massive multi-kiloton LArTPC in a far-detector location as part of a long-baseline neutrino oscillation experiment and proton decay search, among other physics goals.

LArTPCs rely on the ability to drift ionization created in a neutrino interaction through a volume of highly purified liquid argon to a set of instrumented readout planes. The readout planes consist of finely spaced (mm-scale) wires, with neighboring planes oriented at varying angles to

Preprint submitted to Elsevier *March 21, 2011*

- Cross sections for CC QE-like ν and ν̄ from 1-5 GeV
  - Low statistics (but ICARUS 50-liter meas. with ~80 events)
- Initial focus: analyze ~2 weeks of ν-mode data
  - Study inclusive CC sample
  - Data/MC comparisons
- Start to look at ν̄ data this fall…

MicroBooNE

- The MicroBooNE detector will be a liquid argon time projection chamber (LAr TPC) containing 170 tons of liquid argon, and located on the Booster Neutrino Beamline.
- The experiment's goal is to begin operation in 2013; availability of funding may constrain the schedule
  - Fully test the LAr TPC technology at a scope and scale that will help inform the design and operation of very large LAr TPC detectors for next-generation neutrino oscillation experiments.
    - Purity without evacuation; cold electronics; 2.5 m drift

Physics

- Investigate the source of the excess of low energy electron-type neutrinos observed by the MiniBooNE experiment using the unique electron-photon discrimination power offered by a LAr TPC.
- Produce the first high-statistics measurements of neutrino interactions in argon. Currently, such measurements do not exist; they will provide the first constraints for future LAr-based neutrino oscillation experiments.

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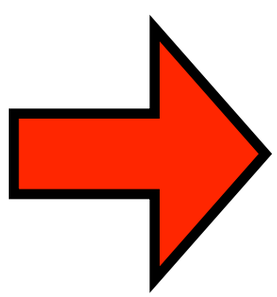

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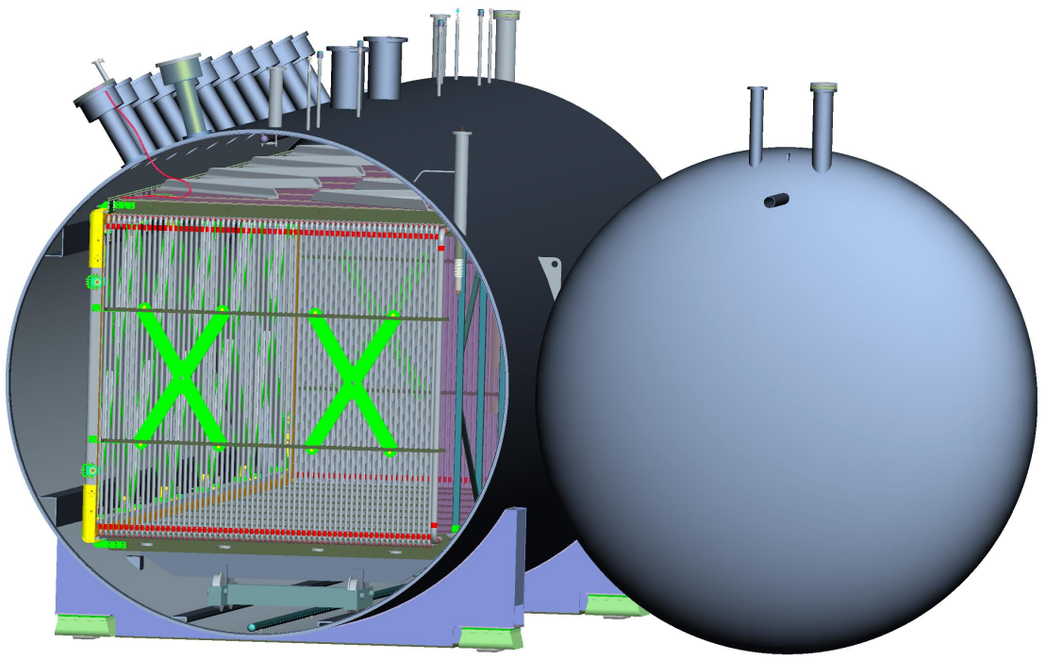
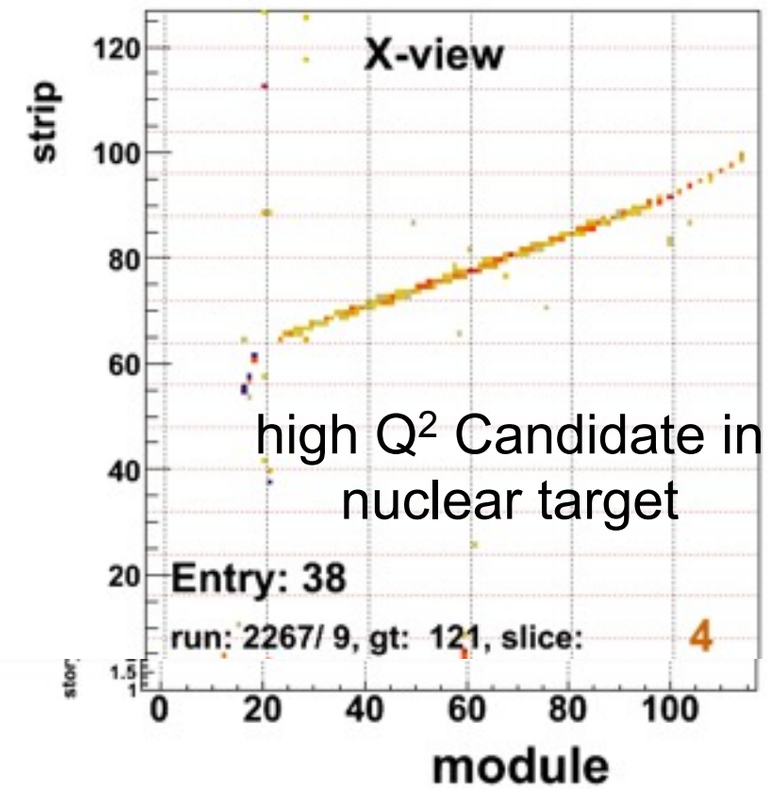


Summary and Conclusions

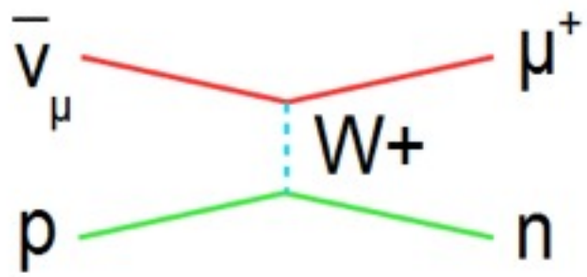
- Project design is nearing completion
- Project team is in the process of optimizing the schedule to determine the earliest technically driven completion date ; aiming for completion in 2013
- CD-2 review is planned for end of July
- Procurement of key elements (building, cryostat and cryogenic equipment) could begin in October if funding is available

MINERνA: Run Plan

- Goals of MINERνA:
  - Low Energy (LE) Beam
    - Exclusive final state reconstruction
      - Supports future oscillation experiments
    - Nuclear effects on exclusive final states
  - Medium Energy (ME) Beam in NOνA era
    - Inclusive scattering measurements
    - Nuclear Parton Distribution Functions
- Construction Project Reviewed & Approved for 4.9e20 POT LE Neutrino Beam, 12e20 in ME
  - MINERνA foresees using 20% of LE run for determining flux using "standard candle" exclusive processes
- LE Antineutrinos: A Mixed Bag for MINERνA
  - Samples will give us access to new measurements
  - But low rates, poor knowledge of flux, lack of 2-track elastic final state will compromise the physics output

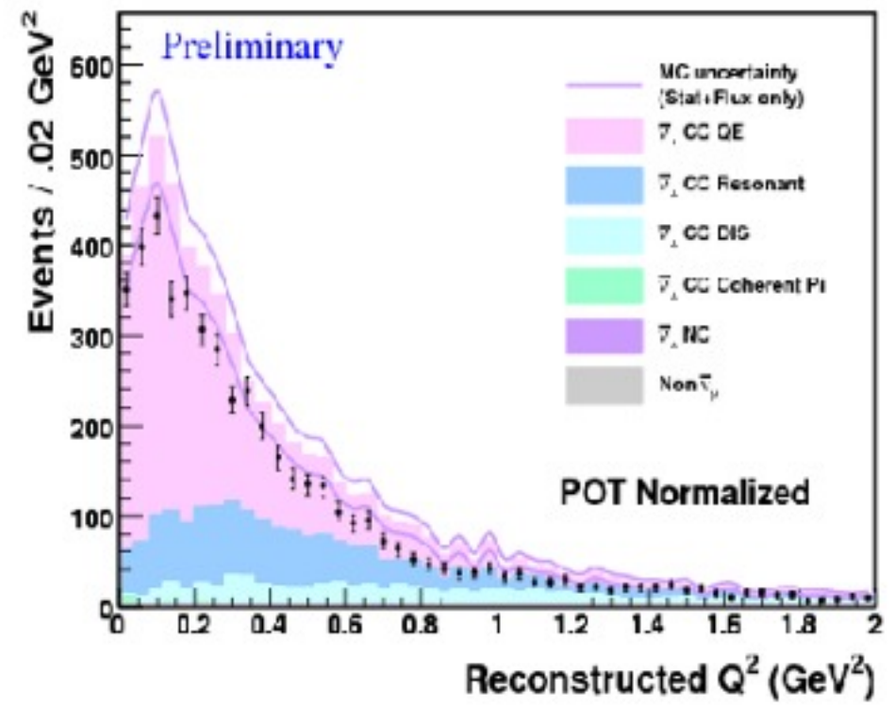


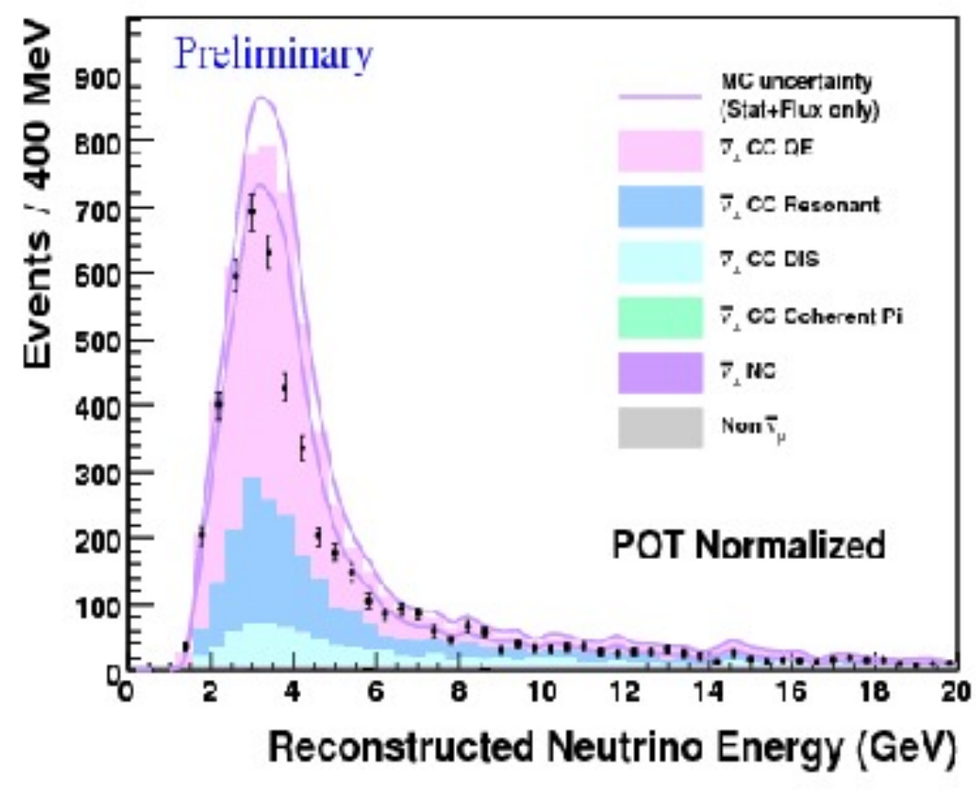
MINERνA: Quasi-Elastic Analysis



- Relatively Simple Final state
- Primary interaction type for neutrino oscillation experiments
- Measuring muon energy and angle (with rexpect to beam) completely reconstructs a quasi-elastic interaction:
  - neutrino energy
  - momentum transfer to nucleon (Q^2)
- Preliminary analysis of first half of anti-neutrino data taken during final detector construction period, represents about 1/15 of total data set in hand.
  - Band on plots shows current flux uncertainty

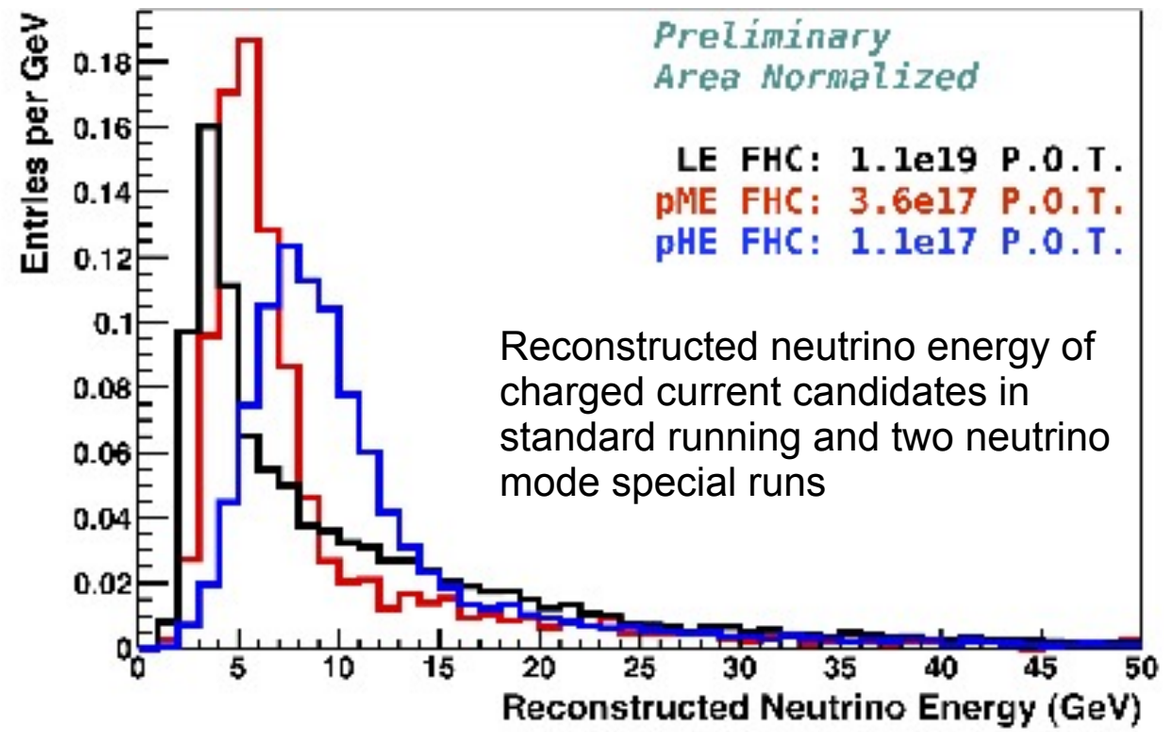
$$Q^2 = 2E^{QE}_{\bar{\nu}_\mu}(E_\mu - p_\mu \cos(\theta_\mu)) - m^2_\mu$$



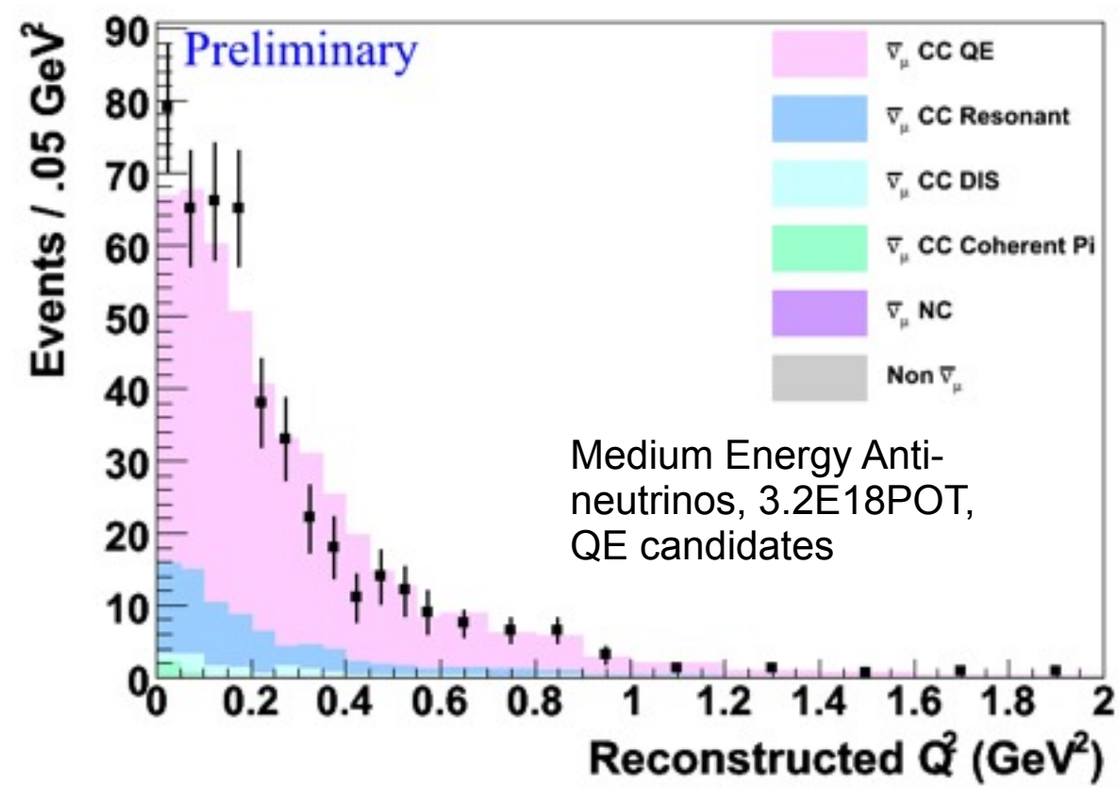


MINERνA: Special Run Status

- MINERvA developing tools to do flux studies with several standard candles
  - Inclusive Charged Current events
  - Quasi-Elastic Events
- Have taken 3 out of 6 run configurations, half statistics per run
  - Medium, High energy target positions
  - Horn off data
- Developing Data Reconstruction and Flux Tuning Infrastructure in parallel



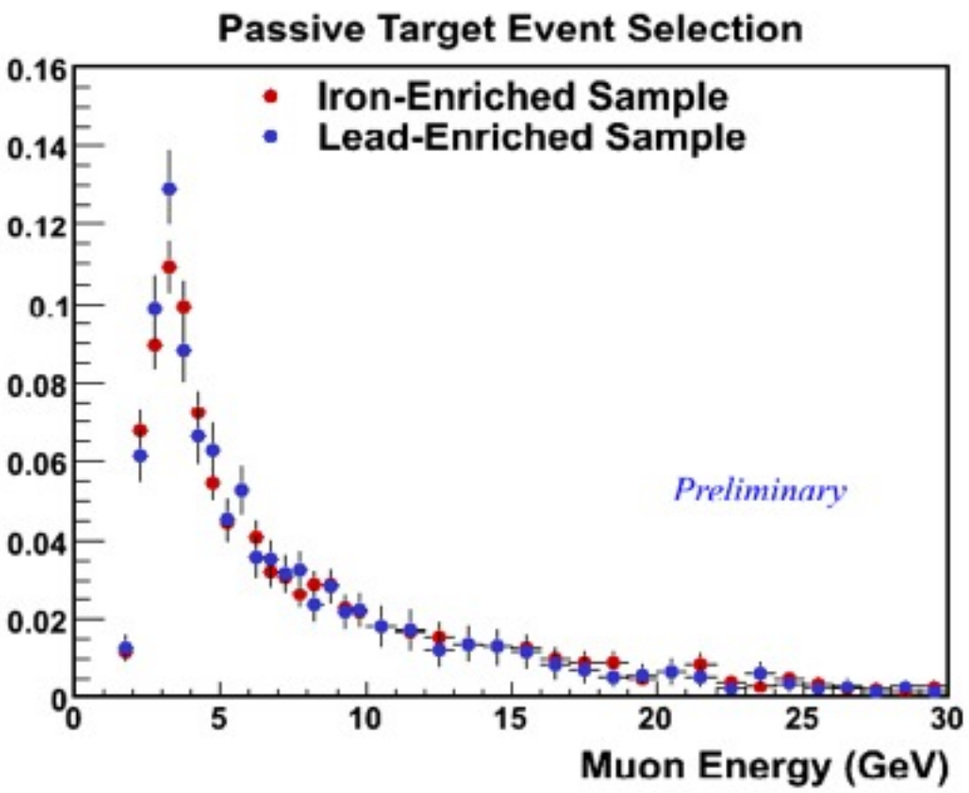
Reconstructed neutrino energy of charged current candidates in standard running and two neutrino mode special runs



Medium Energy Anti-neutrinos, 3.2E18POT, QE candidates

MINERνA: Nuclear Target Analysis

- MINERvA has 5 solid nuclear targets
  - Different thicknesses good for different analyses: most downstream target best for exclusive final state analyses
- First look at inclusive Charged Current (CC) events from Fe and Pb



First muon energy spectra in targets; ratios coming soon! Above for 1.3E20POT, target 5 (1/5 of sample)

Target	Fiducial Mass	ν_μ CC Events in 4E20 POT
Plastic	6.43 tons	1363k
Helium	0.25 tons	56k
Carbon	0.17 tons	36k
Water	0.39 tons	81k
Iron	0.97 tons	215k
Lead	0.98 tons	228k

Proposal to add Deuterium to the cryogenic target: See this afternoon's talk

What about a LAr Target?

Summary and Conclusions:

NuSM

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- microBooNE will address the low energy miniBooNE excess seen in neutrino running
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SM Nu physics (+Technology)

- Important for both NuSM and Beyond NuSM