Fermilab Neutrino Experiments Present & Future

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DOE Tevatron Operations Review

April 20/21 2007

Outline

- Introduction
- Neutrino Cross Sections & Flux
  - MINERνA
  - SciBooNE
  - MIPP (and HARP)
- Neutrino Oscillations
  - MiniBoone
  - MINOS
  - NOνA
  - Future Long Baseline Experiments : Report of FNAL-BNL Study
- Summary & Outlook

Introduction

- **Neutrinos** were invented in order to solve a **"mystery"** (energy non-conservation in beta decays)…

- Since their birth, they have created even more **mysteries** themselves …
  - **Solar neutrino "problem"** (ν_e's from the Sun are less than expected)
  - **Atmospheric neutrino "problem"** (ν_μ's from the atmosphere are less than expected)

- **The "problem" of missing neutrinos can be nicely explained if they posses non-degenerate masses, in which case they can oscillate between the different flavors: (Strong evidence from many experiments, SuperK, K2K, SNO,KAMLAND … indicate that this is the case)**
  - **3 active (LEP/SLC)**
  - **n sterile (After latest MiniBoone results sterile neutrinos highly disfavoured)**

Are there more questions to answer??

- Is there CP violation in the neutrino sector ?? (which might explain why we are here !!!)

- What is the value of the "third" mixing angle (the other two indicate nearly maximal mixing, the limit for the third indicates a pretty low value...) (Reactor experiments, NOVA, TZK)

Are there sterile neutrinos??? (MiniBoone)

What is after all, the neutrino MASS?? (absolute value not mass squared difference) (kinematics of beta decay)

$$\nu_{e(\mu)(\tau)} = \sum_{i=1}^{3} U^{*}_{e(\mu)(\tau)i}\,\nu_i$$

Atmospheric — Cross Mixing — Solar — 0νββ decays — Majorana phases

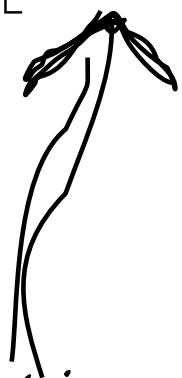
$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & -s_{23} \\ 0 & s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & -s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ s_{13}e^{-i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} e^{ia_1/2} & 0 & 0 \\ 0 & e^{ia_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Do "man made" νμ's oscillate?

- What is "precisely" the mass squared difference and the mixing angle? (K2K - MINOS)

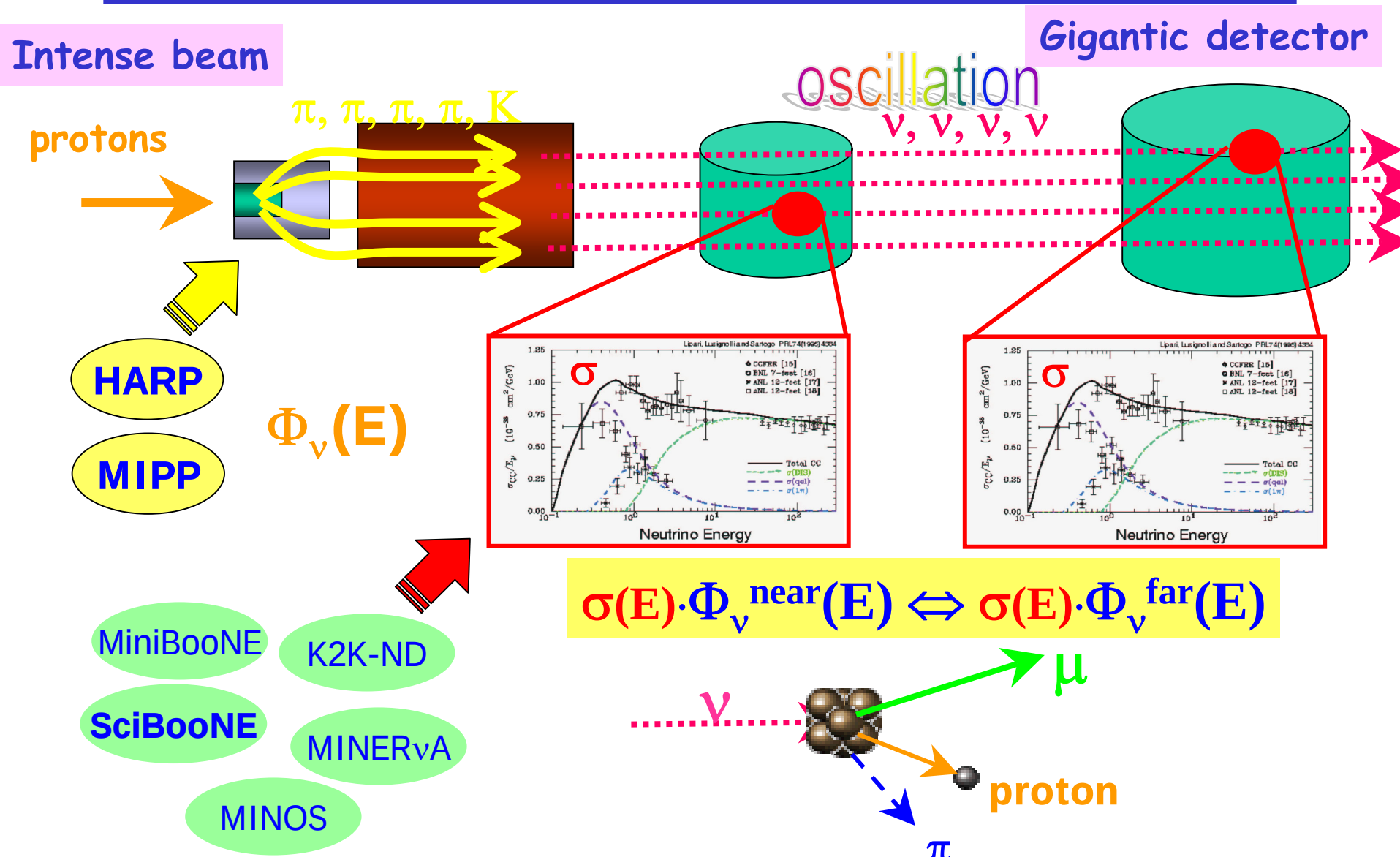
DO NOT FORGET

Which is the heaviest one? (NOVA, TZK)



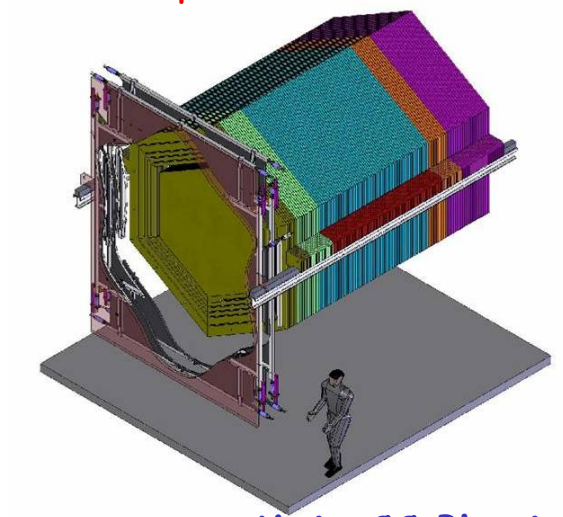
- Are neutrinos and anti neutrinos the same ?? (Majorana particles) (neutrino-less double beta decays)

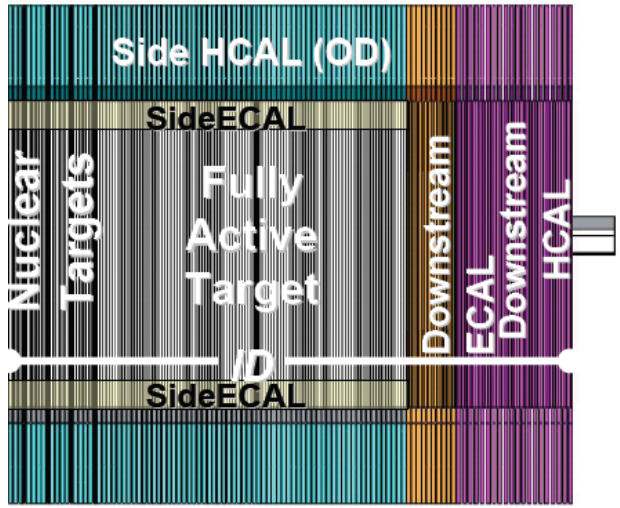
Accelerator ν Oscillation Measurements Require:



MINERvA

- MINERvA is a compact, fully active neutrino detector designed to study neutrino-nucleus interactions with unprecedented detail.



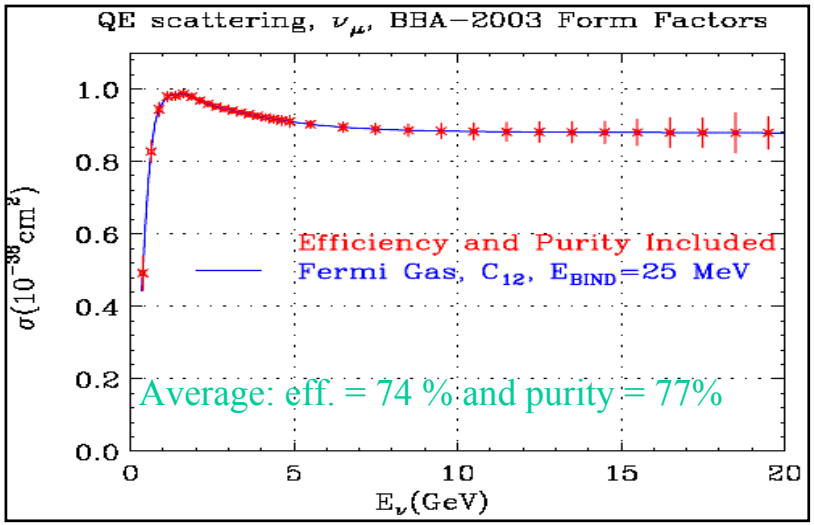


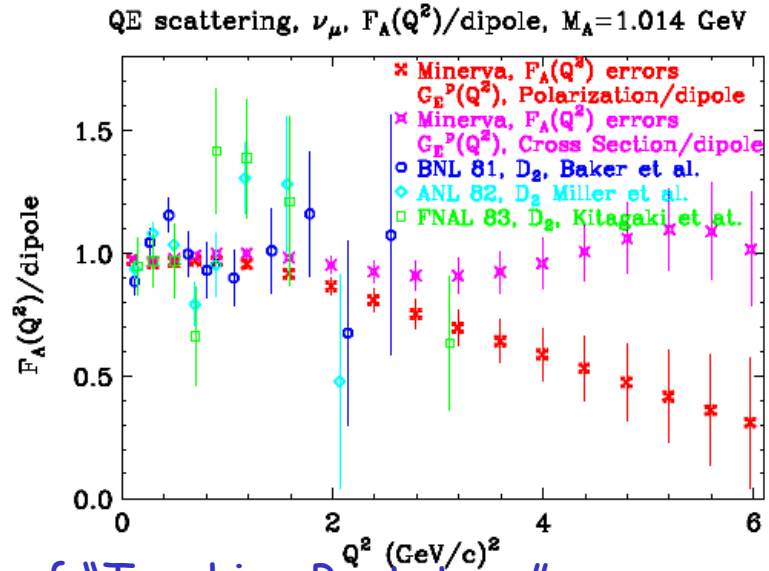
Main CC Physics Topics (Statistics in CH)

- Quasi-elastic — 0.8 M events
- Resonance Production — 1.7 M total
- Transition: Resonance to DIS — 2.1 M events
- DIS, Structure Funcs. and high-x PDFs — 4.3 M DIS events
- Coherent Pion Production — 89 K CC / 44 K NC
- Strange and Charm Particle Production — > 240 K fully reconstructed
- Generalized Parton Distributions — order 10 K events
- Nuclear Effects — He: 0.6 M, C: 0.4 M, Fe: 2.0 M and Pb: 2.5 M

Example : MINERvA CC Quasi-Elastic

Precision measurement of $\sigma(E_\nu)$ and $d\sigma/dQ$ important for neutrino oscillation studies.
Precision determination of axial vector form factor (F_A), particularly at high Q^2
Study of proton intra-nuclear scattering and their A-dependence (C, Fe and Pb targets)

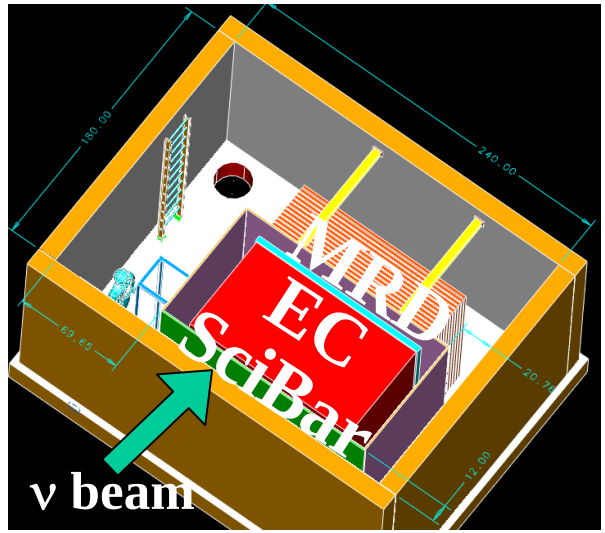




- Late 2007 – early 2008: Construction of "Tracking Prototype"
  - 20 detector modules
  - Will use to study tolerance stackup, tracking, etc.
- Late 2008 : Test beam detector taking data
- 2008-2009: Construction of full detector
- 2010 : Installation/commissioning of detector.

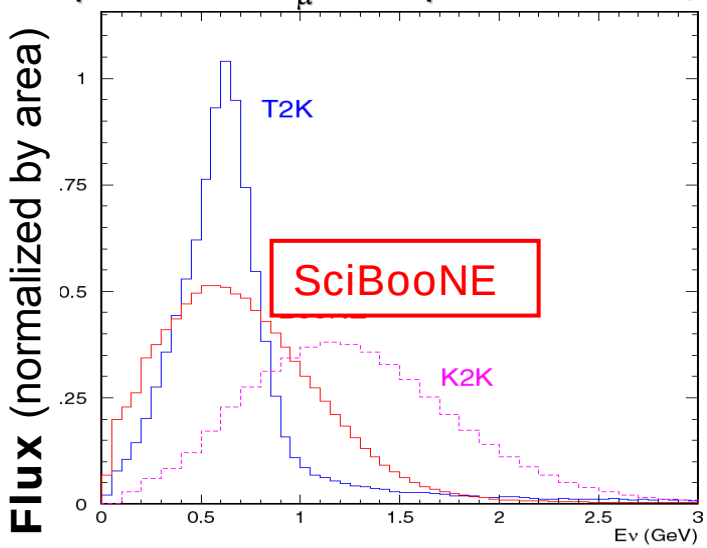
SciBooNE Detector

- SciBar Detector
  - From KEK, Japan
- Electron Catcher
  - From KEK, Japan (CHORUS Reused ECAL)
- Muon Range Detector (MRD)
  - Being built at FNAL from old fixed-target parts (FNAL-E605, KTeV, NuTeV).

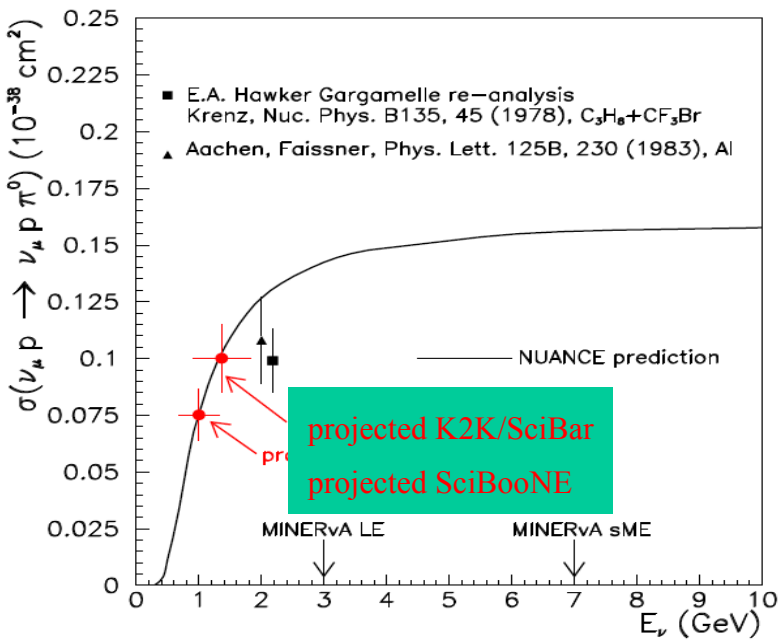


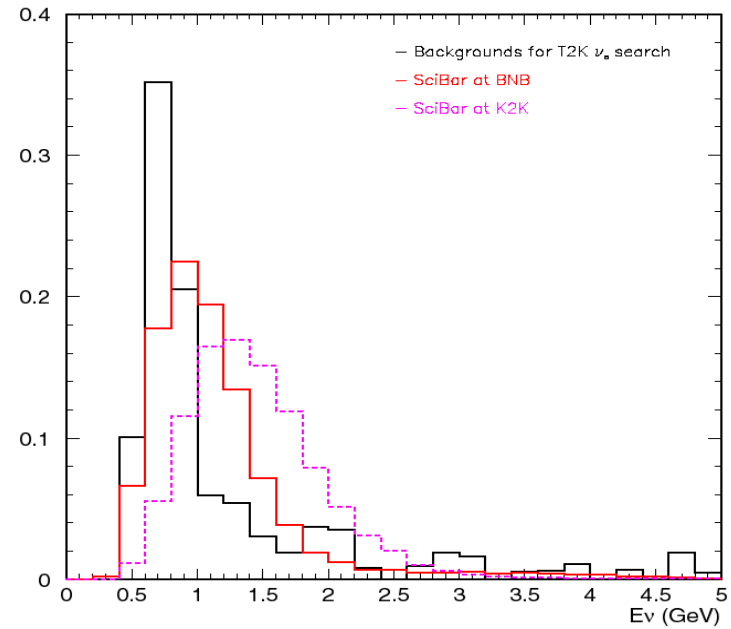
- Measurements
  - CC-1π cross section
  - CCQE s,M_A measurement
  - NC π^0 measurement
  - Search for CC coherent π
  - Search for NC coherent π^0

Comparison of ν_μ flux spectra at K2K, T2K



SciBooNE Example : NC1π^0





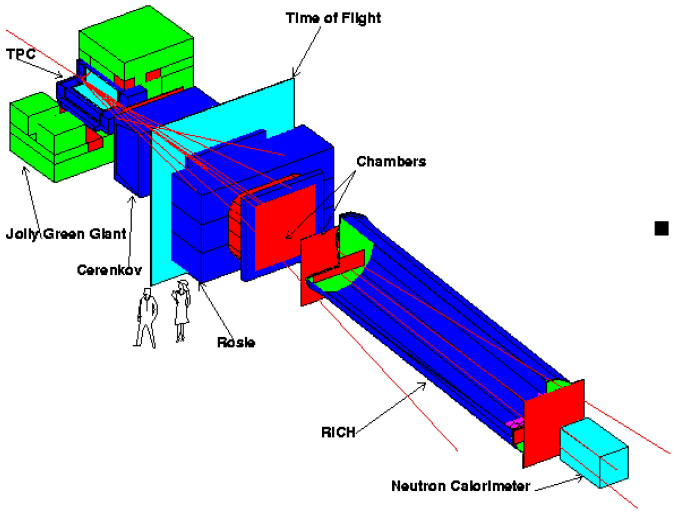
K. Hiraide

- Same detector used to measure NC1π^0 in two beams!
  - Map out σ_ν vs. E_ν
- Combined with MINERνA, great coverage of NC1π^0 induced BGs for T2K

Detector components are assembled in CDF hall (done!)

Will be installed in new SciBooNE detector hall soon

Neutrino Flux is Important : MIPP



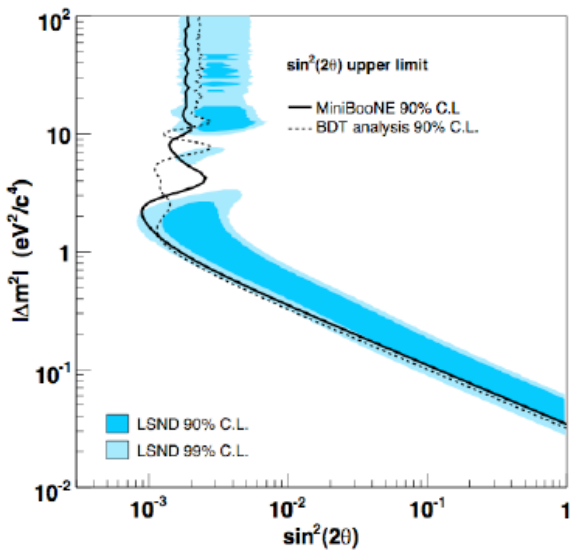
- Better knowledge of Neutrino Flux is important for all accelerator neutrino oscillation experiments (in order to reduce systematic uncertainties)

- Better knowledge of Neutrino Flux is also important for MINERvA , SciBooNE and in general all "Near Detectors" (MINOS included) that want to measure neutrino cross sections precisely (in order to also reduce systematic uncertainties for oscillation measurements)

- MIPP has taken 1.9M events with 120 GeV protons on the MINOS target (Results expected soon)
- MIPP has also taken 20, 58, and 120 GeV secondaries on thin carbon targets and will use them to "reconstruct" the MINOS (or any other carbon target)

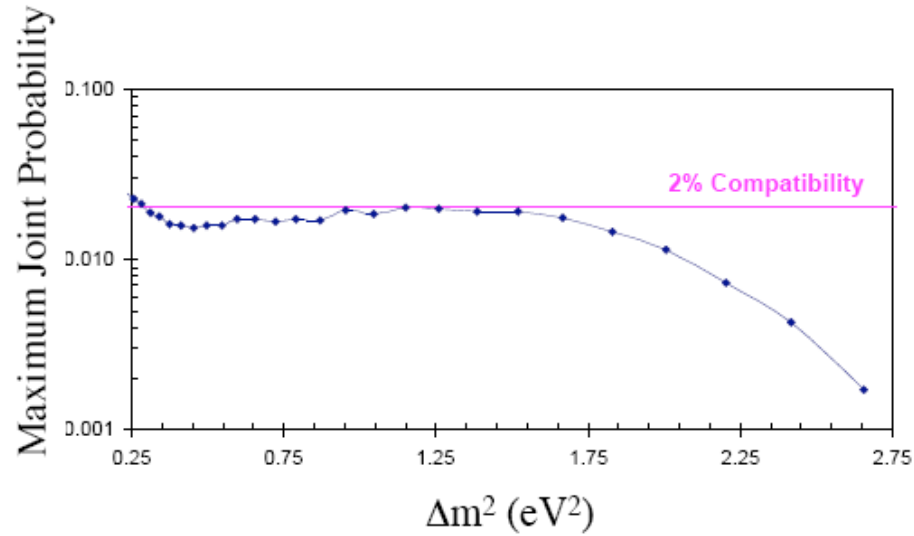
MiniBooNE @ a Glance

Boosted Decision Tree analysis shows no evidence for $\nu_\mu \rightarrow \nu_e$ appearance-only oscillations.



Energy-fit analysis:
solid: TB
dashed: BDT

Independent analyses are in good agreement.



MiniBooNE is incompatible with a $\nu_\mu \rightarrow \nu_e$ appearance only interpretation of LSND at 98% CL

More in Steve's Talk!

MINOS Experiment

MINOS is a two detector long baseline neutrino oscillation experiment.

- **Verify $\nu_\mu \rightarrow \nu_\tau$ mixing hypothesis** and make a precise (<10%) measurement of the oscillation parameters **Phys. Rev. Lett. 97 (2006) 19180**
- **Search for sub-dominant $\nu_\mu \rightarrow \nu_e$** oscillations (not yet seen at this mass-scale)
- Search for/rule out exotic phenomena:
  - Sterile neutrinos
  - Neutrino decay
- Use magnetized MINOS Far detector to study neutrino and anti-neutrino oscillations
  - Test of CPT violation
  - Atmospheric neutrino oscillations:
    First MINOS paper: Phys.Rev. D73 (2006) 072002 and hep-ex/070145

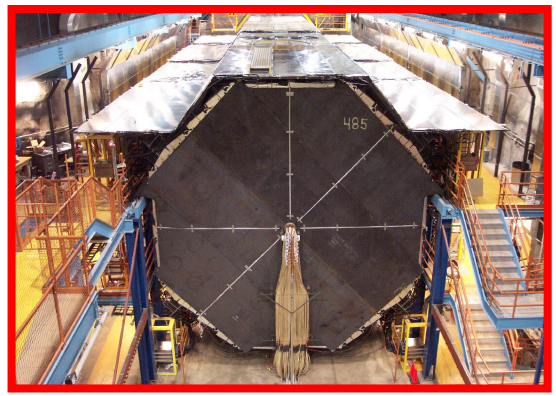
The MINOS Detectors

NEAR

0.98 kt

FAR

5.4kt



- **Basic Idea : Two detectors "identical" in all their important features.**

- Both detectors are tracking calorimeters composed of interleaved planes of steel and scintillator

  - 2.54 cm thick steel planes

  - 1 cm thick & 4.1 cm wide scintillator strips

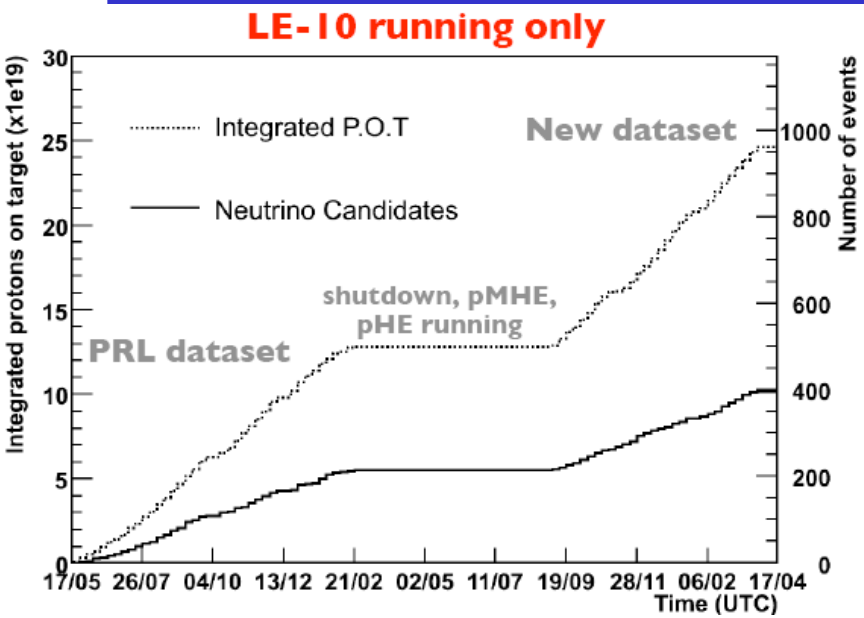
  - 1.5 T toroidal magnetic field.

  - Multi-Anode Hamamatsu PMTs (M16 Far & M64 Near)

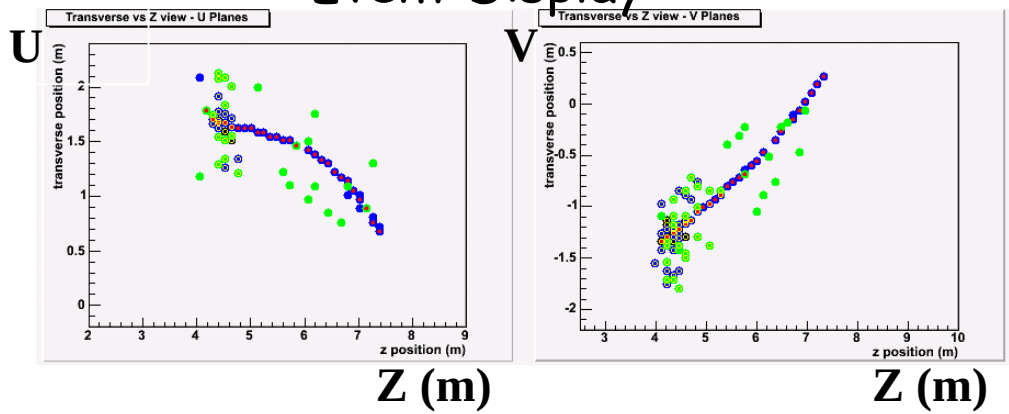
  - Energy resolution: 55%/√E for hadrons, 23%/√E for electrons (measured with Calibration detector at CERN)

  - Muon momentum resolution ~ 6 % from range (~ 12 % from curvature)

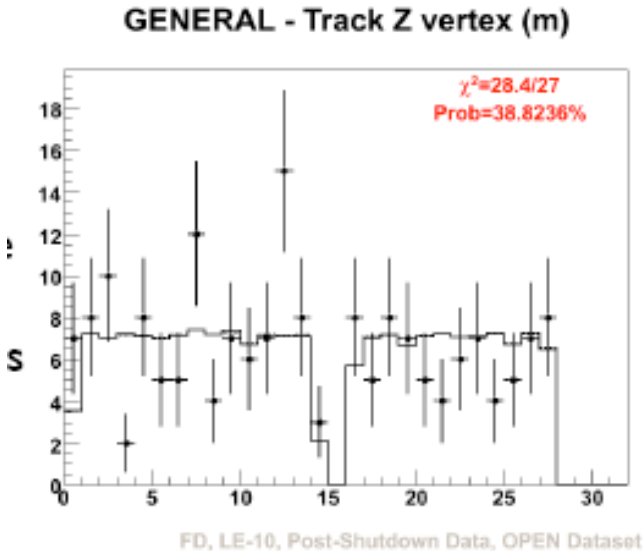
Far Detector Beam Data OPEN SET (old & new)

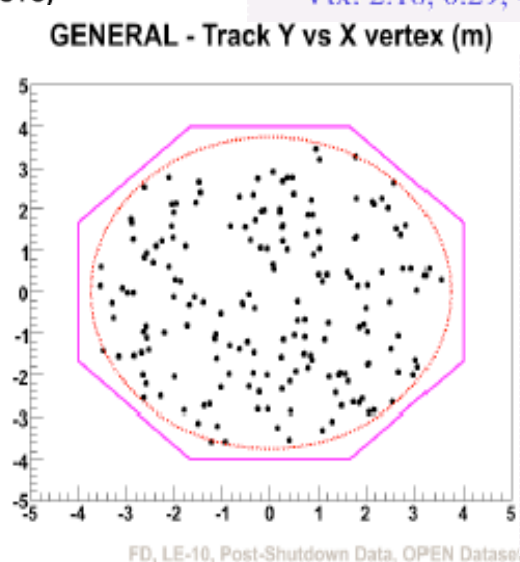


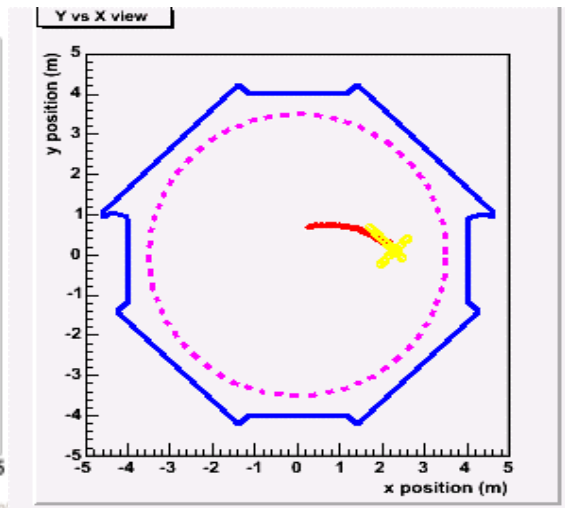
Event Display



q/p: -0.369 +/- 0.026, p/q: -2.708
TrkRangeEnergy: 2.481 RecoShwEnergy: 4.754
Vtx: 2.18, 0.29, 4.11



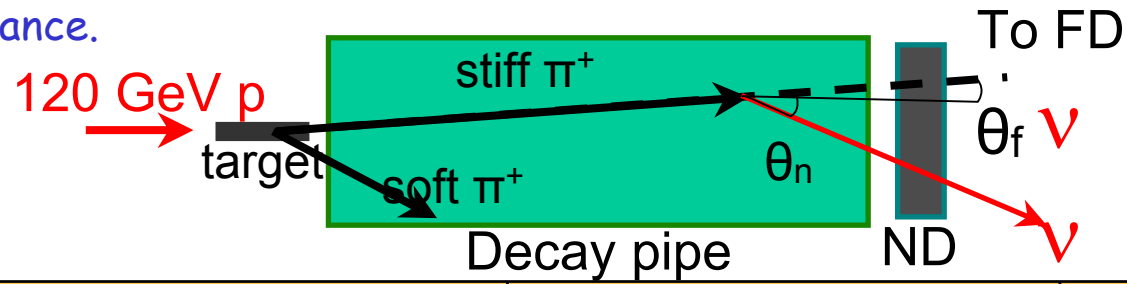




Predicting Unoscillated Far Detector Spectrum :

- Use the "Beam Matrix" method with which Beam modeling & Cross sections uncertainties cancel out between the two detectors.

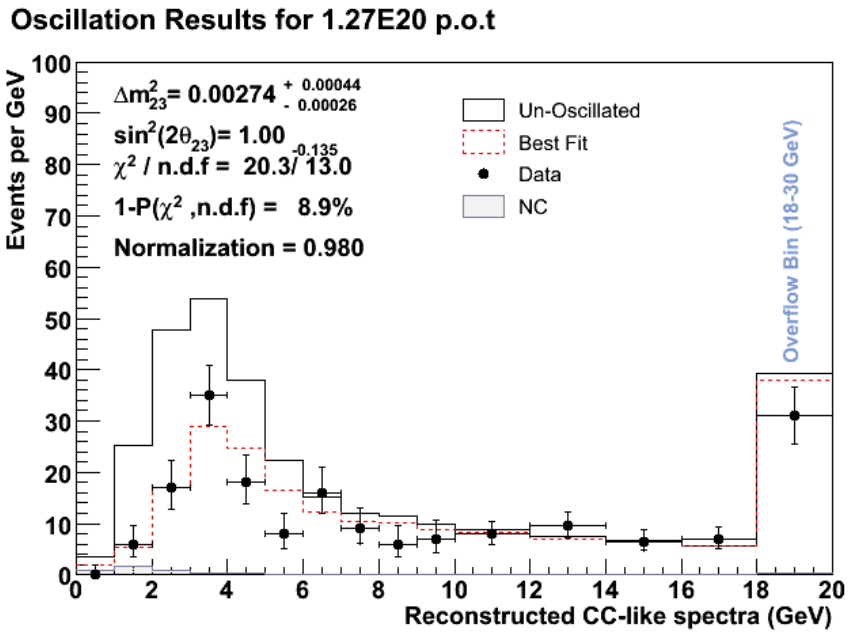
- The "Beam Matrix" method uses :
  - The ND Reconstructed Energy Distribution (Data),
  - The knowledge of pion 2 body decay kinematics & the geometry of our beamline
  - Our Monte Carlo to provide necessary small corrections due to energy smearing and acceptance.

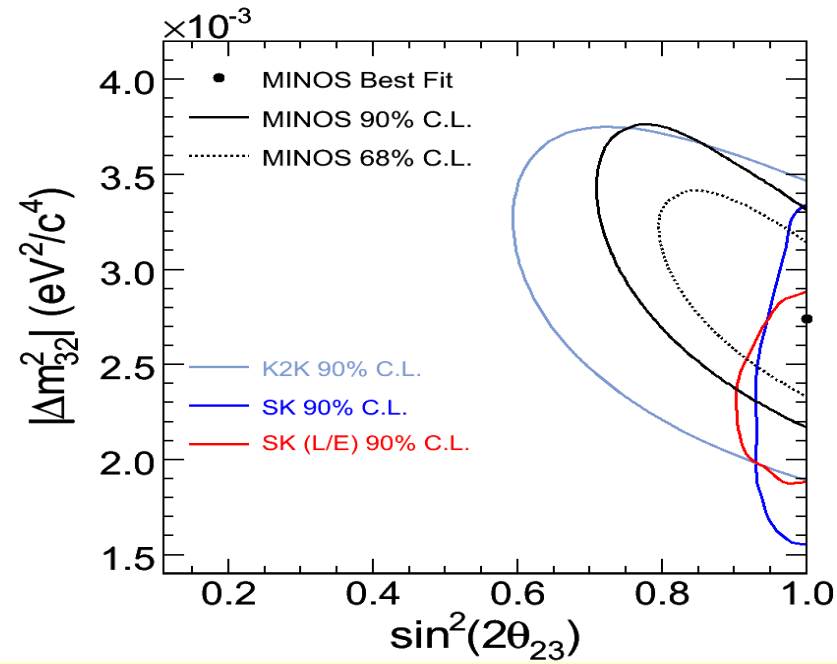


Uncertainty	Shift in Δm^2 (10^{-3} eV^2)	Shift in $\sin^2(2\theta)$
Near/Far normalization ±4%	0.050	0.005
Absolute hadronic energy scale ±11%	0.060	0.048
NC contamination ±50%	0.090	0.050 ←
All other systematic uncertainties	**0.044**	**0.011**
Total systematic	**0.130**	**0.070**
Statistical error (data)	**0.360**	**0.120**

FD CC_{like} Events: Best Fit Spectrum

$$\chi^2(\Delta m^2, \sin^2 2\theta, s_1, \ldots, s_{nsys}) = \sum_{i=1}^{nbins} 2(e_i - o_i) + 2o_i \ln(o_i / e_i) + \sum_{j=1}^{nsys} \Delta s_j^2 / \sigma_{s_j}^2$$

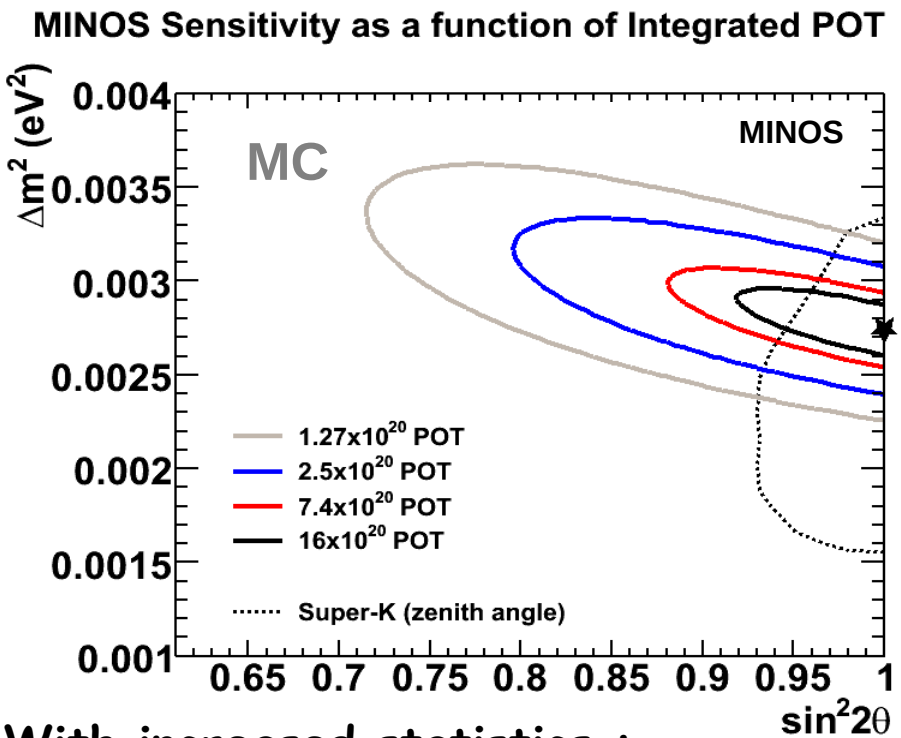




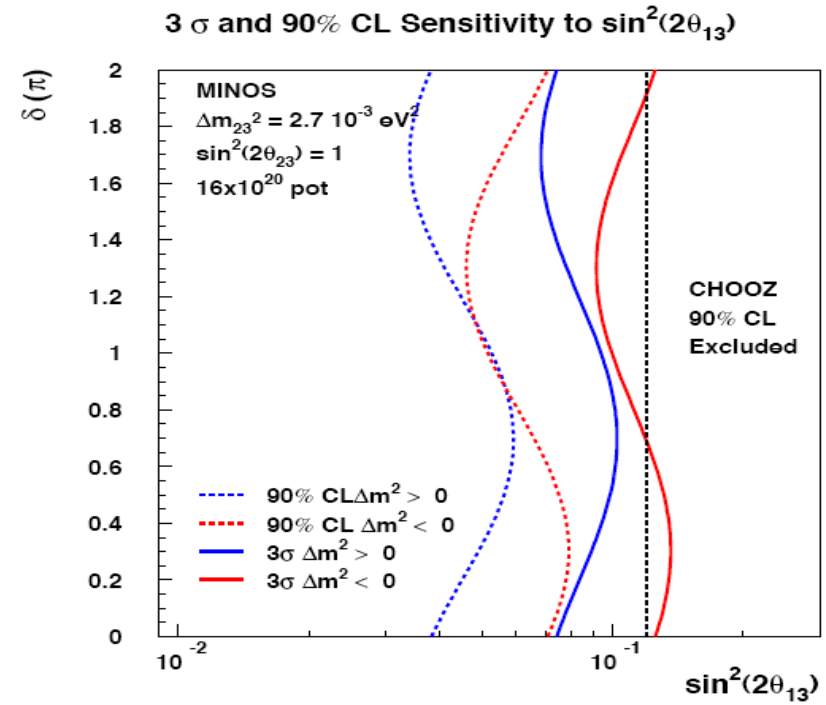
- Strong energy-dependent suppression of ν_μ events observed (**5.9 standard deviation effect below 5 GeV**)
- Consistent with the neutrino oscillation hypothesis
- **With more data, we can test and rule out alternative hypotheses, such as neutrino decay, which predict a different energy dependent suppression of the ν_μ rate**

Projected Sensitivity of MINOS

ν_μ disappearance



$\nu_\mu \rightarrow \nu_e$



- **With increased statistics :**

  -Improve precision on $|\Delta m_{32}^2|$ and $\sin^2(2\theta_{23})$ **and test/rule out alternate models such as neutrino decay.**

  - Could make first measurement on θ_{13} or improve current best limit set by CHOOZ

MINOS Physics Analyses

- ν_μCC disappearance : Δm^2_{32} and $\sin^2(2\theta_{23})$
  - An updated analysis will be presented this summer with a factor of two larger exposure
- Neutral Currents : Set limits on $f_{sterile}$
  - Collaboration has blessed the "ND" NC spectrum
  - Plan 1st "box opening" this summer
- Electron neutrinos
  - ν_e search will see a signal if θ_{13} is around the Chooz limit
- Beam ν_μ-bar
  - Measure oscillations -> Limits on CPT invariance
- Atmospheric neutrinos (ν + ν-bar + ν_e)
  - ν-induced muon events + contained vertex events (1st results on 2-3 years of exposure)
  - Now doing a combined analysis
  - Doubled statistics in ~ 3years
- Cosmic rays (13/sec Near; 1/2sec Far)
  - Charge sign, seasonal variations, moon/sun shadow
- Near Detector Physics
  - Millions of events in a broad band beam
  - Cross sections : ν + ν-bar + ν_e

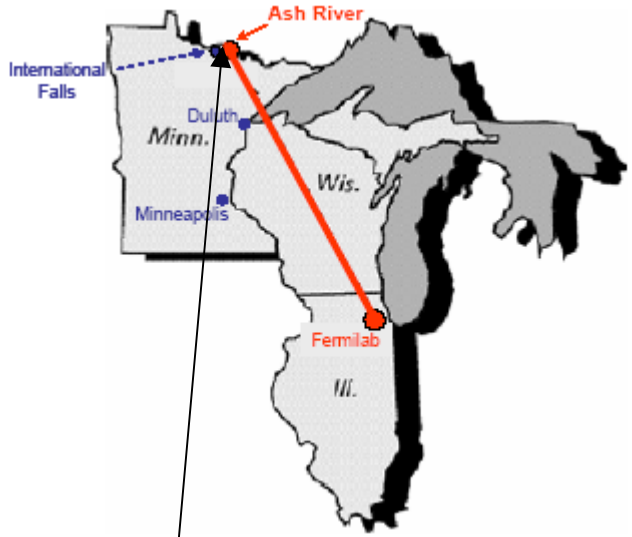
NOνA

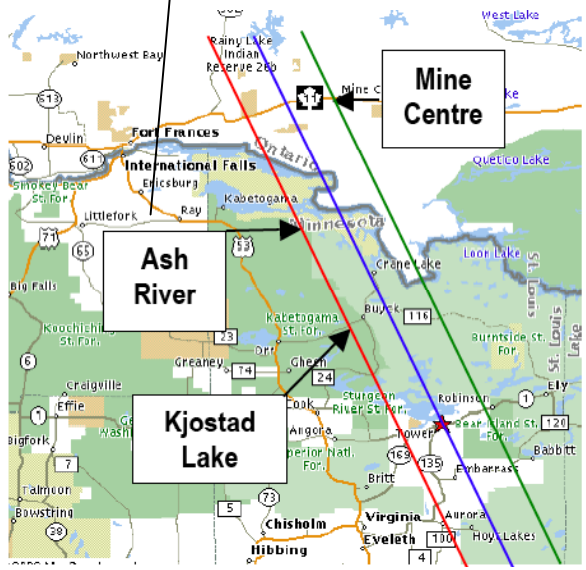
- NOνA is an approved Fermilab experiment optimized for measuring ν_e appearance with the goal of improving MINOS $\nu_\mu \rightarrow \nu_e$ measurement by approximately an order of magnitude.

- The NOνA far detector will be
  - a 20 kT "totally active" liquid scintillator detector
  - located 15 mrad (12 km) off the NuMI beamline axis near Ash River, MN, 810 km from Fermilab

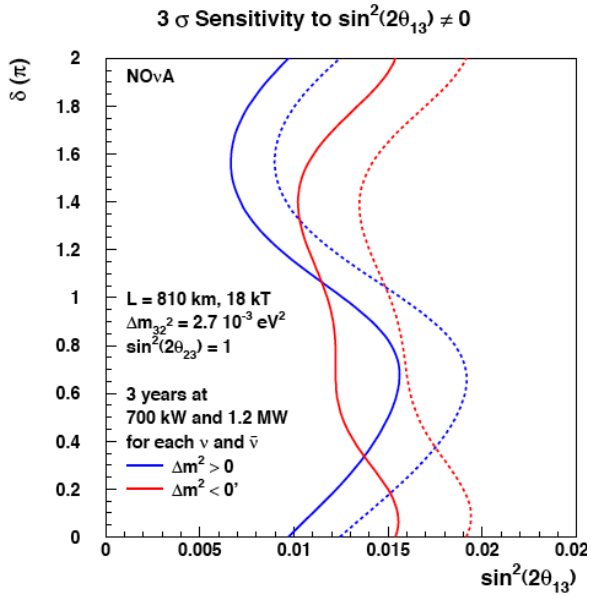
  More in Ron's talk

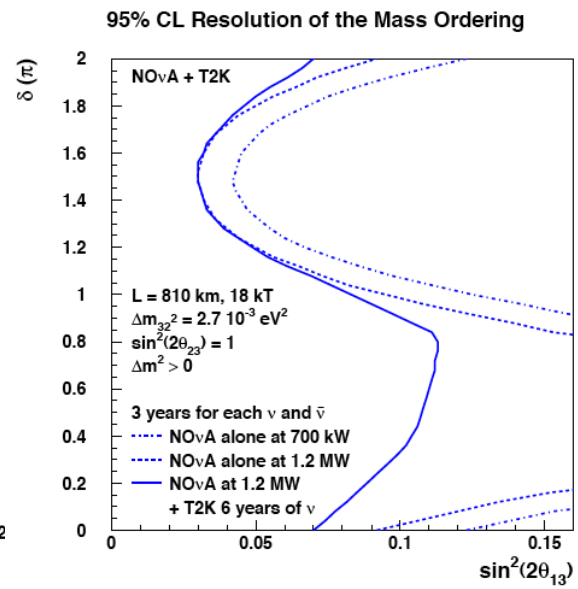
- Depending on the value of the third mixing angle NOνA can determine the neutrino mass hierarchy (normal or inverted)

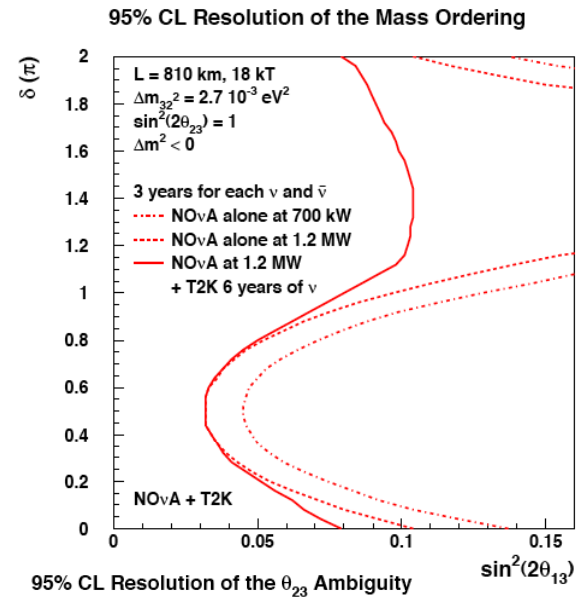


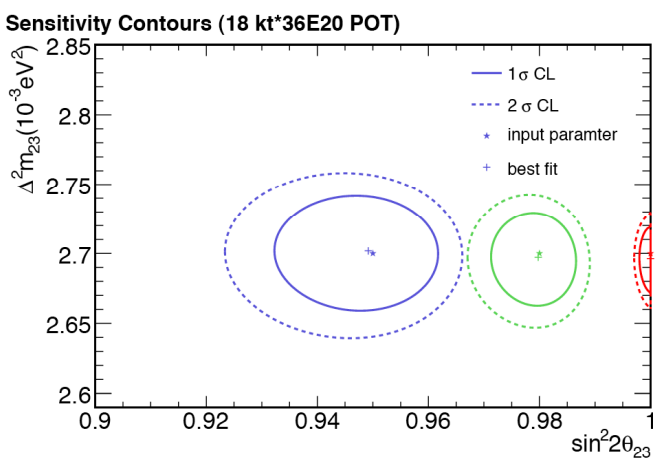


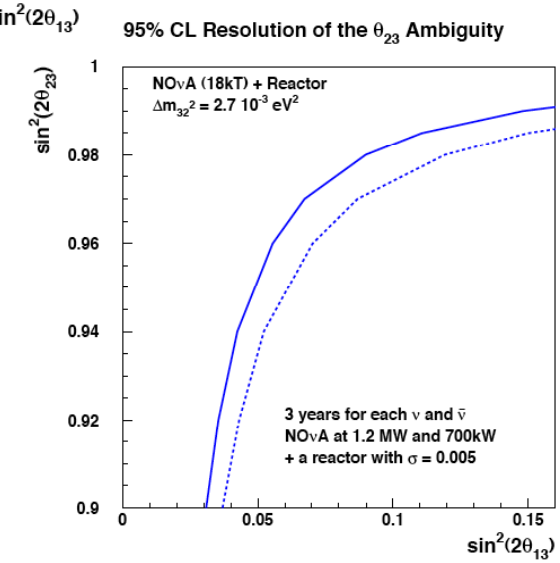
NOvA Physics Reach : $\nu_\mu \to \nu_e$ & $\nu_\mu \not\to \nu_\mu$







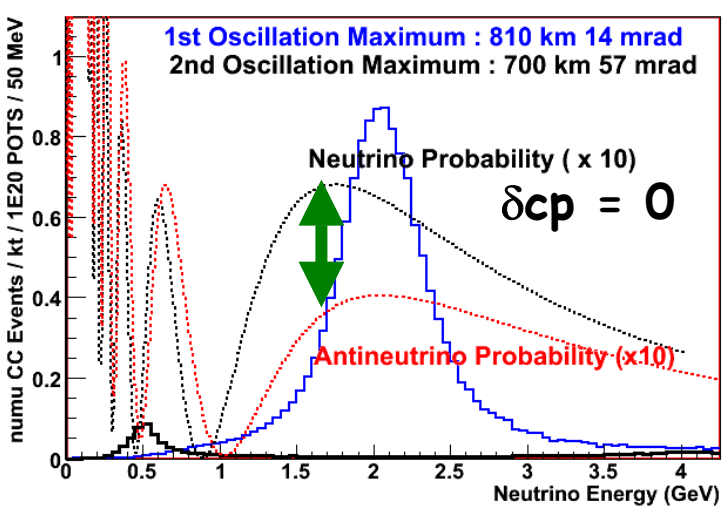


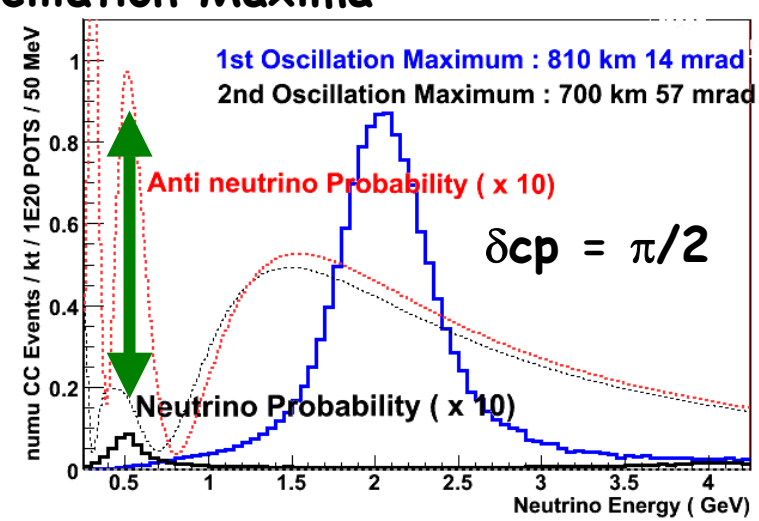


Future ν Oscillation Experiments
using the NUMI (off-axis) Beam

- **Phase II : Develop a Plan based on Phase I Results (NOvA, T2K, Double-Chooz & Daya Bay will inform us of $\sin^2 2\theta_{13}$ down to ~0.02 by ~ 2012-2014).**
- We have explored and studied indicative configurations of detectors (and detector masses), off axis locations and protons on target (beam power).
- Off Axis Beam is a **Narrow Band Beam** but if we choose to place **2 detectors @ different off axis angles we get an off - axis "Pseudo - Wide Band Beam"** Optimization studies are performed placing Detectors @ both Locations.

1st & 2nd Oscillation Maxima





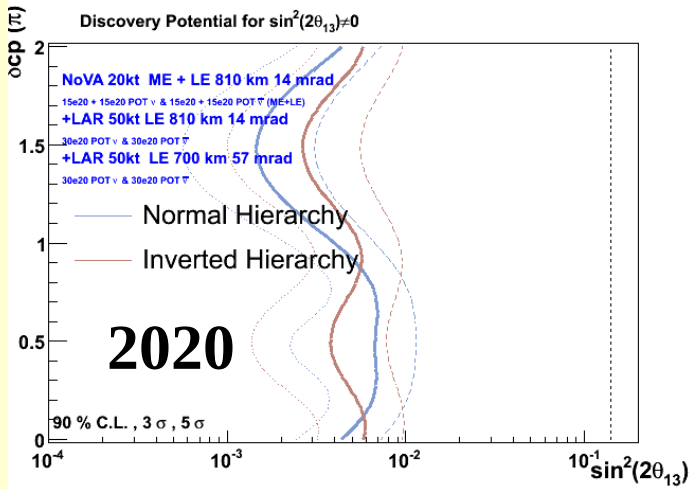
Phase II:Phase I says 0.02 < $\sin^2 2\theta_{13}$< 0.05

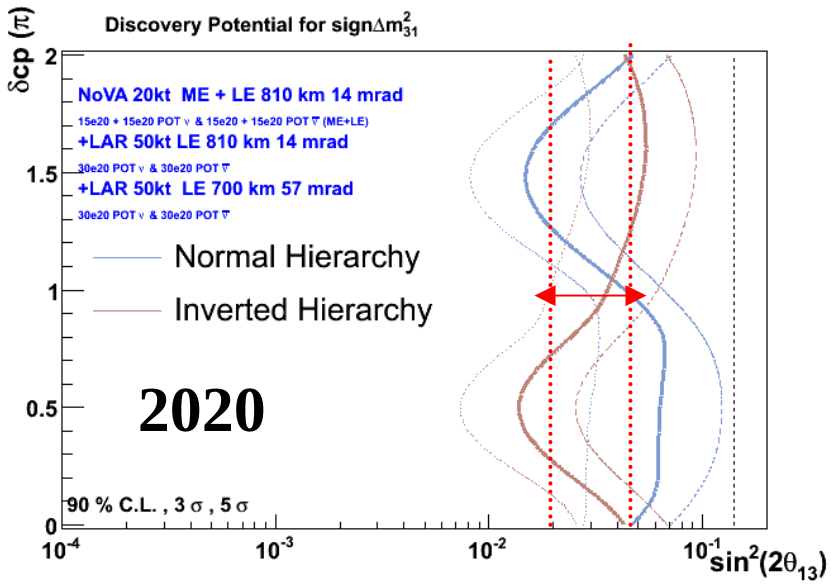
Consider the following scenario :

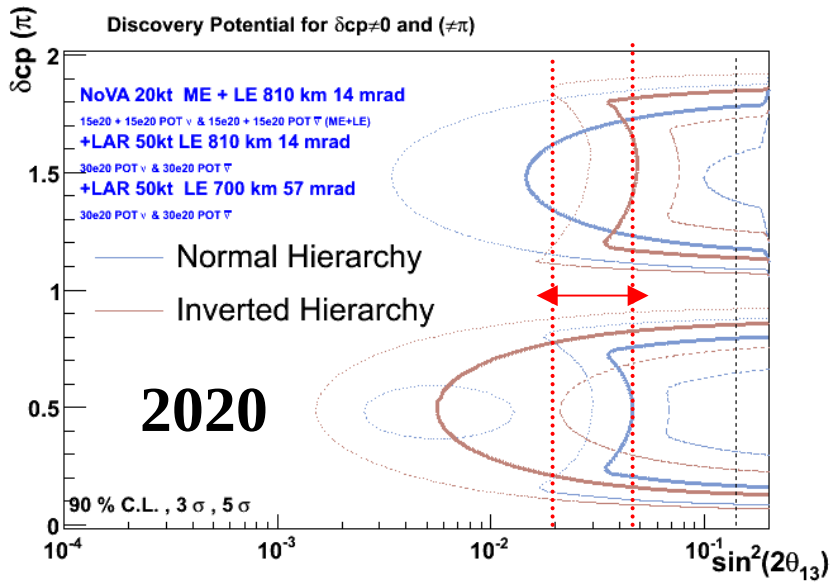
<u>Switch to Low Energy Running</u>

1) Place 50 kT of LAR at the 1st oscillation Maximum (810 km 14 mrad, matter effects important)

2) Place 50 kT of LAR at the 2nd oscillation Maximum (700 km 57 mrad, matter effects not important)







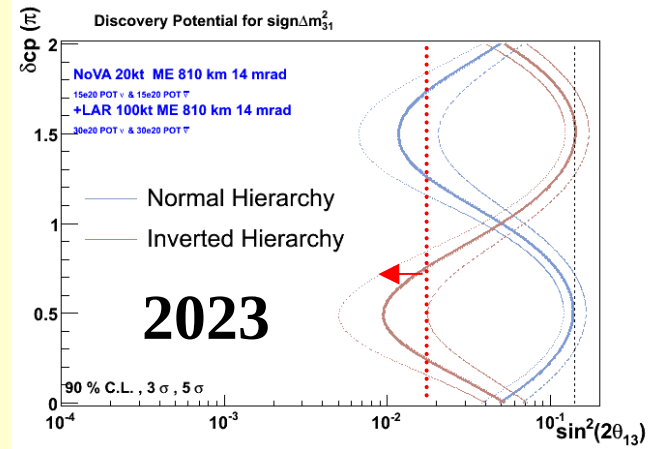
Phase II: Phase I says $\sin^2 2\theta_{13} < 0.02$

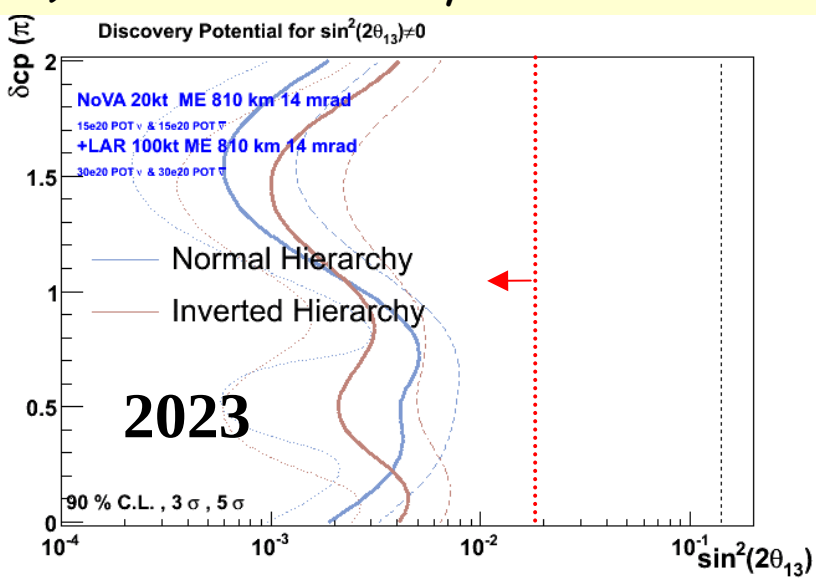
Consider the following scenario:

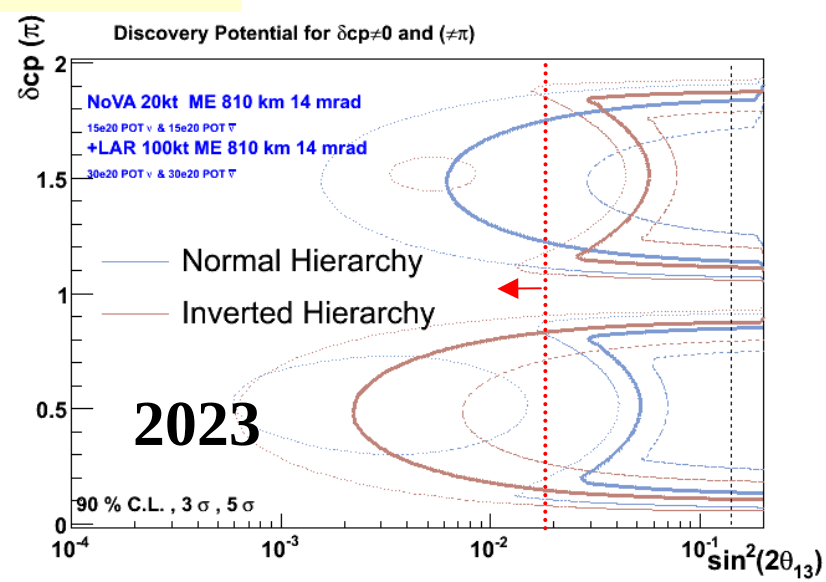
- Try to push the θ_{13} limit further and measure CP violation with existing NuMI Beam and 100 kT LAR Detector at the 1st Maximum (ME beam)
- Or consider other options :

a) New beam and longer baselines (the Protons on target needed and the construction time lead to approximately the same time ~ 2023)

b) Neutrino Factory etc…







Summary & Outlook

- So far the behavior of the "little neutral one" has been full of many "big" surprises.
- Some of the questions in neutrino physics have been answered, but the remaining ones are perhaps more challenging.
- Fermilab has a broad neutrino program aiming to address many of these remaining important issues with respect to neutrino physics and neutrino oscillations:

Neutrino Cross Sections (and Neutrino Flux)

MINERvA
SciBooNE
(MIPP)

Neutrino Oscillations

MINOS
MiniBooNE
NOvA
Study of future plans (FNAL-BNL Joint Study) reporting this spring