



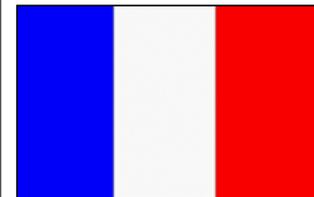
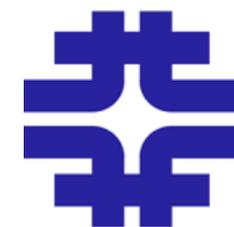
# Status of Running Neutrino Experiments

MINOS, MiniBooNE, SciBooNE, ArgoNeuT

Brian Rebel  
Fermilab  
March 5, 2009



# MINOS



Argonne - Athens - Benedictine - Brookhaven - Caltech - Cambridge - Campinas - Fermilab - Harvard - Holy Cross - IIT - Indiana - Minnesota-Twin Cities - Minnesota-Duluth - Otterbein - Oxford - Pittsburgh - Rutherford - Sao Paulo - South Carolina - Stanford - Sussex - Texas A&M - Texas-Austin - Tufts - UCL - Warsaw - William & Mary

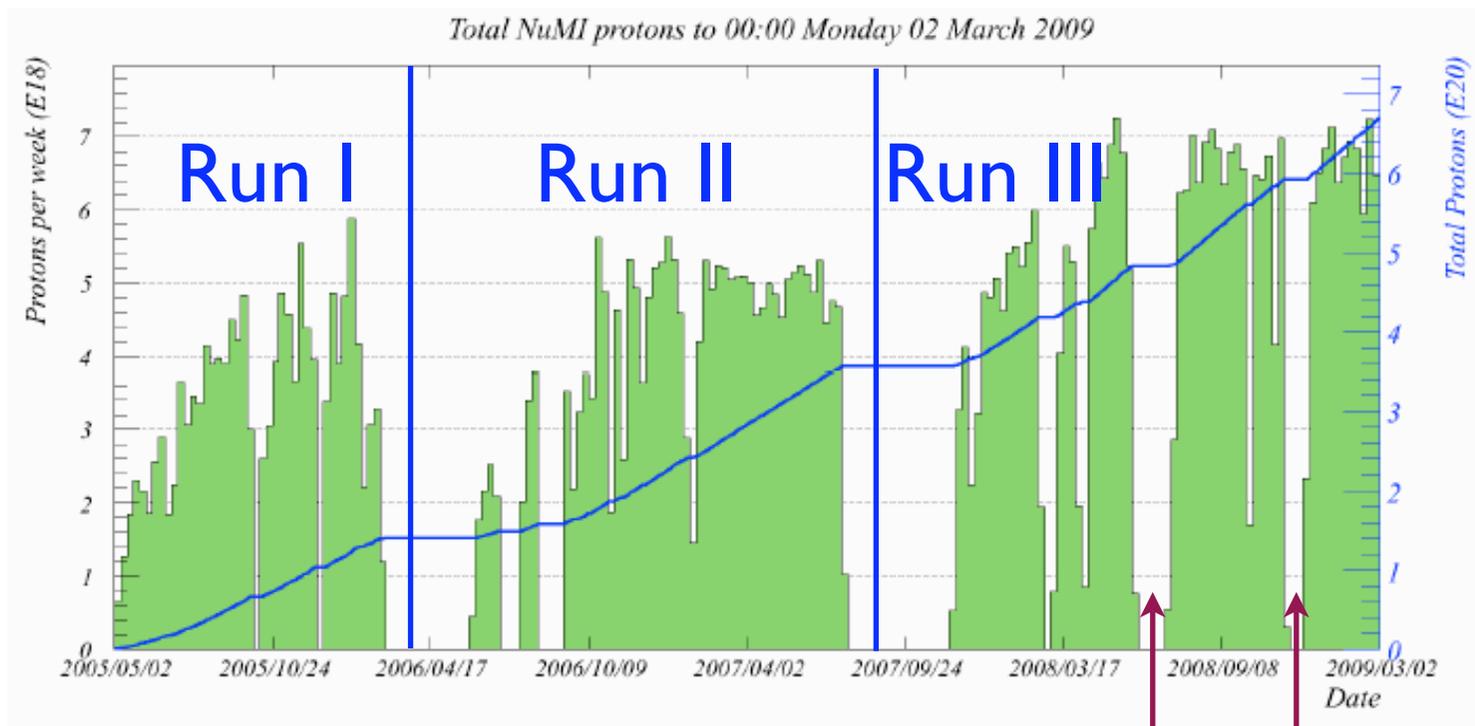
28 institutions, 140 scientists

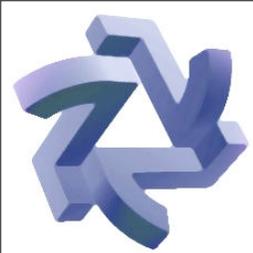


# NuMI Beam Performance



- Passed milestone: total mass of protons delivered  $> 1$  mg
- Fairly stable beam delivered for last quarter
  - $> 6 \times 10^{18}$  POT delivered most weeks
  - $\sim 1$  month down town time because of horn failure
- $6.8 \times 10^{20}$  POT delivered since May 2005, expect to have  $> 7.0 \times 10^{20}$  POT by June shutdown

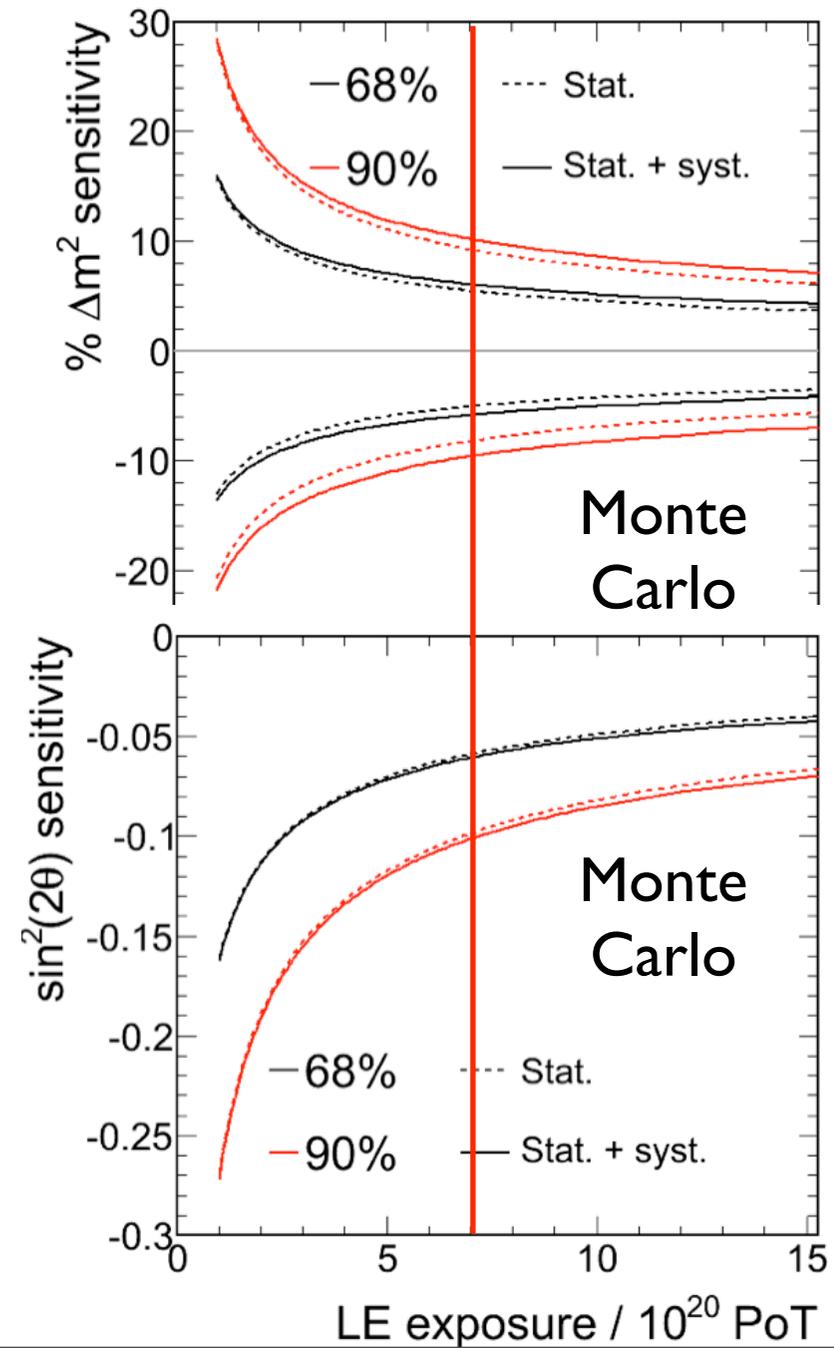




# Charged Current Analysis

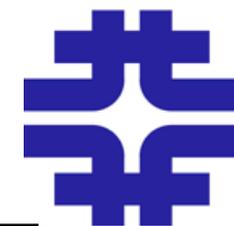


- Next CC result will be based on  $7.0 \times 10^{20}$  POT
- Will include rock  $\mu$  and anti- $\nu_\mu$  along with fiducial  $\nu_\mu$  events
- Plots show how sensitivity in  $\Delta m^2$  and  $\sin^2(2\theta)$  change with increasing exposure
- Smaller incremental changes in 90% contours for exposures  $> \sim 7 \times 10^{20}$  POT
- Plan to release results next year

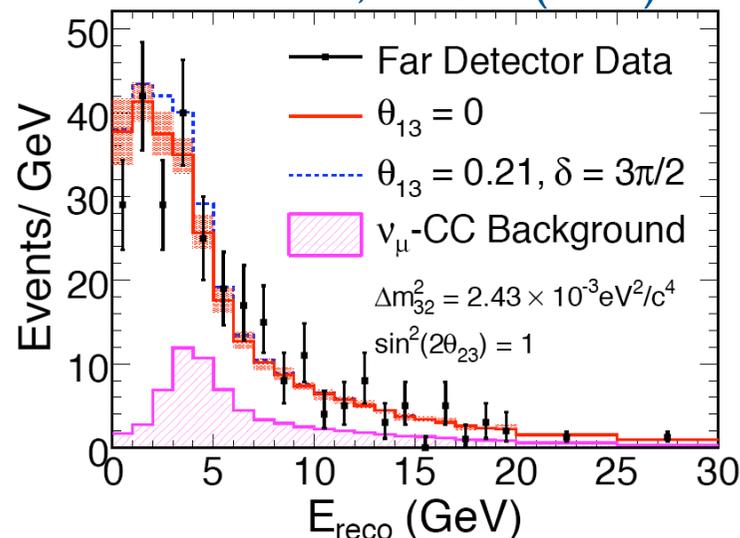




# Neutral Current Analysis



PRL 101, 221804 (2008)



$$f_s \equiv \frac{P_{\nu_\mu \rightarrow \nu_s}}{1 - P_{\nu_\mu \rightarrow \nu_\mu}} < 0.68 \text{ (90\% CL)}$$

$\nu_4$

Possible 4v model to be tested in  $3.2 \times 10^{20}$  POT analysis

$\nu_3$

$\nu_2$

$\nu_1$

$\nu_e$   $\nu_\mu$   $\nu_\tau$   $\nu_s$

$\Delta m^2_{43}$

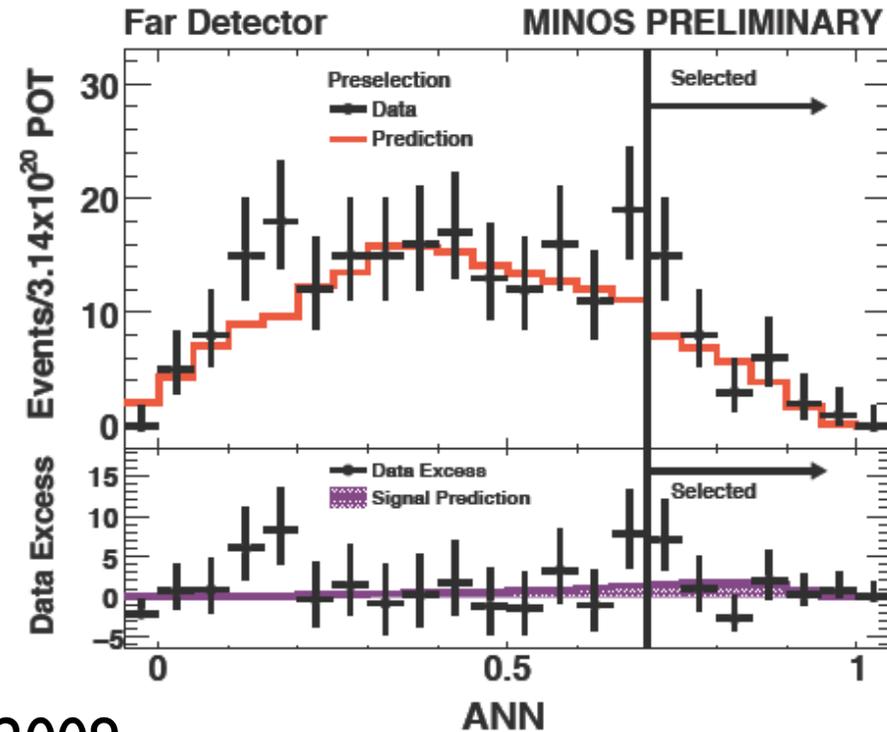
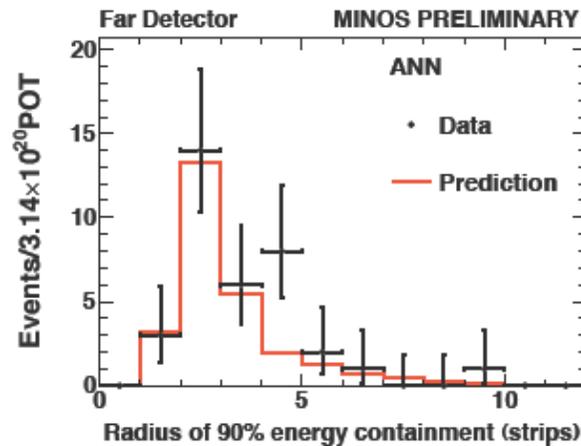
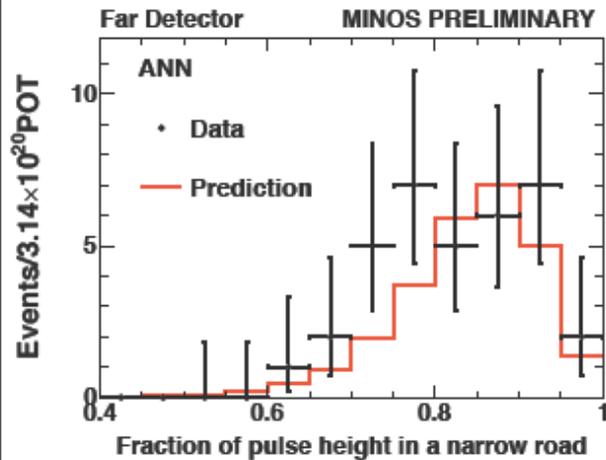
$\Delta m^2_{\text{atm}}$

$\Delta m^2_{\text{sol}}$

- First NC result published in PRL in November,  $2.4 \times 10^{20}$  POT exposure
- Next result to be based on moderately enlarged exposure,  $3.2 \times 10^{20}$  POT
- Next result will be targeted for PRD, test several models for sterile  $\nu$  as well as admixture of decay and oscillations
- Box opening is imminent
- Final NC result will be based on  $7.0 \times 10^{20}$  POT, additional exposure does not significantly improve sensitivities



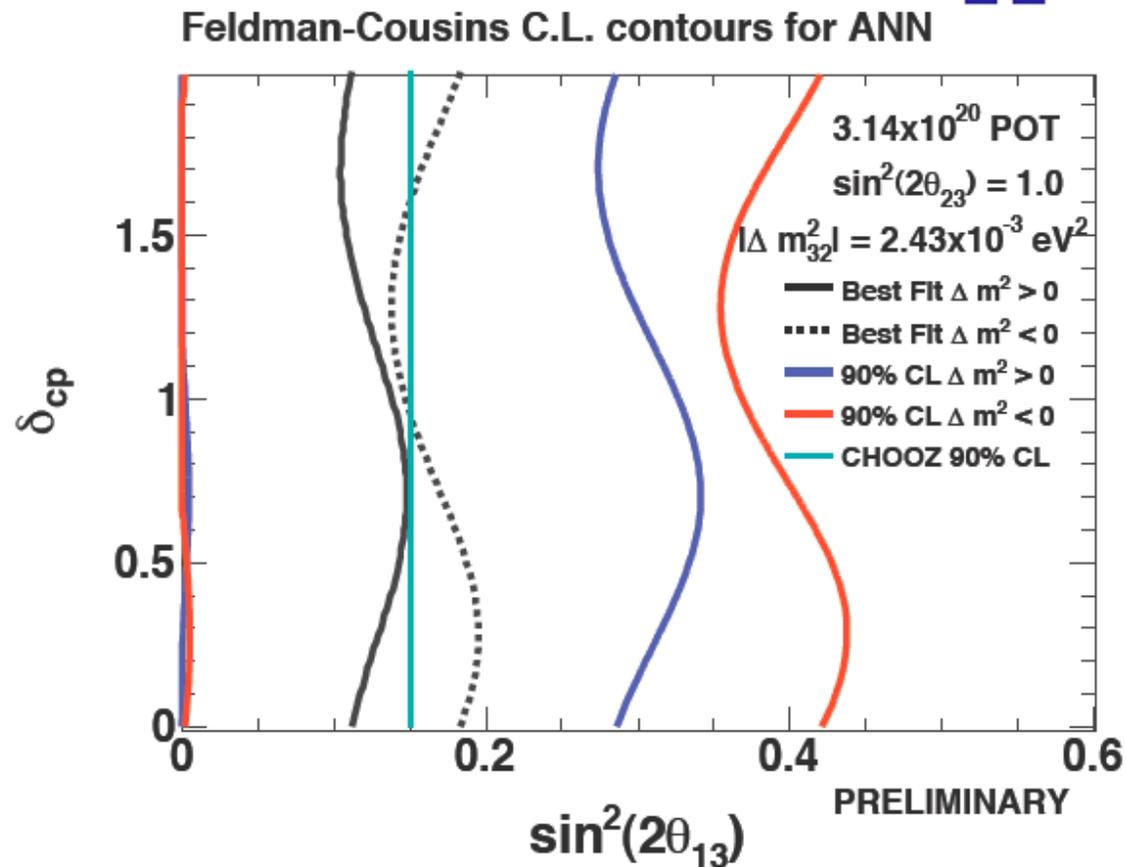
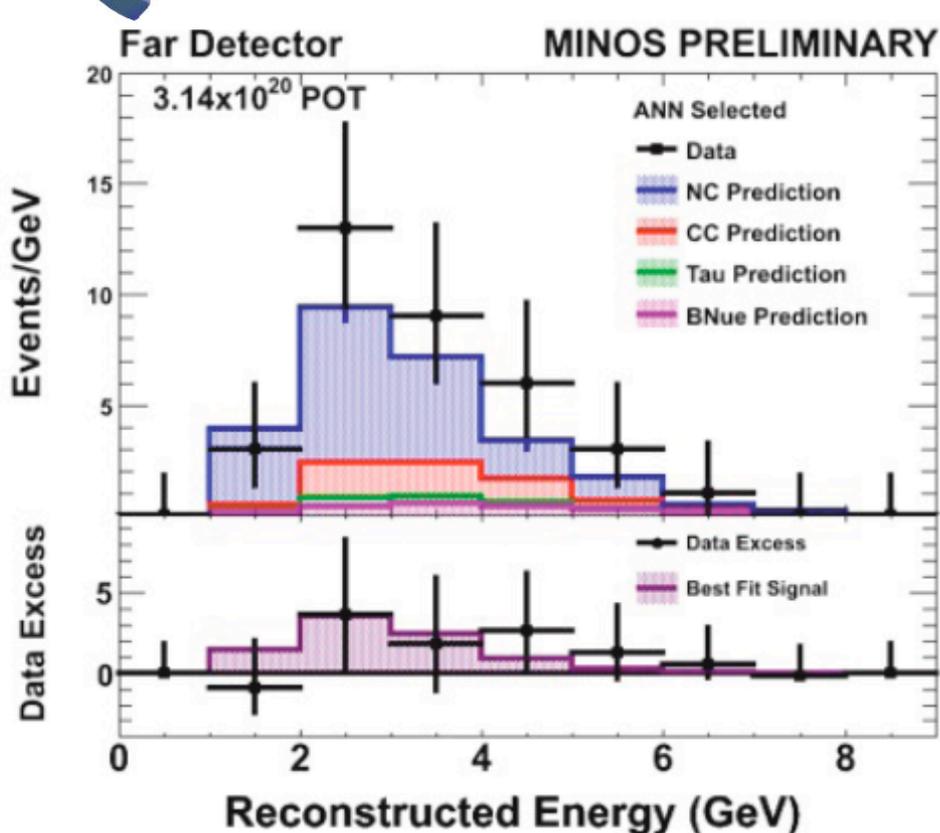
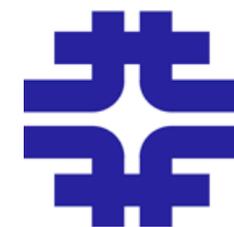
# $\nu_e$ Analysis



- $\nu_e$  results presented at W&C February 27, 2009
- $\nu_e$ -like events selected using an ANN which discriminates on electromagnetic shower-like parameters
- Far detector distributions of some input variables and ANN output shown
- Data and Monte Carlo expectation agree well



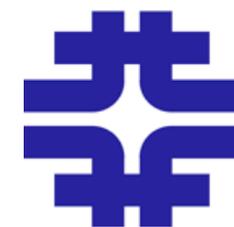
# $\nu_e$ Analysis



- Analysis is based on total number of observed events
- Observe 35 events, Monte Carlo predicts  $27 \pm 5(\text{stat}) \pm 2(\text{syst})$
- Best fit value of  $\theta_{13} \neq 0$ , near CHOOZ limit



# Publications from 2008



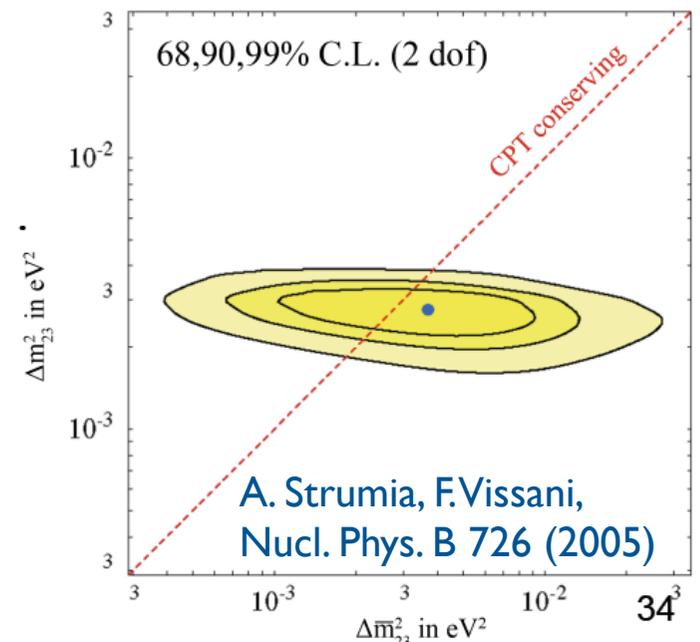
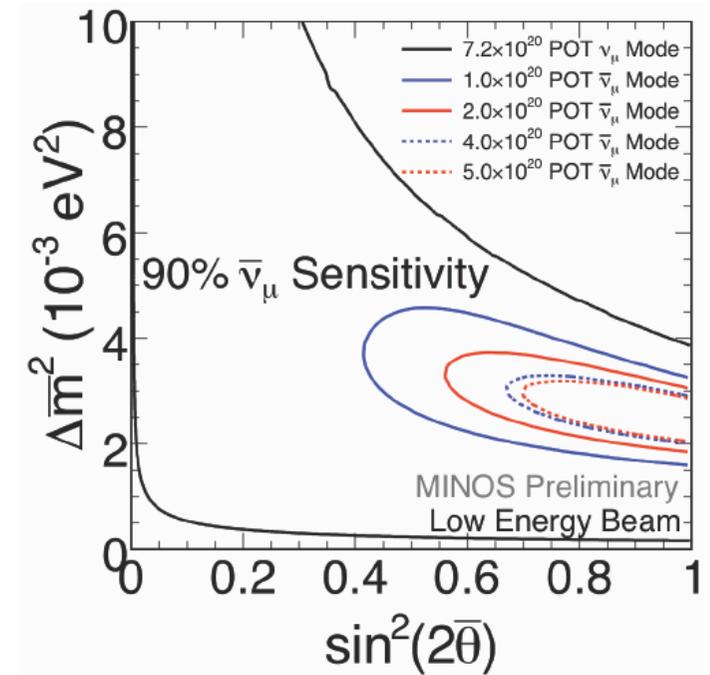
- Sudden stratospheric warmings seen in MINOS deep underground muon data. Geophys. Res. Lett. (in press)
- Comparisons of the MINOS Near and Far Detector Readout Systems at a Test Beam. Submitted to NIM-A
- First Measurement of  $\nu_\mu$  and  $\nu_e$  Events in an Off-Axis Horn-Focused Neutrino Beam. Submitted to PRL (Joint with MiniBooNE)
- Testing Lorentz Invariance and CPT Conservation with NuMI Neutrinos in the MINOS Near Detector. PRL101:151601,2008.
- Search for active neutrino disappearance using neutral-current interactions in the MINOS long-baseline experiment. PRL101:221804,2008.
- Measurement of Neutrino Oscillations with the MINOS Detectors in the NuMI Beam. PRL101:131802,2008.
- The Magnetized steel and scintillator calorimeters of the MINOS experiment. NIM-A 596:190-228,2008.
- A Study of Muon Neutrino Disappearance Using the Fermilab Main Injector Neutrino Beam. PRD 77:072002,2008.
- 8 publications in 2008
- 8 PhD theses also defended in 2008



# Outlook



- CC, NC and  $\nu_e$  groups each plan to release new analyses based on  $\sim 7.0 \times 10^{20}$  POT exposure
- Collaboration would like to take data in anti-neutrino mode after the June shutdown
- Allows direct measurement of oscillation parameters for anti-neutrinos, a direct test of CPT in the neutrino sector
- Precision measurement of  $\Delta\bar{m}^2_{32}$  with a few  $\times 10^{20}$  POT exposure, represents significant improvement over current global fits



# MiniBooNE



University of Alabama  
Bucknell University  
University of Cincinnati  
University of Colorado  
Columbia University  
Embry-Riddle Aeronautical University  
Fermi National Accelerator Laboratory  
University of Florida

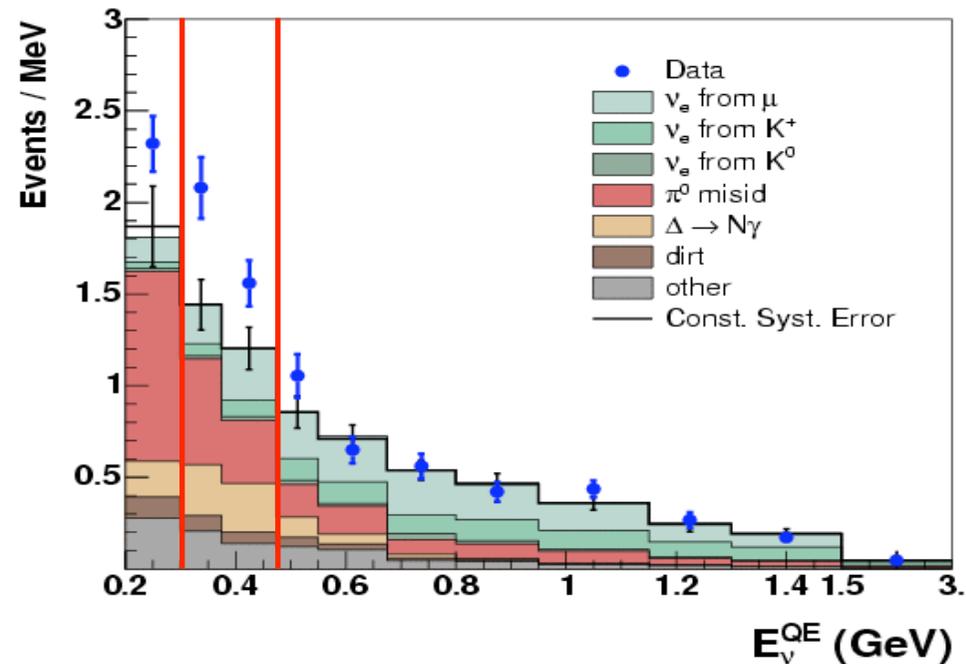
Indiana University  
Los Alamos National Laboratory  
Louisiana State University  
University of Michigan  
Princeton University  
Saint Mary's University of Minnesota  
Virginia Polytechnic Institute  
Yale University

**16 institutions, 80 scientists**



# $\nu_{\mu} \rightarrow \nu_e$ Analysis

- New analysis of neutrino data includes additional data -  $5.58 \times 10^{20}$  POT  $\rightarrow$   $6.46 \times 10^{20}$  POT
- Several improvements made to analysis for this result
  - Checked low level quantities (PID stability)
  - Rechecked background cross-section and rates for ( $\pi^0, \Delta \rightarrow N\gamma$ )
  - Improved coherent  $\pi^0$  production incorporated
  - Better handling of radiative decay of  $\Delta$  resonance
  - Photo-nuclear interactions included
  - Efficiently reject “dirt” events
  - Lowered analysis threshold to 200 MeV with reliable uncertainties
  - Rechecked systematic uncertainties and made some improvements
- Low energy excess still remains
- MC prediction in table includes statistical +systematic uncertainties
- Other category mostly mis-id’ed  $\mu$



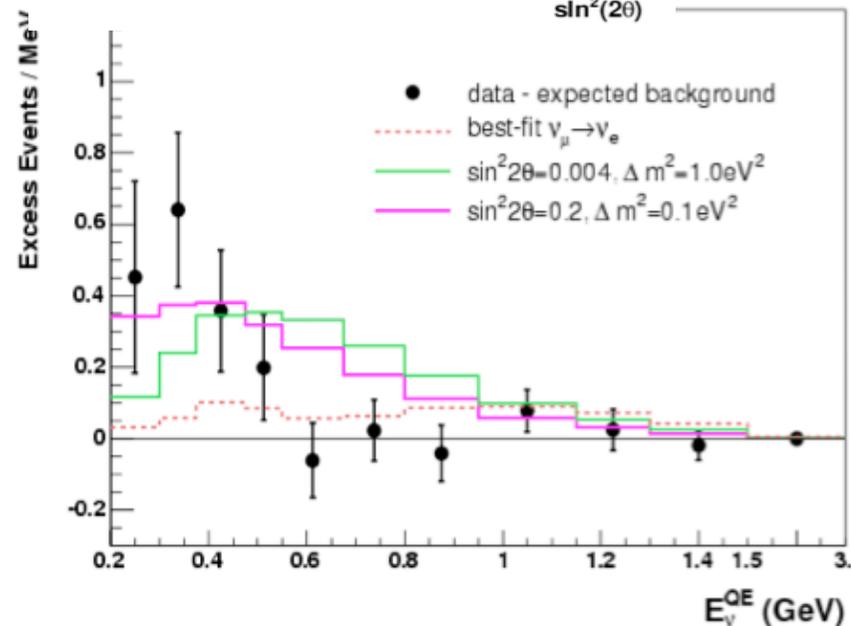
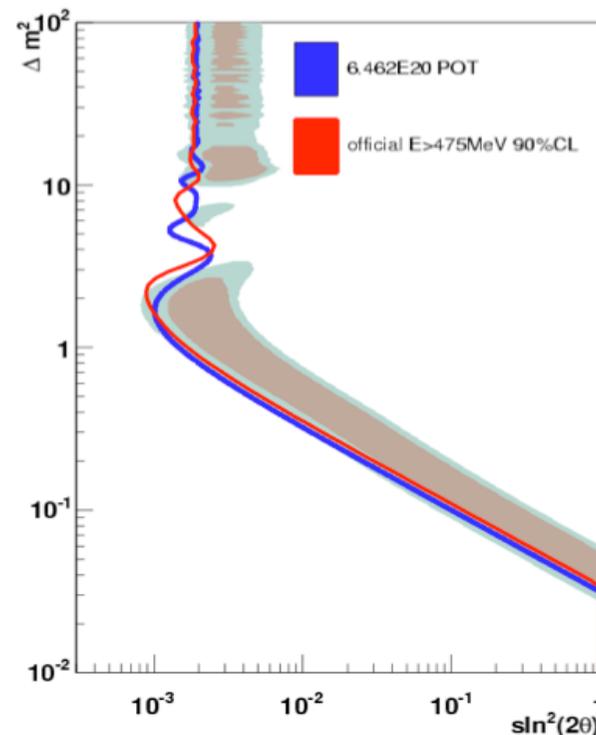
$E_{\nu}$ [MeV]	200-300	300-475	475-1250
<b>total background</b>	<b>186.8<math>\pm</math>26</b>	<b>228.3<math>\pm</math>24.5</b>	<b>385.9<math>\pm</math>35.7</b>
$\nu_e$ intrinsic	18.8	61.7	248.9
$\nu_{\mu}$ induced	168	166.6	137
NC $\pi^0$	103.5	77.8	71.2
NC $\Delta \rightarrow N\gamma$	19.5	47.5	19.4
Dirt	11.5	12.3	11.5
other	33.5	29	34.9
<b>Data</b>	<b>232</b>	<b>312</b>	<b>408</b>
<b>Data-MC</b>	<b>45.2<math>\pm</math>26</b>	<b>83.7<math>\pm</math>24.5</b>	<b>22.1<math>\pm</math>35.7</b>
<b>Significance</b>	<b>1.7<math>\sigma</math></b>	<b>3.4<math>\sigma</math></b>	<b>0.6<math>\sigma</math></b>

Results accepted to PRL -  
arXiv:0812.2243 [hep-ex]



# $\nu_{\mu} \rightarrow \nu_e$ Analysis

- Oscillation fit checked using improved analysis
- 90% CL virtually unchanged when using events with  $E > 475$  MeV
- Inclusion of low energy events does not improve oscillation fit



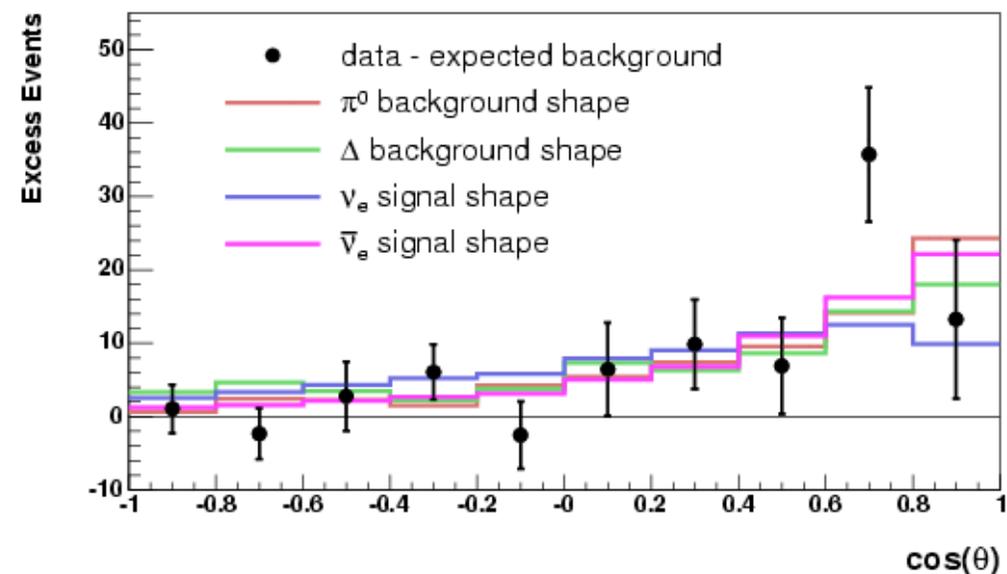
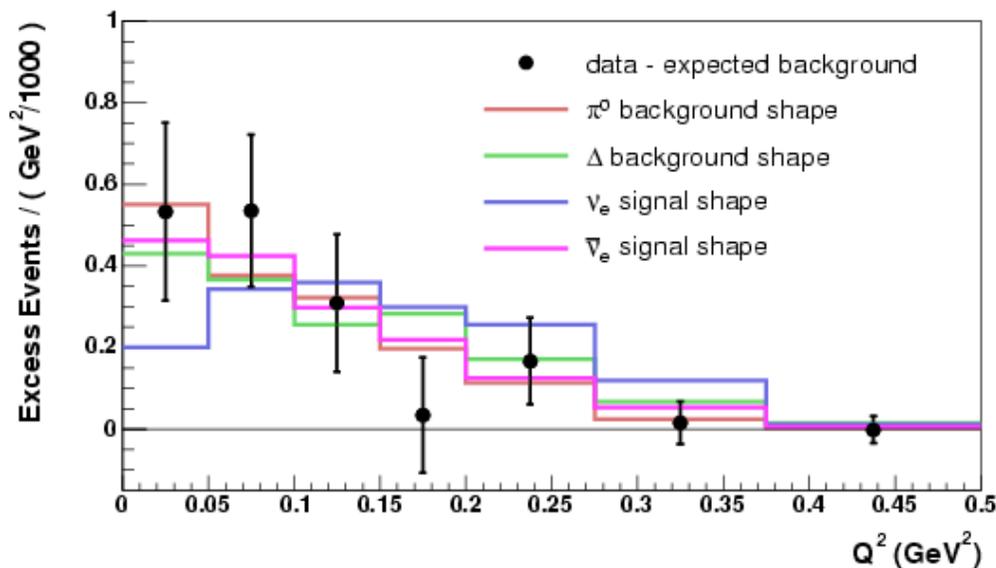
	$E > 200$ MeV	$E > 475$ MeV
Null $\chi^2$	22/19 (28%)	9.1/16 (91%)
Best Fit $\chi^2$	18.3/17 (37%)	7.2/14 (93%)



# $\nu_{\mu} \rightarrow \nu_e$ Analysis

- Used kinematic variable distributions to understand excess in 300 - 475 MeV region
- Shapes of background distributions are in reasonable agreement with excess
- However would have to increase individual processes by  $> 5\sigma$

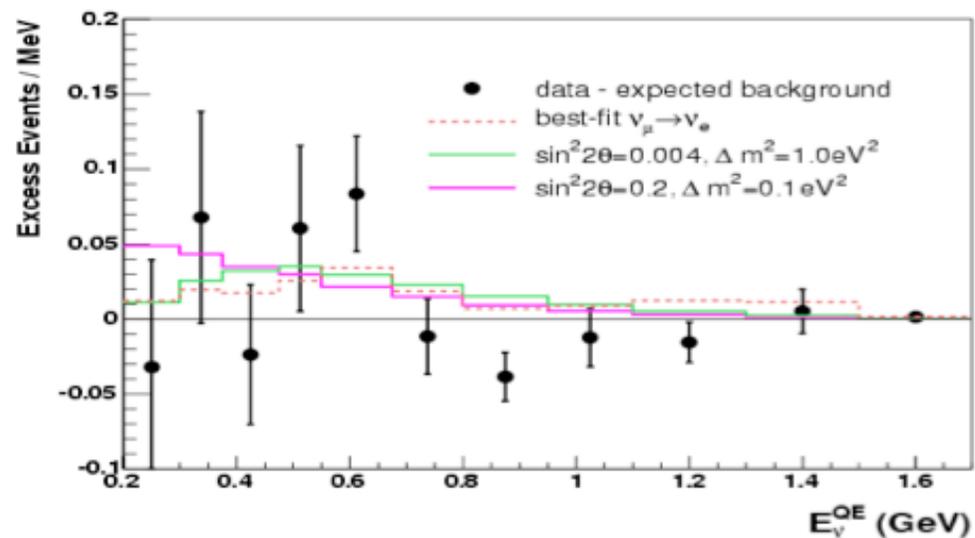
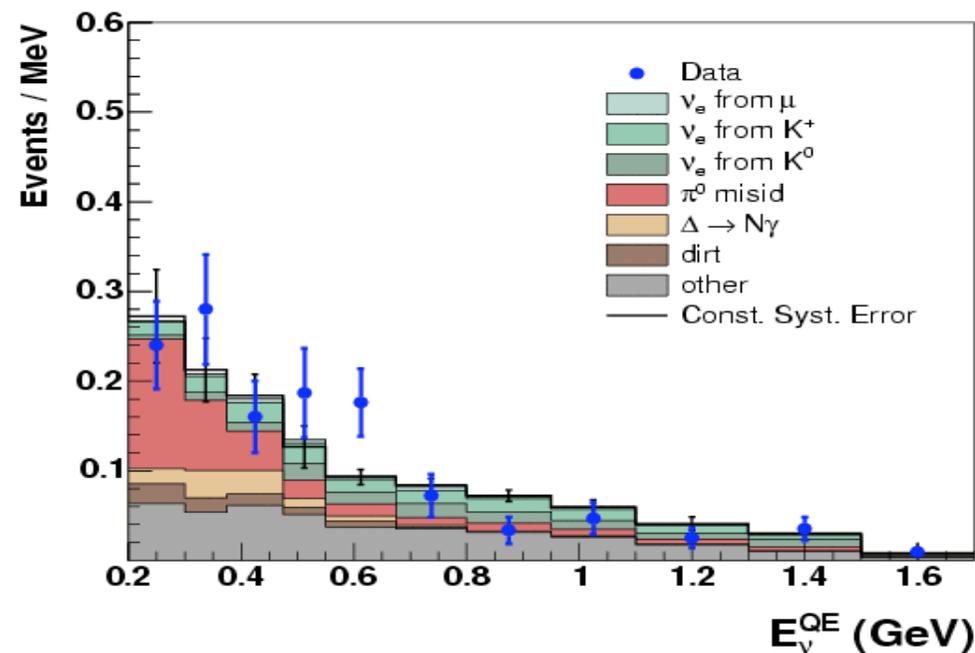
Process	$\chi^2(\cos\theta)/9$ DF	$\chi^2(Q^2)/6$ DF	Factor Increase
NC $\pi^0$	13.46	2.18	2.0
$\Delta \rightarrow N\gamma$	16.85	4.46	2.7
$\nu_e C \rightarrow e^- X$	14.58	8.72	2.4
$\bar{\nu}_e C \rightarrow e^+ X$	10.11	2.44	65.4





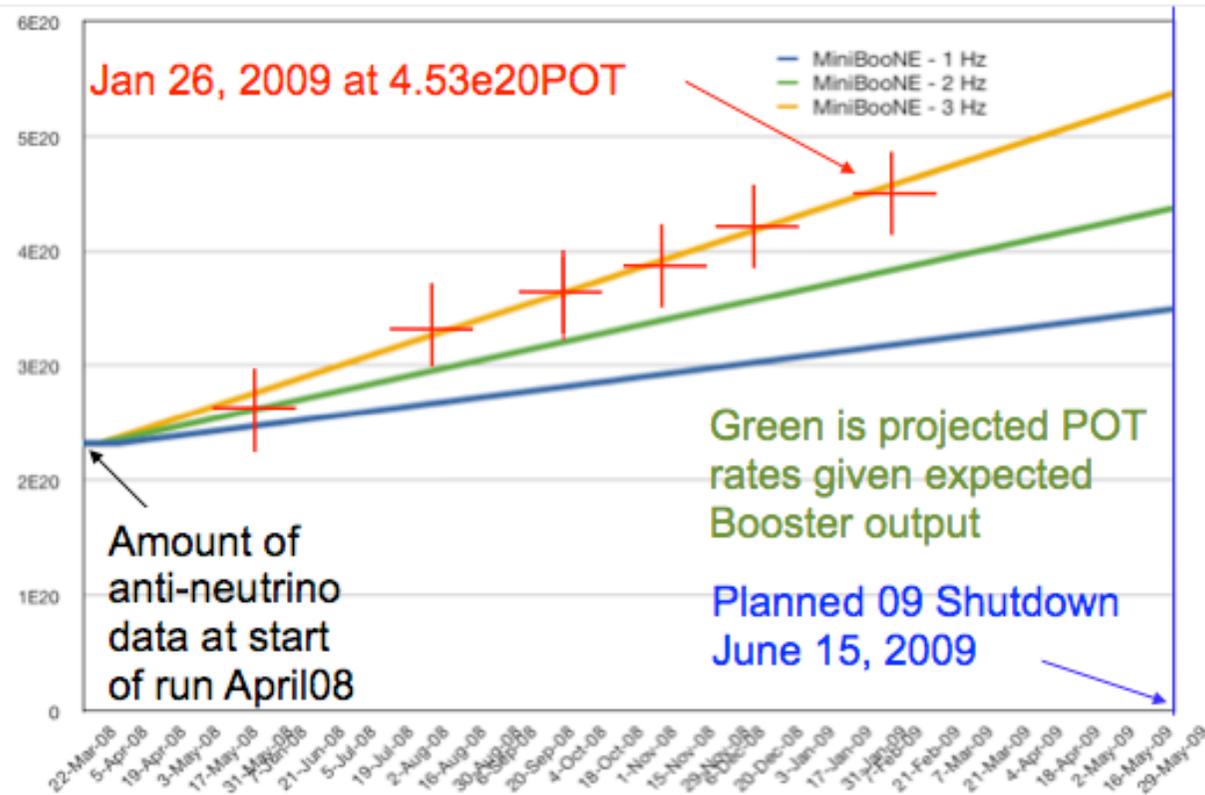
# $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ Analysis

- PAC recommended in November 2007 that MiniBooNE collect  $5 \times 10^{20}$  POT in anti-neutrino mode
- $3.4 \times 10^{20}$  POT analyzed to date
- Box opened in October 2008, results presented at W&C in December
- Good agreement between data and Monte Carlo simulation
- Oscillation fit consistent with either null hypothesis or LSND due to large uncertainties



	$200 < E < 475$ MeV	$E > 475$ MeV
Data - MC	$-0.5 \pm 11.7$	$3.2 \pm 10.0$

# $\bar{\nu}$ Beam Performance



- POT rate consistent with most optimistic expectations, doubles exposure since April 2008
- Booster beam has benefited from NuMI downtimes
- Should have accumulated  $5.2 \times 10^{20}$  POT by the June 2009 shutdown, goal was to get  $5 \times 10^{20}$  POT in anti- $\bar{\nu}$  mode

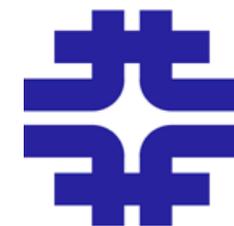
# 2008 Publications



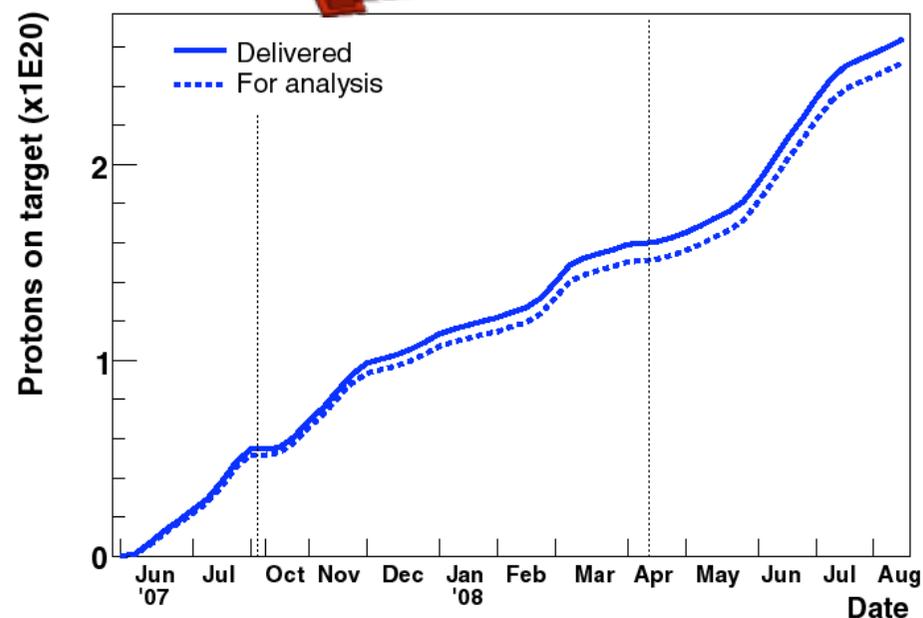
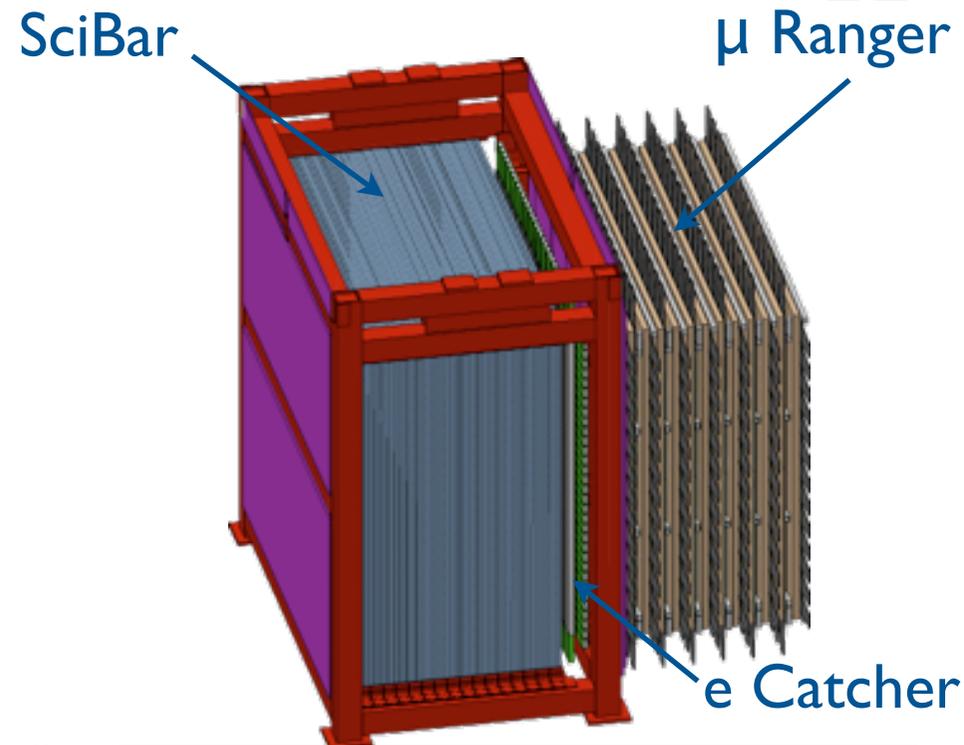
- The Extended-Track Reconstruction for MiniBooNE - submitted to NIM
- Unexplained Excess of Electron-like Events from a 1 GeV Neutrino Beam - accepted by PRL
- First Measurement of  $\nu_{\mu}$  and  $\nu_{e}$  Events in an Off-axis Horn-Focused Neutrino Beam (joint paper with MINOS colleagues) - submitted to PRL
- The MiniBooNE Detector - NIM-A, 28 (2009)
- The Neutrino Flux Prediction at MiniBooNE - accepted by PRD
- Compatibility of High  $\Delta m^2$   $\nu_e$  and  $\bar{\nu}_e$  Neutrino Oscillation Searches - Phys. Rev. D78, 012007 (2008)
- First Observation of Coherent  $\pi^0$  Production in Neutrino-Nucleus Interactions with  $E_\nu < 2$  GeV - Phys. Lett. B664, 41 (2008)
- Measurement of Muon Neutrino Quasi-Elastic Scattering on Carbon - Phys. Rev. Lett. 100, 032301 (2008)
- 8 papers in 2008



19 institutions, 65 scientists



- Ran from June 2007 - August 2008
- 95% of data pass quality cuts
- $2.52 \times 10^{20}$  POT total exposure,  $2.0 \times 10^{20}$  POT requested
  - $\nu$ :  $0.99 \times 10^{20}$  POT
  - $\bar{\nu}$ :  $1.53 \times 10^{20}$  POT
- Detector Decommissioned
  - SciBar PMTs back to Japan, EC PMTs back to Italy
  - All PREP equipment returned
  - Scintillators, Pb modules, Fe plates remain in detector hall



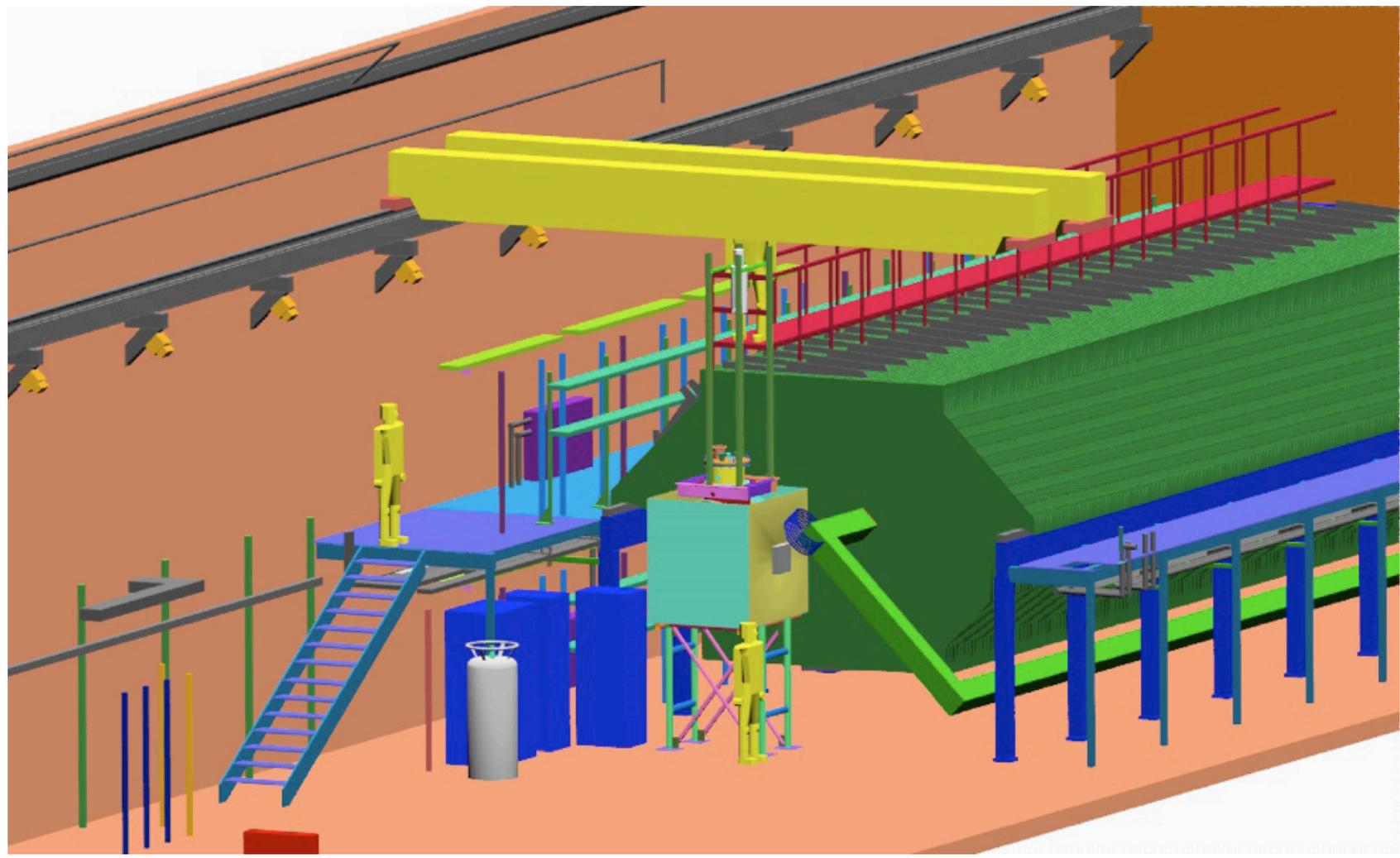


- Limit on CC coherent  $\pi$  production - PRD **78** | 2004 (2008)
- Numerous (15) conference proceedings
- Several student theses finished/in the works
  - PhD: 3 finished, 9 active
  - Masters: 2 finished, 1 active
- Upcoming results
  - NC elastic scattering - Spring 2009
  - Neutrino disappearance, joint with MiniBooNE - Summer 2009
  - Several analyses to be released for NuInt 09 conference (May)
    - $\nu_\mu$  CC quasi-elastic
    - $\nu_\mu$  CC single  $\pi$
    - $\nu_\mu$  NC single  $\pi$
    - $\bar{\nu}_\mu$  CC coherent  $\pi$

Important  
measurements for T2K



# ArgoNeuT



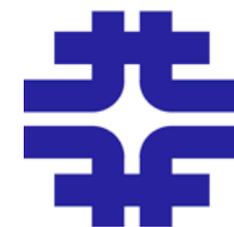
6 institutions, 20 scientists

- Cryostat is underground
- Plumbing connections made, vacuum pumping underway
- Electrical work proceeding
- Muon veto paddles in place and working
- Schedule - ~2 weeks + review time
  - Safety Reviews - ???
  - Final testing - < 1 week
  - Pump down and back fill < 1 week
  - Filling - 2 days

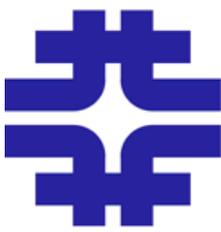




# Summary

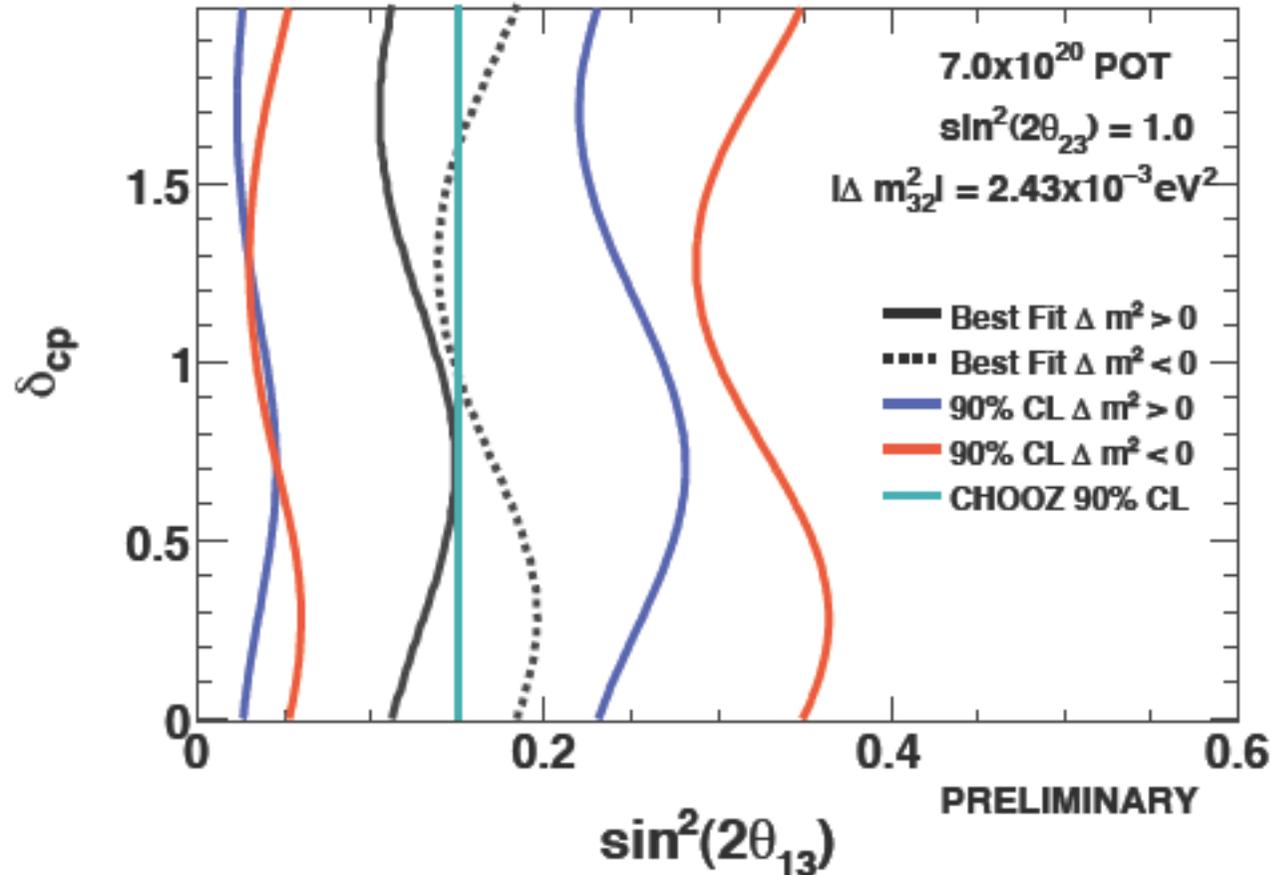


- MINOS steadily producing publications and analyses
  - New result from  $\nu_e$  analysis presented last week
  - New result from NC analysis coming soon
  - Nearly double the data of previous analyses will be in hand by shutdown
- MiniBooNE also steadily producing both cross section and oscillation publications
- SciBooNE has finished data taking and is dismantled, several results relevant to T2K to come out this spring
- ArgoNeuT is nearly ready to be filled and take data



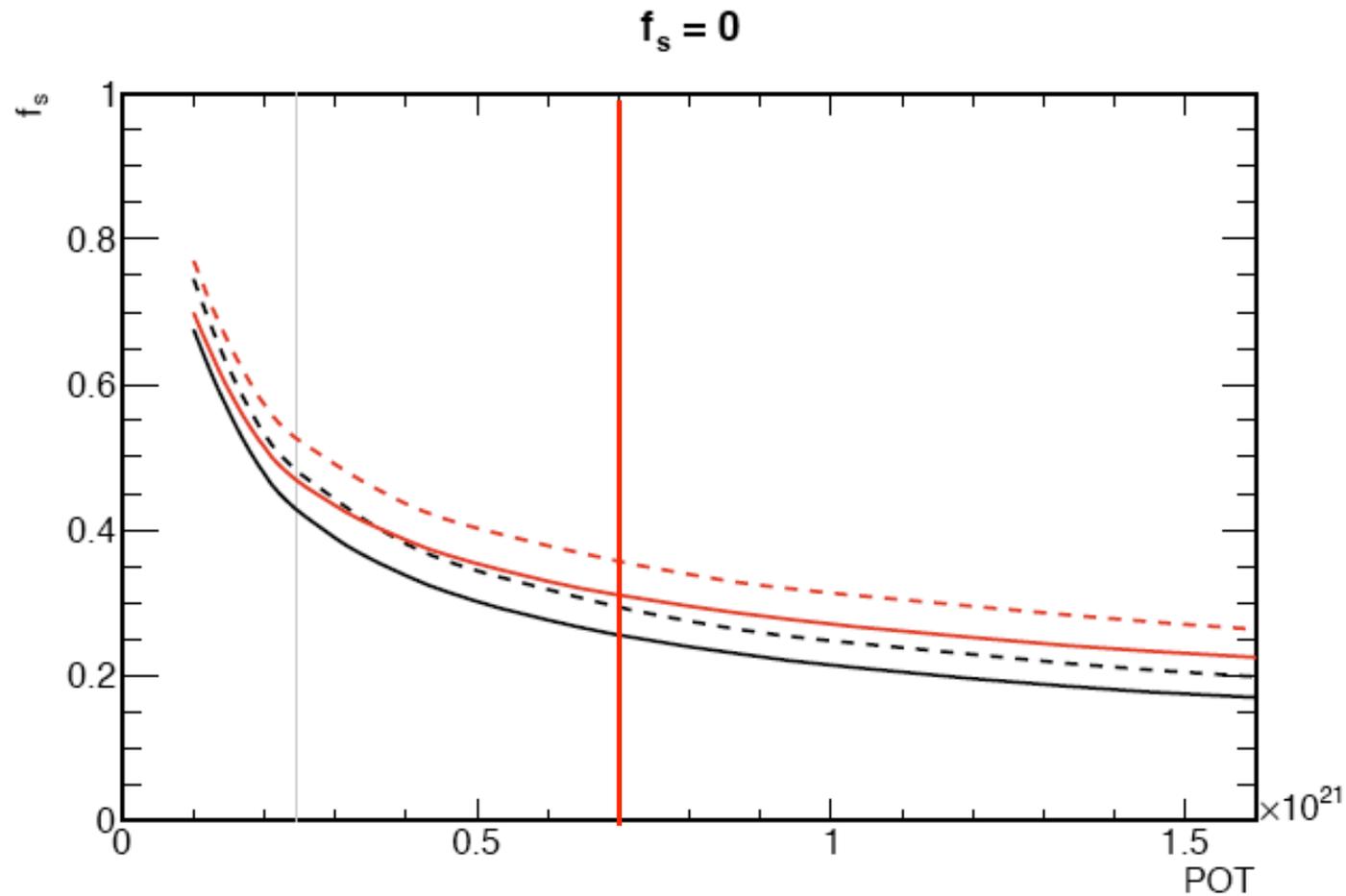
# Future $\nu_e$ Sensitivity

Potential Feldman–Cousins C.L. contours for ANN



- Plot shows sensitivity for  $7 \times 10^{20}$  POT exposure if  $\theta_{13}$  is at current best fit value

# Future NC Sensitivity



- Sensitivity to  $f_s$  improves slowly with increasing exposure