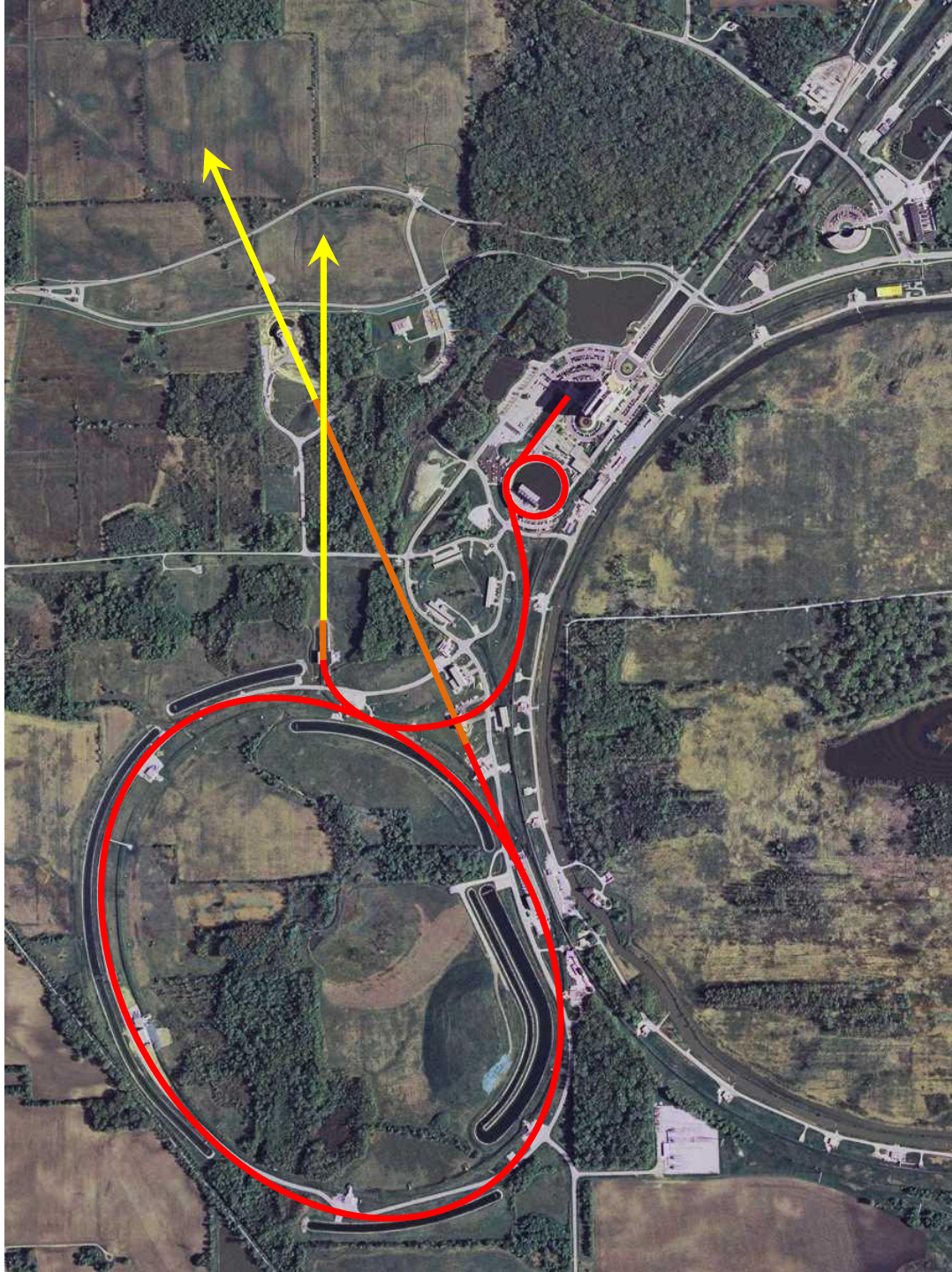
Status of Fermilab Neutrino Experiments

Physics Advisory Committee
December 2011

Ryan Patterson
Caltech



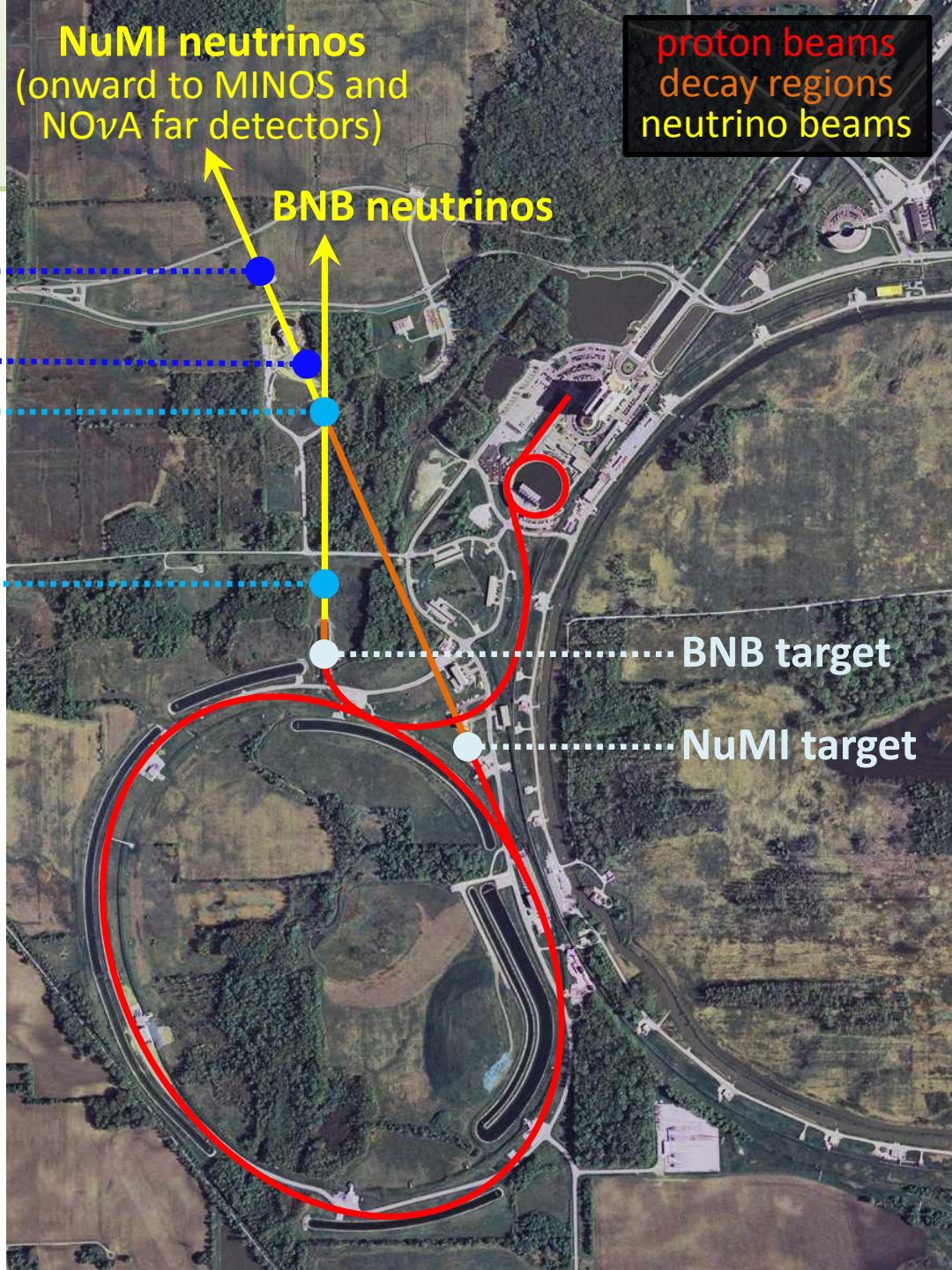
Fermilab Neutrino Complex

MINOS ND, NOνA ND, MINERνA

NOνA ND prototype

MiniBooNE, MicroBooNE

SciBooNE



<u>8 GeV Booster</u> supplies the Booster Neutrino Beam (BNB)

- ***MiniBooNE***
- ***SciBooNE***
- ***MicroBooNE***

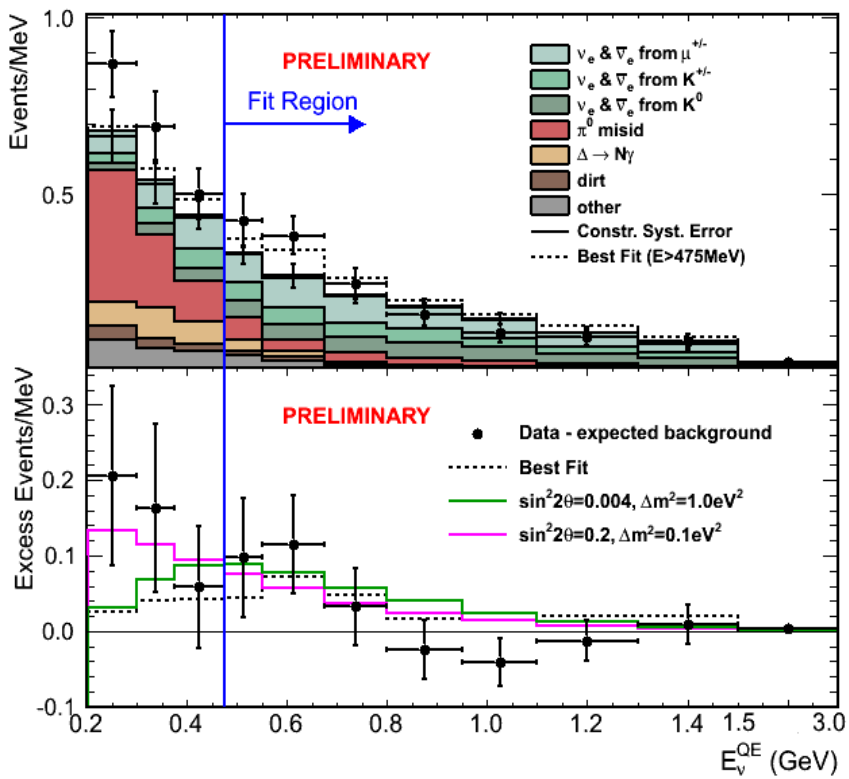
<u>120 GeV MI</u> feeds the Neutrinos from the MI (NuMI) beam

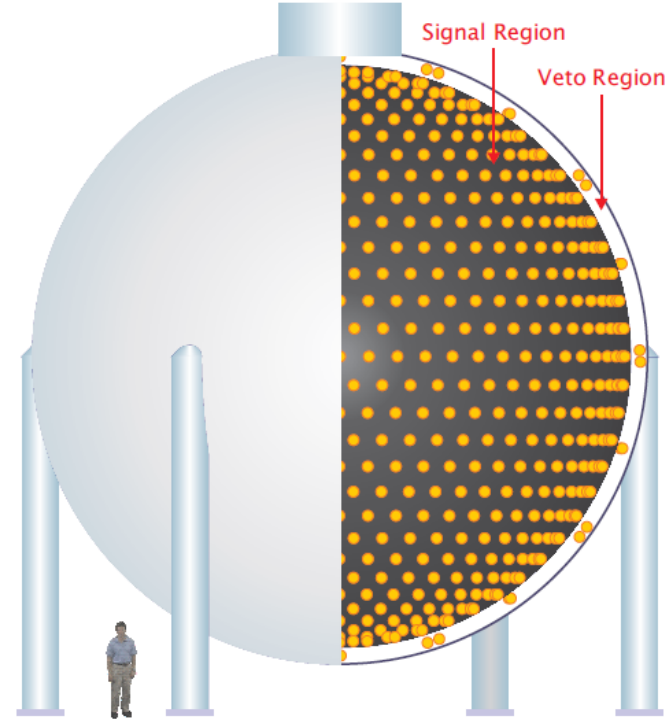
- ***MINOS***
- ***NOνA***
- ***MINERνA***

Ryan Patterson

MiniBooNE

- Testing **LSND $\bar{\nu}_e$ appearance** claim
- Initial MiniBooNE run **used ν_μ beam (6.5x10^{20} p.o.t.)**
  - → **no excess** in signal region ($E_\nu > 475$ MeV)
  - → **excess** at low energy ($E_\nu < 400$ MeV)
- Since then: **$\bar{\nu}_\mu$ beam (8.6x10^{20} p.o.t.)**
- Recent update: **K^+ constraint from SciBooNE**





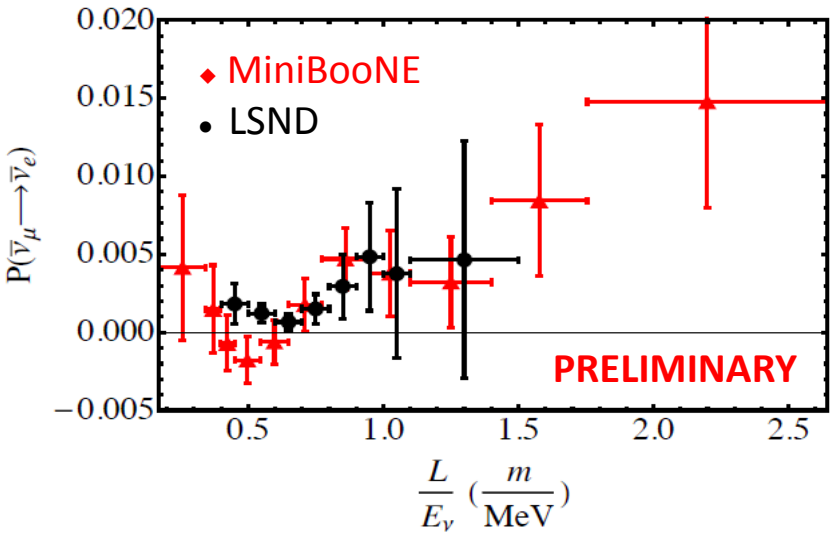
$\bar{\nu}_e$ appearance candidates

	200-475 MeV	475-1250	200-3000
Data	189	168	412
Prediction	150.4	151.7	354.3
Excess	**38.6±18.5**	**16.3±19.4**	**57.7±28.5**

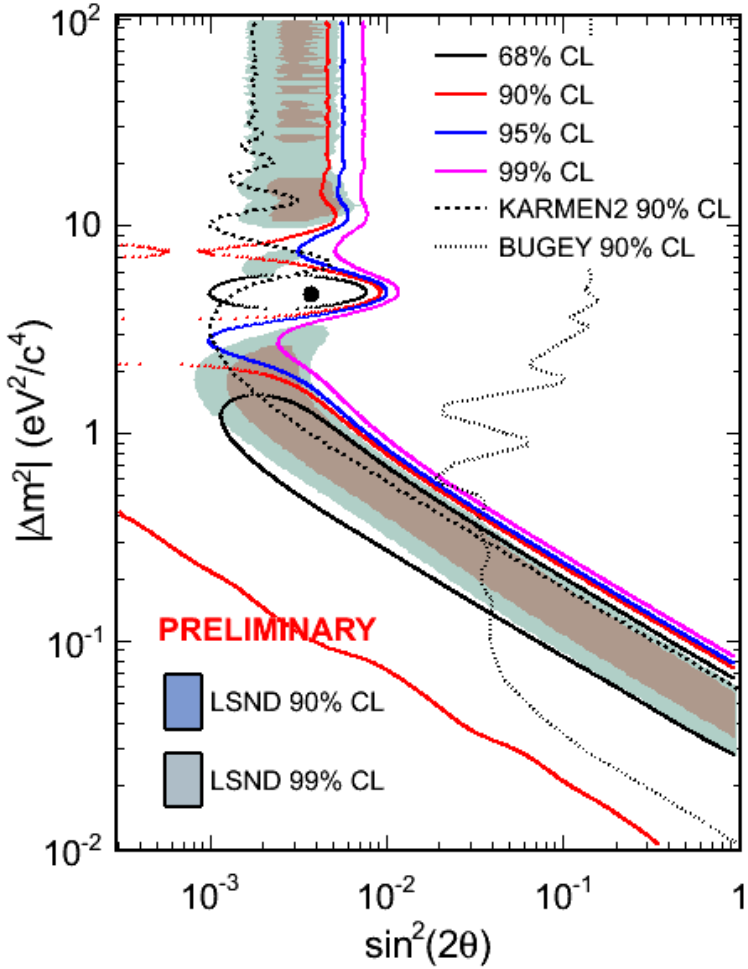
Slight excess at low energies and overall. Shape consistent with LSND-like osc.

MiniBooNE

- **For $\bar{\nu}$ data: 2ν oscillations favored** over background-only hypothesis ($\sim 2\sigma$)
- Excess shown as a function of ***L/E*** :



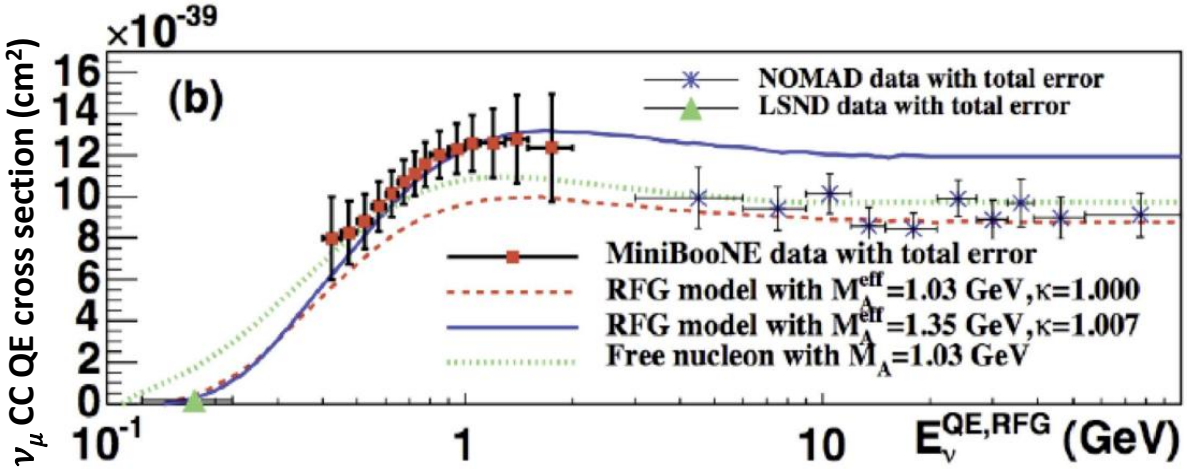
- **$\bar{\nu}$ run goal: 15×10^{20} p.o.t.**
  (latest result: 8.6×10^{20} p.o.t.)
- ***Upcoming:***
  - → **combined ν and $\bar{\nu}$ fits**
  - → **joint $\bar{\nu}$ disappearance w/ SciBooNE** ***(testing 3+N models)***



Task at hand: **understand the relationship between the ν and $\bar{\nu}$ excesses and their possible source(s)** ***(oscillations, exotics, mundane backgrounds, nuclear effects, …)***

MiniBooNE: Cross sections

- Have published **cross sections for 90% of the neutrino interactions** in MiniBooNE
- **Serving as input to oscillation searches**
- Probing **nuclear effects** with **new precision**, and thus…
- **Challenging assumptions** about nuclear effects **at "intermediate" energies**

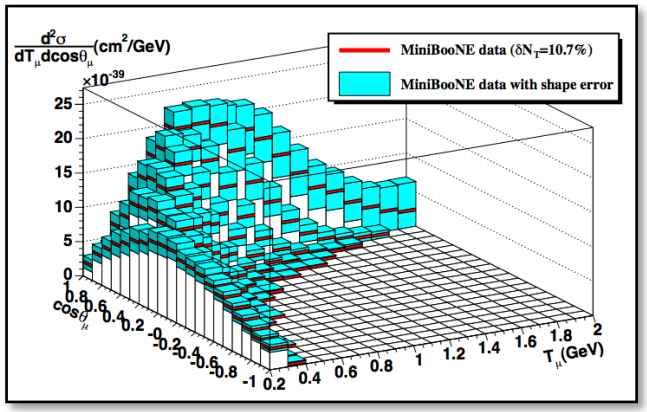


Above: **MiniBooNE and NOMAD ν_μ CC QE cross section measurements**

More than 45 theory papers have been published since 2010 in response to the MiniBooNE measurement.

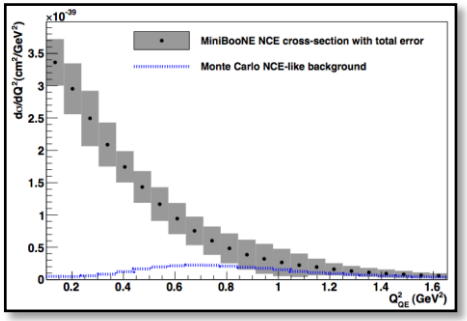
MiniBooNE: Cross sections

- **This is the first time that full kinematics (diff. and doubly diff. cross sections) have been reported for these reactions**



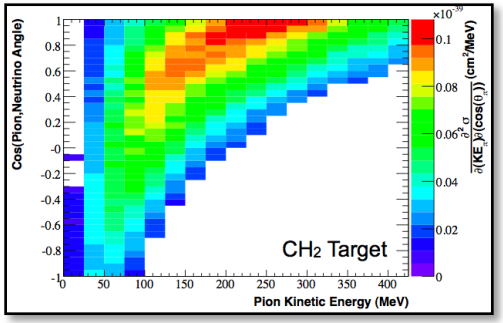
quasi-elastic scattering

- Phys. Rev. Lett. **100**, 032301 (2008)
- Phys. Rev. **D81**, 092005 (2010)



NC elastic scattering

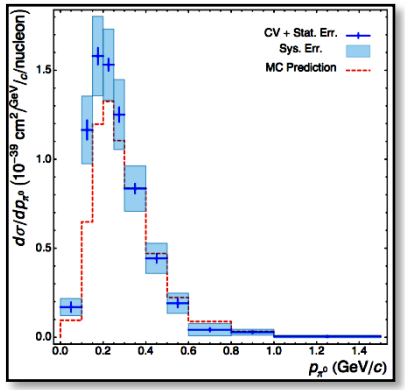
- Phys. Rev. **D82**, 902005 (2010)



CC π^+ production

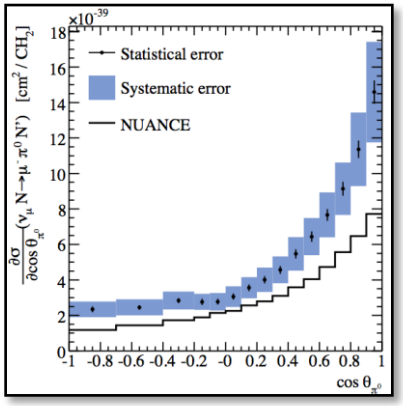
- Phys. Rev. Lett. **103**, 081801 (2009)
- Phys. Rev. **D83**, 052007 (2011)

CC inclusive sample and additional $\bar{\nu}$ channels under analysis now



NC π^0 production

- Phys. Lett. **B664**, 41 (2008)
- Phys. Rev. **D81**, 013005 (2010)



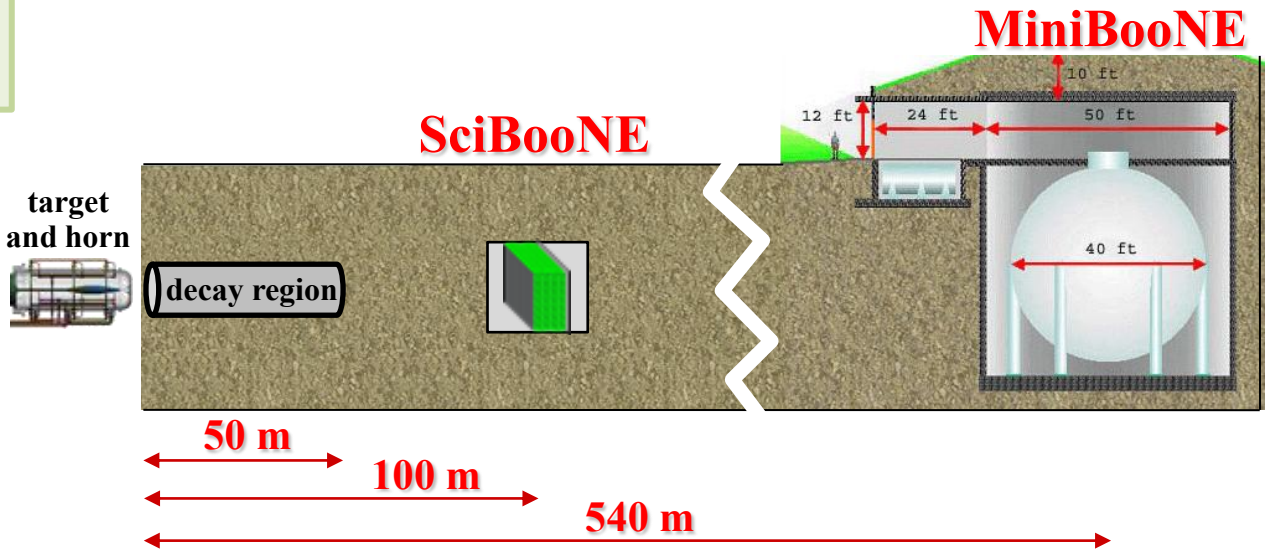
CC π^0 production

- Phys. Rev. D83, 052009 (2011)

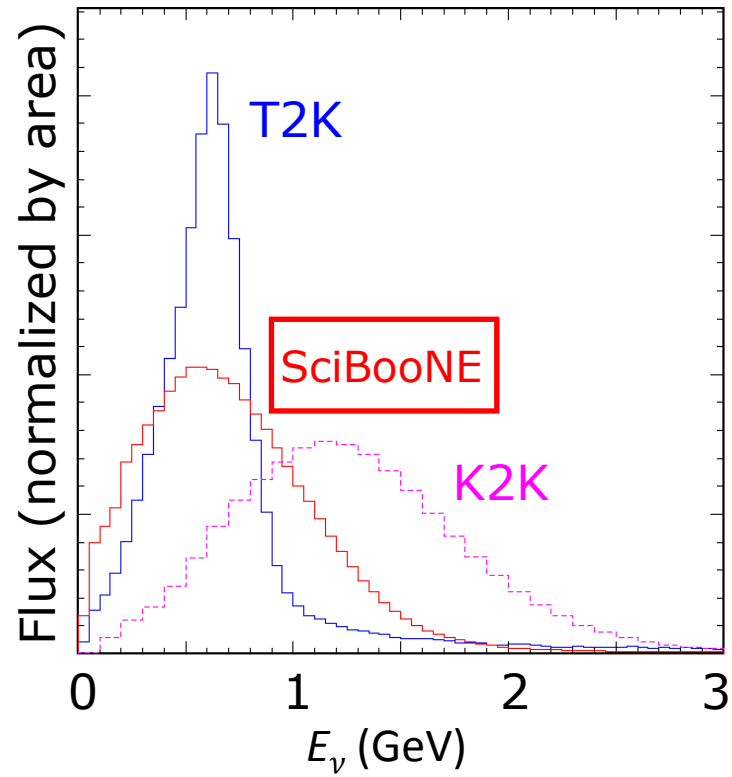
SciBooNE

Booster Neutrino Beam

(not to scale)

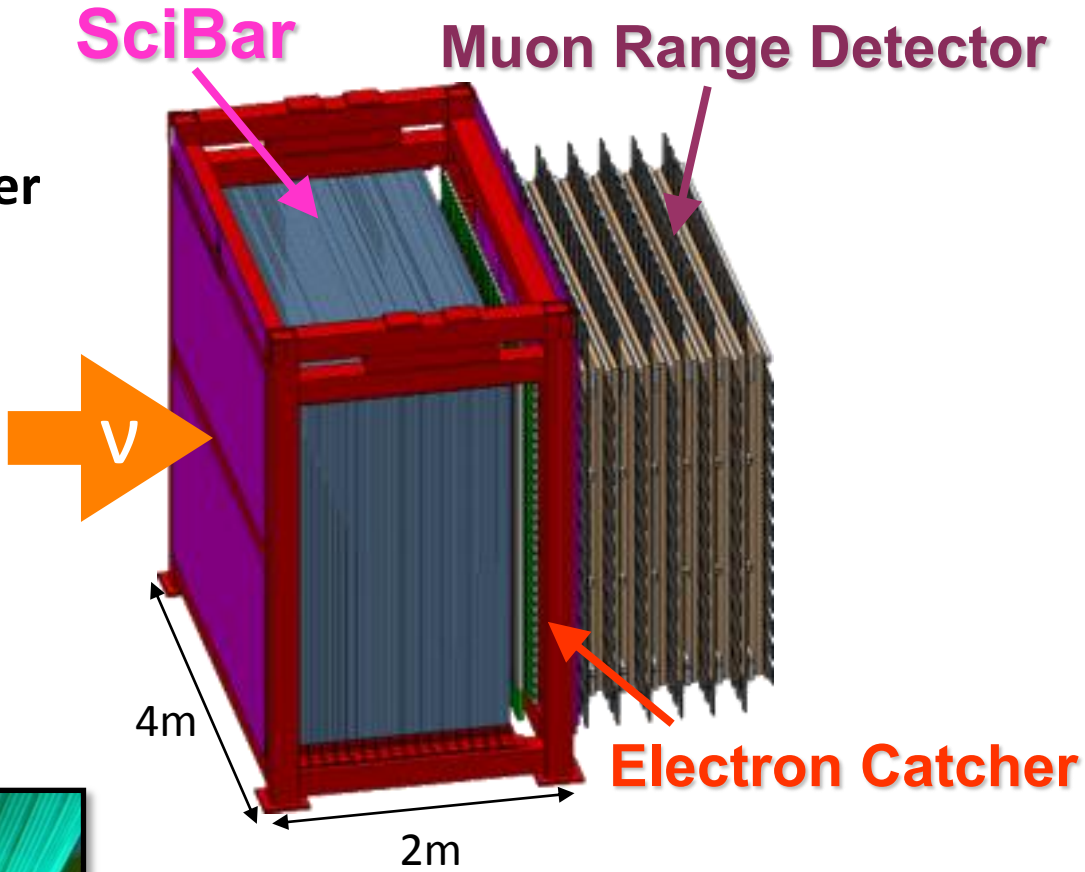


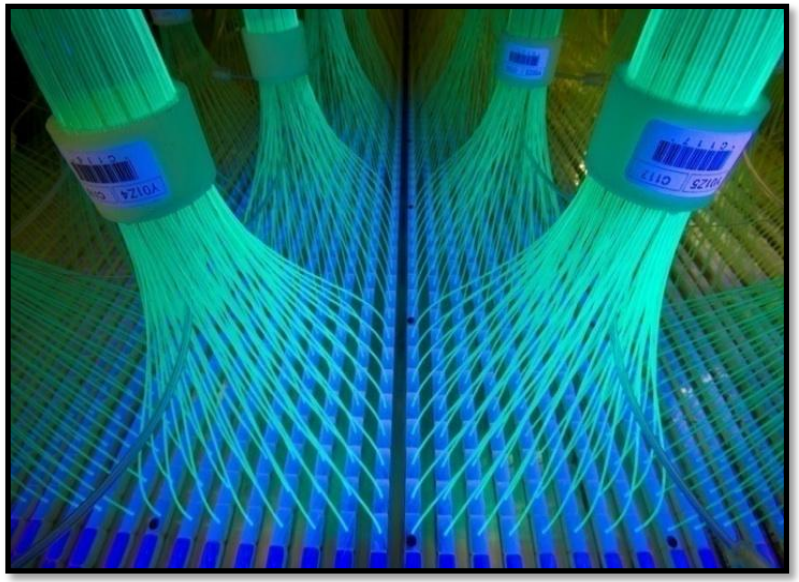
- Precise measurements of ν **and** $\bar{\nu}$ **cross sections** necessary for T2K and other oscillation experiments
- Ability to identify **non-QE interactions**
- Serve as **MiniBooNE near detector**
  - → **Direct measurement of beam** ν_e
  - → ν_μ **disappearance**

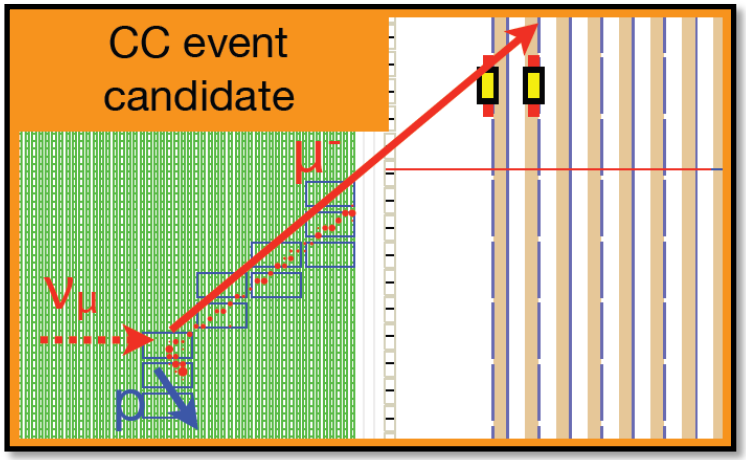


SciBooNE

- "SciBar" *(K2K)* scintillator tracker
  - → 15 tons, 14k channels
  - → $p/\pi^{\pm}$ separation via dE/dx
- Electron catcher *(from K2K, HARP, CHORUS)*
  - → e and π^0 identification
- Muon range detector
  - → up to 1.2 GeV







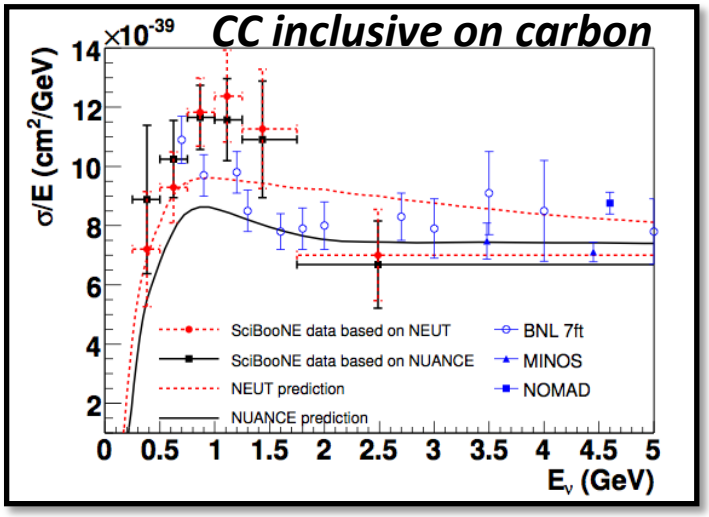
SciBooNE

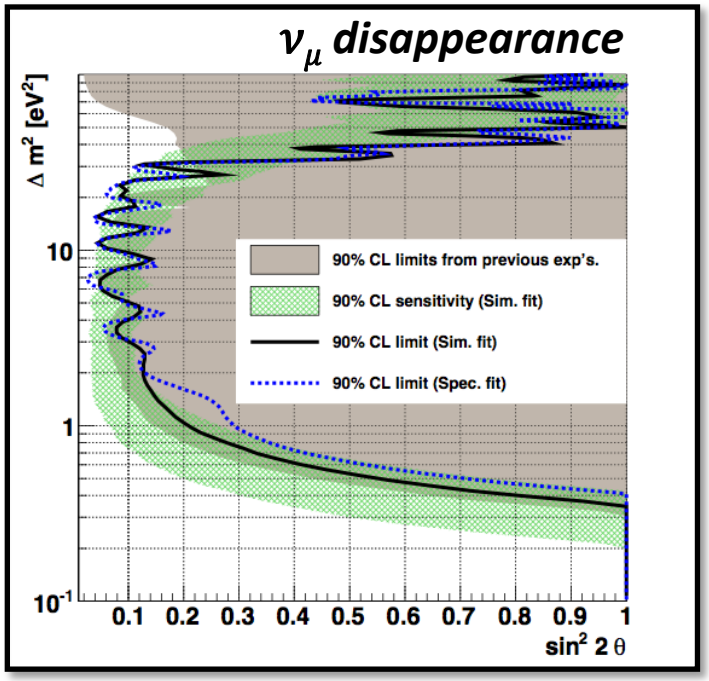
Publications

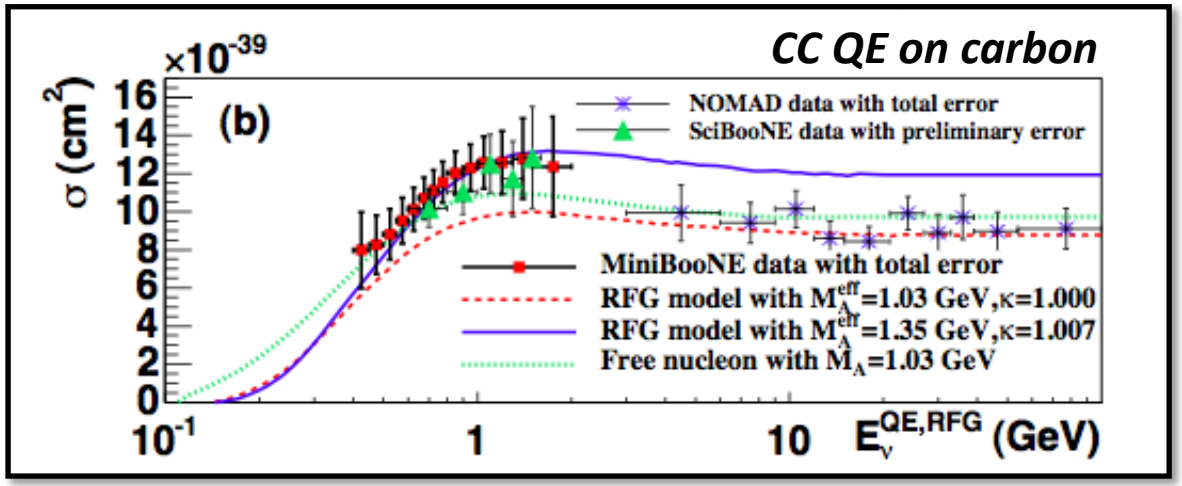
ν_μ disappearance (submitted to PRD)
Kaon neutrino production PRD **84** 012009 (2011)
CC inclusive cross section PRD **83** 012005 (2011)
Coherent NC π^0 production PRD **81** 111102(R) (2010)
Inclusive NC π^0 production PRD **81** 033004 (2010)
Coherent CC π^+ production PRD **78** 112004 (2008)

Upcoming

$\bar{\nu}_\mu$ disappearance (joint with MiniBooNE)
CC QE cross section (early 2012)
$\nu/\bar{\nu}$ CC coherent pion production (early 2012)
NC elastic scattering (mid-2012)
CC π^0 (mid-2012)
Coherent CC π^+ production PRD 78 112004 (2008)

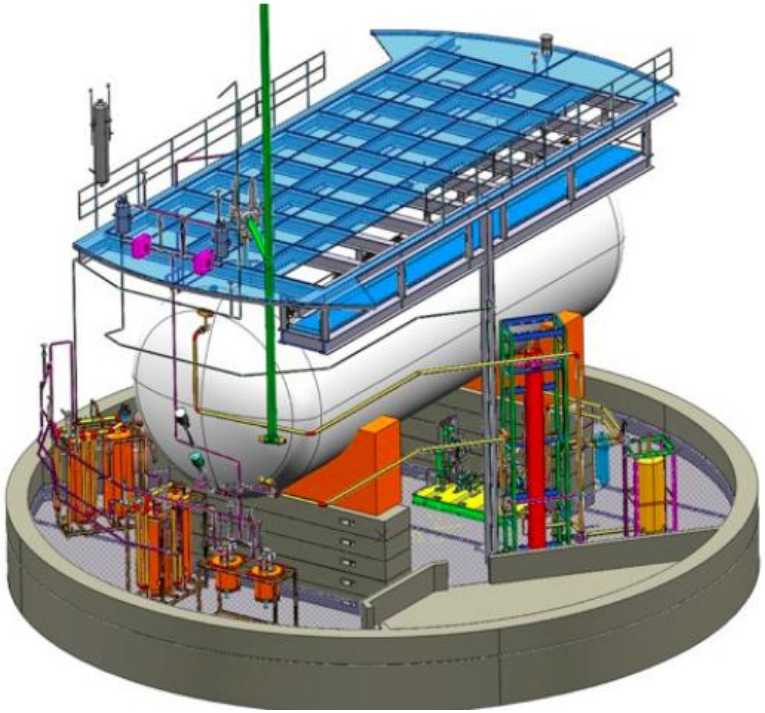






MicroBooNE

- 150-ton LAr TPC
- R&D step *en route* to LBNE-scale LAr
- Explore MiniBooNE low-energy excess (e? γ?)
- Sterile ν searches
- Low energy ν cross sections on argon

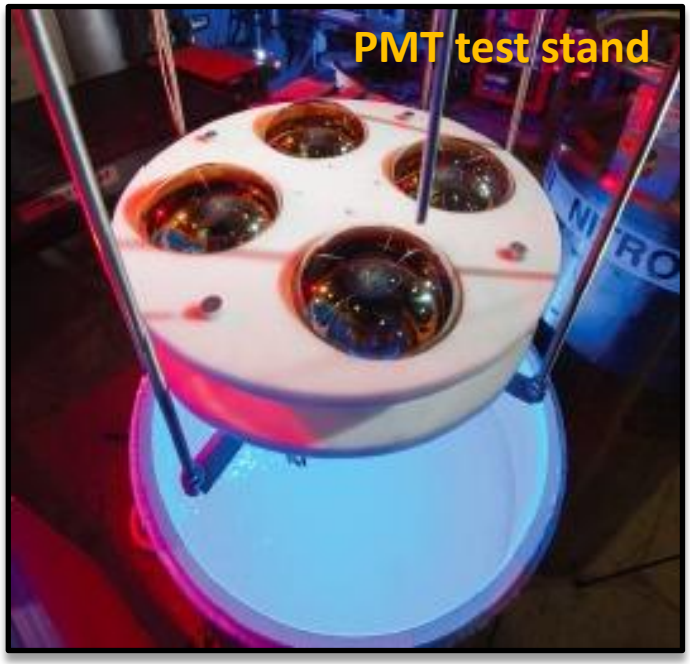


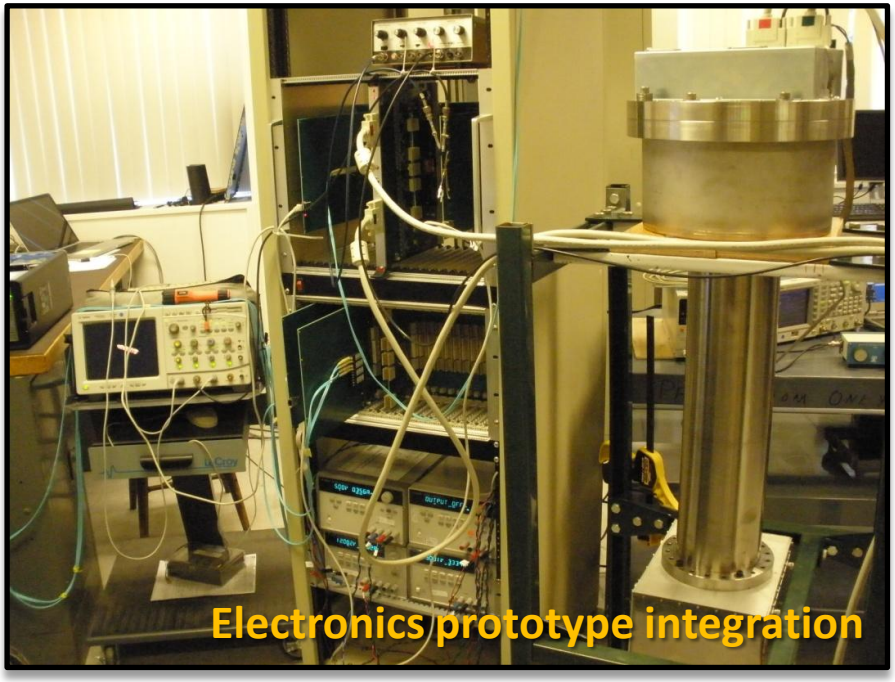
- Successfully completed CD-2/3a, → *August 2011*
- Working towards CD-3b in February
- Breaking ground soon on Liquid Argon Test Facility (LArTF) to house MicroBooNE
- Clearing out D0 assembly hall for MicroBooNE assembly effort

MicroBooNE

Detector design, testing, fabrication:

- **Parts for wire winding machine #1 complete**
- **Machine being assembled at BNL**
- **½ of the parts for machine #2 complete**
- **Stringing to begin at Syracuse and Yale in January**
- **PMT test stand operational and now testing PMTs**
- **Successful Prototype Integration test of electronics chain at Nevis**
- **Cryostat procurement in prep.**





ArgoNeuT

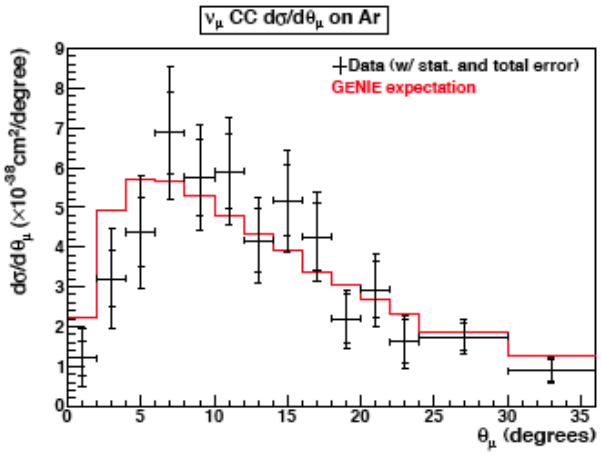


FIG. 2: The ν_μ CC differential cross section (per argon nucleus) in muon angle.

Josh Spitz

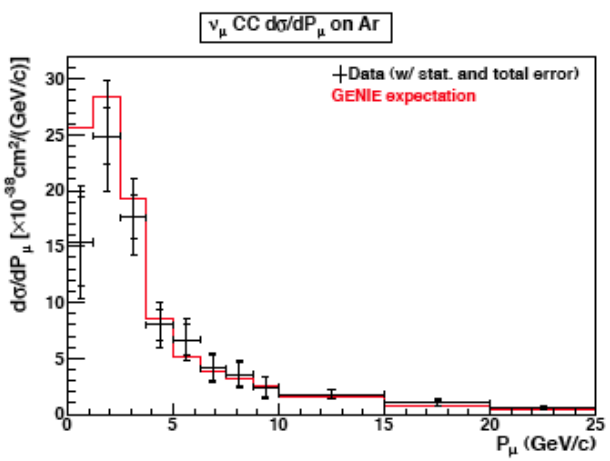
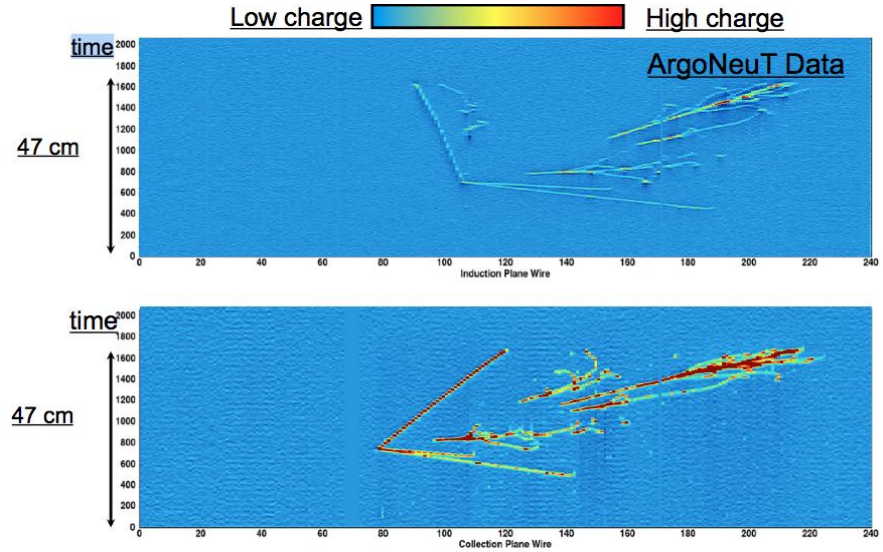


FIG. 3: The ν_μ CC differential cross section (per argon nucleus) in muon momentum.



First Measurements of Inclusive Muon Neutrino Charged Current Differential Cross Sections on Argon

C. Anderson,[1] M. Antonello,[2] B. Baller,[3] T. Bolton,[4] C. Bromberg,[5] F. Cavanna,[6] E. Church,[1] D. Edmunds,[5] A. Ereditato,[7] S. Farooq,[4] B. Fleming,[1] H. Greenlee,[3] R. Guenette,[1] S. Haug,[7] G. Horton-Smith,[4] C. James,[3] E. Klein,[1] K. Lang,[8] P. Laurens,[5] S. Linden,[1] D. McKee,[4] R. Mehdiyev,[8] B. Page,[5] O. Palamara,[2] K. Partyka,[1] A. Patch,[1] G. Rameika,[3] B. Rebel,[3] B. Rossi,[7] M. Soderberg,[3,9] J. Spitz,[1] A.M. Szelc,[1] M. Weber,[7] T. Yang,[3] and G. Zeller[3]

(The ArgoNeuT Collaboration)

[1] *Yale University, New Haven, CT 06520*
[2] *INFN - Laboratori Nazionali del Gran Sasso, Assergi, Italy*
[3] *Fermi National Accelerator Laboratory, Batavia, IL 60510*
[4] *Kansas State University, Manhattan, KS 66506*
[5] *Michigan State University, East Lansing, MI 48824*
[6] *Universita dell'Aquila e INFN, L'Aquila, Italy*
[7] *University of Bern, Bern, Switzerland*
[8] *The University of Texas at Austin, Austin, TX 78712*
[9] *Syracuse University, Syracuse, NY 13244*

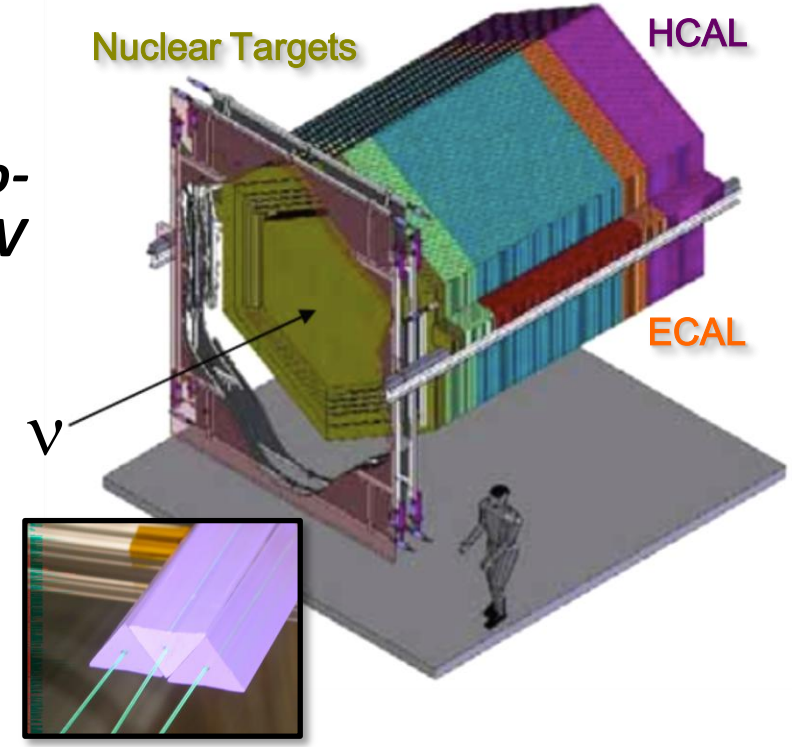
Submitted to PRL

- ***ArgoNeuT:*** **LAr TPC analysis mature enough for new cross section results**
- **Several other cross section analyses underway**

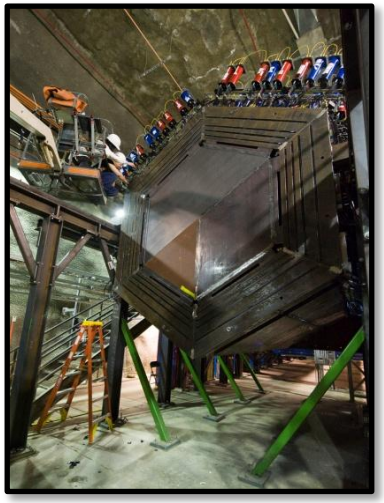
MINERνA

Significantly improve knowledge of neutrino-nucleus interactions between 0.5 and 20 GeV

- **Exclusive final state reconstruction and corresponding cross sections**
  - **→ Supports worldwide neutrino oscillation program**
  - **→ Probing nuclear effects on exclusive states**
- **With NOνA-era beam ("medium" energy)**
  - **→ Inclusive scattering measurements**
  - **→ Nuclear PDFs**
- **Multiple nuclear targets**
  - **→ C, Fe, Pb, He, water**
- **Detector layout:**
  - **→ Solid scintillator tracker (with low thresholds)**
  - **→ ECAL and HCAL**
  - **→ muon charge and momentum from MINOS near detector**



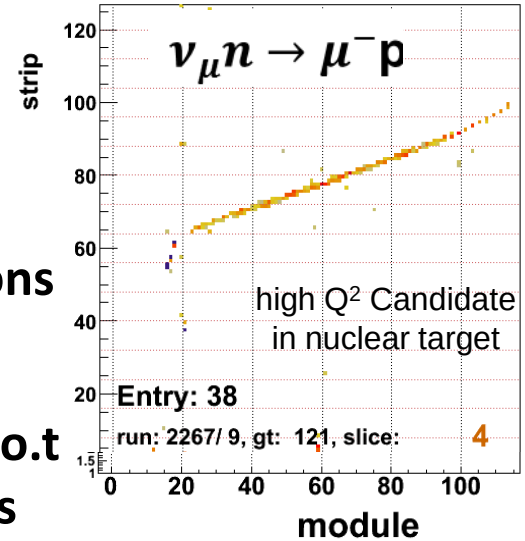
cryogenic target

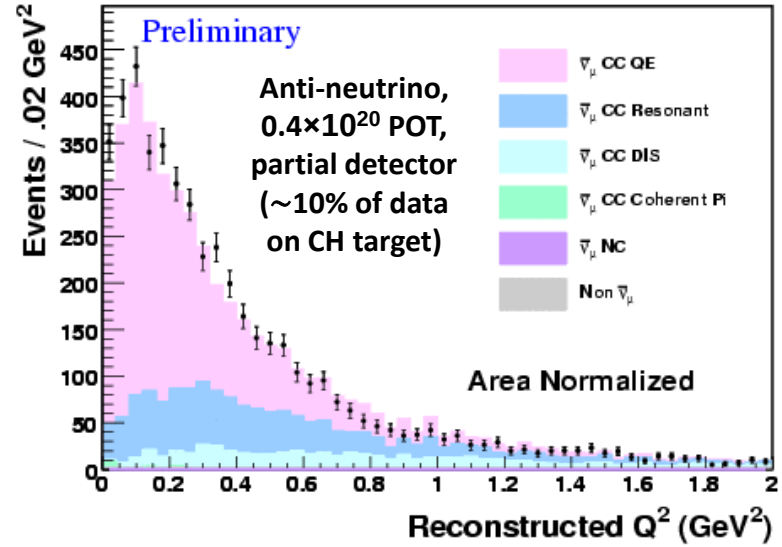


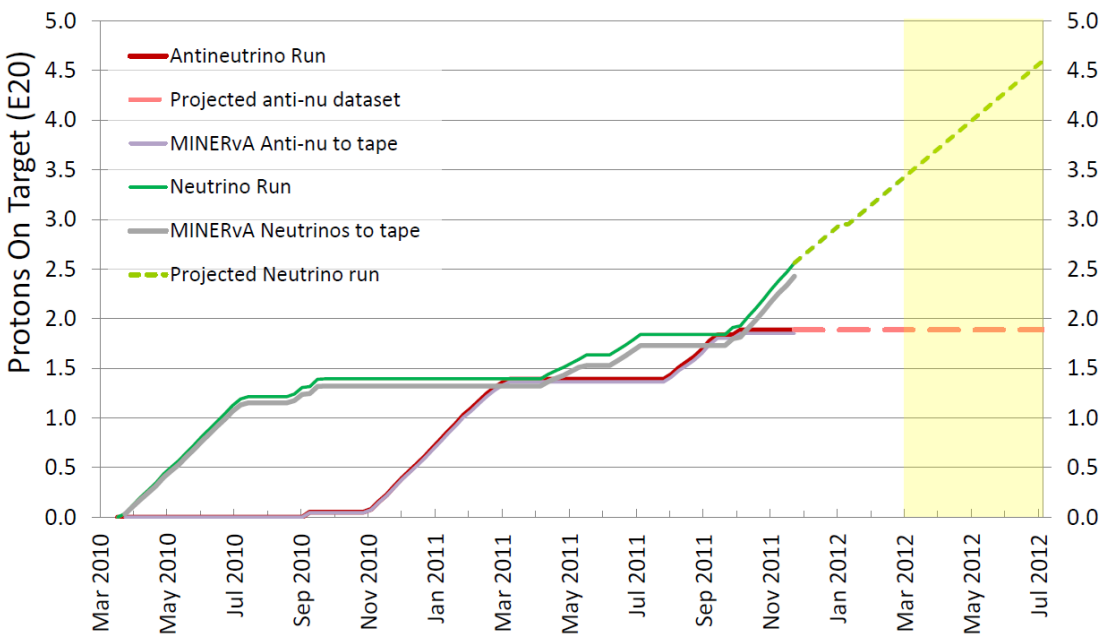
MINERνA

- First quasi-elastic and nuclear target distributions shown at NuINT 2011
- Approved for 4.9×10^{20} p.o.t of LE neutrino beam, plus multi-year run in NOνA era

  → *~20% of LE run for flux determination*



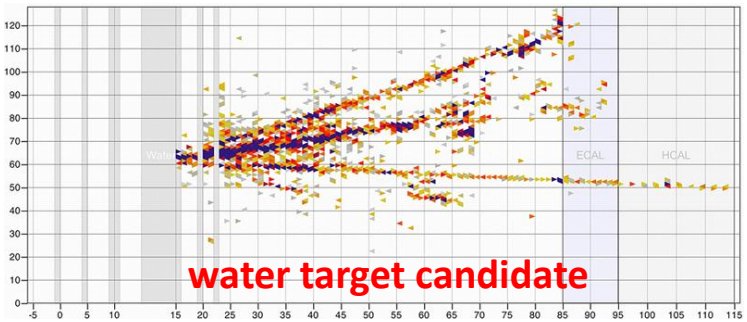


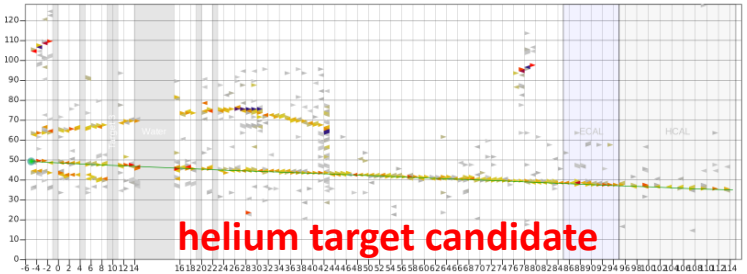


- Have received 50% of total request
- Forecast to receive 70%/80% of request if run ends in March / May
- NT08 (new spare target) expected mid-January

MINERνA

- **Water target successfully installed 3 weeks ago**
  - → *signal, background XS ratios for T2K, LBNE*
- **Cryogenic helium target**
  - → *veto wall commissioned*
  - → *filled in time for Oct. 2011 neutrino run*
  - → *will need empty target running,~30% of run*
  - → *optimal start date depends on NuMI run extension decision*





Deuterium target progress:

- **Have started discussions with ES&H to understand issues with putting 2200 L of liquefied flammable gas underground**
  - → *will propose two designs for external review*
- **Field Work Proposal to be written and sent to DOE to cover design costs**
  - → *consultant's time to evaluate preliminary package ($75k)*
  - → *engineering and drafting for condensation/ventilation/capture system*

cryogenic target

MINERνA

Analysis status and upcoming goals

- **Full reconstruction pass of all data and simulation underway**
- **Goals for spring:**
  - → *quasi-elastic results with a priori flux prediction*
  - → *nuclear target ratios of inclusive CC events versus neutrino energy*
- **Goals for summer:**
  - → *kinematics from one-pion events*
  - → *ν_e and π^0 selections and performance*
  - → *updated energy flow calorimetry*
  - → *flux predictions informed by hadron production data*

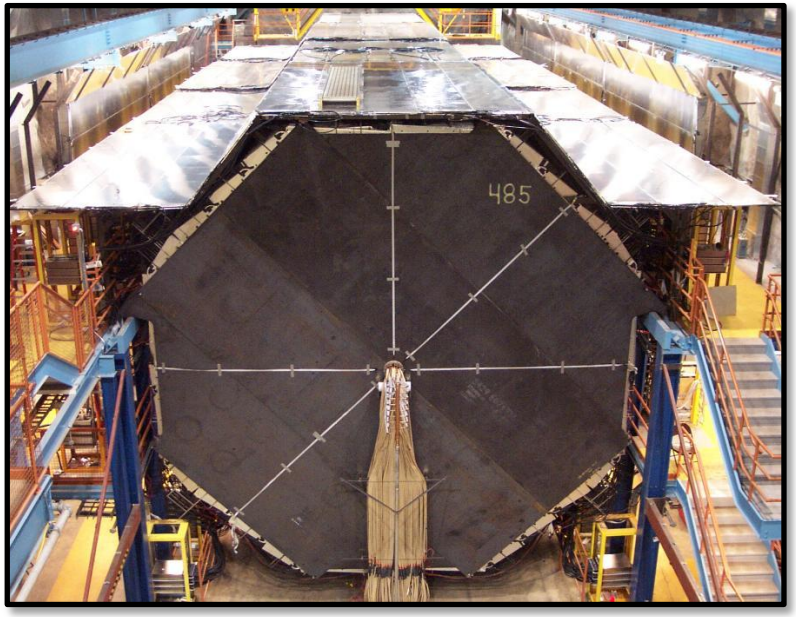
Upcoming needs

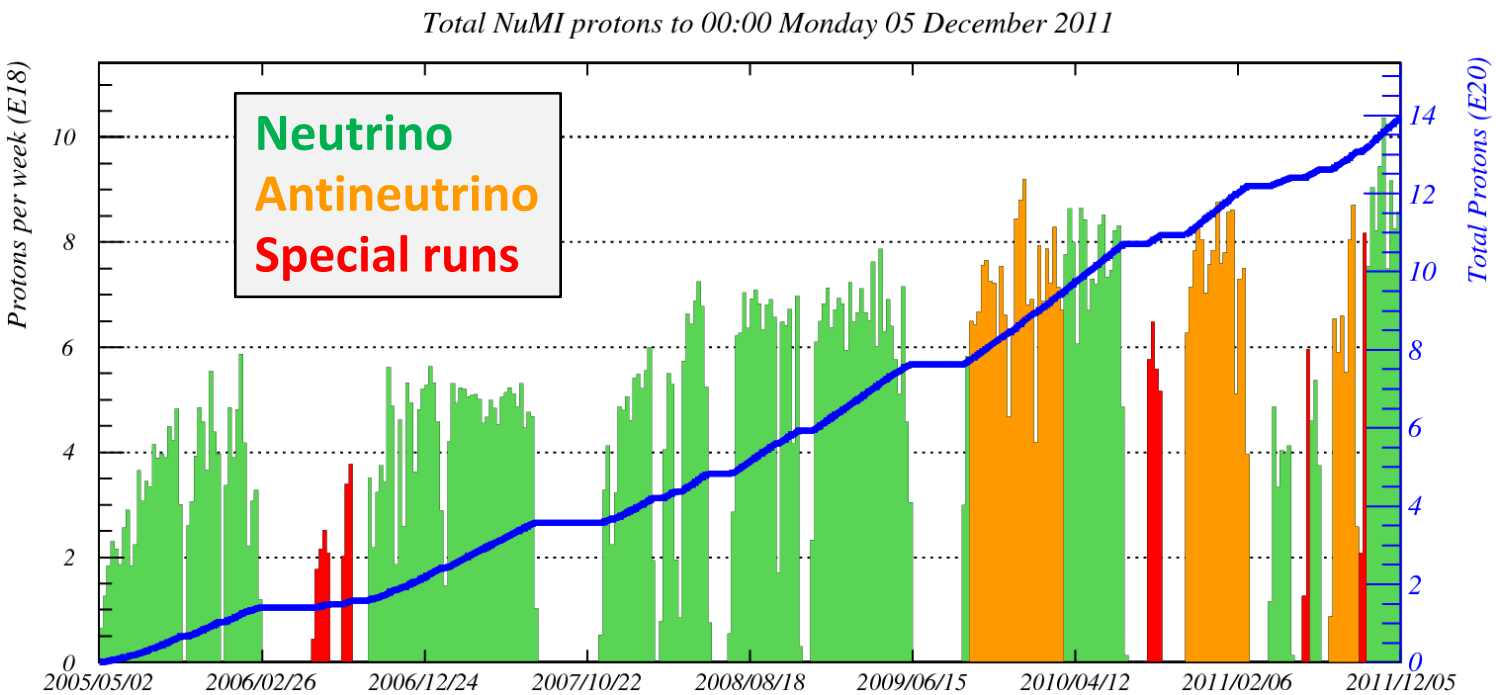
- **NOνA excavation – main concerns:**
  - → *effect of vibrations on PMTs and computer disks*
  - → *loss of helium during long power outages*
  - → *debris and water falling on unprotected detector due to vibrations*
  - → *need coordinated effort to study these issues*
- **Will need significant refurbishment of MINOS near detector DAQ for NOνA-era running; coordination needed**

The long-baseline experiments

MINOS

- **Sensitive atmospheric-scale neutrino oscillation measurements**
- **Multiple cross measurements and new physics searches (sterile neutrinos, Lorentz violation)**
- **Neutrino time-of-flight update underway**
  → *talk by R. Plunkett after the break*



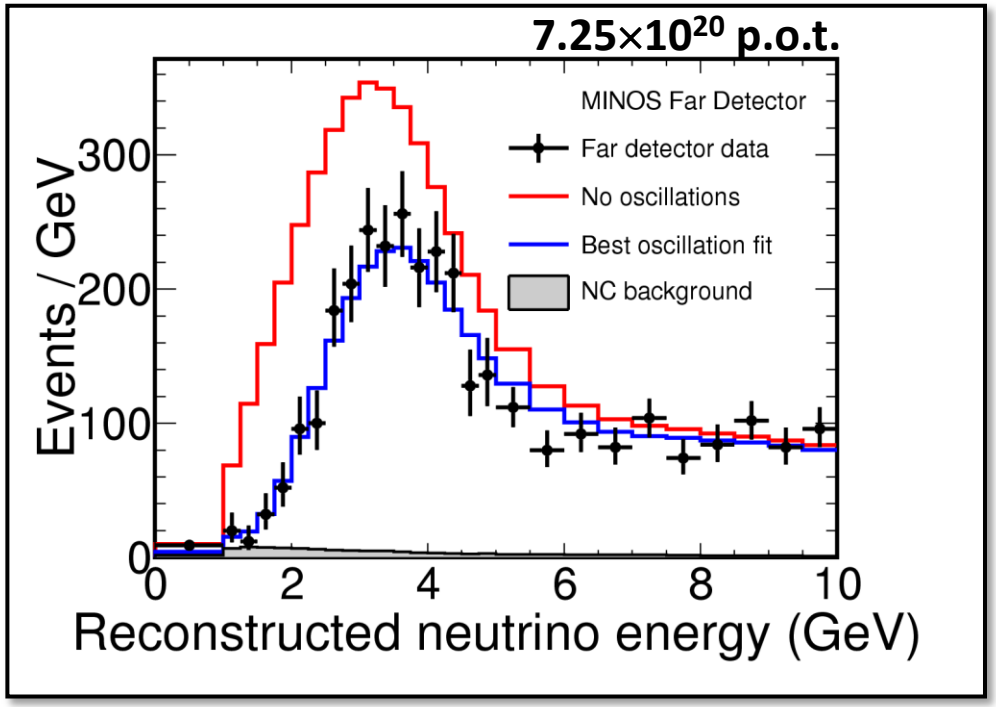


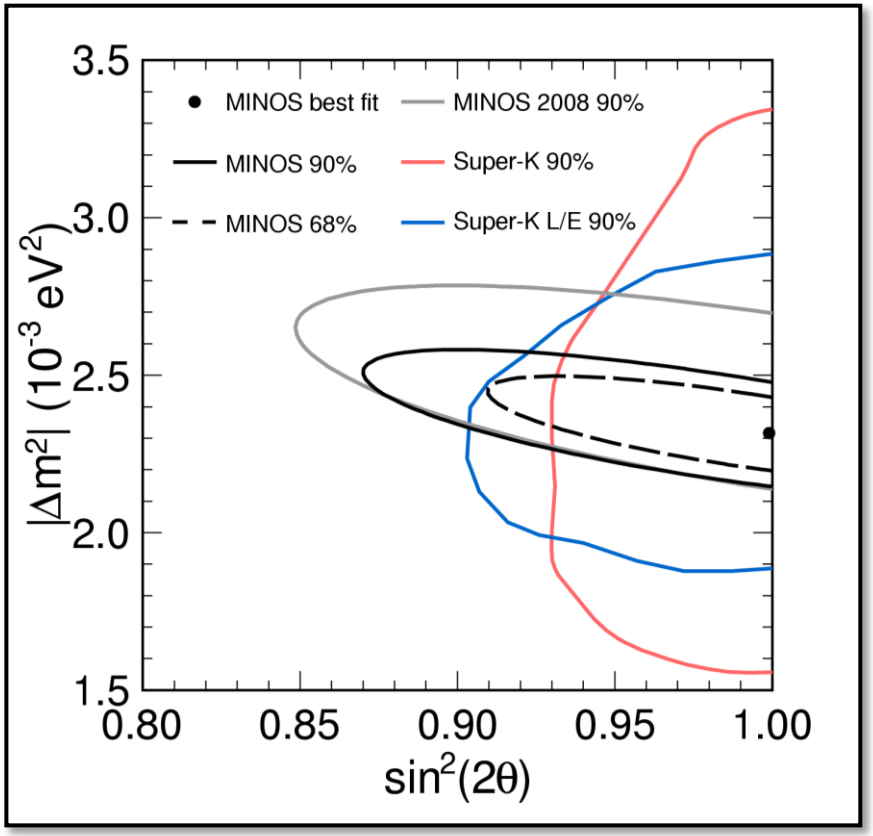
MINOS

- ν_μ **disappearance: many analysis improvements over earlier rounds**
  → shower energy resolution, anti-fiducial events, …
- **Most precise measurement of atmospheric mass splitting**

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

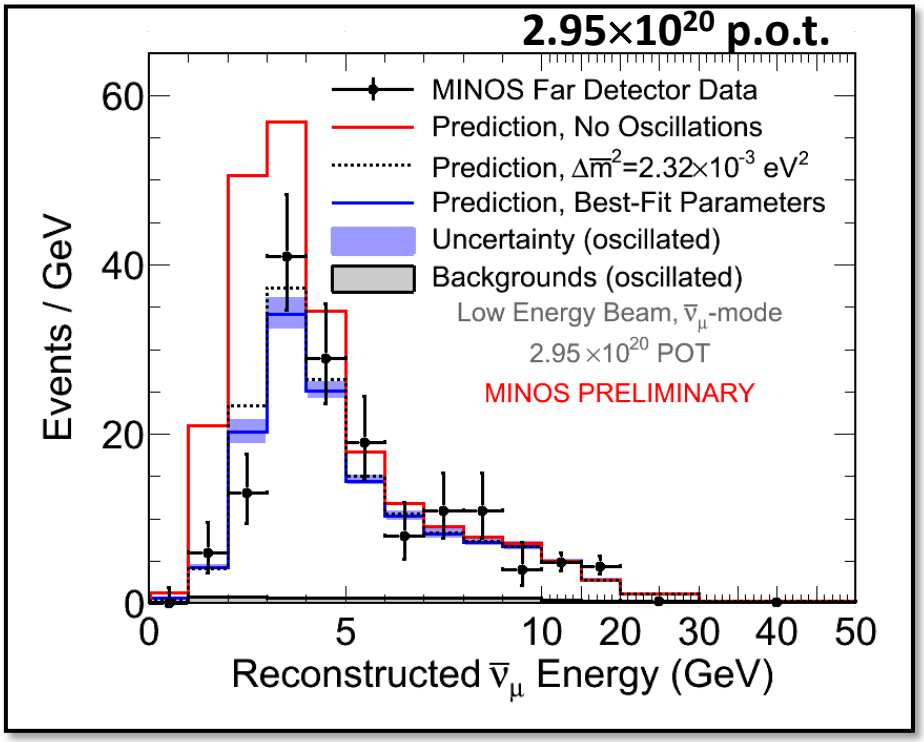
PRL **106** 181801 (2011)

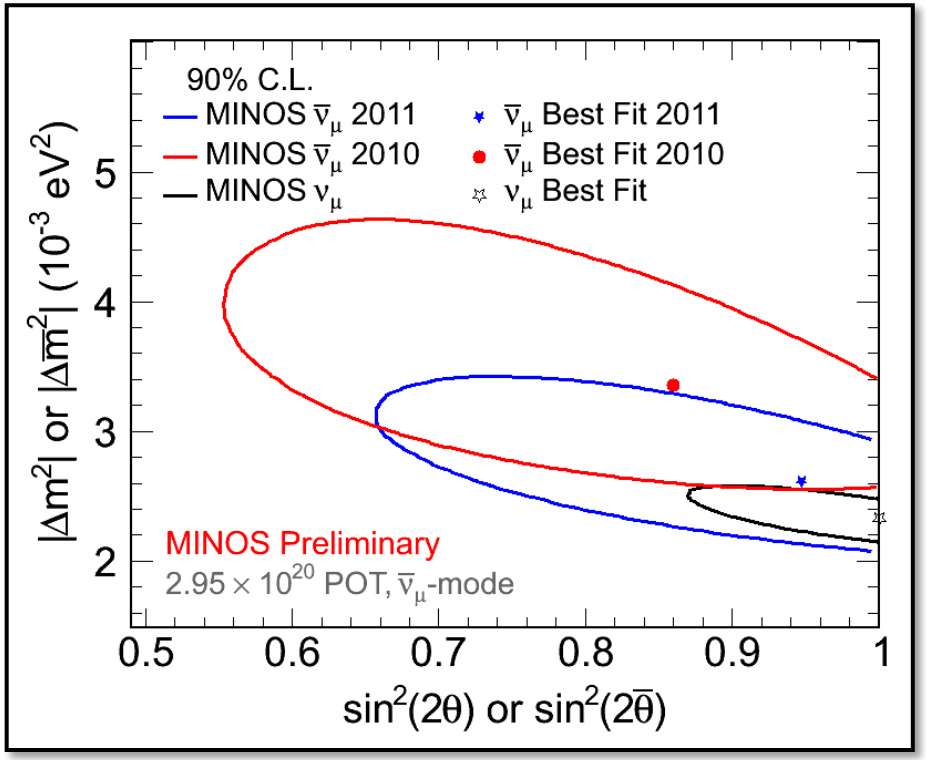




MINOS

- $\bar{\nu}_\mu$ disappearance:
  → 1.7× larger data set over 2010 result
- Tension with the observed ν_μ oscillation parameters is gone





Antineutrinos:

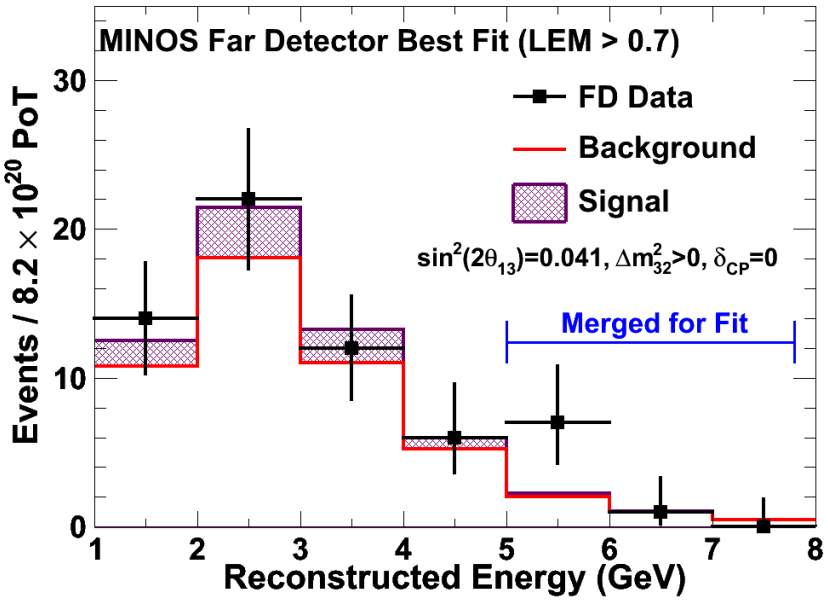
$$\Delta\overline{m}^2_{\rm atm} = (2.62^{+0.31}_{-0.28})\times 10^{-3}\ {\rm eV}^2$$

Neutrinos:

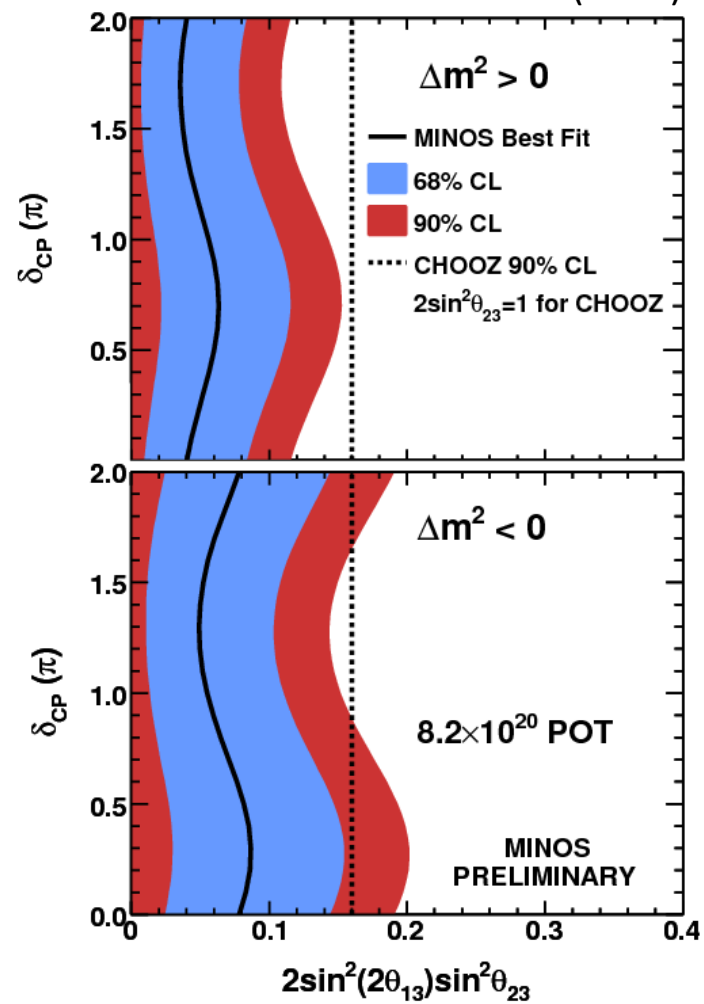
$$\Delta m^2_{\rm atm} = (2.32^{+0.12}_{-0.08})\times 10^{-3}\ {\rm eV}^2$$

MINOS

- ν_e **appearance: search for non-zero** θ_{13}
  → new event selection, spectral fits, additional data



PRL **107** 181802 (2011)



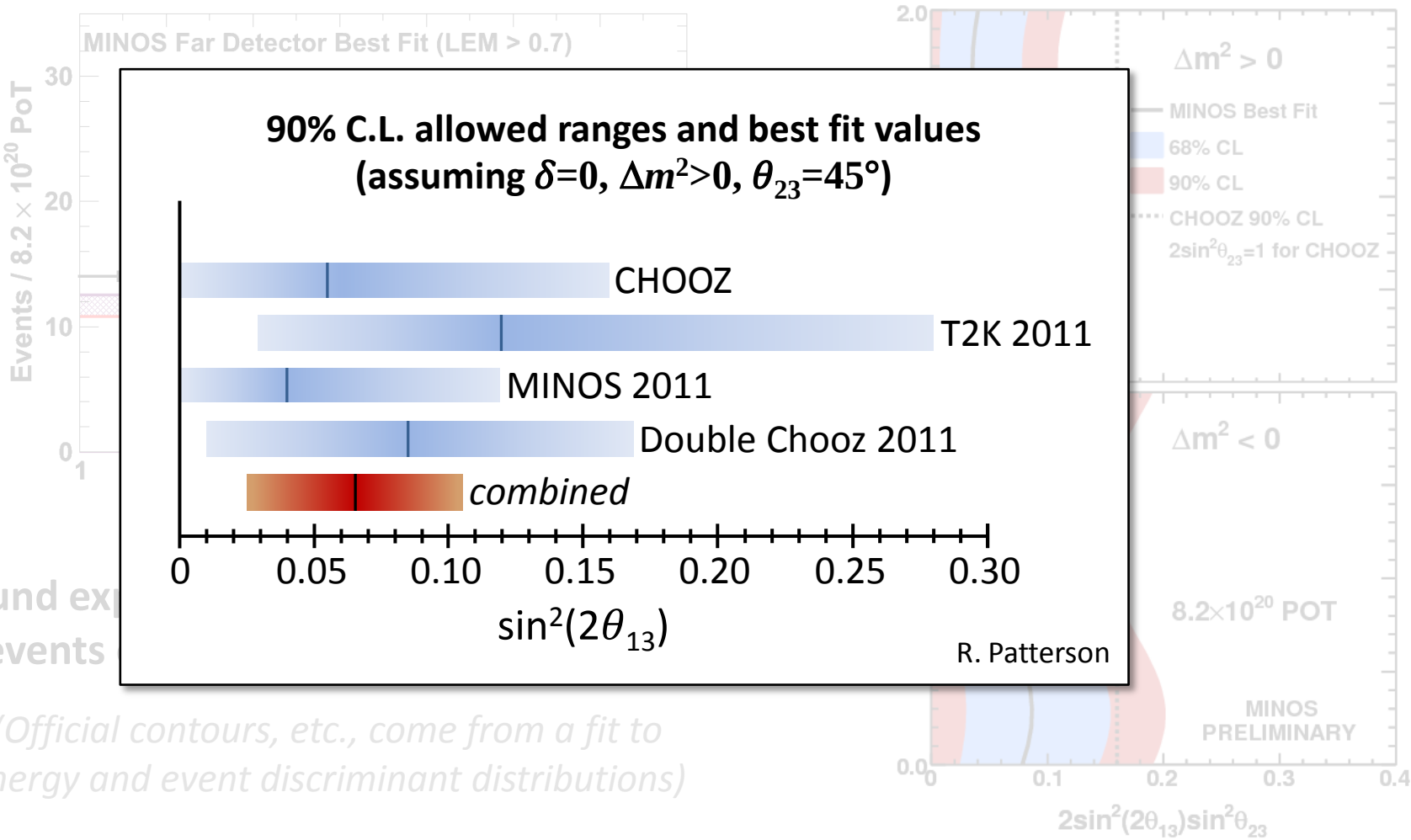
background expectation: 49.6 ± 7.0(stat) ± 2.7(syst)
events observed: 62 (1.7σ above bckgnd.)

(Official contours, etc., come from a fit to energy and event discriminant distributions)

MINOS

- ν_e appearance: search for non-zero θ_{13}
  → *new event selection, spectral fits, additional data*

PRL **107** 181802 (2011)



90% C.L. allowed ranges and best fit values
(assuming δ=0, Δm^2>0, θ_{23}=45°)

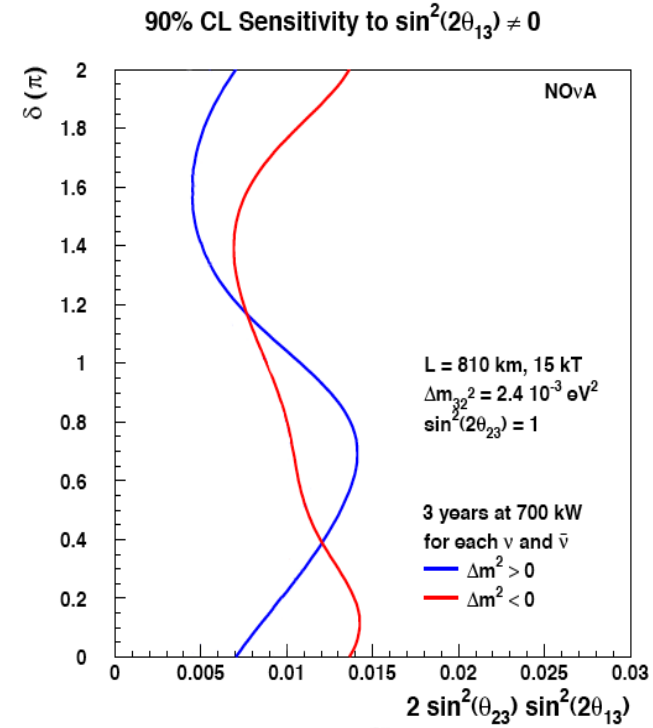
R. Patterson

background exp
events

(Official contours, etc., come from a fit to energy and event discriminant distributions)

NOνA

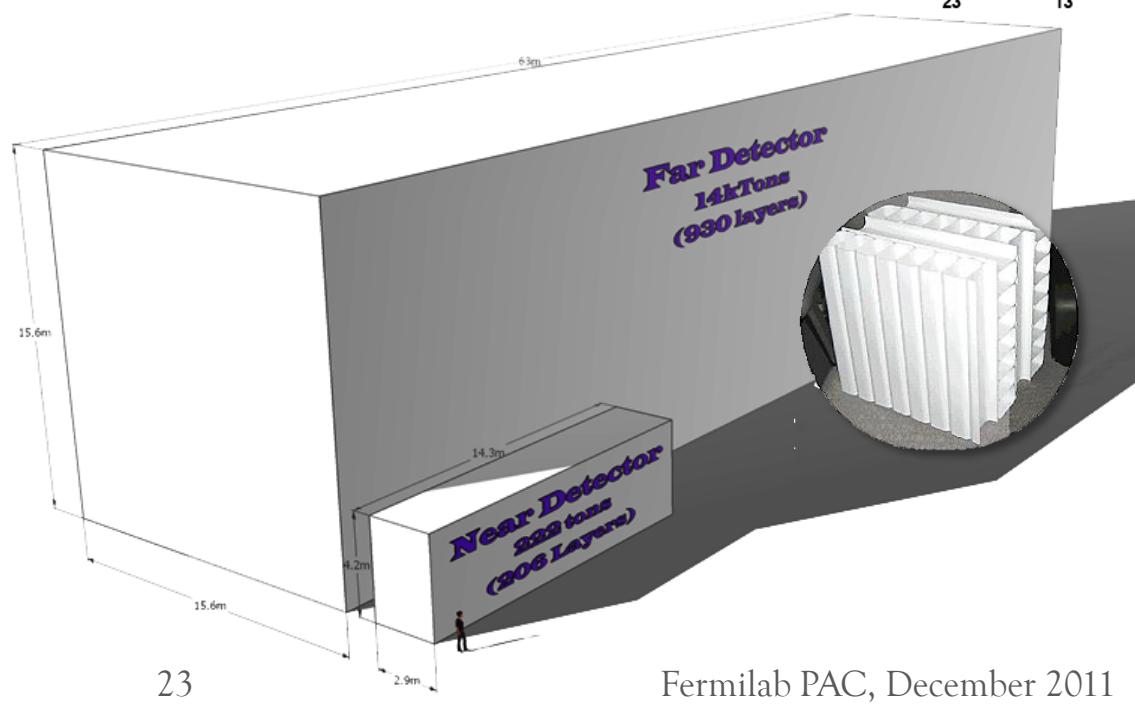
- ***Off-axis beam and fine-grained detector:***
  excellent ν_e selection capabilities
- **$\nu_\mu \rightarrow \nu_e$ search:** ***θ_{13}, CP violation, mass hierarchy***
  Implications spanning: **leptogenesis, mass generation mechanisms, unification, $0\nu\beta\beta$ and Majorana nature, cosmology**
- **ν_μ and $\bar{\nu}_\mu$ disappearance:** ***θ_{23} non-maximal? BSM?***



Sensitivity to θ_{13} "turns on" very rapidly with early protons-on-target

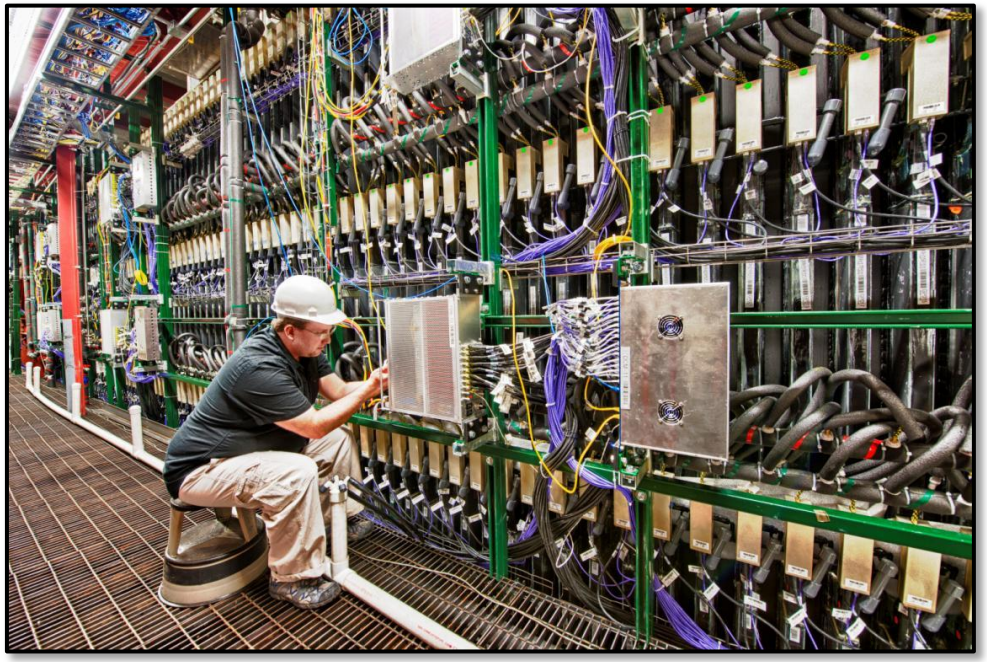
Can already probe down to $\sin^2(2\theta_{13}) \sim 0.03$ (90% C.L.) in only 4 months with <u>half detector</u> and <u>700 kW NuMI</u> beam

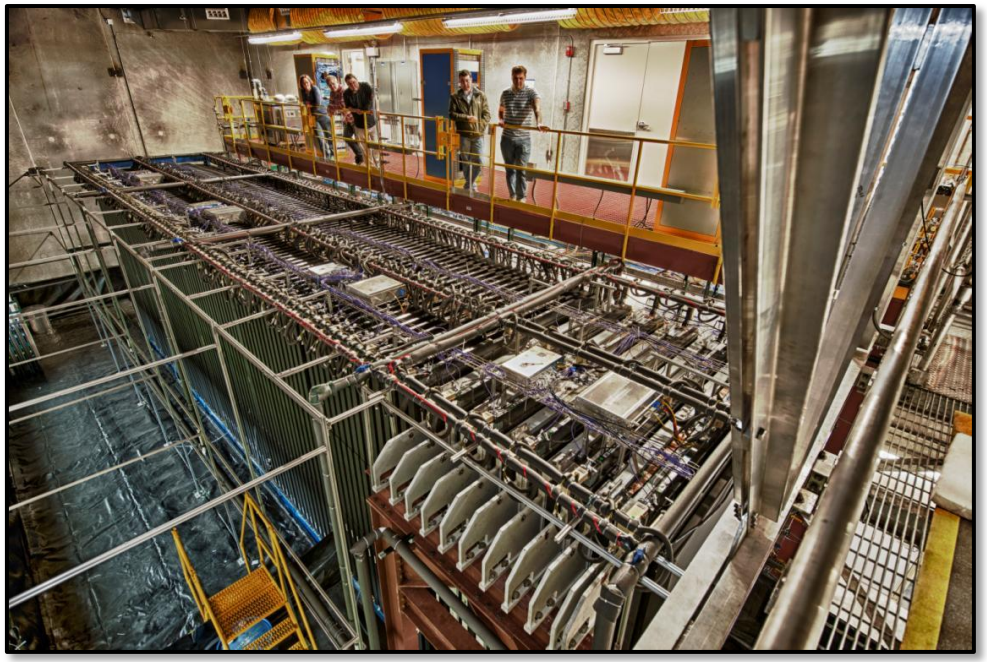
→ Important to get that first proton as soon as possible

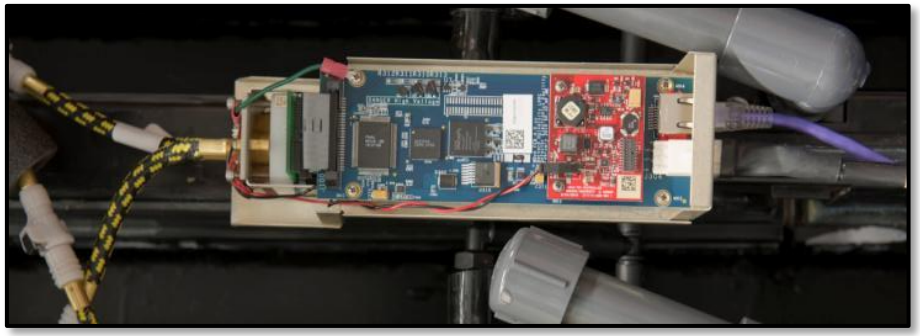


NOνA

- **Near Detector On the Surface (NDOS) is operational**
- **NDOS has served well as assembly prototype**
  - → ***fiber manifold improvements***
  - → ***installation improvements***
  - → ***APD and carrier board coatings***
- **Developing calibration and analysis software using cosmic muon and neutrino data (NuMI and BNB)**

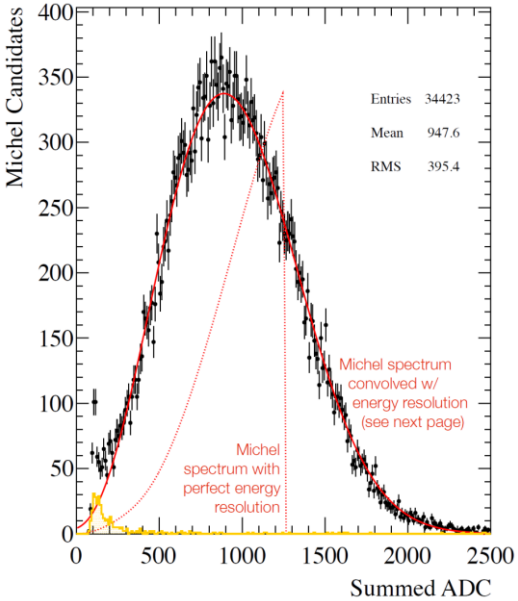




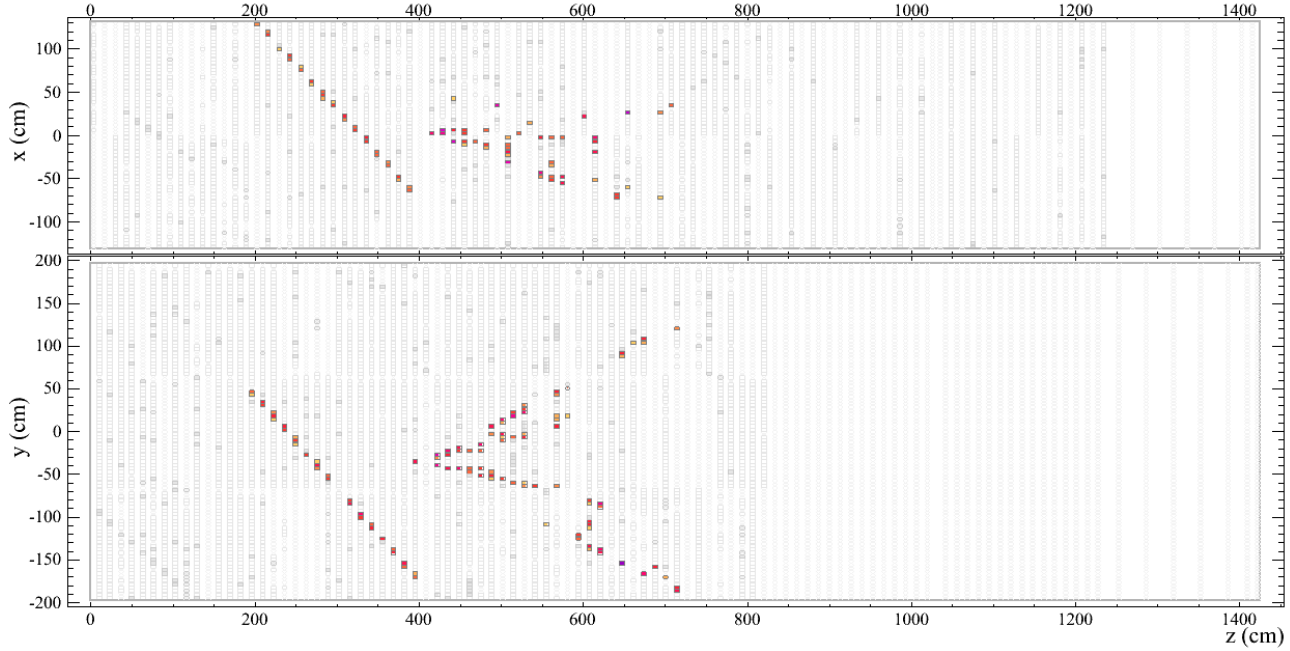


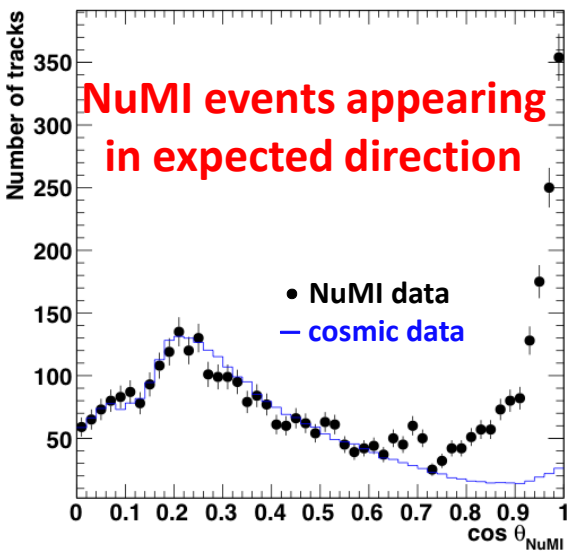
NOνA: NDOS

Michel electrons

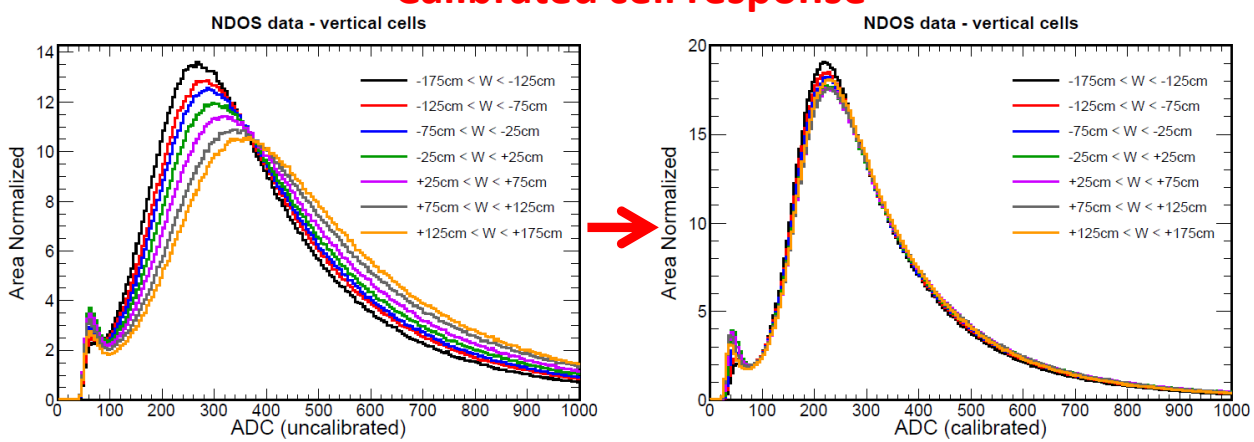


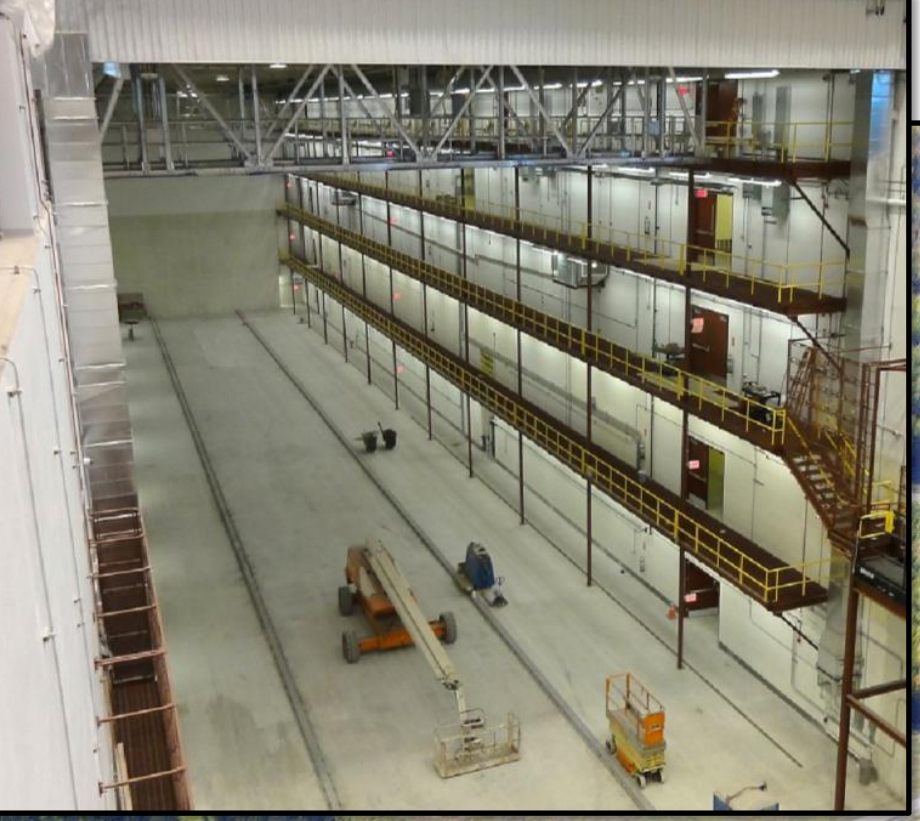
NuMI neutrino event with cosmic ray muon





Calibrated cell response

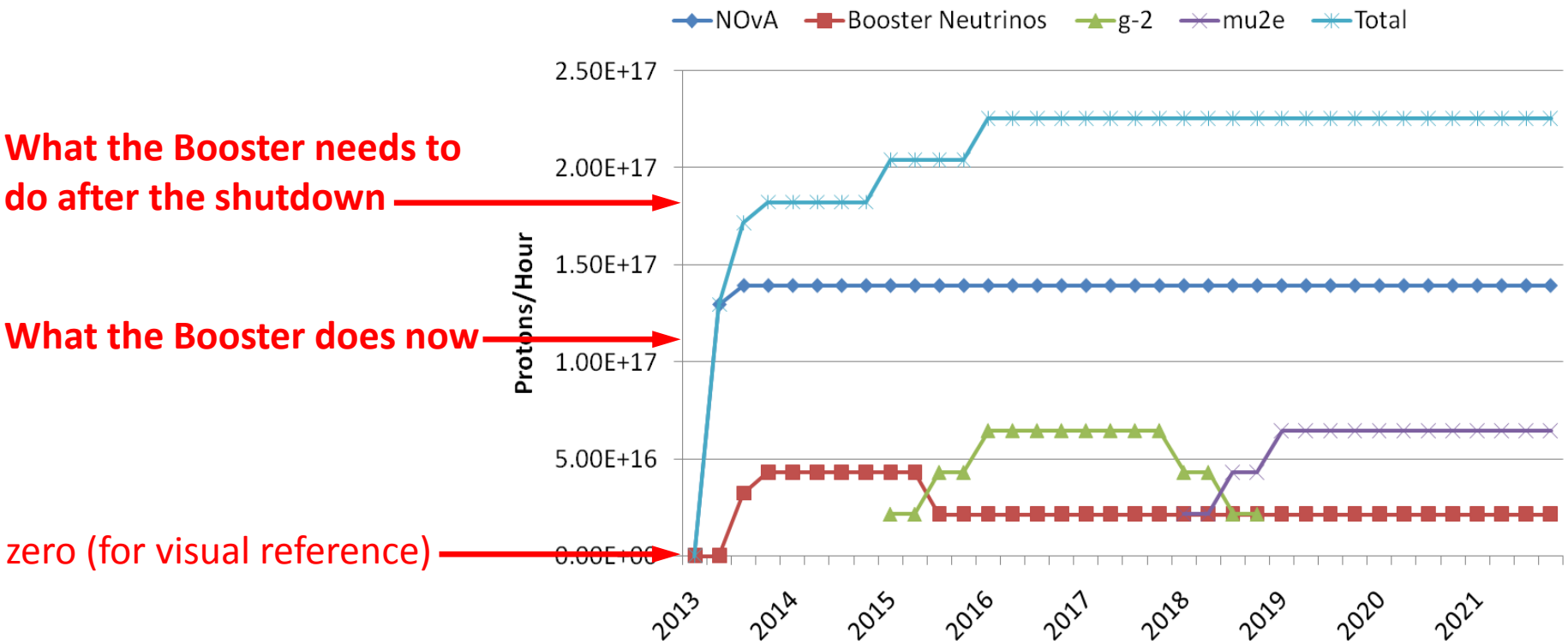




- Beneficial occupancy obtained (April 2011)
- Block pivoter installation underway
- First modules this winter
- Half detector complete by return of beam (February 2013)
- Data taking begins immediately

Protons

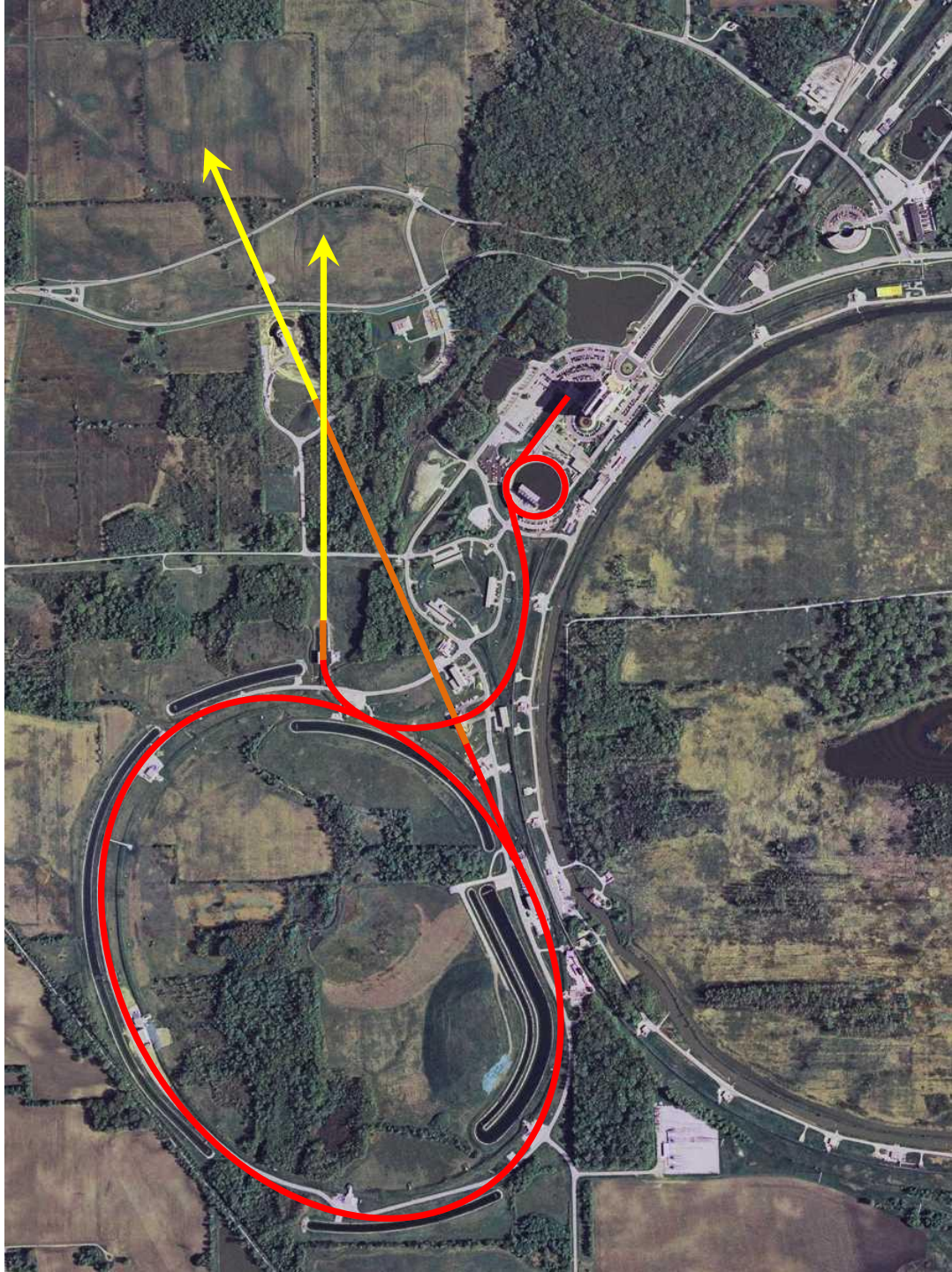
- **700-kW NuMI upgrade requires corresponding improvement in Booster throughput:**



- **Lab's "*Proton Improvement Plan*" is critical to the success of the near-term neutrino program** ***(and the long-term program more generally)***

Summary

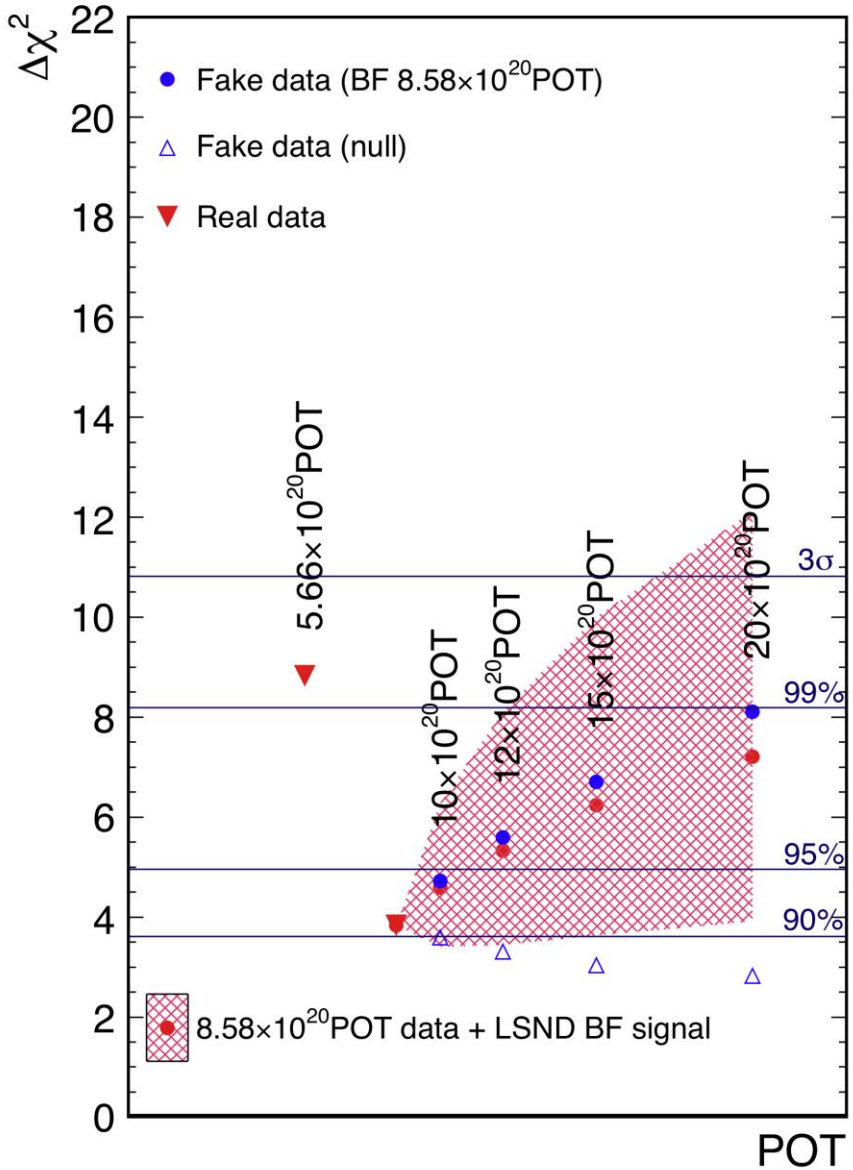
- **Fermilab is the world's leading neutrino physics facility**
- **Positioned to maintain that role**
- **Impressive array of recent & upcoming physics output:**
  - → atmospheric-scale osc.
  - → θ_{13} and θ_{13}-driven physics
  - → hints of new phenomena
  - → sterile ν and other BSM searches
  - → extensive suite of neutrino-nucleus cross sections



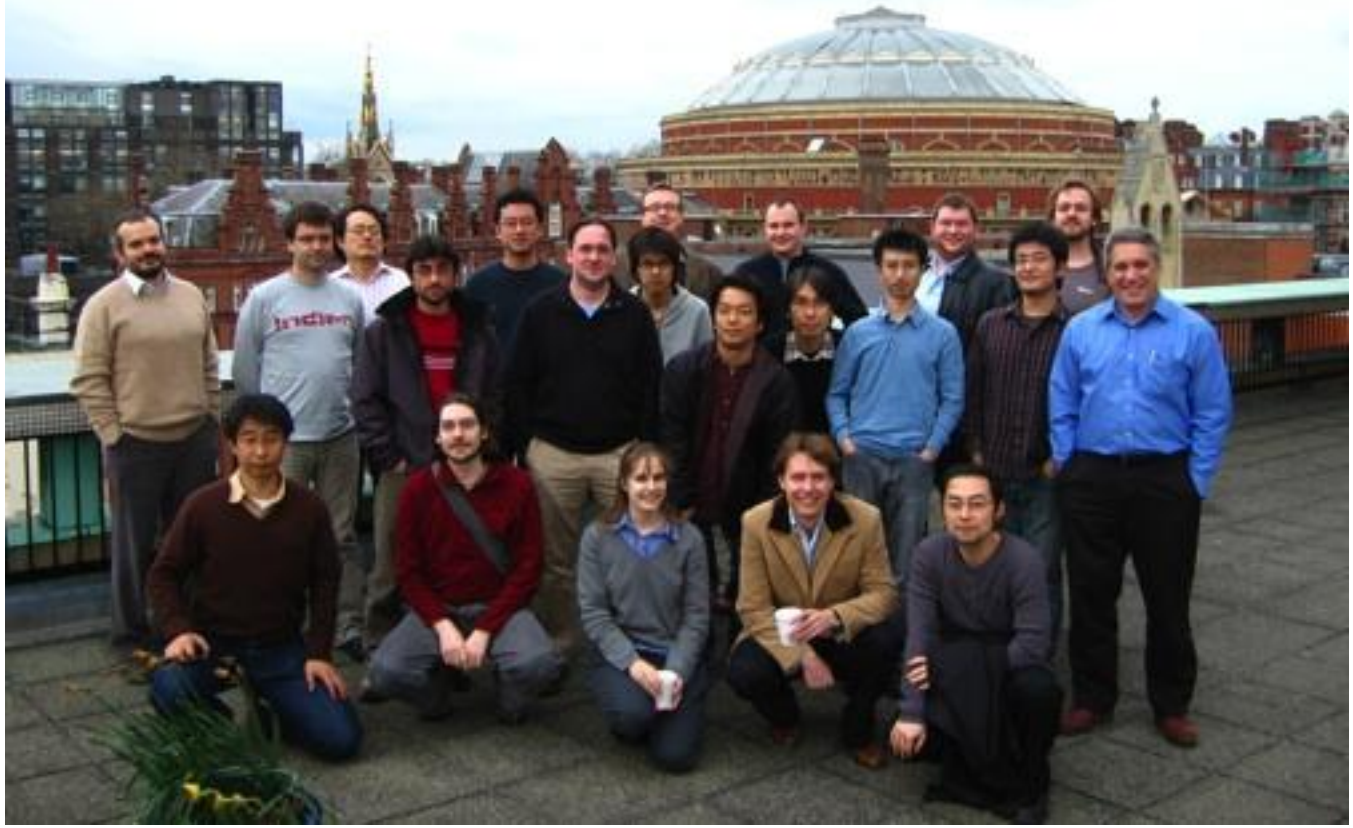
(a few unused graphics)

MiniBooNE near-term

- **Continued antineutrino running to reduce statistical error**
  - **→ Run goal of 15×10^{20} p.o.t. in $\bar{\nu}$ mode**
- **Combined ν and $\bar{\nu}$ oscillation fits with new data**
  - **→ Test 3+1 models with and without CP violation**
- **SciBooNE/MiniBooNE joint disappearance results expected by spring 2012**
  - **→ Test various 3+*N* models**



SciBooNE Collaboration



SciBooNE Collaboration Meeting, London March 2008
(Total collaboration: 60 authors, 17 institutions, 5 nations)

SciBooNE

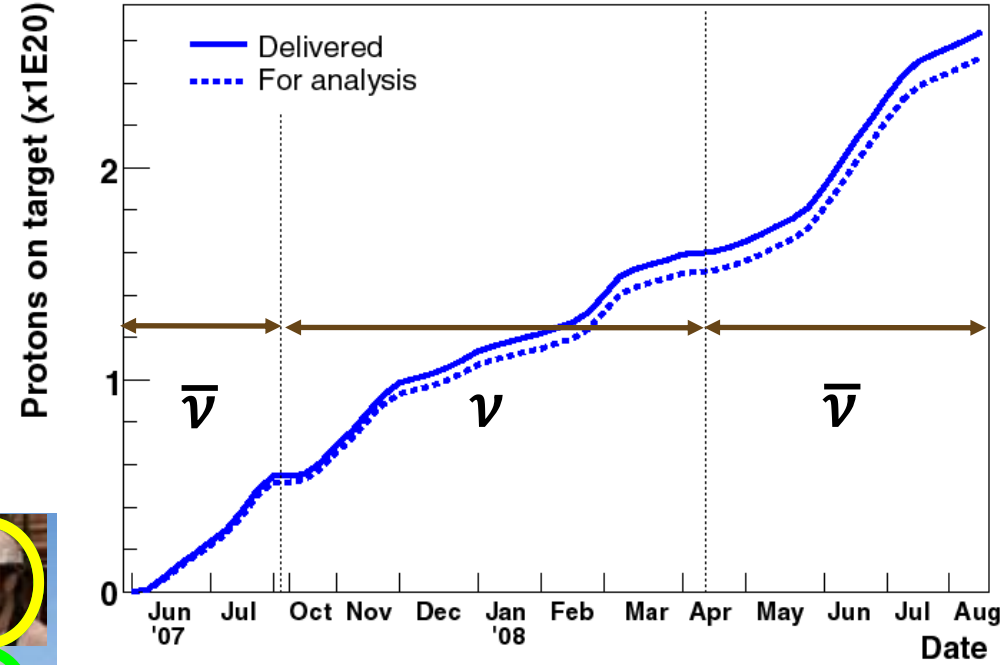
Data collected

June 2007 – August 2008

95% data efficiency

neutrino: 0.99×10^{20} p.o.t.

antineutrino: 1.53×10^{20} p.o.t.



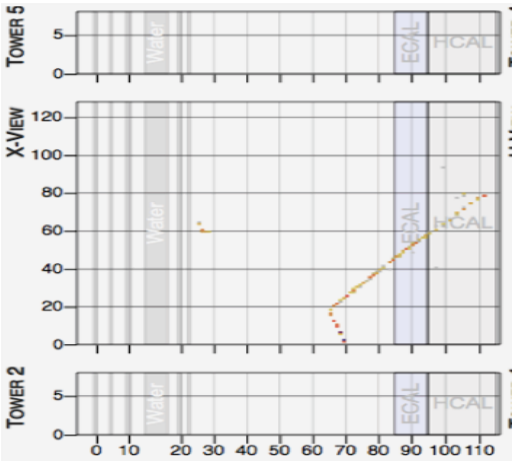
Students

- **Graduated: 8 PhD and 3 Masters**
- **Active: 3 PhD and 1 Masters**

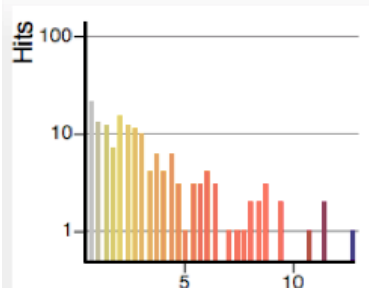
Analysis of neutrino and antineutrino data sets ongoing.

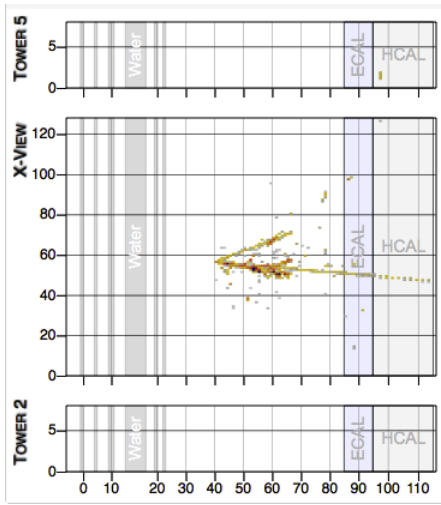
MINERνA Data

- One out of three views shown, color=energy

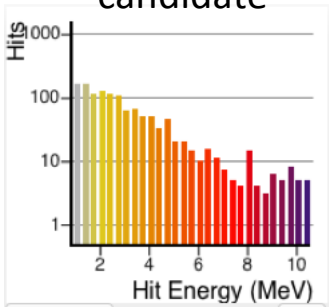


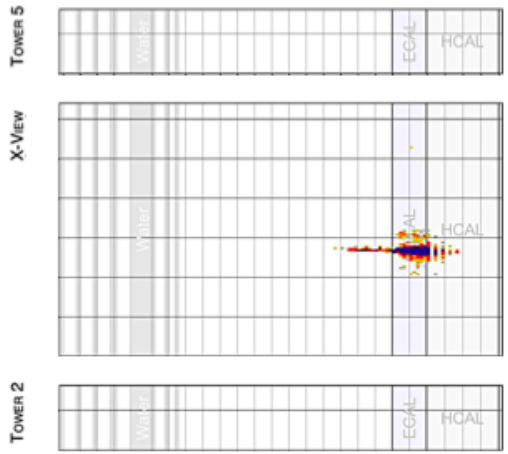
Quasi-elastic candidate



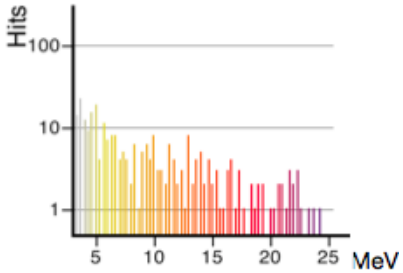


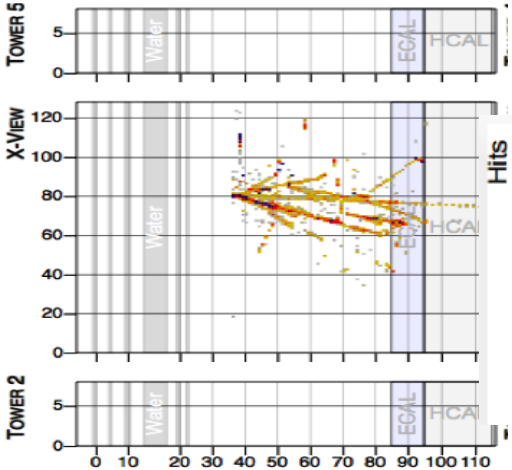
Resonant candidate



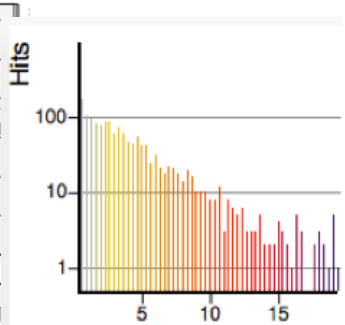


Single Electron candidate

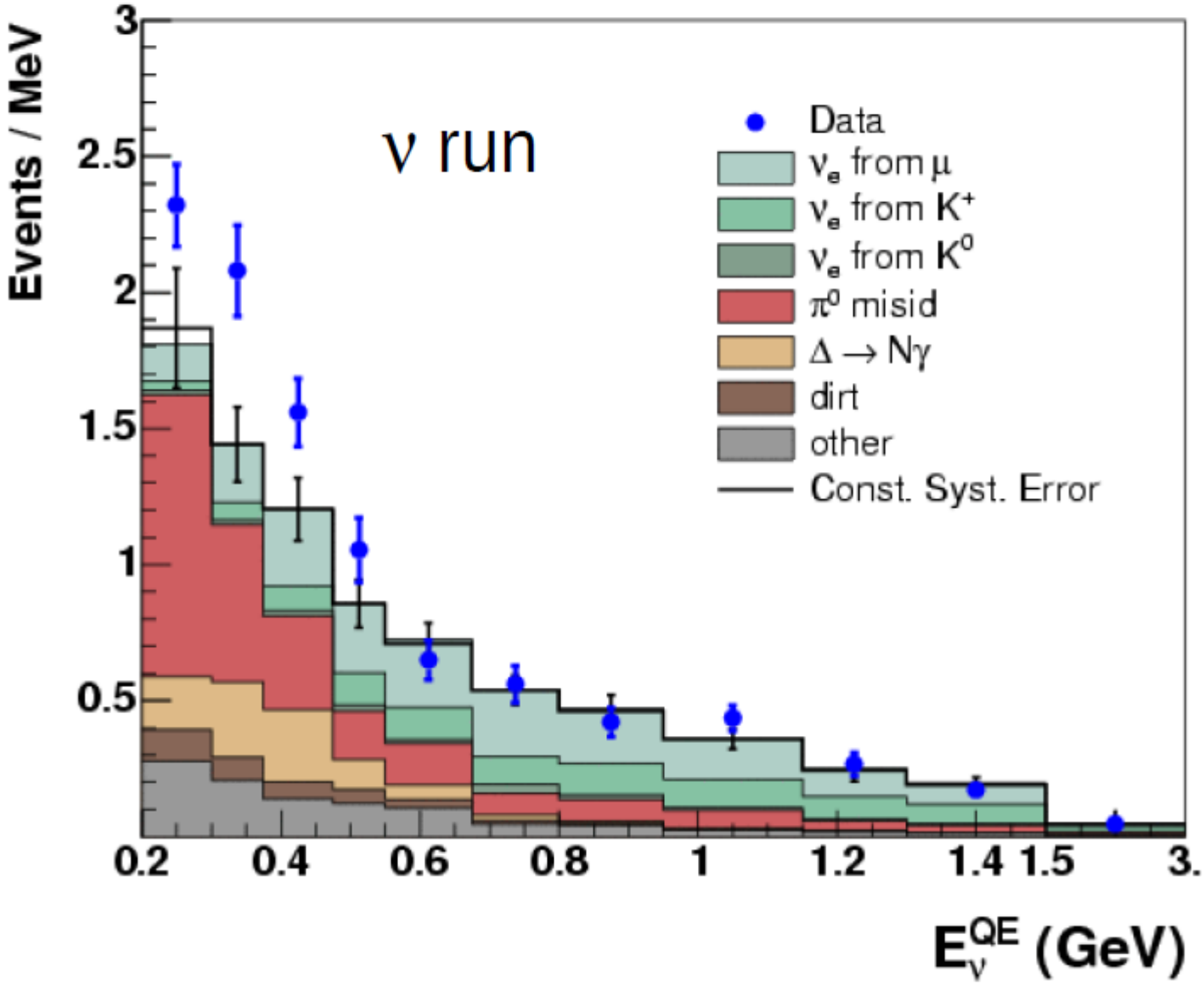




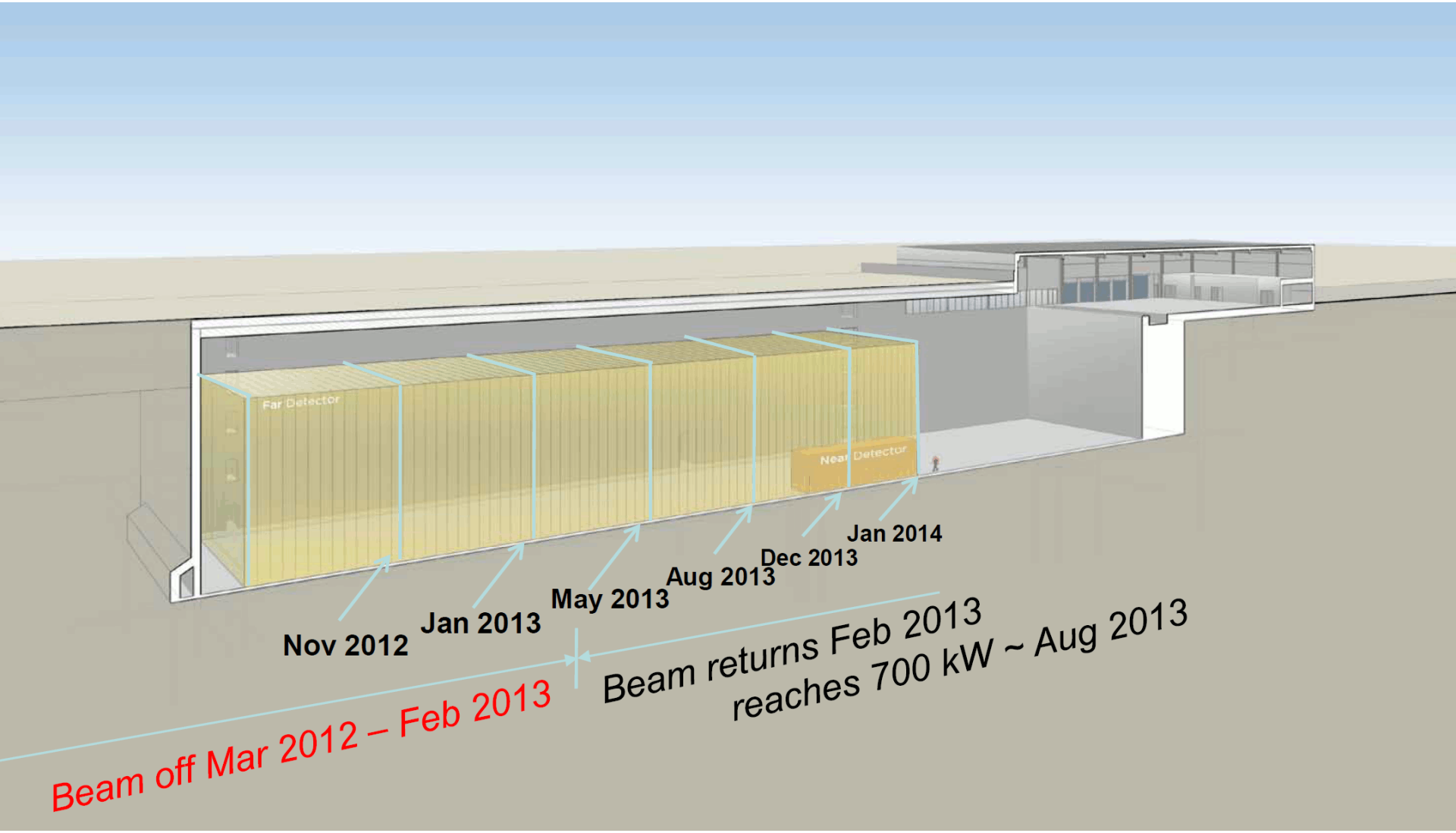
Deep Inelastic Scatter candidate



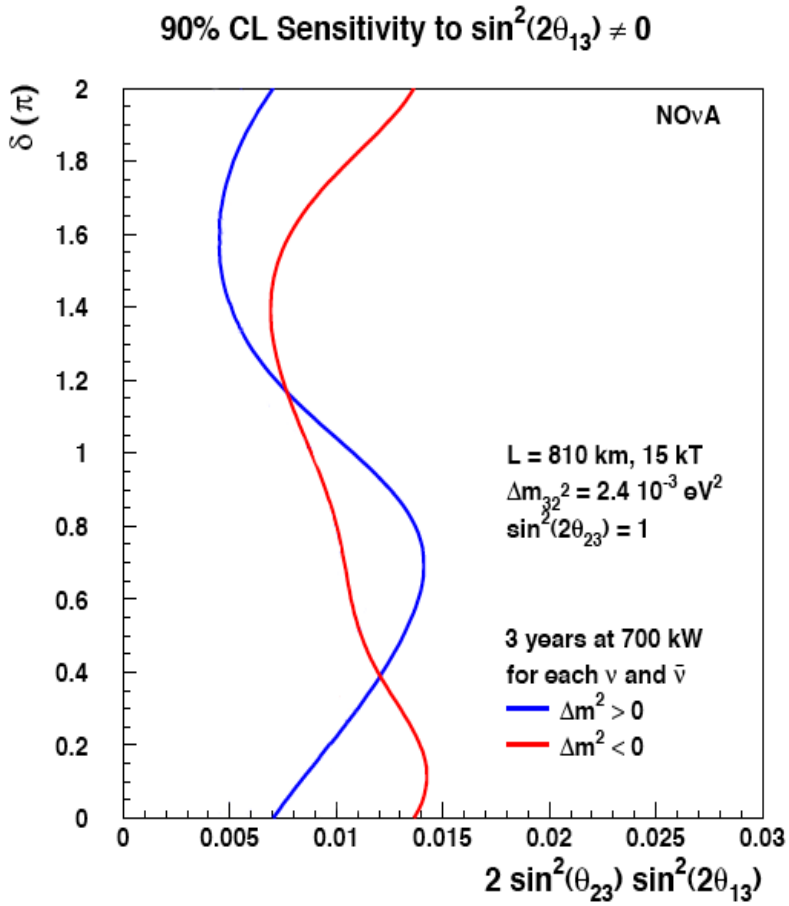
MiniBooNE neutrino-mode data

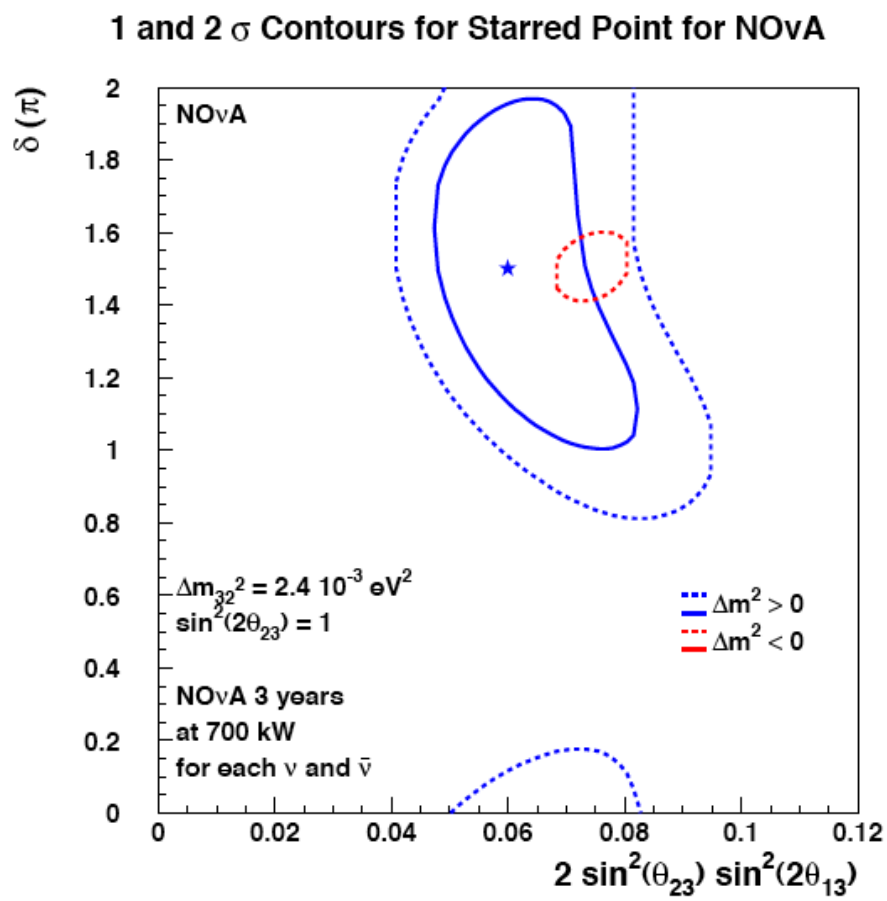
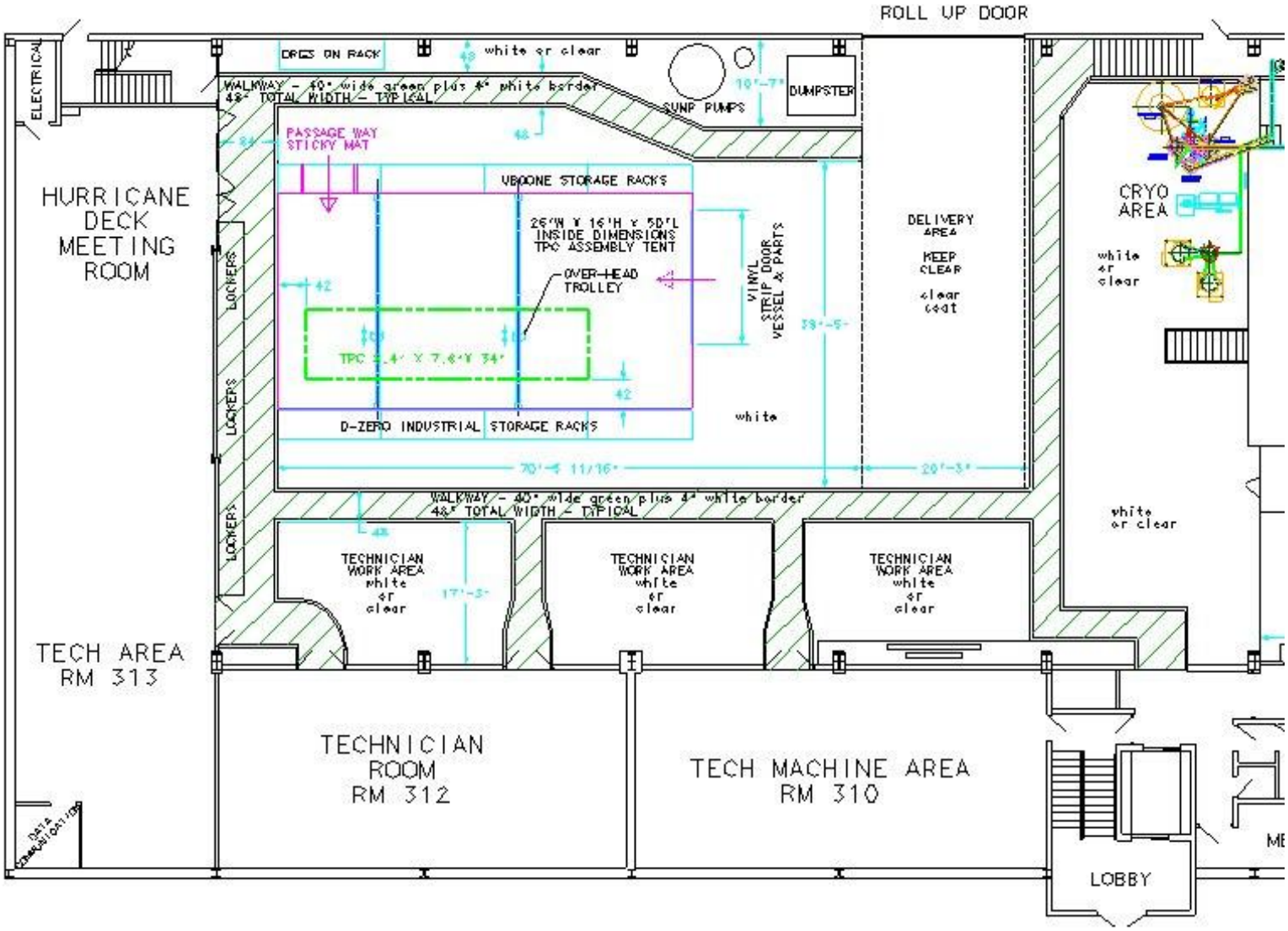


NOνA installation timeline



NOνA example contours





MicroBooNE assembly layout