Neutrino Program Overview

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FRA Physics Visiting Committee

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Big Picture in Neutrino Physics

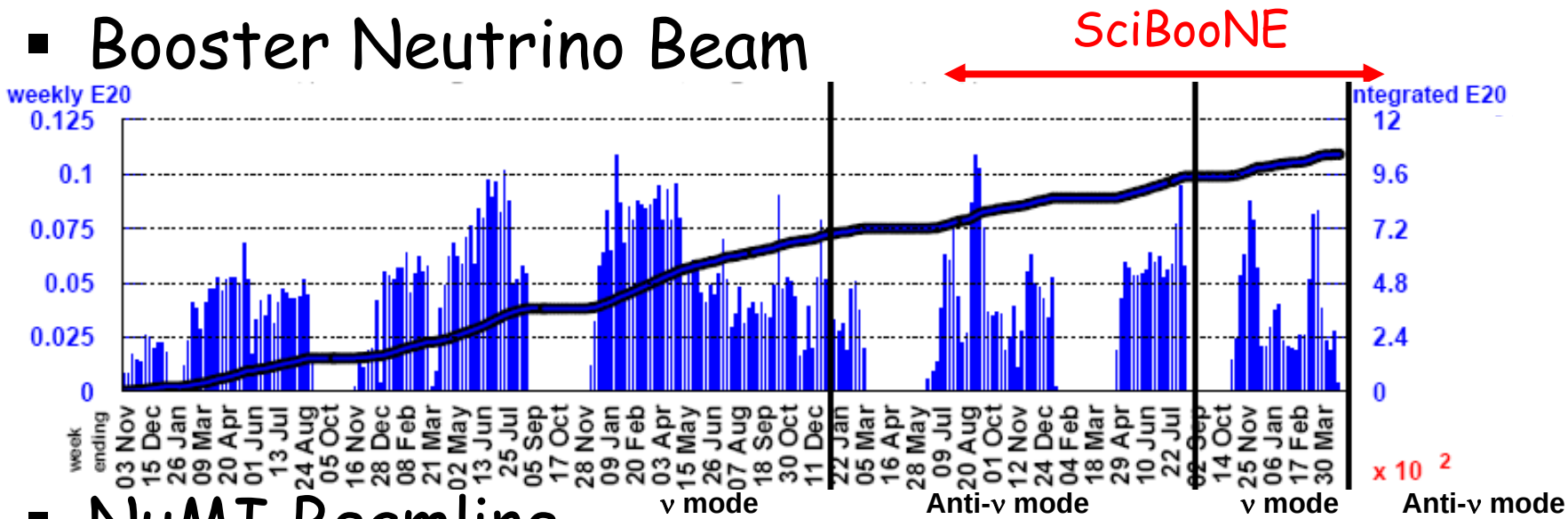
- Neutrinos have mass and oscillate
- It looks like there are two mass splittings
  - MiniBooNE did not confirm LSND, so life is simple again
  - Two mass splittings; 3 mass eigenstates
  - 3x3 mixing matrix: 3 angles and a CP-violating phase
- Current efforts
  - Getting next step in precision on largest mass splitting
  - Taking data to first factor of two in last unmeasured mixing angle (MINOS)
  - Preparing for the next steps: understanding neutrino interactions (SciBooNE and MINERvA)
- Next steps: Discovery that requires precision!
  - Want to see $\nu_\mu \rightarrow \nu_e$ at "atmospheric" Δm^2
  - Want to compare neutrino and antineutrino oscillations
  - Ultimate goal: CP violation and neutrino mass hierarchy

Outline

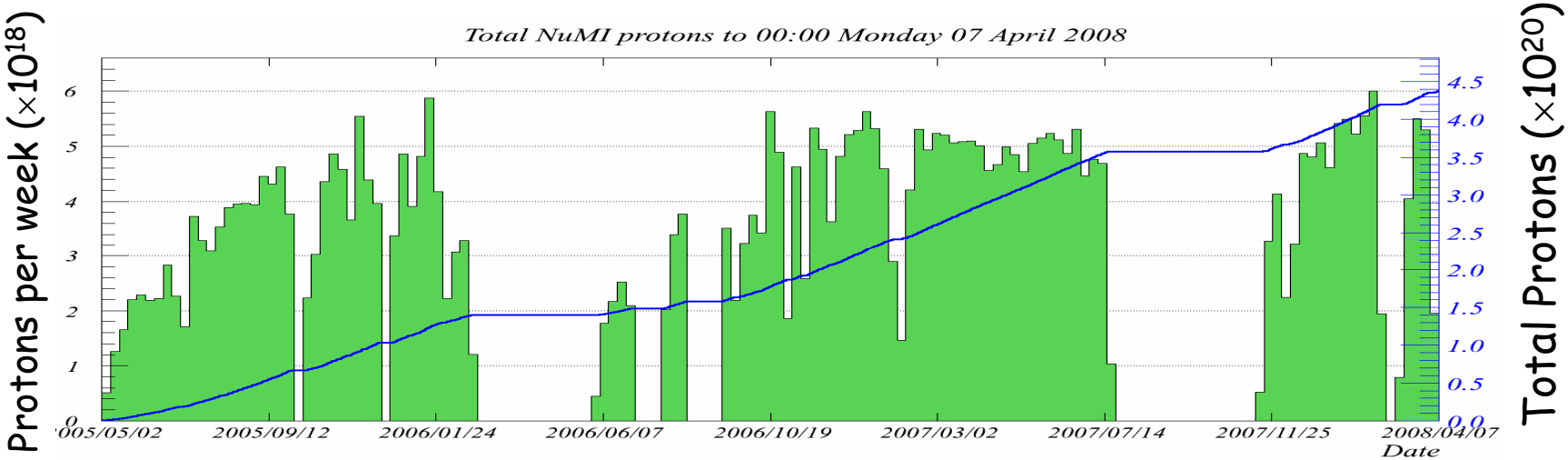
- Status of the Currently Running Experiments
  - MINOS
  - MiniBooNE and SciBooNE
- Physics highlights from Neutrino Program:
  - Ocillations
  - Cross Sections
- Program of Upcoming Experiments
  - MINERvA
  - ArgoNeuT (T962)
  - NOvA
- Long-term Future Planning
  - Phased Liquid Argon R&D Program
  - Physics at Project X
- Conclusions

Proton delivery to ν Beamlines

- Booster Neutrino Beam

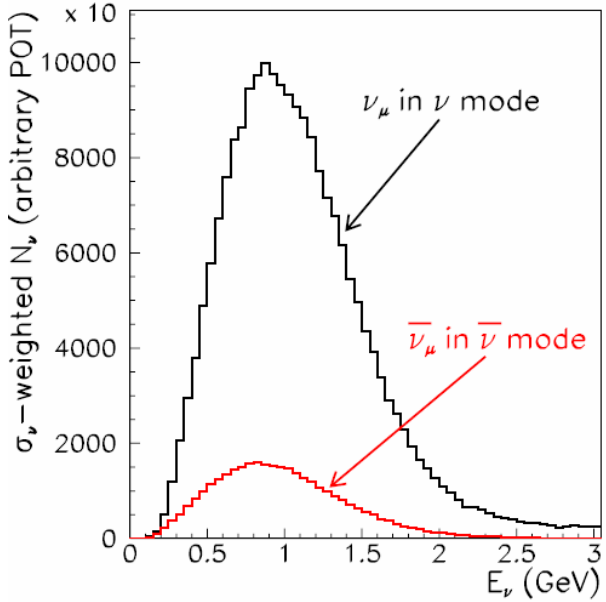


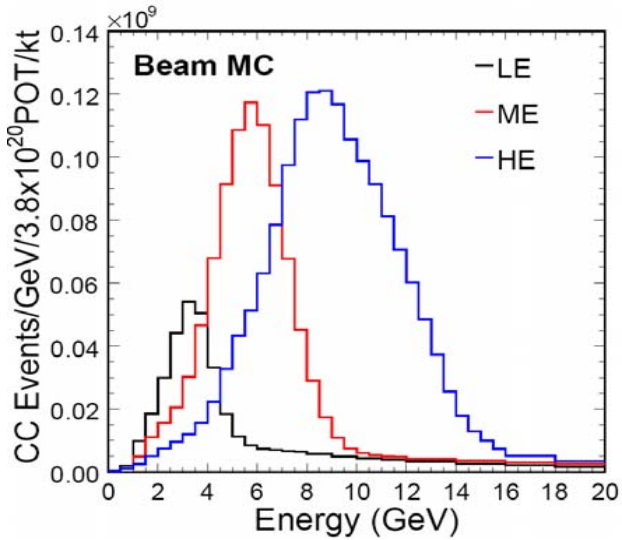
- NuMI Beamline



Neutrino Events

- Booster Beamline
  - MiniBooNE
    - Protons received: 6.6 $\times 10^{20}$ (ν) and 2.3 $\times 10^{20}$ (anti-ν)
    - Events accumulated: 870k
  - SciBooNE
    - Protons received: 1.0 $\times 10^{20}$ (ν) and 0.54 $\times 10^{20}$ (anti-ν)
    - Events accumulated: 24k ν, 5k anti-ν
- NuMI Beamline
  - MINOS
    - Protons received: 4.5 $\times 10^{20}$
    - Near Detector events: 10M
    - Far Detector events: hundreds
    - Variable Energy tunes available





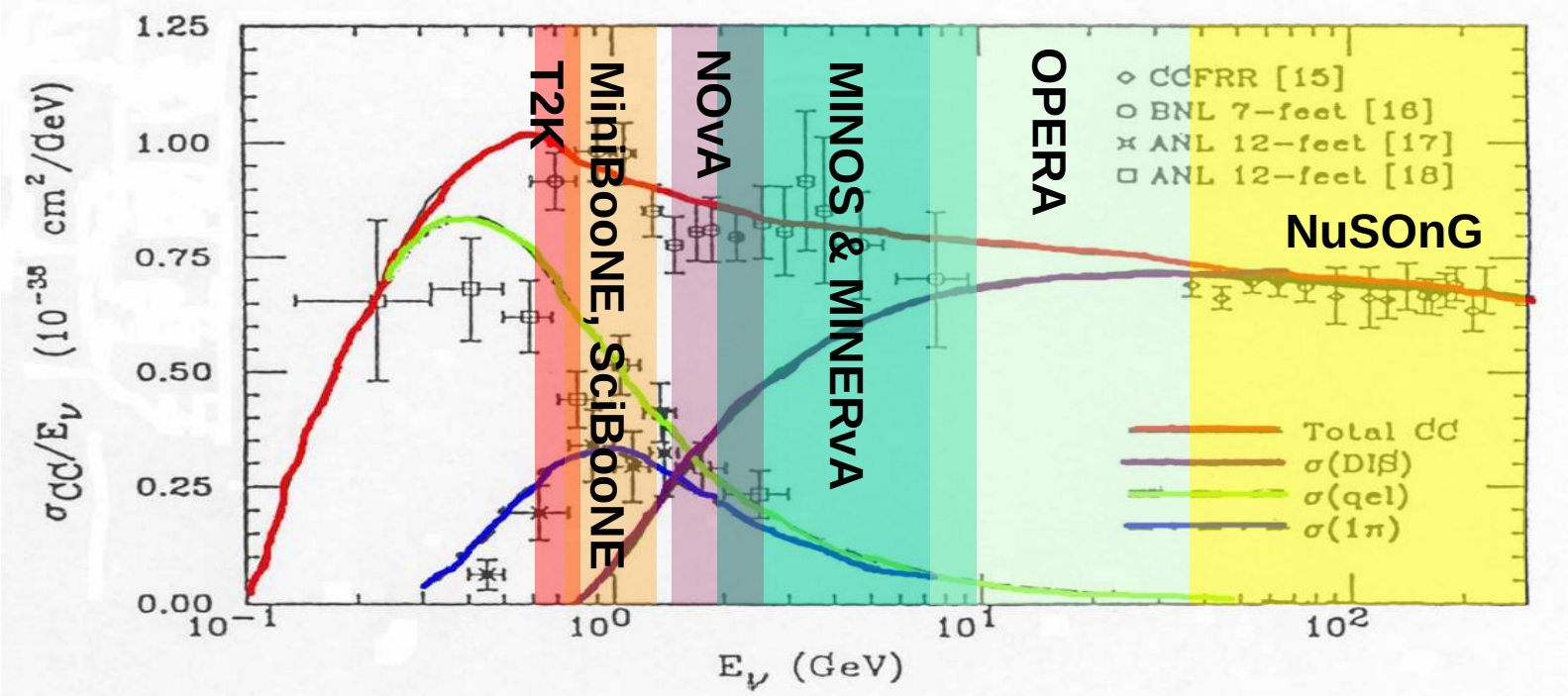
Plot courtesy G.Zeller

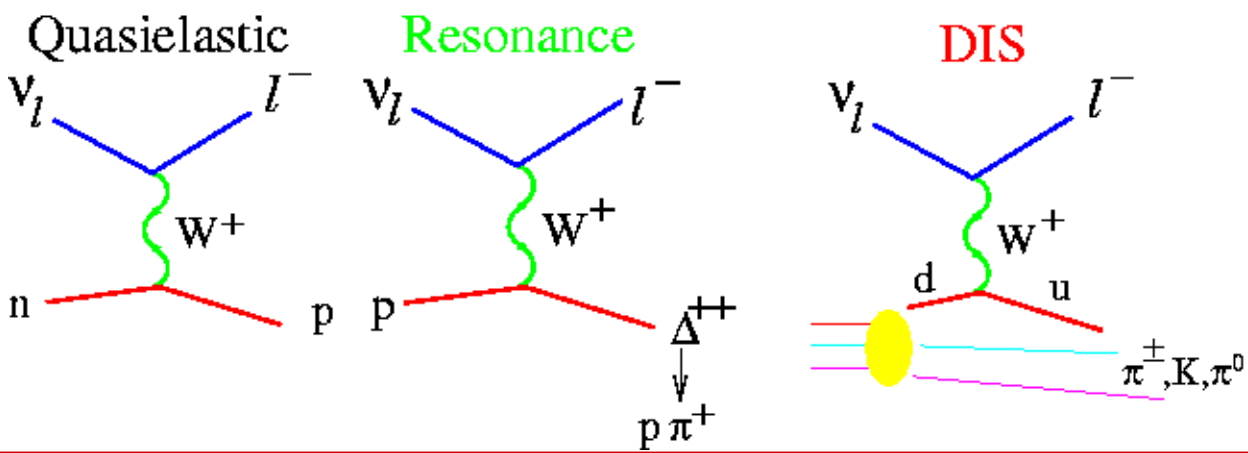
What do beamlines need

- These neutrino spectra and these protons on target depend on many things
- Protons
- Target and Horns
- People who can deliver the protons
- People who can fix components when they break
- Spare components!

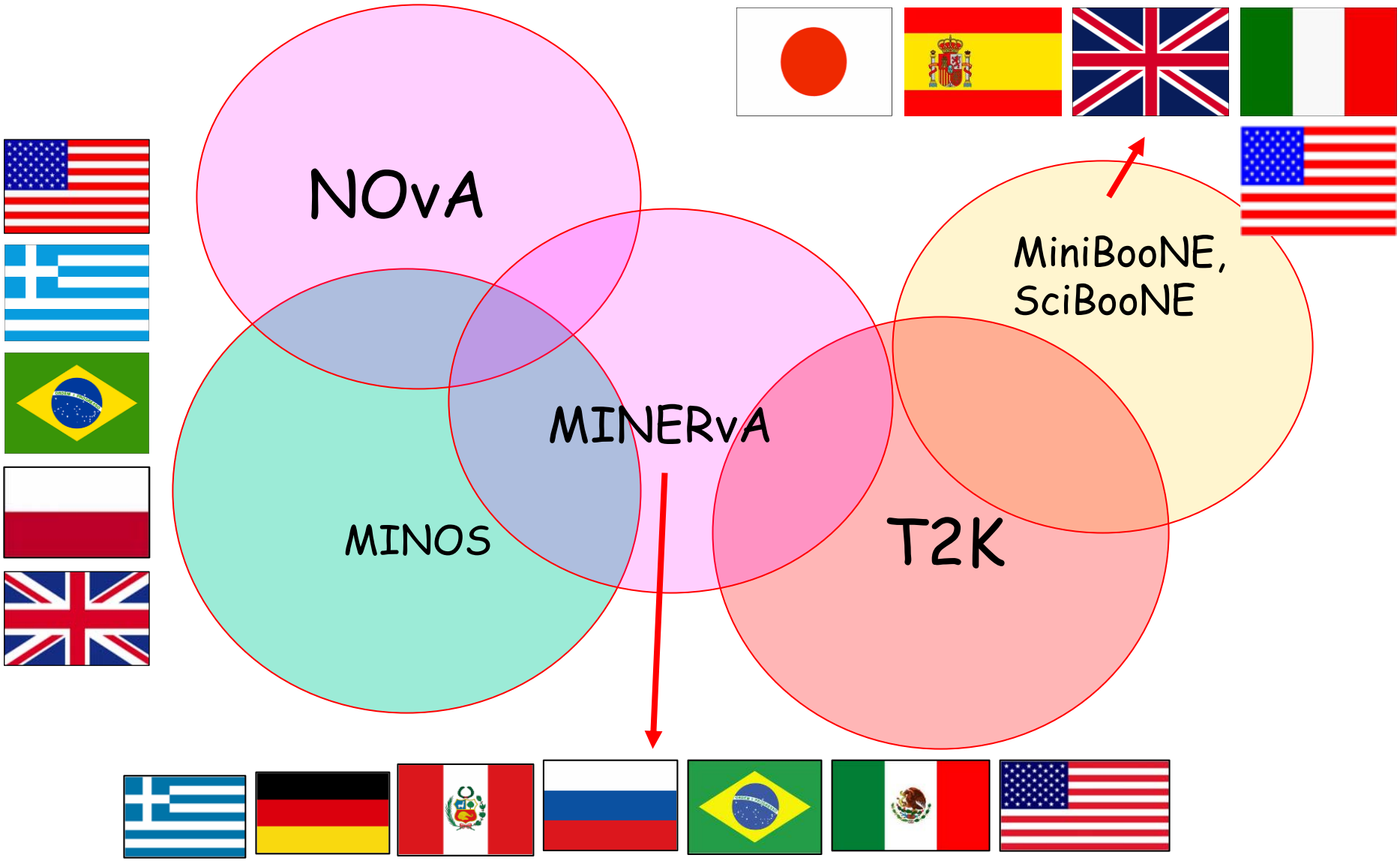
- Cannot continue to assume we have these neutrinos without all of the above ingredients

Neutrino Interactions



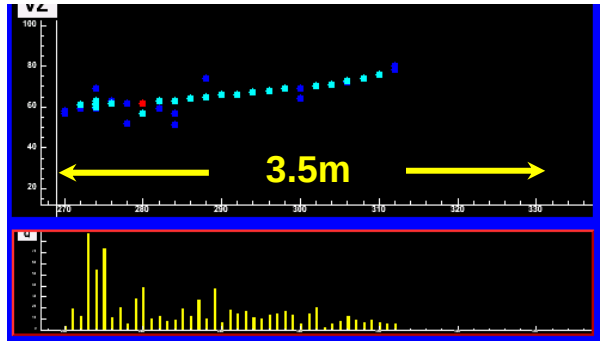


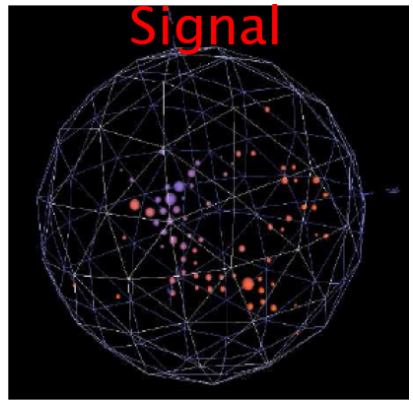
Future Experiments Need Current Program!

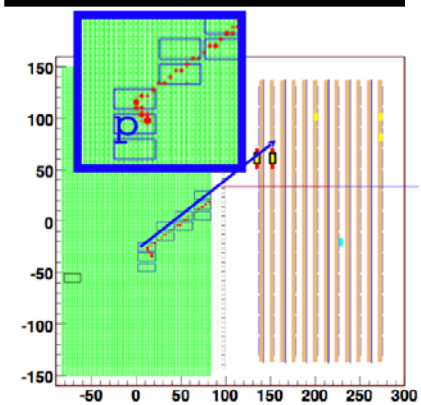


Detectors on line today

- MINOS
  - Magnetized Steel & Solid scintillator
  - 1kton Near, 5.4kton Far
  - Excellent muon charge and momentum
  - Fully contained hadronic showers
  - Some electron/hadron discrimination
- MiniBooNE
  - Oil Cerenkov
  - 1kton
  - Muon/electron identification
  - Excellent quasi-elastic event reconstruction
- SciBooNE
  - Fine-grained solid scintillator
  - Recycled from K2K
  - Electromagnetic and Hadronic calorimetry at downstream end for containment

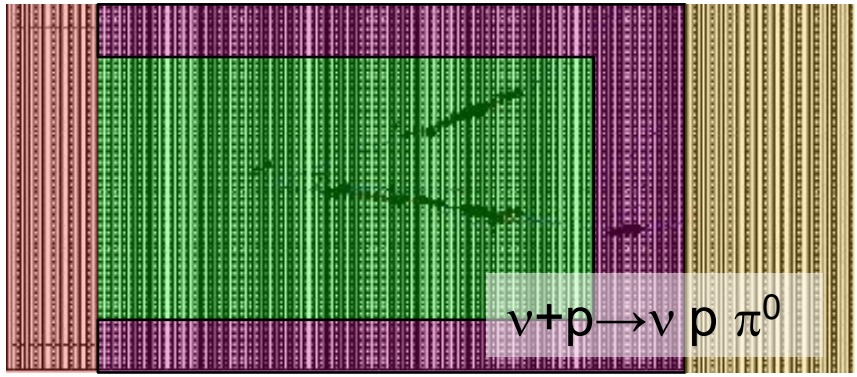


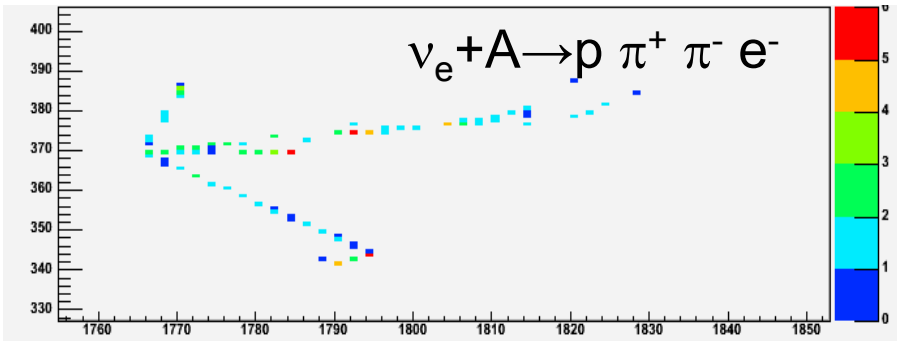


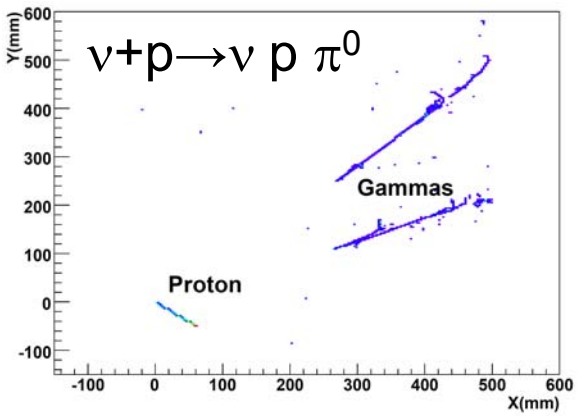


Next steps in Detector Technology

- MINERvA
  - Fine grained solid scintillator
  - ~5 tons fiducial volume, 200 tons total
  - Electromagnetic and Hadronic Calorimetry
  - Simultaneous nuclear targets
- NOvA
  - Liquid Scintillator in 15mx3cmx5cm extrusions
  - 15kton far, 215 tons near
- Liquid Argon TPC
  - "Electronic Bubble Chamber"
  - Staged R&D program
  - 250 liters this spring (T962)
- All of the above
  - Particle ID by dE/dx and shower profiles







Recent Physics Results
and
What to expect next

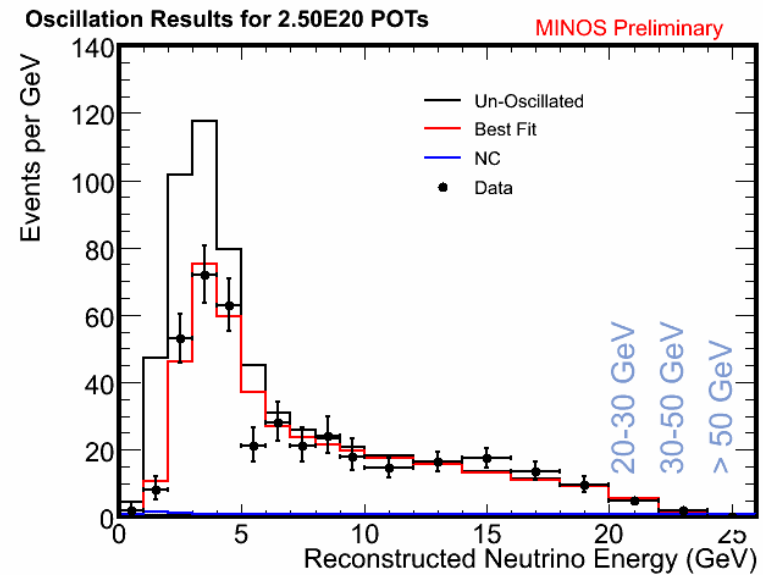
MINOS ν_μ Disappearance Result

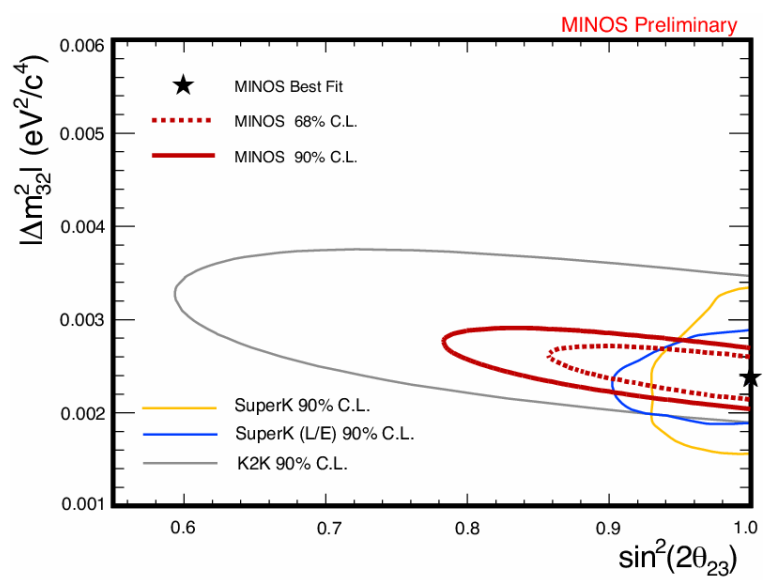
$|\Delta m^2_{32}|$ =
2.38 +0.20 (stat + syst) x 10^{-3} eV^2

$\sin^2 2\theta_{23}$ =
1.00 -0.08 (stat + syst)

Ref: Lepton Photon '07, arXiv:0708.1495

Uncertainty	Shift in Δm^2 (10^{-3} eV^2)	Shift in $\sin^2(2\theta)$
Near/Far normalization ±4%	0.065	<0.005
Absolute hadronic energy scale ±10%	0.075	<0.005
NC contamination ±50%	0.010	0.008
All other systematic uncertainties	0.041	<0.005
Total systematic (summed in quadrature)	**0.11**	**0.008**
Statistical error (data)	**0.17**	**0.080**

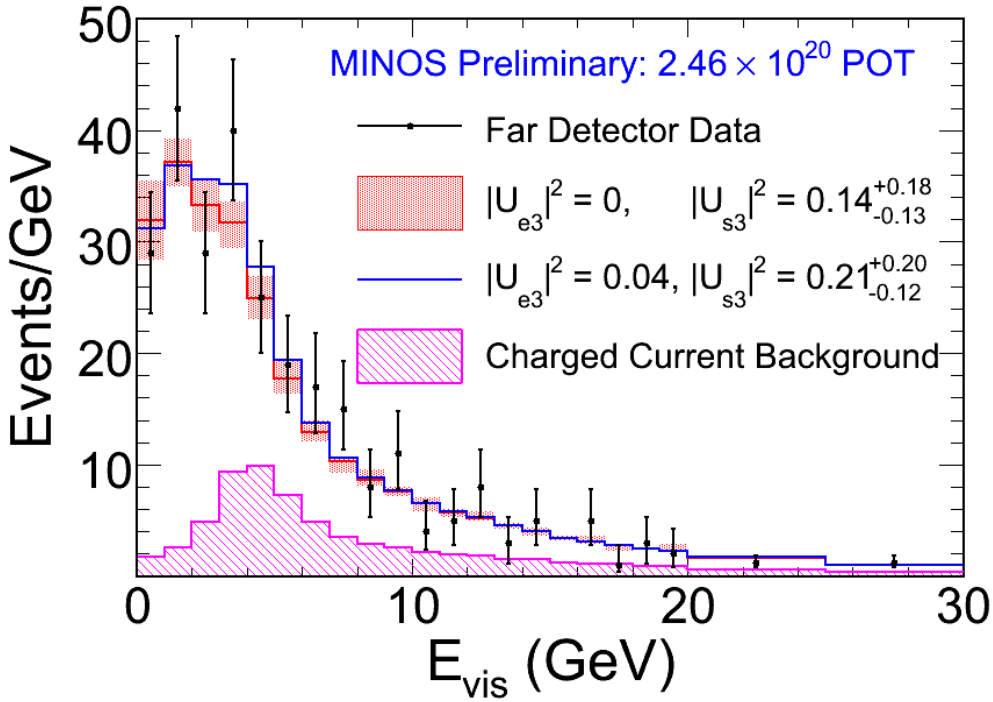




MINOS Neutral Current Result

- If ν_μ's are disappearing, where are they going?
- 4-flavor analysis shown

Uncertainty	Shift in $\lvert U_{s3}\rvert^2$	Shift in $\lvert U_{\mu 3}\rvert^2$
Relative Hadronic Calibration	0.04	0.02
Muon Energy Scale	0.01	0.01
Normalization	0.06	0.03
CC Background in NC Spectrum	0.03	0.01
Near Detector Selection	0.04	0.01
Others not listed	…	…
Total (sum in quadrature)	0.09	0.05
Statistical	0.18	0.18

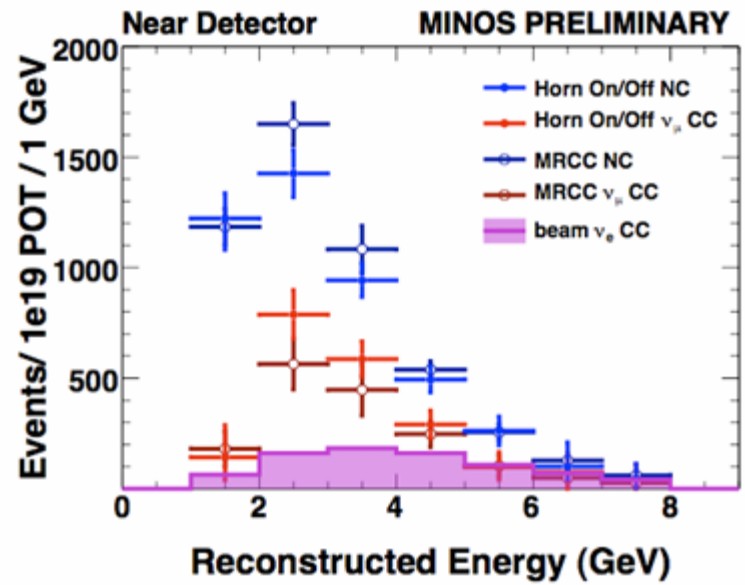


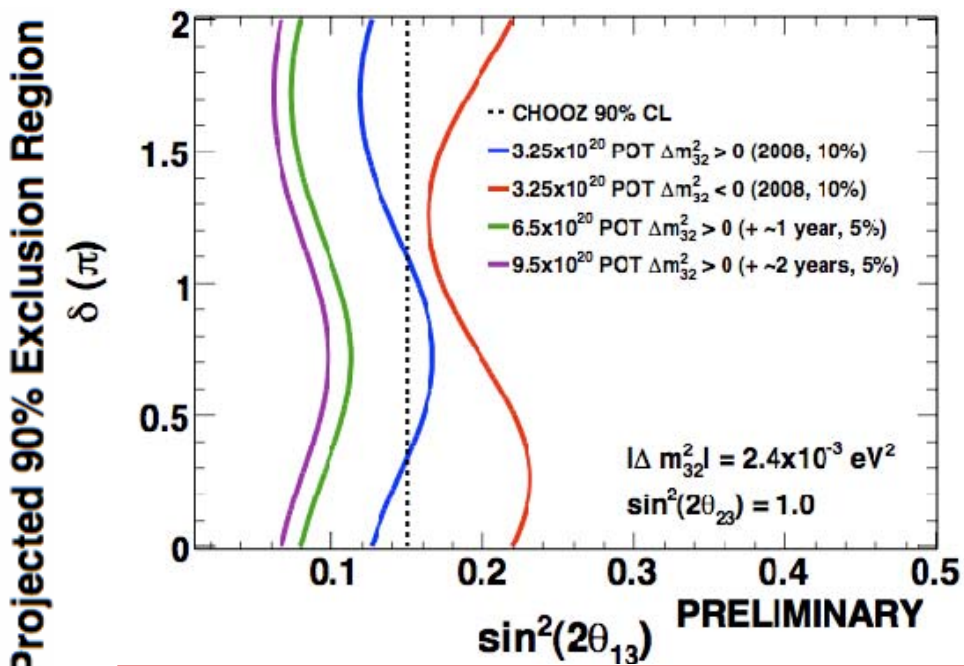
From 3-flavor analysis:
$E < 3$ GeV, $f < 0.35$ to 90% C.L.
Results consistent with no sterile neutrino admixture.

Reference: A. Sousa, FNAL W&C, 4/11/08

MINOS Sensitivity for ν_e Appearance

- Background Components:
  - Neutral Current Events
  - High hadron energy ν_μ Charged current Events
  - Intrinsic ν_e's created in beamline (few %)
- If you see a difference between data and MC, how do you know how to predict far detector ?





MINOS did 2 studies:

Turn off neutrino beamline focusing: changes ratios of 3 backgrounds

Use "shower" from identified ν_μCC events and compare data/MC:

Conclusion: Shower modeling is a major contribution to the disagreement.

Ref: M. Sanchez, Fermilab PAC 4/08

Upcoming MINOS Results

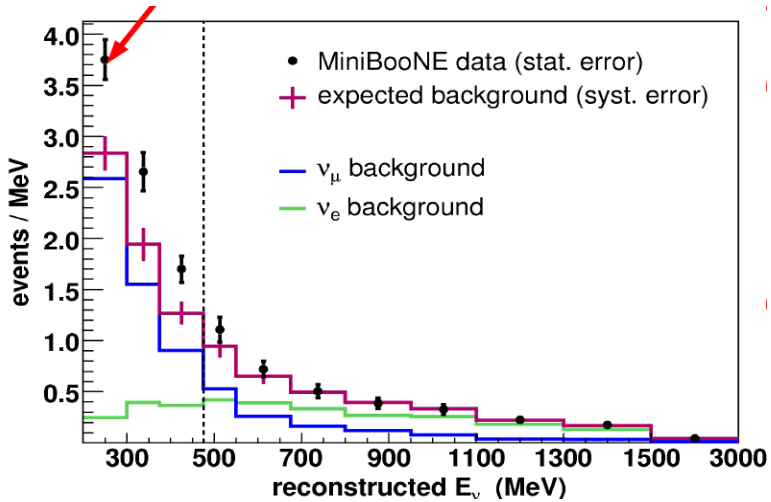
- ν_μ disappearance
  - 3×10^{20} POT (through August 2007)
  - Result very soon
- ν_e appearance
  - Striving for summer conferences with combined Run I+II data set.
  - Stand a chance of making 1st measurement of θ_{13} (if normal Mass Hierarchy)
- Near Detector Physics
  - Total Cross Section - sooner
  - Quasi-Elastic Axial Mass parameter
  - Others in progress

Slide courtesy P.Shanahan

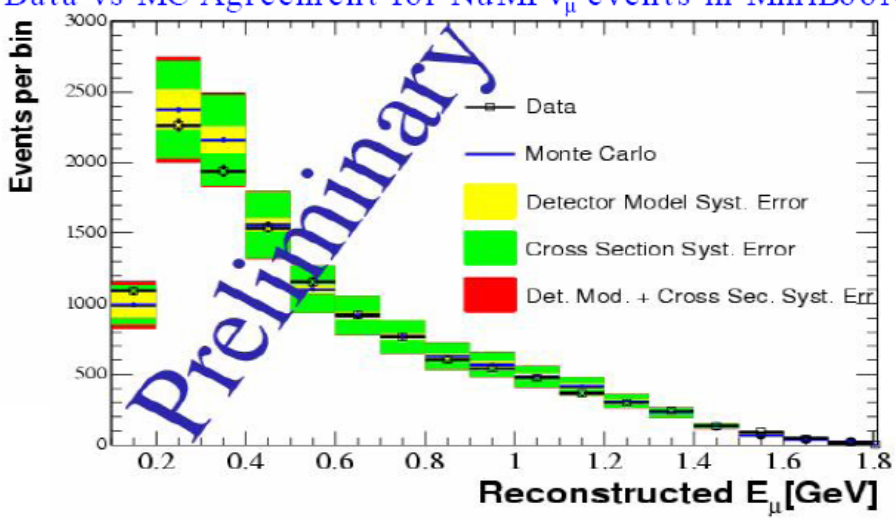
MiniBooNE Oscillation Results

- MiniBooNE sees ν_e events above 450MeV that are consistent with no active oscillations
- Is checking for oscillations in anti-neutrino channel and studying low energy excess
- Has also checked for modeling of neutrino events coming from NuMI Beamline (110mrad off NuMI axis)

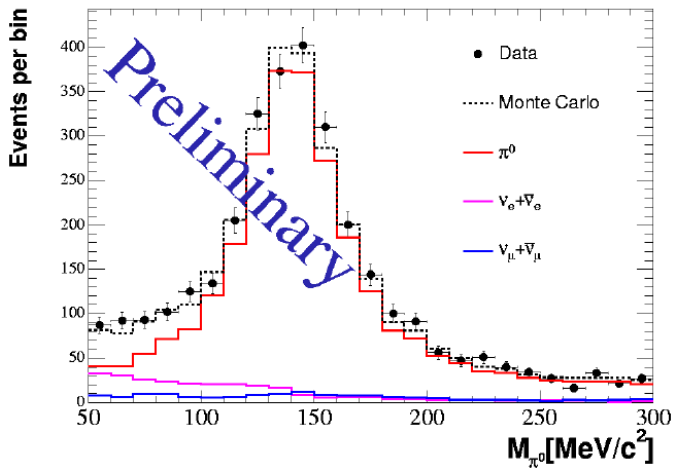
New low energy bin



Data vs MC Agreement for NuMI ν_μ events in MiniBooNE



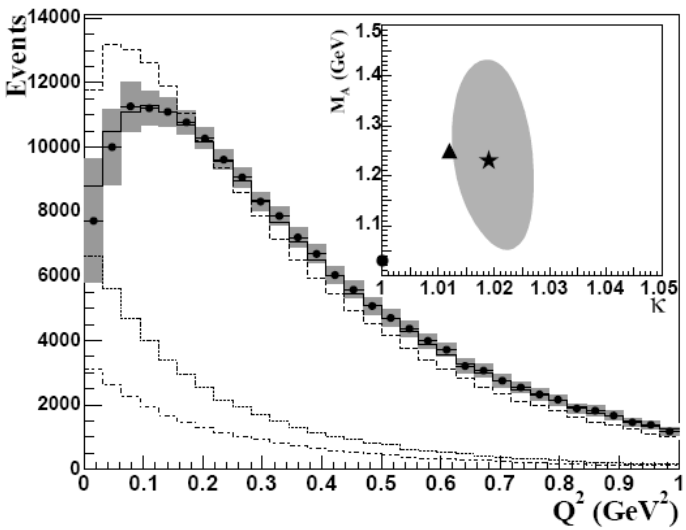
Analysis of π^0 events from NuMI beam



Ref: C.Polly, EWK Moriond '08

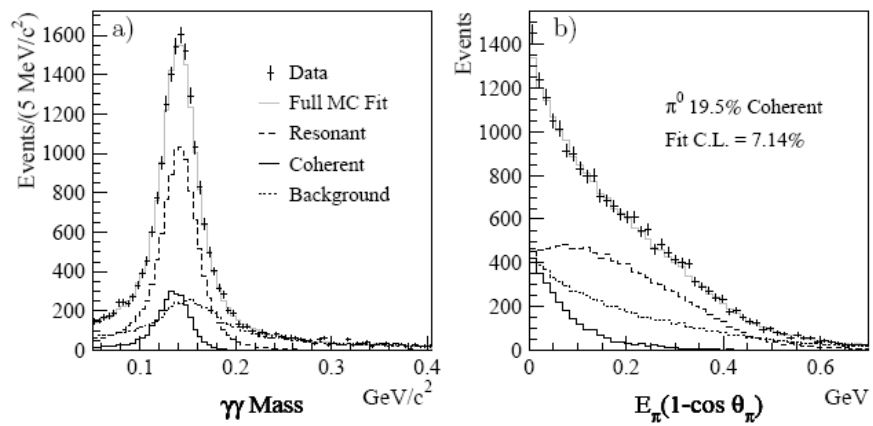
MiniBooNE Cross Section Results

- Charged Current Quasi-elastic Cross Section
  - Axial Mass 1.19±0.20
  - **PRL100**:032301,2008



error source	δM_A^{eff}
data statistics	0.03
neutrino flux	0.04
neutrino cross sections	0.06
detector model	0.10
CC π^+ background shape	0.02
total error	0.20

- Neutral Current Coherent π^0 production
  - Coherent fraction: (19.5±1.1 (stat) ±2.5 (sys))% of exclusive NC p0
  - arXiv:0803.3423 [hep-ex] submitted to PRB



- Now searching in anti-ν mode

Backup Slide: Upcoming MiniBooNE Analyses

- Update to low energy nue candidate excess
- ν_μ disappearance, anti- $\nu_e$appearance
- Interpreting high Δm^2 results in 3+N flavor oscillation context
- Combined analysis of NuMI beam and BNB beam $\nu_e$candidates in MiniBooNE
- $CC\pi^+$/CCQE ratio
- $CC\pi^+$/ absolute, differential cross-section
- CCQE absolute, differential cross-section
- NC π^0 flux averaged, differential cross-section (neutrino and anti-neutrino mode)
- NC elastic flux averaged, differential cross-section

Upcoming SciBooNE Results

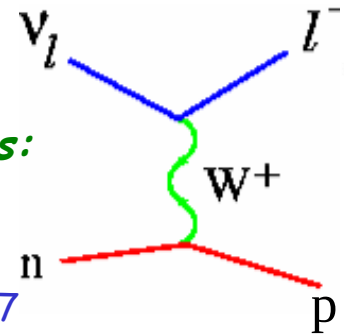
- Within one year
  - ν_μ CC1π/CCQE ratio
  - ν_μ CC coherent π
  - ν_e backgrounds for MiniBooNE appearance search
  - ν_μ disappearance with MiniBooNE
- Within 2 years
  - ν_μ CCQE absolute cross section
  - ν_μ NC π^0 cross section
  - $\bar{\nu}_\mu$ cross sections

Note: April 2008 APS meeting
Session D11: 8 SciBooNE talks
Many with preliminary results!

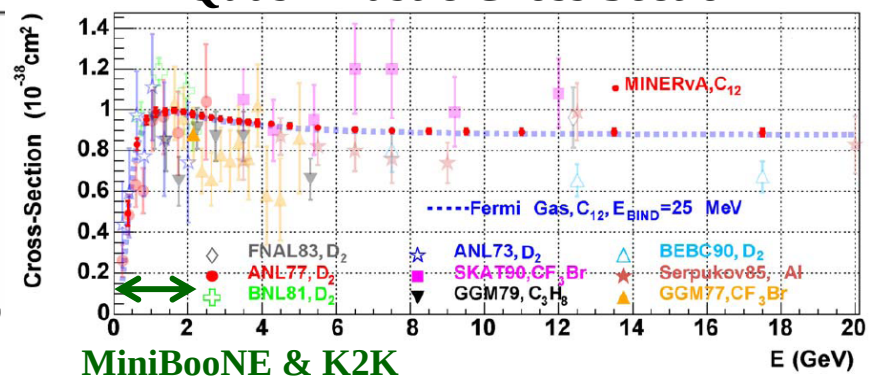
Slide courtesy M. Wascko

MINERνA Physics Reach

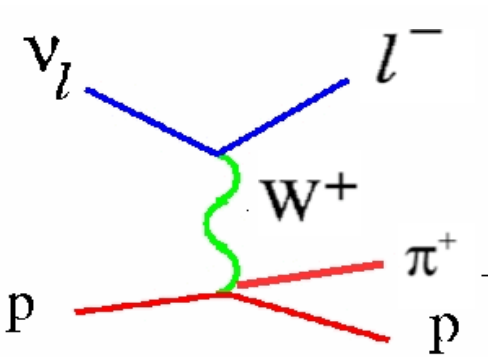
- ***NuMI Beam provides:***
  - Million event statistics for 1 ton targets in 4 year run
  - ν Energies from 1-20GeV
- ***MINERvA Detector provides:***
  - Clean identification of common and rare processes
  - unprecedented comparisons from atomic number 4 to 207
- ***Deep Inelastic Sample: 4.3M events in 4 year run***

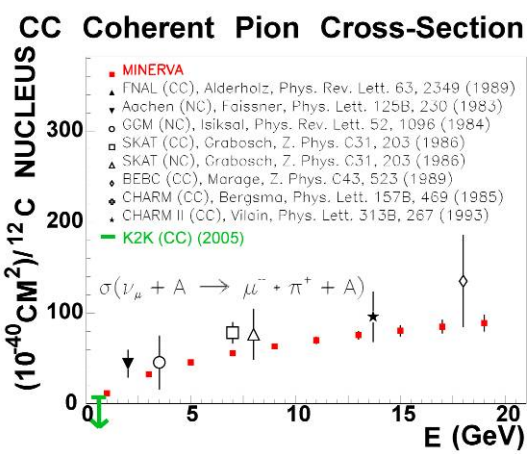


Quasi-Elastic Cross Section



MiniBooNE & K2K measurements

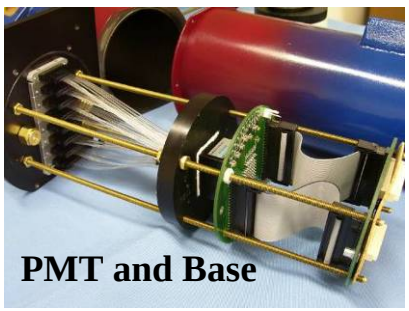


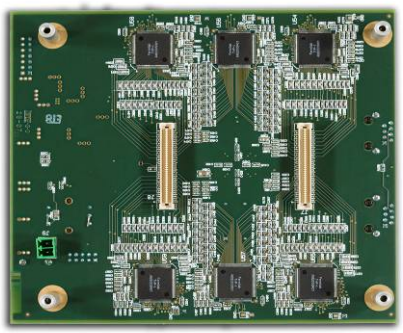


Target Material	Fiducial Mass (ton)	Charged Current Sample
Helium	0.25	0.6M
Hydrocarbon	3	8.6M
Carbon	0.6	1.4M
Iron	1	2.9M
Lead	1	2.9M

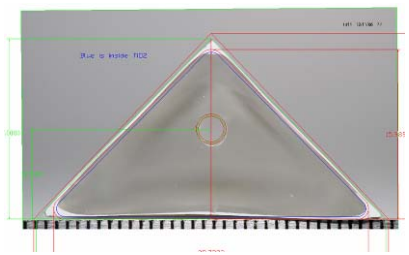
MINERνA History and Future

- Approval Milestones
  - FNAL PAC Stage 1 Approval: April 2003
  - DOE CD-0 Granted and NSF MRI for nuclear targets, calibration systems: June 2006
  - CD-1,2,3a Approval: March 2007
  - CD-3b Approval: November 2007
- Completing prototype "tracking" detector
  - Commission with cosmic rays mid 2008
- Construction (mostly in FY08-09) has begun!
  - Parts fabrication and testing in FY08
  - Module assembly and source testing in FY09
  - Forecast completion in early 2010



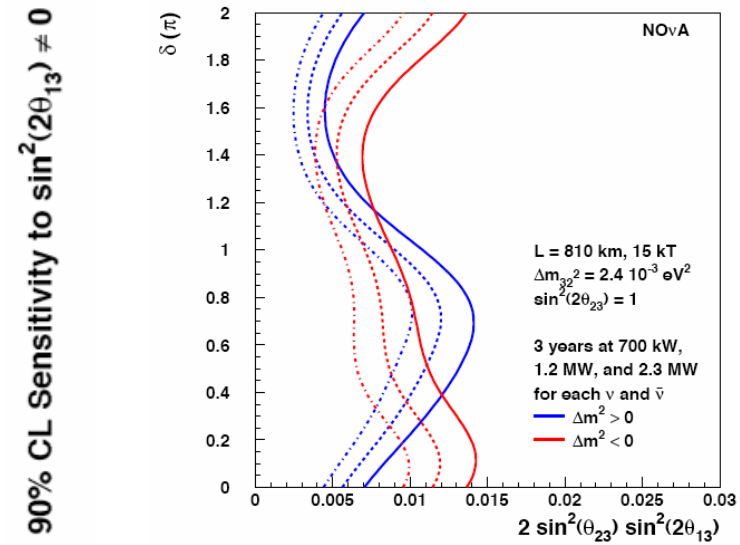


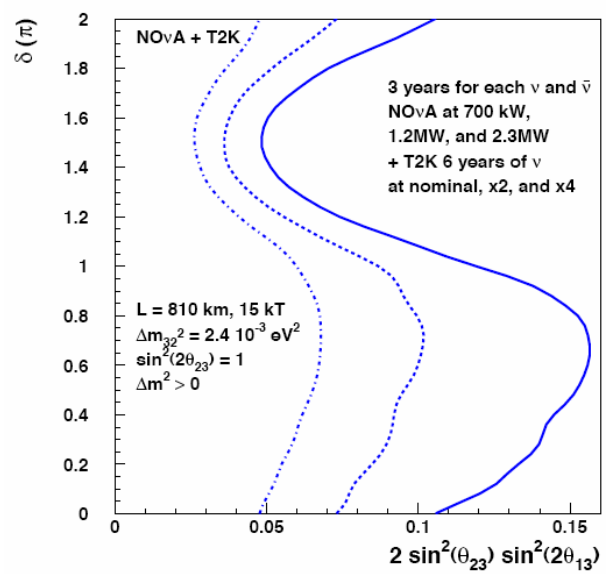
Scintillator Extrusion

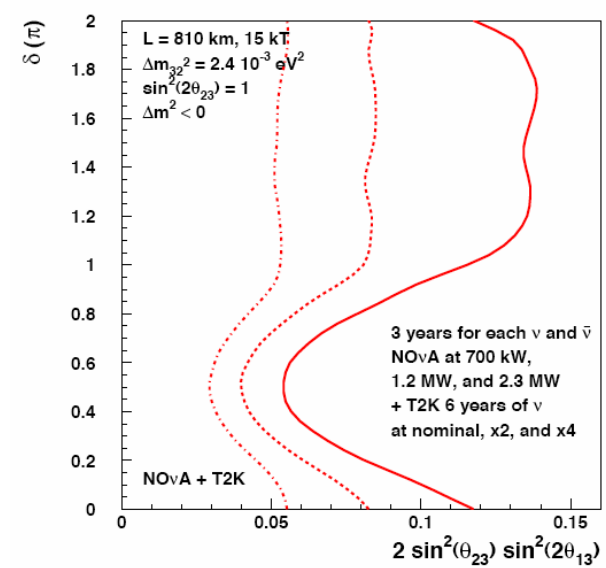


NOvA Physics Reach

- NOvA Optimized for ν_e appearance
- Long baseline (810km) provides unique sensitivity to mass hierarchy
- Sum of NOvA+T2K is better than running either one twice as long
- Much more in next talk by J. Cooper



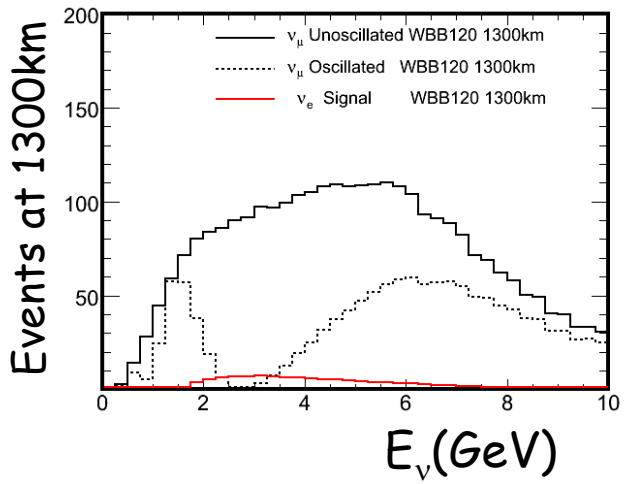




Preparing for the future

- Fermilab and the broader User community is engaged with several avenues of planning
  - Liquid Argon R&D
  - Accelerator R&D for upgrades to Proton Source
  - Long Baseline Oscillation Studies
  - Short Baseline Neutrino Scattering Studies

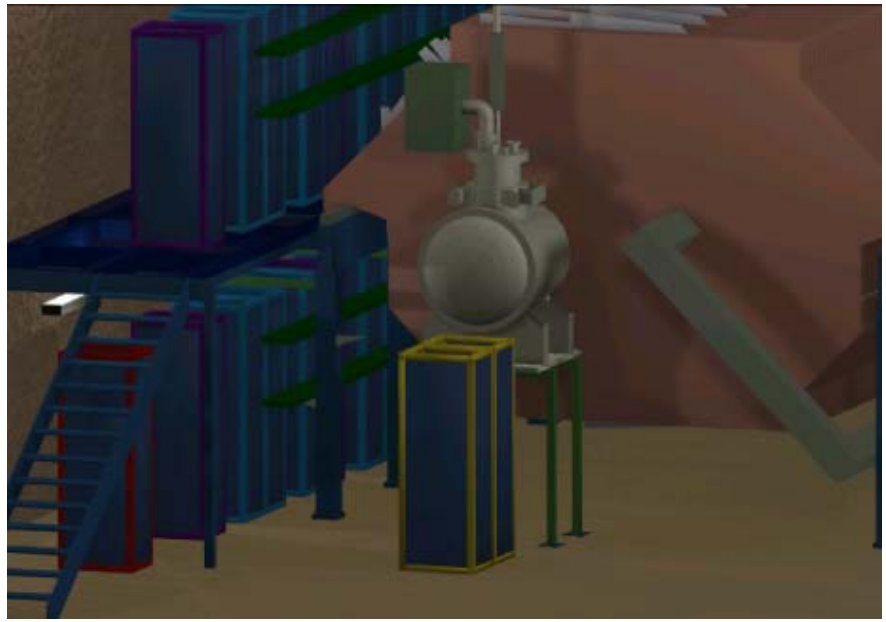
- Many different options are being considered
  - Using NuMI Beamline with Liquid Argon Detector
  - Building Brand New Beamline to send neutrinos to DUSEL
    - Liquid Argon
    - Water Cerenkov



Liquid Argon Prototyping: T972

- Liquid Argon TPC
  - 0.3 ton active volume
  - 0.5 x 0.5 x 1.0 m3 TPC; 500 channels
- See neutrino interactions (~150 events/day)
  - Physics Development:
- Simulation, reconstruction,
- Verification of efficiencies
- and purities
- Long term running conditions
- Underground issues

Slide courtesy B. Fleming

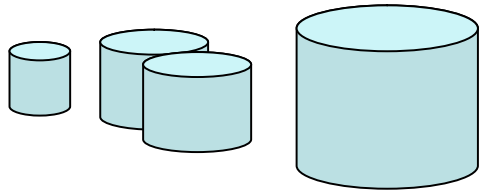


Installation in May, request 6 months of beam time

Evolution of a Liquid Argon Physics Program

R&D

Test stands

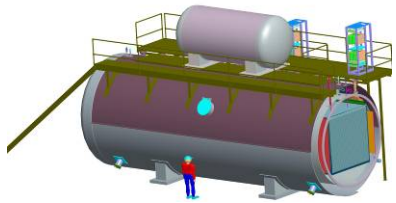


0.1 - 10 tons

R&D | Physics

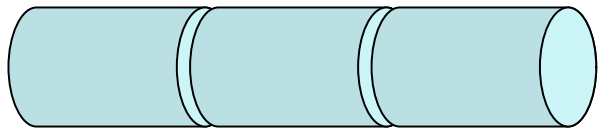
0.5 tons in NuMI Beamline

R&D | Physics



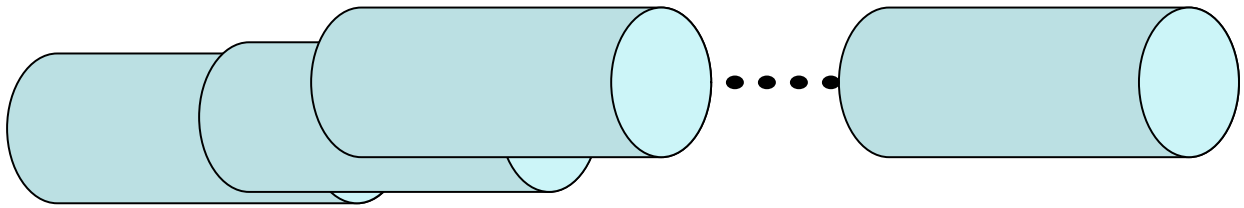
100 - 200 tons in BNB

R&D | Physics



1 - 5 kton @735km

Physics



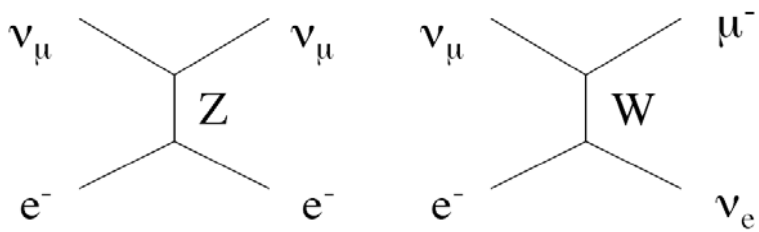
From Project X workshop Series LAr working group

M x N=100 kT

Need to optimize M & N against cost, schedule, and technical feasibility

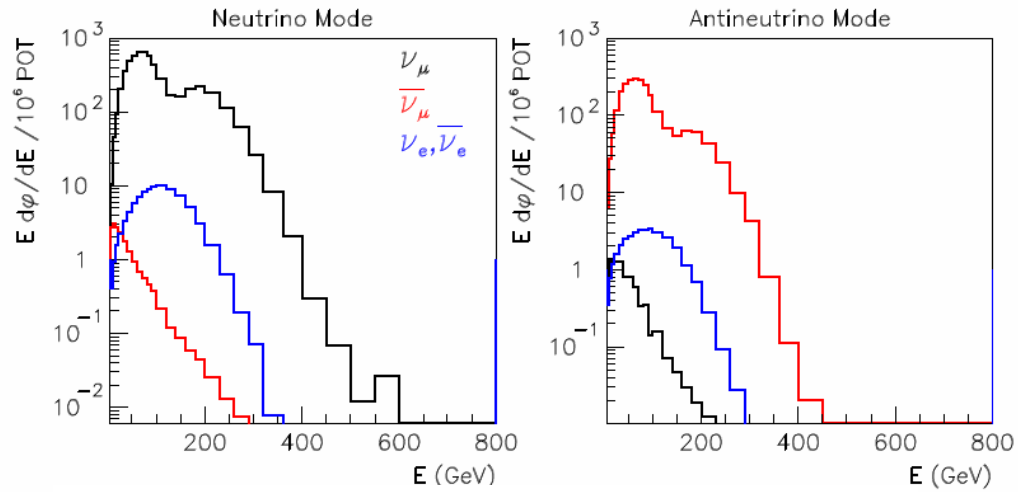
NuSong: What and Why?

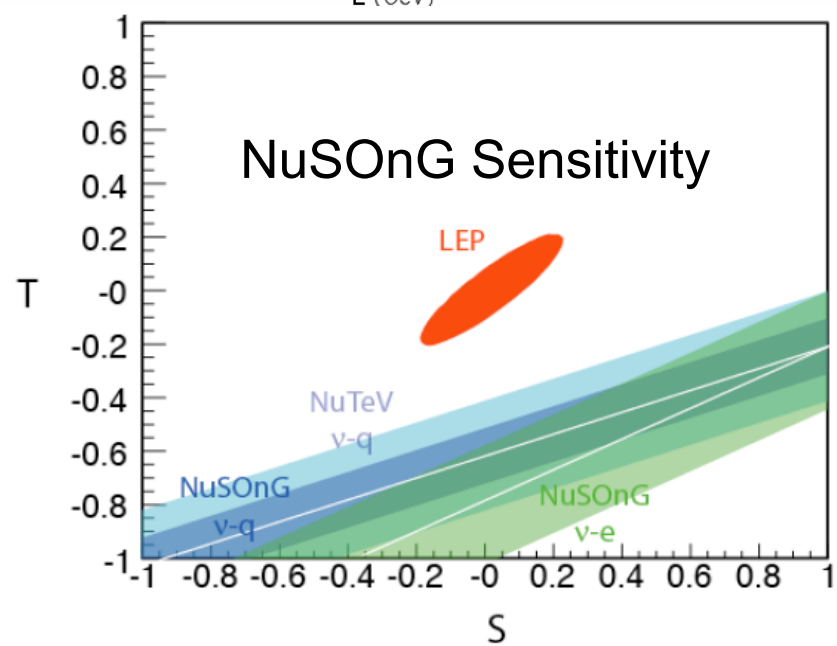
- NuSonG is designed to measure $\sin^2\theta_W$ at 100GeV with ν-electron scattering



- NuTeV beamline design, CHARMII detector design (glass tracker plus calorimetry)

Statistics $\nu/\bar{\nu}$	Mode
600M / 33M	Charged Currents
190M/12M	Neutral Currents
75k/7k	$\nu/\bar{\nu}$ - e^- NC scat.
700k/0k	$\nu/\bar{\nu}$ - e- CC QE



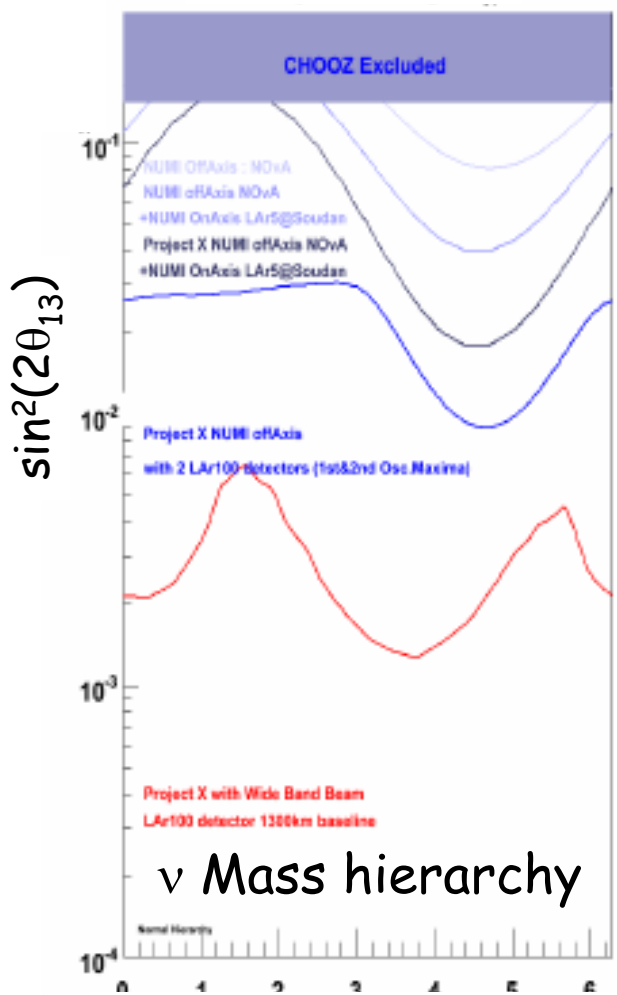


Figures courtesy J. Conrad

Long Baseline Studies: Summary

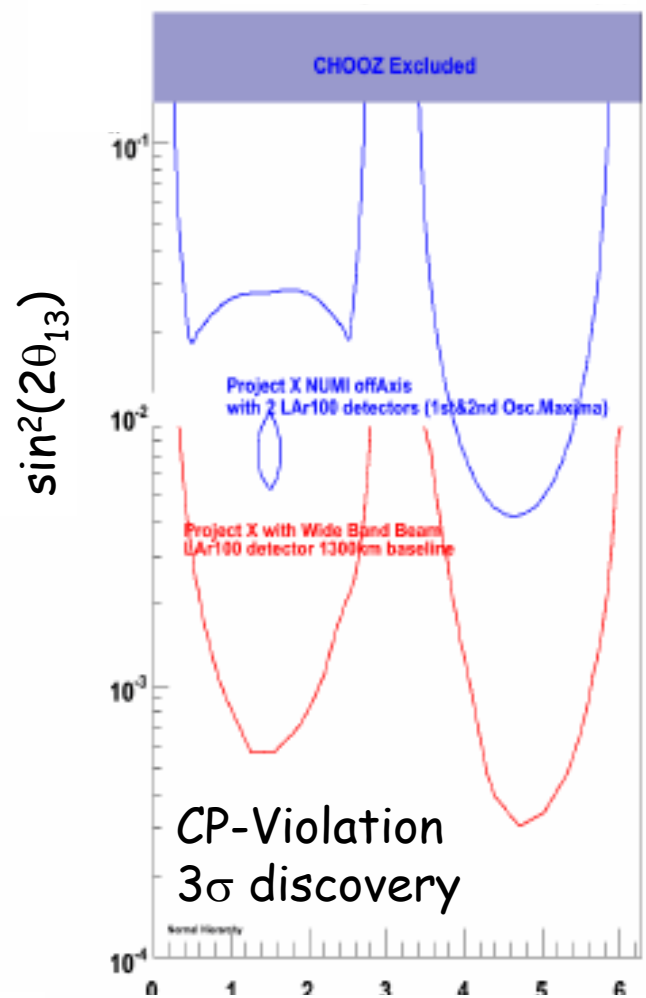
- Studies of Broad and Narrow Band Neutrino Beams
- Studies of Water Cerenkov and Liquid Argon Detector technologies
- Comparisons of 735km to 1300km baselines
- Consideration given to a Staged Program

- See March 2008 PAC: N. Saoulidou



ν Mass hierarchy

CP-violating phase δ



CP-Violation
3σ discovery

CP-violating phase δ

"Near" Term Program

Fiscal Year	2008	2009	2010	2011	2012	2013	2014	2015	2016
Accelerators									
Main Injector Power at 120GeV (kw)	220	300	300	400	400	760	760	760	
Project X	R&D				Construction				
Neutrino Program									
1. Operating									
MiniBooNE	Operation								
SciBooNE	Operation								
MINOS - Far	Operation								
MINOS - Near Detector	Operation								
2. Construction									
MINERvA	Constr	Comm	Operation						
NOvA	R&D	Construction				Comm	Operation		
3. Liquid Argon Detector Evolution									
ArgoNeuT (0.3t)	Operation								
MicroBooNE (170t)	R&D		Construction		Operation				
LAr 5kT at Soudan			R&D		Construction				Operat

Portrait of Long Term Program Options

Fiscal Year	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Accelerators																
Main Injector Power at 120GeV (kw)	220	300	300	400	400	760	760	760		~1000	2300	2300	...			
Project X	R&D				Construction					Comm	Operation					
Neutrino Program																
1. Operating																
MiniBooNE	Operation															
SciBooNE	Operation															
MINOS - Far	Operation															
MINOS - Near Detector	Operation															
2. Construction																
MINERvA	Constr	Comm	Operation													
NOvA	R&D	Construction				Comm	Operation									
3. Liquid Argon Detector Evolution																
ArgoNeuT (0.3t)	Operation															
MicroBooNE (170t)	R&D		Construction		Operation											
LAr 5kT at Soudan			R&D		Construction				Operation							
4. Superbeam to experiment			R&D				Construction						Comm	Operation		
5. Large Detector at DUSEL																
Large Cavern Engineering	R&D															
Water Cerenkov Detector																
PMT production				R&D		PMT Production										
Module Excavation + Inst + Opr								Excavatior			Installatior				Operatio	
AND/OR																
LAr100 - M x N plan																
Module 1 Excavation + Inst + Opr				R&D					Excava	Construction		Installation		Operation		
Module 2 Excavation + Inst + Opr										Excava	Construction		Installation			
Module 3 Excavation + Inst + Opr											Excava	Construction		Installation		

Conclusions

- Vibrant Current Program
  - Multi-pronged approach to long-baseline oscillations with MINOS
  - SciBooNE providing first high-statistics probe of 1-GeV neutrino and anti-neutrino interactions
  - MiniBooNE getting unprecedented anti-neutrino statistics to explore LSND signal region
- Precision Measurements on ν Interactions around the corner
  - MINERvA is forging ahead with construction
- Fermilab needs to maintain a balance: current program needs
  - expertise in accelerator operations,
  - A healthy level of spare parts for beamline operations
- Many connections between now and the future: members of both T2K and NOvA are doing cross section measurements at Fermilab!
- Staged R&D program with Liquid Argon is starting now
- Studies underway to address longer term opportunities with Project X: keeping Fermilab at forefront of ν physics!

BACKUP: List of other MINOS Publications

- Neutrino Time Of Flight
  - M_ν < 50 MeV @99%CL
  - Could eventually reach 10 MeV
  - Phys. Rev. D 76, 072005 (2007)
- Cosmic Charge Ratio
  - Deepest measurement yet of μ^+/μ^- ratio.
  - Increase in ratio relative to L3+C accords with π/K model.
  - Phys. Rev. D 76, 05200 (2007)
- ν Induced Muons
  - 854 live days of Far Detector
  - Ratio of low to high and unknown momentum ν induce μs is consistent with oscillations.
  - Fit in bins of cosθ and momentum bin inconsistent with no-oscillation at 94% CL
  - Ratio μ+/μ- consistent with CPT, but with very weak statistics.
  - Phys. Rev. D 75, 092003 (2007)

Slide courtesy Peter Shanahan