Fermilab’s Intensity Frontier Program

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Fermilab

The Intensity Frontier Program

- The Intensity Frontier Program probes the new physics landscape beyond the Standard Model
- The Program uses intense particle beams of neutrinos, muons, …. to make discoveries.
- The Program follows the existing P5 roadmap
- The Program delivers outstanding physics while designing and building the next generation Intensity Frontier facilities.

Outline

- Neutrino Physics
  - Coherent Overview
  - Long Baseline
  - Short Baseline
- Muon Physics
  - Mu2e & Muon g-2
- Support of Community
  - Reorganization in the lab's divisions
  - Intensity Frontier Fellowship Program

The Present Neutrino Landscape

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2+i\beta} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$\Delta m_{21}^2 = 7.54\ ^{+0.26}_{-0.22} \times 10^{-5}\ eV^2$

$|\Delta m_{32}^2| = 2.42\ ^{+0.07}_{-0.11} \times 10^{-3}\ eV^2$

$m(\nu_e) < 2.3$ eV (95% CL)

$\theta_{12} = 33.6\ ^{+1.1}_{-1.0}$ deg

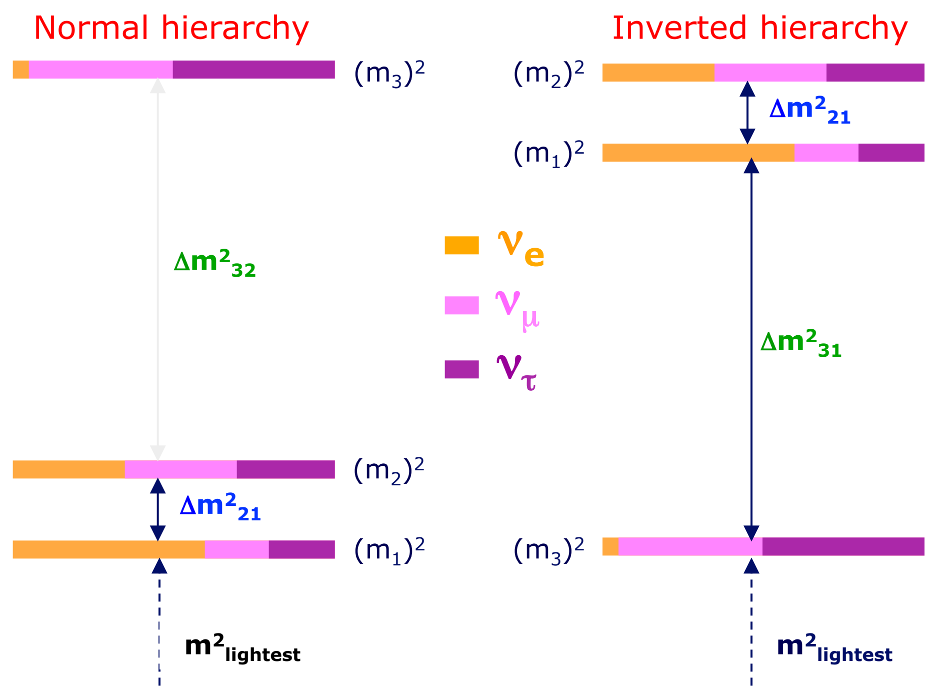
$\theta_{23} = 38.6\ ^{+2.4}_{-1.4}$ deg

$\theta_{13} = 9.0\ ^{+0.4}_{-0.5}$ deg

$m_{lightest} = ?$

sign $\Delta m_{32}^2 = ?$

$\delta = ?$



Marginalized 1D !σ uncertainties, Fogli et al 1205.5254, C.Kraus et al Eur. Phys. J. C40, 447 (2005)

Worldwide Experimental Thrusts in Neutrino Physics

1) Reveal the pattern of neutrino masses and mixings

2) Discover if the situation is more complex than 3 neutrinos with Standard Model interactions

3) Carry out the neutrino engineering measurements that make 1) and 2) possible

Worldwide Experimental Thrusts in Neutrino Physics

1) Reveal the pattern of neutrino masses and mixings
   - Is θ_{23} maximal?
   - How are the masses ordered?
   - Is CP violated?
   - What are the neutrino masses?
   - Are neutrinos their own anti-particles?

2) Discover if the situation is more complex than 3 neutrinos with Standard Model interactions
   - Can we independently check the θ_{13} measured by reactor experiments?
   - Do neutrinos interact with matter in any non-standard ways?
   - Are the LSND and MiniBooNE anomalies new physics?

3) Carry out the neutrino engineering measurements that make 1) and 2) possible

Current and Planned Fermilab Neutrino Experiments

Experiment	Beamline	Status	# institutions (# countries)	# publications
ArgoNeut	NuMI	Completed 2010	9(3)	1 phys, 2 instr
MINOS	NuMI	Completed 2012	30(5)	29 phys, 23 instr
MINERvA	NuMI	Running	21(8)	2 phys, 4 instr
NOvA	NuMI	Under Construction	32(5)	-
MINOS+	NuMI	Running	34(6)	-
MiniBooNE	BNB	Completed 2012	19(2)	24 phys, 1 instr
SciBooNE	BNB	Completed 2008	17(5)	7 phys
MicroBooNE	BNB	Under Construction	16(3)	-
LBNE	LBNE Beamline	Achieved CD1	62(5)	-

The Fermilab Neutrino Program involves 120 institutions from 15 countries

NuMI = Neutrinos from the Main Injector: 120 GeV protons on a carbon target
BNB = Booster Neutrino Beamline: 8 GeV protons on a beryllium target
LBNE Beamline: 60 -120 GeV protons from the Main Injector

Fermilab Neutrino Beam Delivery

		total POT (x10^20)	source
	K2K	0.922	1.049E20 tot, 0.922E20 for phyx, final osc PRD, hep-ex/0606032
	T2K	6.39	as of April 2013, T2K webpage
		7.312	
CNGS	OPERA	1.808	2008-2012 physics run, http://accelconf.web.cern.ch/accelconf/IPAC
		1.808	
NuMI	MINOS	13.9	10.6E20 POT nu, 3.3E20 POT nubar, full data set, arXiv:1301.4581
BNB	MiniBooNE	17.73	6.46E20 POT nu, 11.27E20 POT nubar, final osc arxiv: 1303.2588
		31.63	
total Fermilab		31.63	E20 POT
total Asia+Europe		9.12	E20 POT
	factor:	**3.5**	

the Fermilab complex has delivered almost 4x the POT to its neutrino experiments than the JPARC and CNGS programs combined

Data compiled by Sam Zeller

Fermilab Experimental Thrusts in Neutrino Physics

1) Reveal the pattern of neutrino masses and mixings
   - Is θ_{23} maximal? **MINOS → NOvA → LBNE**
   - How are the masses ordered? **NOvA → LBNE**
   - Is CP violated? **LBNE**
   - What are the neutrino masses? **No plans to address at Fermilab**
   - Are neutrinos their own anti-particles? **No plans to address at Fermilab**

2) Discover if the situation is more complex than 3 neutrinos with Standard Model interactions
   - Can we independently check the θ_{13} measured by reactor experiments? **MINOS → NOvA → LBNE**
   - Do neutrinos interact with matter in any non-standard ways? **MINOS+**
   - Are the LSND and MiniBooNE anomalies new physics? **MiniBooNE → MicroBooNE**

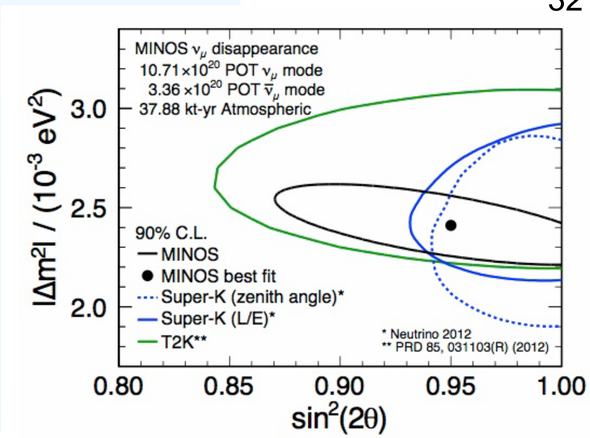
3) Carry out the neutrino engineering measurements that make 1) and 2) possible
   - **MiniBooNE, SciBooNE, MINERvA, ArgoNeut, MicroBooNE**

Long Baseline Neutrino Experiments

Exploring the PMNS Matrix

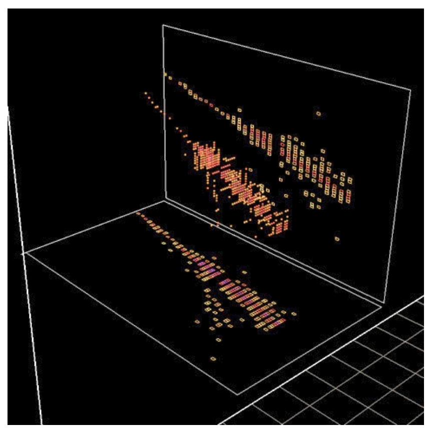
MINOS(+)

Precision Δm_{32}^2 ↘



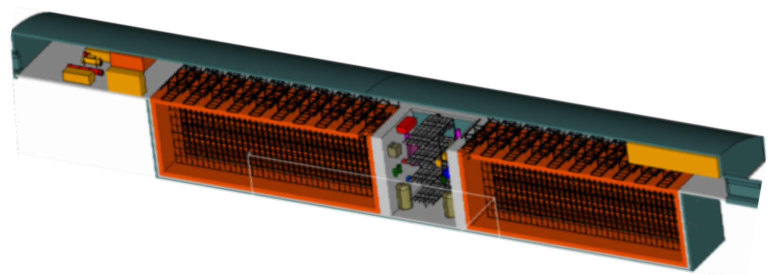
NOvA

Determine hierarchy ↘



LBNE

CP violation search



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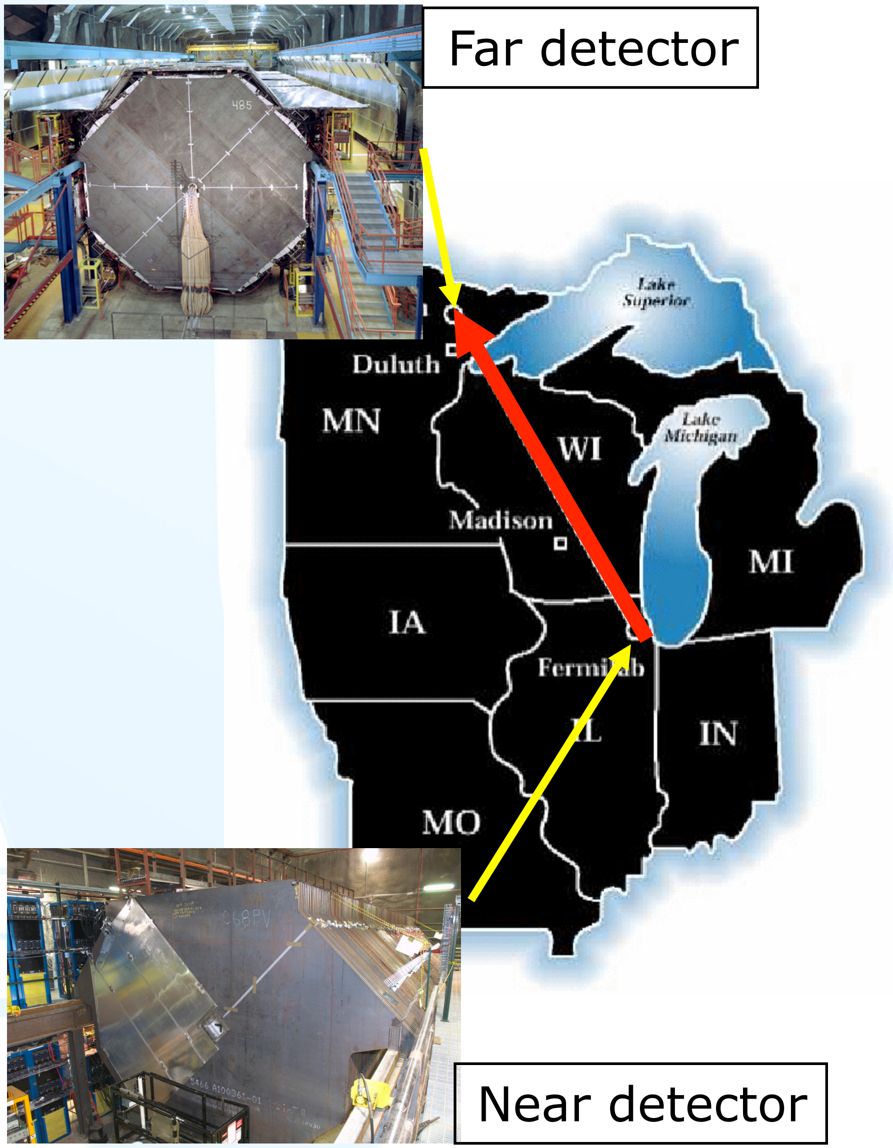
The MINOS(+) Experiment



Far Detector:

Soudan, Minnesota, 735 km from target

5.4 kton mass

484 steel/scintillator planes, 8x8x30 m^3

107 collaborators from 30 institutions in 5 countries

Near Detector:

Fermilab, 1km from target

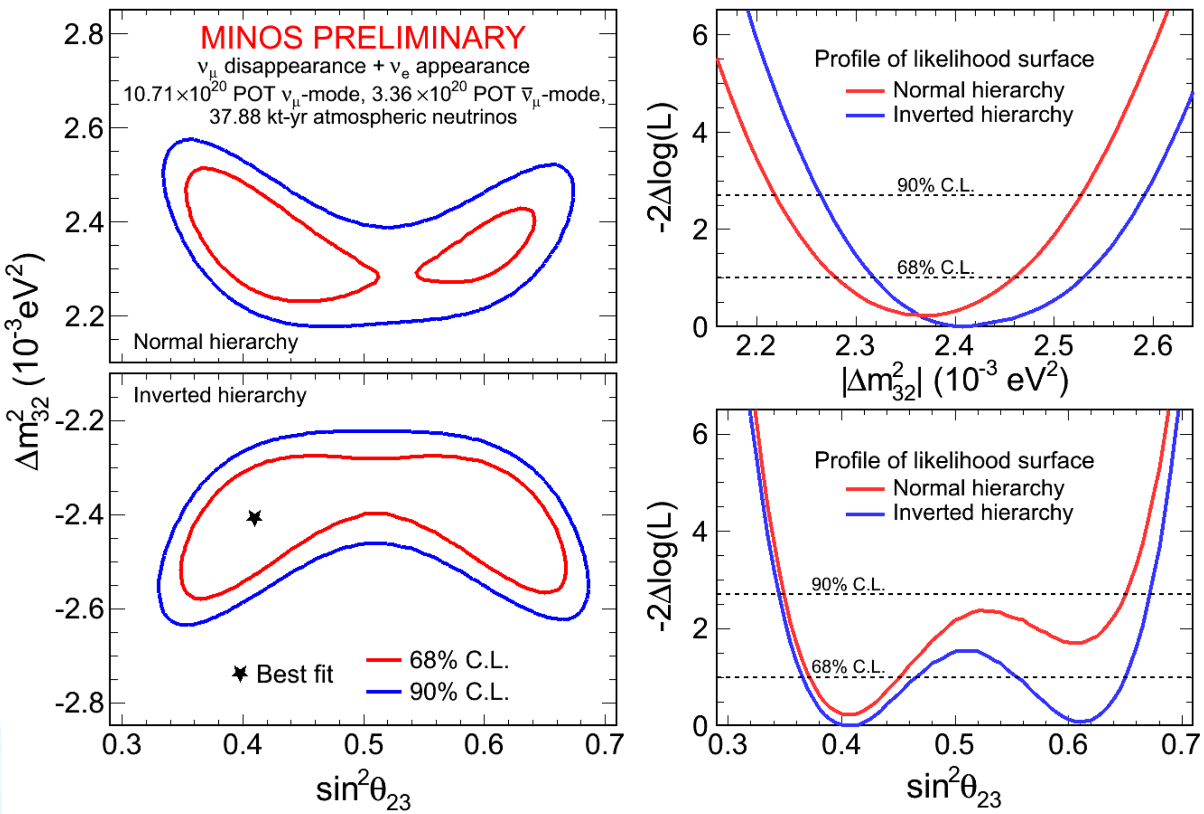
1 kton mass

282 steel planes

153 scintillator planes, 3.8x4.8x15 m^3

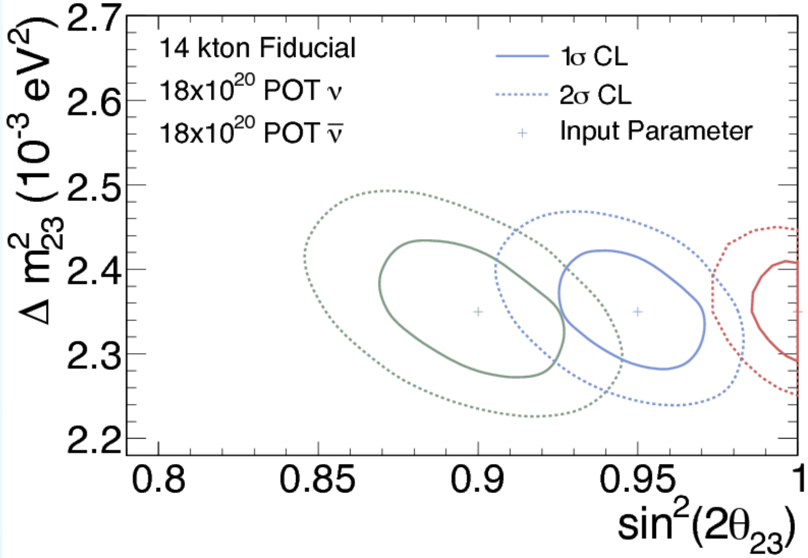
Is θ_{23} Maximal?

MINOS latest results from 3ν fitting



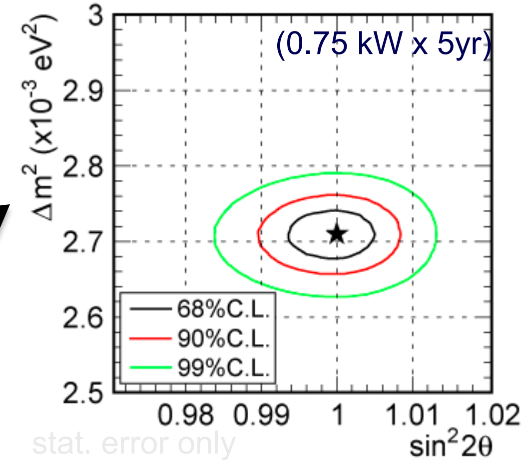
Full dataset – both horn current modes + atmospheric neutrinos
Solar mixing parameters fixed
θ_{13} fit as nuisance parameter, constrained by reactor results
δ_{CP} , θ_{23}, Δm^2 unconstrained
major systematic uncertainties included as nuisance parameters

Is θ_{23} Maximal? – NOvA and T2K Sensitivities

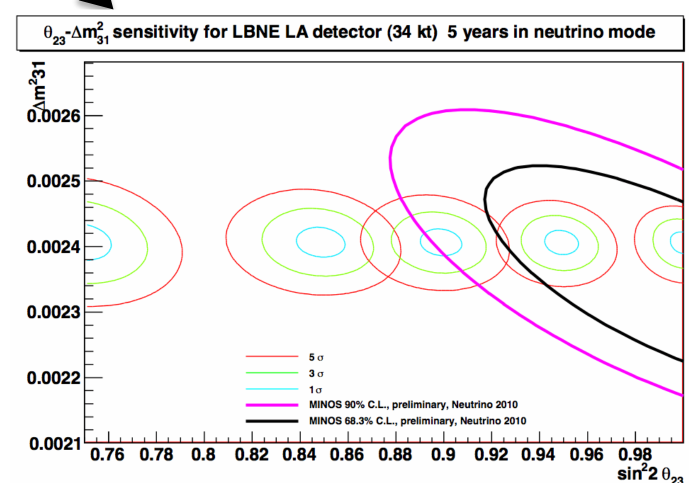


NOvA

T2K

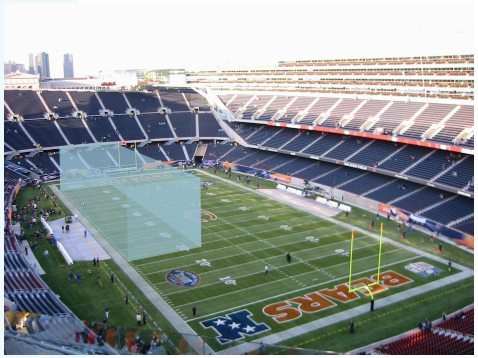


LBNE



- NOvA and T2K measurements may well provide a "no" answer to the question
  - "Octant question" attacked by combining NOvA/T2K and reactor experiments
- If the question is still relevant at the end of the decade then LBNE can weigh in

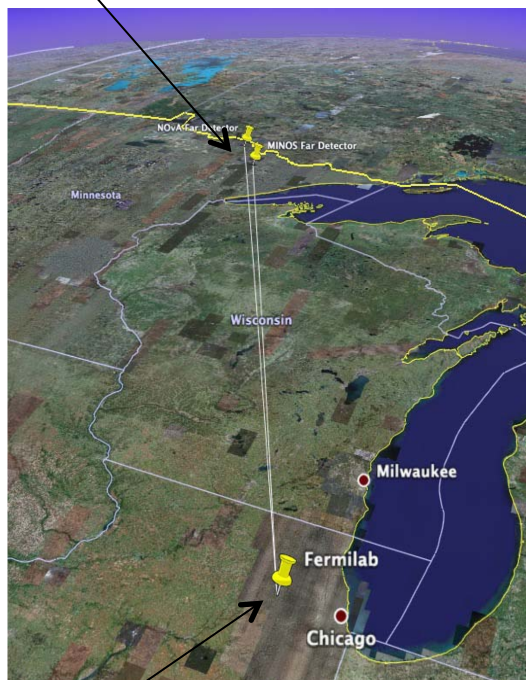
The NOvA Experiment



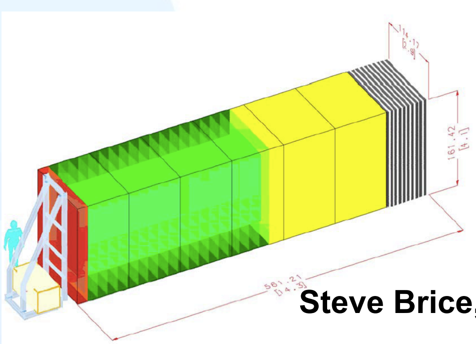
Far Detector:

14 kTon liquid scintillator

Fine grained calorimeter



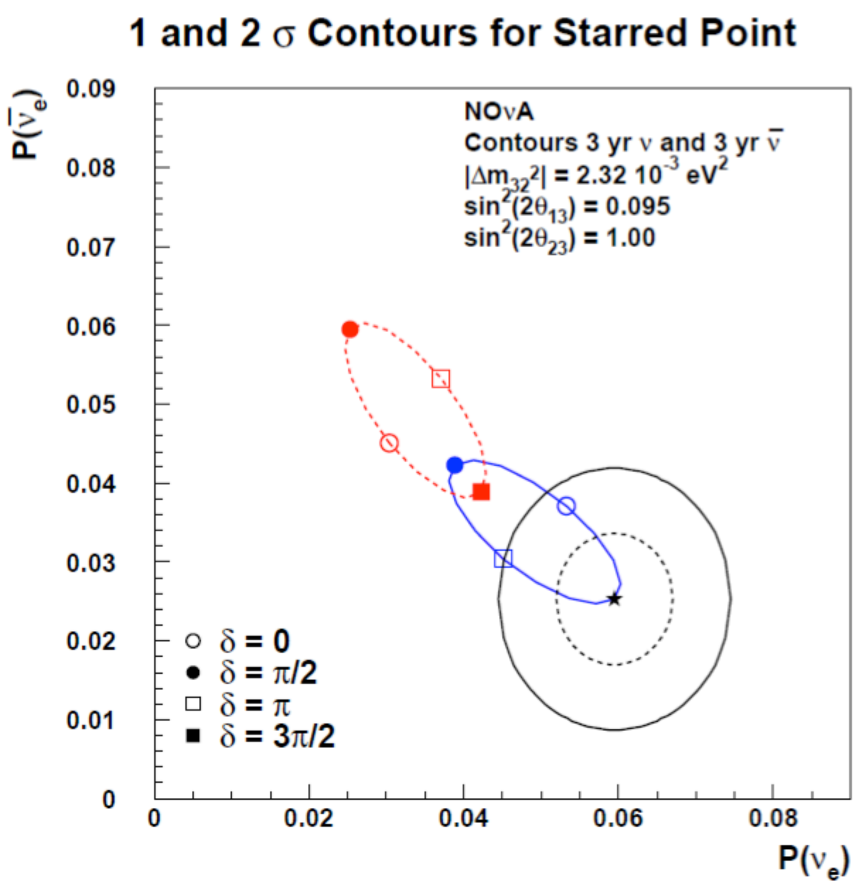
166 collaborators from 32 institutions in 5 countries



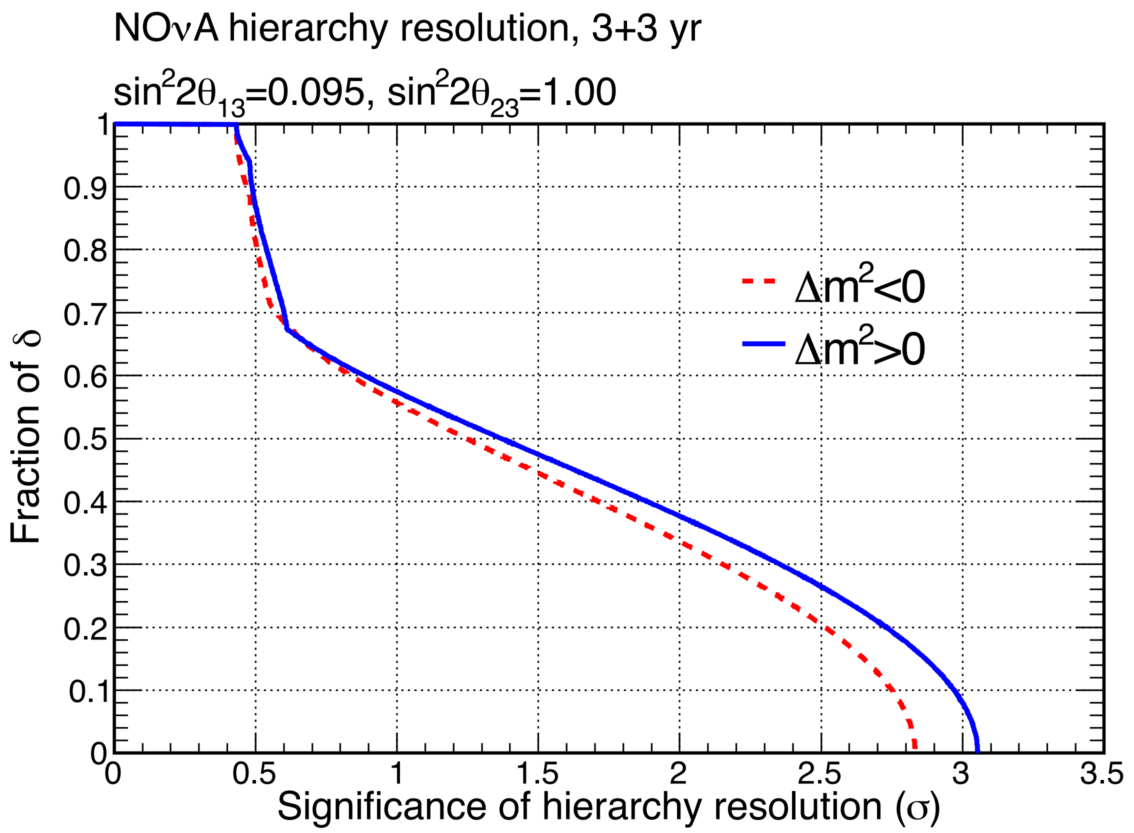
Near Detector:

330 ton version of the far detector

How are the Masses Ordered?



How are the Masses Ordered? NOvA Sensitivity



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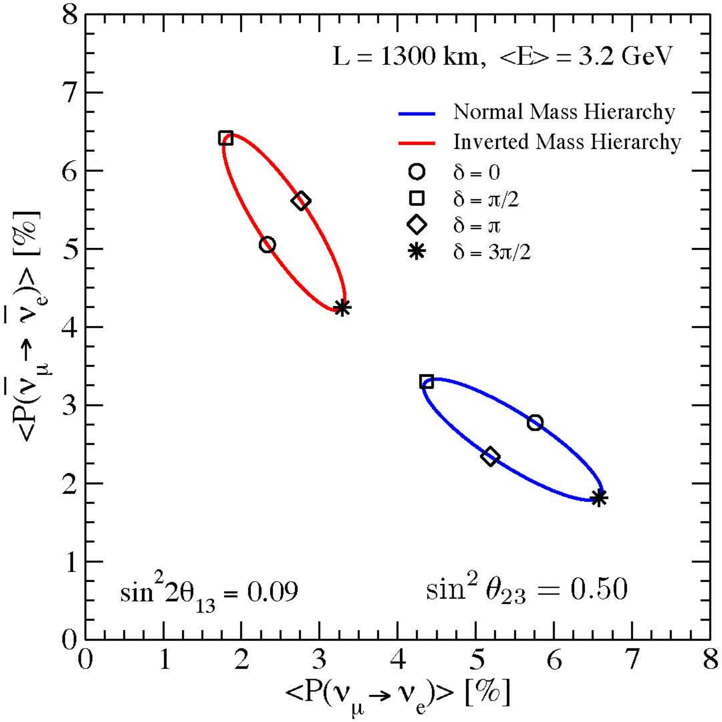
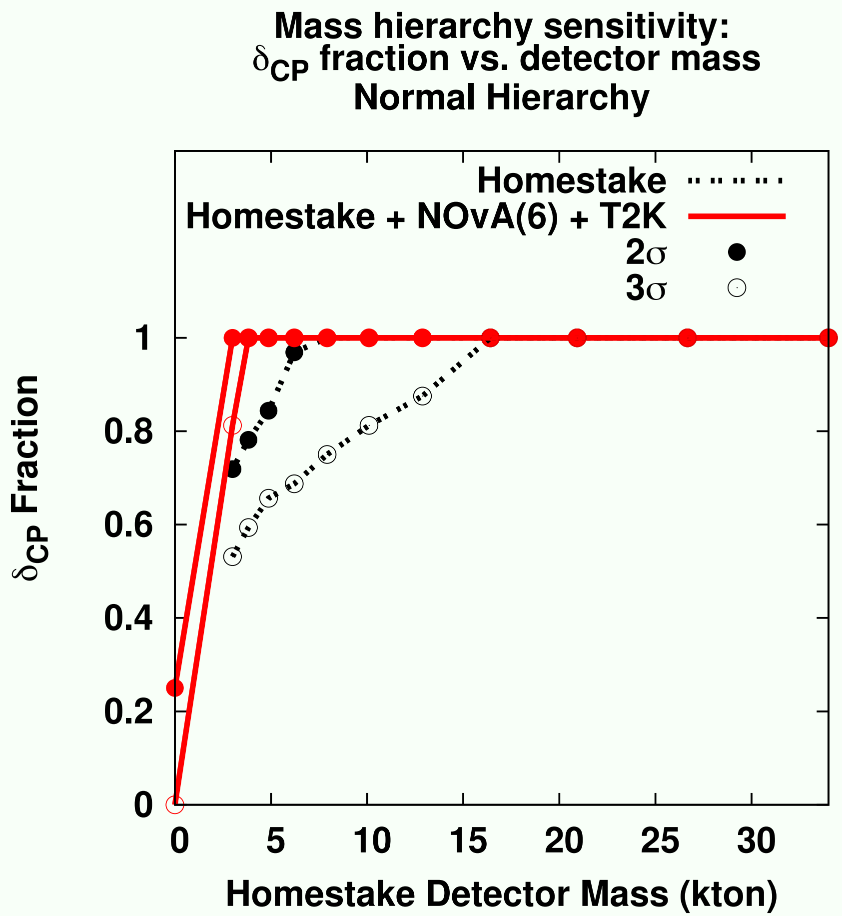
How are the Masses Ordered? – LBNE Sensitivity

LBNE will nail the hierarchy if it hasn't already been determined by NOvA and T2K

same L/E as NOvA





The fraction of δ_{CP} values for which the mass hierarchy can be resolved at 2/3σ (solid/open points) after 10 year run

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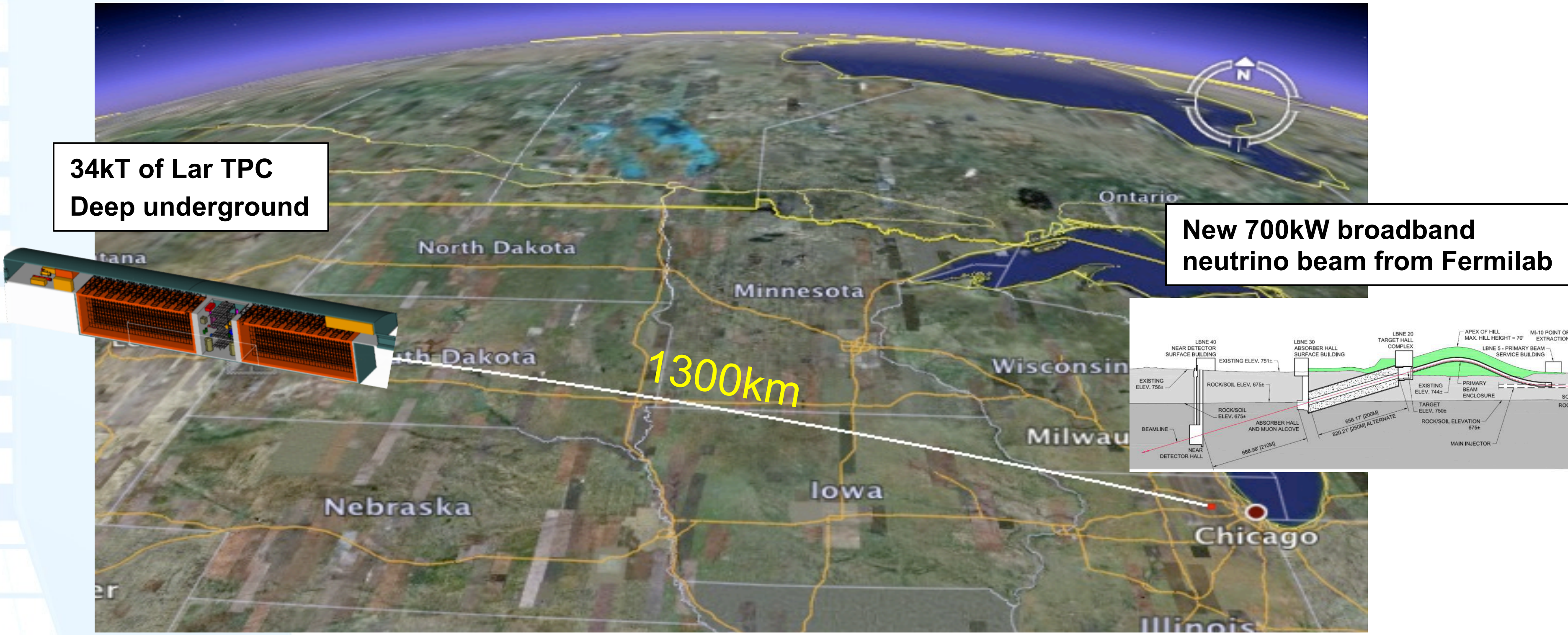
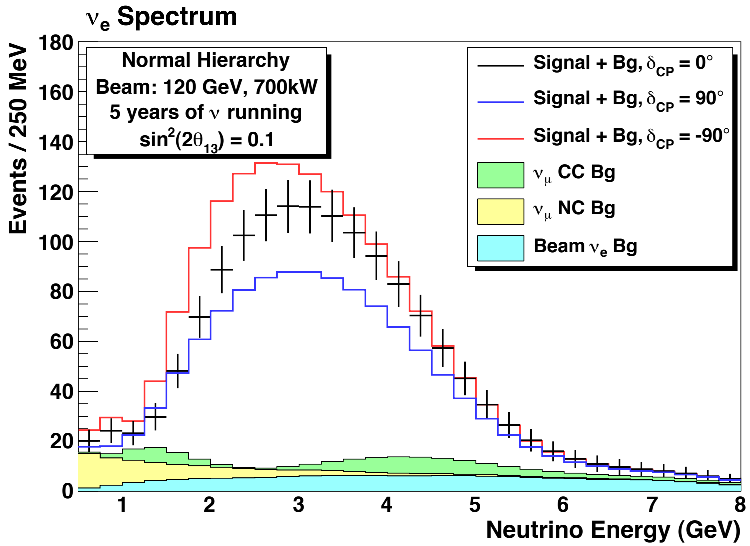
The LBNE Experiment



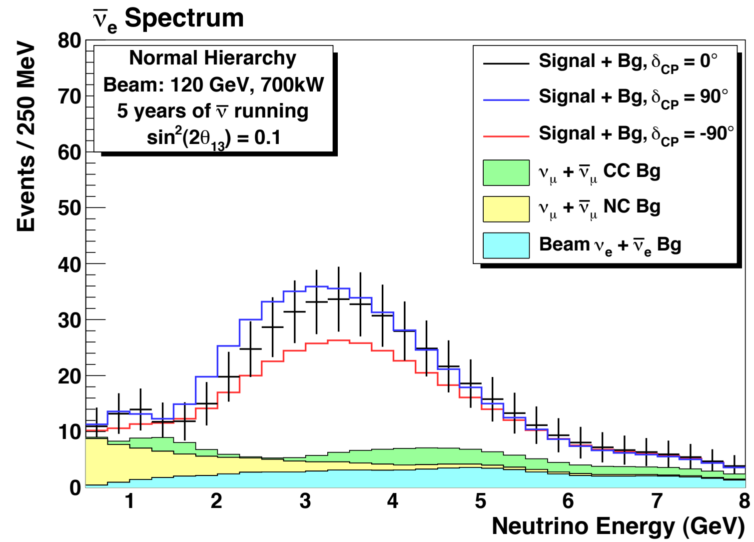
347 collaborators from 62 institutions in 5 countries

CP Violation and Measuring δ_{cp}

LBNE ν mode

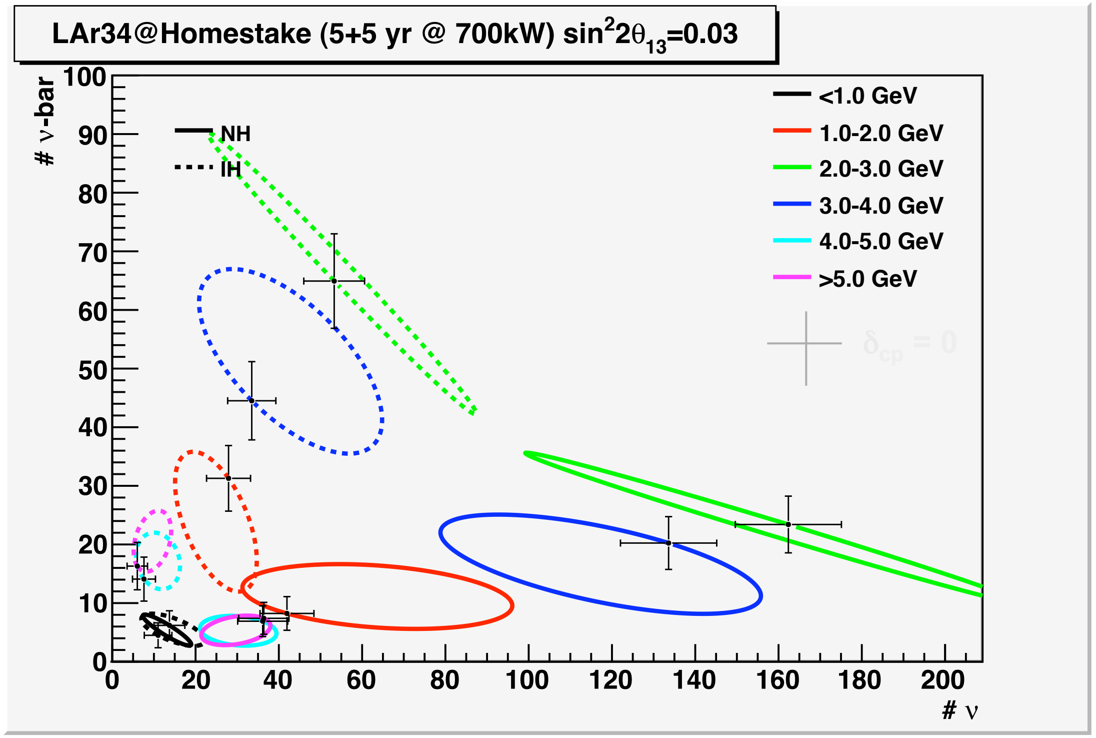


LBNE anti-ν mode

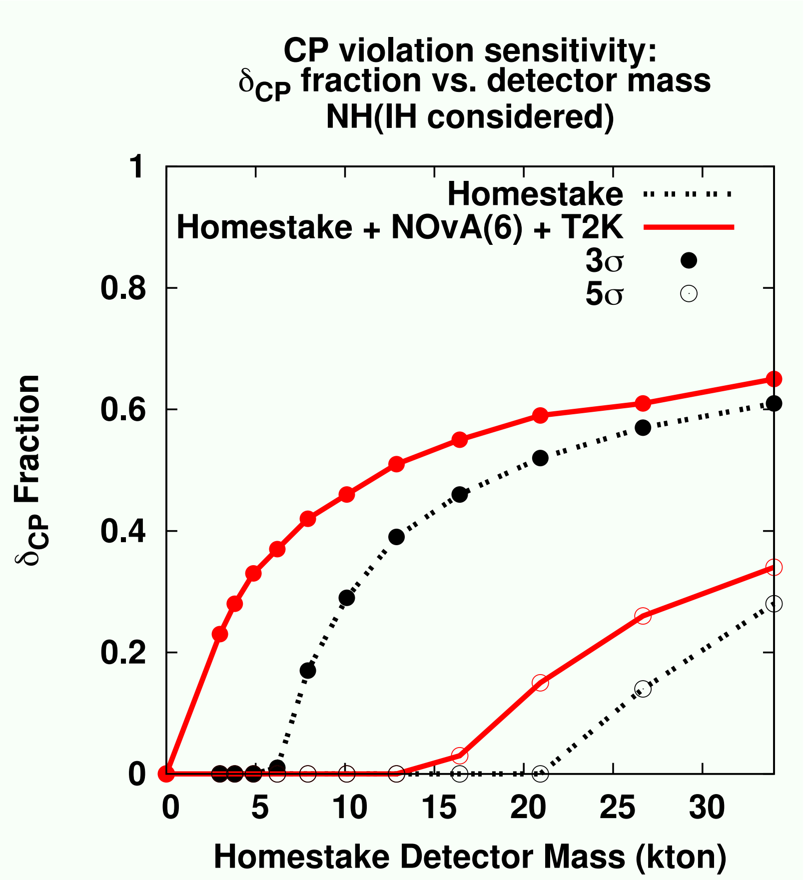


- CP Violation is demonstrated by seeing ν_e and anti-ν_e appearance behave differently
- In principle δ_{cp} can be measured with just ν_e appearance without running in anti-neutrino mode

LBNE Bi-Rate Plot with Statistical Errors

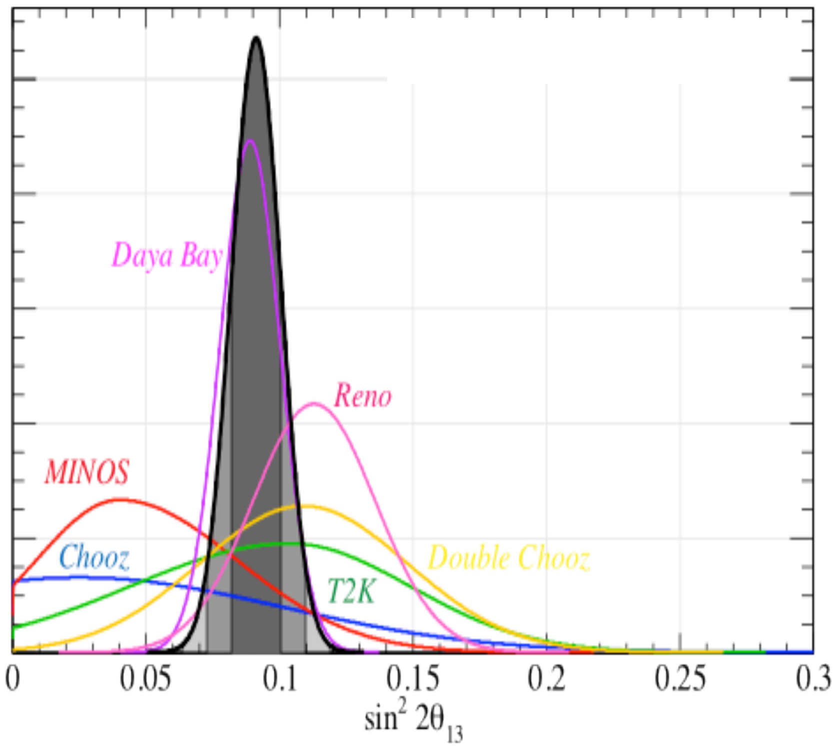


Is CP Violated? – LBNE Sensitivity



The fraction of δ_{CP} values for which CP violation can be resolved at 3/5σ (solid/open points) after 10 year run

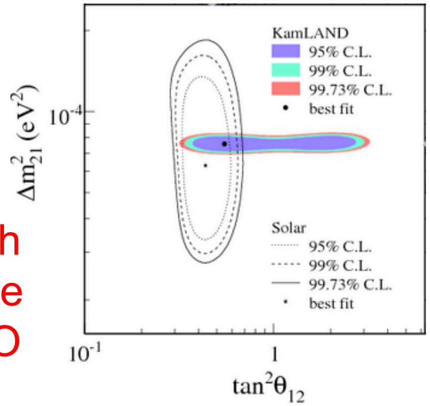
Can we Independently Check the θ_{13} Measured by Reactor Experiments?



Will NOvA and T2K measure ν_e appearance at the expected rate?

- Yes – Then we will have powerful confirmation of our understanding of the 3x3 oscillation matrix
- No – Then we will have a strong indication of some new physics

There is a close analogy here with the solar neutrino problem and the exquisite concordance of the SNO and KamLAND results



KamLAND, PRL. 100, 221803 (2008)

MINOS+ Capabilities

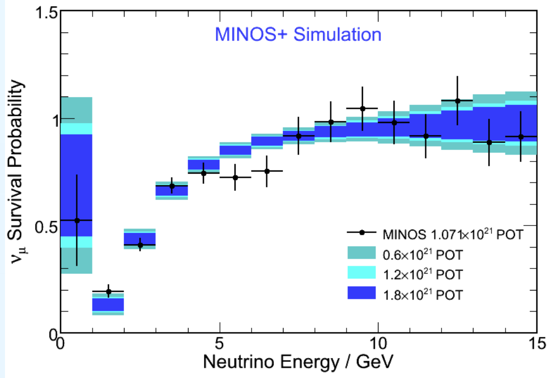
1. Improved measurement of θ_{23} and Δm_{32}^2
2. Study of high energy neutrinos
3. Search for sterile neutrinos
4. Search for tau neutrinos
5. Atmospheric neutrinos
6. Non-standard interactions
7. Measurement of the neutrino time of flight
8. Search for extra dimensions

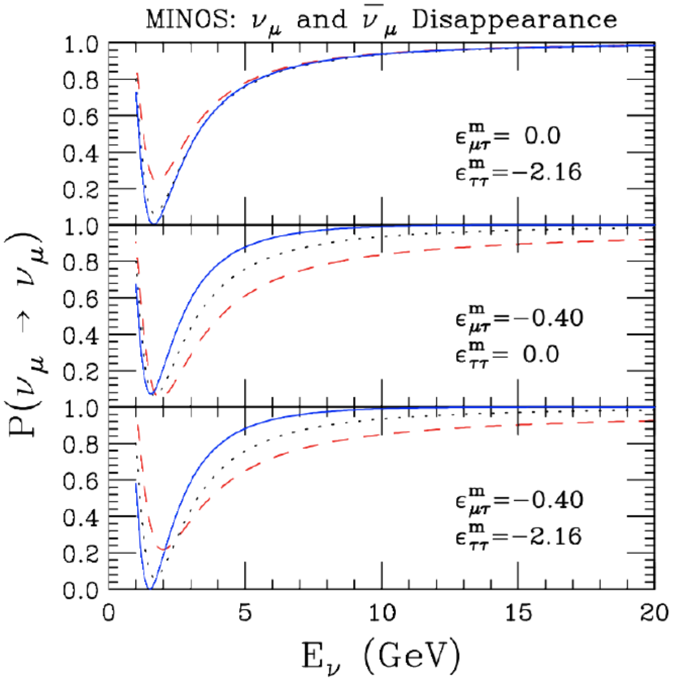
MINOS+ Non-Standard Interactions

If neutrinos have non-standard interactions these will produce additional matter effects beyond those expected when the beam traverses long distances and modify the oscillation probability

e.g. J.Kopp, P.A.N.Machado, and S.Parke Phys. Rev. D82:113002 (2010)

Note the high energy differences between ν_μ and anti-ν_μ disappearance





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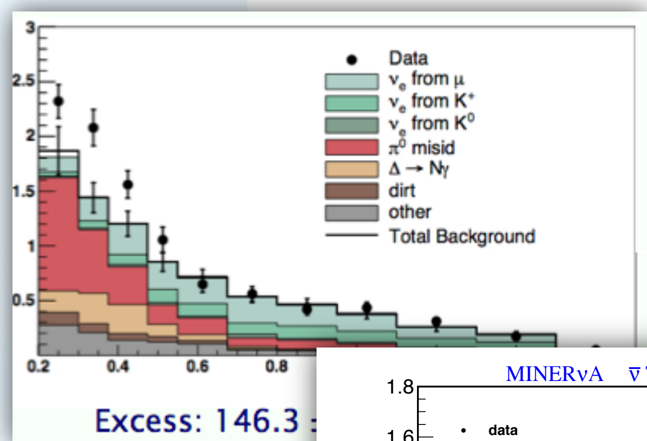
Short Baseline Neutrino Experiments

Cross Section Measurement & Short Baseline Oscillation

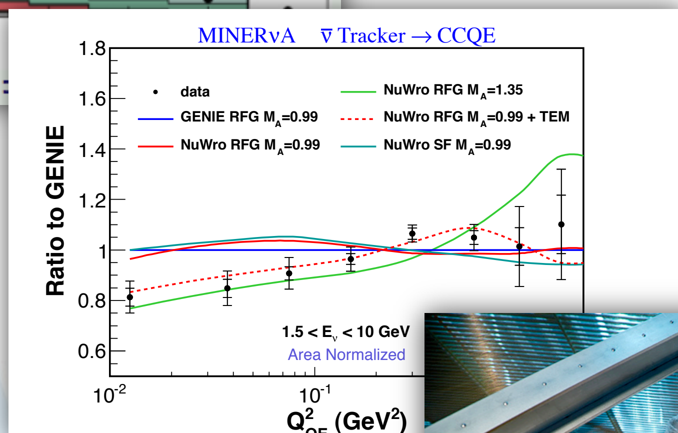


MiniBooNE

Searching for $\nu_\mu \rightarrow \nu_e$

Ground breaking cross-sections

➘



MINERvA

Precision cross-sections

➘

MicroBooNE

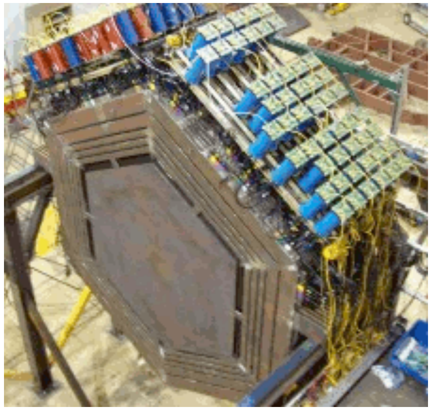
MB low energy excess

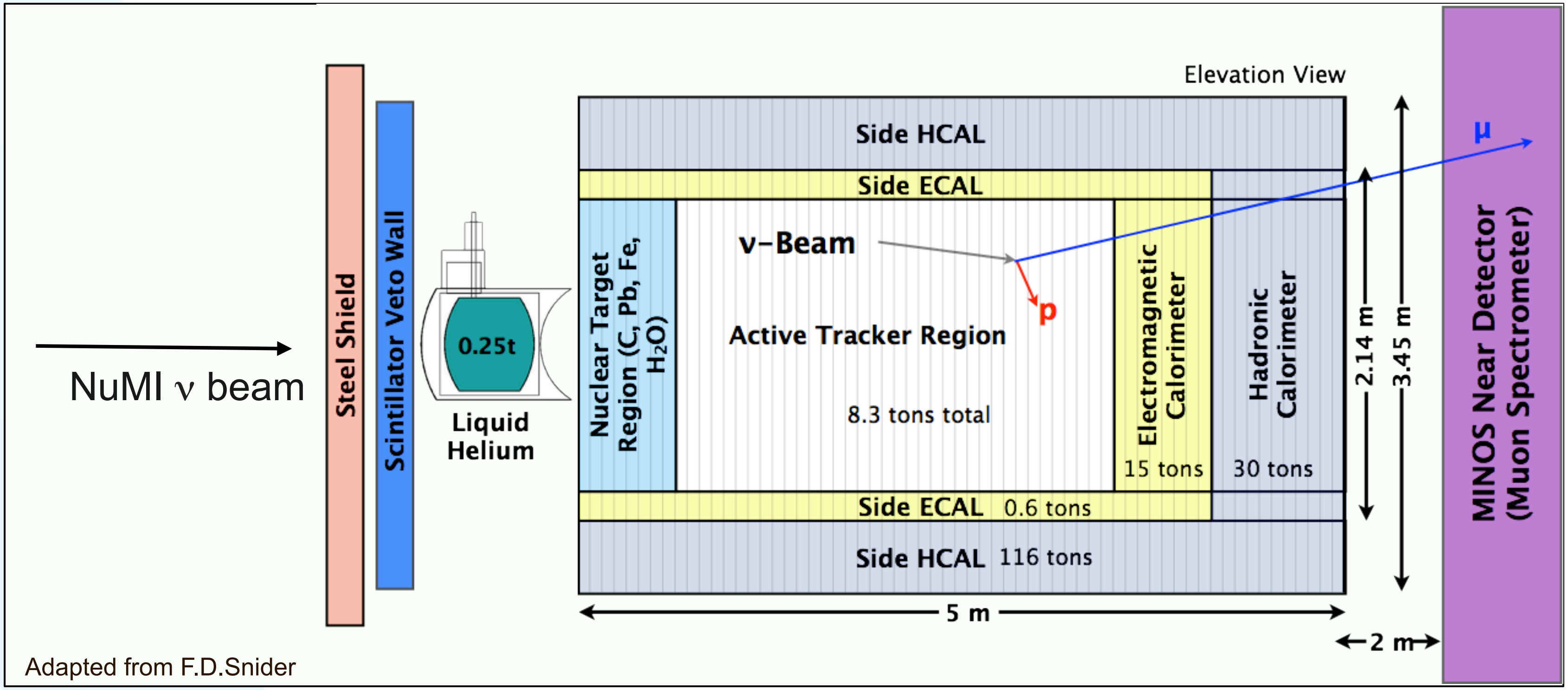
Argon cross-sections

LAr TPC R&D

MINERvA

- 120 stacked modules, mostly planes of scintillator strips
- Fully active, finely-segmented tracking region in center
- LHe and nuclear target region on upstream side
- Side and end EM and hadronic calorimeter regions
- MINOS near detector used as muon spectrometer

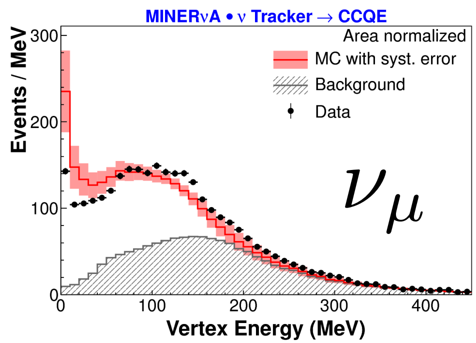


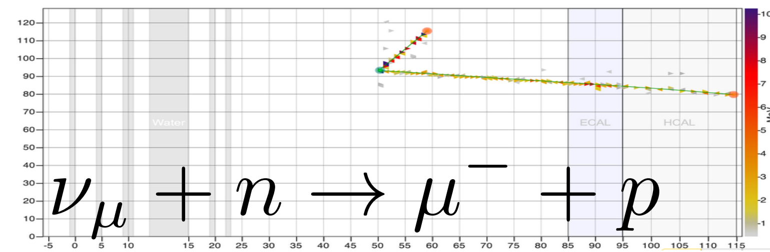


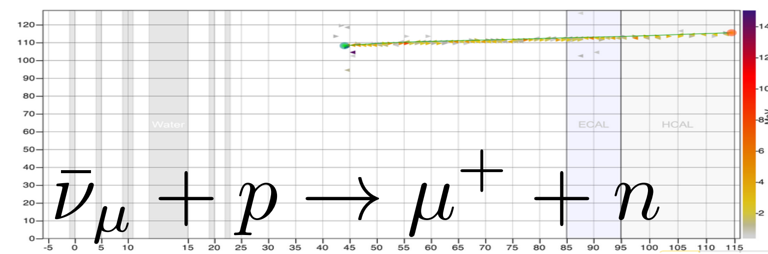
70 collaborators from 21 institutions in 8 countries

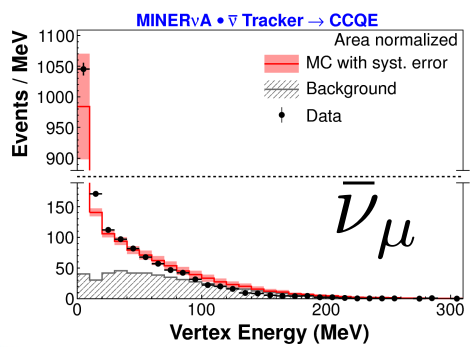
Quasi-elastic Results from MINERvA

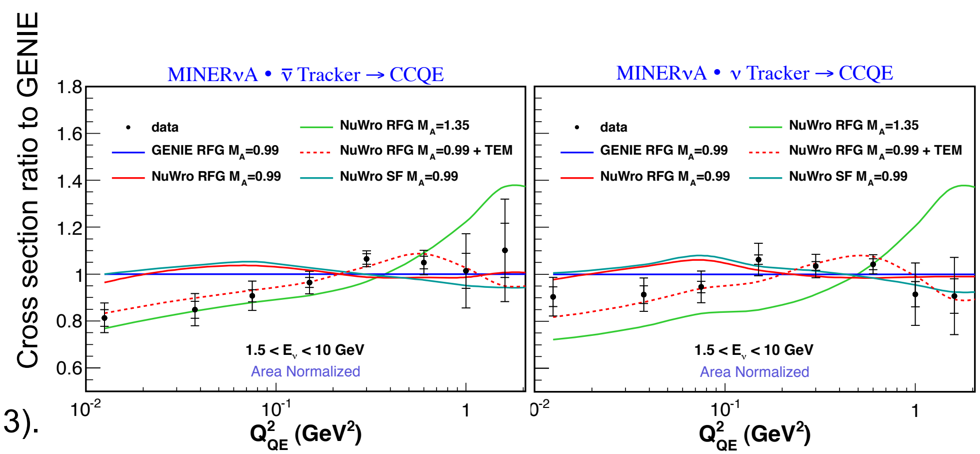
- See evidence in *vertex energy* AND *muon kinematics* for np correlations in the nucleus: would give pp final state in ν scattering, nn final state in anti-ν scattering







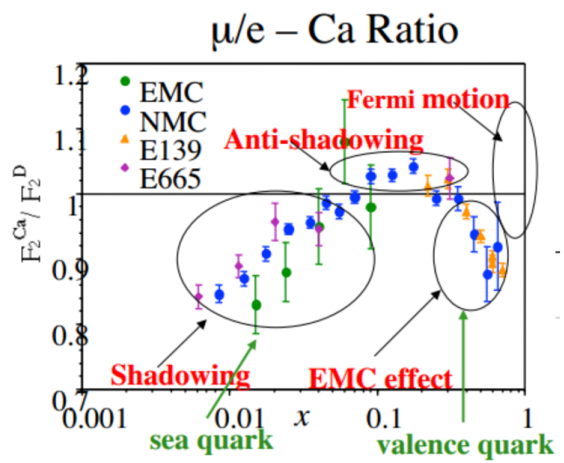




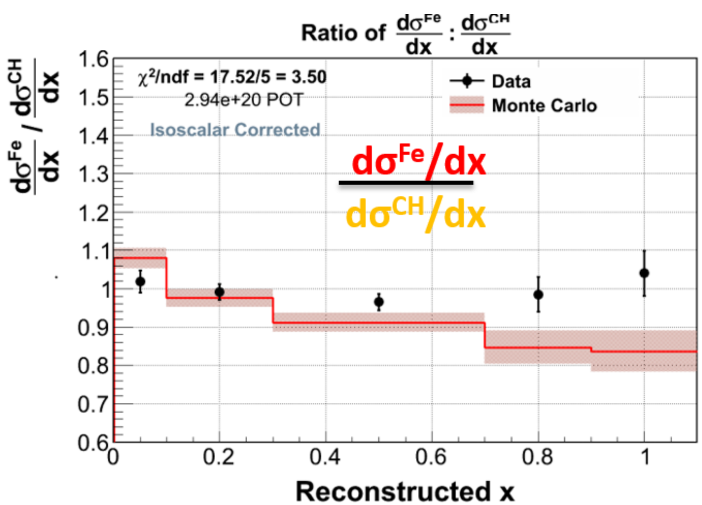
- First physics publications
  - Phys. Rev. Lett. 111, 022502 (2013).
  - Phys. Rev. Lett. 111, 022501 (2013).

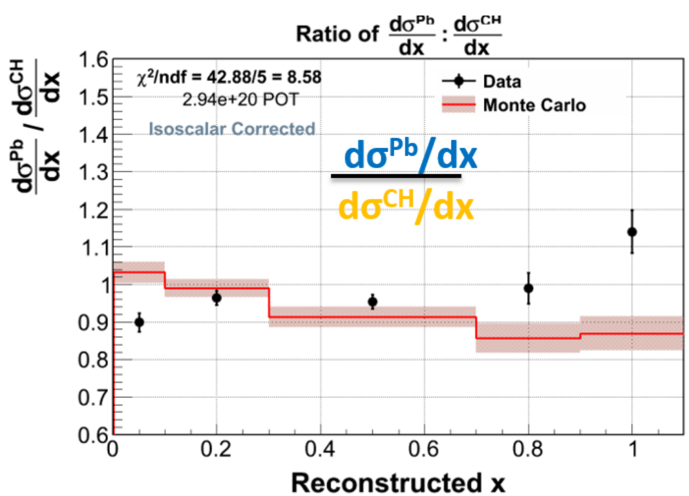
Cross section ratios across several nuclei at MINERvA

- Electron Scattering measures nuclear effects in cross section ratios, origin still not understood
- Neutrinos provide new tool to study this, but no beam has been intense enough to do this to any precision in one experiment until now
- MINERvA compares plastic (CH) to Fe and Pb, see differences not predicted in ratios vs x, but none versus neutrino energy
- B. Tice, Rutgers University, October 11 Wine and Cheese, paper in progress



x: fraction momentum of struck quark

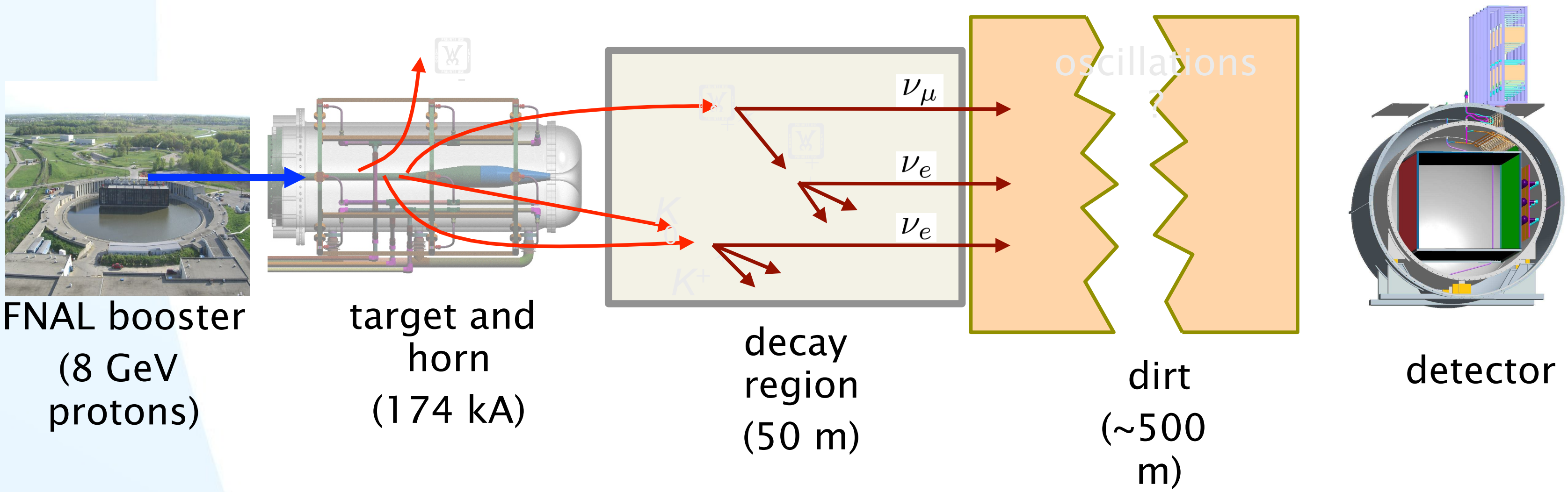




The MicroBooNE Experiment

MicroBooNE: Liquid Argon Time Projection Chamber

70 ton fiducial volume LArTPC to be exposed to the Booster and NuMI Neutrino Beams

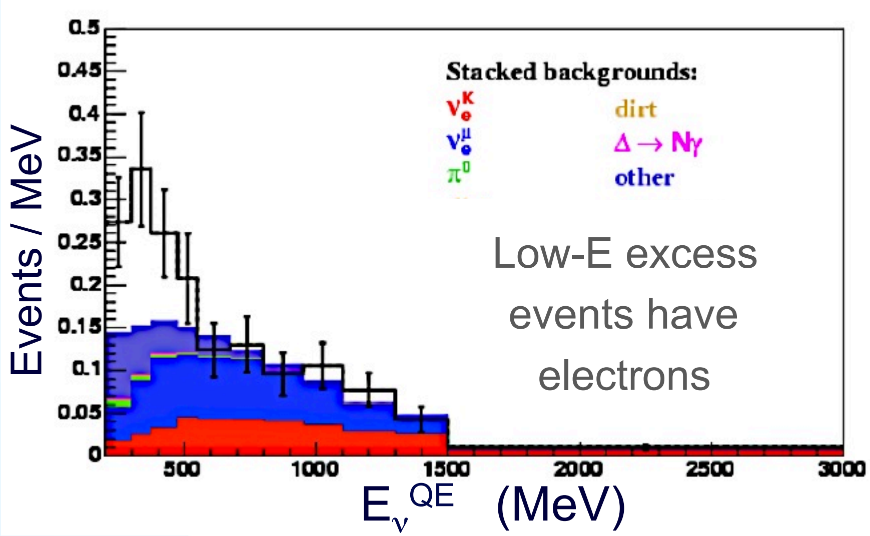


Look for low energy neutrino phenomena

- MiniBooNE low energy excess – distinguish electrons from gammas
- Low energy neutrino cross sections
- R&D for LArTPCs

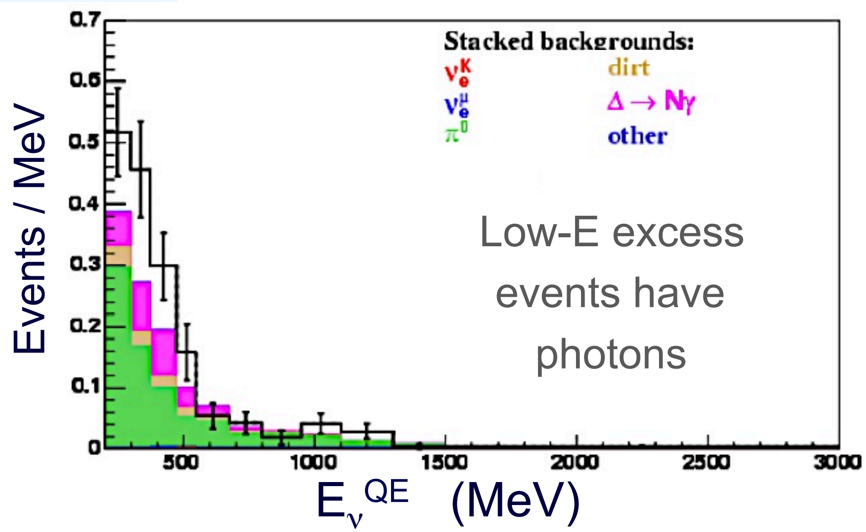
95 collaborators from 16 institutions in 3 countries

MicroBooNE Check of MiniBooNE Low Energy Excess



6 x 10^{20} pot in neutrino mode (2-3 year run, starting 2014)

If the MiniBooNE low energy excess is due to electrons, MicroBooNE expects a 5σ signal

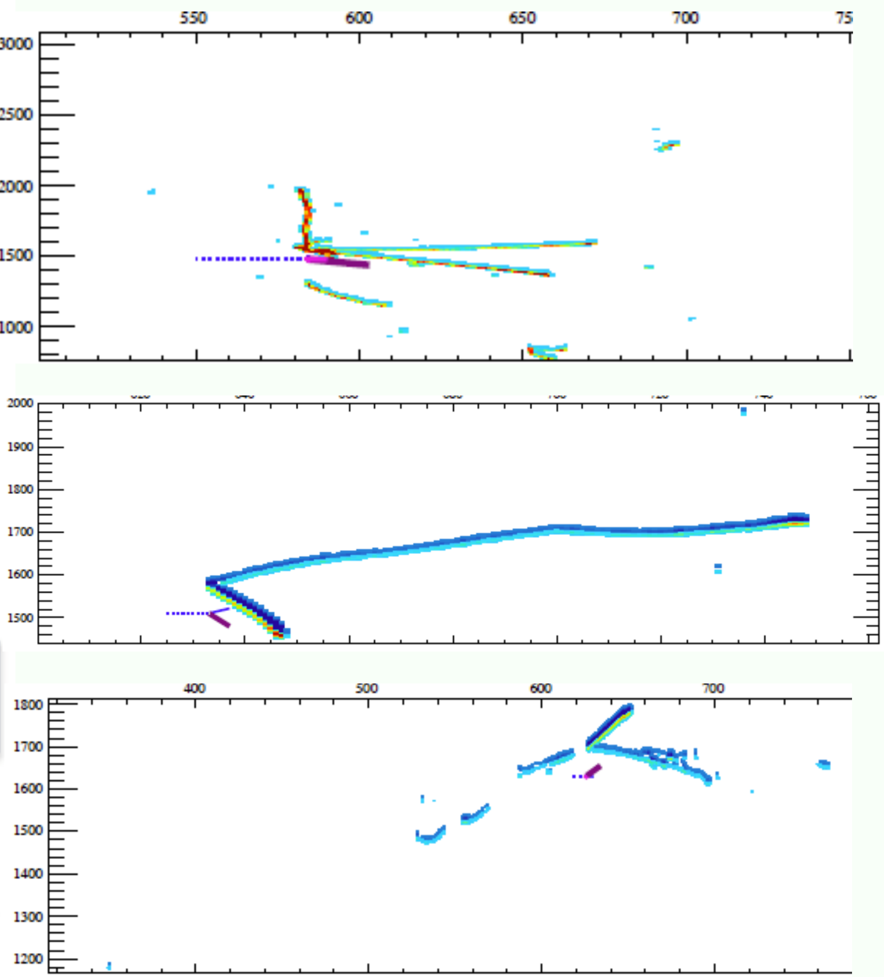


If the MiniBooNE low energy excess is due to photons, MicroBooNE expects a 4σ excess

Future MicroBooNE Cross-Section Measurements

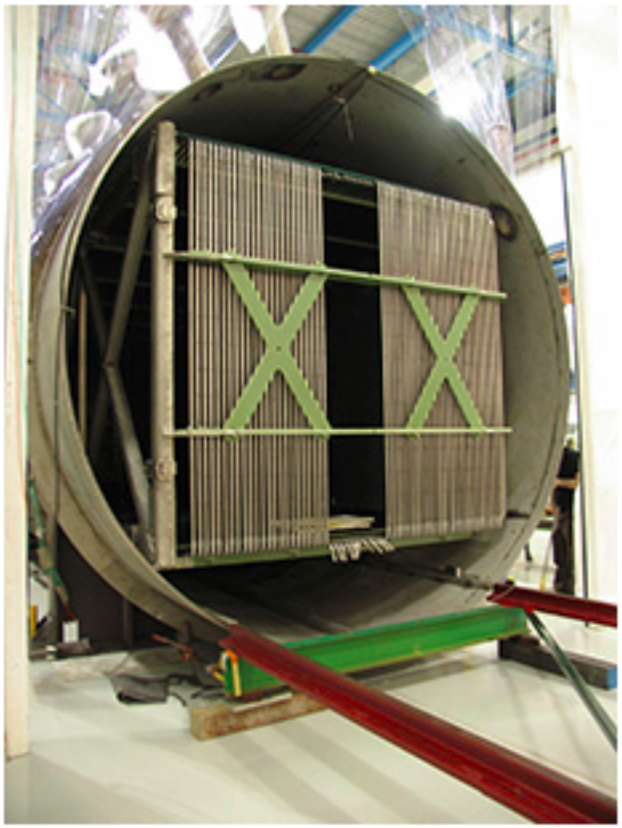
Expected event rates for 6.6 x 10²⁰ POT

production mode	# events
CC QE ($\nu_\mu\, n \rightarrow \mu^-\, p$)	60,161
NC elastic ($\nu_\mu\, N \rightarrow \nu_\mu\, N$)	19,409
CC resonant π^+ ($\nu_\mu\, N \rightarrow \mu^-\, N\, \pi^+$)	25,149
CC resonant π^0 ($\nu_\mu\, n \rightarrow \mu^-\, p\, \pi^0$)	6,994
NC resonant π^0 ($\nu_\mu\, N \rightarrow \nu_\mu\, N\, \pi^0$)	7,388
NC resonant $\pi^\pm$ ($\nu_\mu\, N \rightarrow \nu_\mu\, N'\, \pi^\pm$)	4,796
CC DIS ($\nu_\mu\, N \rightarrow \mu^-\, X$, $W > 2$ GeV)	1,229
NC DIS ($\nu_\mu\, N \rightarrow \nu_\mu\, X$, $W > 2$ GeV)	456
NC coherent π^0 ($\nu_\mu\, A \rightarrow \nu_\mu\, A\, \pi^0$)	1,694
CC coherent π^+ ($\nu_\mu\, A \rightarrow \mu^-\, A\, \pi^+$)	2,626
NC kaon ($\nu_\mu\, N \rightarrow \nu_\mu\, K\, X$)	39
CC kaon ($\nu_\mu\, N \rightarrow \mu^-\, K\, X$)	117
other ν_μ	3,678
total ν_μ CC	98,849
total ν_μ NC+CC	133,580
ν_e QE	326
ν_e CC	657



Feature

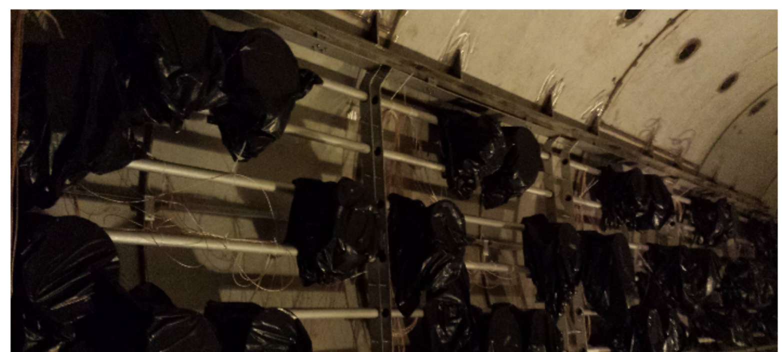
Liquid-argon time projection chamber gets a test fit



A 6-ton time projection chamber now sits inside the MicroBooNE cryostat. *Photo: Sarah Khan*

8256 wires installed!

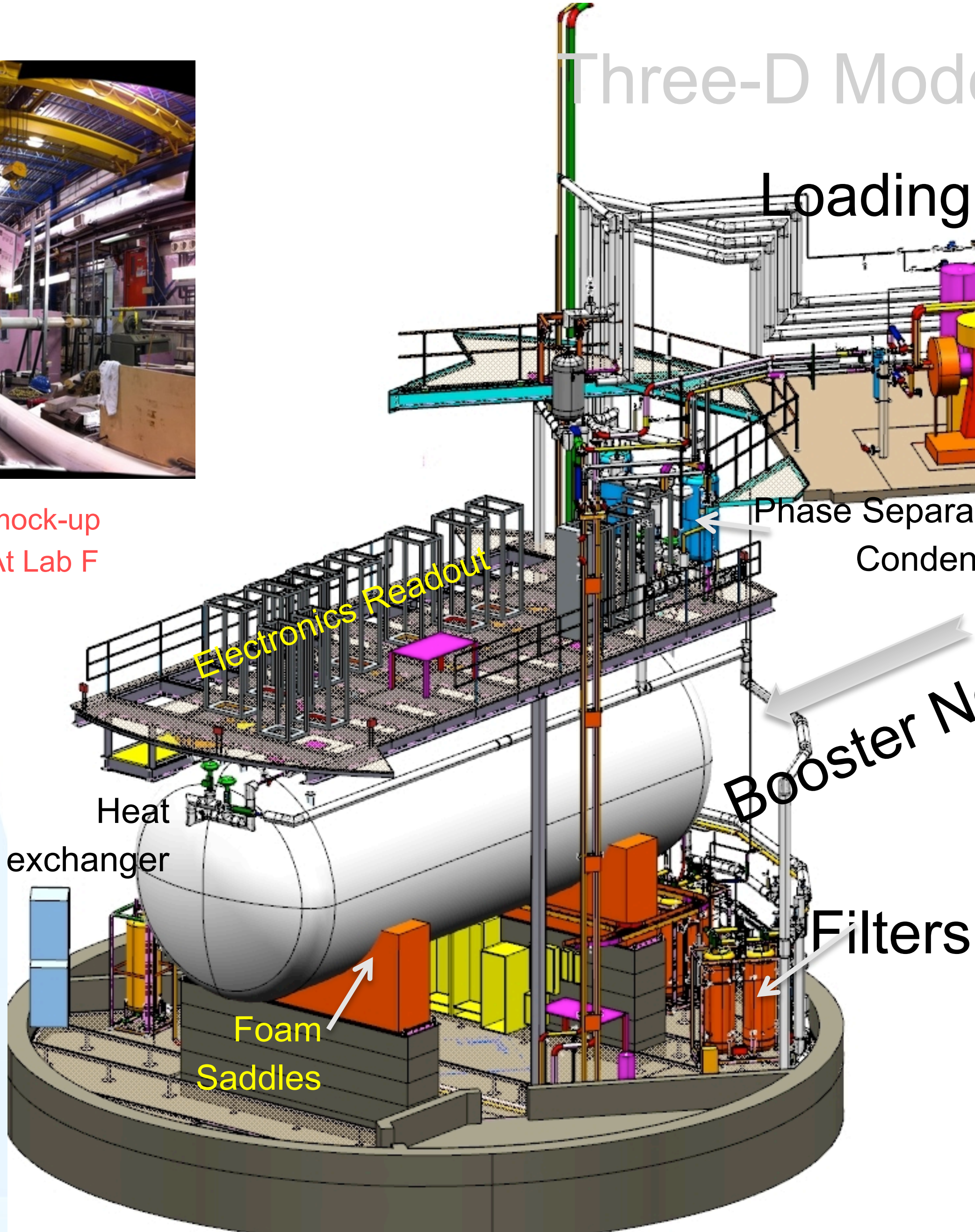
Motherboards installed on the TPC



All 32 PMTs installed inside the cryostat (covered with dark bags for protection)

Three-D Model

Pre-assembly and mock-up
At Lab F



To ensure smooth installation

Muon Experiments

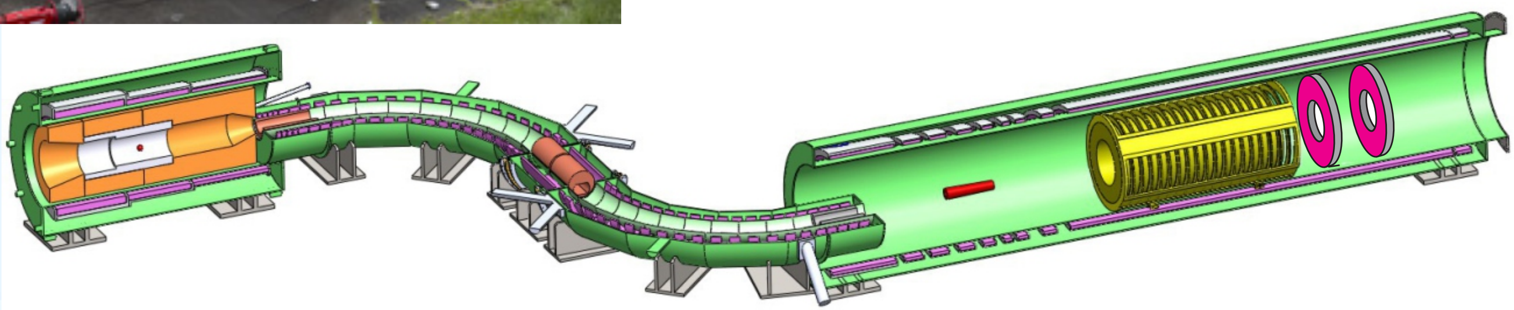
Rare Processes and Precision Measurements
as Windows into New Physics

Muon (g-2)

Muon anomalous mag. mom.

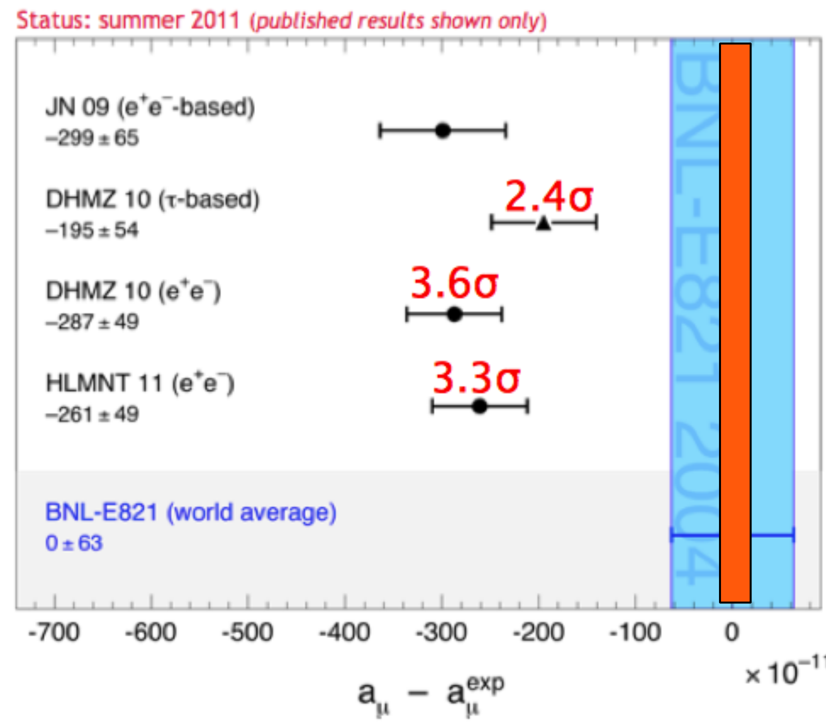
Mu2e

Searching for μ+N ➔ e+N



Muon g-2 Physics

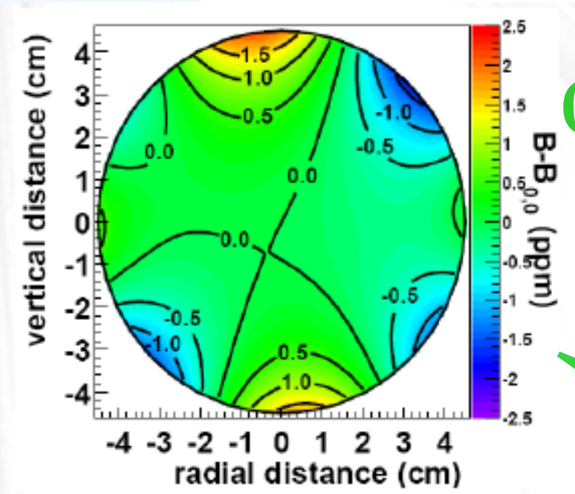
$$\vec{\mu} = g_s \left(\frac{q}{2m}\right) \vec{s}$$



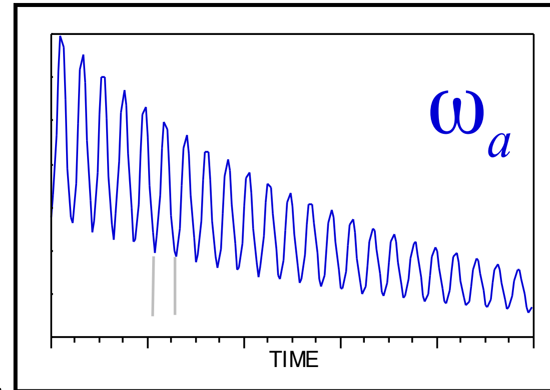
- g≈2 but higher-order corrections
  - QED, EW, hadronic, new physics?

- Muon g-2 is a unique probe of new physics
  - Chirality-flipping while CP and flavor conserving, unlike many other low energy observables

Muon g-2 requires 3 quantities

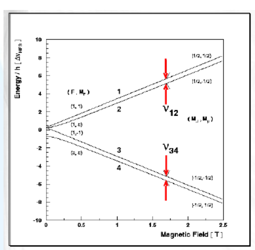


ω_p



ω_a

$$a_\mu = \frac{\dfrac{\omega_a}{\omega_p}}{\dfrac{\mu_\mu}{\mu_p} - \dfrac{\omega_a}{\omega_p}}$$



μ_μ/μ_p = 3.183 345 24(37) (120 ppb)

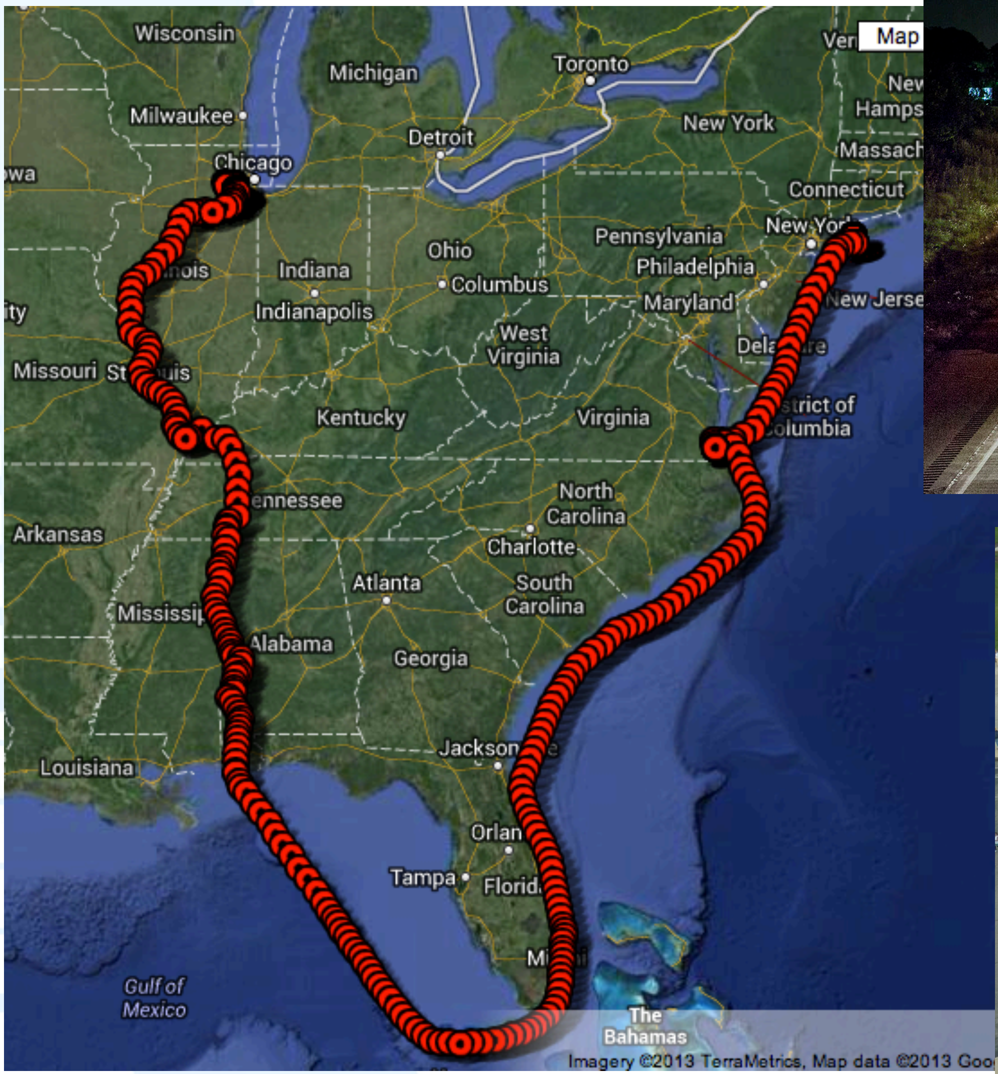
= *3.183 345 39(10) (31 ppb)*

Goals of Muon g-2

- Reduce experimental error by 4
  - 20x more muons than BNL
  - Control systematics on muon precession frequency and magnetic field determination to 0.07 ppm
- If theory and experiment central values unchanged, discrepancy would rise to 5σ even with no further theory improvements
- 3 Major Steps
  - ✓ Bring BNL storage ring and associated equipment to Fermilab
  - Modify anti-proton complex to provide a high-purity beam of 3.094 GeV/c muons
  - Upgrade various subsystems (injection devices, field monitoring, detectors & DAQ) to meet requirements for rates and systematics

Ring transport

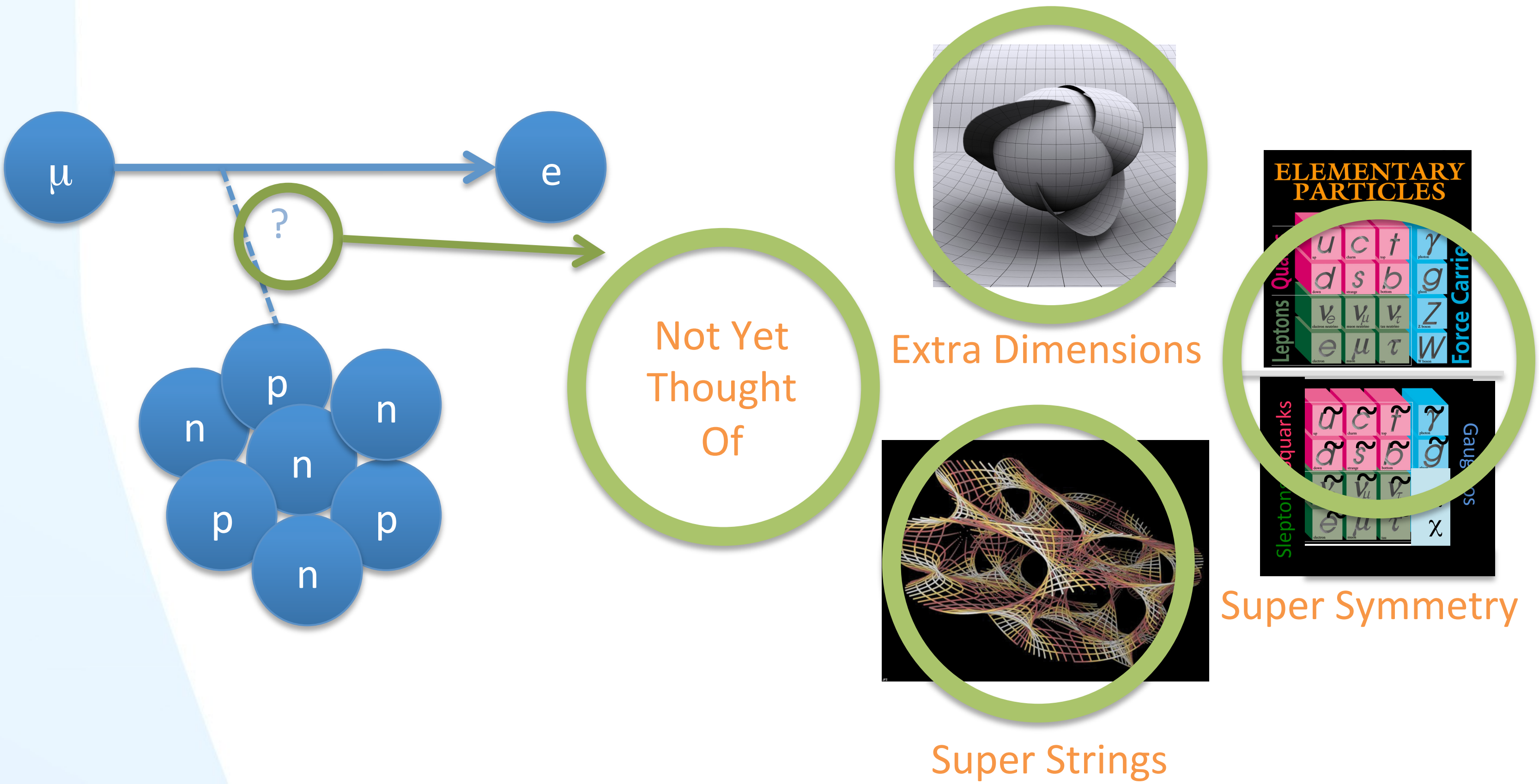
Ring transport



Fermilab

Mu2e Physics

- Muons regularly decay to electrons and neutrinos $\mu^- \rightarrow e^- \nu_e \bar{\nu}_\mu$
- Mu2e will search for charged lepton flavor violation ($\mu N \rightarrow eN$)
  - Neutrino flavor oscillations already observed

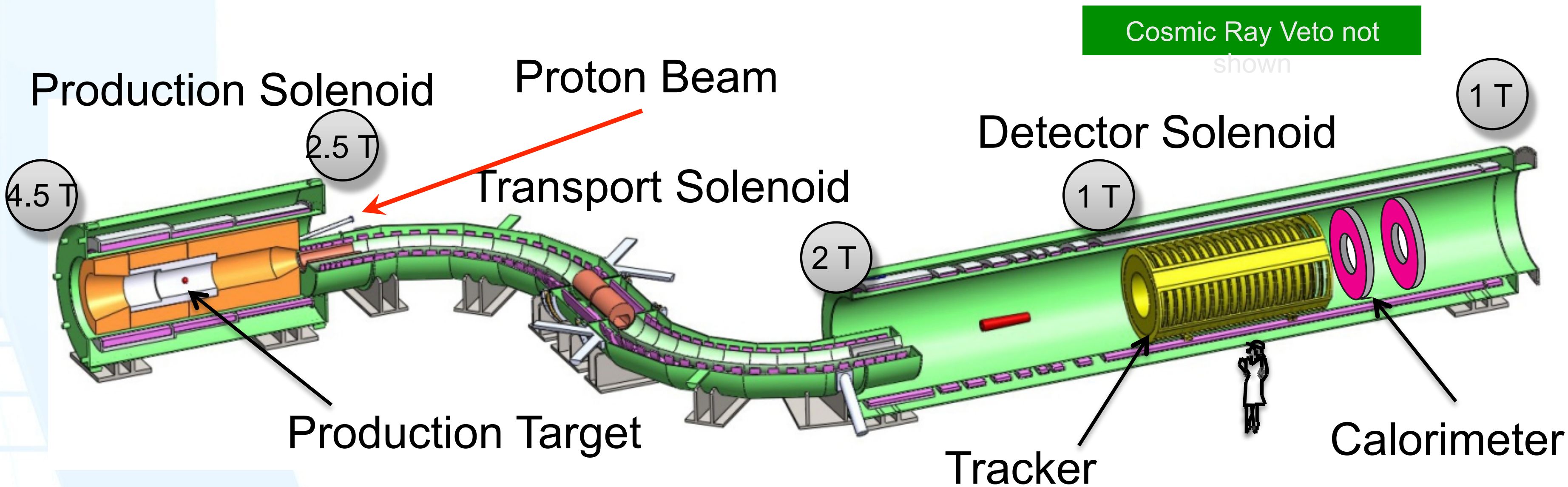


- Conversion rate distinguishes between different theories

Mu2e Measurement

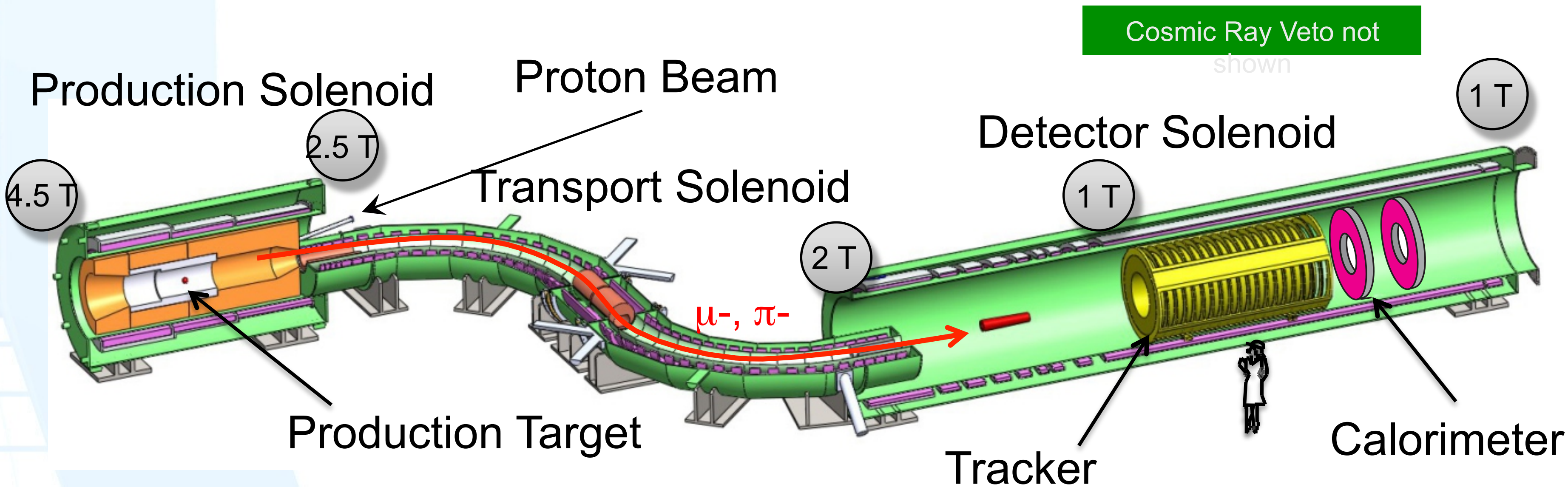
- Generate beam of low-momentum μ^-
- Stop the muons in a target
  - Aim to improve sensitivity by 10^4 over previous experiments
  - Requires ~10^{18} stopped muons
- Stopped muons are trapped in orbit around the nucleus
  - Using Aluminum target (nucleus):
    - lifetime in capture τ_μ^{Al}=864 ns
    - conversion-electron energy 104.97 MeV
    - (maximum decay-e energy 52.8 MeV)
- Extinction system (AC dipole) to prevent prompt background from out-of-time protons hitting production target

Mu2e Apparatus

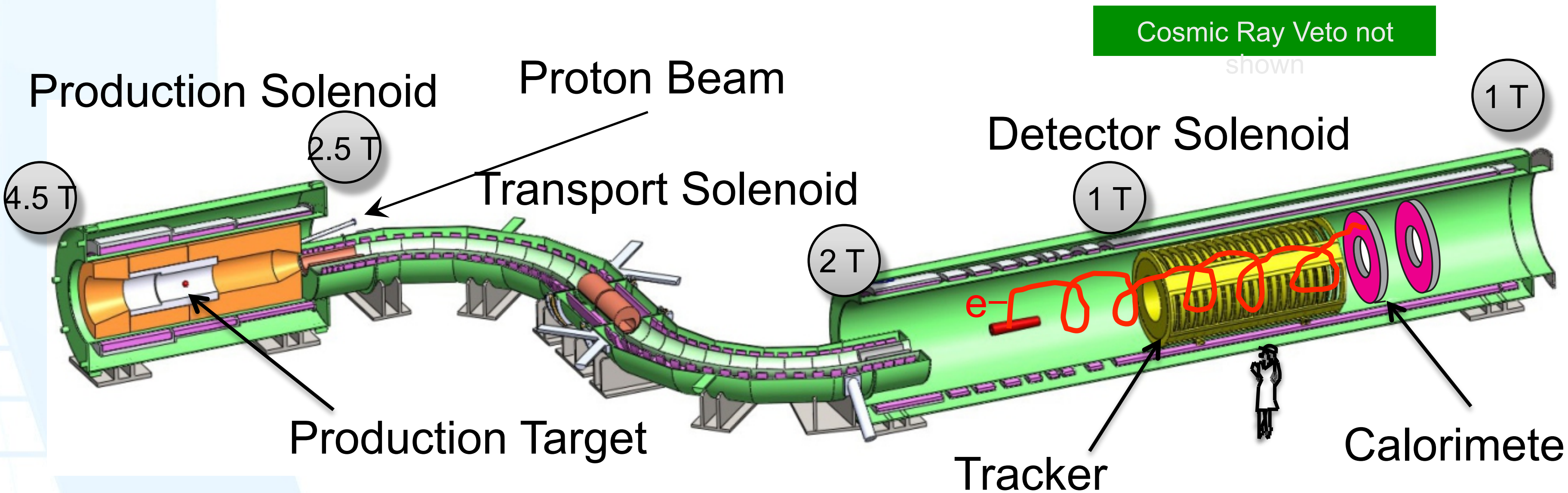


Proton Beam delivered to the production target via the former Antiproton Source beamlines followed by a new external beamline

Mu2e Apparatus



Mu2e Apparatus



Muon Campus Layout

New Initiatives

- LAr1
  - More LAr detectors in the Booster Neutrino Beam
  - New near and far detector options
- νStorm
  - Neutrinos from a muon storage ring aimed at near and far magnetized iron detectors
- Experiments using neutrinos from stopped π/μ decay
  - Booster Neutrino Beam target area as source
  - Cross-sections for supernov detection
  - Coherent Elastic ν-nucleus scattering search
- ORKA
  - $K^+ \rightarrow \pi^+ \nu\nu$ 1000 events
  - Broad K decay program

Scientific Organizational Changes

- Fermilab's Divisions have been changed to focus on the Intensity Frontier
  - In the Accelerator Division
    - Anti-Proton Department dissolved
    - Muon Department created to design and operate the beam lines for the Muon (g-2) and Mu2e experiments.
  - In the Computing Division
    - Established computing liaisons between IF experiments and Division
    - Establishing a common suite of IF tools - ART, LArSoft, ART-DAQ, SAM-IF, Grid Submissions etc
  - In the Particle Physics Division
    - Intensity Frontier Department created
    - Intensity Frontier Operations Support group created
    - DAQ/Online Software Support group created

Intensity Frontier Department

INTENSITY FRONTIER DEPARTMENT
S. Brice, Head
B. Casey, Deputy Head

ADMIN. SUPPORT
(C. Kennedy)
(E. Johnson)
(S. Schuler)

FIXED TARGET
D. Christian, Ldr
(A. Bross)
A. Mazzacane, G
R. Raja
S. Wang, IF

MUON (g-2)
C. Polly, WF Ldr.
(B. Casey)
T. Gadfort
B. Kiburg, LF
(A. Lyon, CD)
H. Nguyen
M. Rominsky, RA
(M. A. Soha)

LBNE/
LIQUID ARGON R&D
B. Rebel, WF, Ldr.
R. Acciarri, RA
C. Escobar, IF
A. Hahn
(H. Jostlein, SE OC)
T. Junk
B. Lundberg
S. Pordes
M. Stancari
(J. Strait, LBNE, PO)
T. Yang, RA
J. Yoo, WF

MICROBOONE
R. Rameika, Ldr
B. Baller
B. Carls, RA
(M. Cooke, RA)
(H. Greenlee)
C. James
R. Krull
S. Lockwitz, RA
J. Raaf
M. Soderberg
G. Zeller

MINERvA
D. Harris, Ldr.
D. Boehnlein, IPA
(D. Hahn)
J. Morfin
D. Martinez Caicedo, IF
J. Osta, RA
L. Rakotondravohitra, IF
(R. Snider, CD)
(D. Torretta)

MINOS+
R. Plunkett, Ldr
(S. Hahn)
(R. Hatcher, CD)
M. Kiveni, RA
(A. Kreymer, CD)
M. Medeiros, IF
R. Pahlka, RA

Mu2e
R. Ray, Ldr.
R. Bernstein
(H. Brown)
A. Gaponenko, WF
M. Gardner
D. Glenzinski
C. Group
(K. Knoepfel, RA)
(R. Kutschke, CD)
S. Moed Sher
A. Mukherjee
G. Piacentino, IF
V. Rusu
G. Tassielli, IF
R. Wagner

NOVA
J. Cooper, Ldr.
H. Brown
X. Bu, RA
H. Ferguson
W. Freeman
D. Jensen
(P. Lukens)
T. Miao
M. Muether, RA
(A. Norman, CD)
D. Perevalov, RA
T. Sarlina
P. Shanahan
R. Tesarek
J. Zalesak, IF

Created to support the scientific effort on IF projects and experiments

Intensity Frontier Fellowship Program

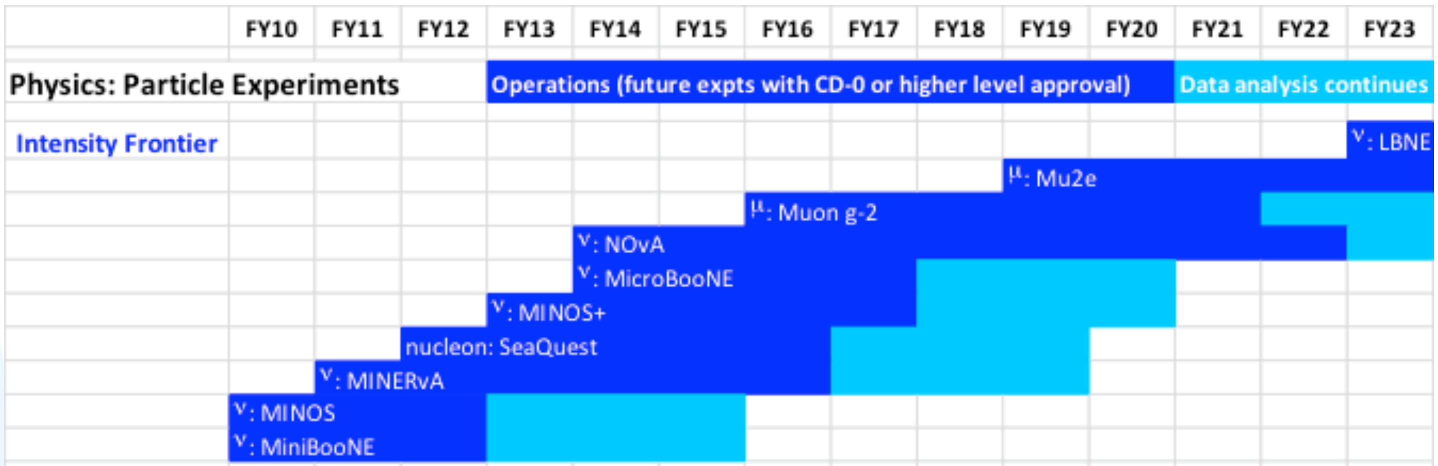
- A community driven mechanism to support an Intensity Frontier intellectual hub at Fermilab

- Support extended visits to Fermilab from university and other lab scientists
  - Work on Intensity Frontier Projects
  - Home institution can be anywhere in the world except Fermilab
  - Emphasis on current and potential future IF research rather than operations
  - Theorists or experimentalists

- Applications are judged by peer review
  - Committee with majority of members from outside Fermilab

- 1^{st} batch of Fellows started in fall 2013
- Currently advertising for 2^{nd} batch of Fellows

Intensity Frontier Experiment Timeline



Intensity Frontier Experiment Output

http://intensityfrontier.fnal.gov/breadth

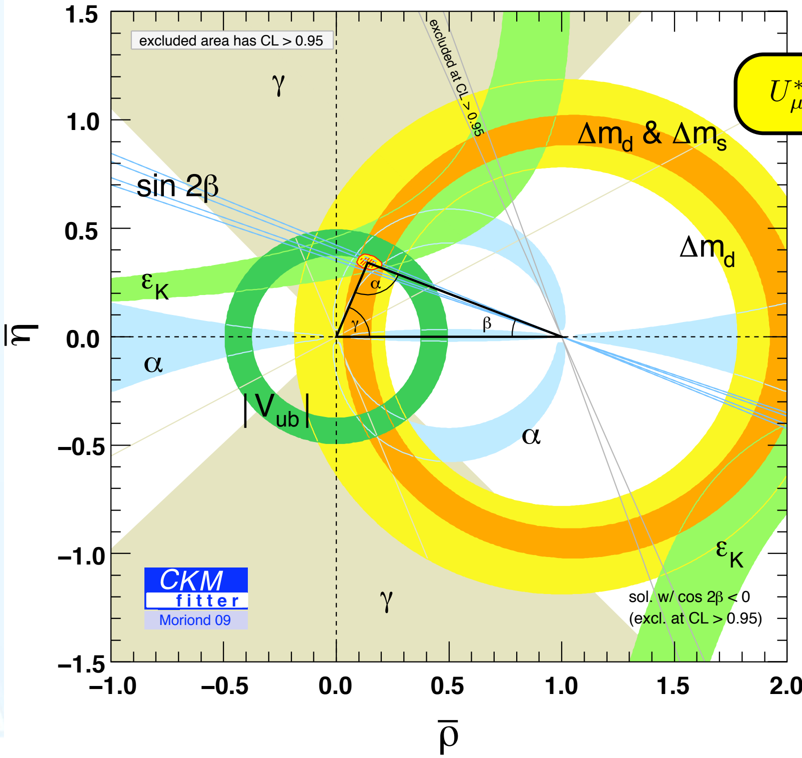
Experiment	# authors	# institutions	Headline measurement(s)	# analysis topics	# physics publications to date	total # citations to date	current h Index	# PhD theses to date
KTeV	78	13	ε/ε'	49	50	2,113	20	32
CDF run II	350 - 700	55 - 63	Higgs search, Single top, B mixing, Electroweak, ...	225	394	18,362	71	241
D0 run II	360 - 580	68 - 84	Higgs search, Single top, B mixing, Electroweak, ...	184	305	14,714	61	275
MiniBooNE	84	18	Test oscillation interpretation of LSND anomaly	28 (+6 MB+)	22	2,055	18	18
MINOS(+)	124	32	Measure θ_{23} and Δm^2_{32}	19	29	2,513	21	65
MINERvA	65-80	23	Neutrino Cross-sections	42	3	1	1	2
NOvA	147	36	Neutrino mass hierarchy	27				1
MicroBooNE	113	19	Probe MiniBooNE low E excess, nu xsecs	33				
Muon g-2	112	26	Muon g-2	6	7 (BNL E821)	2,376 (BNL E821)	8 (BNL E821)	17 (BNL E821)
Mu2e	137	25	Muon to electron conversion	7				
LBNE	377	67	Neutrino CP violation	169 (112ND + 57FD)				

Intensity Frontier Summary

- Each individual experiment only tells part of the scientific story
  - → need a suite of experiments (long baseline neutrinos, short baseline neutrinos, muons, …) to fully explore the landscape of new physics
- The Fermilab IF Program is continually producing scientific results
  - Operating experiments and planning & executing next generation experiments simultaneously
  - e.g. long baseline neutrinos (MINOS → NOvA → LBNE)

Extra Slides

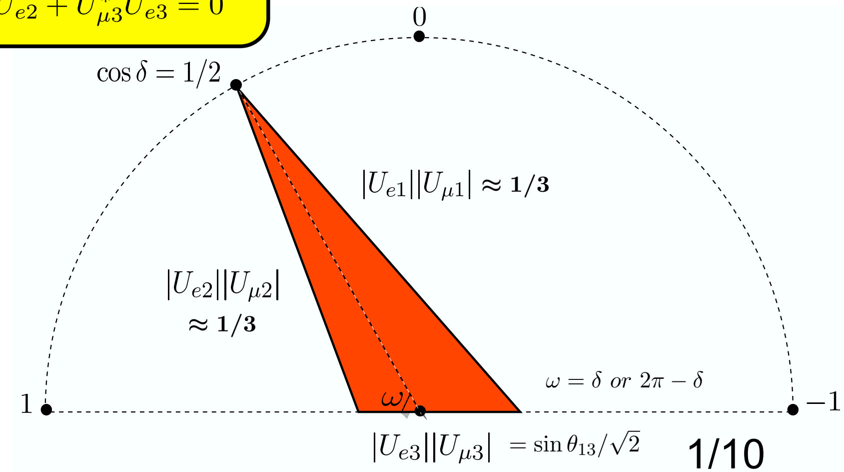
Why Answer the Big Neutrino Questions?



Quarks

Unitarity Triangle:

$$U^*_{\mu 1}U_{e1} + U^*_{\mu 2}U_{e2} + U^*_{\mu 3}U_{e3} = 0$$



$$|J| = 2 \times Area$$

$$J = s_{12}c_{12}s_{23}c_{23}s_{13}c^2_{13}\sin\delta$$

S. Parke

Neutrinos

Why Answer the Big Neutrino Questions?

Models predict relationships between neutrino parameters

- Quark-Lepton Complementarity $\theta_{12} + \theta_C = 45^o$
- Solar sum rules
  - Bimaximal $\theta_{12} = 45^o + \theta_{13}\cos\delta$
  - Tri-bimaximal $\theta_{12} = 35^o + \theta_{13}\cos\delta$
  - Golden Ratio $\theta_{12} = 32^o + \theta_{13}\cos\delta$
  - Plus HO corrections...
- Atm. sum rules
  - Tri-bimaximal-Cabibbo $\theta_{12} = 35^o \quad \theta_{23} = 45^o$, $\theta_{13} = \theta_C/\sqrt{2} = 9.2^o$
  - Trimaximal1 $\theta_{23} = 45^o + \sqrt{2}\theta_{13}\cos\delta$
  - Trimaximal2 $\theta_{23} = 45^o - \frac{\theta_{13}}{\sqrt{2}}\cos\delta$
  - Plus Charged Lepton Corrections...

Now that θ_{13} is measured these predict $\cos\delta$

Precision Parameter Measurement

↓

Model Discrimination

↓

Underlying Physics

Why Answer the Big Neutrino Questions?

- A(The?) Big Question:-
  - Today: B = #(Baryons) - #(Antibaryons) ≠ 0
  - Standard cosmology: Right after the big bang B = 0
  - How did B=0 ➔ B≠0 ?

- B=0 ➔ B≠0 requires CP violation (A.D.Sakharov JETP 5: 24-27 (1967))

- The CP violation in the CKM matrix leads to a Baryon Number B far smaller than that observed

- Leptogenesis ***can*** explain the observed Baryon Number through CP violating heavy neutrino decays (M. Fukugita and T. Yanagida, Phys. Lett. B 174, 45 (1986))

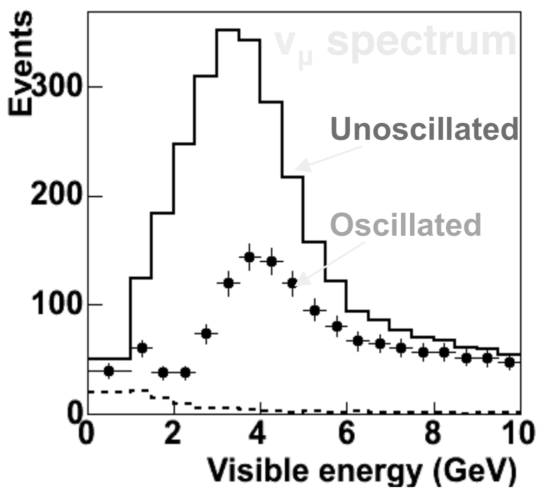
- ***Generically***, leptogenesis and light neutrino CP violation imply each other

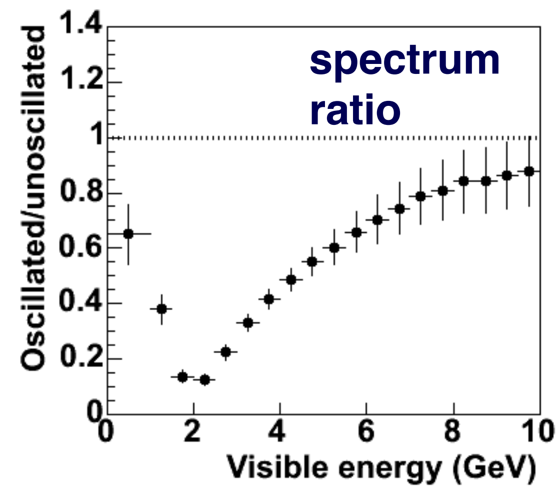
- So look for light neutrino CP violation

Is θ_{23} Maximal?

- Study using ν_μ disappearance

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2(2\theta_{23})\sin^2(1.27\Delta m^2_{32} L/E)$$





- If it is maximal something is making it that way
  - A clue to the mixing parameters more generally?

How are the Masses Ordered?

The mass hierarchy (sign of Δm_{32}^2) can be extracted from a comparison of P(ν_μ to ν_e) to P(anti-ν_μ to anti-ν_e)

$$P(\nu_\mu \to \nu_e) = \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\Delta_{31}^2$$

$$+\cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}^2$$

$$+\cos\delta\sin 2\theta_{23}\sin 2\theta_{12}\sin 2\theta_{13}\cos\Delta_{32}\left(\frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\Delta_{31}\right)\left(\frac{\sin(aL)}{(aL)}\Delta_{21}\right)$$

$$+\sin\delta\sin 2\theta_{23}\sin 2\theta_{12}\sin 2\theta_{13}\sin\Delta_{32}\left(\frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\Delta_{31}\right)\left(\frac{\sin(aL)}{(aL)}\Delta_{21}\right)$$

$$P(\bar{\nu}_\mu \to \bar{\nu}_e): \quad \sin\delta \to -\sin\delta, \quad a \to -a$$

$$\Delta_{ij} \equiv 1.27\Delta m^2_{ij} L/E$$

Matter effect $a \equiv G_F N_e/\sqrt{2} \approx (4000\text{ km})^{-1}$

L(km), E(GeV), m(eV)

Measuring CP Violation in ν_e Appearance

δ_{cp} (and hierarchy together) can be extracted from a comparison of P(ν_μ to ν_e) to P(anti-ν_μ to anti-ν_e)

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) = {} & \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\Delta_{31}^2 \\
& + \cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}^2 \\
& + \cos\delta\sin 2\theta_{23}\sin 2\theta_{12}\sin 2\theta_{13}\cos\Delta_{32}\left(\frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\Delta_{31}\right)\left(\frac{\sin(aL)}{(aL)}\Delta_{21}\right) \\
& + \sin\delta\sin 2\theta_{23}\sin 2\theta_{12}\sin 2\theta_{13}\sin\Delta_{32}\left(\frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\Delta_{31}\right)\left(\frac{\sin(aL)}{(aL)}\Delta_{21}\right)
\end{aligned}
$$

$P(\bar{\nu}_\mu \to \bar{\nu}_e): \quad \sin\delta \to -\sin\delta, \quad a \to -a$

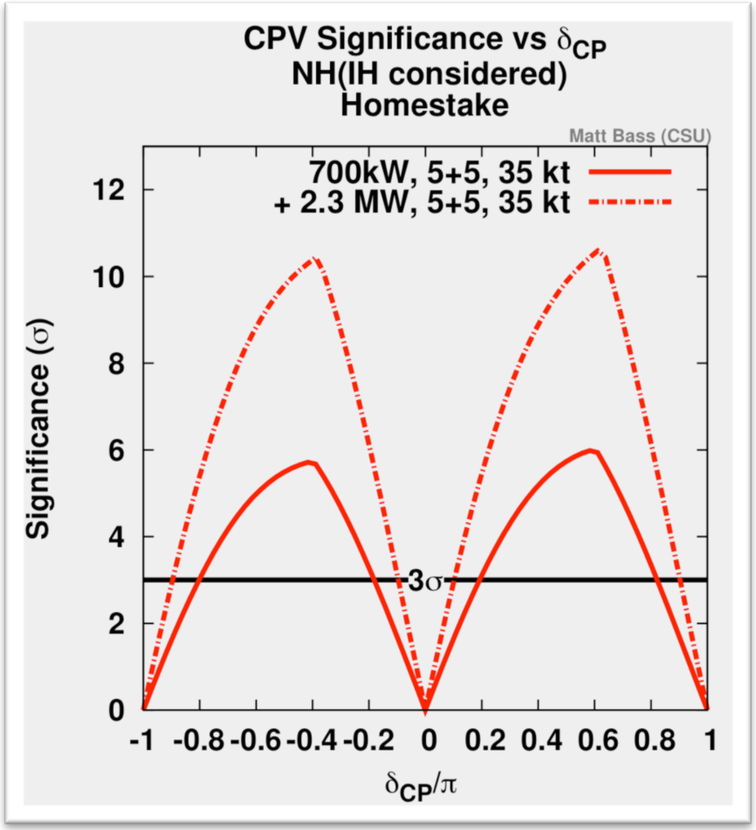
$\Delta_{ij} \equiv 1.27\Delta m^2_{ij} L/E$

Matter effect $a \equiv G_F N_e/\sqrt{2} \approx (4000\ \text{km})^{-1}$

L(km), E(GeV), m(eV)

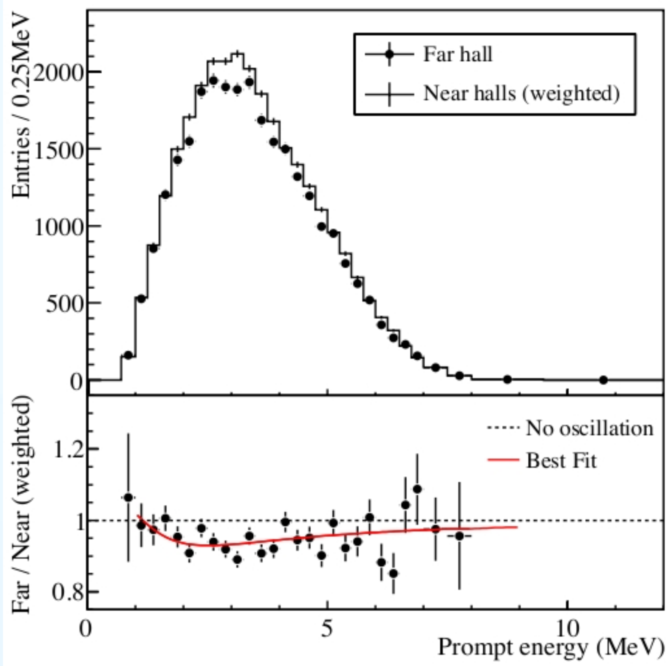
Ultimate LBNE Sensitivity

With a full 35 kton detector and Project X. The CP violation discovery potential is impressive

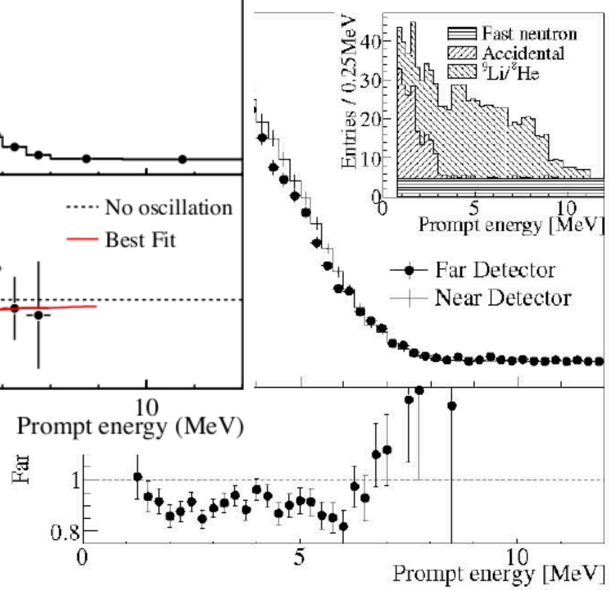


Reactor Measurement of θ_{13}

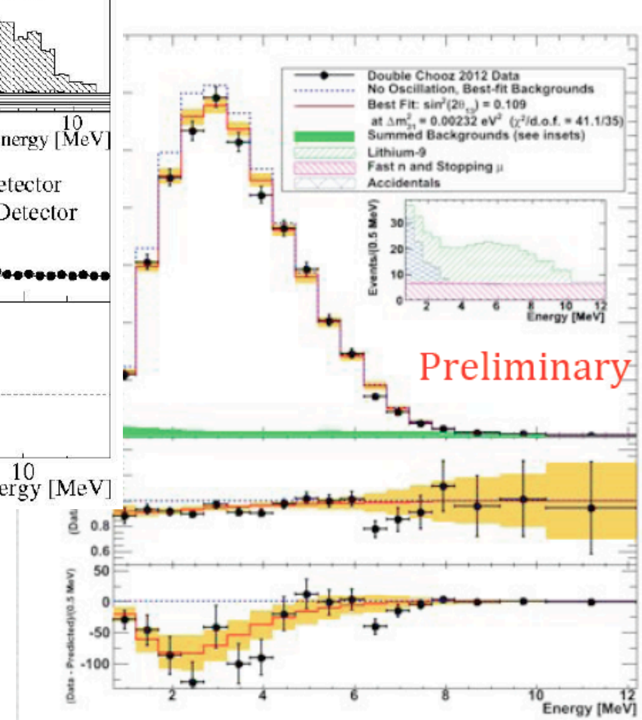
Daya Bay



Reno



Double Chooz



In 4 months this year we went from θ_{13} being almost unknown to it being the best measured mixing angle!

Measuring θ_{13} with ν_e Appearance

θ_{13} controls the size of 3 of the 4 terms in $P(\nu_\mu$ to $\nu_e)$

$$P(\nu_\mu \to \nu_e) = \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\Delta_{31}^2$$
$$+\cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}^2$$
$$+\cos\delta\sin 2\theta_{23}\sin 2\theta_{12}\sin 2\theta_{13}\cos\Delta_{32}\left(\frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\Delta_{31}\right)\left(\frac{\sin(aL)}{(aL)}\Delta_{21}\right)$$
$$+\sin\delta\sin 2\theta_{23}\sin 2\theta_{12}\sin 2\theta_{13}\sin\Delta_{32}\left(\frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\Delta_{31}\right)\left(\frac{\sin(aL)}{(aL)}\Delta_{21}\right)$$

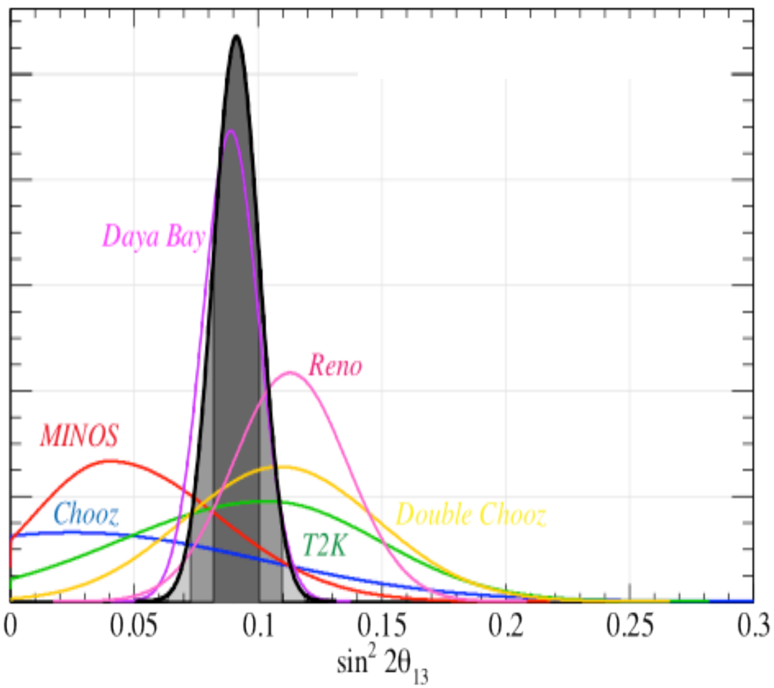
$P(\bar{\nu}_\mu \to \bar{\nu}_e)$: $\sin\delta \to -\sin\delta, \quad a \to -a$

$\Delta_{ij} \equiv 1.27\Delta m^2_{ij} L/E$

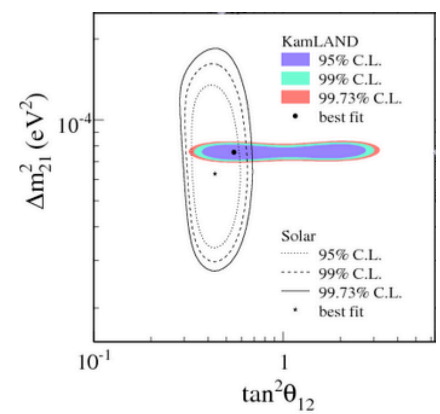
Matter effect $a \equiv G_F N_e/\sqrt{2} \approx (4000\ \text{km})^{-1}$

L(km), E(GeV), m(eV)

Can we Independently Check the θ_{13} Measured by Reactor Experiments?



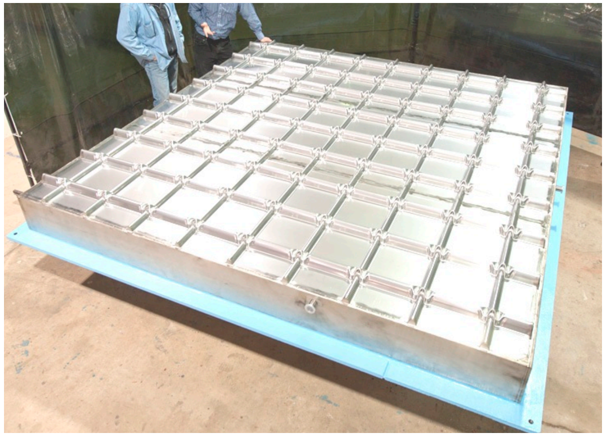
- Will NOvA and T2K measure ν_e appearance at the expected rate?
  - Yes – Then we will have powerful confirmation of our understanding of the 3x3 oscillation matrix
  - No – Then we will have a strong indication of some new physics

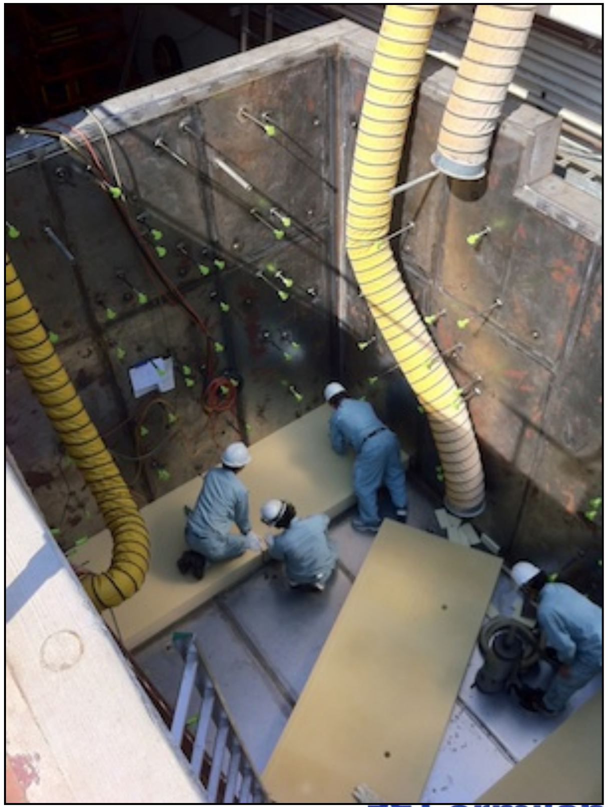


There is a close analogy here with the solar neutrino problem and the exquisite concordance of the SNO and KamLAND results

KamLAND, PRL. 100, 221803 (2008)

LBNE Project Supported LAr R&D

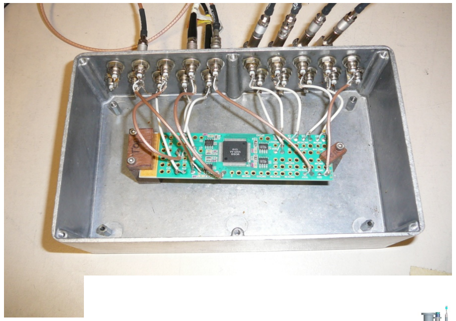


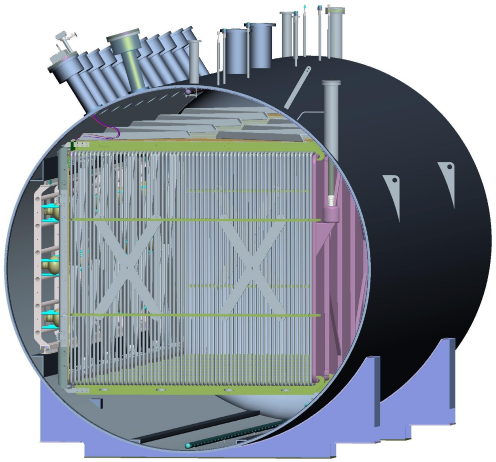


- LAr Far Detector prototyping in LBNE Project is part of larger program.
- Project built 3mx3m membrane wall panel in 2011 to demonstrate technology.
- Currently constructing 35 ton membrane cryostat prototype.
  - Expect to be operational in 2013.
- Planning how to use it beyond cryo testing
  - Subsystem components
  - System test of scaled-down detector

LAr R&D Program Successes So Far

- Purity without evacuation
- Foam insulation
- Membrane cryostats
- Cold electronics
- Long drift





Early career award to Sam Zeller

Liquid Argon In A Testbeam (LArIAT)

- 2009 LAr R&D review asked *How well known are the energy resolution and particle identification capabilities of a LArTPC?*

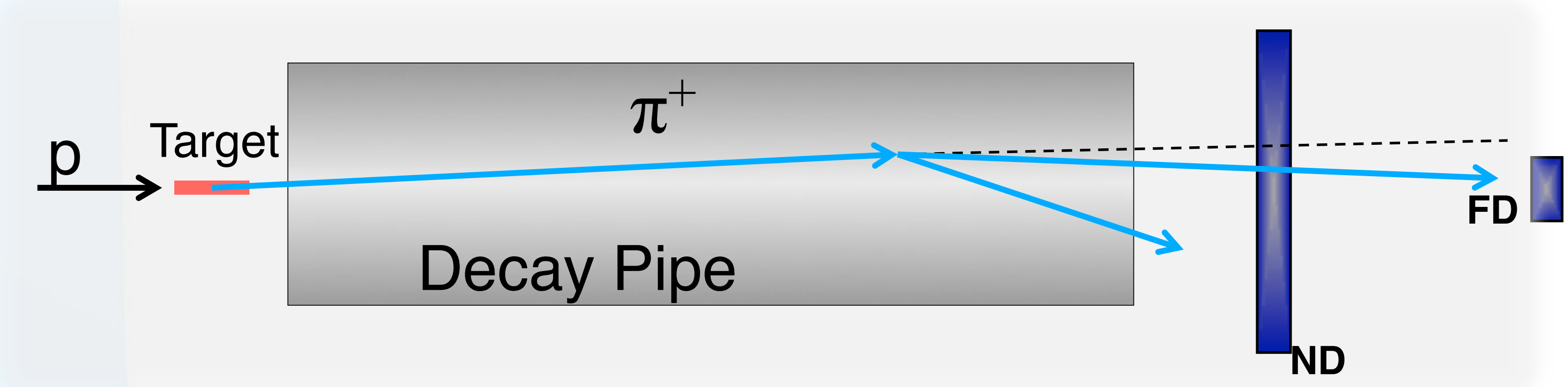
- No comprehensive test beam runs ever performed to look at particles and energies expected in neutrino experiments: e, p, π, μ, look at K with an eye toward nucleon decay

- Use a two-phased approach
  - First phase uses ArgoNeuT to understand charge to energy conversion and single track topologies
  - Second phase will be a much larger TPC to contain EM and hadronic showers

- Both phases look at e/γ separation

The Need for Neutrino Cross-Section Measurements

Far spectrum without oscillations is similar, but not identical to the Near spectrum!



Adapted from P. Vahle

- Near detector predicts Far detector un-oscillated rate up to corrections

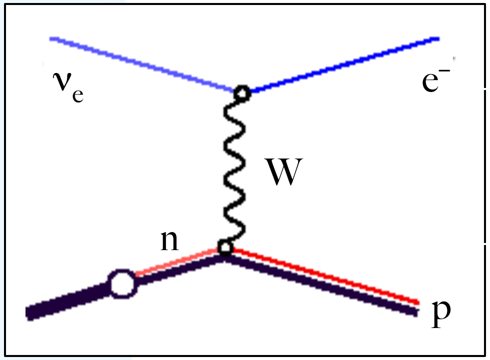
- Neutrino energy depends on angle wrt original pion direction and parent energy
  - Angular distributions different between Near and Far
  - Higher energy pions decay further along decay pipe
  - Neutrino source is pointlike as seen from far detector but not from near detector

$$E_\nu \approx 0.43 \frac{E_\pi}{1+\gamma^2\theta_\nu^2}$$

- Therefore you still need flux prediction and cross-section knowledge for a precision measurement even if you have a Near detector

Some Relevant Cross-Section Examples

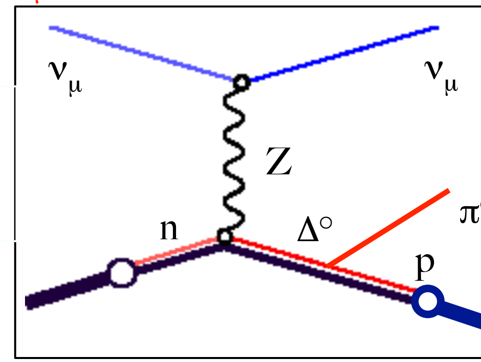
ν_e Charged Current Quasi-Elastic (CCQE)



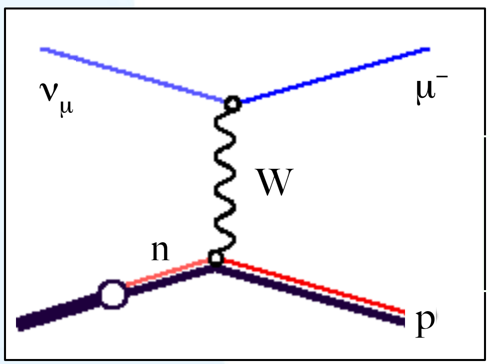
Used as ν_e appearance signal channel

ν_μ Neutral Current π^0 (NCπ^0)

Background to ν_e appearance (π^0 fakes an e^-)



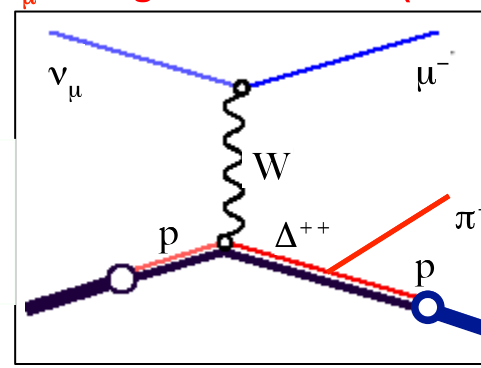
ν_μ Charged Current Quasi-Elastic (CCQE)



Used as ν_μ disappearance signal channel

ν_μ Charged Current π^+ (CCπ^+)

Background to ν_μ disappearance (π^+ gets lost)

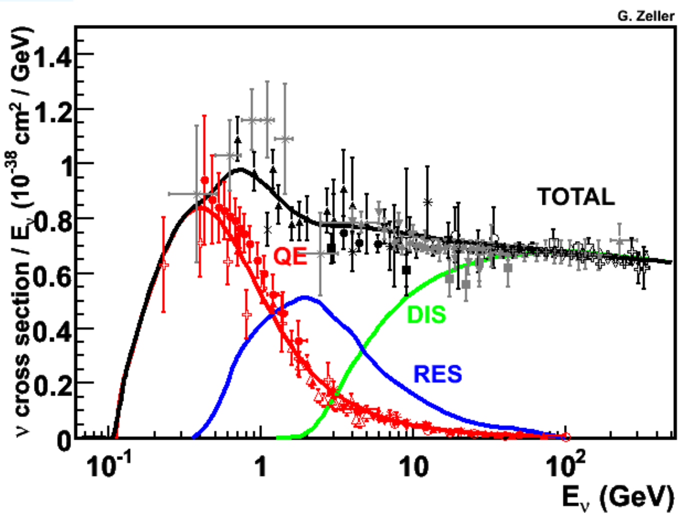


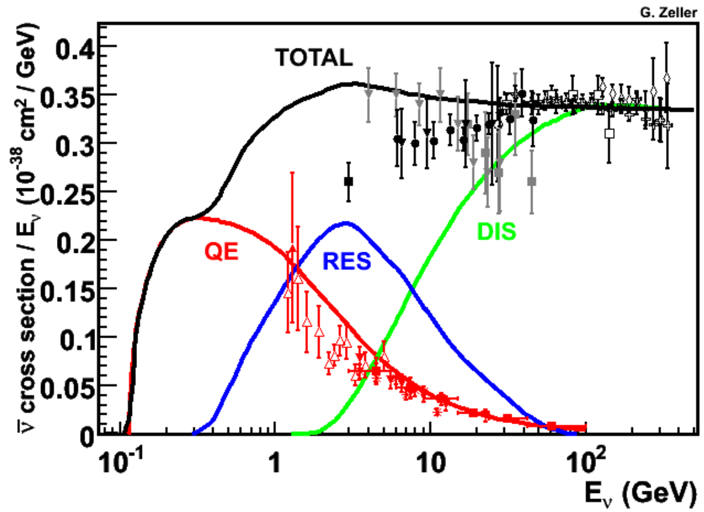
And a number of less common processes (e.g. radiative Δ^0 decay)

And all the anti-neutrino version of these processes

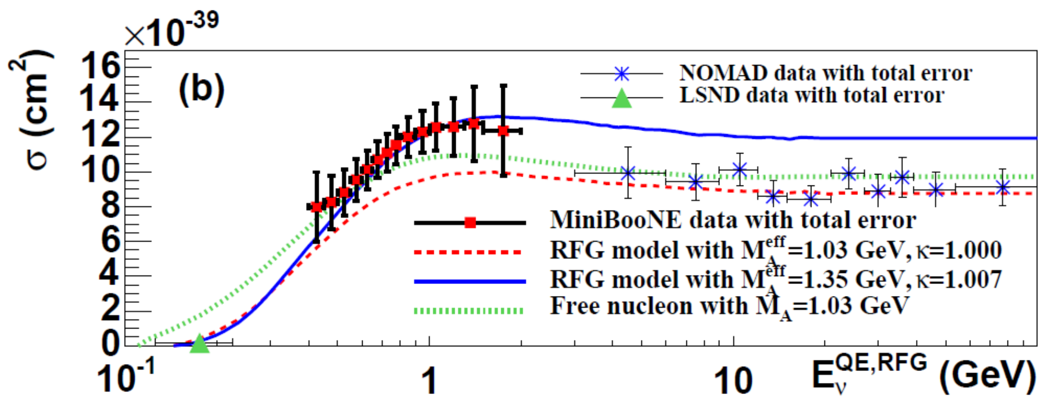
Status of GeV Neutrino Cross-Sections

Neutrino cross-sections around 1 GeV are not very well measured





J.A. Formaggio and G.P. Zeller, "From eV to EeV: Neutrino Cross Sections Across Energy Scales",
to be published in Rev. Mod. Phys., 2012



Energy dependence and scale of measured QE cross-section not sufficiently well understood

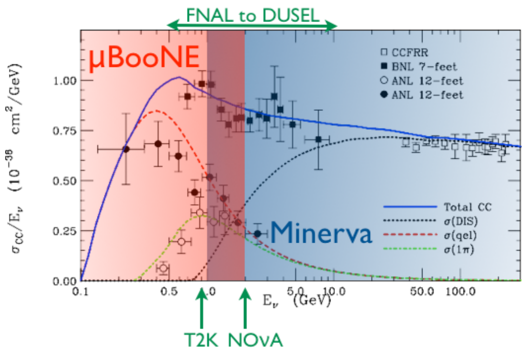
Fermilab Neutrino Cross-Section Measurements

Experiment	Beamline	Status	Nuclear Target	capability
ArgoNeut	NuMI	Completed 2010	Ar	LAr TPC but tiny dataset
MINOS	NuMI	Completed 2012	Fe	No detailed final state ID
MINERvA	NuMI	Running	He, C, O, Fe, Pb	Fine grained tracking calorimeter
NOvA	NuMI	Under Construction	C	Fine grained tracking calorimeter
MINOS+	NuMI	Fermilab Approved	Fe	No detailed final state ID
MiniBooNE	BNB	Completed 2012	C	Some final state ID
SciBooNE	BNB	Completed 2008	C	Small, fine grained tracking calorimeter
MicroBooNE	BNB	Under Construction	Ar	LAr TPC

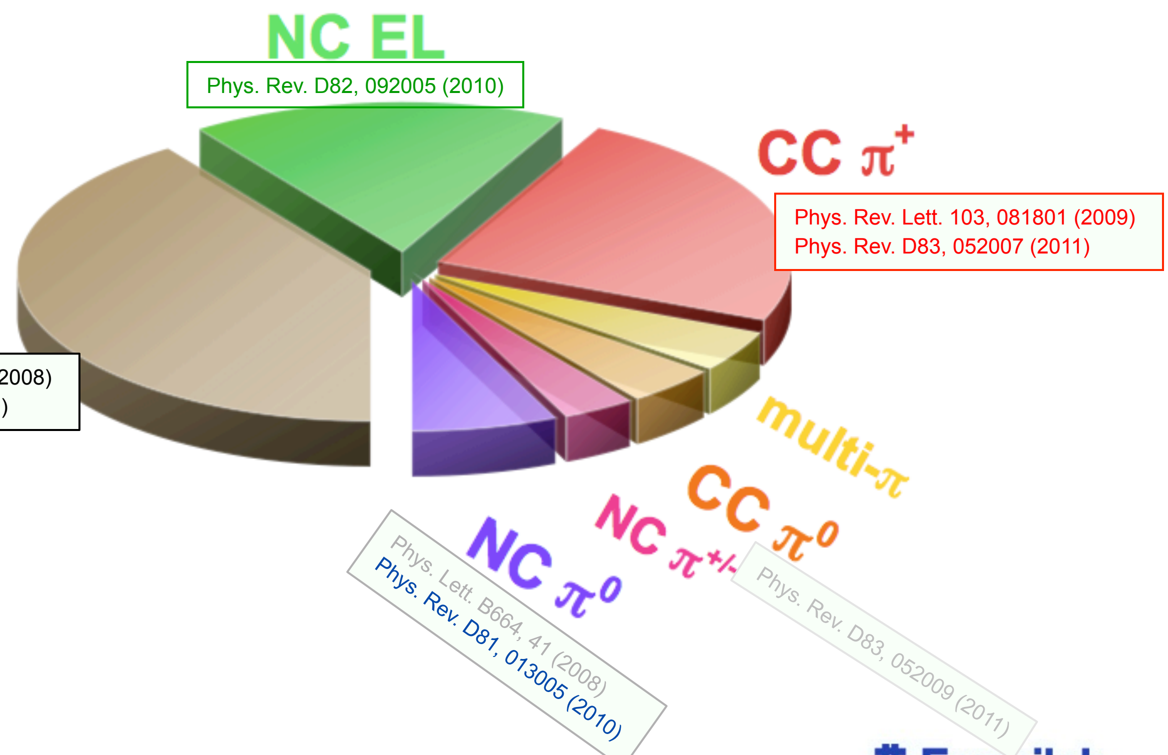
Current and future oscillation experiments need

- Detailed final state information
- On Carbon, Oxygen, and Argon
- For electron neutrinos and muon neutrinos
- For neutrinos and anti-neutrinos

MiniBooNE Cross-Section Results



MiniBooNE measures cross-sections in exactly the 1 GeV range of interest to T2K, NOvA, and LBNE



Fermilab

Project X Example Power Staging Plan

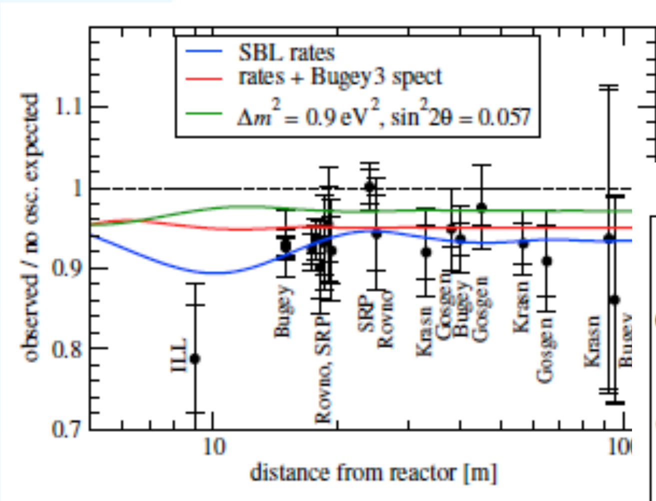
Program:	Onset of NOvA operations in 2013	Stage-1: 1 GeV CW Linac driving Booster & Muon, n/edm programs	Stage-2: Upgrade to 3 GeV CW Linac	Stage-3: Project X RDR	Stage-4: Beyond RDR: 8 GeV power upgrade to 4MW
MI neutrinos	470-700 kW**	515-1200 kW**	1200 kW	2450 kW	2450-4000 kW
8 GeV Neutrinos	15 kW + 0-50 kW**	0-42 kW* + 0-90 kW**	0-84 kW*	0-172 kW*	3000 kW
8 GeV Muon program e.g, (g-2), Mu2e-1	20 kW	0-20 kW*	0-20 kW*	0-172 kW*	1000 kW
1-3 GeV Muon program, e.g. Mu2e-2	-----	80 kW	1000 kW	1000 kW	1000 kW
Kaon Program	0-30 kW** (<30% df from MI)	0-75 kW** (<45% df from MI)	1100 kW	1870 kW	1870 kW
Nuclear edm ISOL program	none	0-900 kW	0-900 kW	0-1000 kW	0-1000 kW
Ultra-cold neutron program	none	0-900 kW	0-900 kW	0-1000 kW	0-1000 kW
Nuclear technology applications	none	0-900 kW	0-900 kW	0-1000 kW	0-1000 kW
# Programs:	4	8	8	8	8
Total max power:	735 kW	2222 kW	4284 kW	6492 kW	11870kW

* Operating point in range depends on MI energy for neutrinos.

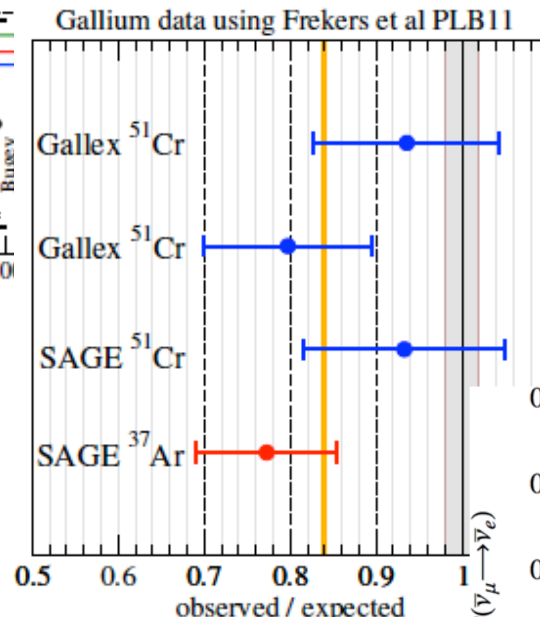
** Operating point in range is depends on MI injector slow-spill duty factor (df) for kaon program.

Hints of Something at ~1eV^2?

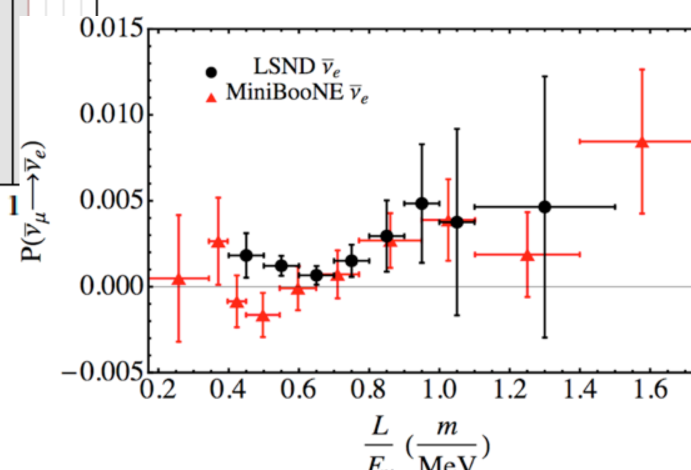
Reactor Neutrino Anomaly



Gallium Anomaly



LSND & MiniBooNE



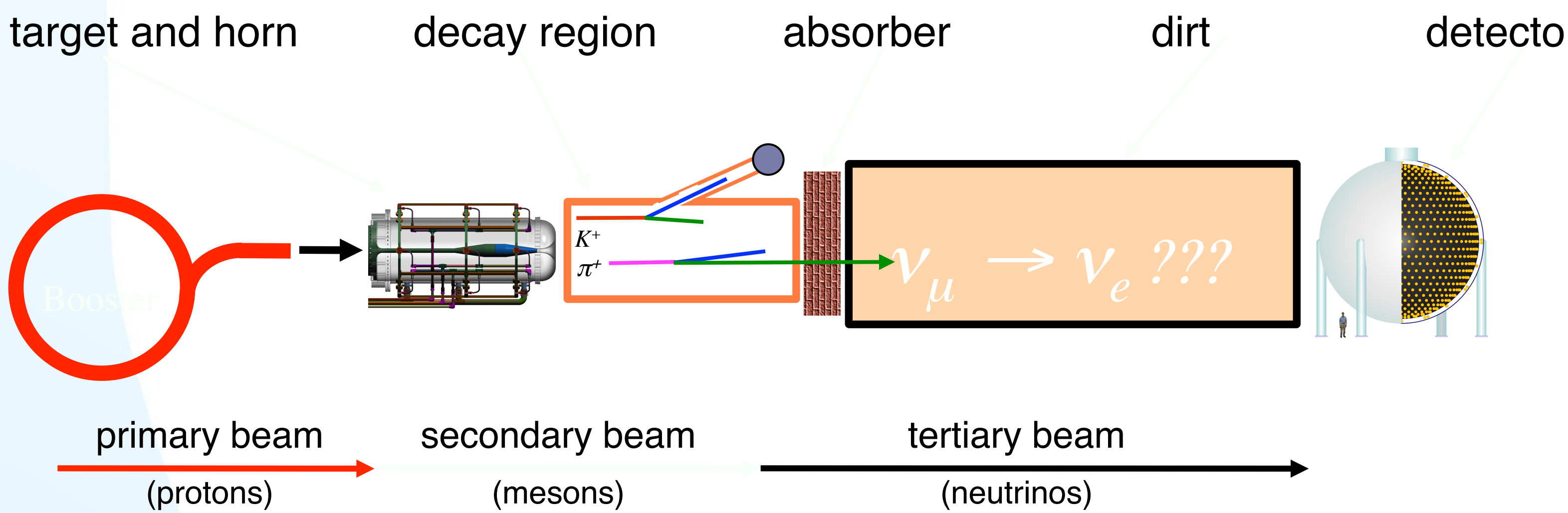
Additionally, cosmology hints at more than 3 neutrino states

The MiniBooNE Experiment

Keep L/E same as LSND

while changing systematics, energy & event signature

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \, \sin^2(1.27\Delta m^2 L/E)$$

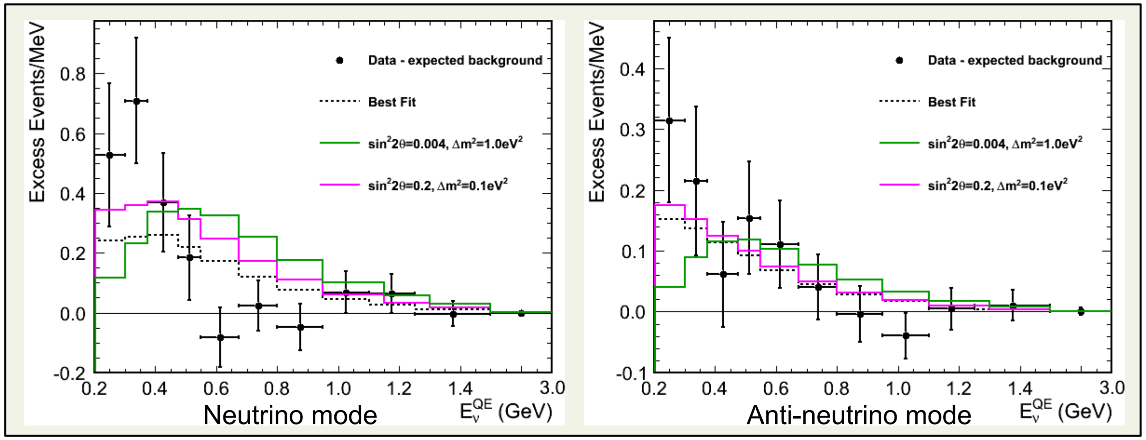


Order of magnitude higher energy (~500 MeV) than LSND (~30 MeV)

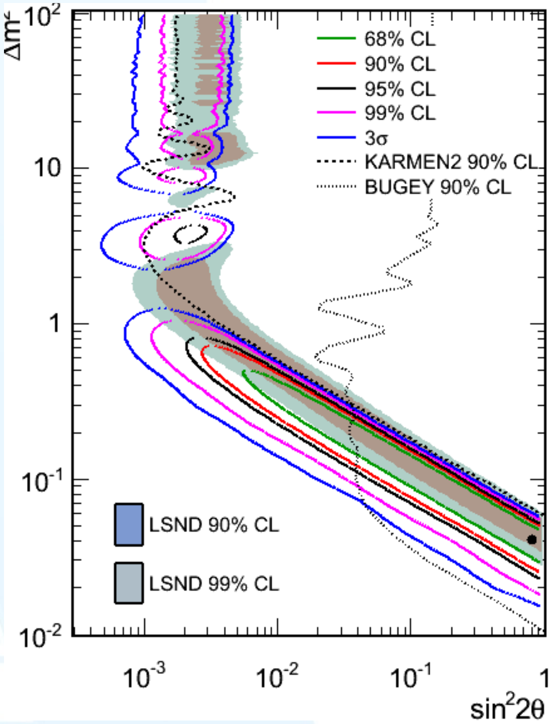
Order of magnitude longer baseline (~500 m) than LSND (~30 m)

86 collaborators from 19 institutions in 2 countries

MiniBooNE Simultaneous 3+1 fit to ν and anti-ν data



Total Excess: 240.3 +/- 34.5 +/- 52.6



E>200 MeV Best Fit preferred at 3.6σ over null

combined	E > 200 MeV	E > 475 MeV
χ^2(null)	42.53	12.87
Prob(null)	0.1%	35.8%
χ^2(bf)	24.72	10.67
Prob(bf)	6.7%	35.8%

Simultaneous fit (E>200 MeV) with fully-correlated systematic to entire MiniBooNE neutrino and anti-neutrino data

Future Short Baseline Possibilities

Currently 2 short baseline experiments are in the process of moving from LOI to Proposal

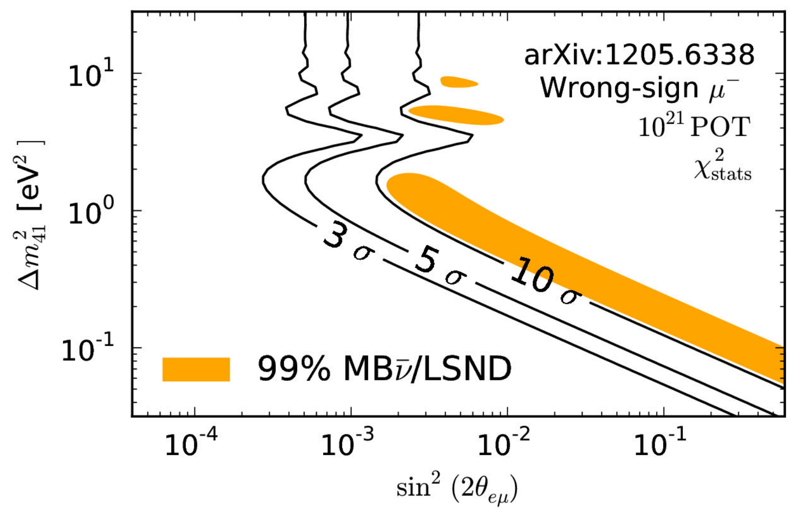
- LAr1
  - Two LAr detectors in the Booster & NuMI beams
- νStorm
  - Neutrinos from a muon storage ring aimed at near and far magnetized iron detectors

νStorm

Magnetized iron detector (a la MINOS) in D0 Building

Few GeV muon storage ring with ~150m straight sections

Near hall with magnetized iron near detector + separate cross-section detector

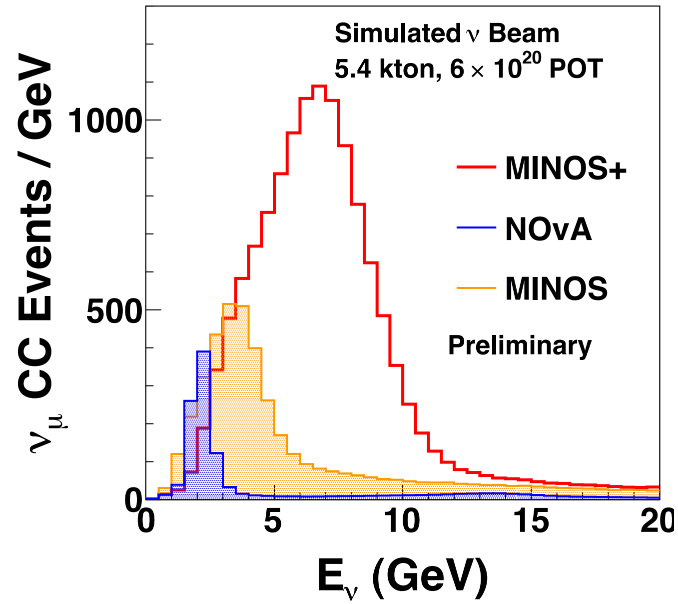


MINOS+

Continued running of the MINOS far detector in the NOvA beam (MINOS near detector will be running anyway for MINERvA)

Running at the higher energies for which the MINOS detector was actually optimized

(Remember that when MINOS was designed the best fit Δm_{32}^2 was higher and so the energies relevant to the FNAL-Soudan baseline were higher)

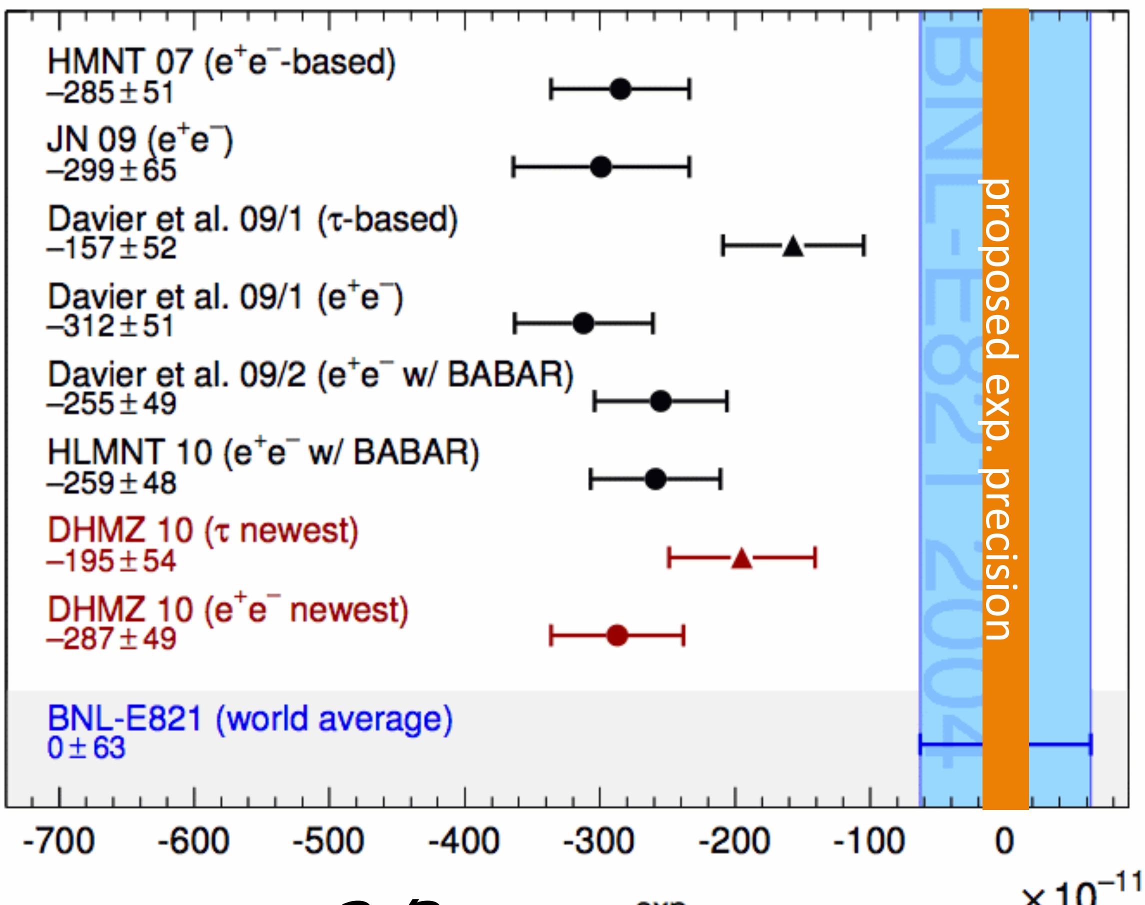


Fermilab

The Anomolous Magnetic Moment and g-2

- g≈2 but higher-order corrections
  - QED, EW, hadronic, new physics?

$$\vec{\mu} = g_s \left(\frac{q}{2m}\right) \vec{s}$$



- Currently ~3σ discrepancy between theory and experiment
- New muon g-2 experiment at Fermilab expected precision could yield ~5σ

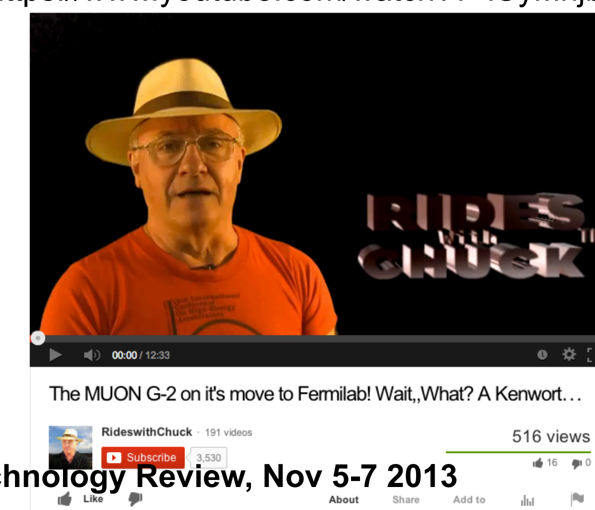
$a = g - 2/2$

Transport of the superconducting coils was the single largest risk to the project…huge relief to see them roll onto the site!

Unprecedented outreach event

- Story of transport picked up by over 100 news outlets
- Video coverage by major news outlets, the Discovery Channel, and ‘Rides with Chuck’
- Tug captain described small groups of people at nearly every town and lock from Alabama to Illinois
- Estimated 150 people/hr came to visit while we staged at Costco parking lot in IL
  - Handed out thousands of flyers
- Over 3000 people on-site at Fermilab
  - Had to close gate when parking overflowed

https://www.youtube.com/watch?v=iUyMnjb1f-g



Fermilab Scientific Leadership (last 3 years)

	Short Baseline Neutrino			Long Baseline Neutrino			Precision Accelerator	
	MiniBooNE	**MINERvA**	**MicroBooNE**	**MINOS**	**NOvA**	**LBNE**	**Muon (g-2)**	**Mu2e**
Co-Spokes person	Brice	Harris, Morfin	Zeller	Plunkett				Bernstein
Analysis Coordinator	Zeller, Polly	Schmitz						
Project Manager/ Director		Harris	Rameika		Cooper	Strait, McCluskey, Rameika	Polly	Ray
Deputy/ Associate Project Manager		Grossman, DeMaat	James		Tesarek, Derwent		Merritt	Glenzinski
Level 2 Manager		Pla-Dalmau	Baller, Bogert, Rebel, Raaf		Lukens, Miao	Baller, Papadimitriou	Casey, Convery, Nguyen	Ginther, Lamm, Mukhergee

Fermilab Intensity Frontier Scientist Community Leadership and Service

- HEPAP
  - Glenzinski, Tschirhart, Rameika
- Scientific Advisory Committees
  - Ice Cube – Merritt
  - JPARC – Tschirhart
  - JPARC Accelerator Technology - Zwaska
  - ICFA Neutrino – Zeller
  - ICFA Instrumentation - Para
  - AIDA – Bross
  - PDG – Harris
- DPF and DPB Roles
  - Bernstein, Johnstone, Strait
- Summer School Organizing Committee Chairs
  - Neutrino – Brice, Harris
  - Hadron Collider – Glenzinski
  - CTEQ – Morfin
- Snowmass Roles
  - Casey, Zeller, Rebel, Kutschke, Wolbers
- Reviewers of SBIR, NSF, DOE, refereed journals, international conference organizers - too numerous to detail

Early Career Awards

Brendan Casey
Muon g-2 Research

Sam Zeller
Liquid Argon TPC Research

Guest & Visitor Programs Supporting HEP Community

- Strong support of Guests and Visitors (G&V) to the lab from all over the world
  - Breakdown of IF G&V spending in closed session
- International Fellows
  - All 6 current fellows working on Intensity Frontier
- Joint Appointments
  - Craig Group (Fermilab/Virginia) working on NOvA and Mu2e
  - Mitch Soderberg (Fermilab/Syracuse) working on LAr
- URA Visiting Scholarships
  - Financial support from the institutions that operate Fermilab
- New Intensity Frontier Research Fellowship Program
  - Coarsely modeled after the successful LPC Fellowships at Fermilab

Student Programs

- International Fellows
  - 4 students working on Intensity Frontier
- South American Student Program
  - 23 Masters students, 11 doctoral students and 3 postdocs in or graduated from the program organized by Jorge Morfin
  - Looking to expand beyond neutrino physics into wider IF
- Indian Student PhD Program
  - 10 Intensity Frontier students in or graduated from the program
  - Ramping up to 20 Intensity Frontier students present at Fermilab
  - Coupled to much larger plans for India-Fermilab
- Summer students
  - About 100 each summer labwide

Current International Fellows

Name	Institution	Position	Project	Period
Michelle de Madeiros	Univ. Federal de Goias, Brazil	Student	MINOS	Jan 2012 – Jan 2014
Carlos Escobar	Campinas, Brazil	Scientist	LBNE	Apr 2011 – Apr 2014
David Martinez	CBPF, Brazil	Student	MINERvA	Nov 2012 – Nov 2013
Laza Rakotondravohitra	Univ. Antananarivo	Student	MINERvA	Aug 2012 – Aug 2014
Su-Yin Wang	Nat. Kaohsiung Normal U, Taiwan	Student	SeaQuest	Oct 2011 – July 2014
Jaroslav Zalesak	Inst. Phys. Acad. Sci. Czech Republic	Scientist	NOvA	Oct 2012 – Oct 2013

Intensity Frontier Operations Center (XOC)

- Control room for IF experiments
- On the main floor of Wilson Hall
- Serious investment already made
  - bid package created