The MINERνA Neutrino Scattering Experiment at Fermilab

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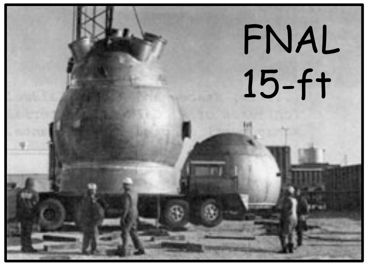
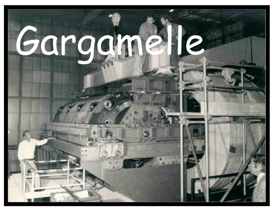
Outline

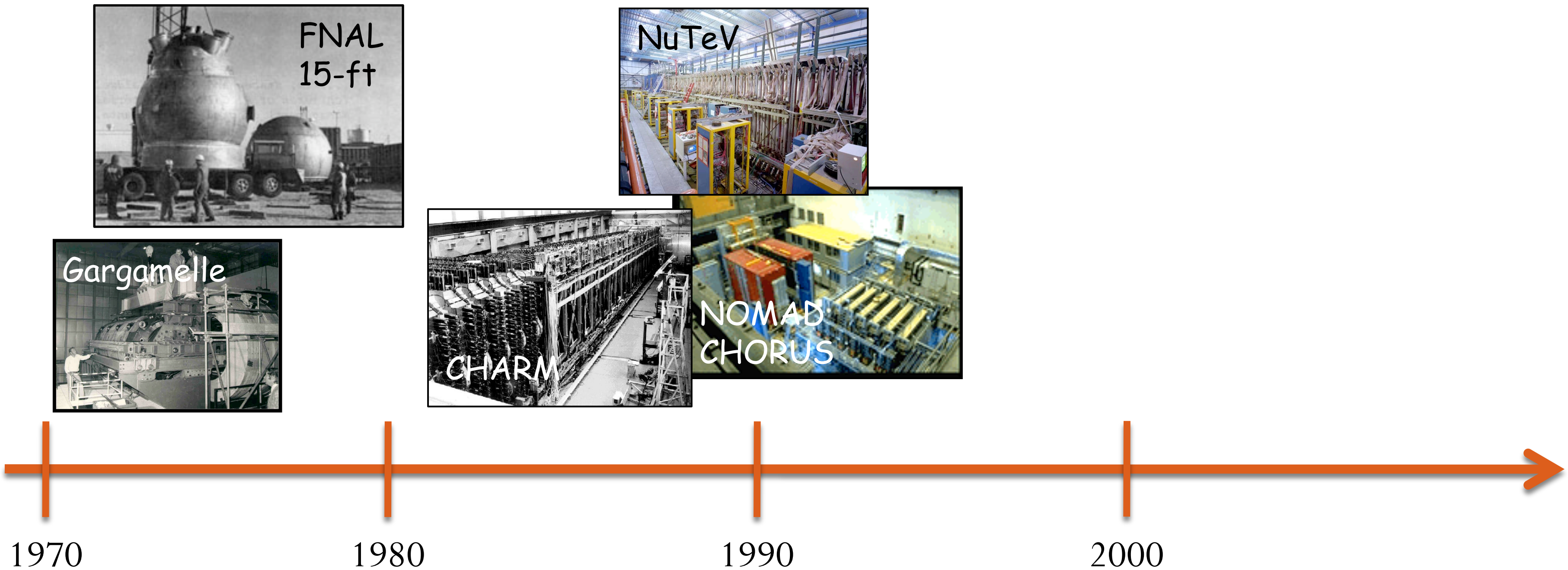
- Introduction: Current Neutrino Physics Landscape
  - Neutrino Oscillations: Present and Future
  - Neutrino-Nucleus Interactions around 1 GeV: Past and Present
- MINERνA
  - The MINERνA Experiment
    - FNAL NuMI beam + multi-purpose detector = rich physics program
  - MINERνA Physics Examples
    - Impact for Future Oscillation Experiments: NOνA
    - Impact for Neutrino-Nucleus Interactions around 1 GeV: CCQE
    - DIS Physics: PDFs and Nuclear Effects in Neutrino Scattering
- Conclusions



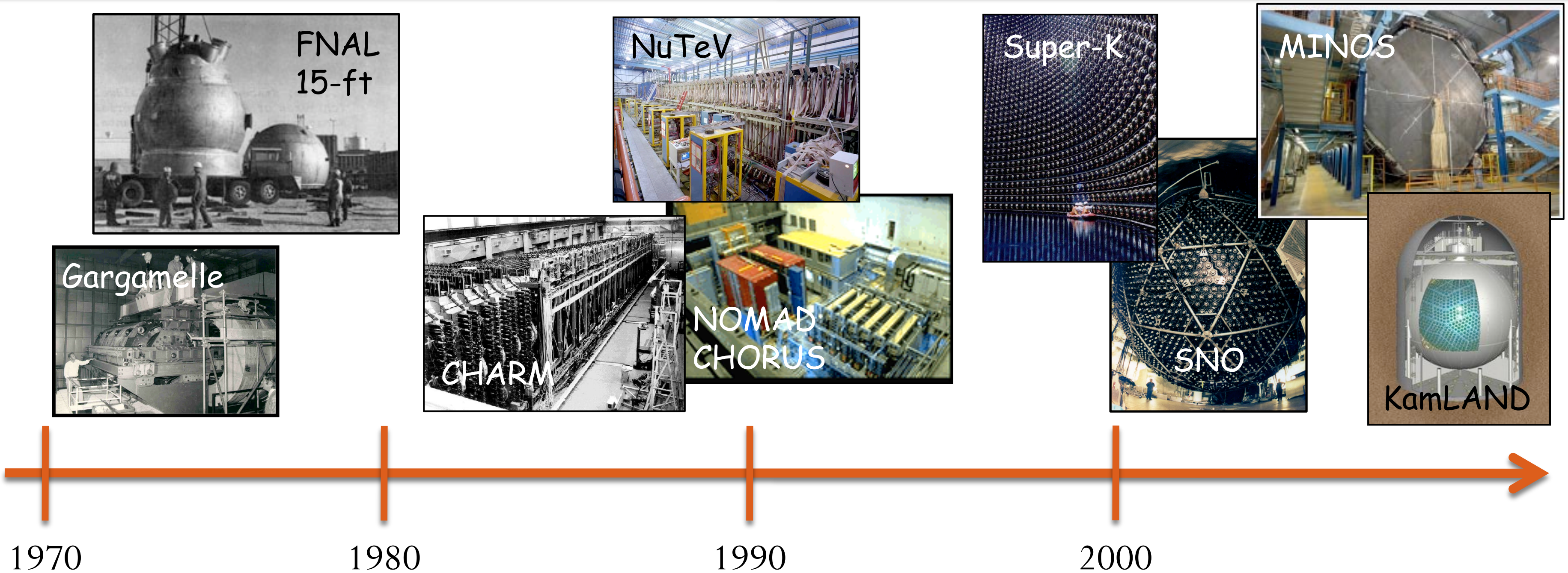


1970 1980 1990 2000

- <u>Bubble Chambers</u> in the 70's and 80's
  - ANL, BNL, FNAL, CERN, IHEP
  - observation of weak currents
  - first neutrino cross-section measurements; some on low Z targets, deuterium
  - experiments had small statistics and often poor knowledge of neutrino fluxes



- <u>Counter Experiments</u> in the 80's and 90's
  - CDHS, CHARM II, CCFR, NuTeV, NOMAD
  - higher statistics
  - neutrino energies generally higher
  - rich physics programs; cross-sections, DIS, structure functions, strange sea, QCD



- Then we figured out that neutrinos oscillate!
  - of course, evidence goes back to Ray Davis' original solar neutrino expt and Kamiokande
  - but it was an entire neutrino industry in the 90's and 00's that started to untangle the parameters
    - SNO, Kamland, Super-K, K2K, MINOS, many more…
  - has brought the field back to lower energies
  - focus on intense sources and precision measurements

- ν oscillations first postulated by Pontecorvo in 1957, based on analogy to kaons
- Non-zero mass implies mass eigenstates ≠ flavor eigenstates

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

flavor states participating in standard weak interactions with charged lepton partners

mixing matrix describing mass state content of flavor states

mass states

- Different ν masses allow for changes in lepton flavor composition as ν propagates:

$$P(\nu_\alpha \to \nu_\beta) = |\langle \nu_\beta | \nu_\alpha(L) \rangle|^2 = \delta_{\alpha\beta} - 4\sum_{i>j} \Re(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin^2[1.27 \Delta m^2_{ij} L/E] + 2\sum_{i>j} \Im(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin^2[2.54 \Delta m^2_{ij} L/E]$$

- U_{xy} : elements of mixing matrix
- $\Delta m_{ij}^2 = m_i^2 - m_j^2$: mass squared splitting between states
- L : the travel path-length of the neutrino
- E : the energy of the neutrino

- ν oscillations first postulated by Pontecorvo in 1957, based on analogy to kaons
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Simplified case of direct 2 neutrino oscillations

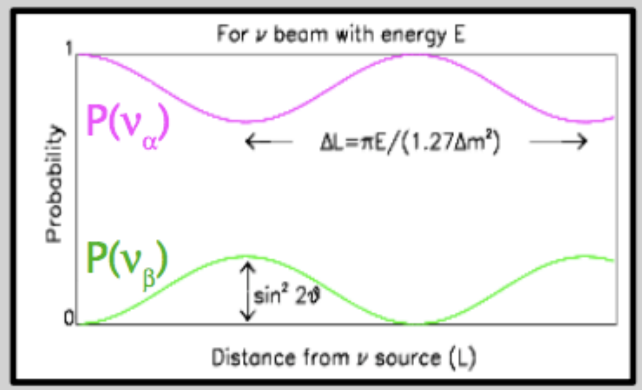
$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos(\theta_{ij}) & \sin(\theta_{ij}) \\ -\sin(\theta_{ij}) & \cos(\theta_{ij}) \end{pmatrix} \begin{pmatrix} \nu_i \\ \nu_j \end{pmatrix}$$

$$\Delta m_{ij}^2 \equiv m_i^2 - m_j^2$$

determines shape of oscillation probability as function of E (or L)

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2(2\theta_{ij}) \sin^2\left(1.27\, \Delta m_{ij}^2 \frac{L}{E}\right)$$

determines amplitude for oscillation ~ probability



- ν oscillations first postulated by Pontecorvo in 1957, based on analogy to kaons
- Non-zero mass implies mass eigenstates ≠ flavor eigenstates
- The two neutrino oscillation formula showed up in my undergraduate quantum mechanics textbook:

> **"This is about the simplest nontrivial quantum system conceivable. It is a crude model for neutrino oscillations. . . . . At present this is highly speculative – there is no experimental evidence for neutrino oscillations; however, a very similar phenomenon does occur in the case of neutral K-mesons."**
>
> **David J. Griffiths – *Introduction to Quantum Mechanics* (Problem 3.58) 1995**

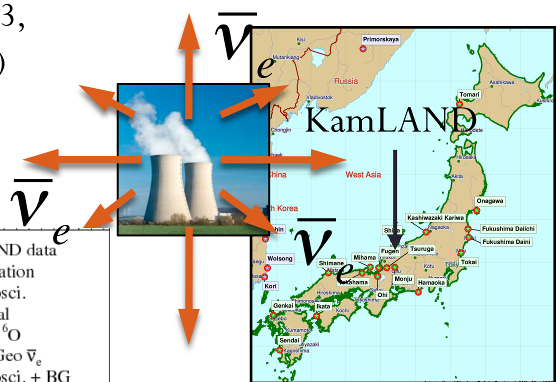
- Let's see how the evidence has changed in 15 short years…

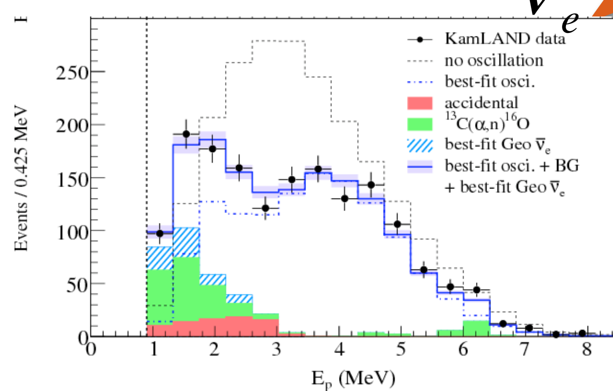
Δm^2_{12}

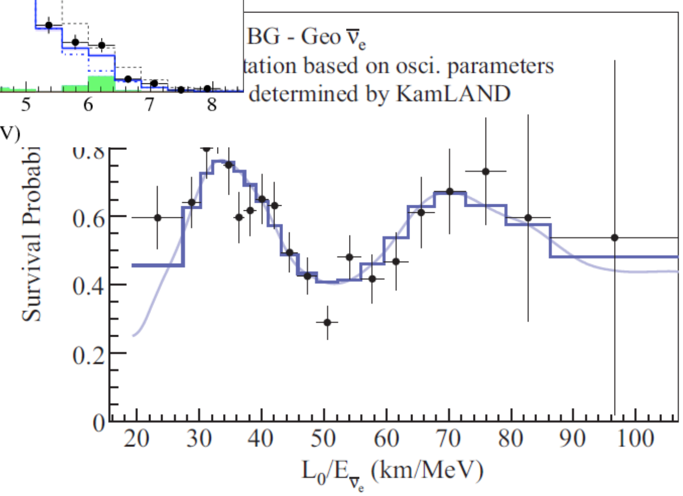
- First experimental evidence came from electron neutrinos from the sun
- Confirmation of the oscillation hypothesis came from the **SNO** solar neutrino experiment which could see all neutrino types through NC interactions
- Precision measurements of Δm^2_{12} and θ_{12} came from **KamLAND** in Japan using anti-neutrinos produced by power reactors

Super-K ν_e seen / ν_e expected: $0.451^{+0.017}_{-0.015}$

Phys. Rev. D 73, 112011 (2006)





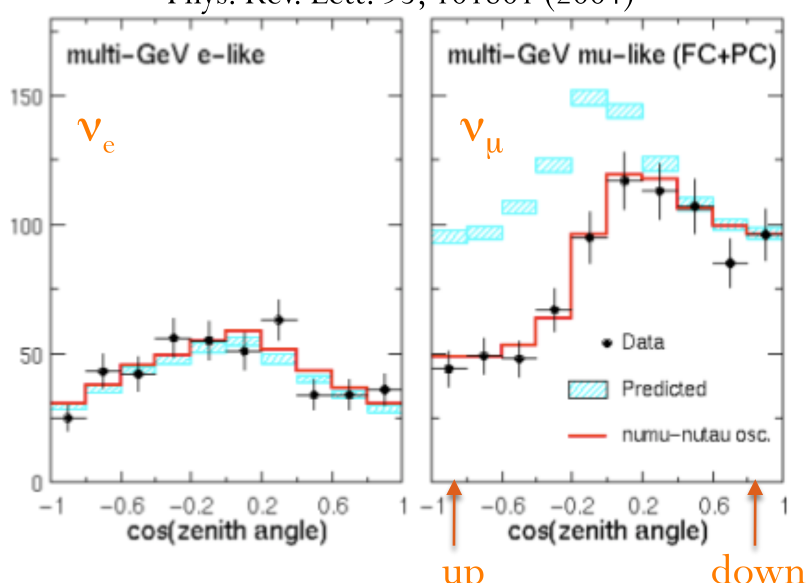


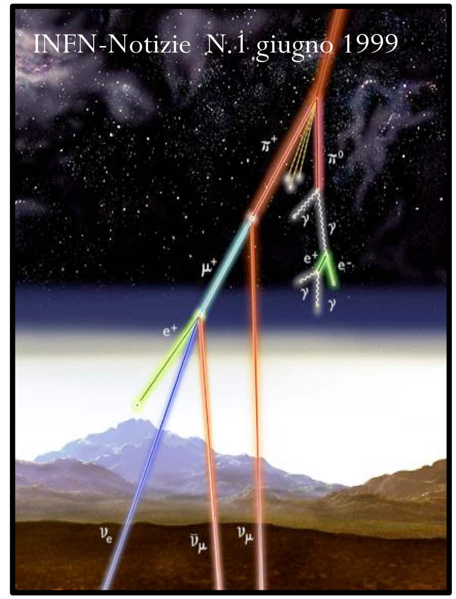
Phys. Rev. Lett. 100, 221803 (2008)

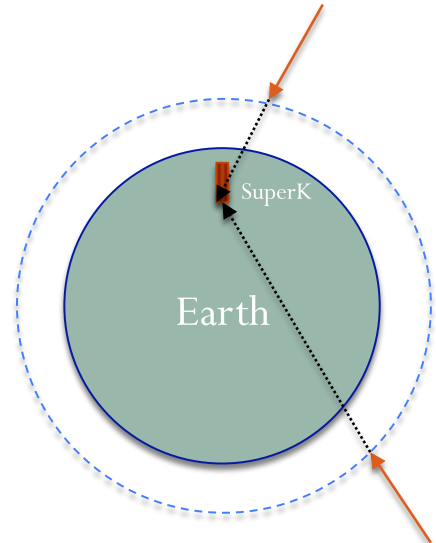
Δm^2_{23}

- First experimental evidence came from neutrinos produced in the atmosphere by cosmic rays
- Again **Super-K** makes a pivotal contribution

Phys. Rev. Lett. 93, 101801 (2004)







$$R = \frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e} \approx 2$$

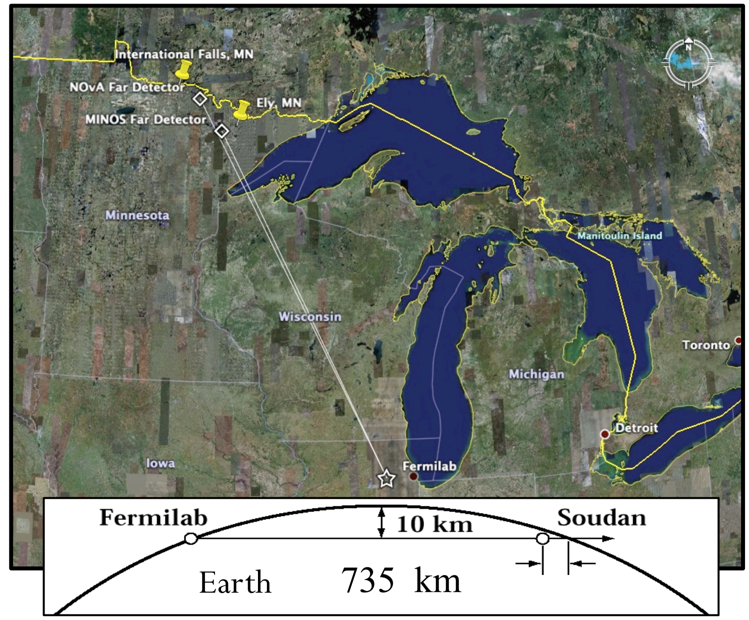
$$\langle E \rangle_{Super-K} \approx 1 - 10\ GeV$$

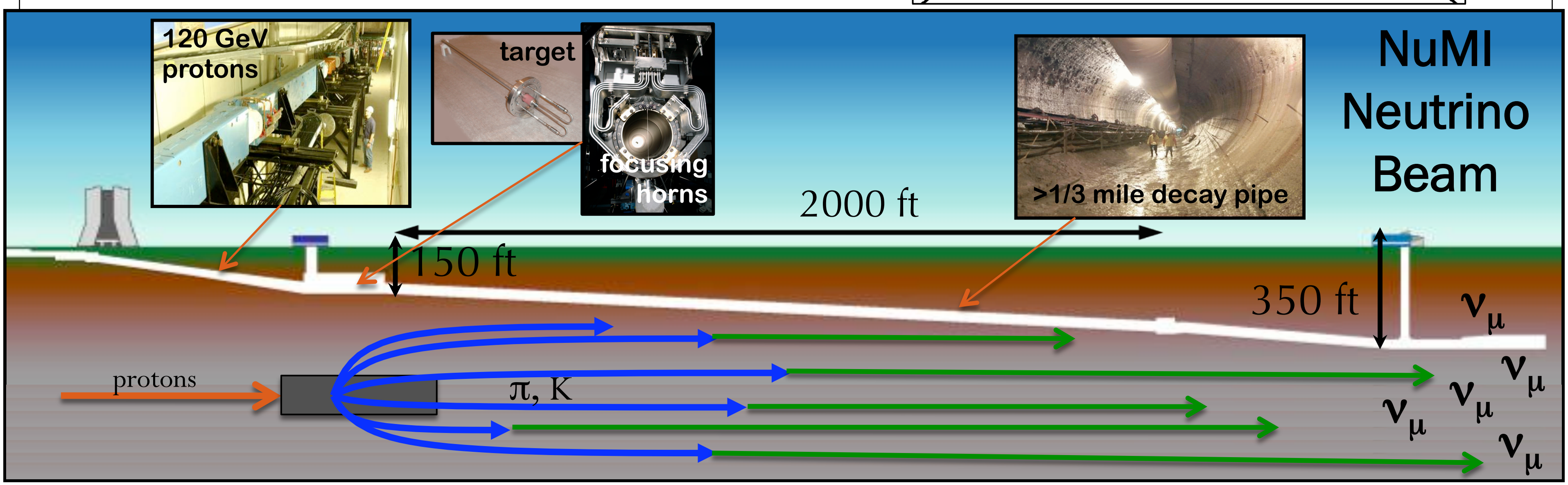
$$\langle L \rangle_{Super-K} \approx 10 - 10^4\ km$$

$$\Delta m^2 \sim 10^{-4} - 1\ eV^2$$

Δm^2_{23}

- First experimental evidence came from neutrinos produced in the atmosphere by cosmic rays
- Most precise measurement of Δm^2_{23} from accelerator-based experiments, **MINOS**.





Δm^2_{23}

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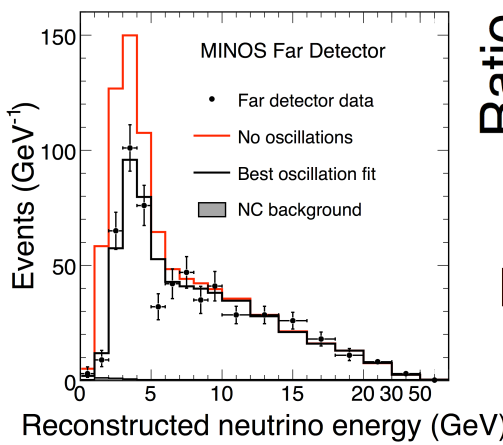
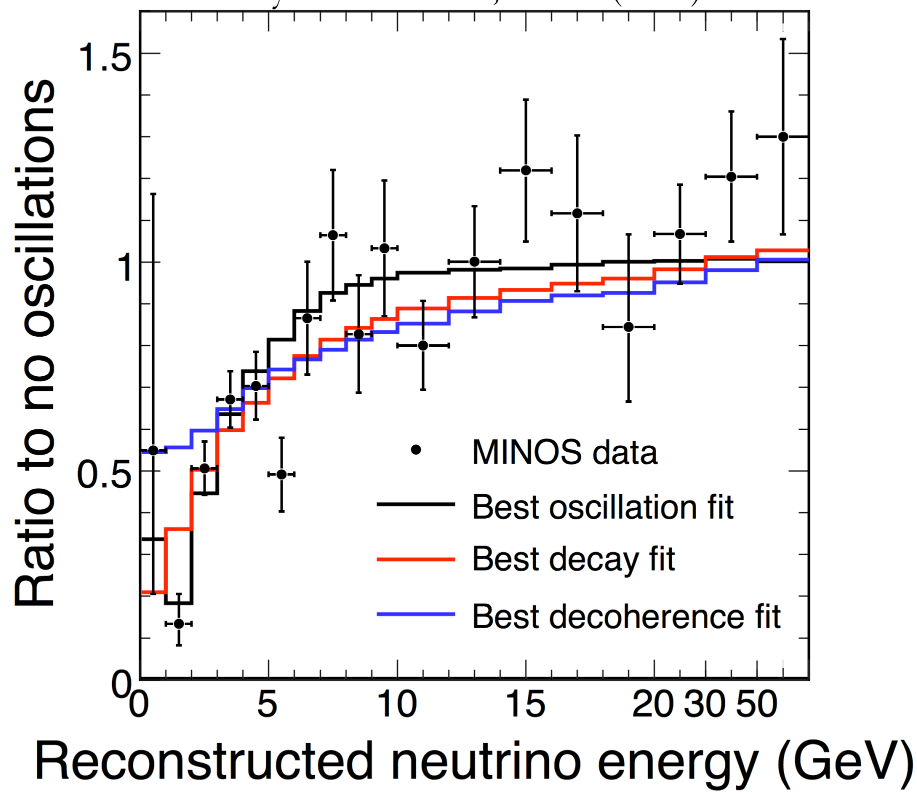
MINOS far detector at Soudan, MN



Phys.Rev.Lett. 101,131802 (2008)



- **<u>Summary:</u>** What we know so far about neutrino oscillations.
- By analogy to the CKM matrix which describes *weak-mass mixing in the quark system*, the ***neutrino weak-mass mixing matrix can be written***:

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}\begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -\sin\theta_{13}e^{-i\delta} & 0 & \cos\theta_{13}\end{pmatrix}\begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

- Discovered in the atmospheric neutrino flux
- Precision measurements using accelerator neutrinos at long baselines

$$\Delta m^2_{23} = 2.51\times 10^{-3} eV^2 \quad (\pm 4.8\%)$$
$$\theta_{23} = 42.3^{+5.3}_{-2.8} \quad (+12.5\%)$$
*

- Discovered in the solar neutrino flux
- Precision measurements using reactor neutrinos at long baselines

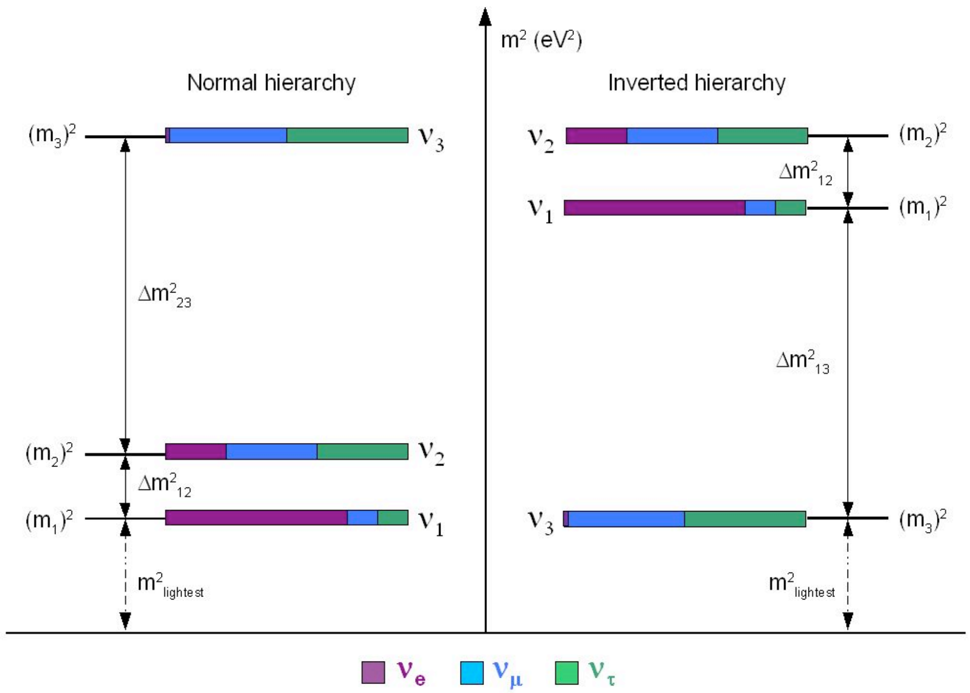
$$\Delta m^2_{12} = 7.59\times 10^{-5} eV^2 \quad (\pm 2.6\%)$$
$$\theta_{23} = 34.4^{+1.0}_{-1.0} \quad (\pm 2.9\%)$$
*

* values taken from most recent global fits performed by Gonzalez-Garcia, Maltoni, and Salvado hep-ph 1001.4524

- **Summary:** But we're not done. What we'd like to learn next…

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=\begin{pmatrix}1&0&0\\0&\cos\theta_{23}&\sin\theta_{23}\\0&-\sin\theta_{23}&\cos\theta_{23}\end{pmatrix}\begin{pmatrix}\cos\theta_{13}&0&\sin\theta_{13}e^{-i\delta}\\0&1&0\\-\sin\theta_{13}e^{-i\delta}&0&\cos\theta_{13}\end{pmatrix}\begin{pmatrix}\cos\theta_{12}&\sin\theta_{12}&0\\-\sin\theta_{12}&\cos\theta_{12}&0\\0&0&1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

- Oscillations are currently our only window on neutrino masses.
- Is the mass hierarchy the same as in the quark sector?
- Is θ_{23} exactly 45 degrees? If so, is that telling us about some kind of unknown symmetry?



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- The remaining mass difference is determined
- But have only upper limits on the remaining mixing angle
- Currently no limits at all on the CP violating phase
  - Could CP violation in the lepton sector explain the observed dominance of matter over antimatter in the Universe?

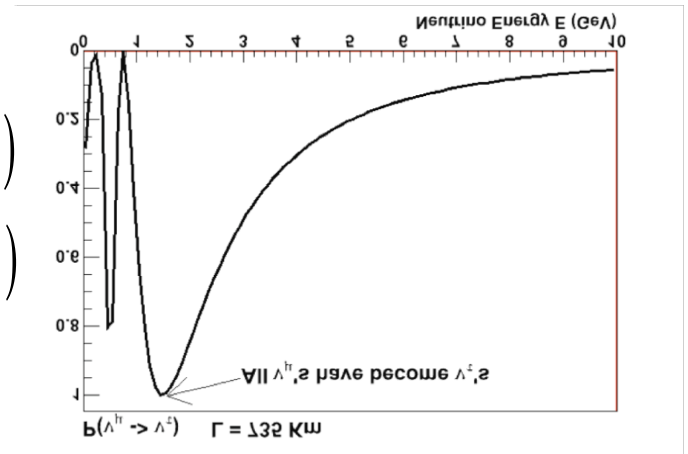
$$\Delta m^2_{13} = \Delta m^2_{12} + \Delta m^2_{23}$$
$$\theta_{13} < 9.4 \quad (1\sigma)$$
$$\delta \in [0,360]$$
*

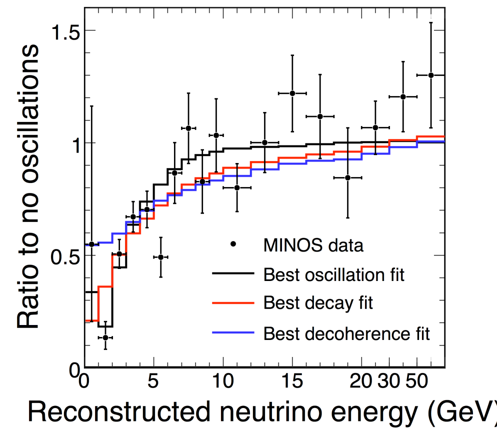
* values taken from most recent global fits performed by Gonzalez-Garcia, Maltoni, and Salvado hep-ph 1001.4524

- **Why the search for θ_{13} and δ^{CP} is a paradigm shift in long-baseline accelerator-based neutrino oscillation experiments**
- K2K and MINOS measured the disappearance of muon neutrinos

$P(\nu_\mu \rightarrow \nu_\tau)$

$P(\nu_\mu \rightarrow \nu_\mu)$





- Transformation to ν_e is a sub-dominant oscillation effect at the Δm^2_{23} scale, so disappearance can be analyzed as an **effective two-neutrino system ν_μ to ν_τ**

$$P(\nu_\mu \rightarrow \nu_\tau) = \sin^2 2\theta_{23} \cdot \sin^2\left(\frac{1.267 \cdot \Delta m^2_{23} \cdot L}{E}\right)$$

- **Why the search for θ_{13} and δ^{CP} is a paradigm shift in long-baseline accelerator-based neutrino oscillation experiments**
- Measuring the conversion to ν_e must be done as a small-scale appearance of ν_e

$$P(\nu_\mu \rightarrow \nu_e) \cong \sin^2 2\theta_{13} T_1 - \alpha \sin 2\theta_{13} T_2 - \alpha \sin 2\theta_{13} T_3 + \alpha^2 T_4$$

$$\alpha = \frac{\Delta m^2{}_{21}}{\Delta m^2{}_{31}}$$

$$T_1 = \sin^2\theta_{23} \frac{\sin^2[(1-x)\Delta]}{(1-x)^2}$$

$$T_2 = \sin\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \sin\Delta \frac{\sin(x\Delta)}{x} \frac{\sin[(1-x)\Delta]}{(1-x)}$$

$$T_3 = \cos\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \cos\Delta \frac{\sin(x\Delta)}{x} \frac{\sin[(1-x)\Delta]}{(1-x)}$$

$$T_4 = \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(x\Delta)}{x^2}$$

$$\Delta = \frac{\Delta m^2{}_{31} L}{4E_\nu} \qquad x = \frac{2\sqrt{2} G_F N_e E_\nu}{\Delta m^2{}_{31}}$$

the matter/anti-matter asymmetric part!

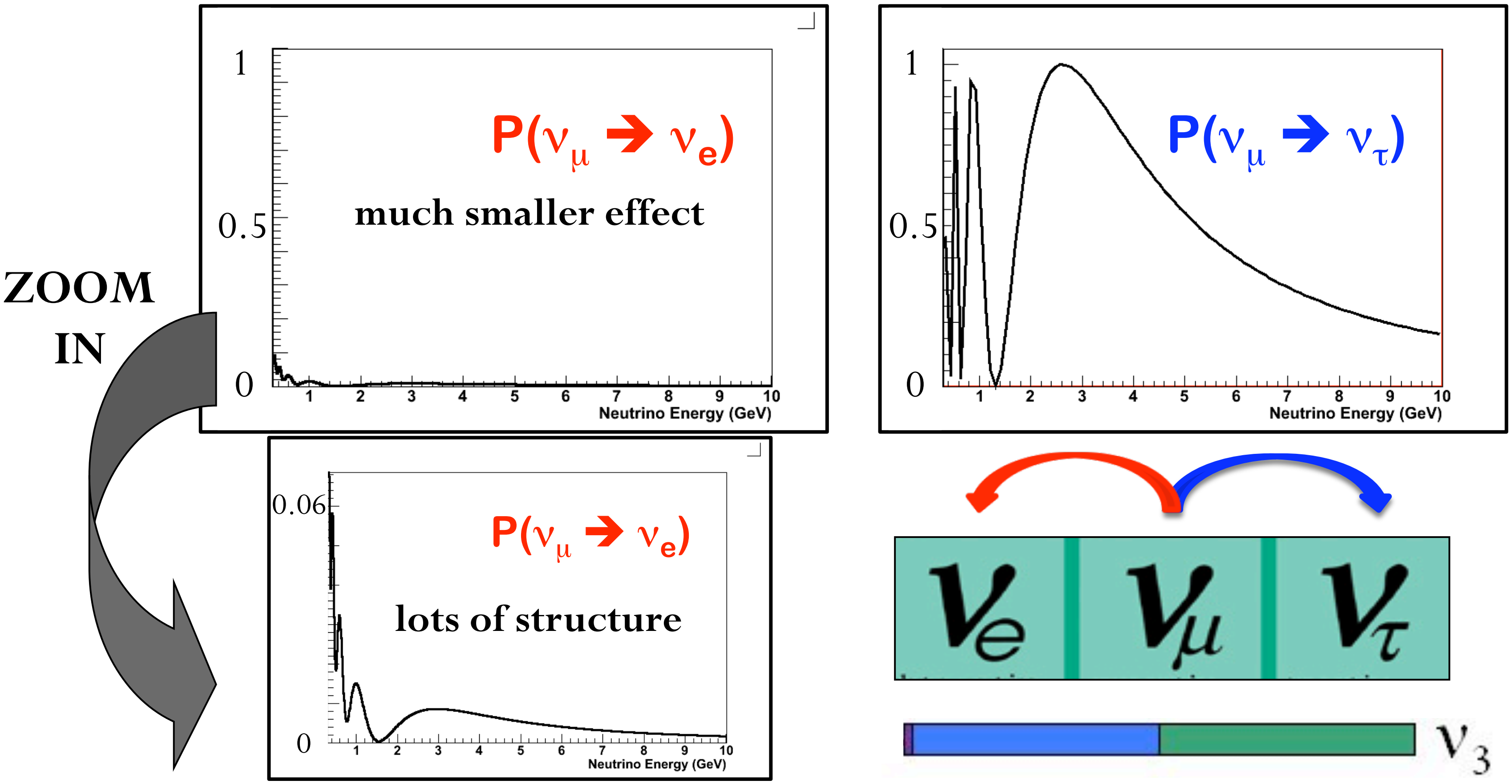
CP Violating

CP Conserving

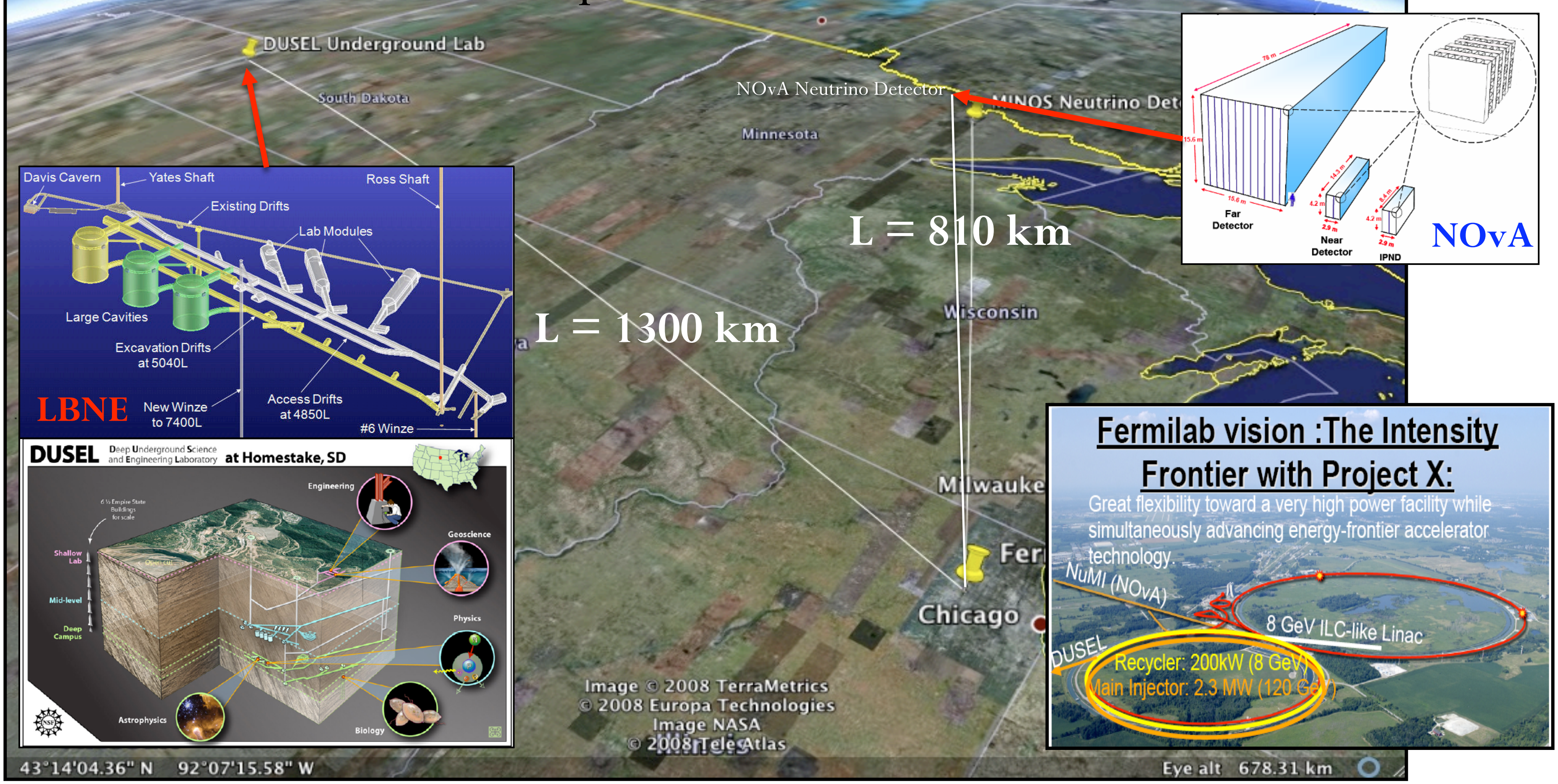
Matter Effects

Rich physics in this next stage!!

- Why the search for θ_{13} and δ^{CP} is a paradigm shift in long-baseline accelerator-based neutrino oscillation experiments



- Next generation US accelerator-based long-baseline (LBL) neutrino oscillation experiments. NOνA, LBNE



- Discovery of neutrino oscillations in the last decade has meant two things for neutrino cross-section physics:

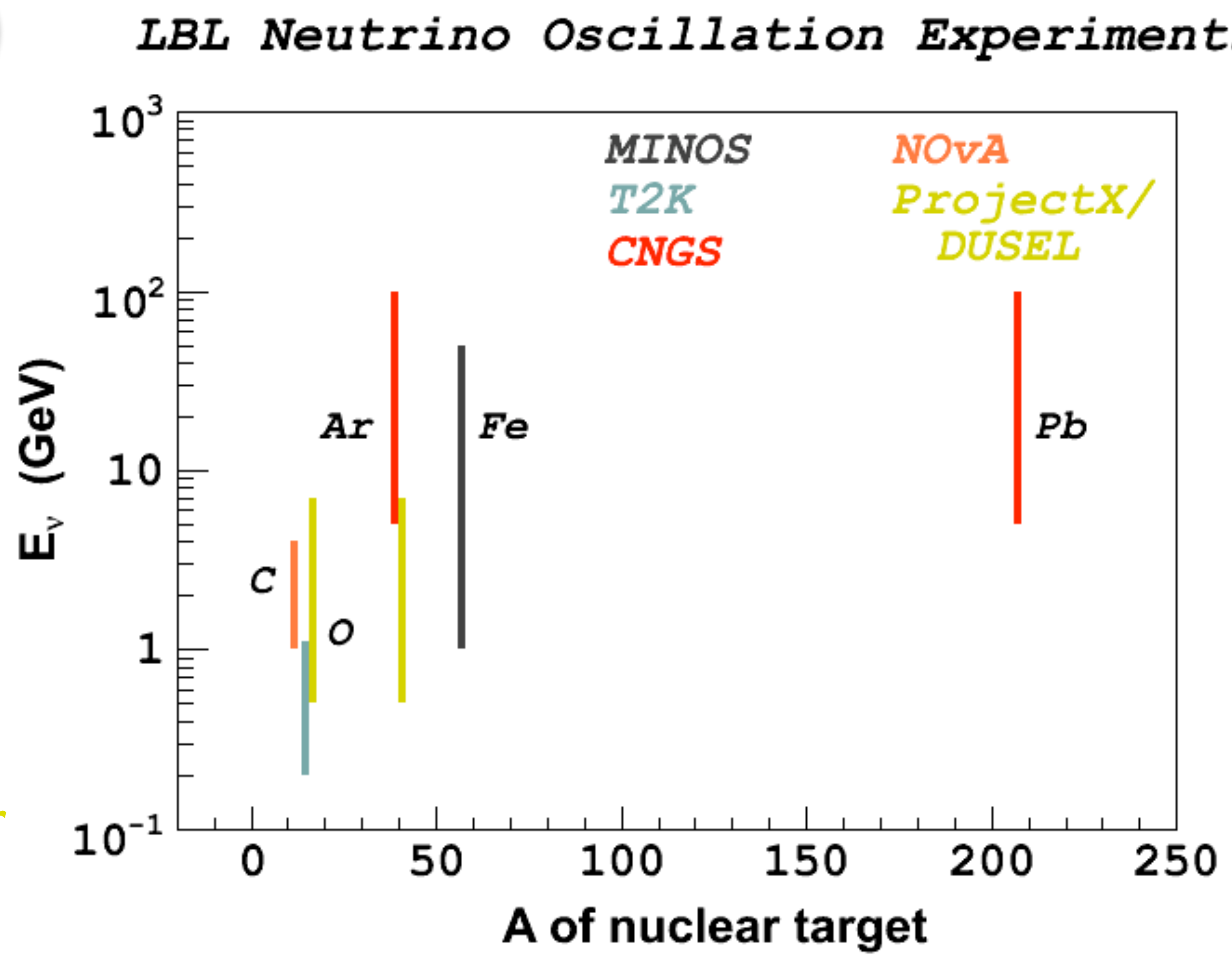
1. suddenly we really care about neutrino cross-sections in the 0.5-10 GeV range where they are not well measured and the channels are complicated

2. suddenly there are lots of high intensity neutrino beams around the world in the 0.5-10 GeV range for making these measurements

- Neutrino energy ranges and detector target materials are crucial aspects of oscillations experiments with regard to neutrino cross-sections
  - The dominant **interaction channels** change rapidly across the few GeV neutrino energy region
  - Many **resonances** must be considered in this energy region
  - **Nuclear effects** are very complicated and not well known, so the target nucleus has a large impact on how well we can remove backgrounds and understand the kinematics of the final state

Nuclear targets
Neutrino energies
Interaction channels

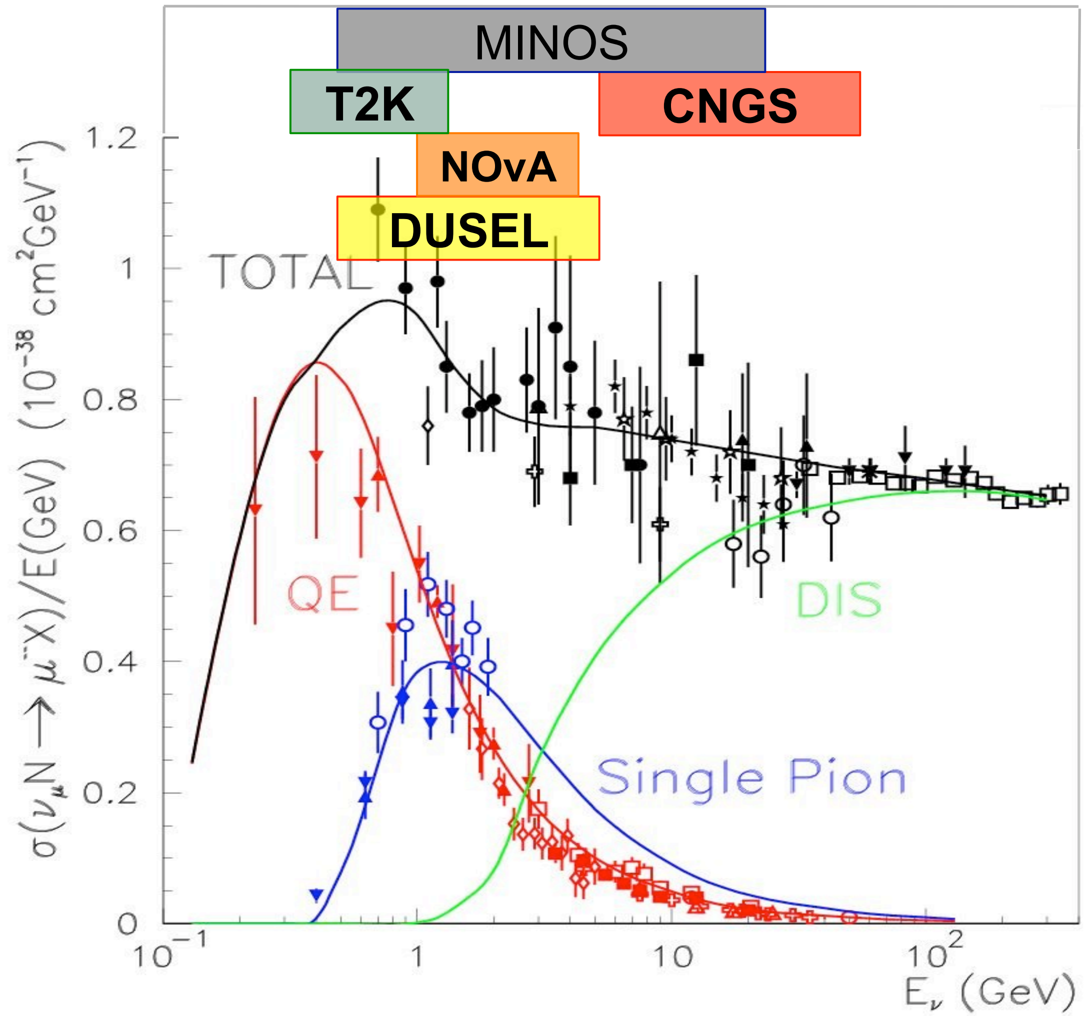
- Target Materials:
  - MINOS = Fe
  - CNGS = Pb, Ar
  - T2K = H_2O
  - NOvA = C
  - DUSEL = H_2O, Ar



Nuclear targets
Neutrino energies
Interaction channels

- projection onto the neutrino energy axis tells us which interactions we are most interested in for these experiments
- data are 20-30 years old
  - 100's of events
  - mostly D_2 targets
- calculations date back to 70's and 80's

ν_μ charged-current cross-sections



Nuclear targets
Neutrino energies
Interaction channels

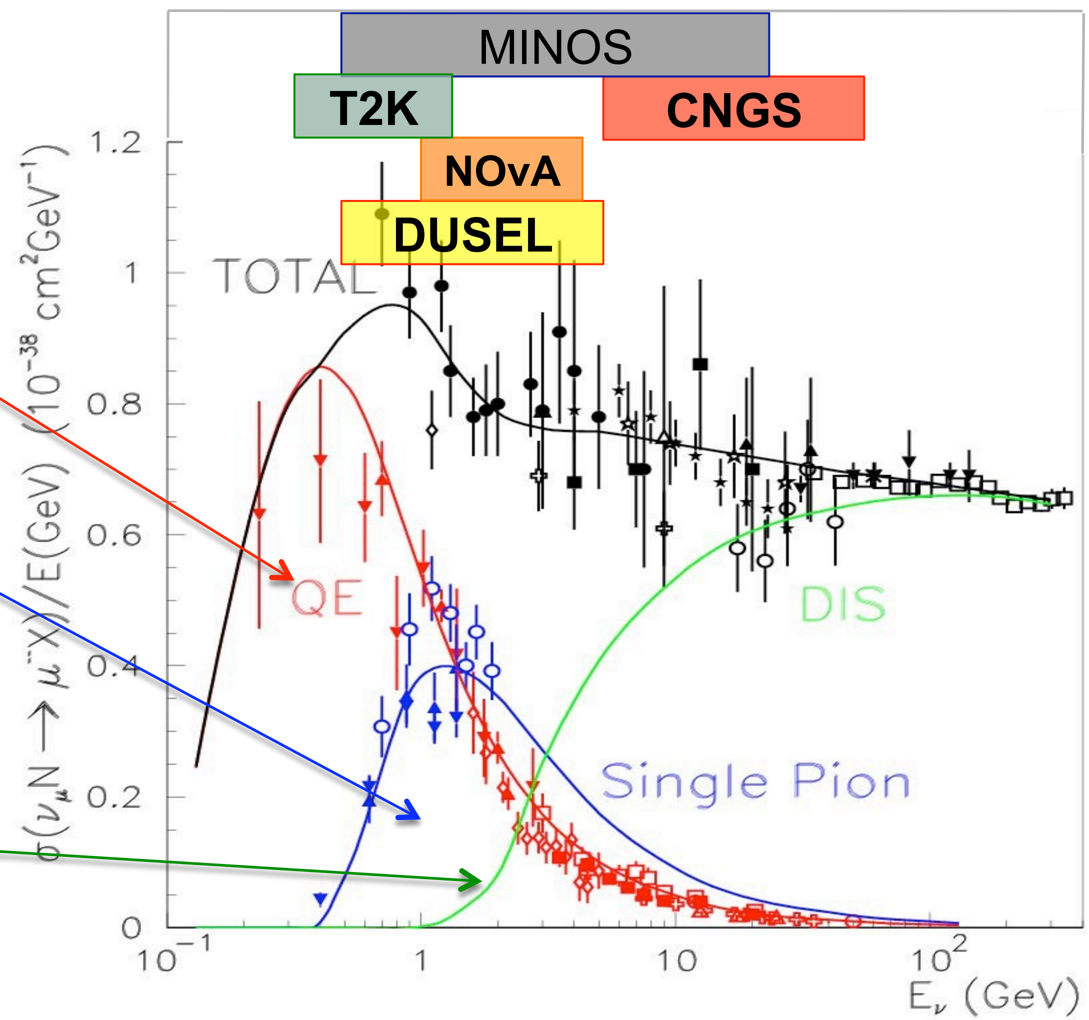
Quasi-Elastic
signal channel in LBL oscillation experiments

NC π^0
background for ν_e appearance

CC π^+
background for ν_μ disappearance

DIS
need to extrapolate into low energy region

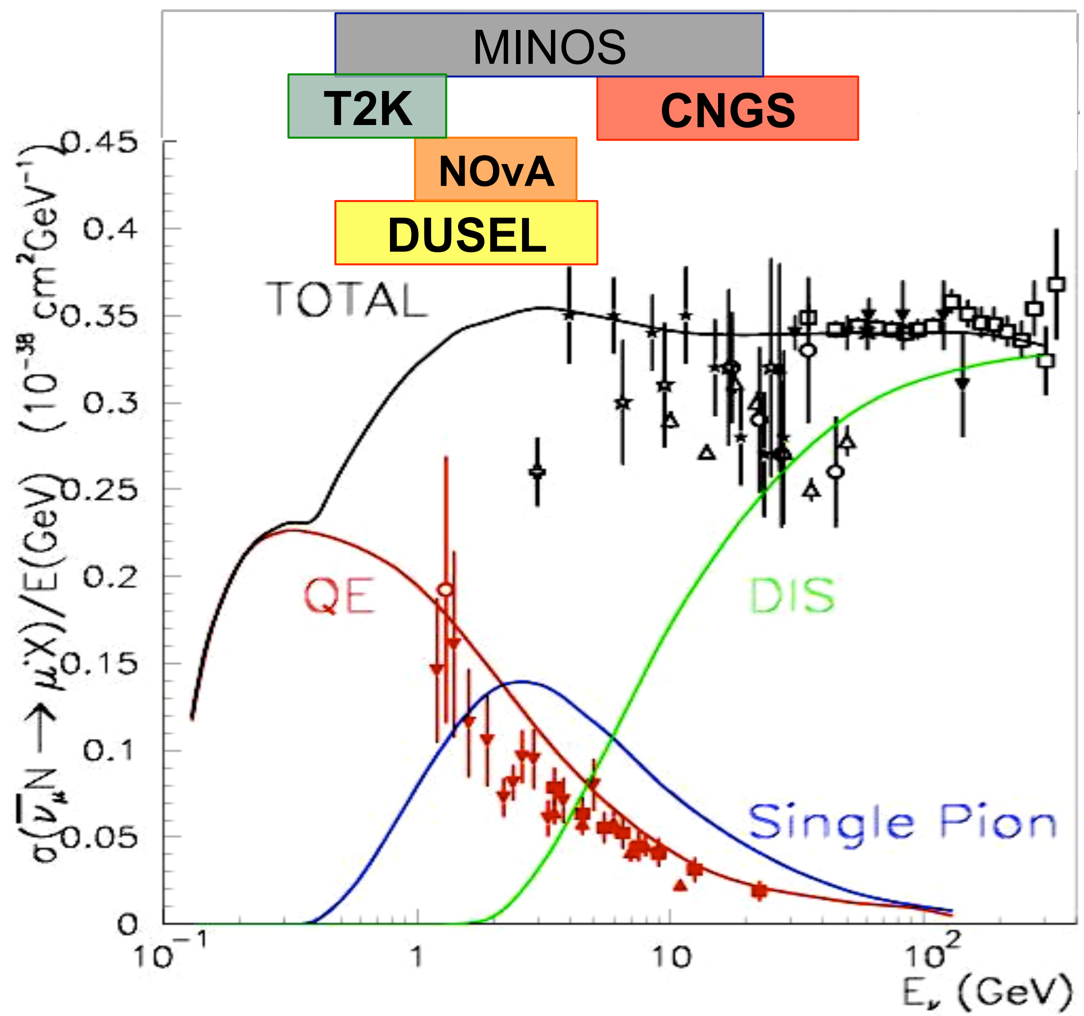
ν_μ charged-current cross-sections

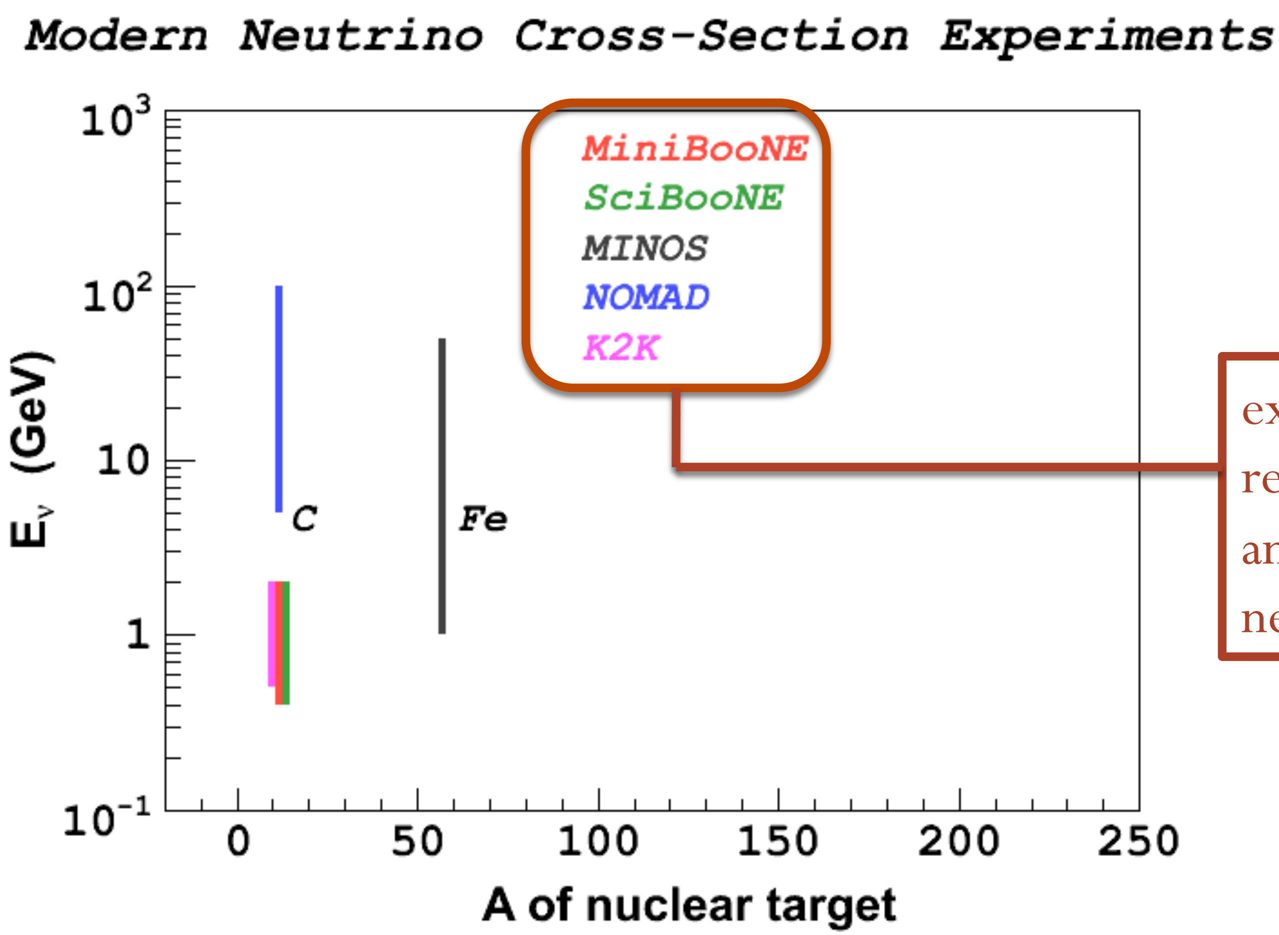


Nuclear targets
Neutrino energies
Interaction channels

- situation is quite a bit worse for antineutrinos
- measure ~~CP~~ by comparing $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

$\bar{\nu}_\mu$ charged-current cross-sections



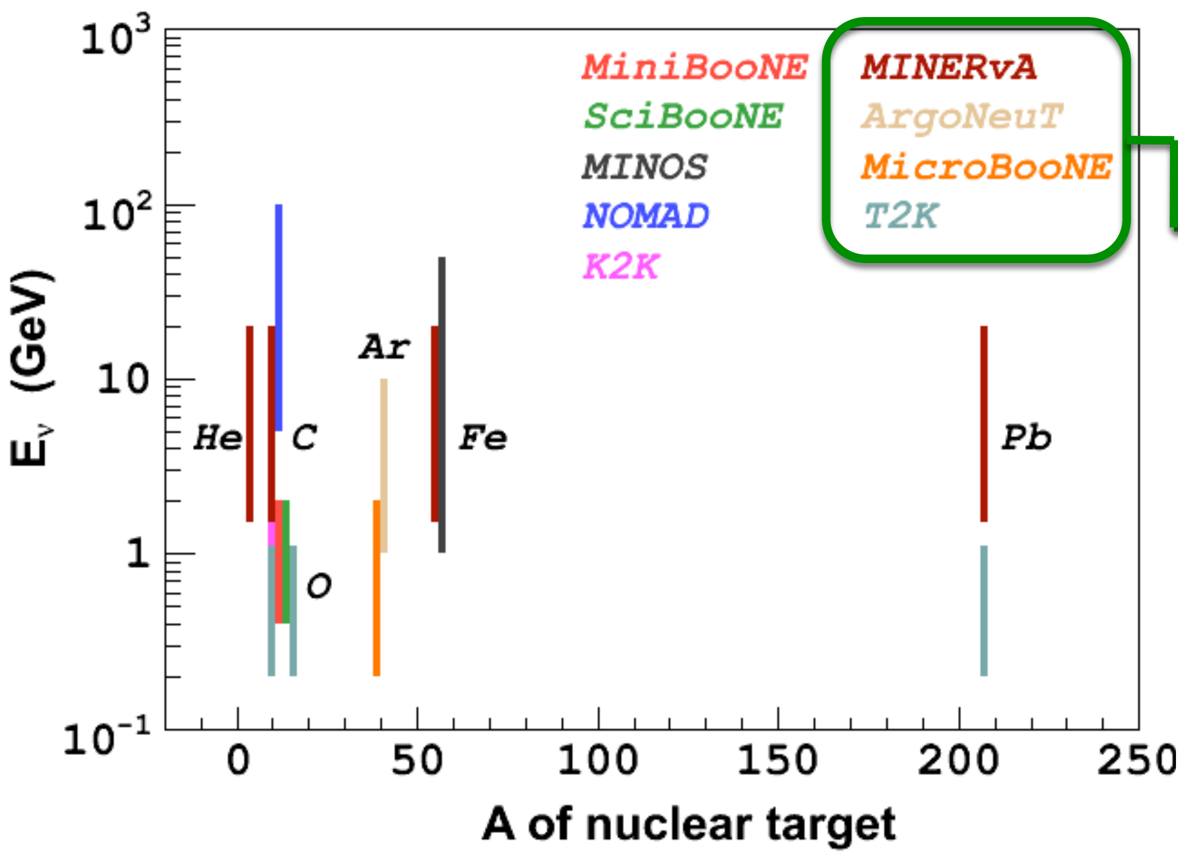


Nuclear targets
Neutrino energies
Interaction channels

experiments with recent results and/or currently analyzing and publishing new cross-section data

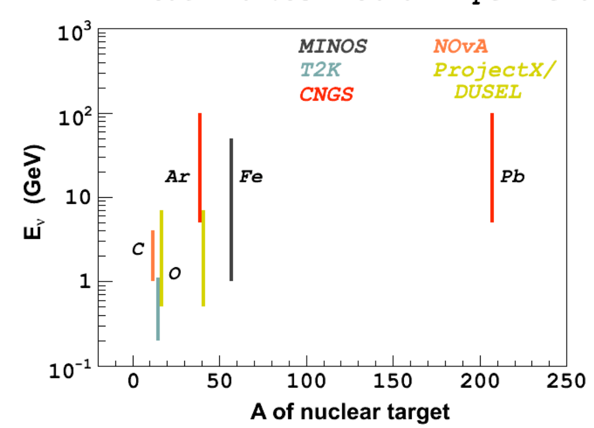
Nuclear targets
Neutrino energies
Interaction channels

Modern Neutrino Cross-Section Experiments

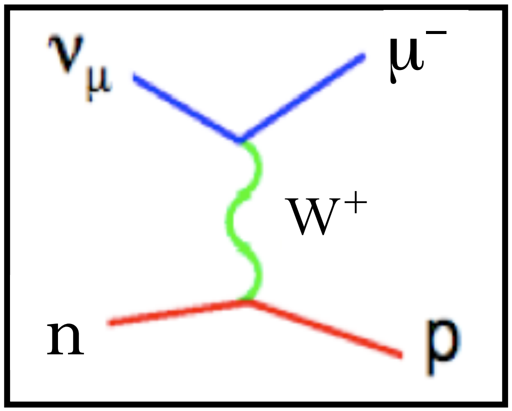


near future neutrino cross-section experiments

LBL Neutrino Oscillation Experiments



- Charged-Current Quasi-Elastic Scattering

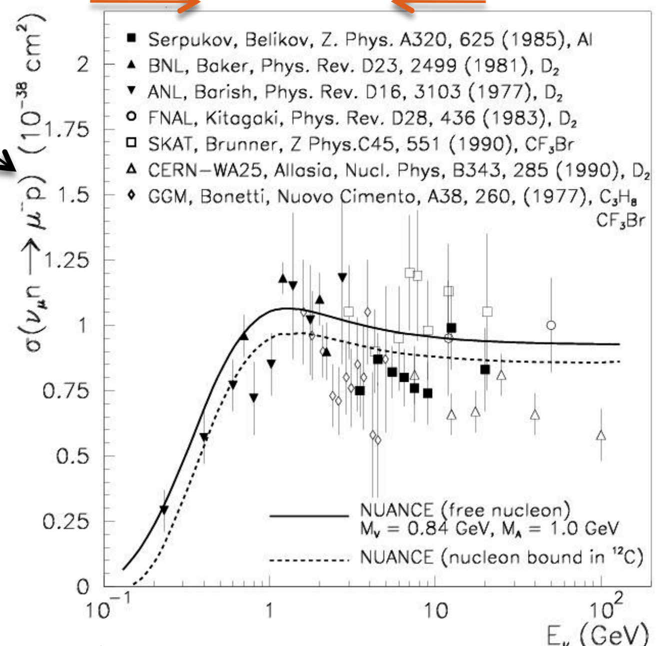


~40% spread across expts

10-20% errors on data sets

no /E(GeV)

relevant for osc expts



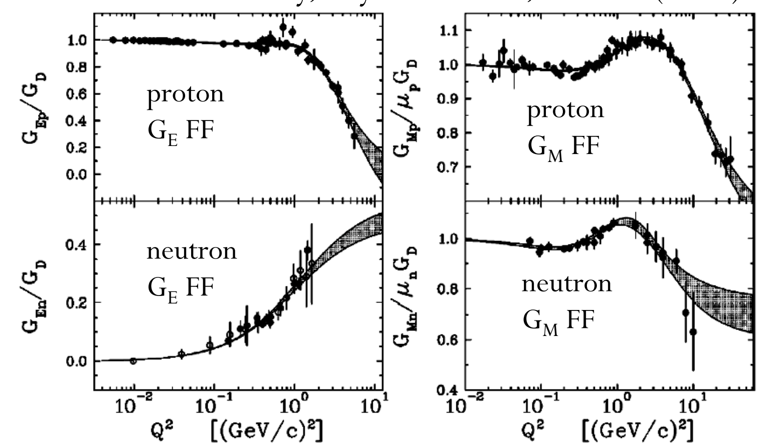
- CCQE is the signal channel for most oscillation experiments
  - a clean final state with two easily identifiable particles (μ,p) or (e,p)
  - muons and electrons simple to separate for ν_μ/ν_e ID
  - final state allows neutrino energy reconstruction with one or both tracks

$$E_\nu^{QE} = \frac{2(m_N - \varepsilon_B) - (\varepsilon_B^2 - 2m_N\varepsilon_B + m_\ell^2 + \Delta M^2)}{m_N + \varepsilon_B - E_\ell + p_\mu \cos(\theta_\ell)}$$

- Charged-Current Quasi-Elastic Scattering

- **Vector Form Factors**
  - well known from e⁻ scattering
  - deviations from dipole form at high Q^2

Kelly, Phys. Rev. **C70**, 068202 (2004)



- **Axial-Vector Form Factor** dominates uncertainty in CCQE cross-section. Assume dipole form:

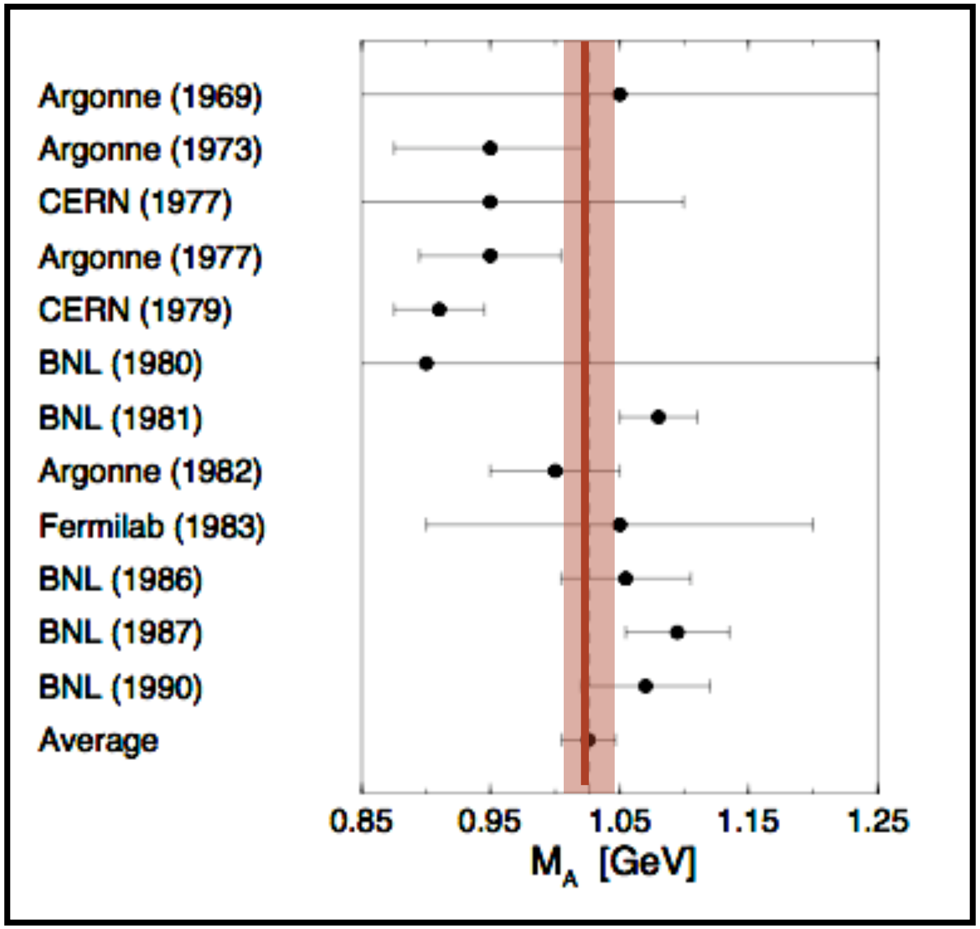
$$F_A(Q^2) = F_A(0)\left(1 + \frac{Q^2}{M_A^2}\right)^{-2}$$

well known from β decay experiments ($Q^2 = 0$)

measured from Q^2 distribution of QE neutrino-nucleon events

- **Nuclear effects** – simulated with Relativistic Fermi Gas Model "RFG" formalism of Smith and Moniz, NP B43, 605 (1972).

- Charged-Current Quasi-Elastic Scattering



Bernard *et al.*, J. Phys. **G28**, R1 (2002)

$$F_A(Q^2) = F_A(0)\left(1 + \frac{Q^2}{M_A^2}\right)^{-2}$$

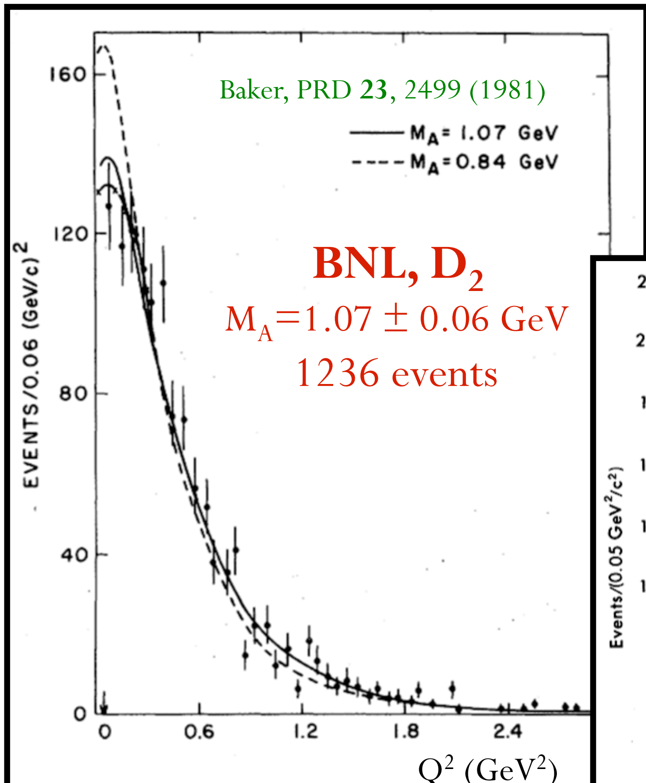
world average: $M_A = 1.03 \pm 0.02$ GeV

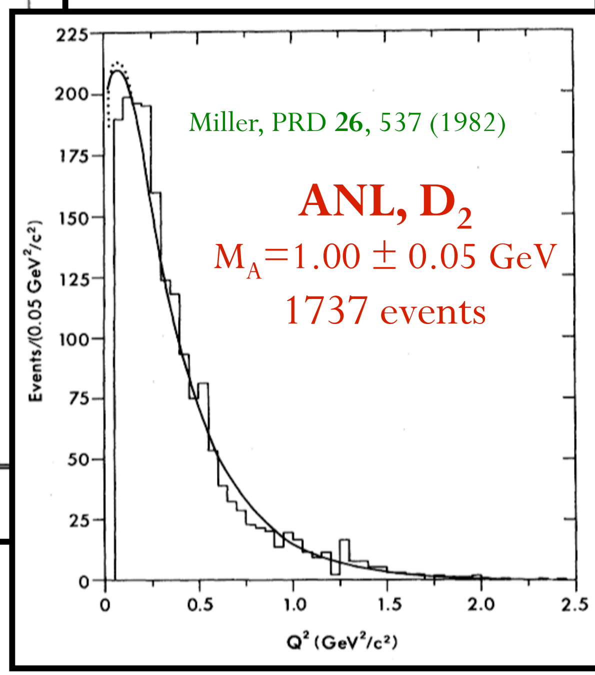
- was the focus of many early bubble chamber experiments

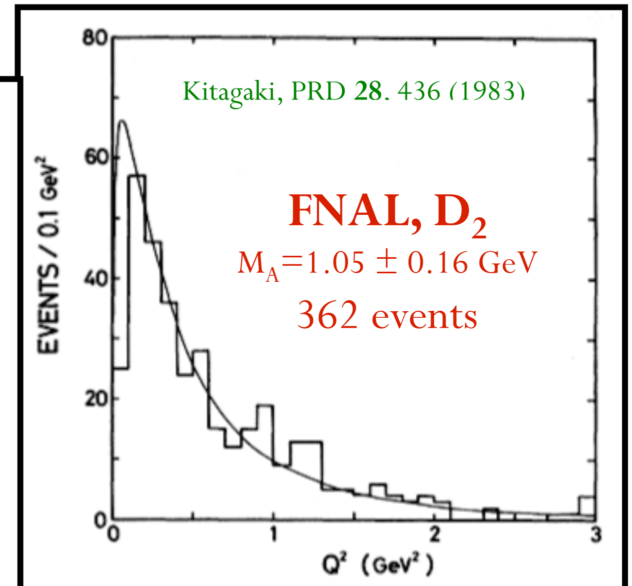
- mostly QE data on D_2 (1969-1990)

- <u>Charged-Current Quasi-Elastic Scattering</u>

$$F_A(Q^2) = F_A(0)\left(1 + \frac{Q^2}{M_A^2}\right)^{-2}$$



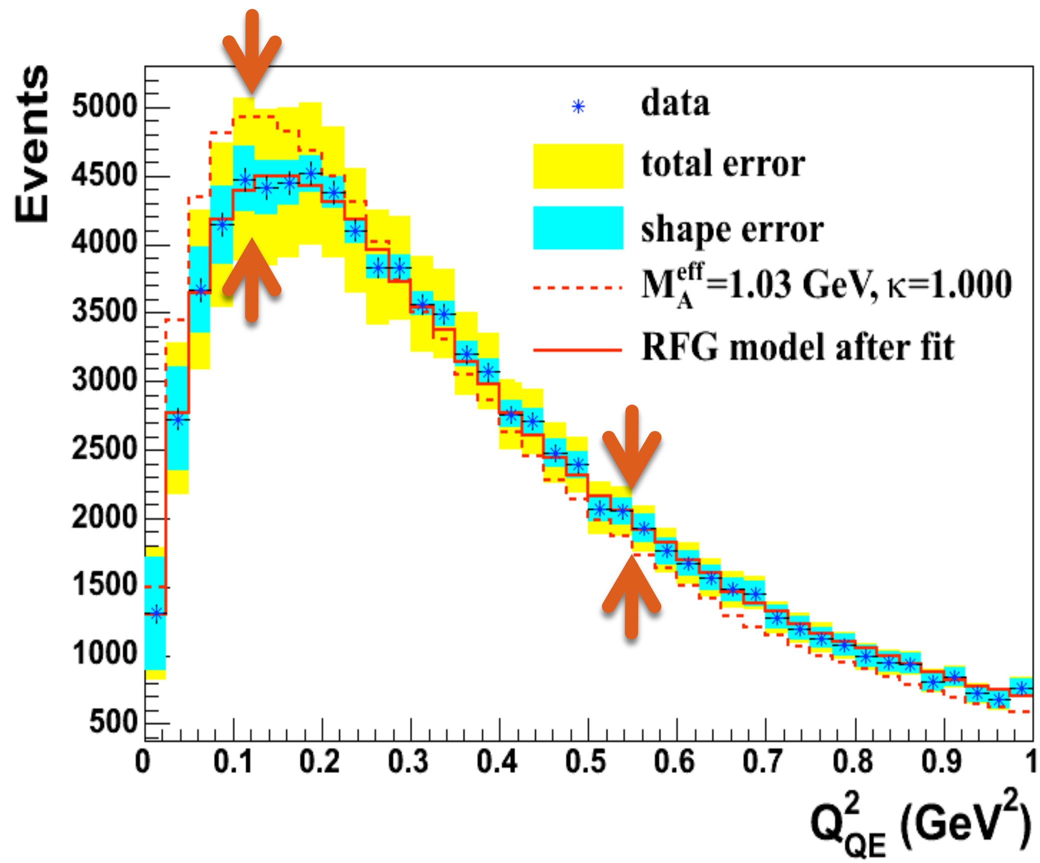




Charged-Current Quasi-Elastic Scattering

- because of important role of CCQE and M_A, modern experiments have looked to re-measure this parameter

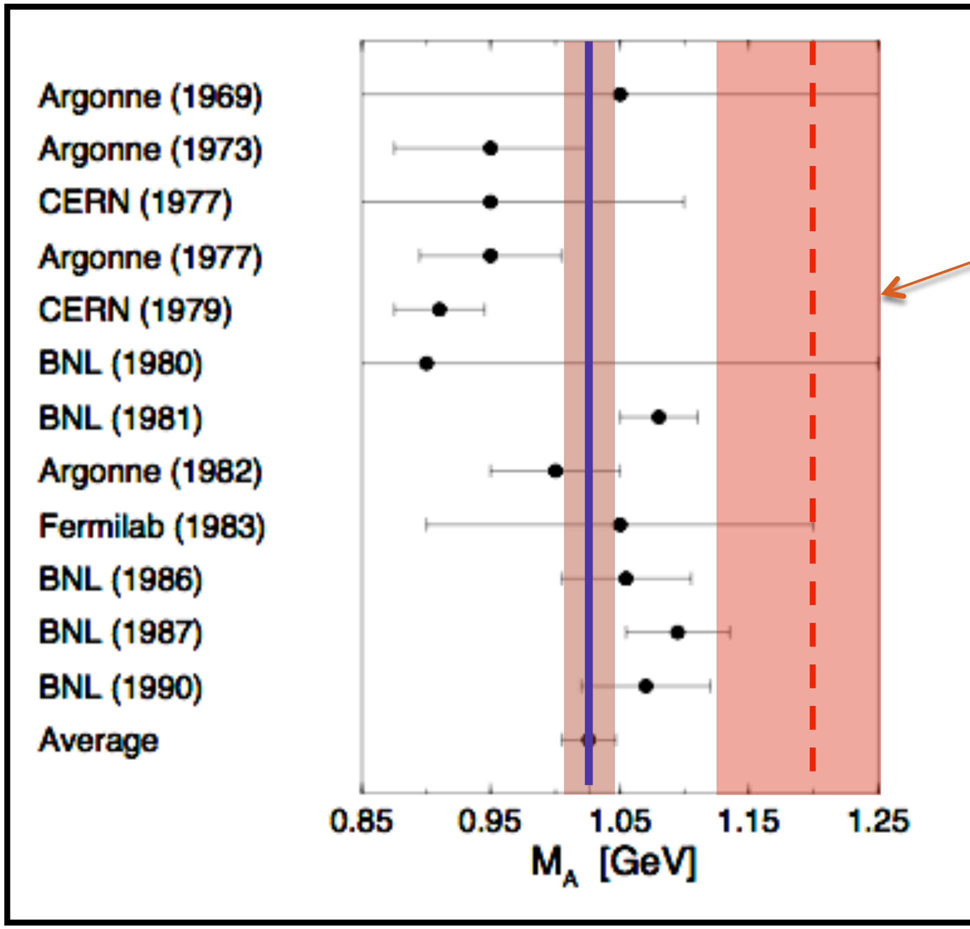
- MiniBooNE data:
  - 146,070 ν_μ QE events on carbon (76% purity)
  - deficit seen at lowest Q^2
  - excess at higher Q^2



$$M_A = 1.35 \pm 0.17\ GeV$$
$$\kappa = 1.007 \pm 0.012$$

scaling parameter to increase Pauli blocking in the mode

- Charged-Current Quasi-Elastic Scattering

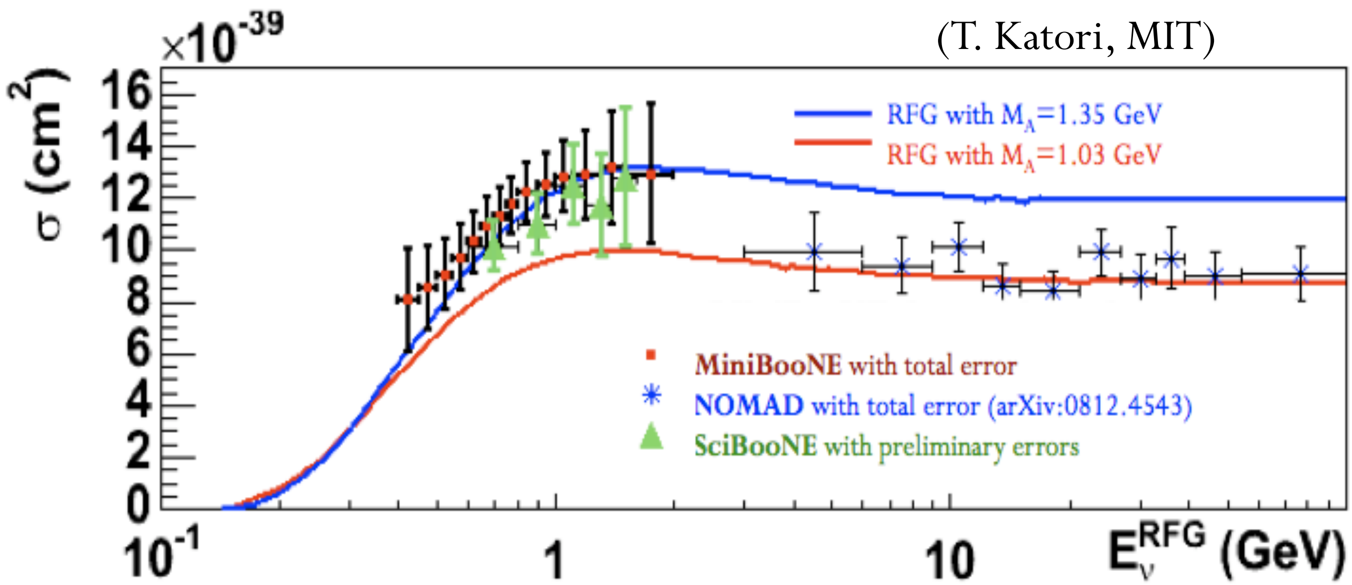


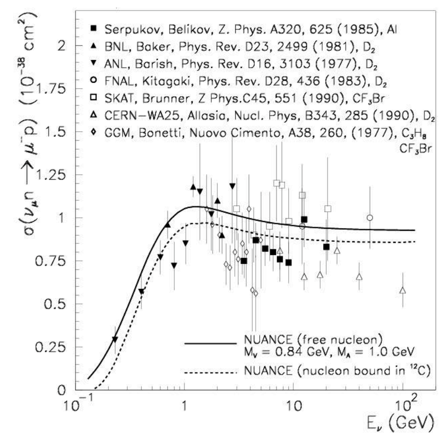
- **K2K SciFi** (^{16}O, $Q^2>0.2$)
  Phys. Rev. **D74**, 052002 (2006)
  $M_A=1.20 \pm 0.12$ GeV
- **K2K SciBar** (^{12}C, $Q^2>0.2$)
  AIP Conf. Proc. **967**, 117 (2007)
  $M_A=1.14 \pm 0.11$ GeV
- **MiniBooNE** (^{12}C, $Q^2>0.25$)
  paper in preparation
  $M_A=1.27 \pm 0.14$ GeV
- **MINOS** (Fe, $Q^2>0.3$)
  NuInt09, preliminary
  $M_A=1.26 \pm 0.17$ GeV

- MiniBooNE results consistent with other modern M_A measurements
  - all on nuclear targets
  - all use Fermi Gas model
  - all see same Q^2 disagreement

- Charged-Current Quasi-Elastic Scattering

(T. Katori, MIT)

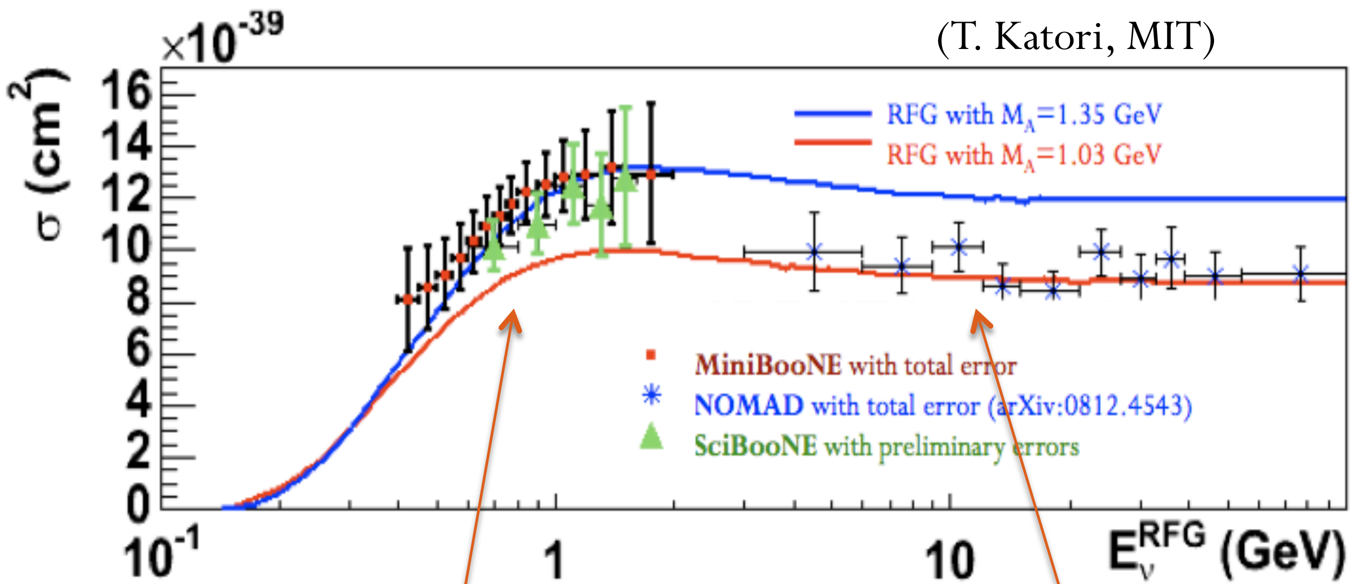


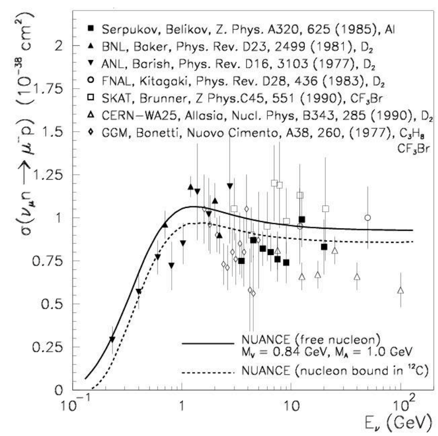


- MiniBooNE/SciBooNE in agreement, but tension with higher energy NOMAD results. All three on carbon. This is not understood.

- Charged-Current Quasi-Elastic Scattering

(T. Katori, MIT)





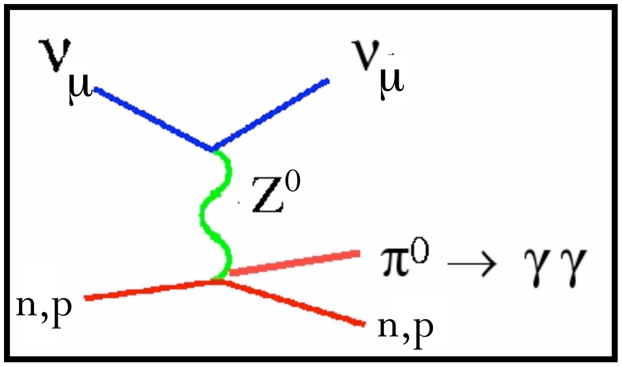
consistent story
QE shape + normalization
$M_A^{MB} = 1.35$ GeV

consistent story
QE shape + normalization
$M_A^{NOMAD} = 1.07$ GeV

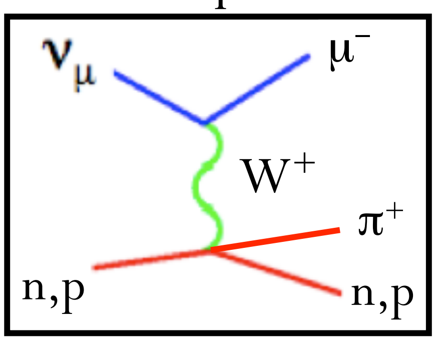
- Leaves one in a dilemma if want to predict how many QE events you expect!

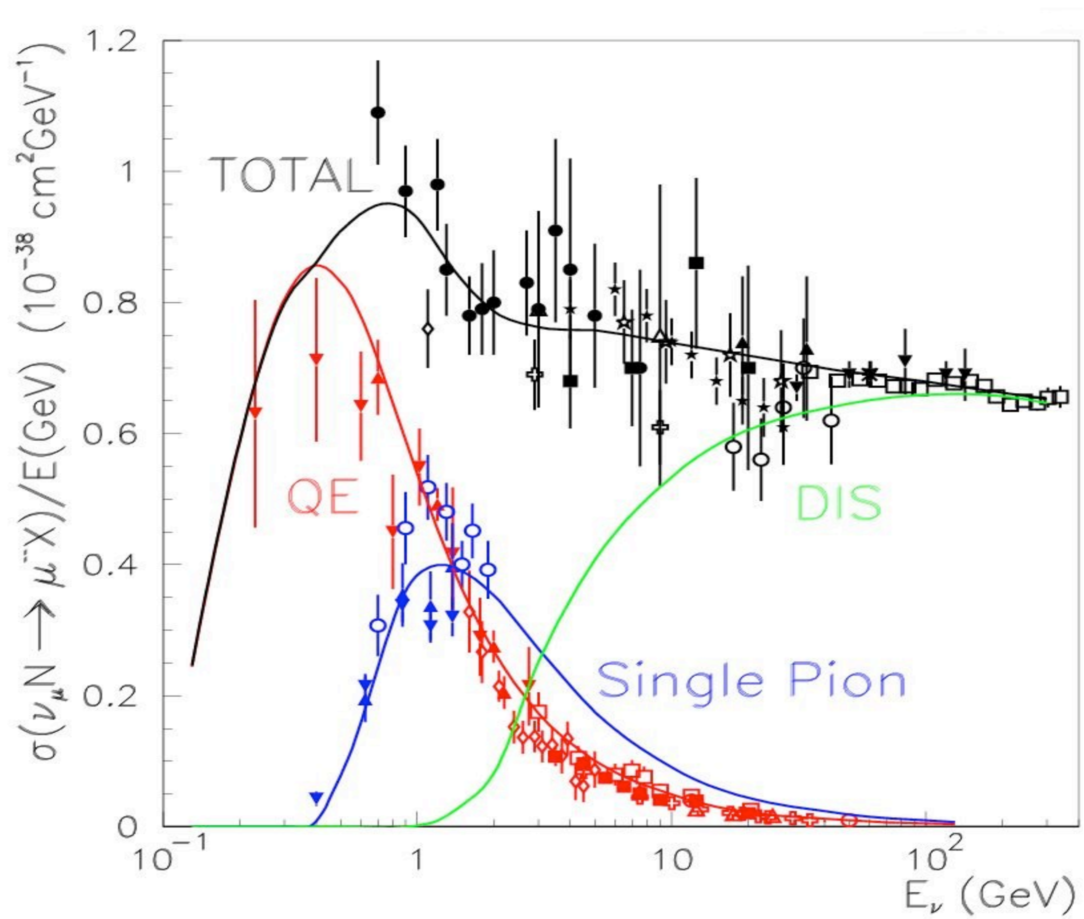
- Single Pion Production

NC π^0 production



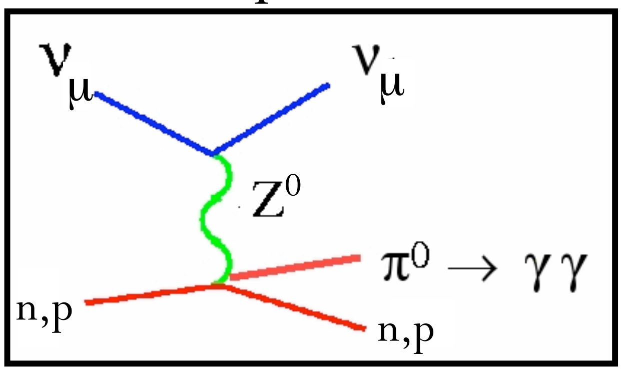
CC π^+/π^0 production

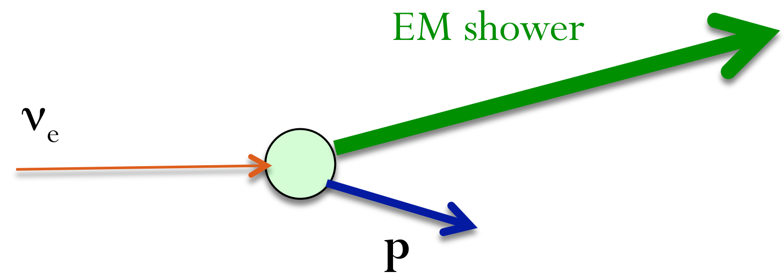




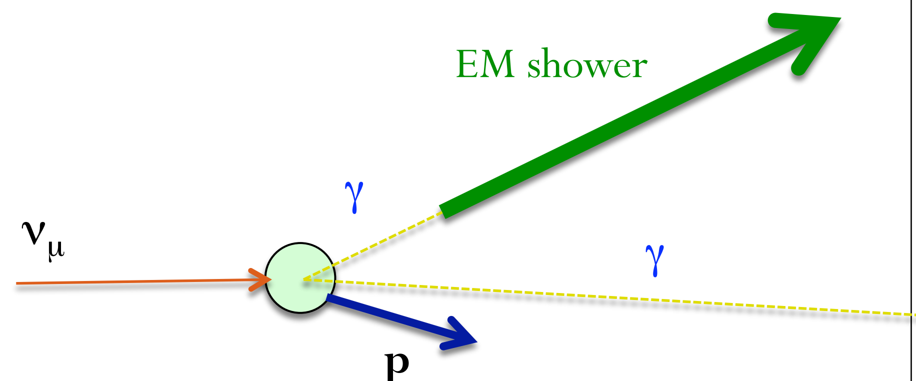
- Single Pion Production

NC π^0 production





$$\nu_e + n \rightarrow p + e^-$$

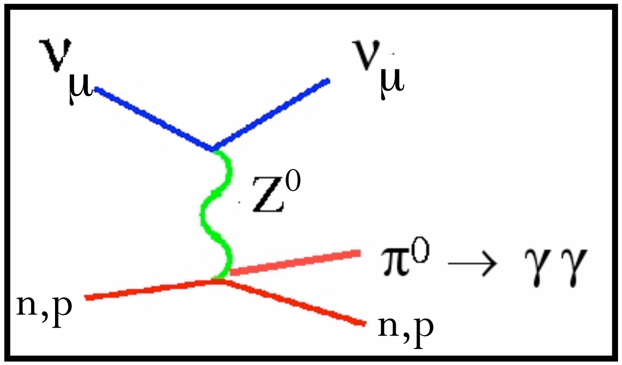


$$\nu_\mu + p \rightarrow p + \pi^0 \rightarrow \gamma + \gamma$$

- Neutral pions create a bkgd to ν_e CCQE if one photon is missed in event reconstruction
- Gamma can be lost when it escapes the detector without converting, the 2 gammas overlap, or in asymmetric π^0 decays with one low energy photon

- Single Pion Production

NC π^0 production

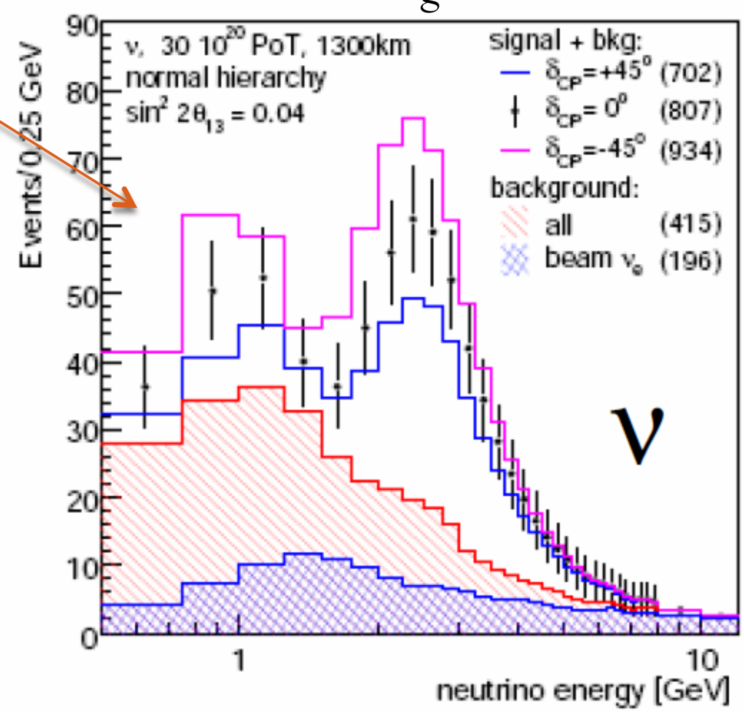


- Neutral pions are largest background in ν_e appearance searches
- LBNE background predictions from US Long-Baseline report

LBNE

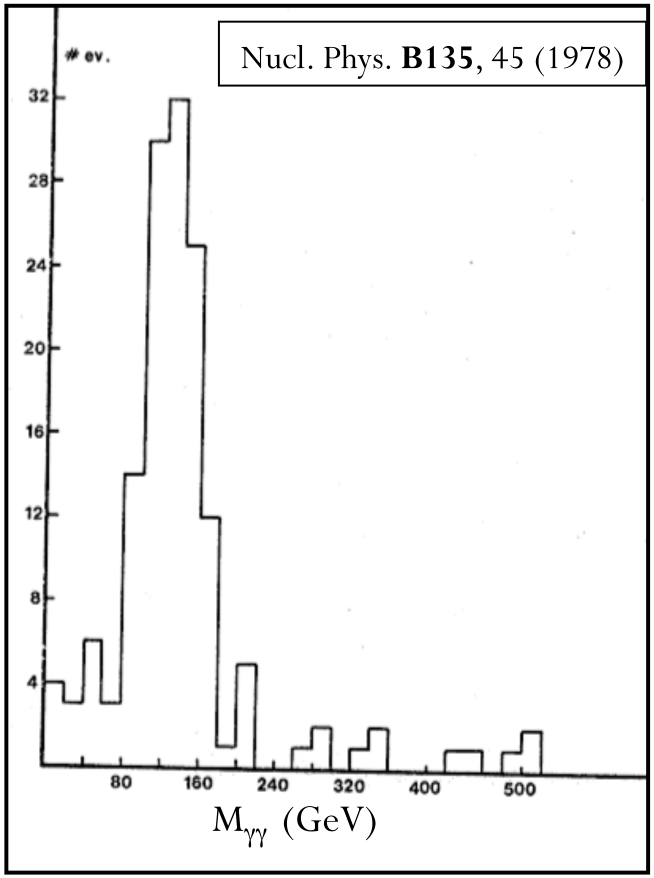
Interaction	E_{rec} range (GeV)					
Bkg 1	0.0-0.5	0.5-1.0	1.0-1.5	1.5-2.0	2.0-3.0	3.0-
CC QE	7%	4%	1%	3%	0%	0%
CC π^0	0%	2%	6%	4%	0%	0%
CC $\pi^\pm$	5%	5%	0%	1%	1%	0%
CC $n\pi$	0%	0%	1%	6%	7%	1%
CC others	0%	0%	2%	0%	0%	0%
NC π^0	20%	54%	62%	50%	26%	0%
NC $\pi^\pm$	53%	9%	6%	0%	0%	0%
NC $n\pi$	0%	13%	5%	21%	62%	99%
NC others	15%	14%	16%	21%	1%	0%

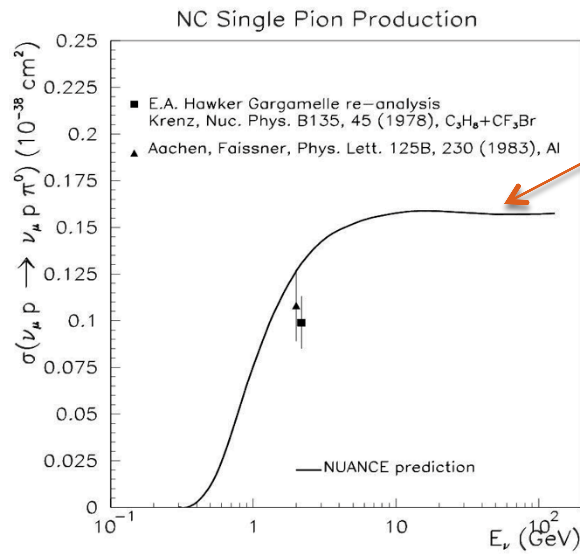
goal: σ < 5-10%



- Single Pion Production

NC π^0 production





this σ tells you how many π^0 background events should expect to have

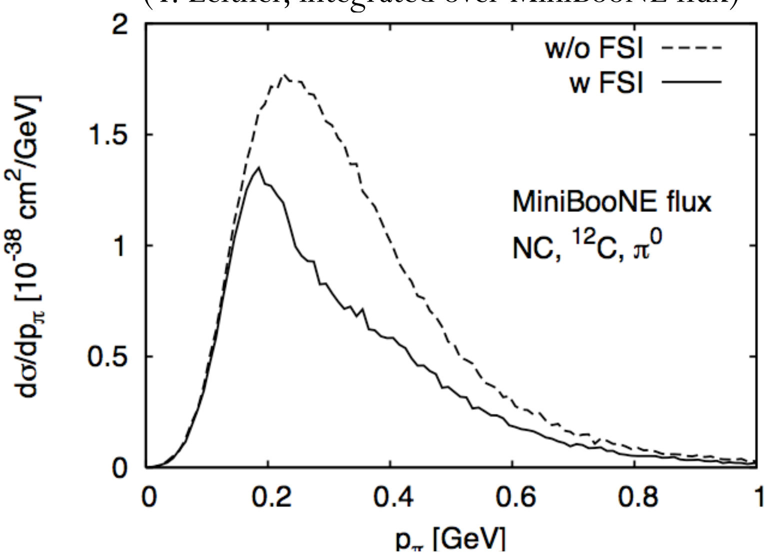
ν osc exps typically assign 25-40% uncertainties to this initial interaction σ

- Gargamelle measurement based on 240 observed NC π^0 events
- Pion kinematics are important to understanding ν_e background rate and energy spectrum as mis-ID

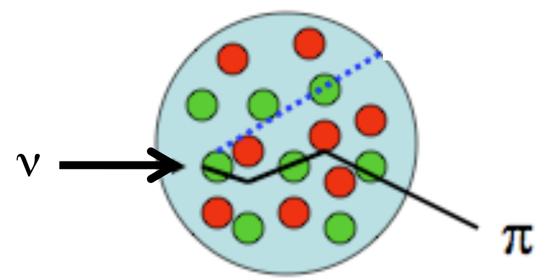
- Single Pion Production

NC π^0 production

(T. Leitner, integrated over MiniBooNE flux)



- **Nuclear effects further complicate this description**



- Example, at $E_\nu = 1$ GeV on carbon
  - ~20% of π^0 get absorbed
  - ~10% charge exchange ($\pi^0 \rightarrow \pi^{+,-}$)

- Single Pion Production

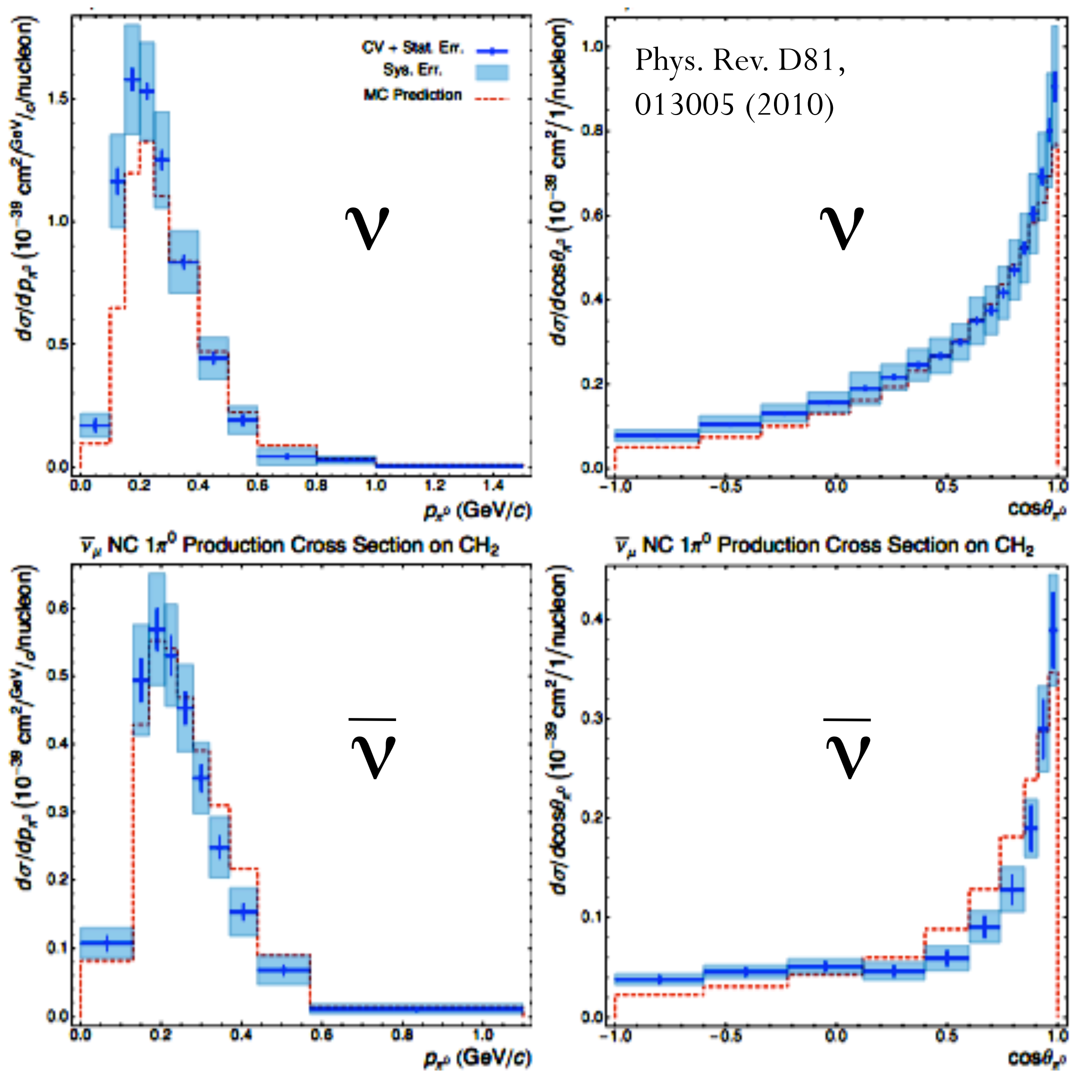
NC π^0 production

- Important new measurements from MiniBooNE including differential cross-sections now available

- On carbon at $<E_\nu> = 0.7$ GeV

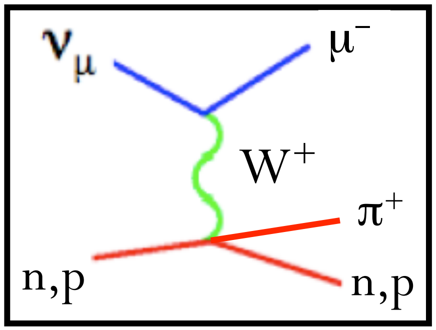
- Did not correct out nuclear effects

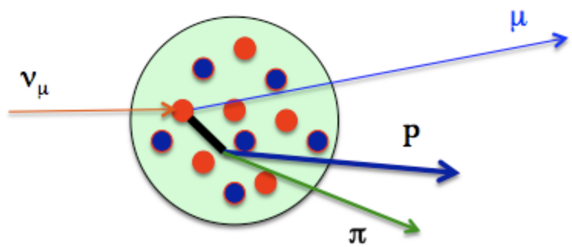
  * total NC π^0 production
  * NC π^0 after π^0 absorption
  * NC $\pi^{+/-} \rightarrow \pi^0$

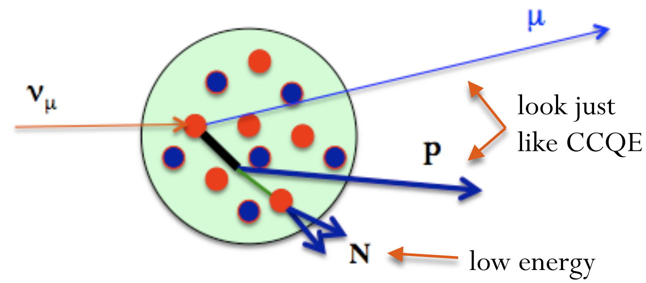


Single Pion Production

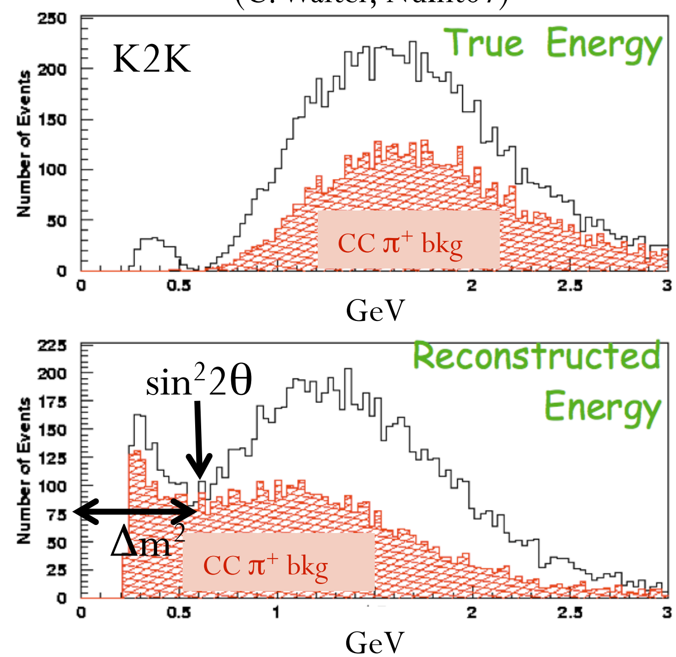
CC π^+ production





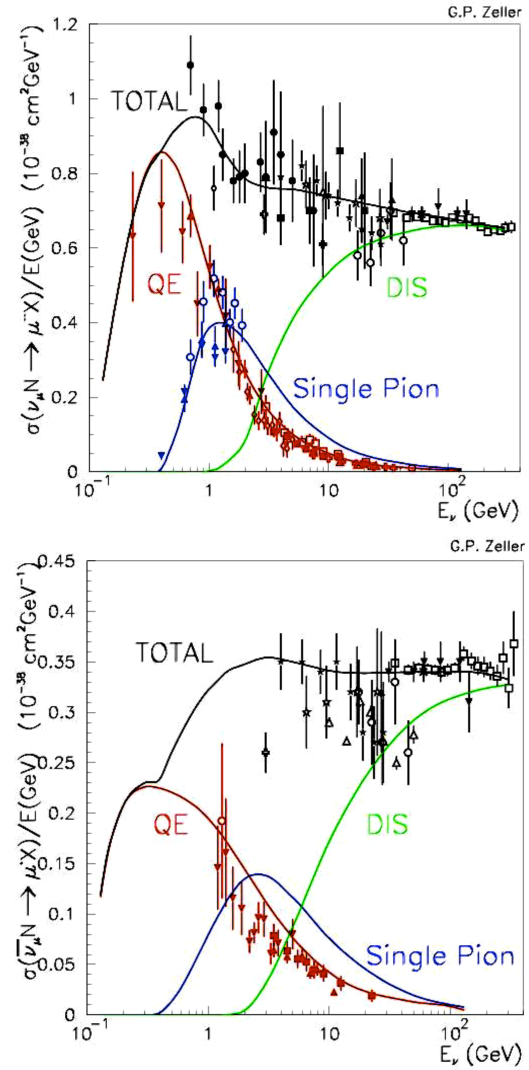


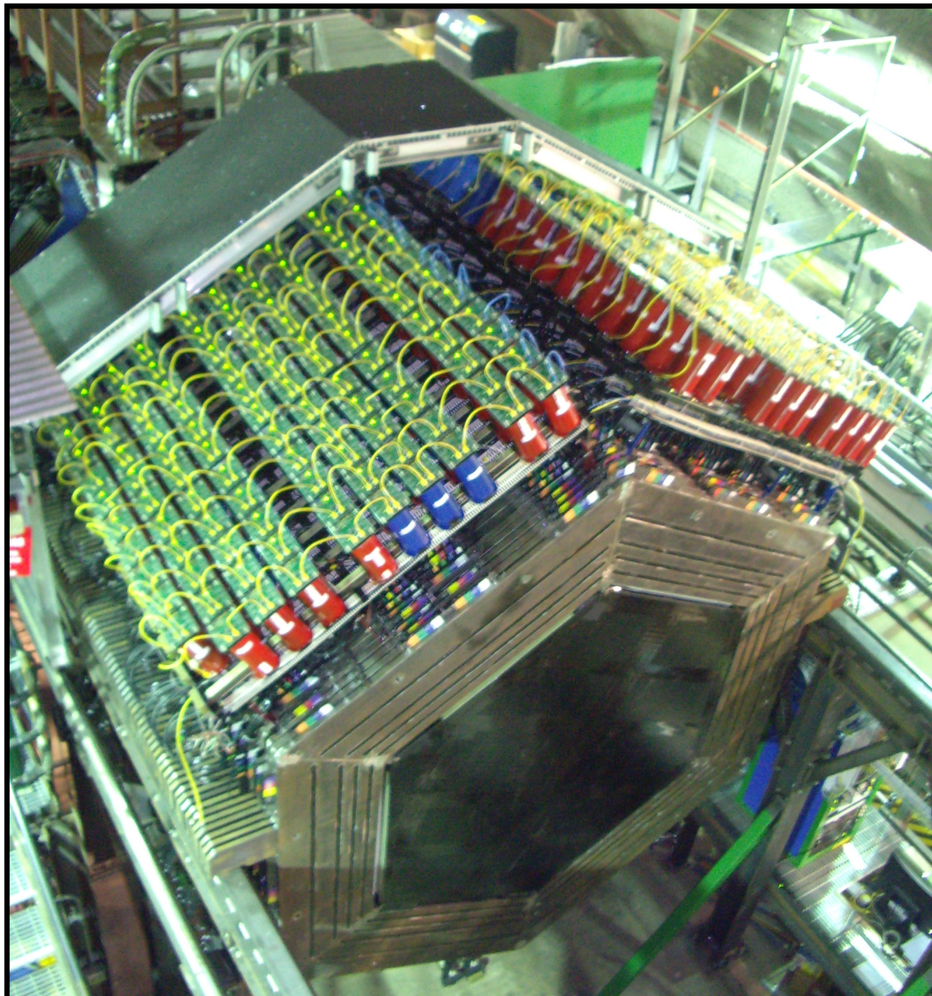
(C. Walter, NuInt07)

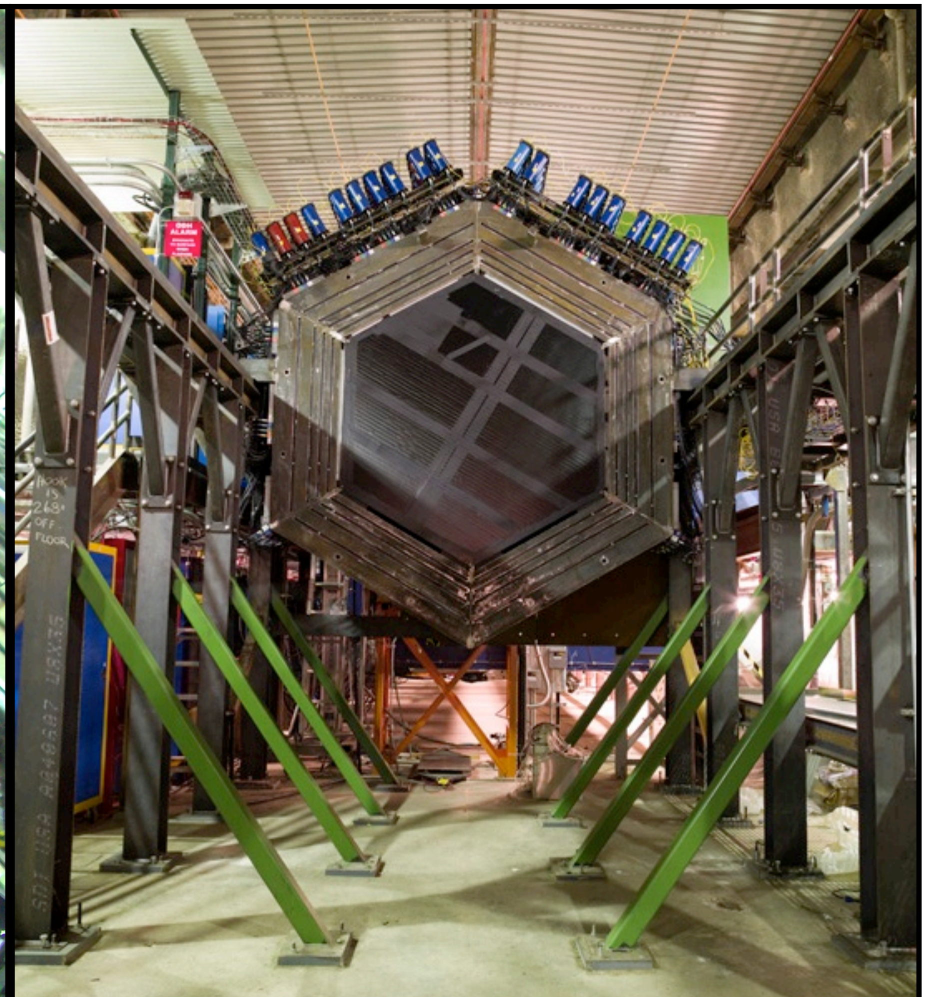


- Pion absorption creates irreducible bkgd to CCQE
- Pion re-interaction σ is large (30-40%) at these energies
- Pion absorption causes missing energy in event reconstruction – affects oscillation measurements
- **Nuclear effects strike again…**

- Have a need for improved measurements of both **neutrino and antineutrino cross-sections**
- But just as important is measuring **differential cross-sections** to map out kinematics of final states – to better predict oscillation signal backgrounds
- Require improved models of **nuclear effects**, particularly for nuclei used in neutrino detectors







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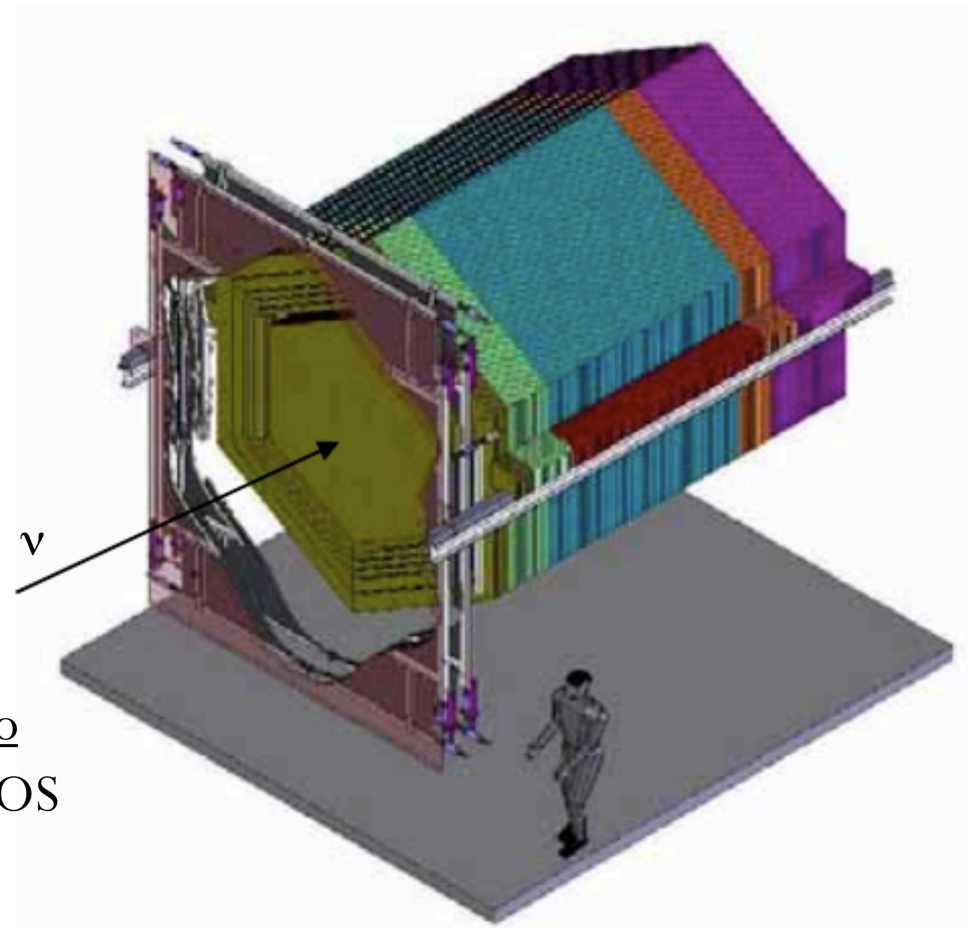
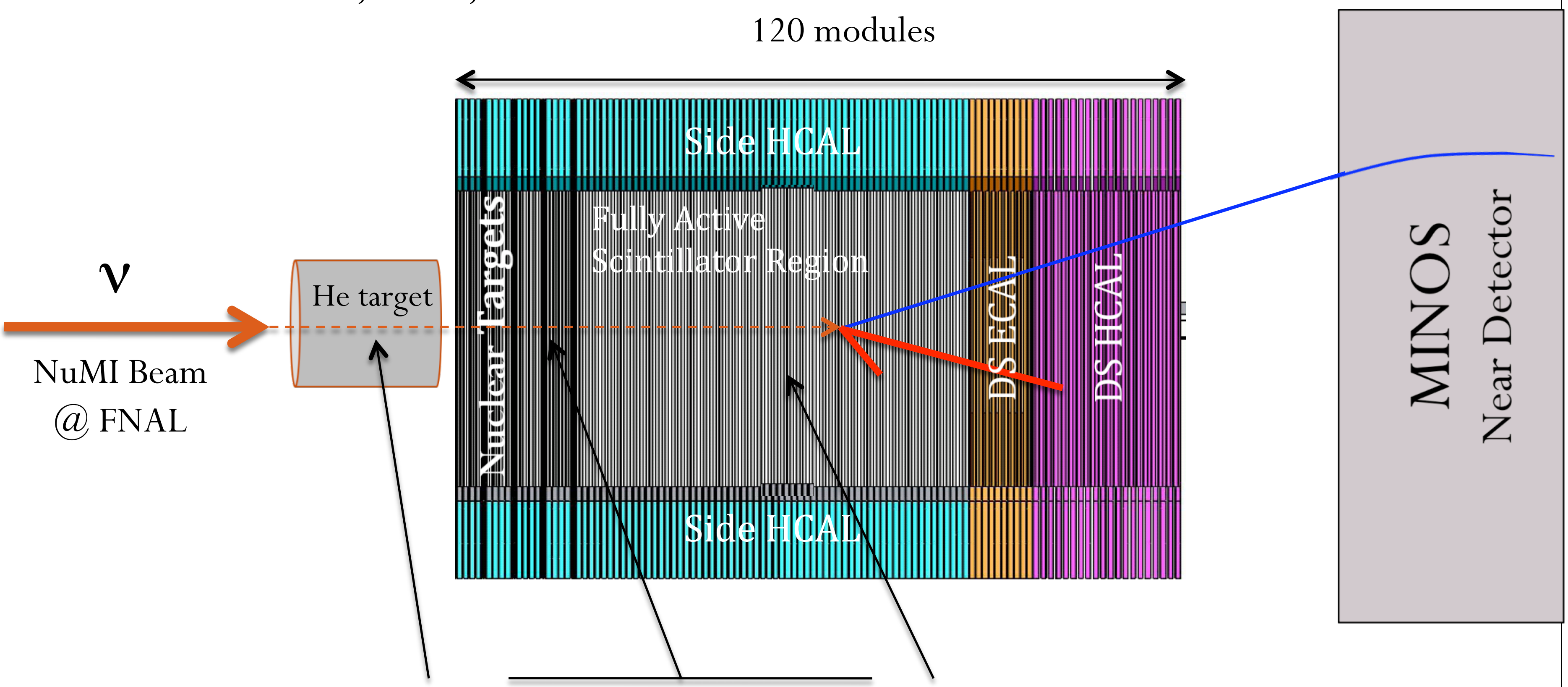
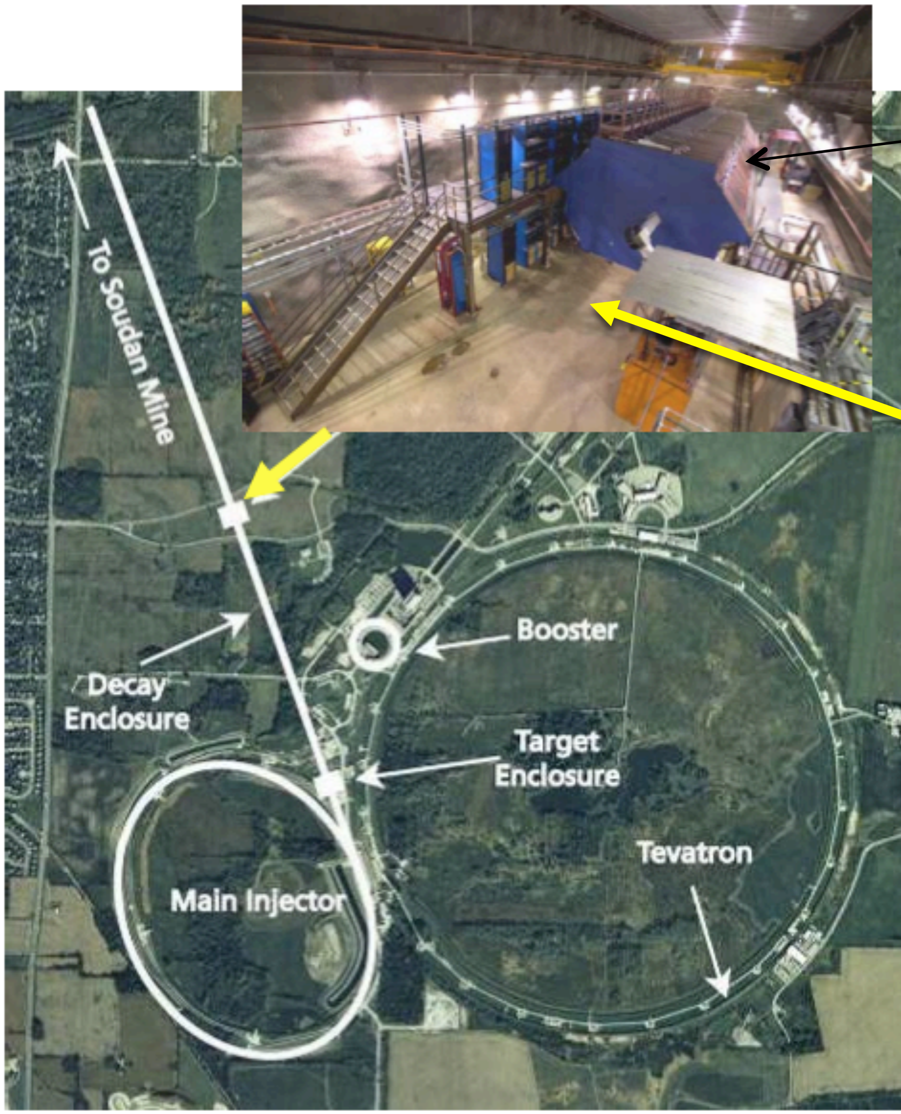
- MINERνA is a dedicated **neutrino-nucleus cross-section** experiment
  - Compact, fully-active detector design
  - Crucial input to future neutrino oscillation experiments
  - Single detector with multiple nuclear targets allows study of nuclear effects in neutino interactions
  - Neutrino interactions provide a unique probe of the nucleus
  - Makes use of the most intense neutrino beam in the world, NuMI, and the MINOS near detector at Fermilab



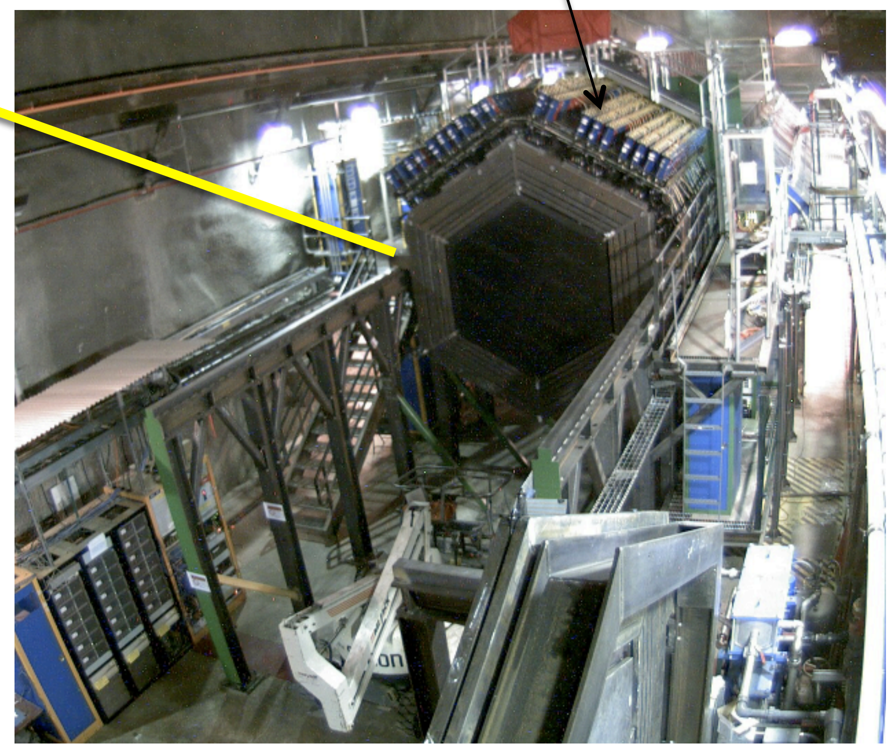
Finely segmented, fully active scintillator tracking region surrounded by ECAL and HCAL, >32,000 channels

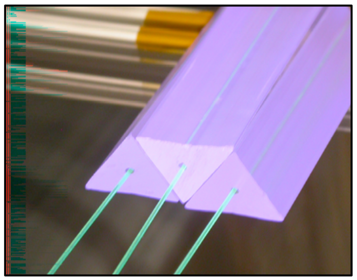


nuclear targets (He, C, Fe, Pb, H_2O, CH)



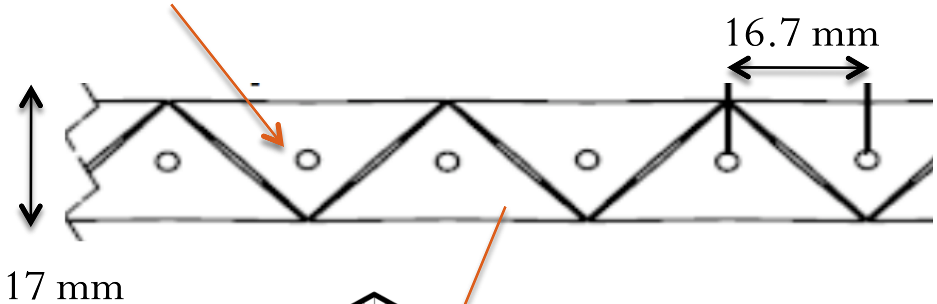
MINOS acts as a muon range detector for MINERνA

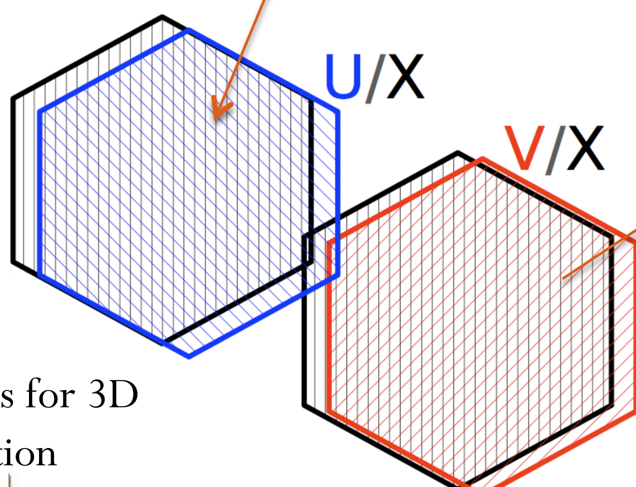




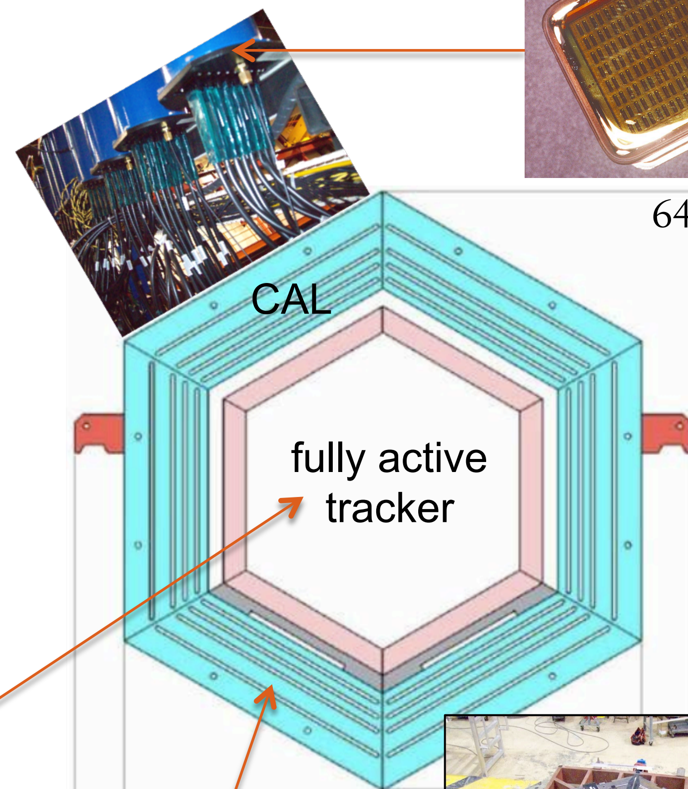
Extruded plastic scintillator
+ wavelength shifting fibers

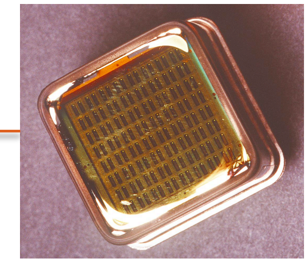
Triangular geometry allows charge sharing for better pos res.





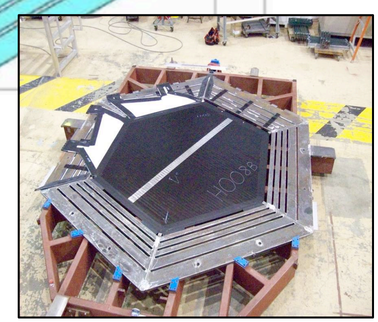
Three views for 3D reconstruction





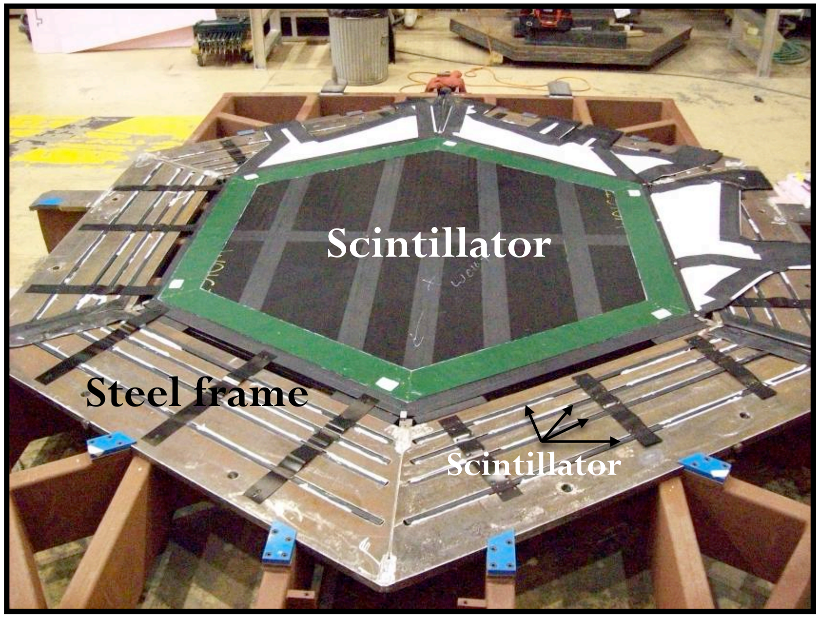
64 anode PMTs

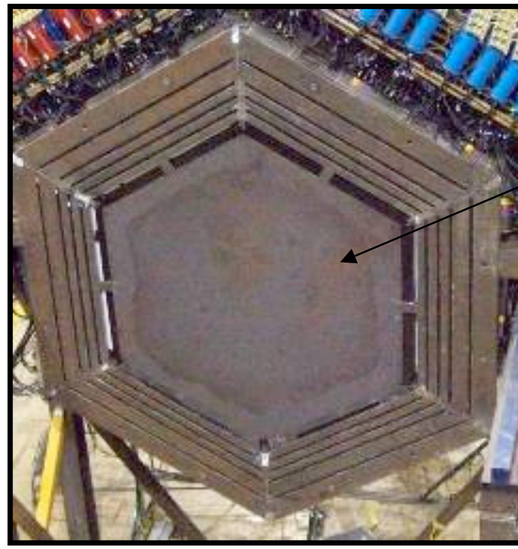
Iron outer detector instrumented for EM calorimetry



- 4 basic module types

Tracker modules have two planes of scintillator

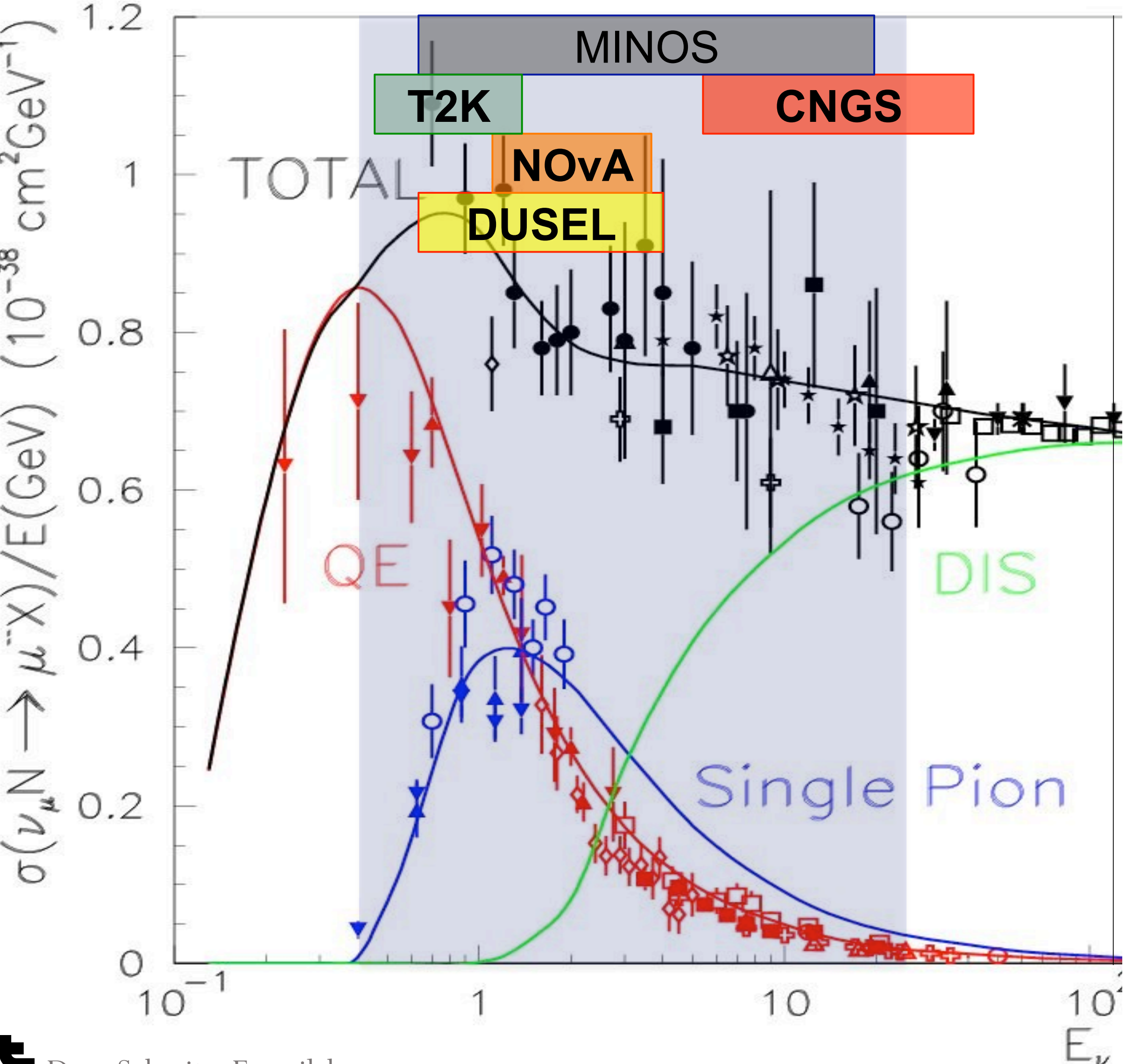


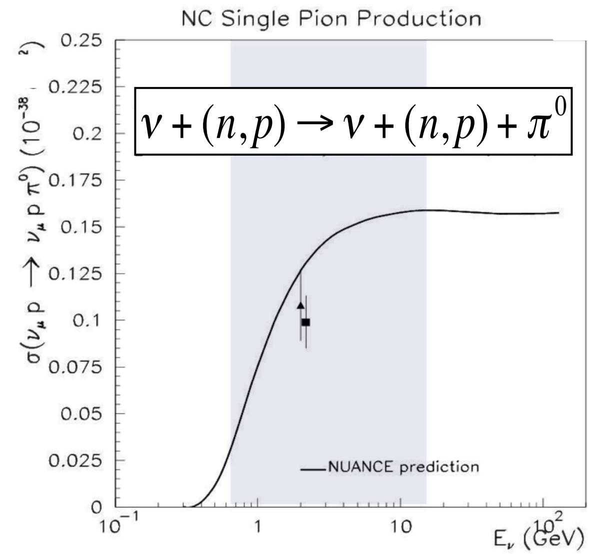


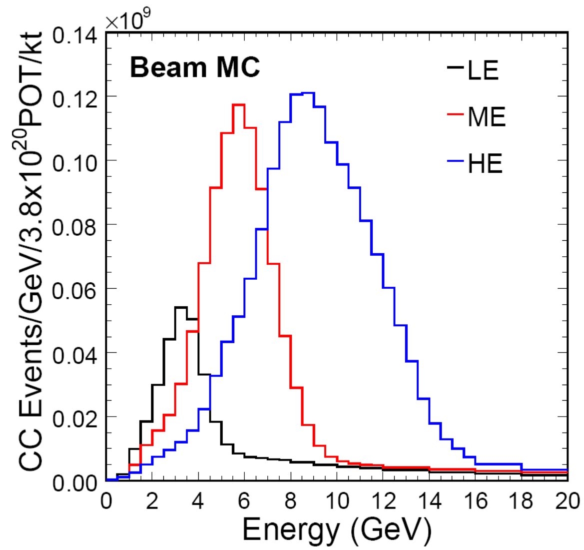
HCAL modules include 1" steel absorber and only one scint. plane

Nuclear Target modules have no central scintillator. Thin metal sheets welded inside outer steel frame.

ECAL modules incorporate 2x2mm Pb absorbers with 2 scint. planes


MINOS
T2K
CNGS
NOvA
DUSEL
TOTAL
QE
DIS
Single Pion
$\sigma(\nu_\mu N \rightarrow \mu^- X)/E(GeV)$ $(10^{-38}$ cm^{2}GeV$^{-1})$
E_ν


NC Single Pion Production
$\nu + (n,p) \rightarrow \nu + (n,p) + \pi^0$
NUANCE prediction
E_ν (GeV)

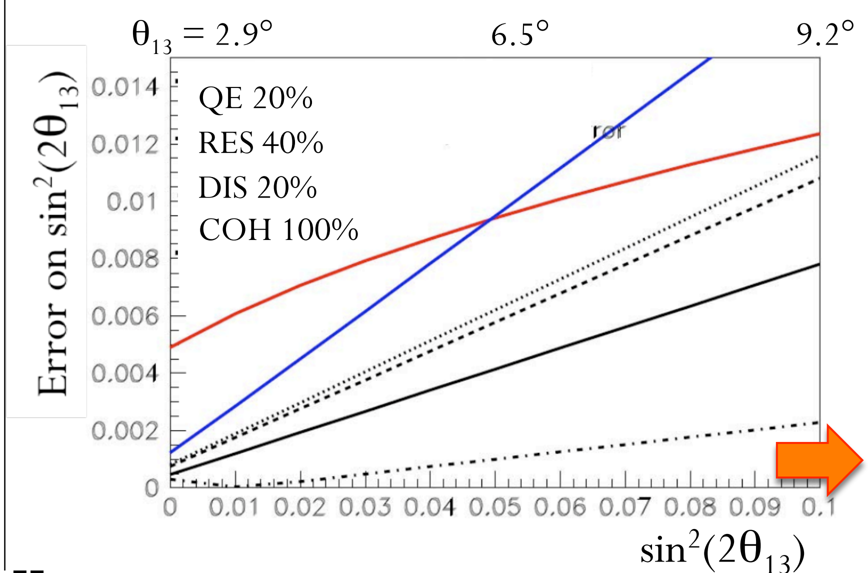

Beam MC
LE
ME
HE
CC Events/GeV/3.8x10^{20}POT/kt
Energy (GeV)

- NOvA $\sin^2\theta_{13}$ sensitivity
  - Toy MC study
  - Expected cross-section uncertainties after MINERvA make σ systematic negligible for all values of $\sin^2\theta_{13}$

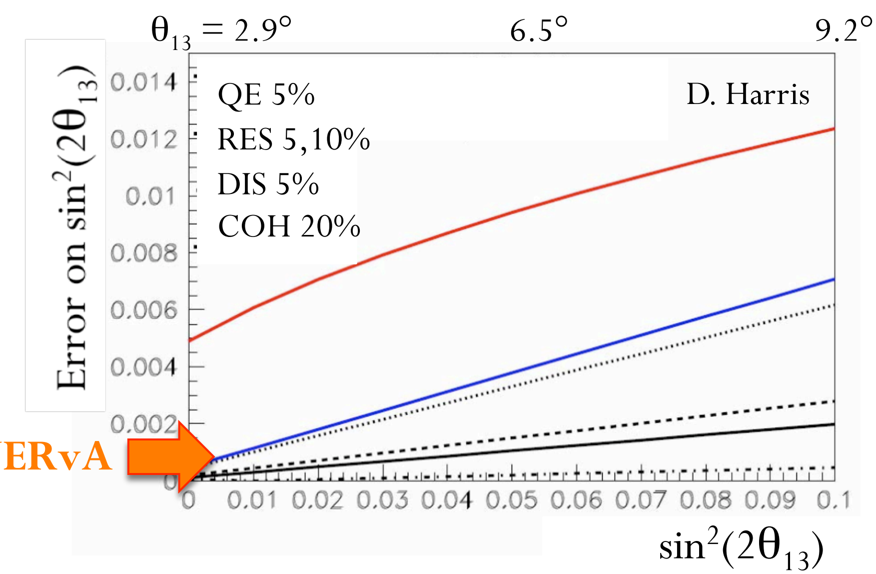
Process	Stats	QE	RES	DIS	COH
Signal ν_e	78 ($\sin^2\theta_{13}$=0.1)	50%	40%	1%	9%
NC	6.6	1%	10%	11%	78%
ν_μ CC	0.7	0%	7%	0%	93%
Beam ν_e	7.2	52%	37%	1%	10%

statistical error on a signal of that size

total systematic error from cross-section uncertainties of the given size

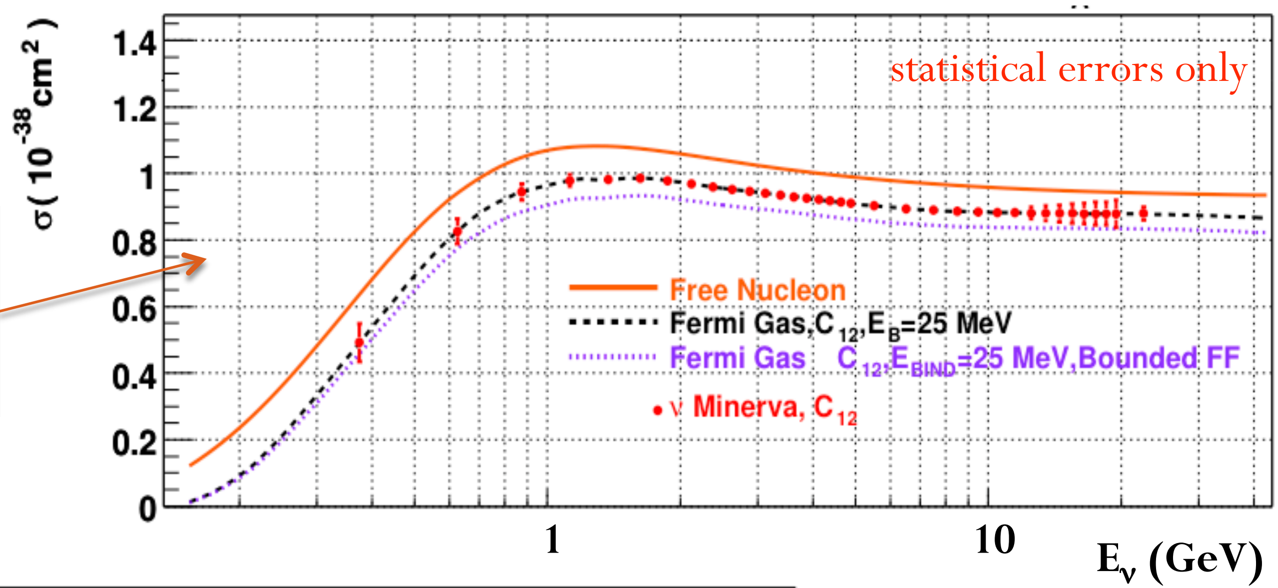


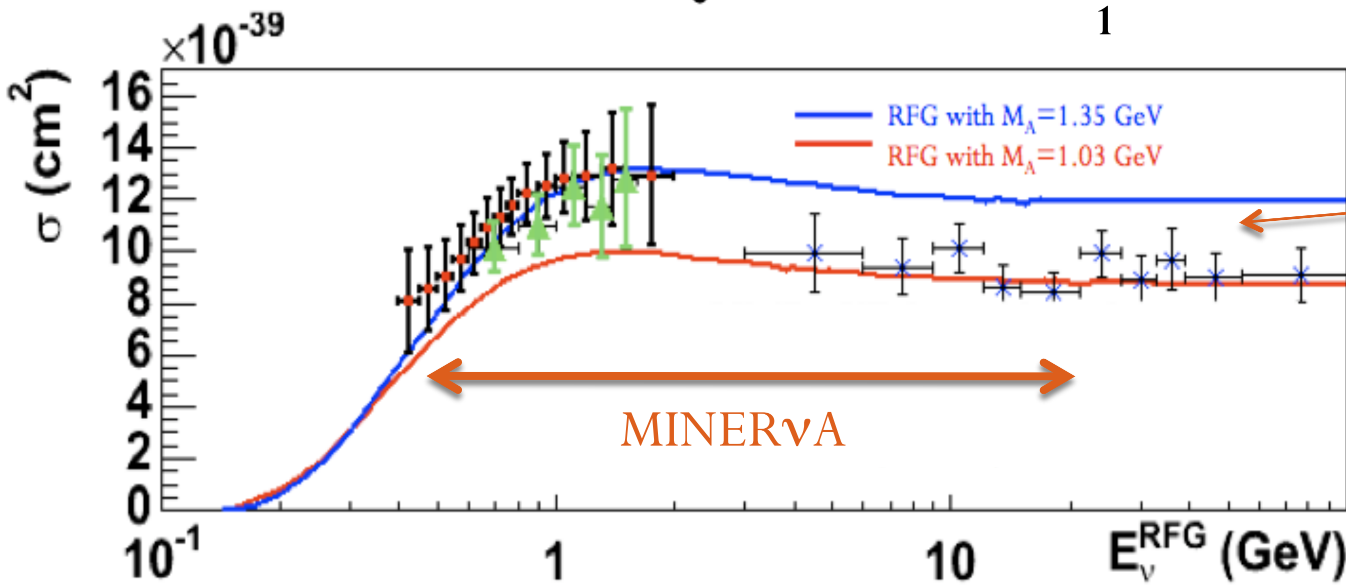
MINERvA



- CC Quasi-Elastic

Expected MINERνA CCQE results including efficiency estimates





MiniBooNE, SciBooNE, NOMAD CCQE data

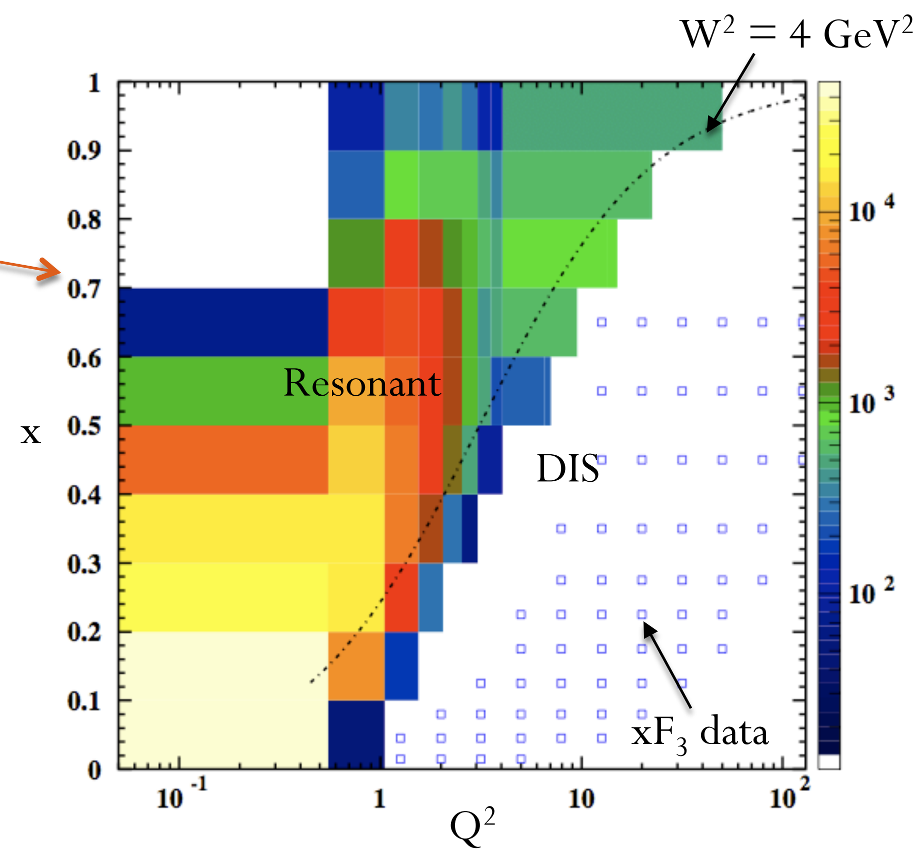
MINERνA should resolve this mystery!

- Deep Inelastic Scattering Physics: PDFs and Nuclear Effects
- The intense NuMI broad-band neutrino beam and the fine-grained high-resolution MINERvA detector provide an opportunity for a lot of physics beyond cross-sections for oscillations

- Expected numbers of events in (x,Q^2) for ~4 years of running in the Resonant → DIS transition region

- Study transition between perturbative and nonperturbative QCD regimes

- High statistics at high x



- Deep Inelastic Scattering Physics: PDFs and Nuclear Effects
- The intense NuMI broad-band neutrino beam and the fine-grained high-resolution MINERvA detector provide an opportunity for a lot of physics beyond cross-sections for oscillations

- Neutrino and antineutrino DIS data are **important for measuring fundamental Parton Distribution Functions within nucleons**

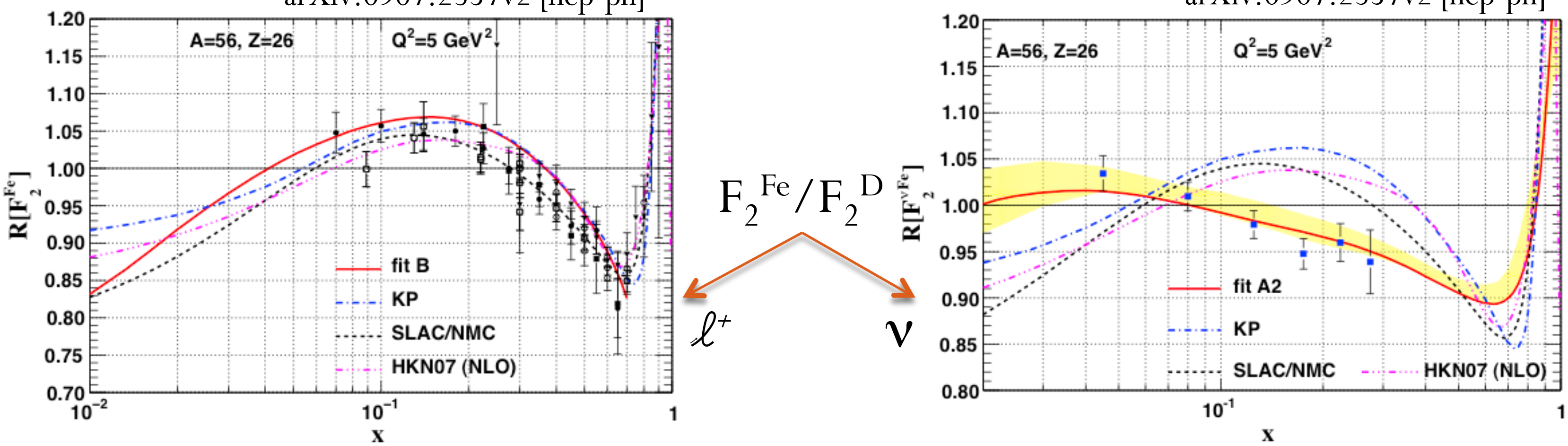
- Due to Weak current's unique ability to sample only particular quark flavors:
  - ν interacts with $d, s, \bar{u}, \bar{c}$
  - $\bar{\nu}$ interacts with $u, c, \bar{d}, \bar{s}$

- Ability to use high x data minimizes contributions from gluons and sea quarks, so one can sample d/u directly in $\nu/\bar{\nu}$ ratios

- Deep Inelastic Scattering Physics: PDFs and Nuclear Effects
- The intense NuMI broad-band neutrino beam and the fine-grained high-resolution MINERvA detector provide an opportunity for a lot of physics beyond cross-sections for oscillations

- Inclusion of neutrino **scattering data on heavy nuclei** in QCD measurements is challenged by significant nuclear effects
- Recent studies indicate that nuclear corrections in ℓ^{+}-A (charged lepton) and ν-A (neutrino) scattering may not be the same

arXiv:0907.2357v2 [hep-ph] | arXiv:0907.2357v2 [hep-ph]



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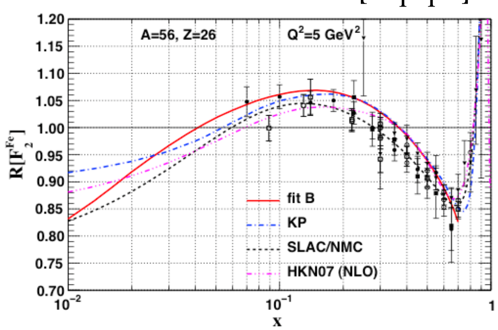
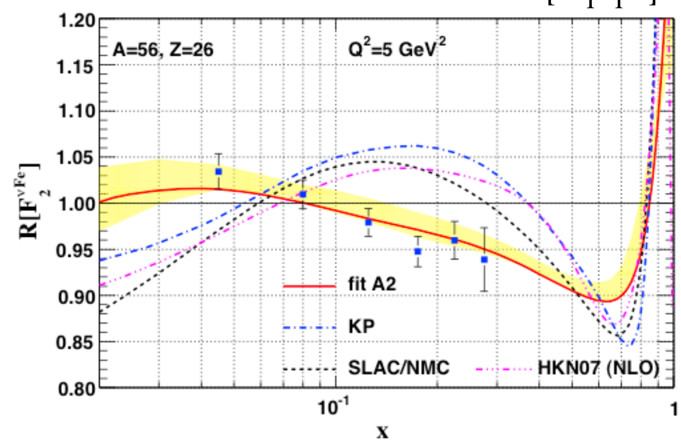


F_2^A/F_2^D : Observable	Experiment	Ref.	# data
D	NMC-97	[31]	275
He/D	SLAC-E139	[18]	18
	NMC-95,re	[32]	16
	Hermes	[33]	92
Li/D	NMC-95	[34]	15
Be/D	SLAC-E139	[18]	17
C/D	EMC-88	[35]	9
	EMC-90	[36]	2
	SLAC-E139	[18]	7
	NMC-95,re	[32]	16
	NMC-95	[34]	15
	FNAL-E665-95	[37]	4
N/D	BCDMS-85	[19]	9
	Hermes	[33]	92
Al/D	SLAC-E049	[38]	18
	SLAC-E139	[18]	17
Ca/D	EMC-90	[36]	2
	SLAC-E139	[18]	7
	NMC-95,re	[32]	15
	FNAL-E665-95	[37]	4
Fe/D	BCDMS-85	[19]	6
	BCDMS-87	[20]	10
	SLAC-E049	[21]	14
	SLAC-E139	[18]	23
	SLAC-E140	[22]	6
Cu/D	EMC-88	[35]	9
	EMC-93(addendum)	[39]	10
	EMC-93(chariot)	[39]	9
Kr/D	Hermes	[33]	84
Ag/D	SLAC-E139	[18]	7
Sn/D	EMC-88	[35]	8
Xe/D	FNAL-E665-92(em cut)	[40]	4
Au/D	SLAC-E139	[18]	18
Pb/D	FNAL-E665-95	[37]	4
Total:			862

- Combined many charged lepton data sets on many different nuclei
- Added **A**-dependent terms to the parameterization to include effects within model

arXiv:0907.2357v2 [hep-ph]



- Only NuTeV iron neutrino data
- Would like to use a similar table of data to properly compare charged and neutral lepton data

- Deep Inelastic Scattering Physics: PDFs and Nuclear Effects

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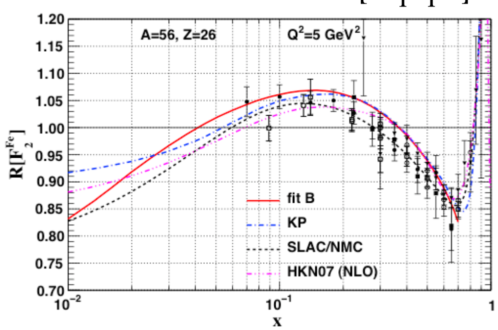

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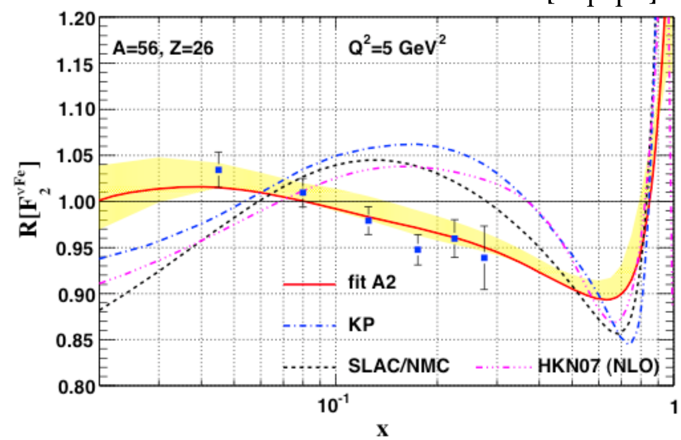
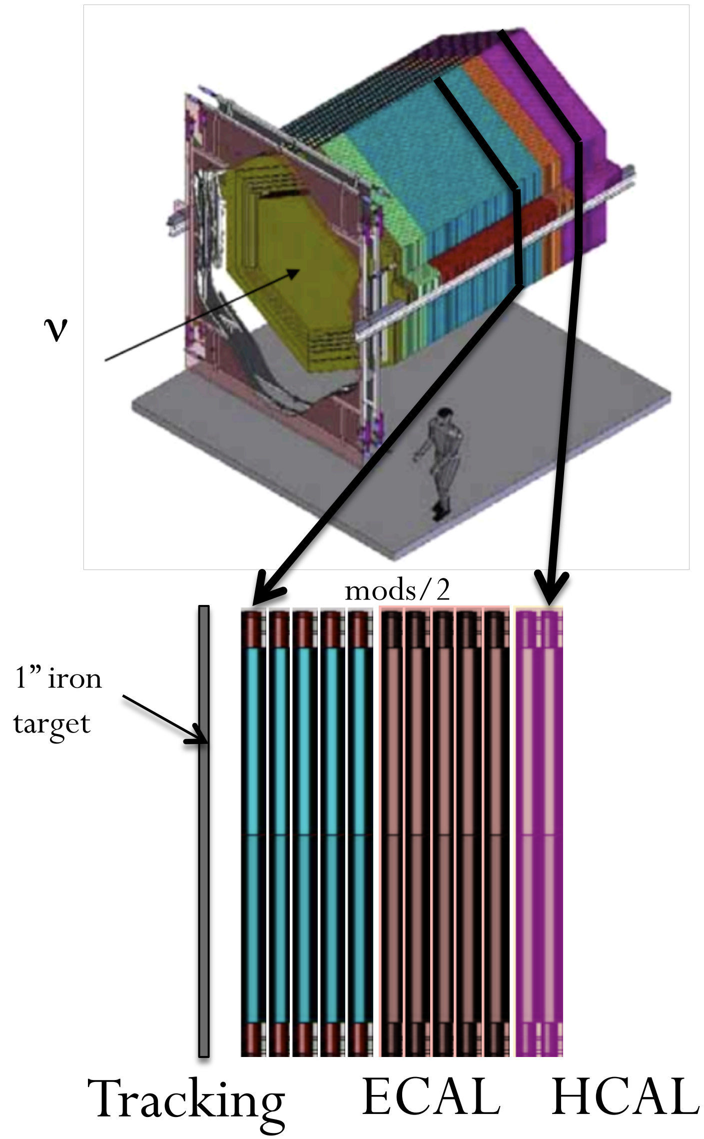
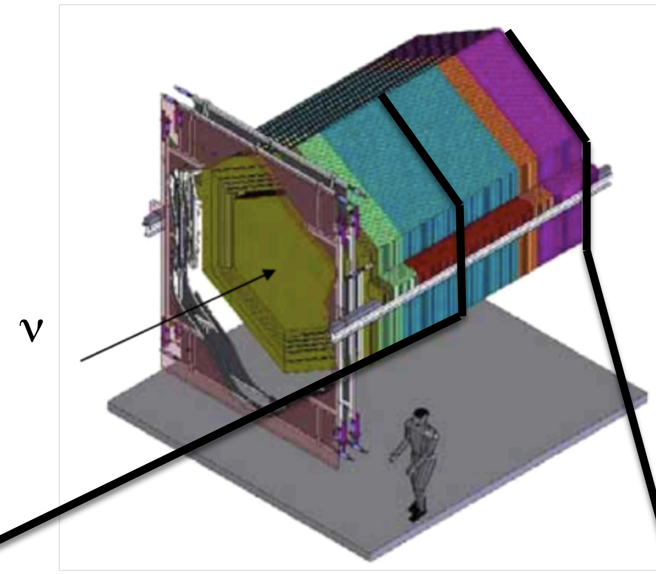


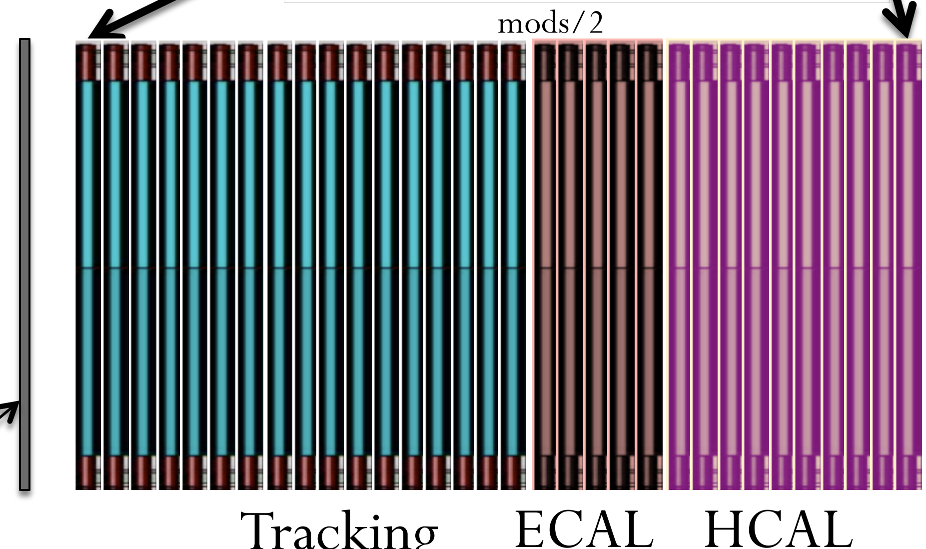
- Only NuTeV iron neutrino data
- Would like to use a similar table of data to properly compare charged and neutral lepton data
- MINERvA provides **<u>He, C, Fe, Pb</u>**

- MINERvA Prototype
  - Installed **24 modules** in NuMI **neutrino beam** for two month prototype run (April-June, 2009)



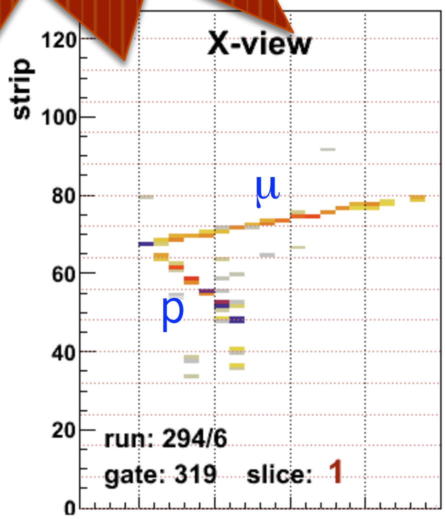
- MINERvA Prototype
  - Installed **24 modules** in NuMI **neutrino beam** for two month prototype run (April-June, 2009)
- MINERvA "Frozen" Detector
  - Removed Prototype modules and started installation of final detector during 2009 summer accelerator shutdown
  - Installed **64 modules**
    34 tracking+10 ECAL+20 HCAL
  - Froze detector installation on November 12 to collect NuMI **antineutrino beam data**
  - One nuclear target module (Fe, Pb) included for 2 mo.



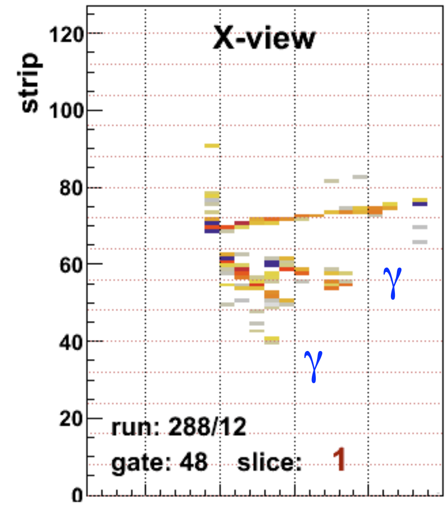


MINERvA Prototype neutrino data

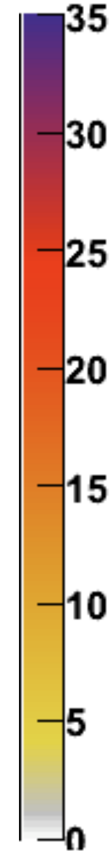
ν_μ CCQE candidate event



ν_μ CC π^0 candidate event

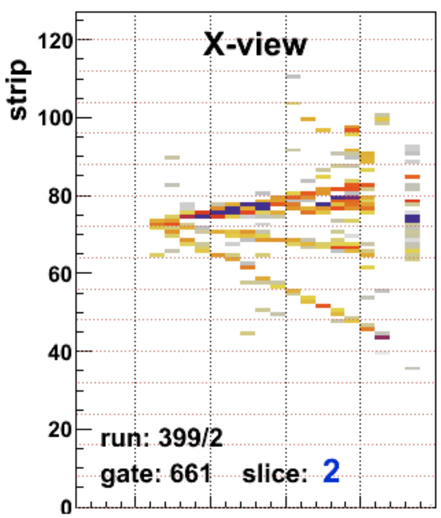


p.e. scale

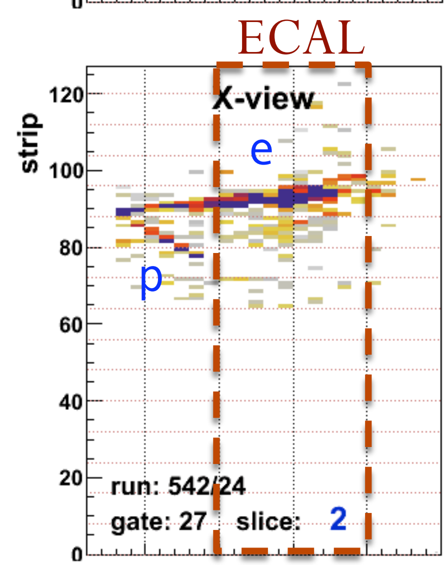


NuMI Beam

DIS candidate event

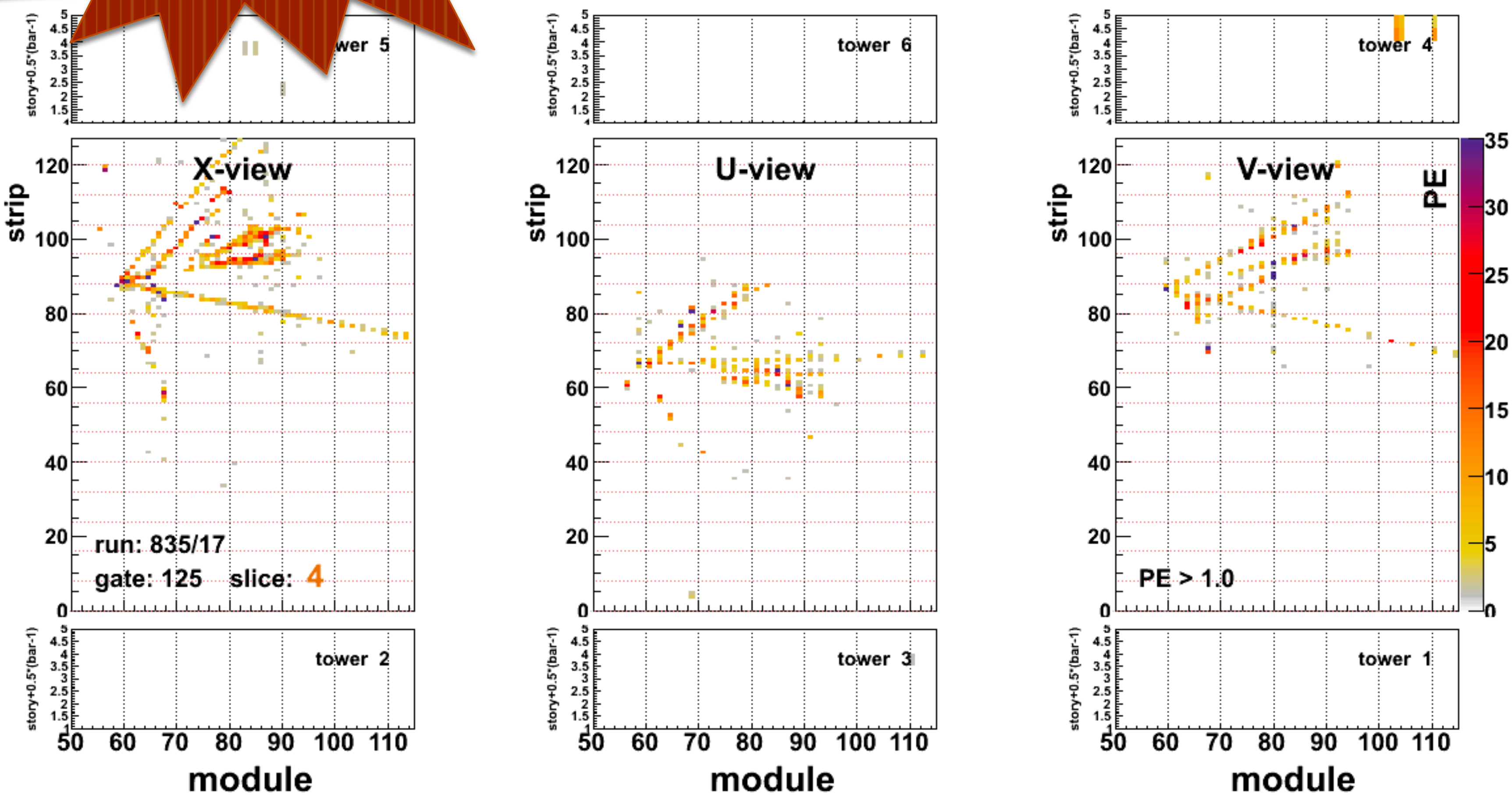


ν_e CCQE candidate event



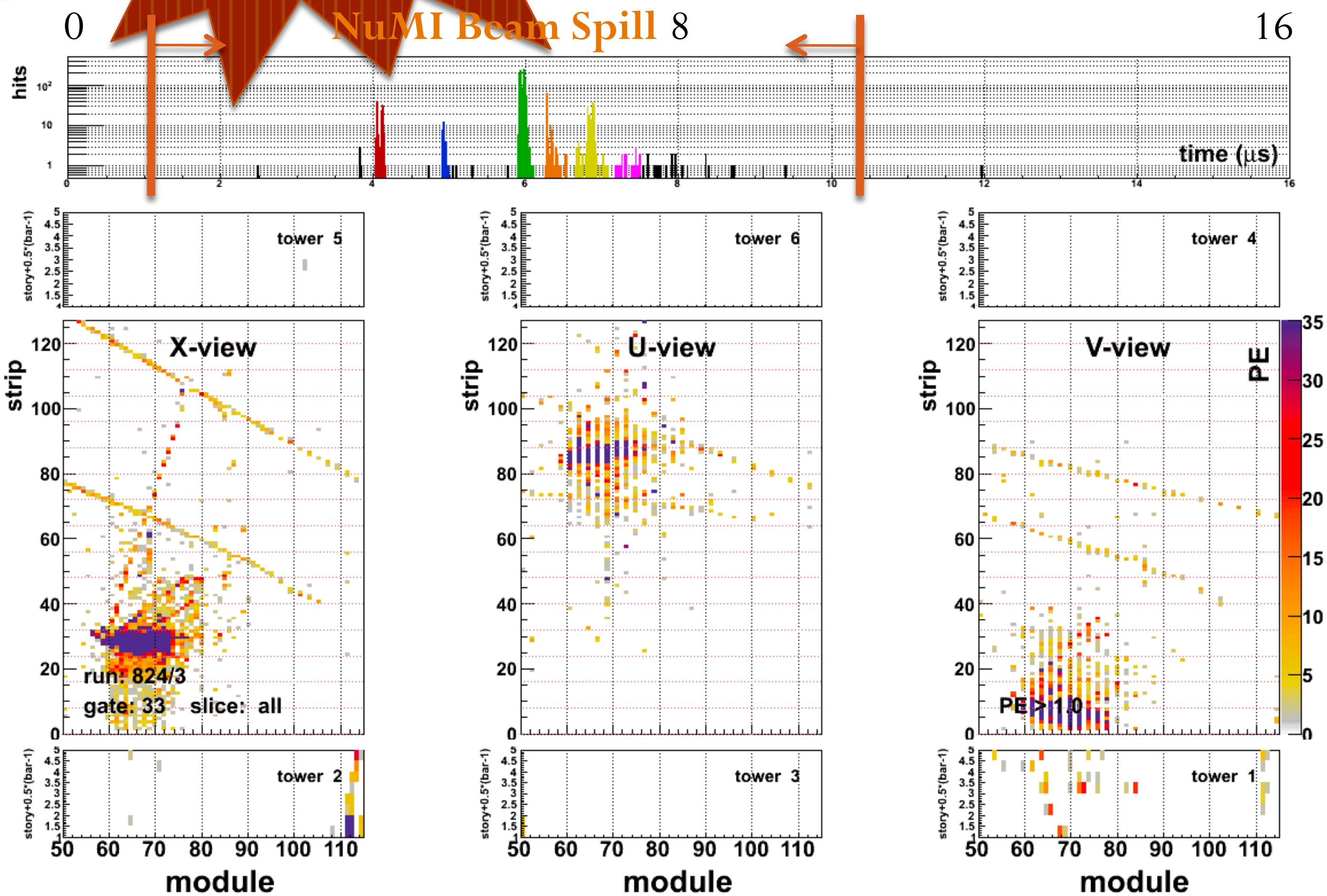
MINOS

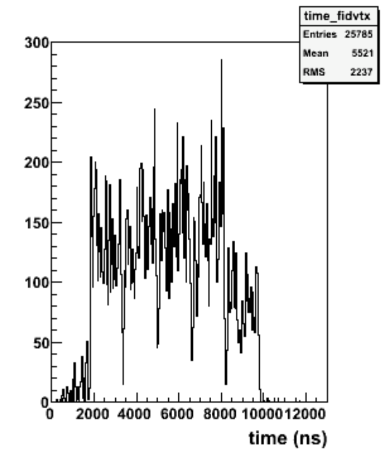
Frozen Detector antineutrino data



Good visibility of tracks in multiple particle final states and secondary interactions.
Will be a lot of fun (and a challenge) to reconstruct!

Frozen Detector antineutrino data



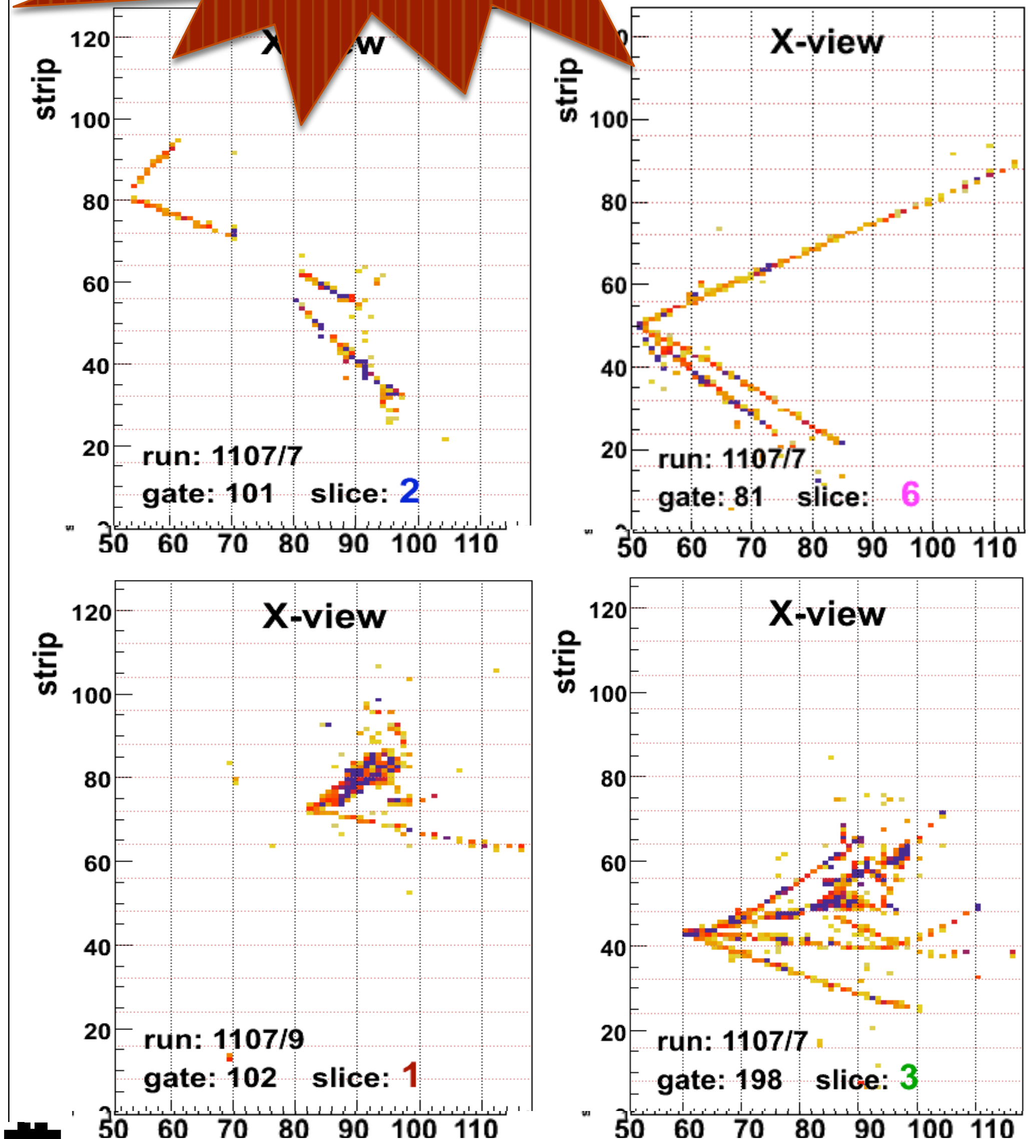


NuMI Beam Spill

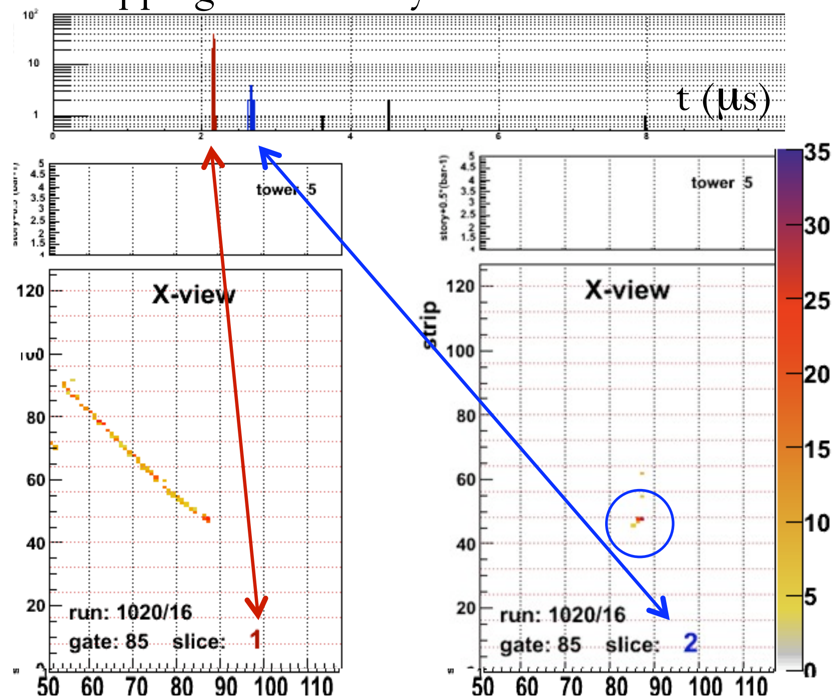
10 µs spill structure every 2.2 seconds from the FNAL Main Injector

NuMI Beam is very intense. Lots of overlapping activity within a beam spill.

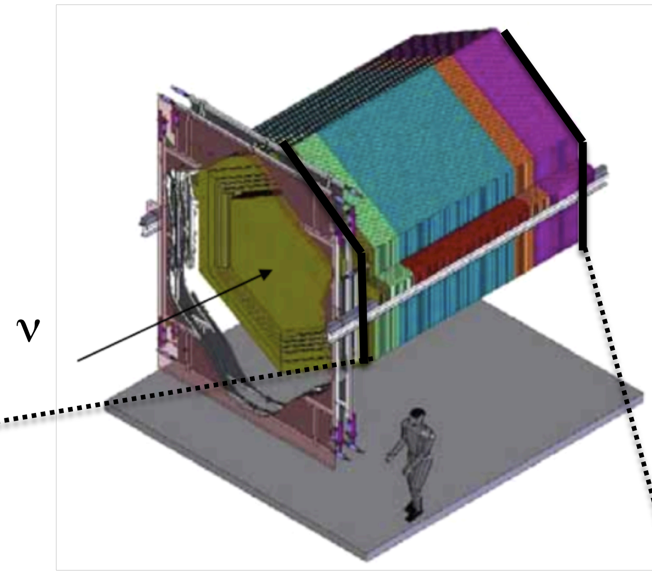
Frozen Detector antineutrino data

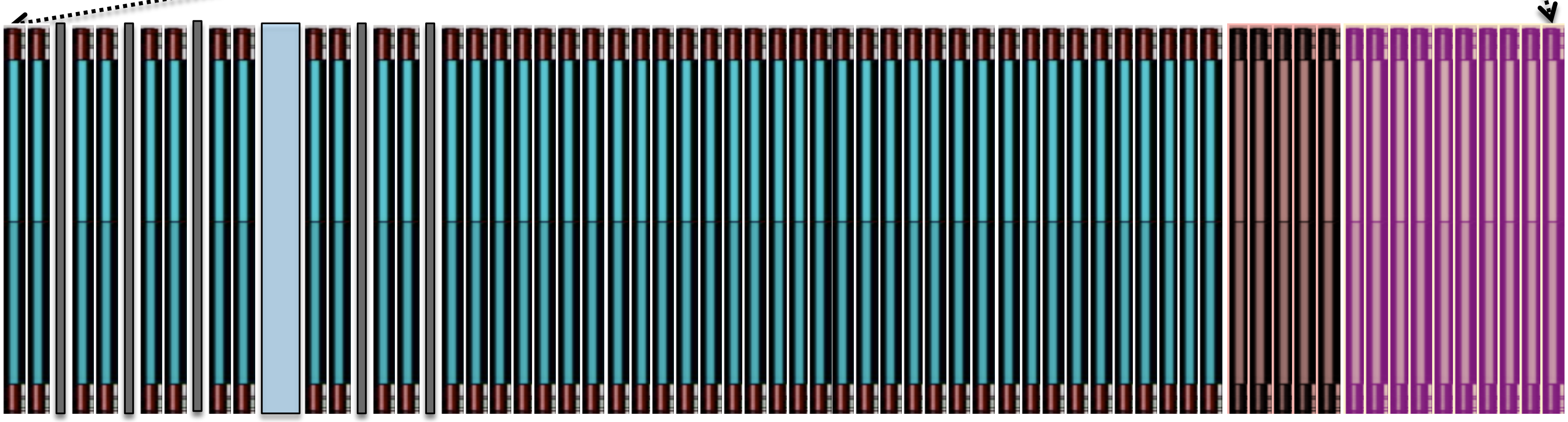


stopping muon decays to Michel electron



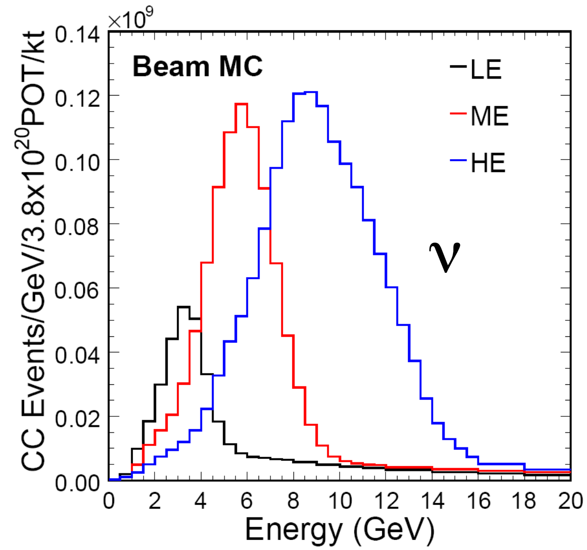
- MINERνA
  - Final installation phase began first week of January
  - **<u>Installation complete by mid-March, 2010!!</u>**
  - Continue to integrate antineutrino data with downstream half of detetor
  - NuMI switches back to **neutrino mode** once installation is complete





- Current Run Plan, beginning in March 2010
  - 4e20 POT low energy beam (3/10 – 3/12)
  - 12e20 POT medium energy beam in NOνA era (ν and $\bar{\nu}$)

Quasi-elastic	**0.8 M**
Resonance production	**1.7 M**
Resonance to DIS transition	**2.1 M**
DIS, structure functions, high-x PDFs	**4.3 M**
Coherent pion production	**89k CC, 44k NC**
charm/strange production	**230 k**
He target	**0.6 M**
C target	**0.4 M**
Fe target	**2.0 M**
Pb target	**2.5 M**



Nuclear Target	Fid .Vol.
CH	3.0t
He	0.2t
C	0.15t
Fe	0.7t
Pb	0.85t

- Lots of new interest and results in neutrino cross-sections in recent years
  - Absolute cross-sections
  - Differential cross-sections
  - Untangling nuclear effects
- Important to get improved measurements
  - Intellectually challenging and interesting
  - Important for the next generation of precision neutrino physics experiments
  - Intense NuMI beam and fine-grained detector opens door to lots of high/low Q^2 and high/low x physics
- The MINERνA experiment at Fermilab will go a long way towards finding many answers starting very soon!

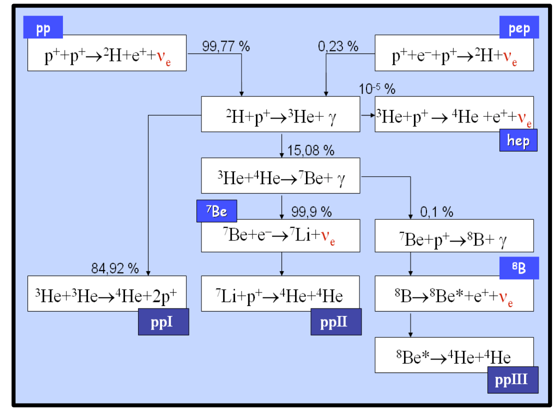
Thank you

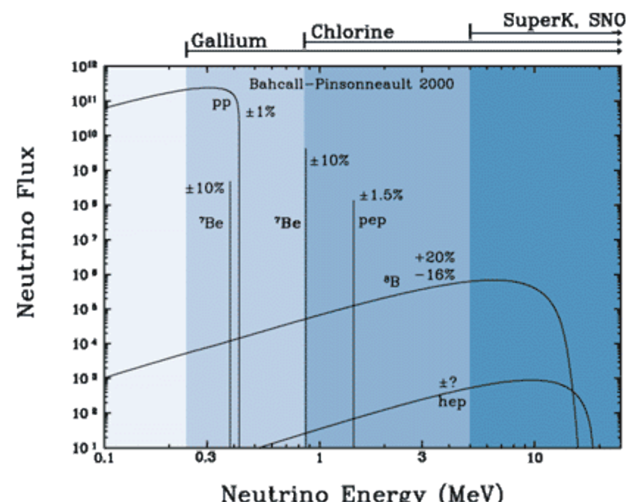
Extras

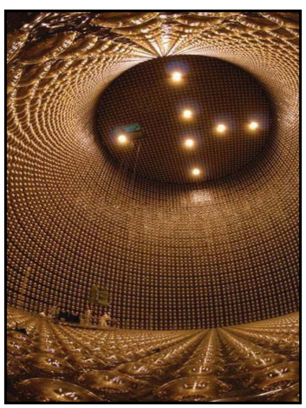
Δm^2_{12}

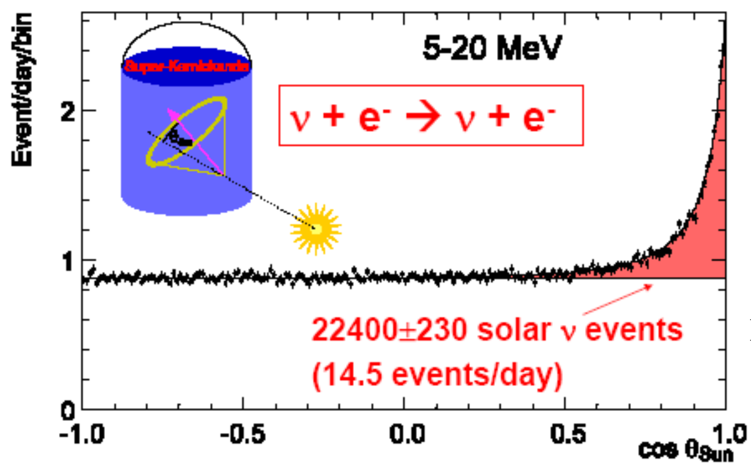
- First experimental evidence came from electron neutrinos from the sun
  - original goal was to demonstrate fusion in the sun, but much fewer than the expected number of ν_e's were detected

Super-K ν_e seen / ν_e expected: $0.451^{+0.017}_{-0.015}$









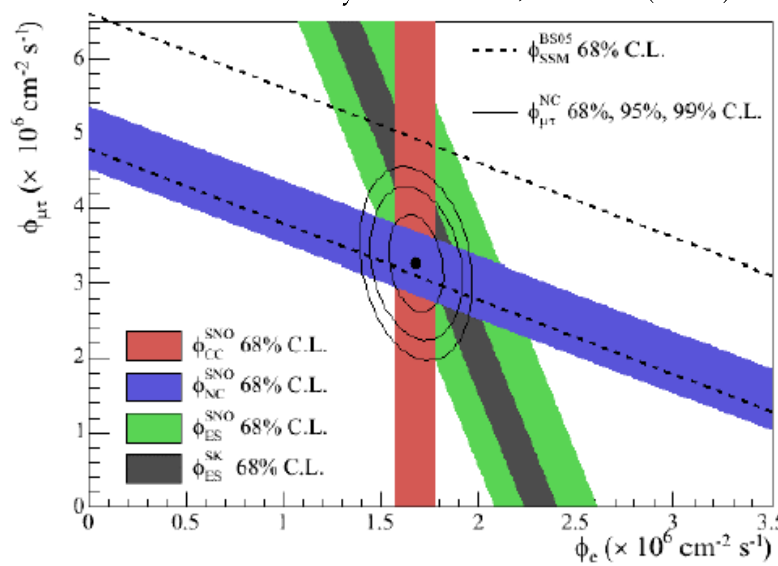
Phys. Rev. D 73, 112011 (2006)

Δm^2_{12}

- First experimental evidence came from electron neutrinos from the sun
- Confirmation of the oscillation hypothesis came from **SNO** which could see all neutrino types

$$\nu_e + d \rightarrow p + p + e^- \quad (CC)$$
$$\nu_x + d \rightarrow p + n + \nu_x \quad (NC)$$
$$\nu_x + e^- \rightarrow \nu_x + e^- \quad (ES)$$

Phys. Rev. C 72, 055502 (2005)



$$\phi_e = 1.76^{+0.05}_{-0.05}(\text{stat.})^{+0.09}_{-0.09}\ (\text{syst.})$$
$$\phi_{\mu\tau} = 3.41^{+0.45}_{-0.45}(\text{stat.})^{+0.48}_{-0.45}\ (\text{syst.})$$

- Total rate matched expectation from solar model, but only 1/3 were electron neutrinos.
  But the sun only makes electron neutrinos!!

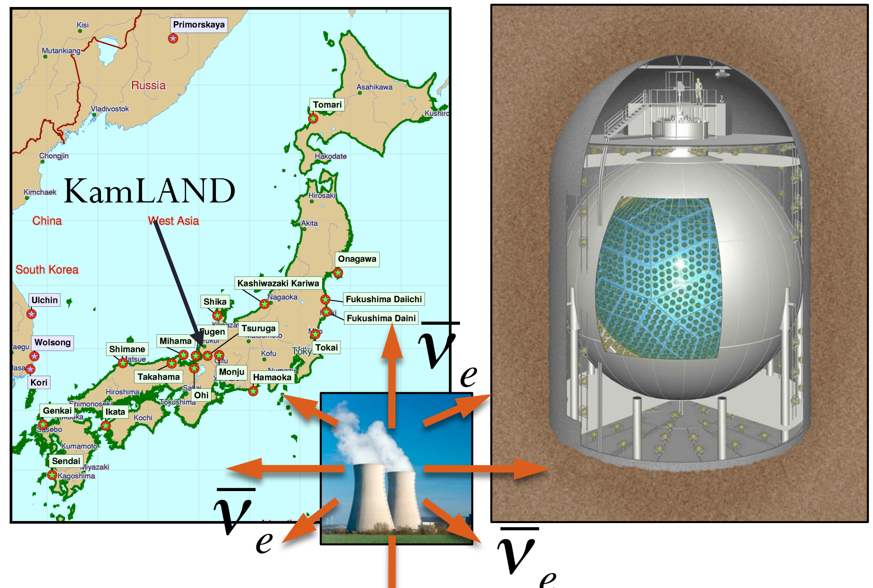
Δm^2_{12}

- First experimental evidence came from electron neutrinos from the sun
- And precision measurements of Δm^2_{12} and θ_{12} came from **KamLAND** in Japan using anti-neutrinos produced by power reactors

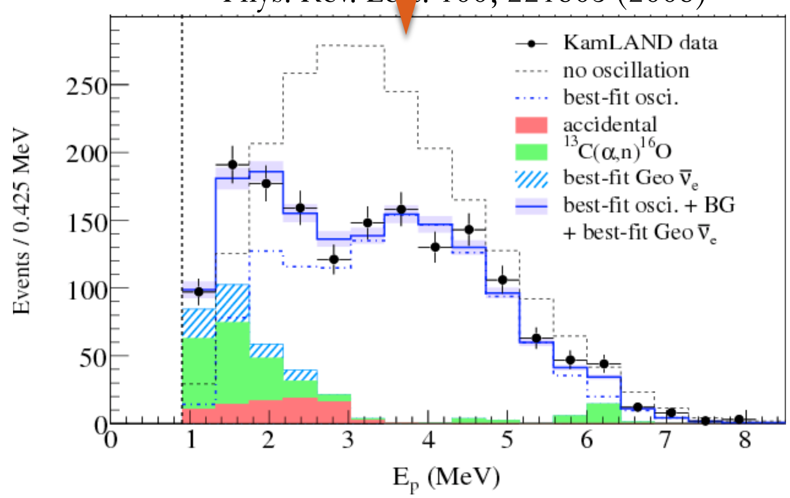
$$\langle E \rangle_{KamLAND} \approx 5\,MeV$$
$$\langle L \rangle_{KamLAND} \approx 180\,km$$

$$for\ \ \sin^2(x) \sim 1$$

$$\Delta m^2 \geq 1 / \left(1.27 * \frac{180\,km}{0.005\,GeV}\right) \sim 10^{-5}\,eV^2$$



Phys. Rev. Lett. 100, 221803 (2008)



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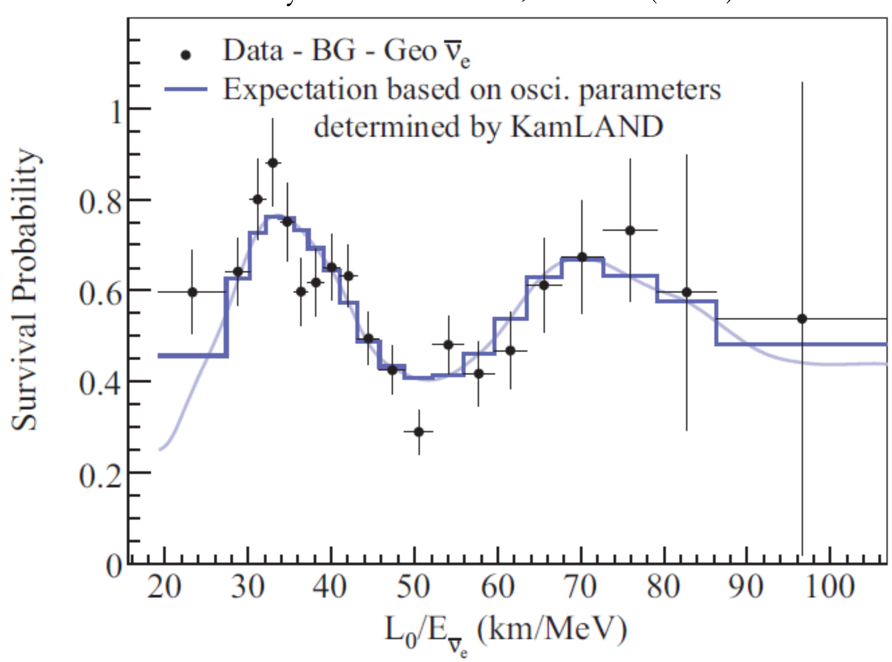
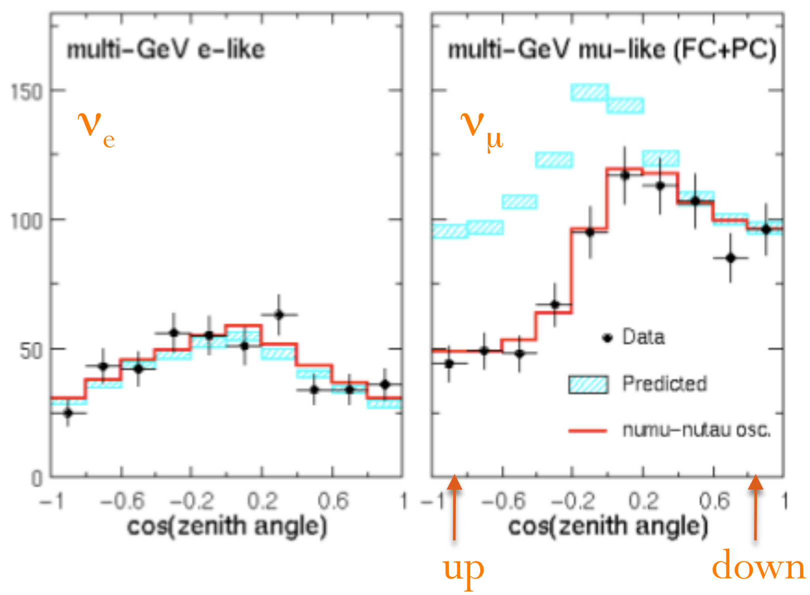
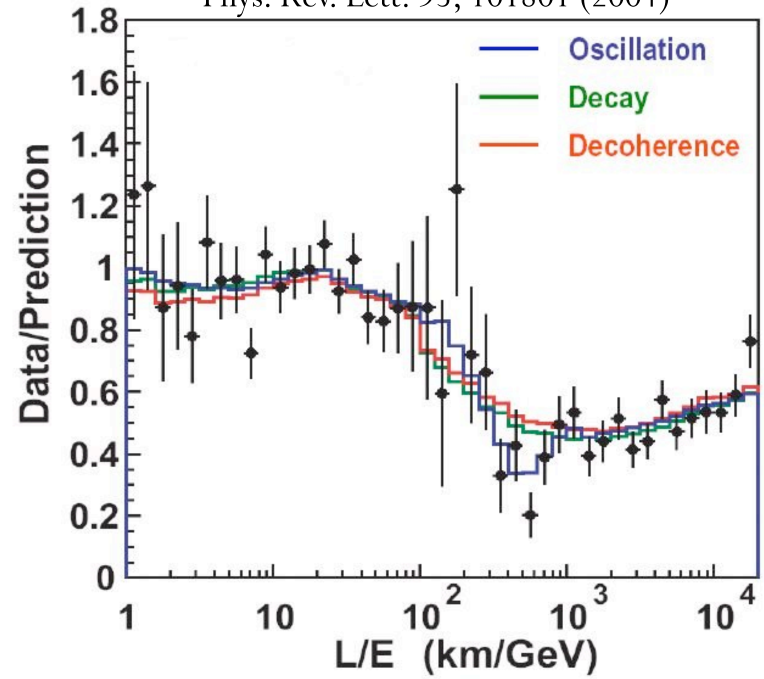


Δm^2_{23}

- First experimental evidence came from neutrinos produced in the atmosphere by cosmic rays
- Again **Super-K** makes a pivotal contribution



Phys. Rev. Lett. 93, 101801 (2004)



$$R = \frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e} \approx 2$$

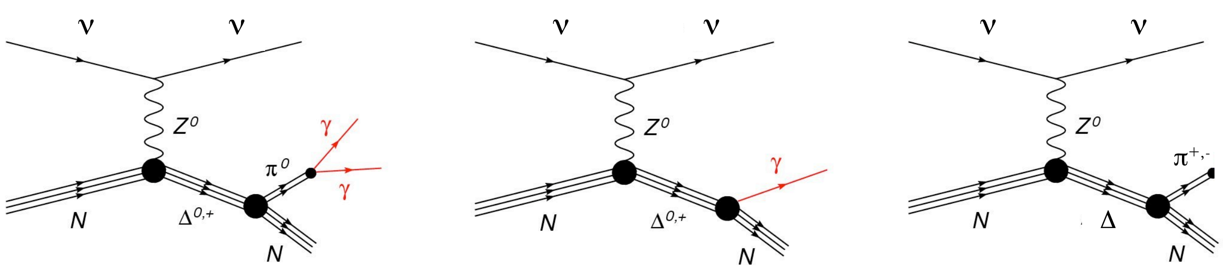
$$\langle E \rangle_{Super-K} \approx 1 - 10\ GeV$$

$$\langle L \rangle_{Super-K} \approx 10 - 10^4\ km$$

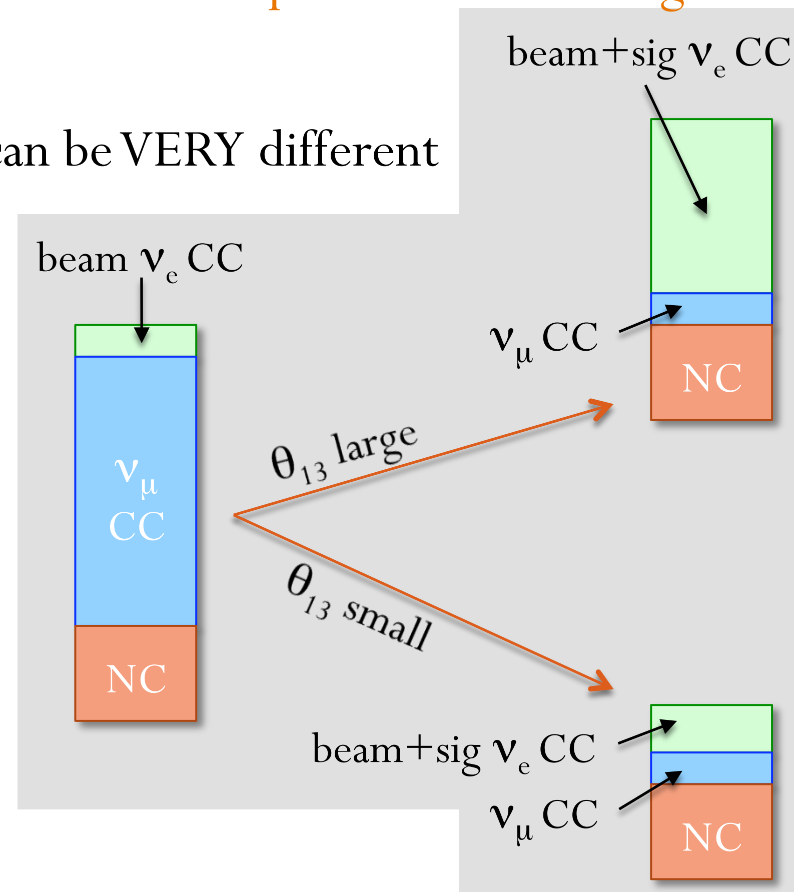
$$\Delta m^2 \sim 10^{-4} - 1\, eV^2$$

- **Why the search for θ_{13} and δ^{CP} is a paradigm shift in long-baseline accelerator-based neutrino oscillation experiments**
- So, one just wants to sample the neutrino flavor content near the beam source and again at a distant detector location

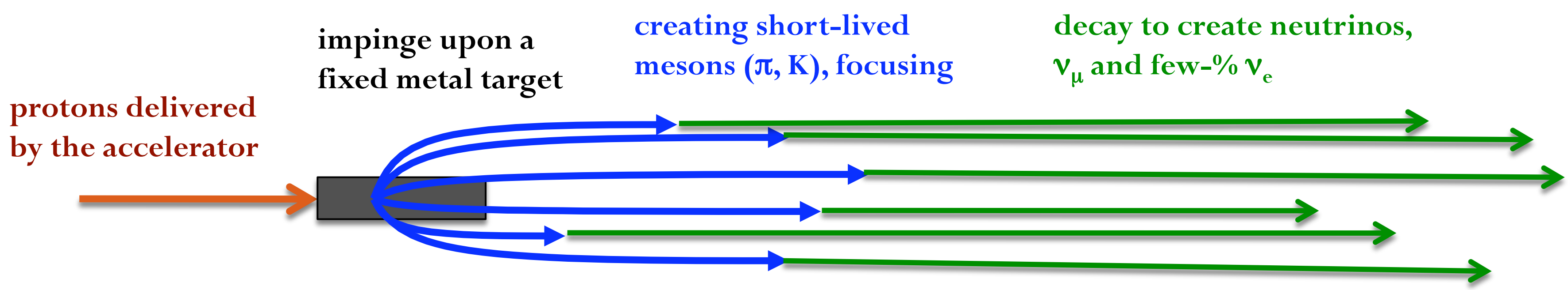
- But, in practice, this is complicated by neutral current backgrounds
  - π^0's/γ's can fake electrons
  - π^{+-}'s can fake muons



- **Why the search for θ_{13} and δ^{CP} is a paradigm shift in long-baseline accelerator-based neutrino oscillation experiments**
- Can't we just cancel cross-section uncertainties once the experiment is running?
- To date, this has worked extremely effectively
- But fluxes & Detectors at Near/Far locations can be VERY different
  - detector designs are not always identical
  - beam acceptances change the fluxes
  - flux oscillates away or appears between detectors
  - flavor content vs. energy changes dramatically
- Large θ_{13}, need better handle on signal cross-sections (ν_e CCQE, RES, DIS)
- Small θ_{13}, need better handle on background cross-sections (NC π^0)



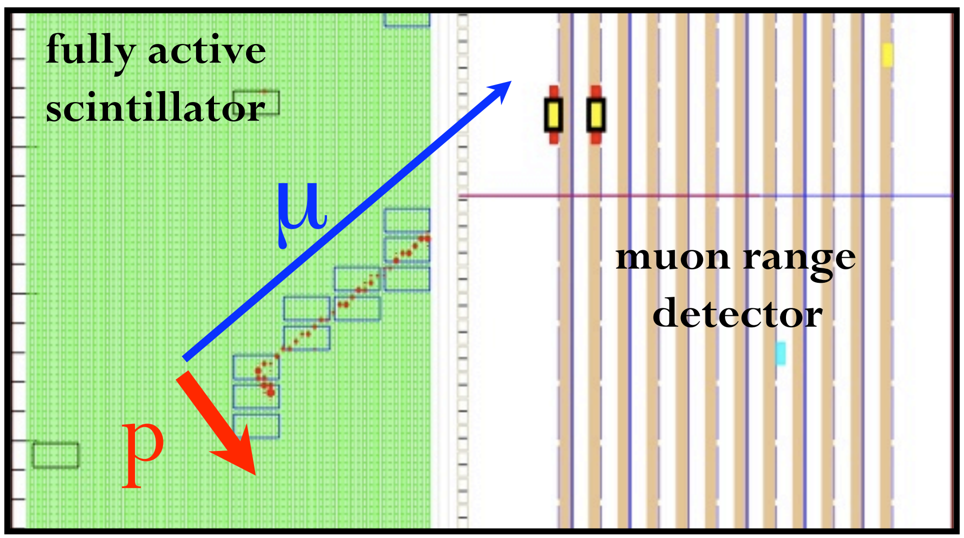
- **Intrinsic electron neutrino rates**

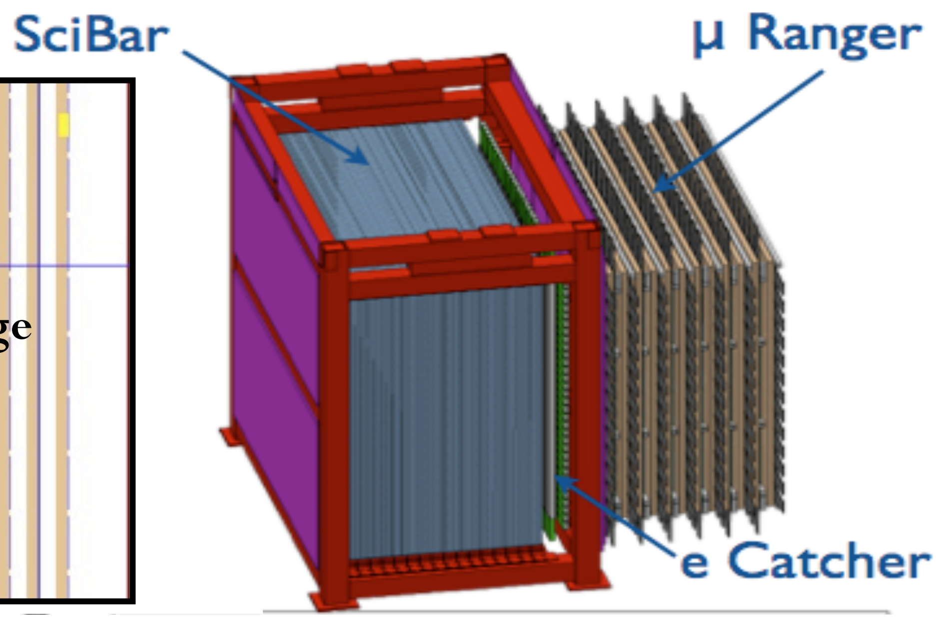


Neutrino Beam	Experiments	approx. ν_e fraction
NuMI (on-axis)	MINOS, MINERvA	1.3%
NuMI (off-axis)	NOvA	few %
Project-X (on-axis)	LBNE at DUSEL	few %
J-PARC (off-axis)	T2K	0.5%
Booster Neutrino Beam	MiniBooNE, MicroBooNE	0.6%

Charged-Current Quasi-Elastic Scattering

- SciBooNE is a fully active scintillator detector/target
- 2,680 2-track ν_μ QE events on carbon (69% purity)
- have preliminary measurement of $\sigma_{CCQE}(E)$ from $E_\nu = 0.6 – 1.6$ GeV
- active analysis
    - 1track vs 2 track; active contained vs muon range detector
    - differential cross-sections

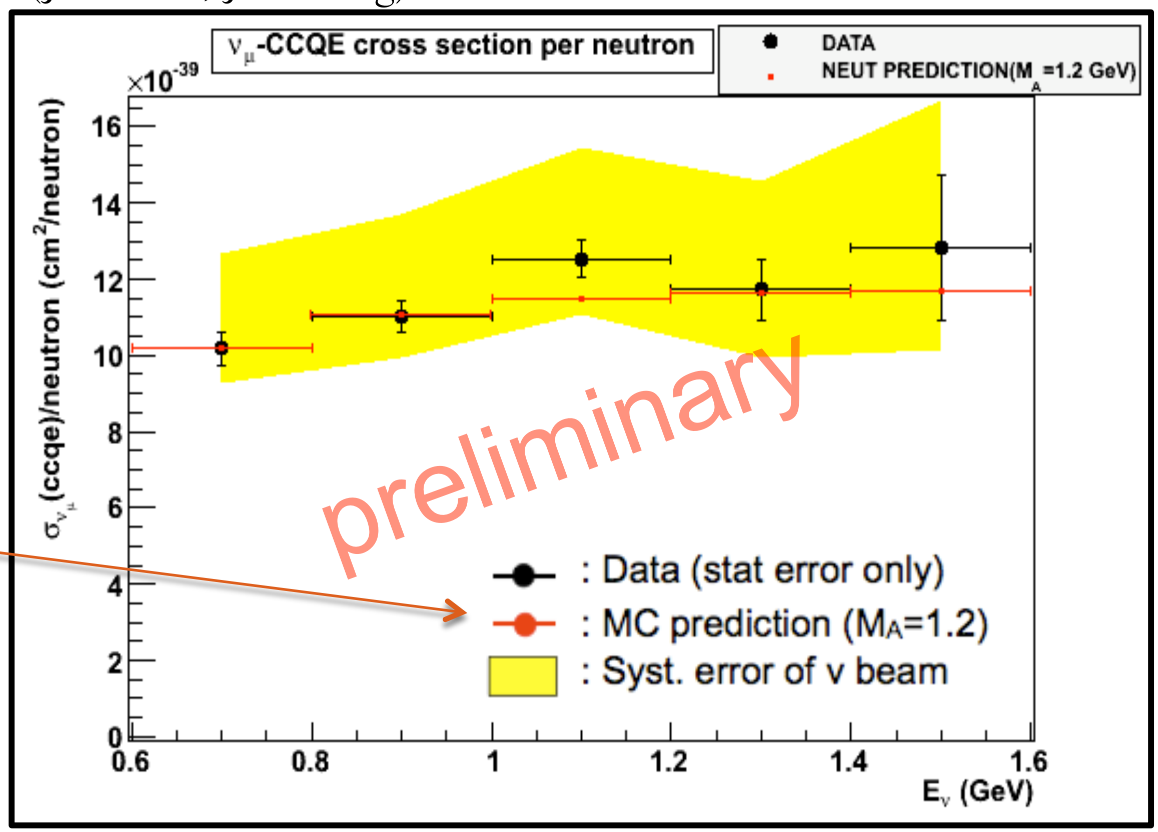




Charged-Current Quasi-Elastic Scattering

- can clearly resolve final state by identifying the proton track as well as the muon
- 2,680 2-track ν_μ QE events (69% purity)
- agrees with model prediction already scaled based on MiniBooNE result (that is, preliminary result consistent with MiniBooNE)

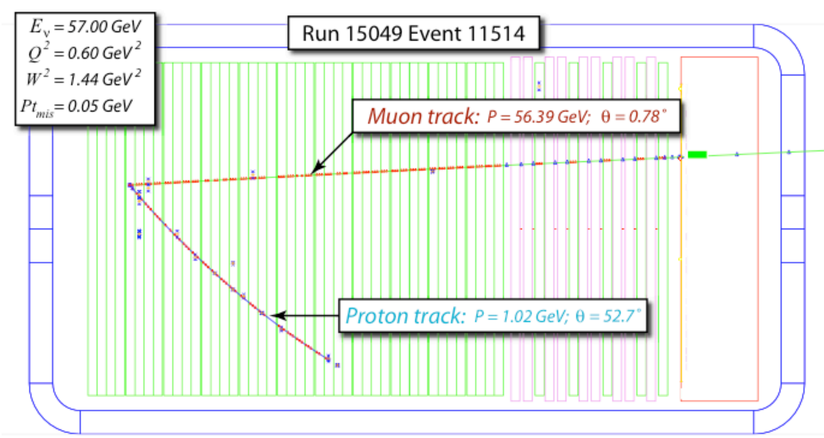
(J. Alcaraz, J. Walding)

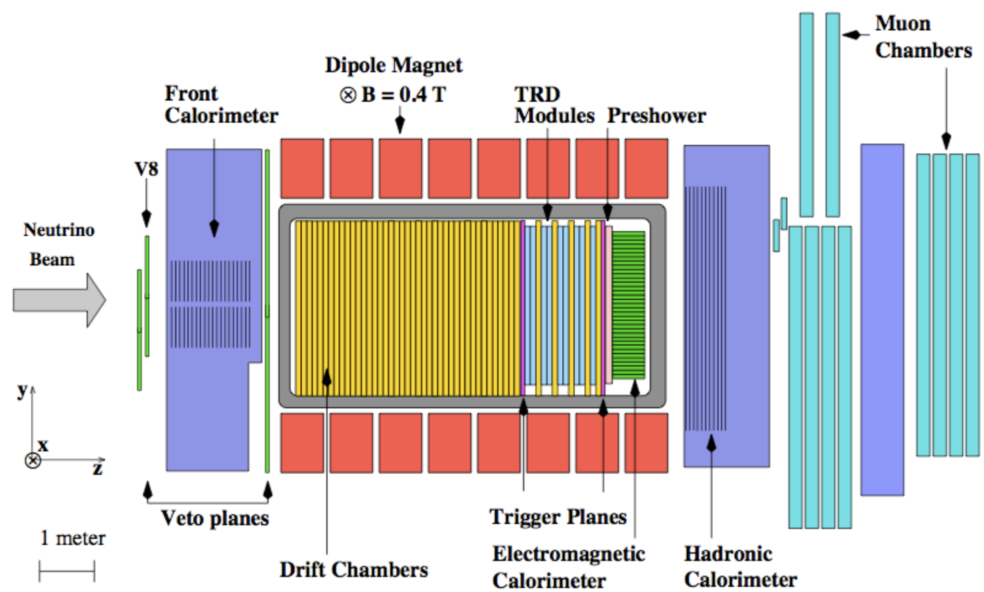


• Charged-Current Quasi-Elastic Scattering

- NOMAD collaboration recently published a quasi-elastic cross-section for neutrinos and antineutrinos
- target nucleus same as BooNEs carbon
- higher energy neutrino flux $E_\nu = 3 - 200$ GeV
- drift chamber tracking detector, high resolution on muon **AND** proton tracks

arXiv:0812.4543v3

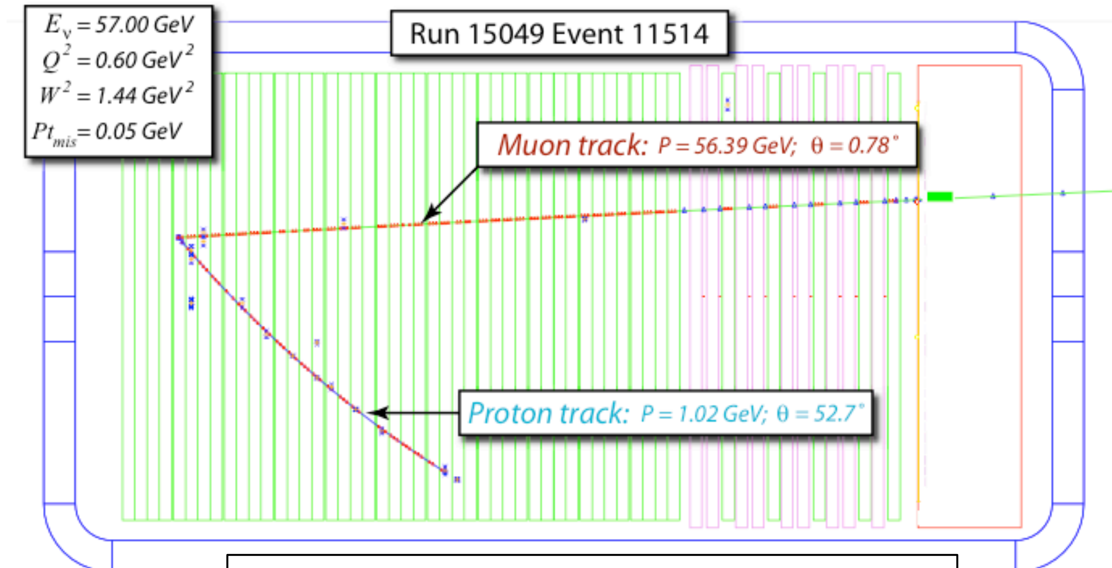


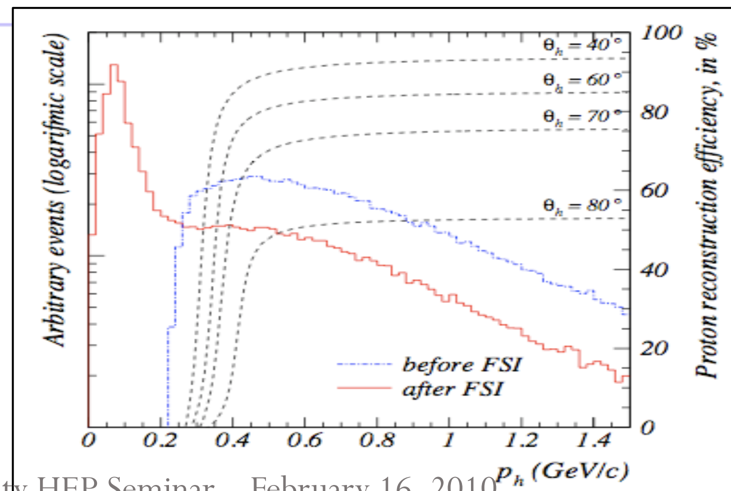


- Charged-Current Quasi-Elastic Scattering

• combined 1-track (muon only) and 2-track (muon+proton) samples for measuring CCQE cross-section

• nuclear effects cause migration from 2-track to 1-track, so inclusion of both minimizes systematic from knowing this migration



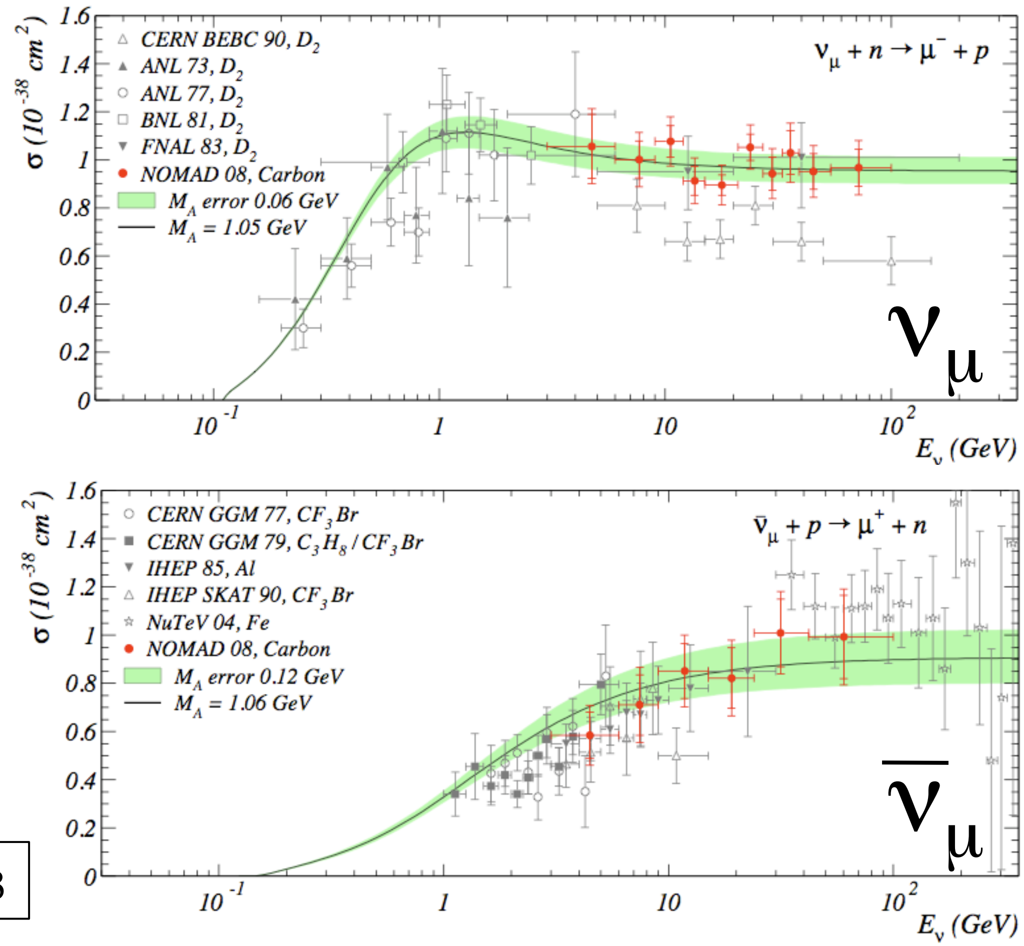


arXiv:0812.4543v3

Charged-Current Quasi-Elastic Scattering

- can identify μ^+ and μ^- from track bend directions

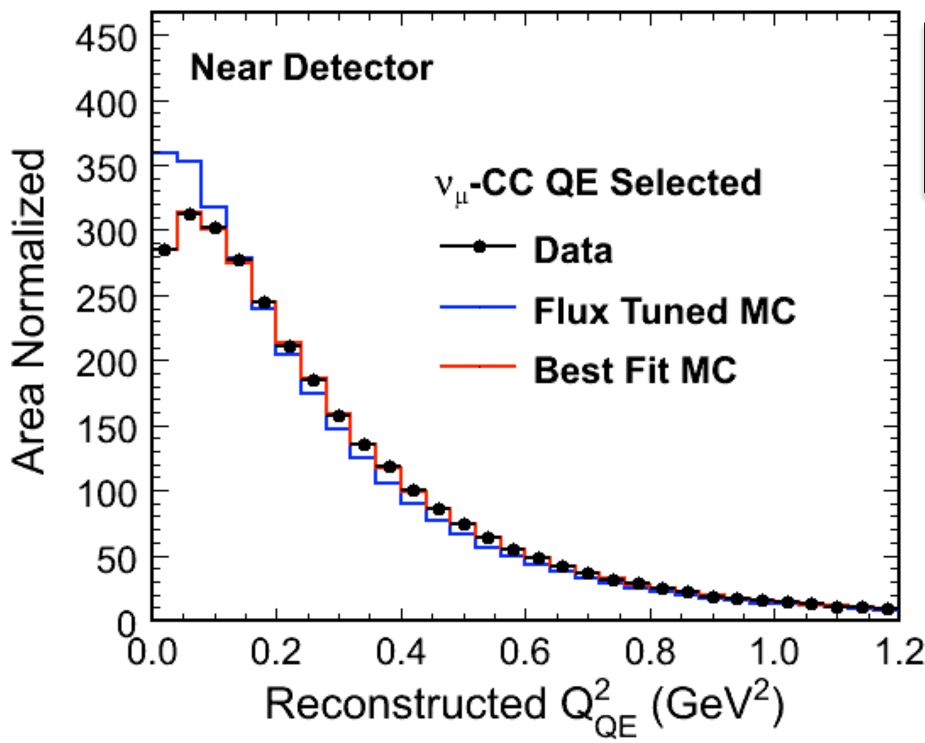
- present both neutrino and antineutrino QE cross-sections above 3 GeV



arXiv:0812.4543v3

- Charged-Current Quasi-Elastic Scattering

MINOS Preliminary



MINOS Preliminary

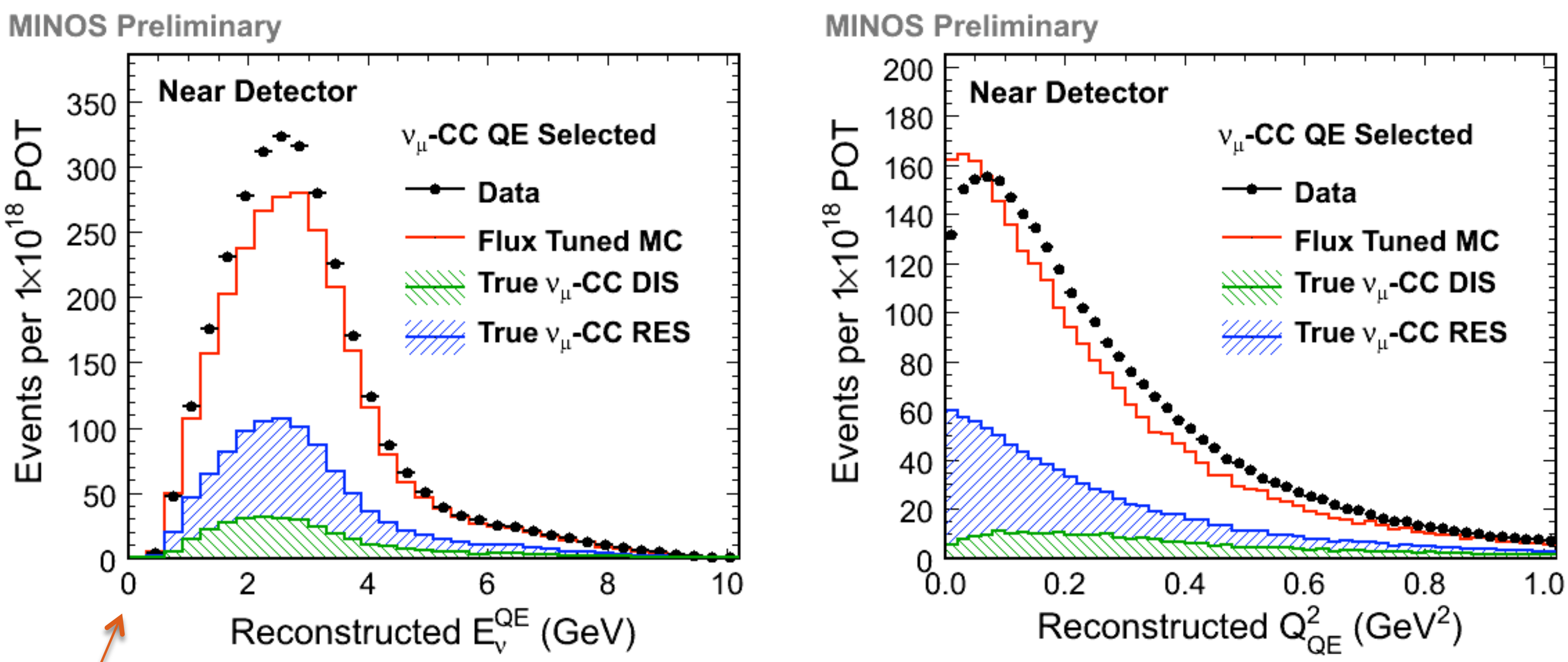
$M_A^{QE} = 1.19\ ^{+0.09}_{-0.10}\,(\text{fit})\ ^{+0.12}_{-0.14}\,(\text{syst})$ GeV

$k^{Fermi} = 1.28 \times k^{Fermi}$

- fit favors a higher value of the axial mass and increases the Fermi momentum by 28% as an effective low Q^2 suppression

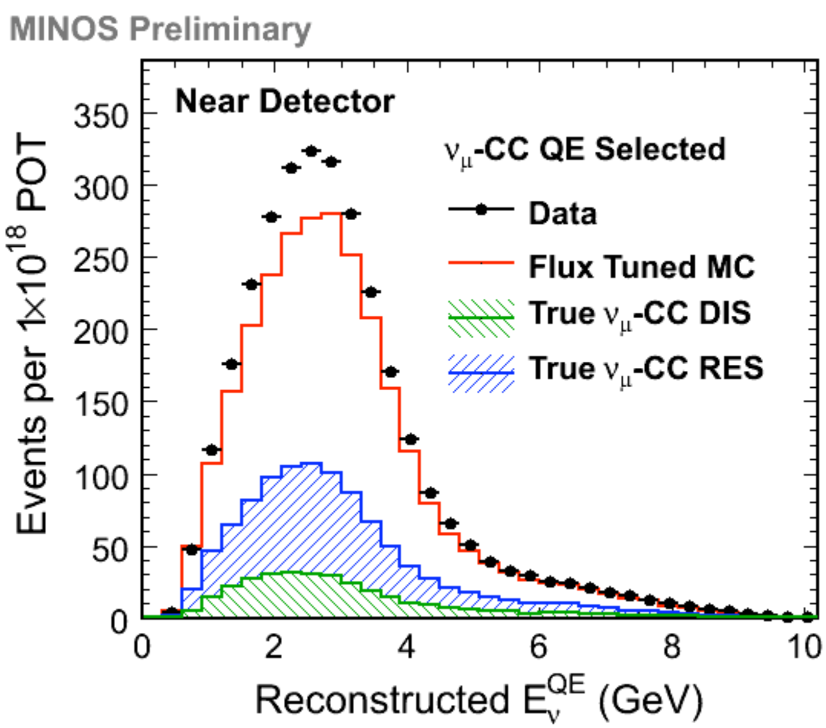
- no absolute cross-section values extracted yet – to come

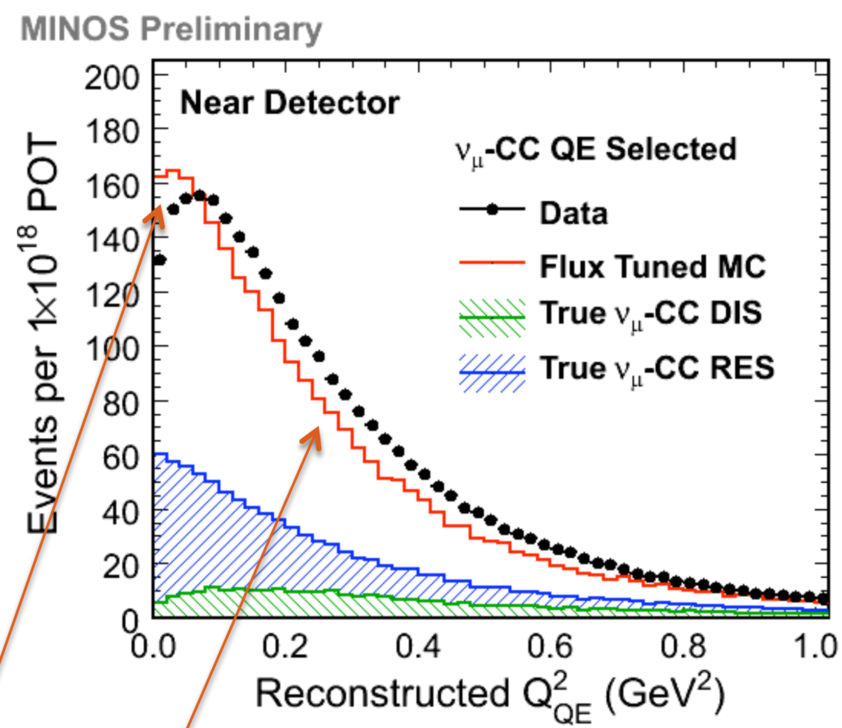
- Charged-Current Quasi-Elastic Scattering



- Similar E_ν excess to those seen in Sci/MiniBooNE data

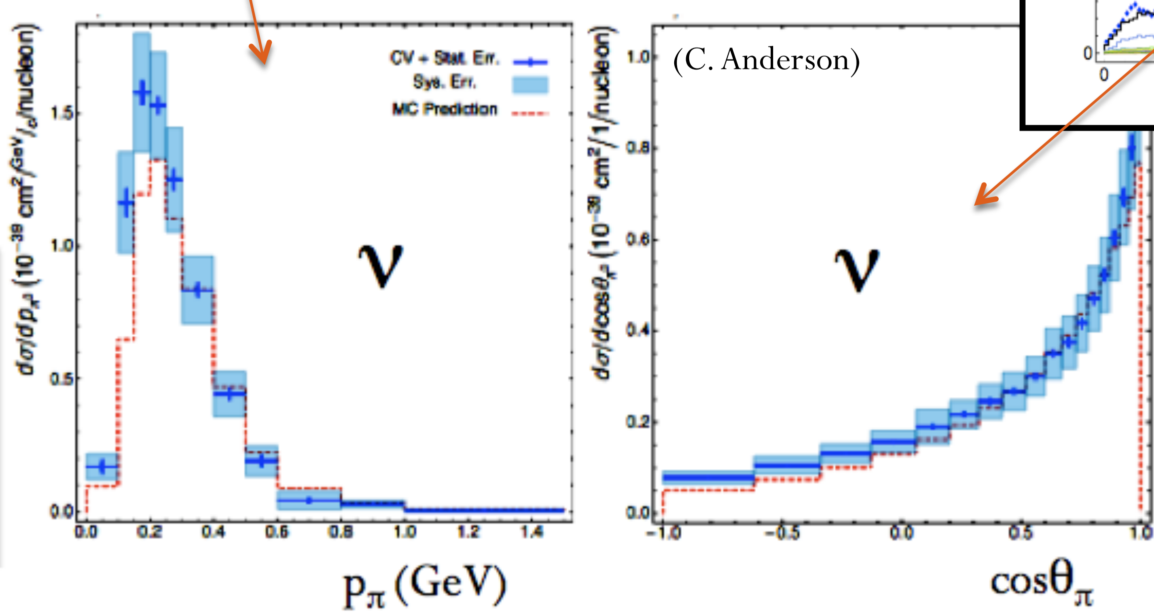
- Charged-Current Quasi-Elastic Scattering

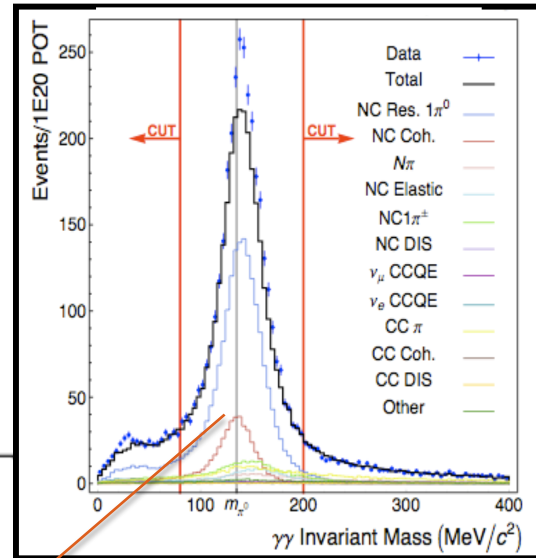




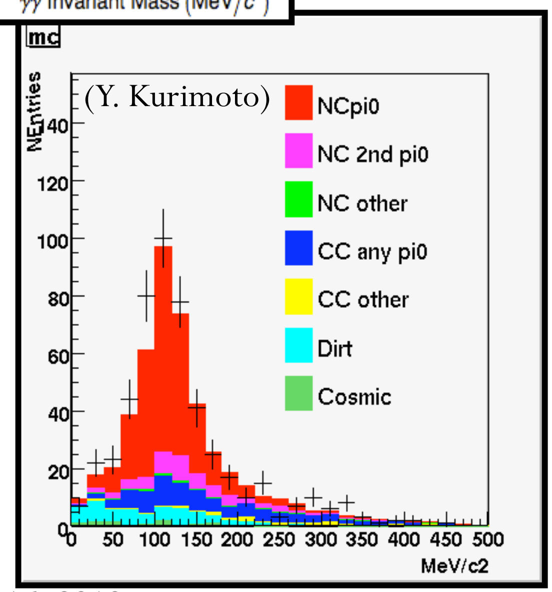
- Similar Q^2 shape disagreements to those seen in MiniBooNE data, but at higher energies and on iron instead of carbon

- Single Pion Production
  - Absolute differential cross-sections possible for the first time



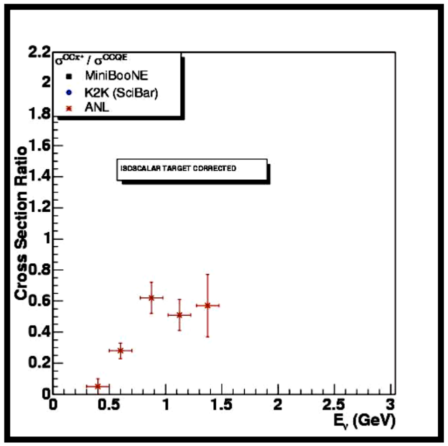


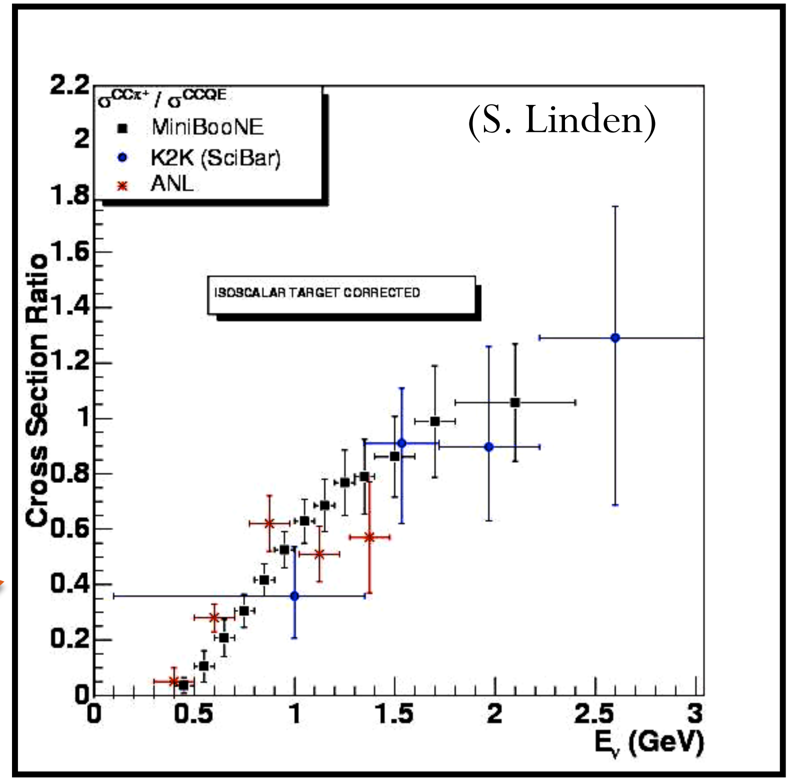
(C. Anderson)



- Single Pion Production

ANL: Phys. Rev. **D25**, 1161 (1982), deuterium





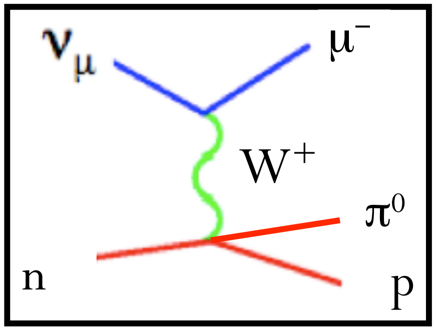
- 26 years between ANL and K2K/MiniBooNE results
- Cross-section ratio to CCQE

K2K: Phys. Rev. **D78**, 032003 (2008)

MiniBooNE: arXiv:0904.3159 [hep-ex]

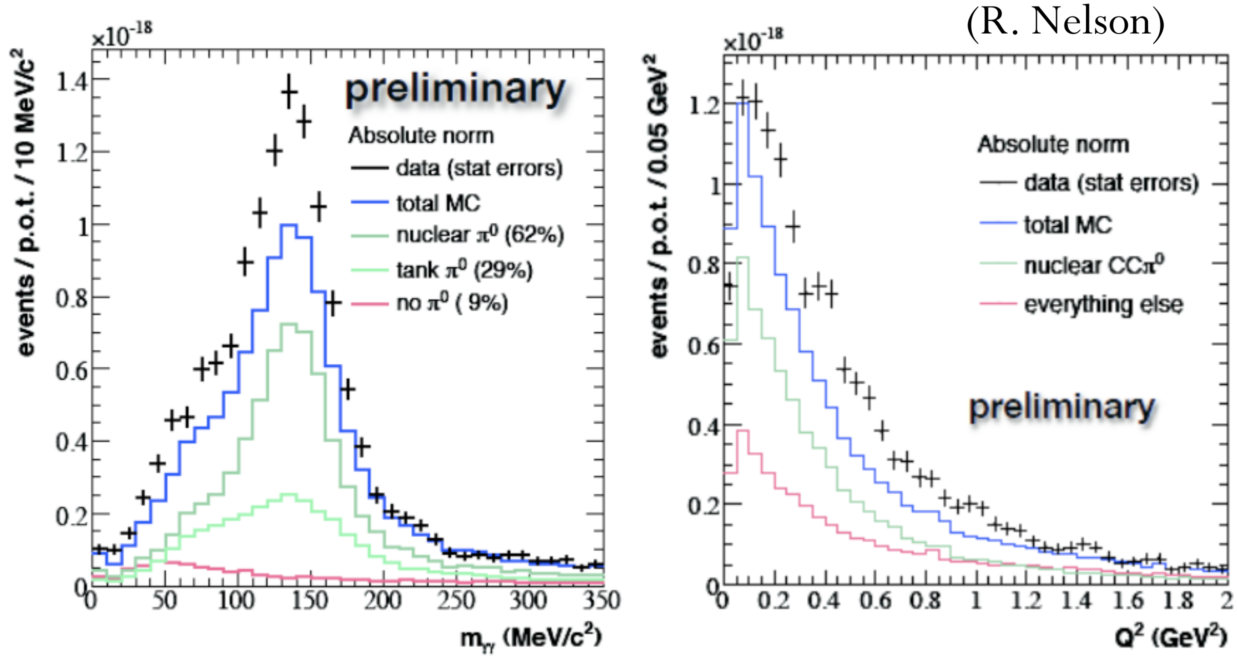
- Single Pion Production

CC π^0 production



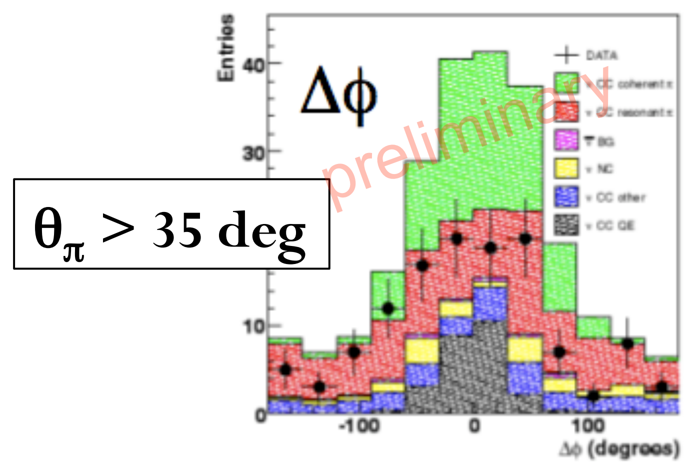
- development of 3 Cherenkov ring fitter has made possible the study of CC π^0 production

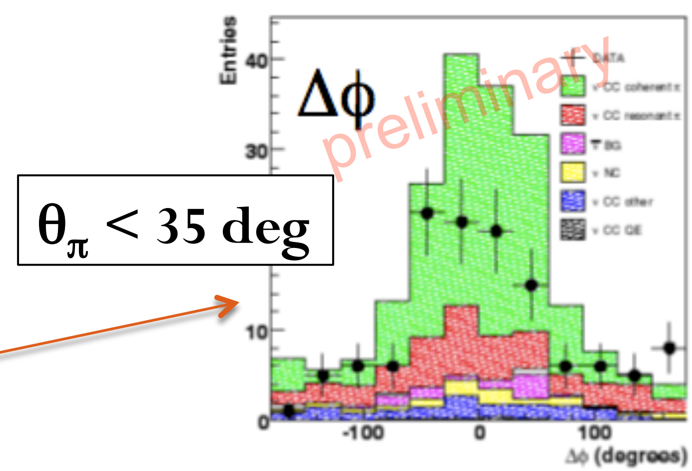
(R. Nelson)



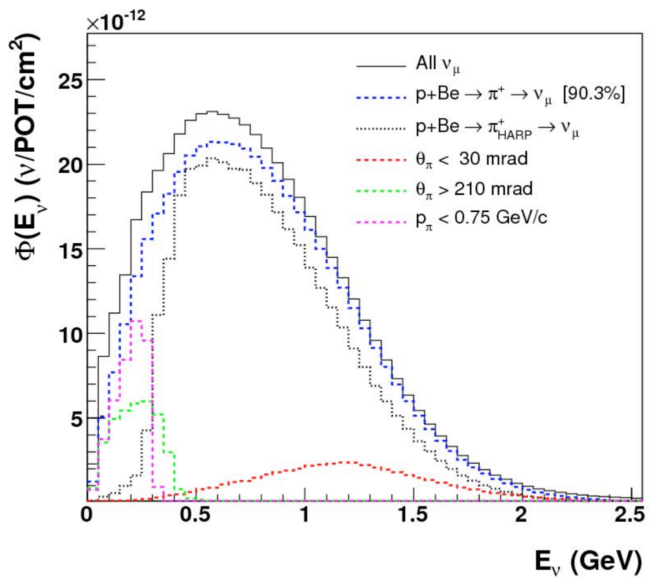
Coherent Single Pion Production (CC/NC)

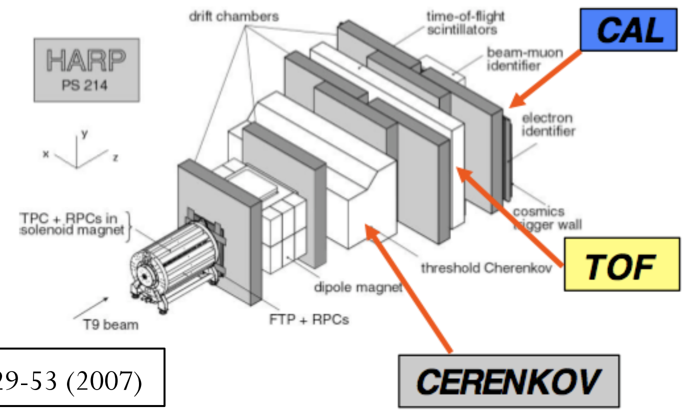
- Coherent interaction with nucleus leaving it intact, but producing a pion
- very small rate compared to inelastic processes
- many intriguing results recently from K2K, MiniBooNE, SciBooNE
  - K2K first to see no evidence for CC coherent pion production
  - MiniBooNE did see evidence for NC coherent pion production, though below the prediction
  - Active analysis for SciBooNE
    - preliminary evidence for some CC coherent, but pions more forward than model predicts



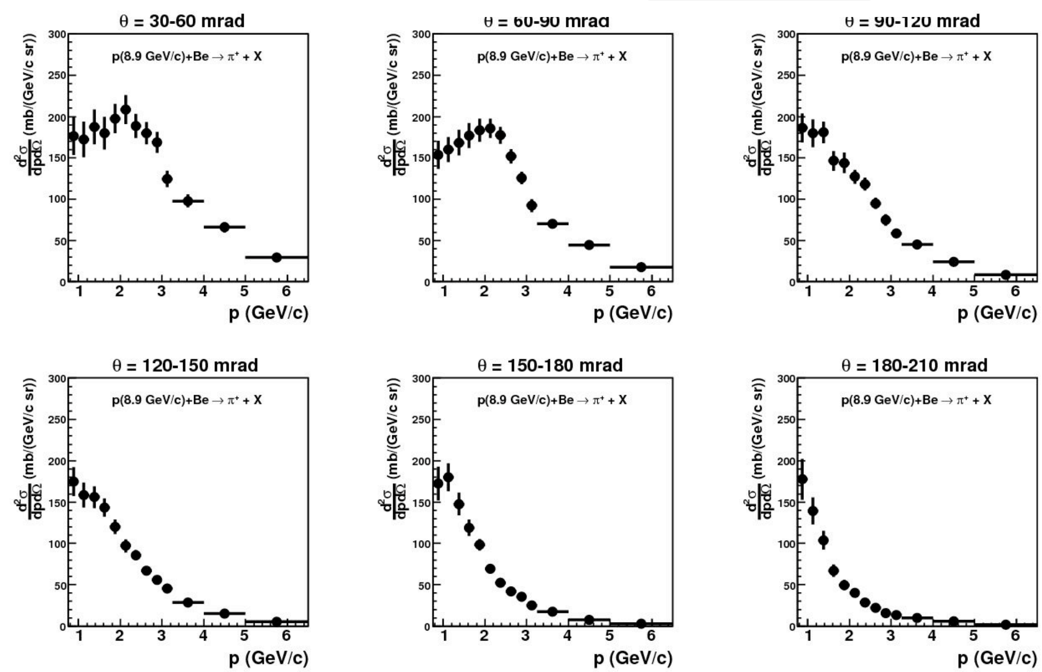


- MiniBooNE and SciBooNE both in Booster Neutrino Beam at Fermilab
  $E_\nu \sim 0.2 - 1.5$ GeV



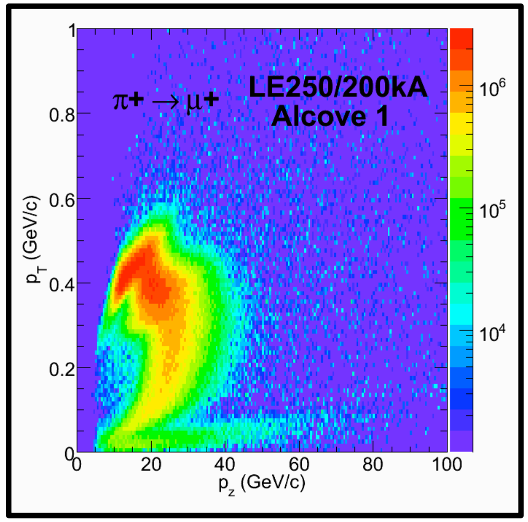


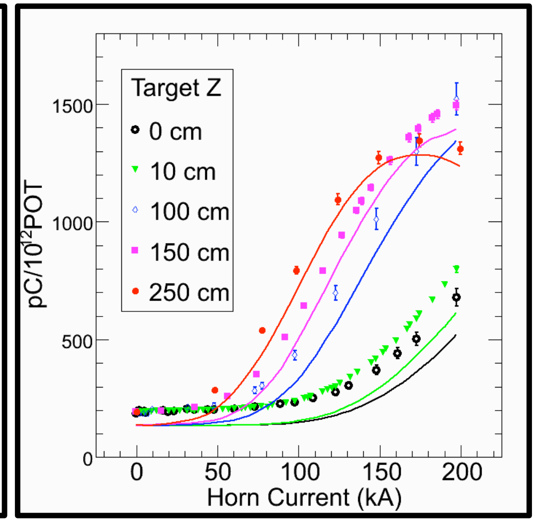
Euro. Phys. J C 52:29-53 (2007)

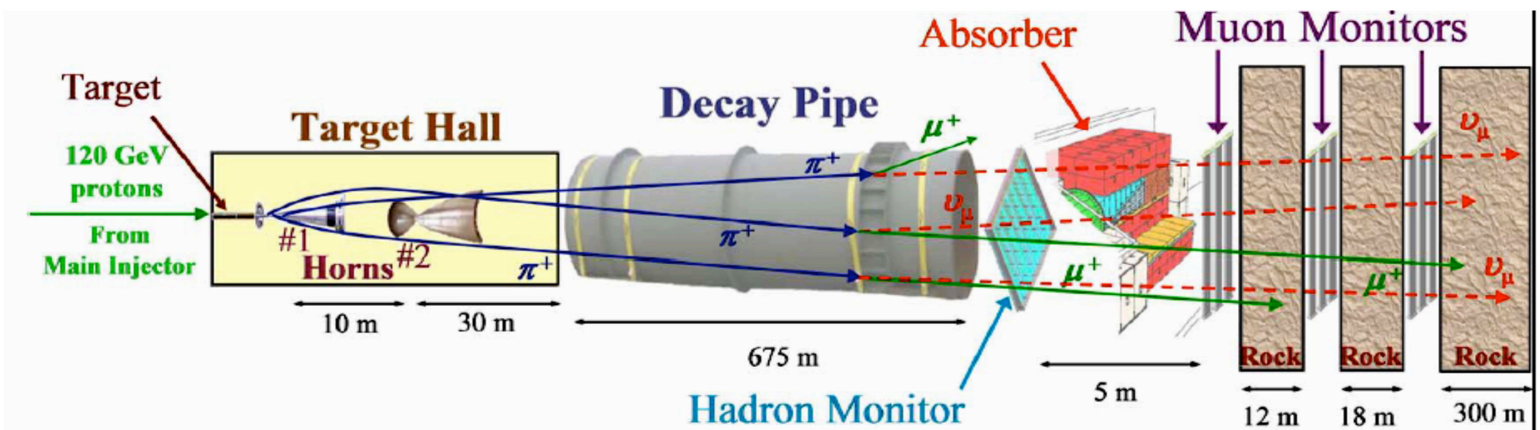


- Absolute normalization of flux using pion production data from the HARP experiment

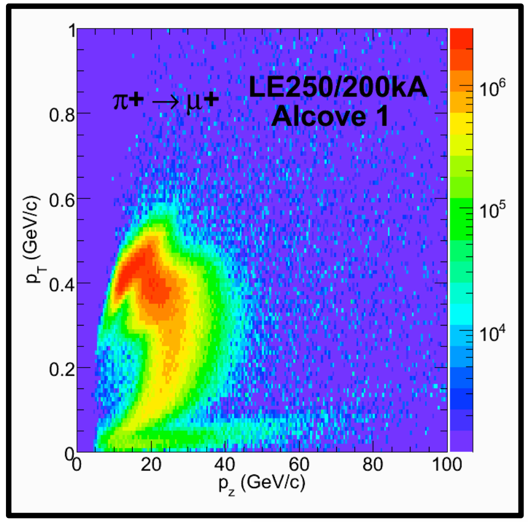
- Goal to reach ~5% absolute flux estimate through a combination of approaches:
  - in situ measurements using muon monitors and beam taken at various horn currents and target positions in the NuMI beamline

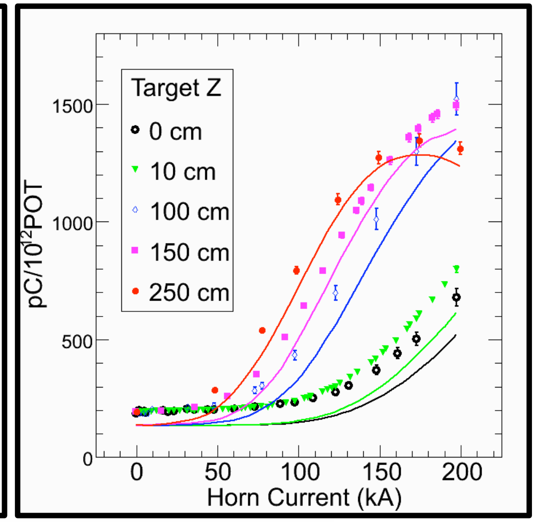


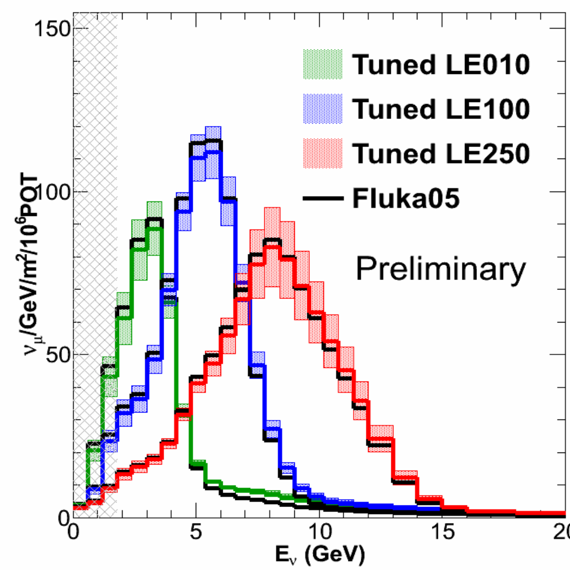




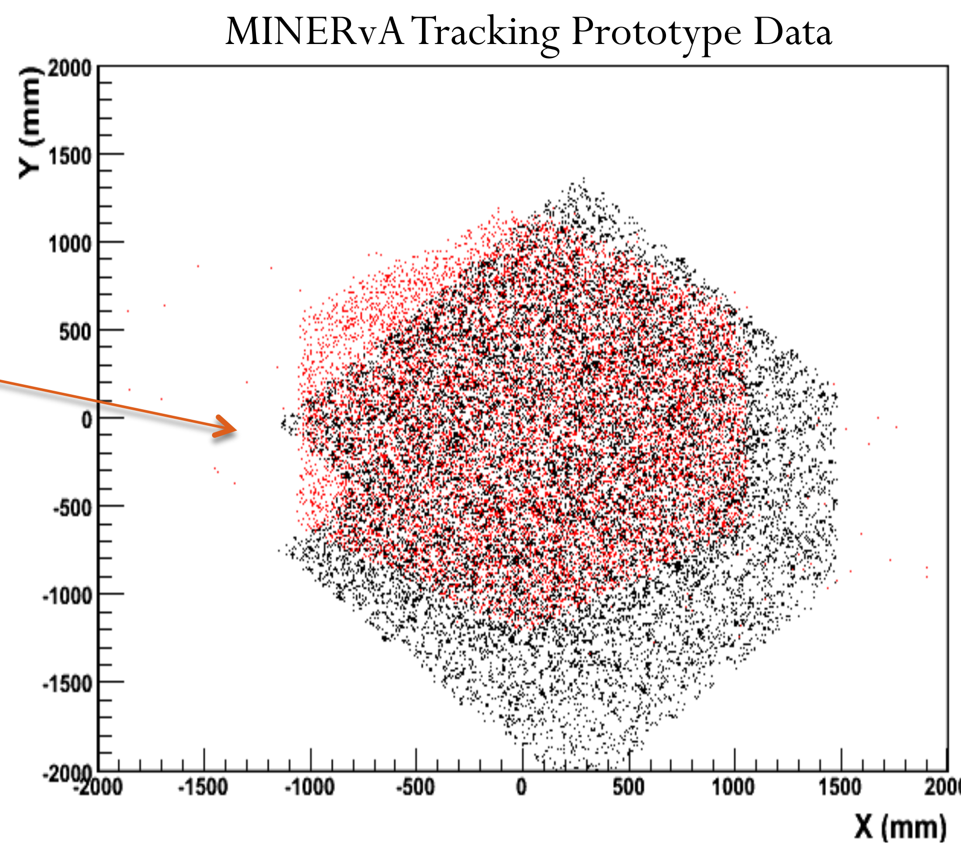
- Goal to reach ~5% absolute flux estimate through a combination of approaches:
  - in situ measurements using muon monitors and beam taken at various horn currents and target positions in the NuMI beamline
  - recent new beam simulation G4
  - particle production experiment MIPP at Fermilab. Analysis in progress of data with NuMI target





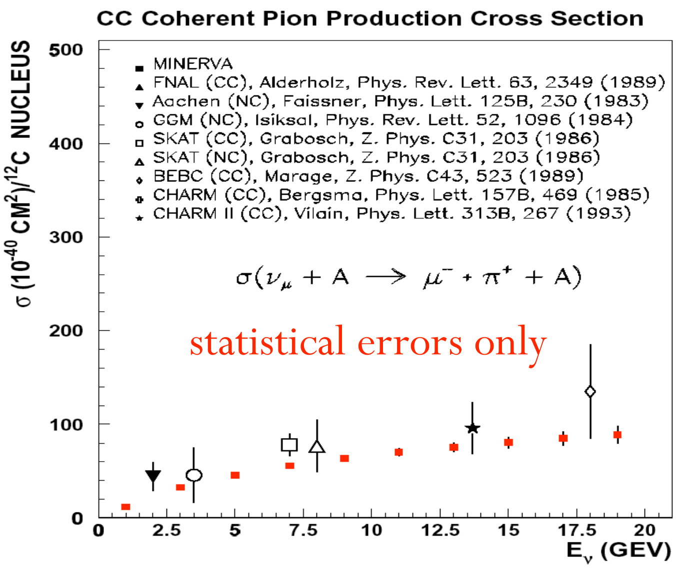


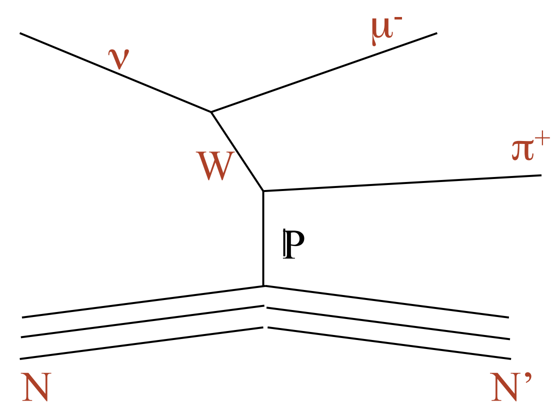
- A unique kind of collaboration
- MINOS kindly shares their data with the MINERνA collaboration to act as a muon spectrometer
- All tracks in MINERνA (red) and MINOS (black) in MINERνA coordinate system
- About 90% of muons (for QE events) escape MINERνA detector
- 92% of those are picked up in the MINOS detector

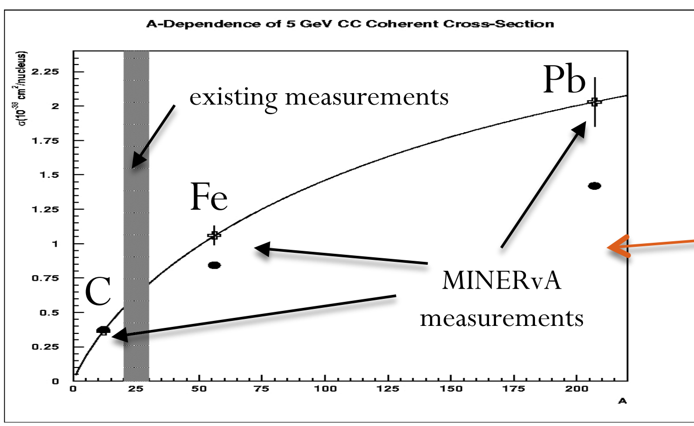


- High statistics CCQE samples show discrepancies with present MC predictions
- We are just now beginning to make real comparisons for other channels between binned data and MC predictions
  - CC π^+/π^0 production
  - NC elastic and NC π^0 production
  - CC/NC coherent interactions off the nucleus as a whole
- Theorists are interested in this problem. Wonderful!
- We must work with them directly or provide data they can use
- **Event rates of exclusive final states off some target nucleus**
  - not corrected back to the nucleon
  - nuclear effects (FSI) are part of this challenging theoretical problem

- Coherent pion production (CC/NC) off the nucleus

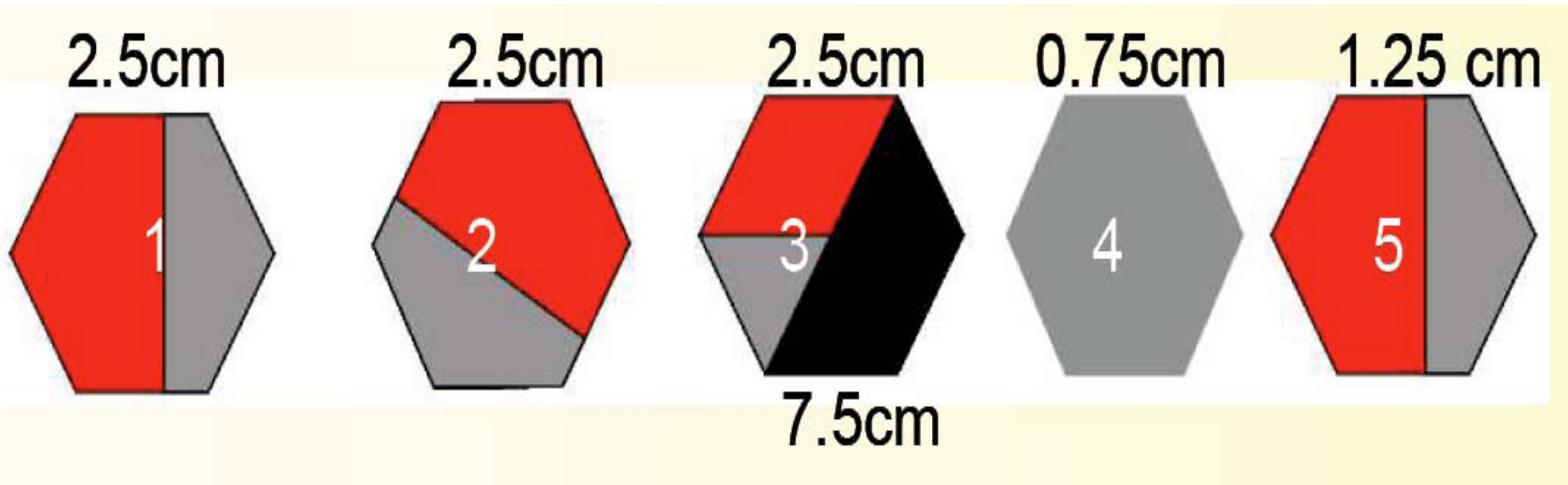




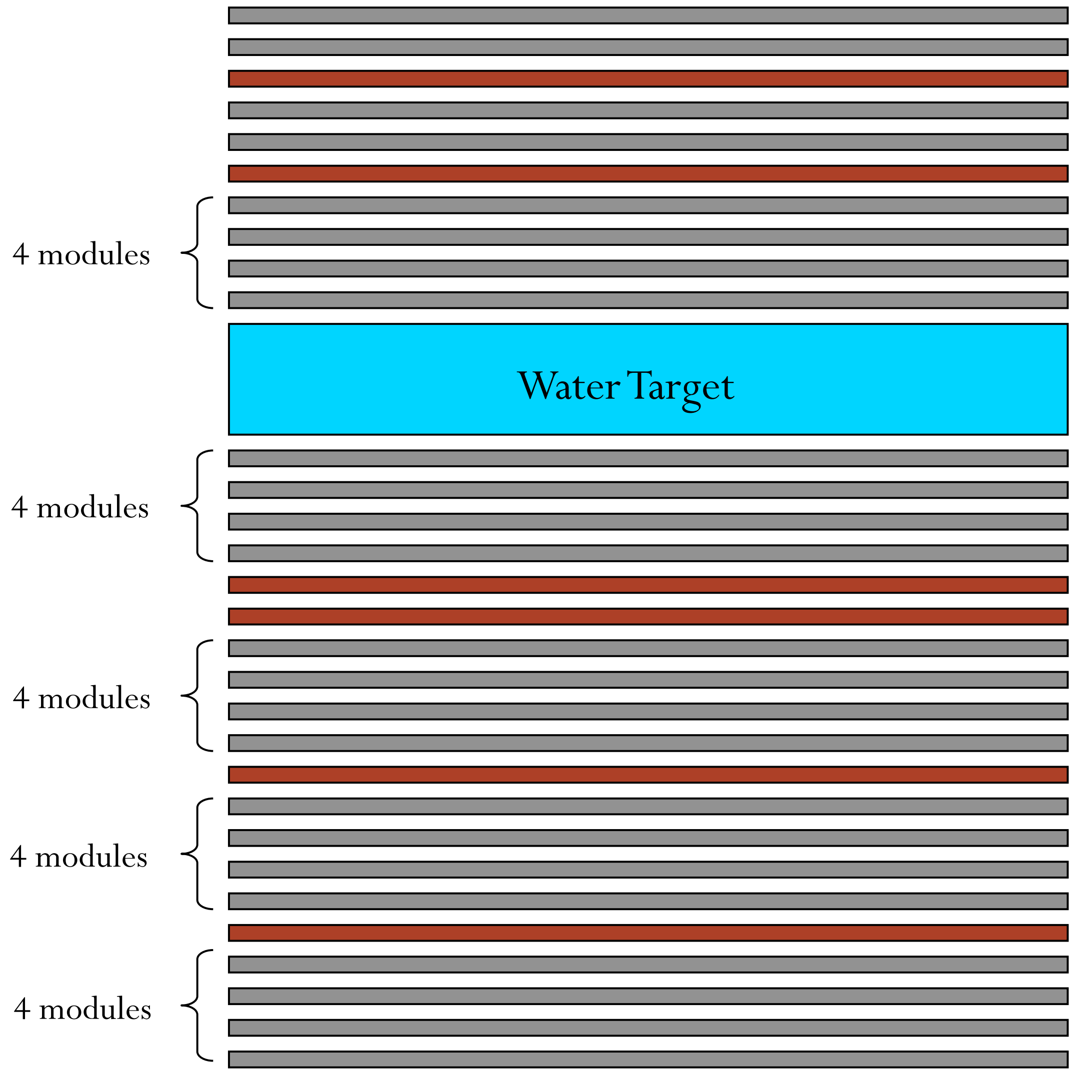


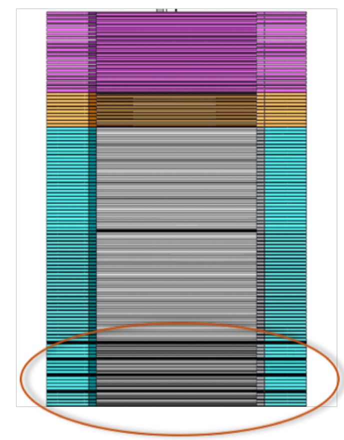
- Scatters off the nucleus as a whole, leaving nucleus in the ground state.
- Comparison with theoretical models
- MINERνA's nuclear targets allow the <u>first measurement of the A-dependence of σ_{coh}</u> across a wide range in a single experiment

- Red = Iron, Grey = Lead, Black = Carbon



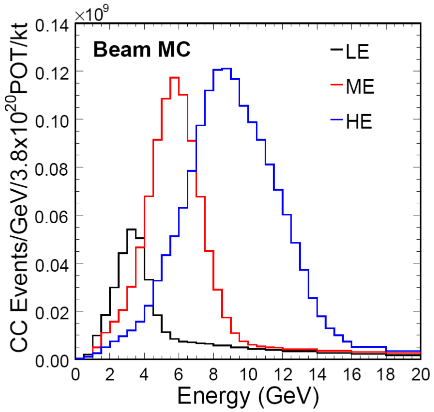
- First two targets: High statistics, compare lead and iron
- Third target: Compare lead, iron, and carbon with same detector geometry
- Last targets: Thin for low energy particle emission studies, high photon detection
- ^{4}He cryogenic target in front of detector


4 modules
Water Target
4 modules
4 modules
4 modules
4 modules



- People often ask, "Isn't water a pretty important nuclear target in neutrino physics?"
- And MINERνA has heard your calls…
- currently manufacturing an "aquarium" target to go in nuclear target region
- T2K water bag

MINERνA Event Rates



NuMI Beam Energy Configurations

14.5 Million CC events for 16 x 10^{20} Protons on Target

Assume 4.0x10^{20} POT in LE and 12.0x10^{20} POT in the ME NuMI beam configurations

Fiducial Volume = 3 tons CH, 0.2t He, 0.15t C, 0.7t Fe and 0.85t Pb
Expected CC event samples:
9.0 M ν events in 3 tons of CH
0.6 M ν events in He
0.4 M ν events in C
2.0 M ν events in Fe
2.5 M ν events in Pb

Main CC Physics Topics (Statistics in CH)

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

MINERνA Running Schedule

Calendar Year		2010	2011	2012	2013
Tevatron Collider		CDF & DZero	CDF & DZero / OPEN		OPEN
Neutrino Program	B	MiniBooNE	MiniBooNE		OPEN
		OPEN	OPEN / MicroBooNE		MicroBooNE
	MI	MINOS	MINOS		OPEN
		MINERvA	MINERvA		MINERvA
		ArgoNeuT			
			NOvA		NOvA
SY 120	MT	Test Beam	Test Beam		Test Beam
	MC	OPEN	OPEN		OPEN
	NM4	E-906/Drell-Yan	E-906/Drell-Yan		E-906/Drell-Yan

RUN/DATA
STARTUP/COMMISSIONING
INSTALLATION
M&D (SHUTDOWN)

Tracking Prototype Run: 4/09 – 6/09
LE AntiNeutrino Run with Increased Fiducial Mass: 11/09 – 3/10
LE Neutrino Run with Full MINERνA: 3/10 – 3/12
ME Neutrino and AntiNeutrino Runs: Starting Spring 2013