New Results in Neutrino Measurements

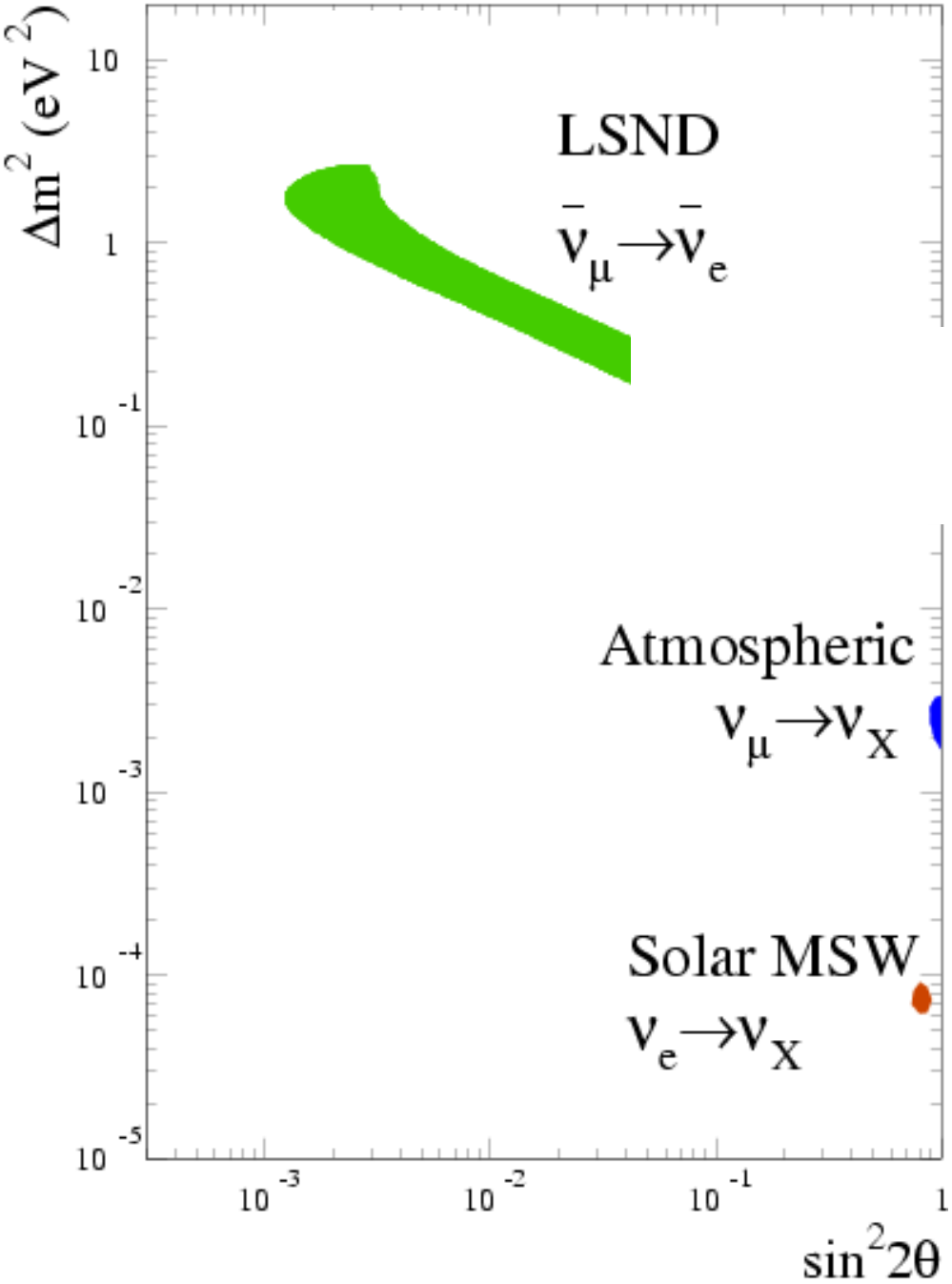
W.C. Louis, LANL

- **Neutrino Past:** Solar & Atmospheric ν Oscillations! Large Δm^2 Neutrino Oscillations?
- **Neutrino Future:** Tritium β Decay, Double β Decay, Reactor θ_{13}, Accelerator θ_{13}, Solar ν, & ν Cross Sections
- **Neutrino Present:** MINOS, MiniBooNE, & K2K σ s
- **Conclusions**

Neutrino Past

- **"Solar" Neutrino Oscillations!** (Homestake, Kamiokande, SAGE, GALLEX, GNO, SNO, KamLAND)
- **"Atmospheric" Neutrino Oscillations!** (IMB, Kamiokande, SOUDAN, Super-K, MACRO, K2K)
- **Large Δm^2 Neutrino Oscillations?** (LSND)

Current Neutrino Oscillation Signals

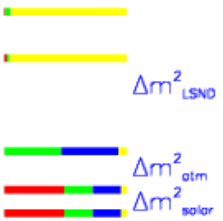


Expt.	Type	$\Delta m^2\ (eV^2)$	$\sin^2 2\theta$
LSND	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	~1	$\sim 3\times10^{-3}$
Atm.	$\nu_\mu \rightarrow \nu_\tau$	$\sim 2\times10^{-3}$	~1
Solar	$\nu_e \rightarrow \nu_{\mu,\tau}$	$\sim 8\times10^{-5}$	~0.8

If the LSND Signal is Confirmed: Physics Beyond the Standard Model & Connections with Astrophysics!

For example:

3+2 Sterile Neutrinos — Sorel, Conrad, & Shaevitz (hep-ph/0305255)



Explain Pulsar Kicks?
Explain R-Process in Supernovae?
Sterile Neutrinos Explain Dark Matter?

MaVaNs & 3+1 Sterile Neutrino — Hung (hep-ph/0010126); Kaplan, Nelson, & Weiner (hep-ph/0401099)

Explain Dark Energy?

CPT Violation & 3+1 Sterile Neutrino — Barger, Marfatia, & Whisnant (hep-ph/0308299)

Explain Baryon Asymmetry in the Universe?

Quantum Decoherence — Barenboim & Mavromatos (hep-ph/0406035)

Lorentz Violation — Kostelecky & Mewes (hep-ph/0406255)

Extra Dimensions — Pas, Pakvasa, & Weiler (hep-ph/0504096)

Sterile Neutrino Decay — Palomares-Ruiz, Pascoli, & Schwetz (hep-ph/0505216)

Probability of Neutrino Oscillations

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\Sigma_i\Sigma_j |U_{\alpha i}\, U^*_{\beta i}\, U^*_{\alpha j}\, U_{\beta j}| \sin^2(1.27\Delta m^2_{ij} L/E_\nu)$$

As N increases, the formalism gets rapidly more complicated!

N	$\#\Delta m^2_{ij}$	$\#\theta_{ij}$	#CP Phases
2	1	1	0
3	2	3	1
6	5	15	10

Fundamental Questions to be Answered

(Neutrinos are still largely unknown!)

- What are the neutrino masses & hierarchy?
- What are all of the neutrino mixings?
- Are neutrinos Dirac or Majorana?
- Is CP conserved in the lepton sector?
- Is CPT conserved in the lepton sector?
- Do light, sterile neutrinos exist?
- What is the resolution of the 3-Δm^2 paradox?

Neutrino Future

(Neutrino Satellite Meeting on Saturday & Sunday!)

- **Tritium β Decay:** KATRIN
- **Double β Decay:** CUORE, EXO, GERDA, MAJORANA, MOON, Super NEMO
- **Reactor θ_{13} :** Double CHOOZ, Braidwood, Daya Bay
- **Accelerator θ_{13} :** T2K, NOνA, BNL, KASKA
- **Solar ν :** Borexino, KamLAND/7Be, CLEAN, HERON
- **Large Δm^2 Oscillations:** BooNE, OscSNS
- **Cross Sections:** ν SNS, MINERν A, FINeSSE, J-PARC

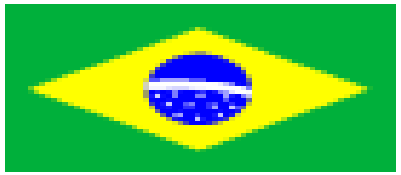
Neutrino Present

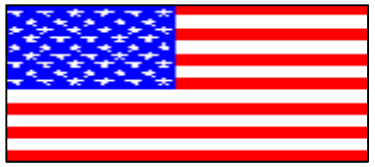
- **MINOS:** A Definitive Measurement of Atmospheric Neutrino Oscillations (Parallel Session Talk by Tzanakos)
- **MiniBooNE:** A Definitive Test of the LSND Neutrino Oscillation Evidence (Parallel Session Talks by Conrad, Djurcic, Wascko, Nelson, & Aguilar-Arevalo)
- **K2K:** Measurement of Neutrino Cross Sections (Has already confirmed atmospheric oscillations)

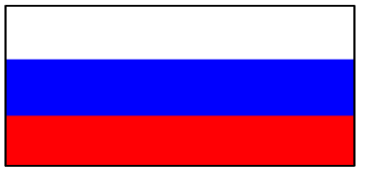
MINOS: A Definitive Measurement of Atmospheric Oscillations

Measure $\nu_\mu \rightarrow \nu_x$

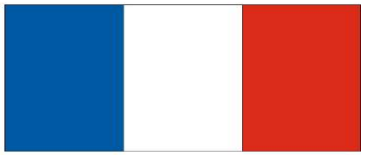
6 nations







175 physicists



32 institutions

Argonne – Athens – Benedictine – Brookhaven – Caltech – Cambridge – Campinas – Fermilab – College de France – Harvard – IIT – Indiana – ITEP Moscow – Lebedev – Livermore – Minnesota, Twin Cities – Minnesota, Duluth – Oxford – Pittsburgh – Protvino – Rutherford Appleton – Sao Paulo – South Carolina – Stanford – Sussex – Texas A&M – Texas-Austin – Tufts – Univ. College London – Western Washington – William & Mary - Wisconsin

NuMI/MINOS:

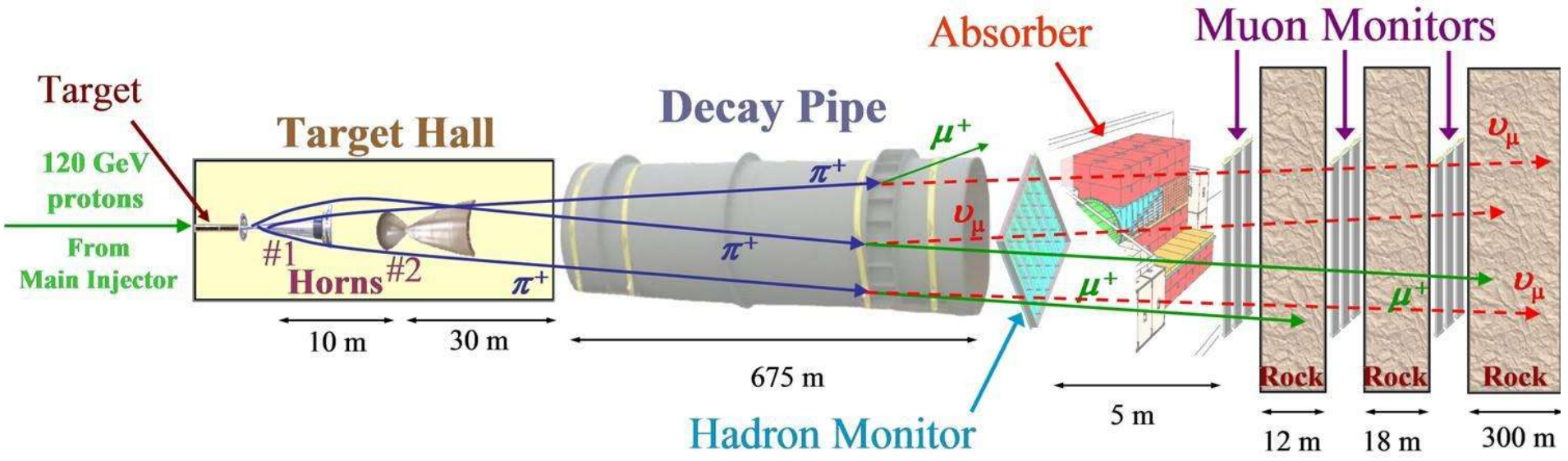
735 km Baseline

ν_μ Disappearance

$\nu_\mu \rightarrow \nu_e$ Appearance

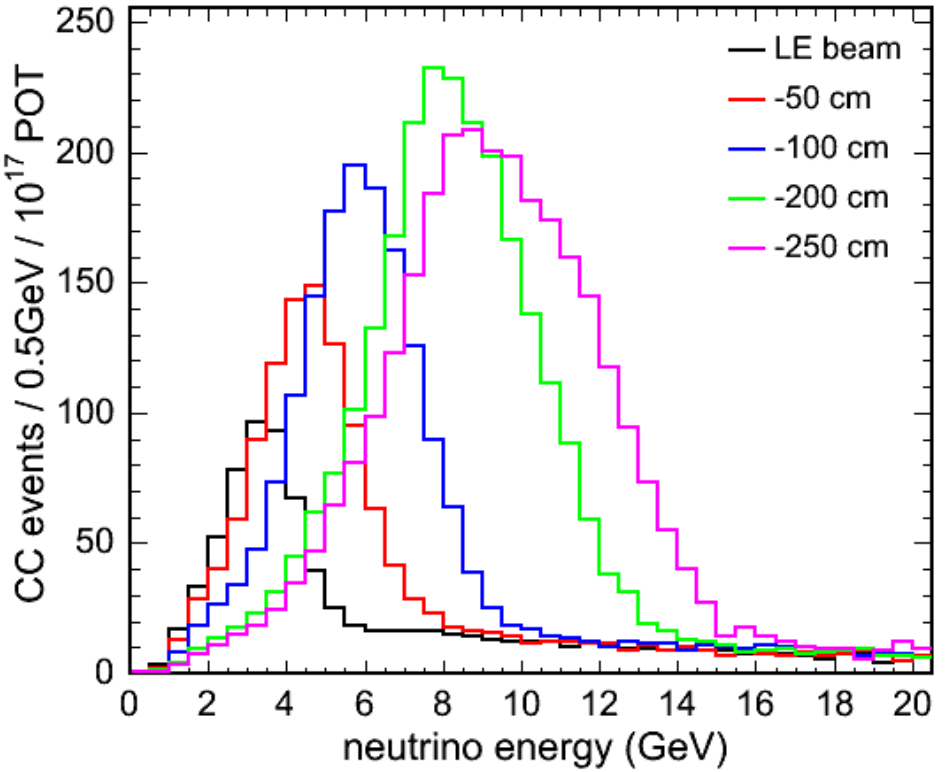
Sterile Neutrino Search

Atmospheric Neutrinos



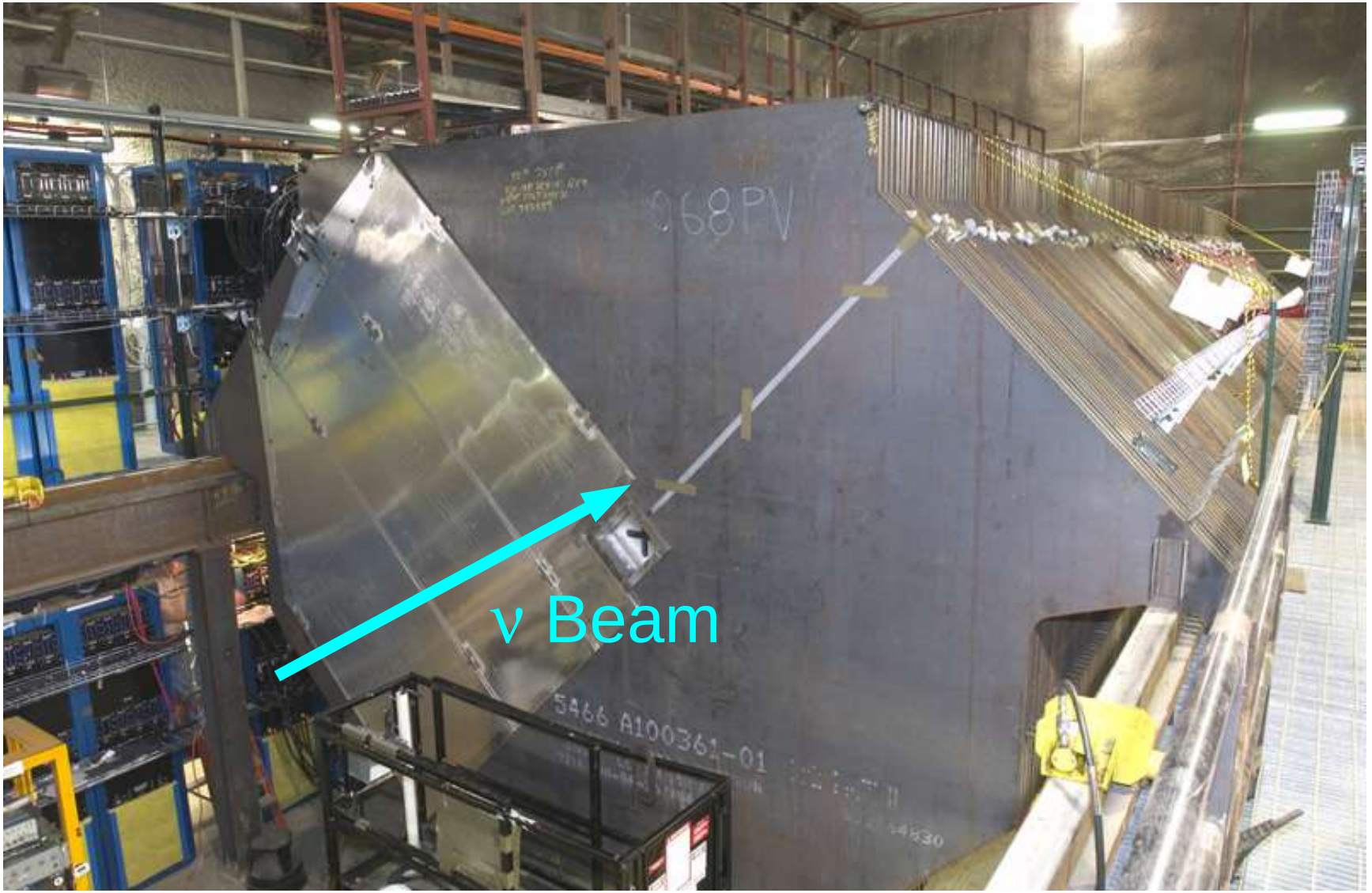
NuMI Beamline

Neutrino energy can be adjusted by varying target/horn distances



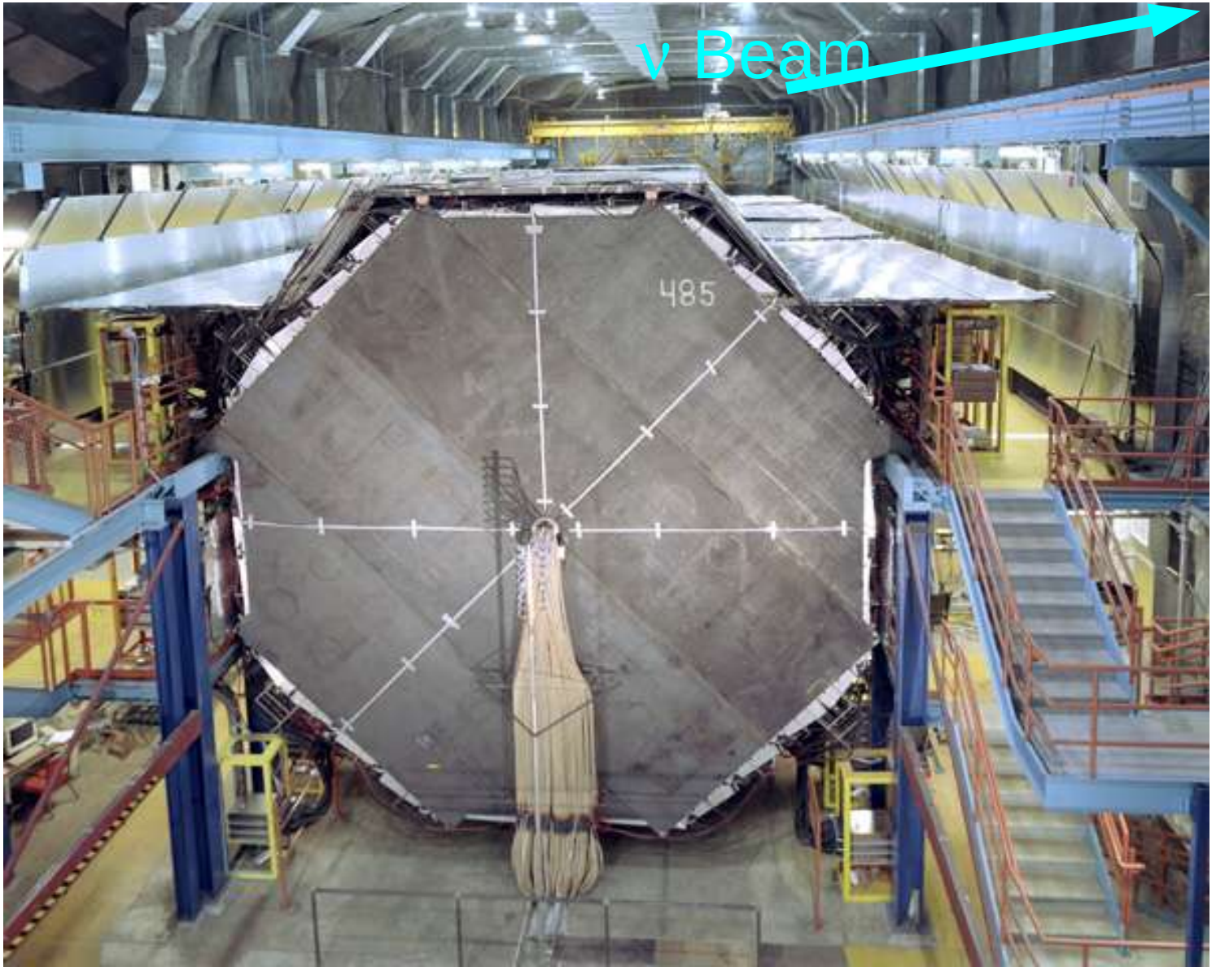
MINOS Near Detector

- 0.98 kton steel & scintillator
- 1 km from target
- 292 steel planes (B=1.2 T)



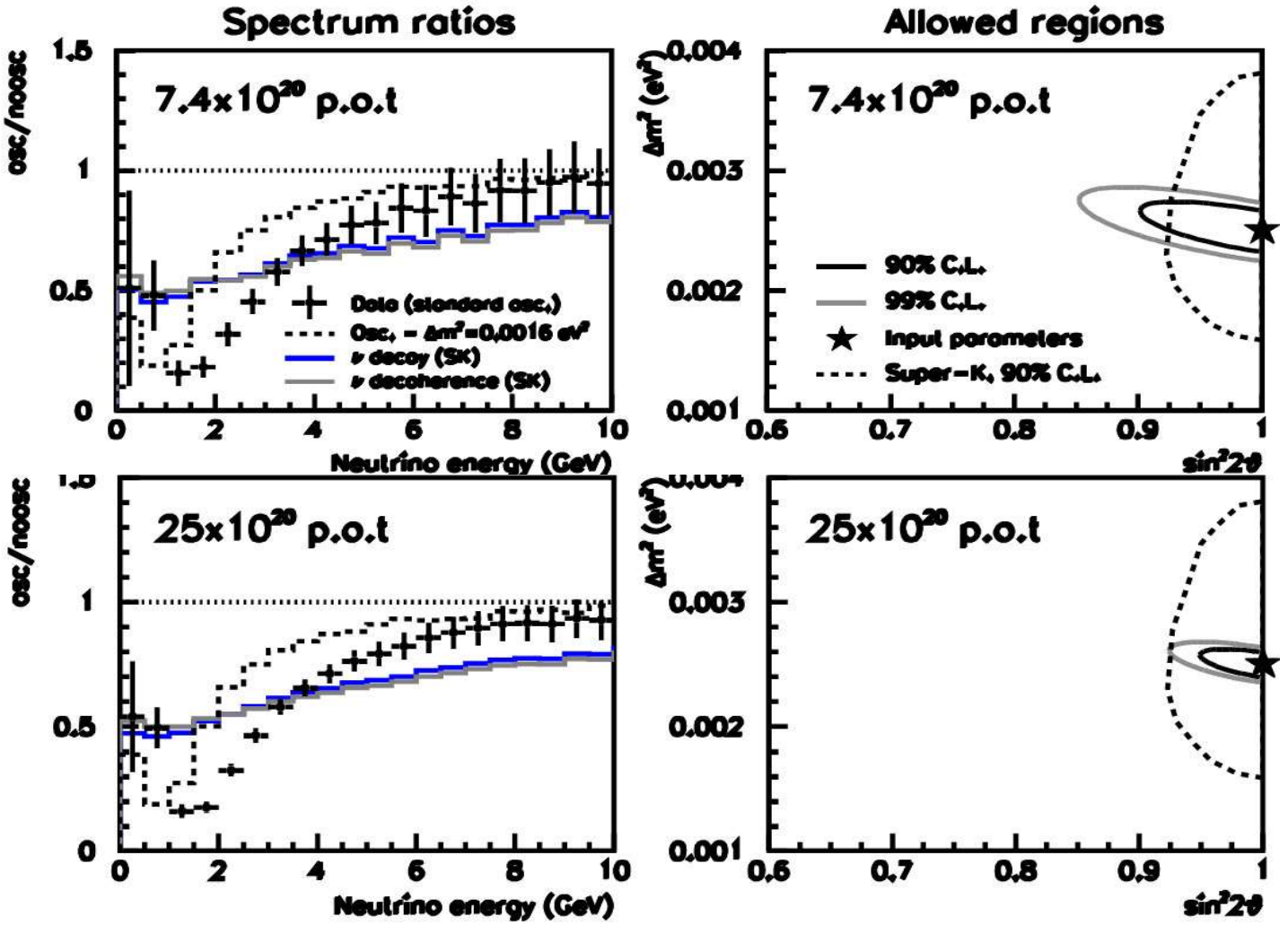
MINOS Far Detector

- 5.4 kton steel & scintillator
- 735 km from target
- 486 steel planes (B=1.3 T)



Muon Neutrino Disappearance

MC Prediction for $\Delta m^2 = 0.0025\ eV^2$, $\sin^2 2\theta = 1.0$

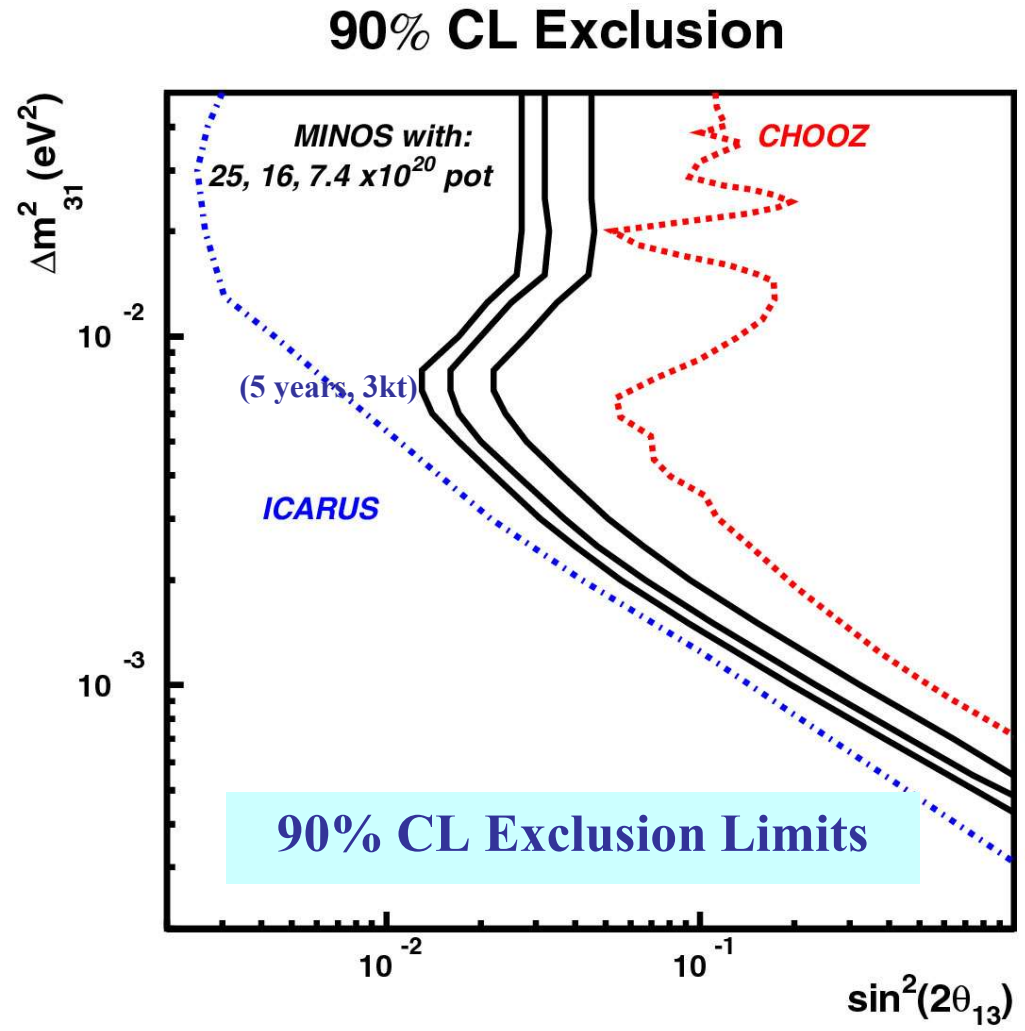


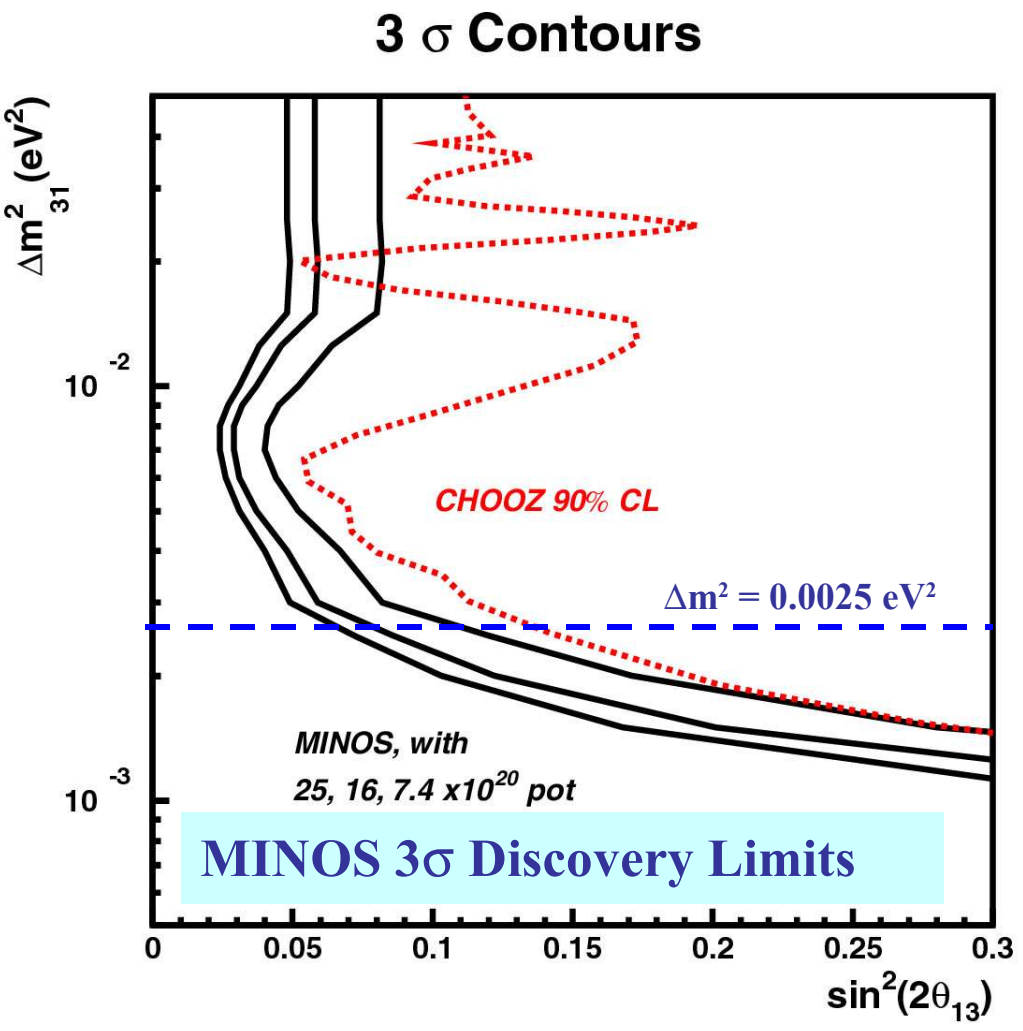
Oscillated/unoscillated ratio of number of ν_μ CC events in the far detector vs E_{obs}

MINOS 90% and 99% CL allowed oscillation parameter space.

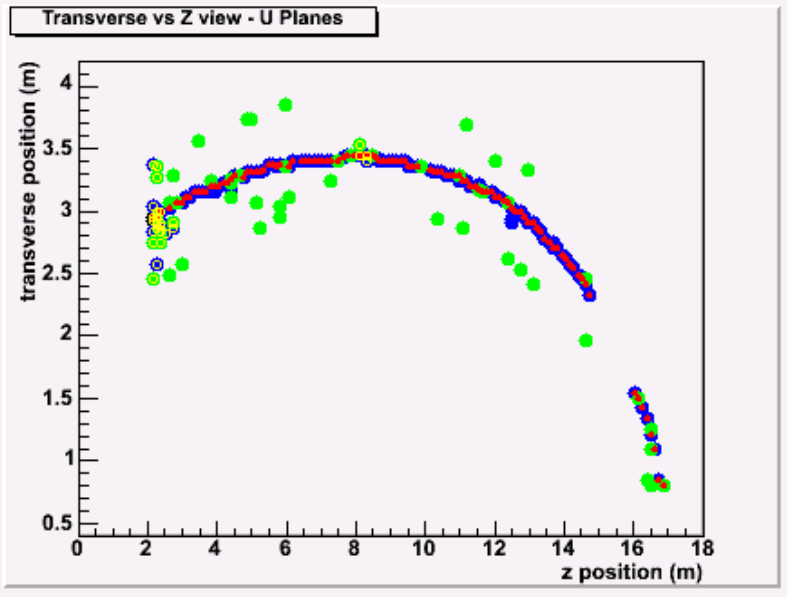
Electron Neutrino Appearance

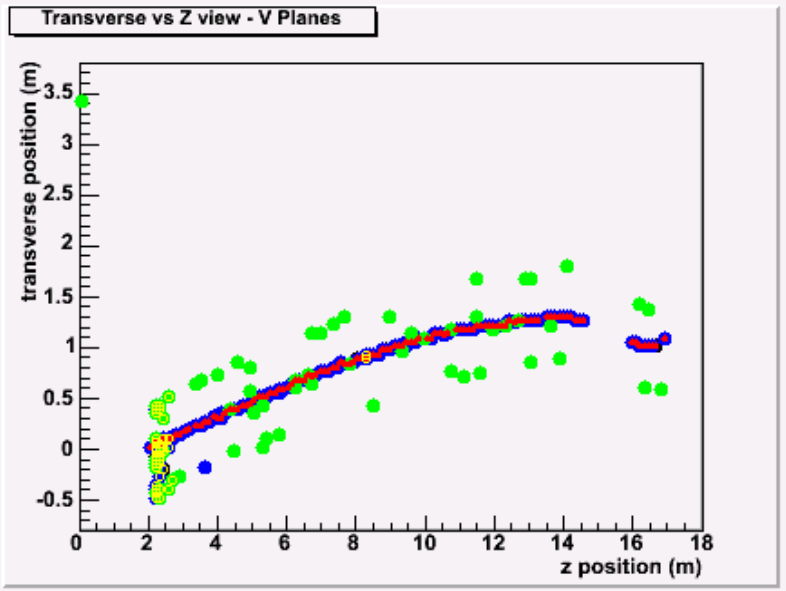
- MINOS sensitivities based on varying numbers of protons on target





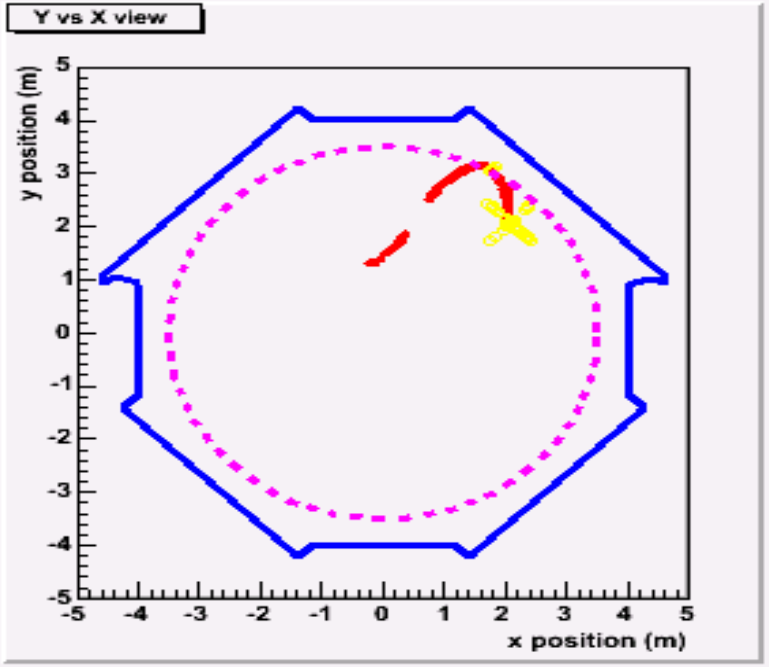
Far Detector: Numu CC Event





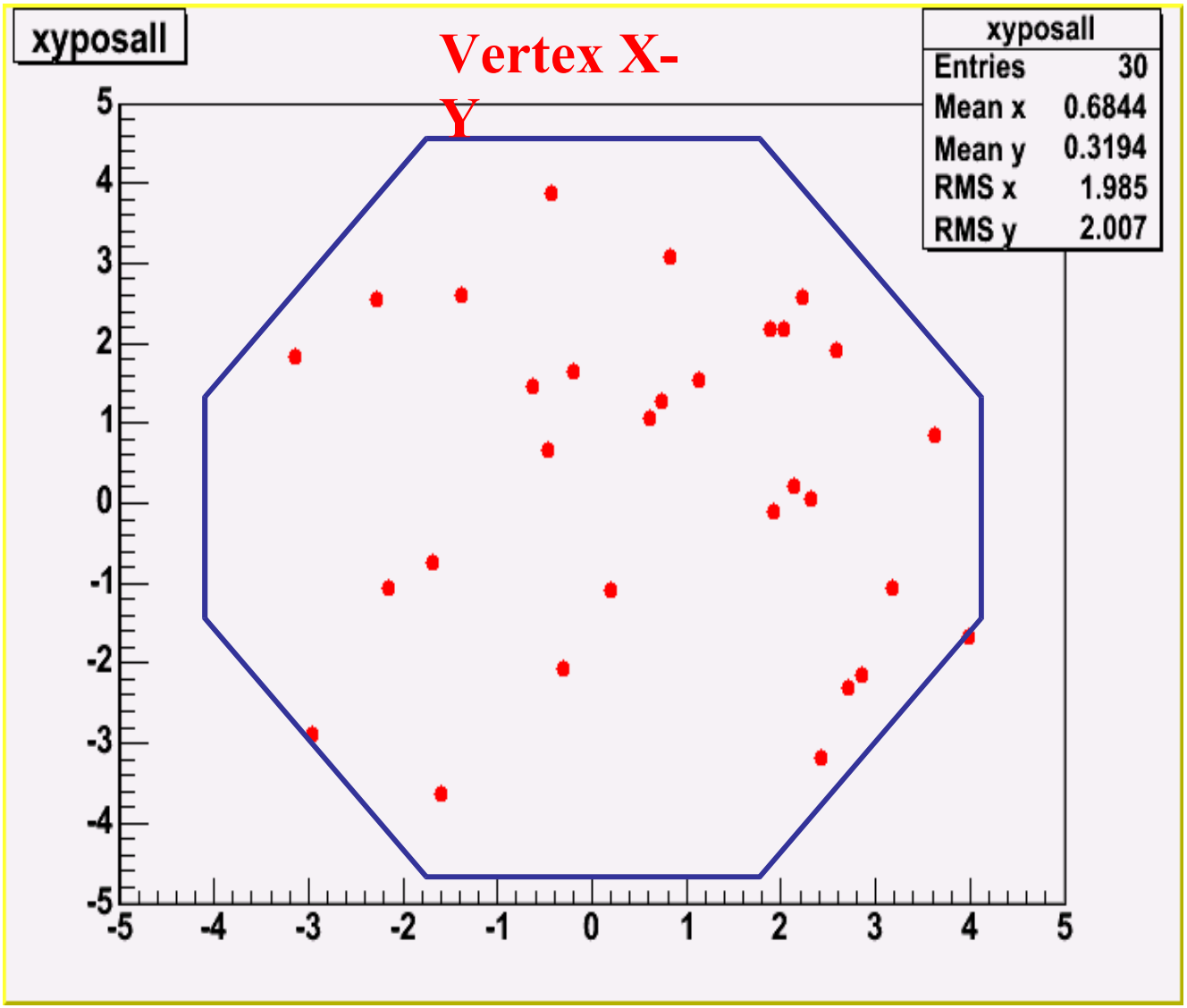
An Example:

14.7 GeV Netrino interaction (HE beam run)

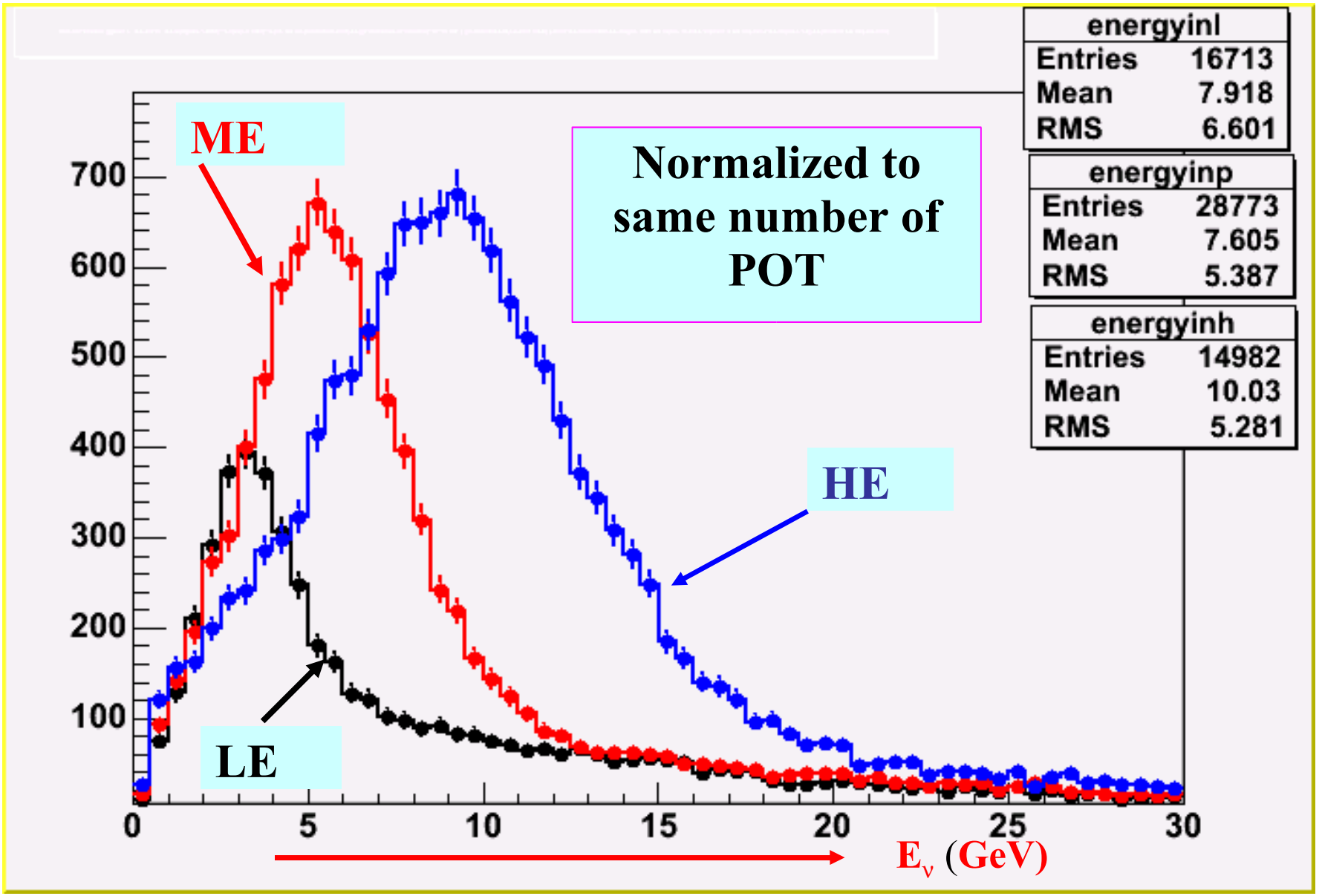


Far Detector: ν-event Analysis

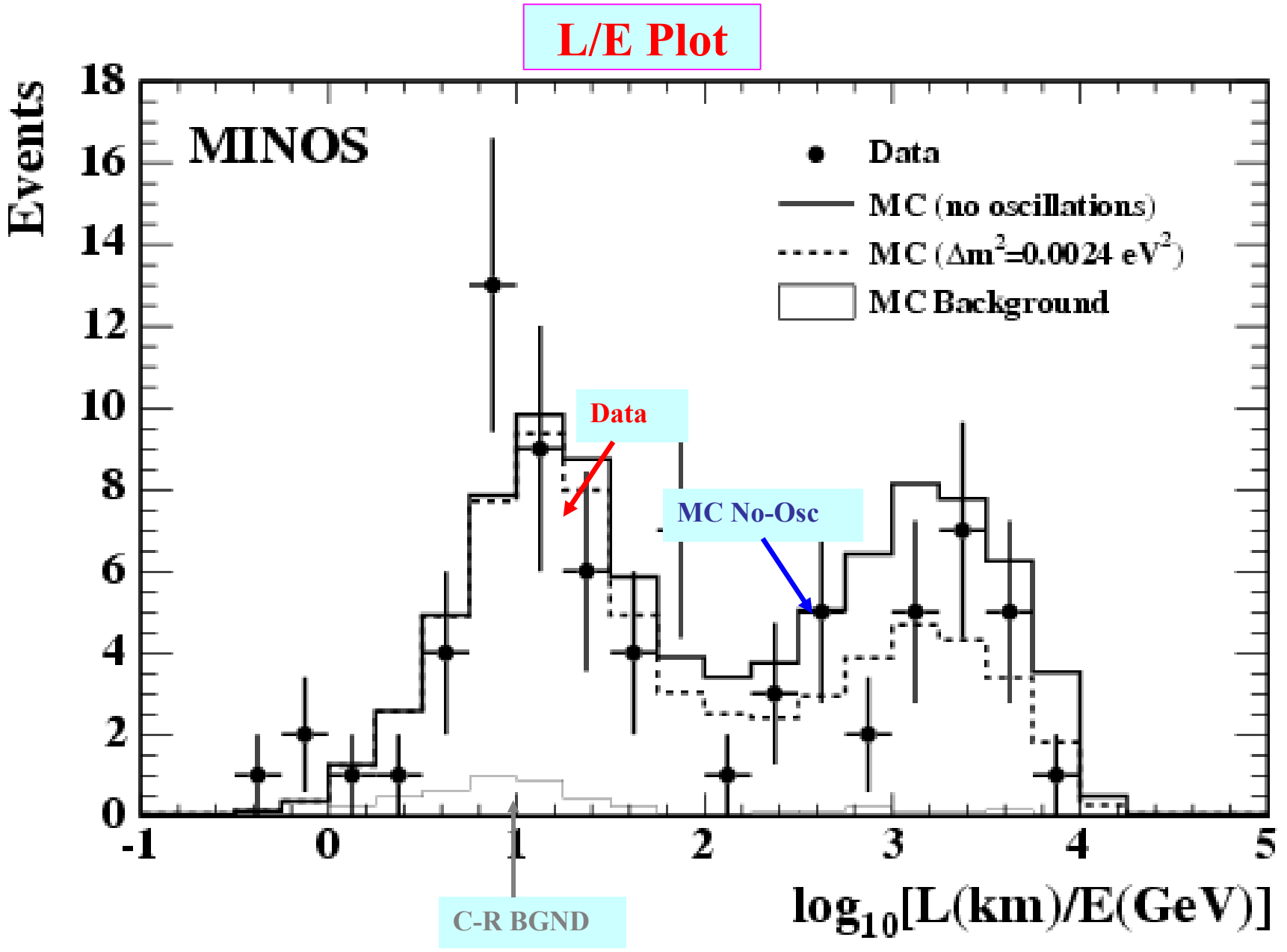
- Event characteristics in agreement with expectations
  - Blind Analysis employed in the Far Detector Data



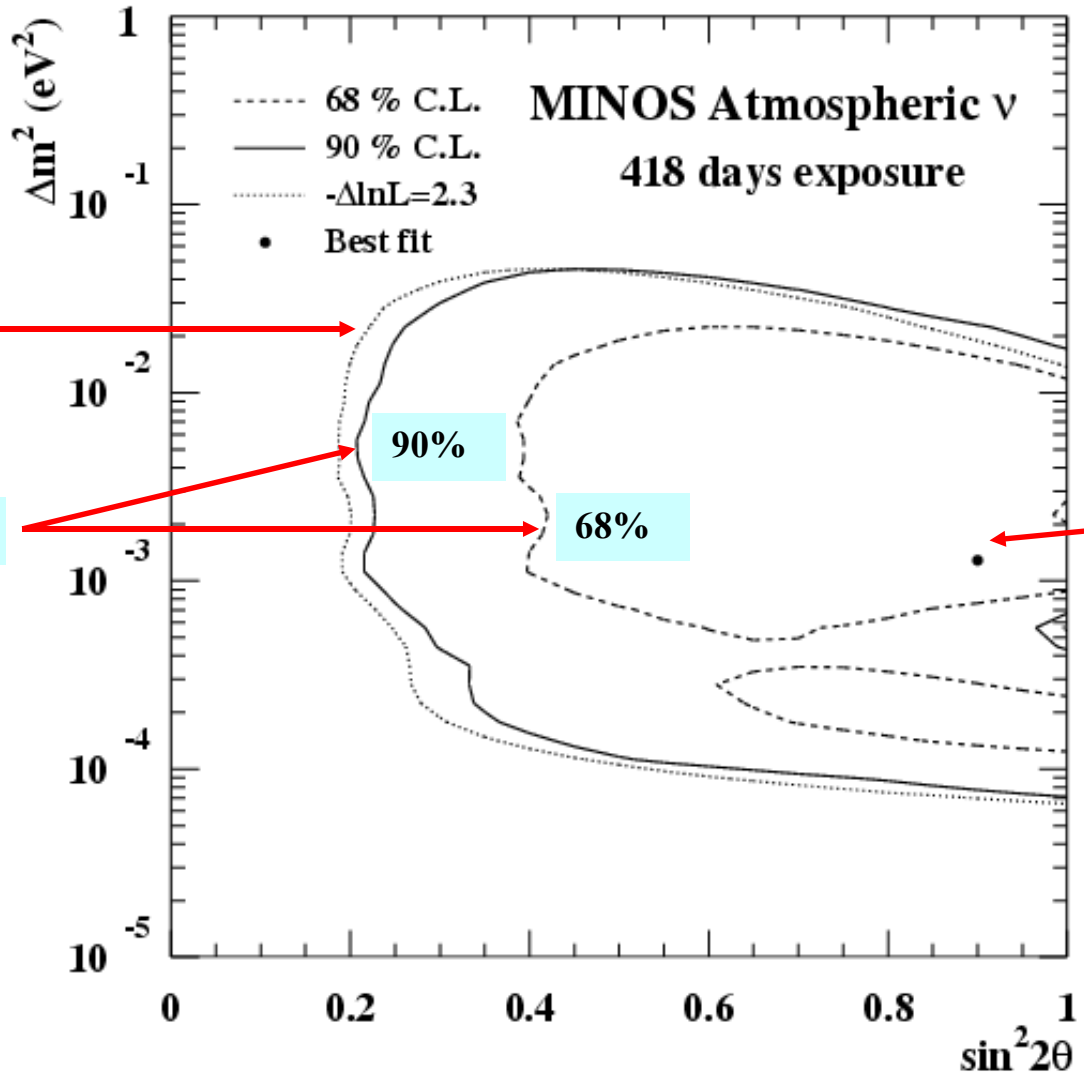
Near Detector Data: Energy Scan



Atmos FC + PC: Oscillation Analysis



MINOS ATMOS: Oscil Limits



$-\Delta\ln L = 2.3$
90% CL

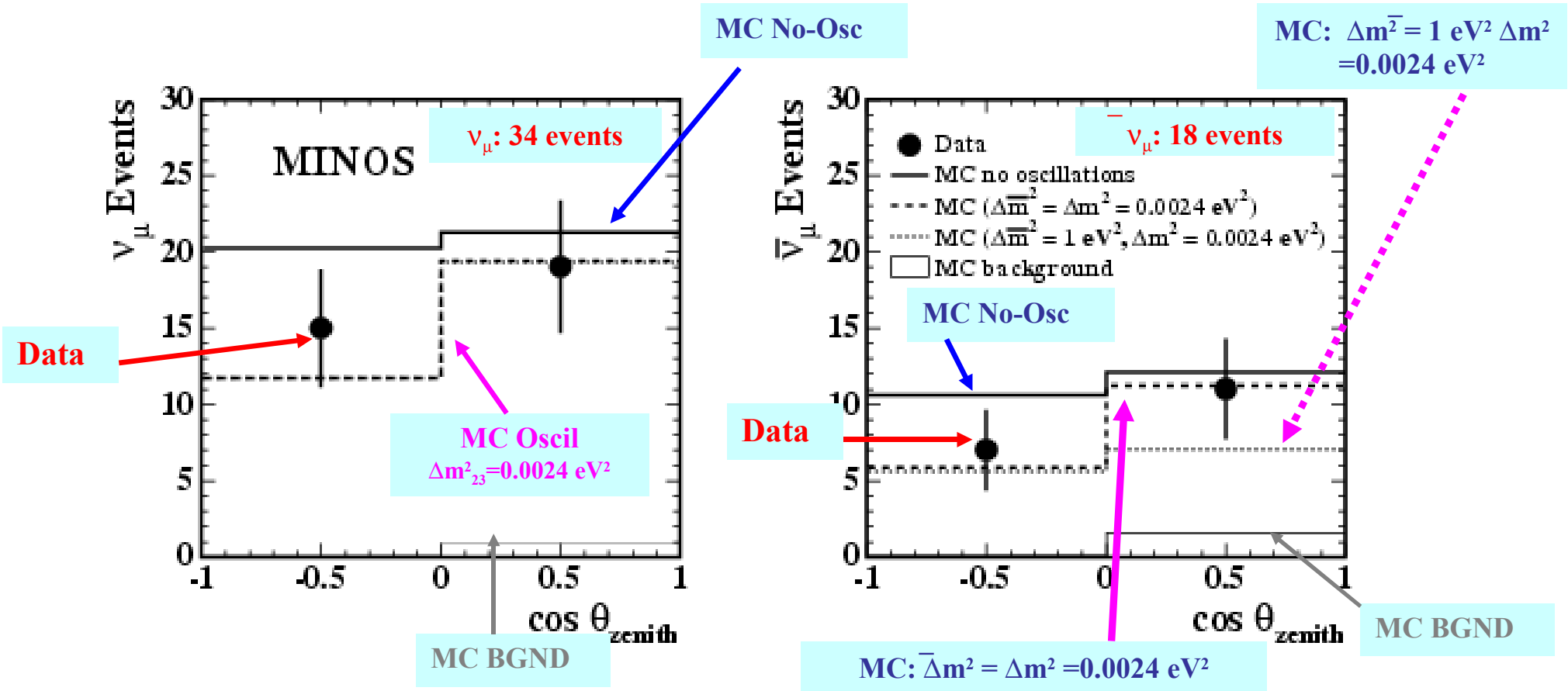
Feldman - Cousins

90%

68%

Best Fit
$\nu_\mu \leftrightarrow \nu_\tau$
$\sin^2 2\theta_{23} = 0.90$
$\Delta m^2_{23} = 0.0013$ eV^2

ATMOS: Charge Separated Up/down Distributions



Data consistent with ν_μ and $\bar{\nu}_\mu$ oscillating with same parameters.

CPT violating scenarios with large Δm^2_{23} not excluded with current data

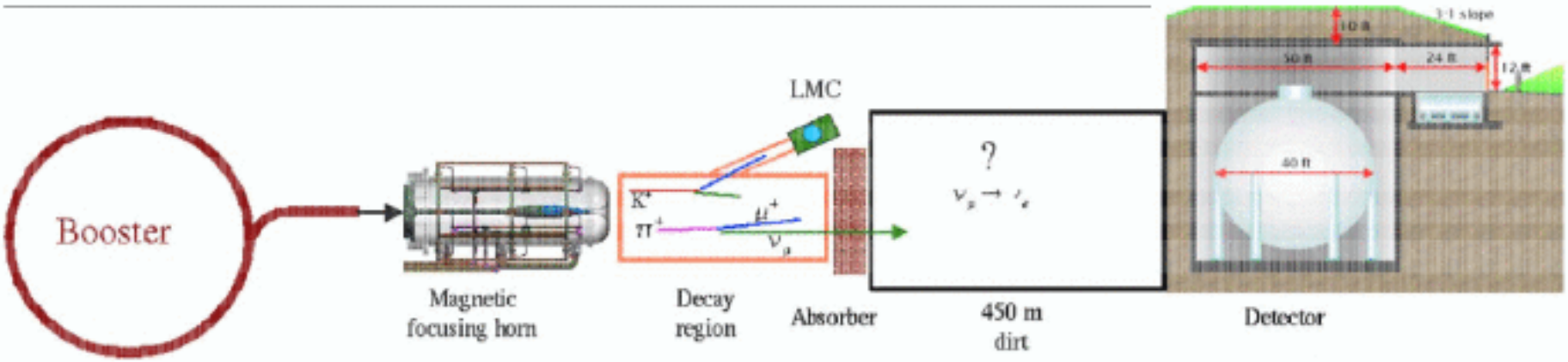
MINOS Schedule

- The MINOS Detectors and NuMI Beam construction and Commisioning have been succesfully completed.
- Collecting Atmospheric Neutrino data since July 2003
- Collecting Accelerator Neutrino Data since March 2005
- First Results of FC and PC atmospheric neutrinos: Expect preprint in hep server soon.
- NuMI beam intensity is continuously improving, expect to have $1x10^{20}$ POT by the end of 2005.
- Both MINOS detectors operating satisfactorily
- Expect first physics results from NuMI beam neutrinos in 2006

MiniBooNE: A Definitive Test of the LSND Evidence for Oscillations: Search for $\nu_\mu \rightarrow \nu_e$

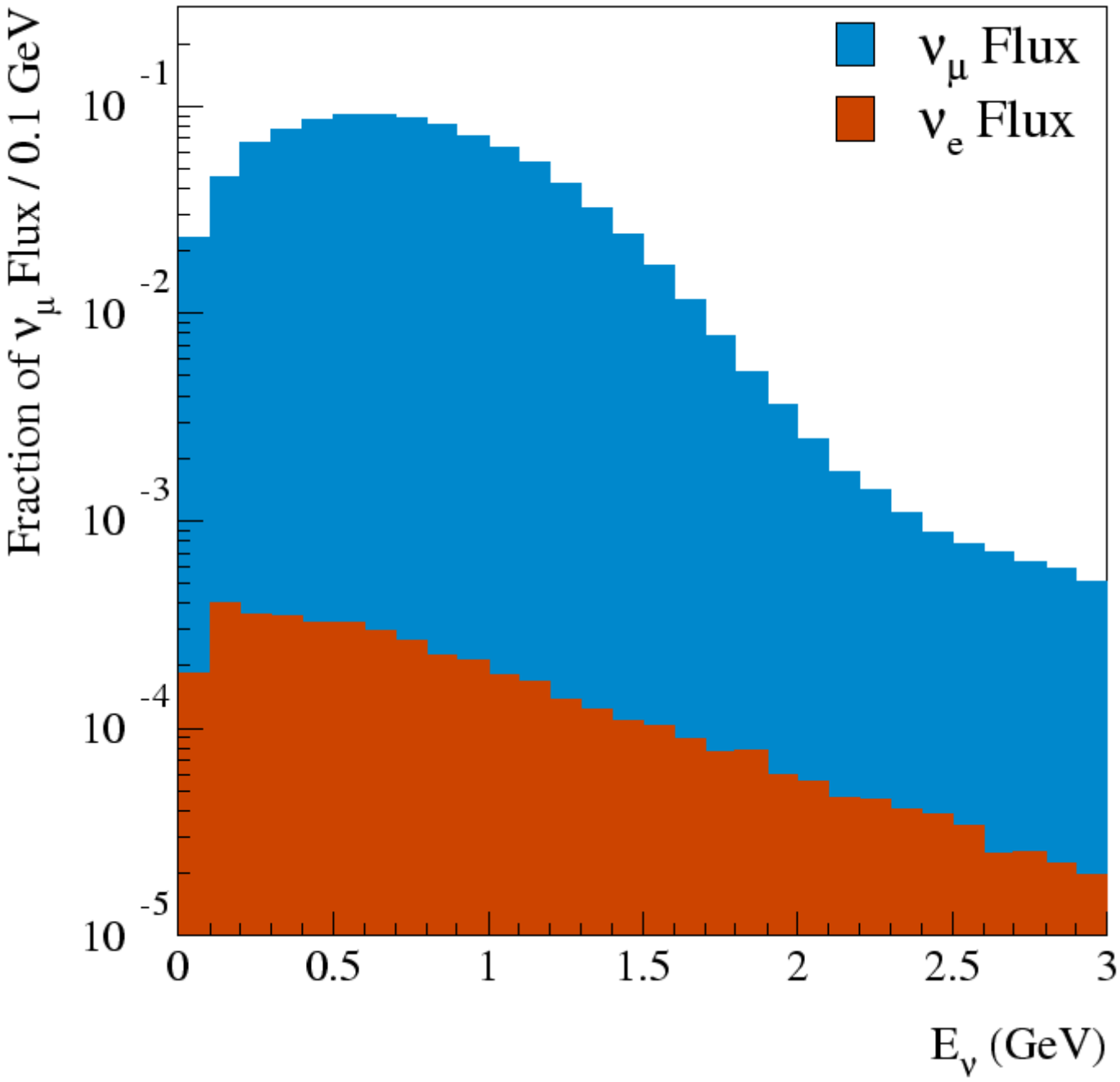
Alabama, Bucknell, Cincinnati, Colorado, Columbia, Embry-Riddle, Fermilab, Indiana, Los Alamos, LSU, Michigan, Princeton, St. Mary's, Western Illinois, Yale

MiniBooNE - A Definitive Test of the LSND Evidence for ν Oscillations



- Booster - 8 GeV proton beam (5 x 10^{20} POT/y)
- Target - 71 cm Be
- Horn - 5 Hz, 170 kA, 143 μs, 2.5 kV, 10^{8} pulses/y
- Decay Pipe - 50 m (adjustable to 25 m)
- Neutrino Distance - ~ 0.5 km
- $\langle E_\nu \rangle$ ~ 1 GeV
- (ν_e / ν_μ) ~ 5×10^{-3}
- Detector - 40' diameter spherical tank
- Mass - 800 (450) tons of mineral oil
- PMTs - 1280 detector + 240 veto, 8" diameter

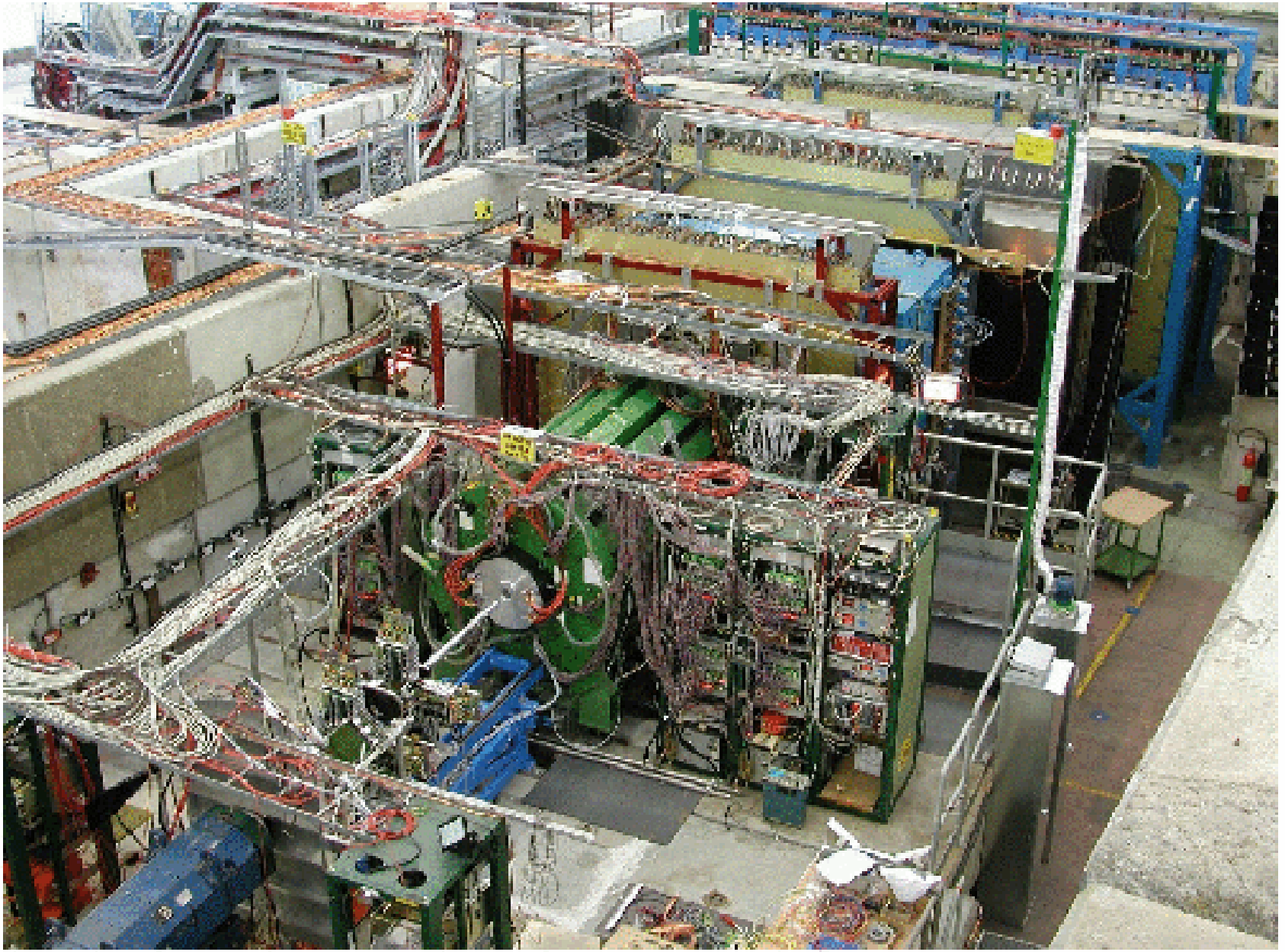
MiniBooNE Neutrino Flux



E910 at BNL
HARP at CERN

HARP Experiment at CERN

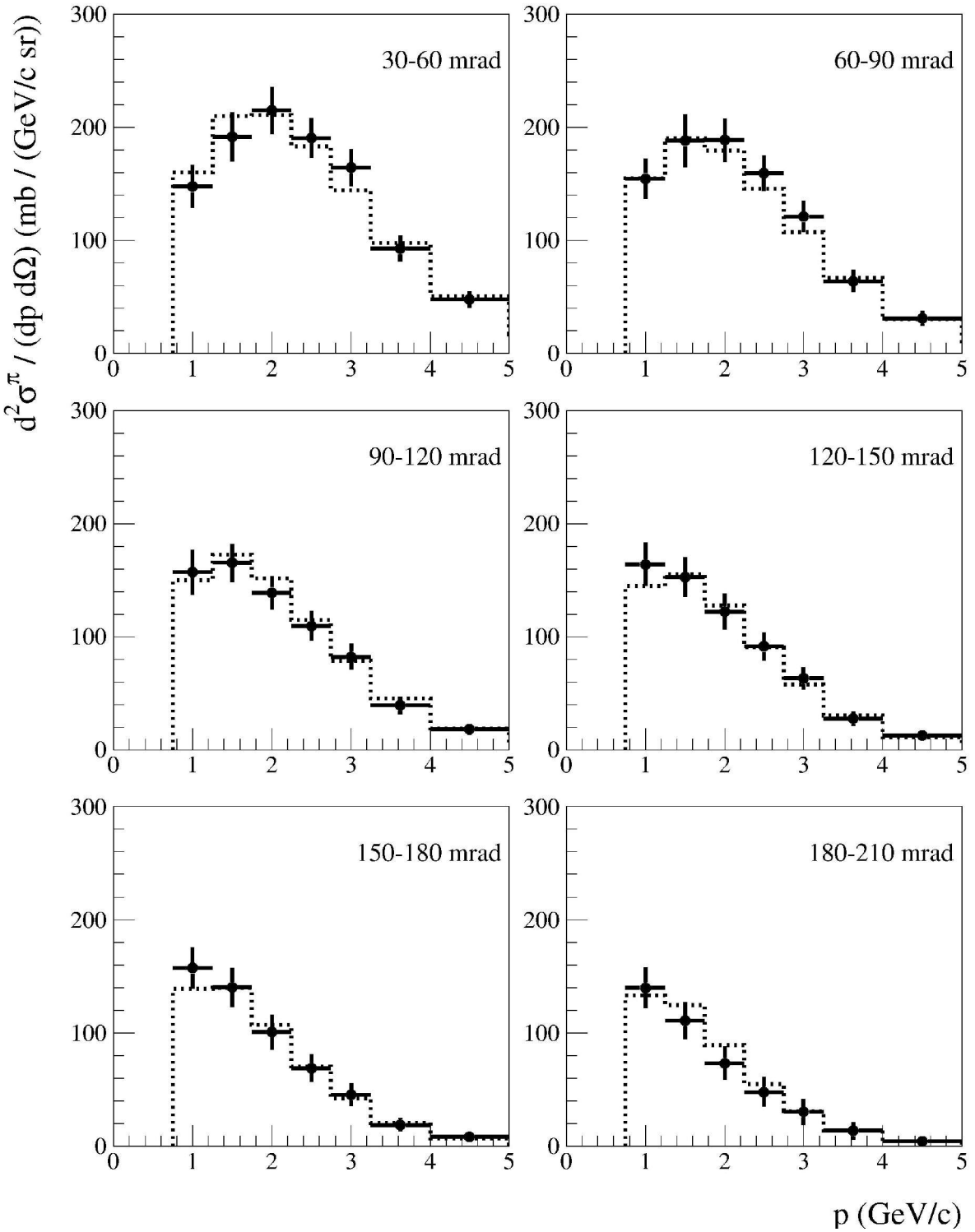
(parallel session talk by Borghi)



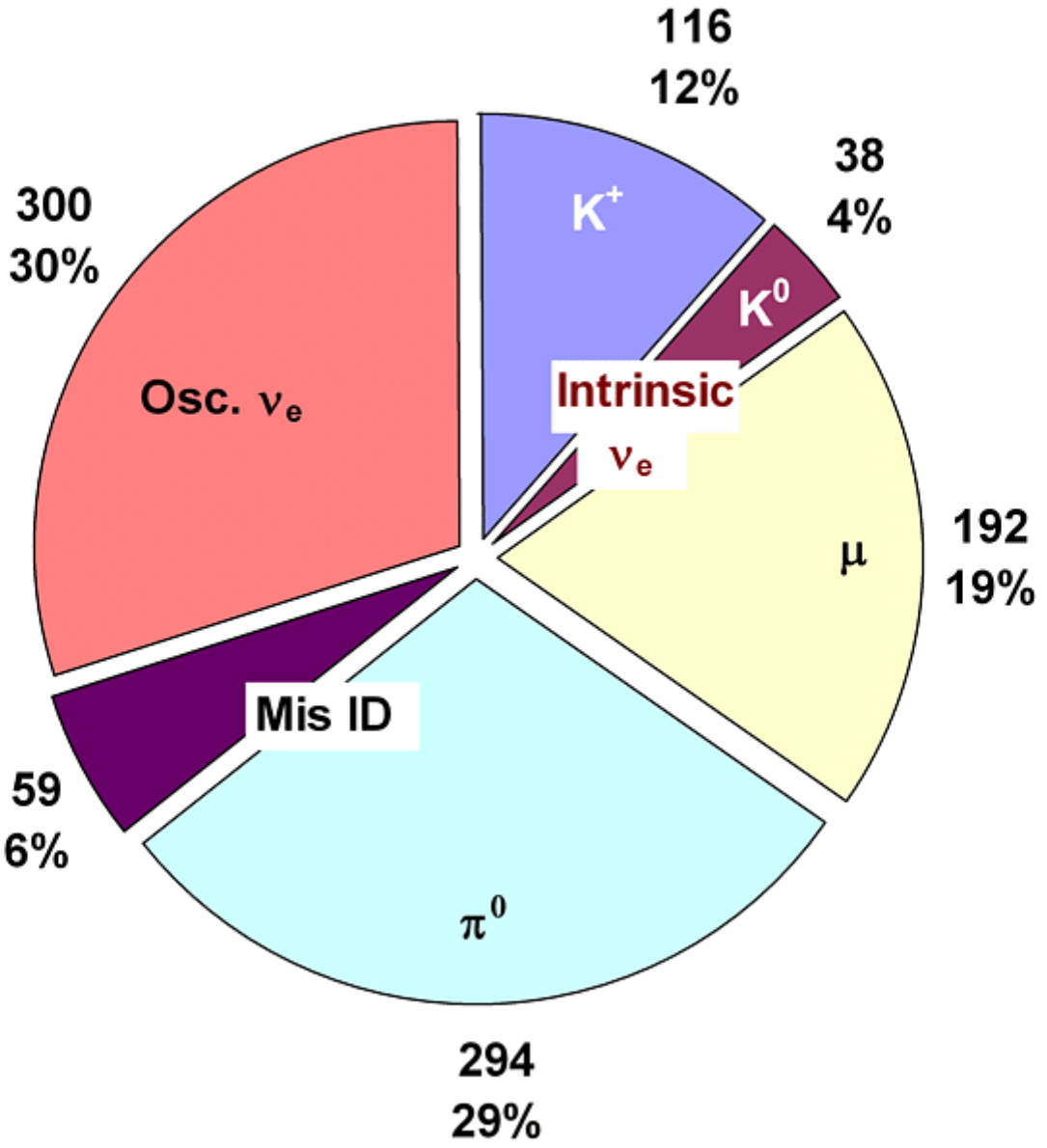
Preliminary HARP results for 8.9 GeV/c Be data: Important for MiniBooNE

Fit to Sanford-Wang parameterization of production cross section (dotted line)

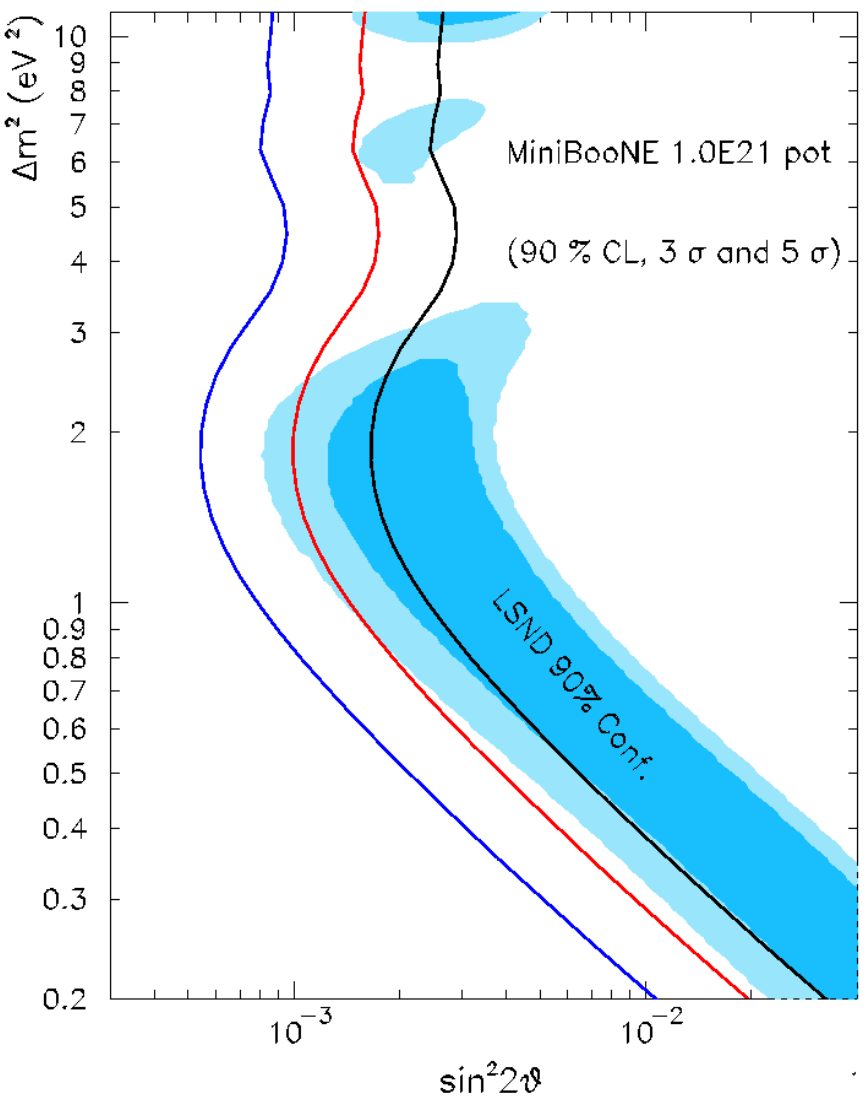
The preliminary p-Be π^+ production cross sections are consistent at the 10-15% level with previous p-Be π^+ production measurements

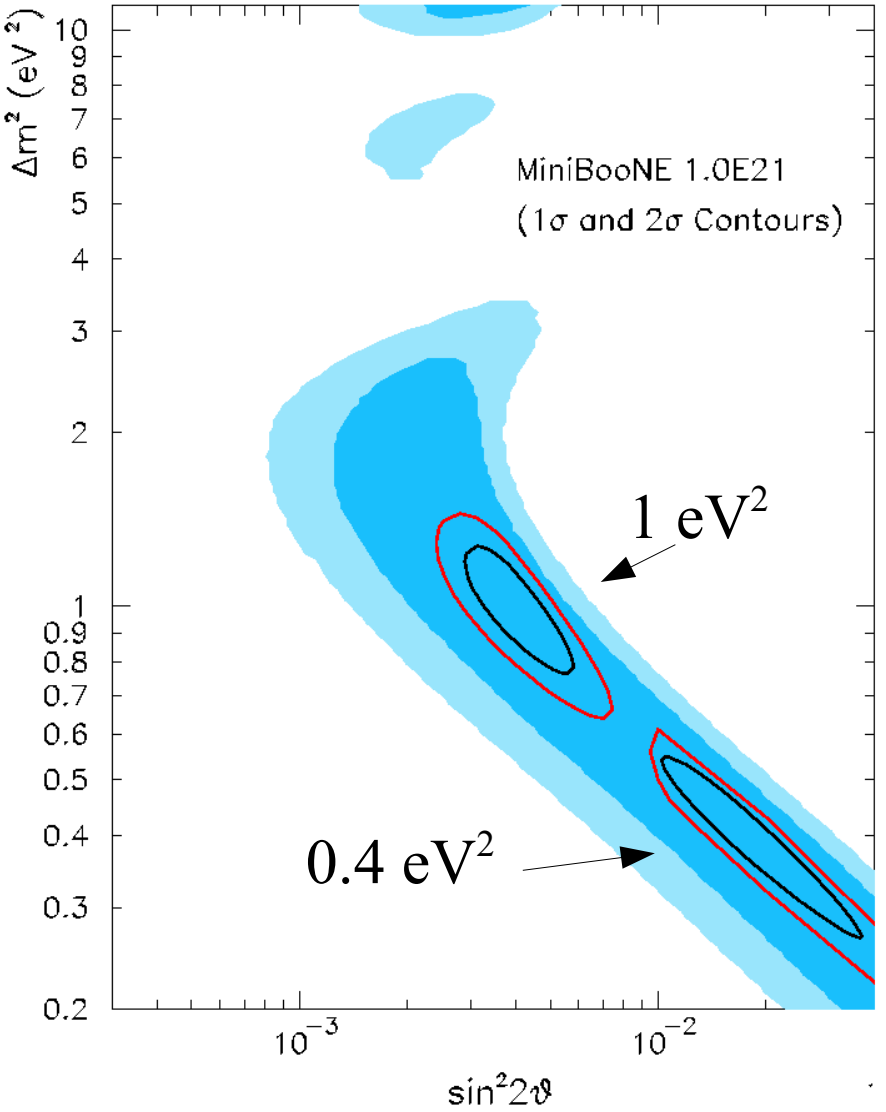


NUANCE Prediction After PID Selection



Expected MiniBooNE Sensitivity

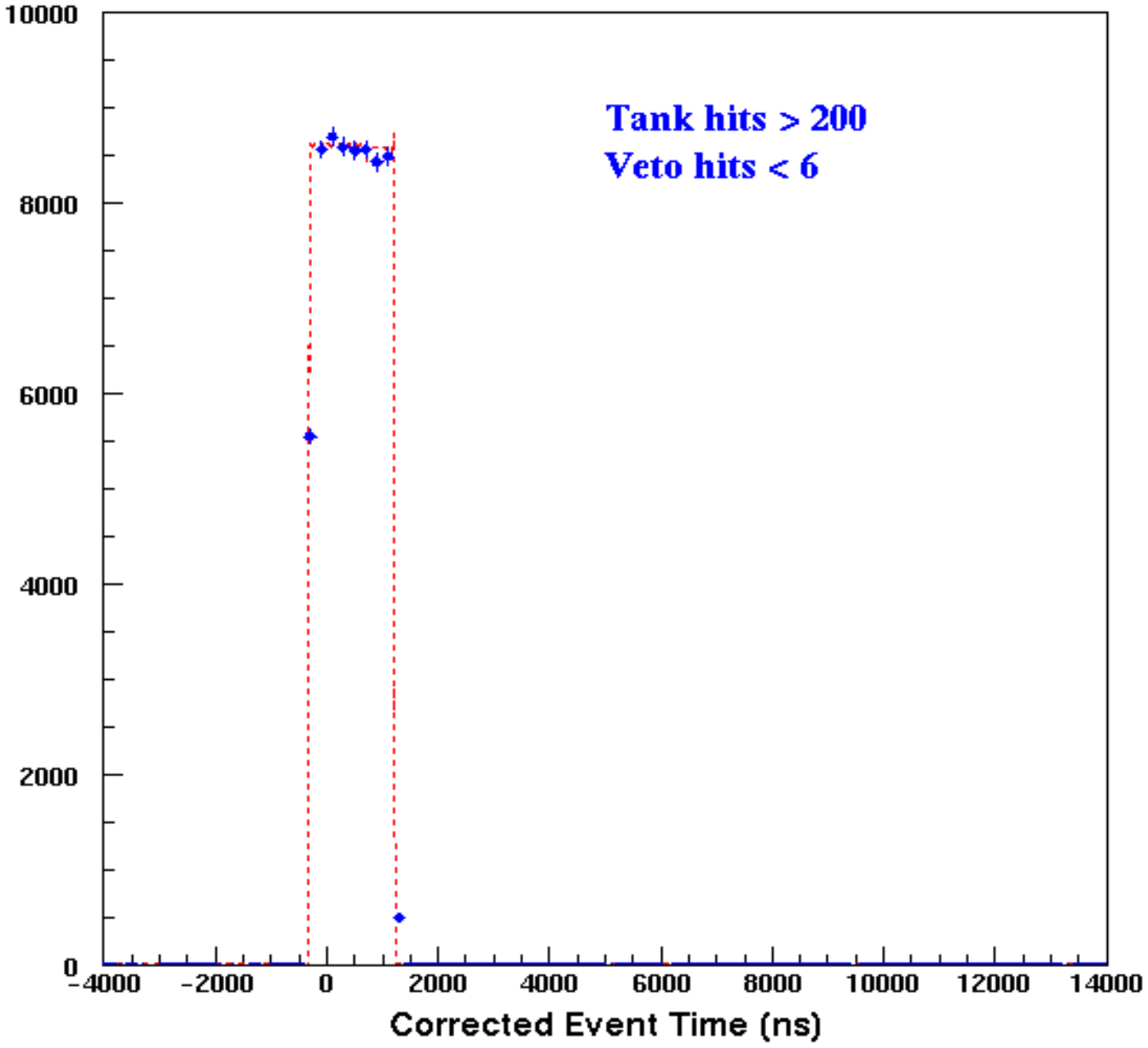




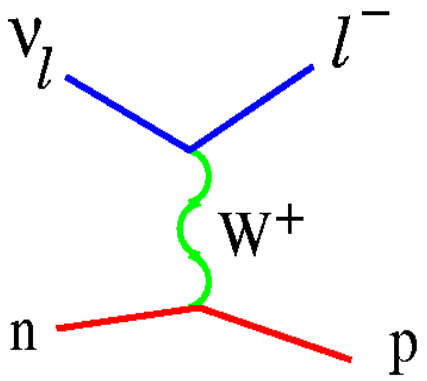
MiniBooNE Neutrino Events Are Very Clean!

Neutrino Signal to Cosmic-Ray Background ~ 5000 to 1!

Have collected a total of ~700K neutrino events from ~6.5E20 POT



I. CCQE Events $\nu_\mu\ ^{12}C \rightarrow \mu^-\ p\ ^{11}C^*$



About 48% of the MiniBooNE events are **CCQE**

MiniBooNE now has one of the largest sample of **CCQE** events!

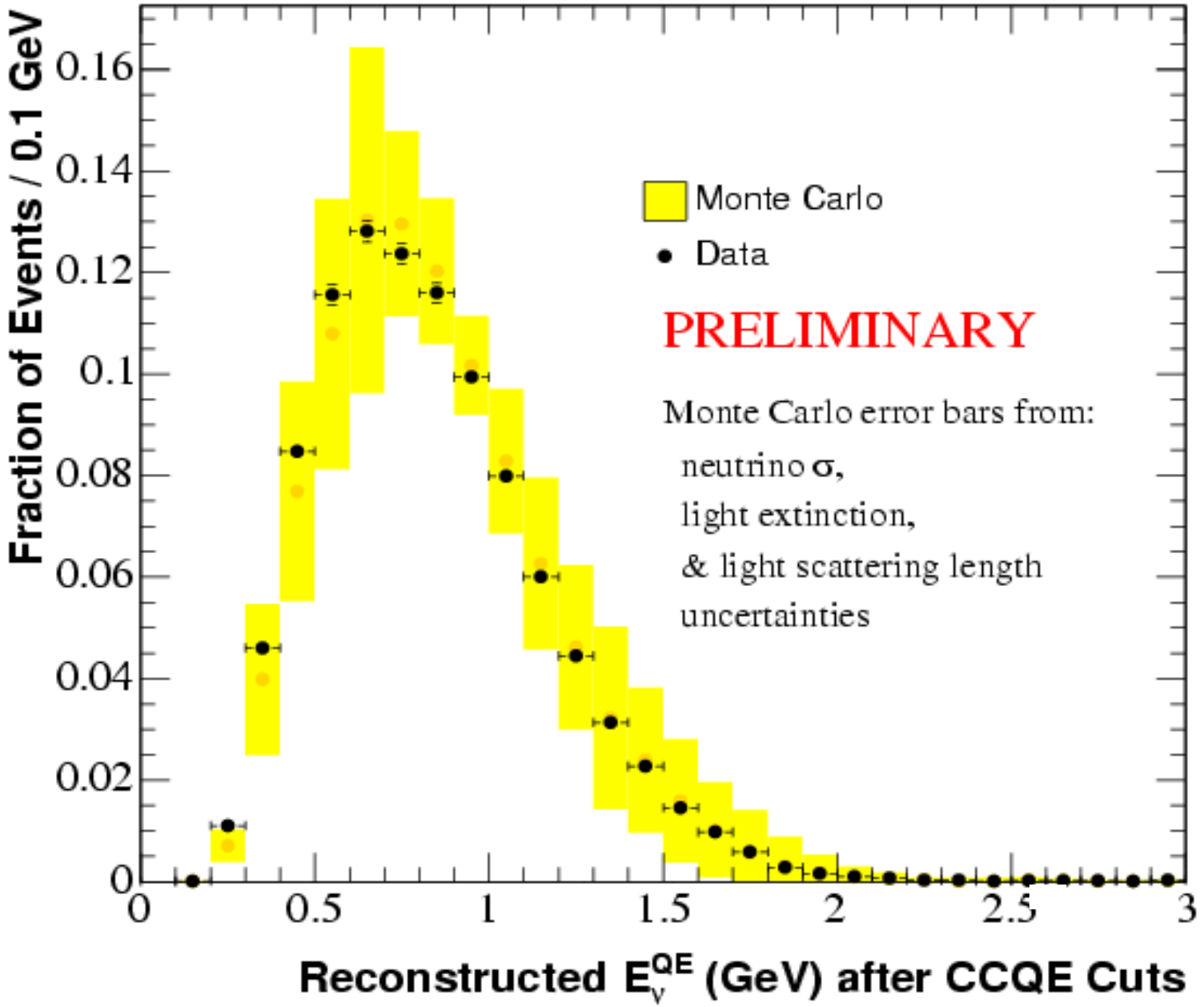
Important for ν_μ Disappearance & ν_e Appearance Background

Serves as the "Golden Mode" for Measuring Cross Sections

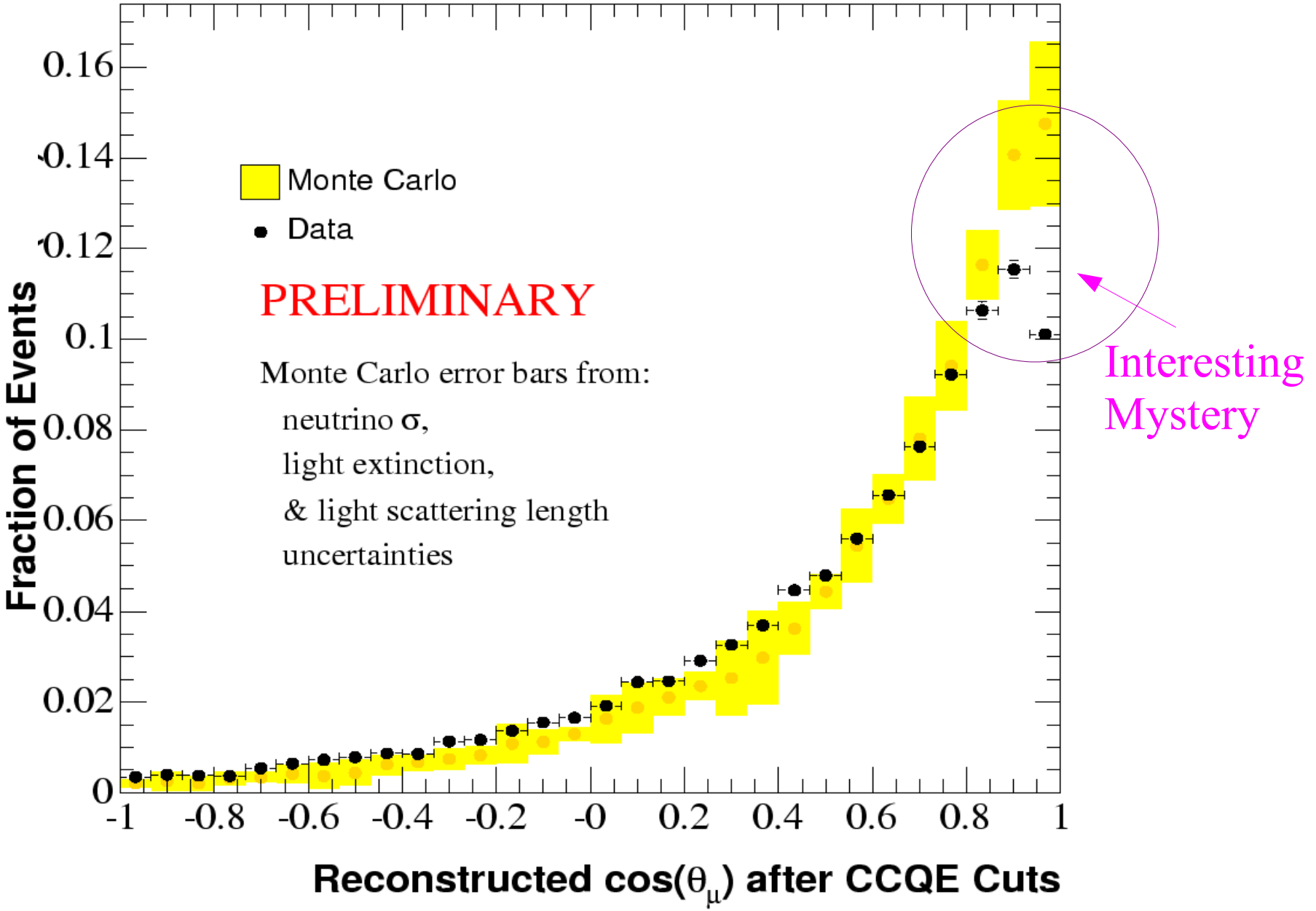
Selection: Single ring event, consistent with a muon

CCQE Energy Distribution

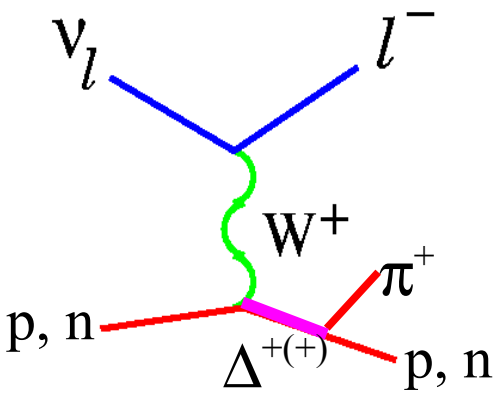
~10% energy resolution



CCQE Angular Distribution



II. CC π^+ Events $\nu_\mu\ ^{12}C \rightarrow \mu^-\pi^+X$



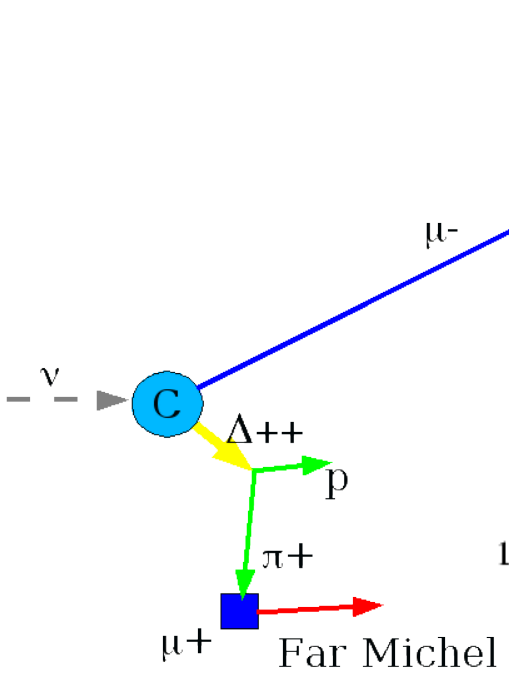
Not Well Measured at Low Energies

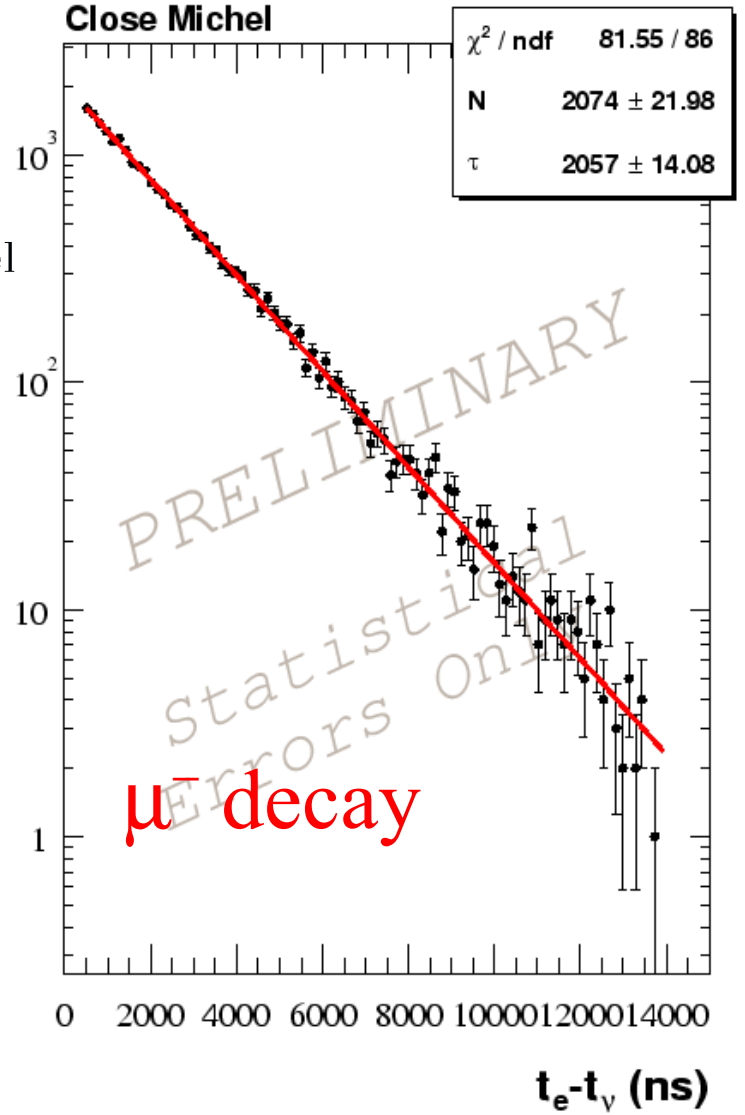
About 31% of the MiniBooNE events are **CC** π^+

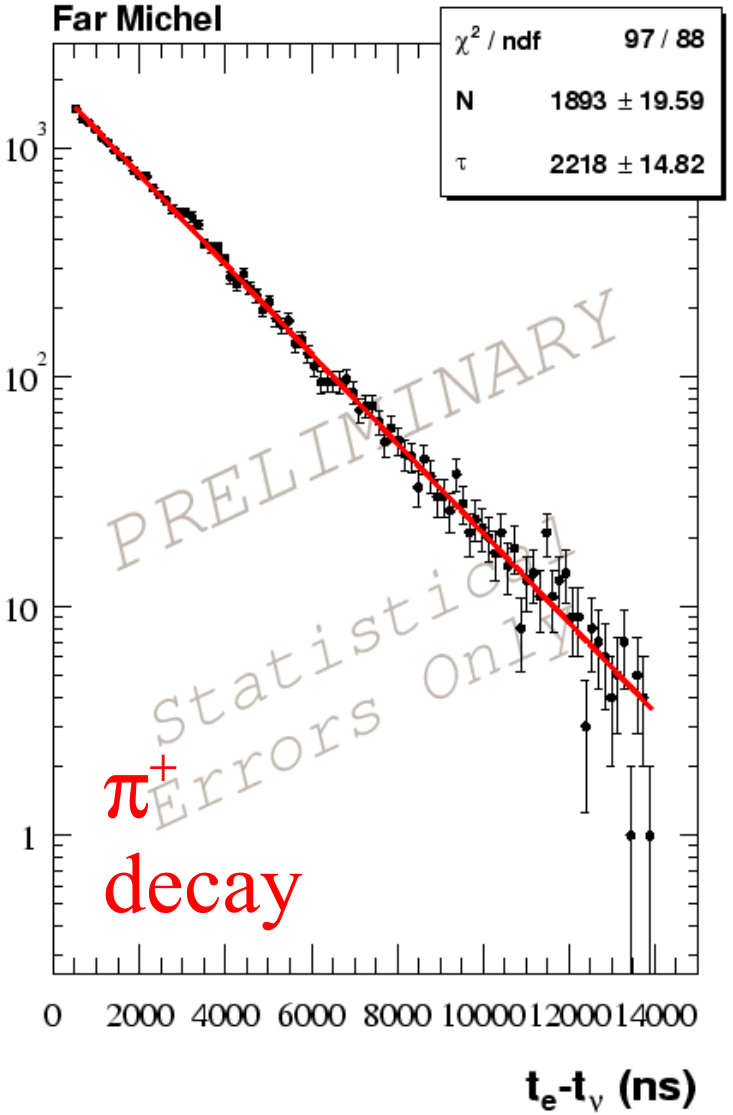
MiniBooNE now has the world's largest sample of **CC** π^+ events!

Important for ν_μ Disappearance & ν_e Appearance Background

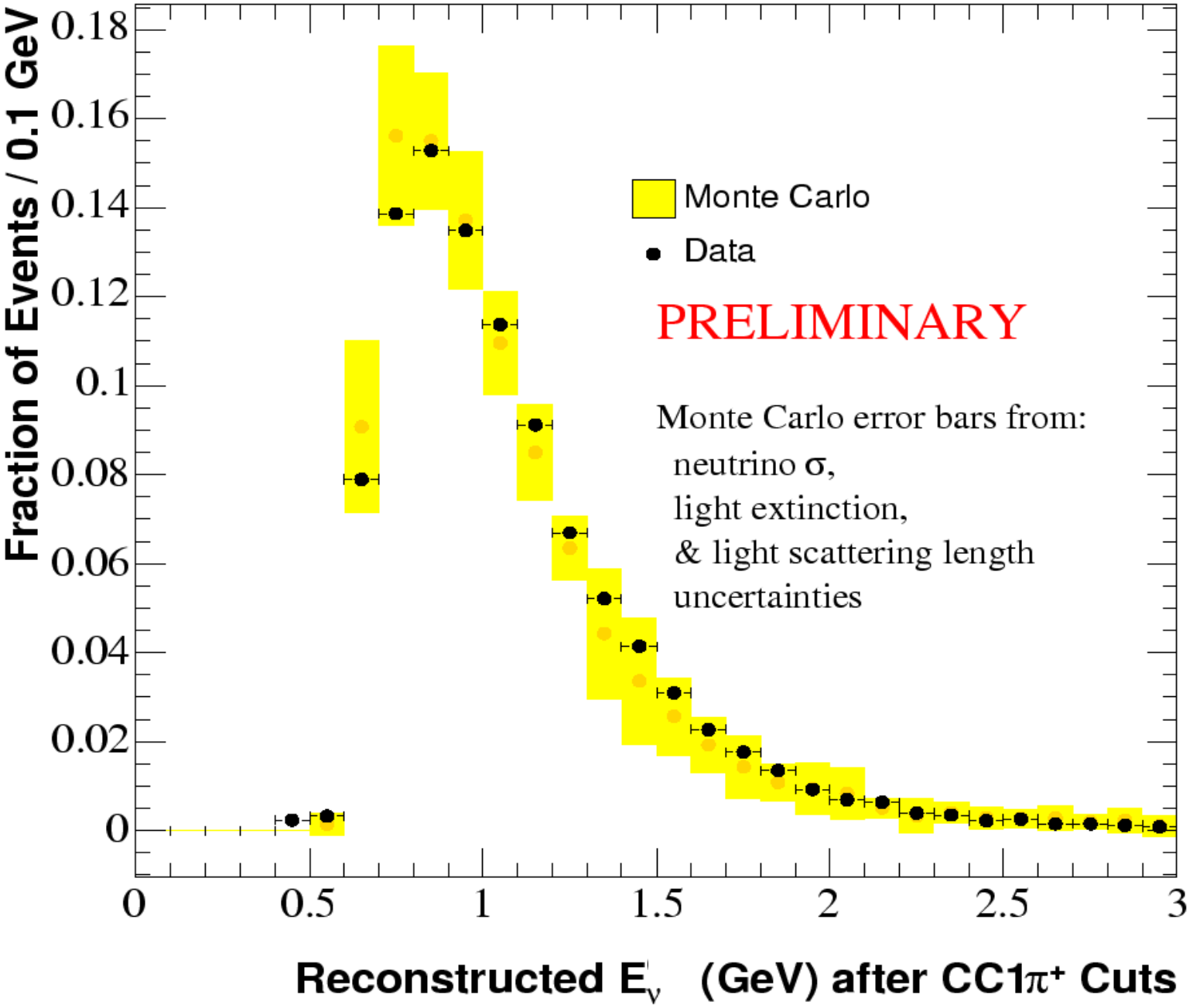
Selection: Double-ring event with 2 Michel-electrons


Close Michel
μ-
ν
C
Δ++
p
π+
μ+
Far Michel

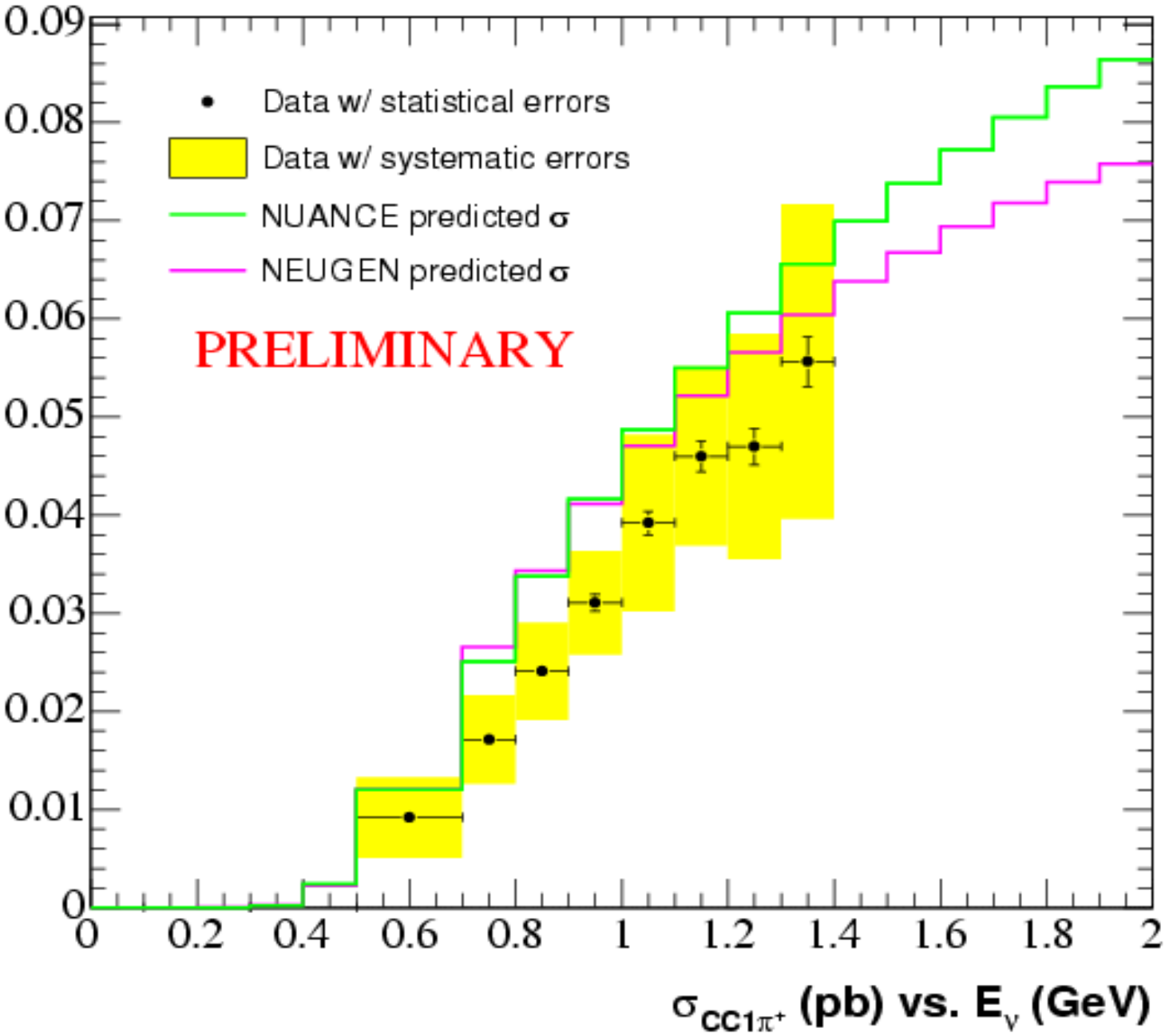

Close Michel
χ² / ndf 81.55 / 86
N 2074 ± 21.98
τ 2057 ± 14.08
PRELIMINARY
Statistical Errors Only
μ⁻ decay
t_e-t_ν (ns)


Far Michel
χ² / ndf 97 / 88
N 1893 ± 19.59
τ 2218 ± 14.82
PRELIMINARY
Statistical Errors Only
π⁺ decay
t_e-t_ν (ns)

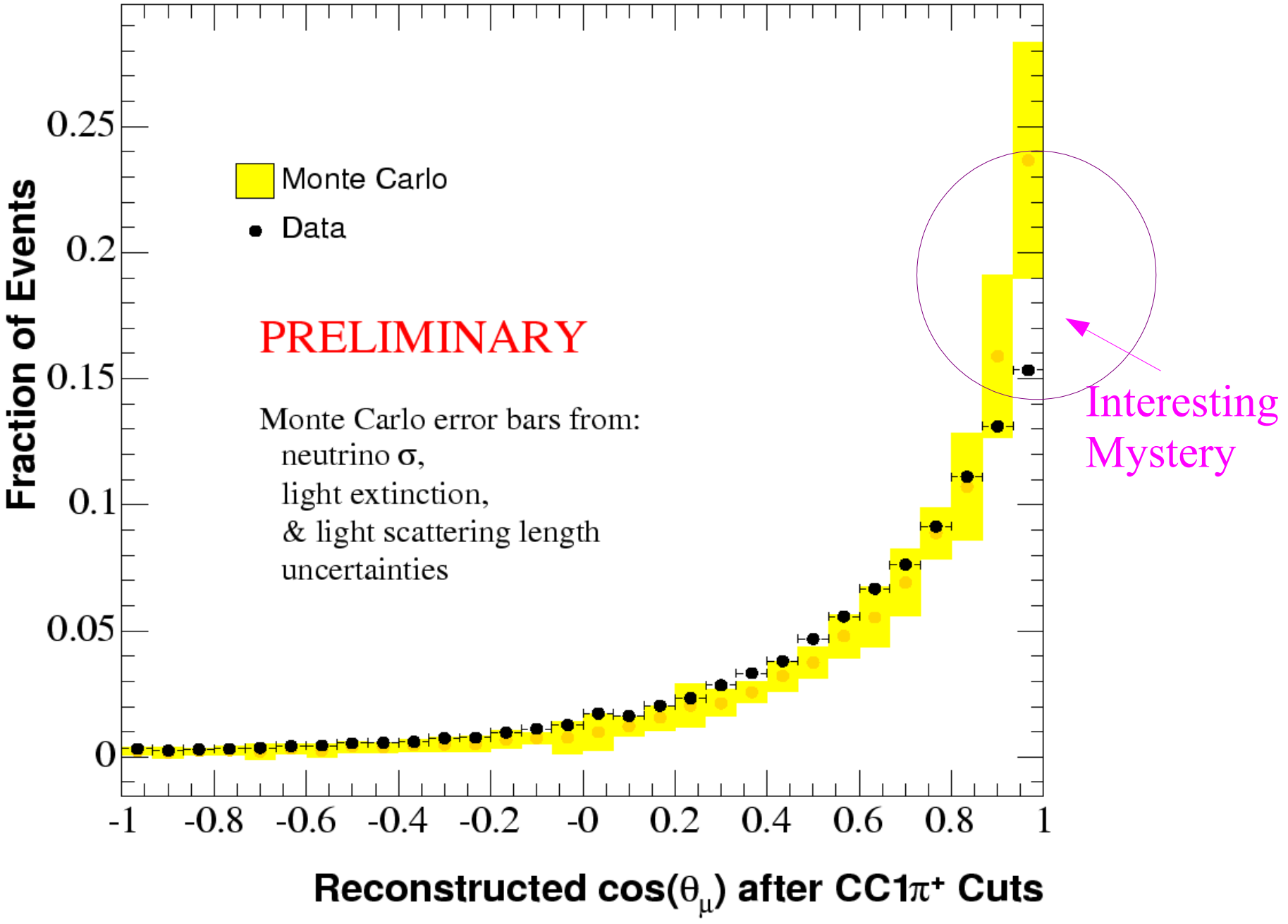
CCπ^+ Energy Distribution



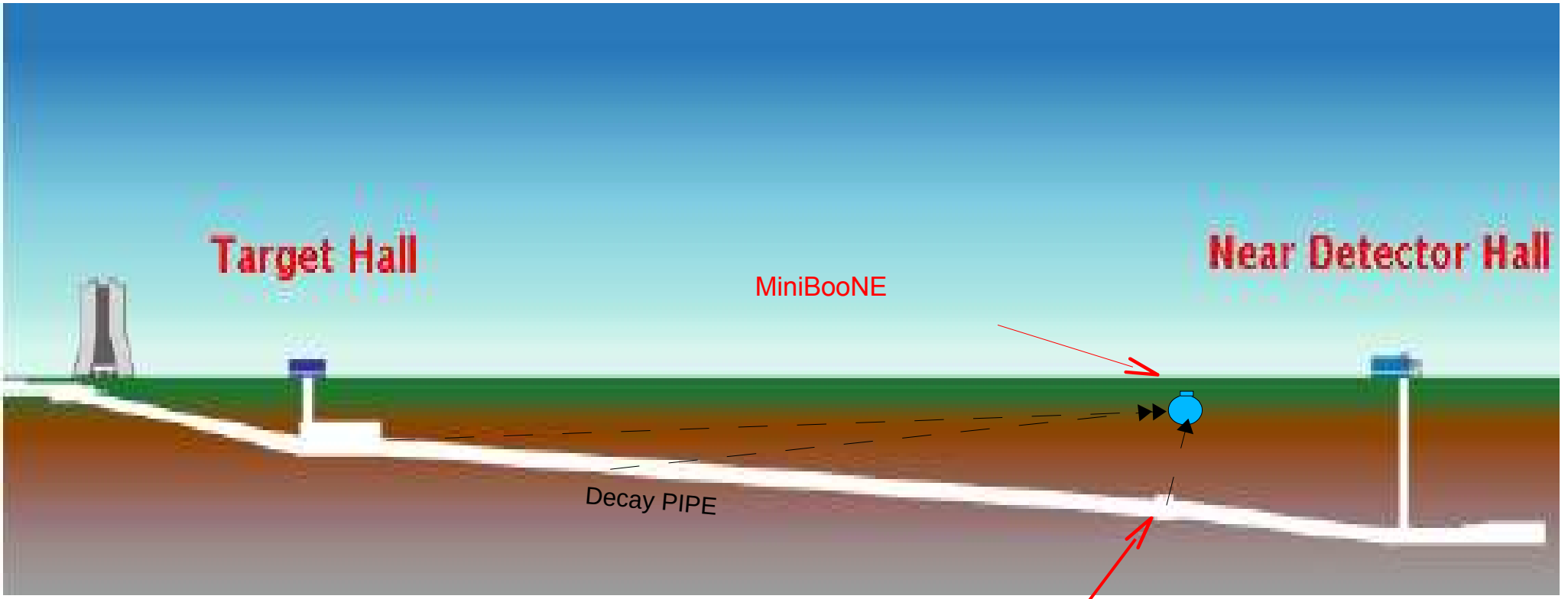
$CC\pi^+$ Cross Section
(from $CC\pi^+$/CCQE Ratio)



CCπ^+ Angular Distribution

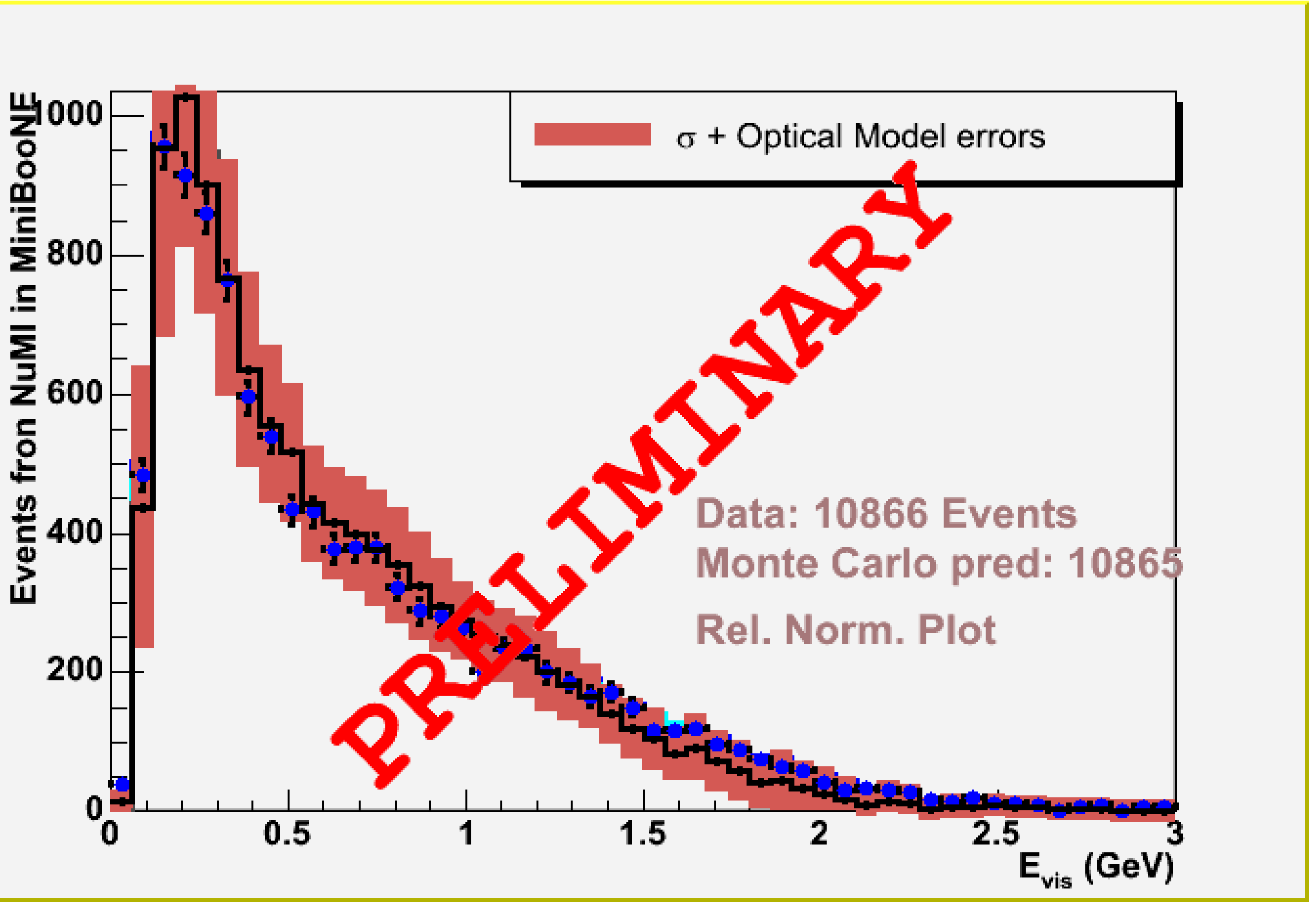


MiniBooNE Observes Events from both the 8-GeV Beamline & from NuMI



NuMI beam line

NuMI/MiniBooNE Data/MC Comparison

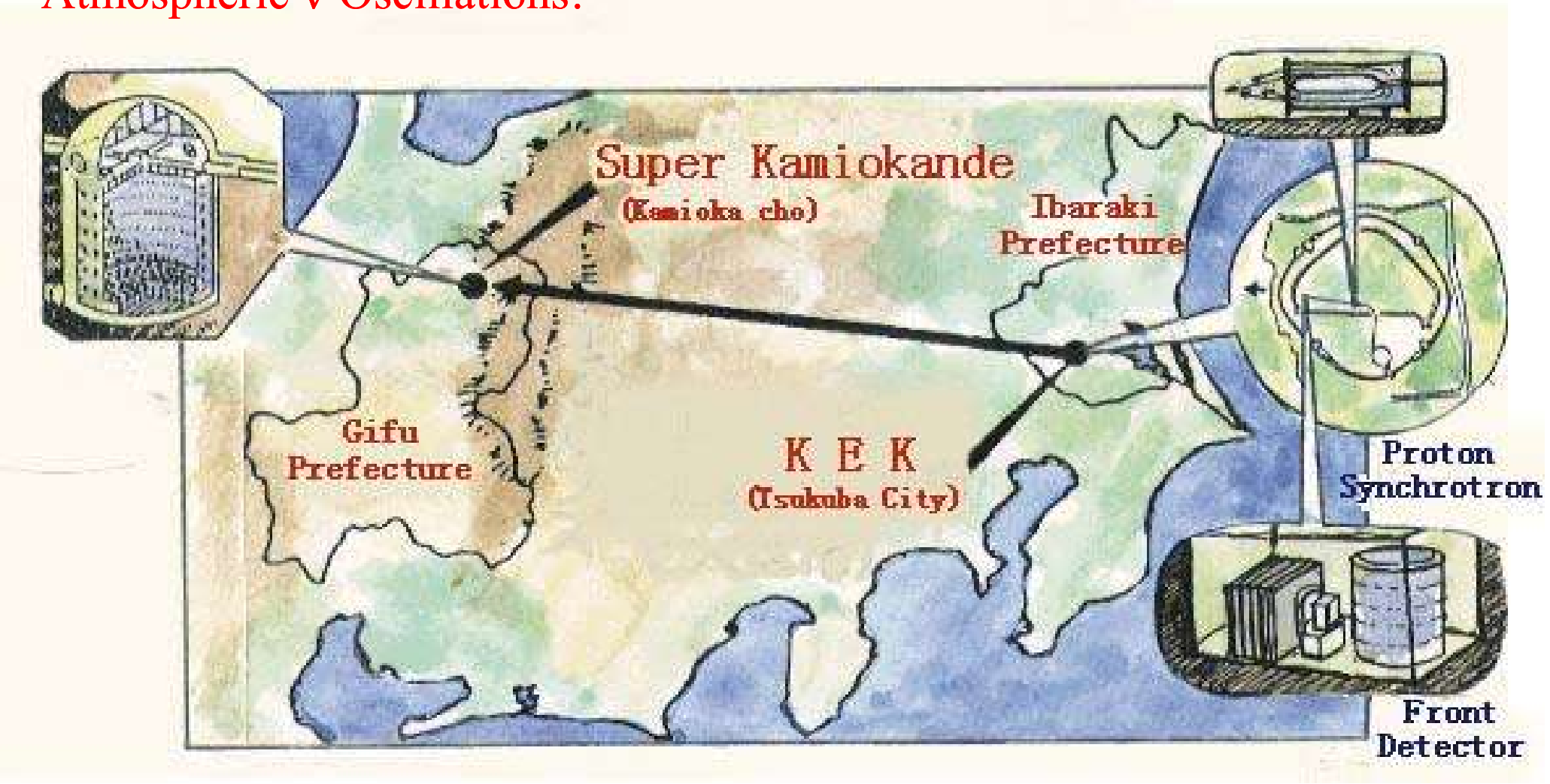


MiniBooNE Schedule

- Publish CCQE, CCπ^+, NCπ^0 Cross Section Results
- Complete "Blind" Oscillation Analysis (Good agreement between data & MC) & Present Oscillation Results
- Run Antineutrinos (and/or Neutrinos) in 2006
- If MiniBooNE Confirms LSND
  => Physics Beyond the Standard Model!

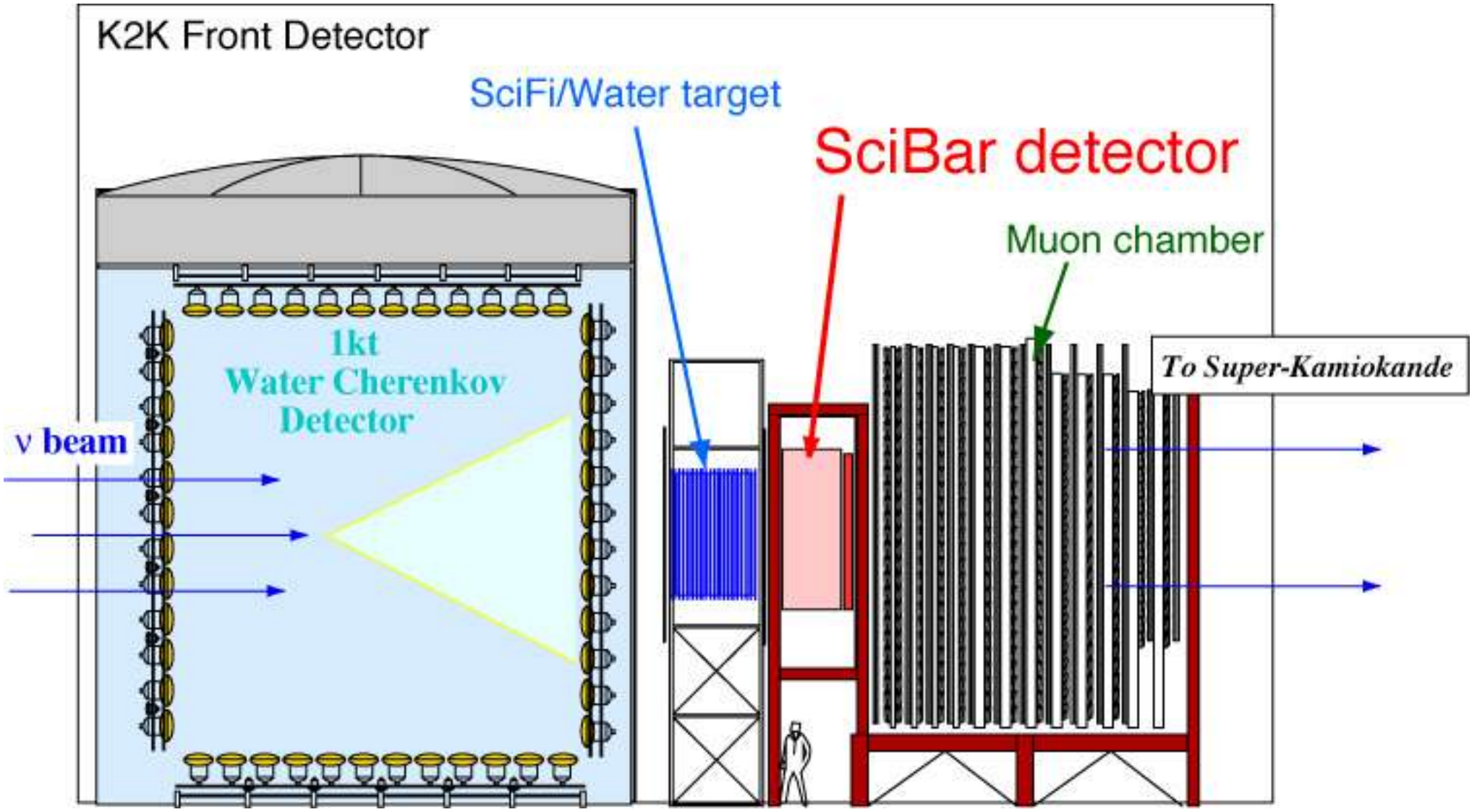
K2K Experiment

Atmospheric ν Oscillations!



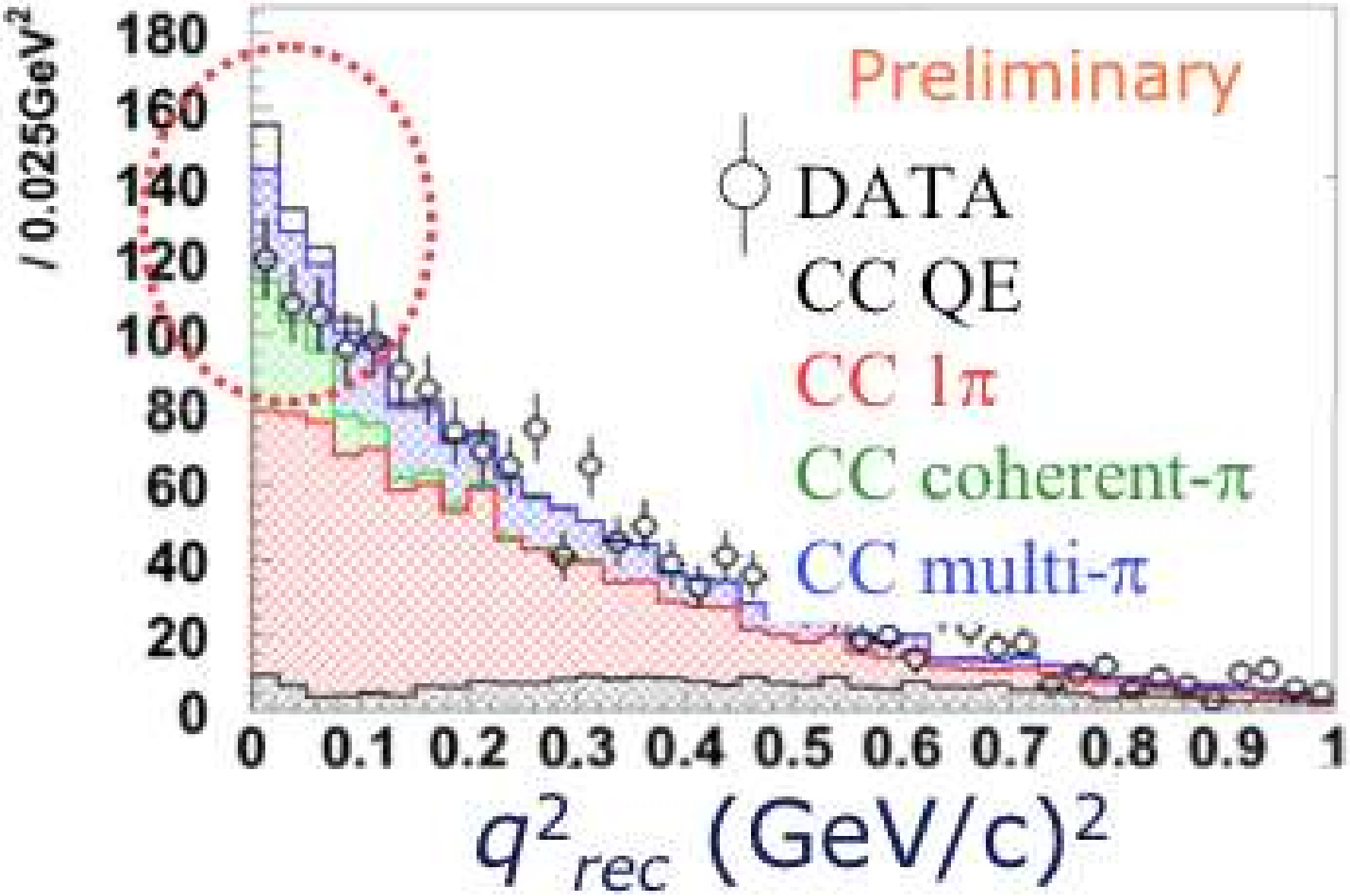
ν Cross Sections!

K2K Near Detectors



Low-q^2 puzzle in K2K SciBar Detector

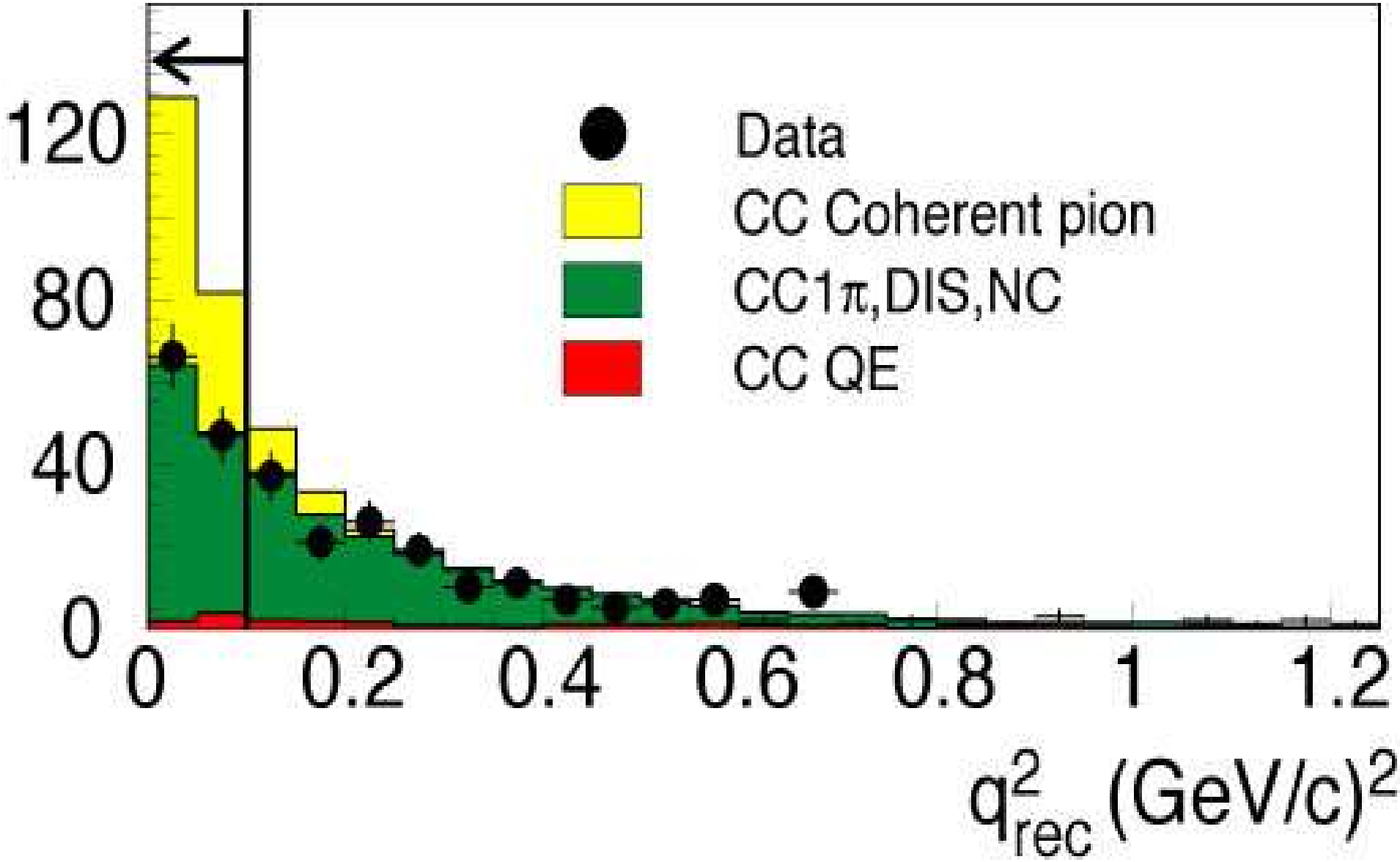
1.7E19 POT



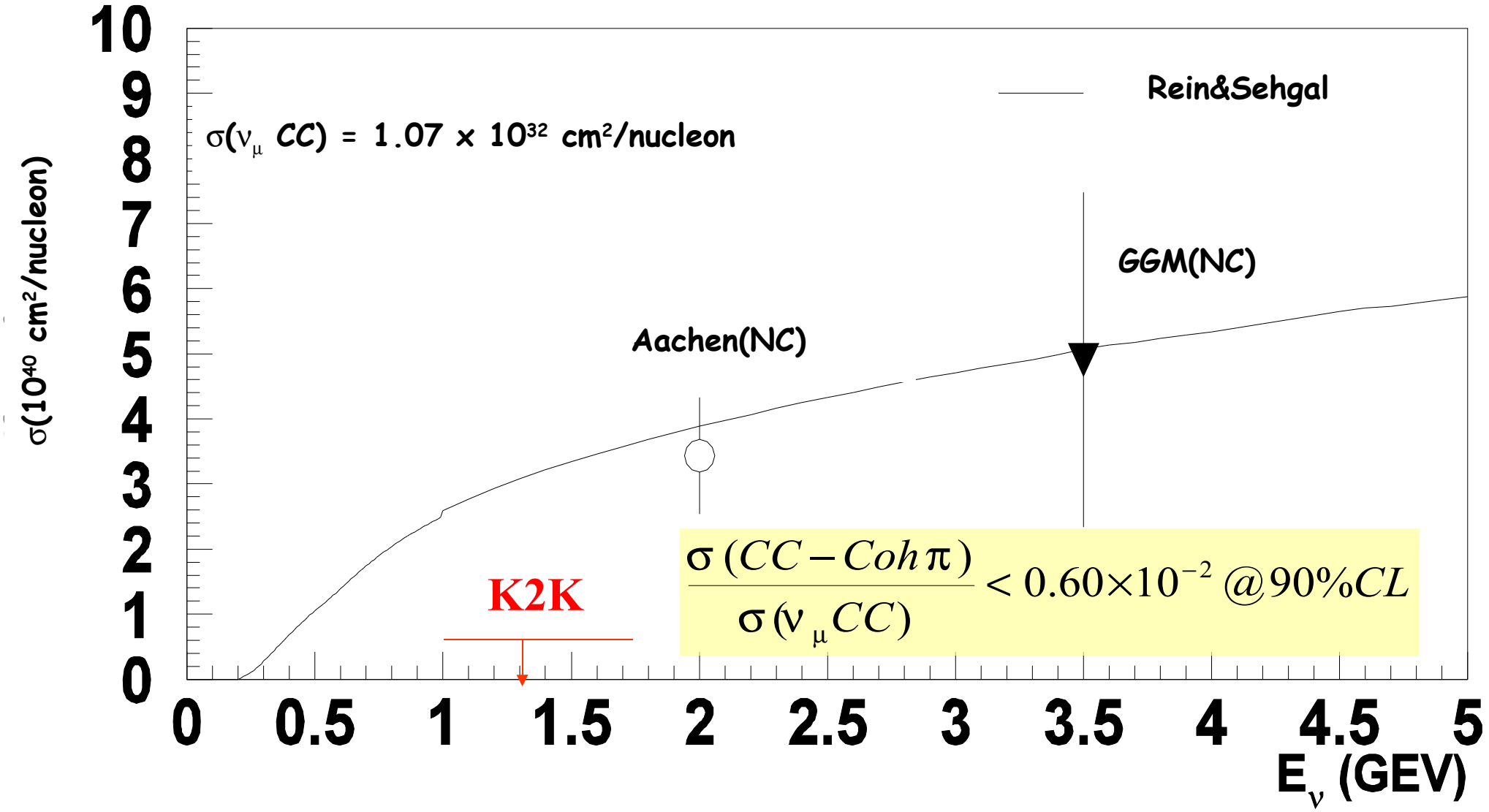
K2K observes no evidence for CCπ^+ coherent scattering!

hep-ex/0506008: **CCπ^+/CC = (0.04+-0.29+0.32-0.35)%**

< 0.60% (90% CL)



Comparison with other Experiments



Conclusions

- Neutrino Physics has been spectacularly successful in recent years, culminating with the discovery of Neutrino Oscillations and Neutrino Mass!
- Nevertheless, this may be just the "Tip of the Iceberg"!
- The ongoing MiniBooNE and MINOS experiments at Fermilab will make definitive tests of the LSND result and measurements of atmospheric oscillations
- Exciting future neutrino experiments are planned: Tritium β Decay, Double β Decay, Reactor θ_{13}, Accelerator θ_{13}, Solar ν, & ν Cross Sections