Searching for ν Oscillations with MiniBooNE

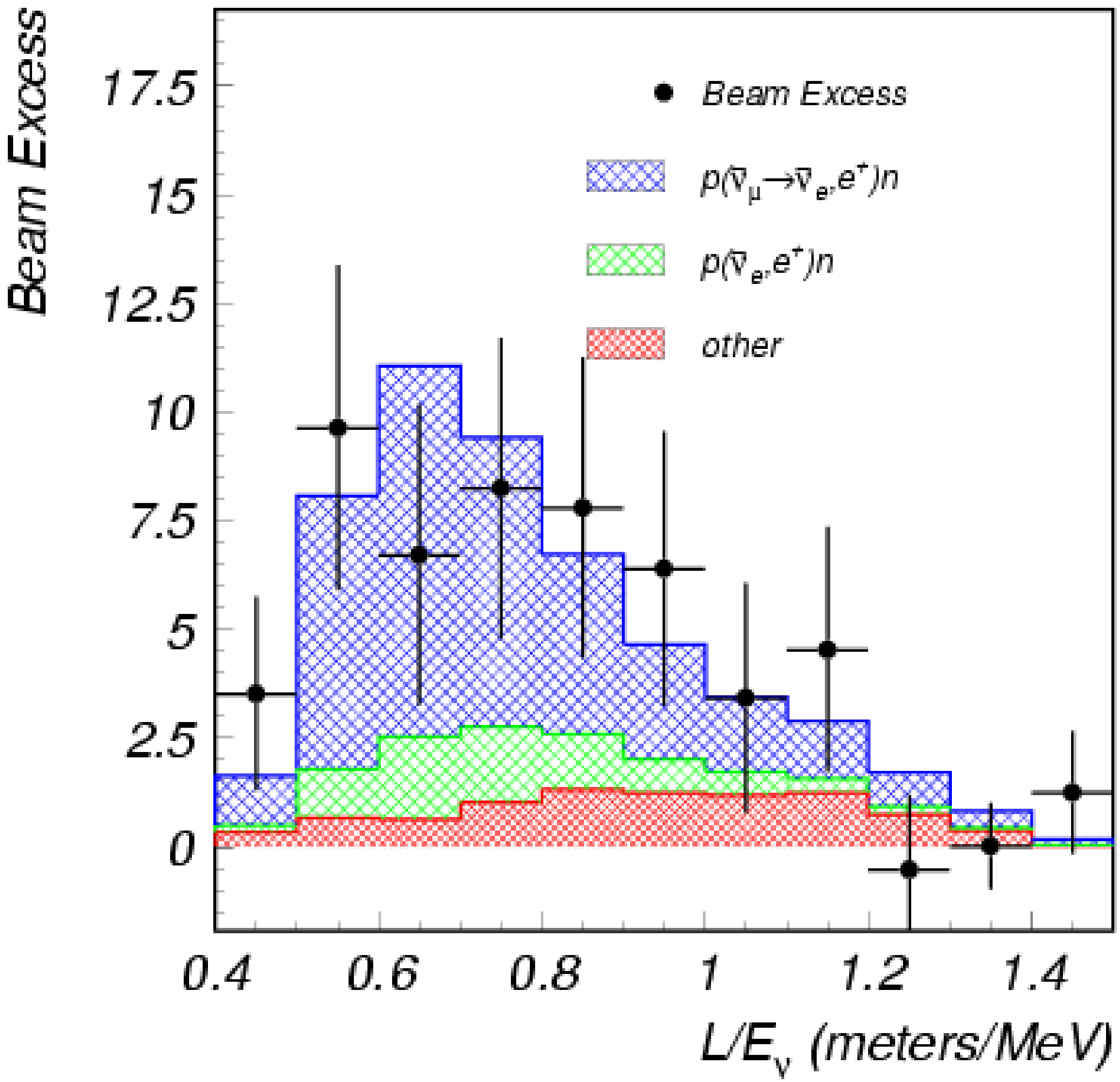
W.C. Louis, LANL

- Neutrino Oscillations & the 3 Δm^2 Problem!?!
  (Sterile Neutrinos?)

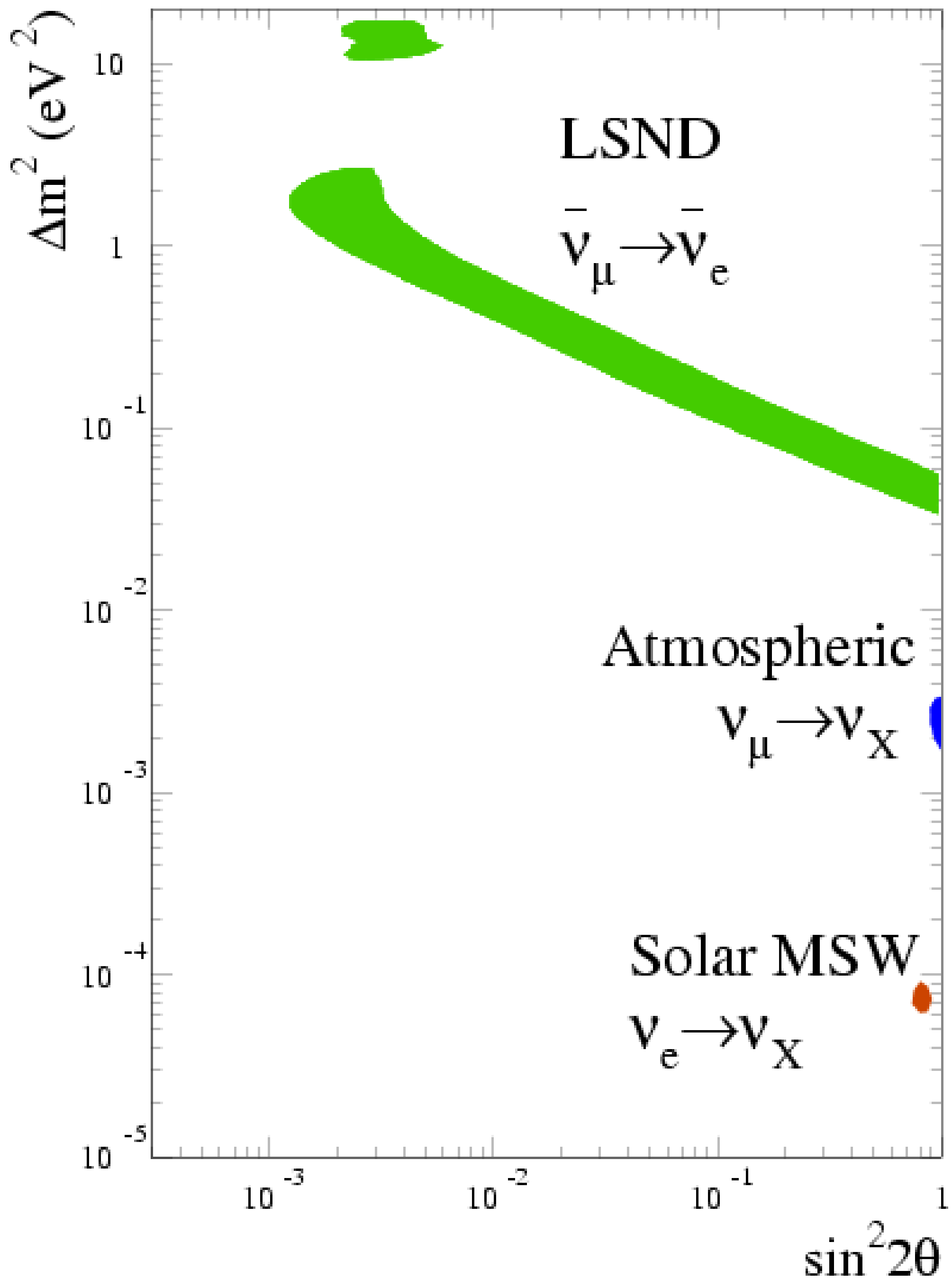
- MiniBooNE: A Definitive Test of the LSND Neutrino Oscillation Signal

- Future Neutrino Experiments: BooNE & OscSNS

Evidence for Oscillations from LSND



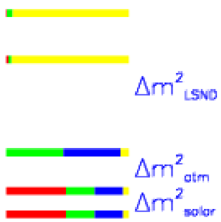
Current State of Neutrino Oscillation Evidence



Expt.	Type	Δm^2 (eV^2)	$\sin^2 2\theta$
LSND	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	~1	~3x10^{-3}
Atm.	$\nu_\mu \rightarrow \nu_x$	~2x10^{-3}	~1
Solar	$\nu_e \rightarrow \nu_x$	~8x10^{-5}	~0.8

If MiniBooNE Confirms LSND: Physics Beyond the Standard Model & Connections with Astrophysics!

3+2 Sterile Neutrinos



Sorel, Conrad, & Shaevitz (PRD70(2004)073004)

Explain Pulsar Kicks?

Explain R-Process in Supernovae?

Explain Dark Matter?

MaVaNs & 3+1 Sterile Neutrino

Hung (hep-ph/0010126)

Kaplan, Nelson, & Weiner (PRL93(2004)091801)

Explain Dark Energy?

CPT Violation & 3+1 Sterile Neutrino

Barger, Marfatia, & Whisnant (PLB576(2003)303)

Explain Baryon Asymmetry in the Universe?

Quantum Decoherence

Barenboim & Mavromatos (PRD70(2004)093015)

Lorentz Violation

Kostelecky & Mewes (PRD70(2004)076002)

Katori, Kostelecky, Tayloe (hep-ph/0606154)

Extra Dimensions

Pas, Pakvasa, & Weiler (PRD72(2005)095017)

Sterile Neutrino Decay

Palomares-Ruiz, Pascoli, & Schwetz (JHEP509(2005)48)

Probability of Neutrino Oscillations

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

As N increases, the formalism gets rapidly more complicated!

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

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

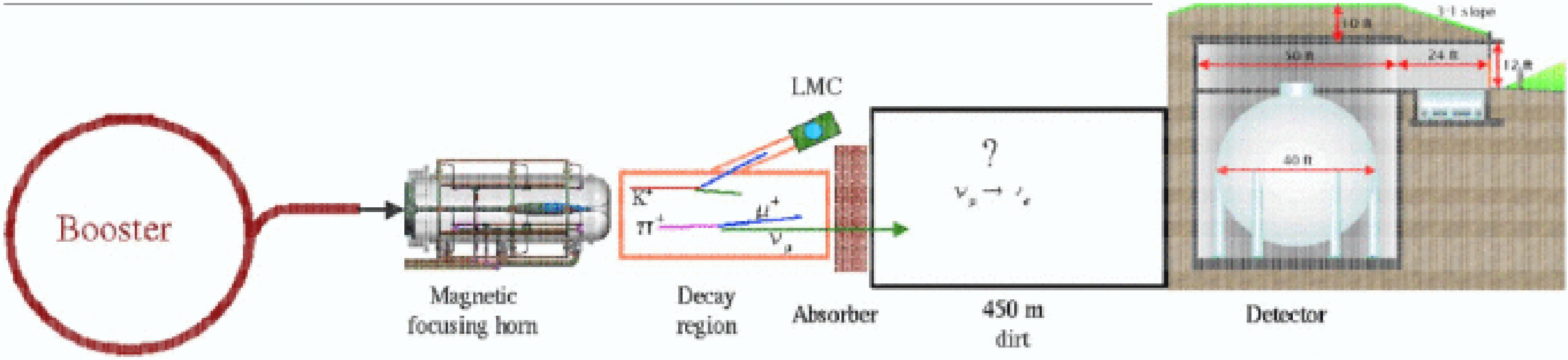
Completely different systematic errors than LSND

Much higher energy than LSND

Blind Analysis

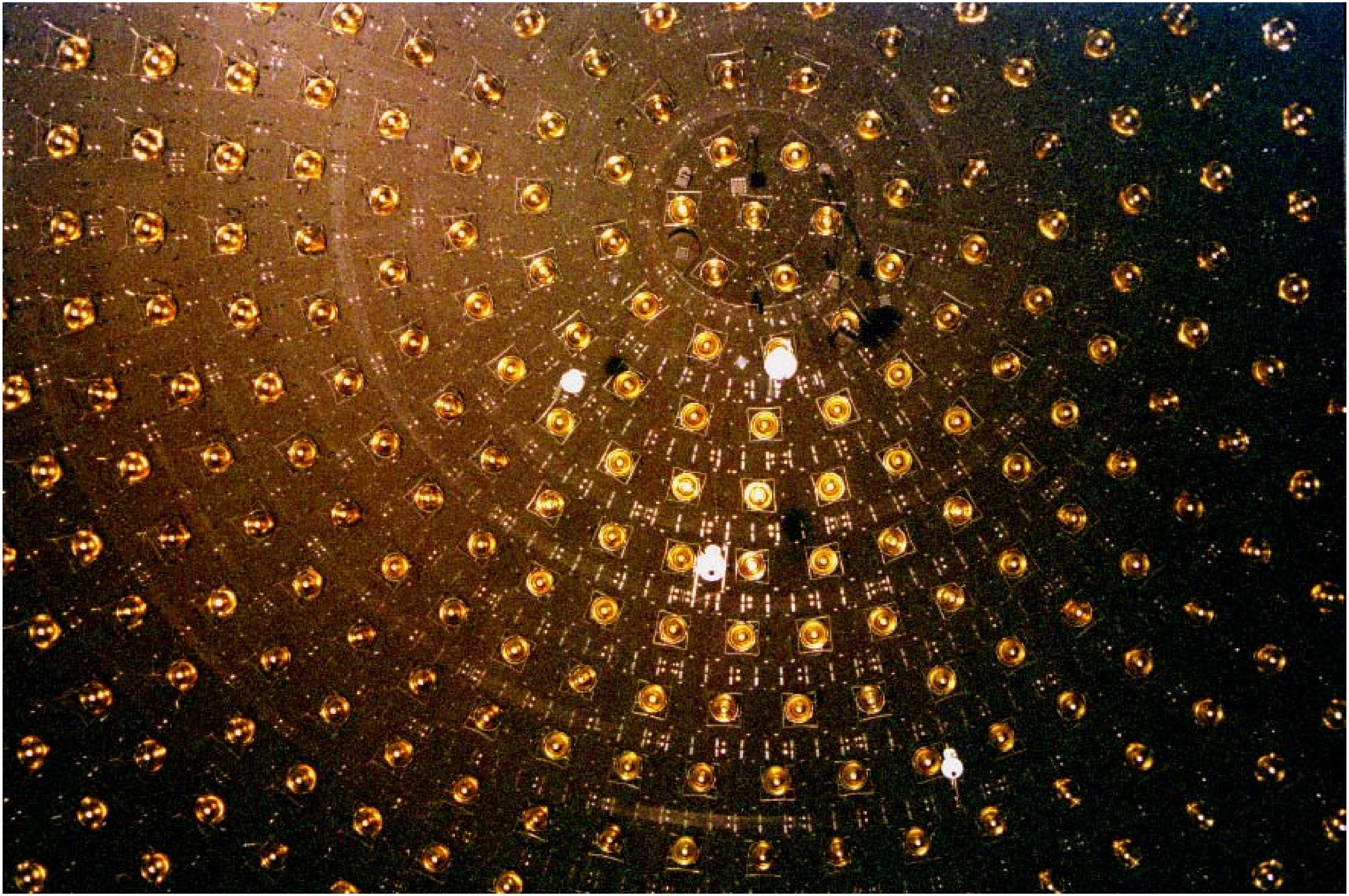
Alabama, Bucknell, Cincinnati, Colorado, Columbia, Embry-Riddle, Fermilab, Indiana, Los Alamos, LSU, Michigan, Princeton, St. Mary's, Western Illinois, Yale

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) ~ $5\text{x}10^{-3}$
- Detector - 40' diameter spherical tank
- Mass - 800 (450) tons of mineral oil
- PMTs - 1280 detector + 240 veto, 8" diameter

Inside the MiniBooNE Detector



Hamamatsu 8" PMT

R1408 (1220 from DOE/NP)
R5912 (330 from NSF)

#stages = 9 (old)
10 (new)

σ_t ~ 1.7 ns (old)
1.2 ns (new)

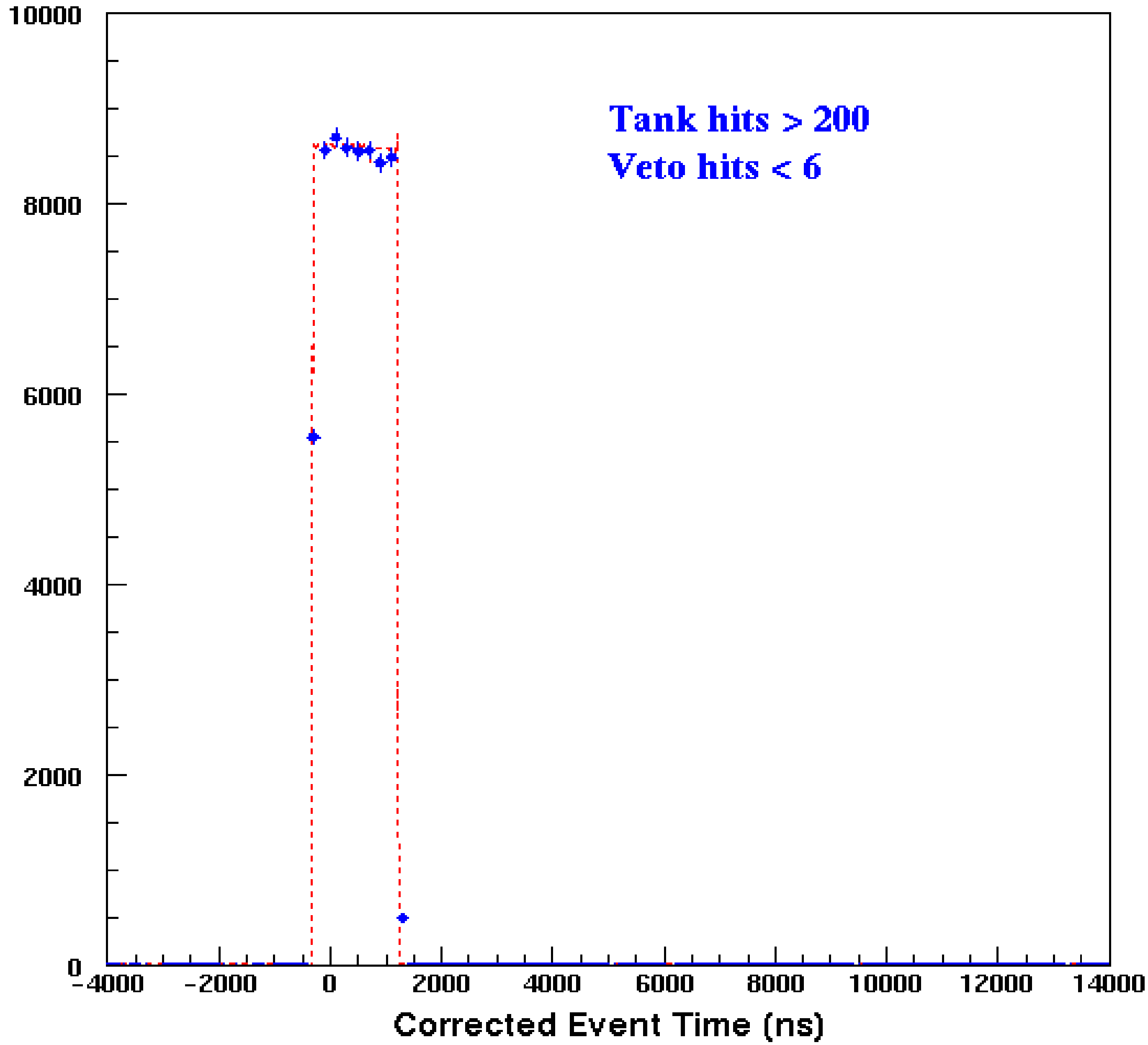
peak/valley ~ 1.1 (old)
1.5 (new)

MiniBooNE Highlights

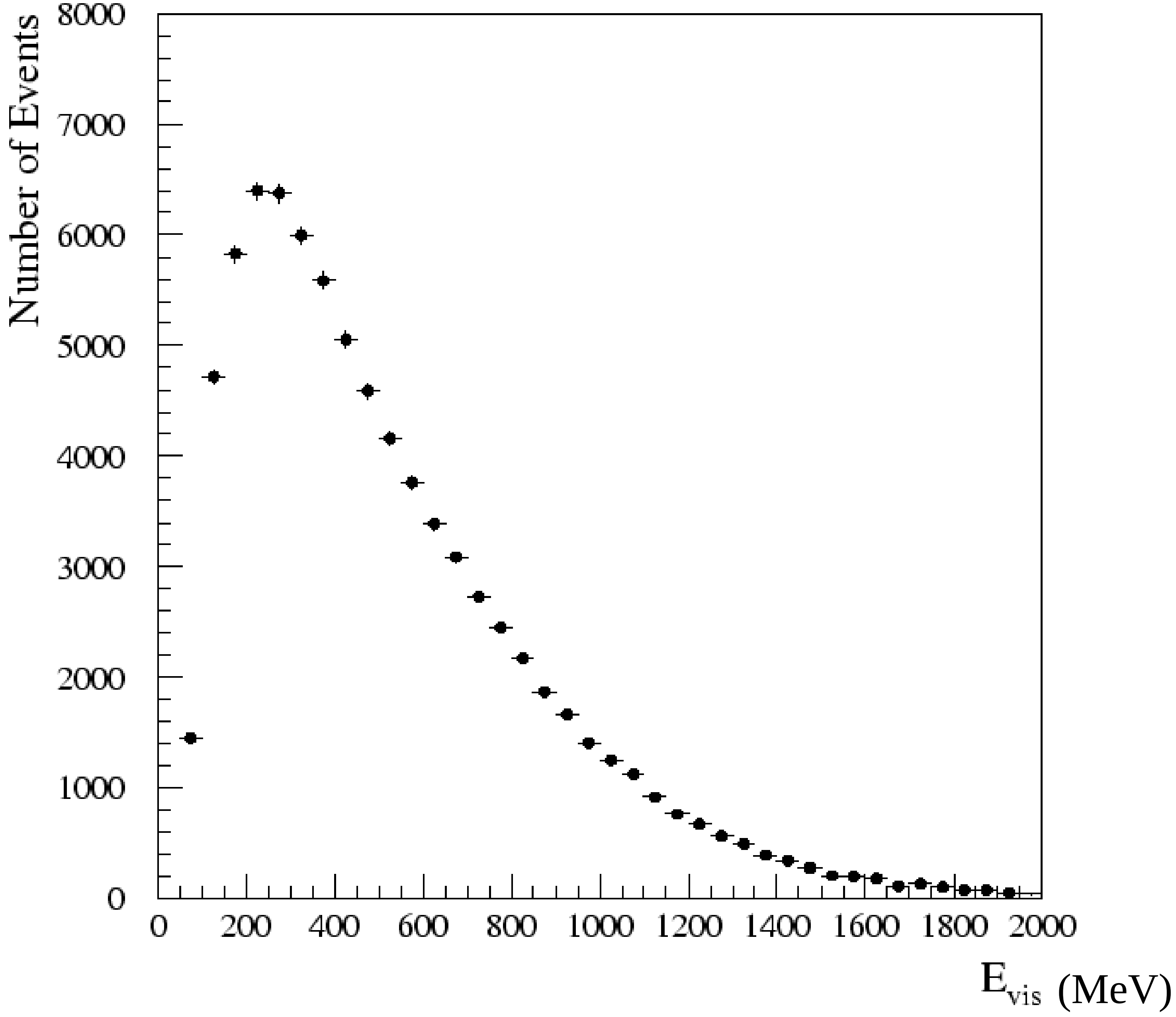
- MiniBooNE began taking data in September 2002 and has collected ~750K neutrino events from ~7E20 Protons on Target; Oscillation analysis will use ~600K events from ~5.7E20 POT
- Experiment is working well (99% livetime & 99% of PMT channels working well)
- Clearly reconstructing CCQE, CCPI+, NCPI0, & NCEL events
- First focussing horn was replaced during 2004 fall shutdown and set a world record of 96M pulses (previous record set at BNL with 13M pulses)
- Now taking data with Antineutrinos (since January)

MiniBooNE Neutrino Events Are Very Clean

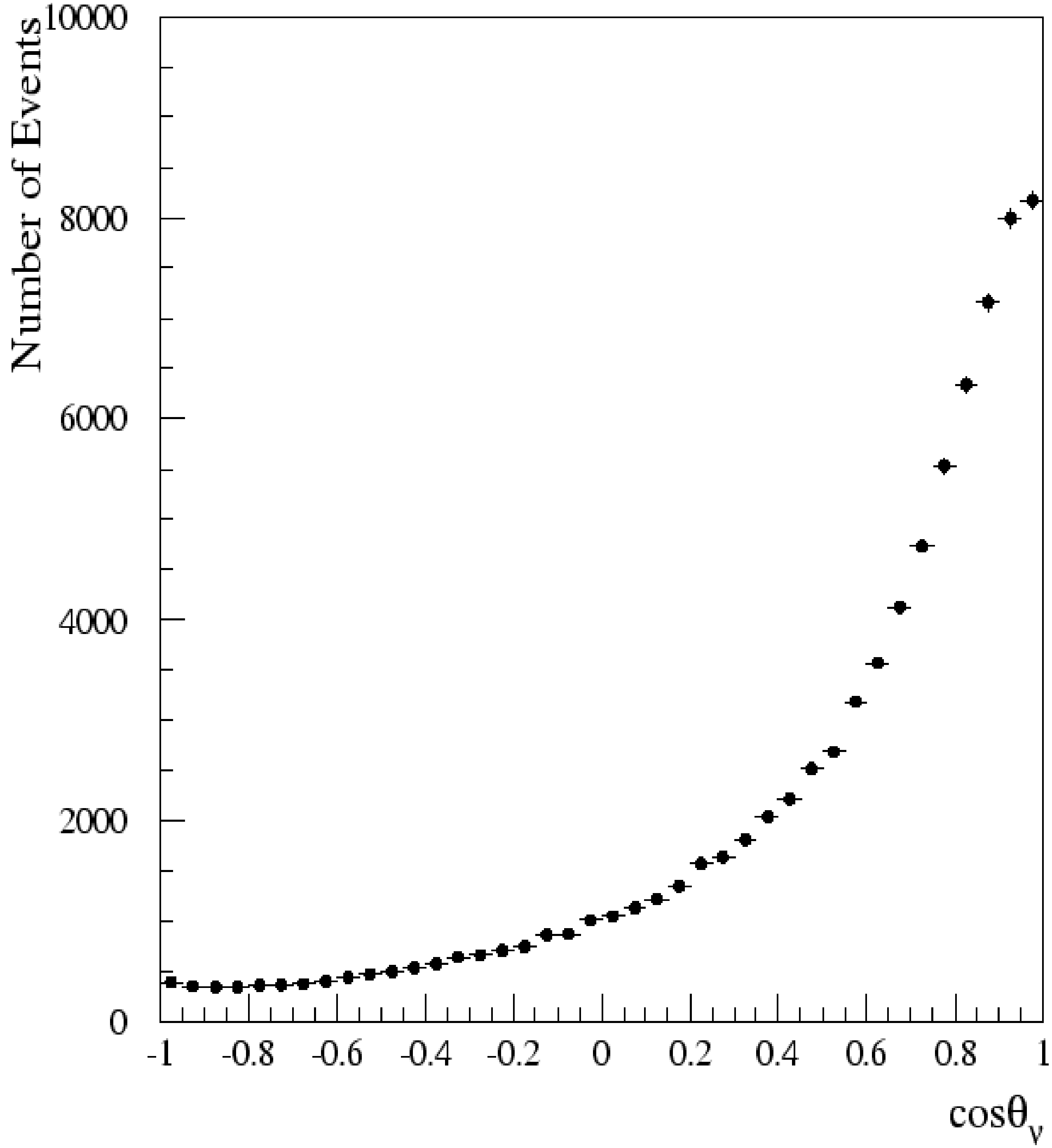
Neutrino Signal to Cosmic-Ray Background ~ 5000 to 1!



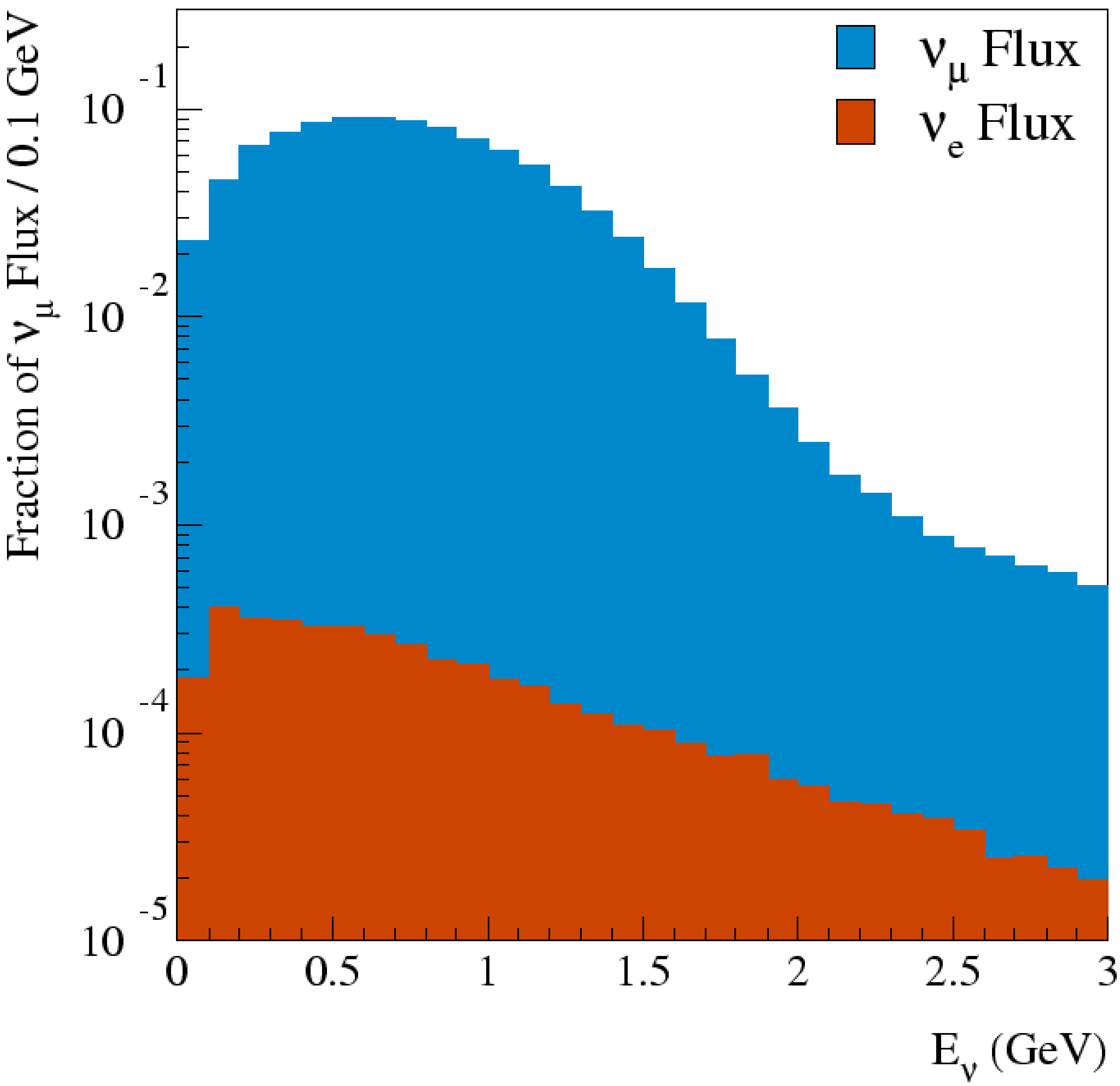
Contained Neutrino Event Visible Energy Distributon



Contained Neutrino Event Angular Distribution

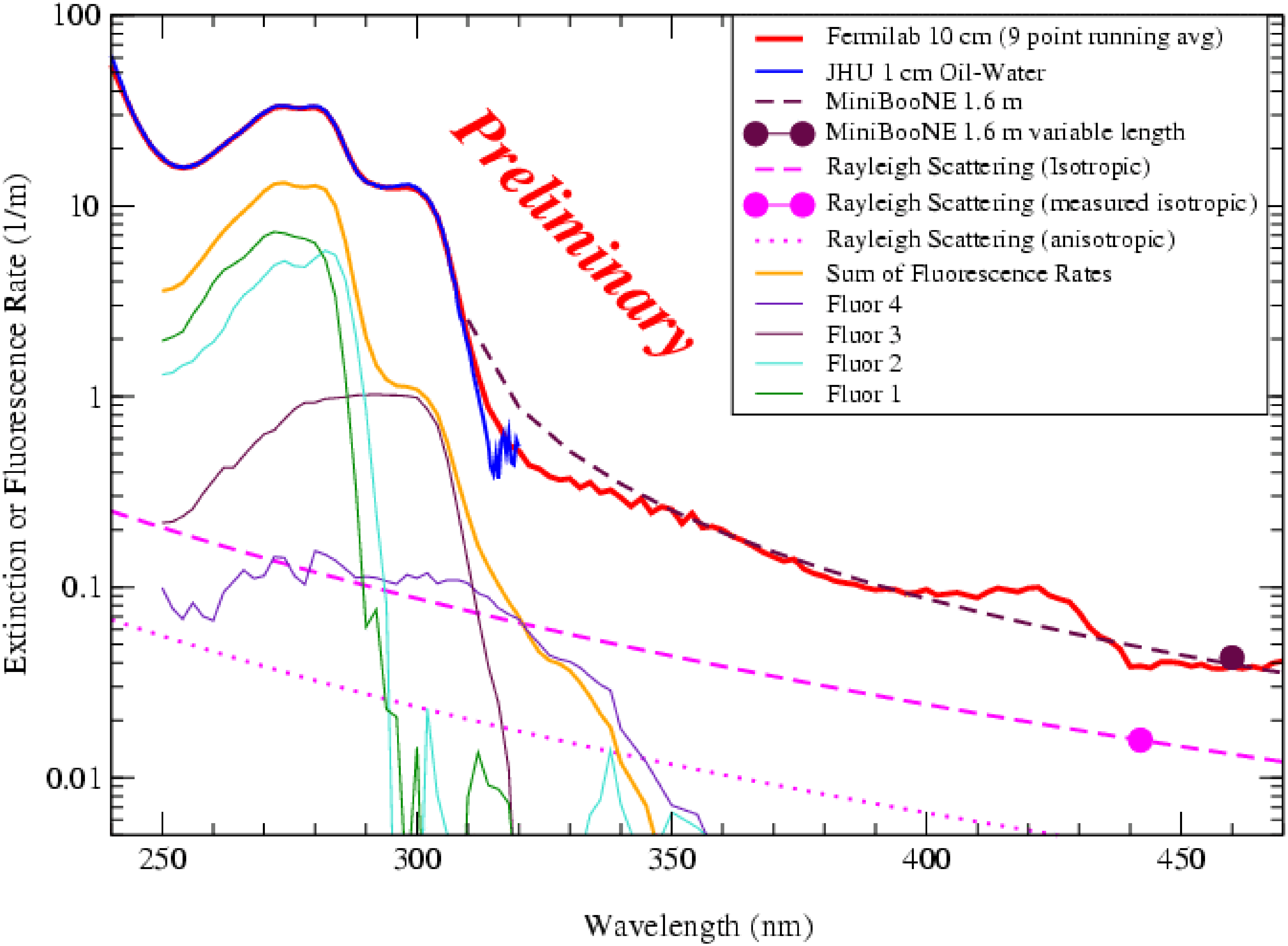


MiniBooNE Neutrino Flux

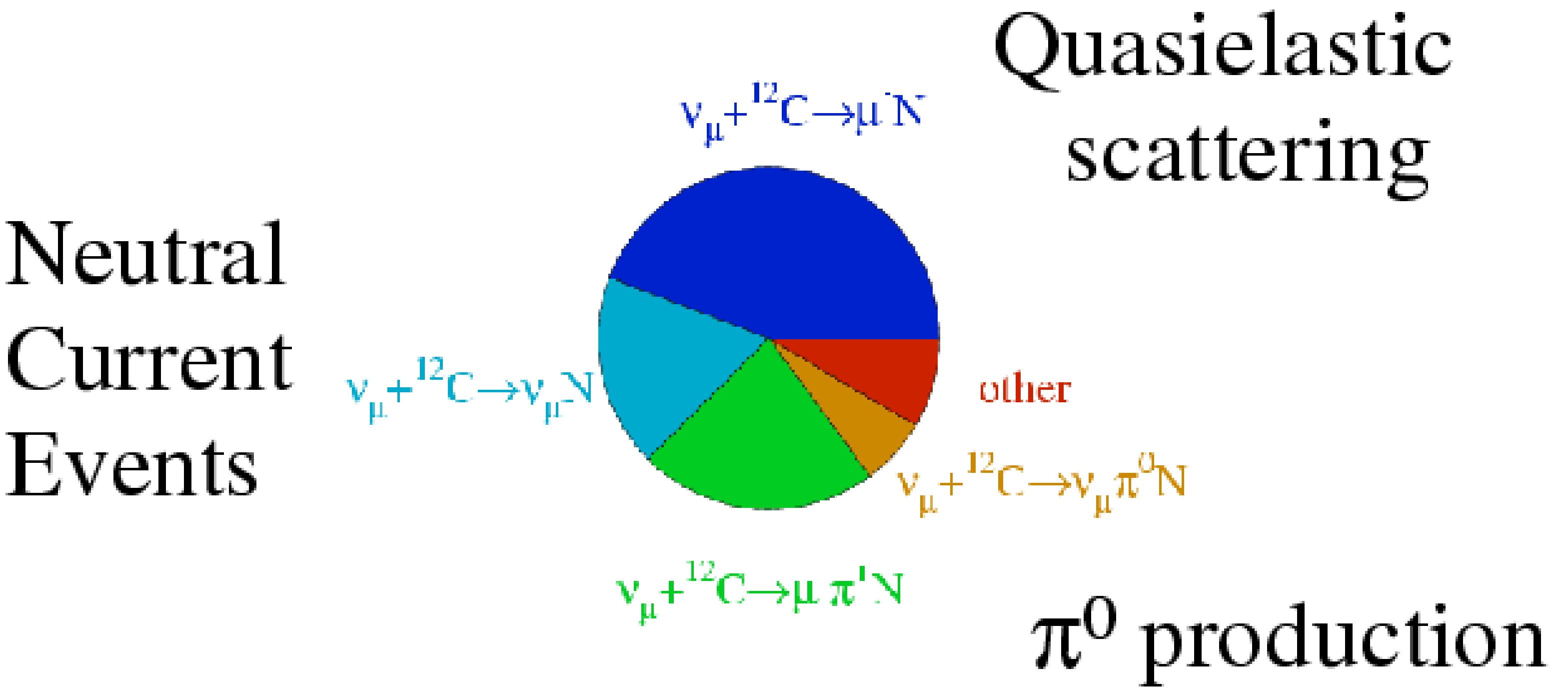


HARP at CERN
E910 at BNL

Extinction Rate for MiniBooNE Marcol 7 Mineral Oil

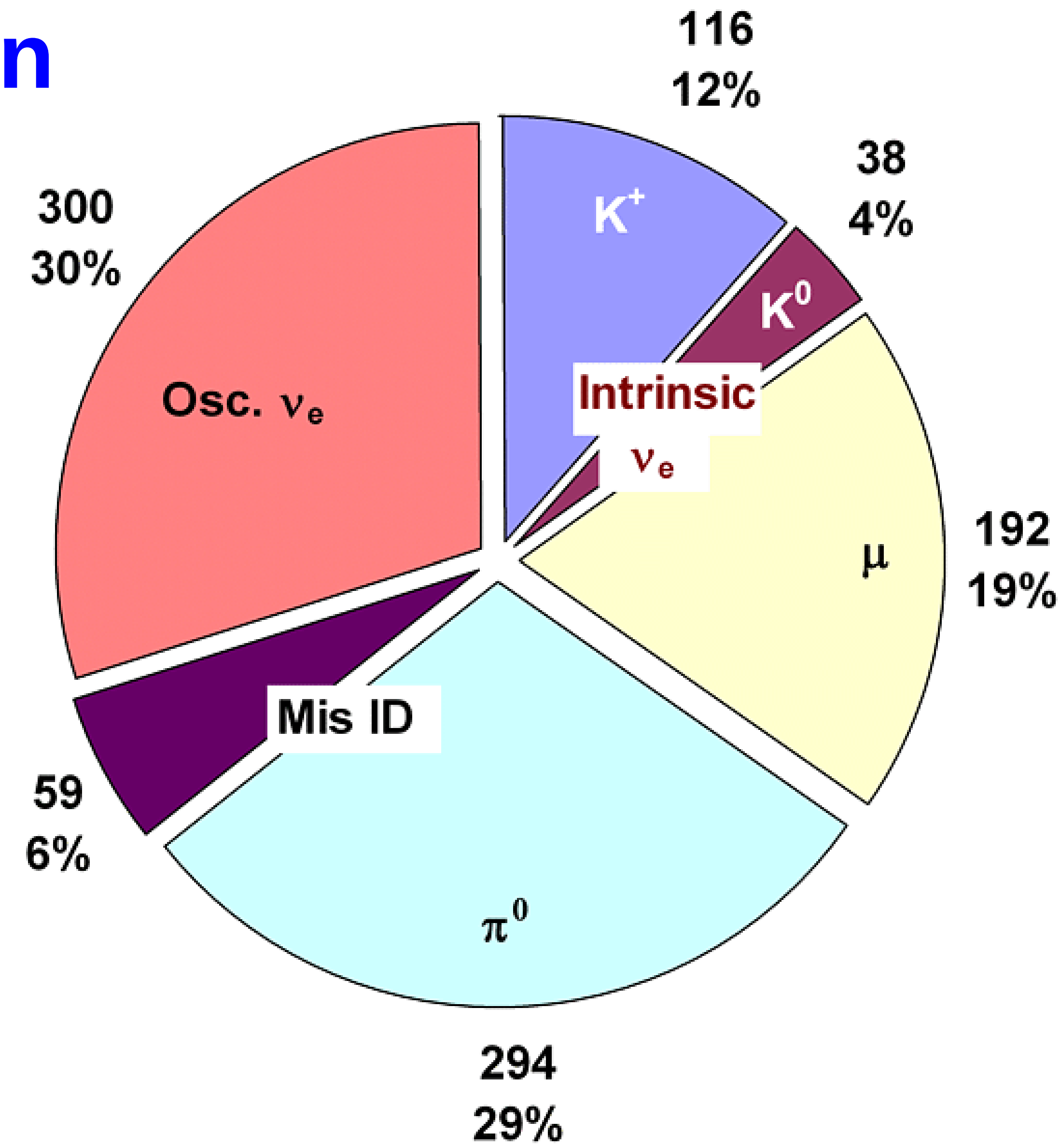


Expected MiniBooNE Event Rates

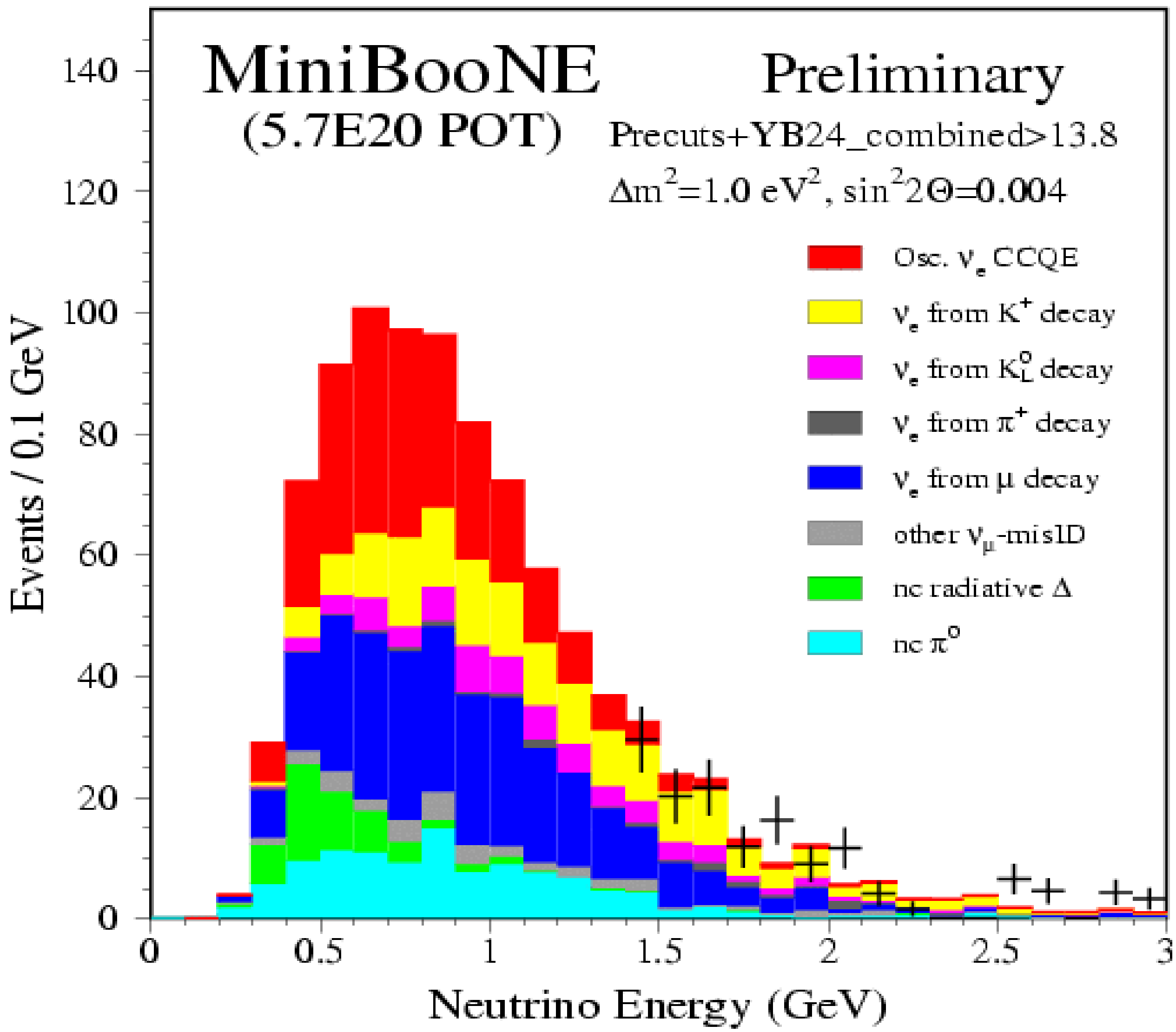


Use NUANCE Cross Section Package

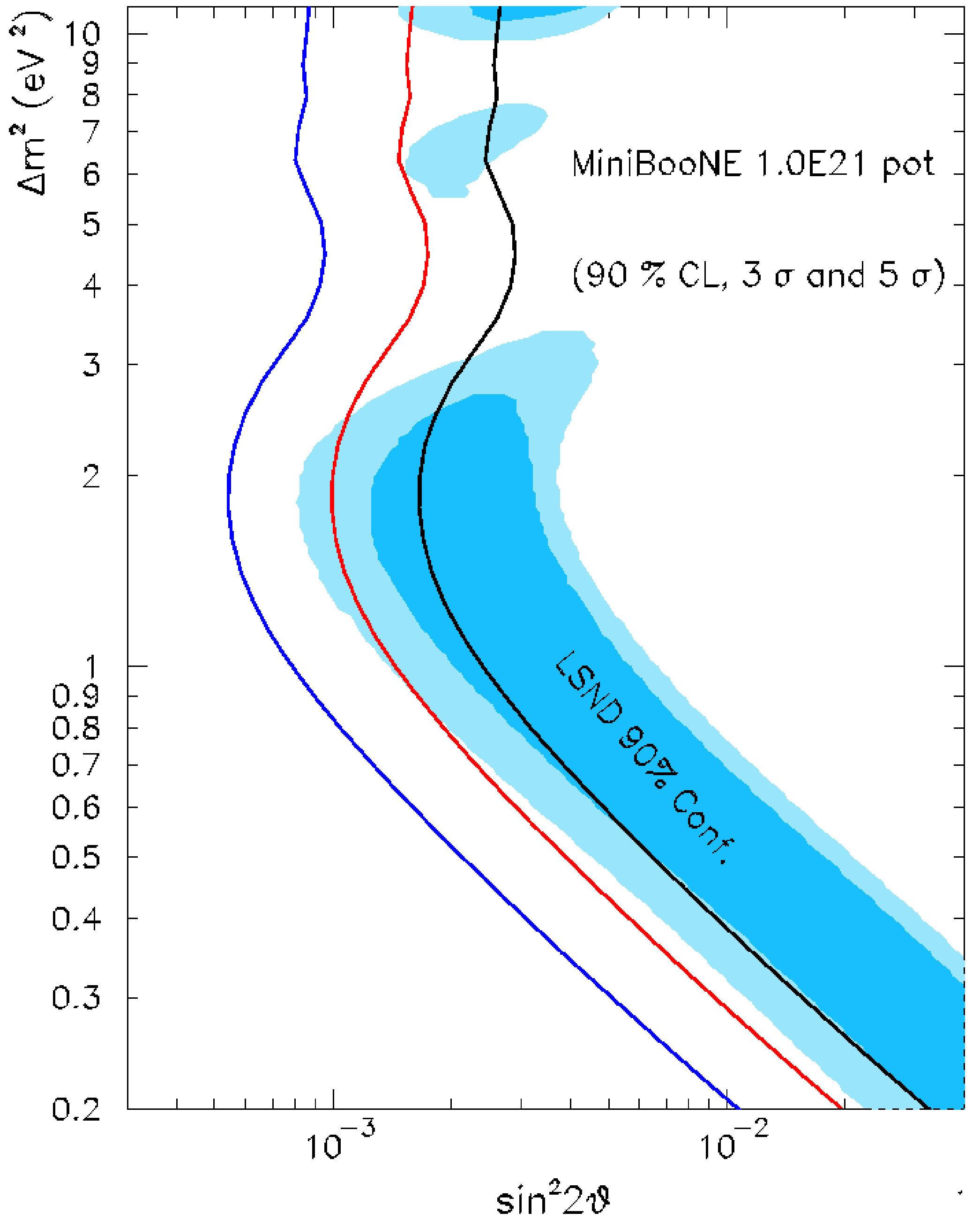
After ν_e PID Selection



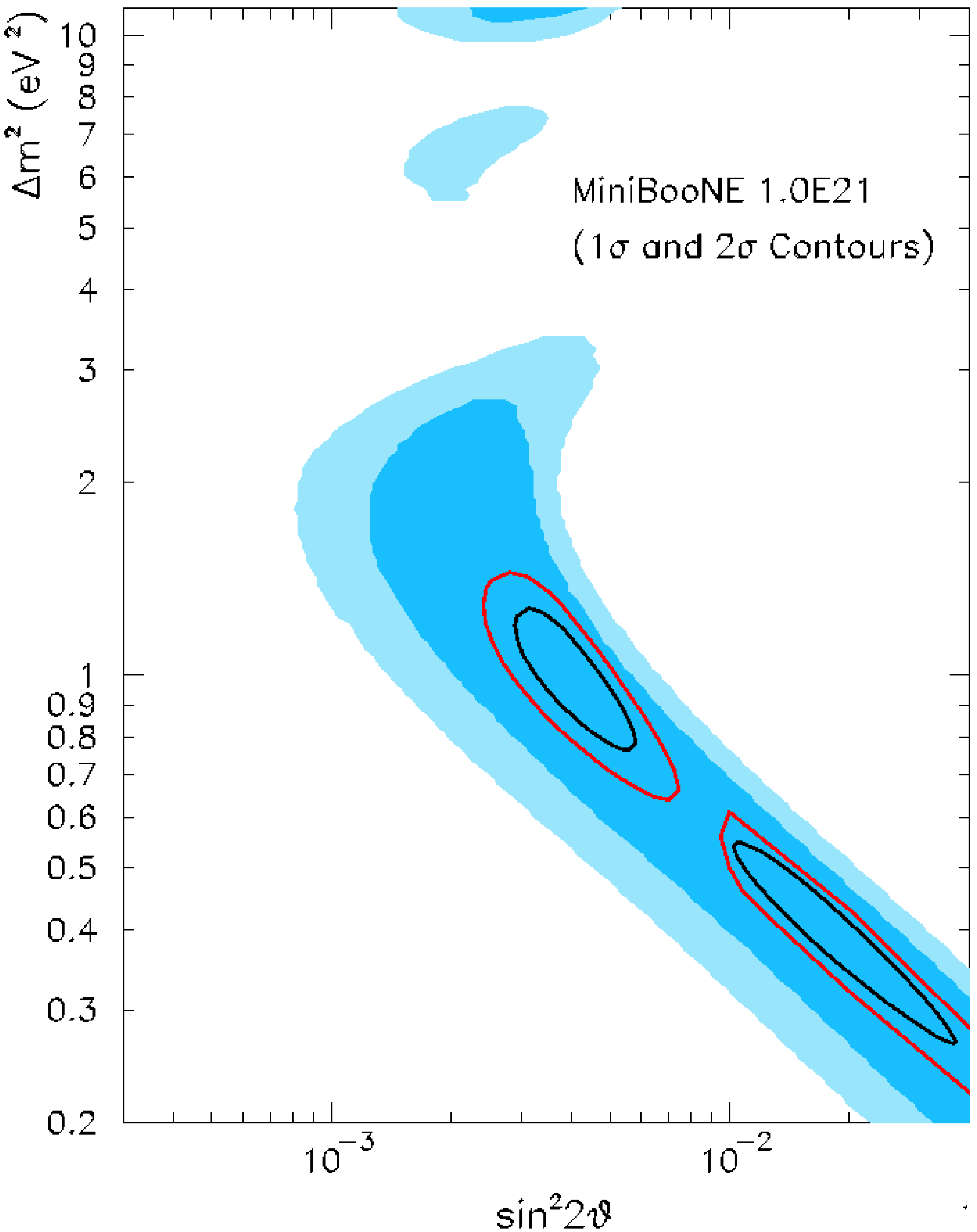
Expectations for 5.7E20 Protons on Target



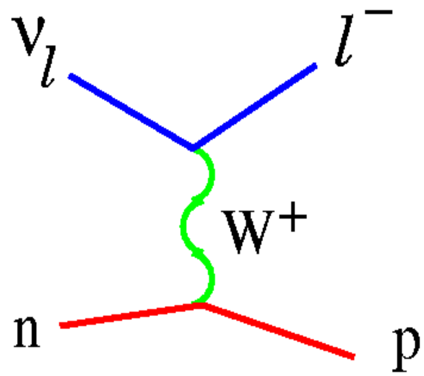
Expected MiniBooNE Sensitivity



Measurement of Oscillation Parameters



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



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

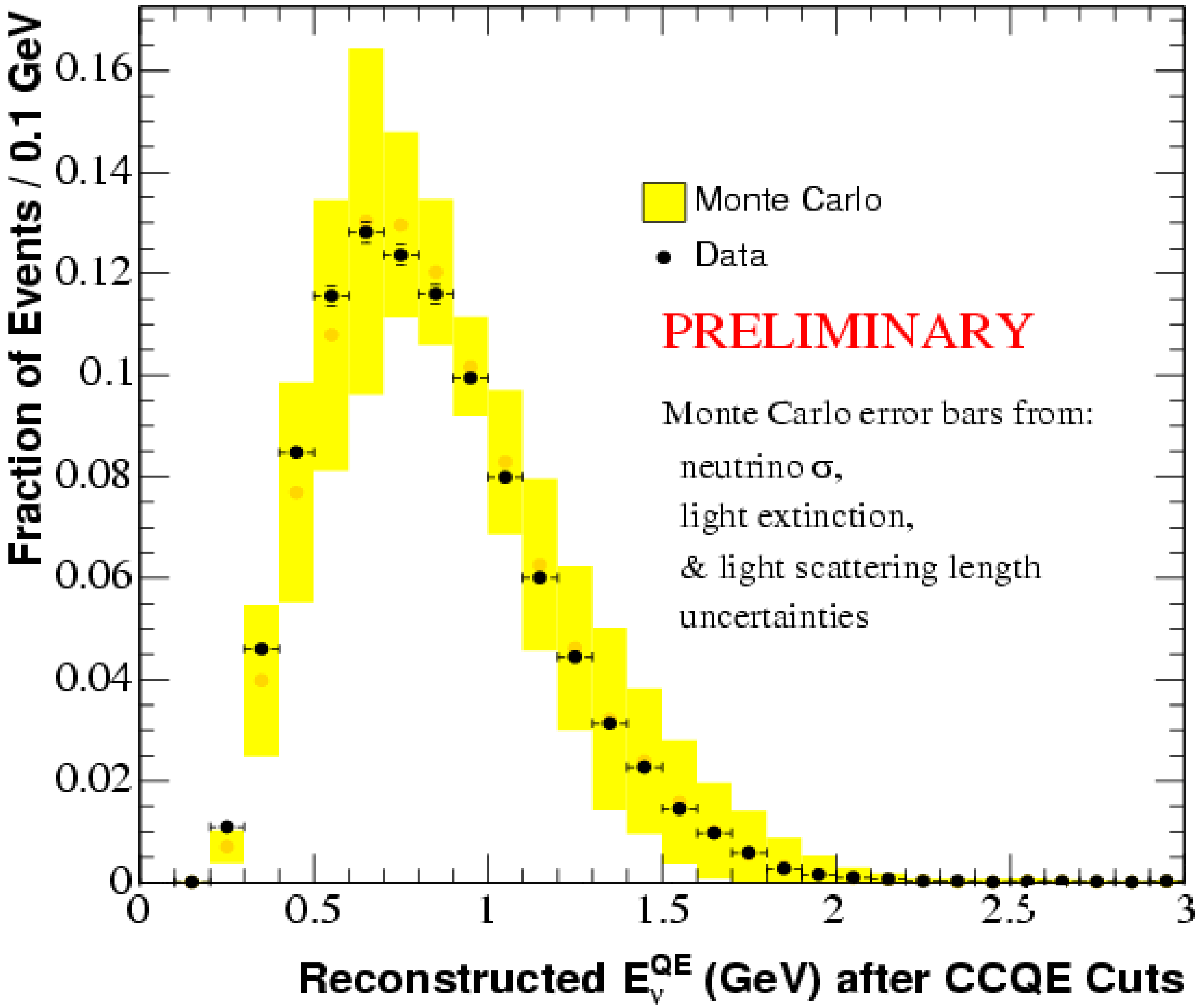
MiniBooNE now has one of the largest samples of **CCQE** events!

Important for ν_μ Disappearance & ν_e Appearance Background

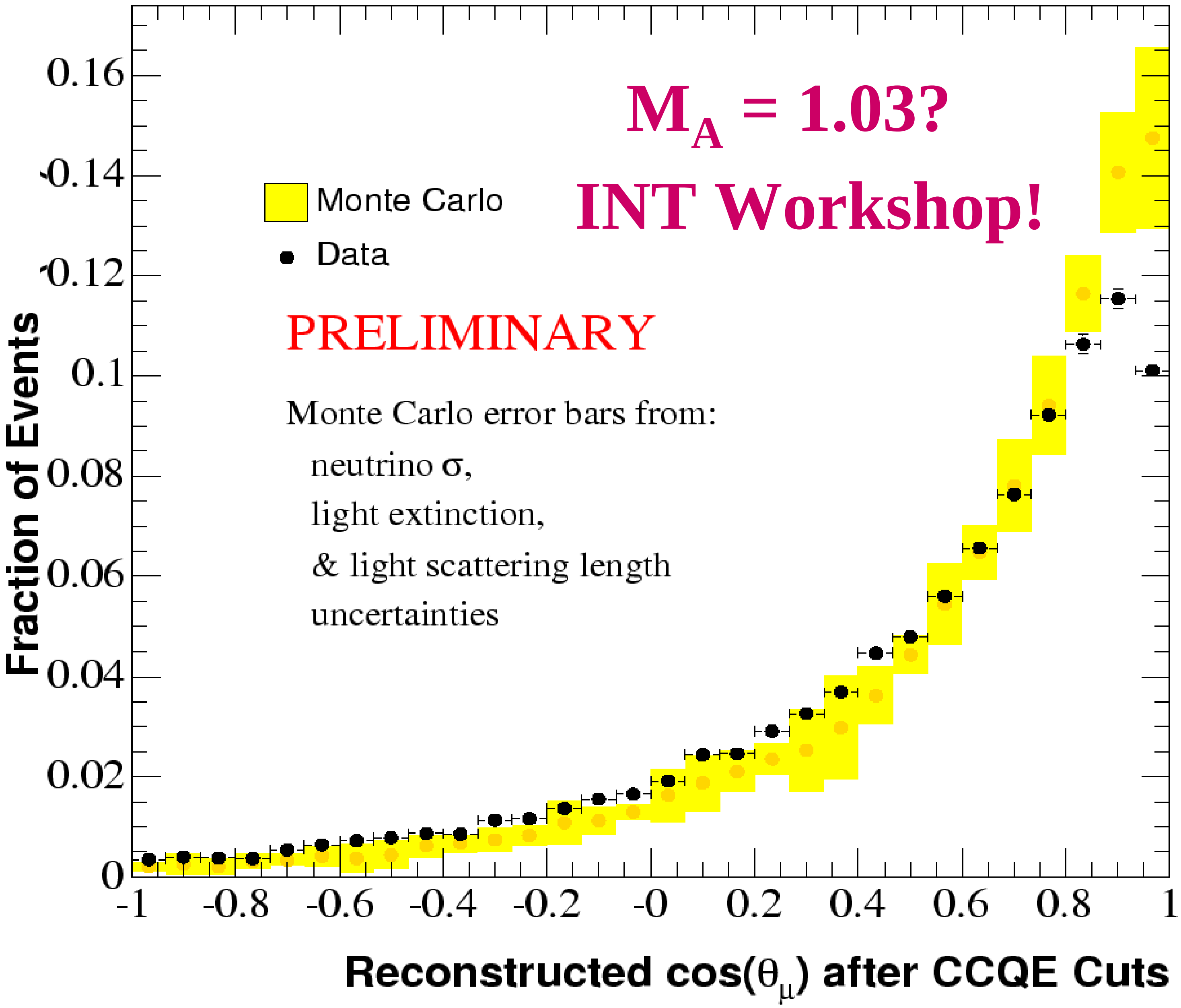
Selection: Single ring event, consistent with a muon

CCQE Energy Distribution

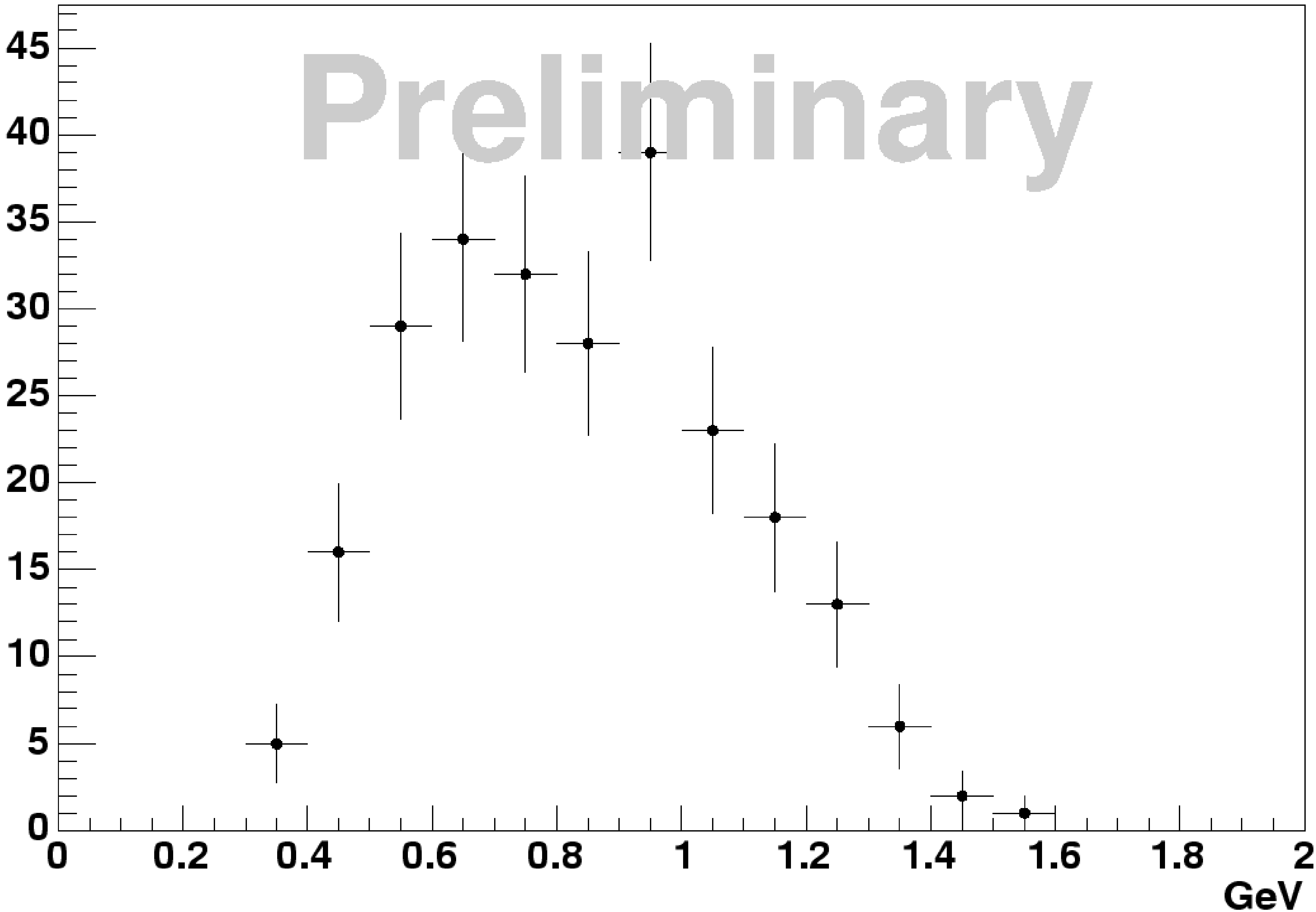
~10% energy resolution



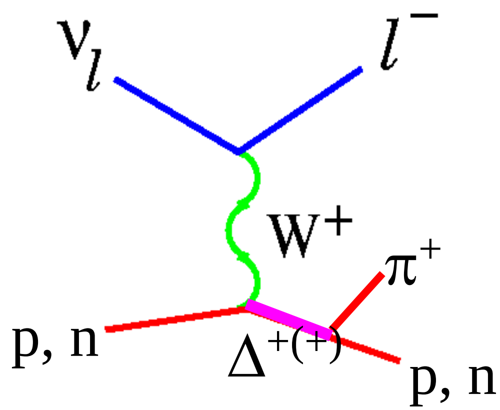
CCQE Angular Distribution



Quasi-Elastic Energy Distribution for Muon Anti-Neutrinos



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



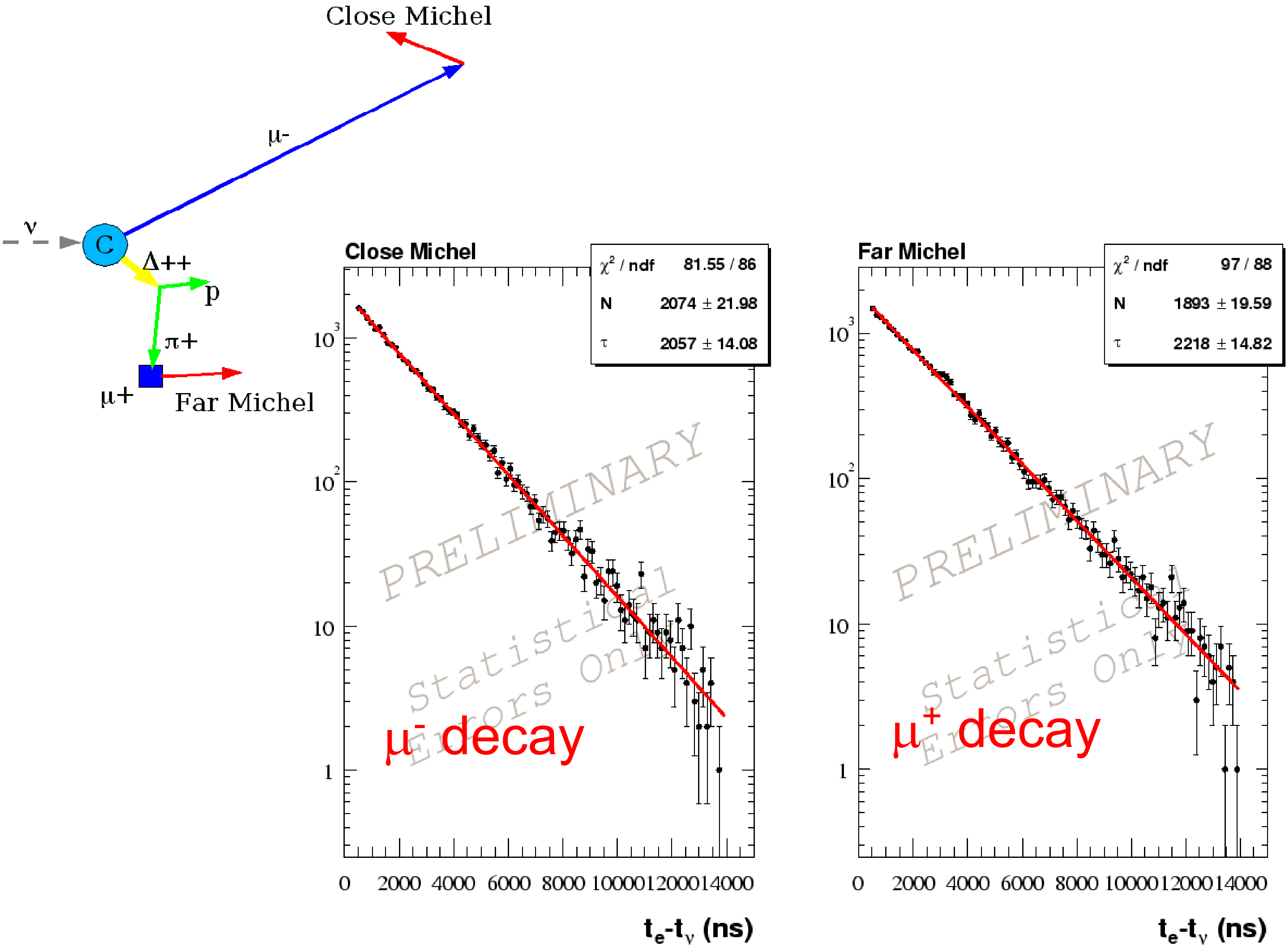
Not Well Measured at Low Energies

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

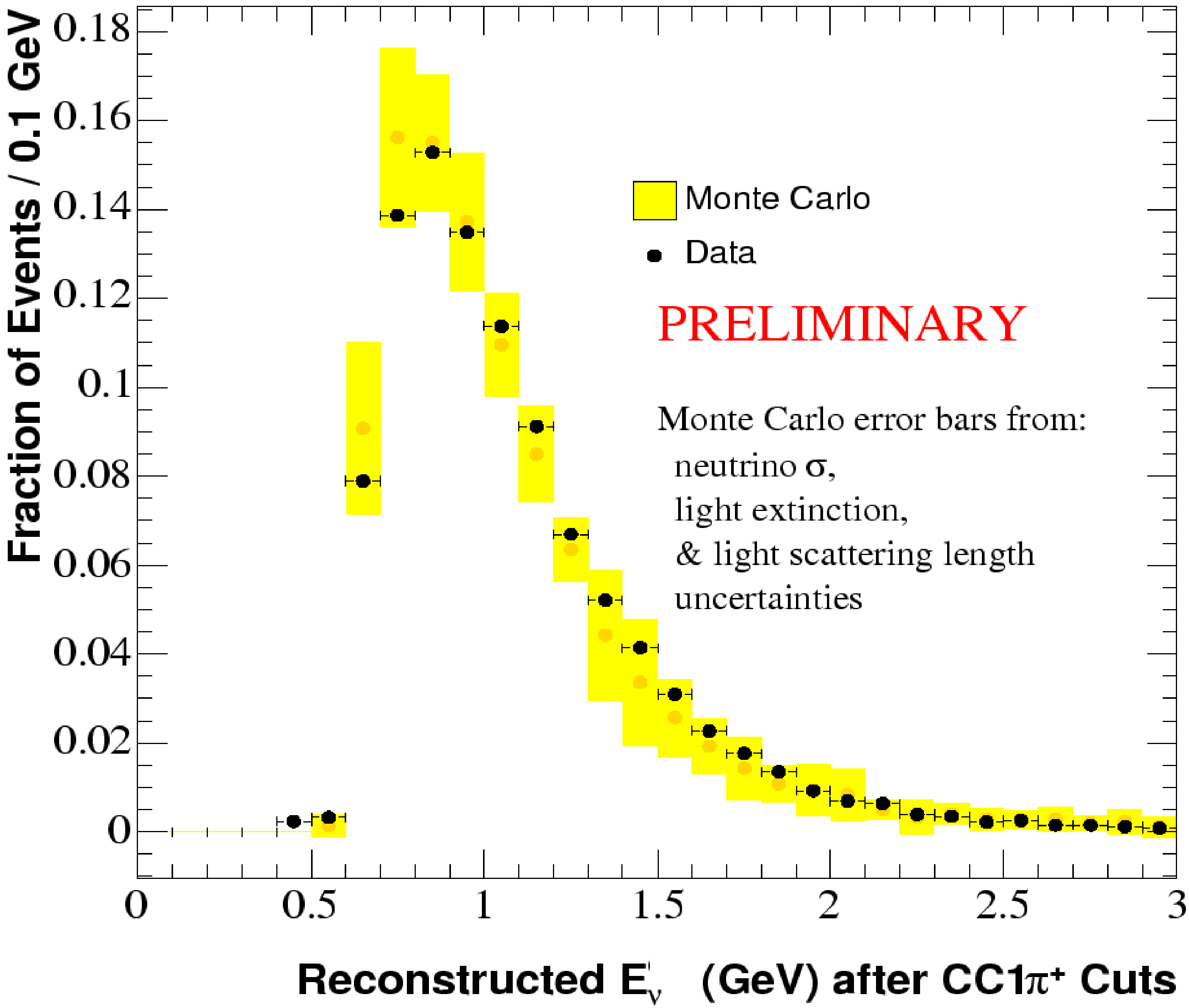
MiniBooNE now has the world's largest sample of **CC**π^+ events!

Important for ν_μ Disappearance & ν_e Appearance Background

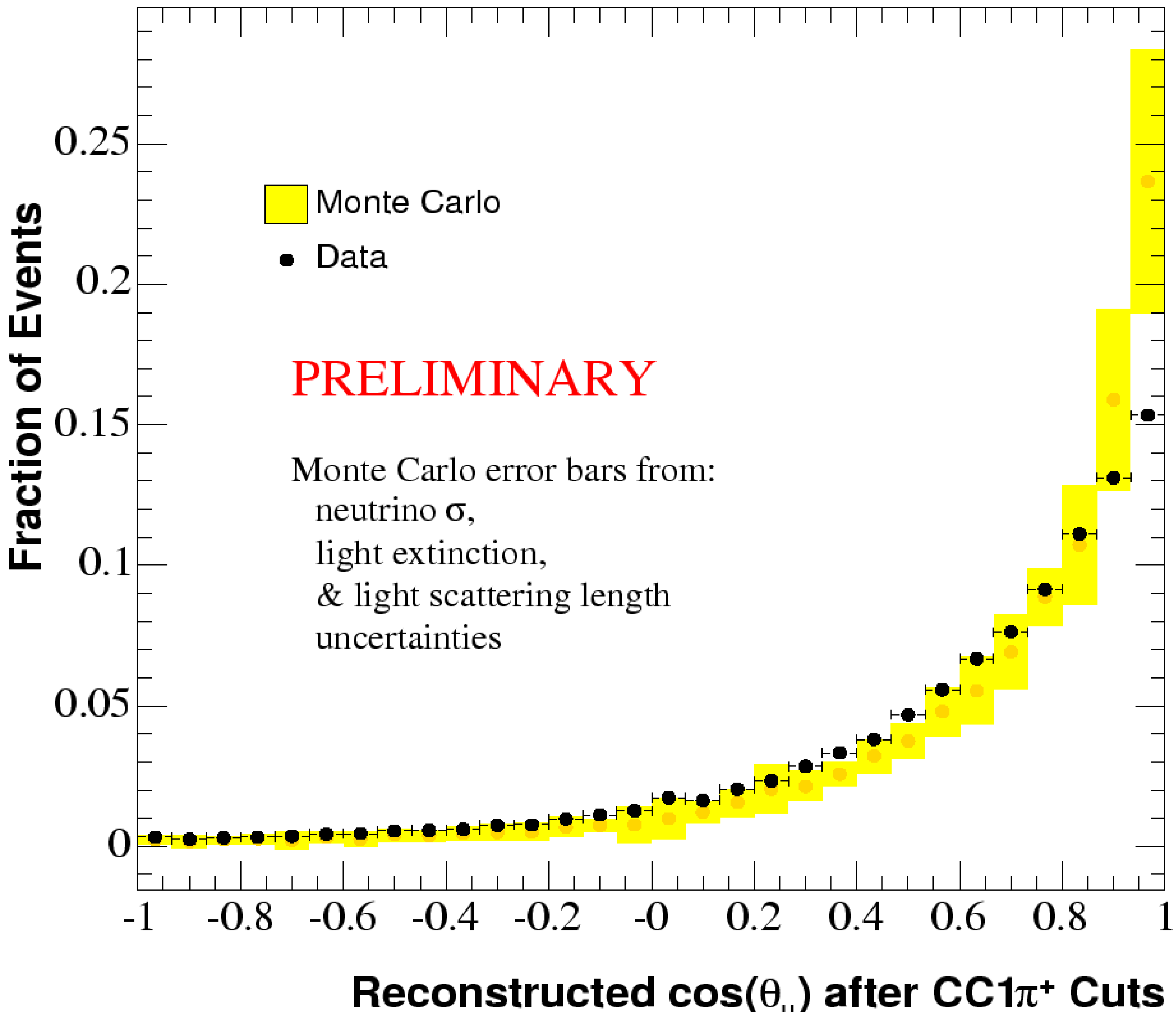
Selection: Double-ring event with 2 Michel-electrons


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
μ⁺ decay
t_e-t_ν (ns)

CCπ^+ Energy Distribution



$CC\pi^+$ Angular Distribution



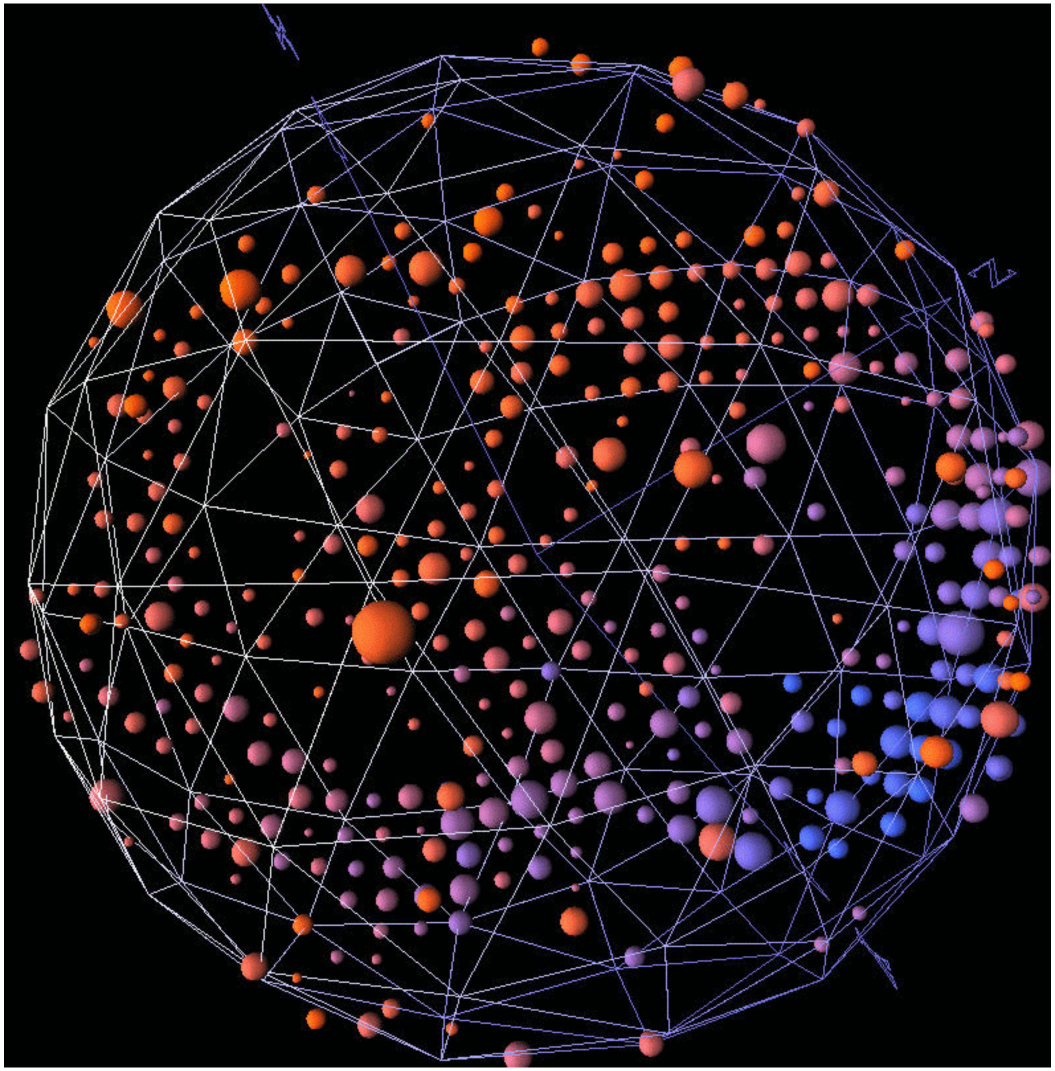
III. NC π^0 Events $\nu_\mu\ {}^{12}\mathrm{C} \rightarrow \nu_\mu\ \pi^0\ {}^{12}\mathrm{C}^*$

Contributions from:

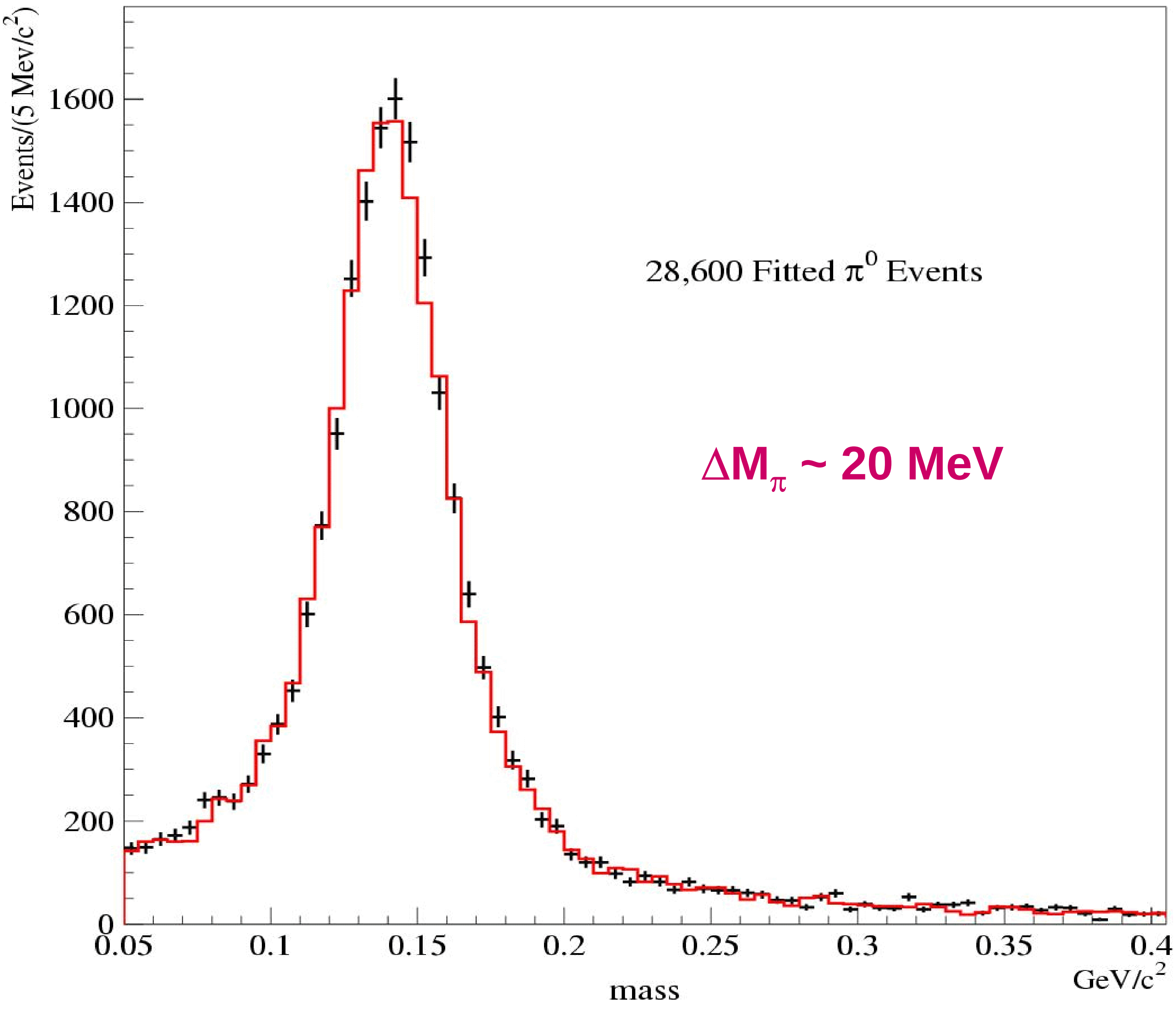
Resonance Production

Coherent Production

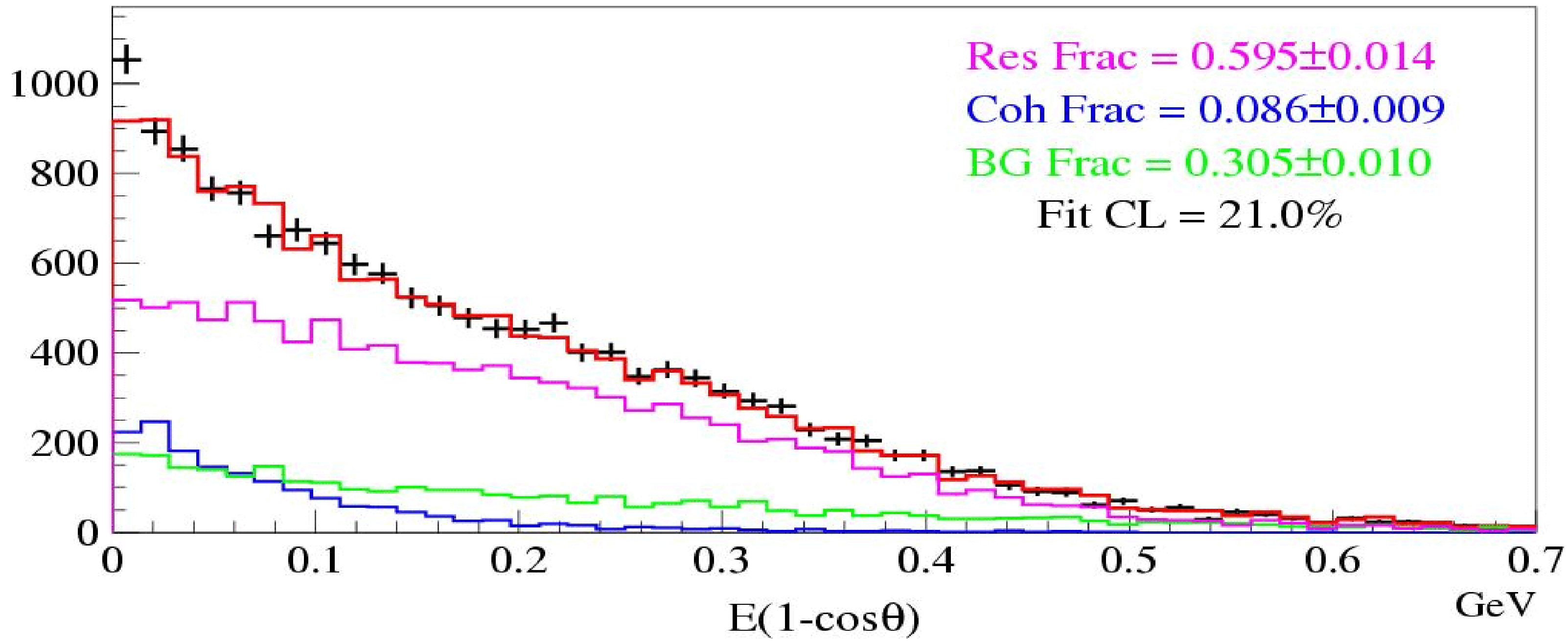
Selection: Double Ring Event with no Michel-electrons

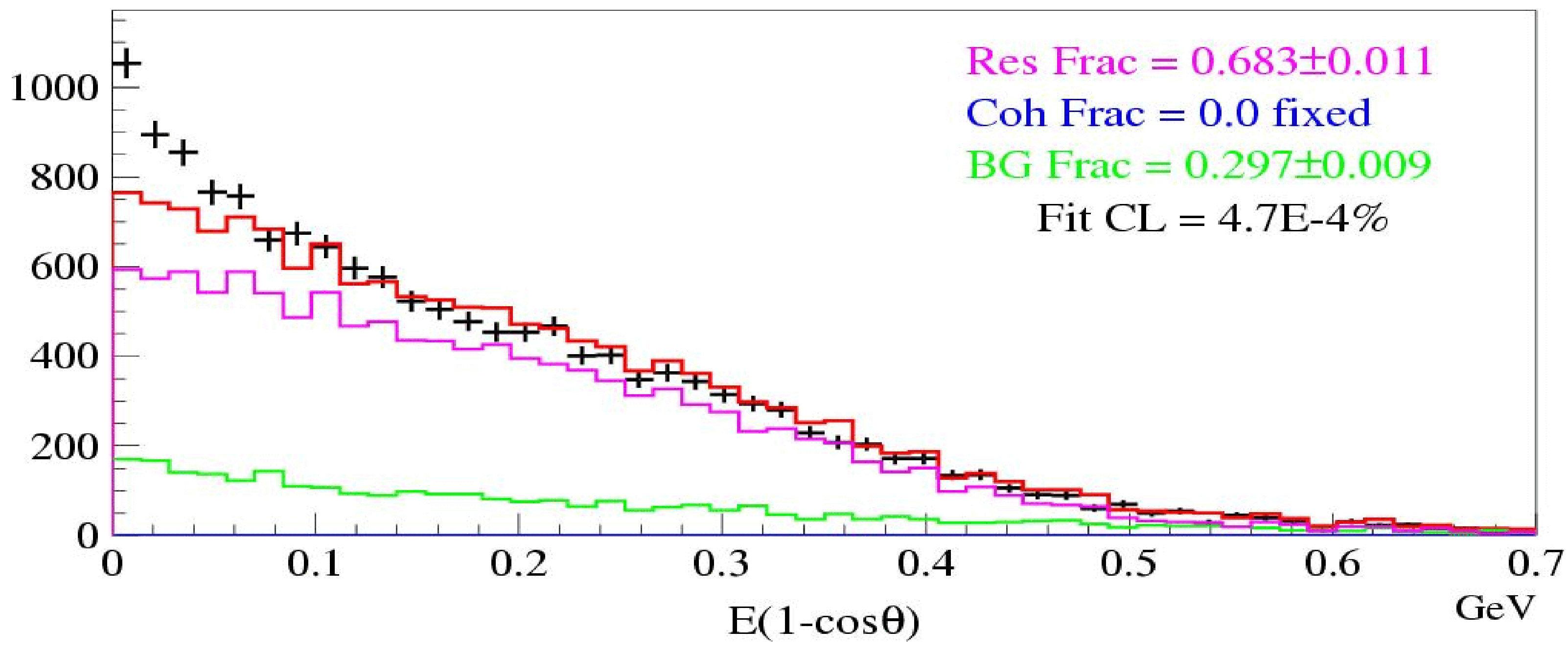


MiniBooNE NC π^0 Reconstruction

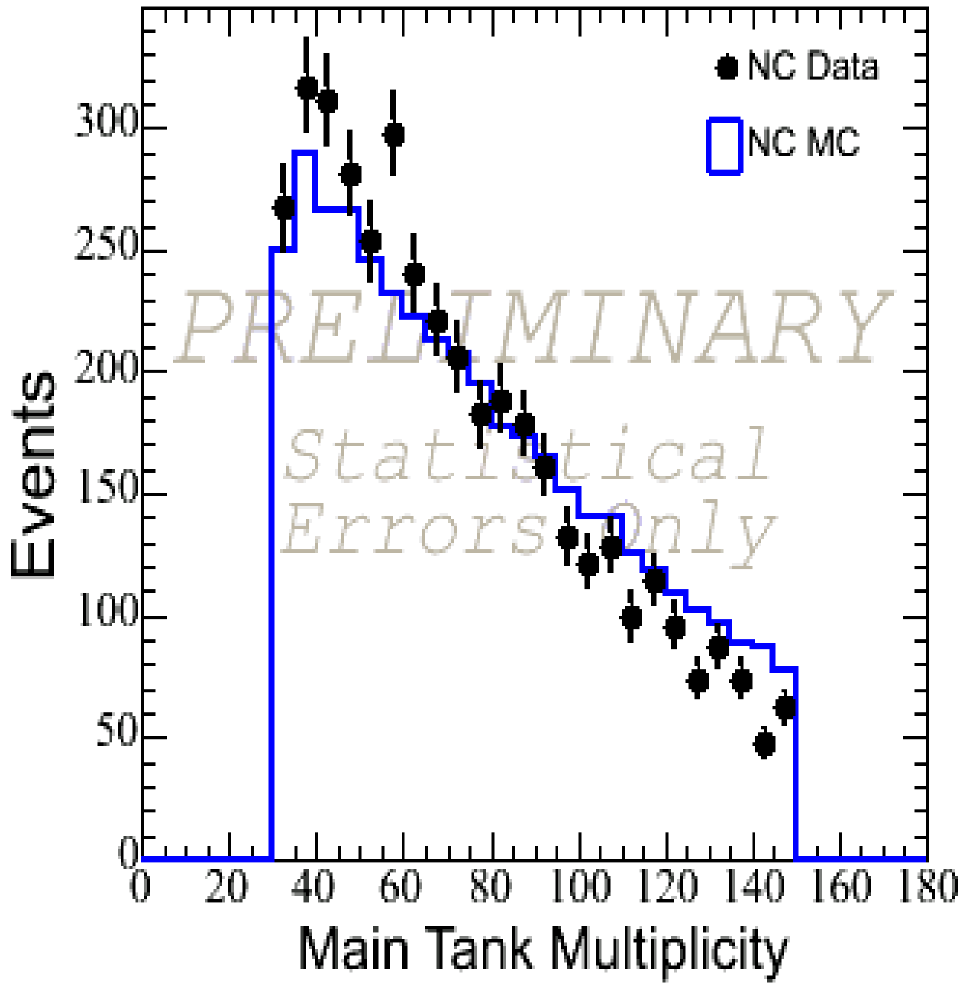


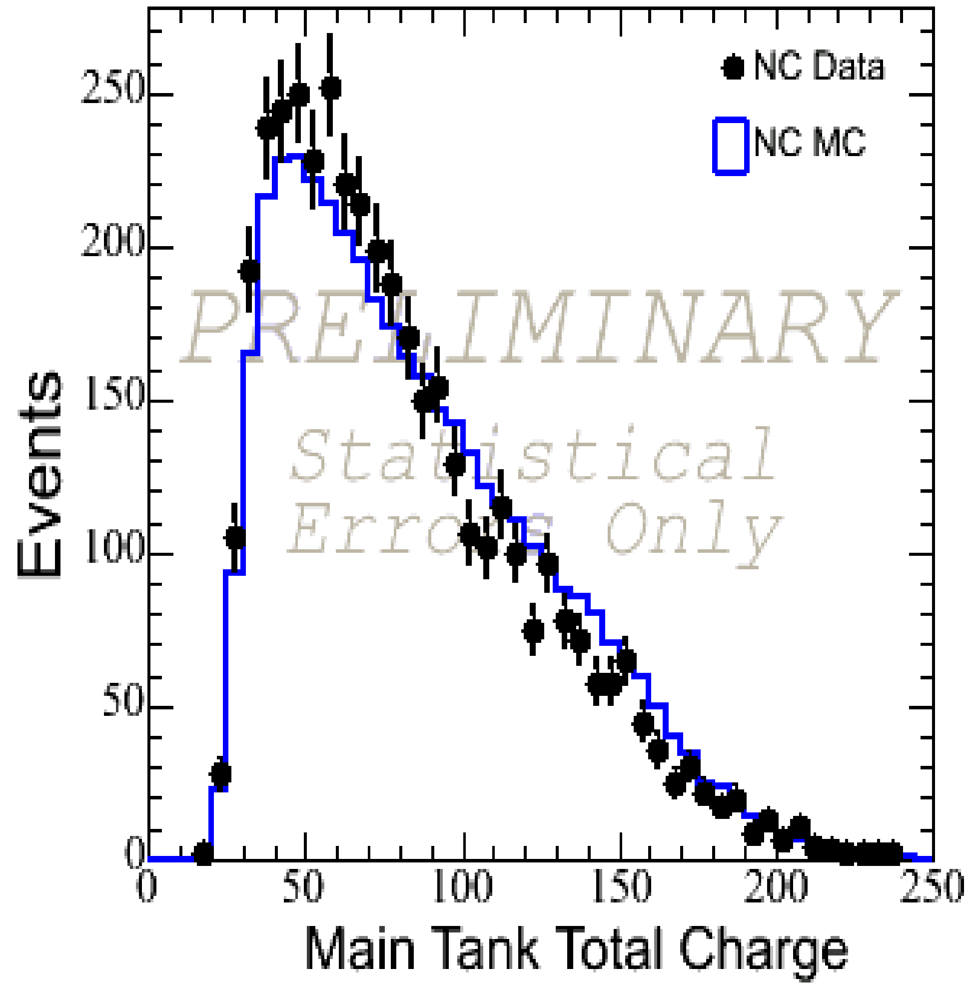
MiniBooNE NC π^0 Coherent Fraction





IV. NC Elastic Events $\nu_\mu C \rightarrow \nu_\mu NX$





V. $\nu_\mu \rightarrow \nu_e$ Oscillations $\nu_e\,{}^{12}C \rightarrow e^- p\,{}^{11}C^*$

Blind Analysis

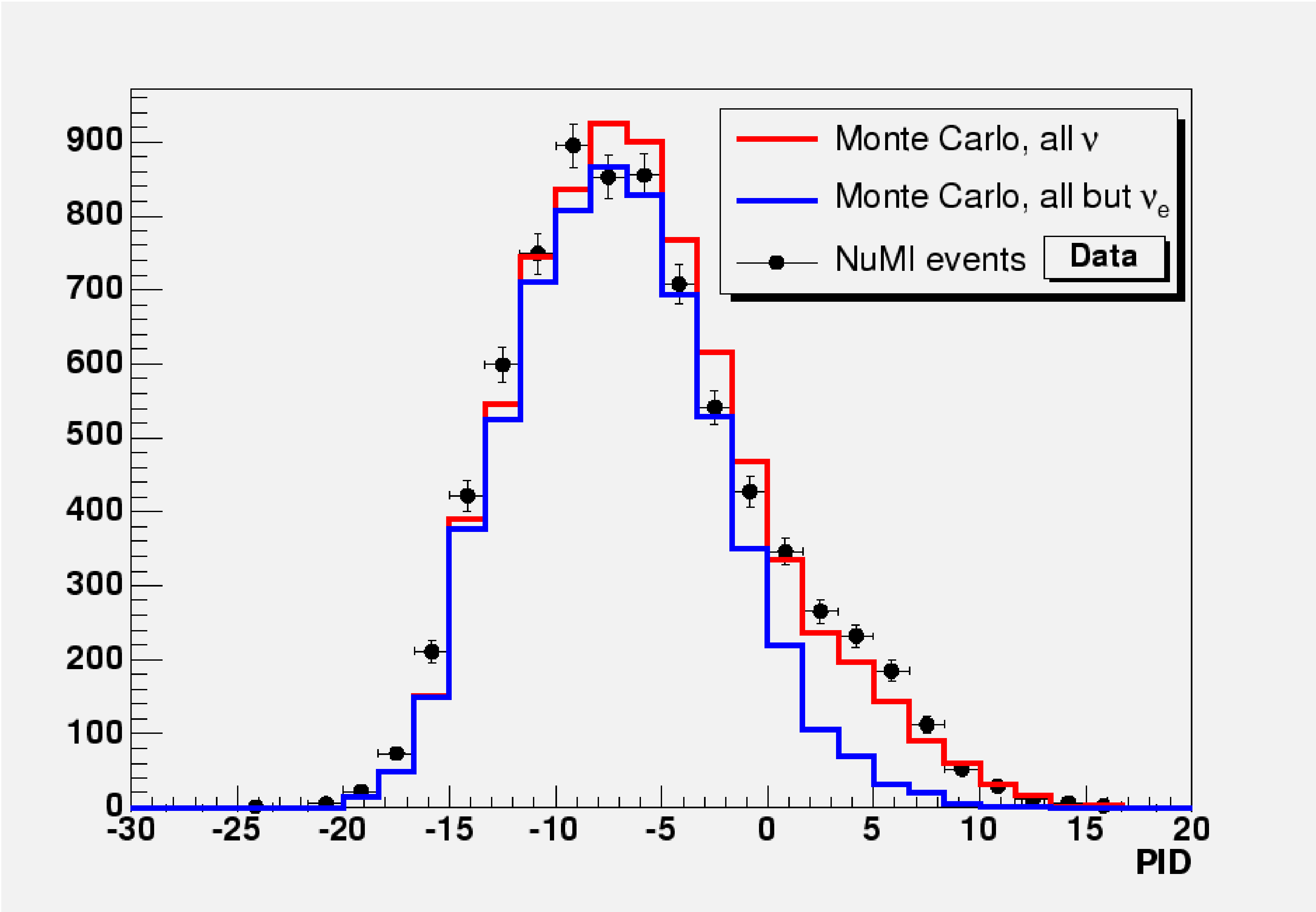
On track for results as soon as this summer

Have obtained good agreement between data & MC

Using Boosted Decision Trees for PID

- See NIM A543 (2005) 577 (Roe, Yang, Zhu, Liu, Stancu, McGregor) & NIM A555 (2005) 370 (Yang, Roe, & Zhu) for discussions of Boosted Decision Trees, which give better performance than ANN

Boosting PID Distribution for NuMI Contained 1 Sub-Events



MiniBooNE Schedule

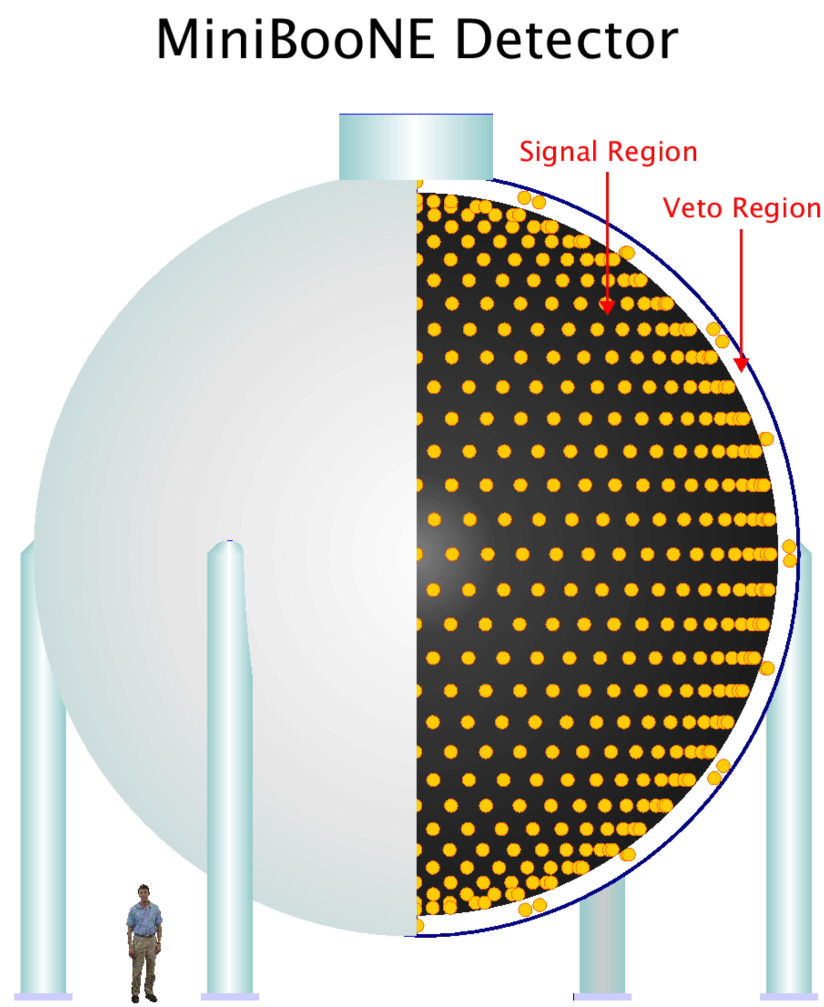
- **Run Antineutrinos in 2006**
- **Complete Neutrino Oscillation Analysis (Estimate systematic errors from neutrino flux, cross sections, detector MC)**
- **Open “Box” and Present Results**
- **If MiniBooNE Confirms LSND => *Physics Beyond the Standard Model!***

Future Experiments: BooNE & OscSNS

What new physics is there Beyond the Standard Model?

BooNE would involve a second "MiniBooNE-like" detector (~$8M) at a different distance; with 2 detectors, many of the systematics would cancel

OscSNS would involve building a "MiniBooNE-like" detector (~$12M) with higher PMT coverage at a distance of ~60 m from the SNS beam stop



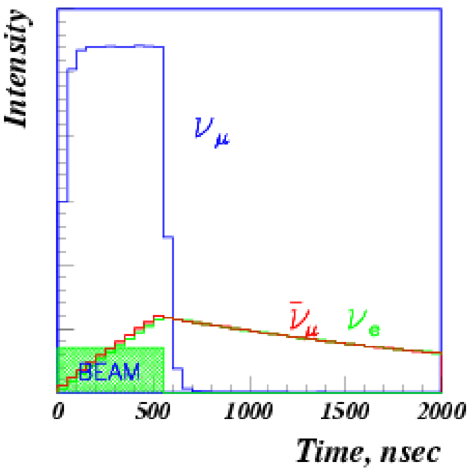
BooNE at FNAL

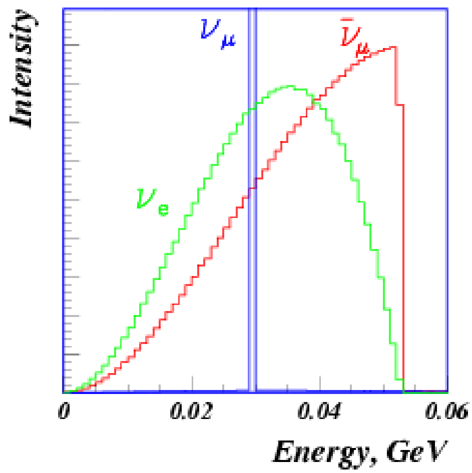
Two identical detectors at different distances

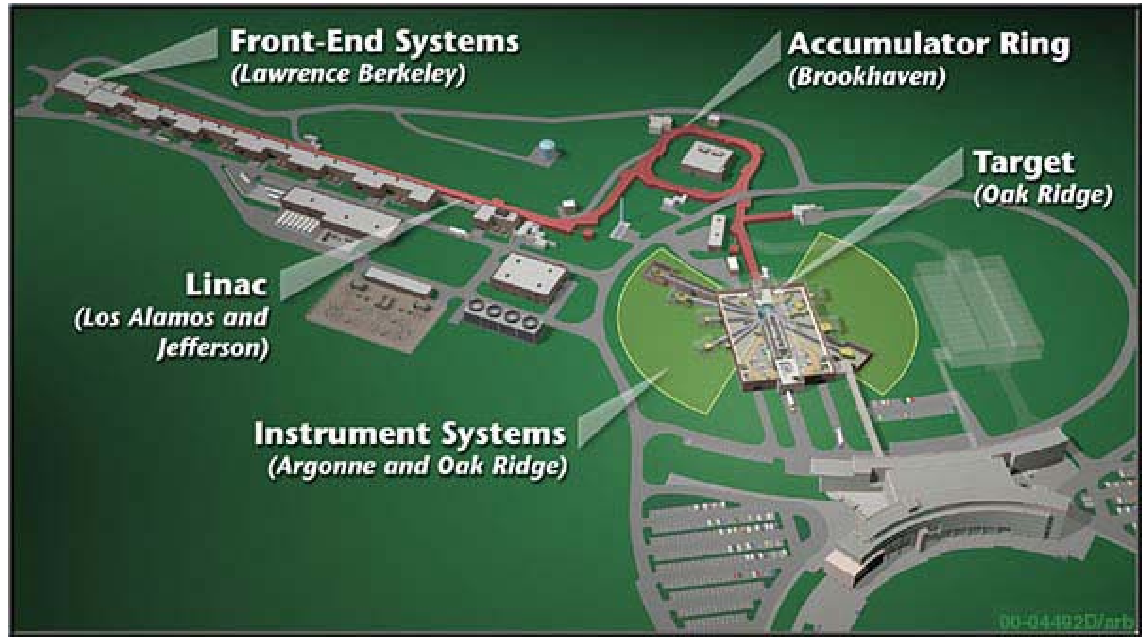
Search for sterile neutrinos via **NCPI0** scattering & **NCEL** scattering

Problem: imprecise ν energy determination smears oscillations!

OscSNS at ORNL







SNS: ~1 GeV, ~1.4 MW

$\bar{\nu}_\mu$ -> $\bar{\nu}_e$ $\Delta(L/E) \sim 3\%$; $\bar{\nu}_e$ p -> e^+ n

ν_μ -> ν_s $\Delta(L/E) < 1\%$; **Monoenergetic** ν_μ !; ν_μ C -> ν_μ C*(15.11)

OscSNS would be capable of making precision measurements of ν_e appearance & ν_μ disappearance and proving, for example, the existence of sterile neutrinos! (see Phys. Rev. D72, 092001 (2005)). Flux shapes are known perfectly and cross sections are known very well.

SNS $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ Experiment vs LSND

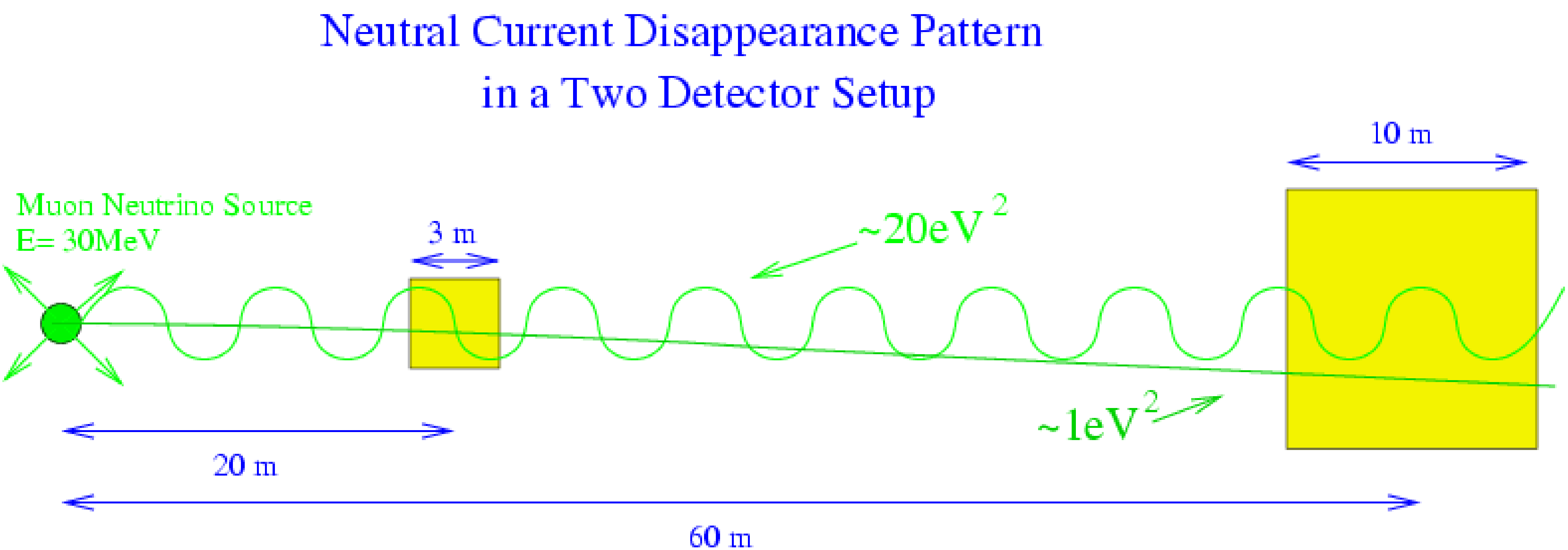
(assuming $\Delta m^2 < 1$ eV^2)

- ***More Detector Mass (x5)***
- ***Higher Intensity Neutrino Source (x2)***
- ***Lower Duty Factor (x100) (less cosmic bkgd)***
- ***No DIF Background (backward direction)***
- ***Lower Neutrino Background (x4) (60 m vs 30 m)***
- ***Better Signal/Background (x4)***
- ***Better L/E Resolution (x2) (more scint & better PMTs)***
- ***For LSND parameters, expect ~350 ν_e oscillation events & <50 background events per year!***

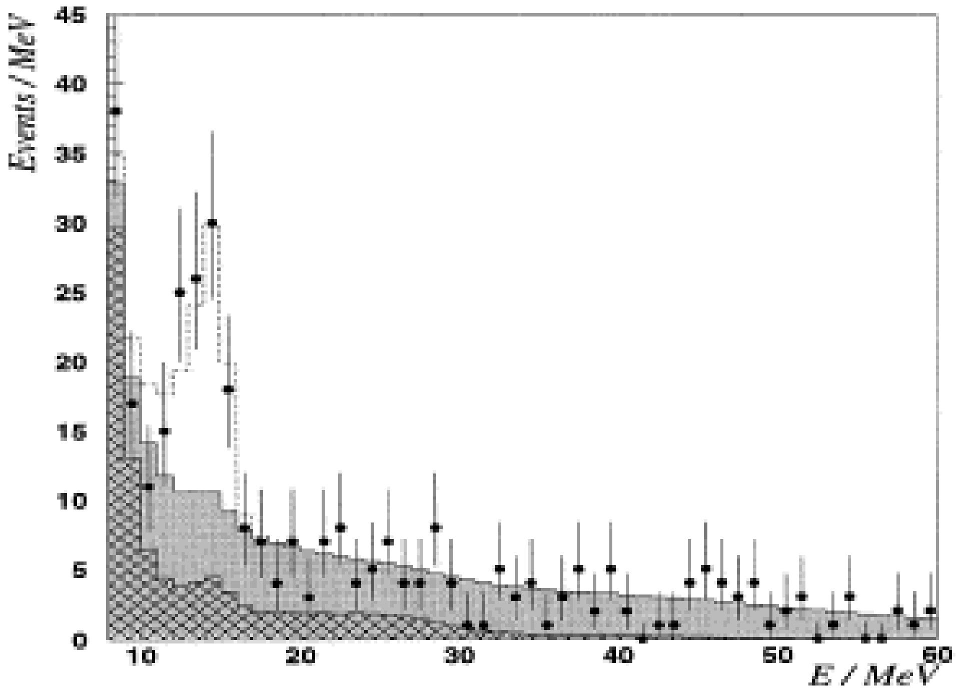
Search for Sterile Neutrinos with OscSNS Via Measurement of NC Reaction:

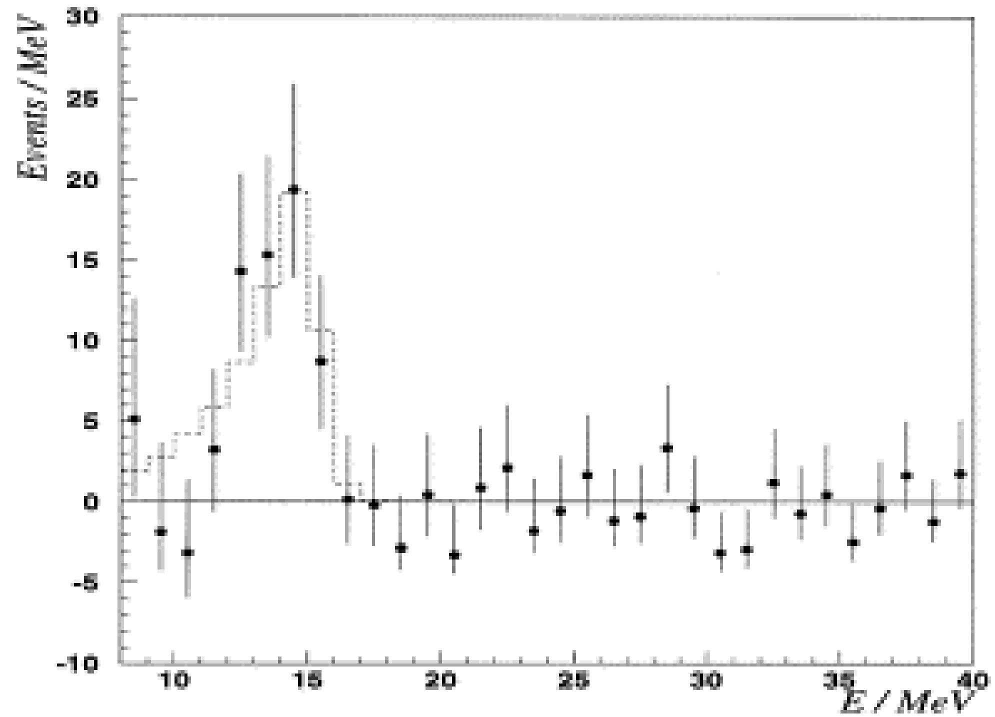
ν_μ C -> ν_μ C*(15.11)

Garvey et al., Phys. Rev. D72 (2005) 092001



KARMEN Measurement of ν_μ C -> ν_μ C*(15.11)



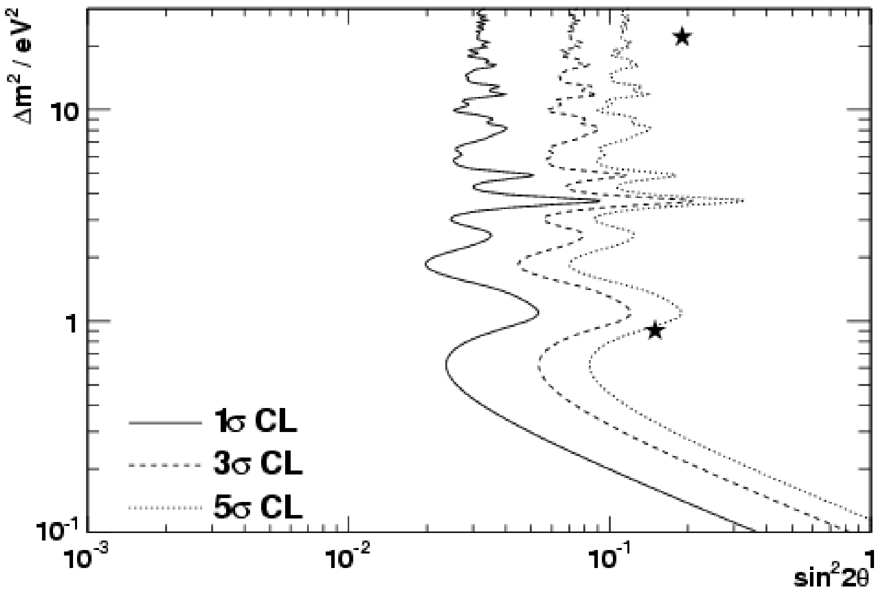


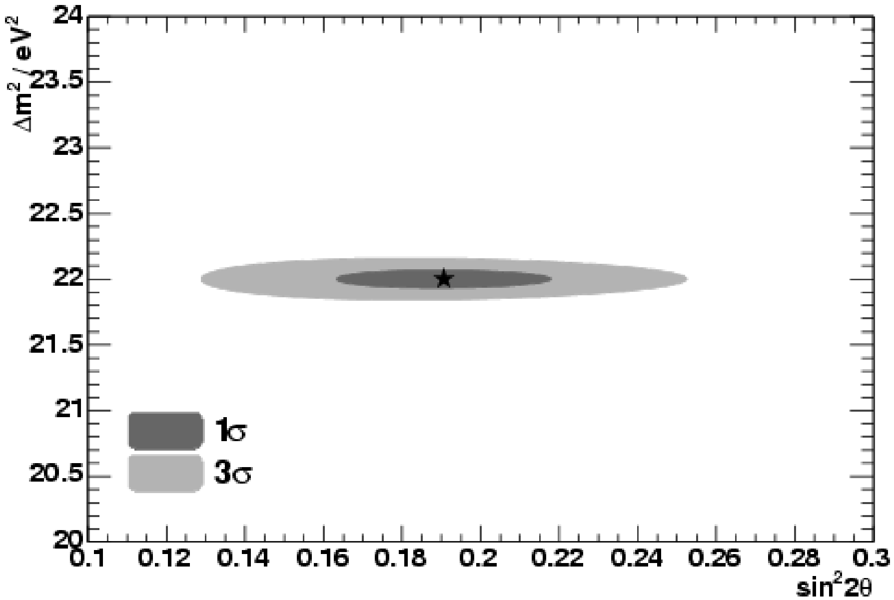
σ_{NC} = (3.2+-0.5+-0.4)x10^{-42} cm^2 (B. Armbruster et al., Phys. Lett. B423 (1998) 15)

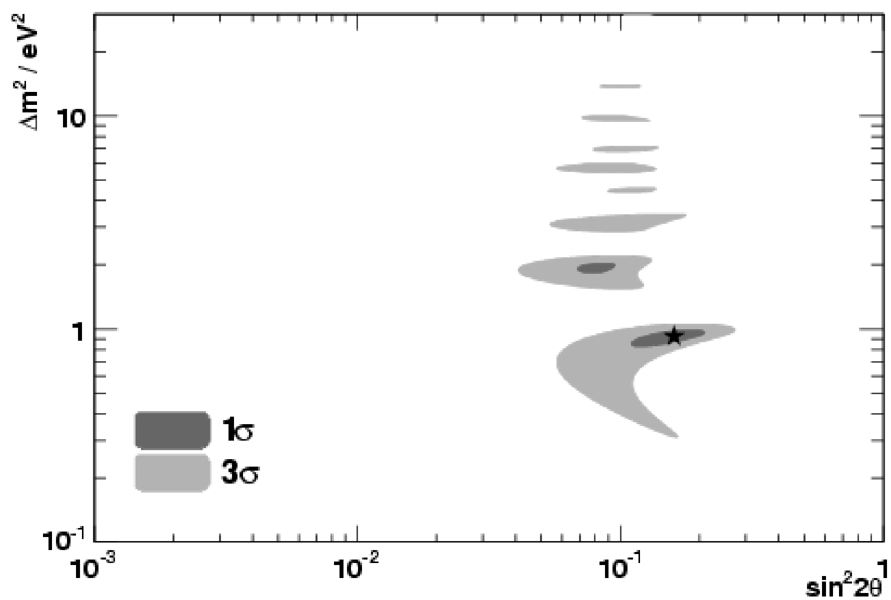
σ_{NC} ~2.8x10^{-42} cm^2 (Kolbe, Langanke, & Vogel, Nucl. Phys. A652 (1999) 91)

Measurement of 3+2 Model with OscSNS

(Sorel et al., Phys. Rev. D70 (2004) 073004)







Conclusions

MiniBooNE will soon test the LSND Oscillation Signal

If the LSND Signal is Confirmed, then Future Oscillation Experiments Would Provide a Great Opportunity for Nuclear Physics: BooNE at FNAL & OscSNS at ORNL

Make Precision Measurements of Oscillation Parameters

Resolve 3 Δm^2 Paradox & Explore Physics Beyond the Standard Model! (e.g. Sterile Neutrinos)