

# Latest Cross Section Results from MiniBooNE

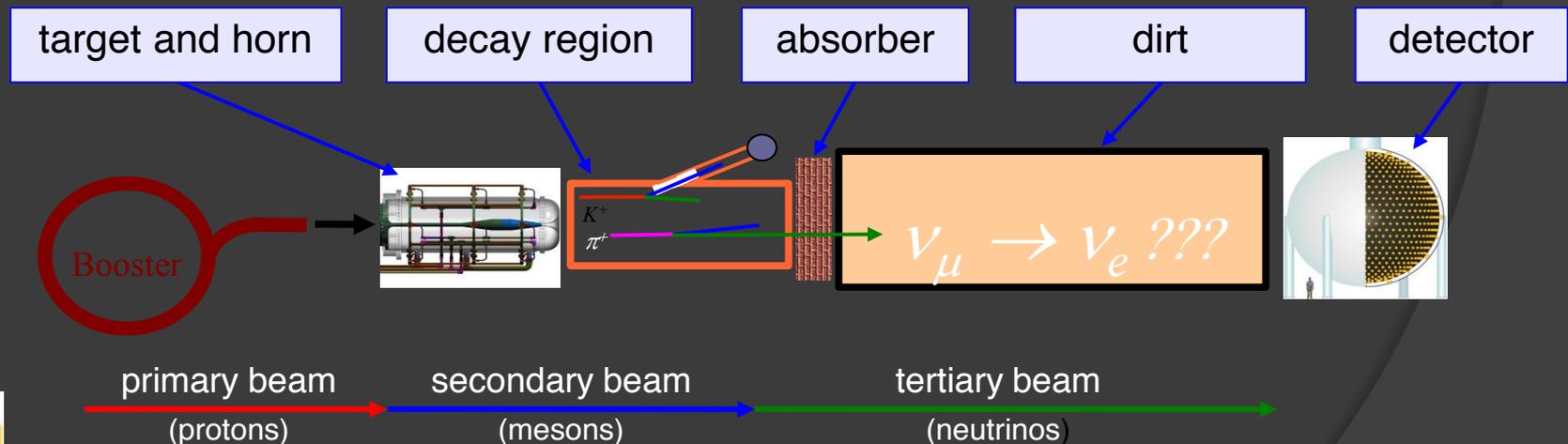
M. Tzanov  
*Louisiana State University*

NuFact Workshop, Williamsburg, July 23-28, 2012

# MiniBooNE Experiment – E898 at Fermilab

Test of LSND within the context of  $\nu_{\mu} \rightarrow \nu_e$  appearance only is an essential first step:

- Keep the same L/E
- Higher energy and longer baseline –  $E=0.5 - 1$  GeV;  $L=500$ m
- Different beam
- Different oscillation signature  $\nu_{\mu} \rightarrow \nu_e$
- Different systematics
- Antineutrino-capable beam



# Flux - $\pi^+$ Production from HARP

HARP (CERN) measured the  $\pi^+$  production cross section

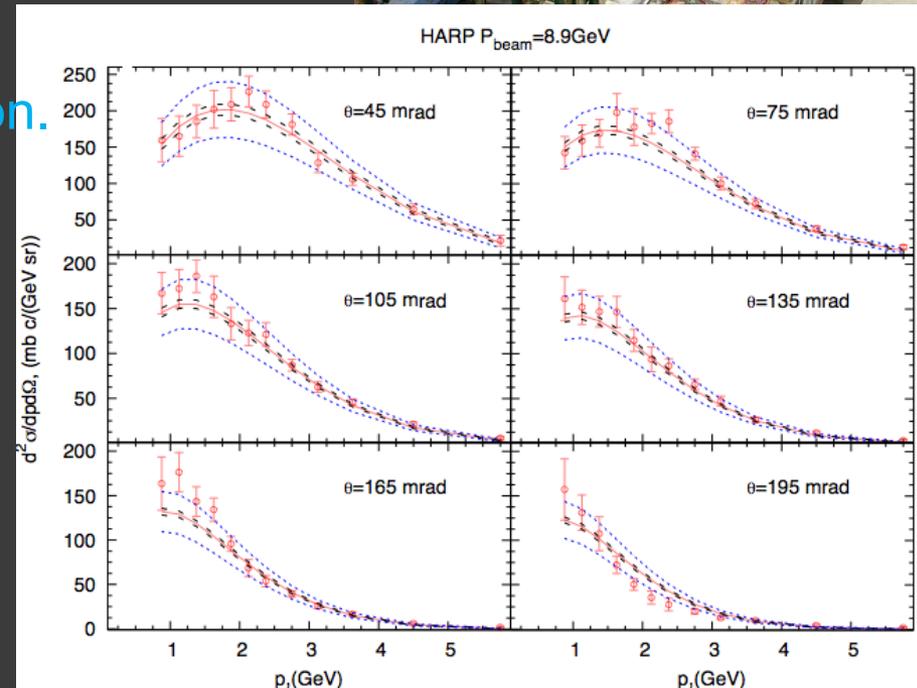
- 5%  $\lambda$  Beryllium target
- 8.9 GeV proton beam momentum



$\pi^+$  production cross section is parameterized from a fit to HARP  $\pi^+$  production cross section, using the standard Sanford-Wang parameterization.

Covers 80% of the pion phase space relevant for MB. Pion production uncertainty is 7%.

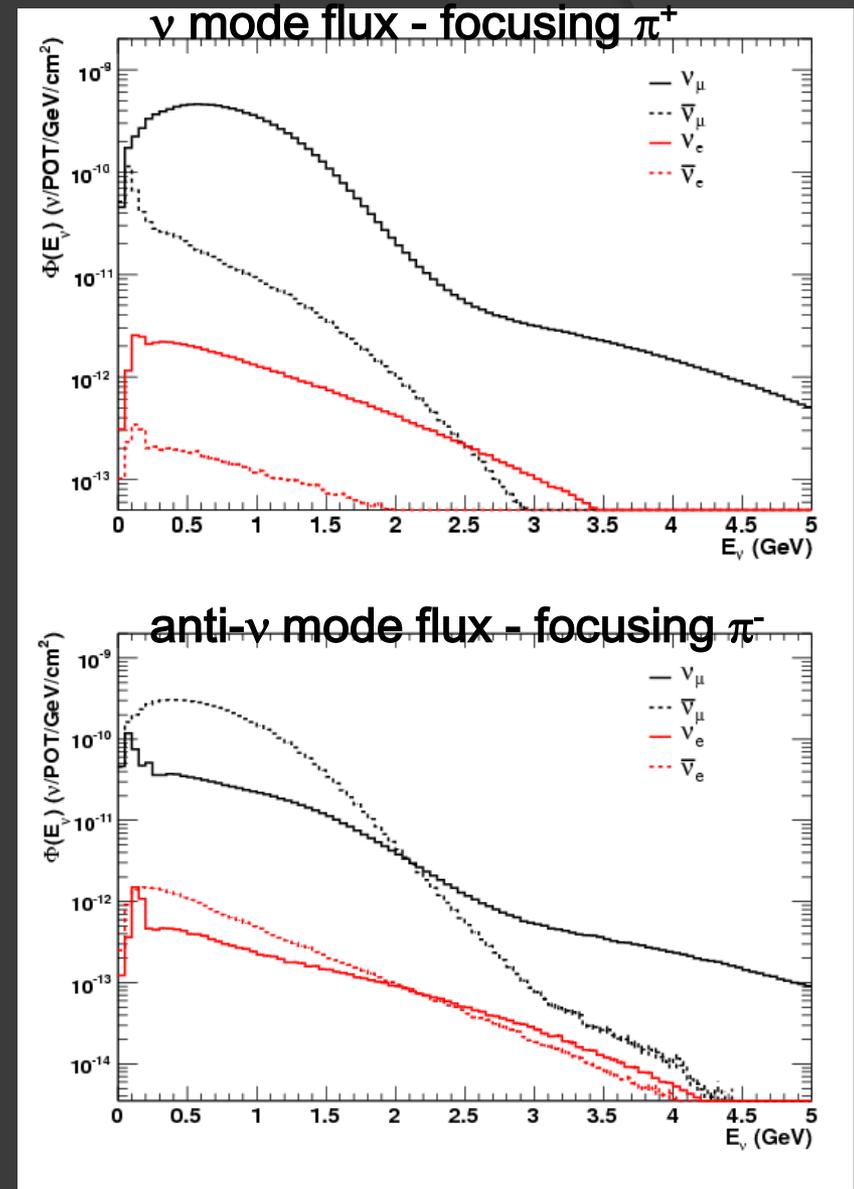
Makes cross section measurements possible.



# MiniBooNE Predicted Flux

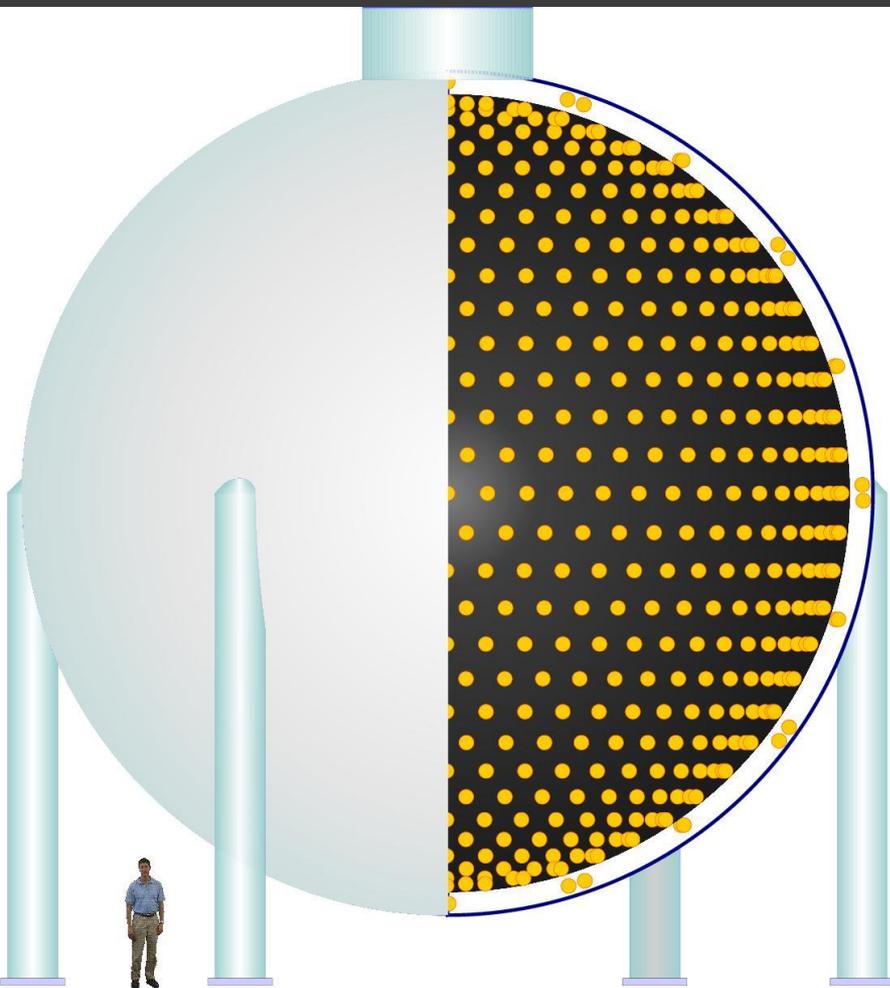
- ~1,000,000 interactions in fiducial volume in  $\nu$  mode with small anti- $\nu$  component.
- greater than 100 k interactions in fiducial volume in anti- $\nu$  mode with 30%  $\nu$  component.

Largest sample neutrino and anti-neutrino interactions in the ~1GeV region to date.



*A.A. Aguilar-Arevalo et al., PRD 79, 072002 (2009)*

# The MiniBooNE Detector

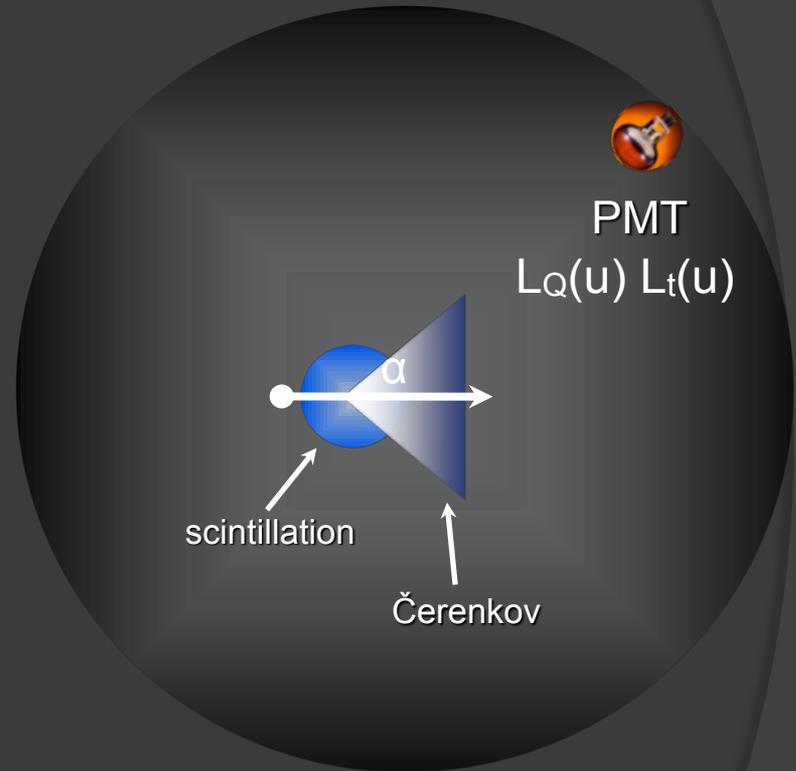


- 541 meters downstream of target
- 3 meter overburden
- 12 meter diameter sphere  
(10 meter “fiducial” volume)
  - Filled with 800 t of pure mineral oil ( $\text{CH}_2$ )  
(Fiducial volume: 450 t)
  - 1280 inner phototubes,  
240 veto phototubes

*A. A. Aguilar-Arevalo et al., NIM A599, 28 (2009)*

# Track Fitting

- A particle is parametrized as a “track” in the oil.
  - Vertex:  $(x,y,z)$
  - Time:  $(t)$
  - Direction:  $(\theta,\varphi)$
  - Kinetic energy:  $(E)$
- At each point of the track scintillation and Čerenkov light is produced. This depends on the type of particle.
- This light propagates through the mineral oil to the PMTs.



# Neutrino Cross Sections Extraction Technique

$$\sigma(E_\nu)_i = \frac{\sum_j^{bins} U_{ij} (N_j - B_j)}{\varepsilon_i \Phi_i N_{targs}}$$

$\sigma$  – cross section,

$E_\nu$  – neutrino energy,

$U_{ij}$  – unfolding matrix,

$N_j$  – measured rate in bins,

$B_j$  – measured/predicted background rate in bins,

$\Phi_i$  – flux,

$\varepsilon$  – efficiency.

# Unfolding

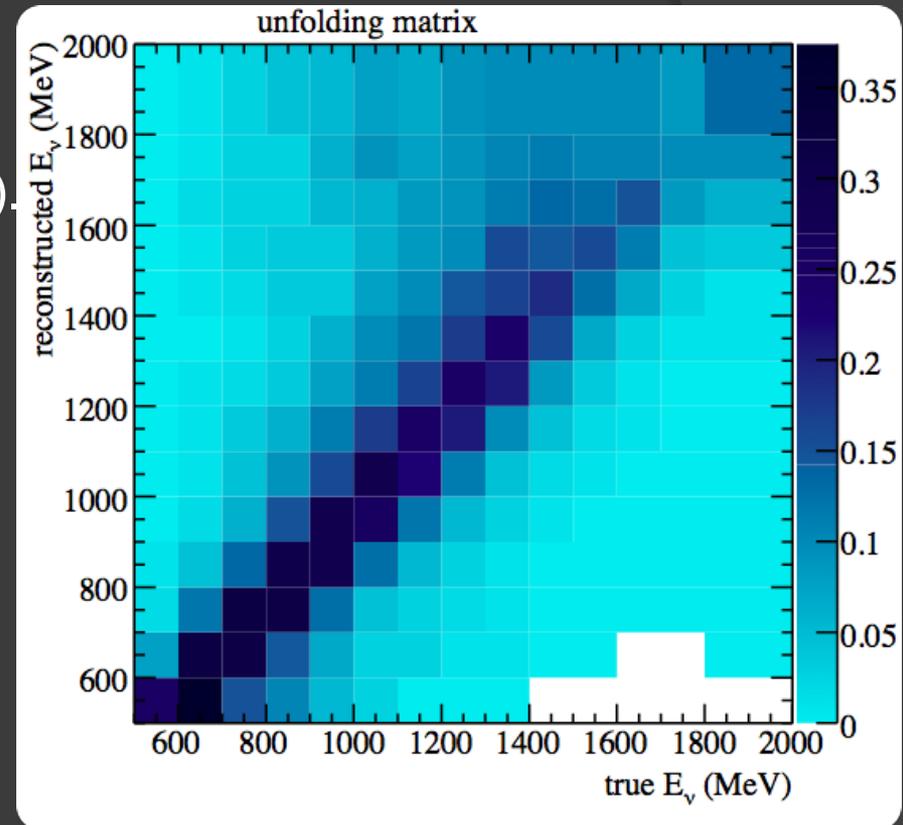
Unfolding is used to correct for detector effects (smearing and mis-reconstruction).

- bin migration matrix inversion is unbiased, but it's unstable and leads to large statistical uncertainty.

Bayesian unfolding:

$$U_{ij} = P(t_i | r_j) = \frac{P(r_j | t_i) P(t_i)}{\sum P(r_j | t_n) P(t_n)}$$

- small statistical uncertainty,
- small bias is the price.

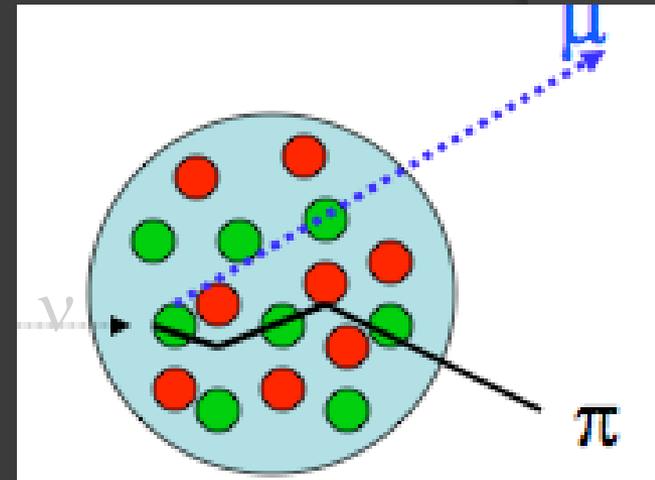


CC $\pi^0$  unfolding matrix.

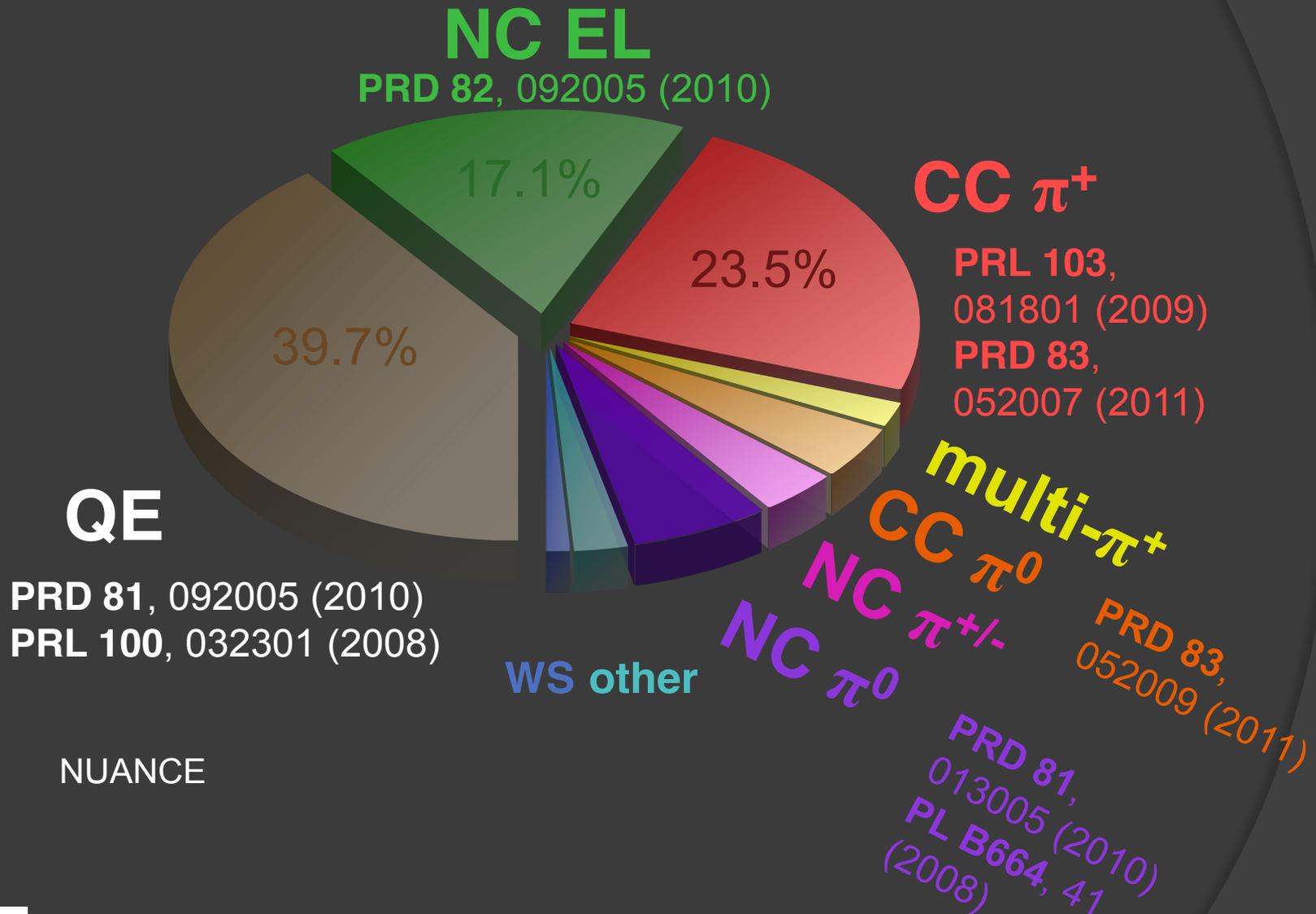
# Observable Cross Sections

$$\sigma(E_\nu)_i = \frac{\sum_j^{bins} U_{ij} (N_j - B_j)}{\epsilon_i \Phi_i N_{targs}}$$

- nuclear target – re-interactions in the nucleus.
- different primary neutrino interactions become indistinguishable experimentally.
- Final State Interactions (FSI) model is needed to extract nucleon cross section – large uncertainties.
- MiniBooNE measures observable cross sections. CC $\pi^+$  observable signal include all events with a  $\mu^-$  and a  $\pi^+$  emerging from the nucleus.

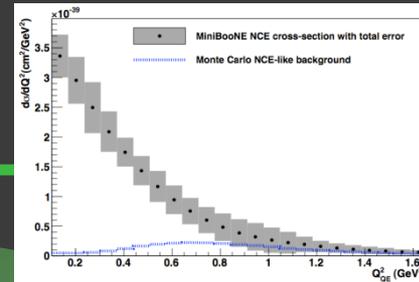


# MiniBooNE $\nu$ Cross Section Measurements



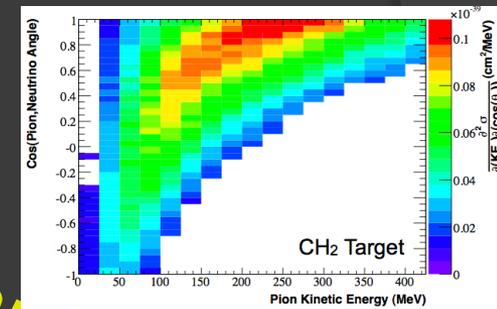
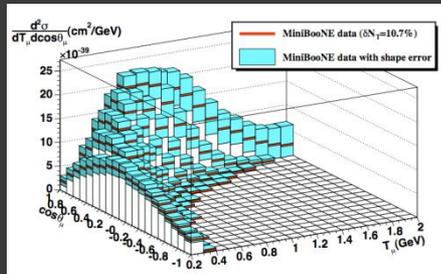
# MiniBooNE $\nu$ Cross Section Measurements

NC EL



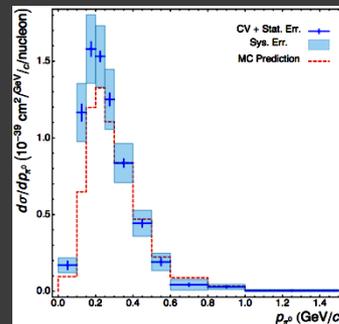
Collected  $\nu$  data  
2002-2005, 2007  
6.46e20 POT

CC  $\pi^+$

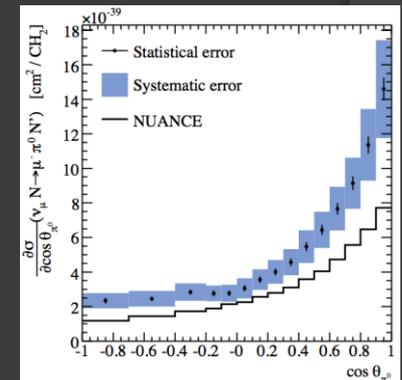


QE

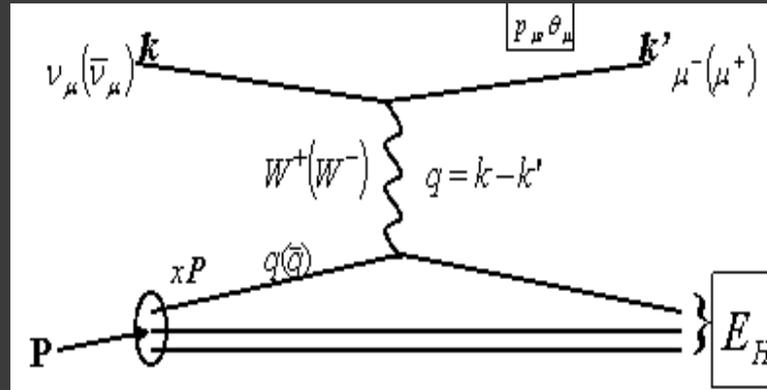
1<sup>st</sup> time full kinematics  
have been reported for  
many of these reaction  
channels!



multi- $\pi^+$   
CC  $\pi^0$   
NC  $\pi^+/-$   
NC  $\pi^0$



# MiniBooNE CC Inclusive Cross Section



Can't we just add CCQE, CC $\pi^+$  and CC $\pi^0$ ?

- Yes, we can add the cross sections, but we'll be adding the systematics as well.
- Complicated model dependent correlations – each of the exclusive channels is a background for the others through FSI model.

It's important to have a full suite of cross section measurements from one experiment – same flux systematics.

# CC Inclusive Sample in MiniBooNE

Selection criteria:

- Events are tagged by at least one Michel electron,
- Veto and Containment – Maximum of five VETO hits in all subevents,
- Minimum PMT hits in the first subevent to remove beam unrelated backgrounds.
- Fiducial volume of 5m diameter.

CCQE – 52%

CCpip - 36%

CCpi0 - 5%

Other CC – 3%

NC – 3%

Data events after cuts 344k. 96% purity.

# CC Inclusive Event Reconstruction

New event reconstruction for MiniBooNE

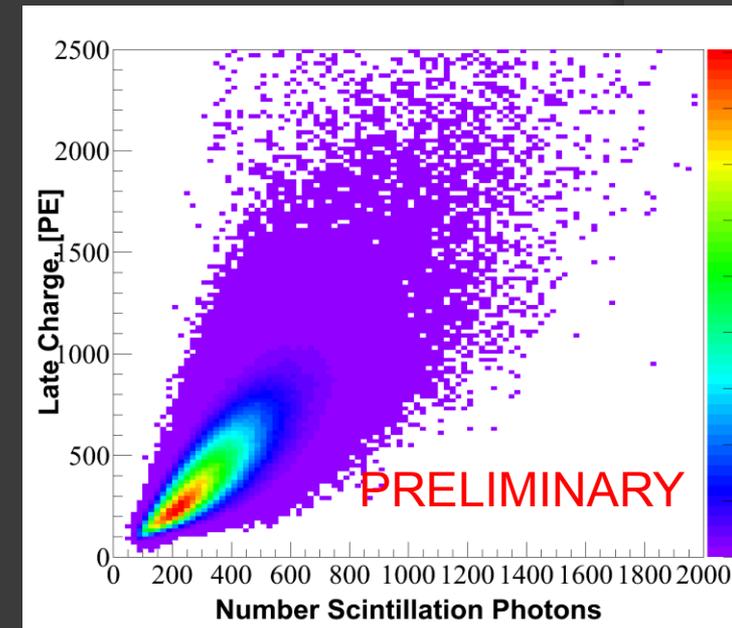
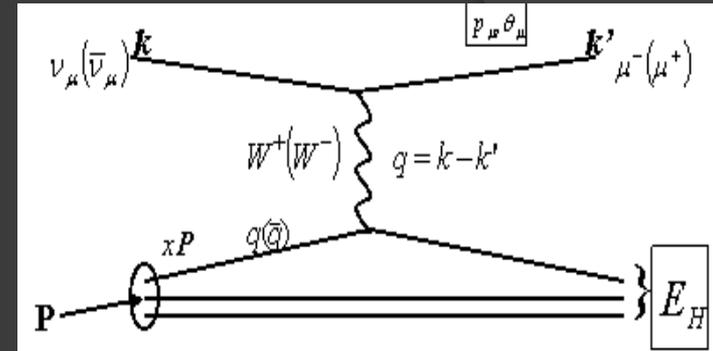
- Muon kinematics from 2-track likelihood fit:

Second ring of the fit absorbs the bias due to second most prominent ring.

- Neutrino energy – MiniBooNE detector as calorimeter.

Small scintillation light component produces late hits in the event. The charge of the late hits is used as a measure of the neutrino energy.

**Fully reconstruct the lepton vertex – no assumptions for the target!!!**



Plots are from MC.

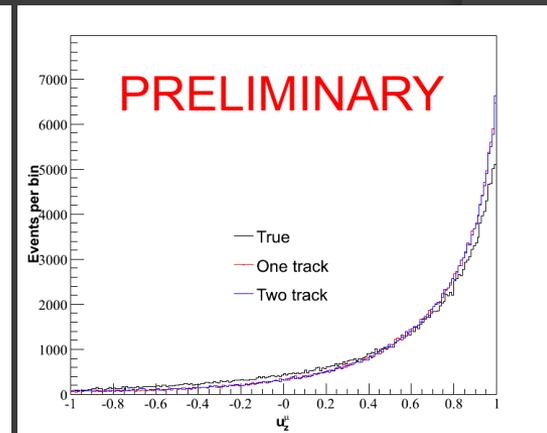
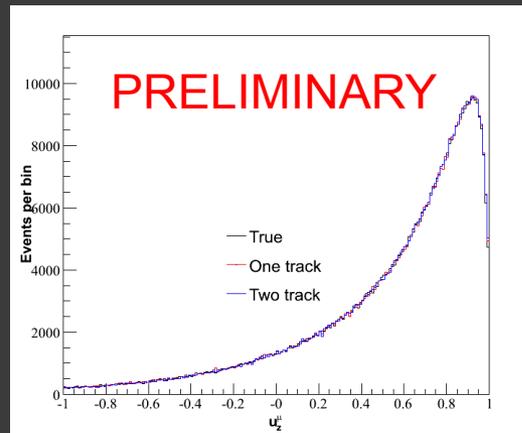
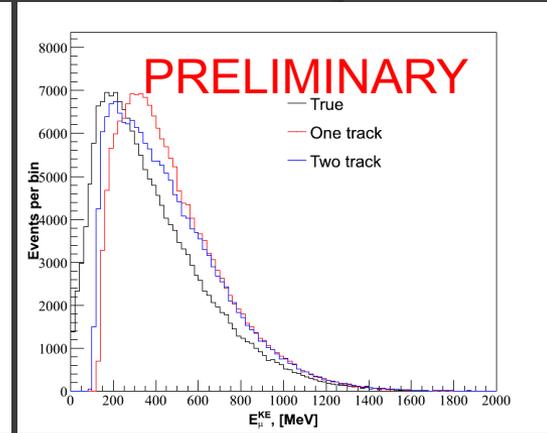
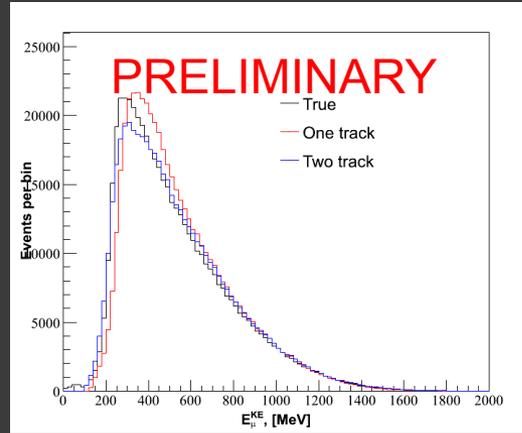
# Muon Kinematics Reconstruction Performance

2-track fit improves significantly the reconstruction of the muon kinetic energy compared to one track fit. Muon kinetic energy resolution is about 5%.

$T_\mu$

No significant improvement for the muon angle. Muon angle resolution is better than  $1^\circ$ .

$u_z^\mu$



CCQE

CC $\pi^+$

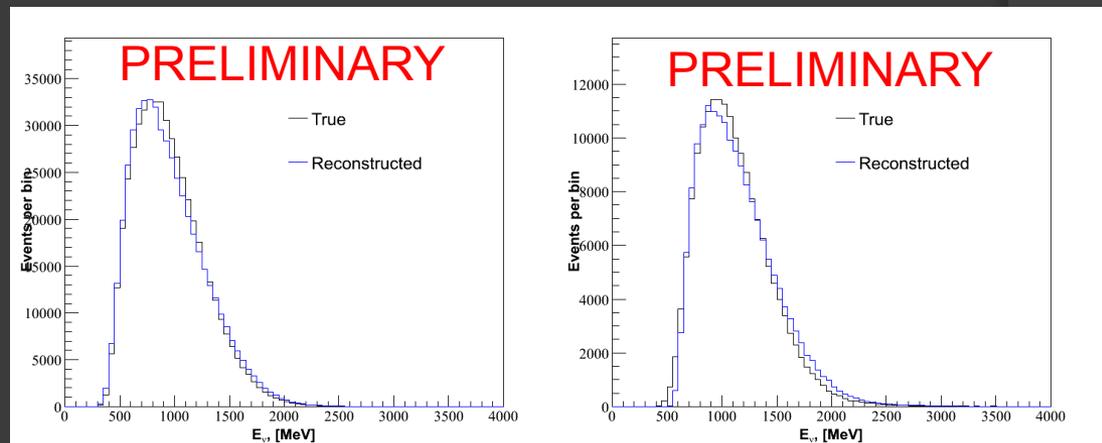
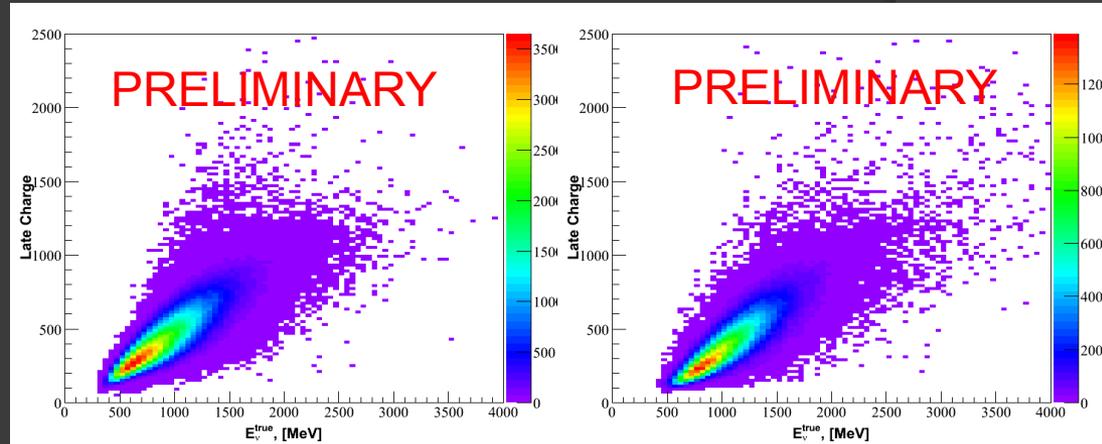
Plots are from MC.

# Neutrino Energy Reconstruction Performance

Neutrino energy reconstruction is obtained from the late light charge which is linearly correlated with the true neutrino energy.

The parameters of the reconstruction come from a linear fit to both CCQE and  $CC\pi^+$  enhanced samples. the slope parameter is the same in both cases while the Intercept is different.

Energy reconstruction resolution is about 18%.



CCQE

$CC\pi^+$

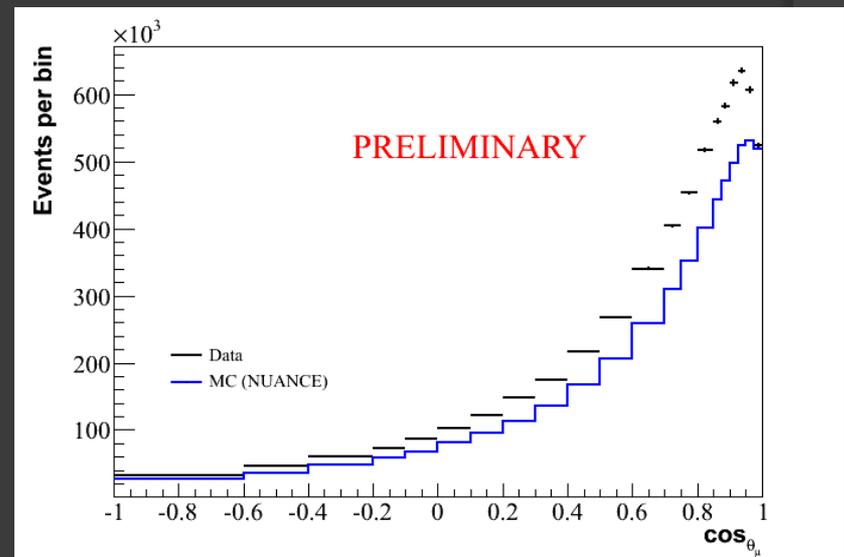
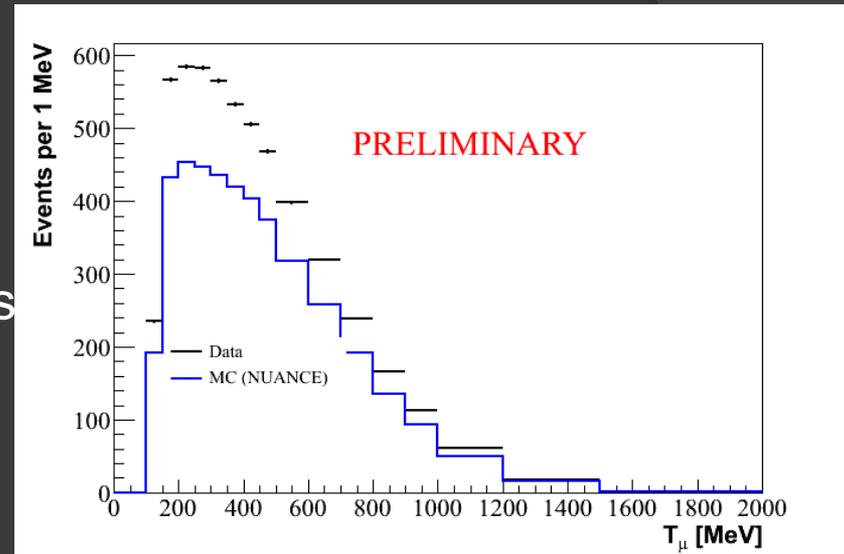
Plots are from MC.

# Neutrino Energy– Data Calibration

- So far pure MC – detector response was never tuned for this regime.
- Compare CC Inclusive reconstruction to CCQE and  $CC\pi^+$  reconstructions (need to have the same underlying distribution) – reweight MC to the measured  $CC\pi^+$  cross section.
- Event-by-event comparison between CC Inclusive and the other reconstructions
- Compare the differences between the reconstructions in data and MC – a way to calibrate.

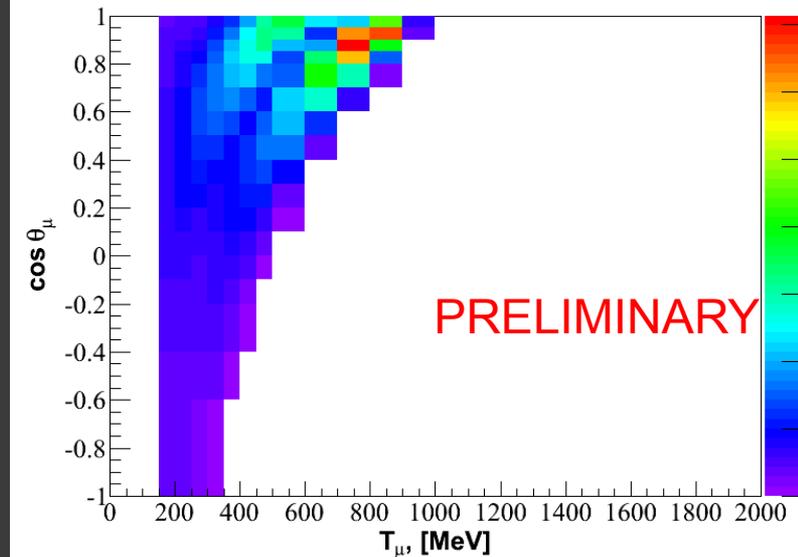
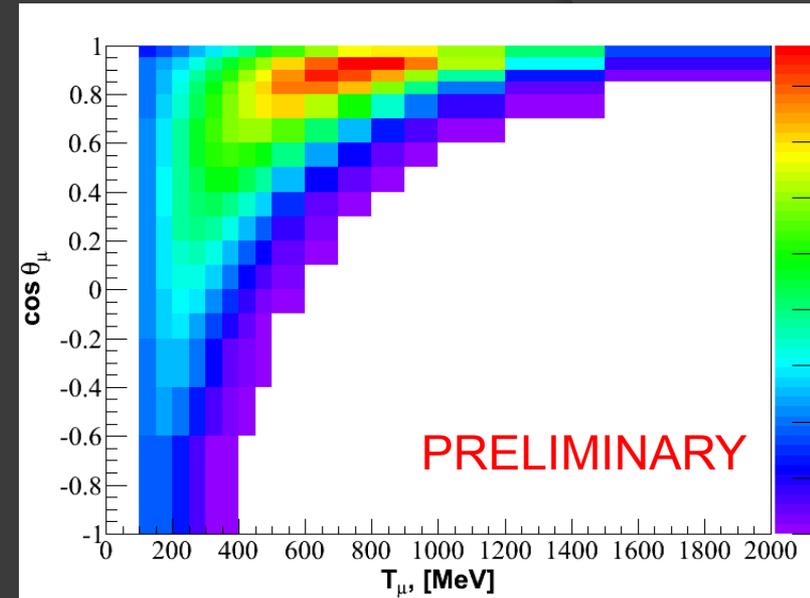
# MiniBooNE CC Inclusive Cross Sections

- Data rate is higher than predicted as suggested by the exclusive channels
- Largest neutrino sample in this region to date - 344000 CC inclusive interactions after cuts.
- $4\pi$  detector geometry – full coverage of phase space.



# MiniBooNE CC Inclusive Cross Sections

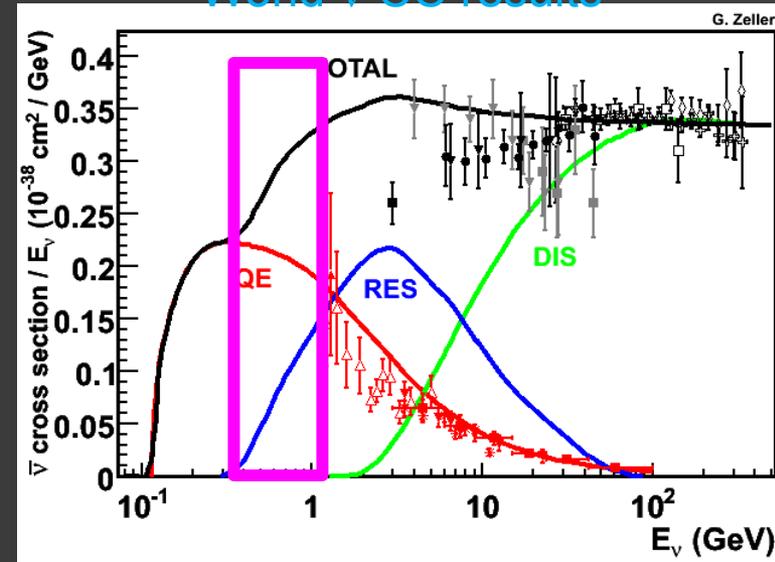
- Complete suite of CC inclusive cross sections.
- Full reconstruction of the lepton vertex without any assumptions for the target!!!
- No dependence on FSI.
- MB will measure  $\sigma(E_\nu)$ ,  $d\sigma/dT_\mu(E_\nu)$ ,  $d\sigma/d\cos\theta_\mu(E_\nu)$ ,  $d\sigma/dQ^2(E_\nu)$ , flux integrated  $d^2\sigma/dT_\mu d\cos\theta_\mu$ ,  $d^2\sigma/dT_\mu d\cos\theta_\mu(E_\nu)$ .



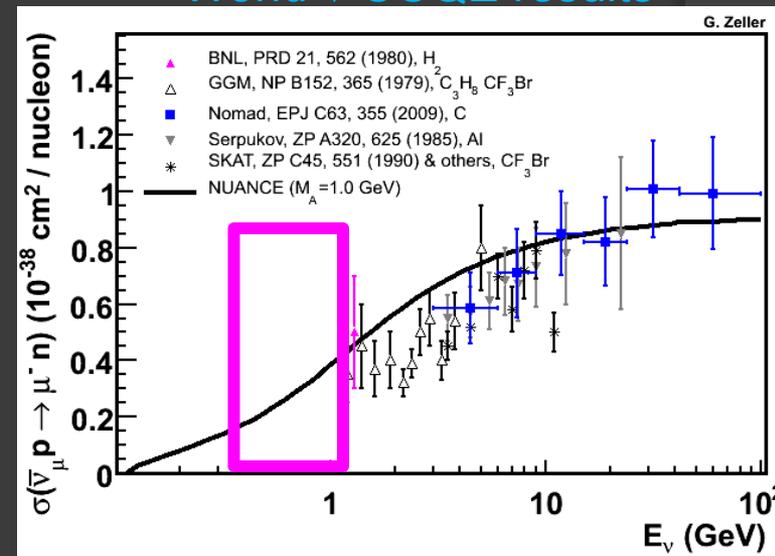
# MiniBooNE $\bar{\nu}$ Cross Section Measurements

World  $\bar{\nu}$  CC results

- Lack of measurements below 1 GeV.
- Latest data from NOMAD but in a higher energy region.



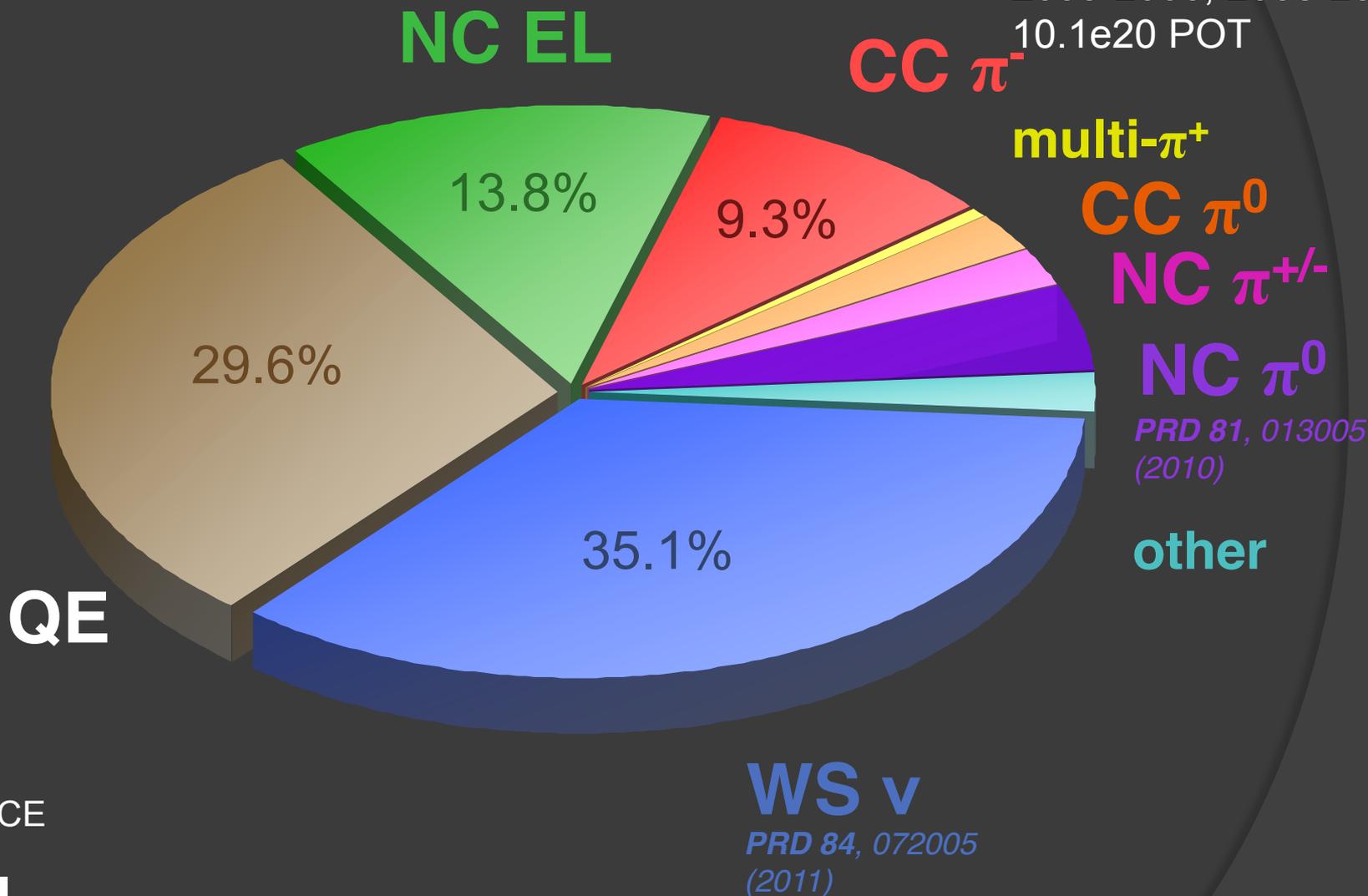
World  $\bar{\nu}$  CCQE results



J. Formaggio and G. Zeller, RMP, to be published (2012)

# MiniBooNE $\bar{\nu}$ Cross Section Measurements

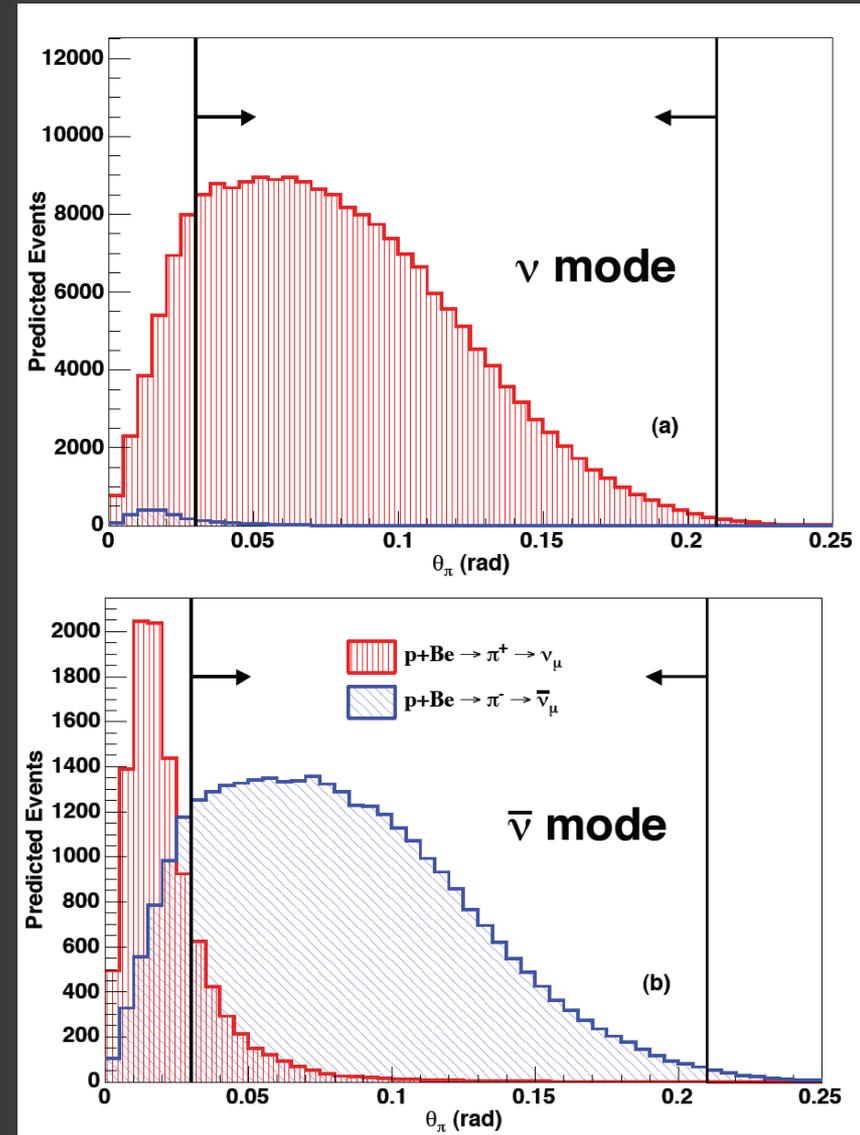
Collected  $\bar{\nu}$  data  
2005-2006, 2008-2012  
10.1e20 POT



NUANCE

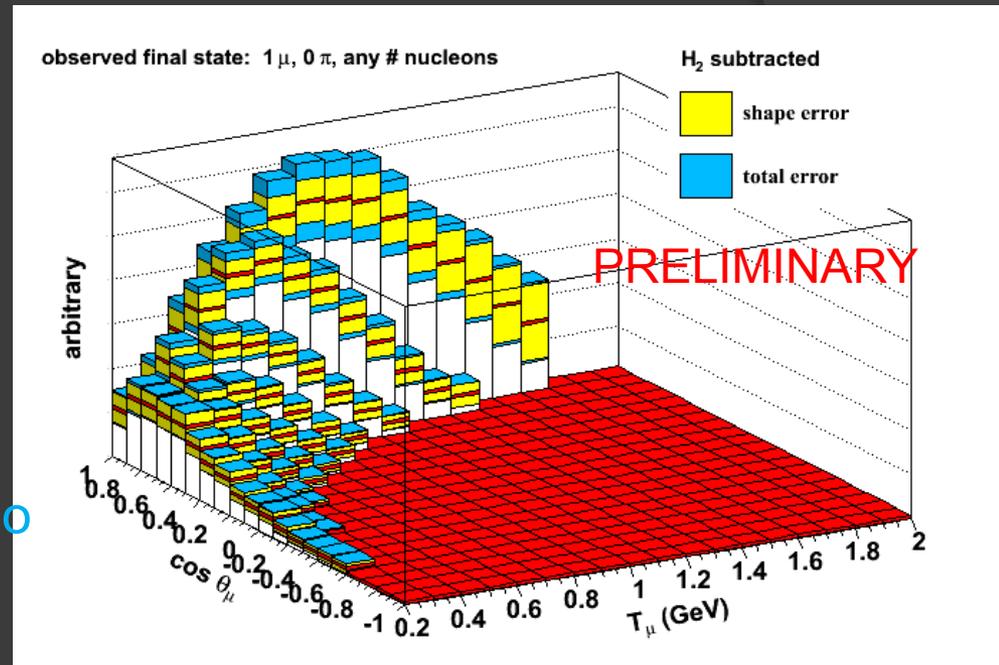
# MiniBooNE Wrong Sign $\nu$ Component

- Large neutrino component in anti-neutrino mode due to forward pion scattering.
- Not covered by HARP data.
- Constrained by data!!! A first in a non-magnetized detector!!!



*Phys. Rev. D84, 072005 (2011)*

# MiniBooNE $\bar{\nu}$ CCQE Cross Section

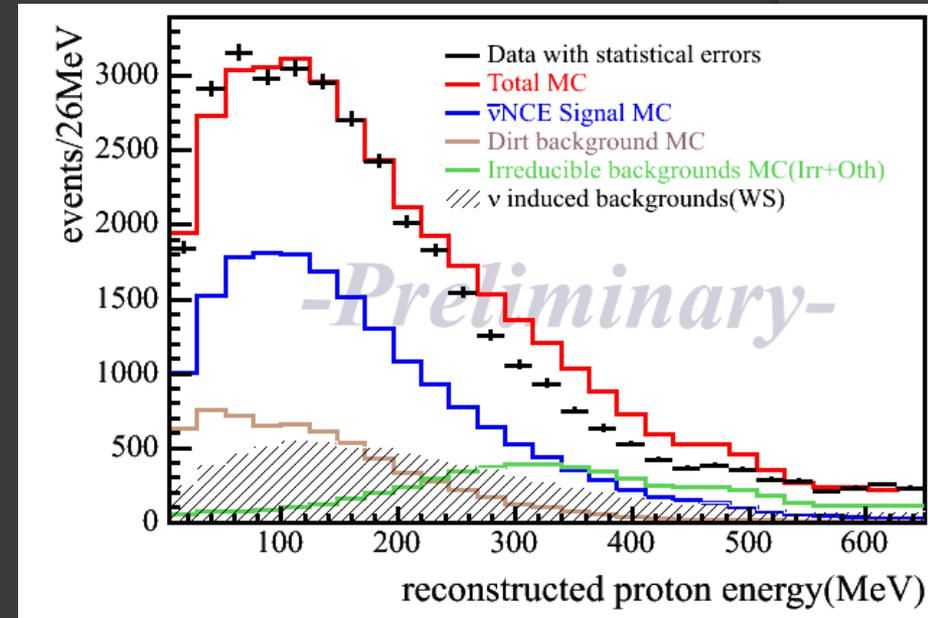


*J. Grange, University of Florida*

- Full  $10.1e20$  POT
- Repeat the analysis for anti-neutrino mode with the same cuts.
- 77,000 anti-neutrino events after CCQE cuts.
- Next step is to measure the  $\nu/\bar{\nu}$  ratio to cancel systematic errors and constrain the models better.

# MiniBooNE $\bar{\nu}$ NC Elastic Cross Section

- Final state – only 1 nucleon mostly below Cherenkov threshold.
- Using scintillation light for reconstruction - calorimeter.
- Using likelihood ratio to separate protons from electrons.
- 7.4e20 POT
- ~44,000 NCE events, 40% purity
- Next step is to measure the  $\nu/\bar{\nu}$  ratio to cancel systematic errors and constrain the models better.



*R. Dharmapalan, University of Alabama*

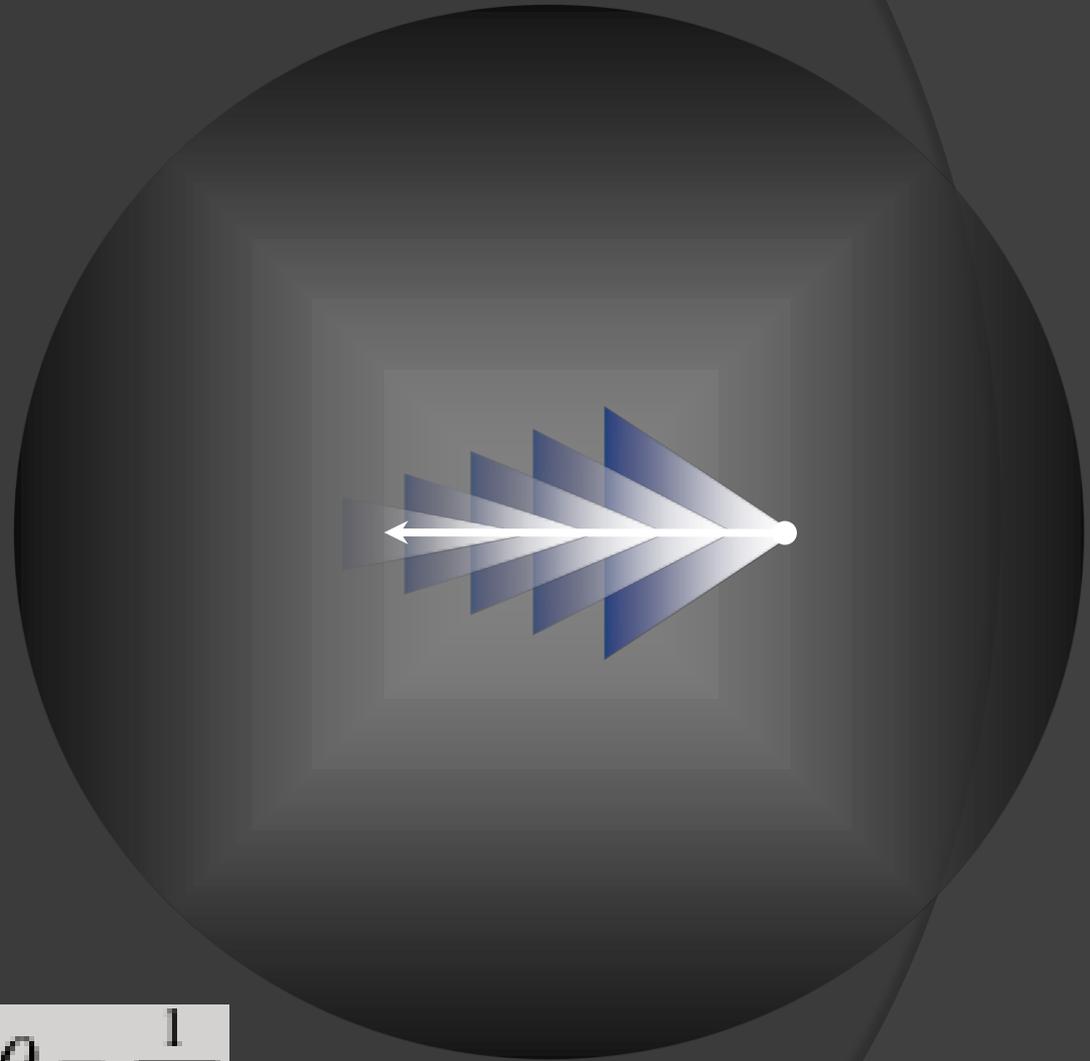
# Future MiniBooNE Cross Sections Results

New cross section results are coming soon!!!

- Neutrino CC inclusive,
- Anti-neutrino CCQE (Joe Grange, U Florida),
- Anti-neutrino NC elastic (Ranjan Dharmapalan, U Alabama),
- Neutrino CCQE with proton reconstruction (Athula Wickremasinghe, U Cincinnati).

# Čerenkov radiation

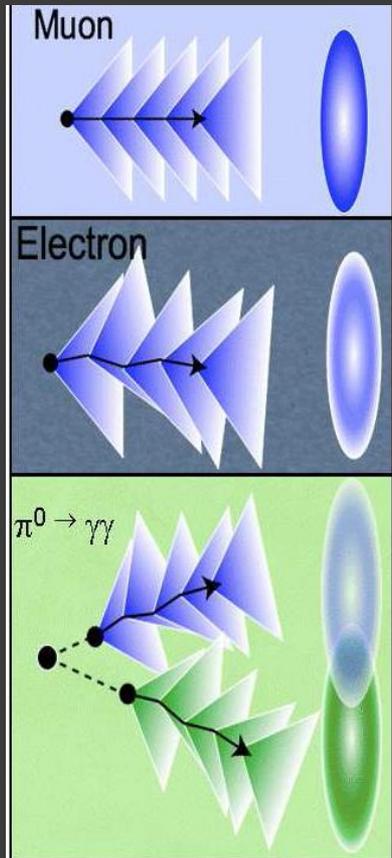
- Speed of light in mineral oil is 20 cm/ns.
- Threshold is  $KE > 0.3$  mass.
- The angle of the cone is related to the velocity.
- As the particle slows down, the angle gets narrower and the intensity reduces.



$$\cos \theta = \frac{1}{n\beta}$$

# Track Topologies in MiniBooNE Detector

In order to extract a cross section we need to reconstruct the final state particles.



Muon event

- long track, small scattering

Electron/photon event – fuzzy ring

- short track, large scattering
- $\gamma$  converts and looks like electrons

$\pi^0$  event – two fuzzy rings

$4\pi$  geometry – excellent  $\pi^0$  detector