# Charged-Current Inclusive Cross Sections from MiniBooNE

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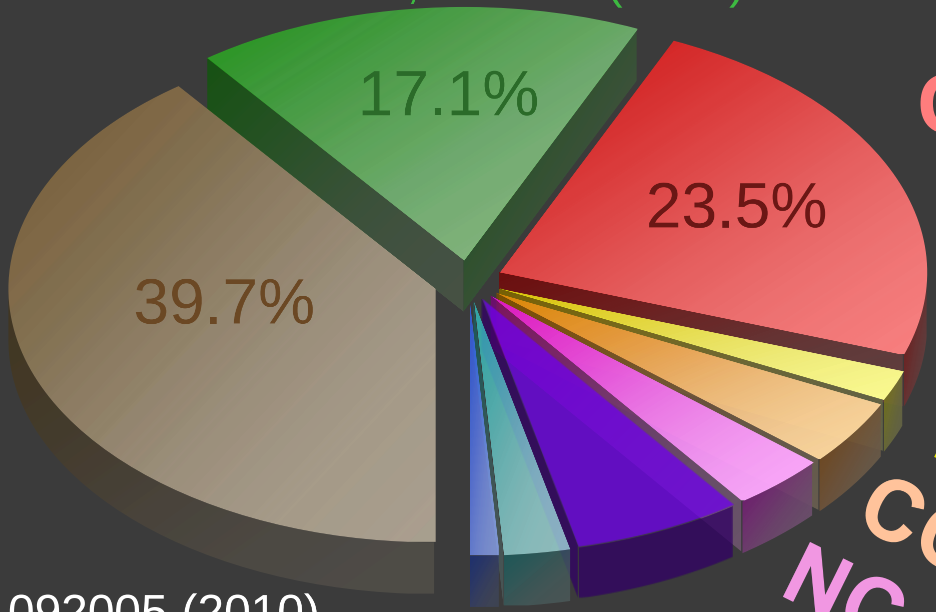
# MiniBooNE ν Cross Section Measurements

**NC EL**

**PRD 82**, 092005 (2010)




**CC $\pi^+$**

**PRL 103**, 081801 (2009)
**PRD 83**, 052007 (2011)

**multi-$\pi^+$**

**CC $\pi^0$**

**PRD 83**, 052009 (2011)

**NC $\pi^{+/-}$**

**NC $\pi^0$**

**PRD 81**, 013005 (2010)
**PL B664**, 41 (2008)

**QE**

**PRD 81**, 092005 (2010)
**PRL 100**, 032301 (2008)

**WS other**

NUANCE

# MiniBooNE $\nu$ Cross Section Measurements

NC El

Published measurements:

~95% CC - exclusive channels

(CCQE, $CC\pi^+$, $CC\pi^0$)

~80% NC - exclusive

(NCE, $NC\pi^0$)

PF

PF

011)

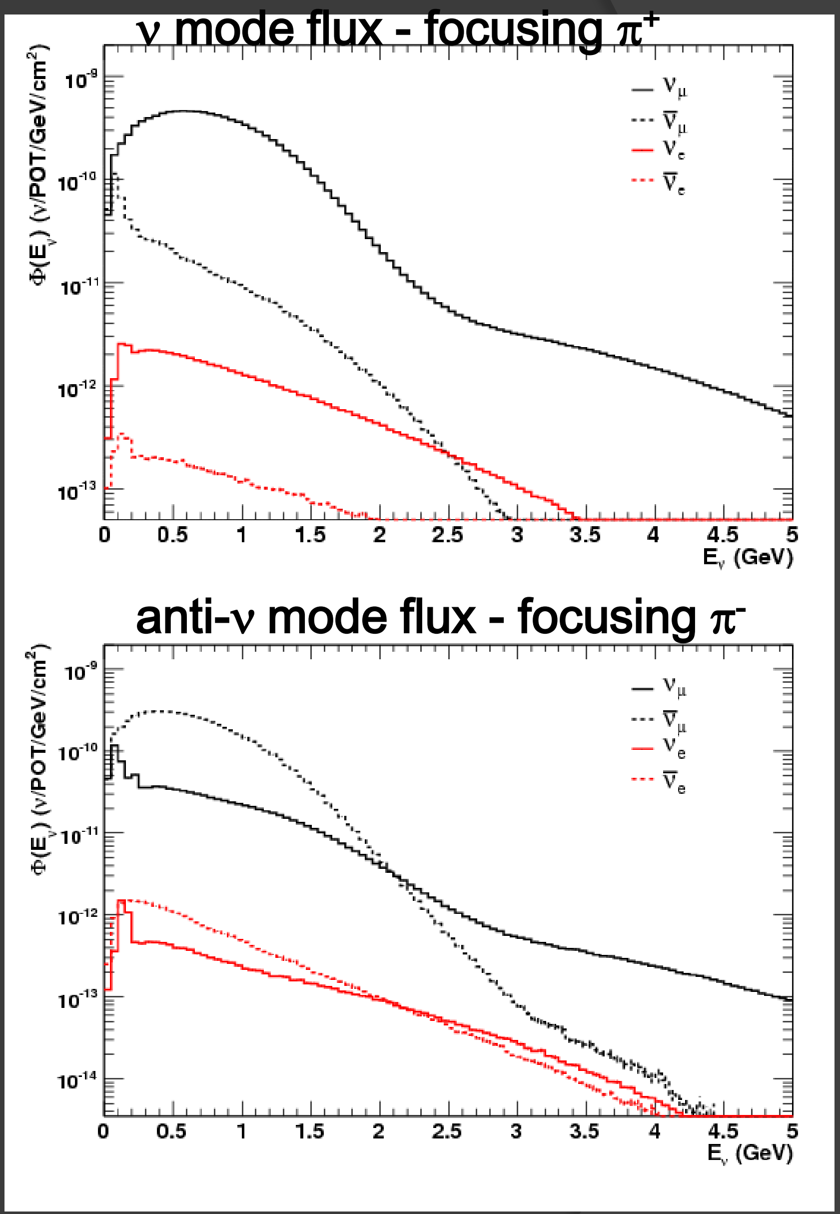
B664, 41 (2008)

(2010)

# MiniBooNE Predicted Flux

- ~1,000,000 interactions in fiducial volume in $\nu$ mode with small anti-$\nu$ component.
- greater than 150k 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)*

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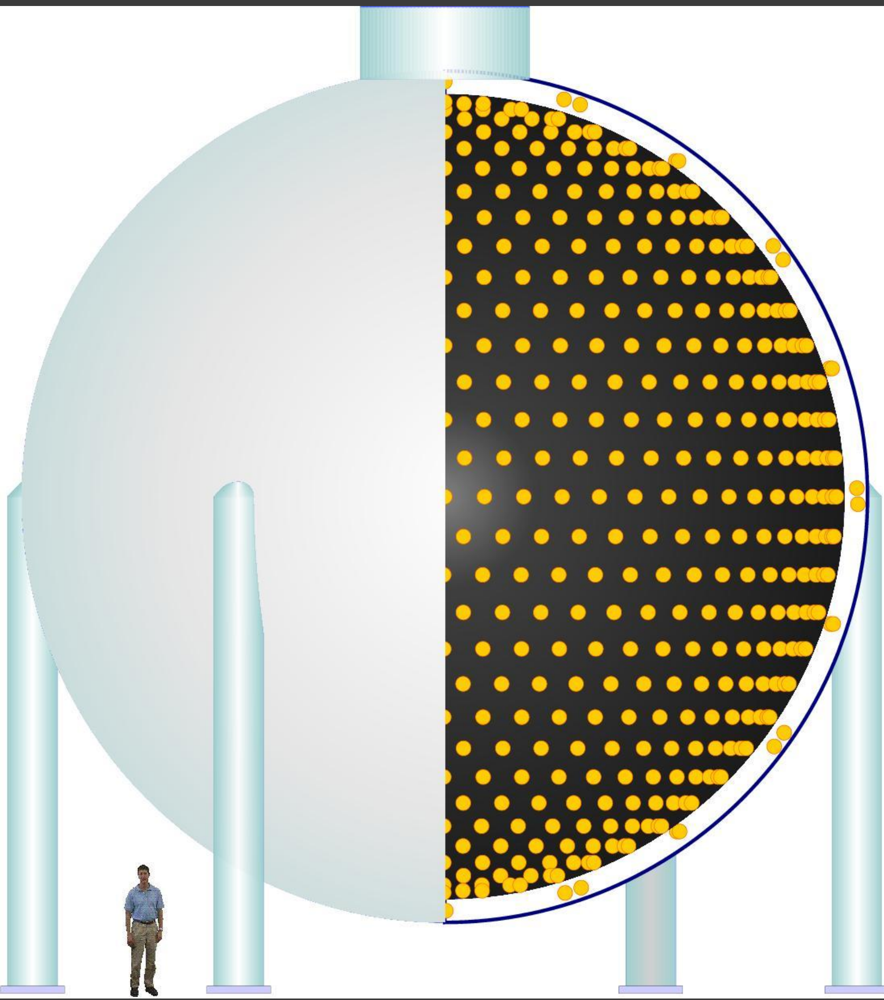
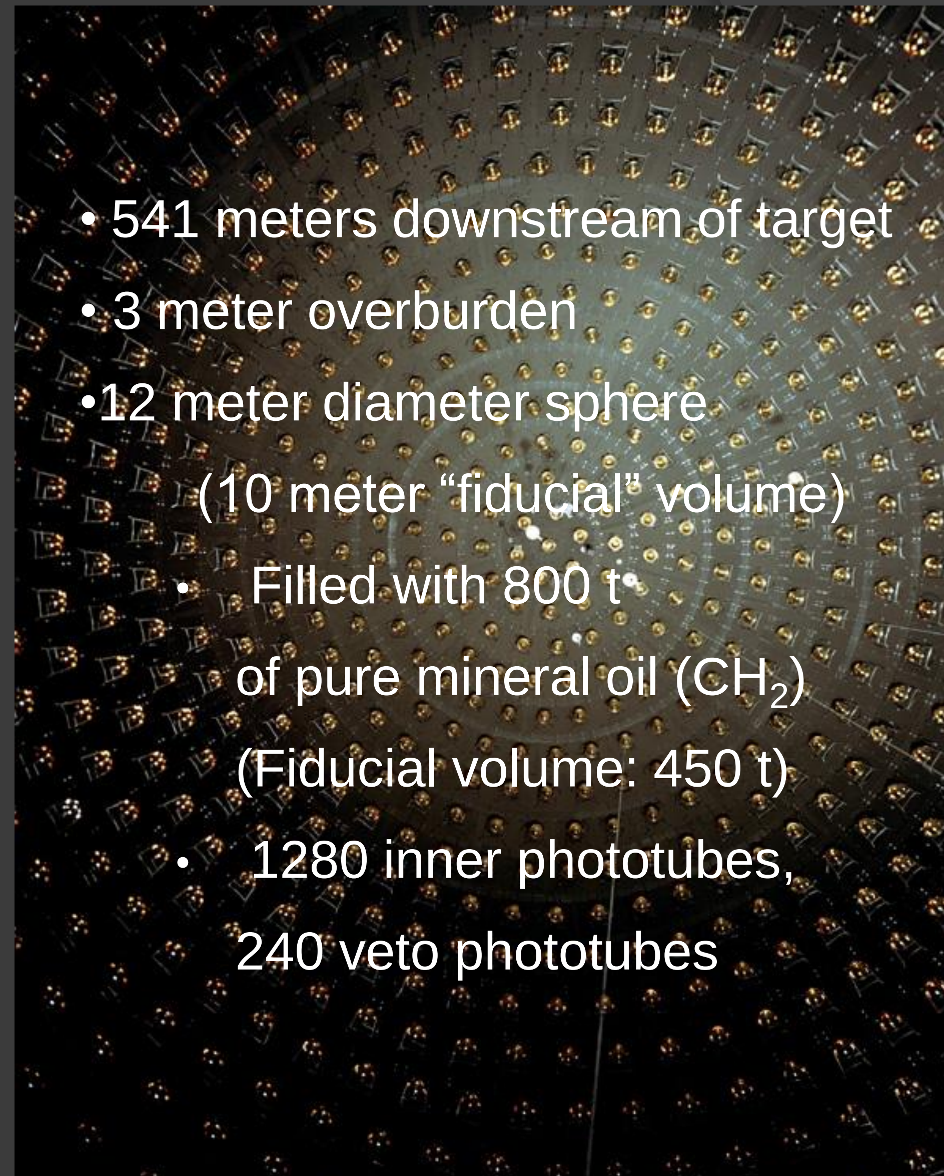
# The MiniBooNE Detector



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



- 541 meters downstream of target
- 3 meter overburden
- 12 meter diameter sphere

  (10 meter “fiducial” volume)

  - Filled with 800 t

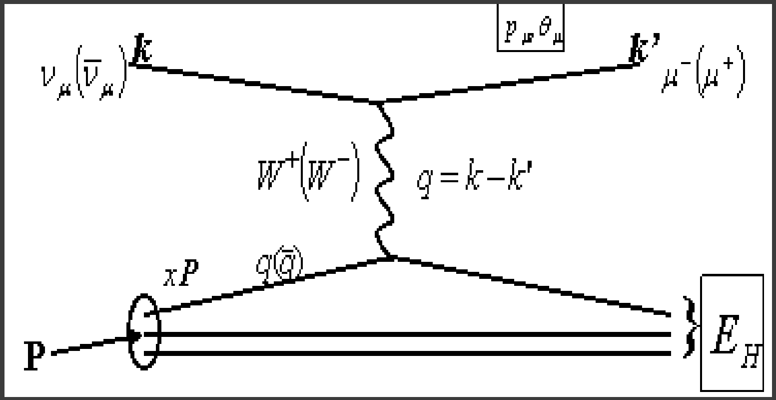
    of pure mineral oil ($CH_2$)

    (Fiducial volume: 450 t)

  - 1280 inner phototubes,

    240 veto phototubes

# CC Inclusive Events




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

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.

- CC events like pion absorption in the oil are not included in any of these samples.

# 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 - Reconstructed vertex within 5m radius.

Event rates at the generator level:

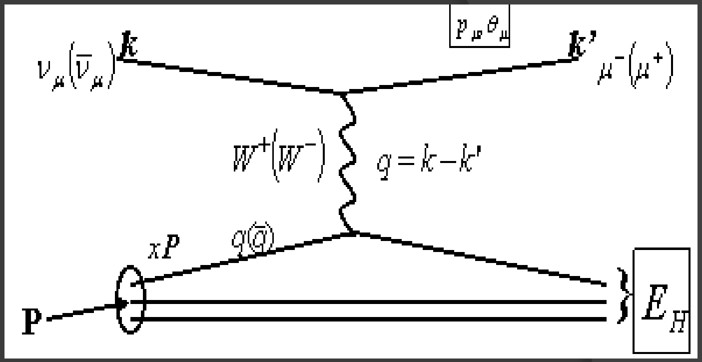
CCQE – 52%; $CC\pi^+$ - 34%;
$CC\pi^0$ - 5%; Other CC – 3%;
NC – 3%; antineutrino – 1%.

FSI's change the fractions of different event topologies.

Data events after cuts 344k. 96% purity.

# CC Inclusive Event Reconstruction

New event reconstruction for MiniBooNE

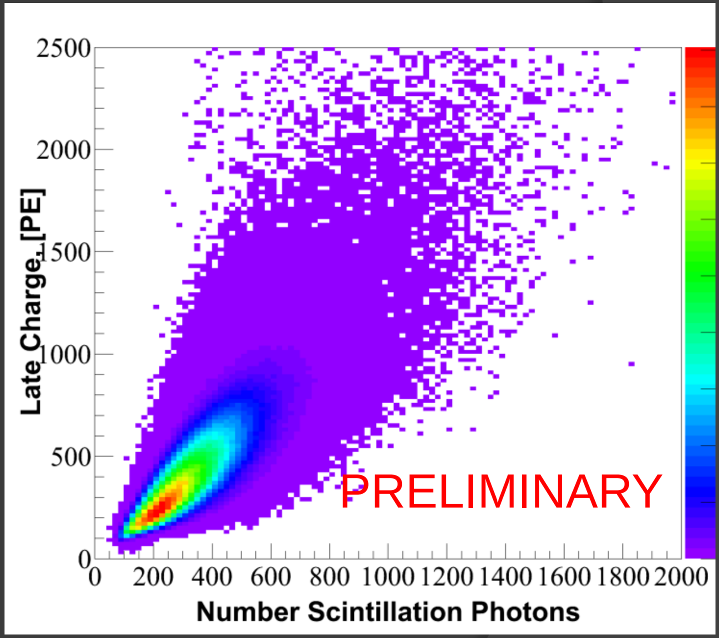



- Muon kinematics from 2-track likelihood fit:

  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!!!**

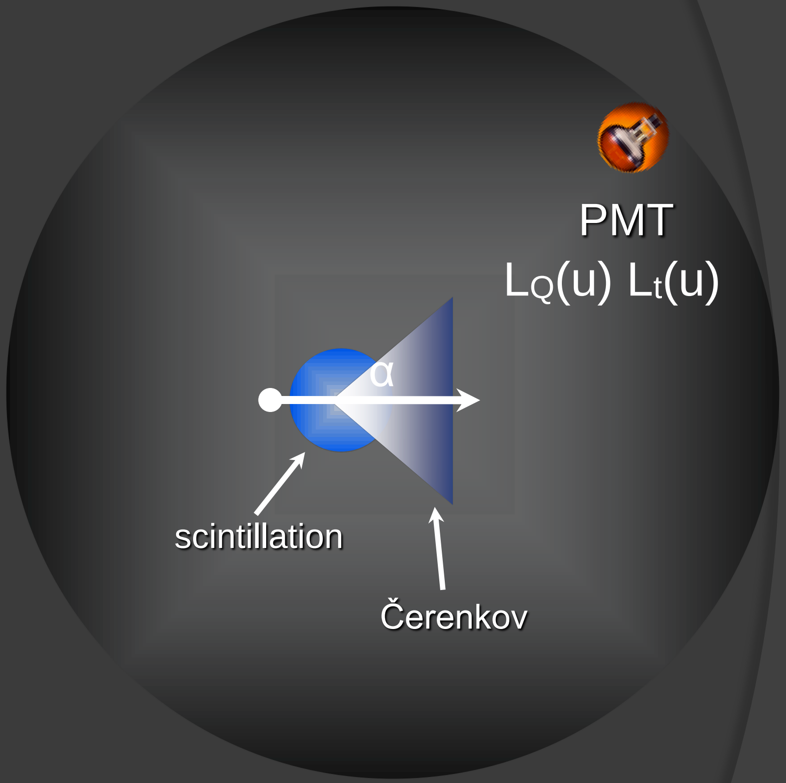
Plots are from MC.

# Event Reconstruction

- A particle is parametrized as a "track" in the oil.
  - Vertex: (x,y,z)
  - Time: (t)
  - Direction: (θ,φ)
  - 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.



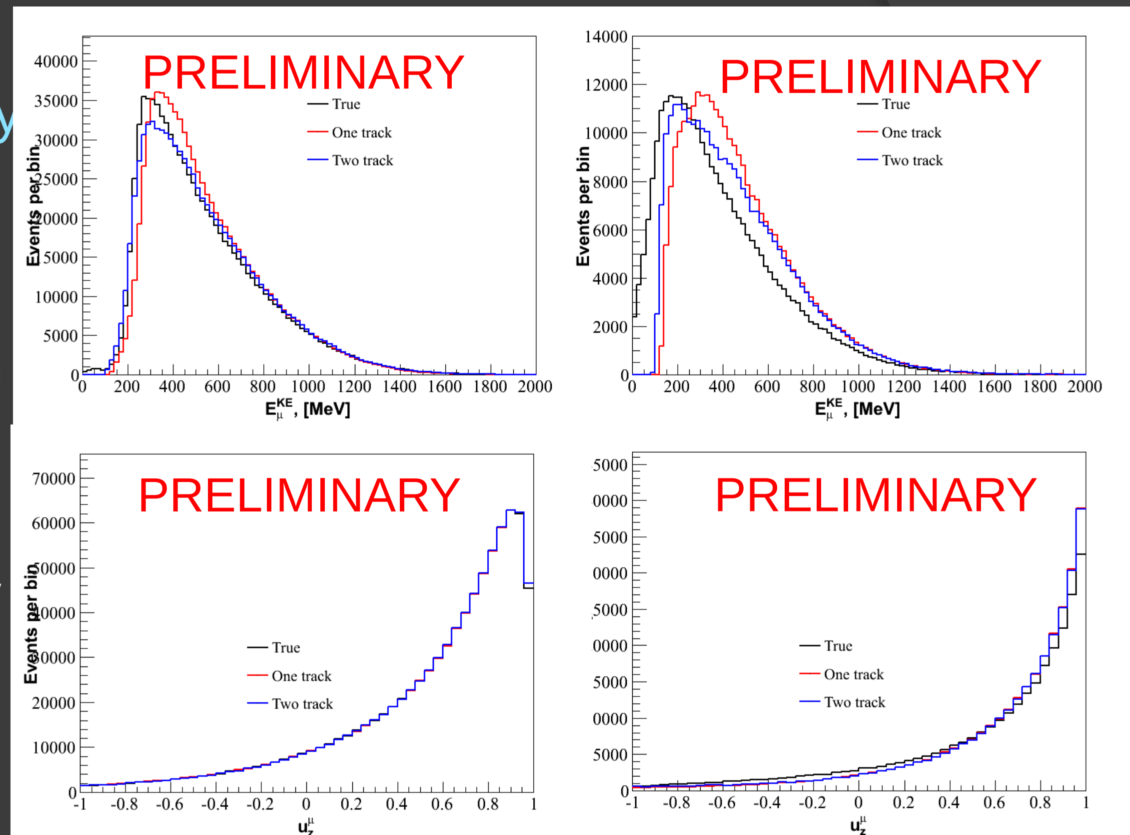

*R.B. Patterson et al., Nucl. Instrum. Meth. A608, 206 (2009)*

# Muon Kinematics Reconstruction Performance

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

$T_\mu$

$u_z^\mu$




CCQE

CC$\pi$+

No significant improvement for the muon angle. Muon angle resolution is better than 1°.

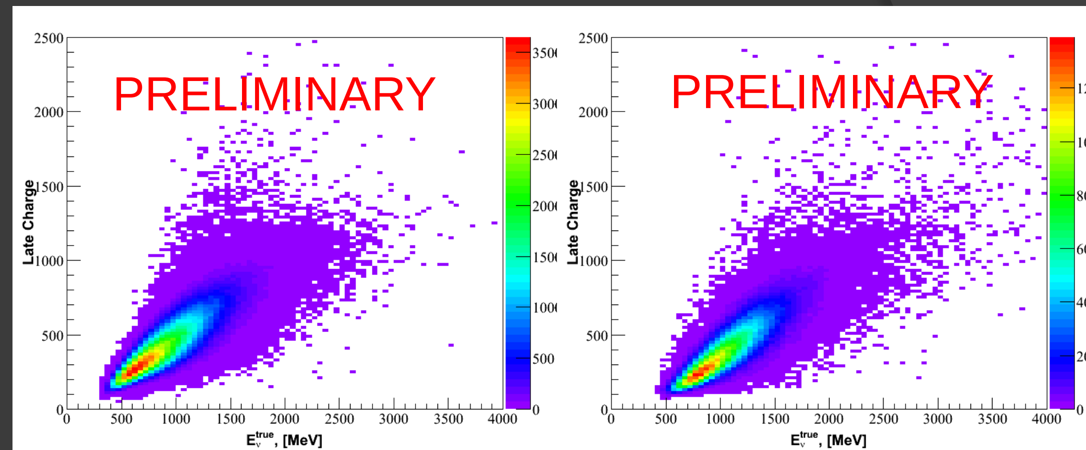
Plots are from MC.

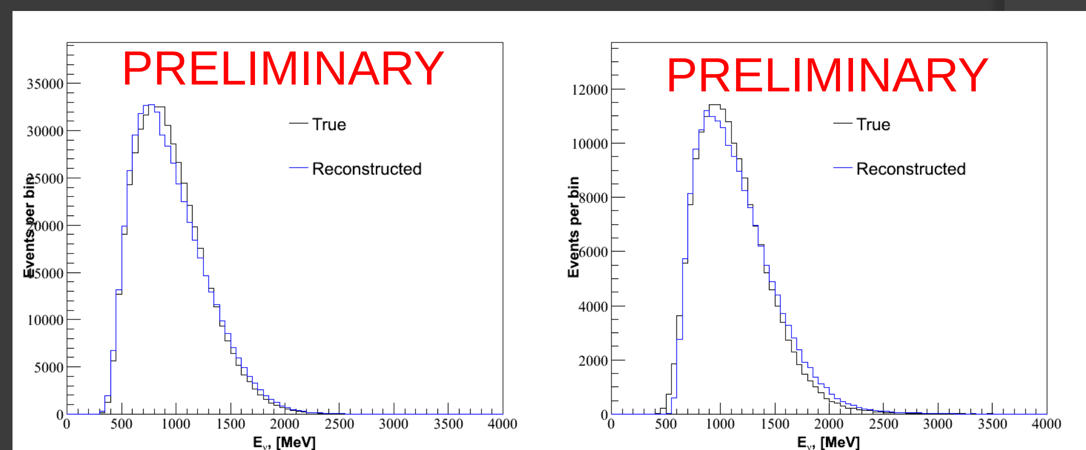
# Neutrino Energy Reconstruction Performance

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%.



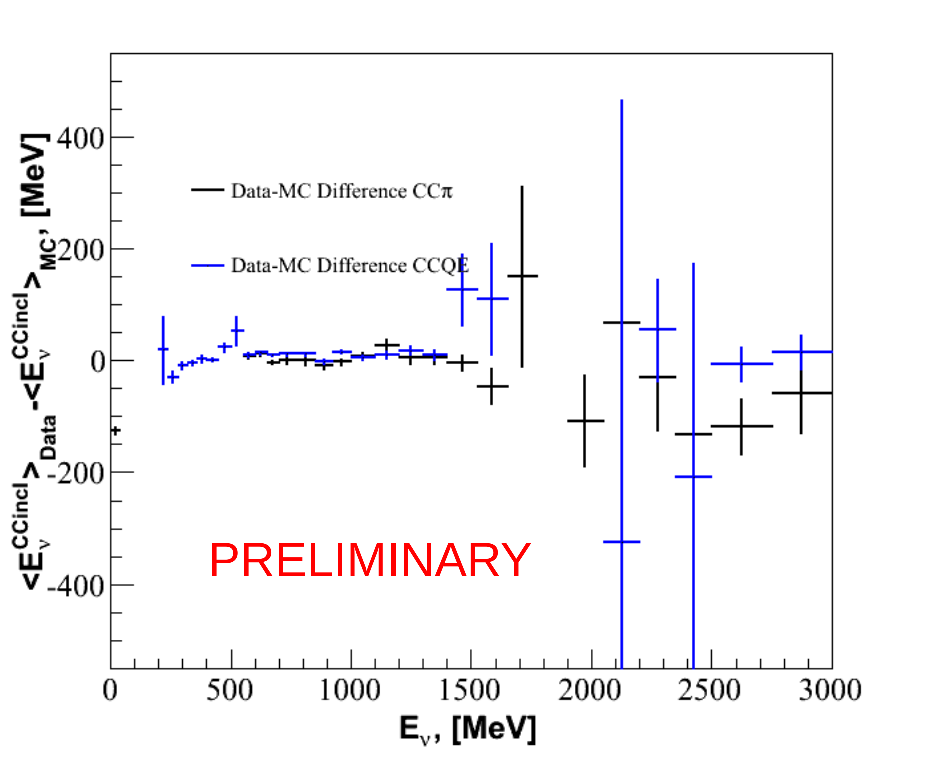

CCQE

$CC\pi+$

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.

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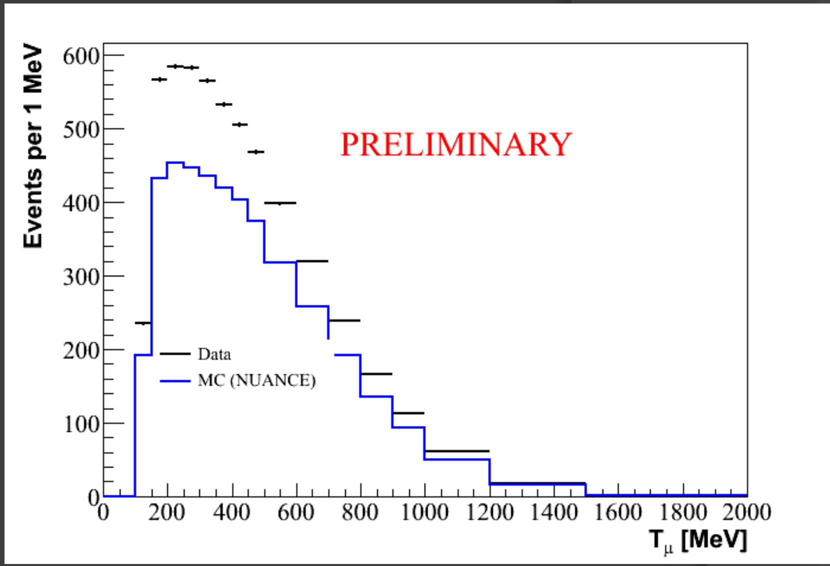
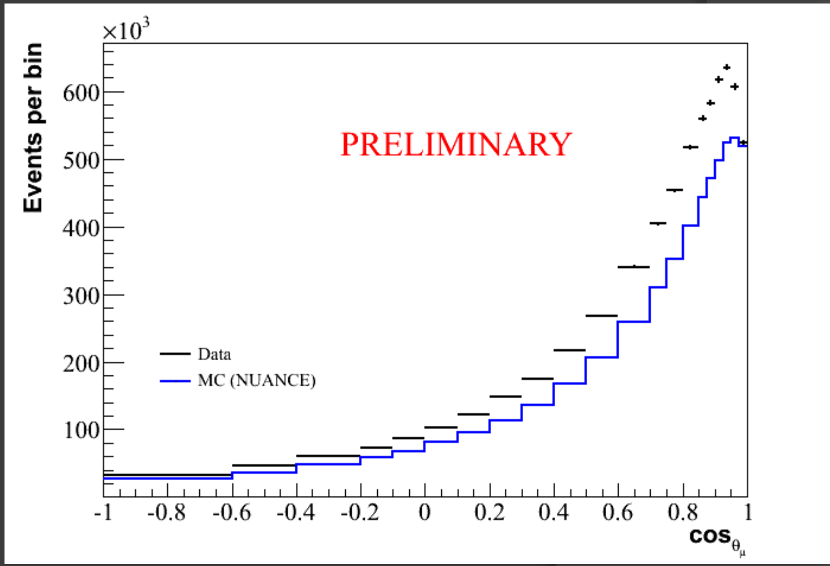
# MiniBooNE CC Inclusive Cross Sections

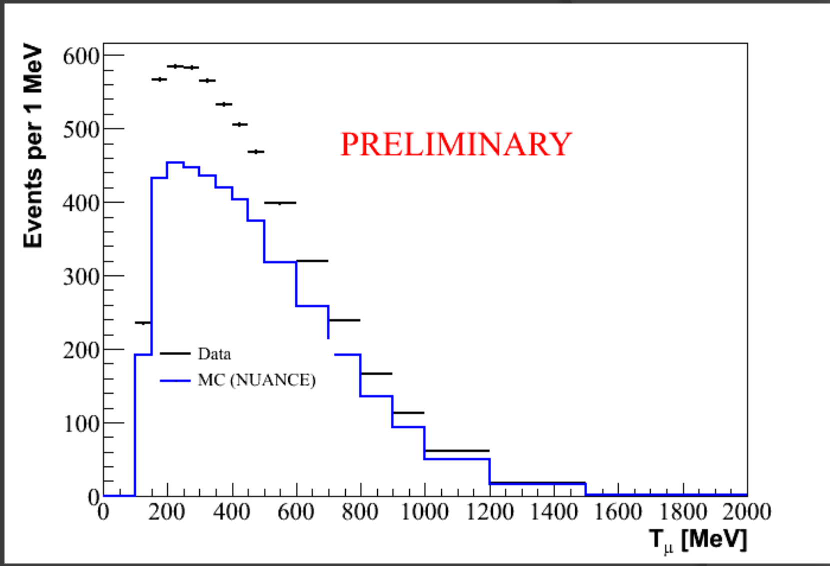
- Data rate is higher than predicted as suggested by the exclusive channels.
- Largest neutrino sample in this region to date - 344000 CC inclusive interactions after cuts.
- $4\pi$ detector geometry – full coverage of phase space.

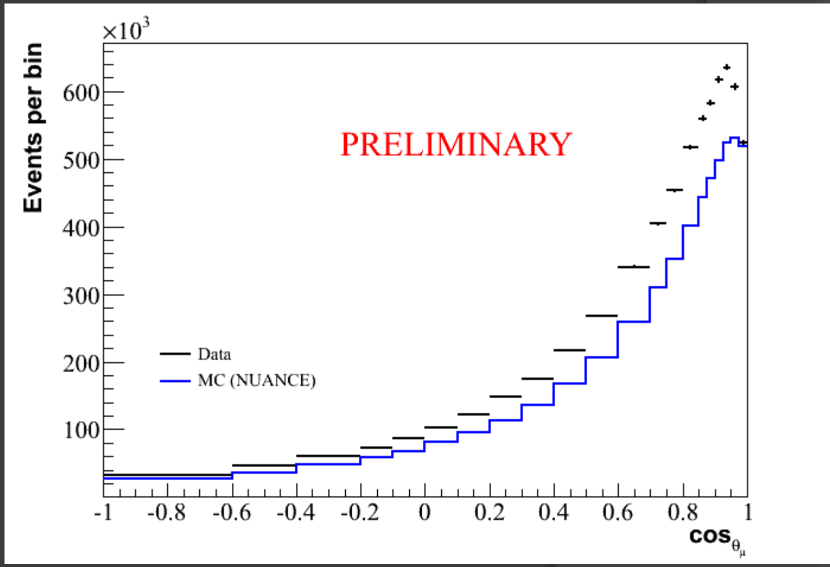


# MiniBooNE CC Inclusive Cross Sections

- 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 $d^2\sigma/dT_\mu d\cos\theta_\mu$, $d^2\sigma/dT_\mu d\cos\theta_\mu\ (E_\nu)$.



# Neutrino Cross Sections Extraction Technique

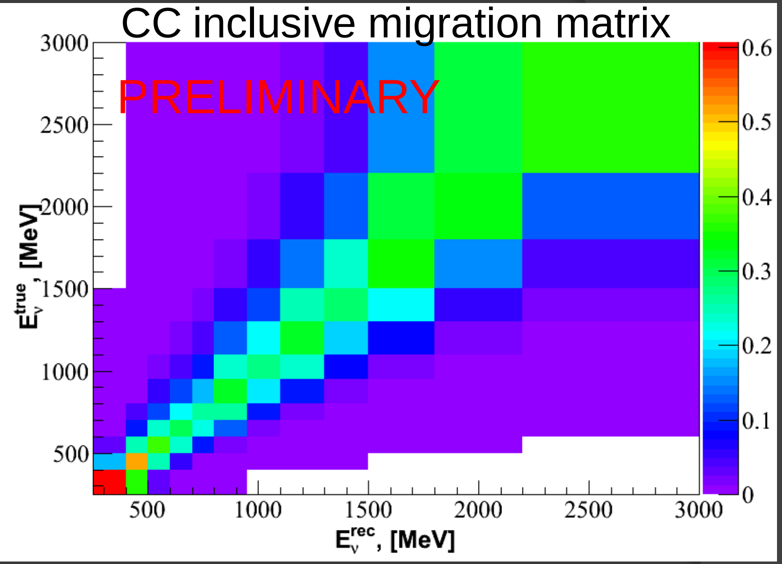
$$\sigma(E_\nu)_i = \frac{\sum_j^{bins} U_{ij}\left(N_j - B_j\right)}{\varepsilon_i \Phi_i N_{targs}}$$

$\sigma_i$ – cross section in energy bin $i$,
$E_\nu$ – neutrino energy,
$U_{ij}$ – unfolding matrix,
$N_j$ – measured rate in energy bin $i$,
$B_j$ – measured/predicted background rate in bin $i$,
$\Phi_i$ – integrated flux in energy bin $i$,
$\varepsilon_i$ – efficiency in energy bin $i$,
$N_{targs}$ – number of targets.

# Unfolding

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

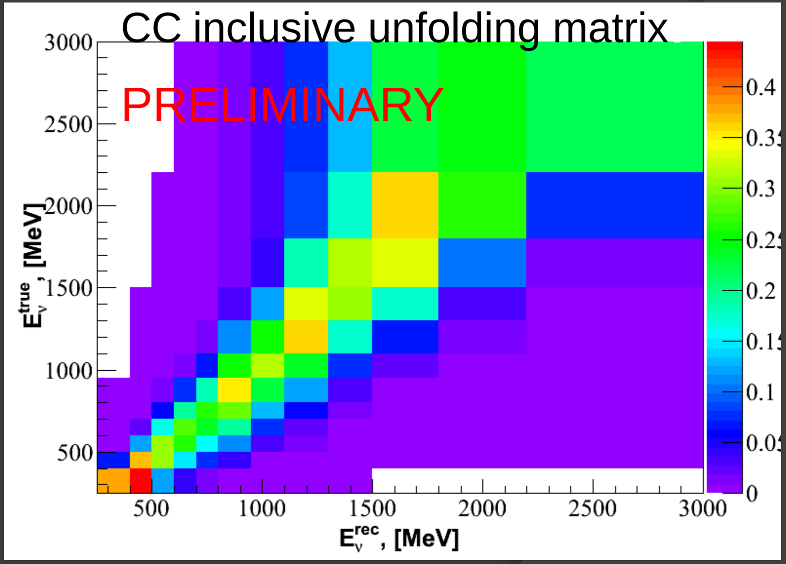
• bin migration matrix inversion is unbiased, but it’s unstable and it leads to a large statistical uncertainty.




Bayesian unfolding:

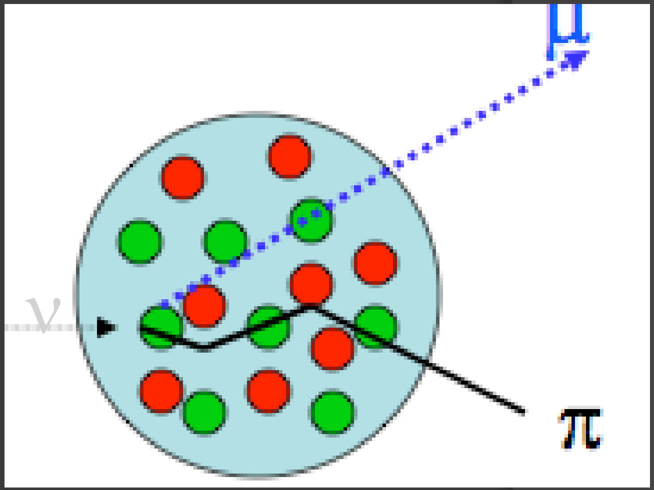
$$U_{ij} = P(t_i | r_j) = \frac{P(r_j | t_i)\, P(t_i)}{\Sigma P(r_j | t_n)\, P(t_n)}$$

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



# Observable Cross Sections

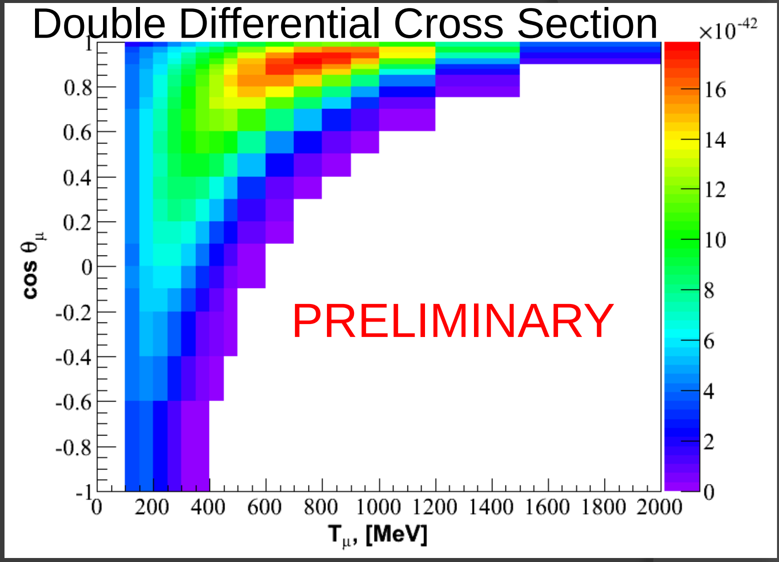
$$\sigma(E_\nu)_i = \frac{\sum_j^{bins} U_{ij}\left(N_j - B_j\right)}{\varepsilon_i \Phi_i N_{targs}}$$

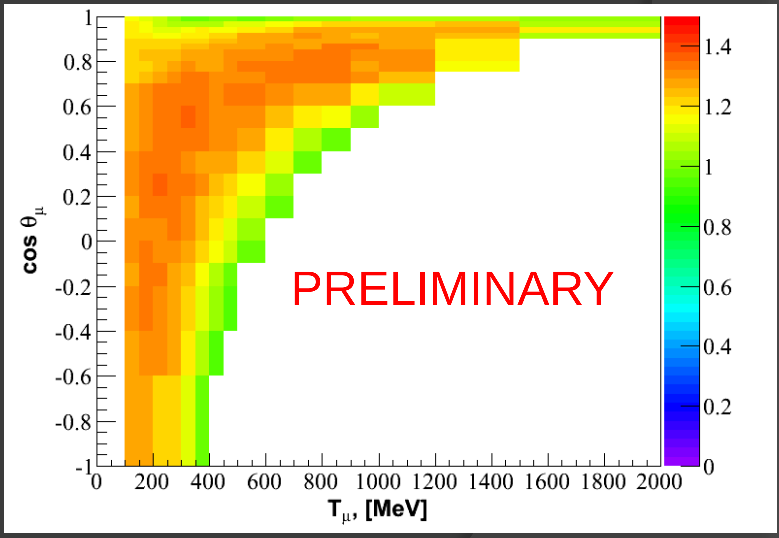



- nuclear target – re-interactions in the nucleus.
- different primary neutrino interactions become indistinguishable experimentally.
- Final State Interactions (FSI) model is needed to extract nucleon cross section – large uncertainties.
- MiniBooNE measures observable cross sections. $CC\pi^+$ observable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

# MiniBooNE CC Inclusive Cross Sections In Muon Kinematics

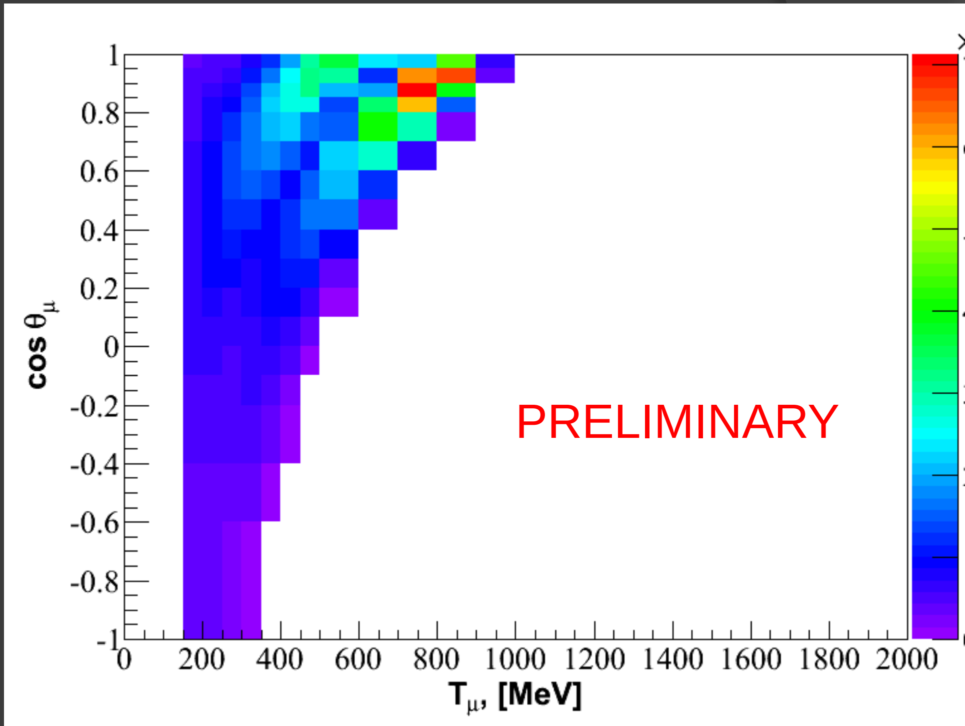
- Top plot shows the flux integrated double differential cross section in muon kinematics $d^2\sigma/dT_\mu d\cos\theta_\mu$.
- Bottom plot shows the ratio with the model (NUANCE).
- In the model:
  Fermi gas model (Smith-Moniz),
  $M_A^{QE} = 1.23$ GeV,
  $\kappa=1.019$,
  Rein-Seghal $M_A^{res}$.



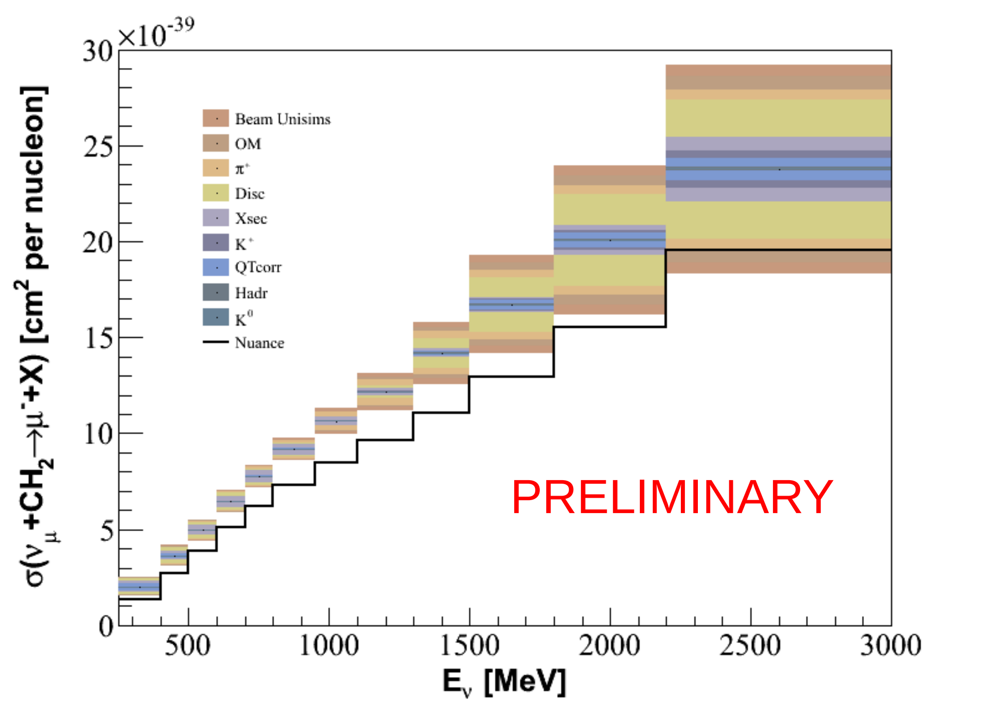
# Double Differential Teaser

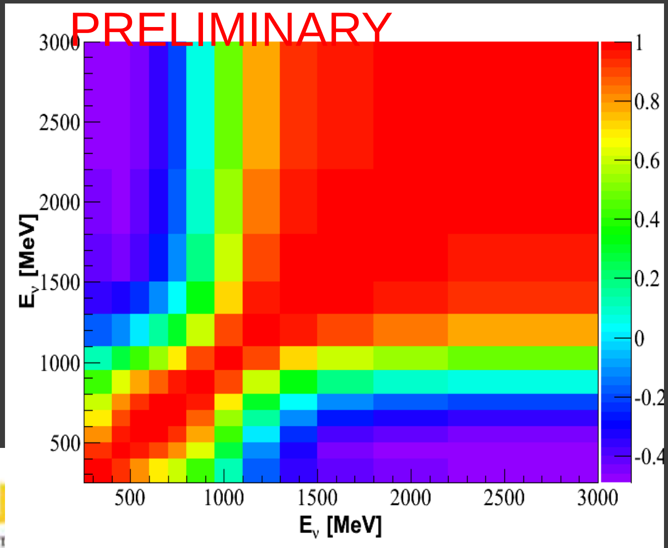
- The goal is to obtain $d^2\sigma/dT_\mu d\cos\theta_\mu\ (E_\nu)$.
- Reconstruction of the lepton vertex allows direct access to nuclear effects. (Similar to charged lepton scattering). Spectral function from neutrino scattering.
- CCQE and CCRes are separated from muon phase space. MEC in the “valley” between.
- Perhaps a new golden mode for neutrino oscillation experiments. (Not as easy as it sounds).

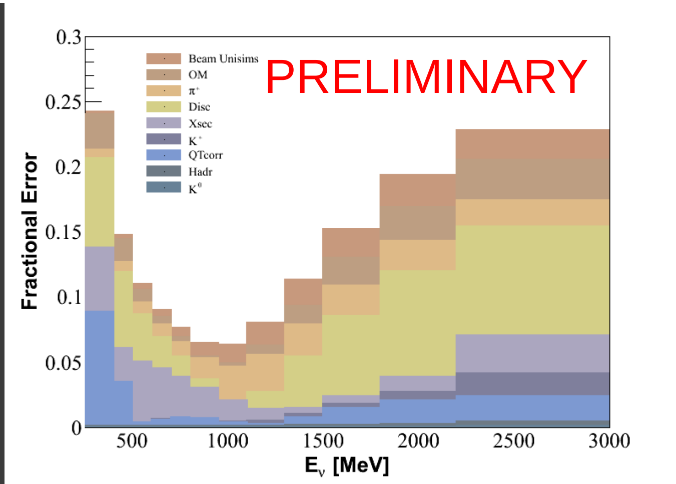


# MiniBooNE CC Inclusive Total Cross Section In Neutrino Energy

- Error bars show diagonal errors.
- Bottom right plot shows fractional diagonal errors.
- Bottom left plot shows the bin-to-bin correlation matrix.

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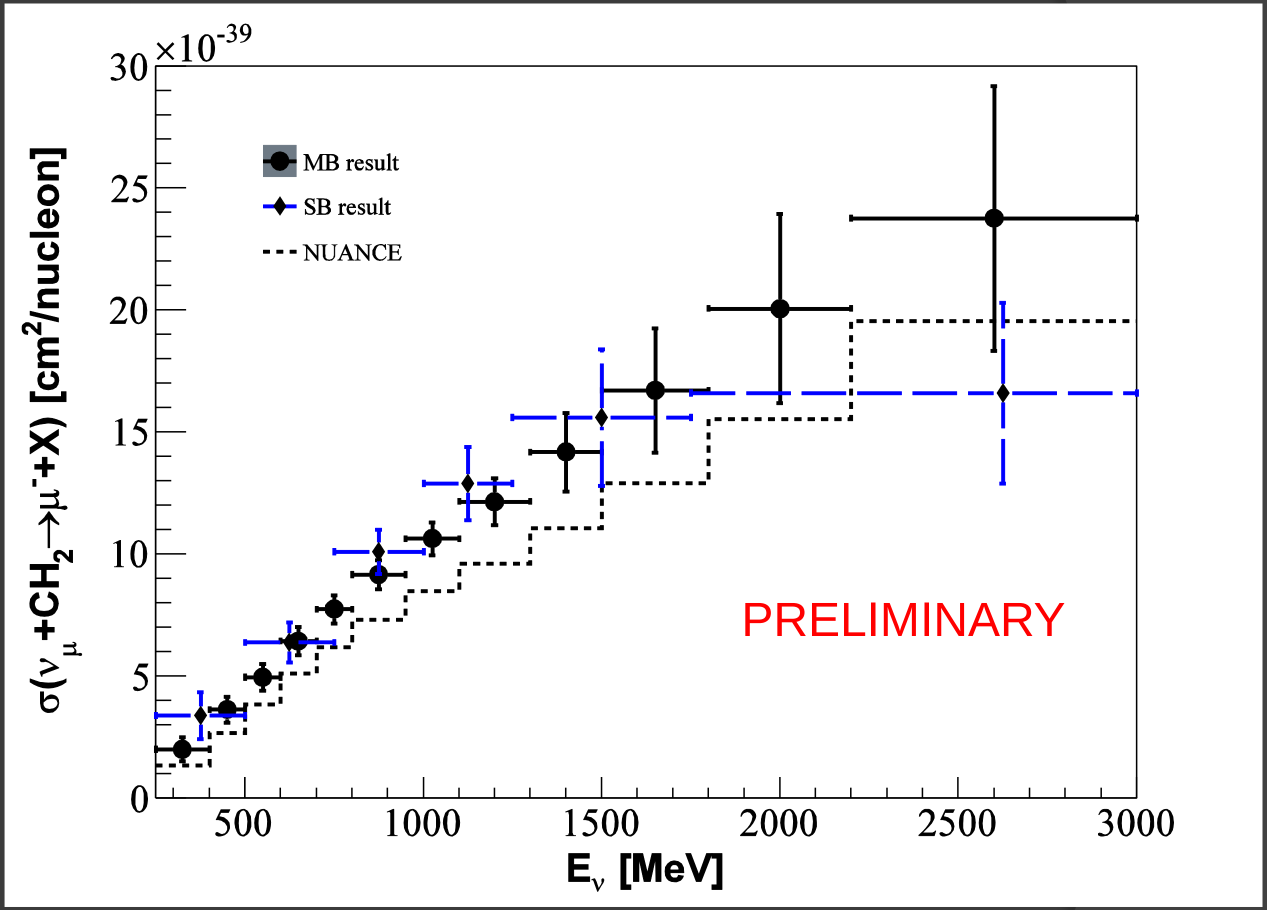
# MiniBooNE CC Inclusive Total Cross Section In Neutrino Energy

- Error bars show diagonal errors.




*SciBooNE CC Inclusive paper - Phys. Rev. D 83, 012005 (2011)*

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# Summary and Future

New cross section results are coming soon!!!

Neutrino CC inclusive cross sections:

- the largest neutrino sample,
- the most comprehensive measurement,
- lepton vertex is completely reconstructed,
- $4\pi$ detector – entire phase space.

More cross section results from MiniBooNE are on the way:

- antineutrino QE (Joe Grange) - see Joe’s talk,
- antineutrino NC elastic (Ranjan Dharmapalan) – see Joe’s talk,
- muon + proton (Athula Wickremasinghe).

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*OBRIGADO!!!*

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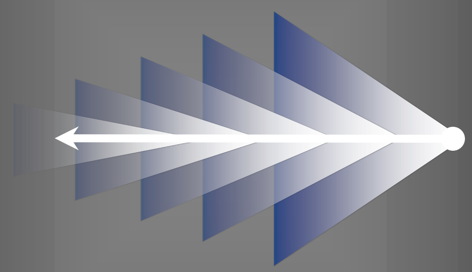
# *Backups*

# 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.



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

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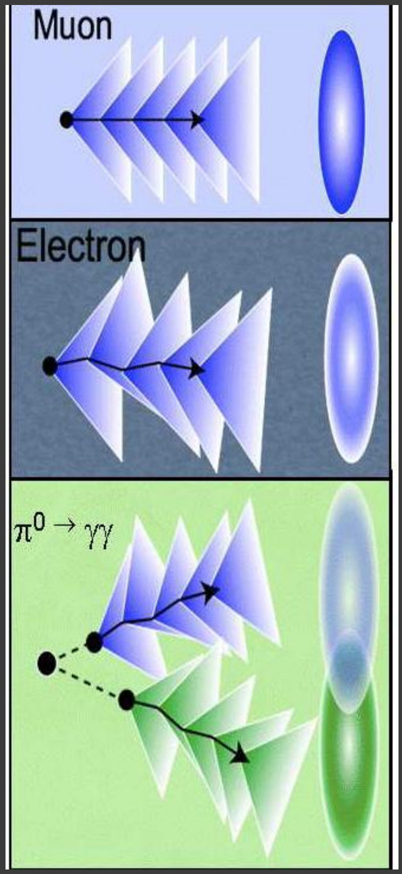
# Track Topologies in MiniBooNE Detector

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

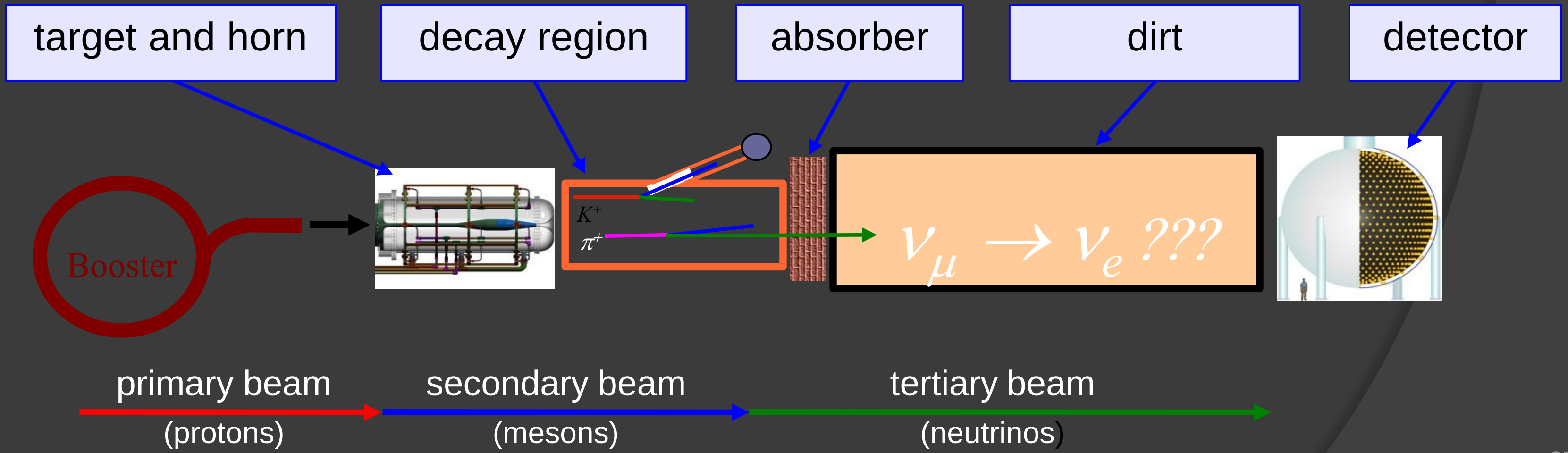
$\pi^0$ event – two fuzzy rings

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

# MiniBooNE Experiment – E898 at Fermilab

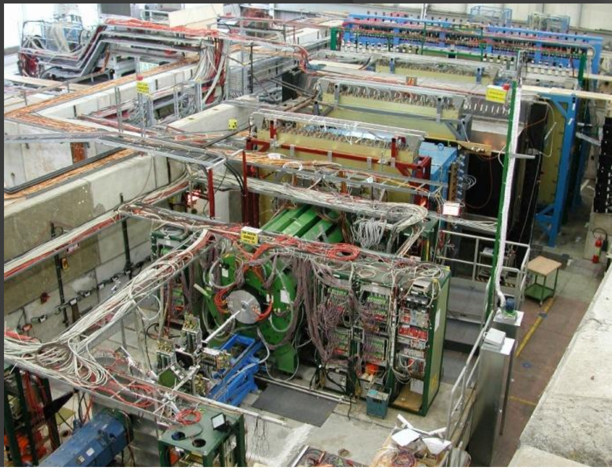
Test of LSND within the context of $\nu_\mu \rightarrow \nu_e$ appearance only is an essential first step:

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

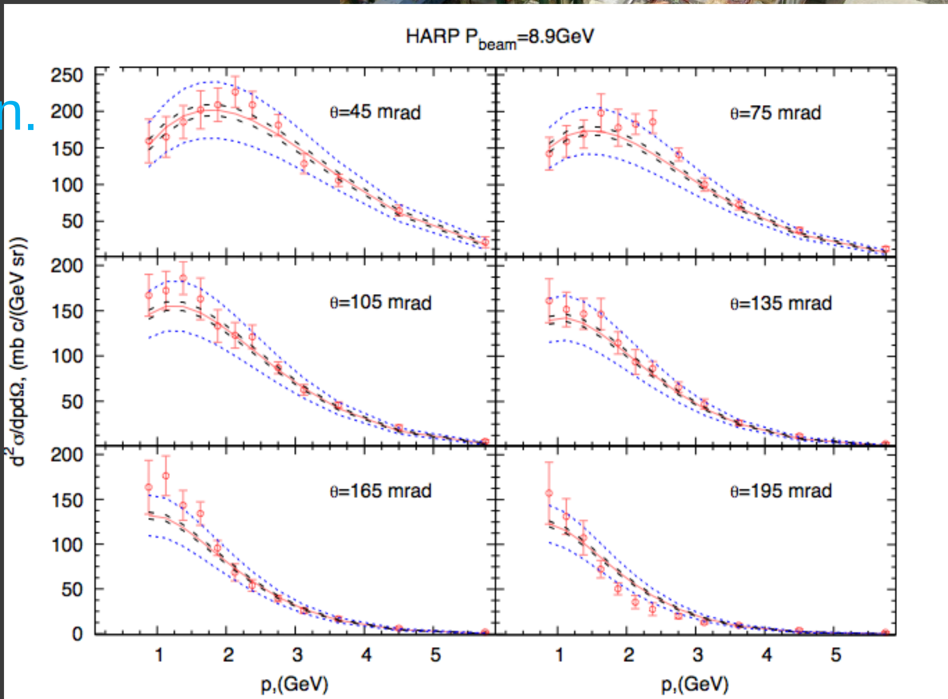


# Flux - $\pi^+$ Production from HARP

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.



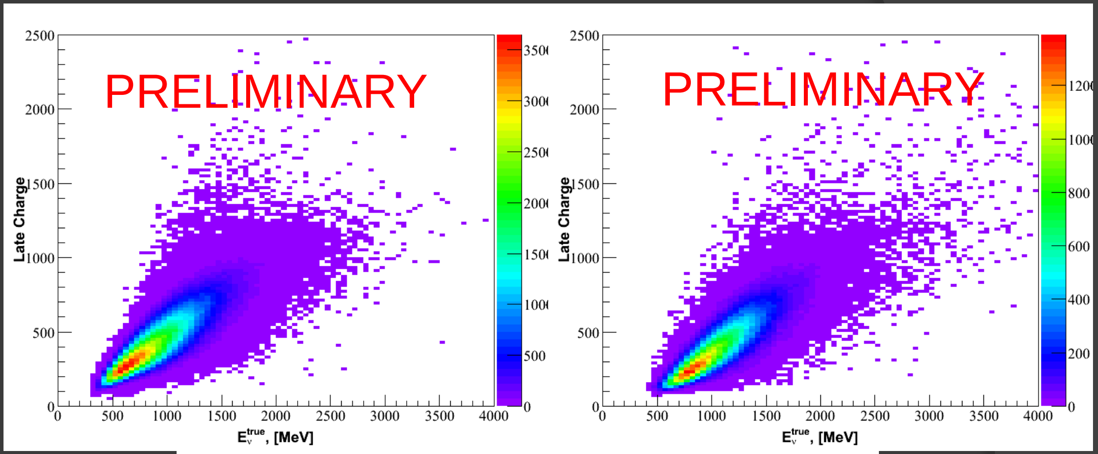

Covers 80% of the pion phase space relevant for MB. Pion production uncertainty is 7%.

Makes cross section measurements possible.

*M. Catanesi et al., Eur. Phys. J. C52, 29 (2007)*

# Neutrino Energy Reconstruction Performance

CCQE CCπ+

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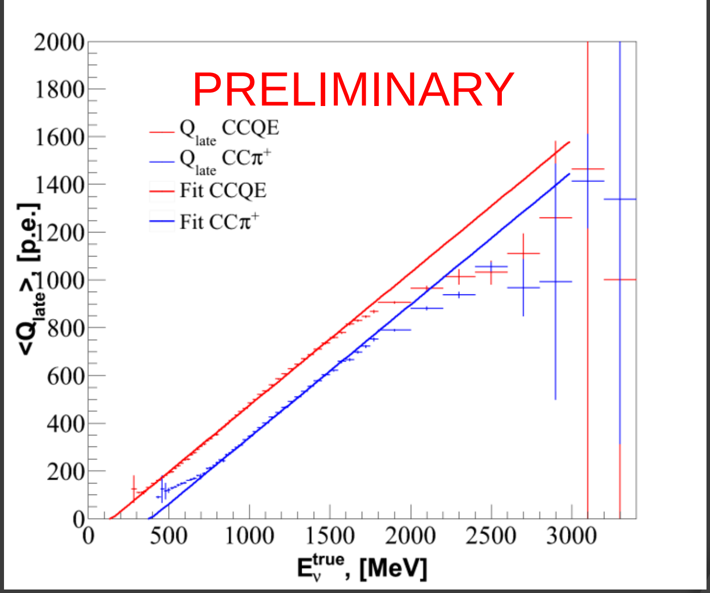


Energy reconstruction resolution is about 18%.

Plots are from MC.