$CC\pi^+$ Cross Section Results from MiniBooNE

Mike Wilking

TRIUMF / University of Colorado

NuInt

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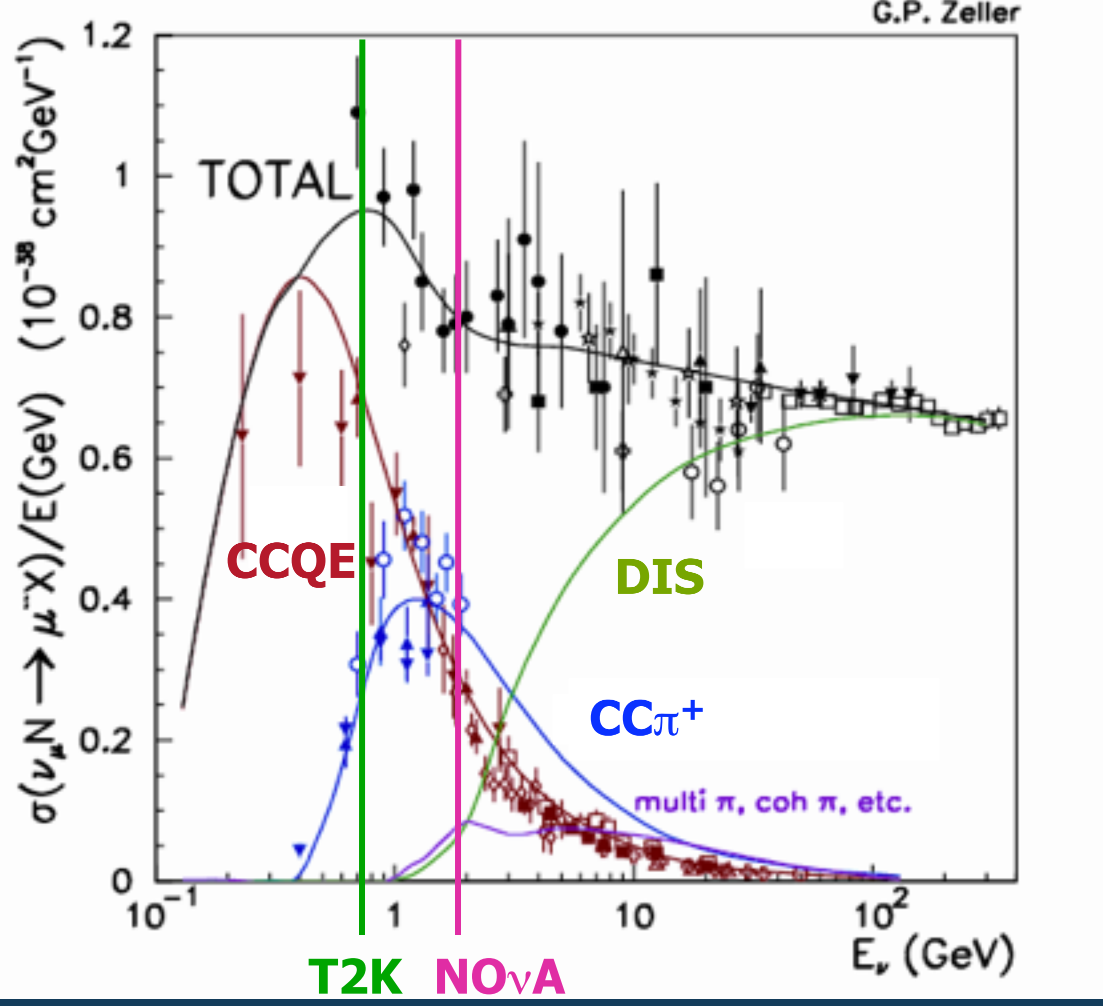
$CC\pi^+$ in Oscillation Experiments

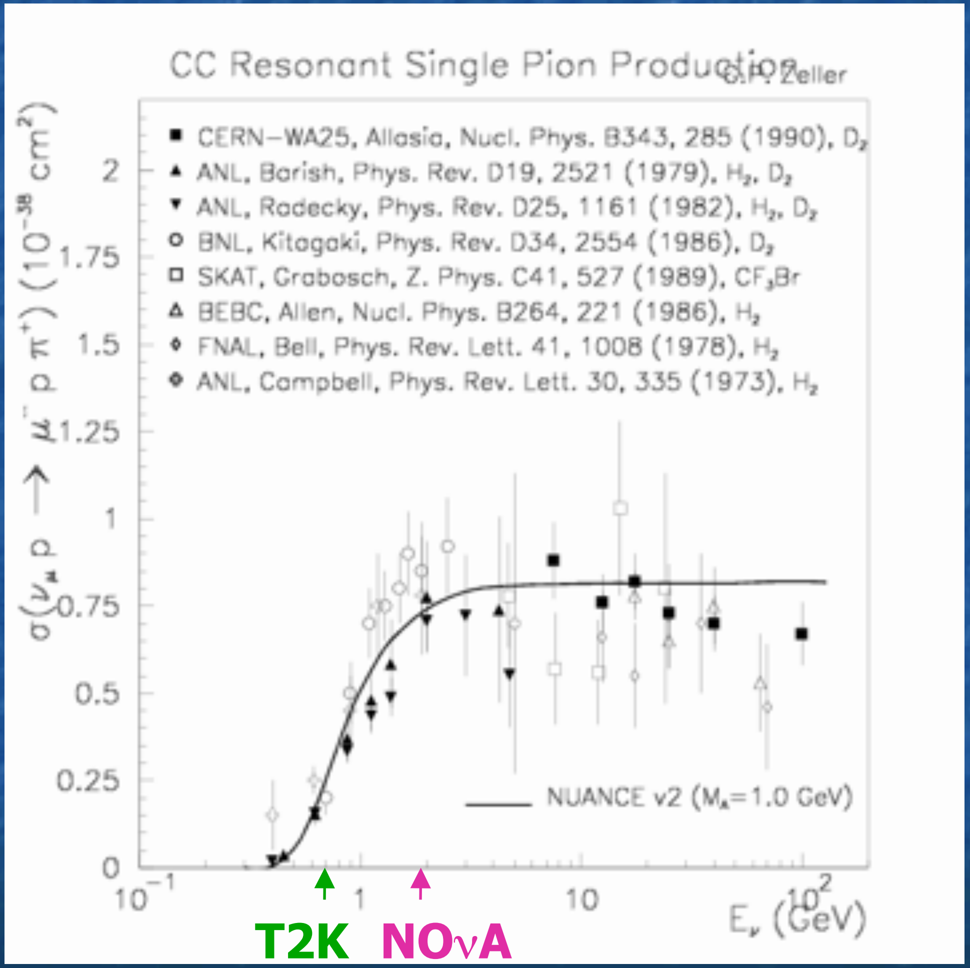
- The next generation of ν oscillation experiments lie at low, mostly unexplored ν energies
- CCQE is the signal process for oscillation measurements
- At these energies, $CC\pi^+$ is the dominant charged-current background

Charged Current Cross Sections

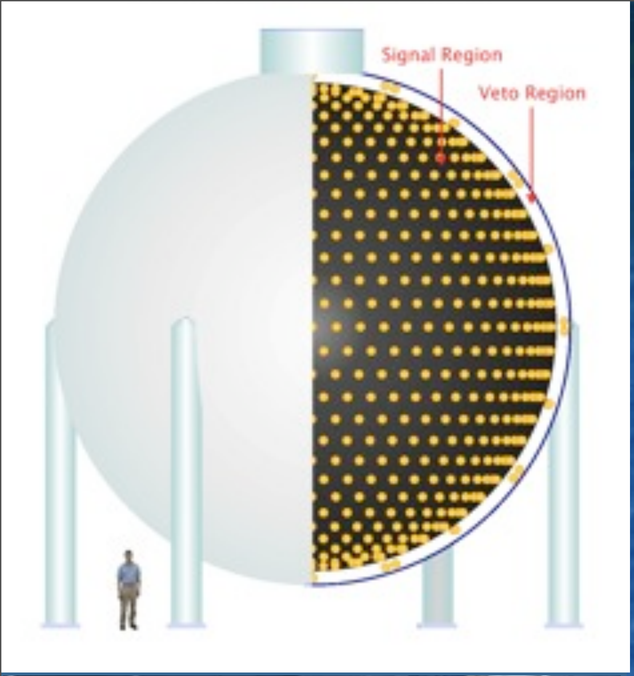


Previous CCπ^+ Measurements

- The plot shows previous absolute cross section vs E_ν measurements
  - (not including K2K; revisited in a few slides)
- Fewer than 8,000 events have been collected in all of these experiments combined
- Only one experiment was performed on a nuclear target (with E_ν > 3 GeV)
  - Next-generation oscillation experiments use nuclear targets



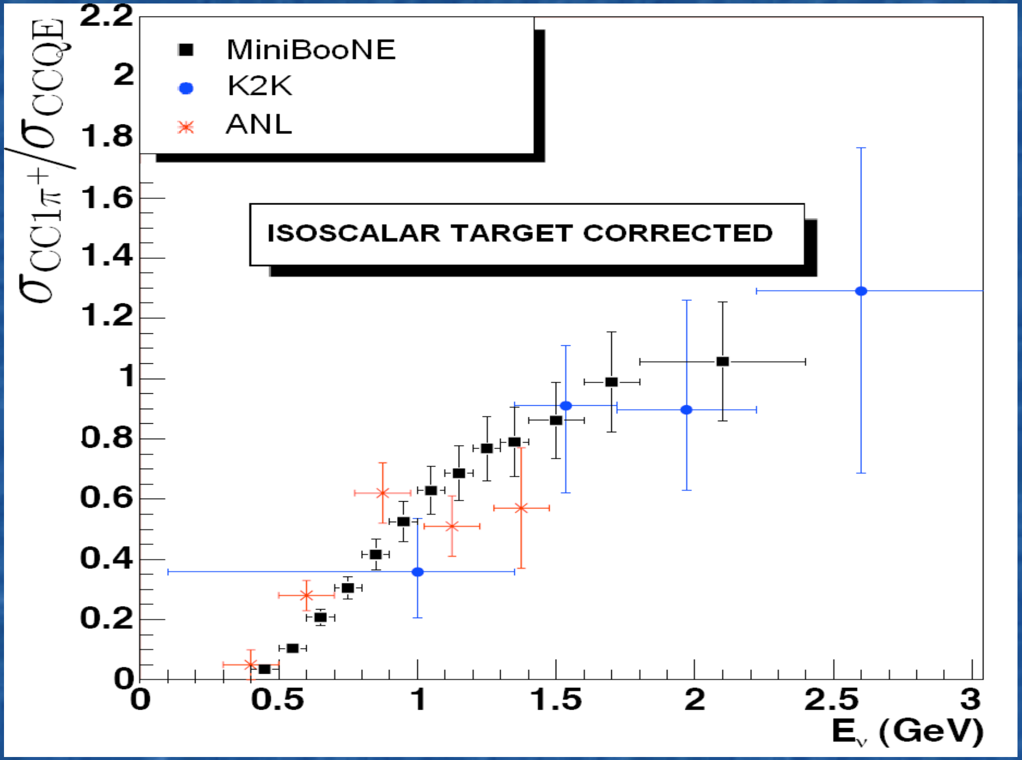
The MiniBooNE Detector



- Particle reconstruction is based primarily on detection of Cherenkov radiation (additional information is gained from delayed isotropic light)
- The tank is filled with 800 tons of ultra-pure mineral oil (modeled as CH_2)
- 1280 8" phototubes are attached to the inside surface of the tank (10% coverage)
- Outside the main tank is a thin spherical shell containing 240 phototubes to veto entering particles

MiniBooNE CCπ^+/CCQE Measurement

- The ratio of the CCπ^+ cross section to CCQE has been measured at several neutrino energies
- Neutrino energies are determined from the reconstructed muon kinematics
- Results are in agreement with previous measurements from K2K and ANL
- Results were recently submitted to PRL
- See poster by J. Nowak

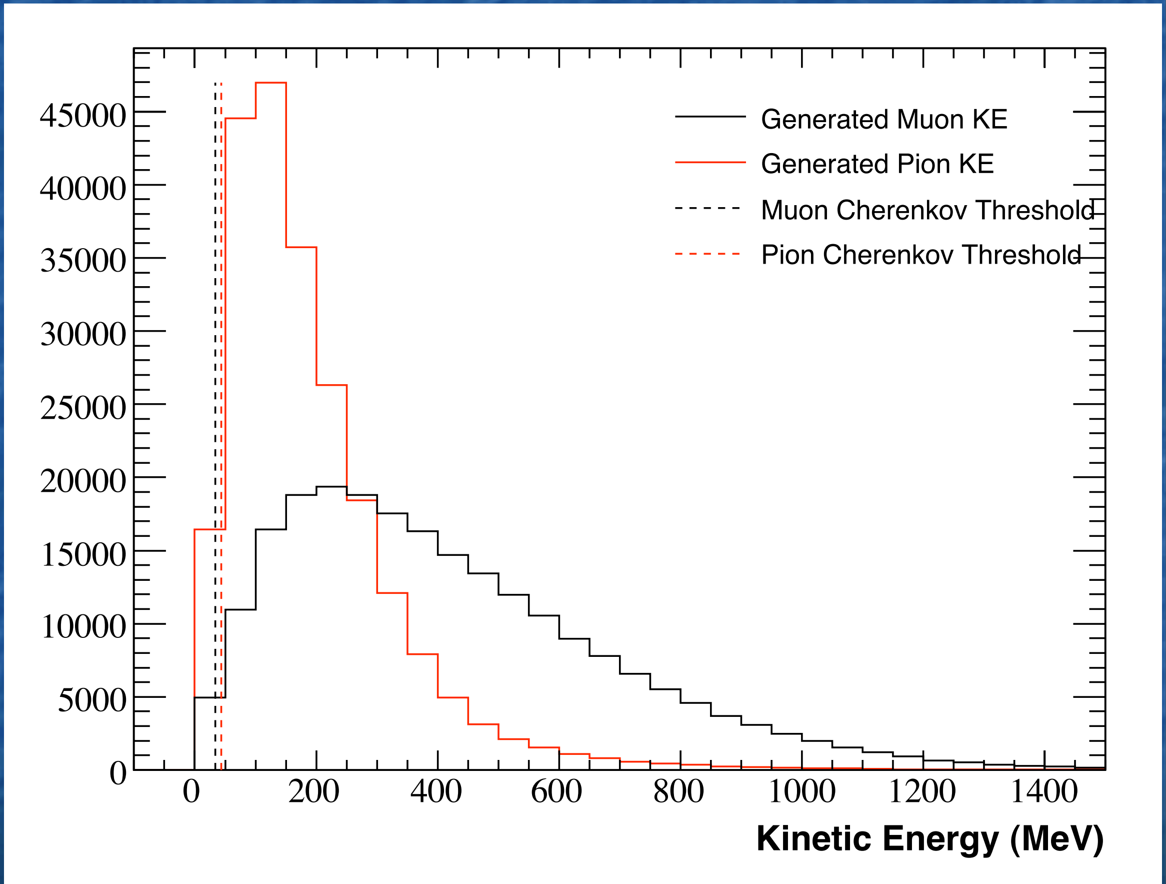


arXiv:0904.3159

Reconstruction Improvements

- In the MiniBooNE detector, the muon and pion produced in $CC\pi^+$ interactions are often both above Cherenkov threshold
- To better reconstruct each event, both the muon and pion can be included in a simultaneous fit
- In addition to reconstructing both particles, we further need the ability to distinguish the muon from the pion

Monte Carlo predicted muon and pion kinetic energy

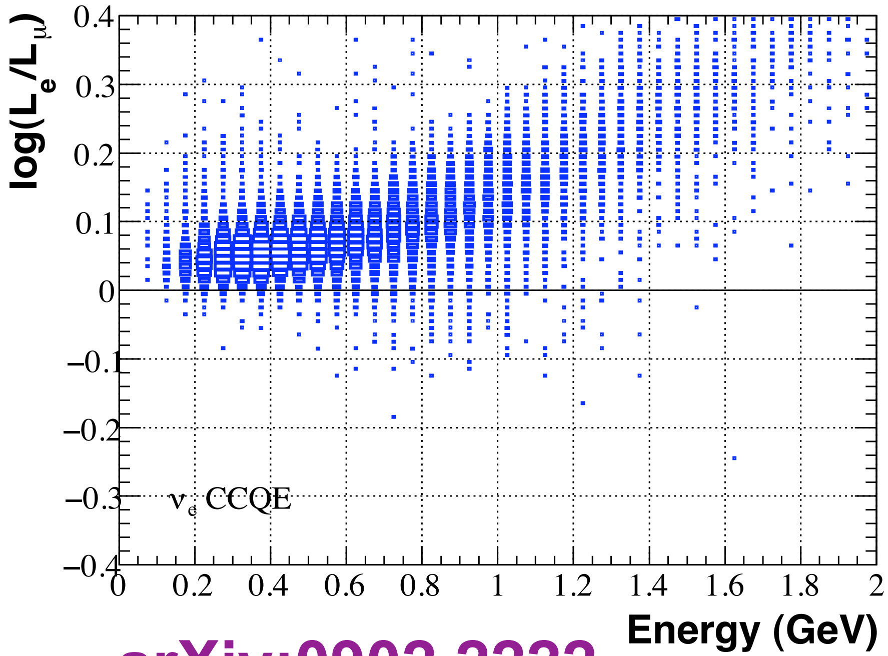


Event Reconstruction Overview

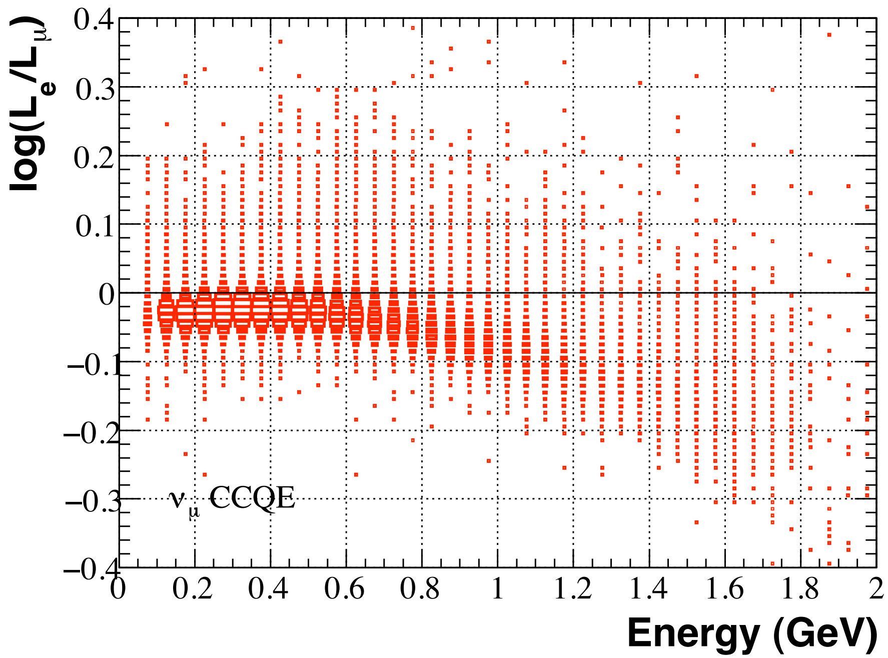
- The reconstruction relies on a detailed analytic model of extended-track light production in the detector
- Each track is defined by 7 parameters:
  - vertex (X,Y,Z,T)
  - direction (θ,ϕ)
  - energy (E)
- For a given set of track parameters, the charge and time probability distributions are determined for each PMT
- Fitting routine varies these parameters to best fit the measured charges and times

Particle Identification

- The one track fit requires a particle hypothesis (e.g. μ or e)
- Particle identification is achieved by comparing fit likelihoods from different track hypotheses
- The ratio of the μ and e hypothesis fit likelihoods vs fit energy provides nice separation between electrons (top) and muons (bottom)



arXiv:0902.2222



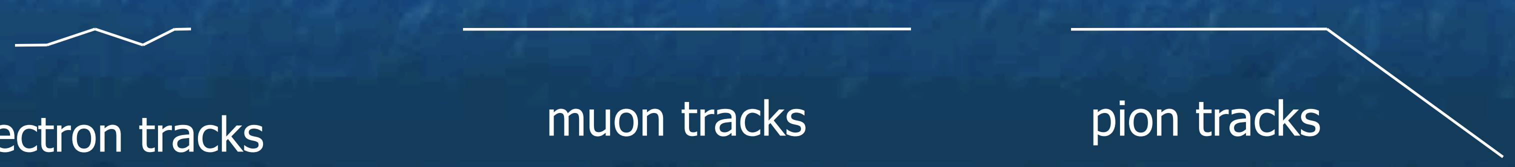
Pion Reconstruction

- In addition to reconstructing the pion kinematics, the goal of a pion fitter is to provide a means by which pions can be distinguished from muons
  - Pions and muons propagate in a very similar fashion (similar masses)
  - To separate, must exploit any differences

- Pions tend to travel in very straight paths (much like muons) except that they occasionally interact hadronically and abruptly change direction

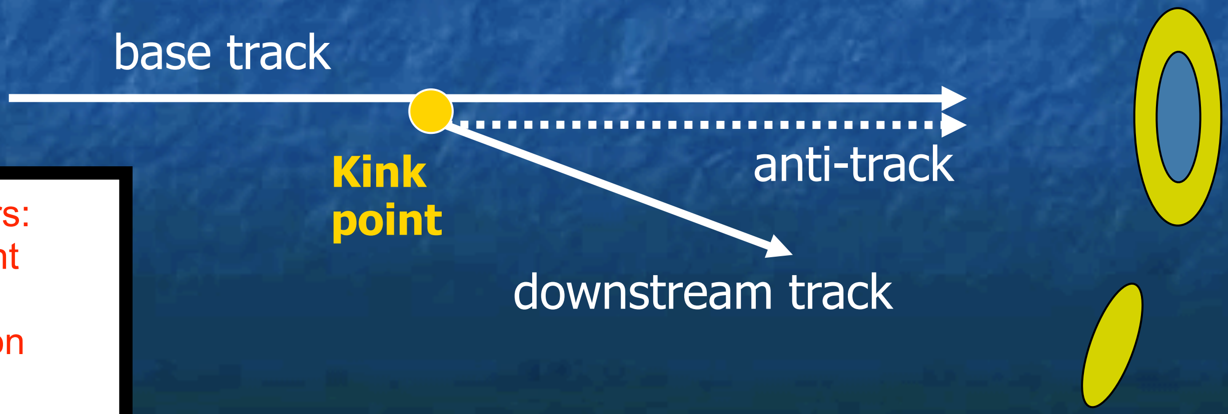
- Since the nuclear debris emitted in these interactions usually doesn't produce any light, the pion trajectories are straight lines with a sharp "kink" in the middle

- To improve the reconstruction of these tracks, a kinked track fitter is needed



Creating a Kinked Fitter

- The default track hypotheses assume that tracks start at one energy and finish with zero energy
- For a kinked track likelihood function, the predicted charges are calculated for an unkinked "base track" at the desired energy
- An "anti-track" is then created collinear with the base track and downstream of the original vertex (with proportionately less energy)
- The predicted charges for the anti-track are subtracted from the base track
- Finally, a "downstream track" is created at the vertex of the anti-track but with even less energy (due to ΔE_{kink}) and pointing in a new direction

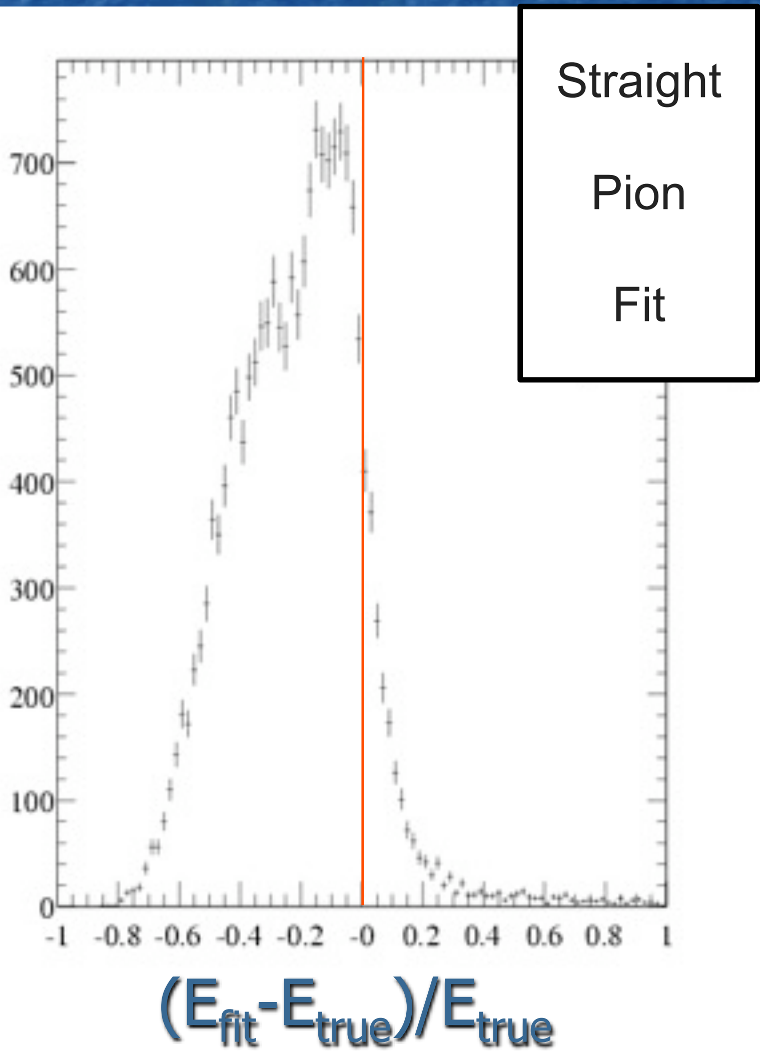


4 new track parameters:

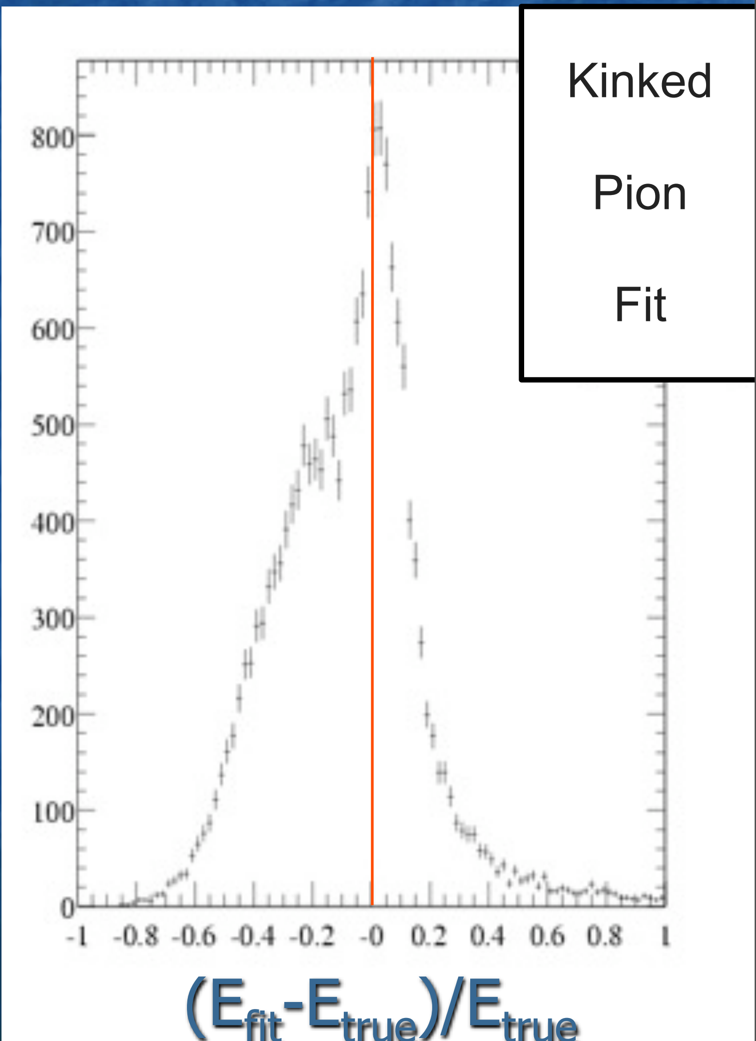
- distance to kink point
- kink energy loss
- downstream direction (θ and φ)

Energy Reconstruction:

Monte Carlo simulation of single pion events

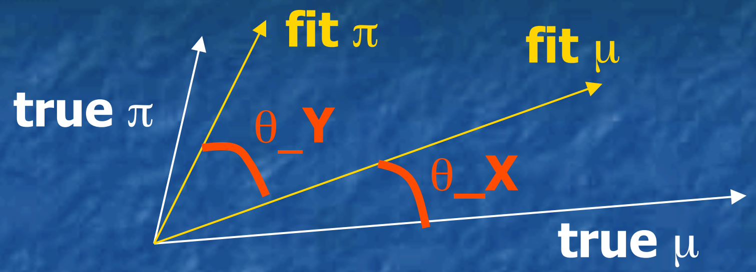


- The peak from the kinked fit is centered on zero (straight track peak is ~10% low)
- Kinked peak is narrower
- Low E_{fit} "shoulder" from high energy pions is much smaller in kinked fit

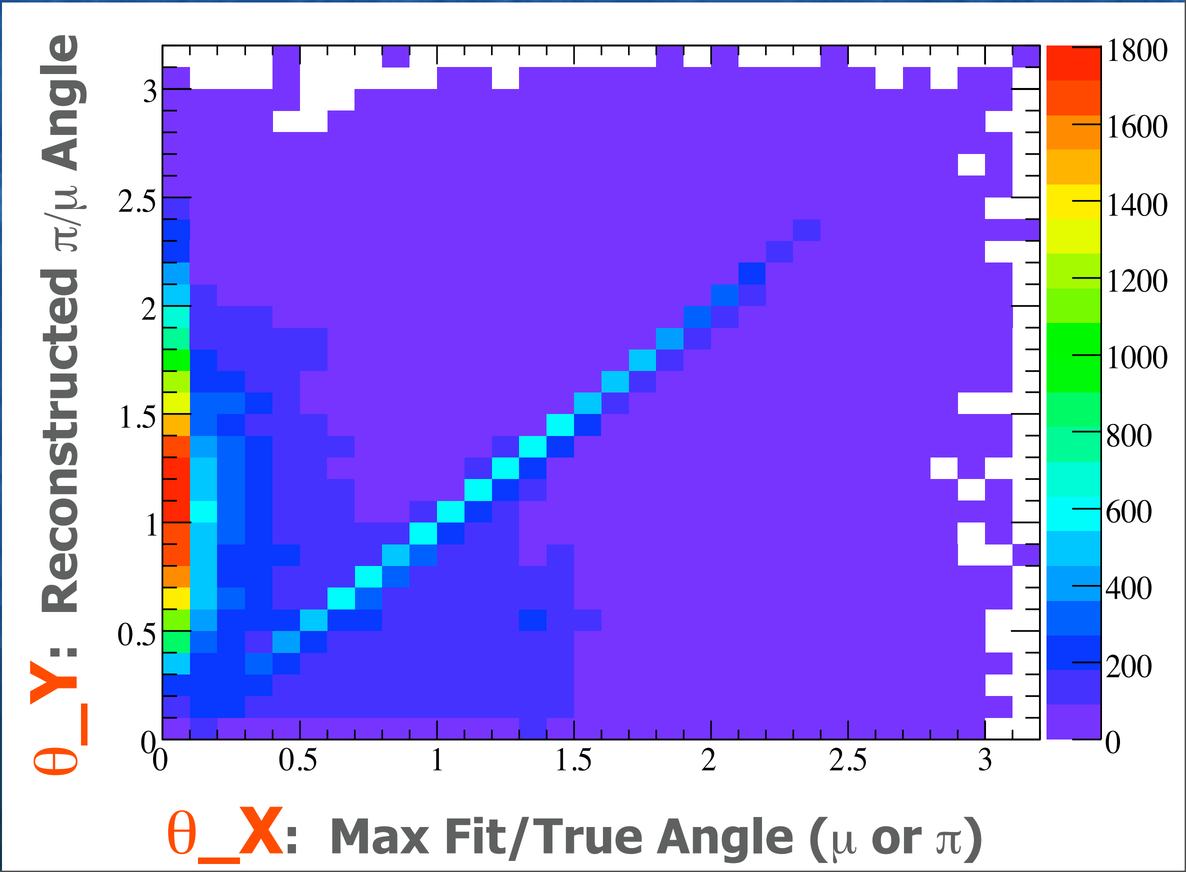


Angle Reconstruction

- The plot shows the reconstructed μ/π angle versus the WORSE of the two true/ reconstructed angles



- At low reconstructed μ/π angle, the fitter is slightly less accurate
  - When one track is below Cherenkov threshold, the fitter tends to place it on top of the other track
- The bins on the diagonal are events where the μ is misidentified as the π (and vice versa)



Neutrino Energy Reconstruction

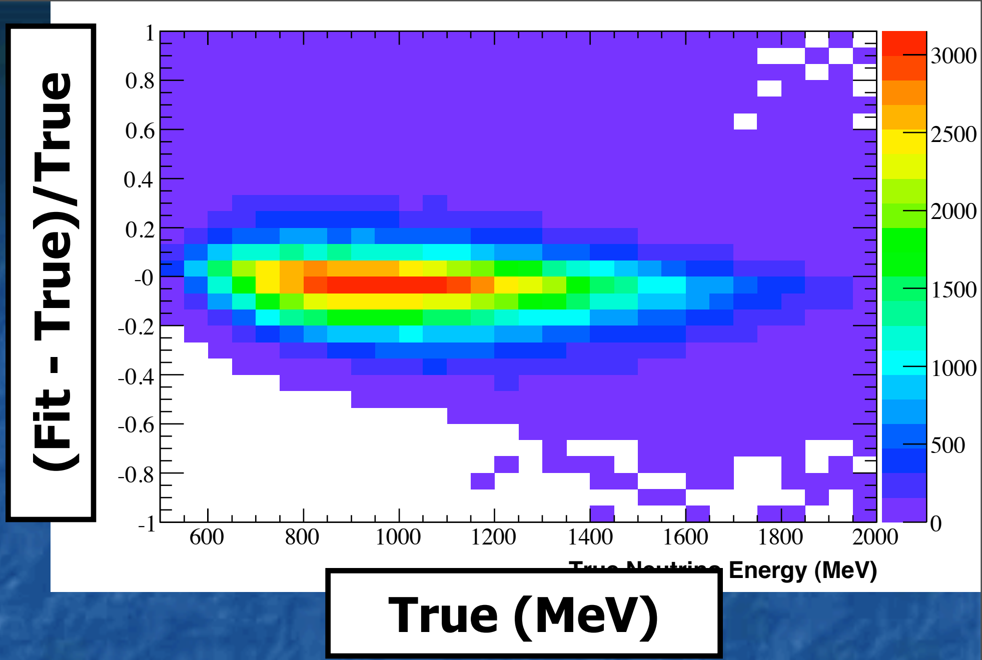
$$E_\nu = \frac{m_\mu^2 + m_\pi^2 - 2m_N\,(E_\mu + E_\pi) + 2p_\mu \cdot p_\pi}{2\,(E_\mu + E_\pi - |\mathbf{p}_\mu|\cos\theta_{\nu,\mu} - |\mathbf{p}_\pi|\cos\theta_{\nu,\pi} - m_N\,)}$$

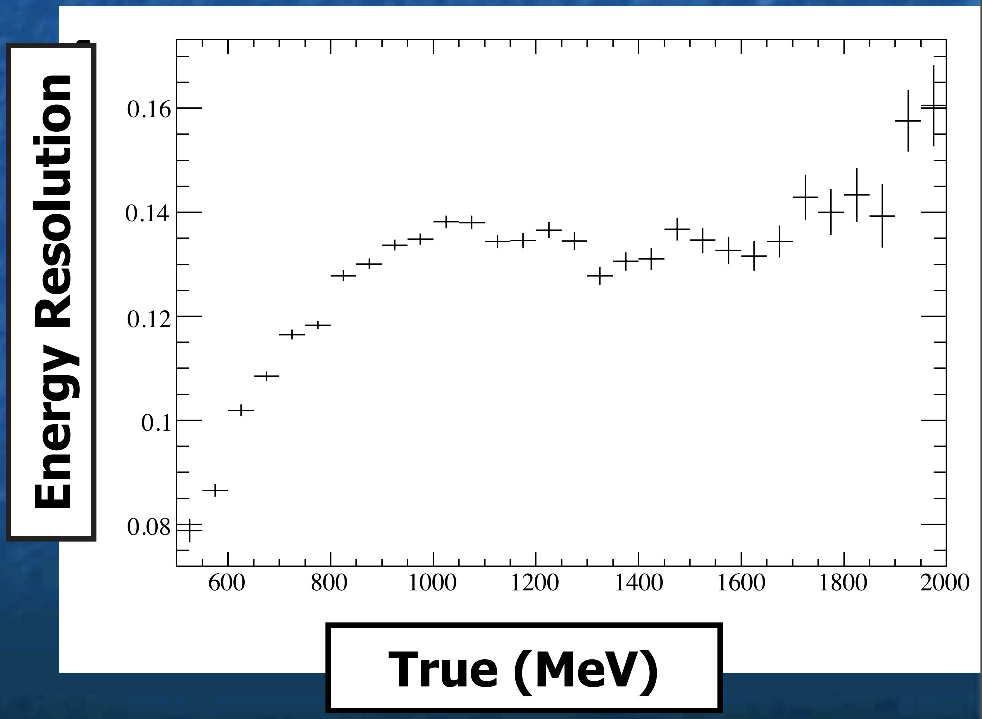
- Since both the muon and pion are reconstructed, the event kinematics are fully specified assuming
  - Target nucleon is at rest
  - Neutrino direction is known
  - Recoiling nucleon mass is known
- Unlike previous analyses that have only reconstructed the muon, no assumption is needed about the mass of the recoiling Δ particle created in the interaction
- Fairly insensitive to misidentifying the muon and pion since both particles have similar mass

Neutrino Energy Resolution

- The reconstructed neutrino energy is centered on the true energy

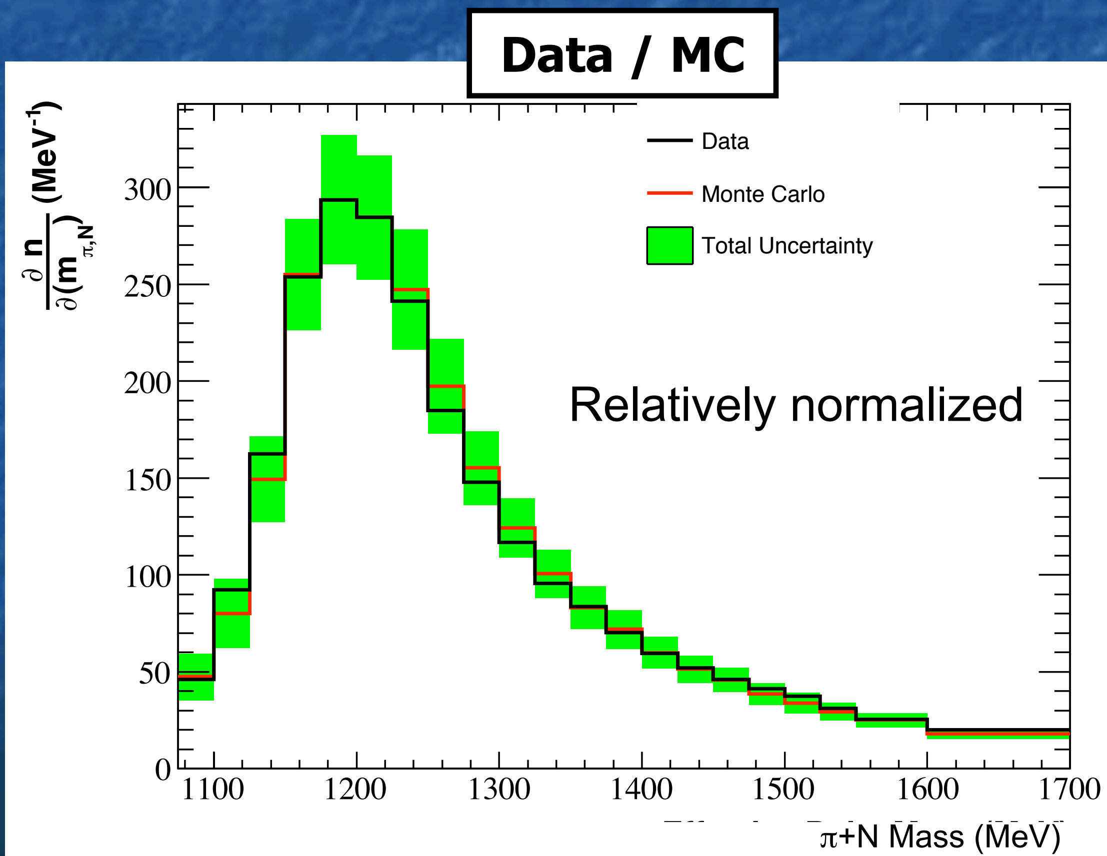
- The resolution is ~13.5% over most of the measured energy range: (0.5 - 2.0 GeV)

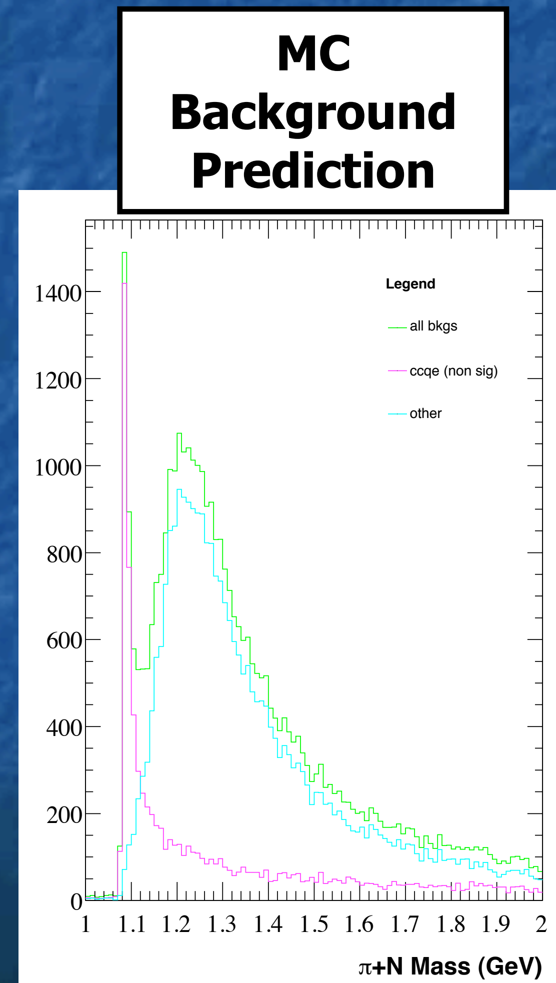




π^++N Mass

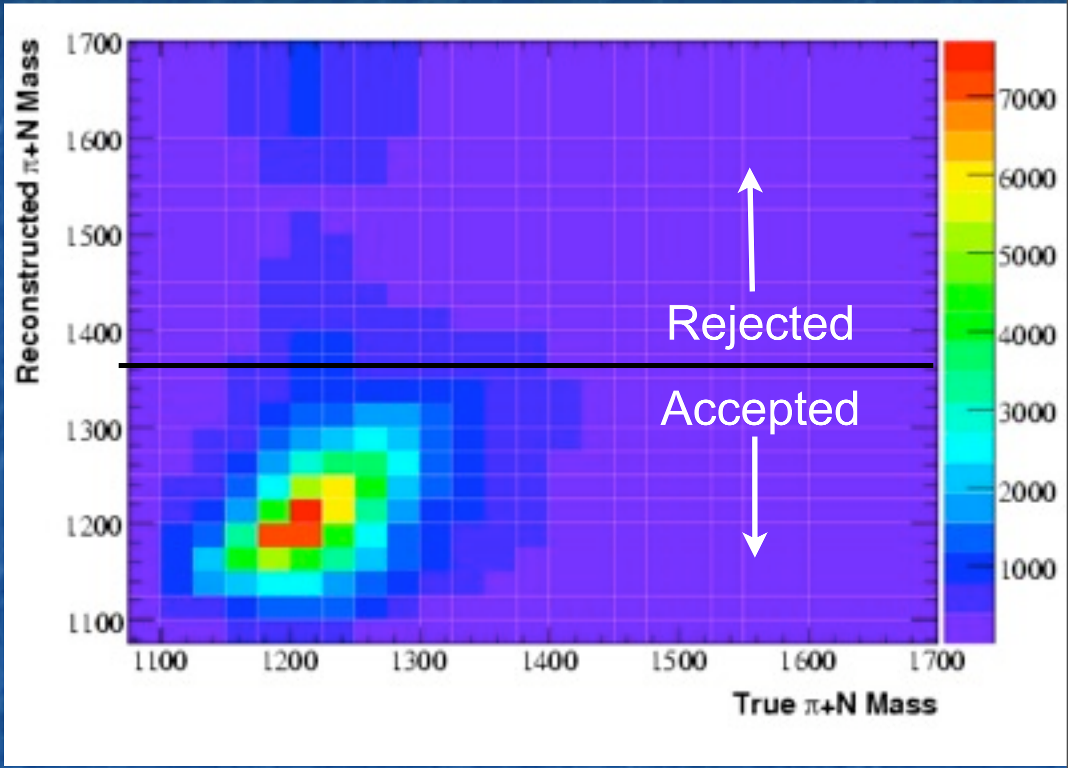
- Since we make no assumptions about the delta mass, we can reconstruct it
- The CCQE background piles up at low delta mass





π^++N Mass Cut

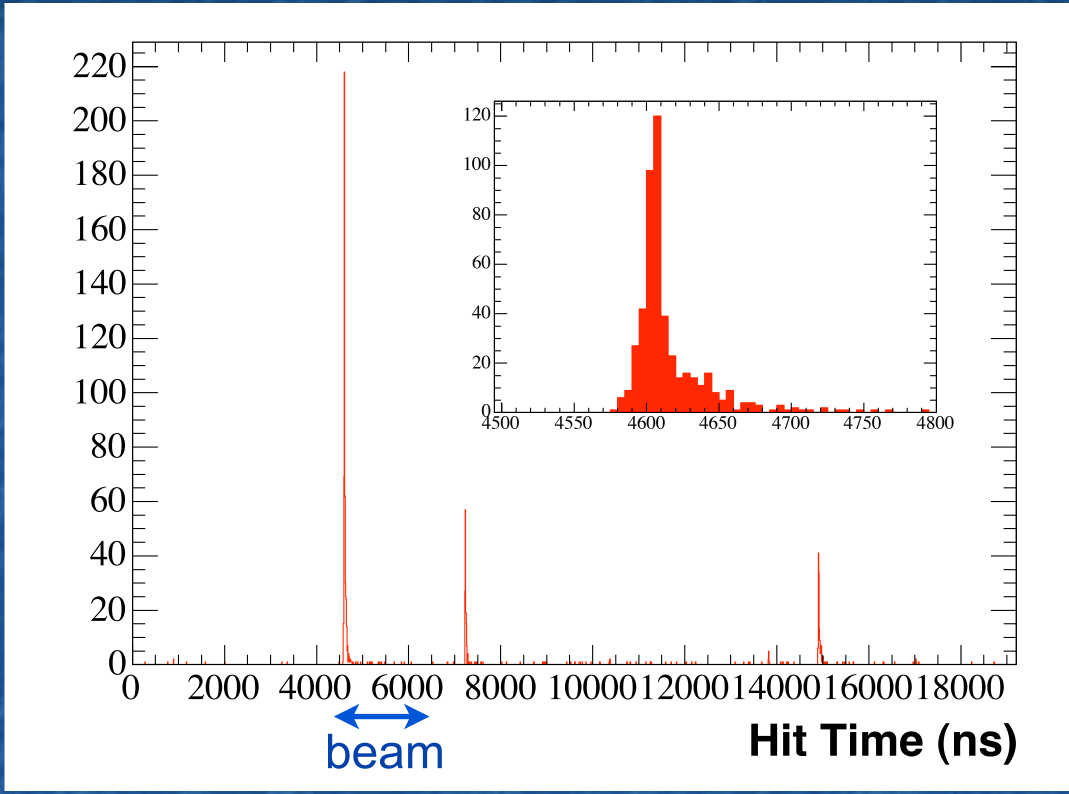
- The plot shows the reconstructed π^++N mass vs the generated value for Monte Carlo events
- At low masses, there is a correlation between these quantities, as expected



- Events in which a high energy muon is mis-reconstructed as a pion tend to accumulate at high reconstructed mass
- A cut has been placed at 1350 MeV to removed these mis-reconstructed events

Selection Cut Summary

- 3 subevents
- Subevent 1:
  - thits > 175
  - vhits < 6
- Subevents 2 and 3:
  - 20 < thits < 200
  - vhits < 6
- Fiducial volume cut



- Reconstructed π^{+}+N mass < 1350 MeV
- These cuts result in 48,000 events with a 90% purity, and a correct muon/pion identification rate of 88%

Observed CCπ^+ Cross Section

- Neutrino interactions are often modeled in terms of single nucleon cross sections plus additional nuclear processes that alter the composition of the final state
- Since the details of intra-nuclear processes are not accessible to experiment, we do not attempt to extrapolate our observations to the single nucleon cross section
  - greatly reduces model dependence
- Instead, we define an observed CCπ^+ event to be any interaction that produces the following final state:
  - one and only one muon
  - one and only one pion
  - any number of photons and baryons from the breakup of the nucleus

Measuring the Cross Section

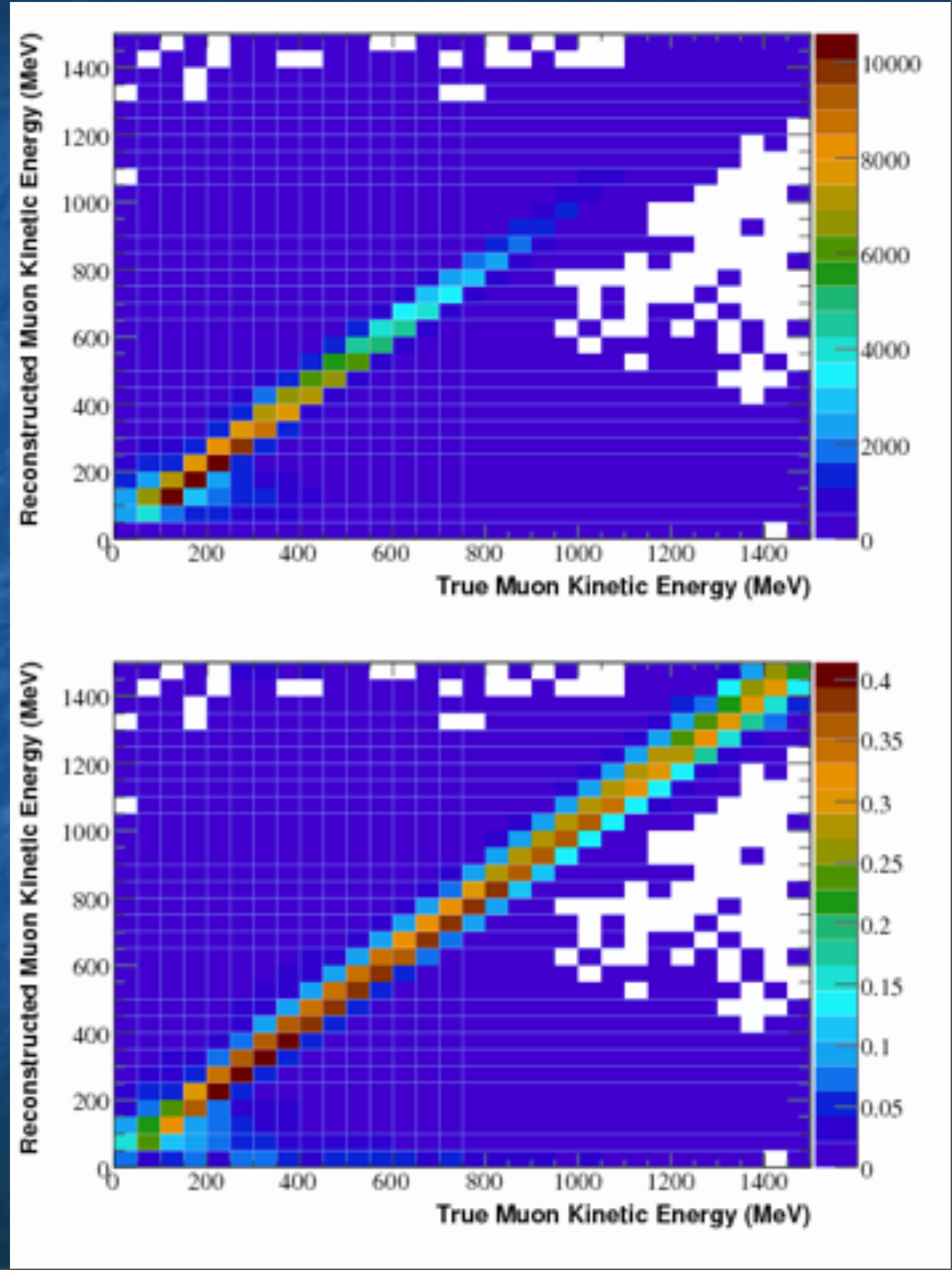
$$\frac{\partial \sigma}{\partial v}(v_i) = \frac{\sum_j M_{ij}(D_j - B_j)}{\epsilon_i \Delta v_i N_{targ} \Phi}$$

- Cross sections are calculated as a function of any variable(s) in the interaction

- The calculation uses the above formula (i = reconstructed bin; j = true bin)
  - v_i: any 1D or 2D distribution
  - D_i: reconstructed data distribution of v
  - B_i: background prediction of v
  - M_{ij}: unfolding matrix (see next slide)
  - ε_j: MC efficiency in unfolded bins
  - $\phi_{(j)}$: integrated flux (or flux histogram in the case of $E\nu$)
  - POT: protons on target
  - N_{targ}: number of targets = volume*density*N_A/(target molecular weight)

Unfolding Matrix

- Top: the reconstructed vs true muon kinetic energy histogram
- Bottom: each row has been normalized to one to produce the unfolding matrix, M_{ij}
- Each row of the matrix gives the probability that an event reconstructed in bin i should be placed in true bin j



Systematic Errors

- For each error source, all parameters are varied according to a full covariance matrix
- For each new set of parameters, a new set of systematically varied events, or "multisim", is produced
- To determine the systematic errors on each cross section measurement, the cross section calculation is repeated using the multisim as though it were the central value Monte Carlo simulation
- For the absolute $CC\pi^+$ cross section measurements, the dominant systematic uncertainties are:
  - flux prediction
  - modeling of pion absorption and charge exchange interactions in the tank

Cross Section Measurements

One-Dimensional Measurements

- $\sigma(E_\nu)$: neutrino energy
- $d\sigma/d(Q^2)$: momentum transfer
- $d\sigma/d(KE_\mu)$: muon kinetic energy
- $d\sigma/d(\cos\theta_{\mu,\nu})$: muon/neutrino angle
- $d\sigma/d(KE_\pi)$: pion kinetic energy
- $d\sigma/d(\cos\theta_{\pi,\nu})$: pion/neutrino angle

Results in gold will be shown on the following slides

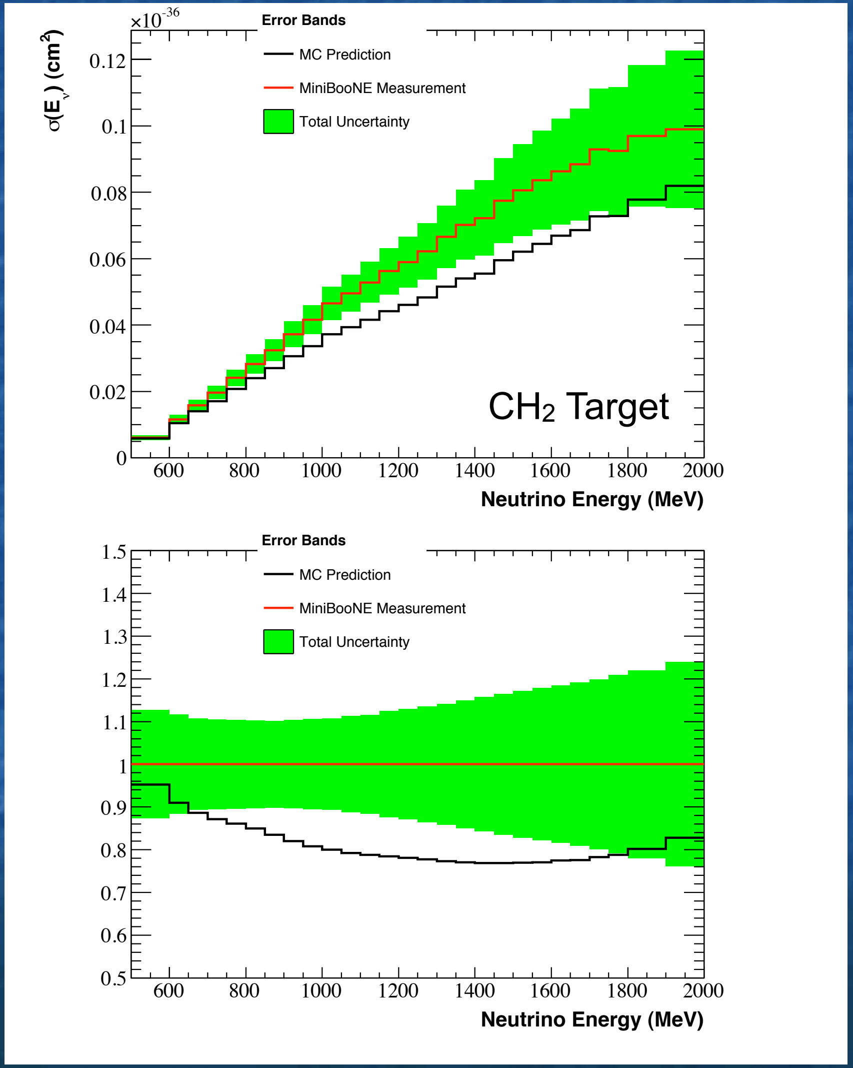
Double Differential Cross Sections

- $d^2\sigma/d(KE_\mu)d(\cos\theta_{\mu,\nu})$: muon kinetic energy vs angle
- $d^2\sigma/d(KE_\pi)d(\cos\theta_{\pi,\nu})$: pion kinetic energy vs angle
- (emphasize not FSI corrected)

Each of the Single Differential Cross Sections has also been measured in two-dimensions as a function of neutrino energy

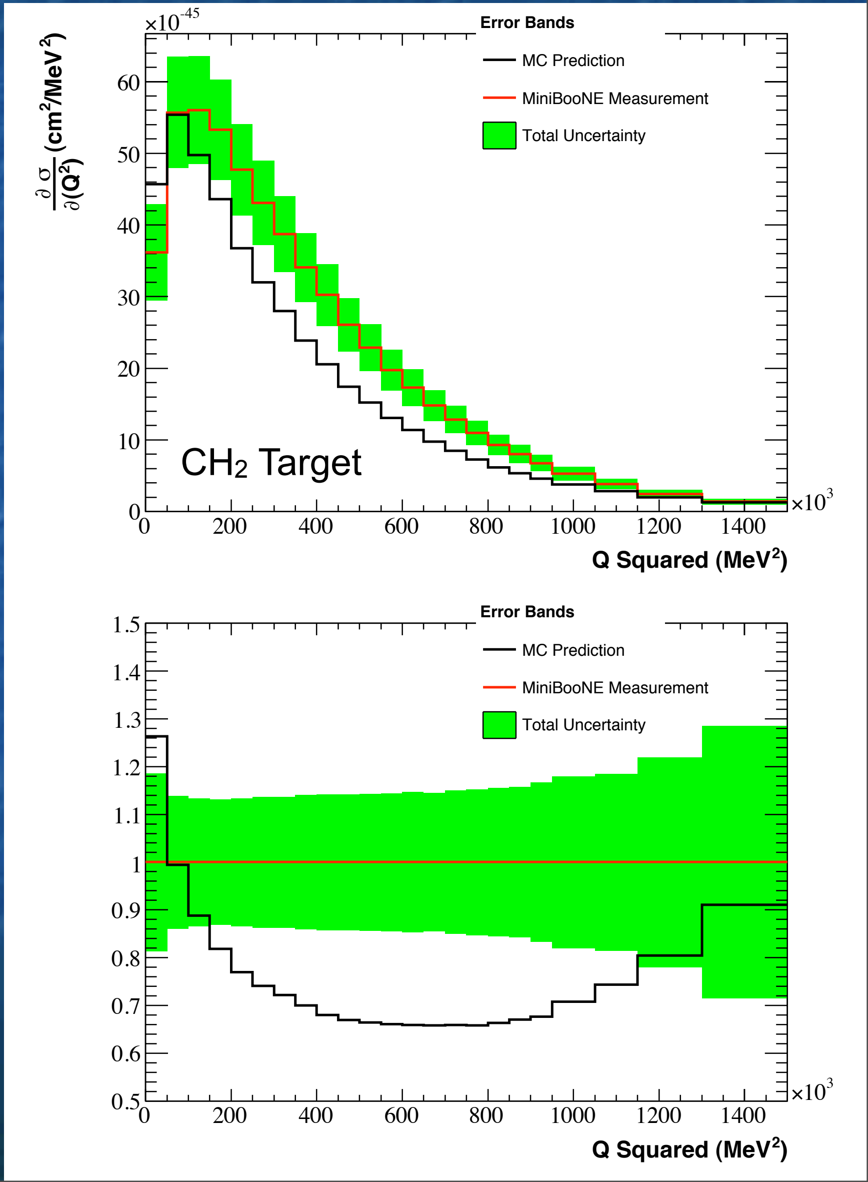
Absolute $CC\pi^+$ Cross Section in Neutrino Energy

- The measured cross section is shown in red, and the total uncertainty is given by the green error band
- The lower plot gives the fractional error and the ratio of the Monte Carlo prediction to the measured cross section
- The Monte Carlo prediction is shown in black for comparison
- In addition to the diagonal errors shown, full correlated error matrices have been produced for all measurements



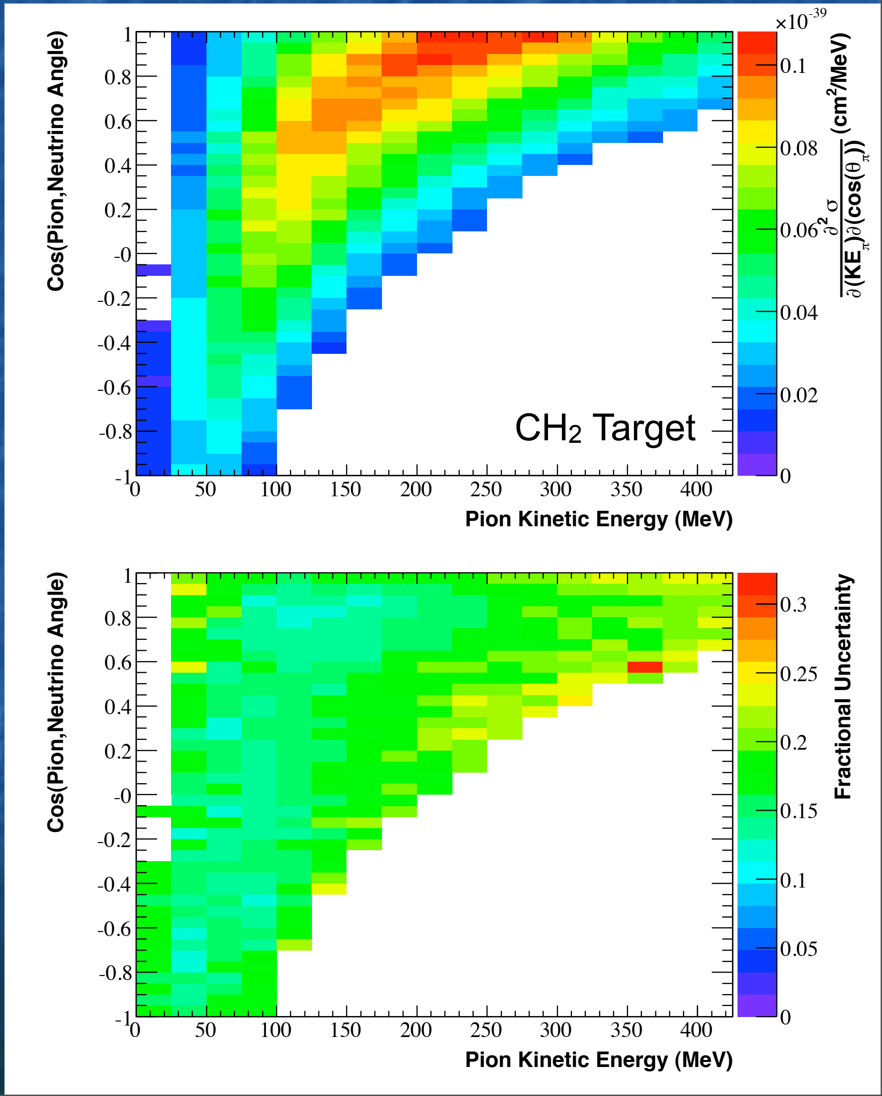
Absolute CCπ^+ Cross Section in Q^2

- Top: measured cross section with error bands (with Monte Carlo prediction for comparison)
- Bottom: fractional uncertainties in each bin (with MC prediction ratio)
- Just like CCQE, the data turn over faster relative to Monte Carlo at low Q^2
- This measurement is flux averaged, so each bin has a minimum uncertainty of 12%



Double Differential Cross Section in Pion Energy and Angle

- Top: measured double differential cross section in pion kinetic energy and $\cos(\theta_{\pi,\nu})$
- Bottom: fractional measurement uncertainty in each bin
- A full correlated error matrix has been calculated that includes each measured 2D bin



Summary

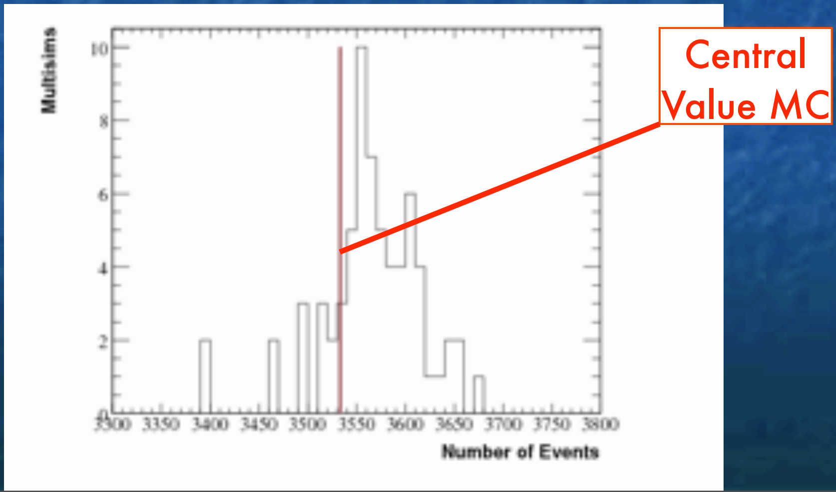
- MiniBooNE recently submitted a measurement of the $CC\pi^+/CCQE$ cross section ratio to PRL
- By exploiting the hadronic interactions of charged pions, we can now reconstruct both the pion and the muon
- With a few simple cuts, we can achieve an event purity of 90%, while correctly identifying muon & pion tracks with an 88% success rate
- Using this new fit technique, we have produced the first ever differential and double-differential $CC\pi^+$ cross section measurements in both muon and pion final state kinematic variables
- We plan to publish these results this summer

Backups

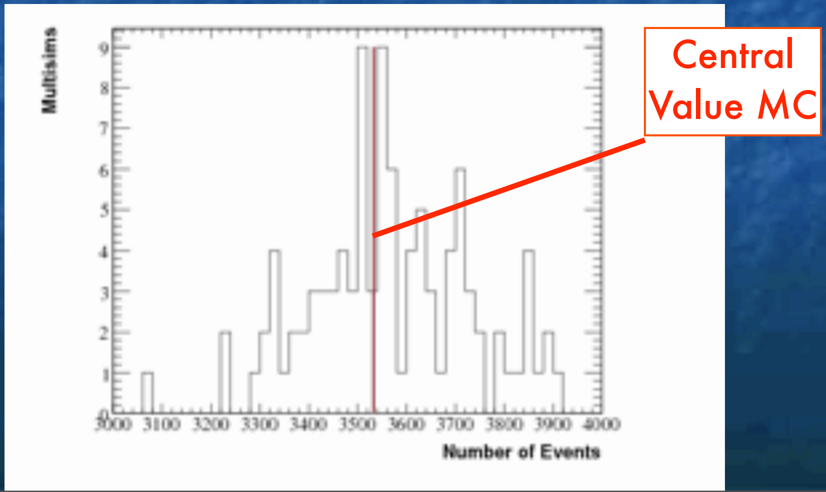
Multisim Production

- For systematic uncertainties that only affect the probability of an event occurring (e.g. flux & cross sections), multisims can be created via reweighting
- For the optical model, 67 unisims were generated from scratch
- Below are multisim error examples for a single reconstructed neutrino energy bin ($1000 < E_\nu < 1050$ MeV)

67 Optical Model multisims



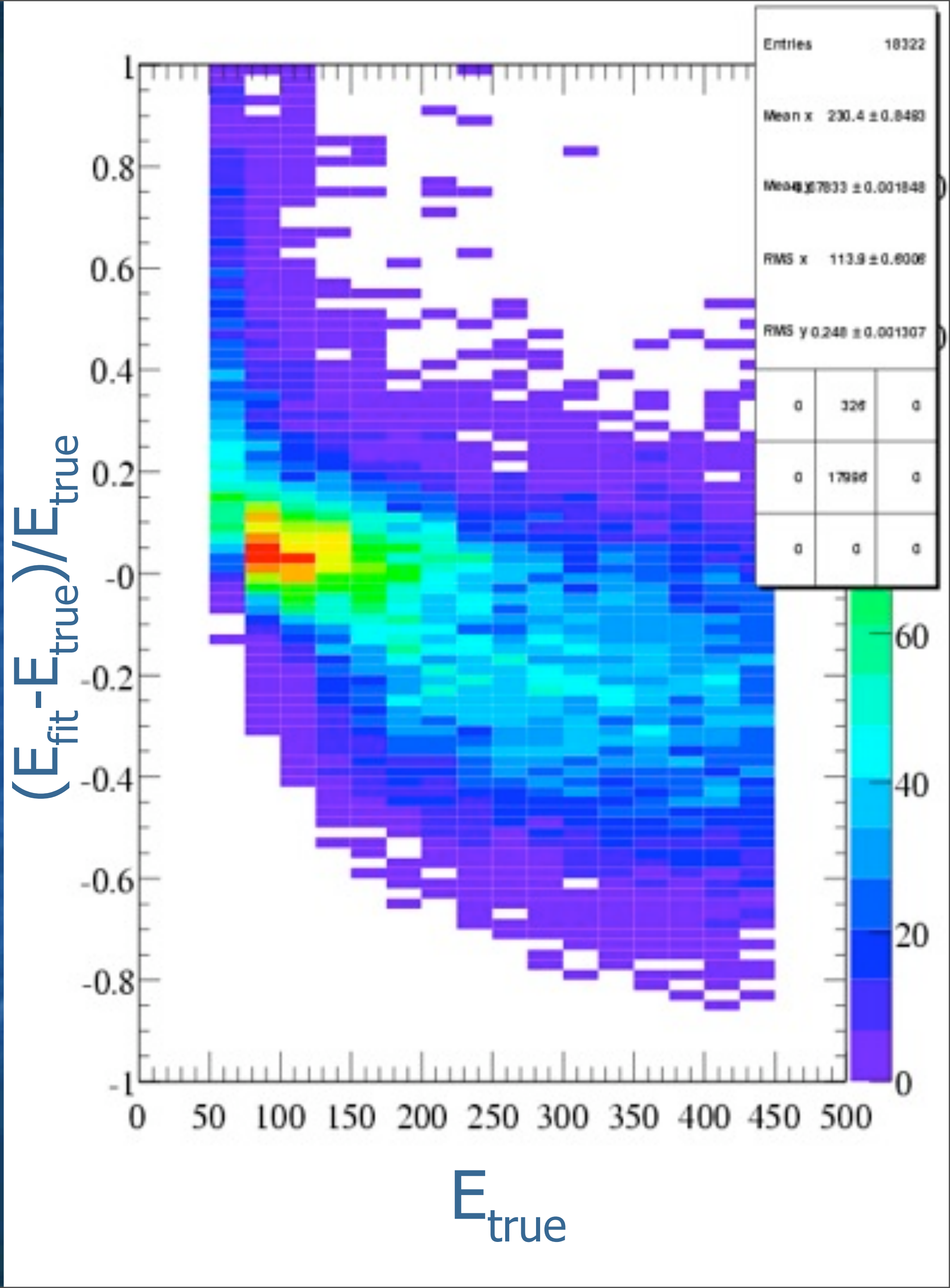
100 π^+ reweighting multisims



Energy Shoulder

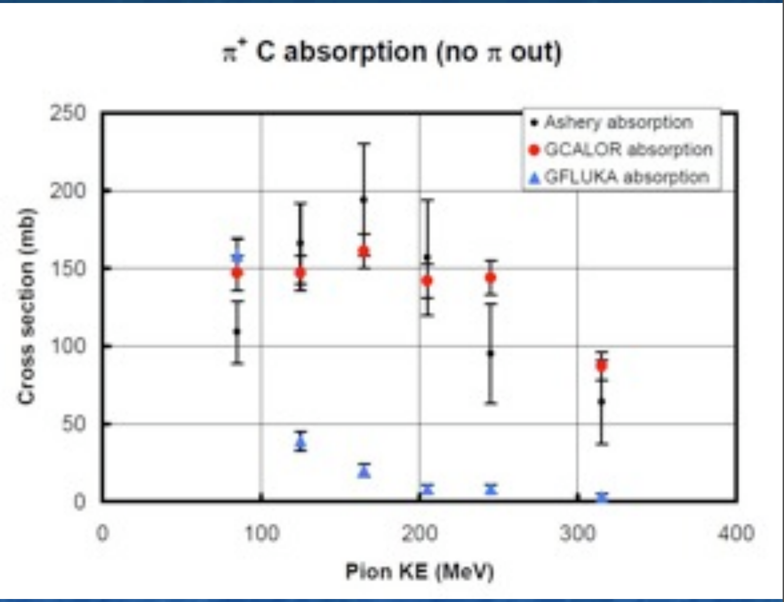
From a Monte Carlo simulation of single pion events generated uniformly between 50 and 450 MeV

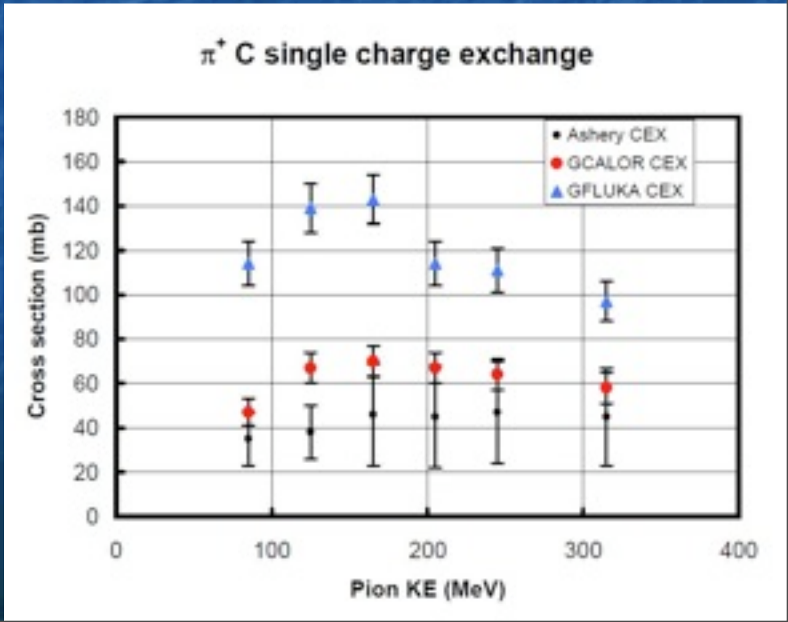
- The low fit energy shoulder in $(E_{fit}-E_{true})/E_{true}$ comes from higher energy events
  - more energy lost in kinks
  - more kinks



Detector Simulation Uncertainties

- The optical model contains 35 parameters that control a variety of different phenomena, such as
  - scattering
  - extinction length
  - reflections
  - PMT quantum efficiency
- Each parameter is simultaneously varied within its measured error in an attempt to ascertain information about parameter correlations
- The default GFLUKA model has been replaced by GCALOR, which more accurately represents pion absorption and charge exchange data
  - The residual discrepancy is taken as a systematic uncertainty





Beryllium/Aluminum Cross Sections

- Nucleon and pion cross sections have several components related by:

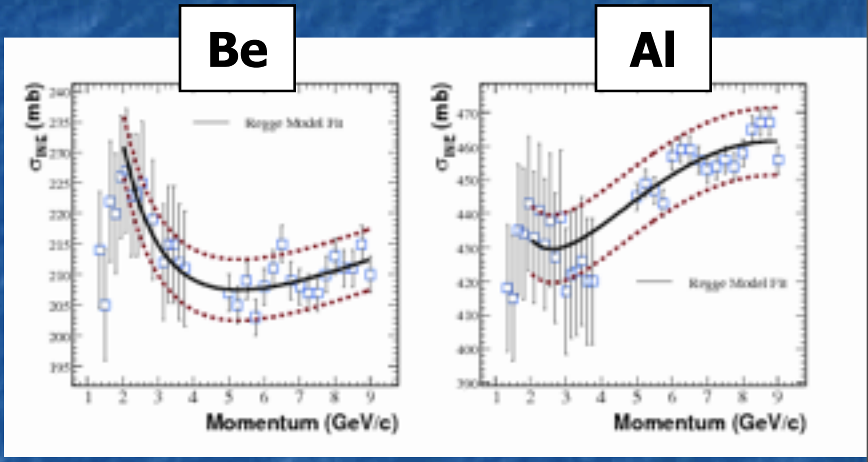
$$\sigma_{TOT}=\sigma_{ELA}+\sigma_{INE}=\sigma_{ELA}+(\sigma_{QE}+\sigma_{REA})$$

  - σ_{TOT}: total interaction cross section
  - σ_{ELA}: elastic scattering cross section
  - σ_{INE}: inelastic scattering cross section
  - σ_{QE}: quasi-elastic scattering (target breakup; incident particle intact)
  - σ_{REA}: "reaction" cross section (all non-QE inelastic scattering)

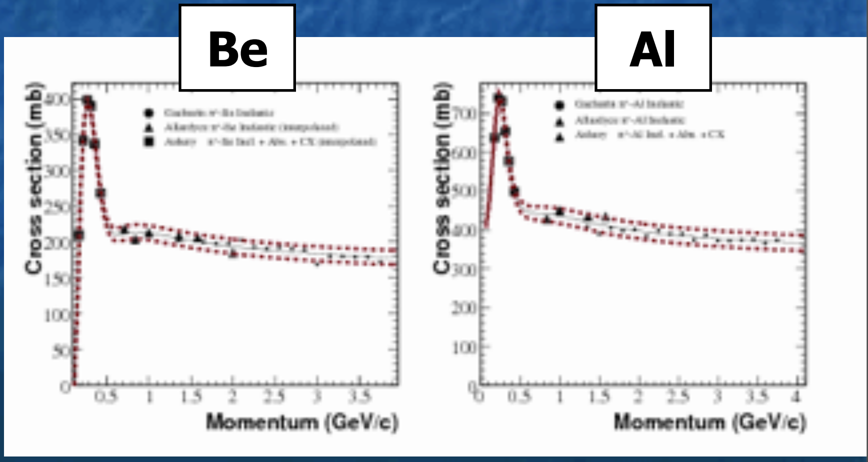
- Custom models have been built for the total, quasi-elastic, and inelastic cross sections

  - σ_{TOT}: Glauber model for elastic scattering (coherent nucleon sum) + optical theorem
  - σ_{QE}: incoherent nucleon sum + shadowed multiple scattering expansion
  - σ_{INE}: Regge model parametrization; fit to data

Nucleon Inelastic Cross Sections



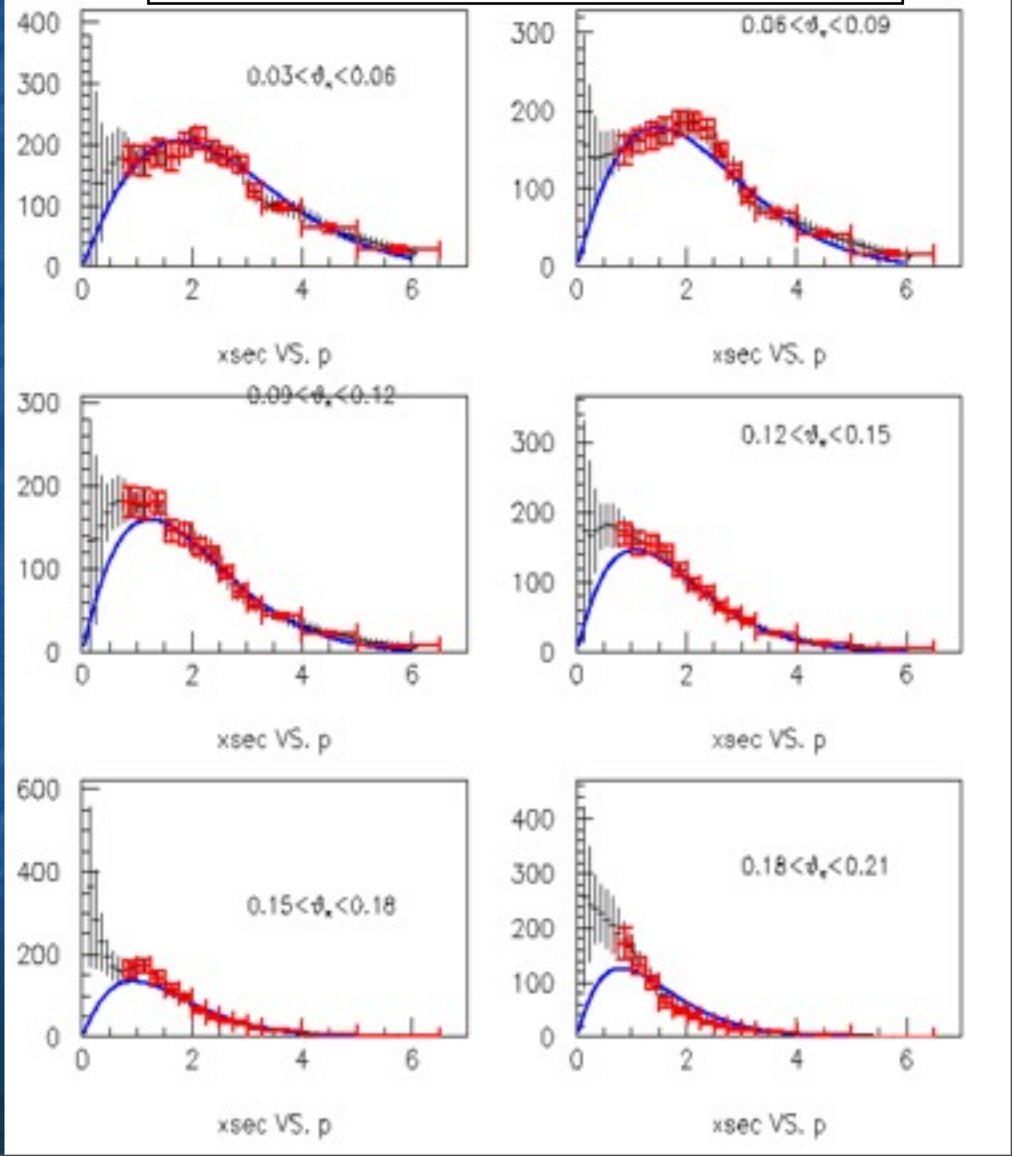
Pion Inelastic Cross Sections



Pion Production Uncertainties

- The Sanford-Wang function fit to the HARP data produces a χ^2/dof of 1.8
- To account for this discrepancy, the normalization uncertainty has effectively been inflated to 18%
  - The intrinsic HARP uncertainties are an uncorrelated 7%
- Rather than artificially inflate the normalization to cover an incompatibility in the shape of the parametrization, the HARP data is fit to a spline function
- The spline function passes through the data points and the uncertainties blow up in regions with no data
- The SW function is still used to generate Monte Carlo
  - the uncertainties are given by the distance between each spline variation and the SW central value
  - this inflates the error in regions where the SW and spline central values disagree

pion cross section vs momentum in bins of pion angle

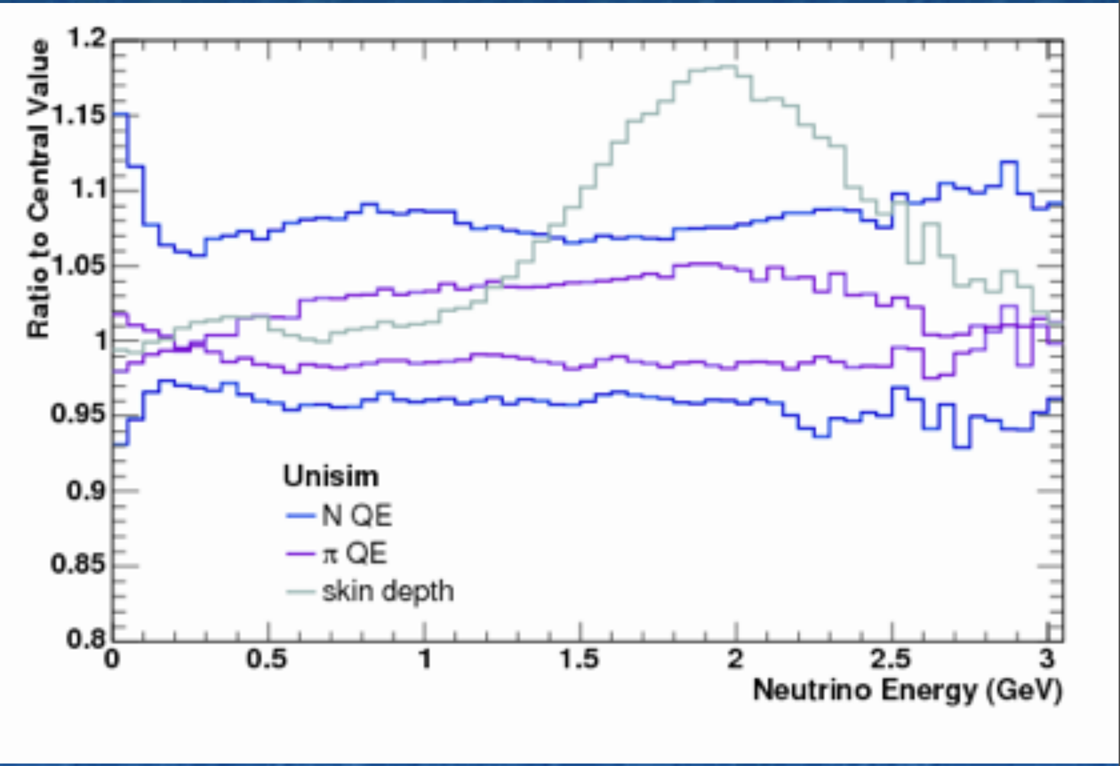


Flux Uncertainties

- Several components of the simulation have been varied to assess the effect they have on the ν_μ flux (called "unisims")
  - horn current
  - horn current skin depth in the inner conductor
  - all measured (or calculated) components of the p,n,π-Be,Al cross sections (while holding the other components fixed

$$\sigma_{TOT}=\sigma_{ELA}+\sigma_{INE}=\sigma_{ELA}+(\sigma_{QE}+\sigma_{REA})$$

- The plot shows the variations that produce an effect larger than 2%
  - The skin depth produces a large effect at high energies
  - The quasi-elastic cross section calculations are the least constrained by data → largest error



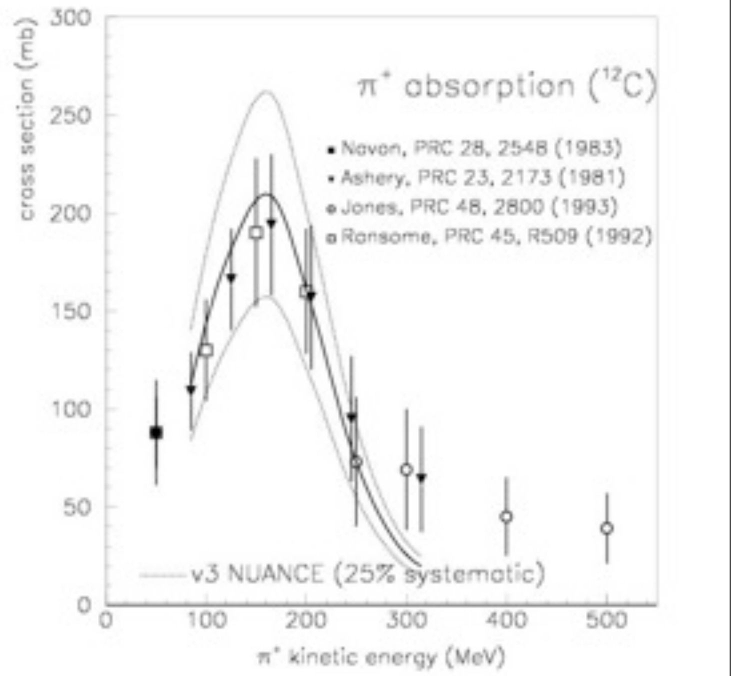
- π^+ production uncertainties are given by the spline fit covariance matrix (taken about the SW central value)
- K^+ uncertainties are given by the Feynman Scaling fit covariance matrix

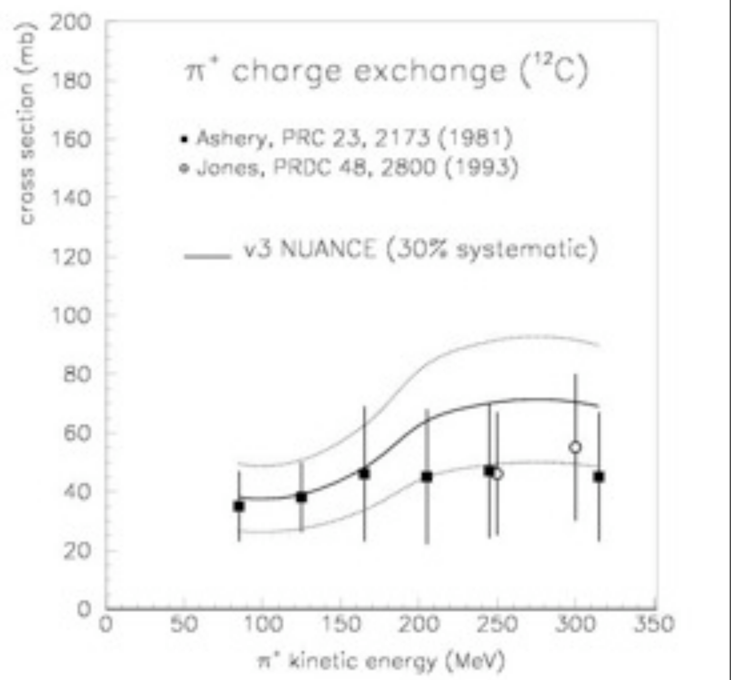
Nuance Uncertainties

- Several parameters of the cross section model are varied; the most important are as follows

- Each of the background processes are varied
  - CCQE: $M_A = 1.234 \pm 0.077$ GeV (6.2%)
  - CC multi π: $M_A = 1.30 \pm 0.52$ GeV (40%)
  - DIS: normalization varied by 25%

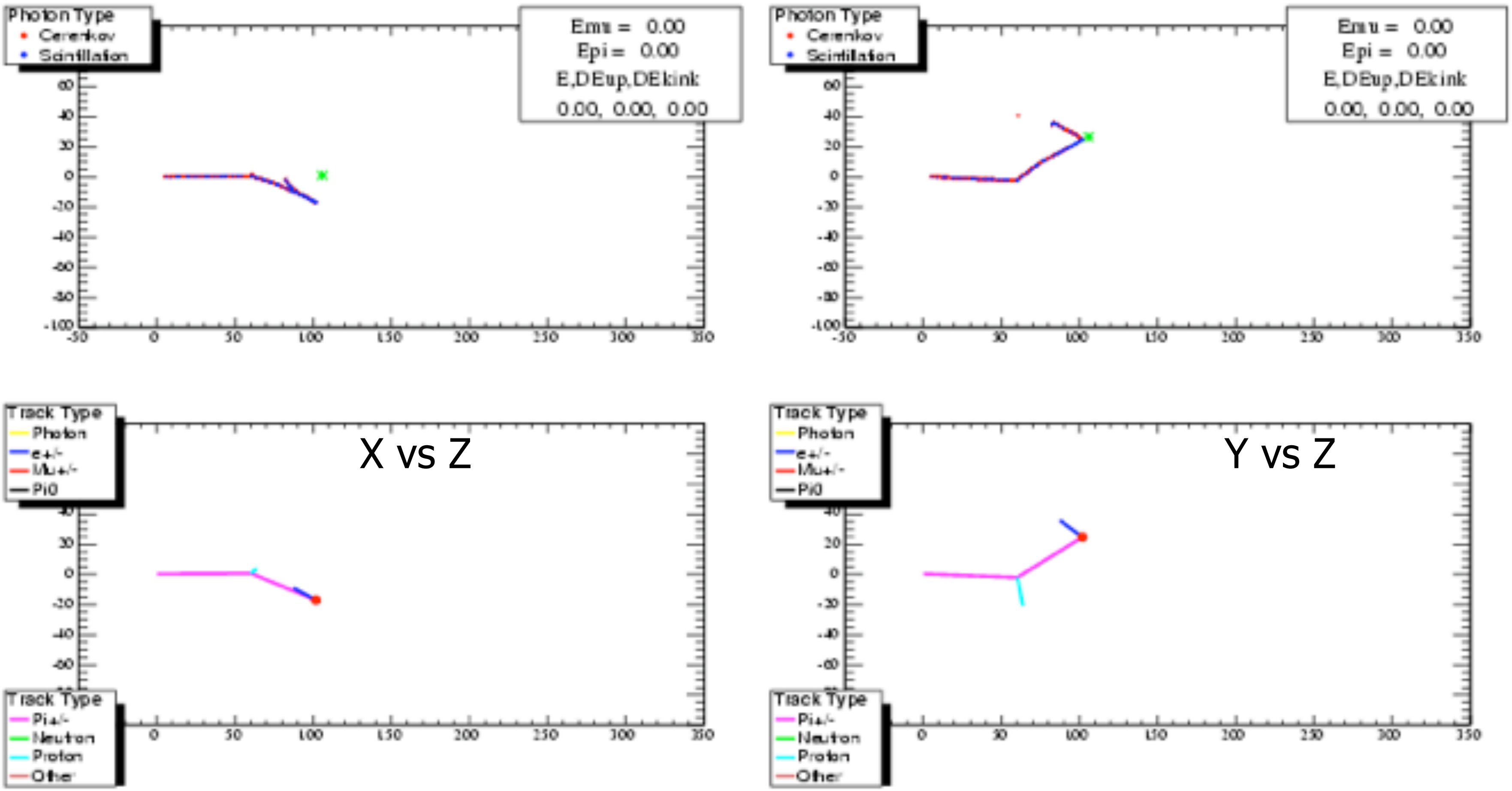
- Several important nuclear model parameters are varied as well
  - binding energy: 34 ± 9 MeV (26%)
  - Fermi momentum: 220 ± 30 MeV/c (14%)
  - pion absorption: 25%
  - pion charge exchange: 30%
  - $\Delta + N \rightarrow N + N$: 100%





How Do Pions Behave in the Oil?

- The top plots show the vertices of every emitted photon that hits a phototube for a typical 300 MeV pion
- The bottom plots show the Monte Carlo truth information



Sample Fit

Top plot fit result legend:

- Black line = pion OneTrack fit
- Red line = muon OneTrack fit
- Magenta line = pion OneTrackKinked fit