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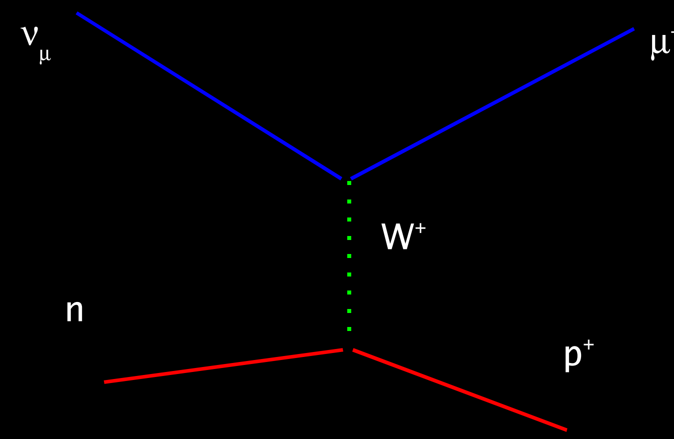
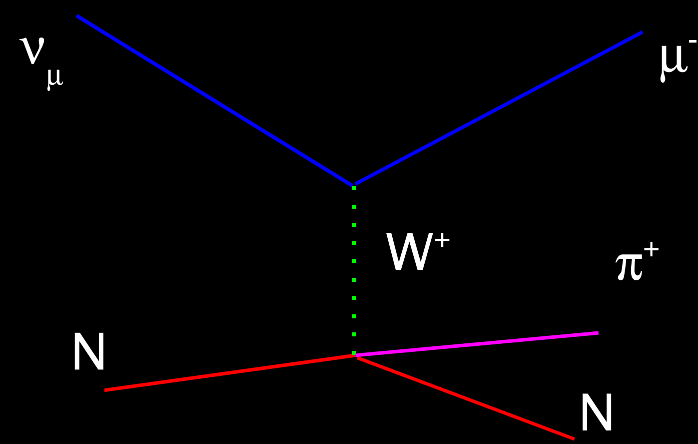
Measuring ν_μ CC Interactions at MiniBooNE

- Muon Energy Measurement and Calibration at MiniBooNE
- Charged Current Quasi-Elastic (CCQE)
- Charged Current Resonant Single Pion (CCPiP)





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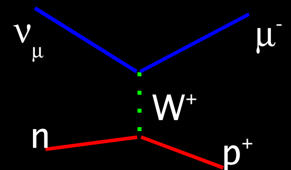
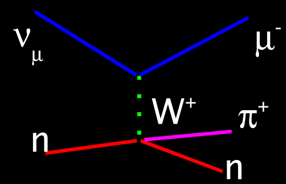
MiniBooNE Event Rate Predictions

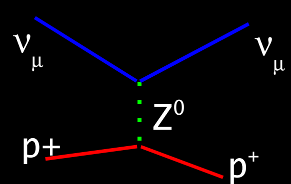
- >380,000 neutrino events. (>1 million expected)
  - 148k CCQE



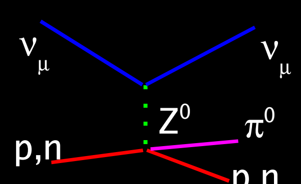
  - 94k CC $1\pi^\pm$



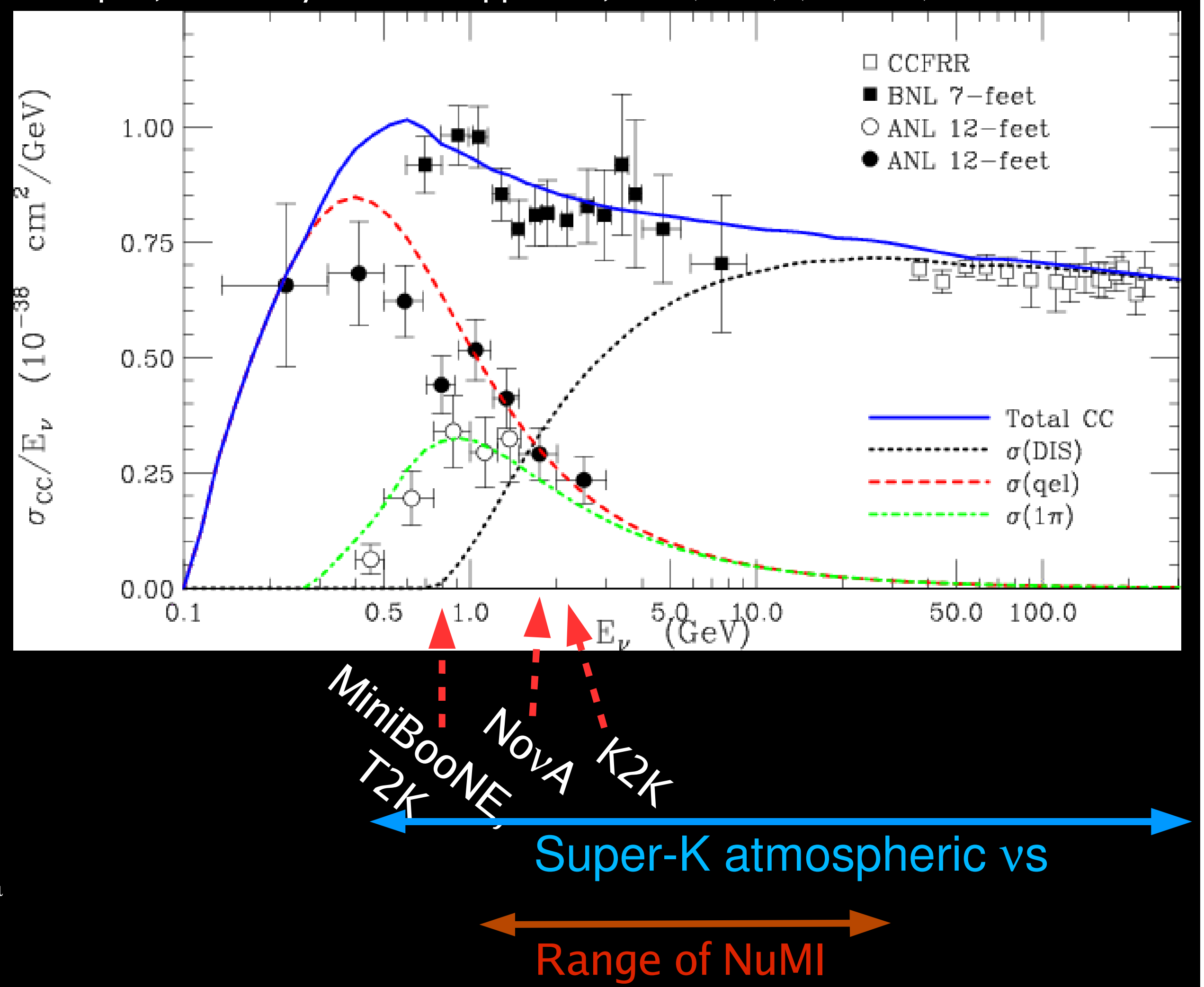
  - 60k NC E



  - 26k NC π^0



P. Lipari, Nucl. Phys. Proc. Suppl. 112, 274 (2002) (NuInt01)



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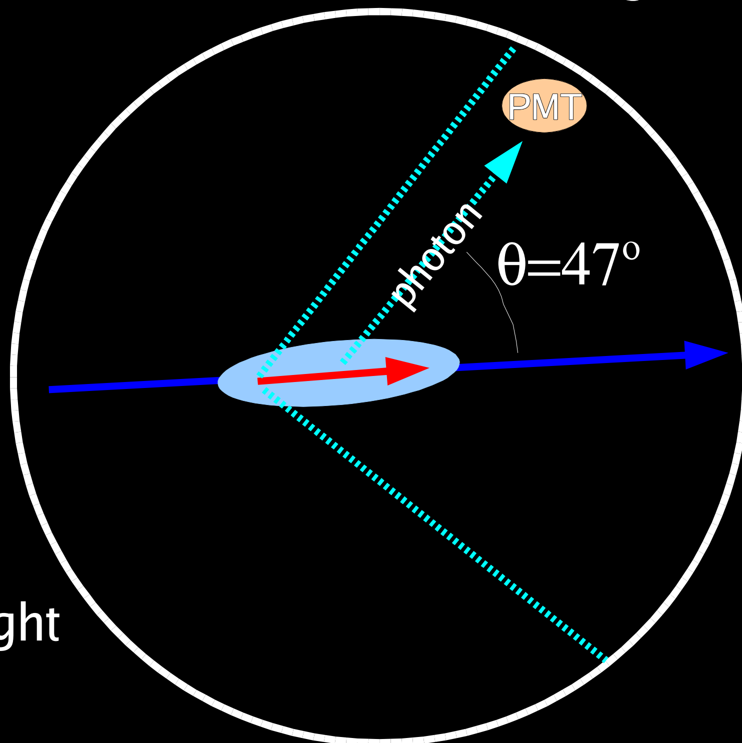
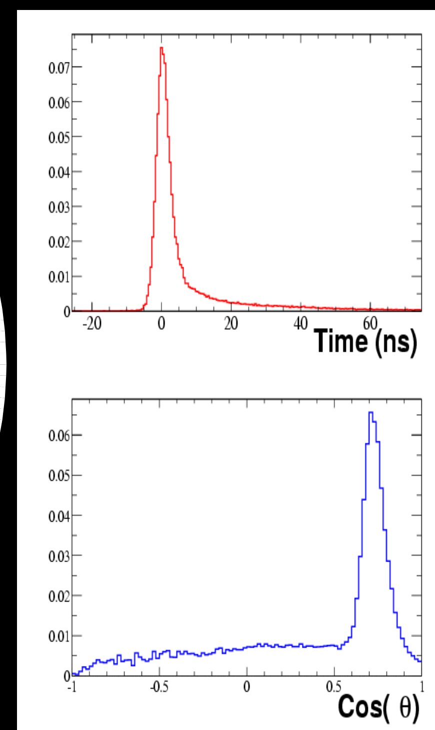
Muons in the MiniBooNE Detector

- 800 tons of pure mineral oil
- 12m diameter sphere
- 1520 8" PMTs
  - 1280 in main tank (sphere)
  - 240 in veto region (shell)





- Charged particles cause Cherenkov and scintillation light emission in oil
- PMTs collect photons, record t,Q

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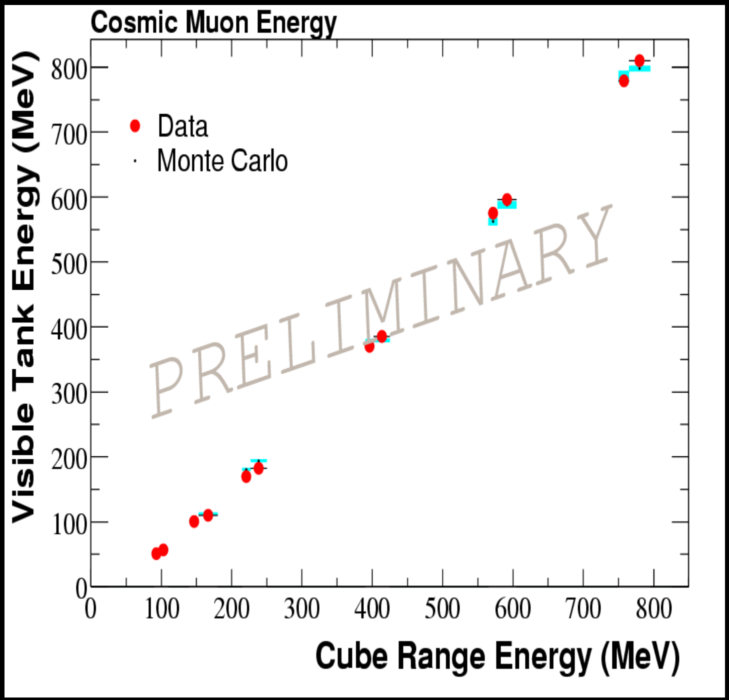
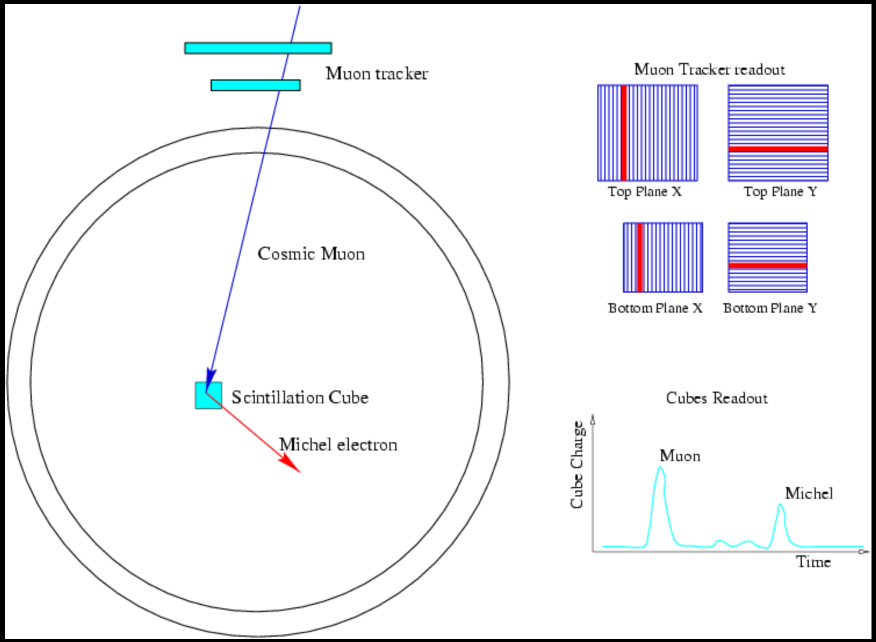
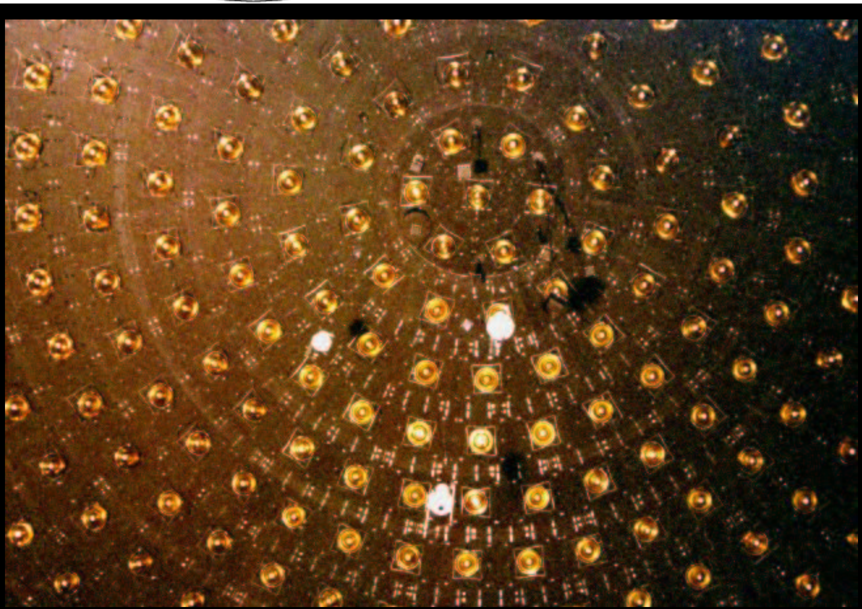
Detector Calibration: Muons

- Muon tracker hodoscope above tank
- Six scintillation cubes at different depths in the oil
- Tag entry, stopping point of muons
- Calibrate energy reconstruction from range in oil







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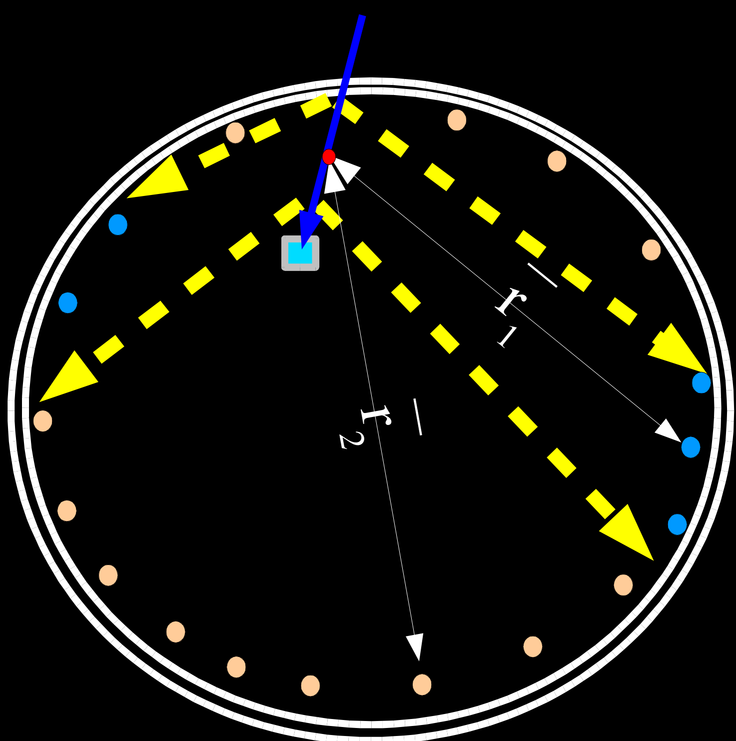
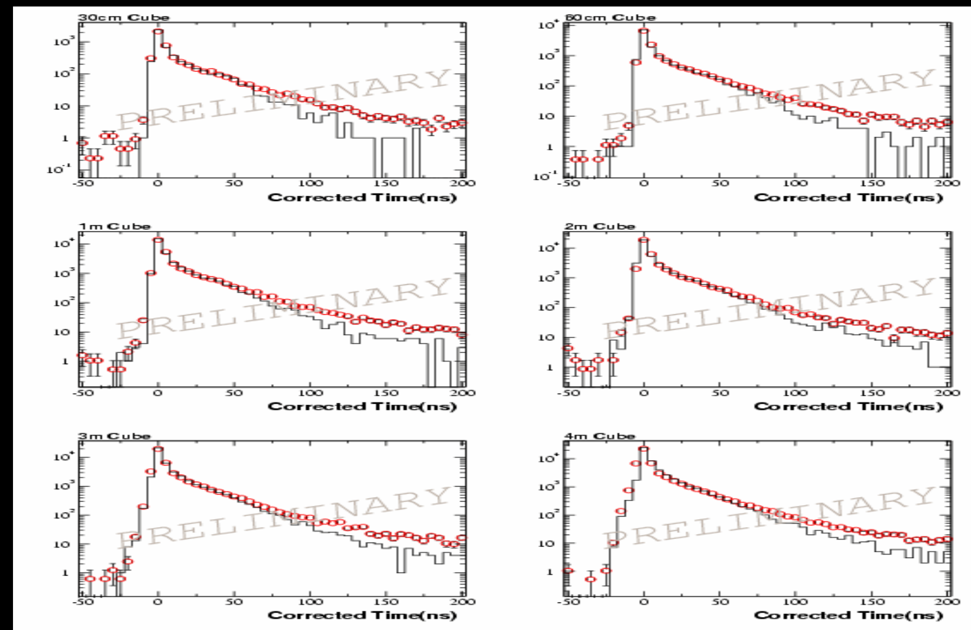
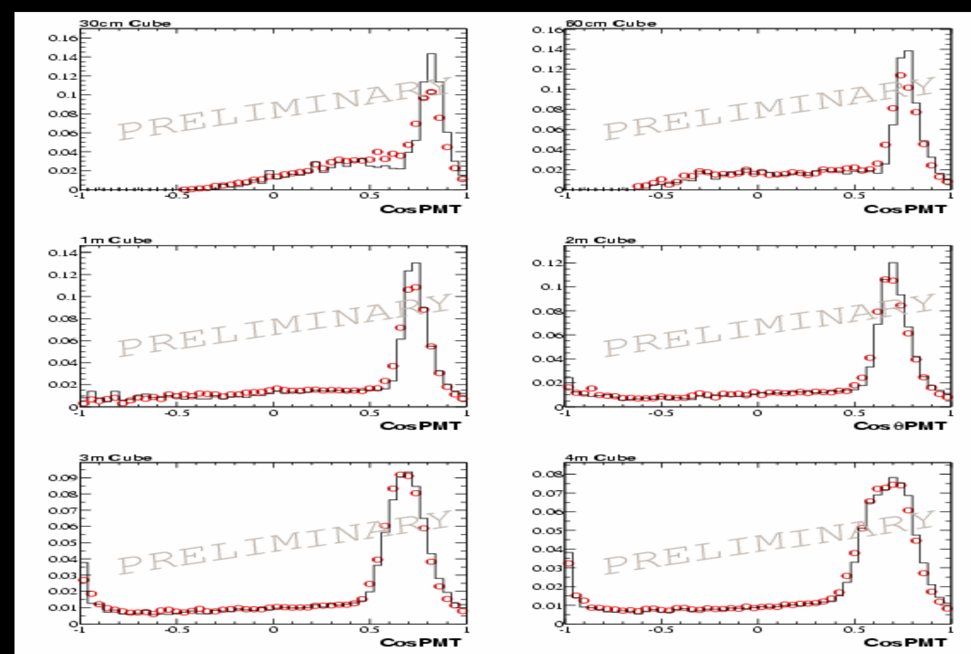
Detector Calibration: Muons

- Use calibration hardware to determine the event paramters (x, t, u)
- Assemble corrected times, angles using known track center
- Find Cherenkov rings and time peaks, isotropic and delayed emission







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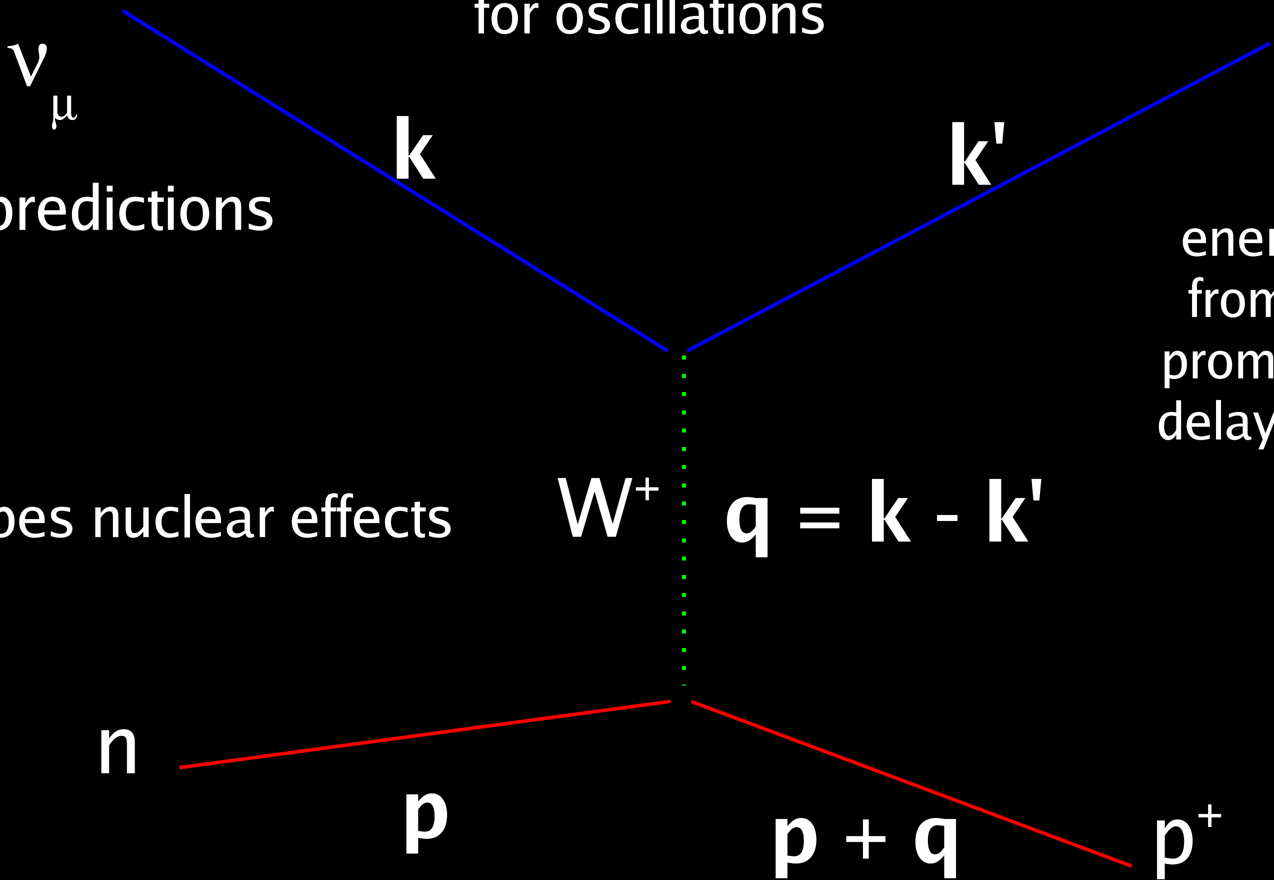
CCQE ν Events

Reconstruct E_ν to search for oscillations



Flux, σ predictions

Measure energy and angle from visible light: prompt Cherenkov, delayed scintillation

q^2 probes nuclear effects

Fermi motion of target nucleon, binding energy

isotropic scintillation light, nuclear interactions

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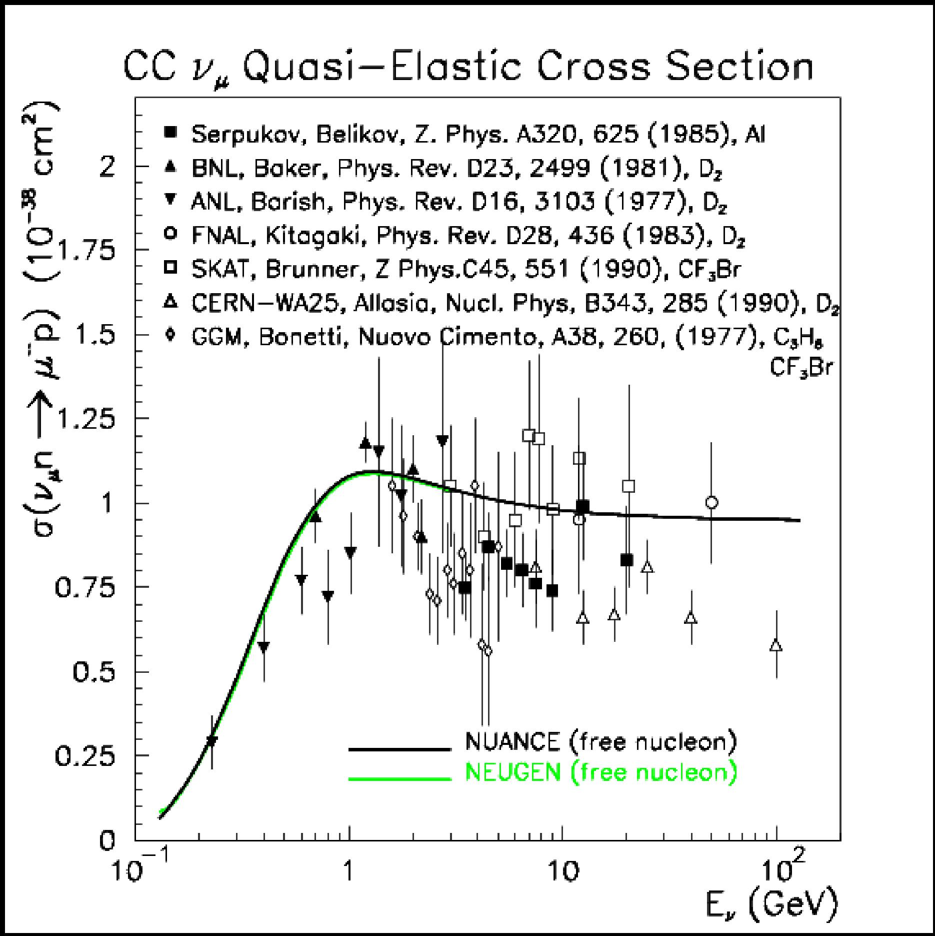
CCQE ν Events

- CCQE cross section measurements from past experiments
  - $E_\nu > 2$ GeV
  - mostly on light nuclear targets
- this data set is 1.6E20 POT
  - ~60,000 events after cuts
- MiniBooNE σ measurement valuable for oscillation experiments
  - Carbon target



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CCQE Event Selection

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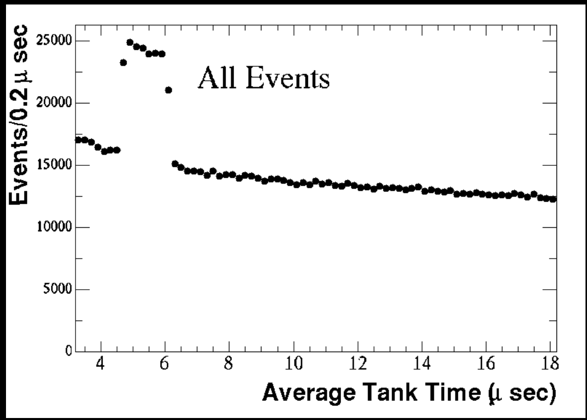
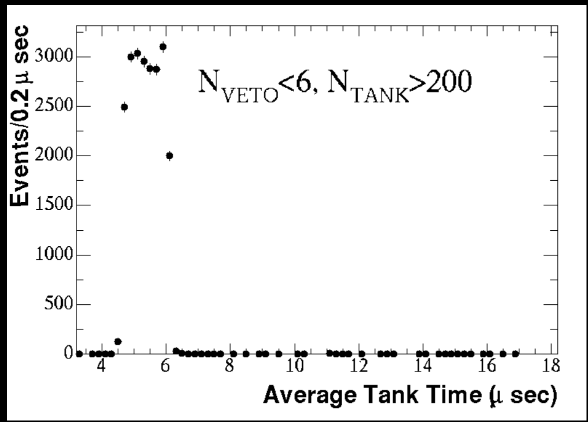
first: $\nu_\mu\, n \to \mu^- p$ ... time passes ... $\mu^- \to e^- \nu_\mu\, \nu_e$

- Simple cuts: eliminate cosmic rays, beam-induced background
  - Tank hits > 100
  - Veto hits < 6



- Intermediate cuts: ensure good energy reconstruction, select events with 1 μ decay
  - reconstructed R < 500 cm.
  - 0 < subevents < 3
    - subevent = cluster of hits in time



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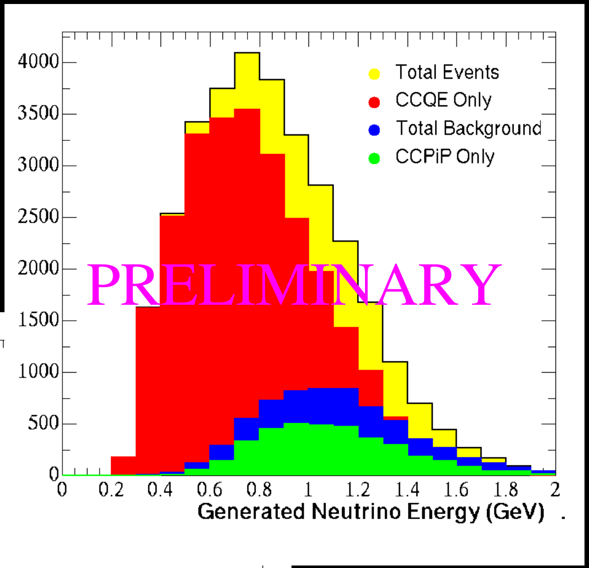
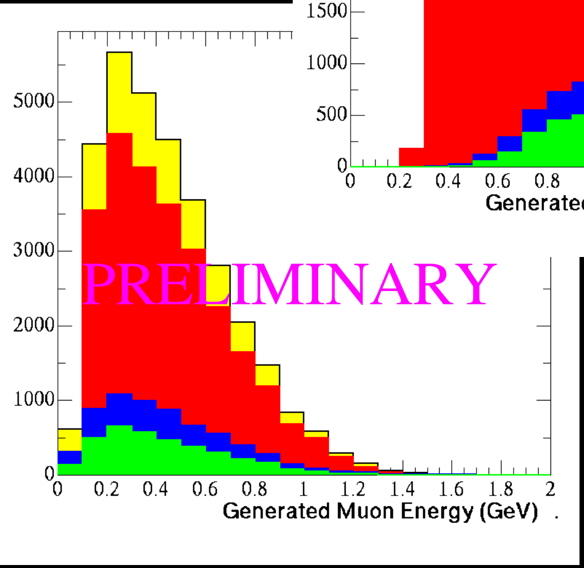
CCQE Event Selection

first: $\nu_\mu\, n \rightarrow \mu^- p$ .... time passes ...... $\mu^- \rightarrow e^- \nu_\mu \nu_e$

- CCQE PID cuts: Fisher discriminant
  - event topology
  - fraction of prompt (Cherenkov) vs. late (scintillation) light
  - fraction of "on-ring" charge
- Signal purity: 80%
- Signal-like purity: 88%
  - Signal-like = events with 1 lepton and 1 nucleon in final state, and no photons with E > 50 MeV (from MC).
- Dominant source of background from CCPiP where π+ produced below Cherenkov threshold





CCQE Observables

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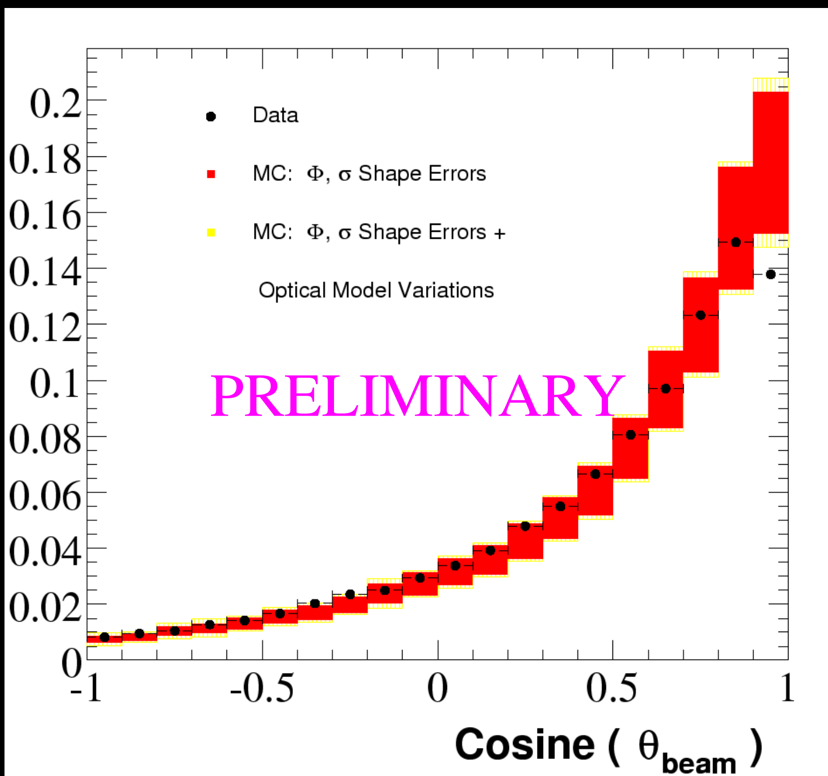
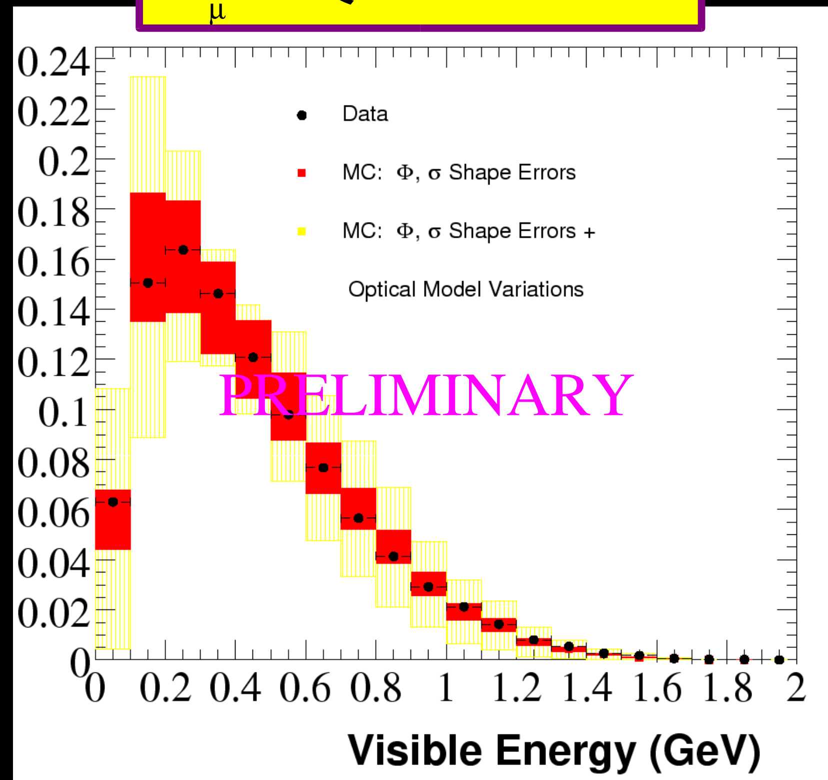
- Measure:
  - muon energy: ±5-7%
  - muon direction ±45mrad



ν_μ CCQE Candidates



- Uncertainties:
  - Red: flux & CCQE xsec in quad.
  - Yellow: flux & CCQE xsec & optical model variations in quad.

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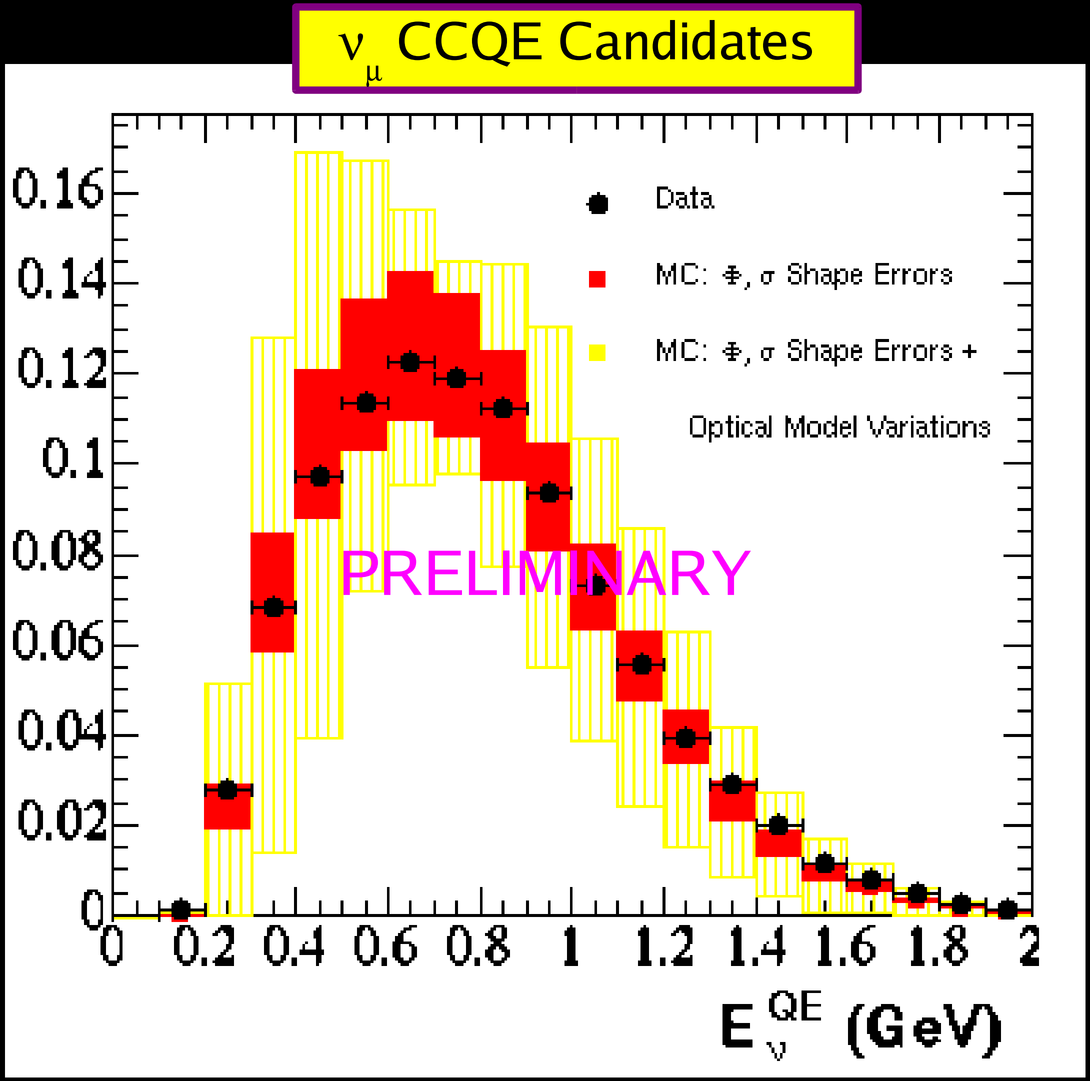
CCQE ν Energy Reconstruction

- Calculate ν Energy
  - Neutrino energy resolution: 15-20% with background ~10% with no background

$$E_\nu^{QE} = \frac{1}{2}\frac{2M_pE_\mu - m_\mu^2}{M_pE_\mu + \sqrt{(E_\mu^2 - m_\mu^2)}\cos\theta_\mu}$$

  - empirically correct for target nucleon Fermi motion
  - analytically correct for nucleon binding energy



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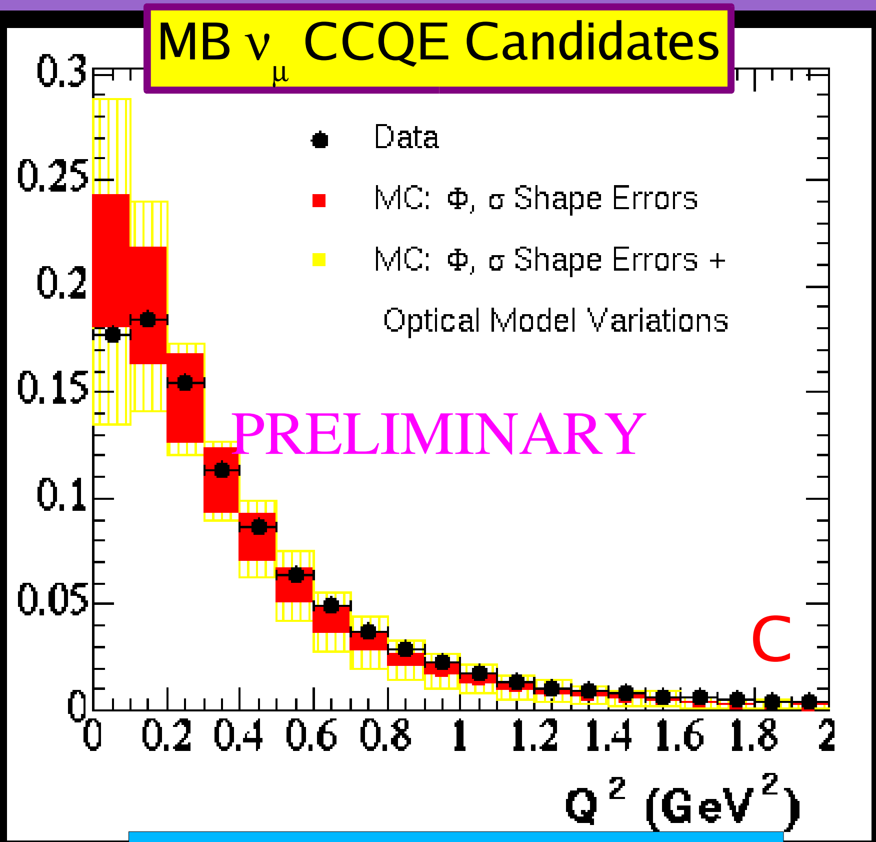
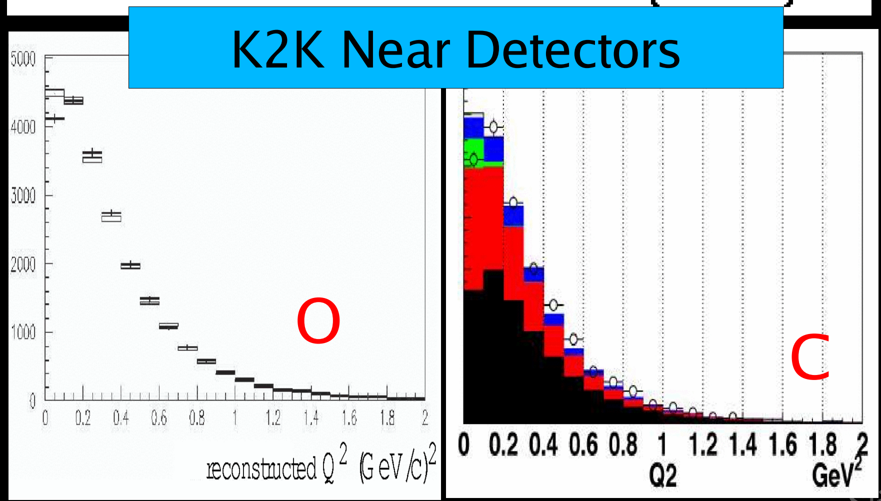
Neutrino Kinematics

- Nuclear effects important at MiniBooNE neutrino energies
  - Pauli blocking and simple nuclear effects included in NUANCE MC - neutrino simulation used by MiniBooNE
- Observed reduction exceeds Pauli blocking prediction
  - Model deficiency?
    - interesting physics?
  - Also observed by K2K near detectors
  - Larger non-CCQE background than MiniBooNE





Rik Gran, NuInt04

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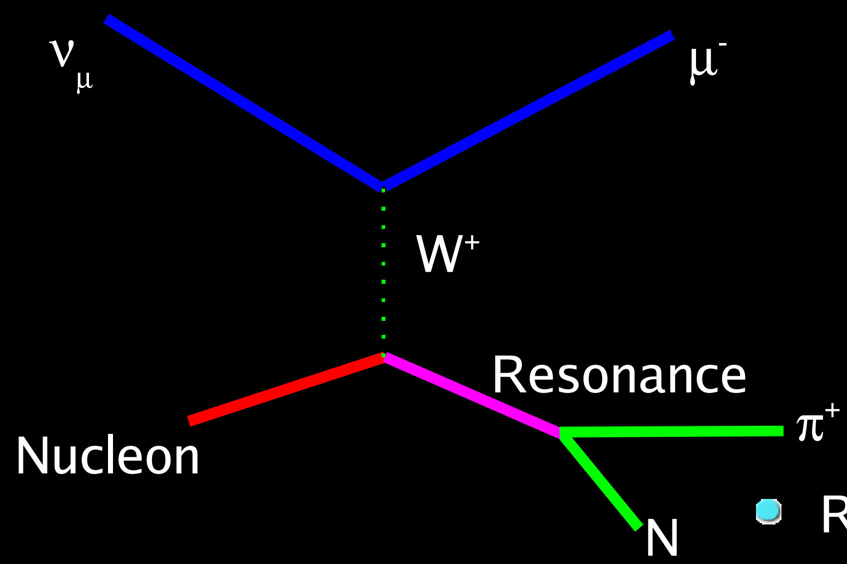
CCPiP Events

- ν_μ:
  - Goal: reconstruct ν parameters



- Target Nucleon:
  - proton
    - free or bound
  - neutron
    - bound only

- μ^-:
  - Tag with decay electron
  - Reconstruct Cherenkov ring to get energy, momentum vector

- Resonance:
  - Decays promptly
    - Pion
      - Cherenkov ring
      - Michel electron
    - Nucleon
      - Scint. only

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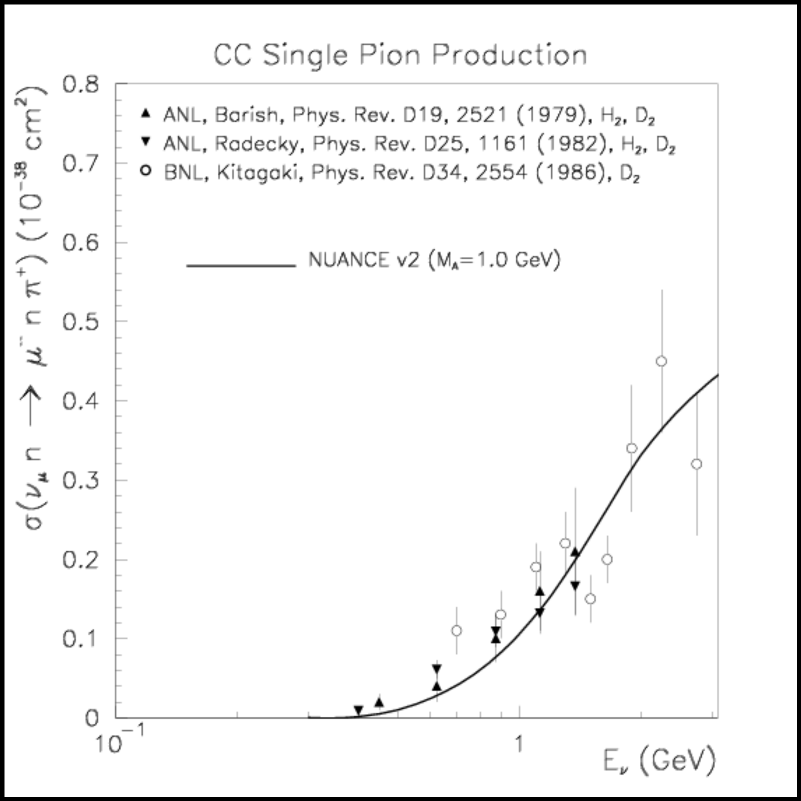
CCPiP History

- CC π^+: measurements at bubble chambers
  - $\nu_\mu n \rightarrow \mu^- \pi^+ n$, and $\nu_\mu p \rightarrow \mu^- \pi^+ p$



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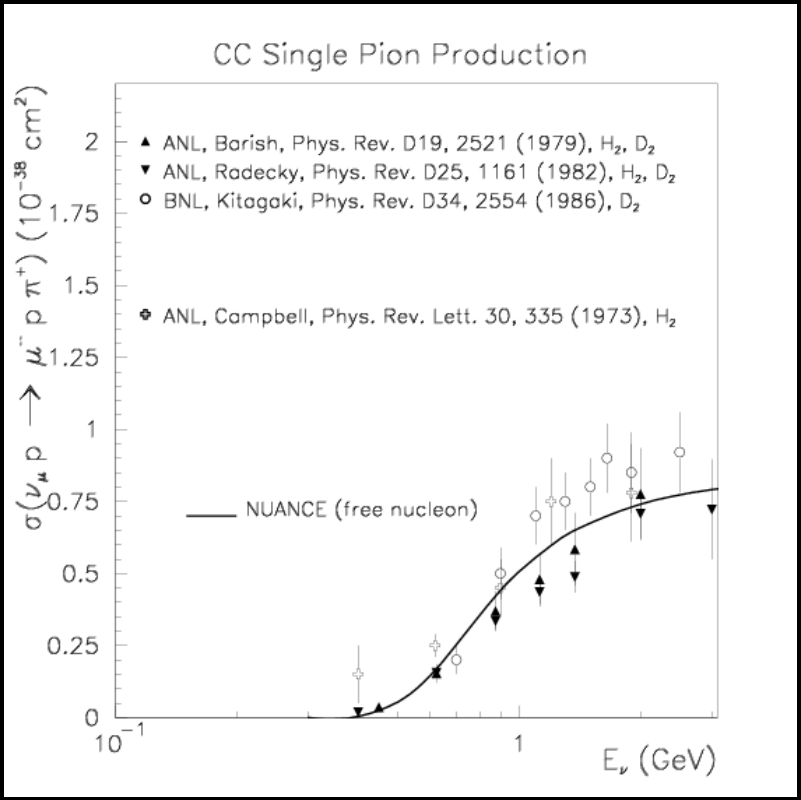

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- Total bubble chamber data sets: ~7000 events
- Few at low energy
  - All low E on light nuclear targets

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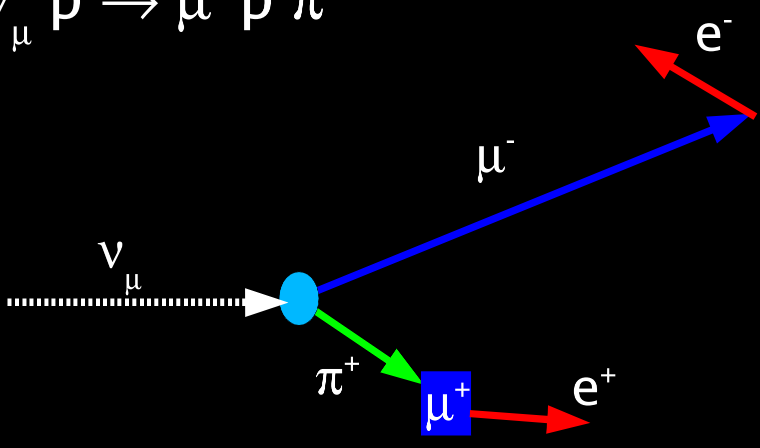
CCPiP Event Selection

- Neutrino events with 2 Michels: e.g. $\nu_\mu\ p \rightarrow \mu^-\ p\ \pi^+$
  - First (Neutrino) subevent
    - must be in beam spill
    - Tank Hits>175, Veto Hits<6
  - Need at least 2 Michels:
    - 20<Tank Hits<200, Veto hits<6



- Monte Carlo Event breakdown:
    - 78% Resonant single pion - all resonant channels
    - 9% Coherent pion production
    - 13% BG (Multi pion 7%, QE 4%, DIS 2%)
- this data set is 2.62E20 POT
- 36028 events
  - 4-5 times more than bubble chamber data sets combined!

Vetting the Data Sample

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- Energy distribution fits Michel spectrum
- Separate Michels into "Close" and "Far" samples
  - distance to muon track
  - Close: μ^-, Far μ^+

- μ^- capture on C (8%)
  - τ=2026±1.5 ns
  - Close Michels τ=2057±14ns
- μ^+ do not capture
  - τ=2197.03±0.04 ns
  - Far Michels τ=2215±15 ns

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Reconstructing the muon track

- Results of single ring fitter run on data and Monte Carlo events
  - Energy in Cherenkov ring only
  - Not total charge

- statistical errors only on data and MC!
- Reasonable agreement in muon energy
- Difference in muon direction may be more significant - physics implications?

CCPiP E_ν Reconstruction

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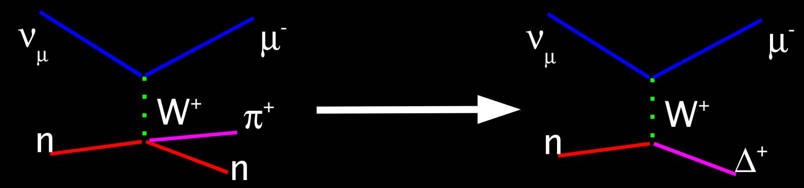

- Starting out with simplest possible assumptions
- Reconstruct CCPiP interaction as quasi-elastic, with a resonant state instead of a recoil nucleon
  - Assume target nucleon is at rest
  - Assume the resonance is a Δ(1232)
  - Assume the single ring fitter picks out the muon
    - MC: this is true ~75%

$$E_\nu^{QE} = \frac{1}{2}\,\frac{2M_pE_\mu + m_\Delta^2 - m_p^2 - m_\mu^2}{M_p - E_\mu + p_\mu\cos\theta_\mu}$$

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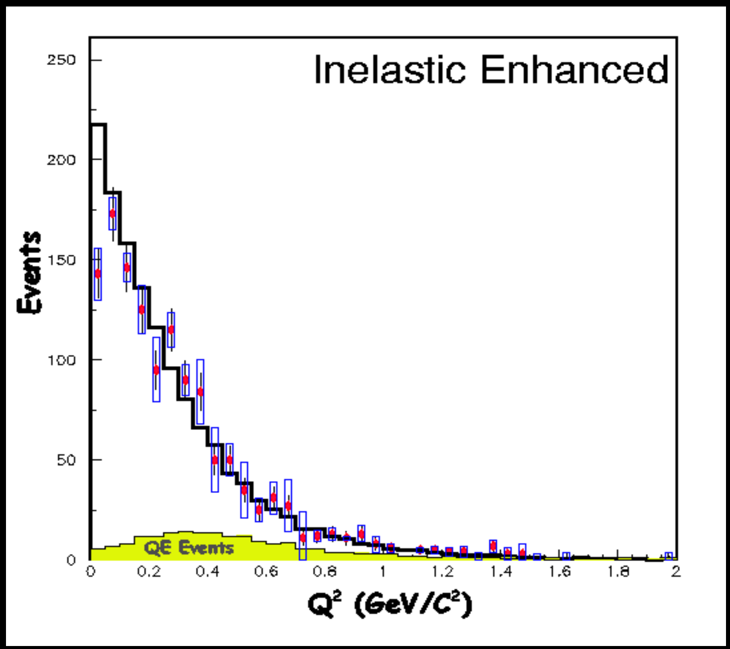
CCPiP Q^2 Distribution

$$Q^2 = 2E_\nu\left(E_\mu - p_\mu \cos\theta_\mu\right)$$

- Low Q^2 suppression
  - larger than in CCQE sample
  - CCQE/CCPiP comparisons may help disentangle nuclear model
- K2K sees it too!

Rik Gran, NuInt04



Conclusions

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- MiniBooNE data set is already the largest ever at these energies
- All CC measurements depend on muon reconstruction
  - Muon calibration system works well
  - provides valuable input for reconstruction of ν data
- CCQE data analysis is well underway
  - cross section, ν_μ disappearance results coming soon
  - interesting hint/model deficiency at low Q^2
- Beginning CCPiP data analysis
  - will help disentangle nuclear interaction model
  - ν energy reconstruction looks promising
  - high statistics CCPiP oscillation search?

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Optics of Mineral Oil

Creation

- Čerenkov light
  - proportional to β
- Scintillation
  - dE/dx
  - time delay

Propagation

- Scattering (Rayleigh)
  - prompt
  - $1+\cos^2\theta$
  - λ^4
- Fluorescence
  - isotropic
  - time delay
  - spectrum
- Absorption

In Situ

- Michel electrons
- Cosmic muons
- Laser: diffuse light
- Laser: pencil beam

Ex Situ

- Scintillation (IUCF) w/p^+
- Scintillation (FNAL) w/μ
  - repeated w/p^+ (IUCF)
- Goniometry (Princeton)
- Fluorescence spectroscopy (FNAL)
- Time resolved spectroscopy (JHU)
- Attenuation (FNAL)
  - multiple devices

Work in progress...

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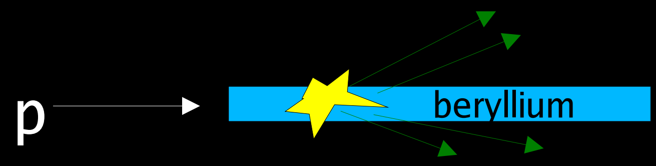
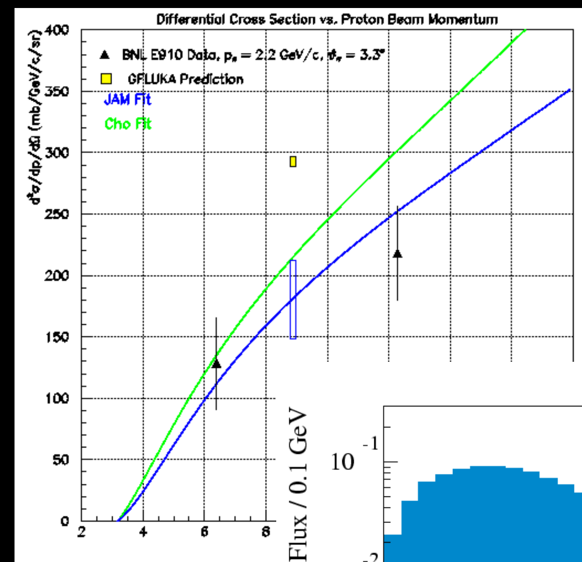
External Flux Prediction

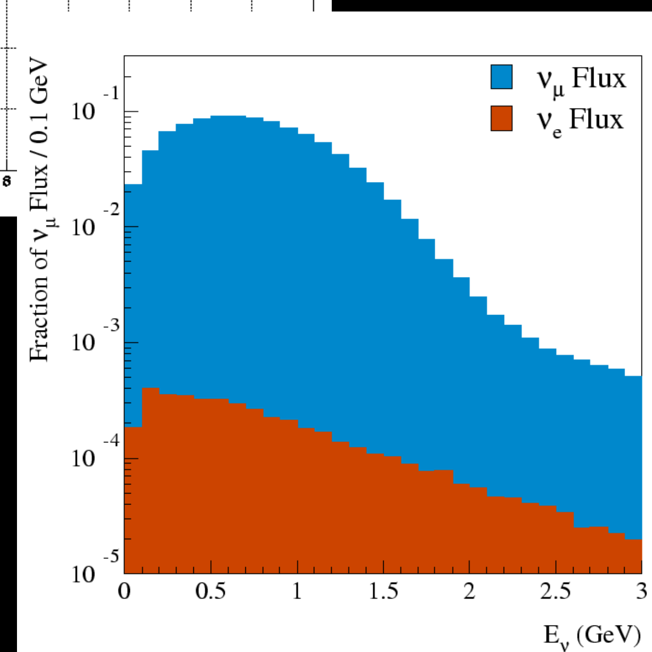


$\pi^+/K^+ \rightarrow \mu^+\nu_\mu$
$\hookrightarrow e^+\ \bar{\nu}_\mu \nu_e$

$K^+/K^0_L \rightarrow \pi e \nu_e$

- Meson production σ modelled as a function of p_p, p_π,
- Predictions based on π data:
  - **E910(BNL):** recent p data on Be target
    - 6.3, 12.4, 17.5 GeV/c beam momenta
  - **Near future:**
    - HARP (CERN): measure σ at 8.9 GeV/c
    - high statistics, MiniBooNE replica target
- Pion,kaon fluxes put into GEANT4 Monte Carlo
  - effects of horn
  - decay pipe
  - calculate ν flux at detector





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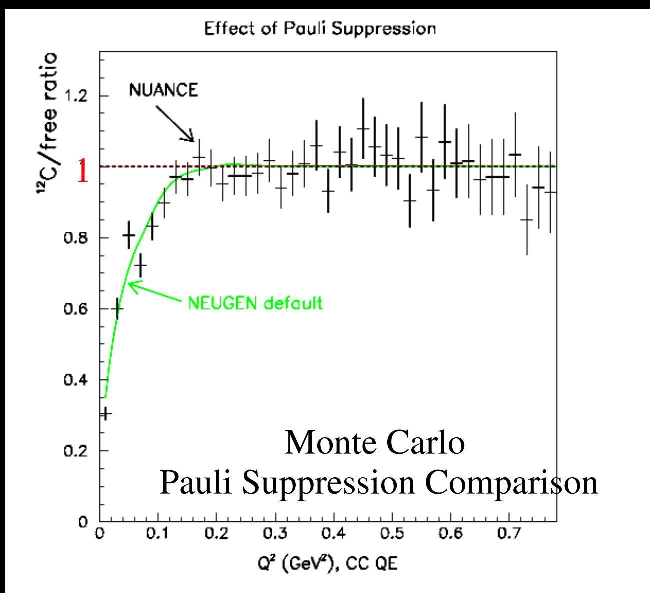
Nuclear Effects

- Pauli Blocking
  - to get out of the nucleus, final state lepton must have $p > p_F$

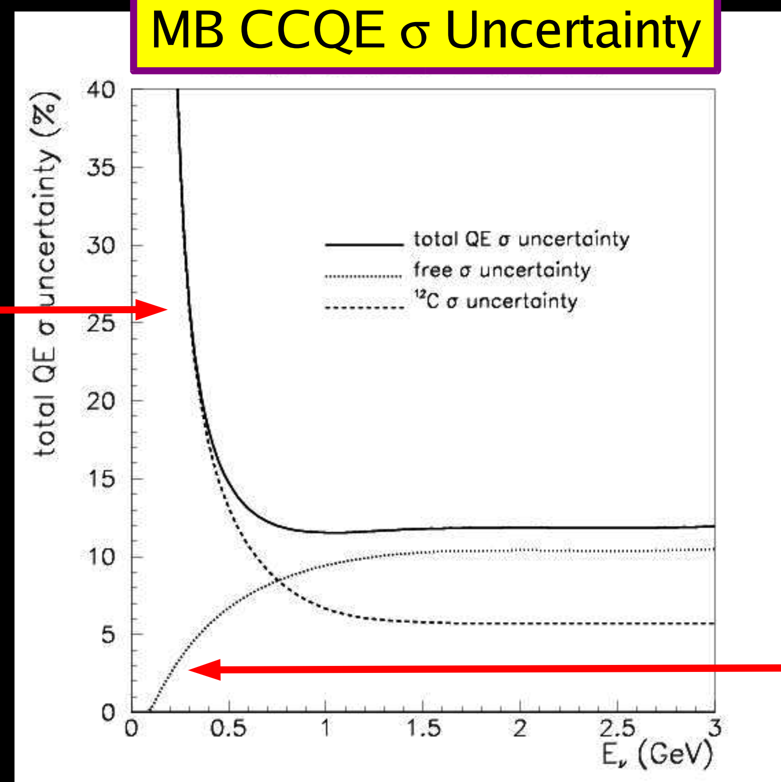


  - dominant low Q^2 effect
  - has large effect on cross section uncertainty at low energy!

60% uncertainty in Pauli suppression to cover LSND σ_{QE} at low energy

10% uncertainty in m_A to cover range in m_A from light vs. heavy target ν data fits

MB CCQE σ Uncertainty



Nuclear Effects

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- Nuclear Shadowing
  - first suggested by Bell that ν interactions at low Q^2 should be less probable than expected from nucleon counting

J. S. Bell, PRL 13, 57 (1964)

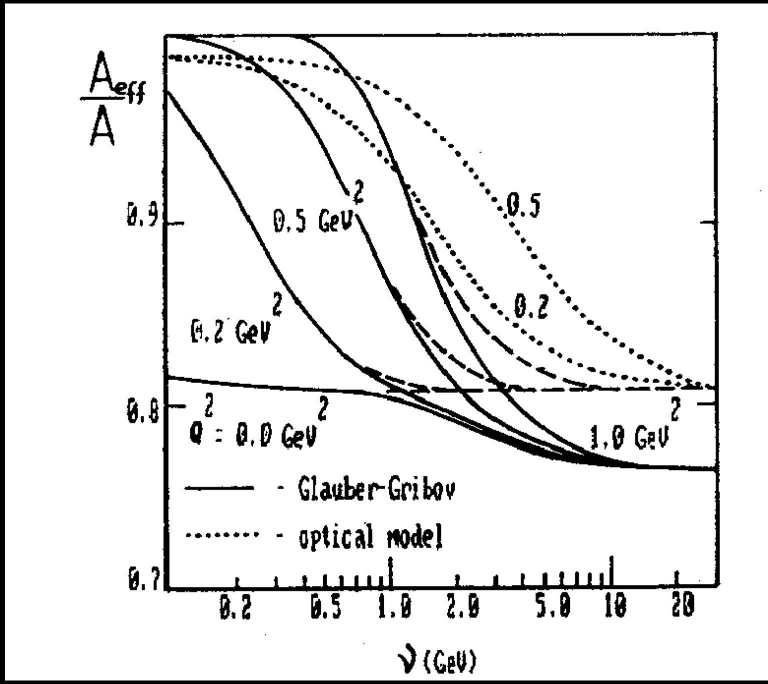

Figure from B. Kopeliuvich, Phys. Lett. B227, 461 (1989)

- Can have large effect at low ν (energy transfer to hadronic system) and low Q^2
  - CCQE and CCPiP probe different regions in Q^2 vs. ν