MiniBooNE
ν_μ Charged Current Analysis Progress

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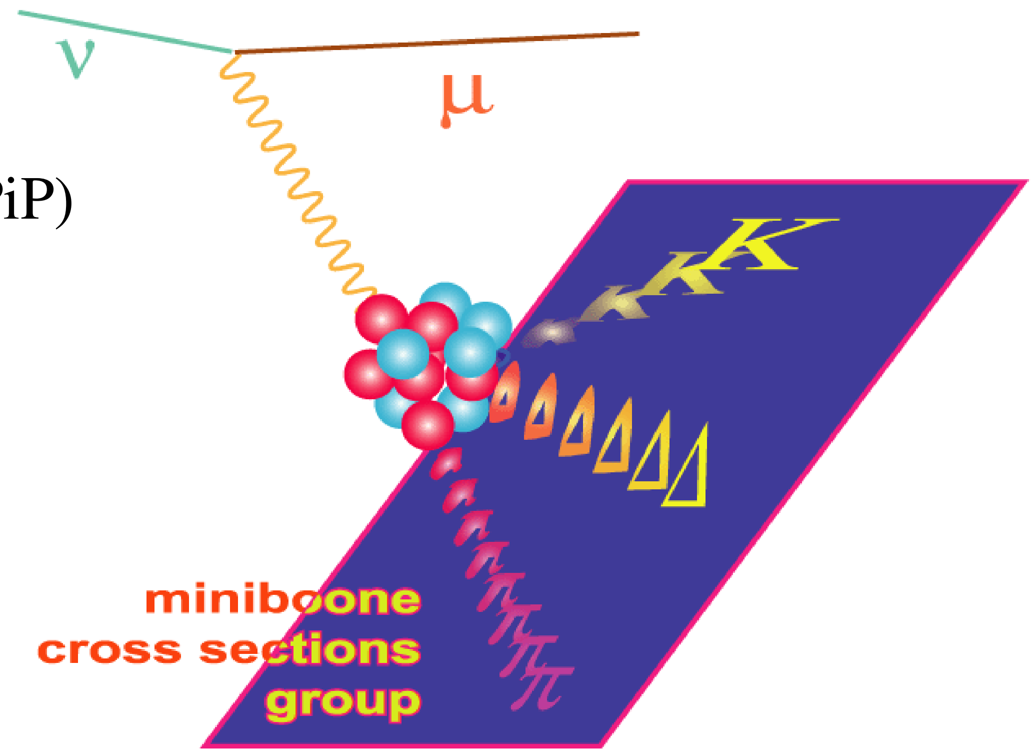
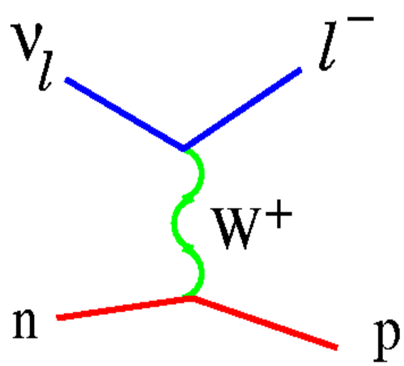
- CC interactions
  - Quasi-Elastic (CCQE)
  - Single Pion Production (CCPiP)
- Measuring CC Interactions
- Modelling CC Interactions
- CCPiP/CCQE Cross Section

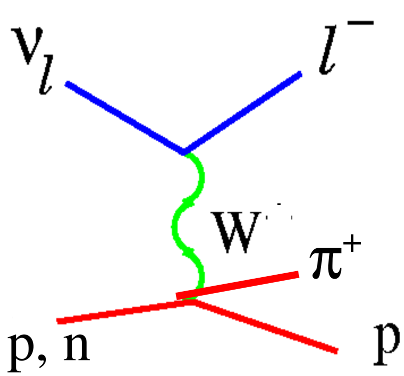


Charged Current Interactions

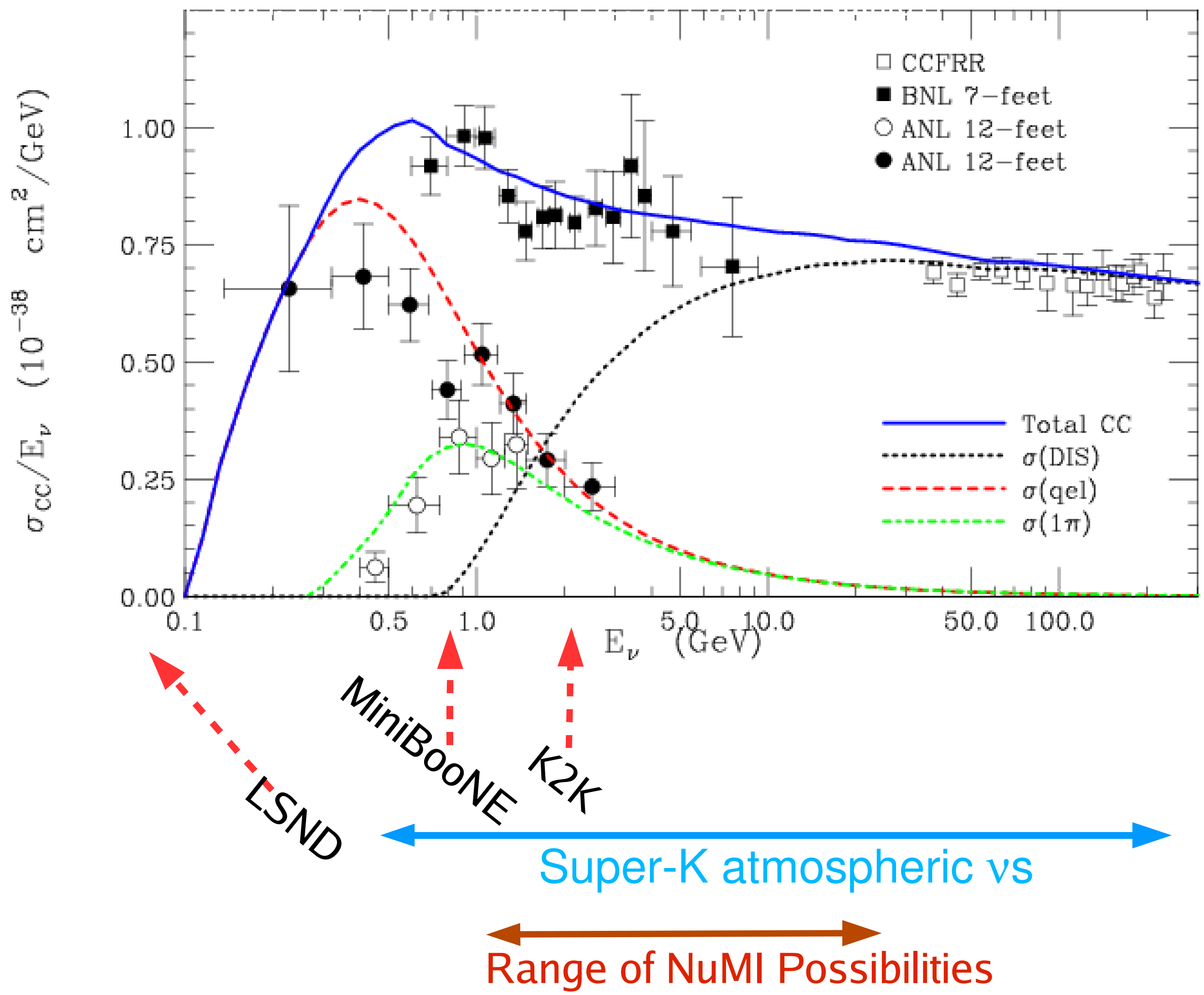
- Quasi-Elastic (CCQE)



- Single π^+ (CCPiP)

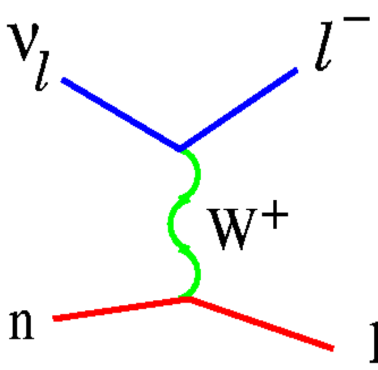


P. Lipari, Nucl. Phys. Proc. Suppl. 112, 274 (2002) (NuInt01)



Charged Current Quasi-Elastic Interactions

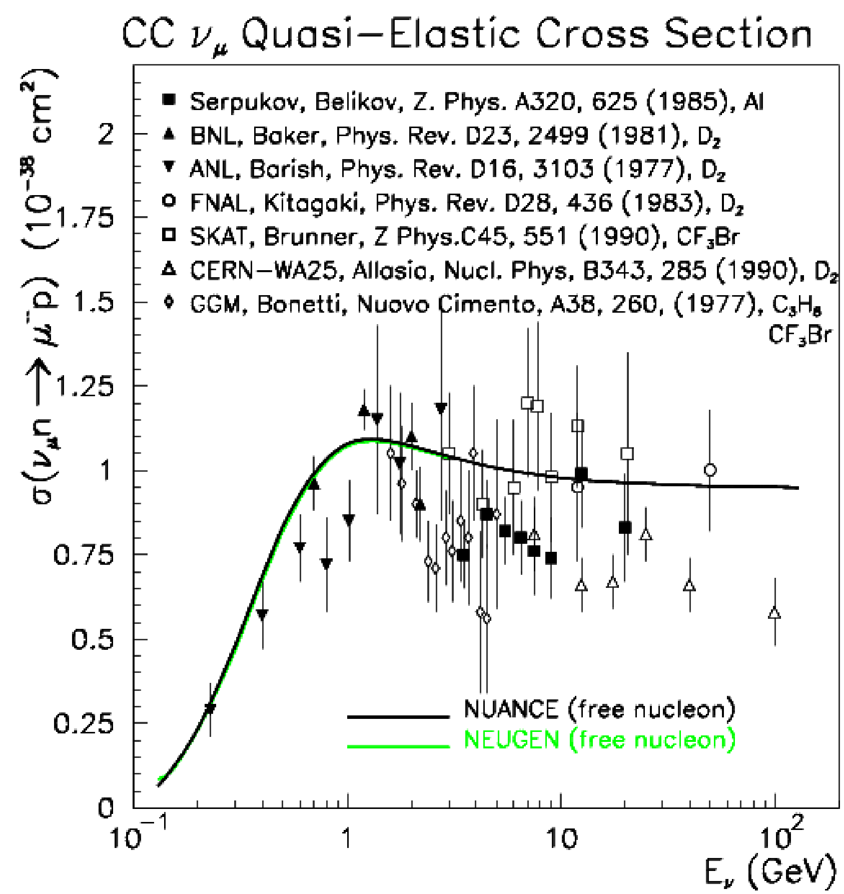
- Simple kinematics:
  - measure lepton energy, angle
  - then calculate ν energy



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

- Fairly well known σ at low ν energy
  - important error contribution to oscillation searches

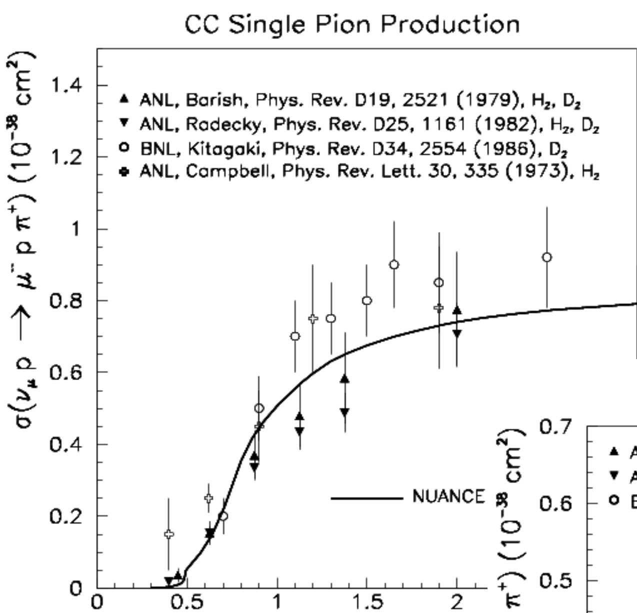
- Past data:
  - not much below ~few GeV
  - only light targets

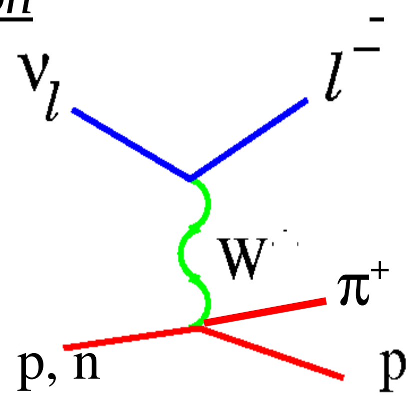


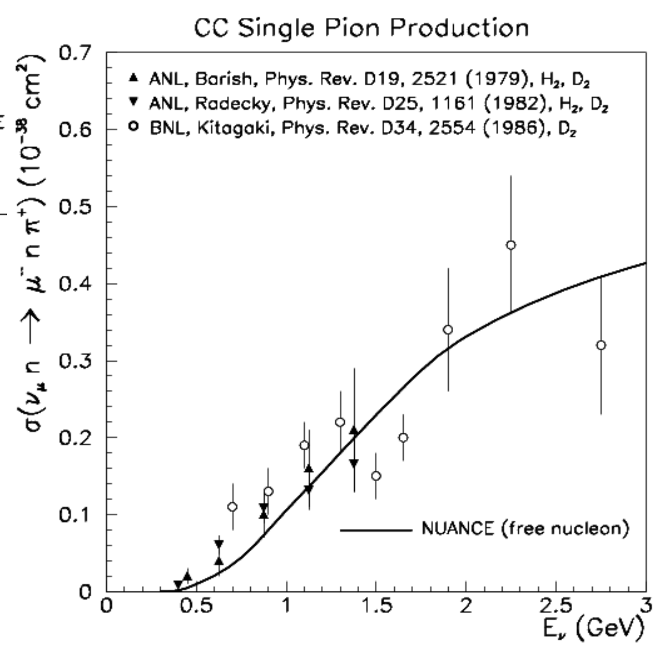
Charged Current Single π^+ Interactions

- More complex kinematics due to π^+ and μ in final state

Resonant Production

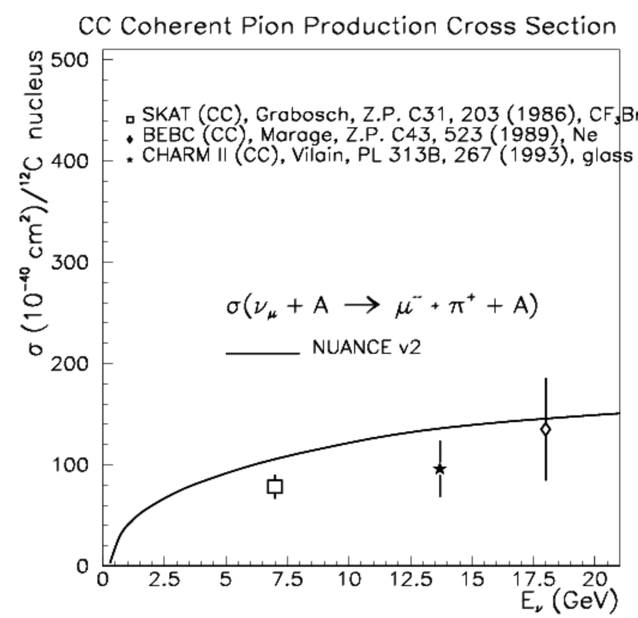


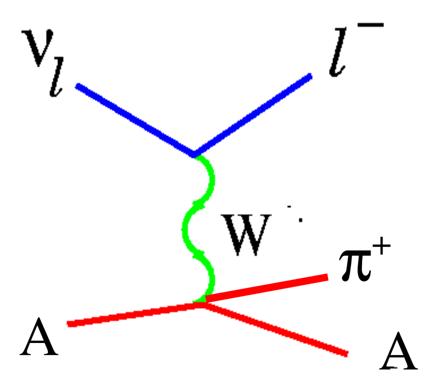




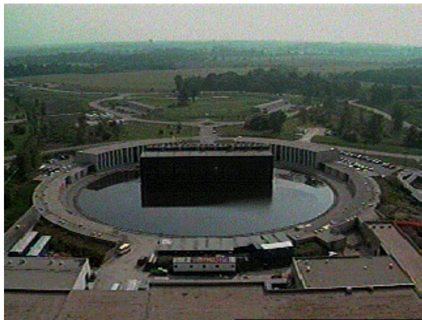
- no heavy target data below 3 GeV

Coherent Production

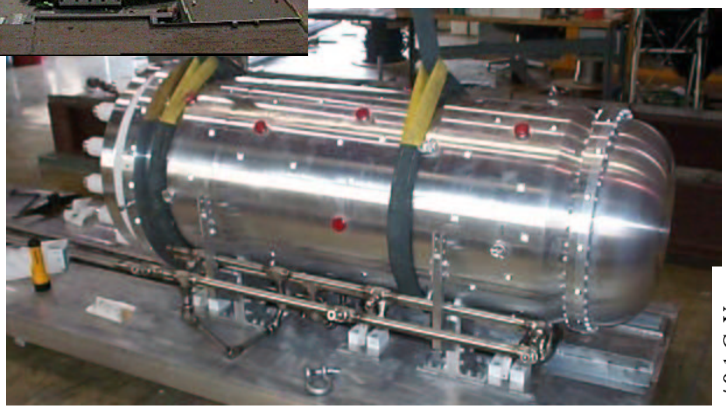




MiniBooNE Overview

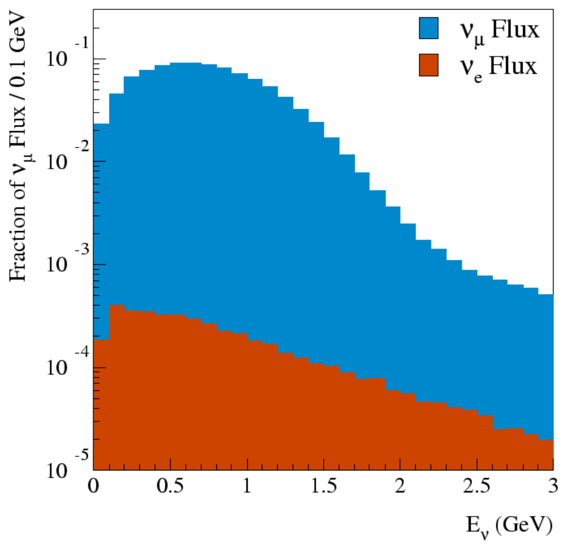


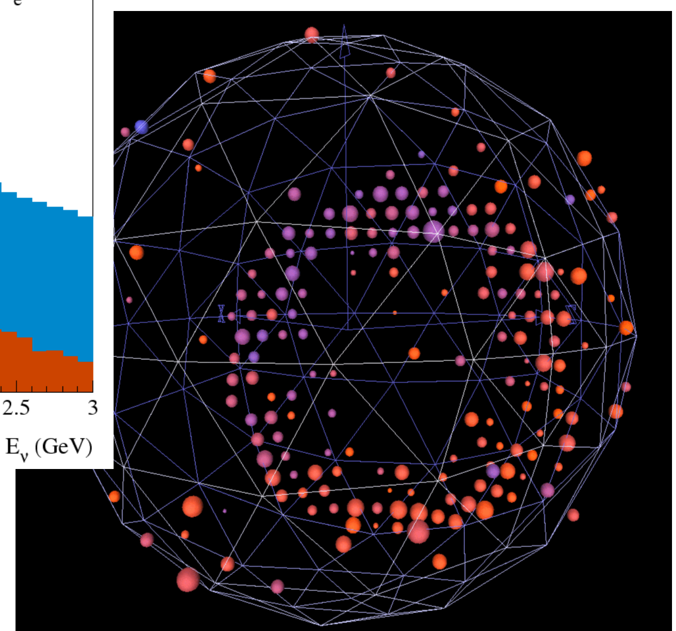
- 8 GeV KE protons from Fermilab Booster Accelerator
- 1.7 λ Beryllium target (HARP results coming soon!)



- horn focusses + sign mesons
- π and K
- Can reverse polarity (anti-ν beam)

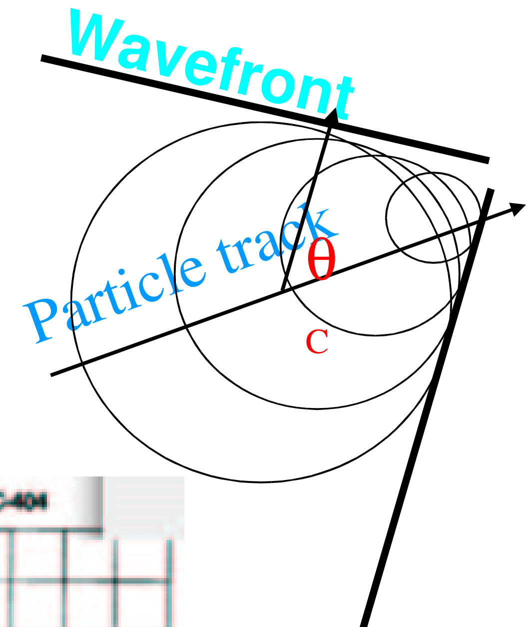
- 50 m decay region
- >99% pure ν_μ flavor beam
- 540 m dirt berm
- 800 ton CH_2 detector
- 1520 PMTs
  - 1280 + 240 in veto





Measuring CC Interactions at MiniBooNE

- We measure visible light produced by charged final state particles in mineral oil

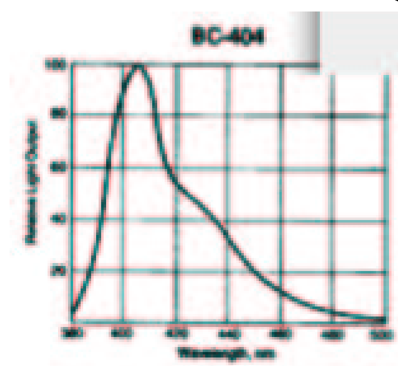


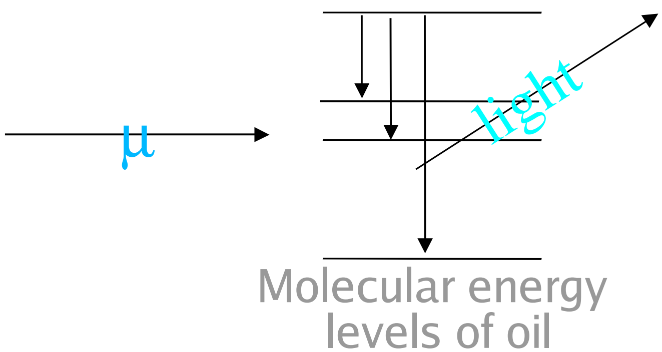
<u>Cherenkov radiation</u>

  - Light emitted by oil if particle v > c / n
  - forward and prompt in time

<u>Scintillation</u>

  - Excited/ionized molecules emit light when electrons drop to lower E levels
  - isotropic and late in time





- … **after** the γ s travel to edge of detector
  - Absorption
  - Scattering (Rayleigh)
  - Flourescence

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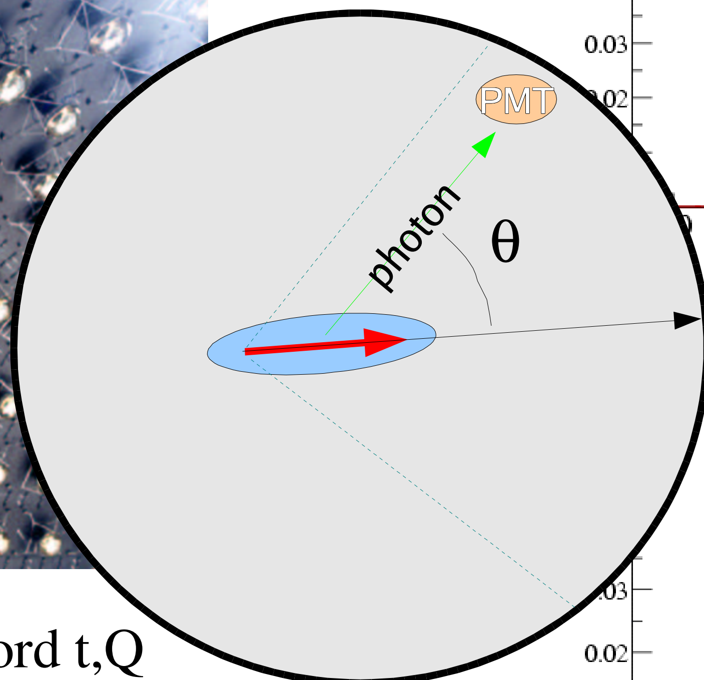
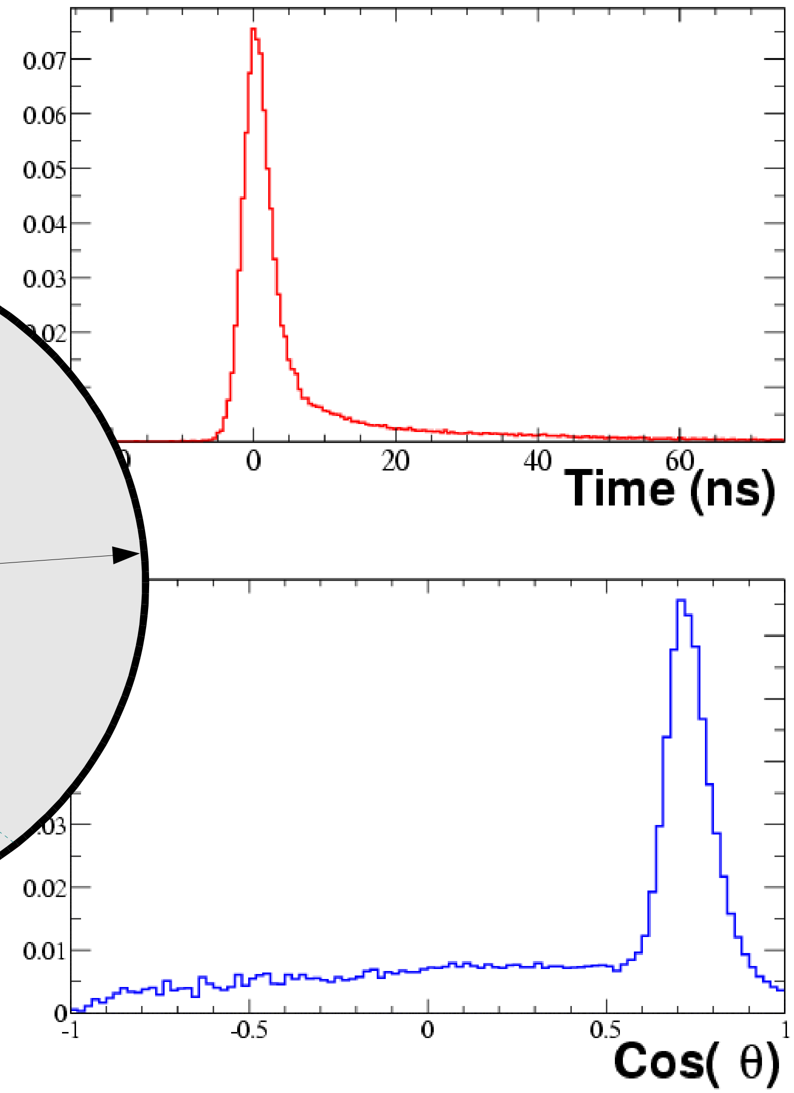
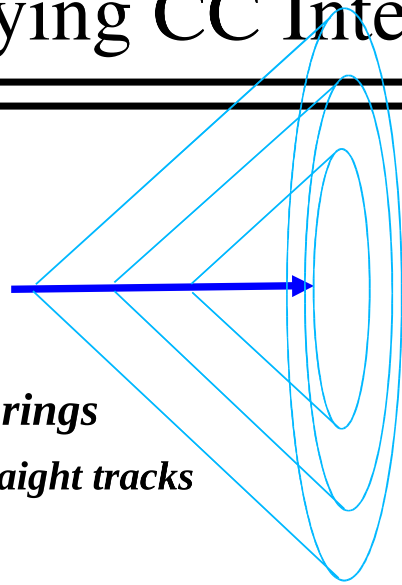
Reconstructing CC Interactions at MiniBooNE



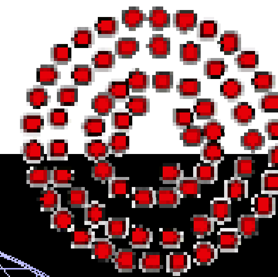


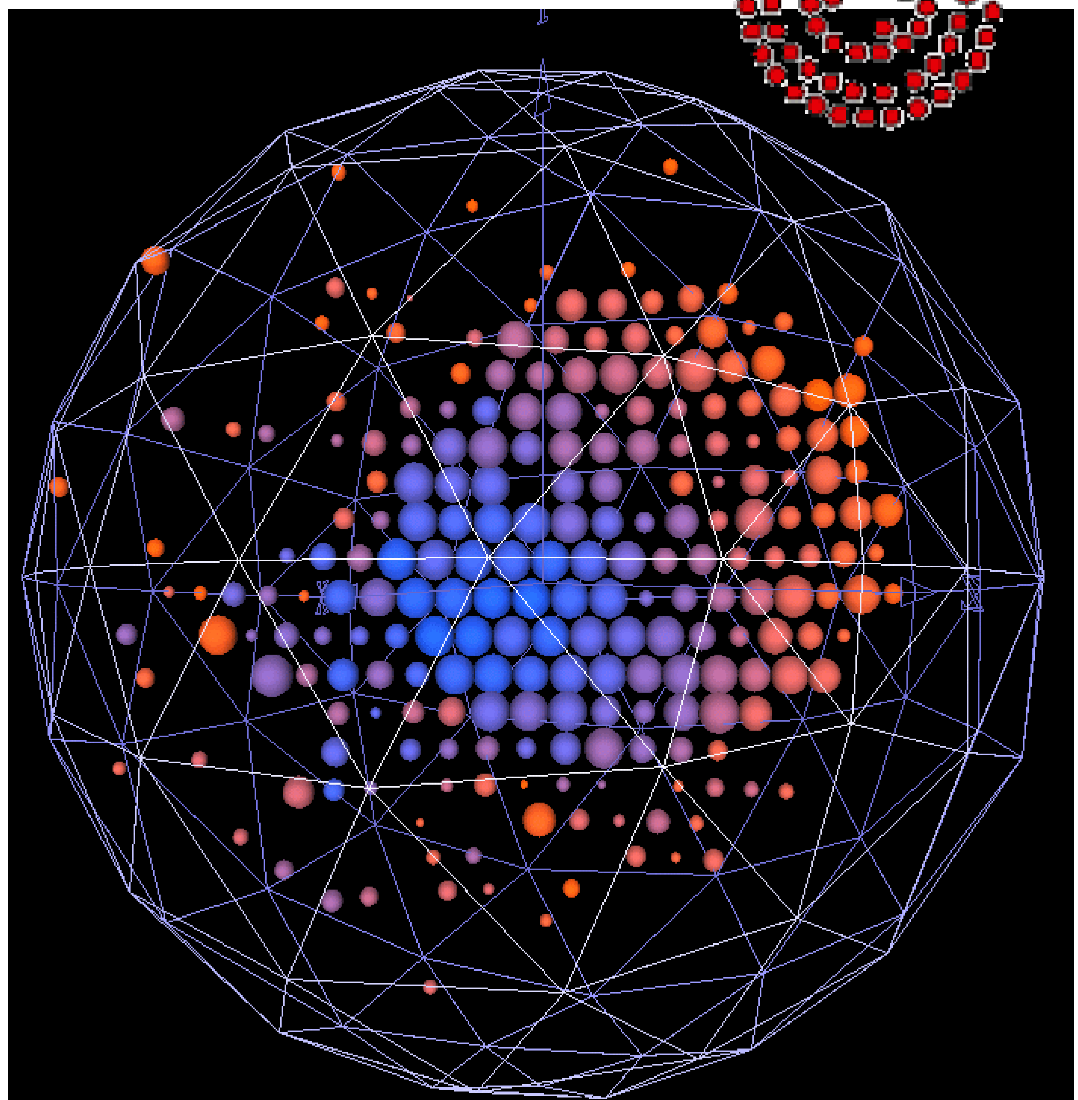
- PMTs collect γ s, record t,Q
- Reconstruct tracks by fitting time and angular distributions

Identifying CC Interactions at MiniBooNE



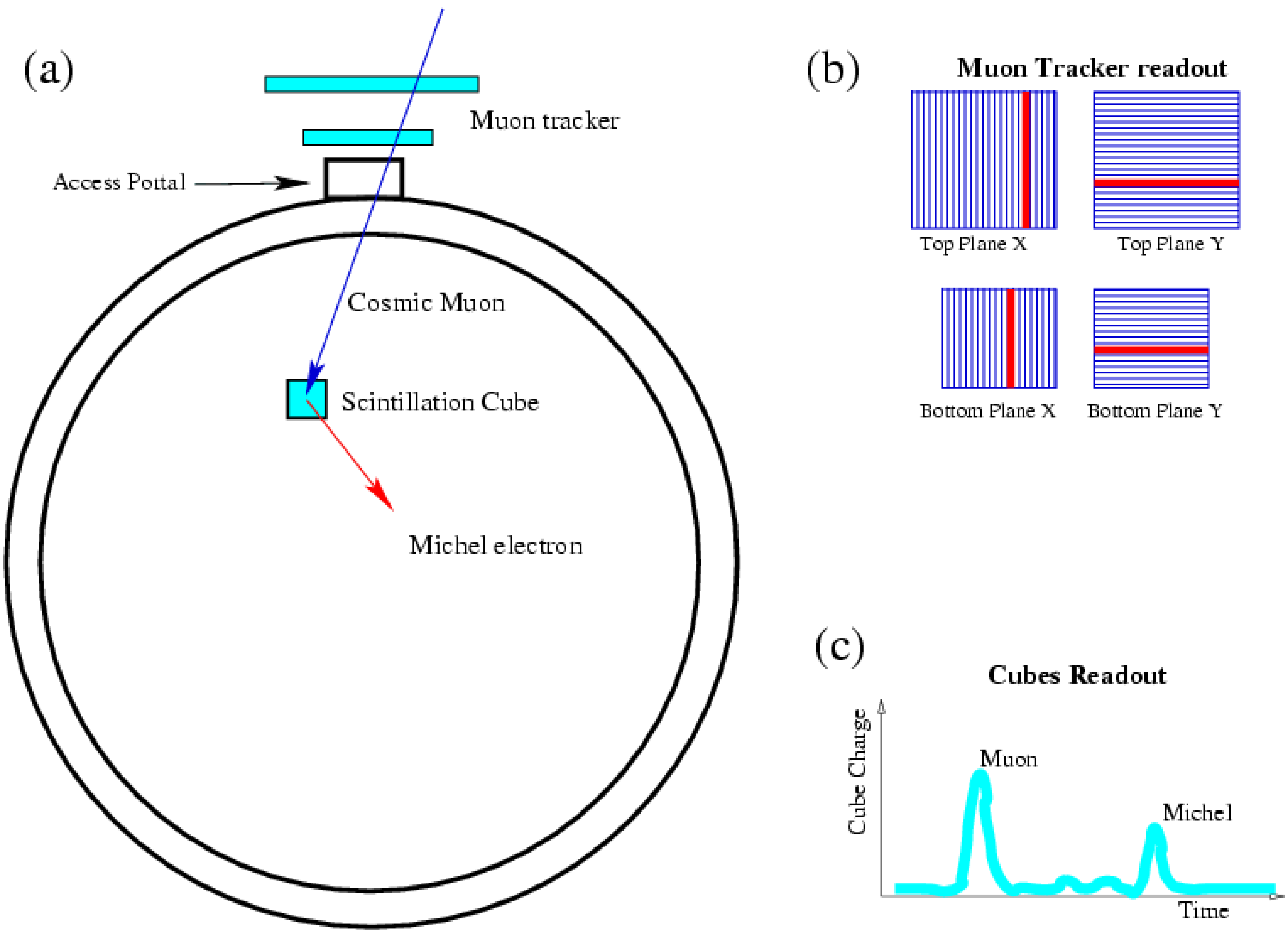
- ***Muons***
  - ***Sharp, clear rings***
    - ***Long, straight tracks***
- Electrons
  - Scattered rings
    - Multiple scattering
    - Radiative processes
- Neutral Pions
  - Double rings
    - Decays to two photons
    - Photons pair produce





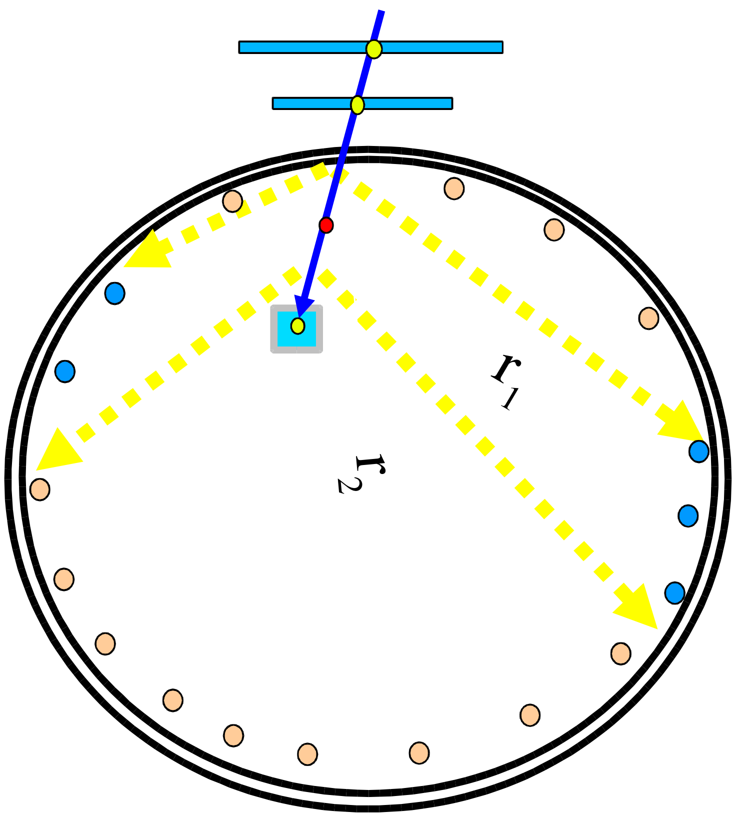
Calibrating CC Interactions at MiniBooNE

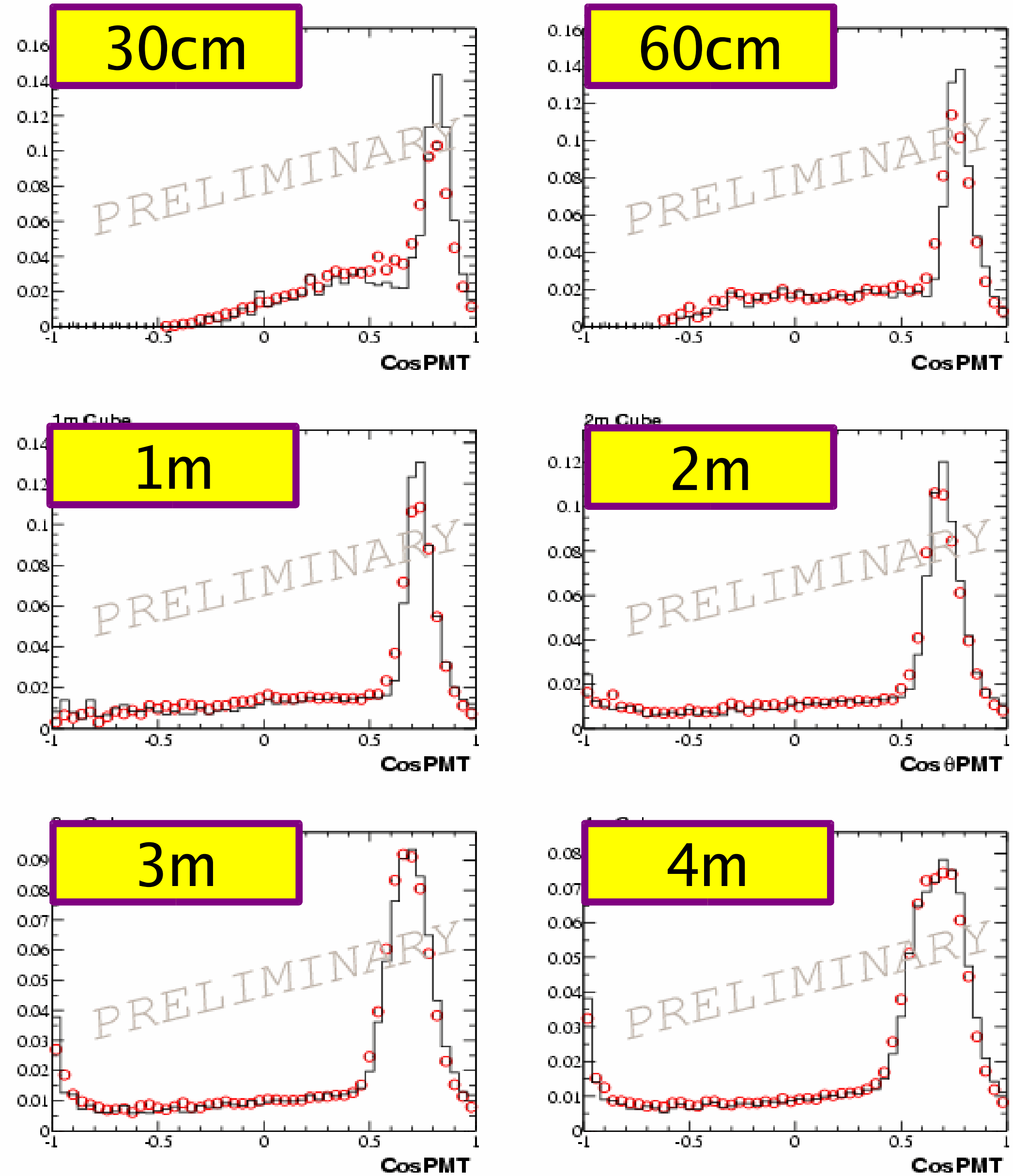
- Hodoscope + 7 Scintillator-Filled Cubes Track Cosmic Rays



Calibrating CC Interactions at MiniBooNE

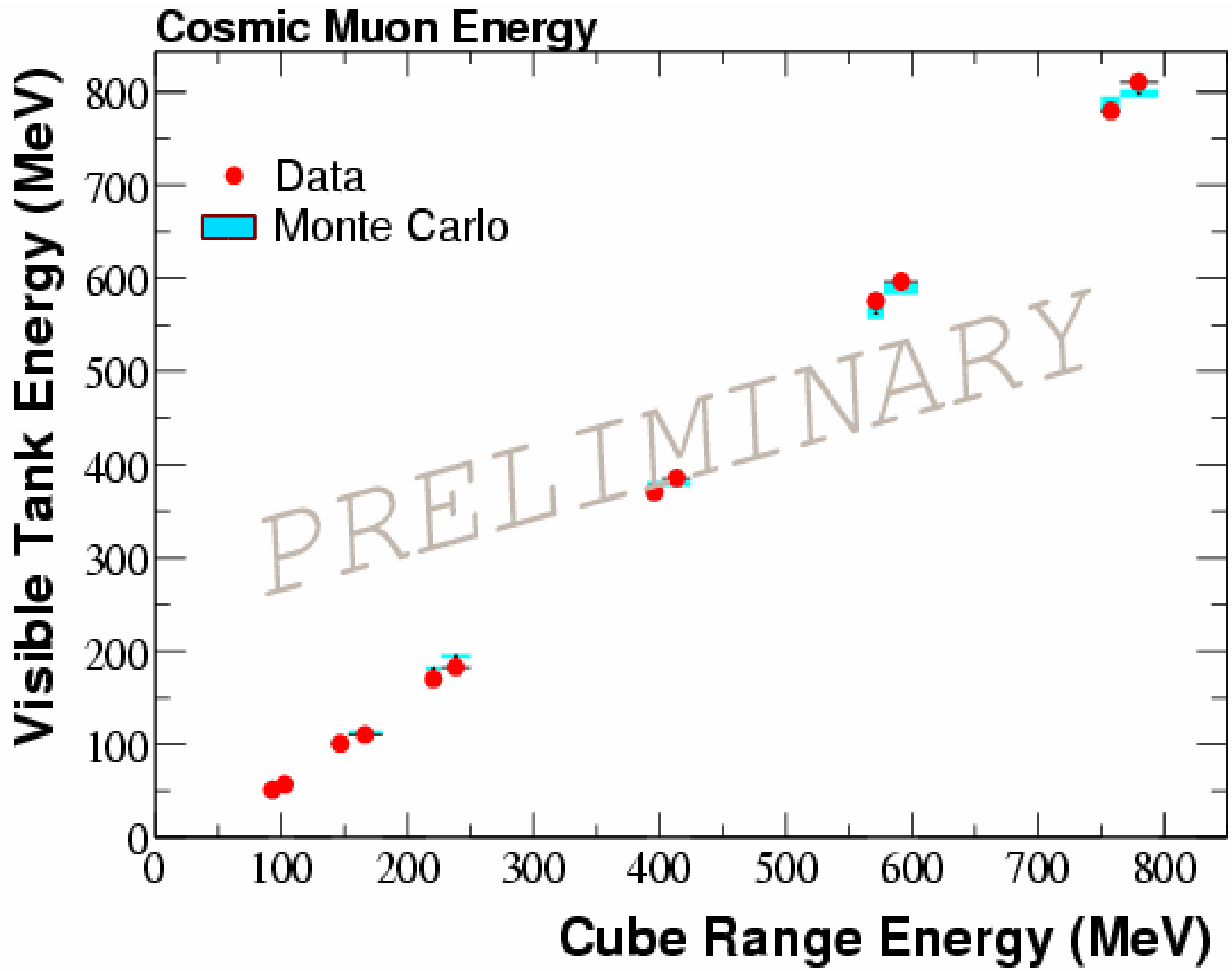
- **Use muon tracker system to determine the event parameters (x, t, u)**
- **Assemble corrected times, angles using known track center**
- **Find Cherenkov rings and time peaks, isotropic and delayed emission**



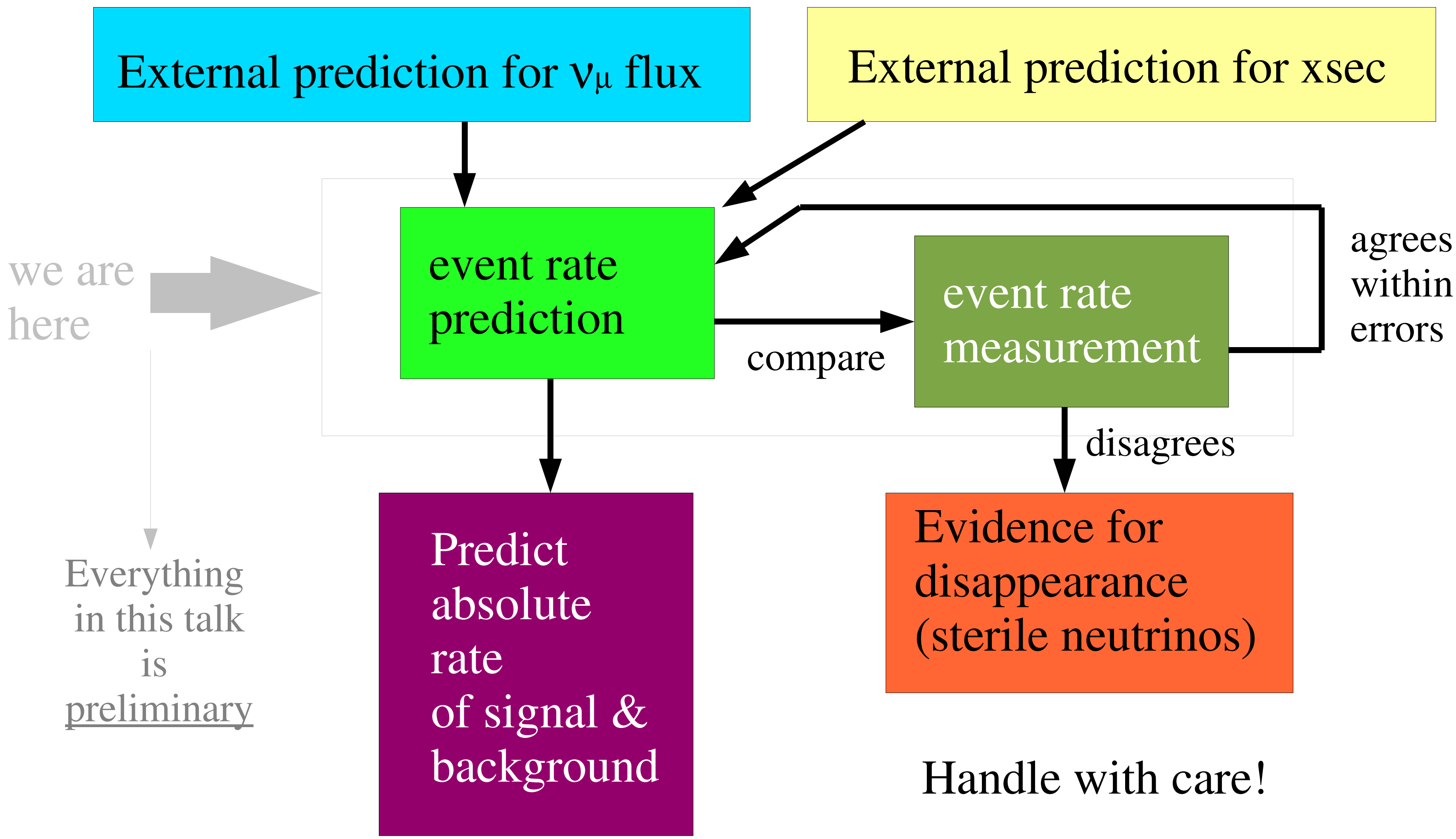


Calibrating CC Interactions at MiniBooNE

- Calibrate μ energy reconstruction using range measured with cubes + tracker
- Muon Tracker system energy resolution ~5%
- Will be used to set μ energy scale vs. energy (analysis in progress)

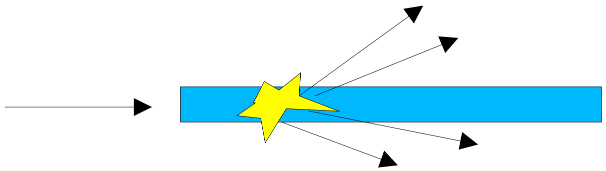


Modelling CC Interactions at MiniBooNE



Handle with care!

External Prediction for ν_μ Flux

p 

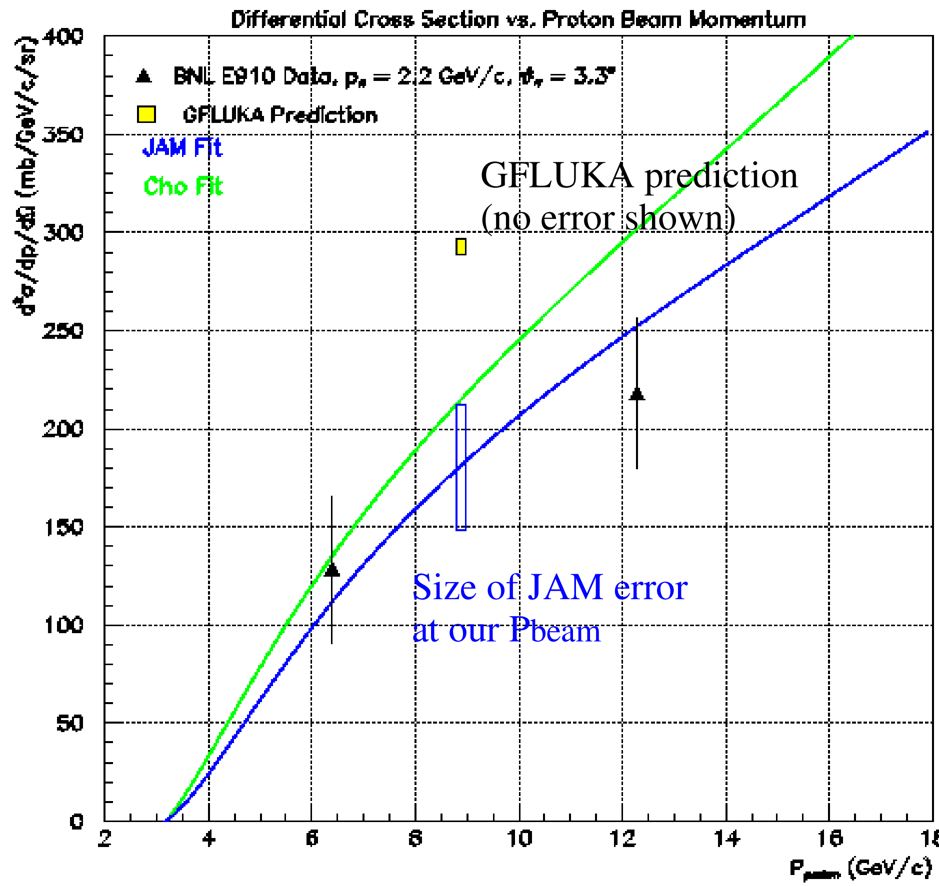
$$\pi^+ / K^+ \to \mu^+ \nu_\mu \quad \& \quad K^+ / K^0_L \to \pi\, e\, \nu_e$$
$$\hookrightarrow e^+ \bar{\nu}_\mu \nu_e$$

Production of secondaries in Be target:

- Geant4 Secondary Beam Monte Carlo
- GFLUKA or MARS (p, n)
- Sanford-Wang parametrization (π,K)

  fit to production data ("JAM") over
  $10 < p_{proton} < 23$ GeV/c
- Publication in preparation *(J. Link, JM, et al.)*

$$\frac{d^2\sigma}{dp\, d\Omega} = W_1 p_\pi^{W_2}\left(1 - \frac{p_\pi}{p_{proton}}\right) x$$
$$\exp\left(\frac{-W_3 p_\pi^{W_4}}{p_{proton}^{W_5}} - W_6 \theta_\pi (p_\pi - W_7 p_{proton} \cos^{W_8} \theta_\pi)\right)$$



\Y. Cho et al., Phys. Rev. **D4**, 1967 (1971)

Near future:

- Measure σ (p Be $\to \pi^+$ X) at 8 GeV at HARP with high statistics and MiniBooNE target

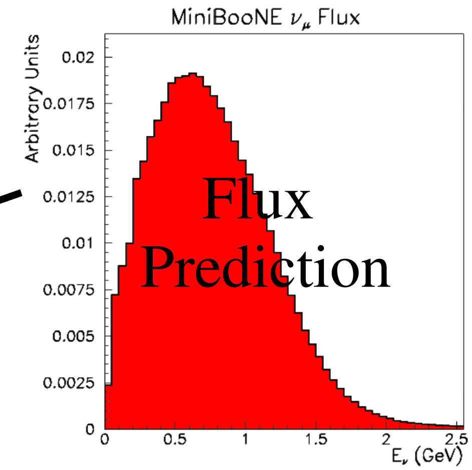
External Prediction for σ_ν

σ Predictions from NUANCE v3 MC produce Event Rate Predictions via:

Theoretical inputs

- Llewellyn Smith free nucleon QE xsec
  - non-dipole BBA03 vector form factors
  - $m_A = 1.03$ GeV
- Rein-Sehgal resonance cross sections
  - $m_A = 1.1$ GeV
- Bodek-Yang DIS formula for low Q^2
- standard DIS formula for high Q^2
- Smith & Moniz Fermi Gas Model
- π absorption model tuned on π data
- FSI model rescatters nucleons

Analysis Chain



NUANCE v3 →

MiniBooNE Detector Monte Carlo (Geant3.21) →

MiniBooNE Analysis Framework (reconstruction, etc.) →

Compare with Data!

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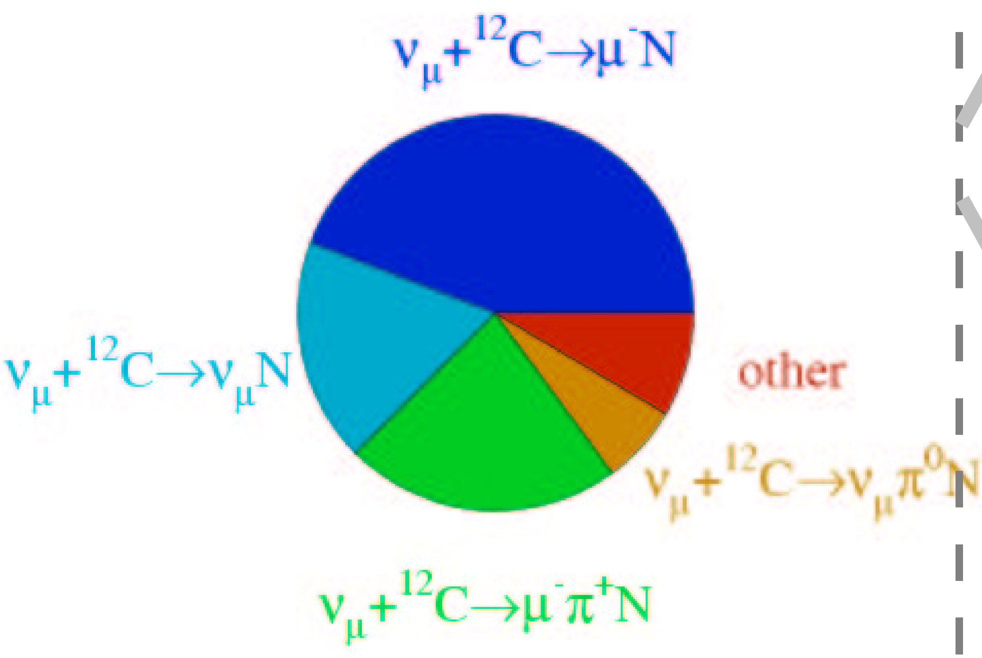
Event Rate Prediction

- 39% CCQE
- 25% CCPiP
- 16% NC Elastic
- 7% NC π^0
- 13% Other



... use Monte Carlo to develop event selection cuts to identify specific final states ...

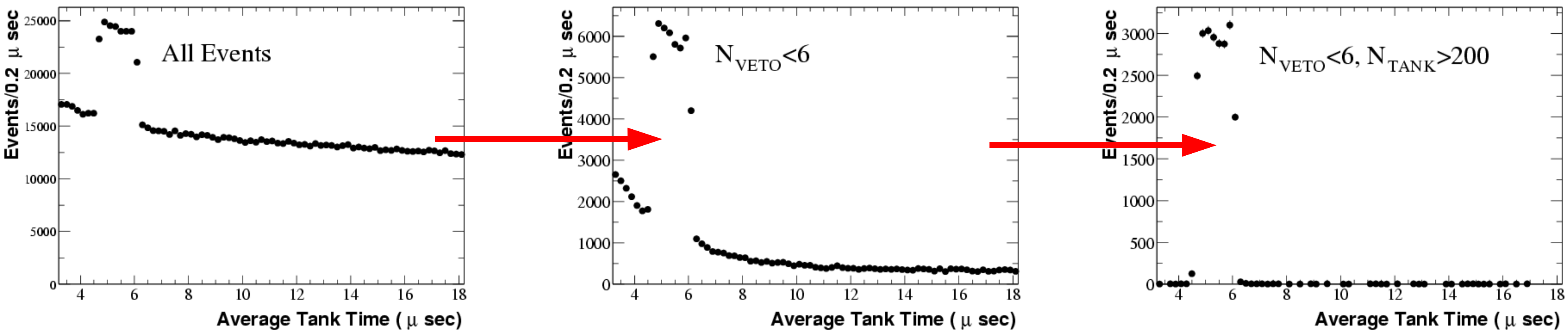
Today:

- 3.2E20 protons on target
  - **60k** CCQE events (after selection cuts)
  - **40k** CCPiP events (after selection cuts)
- ~ half of current MiniBooNE protons on target collected

... use Monte Carlo to correct for cut efficiencies ...

Neutrino-Induced Event Selection

- Neutrino Beam Trigger Window with 1.6 μs ν Beam Spill



Need Simple Cuts to Eliminate:

- Cosmic Rays
- Electrons from Stopped CR Decays (Michel Electrons)
- Beam-Induced Background

Neutrino Candidate Cuts

- Applied to 1st Cluster of Hits (Sub-Event) in Trigger Window
- Number of Veto Hits < 6
- Number of Tank Hits > 200

Charged Current Event Selection

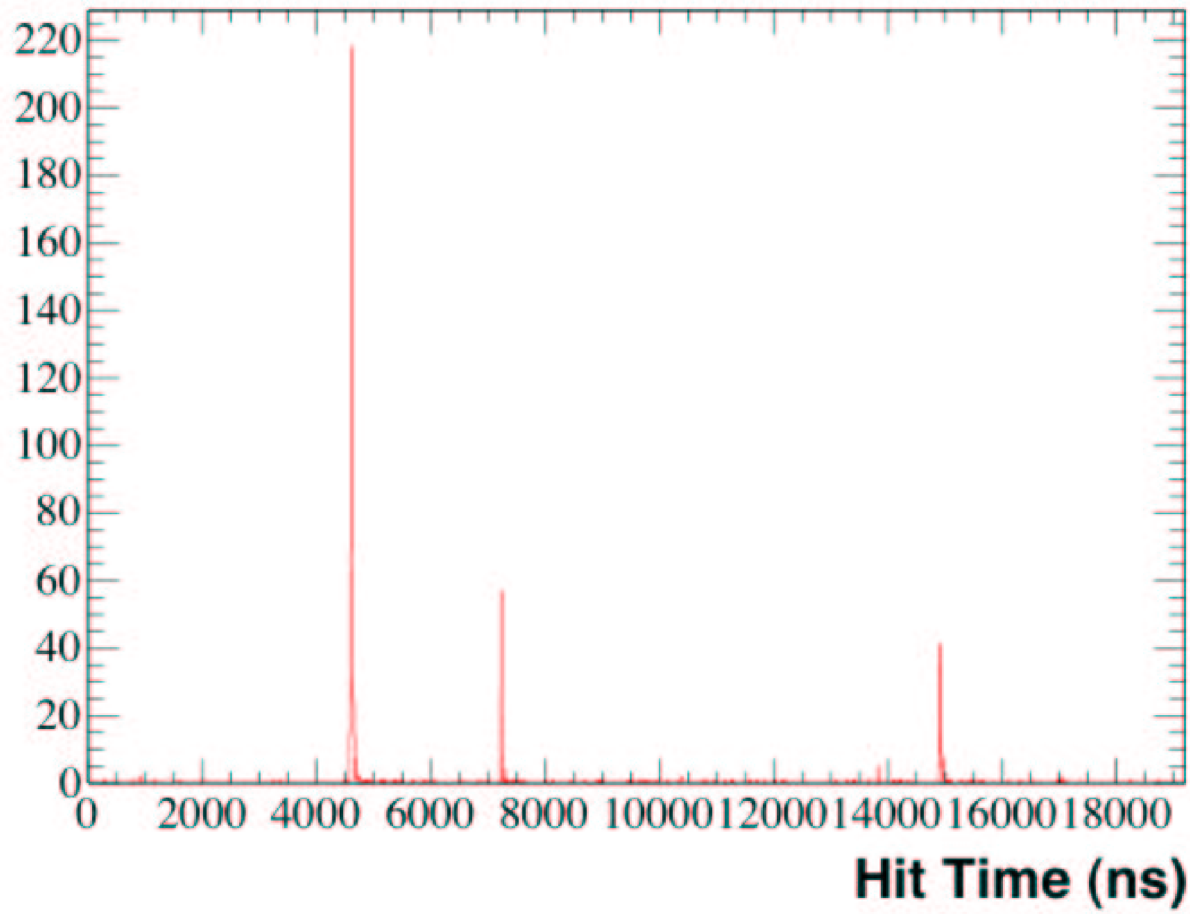
- Use Muon Decay to Identify Charged Current Event Candidates

  Signal: $\nu_\mu\, n \rightarrow \mu^- \, p\, X$ .... time passes ...... $\mu^- \rightarrow e^- \,\bar{\nu}_\mu\, \nu_e$

- Distribution of Tank PMT Hits in Time w.r.t. Beam Trigger Window start

- CC Events have > 1 cluster of hits in time (sub-event) due to μ-decays

- Counting Michel electrons is a powerful and simple cut!



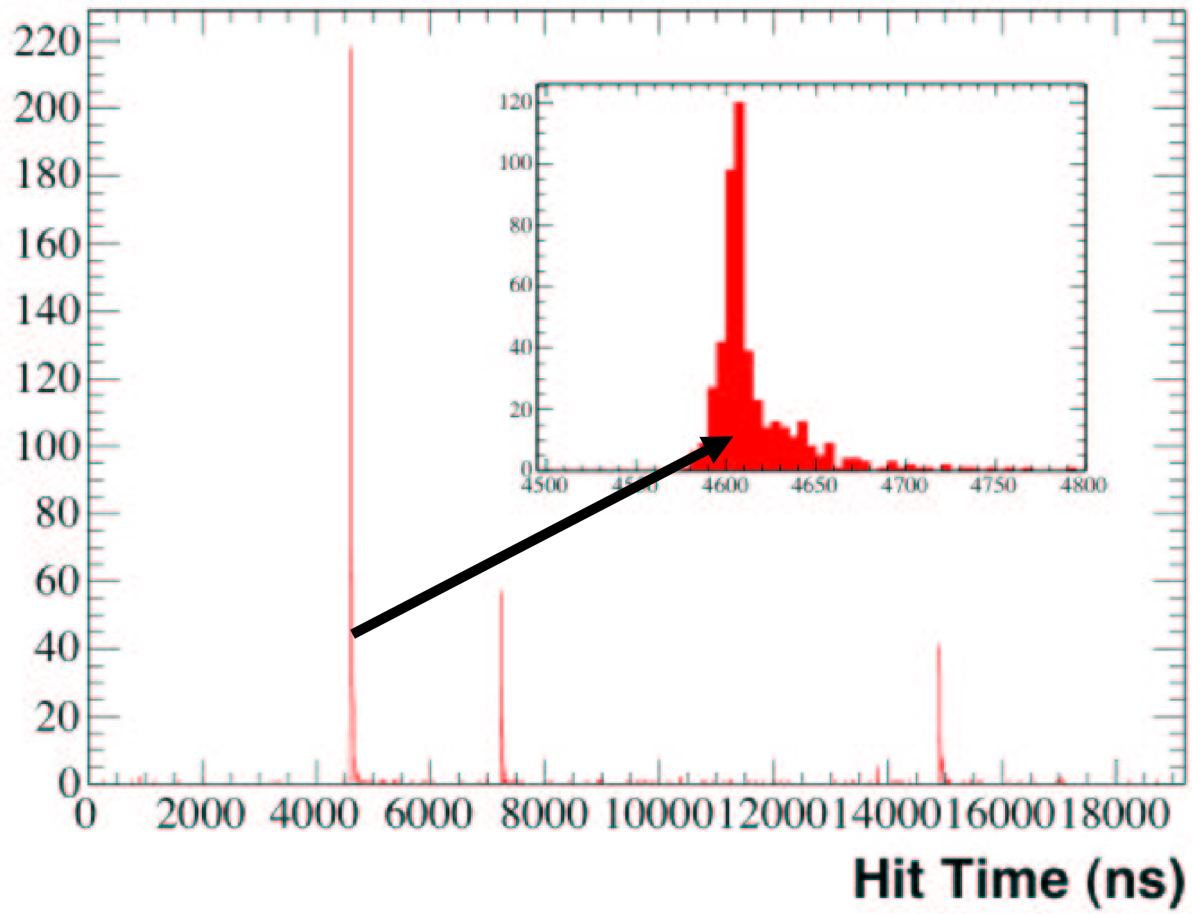
Charged Current Event Selection

- Use Muon Decay to Identify Charged Current Event Candidates
  Signal: $\nu_\mu\, n \rightarrow \mu^-\, p\, X$ .... time passes ...... $\mu^- \rightarrow e^-\, \bar{\nu}_\mu\, \nu_e$

- Distribution of Tank PMT Hits in Time w.r.t. Beam Trigger Window start

- First Sub-Event is the μ in CC interactions

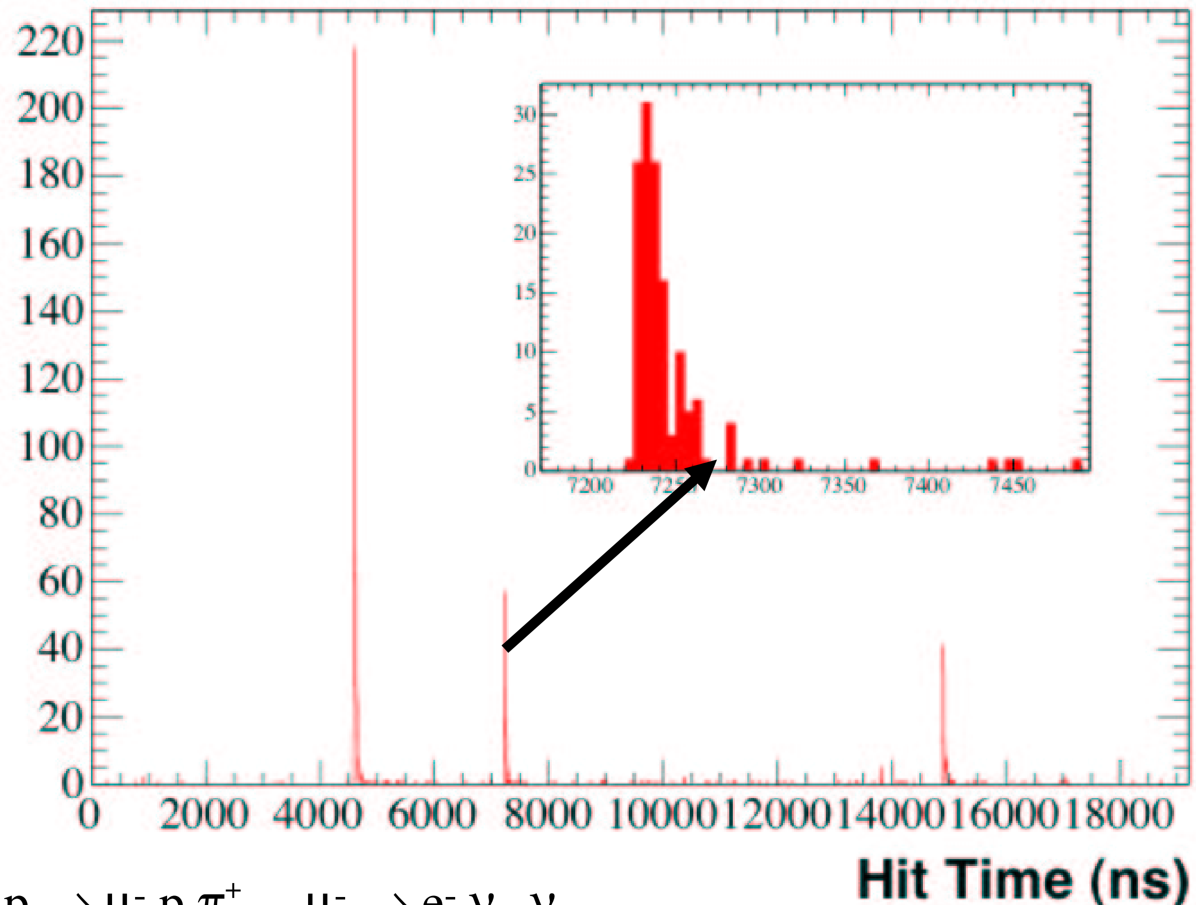
- Use these PMT hits to reconstruct muon energy and angle



Charged Current Event Selection

- Use Muon Decay to Identify Charged Current Event Candidates
  Signal: $\nu_\mu\, n \rightarrow \mu^-\, p\, X$ .... time passes ...... $\mu^- \rightarrow e^-\, \bar{\nu}_\mu\, \nu_e$

- Distribution of Tank PMT Hits in Time w.r.t. Beam Trigger Window start



- Second Sub-Event is the μ-decay e in CC interactions

- Typically Michel e- have < 200 PMT hits

- CCQE have 2 sub-events, while CCPiP have 3: $\nu_\mu\, p \rightarrow \mu^-\, p\, \pi^+$ ... $\mu^- \rightarrow e^-\, \nu_\mu\, \nu_e$
  ... $\pi^+ \rightarrow \mu^+\, \nu_\mu$ ... $\mu^+ \rightarrow e^+\, \nu_\mu\, \nu_e$

CCQE Event Selection

First Level of Cuts:

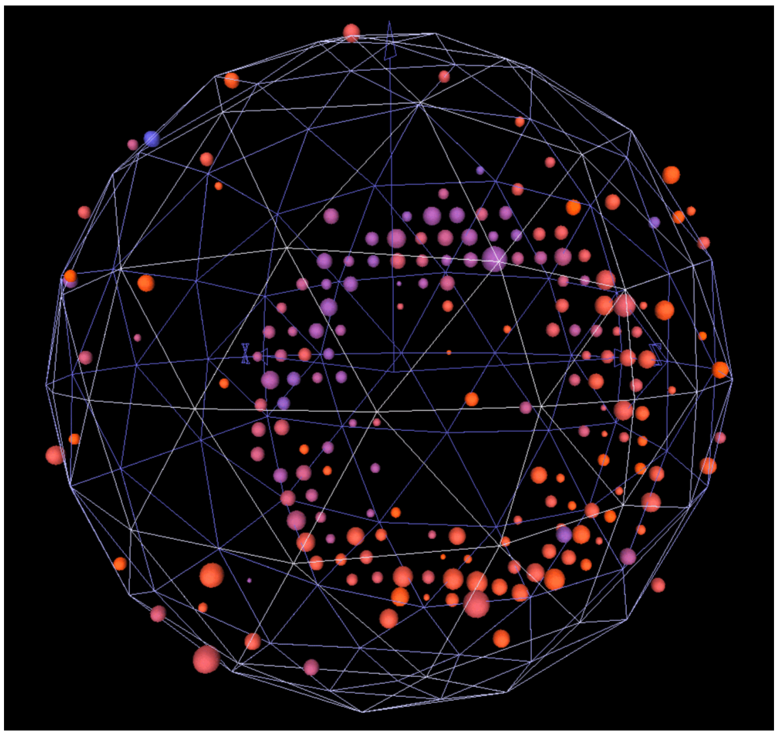
- Neutrino-Induced Event Selection Cuts
- CC Selection Cut
  - < 3 sub-events

Signal:

$\nu_\mu\, n \rightarrow \mu^-\, p$

.... time passes ......

$\mu^- \rightarrow e^-\, \nu_\mu\, \nu_e$

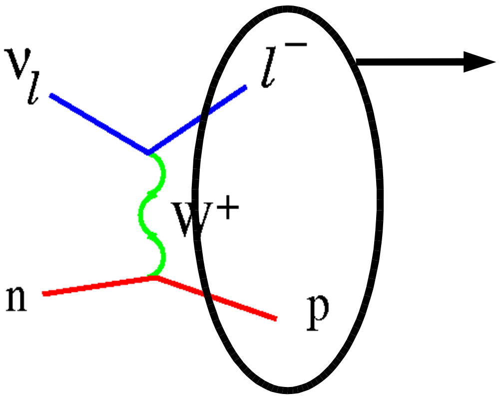


Second Level Cuts: Final State ID

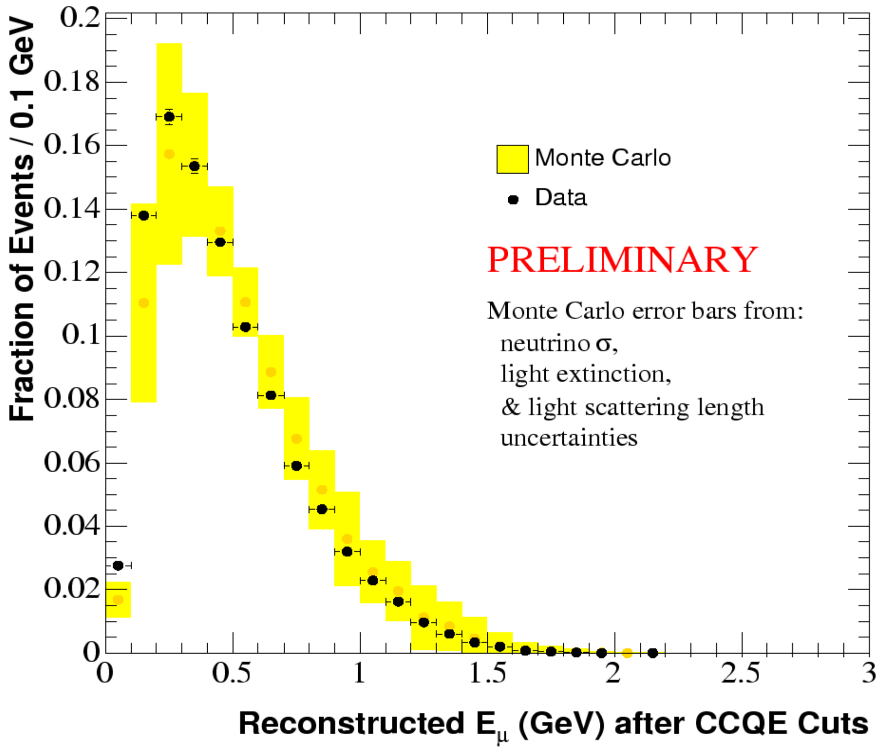
- event topology
  - fraction of on- vs. off- ring light
- PMT hit timing
  - fraction of prompt vs. late light
- μ-like energy loss
  - given E, is track length consistent with μ?
- 10 variable Fisher descriminant

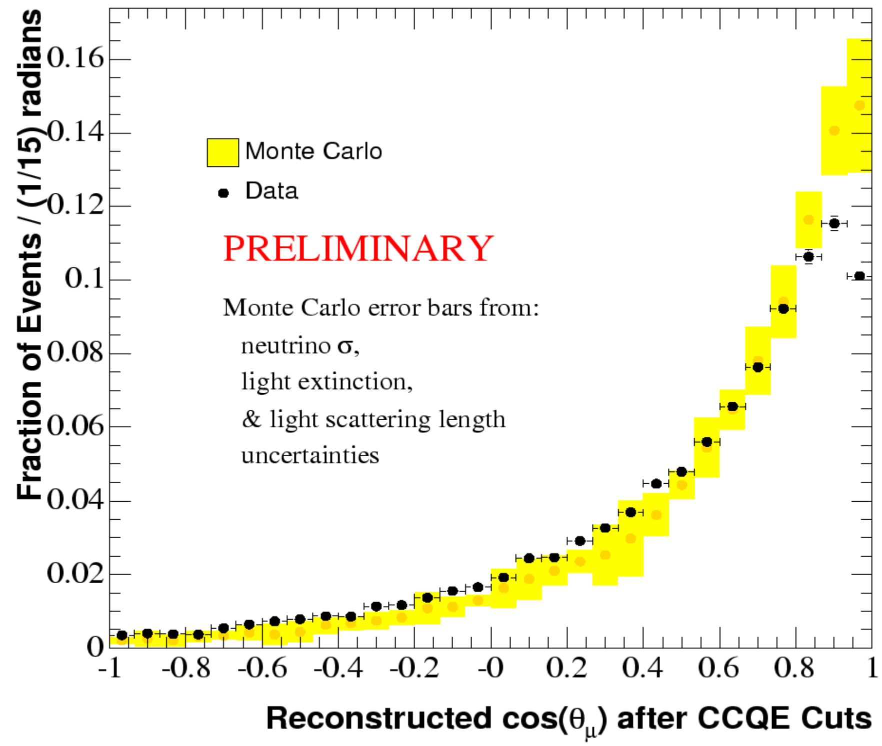
- Result: 86% CCQE purity
  - most of background from CCPiP
  - more pure than in past presentations

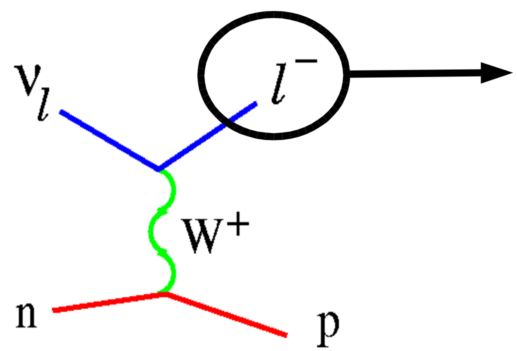
CCQE Data



measure visible energy (mostly Cerenkov from μ, + a little scintillation light from proton)

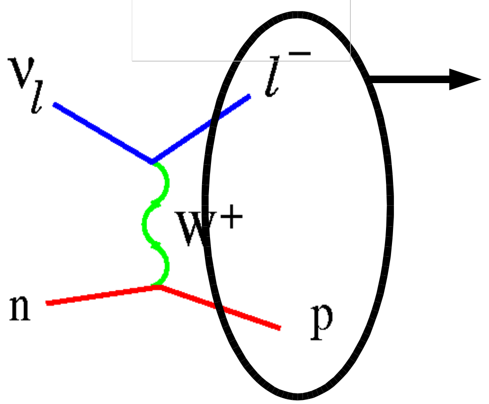






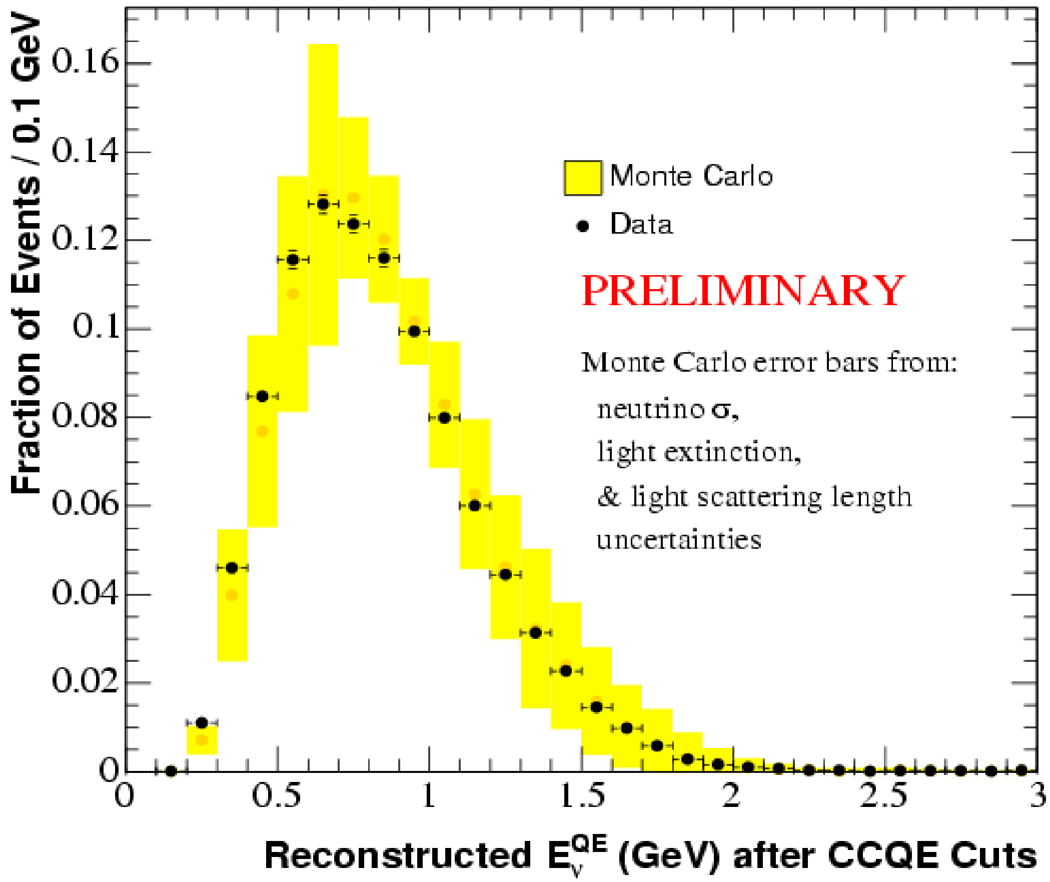
reconstruct μ direction from Cerenkov light, $\cos(\theta) = 1 \sim$ low Q^2

CCQE Data

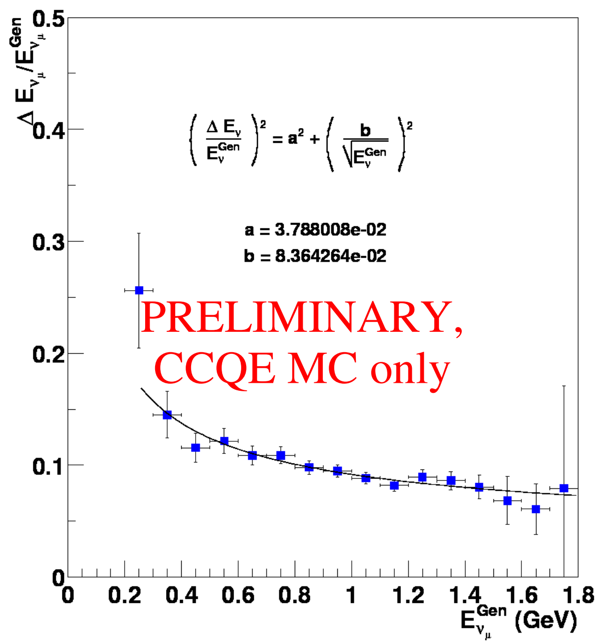


use measured μ visible energy and angle to reconstruct E_ν^{QE}

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



Neutrino Energy Reconstruction



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CCPiP Event Selection

First Level of Cuts:

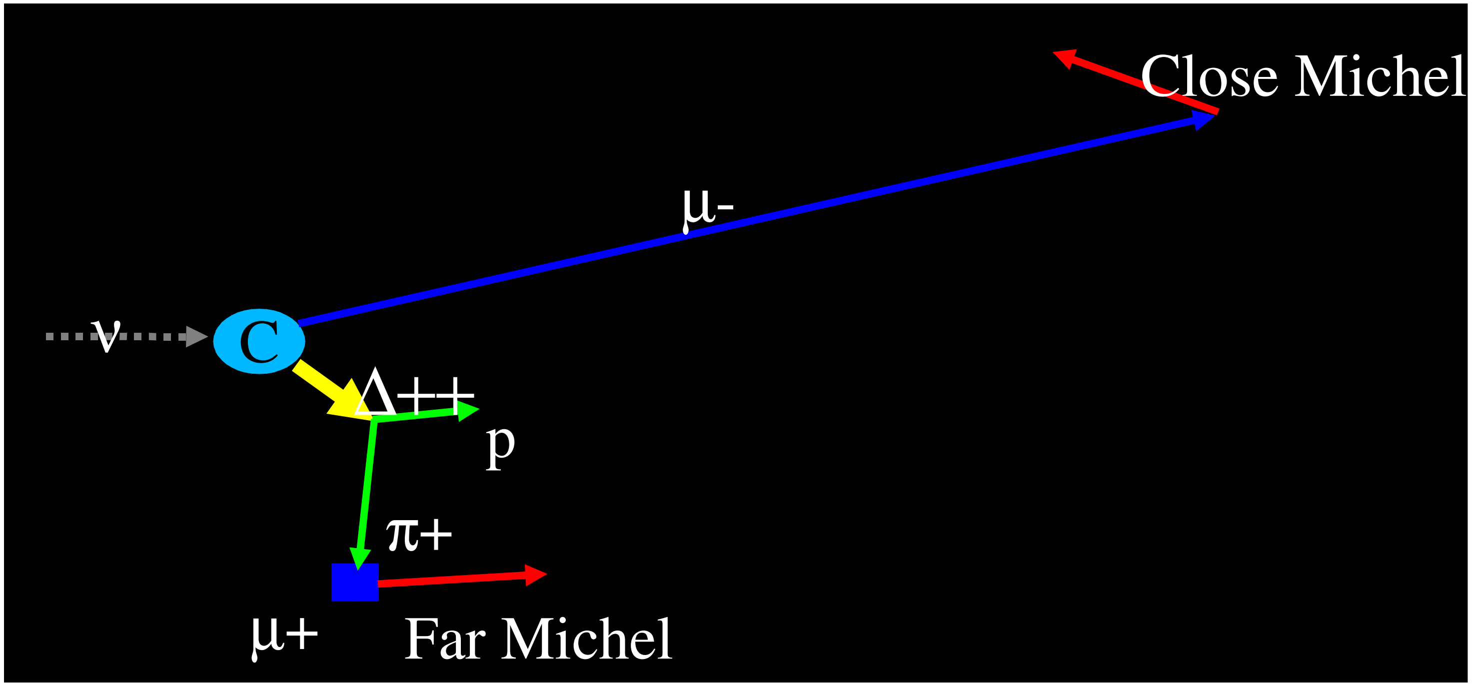
- Neutrino-Induced Event Selection Cuts
- CC Selection Cut
  - exactly 3 sub-events
  - 2^{nd} 2 sub-events consistent with Michel e^- ($20 < N_{PMT} < 200$)

Signal:

$\nu_\mu \, p \rightarrow \mu^- \, p \, \pi^+$ ....

$\pi^+ \rightarrow \mu^- \nu_\mu$ and $\mu^- \rightarrow e^- \nu_\mu \nu_e$ ....

$\mu^+ \rightarrow e^+ \nu_\mu \nu_e$



No Final State ID Cuts yet ... these events are messy!

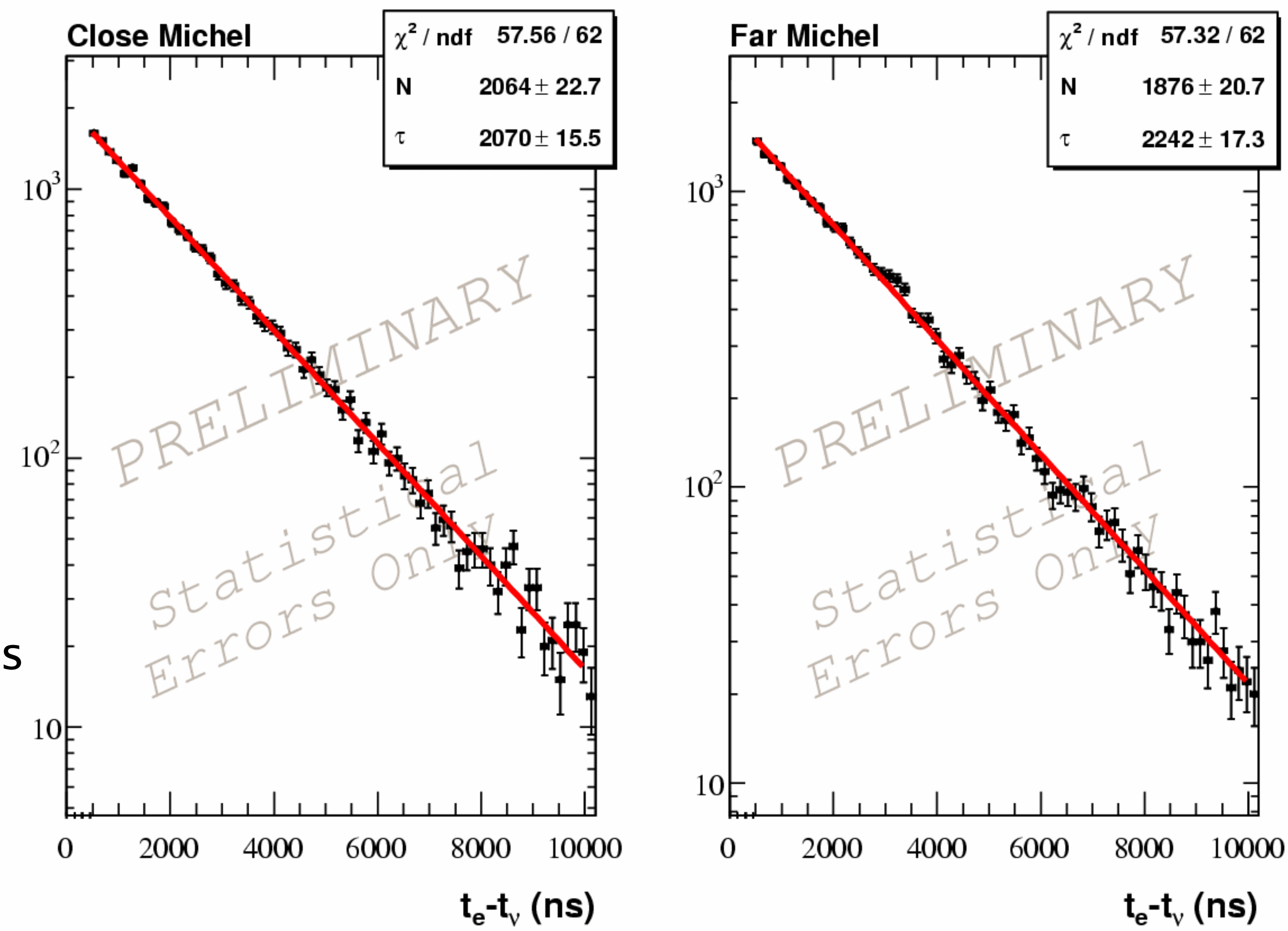
84% purity with 1^{st} level cuts, bgnd from $N\pi$ and QE

CCPiP Event Selection Validation

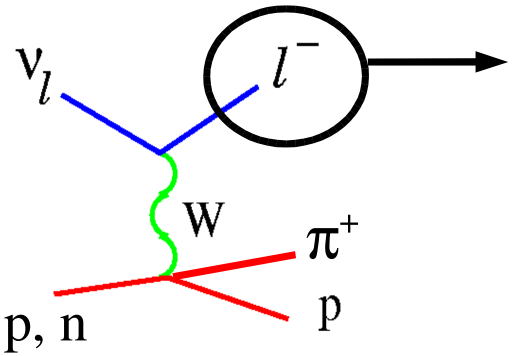
- validate CCPiP event selection with μ^+ and μ^- lifetime measurement
  - separate Michels from μ^+ and μ^- by distance to μ^- track

- close:
  μ^- capture (8%)
  expect
  τ=2026±1.5 ns
  measure
  τ=2070±15.5 ns

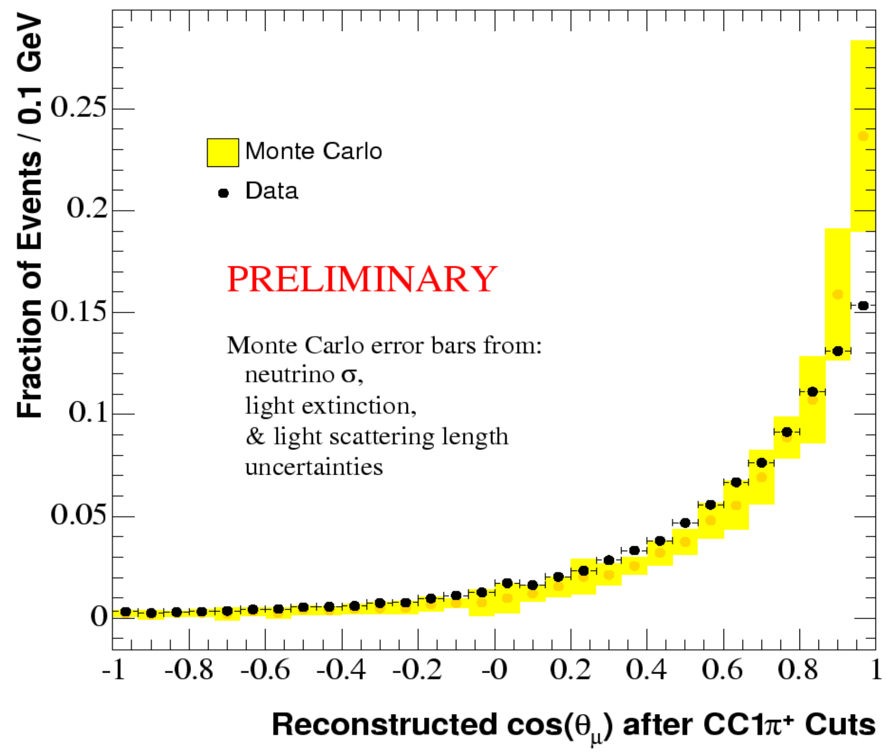
- far:
  μ^+ do not capture
  expect
  τ=2197.03±0.04 ns
  measure
  τ=2242±17.3 ns

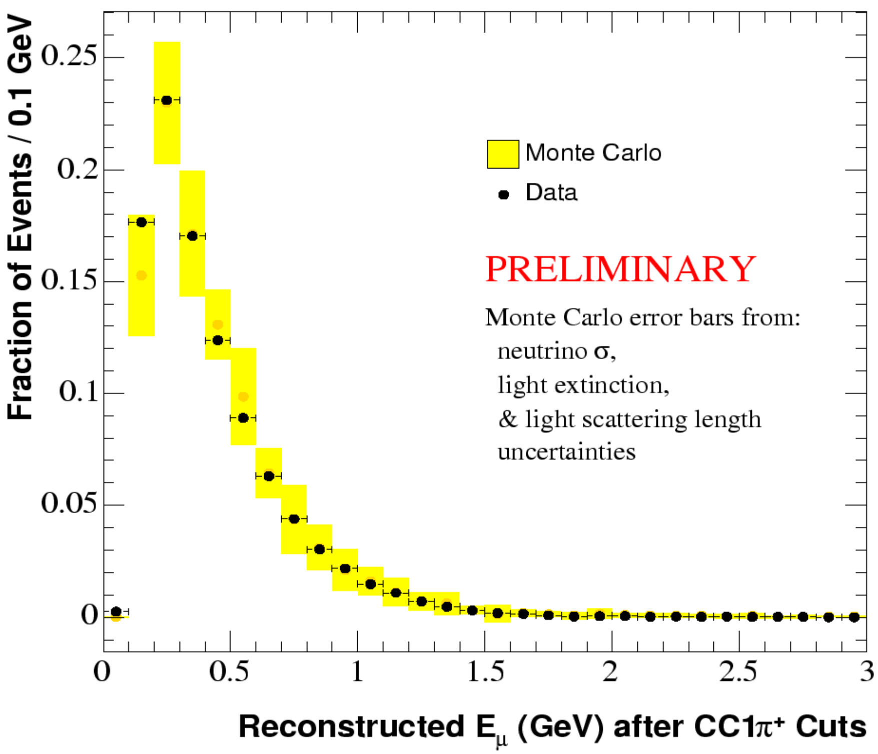


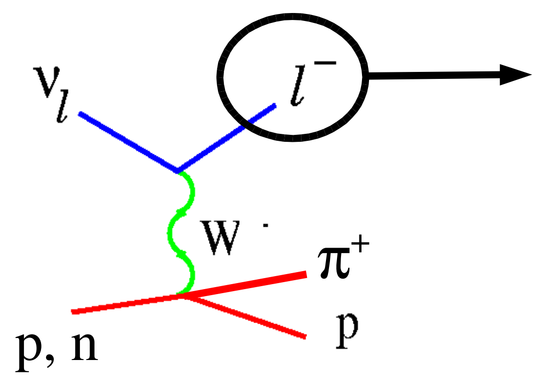
CCPiP Data



measure visible energy from Cerenkov light only (to avoid scintillation light from π+)

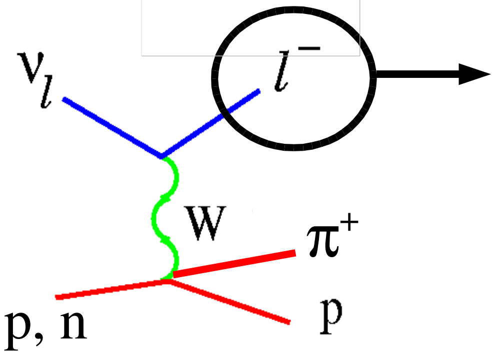






reconstruct μ direction from Cerenkov light, cos(θ) = 1 ~ low Q^2

CCPiP Data

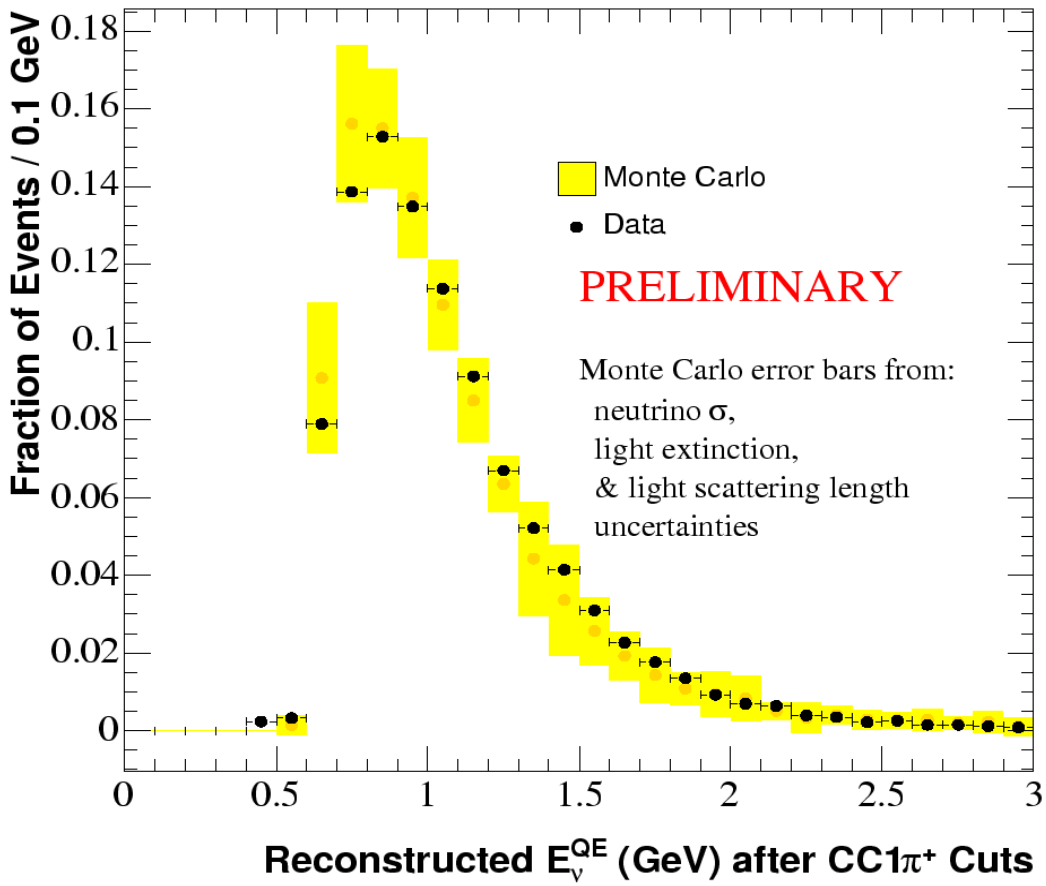


use measured μ visible energy and angle to reconstruct E_ν^{QE}

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

<ins>*Neutrino Energy Reconstruction*</ins>

- Assume 2 body (QE) kinematics
- Assume Delta 1232 in final state instead of a proton (as in CCQE)
- ~20% resolution



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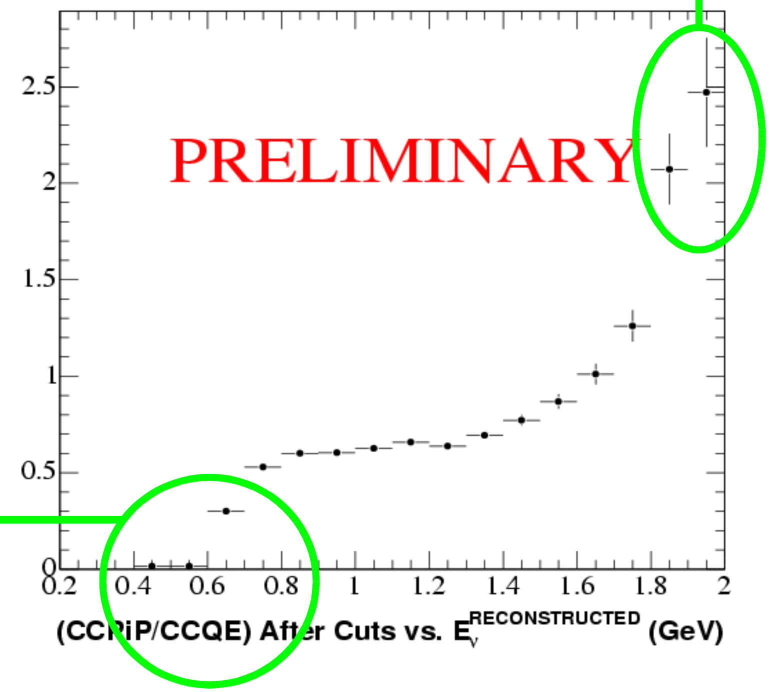
CCPiP/CCQE Ratio

- Without cut efficiency corrections:
  - measured N(CCPiP)/N(CCQE) vs. E_ν^{QE}
    - CCQE cut efficiency degrades at high E due to exiting μ
    - CCPiP threshhold > CCQE



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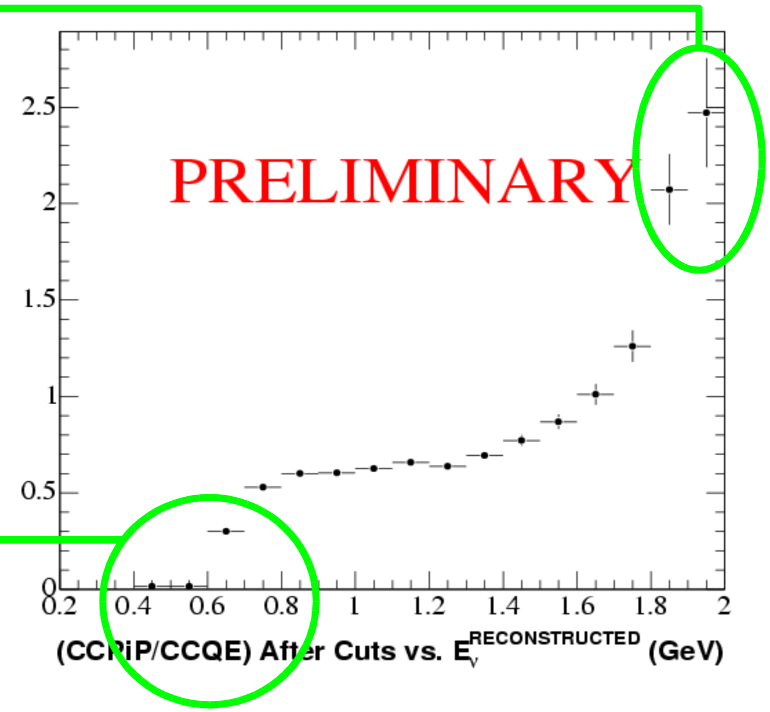

- Motivation for measuring (CCPiP/CCQE) ratio:
  - possibility of ν_μ disappearance
  - like branching ratio measurements, normalize to ``golden mode'' in our own data
  - CCQE is the ``golden mode'' of ν σs

CCPiP/CCQE Ratio

- Without cut efficiency corrections:
  - measured N(CCPiP)/N(CCQE) vs. E_ν^{QE}
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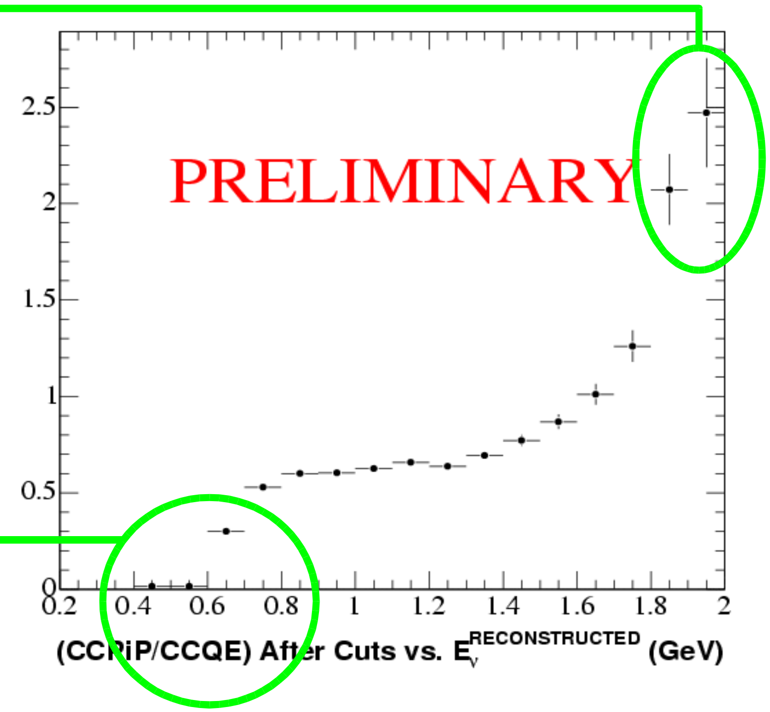
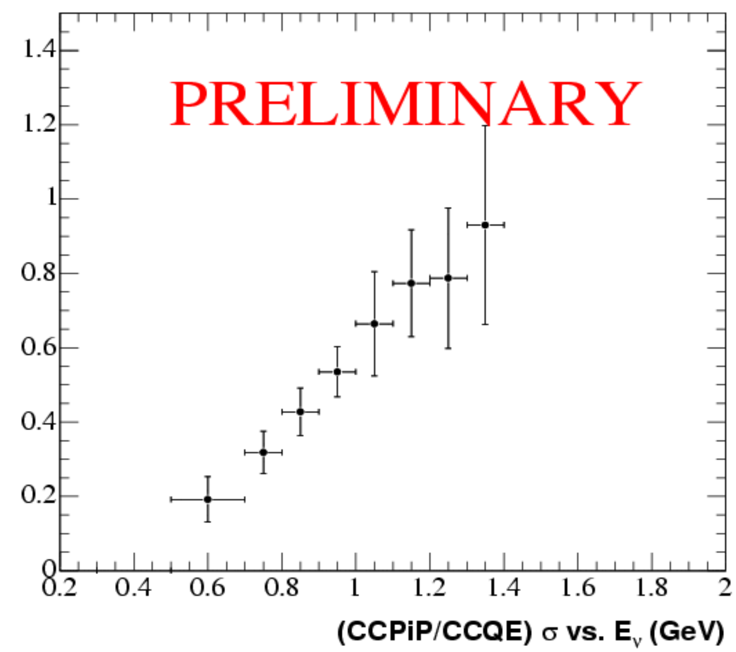
- Motivation for measuring (CCPiP/CCQE) ratio:
  - possibility of ν_μ disappearance
  - like branching ratio measurements, normalize to ``golden mode'' in our own data
  - CCQE is the ``golden mode'' of ν σs
- Efficiency corrected ratio measurement:
  - estimate efficiency correction in MC
  - systematic errors due to ν cross sections (~15%), γ extinction and scattering length in oil (~20%), energy scale (~10%)
  - $\delta^{SYS}_{TOTAL}(E_\nu)$ ~ 20 to 30%, $\delta^{STAT}(E_\nu)$ ~ 5 to 6%





Sources of Uncertainty

ν cross section uncertainties:

source	*parameter varied*	*variation amount*
coherent-	coherent pion production	-100% (off)
deltawidth+	Breit-Wigner full width	+4.2%
fermigasmodel+	$\mathrm{E}_{Binding}$, p_{Fermi}	+100%,+14%
ma1pi+	$M_A(1\pi)$	+20%
mamultipi+	$M_A(\mathrm{n}\pi)$	+35%
maqe+	$M_A(\mathrm{QE})$	+10%
pionabs+	$\sigma_{\pi\to X}$	+25%
pionce+	$\sigma_{charge-exchange}$	+30%
pionlessdeltadecay+	$\mathrm{P}(\Delta N \to NN)$	+50%

- assessed inside the nucleus (in the NUANCE Monte Carlo)
- size of parameter variations estimated from past data
- parameters are assumed to be uncorrelated for now

- CCPiP:
  - no errors on signal, all errors on background

- CCQE:
  - Fermi Gas Model & m_A^{QE} errors on signal, all errors on background

Sources of Uncertainty

γ propagation in detector oil (optical model) uncertainties:

source	*parameter varied*	*variation amount*
attenuation	extlen(460nm)	+33%
scattering lengths	Rayleigh A & B, Raman	-16% (all)

- assessed inside the detector oil (in the Geant3 Detector Monte Carlo)
- size of parameter variations estimated from external and internal measurements
- parameters are assumed to be uncorrelated for now
- incomplete list

P R E L I M I N A R Y

Sources of Uncertainty

γ propagation in detector oil (optical model) uncertainties:

source	*parameter varied*	*variation amount*
attenuation	extlen(460nm)	+33%
scattering lengths	Rayleigh A & B, Raman	-16% (all)

- assessed inside the detector oil (in the Geant3 Detector Monte Carlo)
- size of parameter variations estimated from external and internal measurements
- parameters are assumed to be uncorrelated for now
- incomplete list

ν Flux Uncertainties

- do not enter here because we normalize to ``golden mode'' in our own data (effectively enter through CCQE σ uncertainties)

PRELIMINARY

Sources of Uncertainty

γ propagation in detector oil (optical model) uncertainties:

source	*parameter varied*	*variation amount*
attenuation	extlen(460nm)	+33%
scattering lengths	Rayleigh A & B, Raman	-16% (all)

- assessed inside the detector oil (in the Geant3 Detector Monte Carlo)
- size of parameter variations estimated from external and internal measurements
- parameters are assumed to be uncorrelated for now
- incomplete list

ν Flux Uncertainties

- do not enter here because we normalize to ``golden mode'' in our own data (effectively enter through CCQE σ uncertainties)

Preliminary → Final:

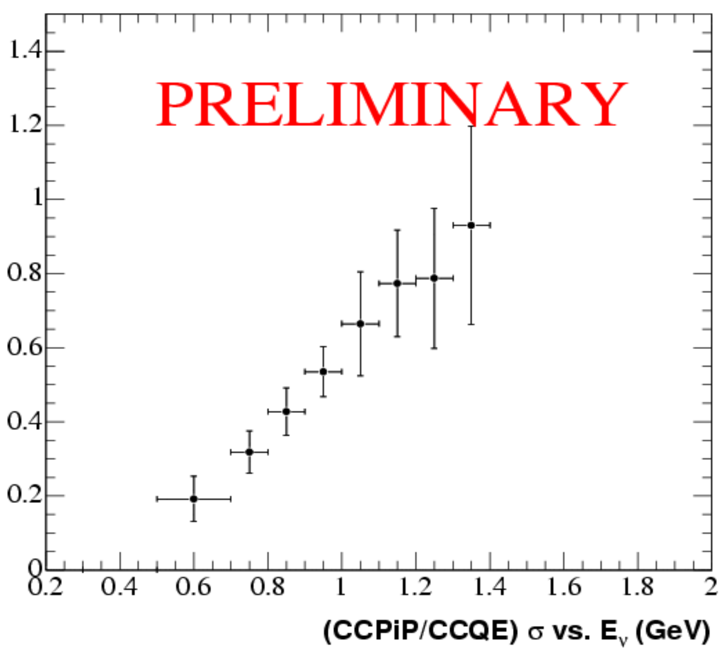
- estimate / measure parameter correlations
- reduce detector optical model uncertainties with continued analysis of calibration data
- reduce ν σ uncertainties with analysis of electron scattering data
- propagate relevant ν σ uncertainties through detector Monte Carlo (e.g. π absorption)

CCPiP/CCQE Ratio

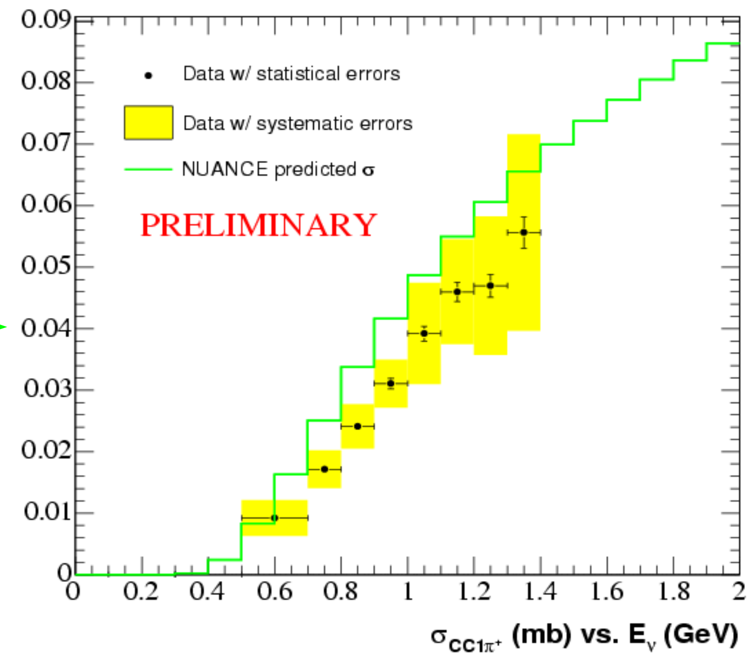
- efficiency corrected measurement as a function of ν energy:

$$N(\text{CCPiP}) / N(\text{CCQE}) = \sigma(\text{CCPiP}) / \sigma(\text{CCQE}) = R_{\text{MEASURED}}$$

- convert to σ(CCPiP) via $R_{\text{MEASURED}} \times \sigma_{\text{NUANCE}}(\text{CCQE})$
- compare with predicted $\sigma_{\text{NUANCE}}(\text{CCPiP})$
- recall this is $\nu_\mu\, p \rightarrow \mu^-\, p\, \pi^+$, $\nu_\mu\, n \rightarrow \mu^-\, n\, \pi^+$, and $\nu_\mu\, A \rightarrow \mu^-\, A\, \pi^+$



Multiply by NUANCE MC σ CCQE

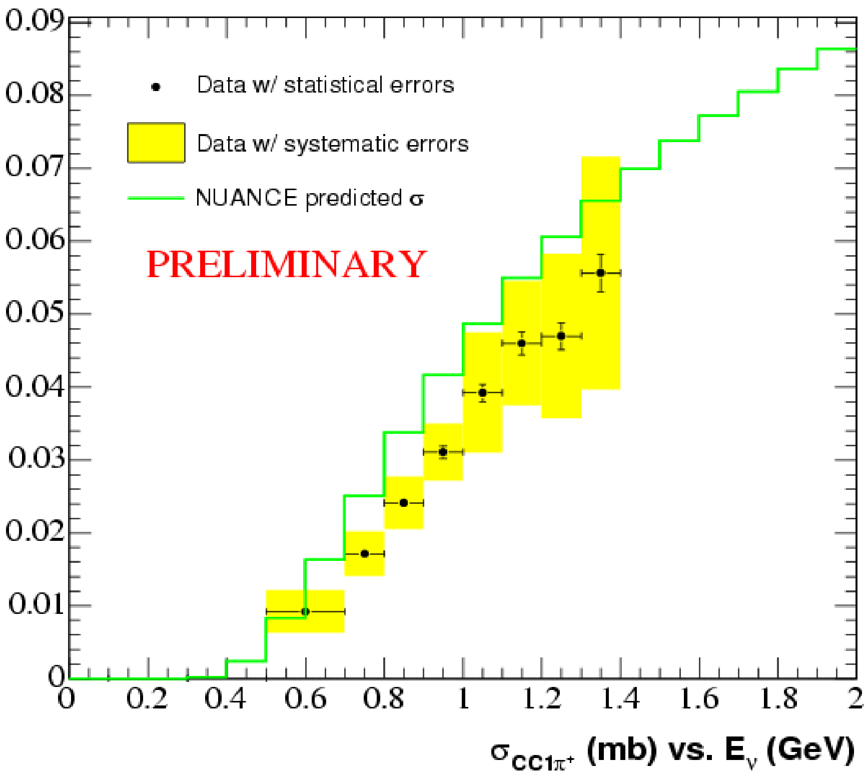


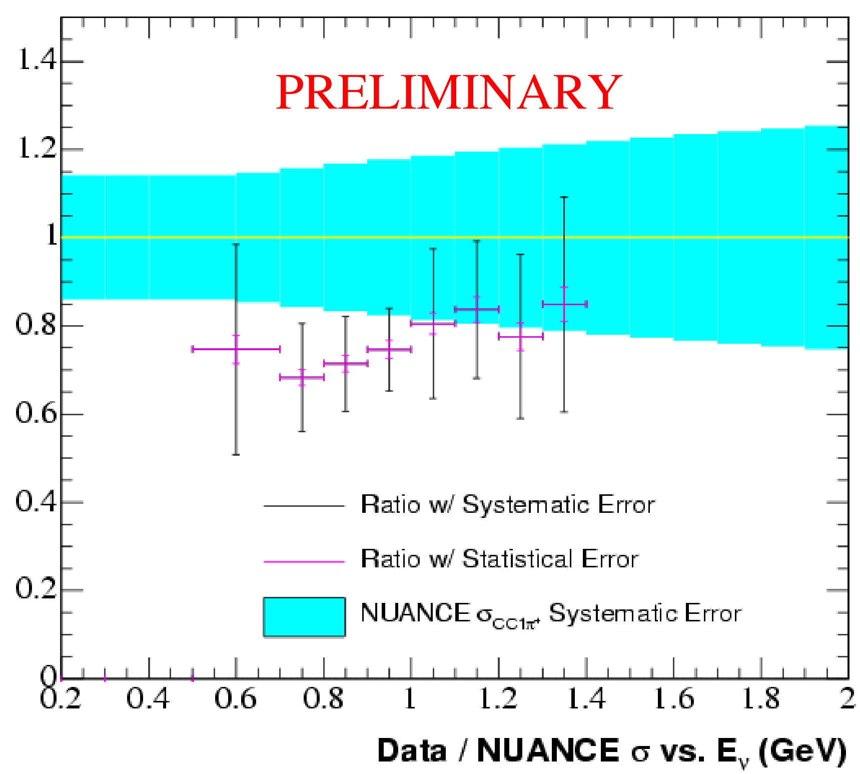
CCPiP/CCQE Ratio

- efficiency corrected measurement as a function of ν energy:

$$N(CCPiP) / N(CCQE) = \sigma(CCPiP) / \sigma(CCQE) = R_{MEASURED}$$

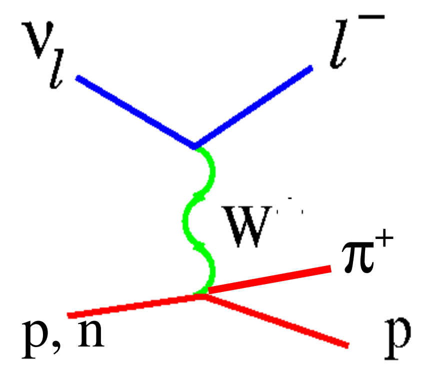
- convert to σ(CCPiP) via $R_{MEASURED} \times \sigma_{NUANCE}(CCQE)$
- ratio to predicted $\sigma_{NUANCE}(CCPiP)$ is ~75%, but ~within $\delta\sigma_{NUANCE}(CCPiP)$





effective CCPiP/CCQE Ratio

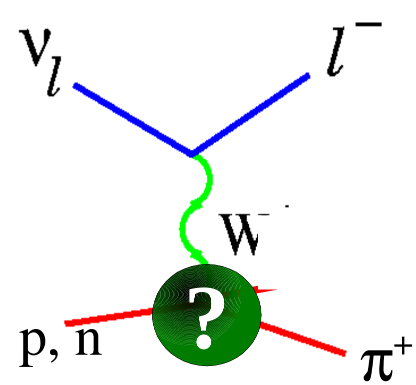
- MC efficiency correction includes NUANCE MC final state interaction model since we use MC to correct back to generated CCPiP events



Final State Interactions (with uncertainty):

- σ pion absorption (δ_{NUANCE} = 25%)
- σ charge exchange (δ_{NUANCE} = 30%)
- P (Δ N $\rightarrow$ N N) π–less Δ decay (δ_{NUANCE} = 50%)

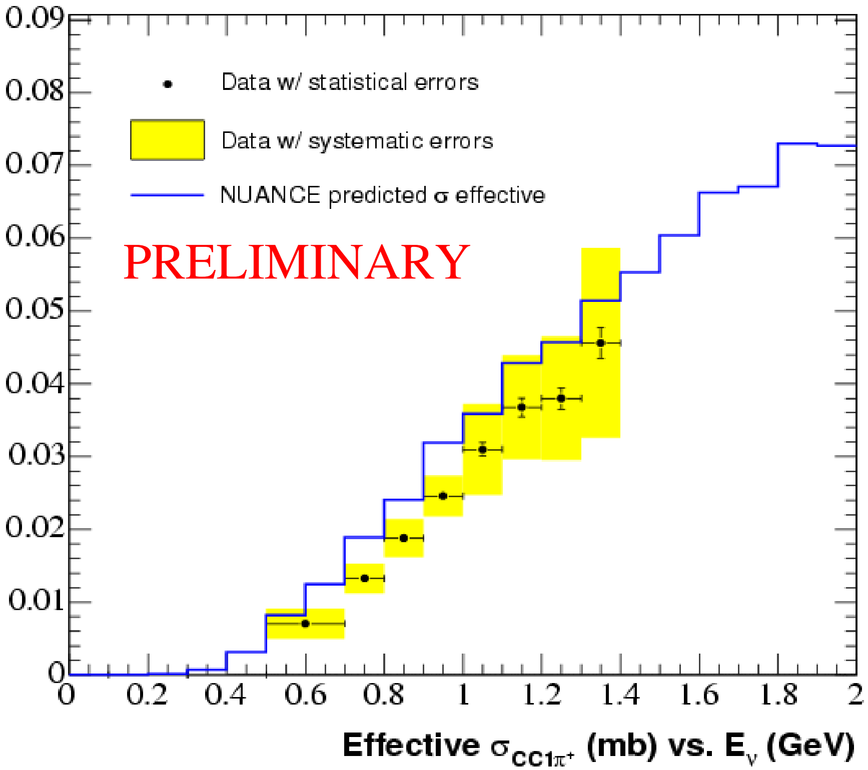
- MiniBooNE can also measure ``effective'' σ(CCPiP)
  - define numerator of MC efficiency correction as anything CCPiP-like, not just $\nu_\mu\, p \rightarrow \mu^-\, p\, \pi^+$, $\nu_\mu\, n \rightarrow \mu^-\, n\, \pi^+$, and $\nu_\mu\, A \rightarrow \mu^-\, A\, \pi^+$
  - CCPiP-like = 1 μ and 1 π^+ in final state (before particles decay)

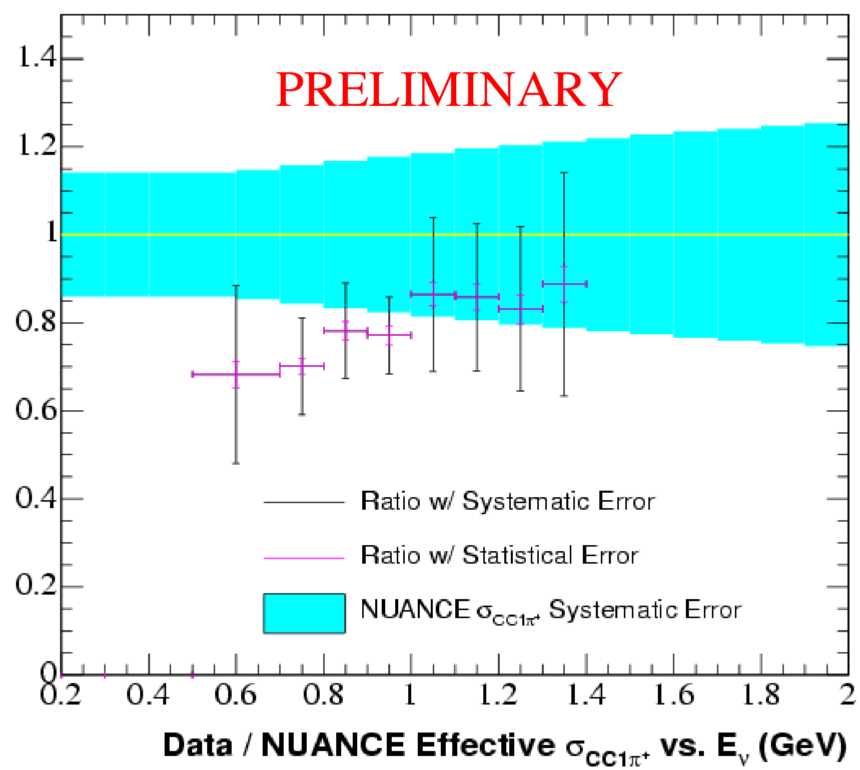


- N(CCPiP-like) / N(true CCPiP) = 0.8
  - 24% true CCPiP are not CCPiP-like (no π^+)
  - 7% true non-CCPiP are CCPiP-like

effective CCPiP/CCQE Ratio

- cross check NUANCE FSI by comparing (Data/MC) $\sigma_{EFFECTIVE}$ to σ_{CCPiP}
  $(R_{MEASURED})^{EFFECTIVE}$ = N(CCPiP-like) / N(CCQE) = σ(CCPiP-like) / σ(CCQE)
- convert to σ(CCPiP-like) via $(R_{MEASURED})^{EFFECTIVE}$ x σ_{NUANCE}(CCQE)
- ratio to predicted σ_{NUANCE}(CCPiP-like) is similar to $\sigma_{MEASURED}$(CCPiP) result





Outlook and Conclusions

CCPiP Analysis Plan:

- Extract coherent vs. resonant fractions with 2D fits to kinematic distributions
- reconstruct Δ invariant mass, feed back into ν energy reconstruction
- reduce σ systematic uncertainties by integrating μ tracker calibration
- iterate σ analysis in NUANCE
- compare measured σ(CCPiP) / σ(CCQE) with other low energy ν MCs

MiniBooNE σ Outlook:

- Summer '05:
  - CCPiP paper this fall
  - NC π^0 preliminary σ measurement

- Fall '05
  - CCQE ν_μ disappearance analysis result

Grazie Mille!

INFN for generous travel support

Backup Slides

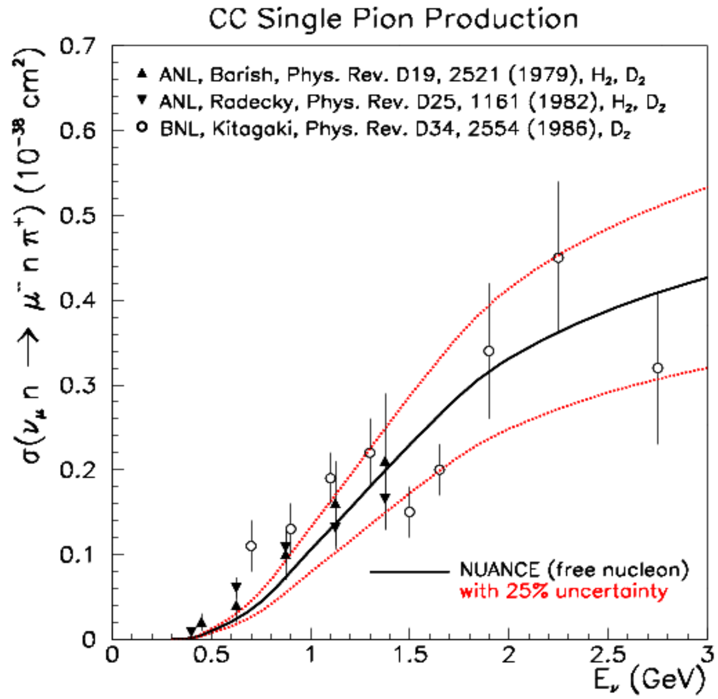
CCPiP σ Errors

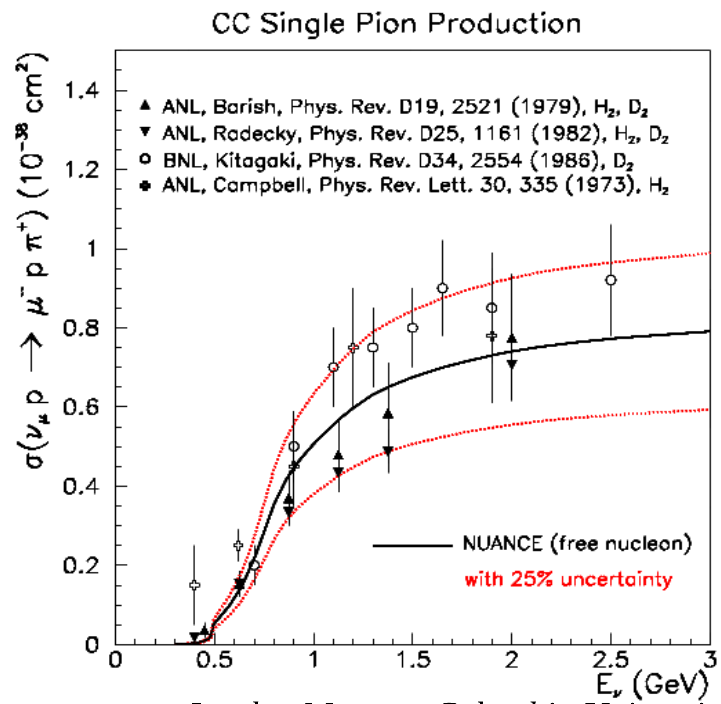
CCPiP cross section uncertainties:

- 25% uncertainty on $m_A^{1\pi}$

- 100% uncertainty on level of coherent π production

- 25% uncertainty
- derived from external data
  - driven by difference between ANL and BNL measurements





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effective CCPiP σ Errors

Final State Interaction uncertainties:

- 25% uncertainty on σ(π absorption)
- 30% uncertainty on π σ(charge exchange)
- 50% uncertainty on level of probability P (Δ N $\rightarrow$ N N)

- derived from external π scattering data
  - NUANCE v3 tuned to match
  - how to get error on P (Δ N $\rightarrow$ N N)?

The plot that compares absorption , c.e. cross sections with Ashery pion scattering data

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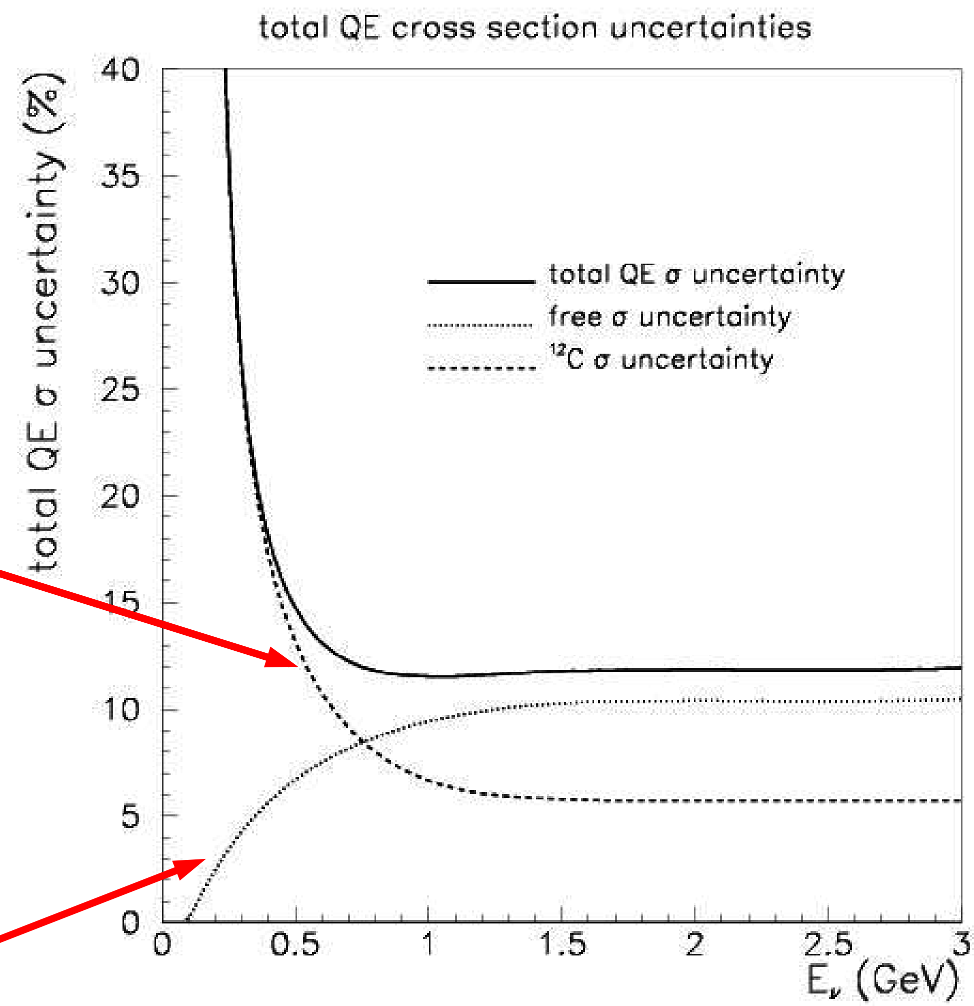
Cross Section Errors

CCQE cross section uncertainties include:

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

- 5 MeV shift in cross section
  to estimate uncertainty in σ at threshold

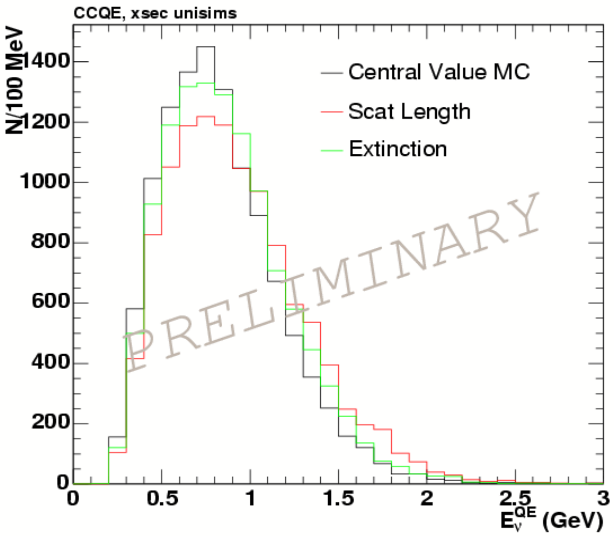
- 10% uncertainty in m_A
  to cover range in m_A from light vs. heavy target ν data fits, as well as K2K choice



Systematic Error Calculation

Estimate uncertainties by constructing an error matrix from MC to calculate 1st derivatives with respect to each source of systematic error

1. vary parameter(s) for a source of systematic error, e.g.
   - total γ extinction (attenuation length $\lambda_A \rightarrow \lambda_A + \delta\lambda_A$)
   - scattering length ($\lambda_S \rightarrow \lambda_S + \delta\lambda_S$)



2. measure the first derivative F_i in each bin i
   - $F_i^{\,A} = [\, N_i\,(\lambda_A + \delta\lambda_A) - N_i\,(\lambda_A)\,] \,/\, \delta\lambda_A$
   - $F_i^{\,S} = [\, N_i\,(\lambda_S + \delta\lambda_S) - N_i\,(\lambda_S)\,] \,/\, \delta\lambda_S$

3. construct first derivative matrix $F_{i,j}$
   - i indexes energy hins, j indexes systematic error parameters

4. construct error matrix $M_{i,l}$ from parameter correlation matrix $P_{j,k}$ and $F_{i,j}$
   - $M_{i,l} = (\, F_{i,j})^T \; P_{j,k} \; F_{i,j}$

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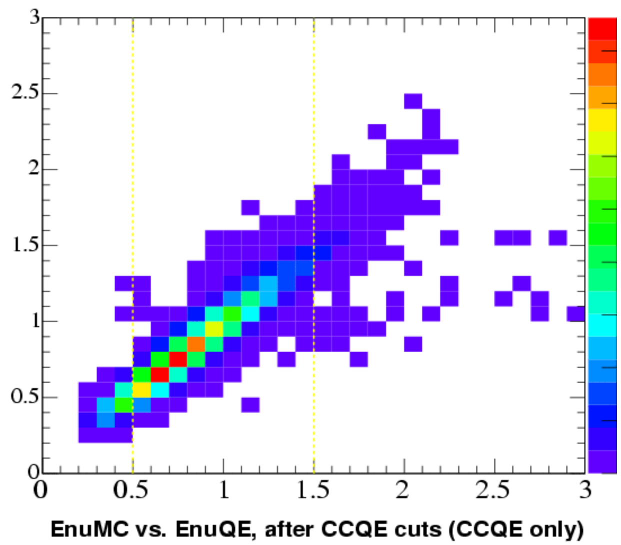
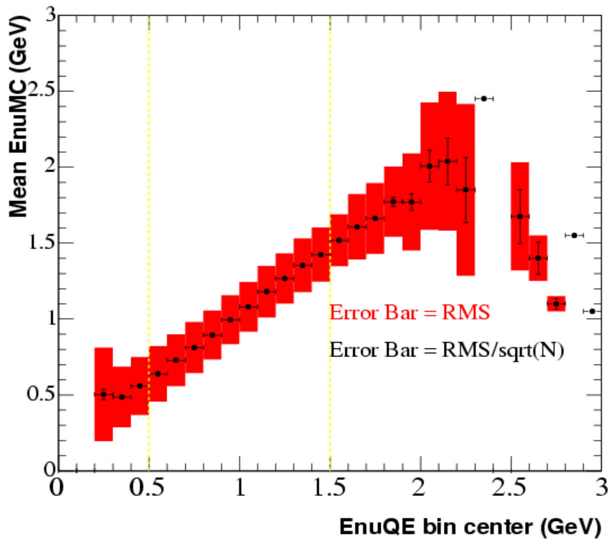
Energy Scale Uncertainty

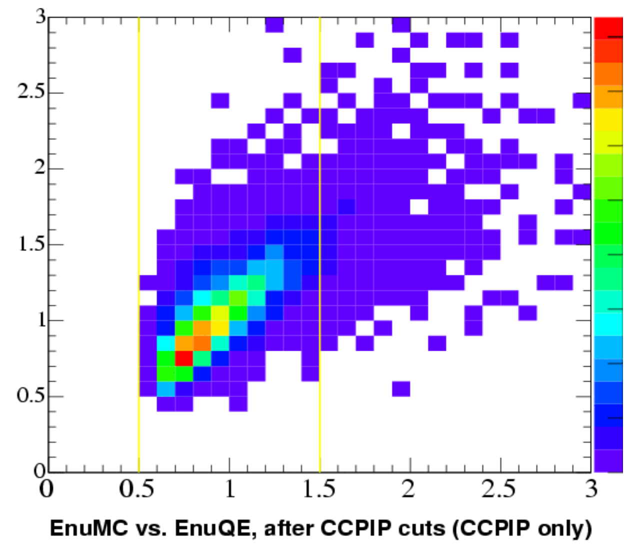
Energy scale uncertainty comes from difference performance between CCPiP and CCQE neutrino energy reconstruction.

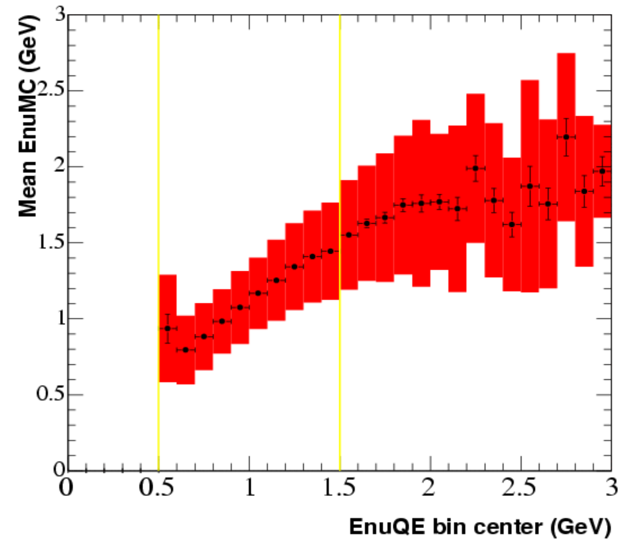
- CCQE



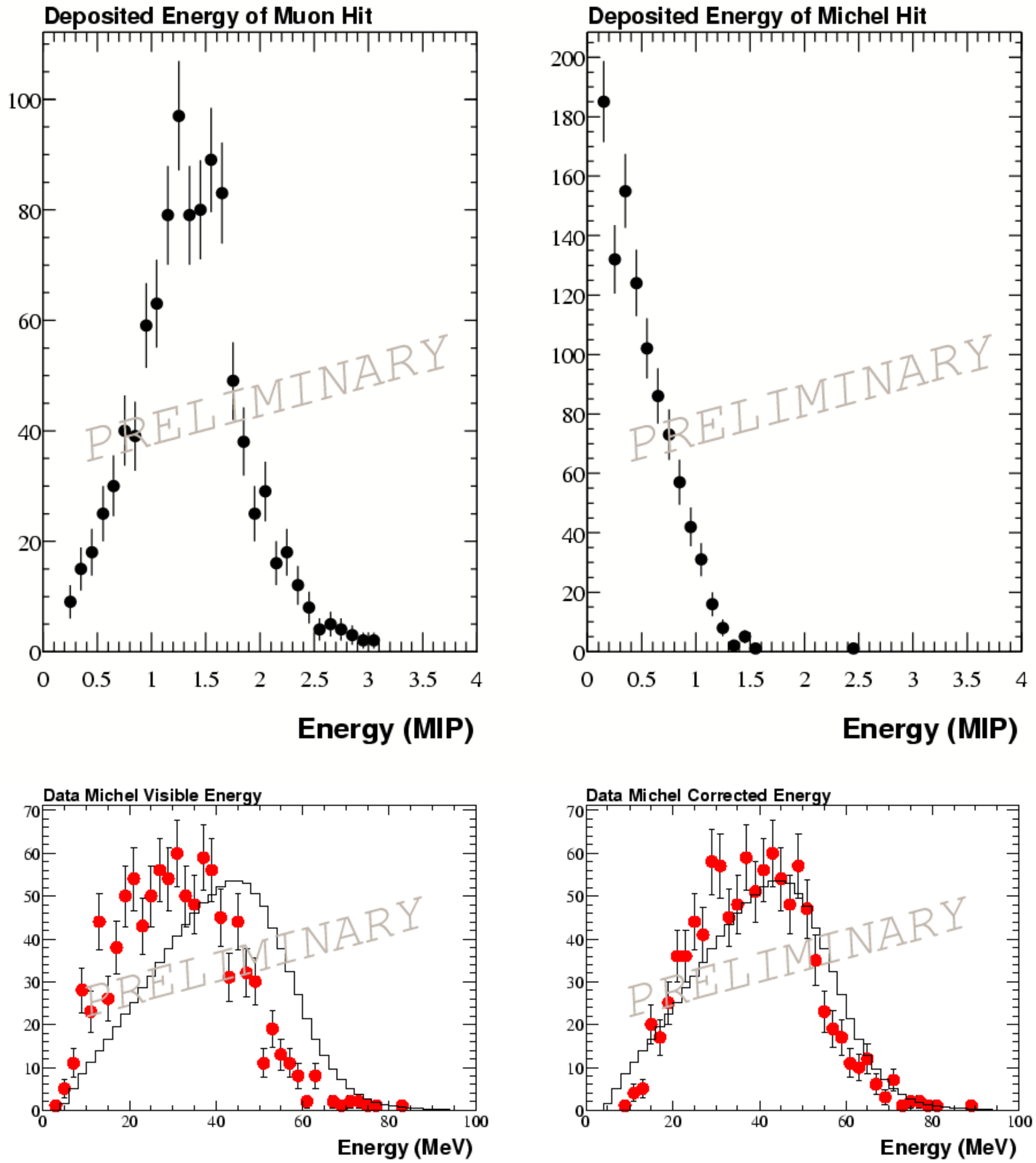


- CCPiP





Muon System Calibration Checks



- Through-going muons calibrate correction for energy lost in cube
- Amount of charge seen by cube PMT converted to energy deposited (MIPs)
- Use Michels to verify that the energy correction works
- Applying correction to Michels from cubes gives a much better match to Michels in oil

CCQE ``Golden Mode'' : MC Comparisons

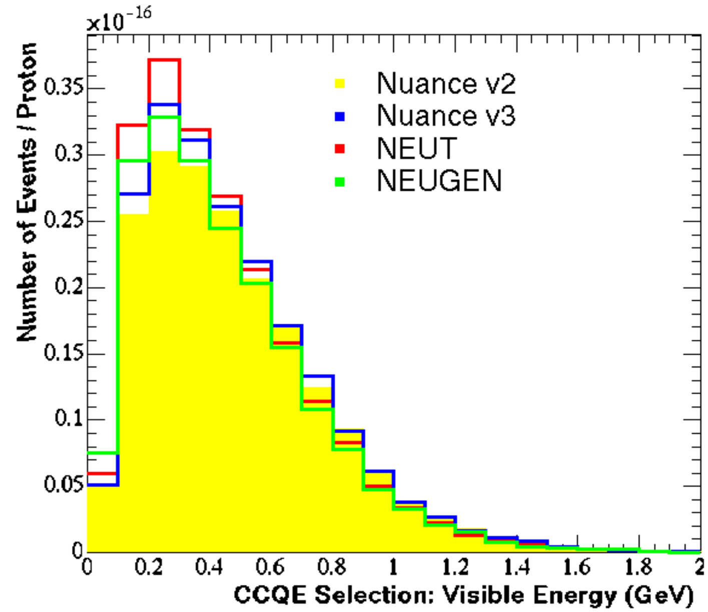
Same CCQE cuts, different Monte Carlos ...

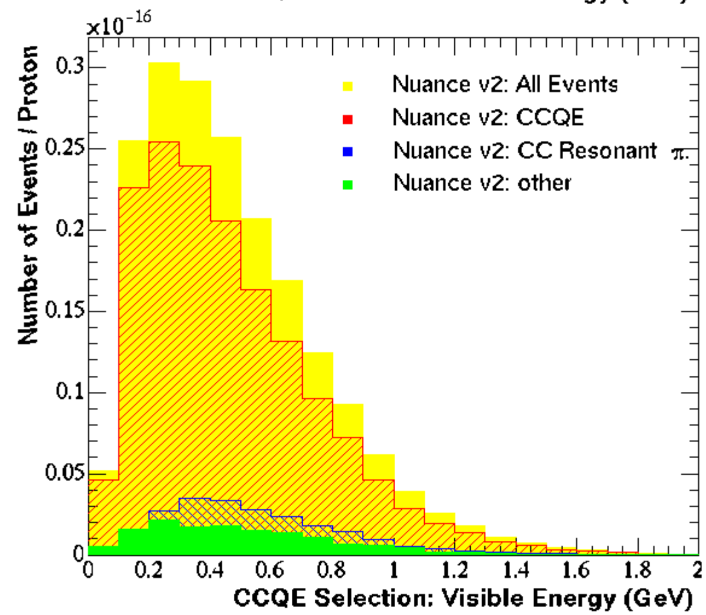
- Absolute normalization

Monte Carlo	CCQE (%)	Efficiency of cuts (%)	(Rate / proton after cuts) / v2
NUANCE v2	38.7	24.8	1.0
NUANCE v3	39.8	24.8	1.05
NEUT	38.0	24.5	1.07
NEUGEN	38.0	25.2	1.0

- After CCQE event selection: signal purity

Monte Carlo	CCQE (%)	Resonant 1 π (%)	total (%) background
NUANCE v2	83	14	17
NUANCE v3	80	16	20
NEUT	78	13	22
NEUGEN	80	16	20



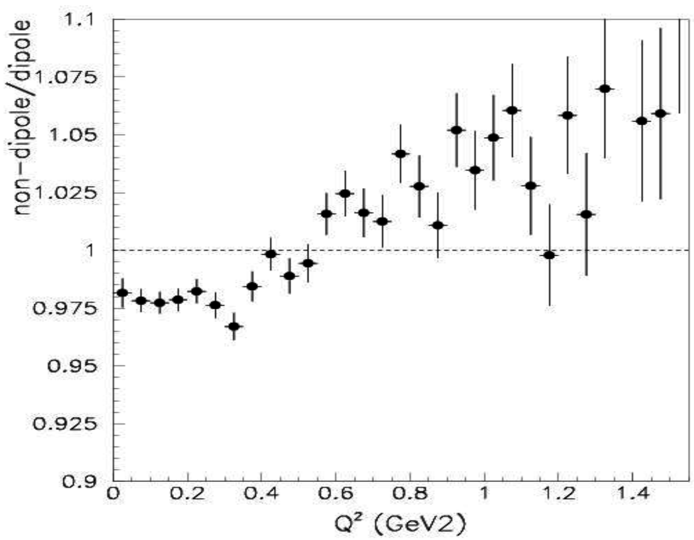


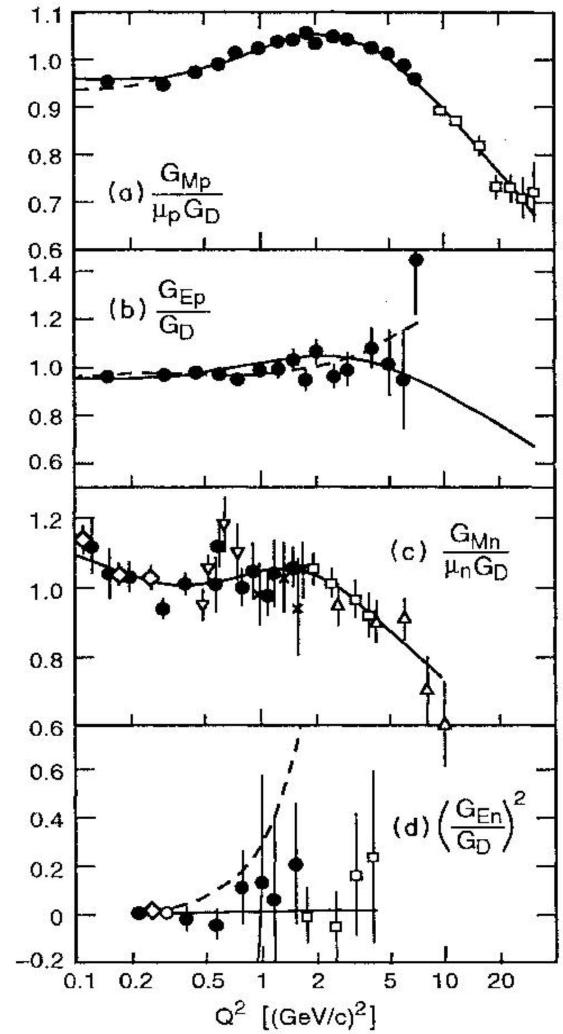
Non-Dipole Vector Form Factors (NUANCE v3)

- largest change was seen in going from dipole to non-dipole form factors (Bosted 1995)
  few-% effect on Q^2 distribution for QE events ...

$$G_M^p(Q^2) = \mu_p/(1+0.35Q+2.44Q^2+0.5Q^3+1.04Q^4+0.34Q^5)$$
$$G_E^p(Q^2) = 1/(1+0.62Q+0.68Q^2+2.8Q^3+0.83Q^4)$$
$$G_M^n(Q^2) = \mu_n/(1-1.74Q+9.29Q^2-7.63Q^3+4.63Q^4)$$
$$G_E^n(Q^2) = -1.25\mu_n\tau/(1+18.3\tau)(1+Q^2/0.71)^2,\ \tau=Q^2/4M^2$$

effect on Q^2 distribution of generated QE events:





P.E. Bosted,
Phys. Rev. **C51**, 409 (1995)

Non-Dipole Vector Form Factors (NUANCE v3)

NUANCE MC v3 uses BBA2003:

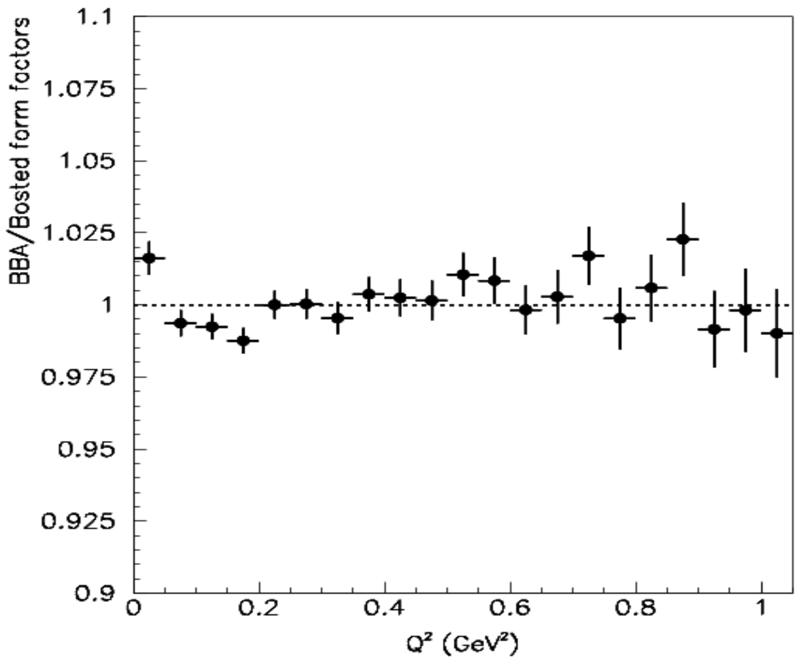
$$G_M^p(Q^2) = \mu_p/(1+3.104Q^2+1.428Q^4+0.1112Q^6-0.006981Q^8+0.0003705Q^{10}-0.7063E\text{-}5Q^{12})$$

$$G_E^p(Q^2) = 1/(1+3.253Q^2+1.422Q^4+0.08582Q^6+0.3318Q^8-0.09371Q^{10}+0.01076Q^{12})$$

$$G_M^n(Q^2) = \mu_n/(1+3.043Q^2+0.8548Q^4+0.6806Q^6-0.1287Q^8+0.008912Q^{10})$$

$$G_E^n(Q^2) = -0.942\mu_n\tau/(1+4.61\tau)(1+Q^2/0.71)^2, \qquad \tau=Q^2/4M^2$$

effect on Q^2 distribution of generated QE events (BBA/Bosted)



Bodek, Budd, Arrington BBA-2003 fit values (hep-ex/0308005)