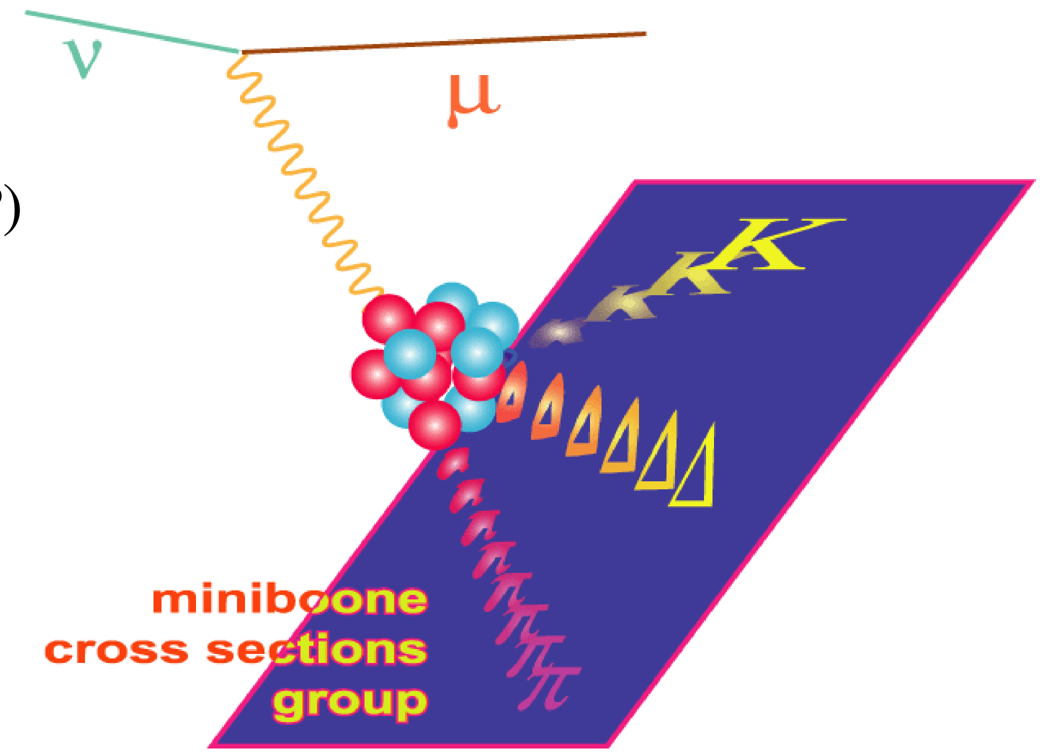
MiniBooNE
ν_μ Charged Current Analysis Progress

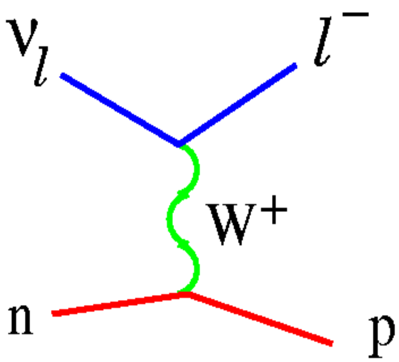
Jocelyn Monroe, Columbia University
Morgan Wascko, Lousiana State University

- CC interactions
  - Quasi-Elastic (CCQE)
  - Single π^+ Production (CCPiP)
- Measuring CC Interactions
- Modelling CC Interactions
- (CCPiP / CCQE) σ Ratio

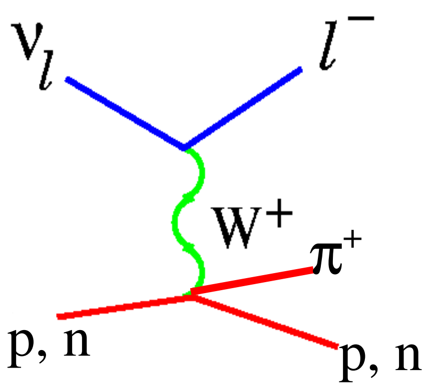


Charged Current Interactions

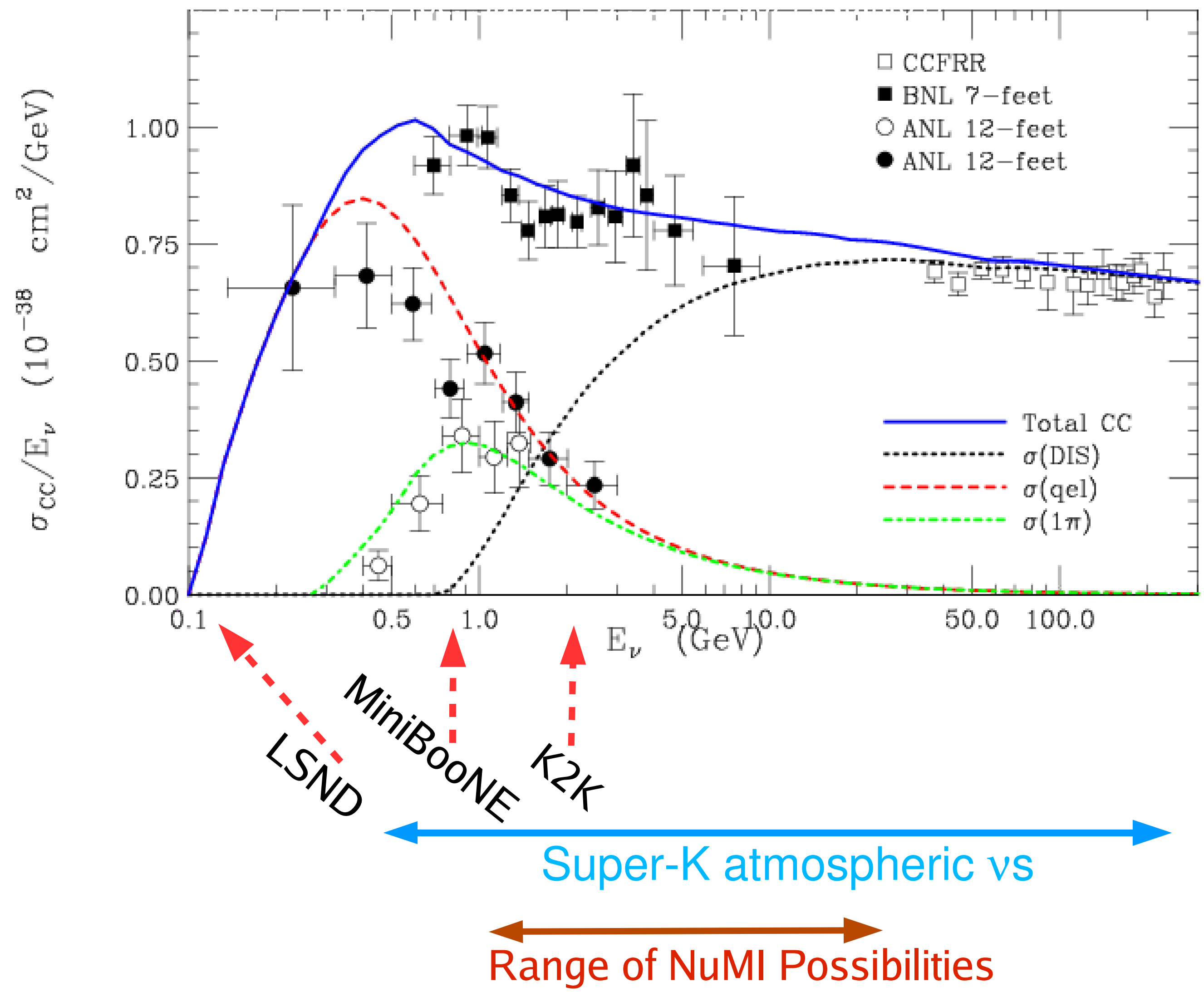
- Quasi-Elastic (CCQE)



- Single π^+ (CCPiP)



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



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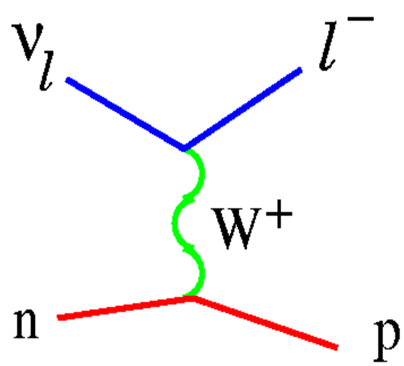
Charged Current Quasi-Elastic Interactions

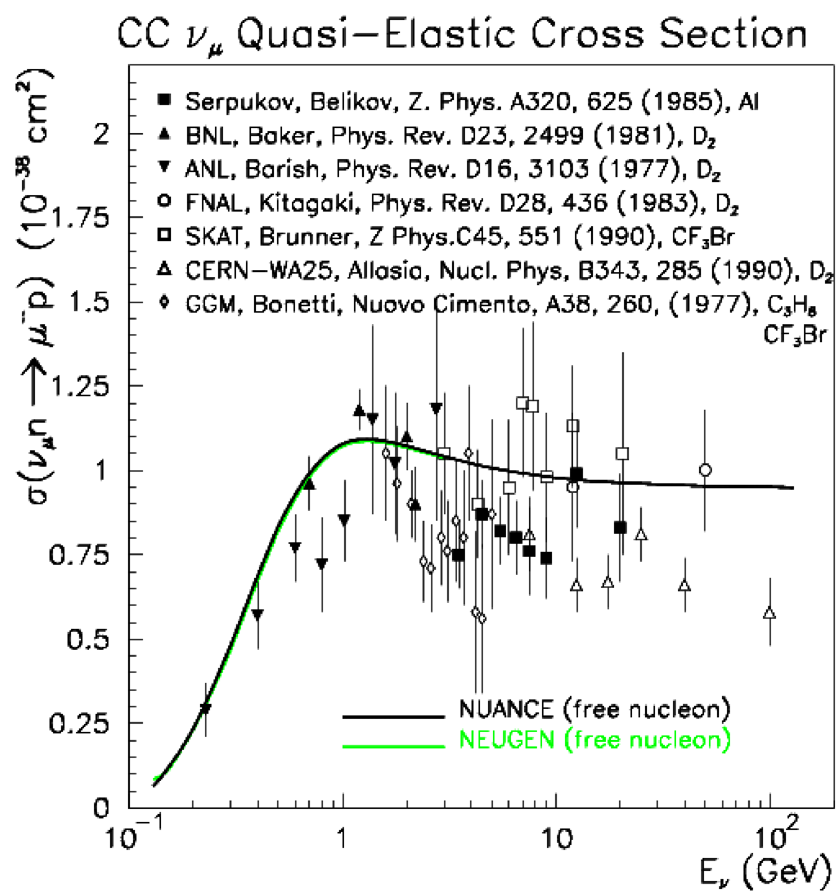
- Simple kinematics:
  - measure lepton energy, angle
  - then calculate ν energy



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

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

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



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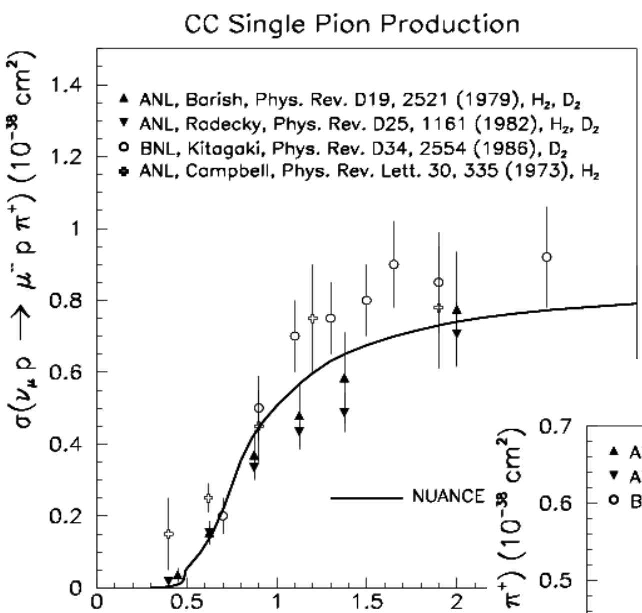
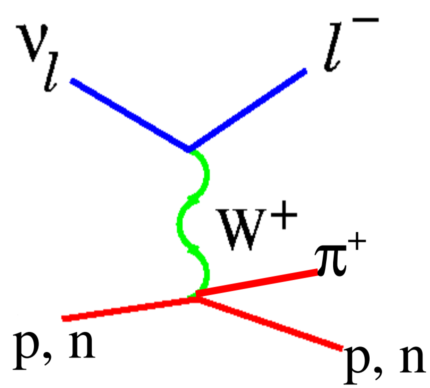
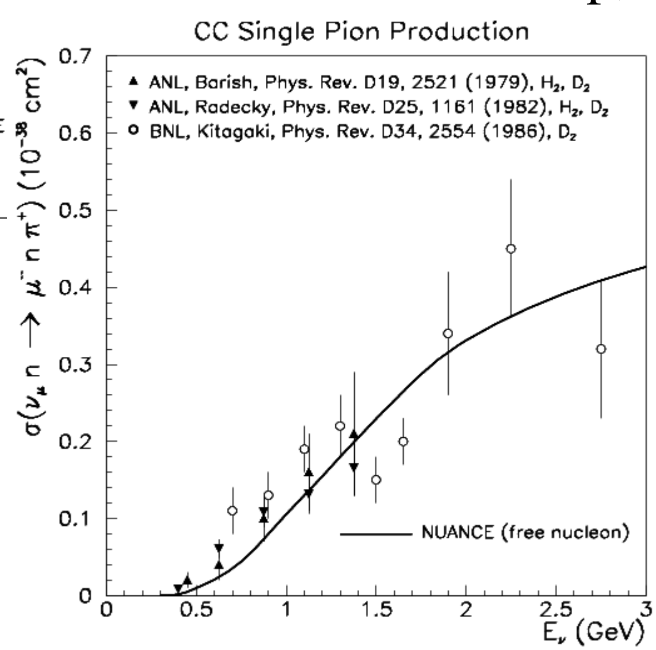
Charged Current Single π^+ Interactions

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

Resonant Production

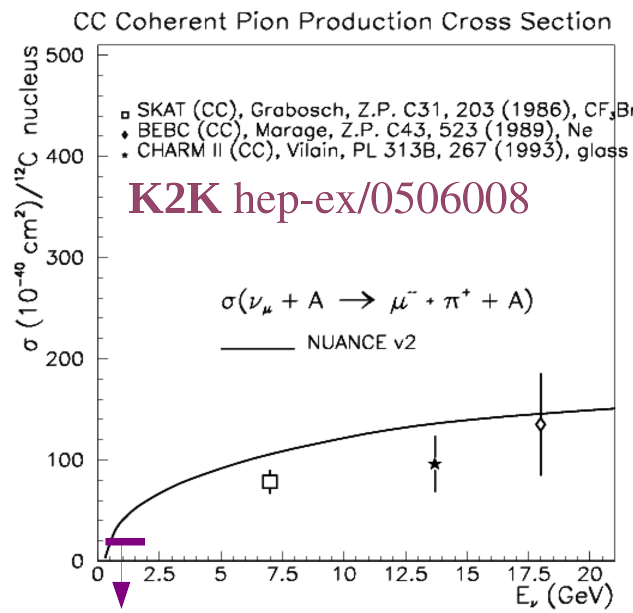


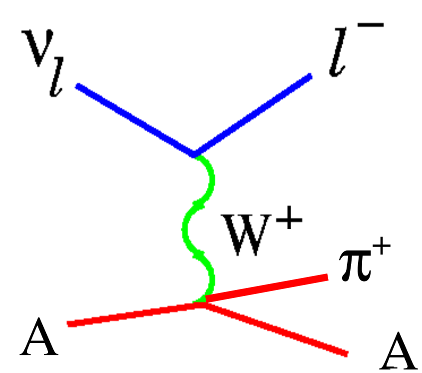




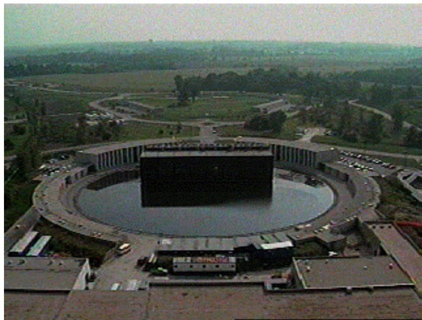
- no heavy target data below 3 GeV

Coherent Production

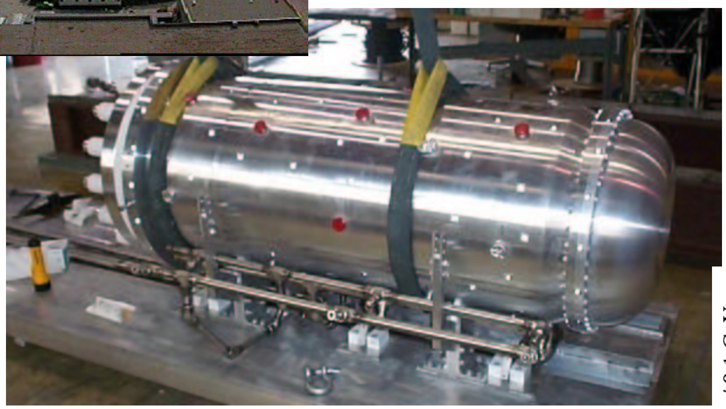




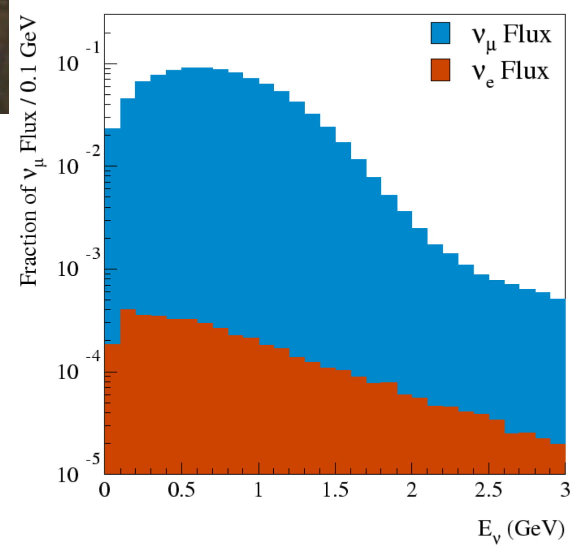
MiniBooNE Overview

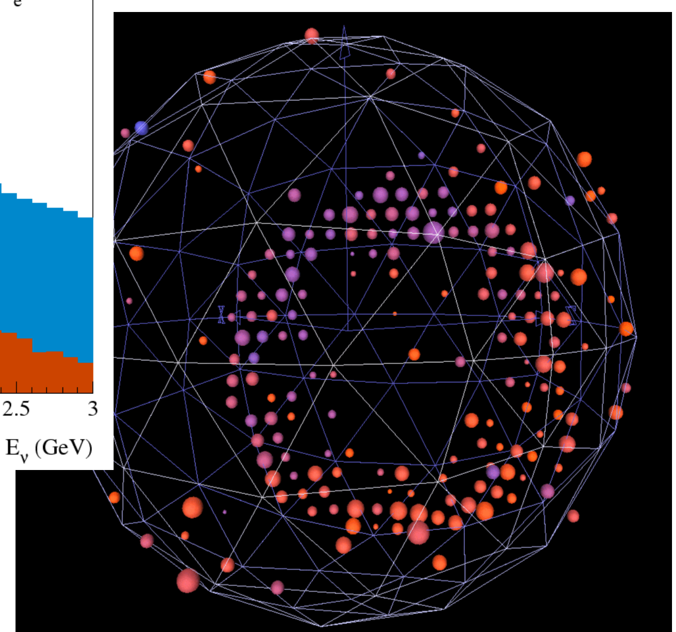


- 8 GeV KE protons from Fermilab Booster Accelerator
- 1.7 λ beryllium target (HARP results coming soon!)



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

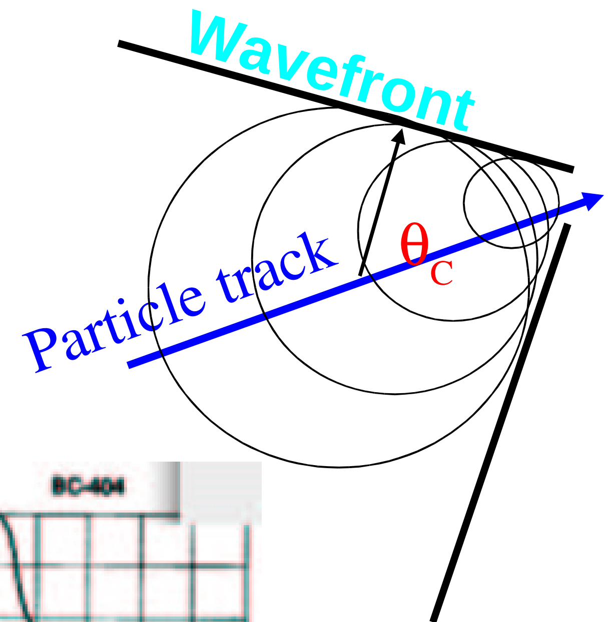




- 50 m decay region
- >99% pure ν_μ flavor beam
- 490 m dirt berm
- 800 ton CH_2 detector
- 1520 PMTs
  - 1280 + 240 in veto

Measuring CC Interactions at MiniBooNE

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

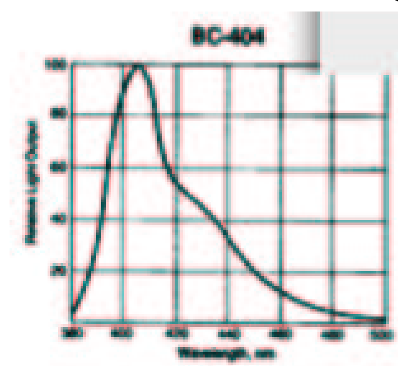


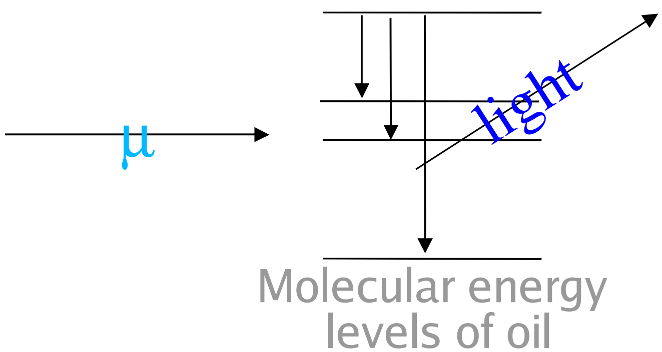
Cherenkov radiation

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

Scintillation

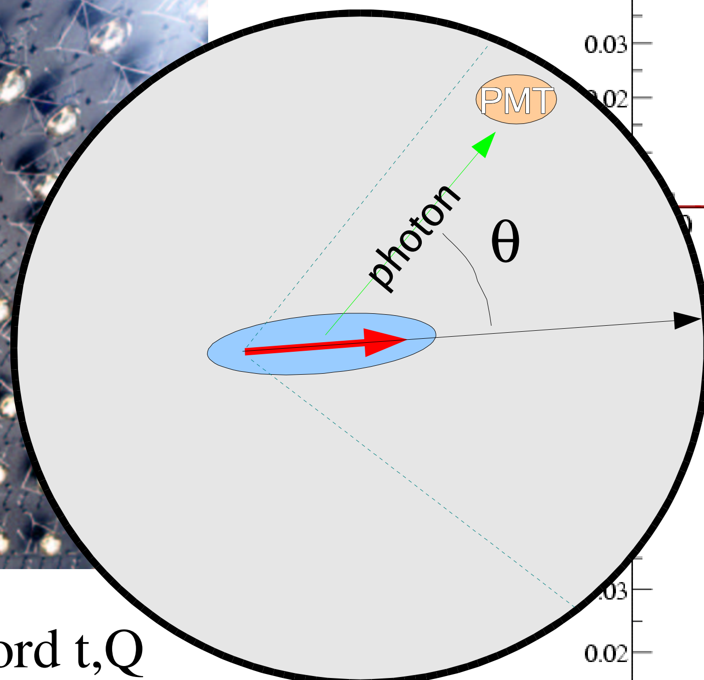
- Excited/ionized molecules emit light when electrons drop to lower E levels
- isotropic and late in time

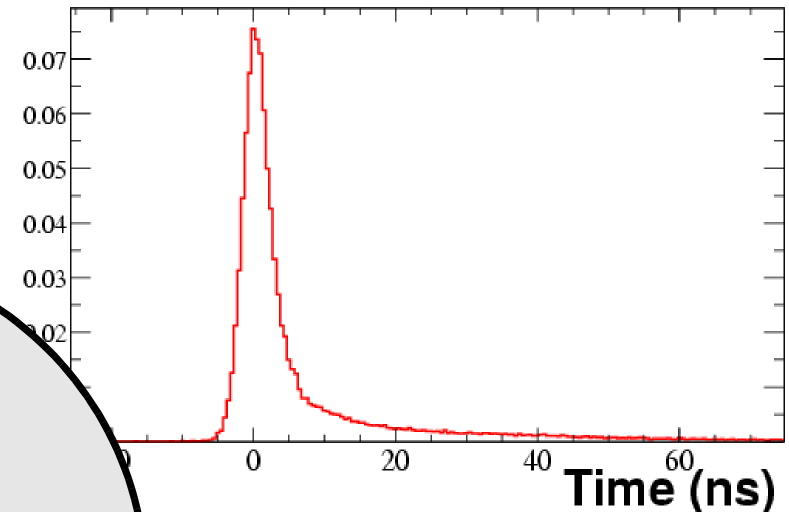


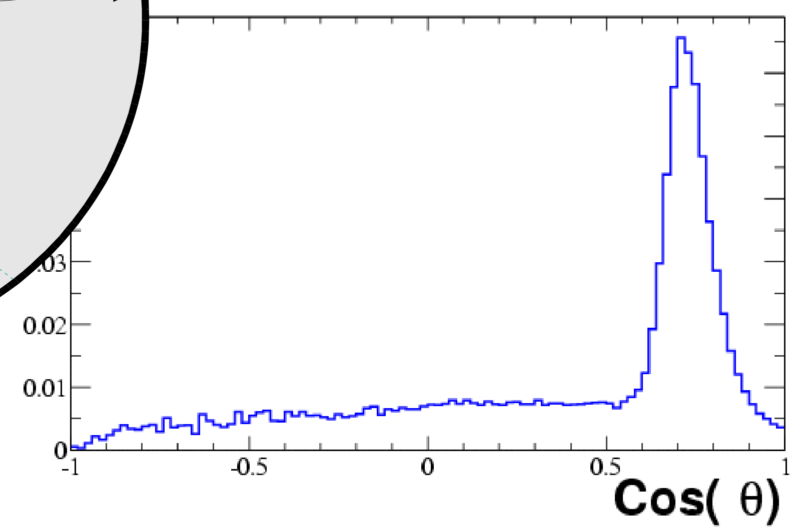


- ... **after** the γ s travel to edge of detector
  - Absorption
  - Scattering (Rayleigh)
  - Flourescence

Reconstructing CC Interactions at MiniBooNE

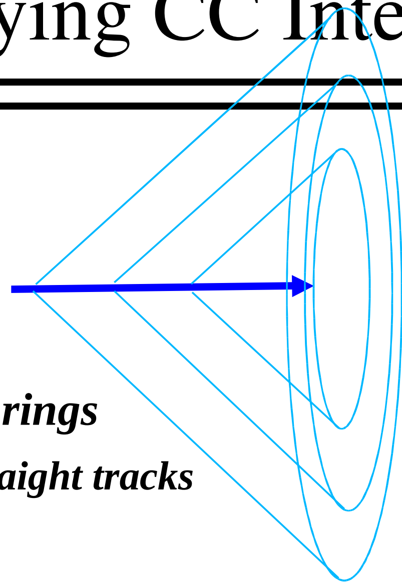




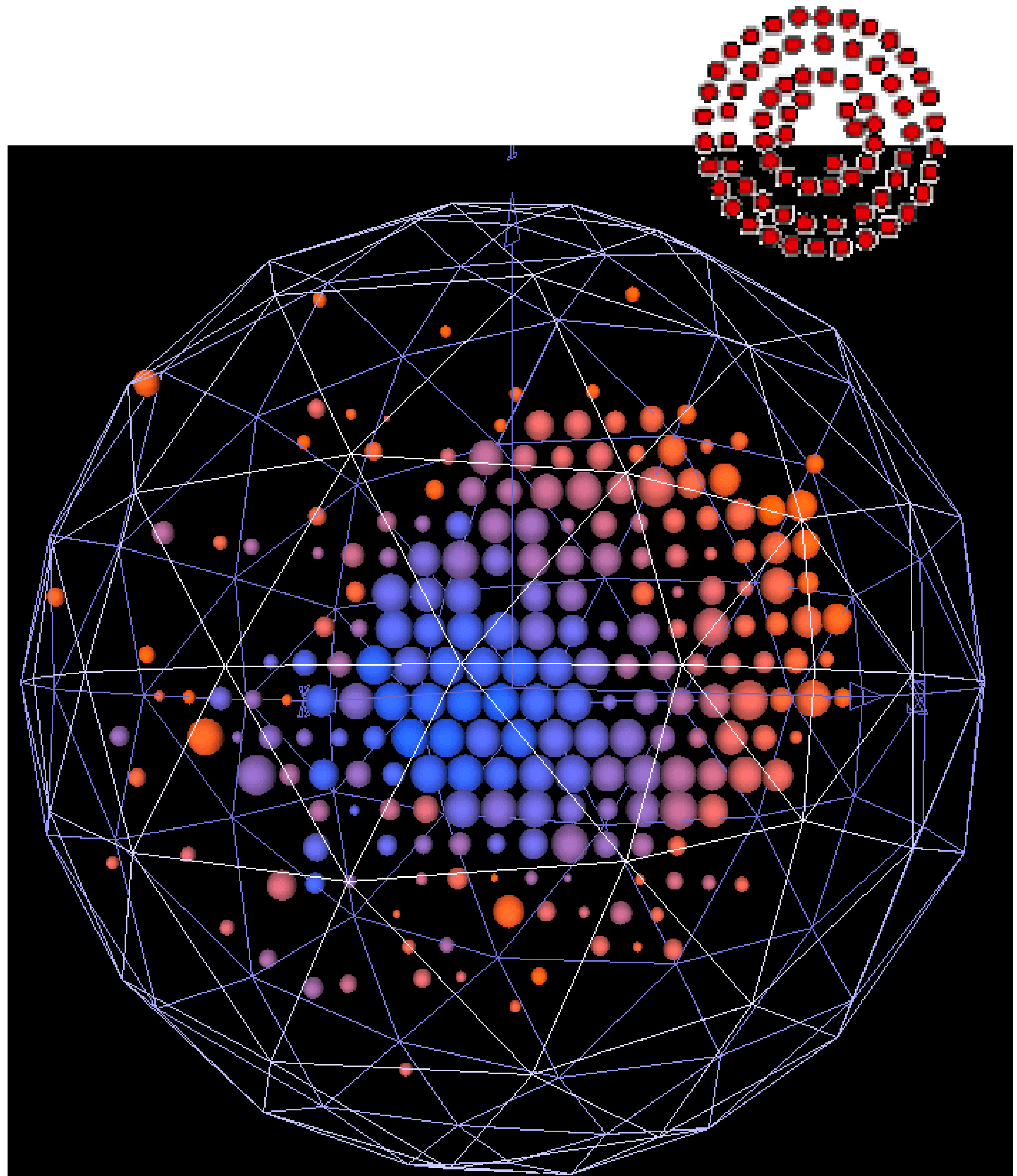


- PMTs collect γ s, record t,Q
- Reconstruct tracks by fitting time and angular distributions

Identifying CC Interactions at MiniBooNE

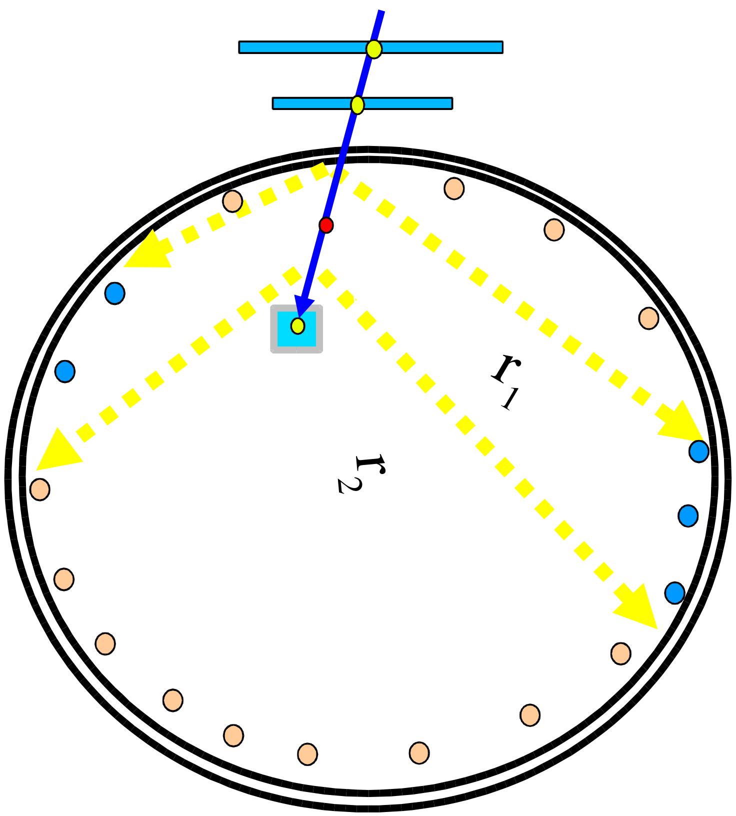


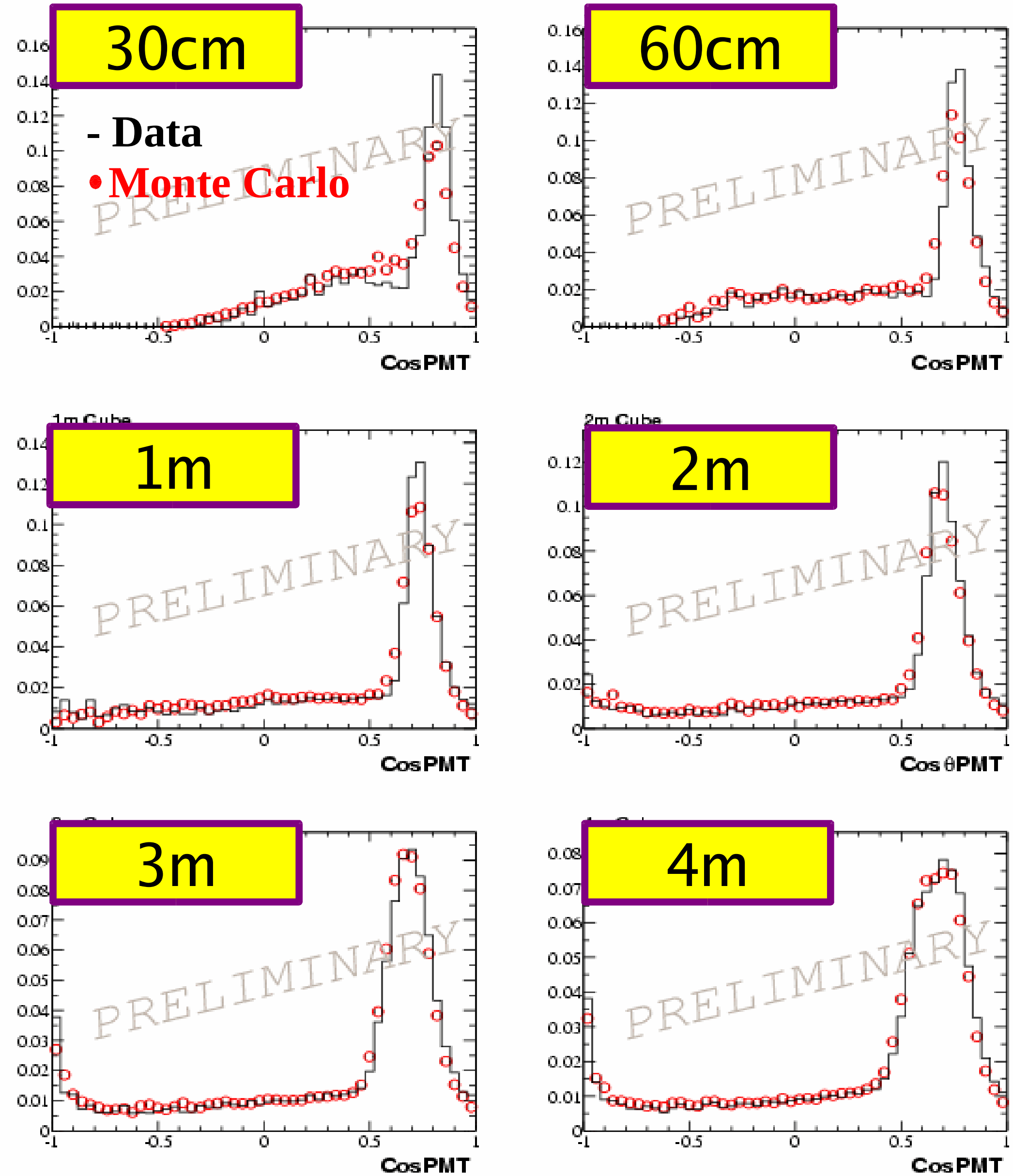
- ***Muons***
  - ***Sharp, clear rings***
    - ***Long, straight tracks***
- Electrons
  - Scattered rings
    - Multiple scattering
    - Radiative processes
- Neutral Pions
  - Double rings
    - Decays to two photons
    - Photons pair produce



Calibrating CC Interactions at MiniBooNE

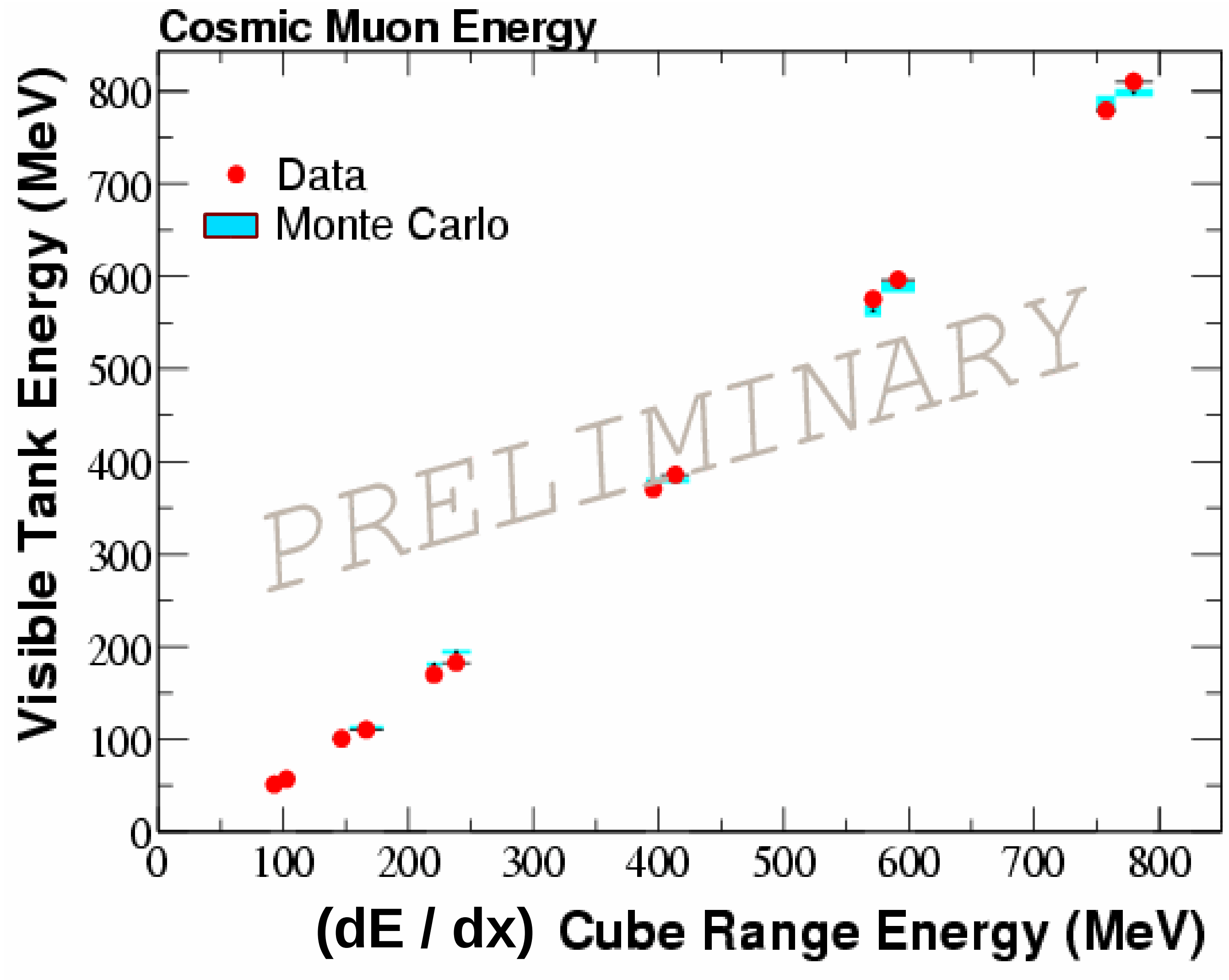
- **Use muon tracker system to determine the event parameters (x, t, u)**
- **Assemble corrected times, angles using known track center**
- **Find Cherenkov rings and time peaks, isotropic and delayed emission**



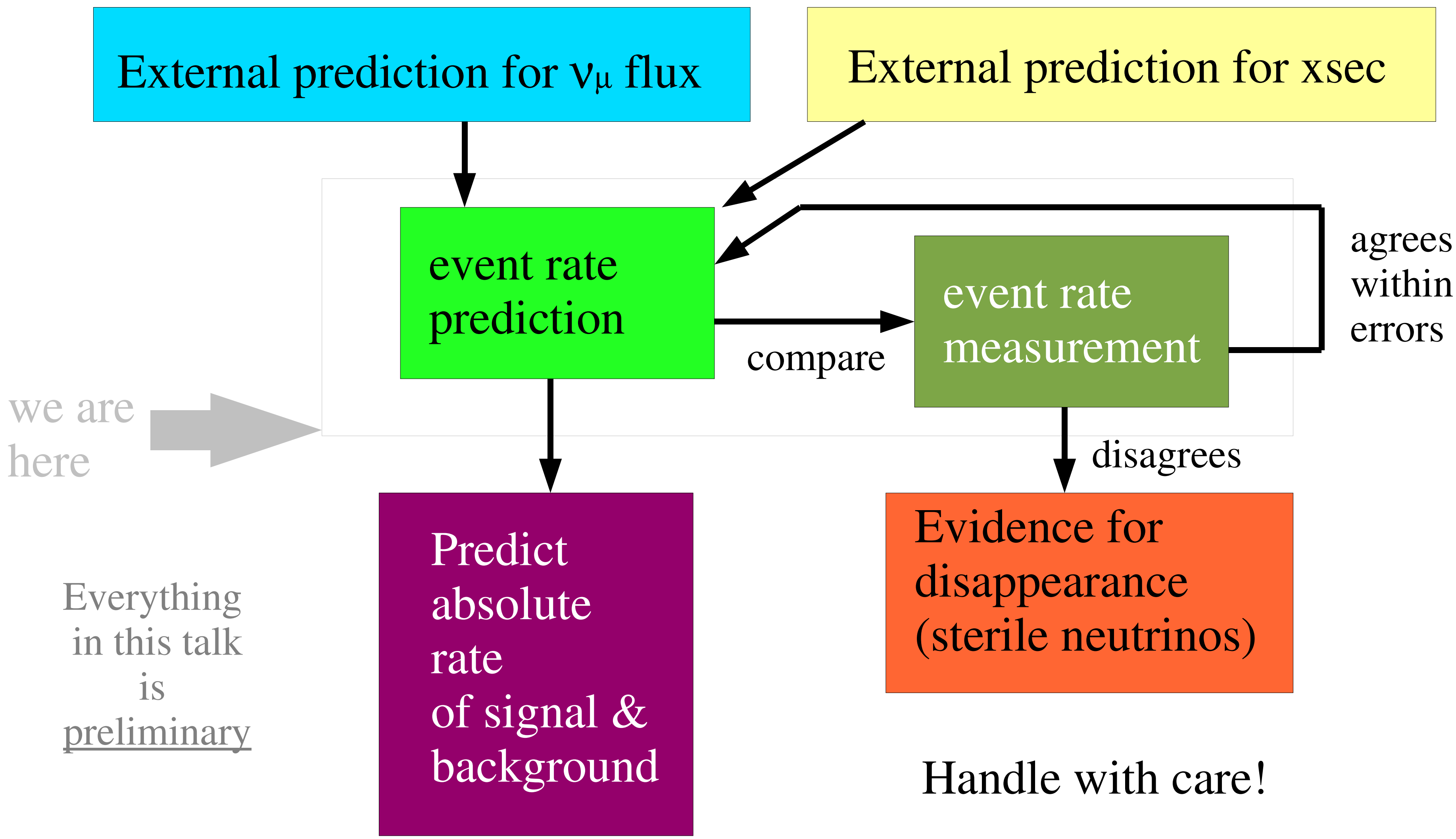


Calibrating CC Interactions at MiniBooNE

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



Modelling CC Interactions at MiniBooNE



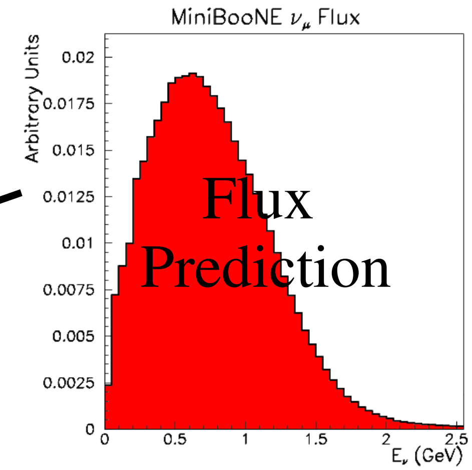
External Prediction for σ_ν

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
- Rein-Sehgal coherent cross section
  - m_A = 1.03 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)

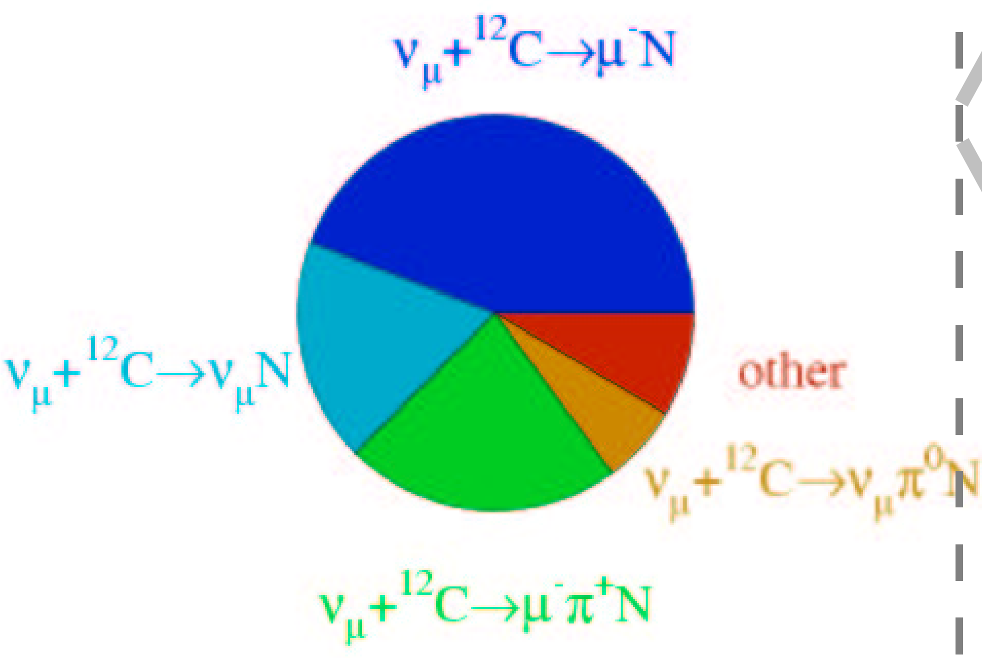
MiniBooNE Analysis Framework (reconstruction, etc.)

Compare with Data!

Jocelyn Monroe, Columbia University

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 ...

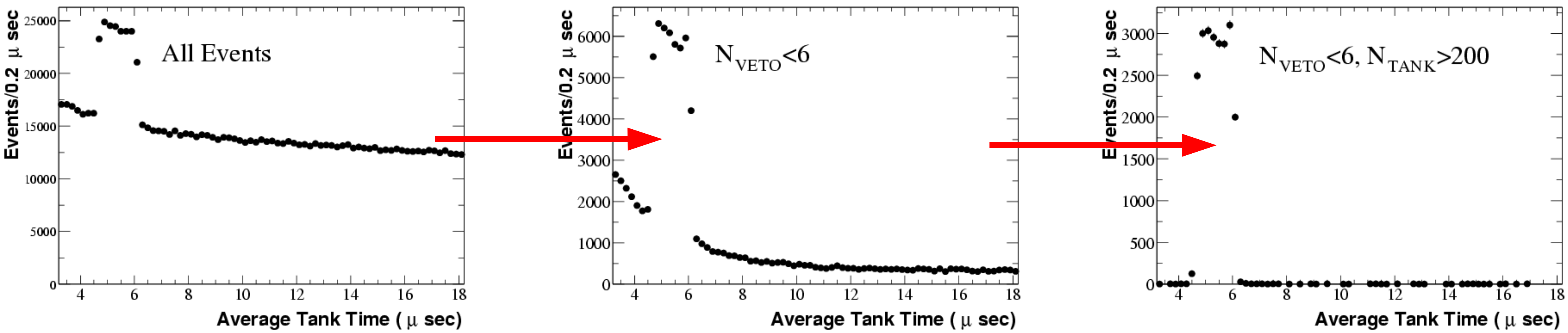
This Analysis:

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

... 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

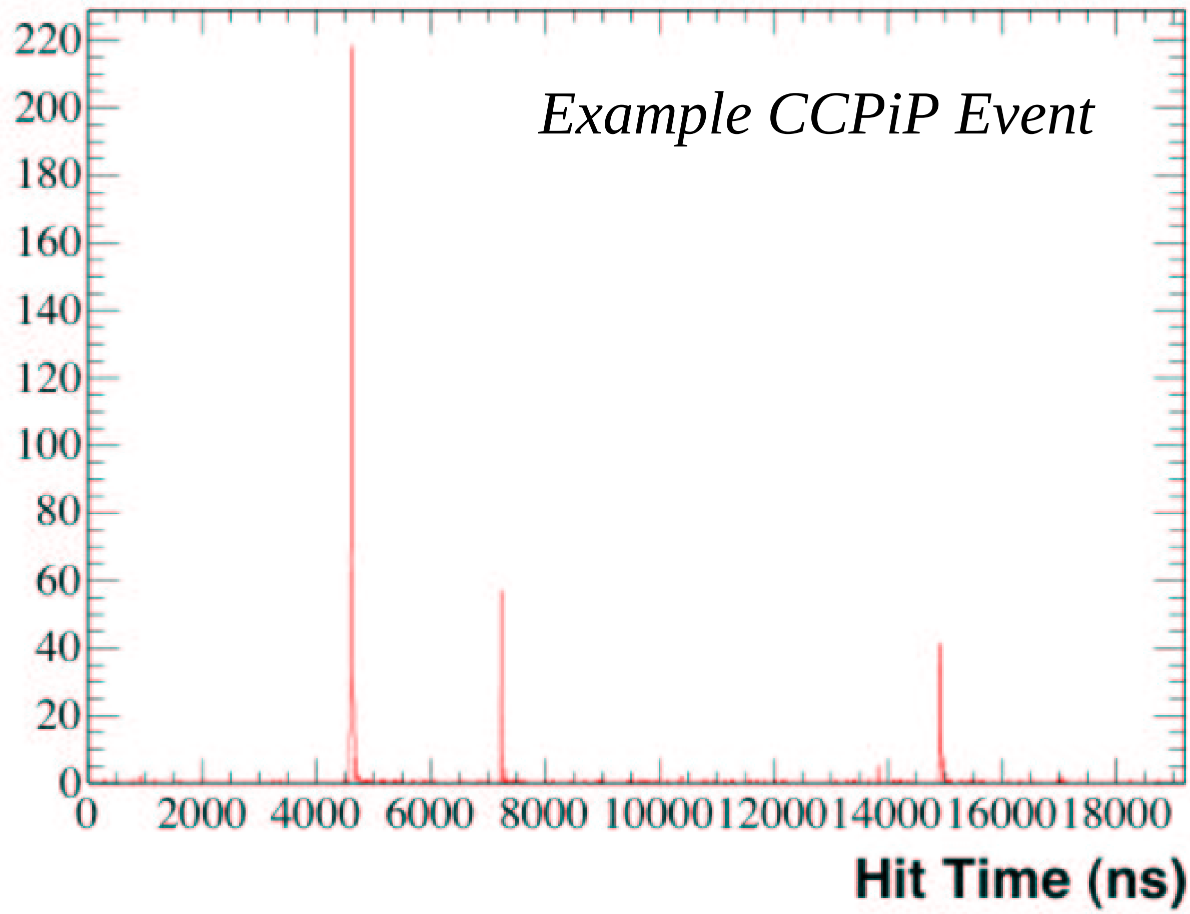
- Use Muon Decay to Identify Charged Current Event Candidates

  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!



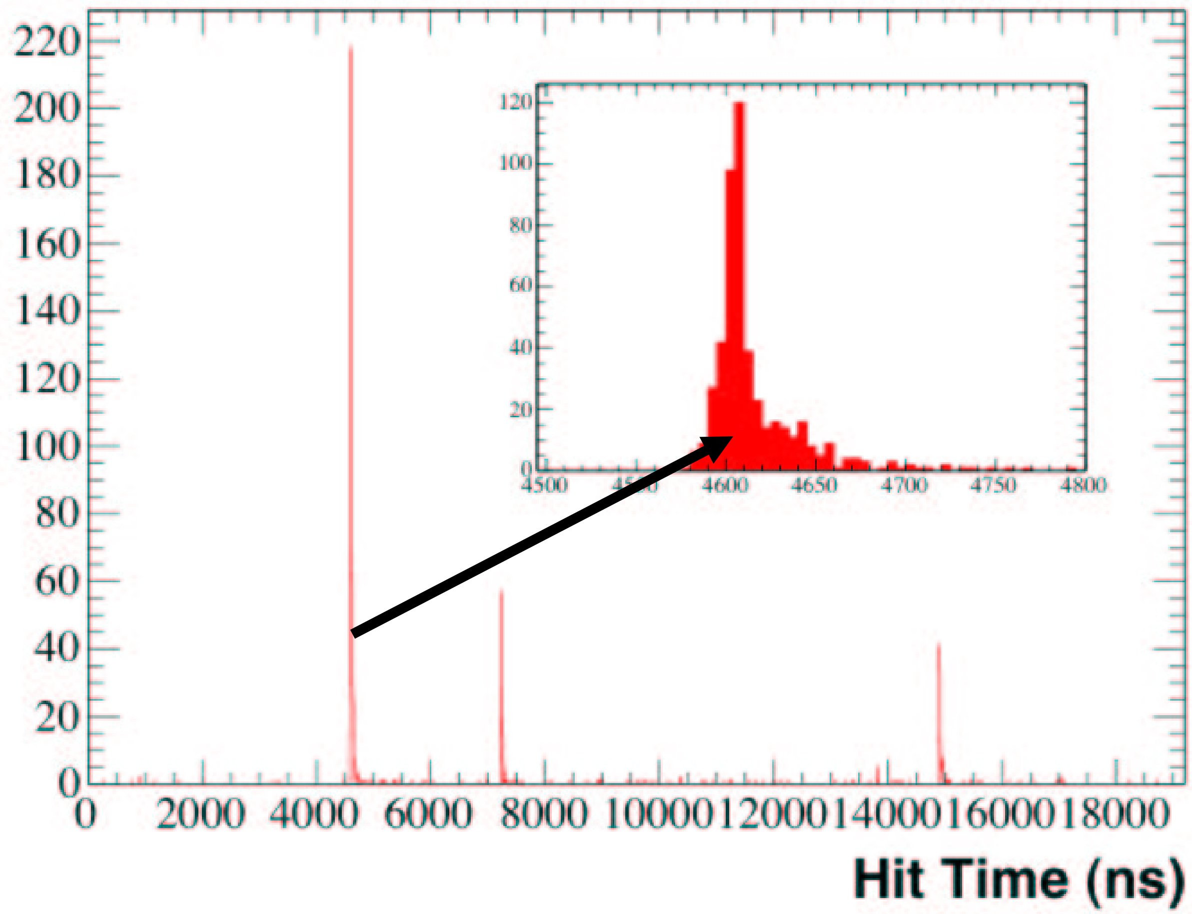
Charged Current Event Selection

- 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



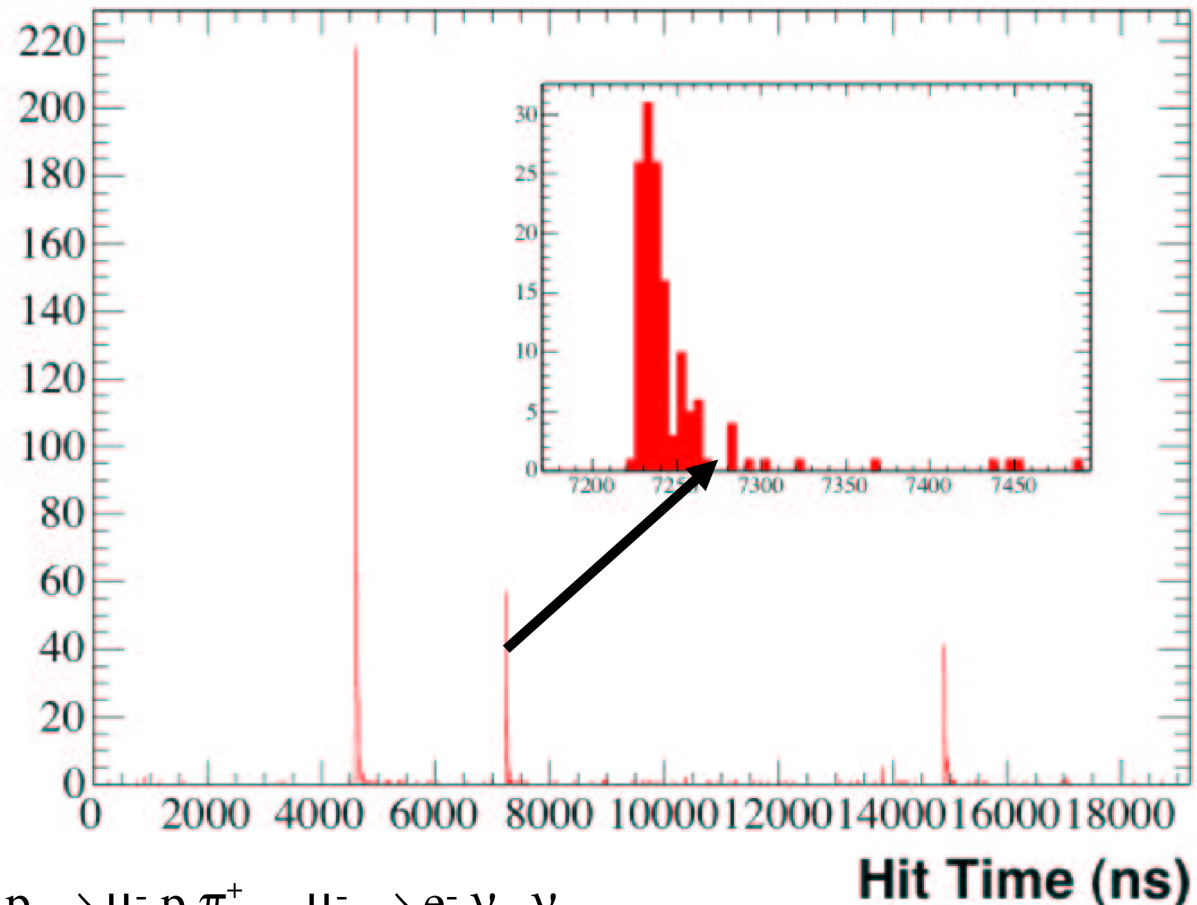
Charged Current Event Selection

- 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:

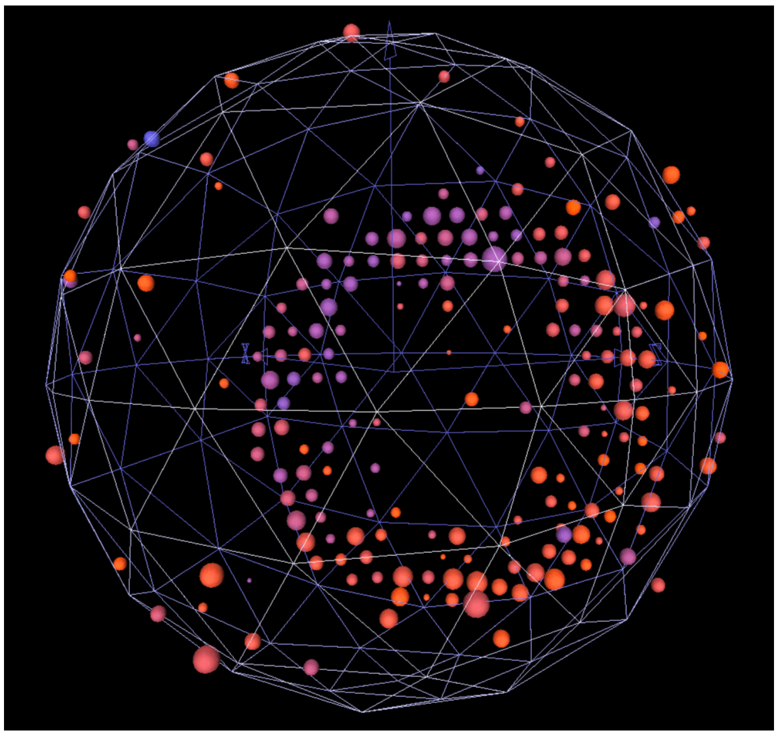
- Neutrino-Induced Event Selection Cuts
- CC Selection Cut
  - < 3 sub-events

Signal:

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

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

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

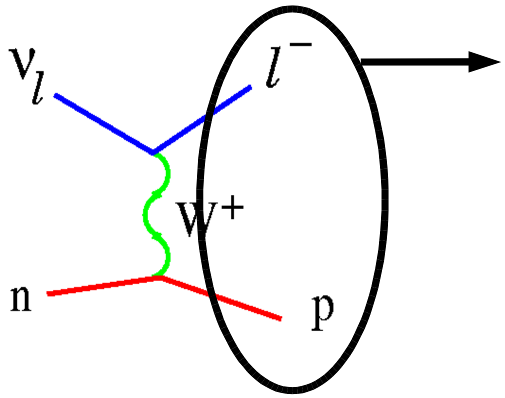


Second Level Cuts: Final State ID

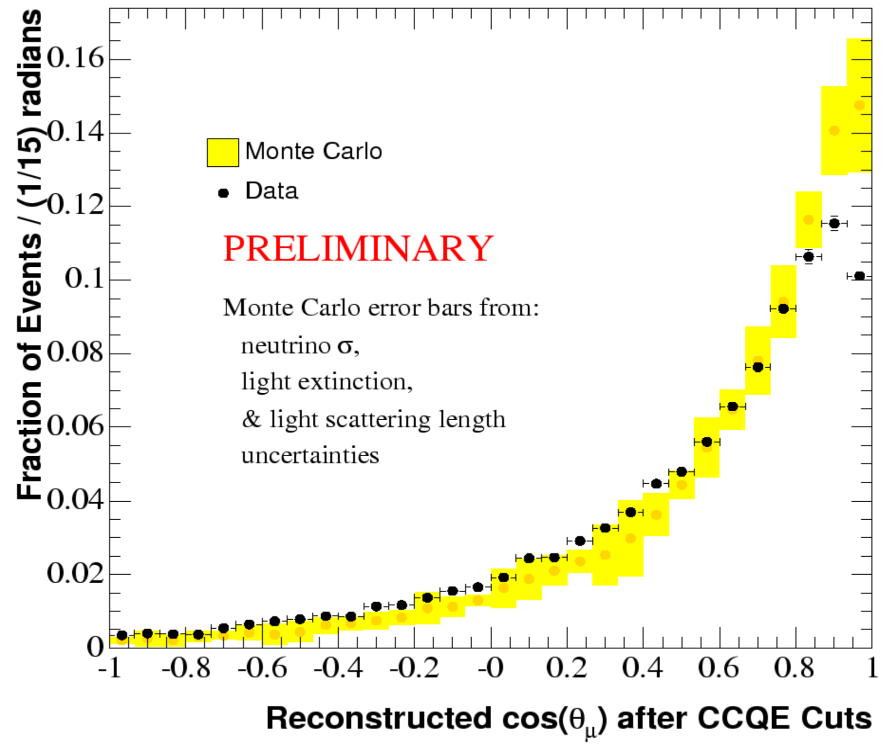
- event topology
  - fraction of on- vs. off- ring light
- PMT hit timing
  - fraction of prompt vs. late light
- μ-like energy loss
  - given E, is track length consistent with μ?
- 10 variable Fisher discriminant

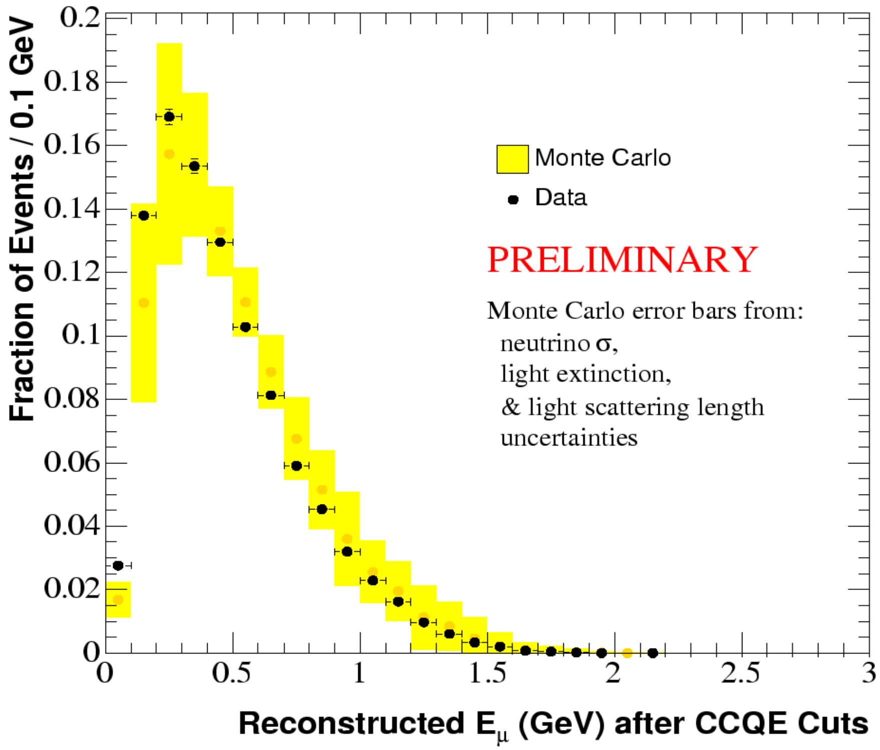
- Result: 86% CCQE purity
  - most of background from CCPiP
  - more pure than in past presentations

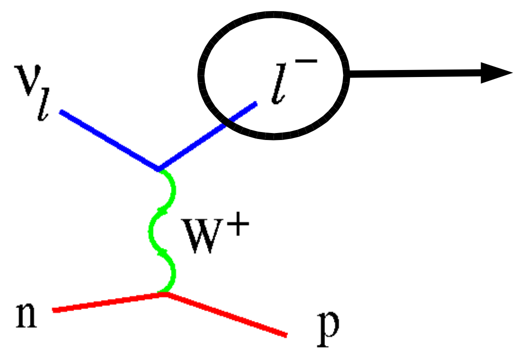
CCQE Data



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

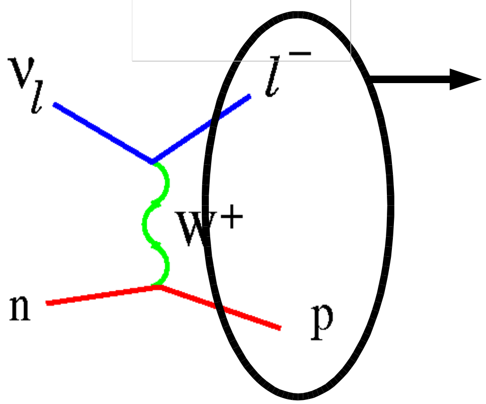






reconstruct μ direction from Cherenkov light, cos(θ) = 1 ~ low Q^2

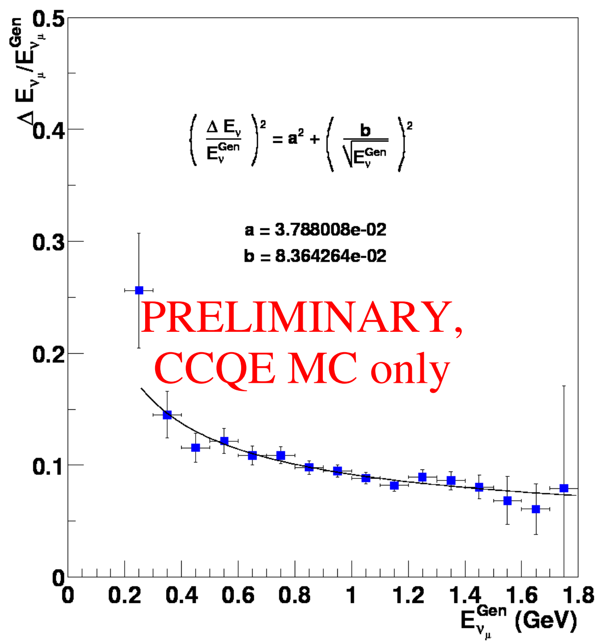
CCQE Data

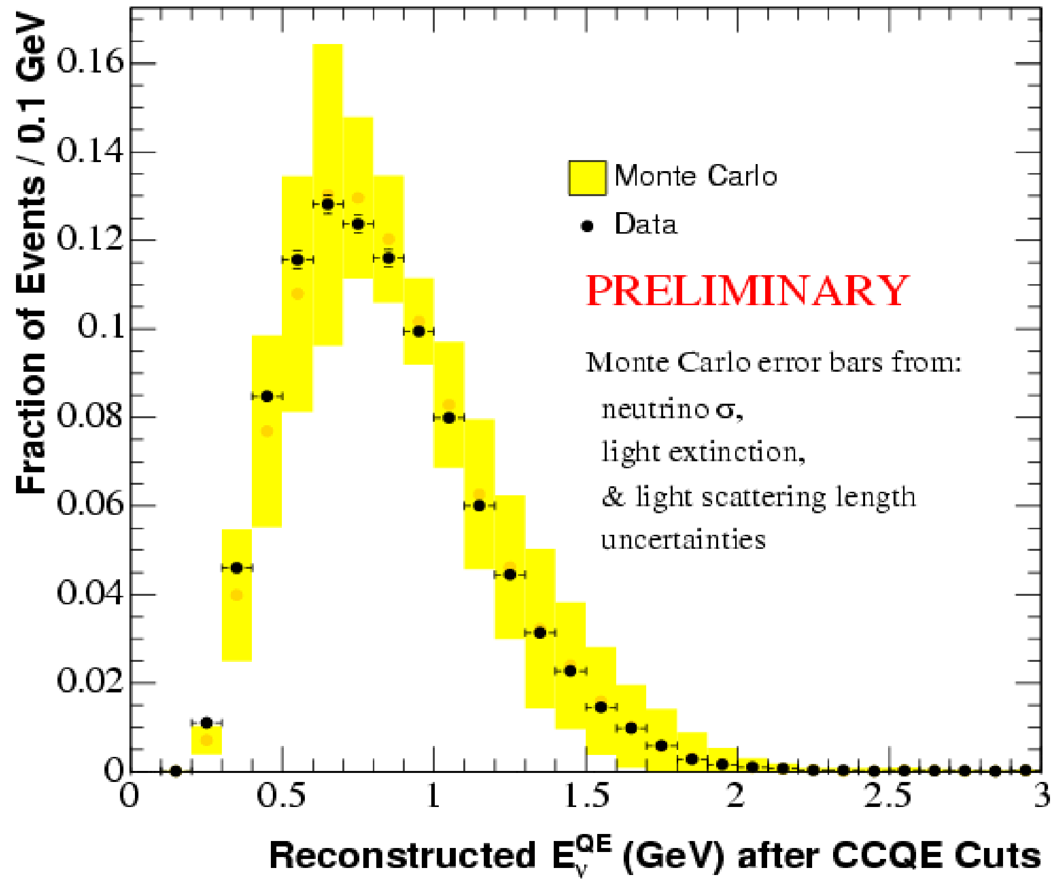


use measured μ visible energy and angle to reconstruct E_ν^{QE}

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

Neutrino Energy Reconstruction





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CCPiP Event Selection

First Level of Cuts:

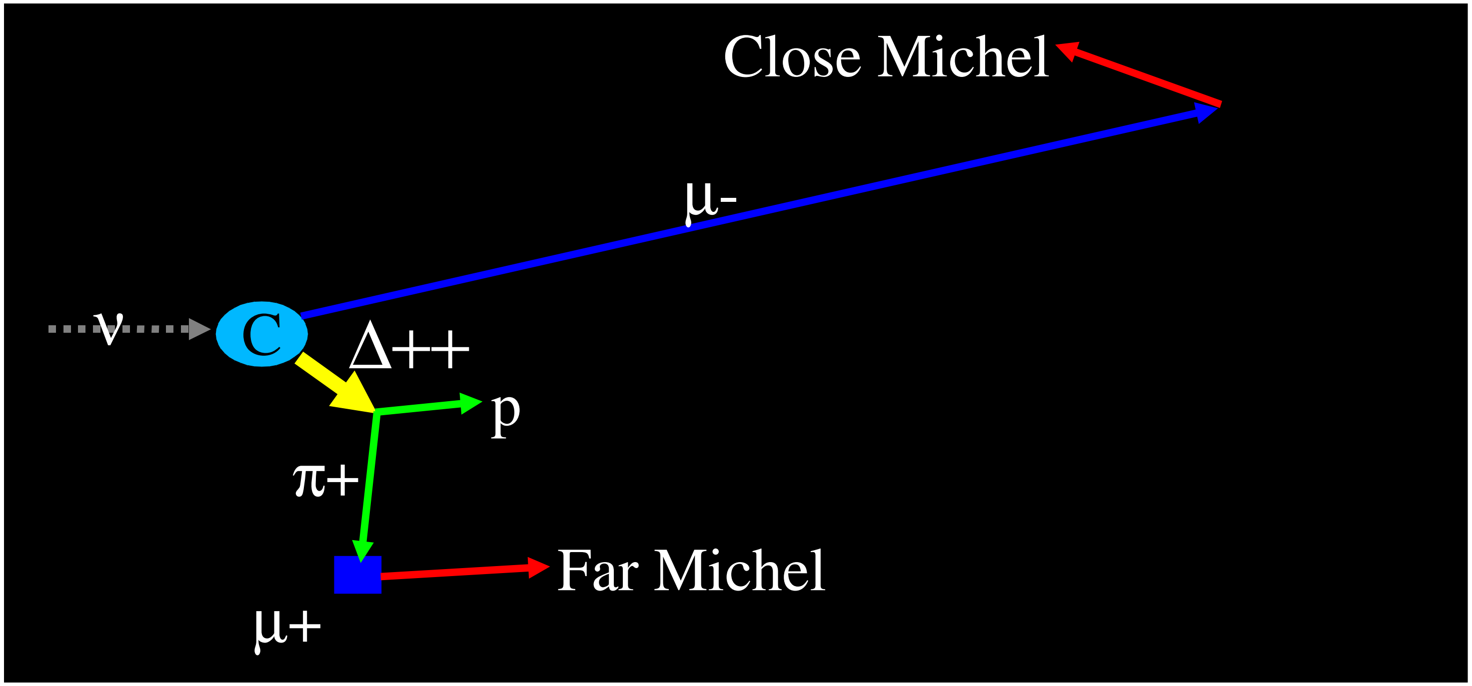
- Neutrino-Induced Event Selection Cuts
- CC Selection Cut
  - exactly 3 sub-events
  - 2nd 2 sub-events consistent with Michel e^- ($20 < N_{PMT} < 200$)

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 complex!

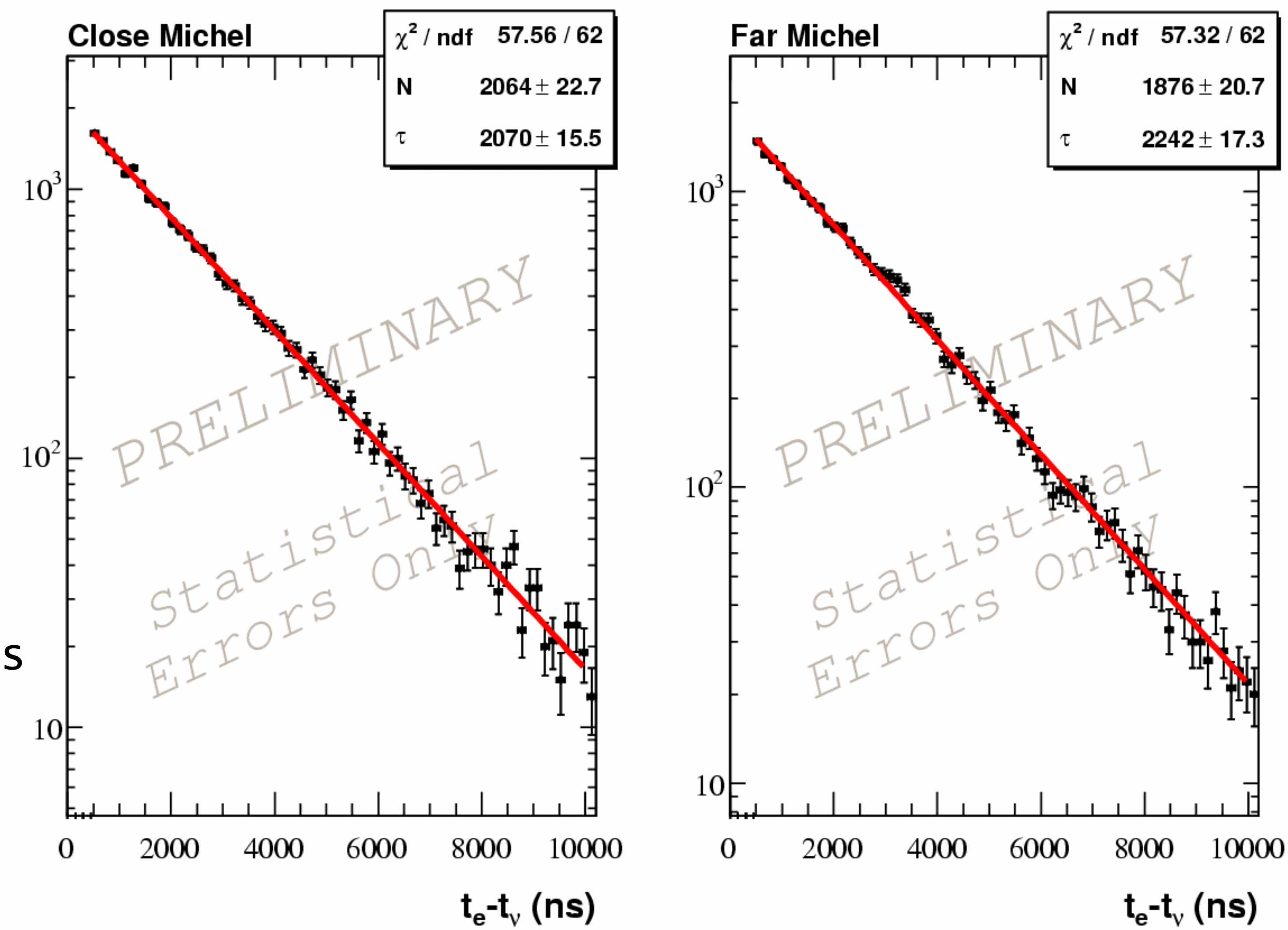
84% purity with 1st level cuts, bgnd from Nπ and QE

CCPiP Event Selection Validation

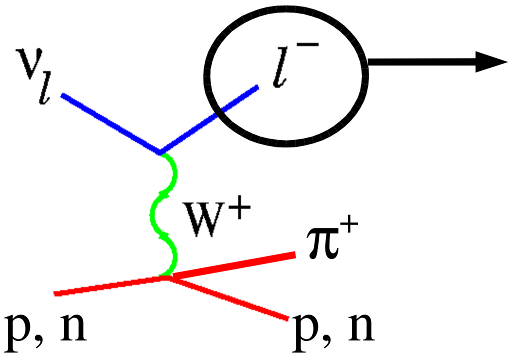
- validate CCPiP event selection with μ^+ and μ^- lifetime measurement
  - separate Michels from μ^+ and μ^- by distance to μ^- track

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

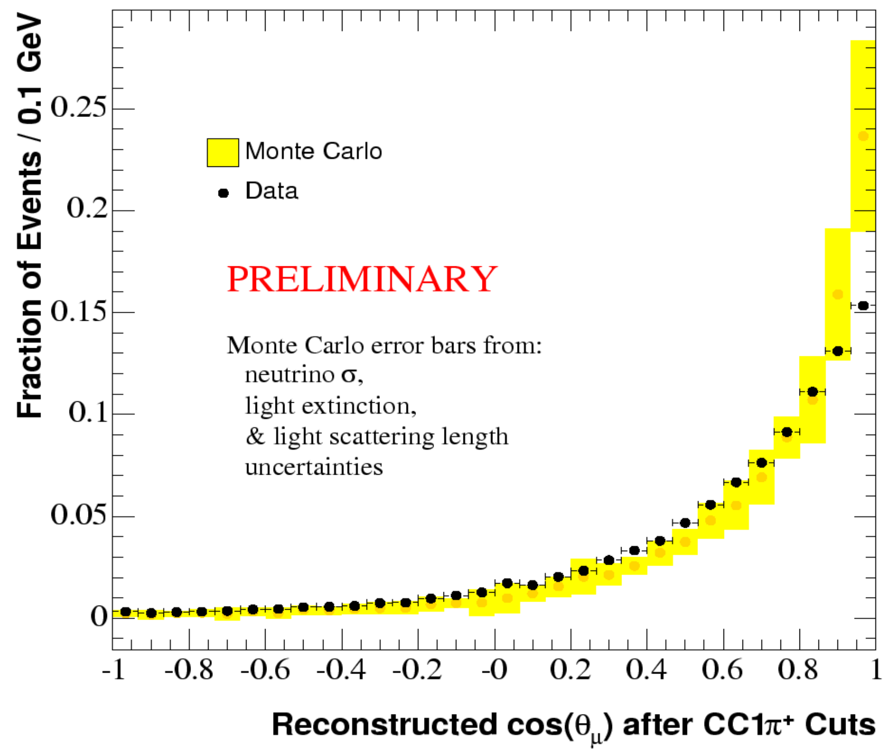
- far:
  μ^+ do not capture
  expect
  τ=2197.03±0.04 ns
  measure
  τ=2242±17.3 ns

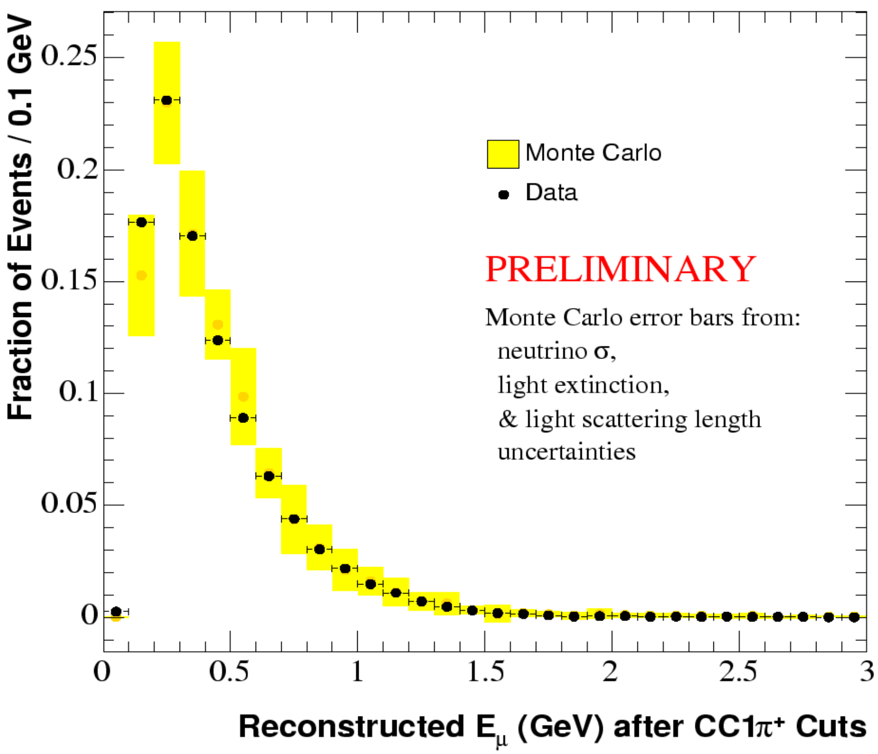


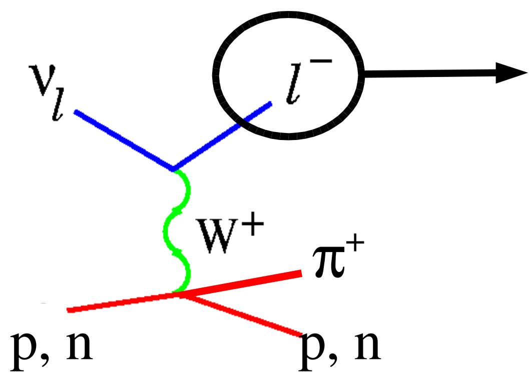
CCPiP Data



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

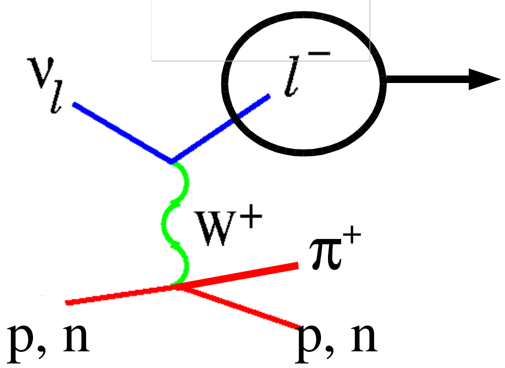






reconstruct μ direction from Cherenkov light, $\cos(\theta) = 1 \sim$ low Q^2

CCPiP Data

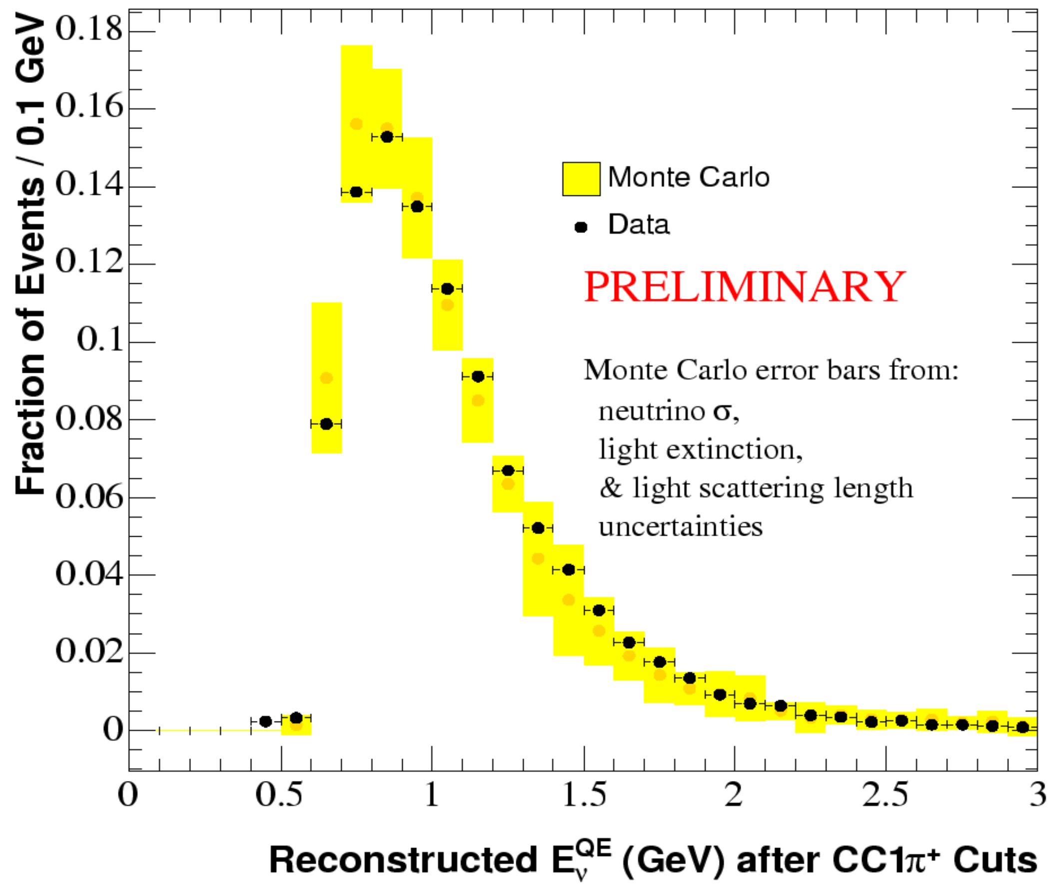


use measured μ visible energy and angle to reconstruct E_ν^{QE}

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

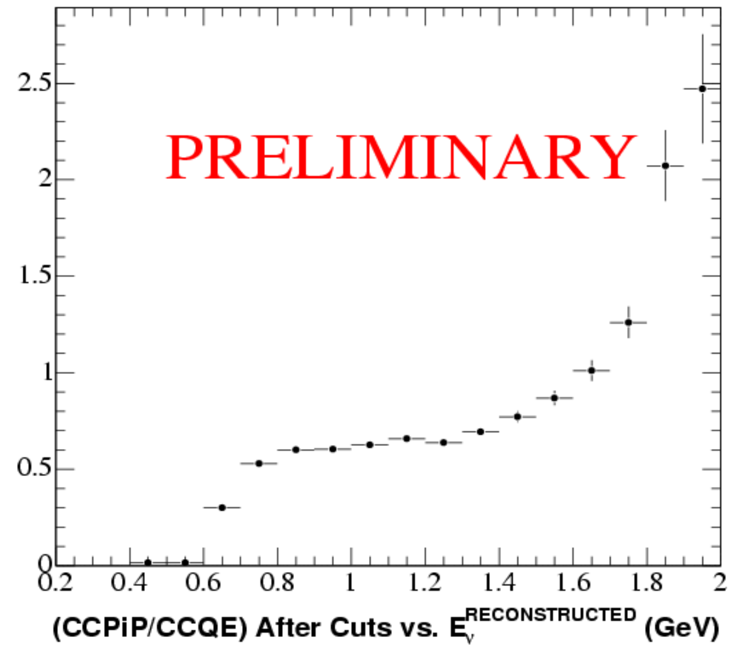
Neutrino Energy Reconstruction

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



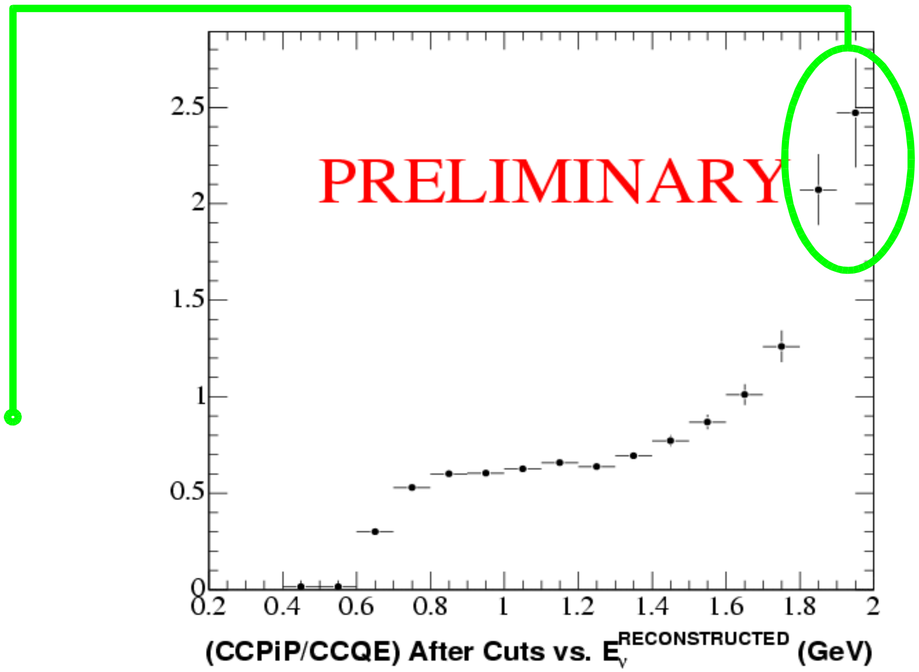
CCPiP/CCQE Ratio

- Without cut efficiency corrections:
  - measured N(CCPiP)/N(CCQE) vs. E_ν^{QE}



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



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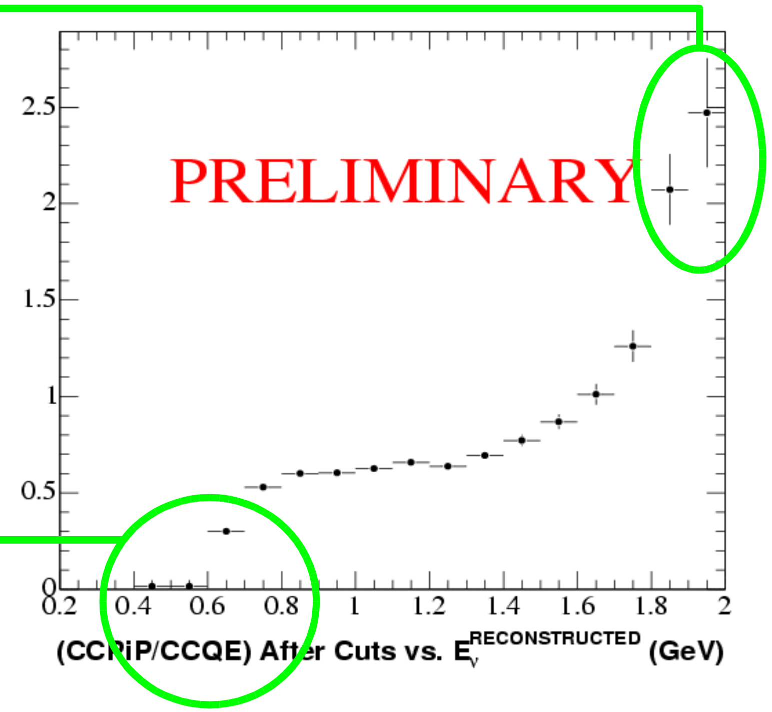
    - CCQE cut efficiency degrades at high E due to exiting μ
    - CCPiP threshold > CCQE



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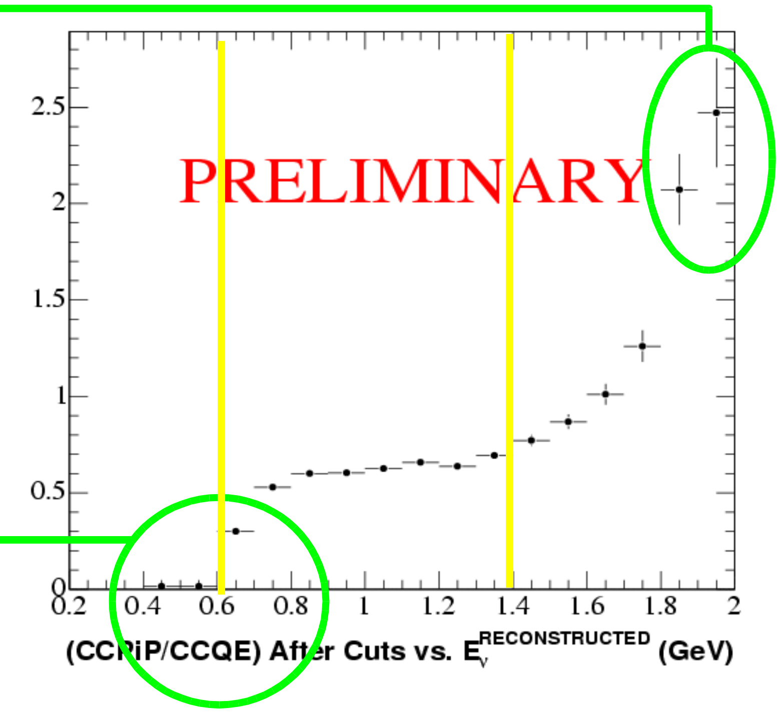
- Motivation for measuring (CCPiP/CCQE) ratio:
  - possibility of ν_μ disappearance
  - like branching ratio measurements, normalize to ``golden mode'' in our own data
  - CCQE is the ``golden mode'' of low E ν σs



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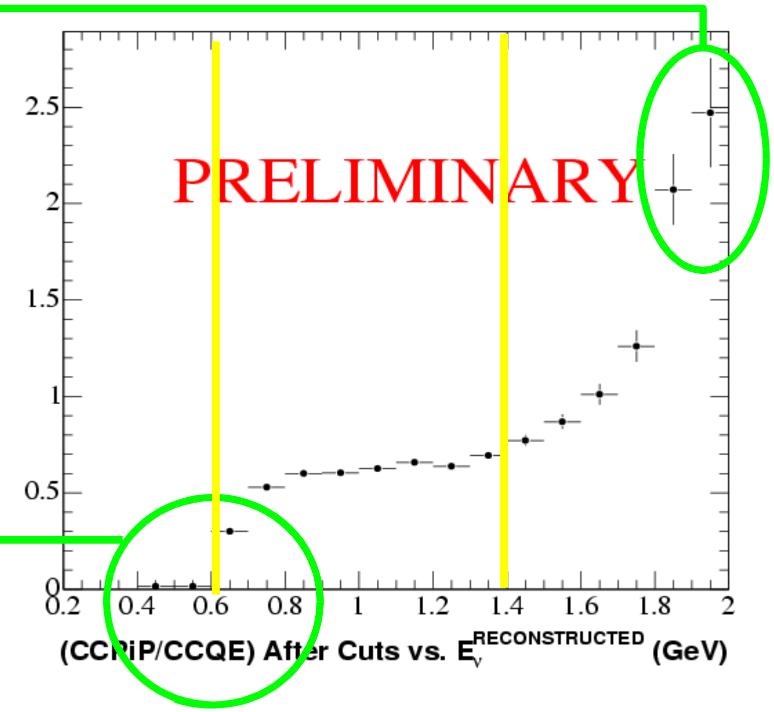

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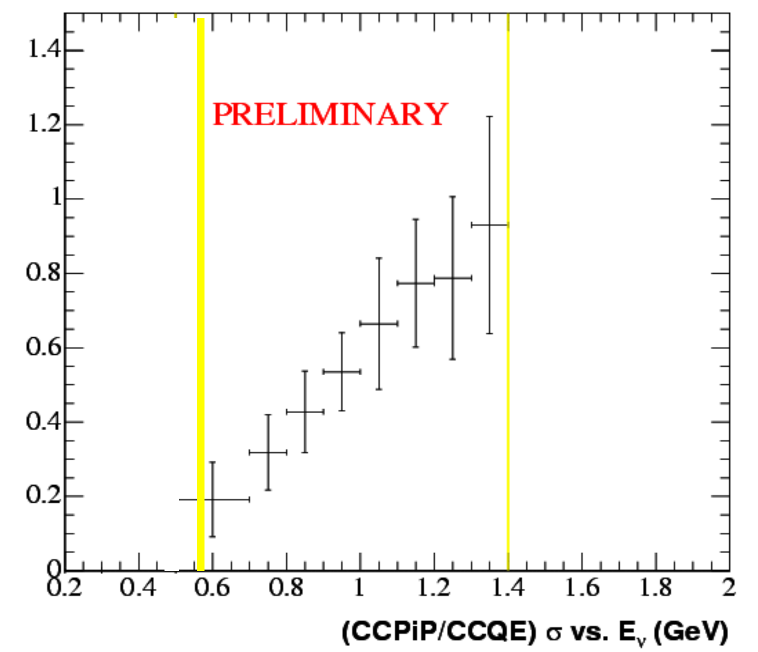

- Efficiency corrected ratio measurement:
  - estimate efficiency correction in MC
  - systematic errors due to ν cross sections (~15%), γ extinction and scattering length in oil (~20%), energy scale (~10%)
  - $\delta^{SYS}_{TOTAL}(E_\nu)$ ~ 20 to 30%, $\delta^{STAT}(E_\nu)$ ~ 5 to 6%

Sources of Uncertainty

ν cross section uncertainties:

PRELIMINARY

parameter varied	*variation amount*
coherent pion production	-100% (off)
Breit-Wigner Δ width	+4.2%
$E_{Binding}$, p_{Fermi}	+100%,+14%
$M_A(1\pi)$	+20%
$M_A(\mathrm{n}\pi)$	+35%
$M_A(\mathrm{QE})$	+10%
$\sigma_{\pi\to X}$	+25%
$\sigma_{charge-exchange}$	+30%
$\mathrm{P}(\Delta N \to NN)$	+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

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ν Flux Uncertainties

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

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- 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)

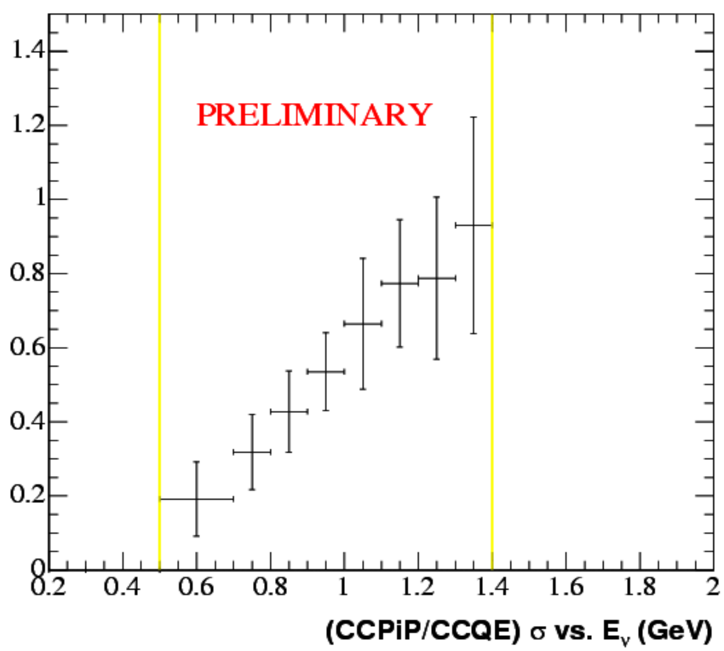
Preliminary → Final:

- 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 ratio measurement as a function of ν energy:

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



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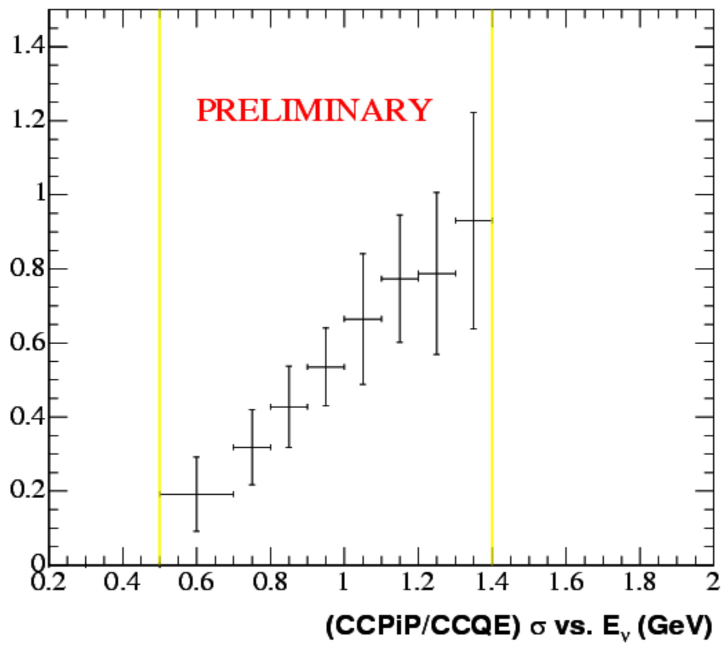
$$R_{MEASURED} = \frac{N(CCPiP)}{N(CCQE)} = \frac{\sigma(CCPiP)}{\sigma(CCQE)}$$

- use ``golden mode'' to convert to σ(CCPiP):

$$\sigma(CCPiP) = R_{MEASURED} \times \sigma_{NUANCE}(CCQE)$$



Multiply by NUANCE MC σ CCQE

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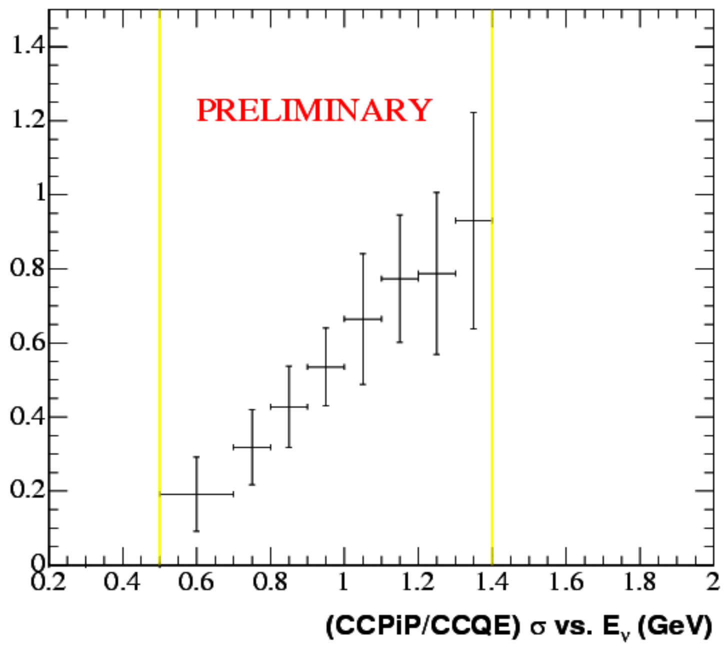

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Drumroll Please ...

CCPiP/CCQE Ratio

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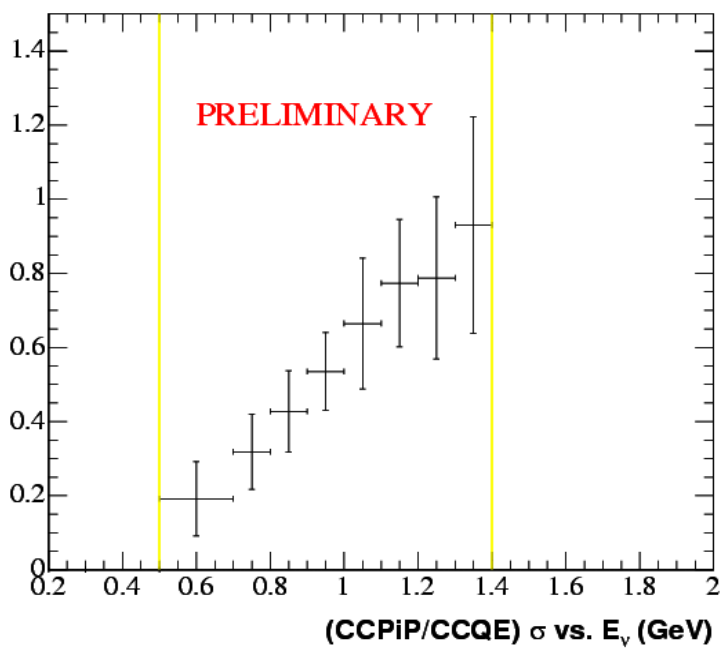

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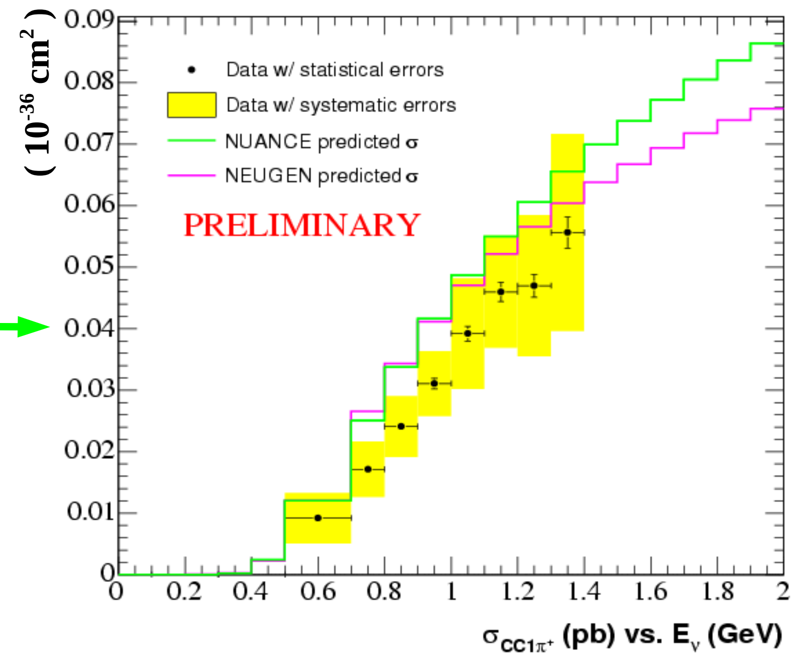
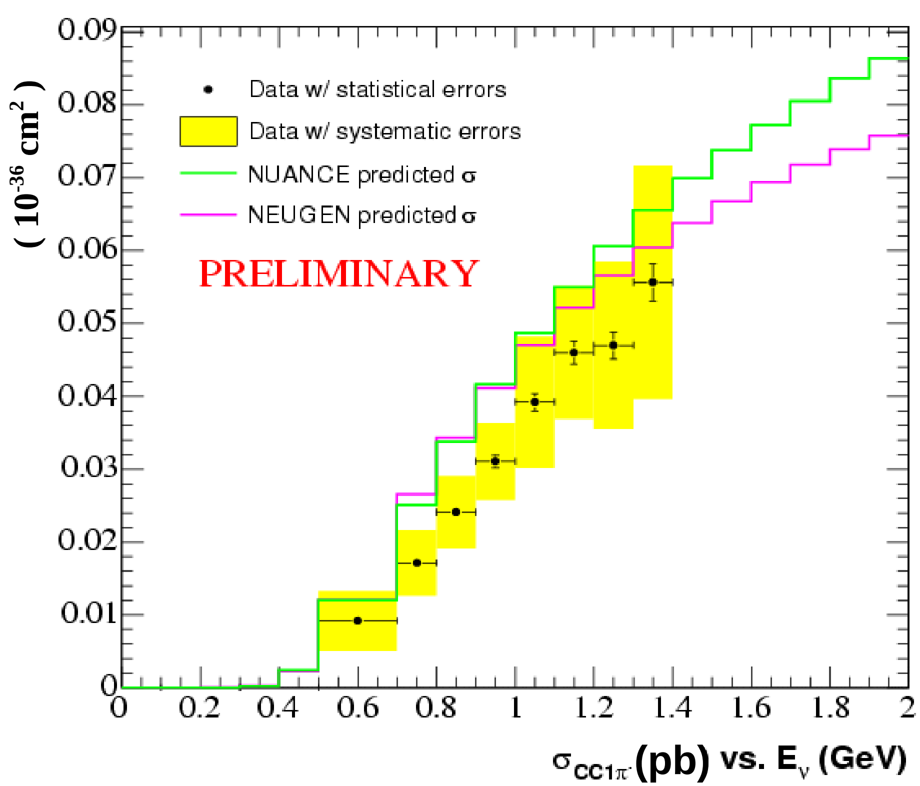
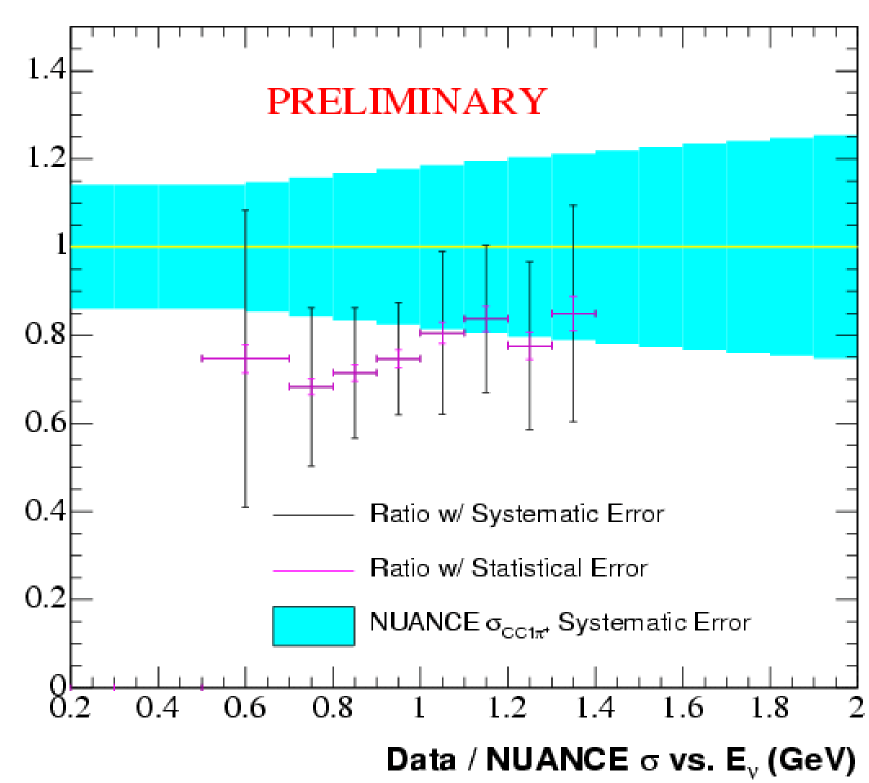


CCPiP/CCQE Ratio

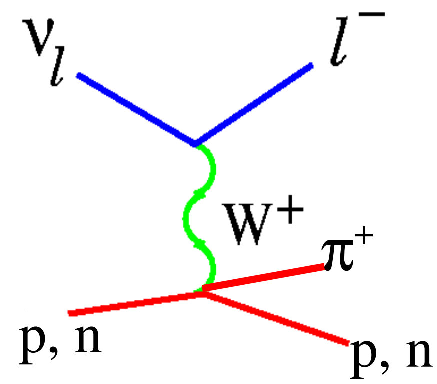
- compare with NUANCE MC prediction
- recall σ(CCPiP) includes $\nu_\mu\, p \rightarrow \mu^-\, p\, \pi^+$, $\nu_\mu\, n \rightarrow \mu^-\, n\, \pi^+$, and $\nu_\mu\, A \rightarrow \mu^-\, A\, \pi$
- ratio to predicted σ_{NUANCE}(CCPiP) is ~75%, but ~within $\delta\sigma_{NUANCE}$(CCPiP)





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%)

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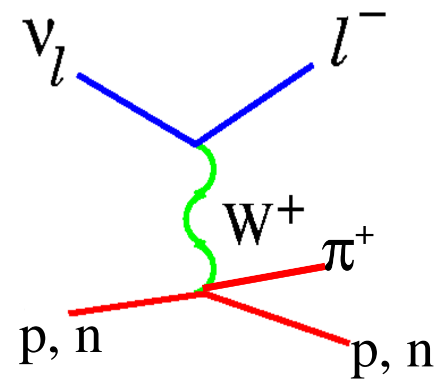

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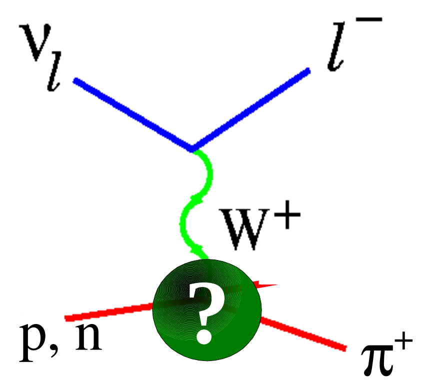
- MiniBooNE can also measure ``effective'' σ(CCPiP)
  - define numerator of MC efficiency correction as anything CCPiP-like, not just $\nu_\mu\, p \rightarrow \mu^- p\, \pi^+$, $\nu_\mu\, n \rightarrow \mu^- n\, \pi^+$, and $\nu_\mu\, A \rightarrow \mu^- A\, \pi^+$
  - CCPiP-like = 1 μ and 1 π^+ in final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



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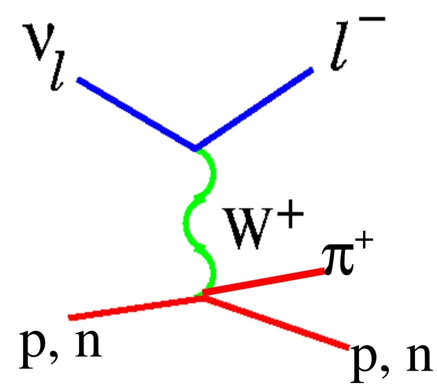

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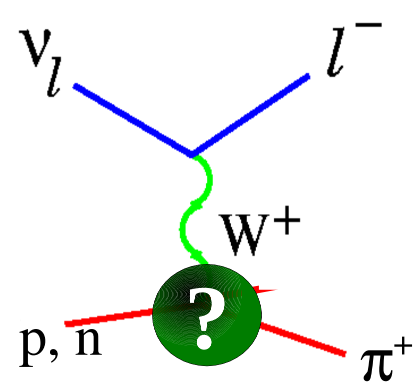


- from MC: N (CCPiP-like) / N (true CCPiP) = 0.8
  - 24% true CCPiP are not CCPiP-like (π^+ absorption wins)
  - 7% true non-CCPiP are CCPiP-like

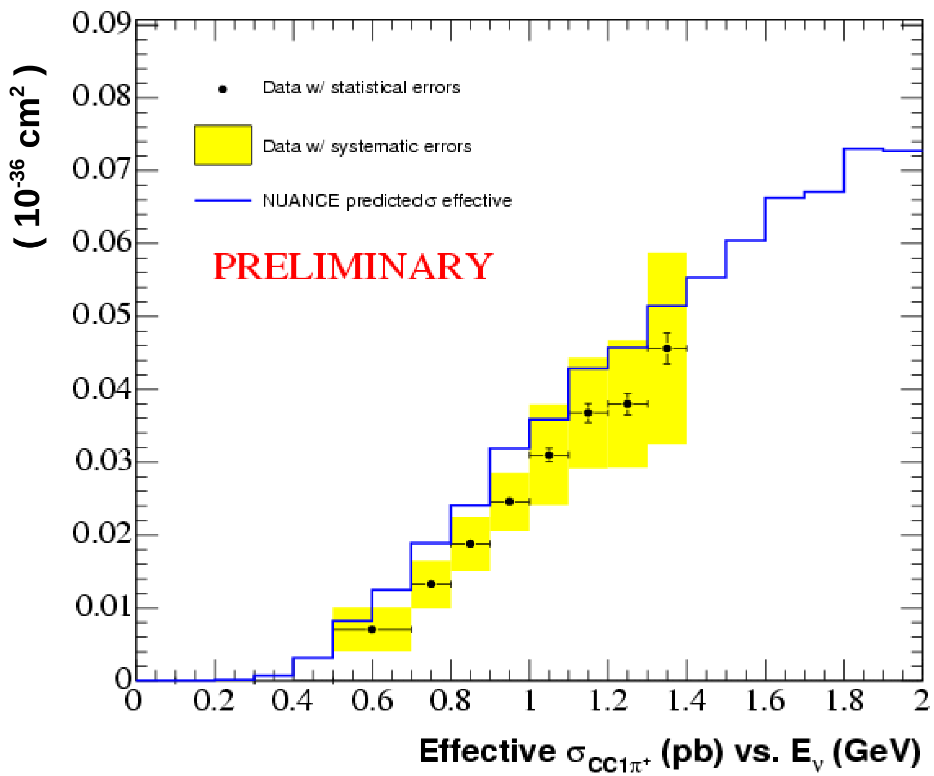
effective CCPiP/CCQE Ratio

- efficiency corrected ratio measurement as a function of ν energy:

$$R^{EFFECTIVE}_{MEASURED} = \frac{N(CCPiP-like)}{N(CCQE)} = \frac{\sigma(CCPiP-like)}{\sigma(CCQE)}$$

- use ``golden mode'' to convert to σ(CCPiP-like)

$\sigma_{\text{EFFECTIVE}}$

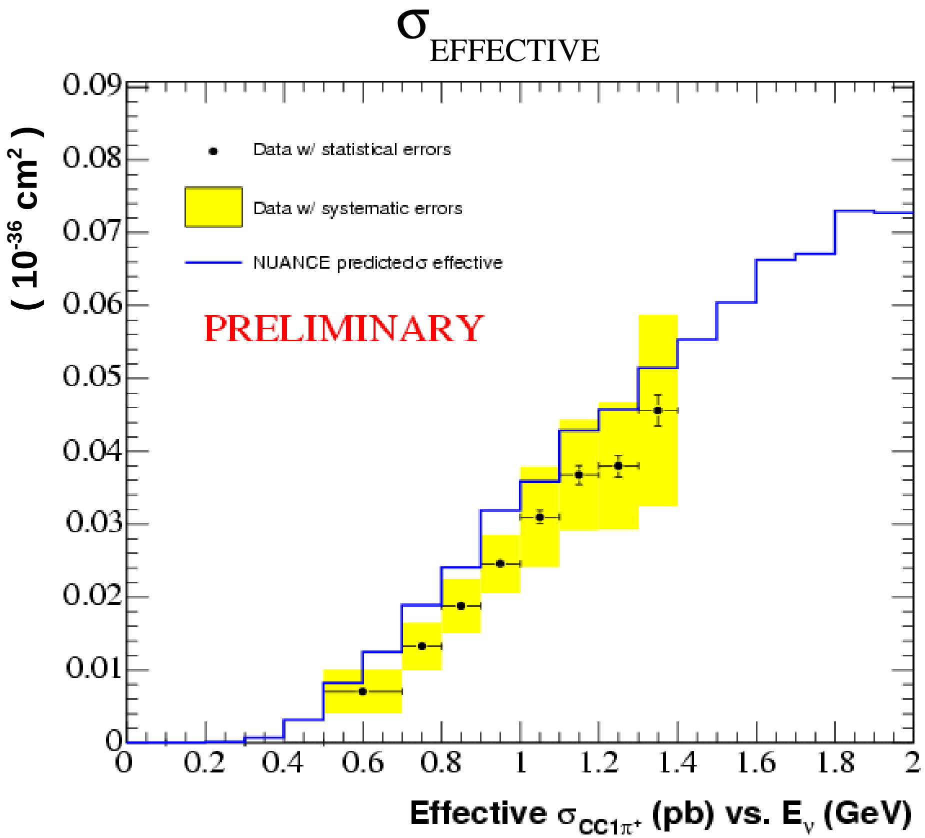


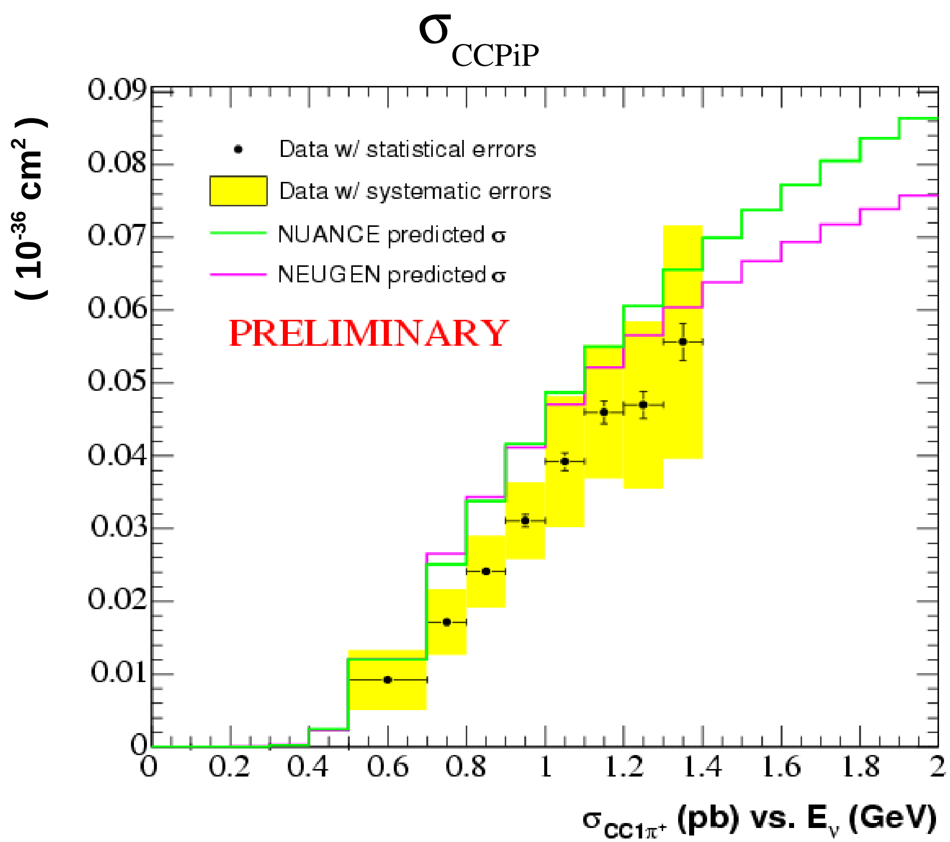
effective CCPiP/CCQE Ratio

- efficiency corrected ratio measurement as a function of ν energy:

$$R^{EFFECTIVE}_{MEASURED} = \frac{N(CCPiP-like)}{N(CCQE)} = \frac{\sigma(CCPiP-like)}{\sigma(CCQE)}$$

- use ``golden mode'' to convert to σ(CCPiP-like) and compare with σ(CCPiP)

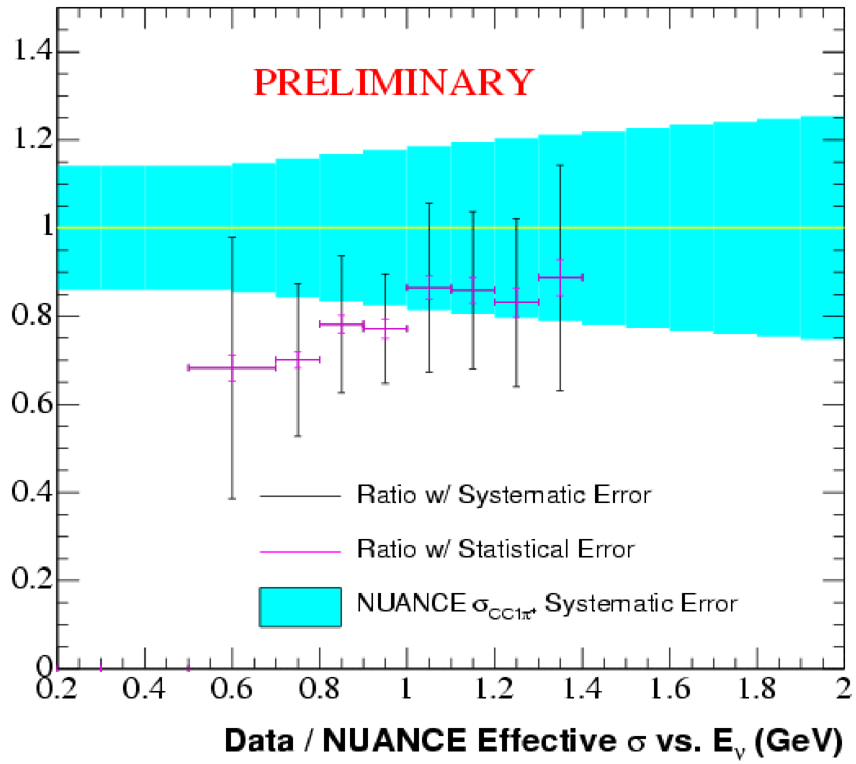




effective CCPiP/CCQE Ratio

- cross check NUANCE FSI by comparing (Data/MC) $\sigma_{EFFECTIVE}$ to σ_{CCPiP}

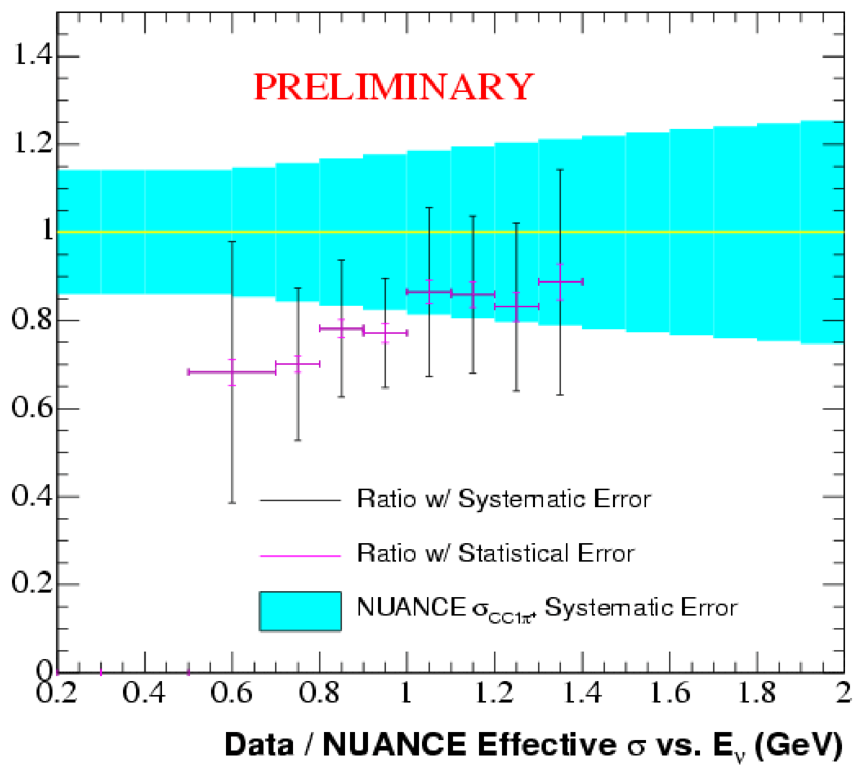
(Data/MC) $\sigma_{EFFECTIVE}$



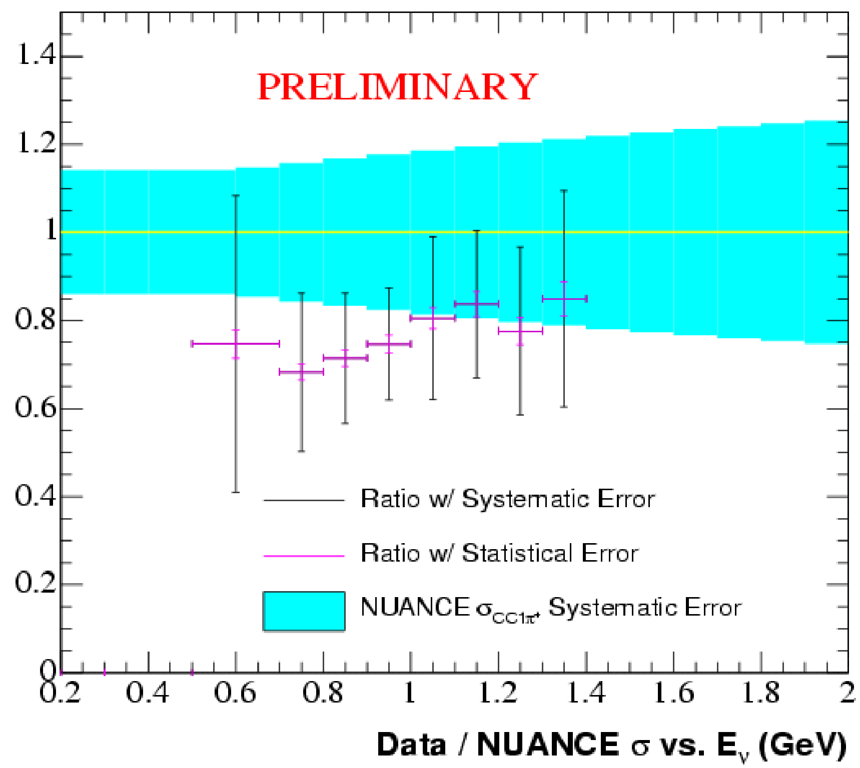
effective CCPiP/CCQE Ratio

- cross check NUANCE FSI by comparing (Data/MC) $\sigma_{EFFECTIVE}$ to σ_{CCPiP}
- ratio to predicted σ_{NUANCE}(CCPiP-like) is similar to σ(CCPiP) result

(Data/MC) $\sigma_{EFFECTIVE}$



(Data/MC) σ_{CCPiP}



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 σ measurement
- Fall '05
  - CCQE ν_μ disappearance result

Grazie Mille!

INFN for generous travel support

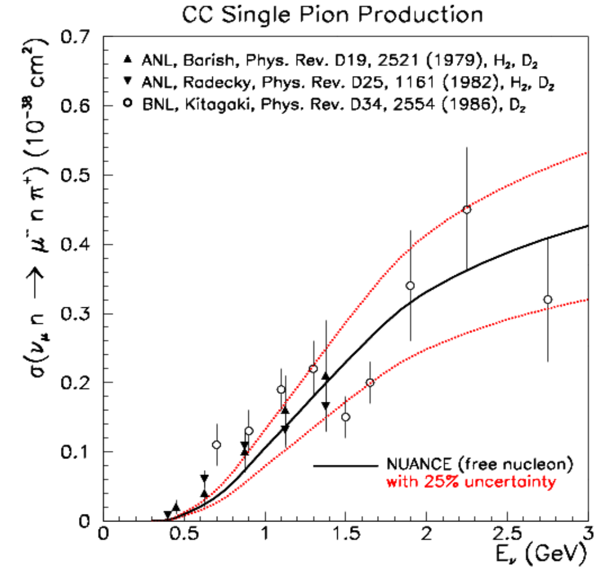
Backup Slides

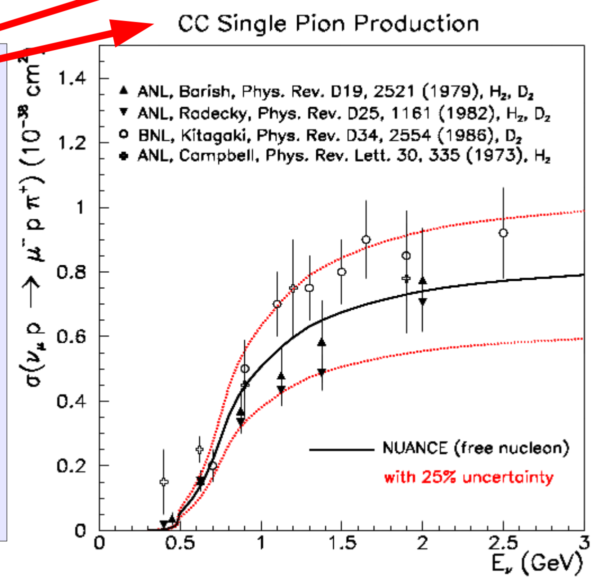
CCPiP σ Errors

CCPiP cross section uncertainties:

Resonant Production

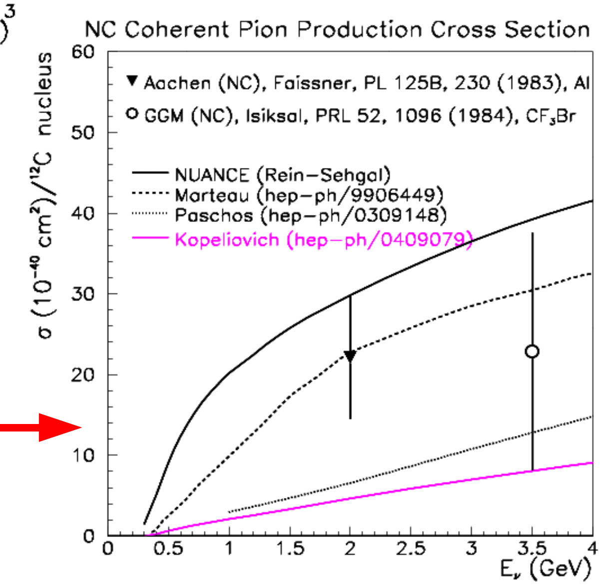
- 25% uncertainty on $m_A^{1\pi}$
- derived from external data
- size of error driven by difference between ANL and BNL measurements





Coherent Production

- 100% uncertainty on σ
- no CC data below 7 GeV + K2K sets limit (1.3 GeV)
- lower energy NC coherent data exists, but wide range of theoretical predictions for size of σ

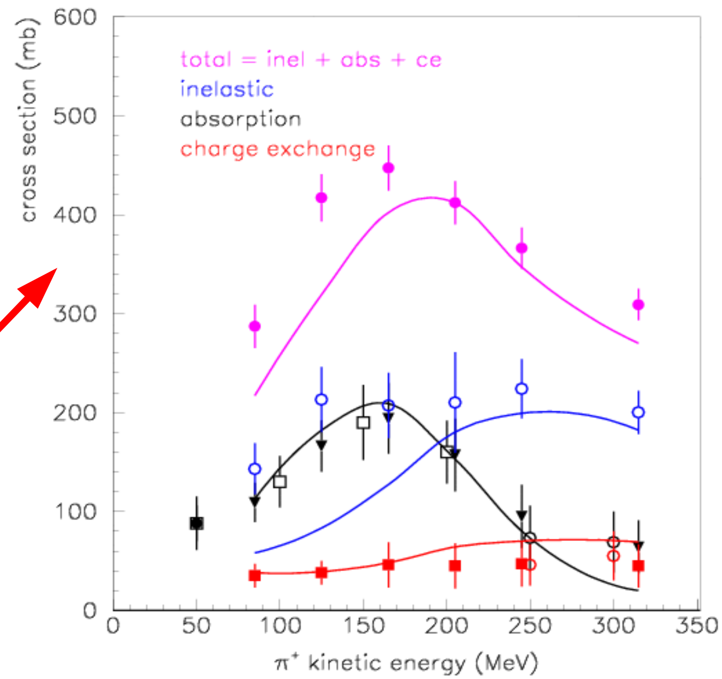


effective CCPiP σ Errors

<u>Final state interaction uncertainties:</u>

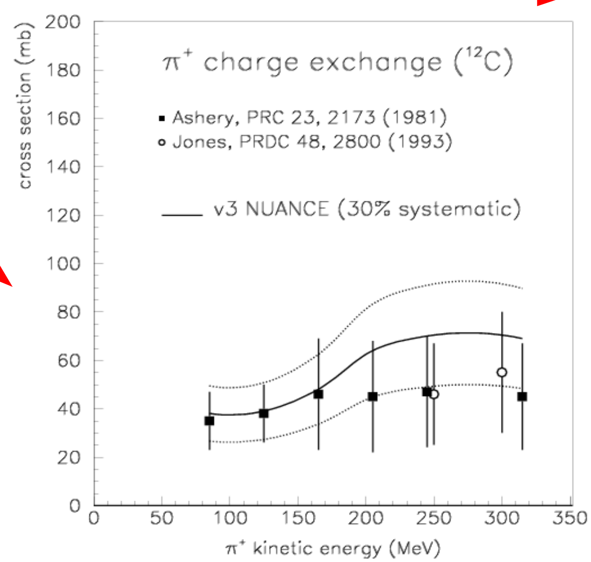
NUANCE FSI model tuned to reproduce external π scattering data

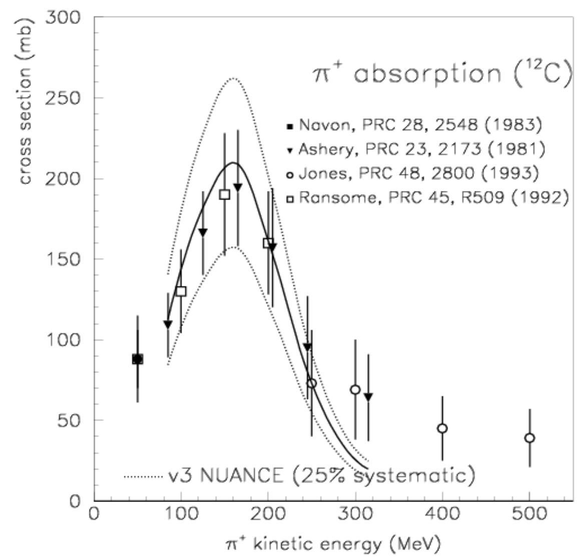
- Comparison between NUANCE and data



Uncertainties on NUANCE compared with external data

- 25% on σ(π absorption)
- 30% π σ(charge exchange)



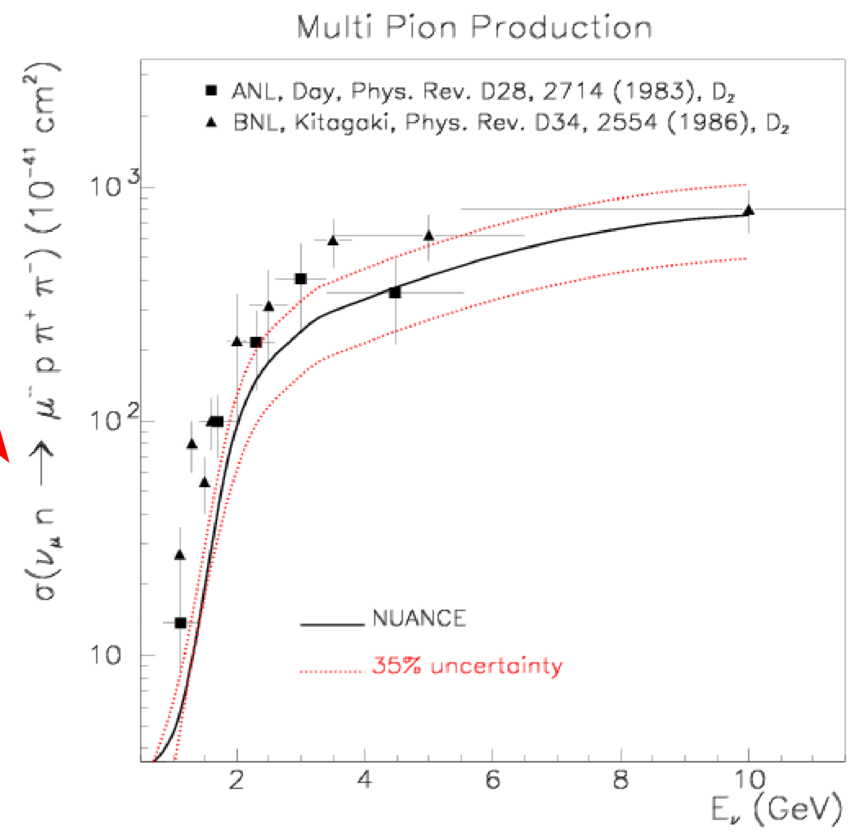


effective CCPiP σ Errors

Uncertainties on CCPIP-like processes:

Multi-Pion Production

- Comparison between NUANCE and external data
  - 35% uncertainty on $m_A^{N\pi}$



Uncertainties from PDG

- Δ decay width
  - 4% uncertainty

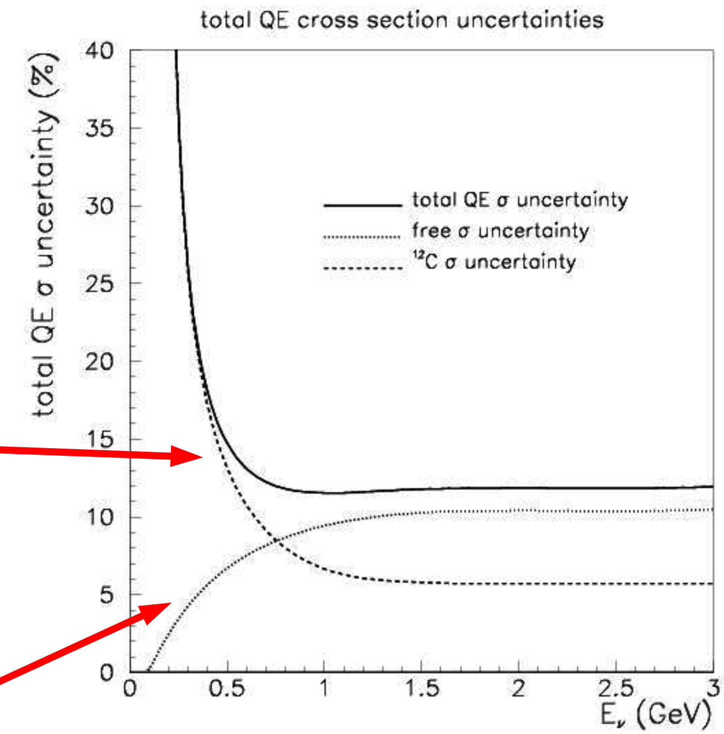
Conservative Guess

- Pion-less Δ decay: P (Δ N → N N)
- 50% uncertainty for now, constrain in future with e- data

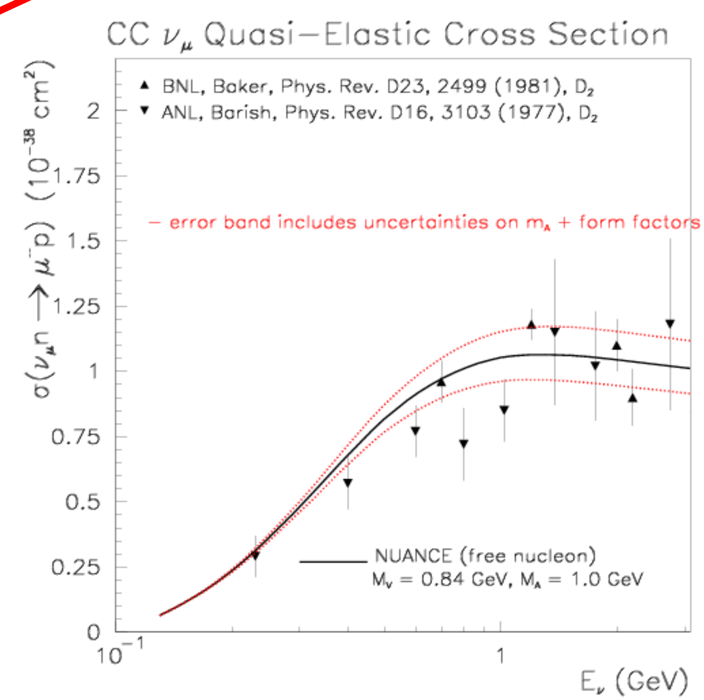
CCQE σ Errors

CCQE cross section uncertainties

- 60% uncertainty in Pauli suppression
  - vary E_B by 25 MeV (100%)
  - vary p_F by 15 MeV (14%)
  - size of variations set 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, as well as K2K choice

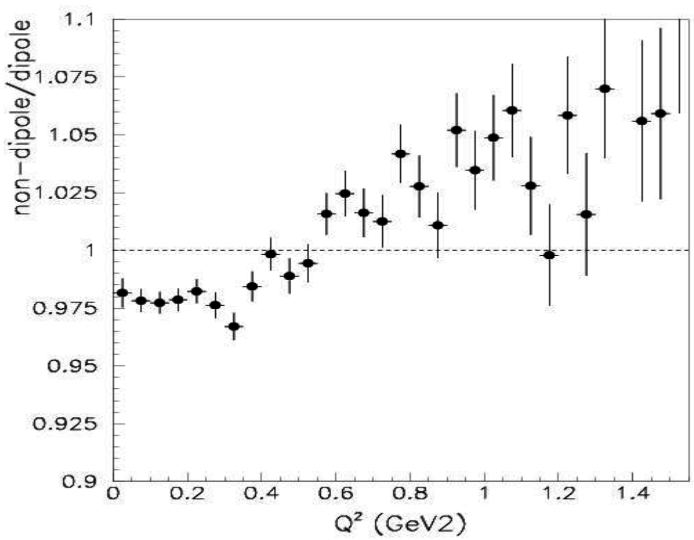


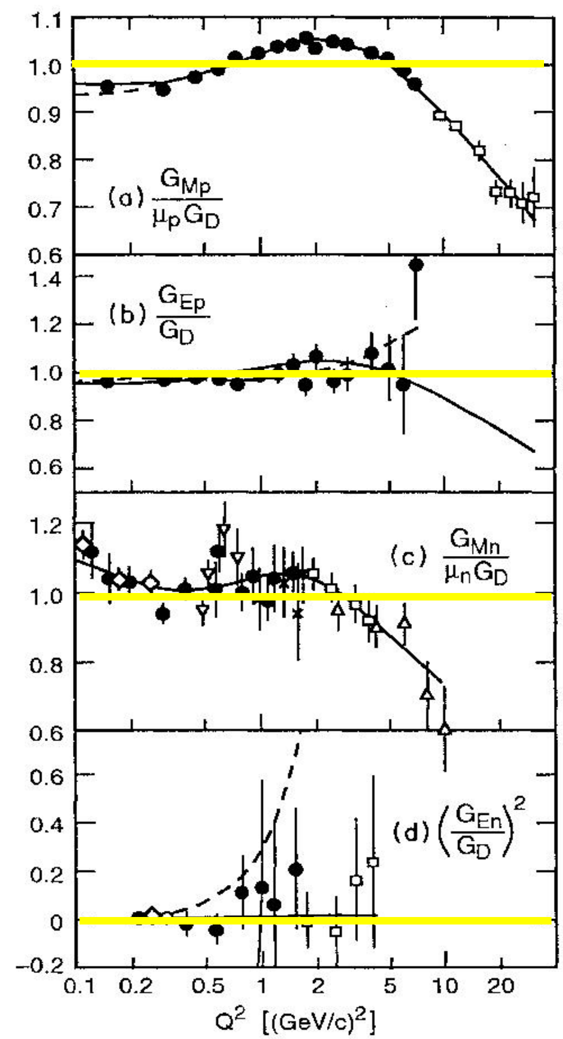
Non-Dipole Vector Form Factors (NUANCE v3)

- largest effect is 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:

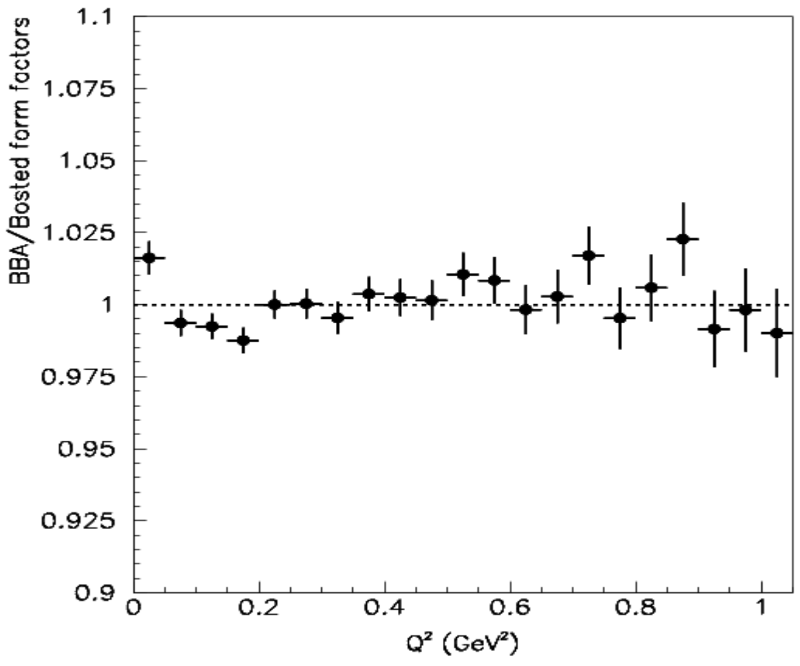
$$G_M^p(Q^2) = \mu_p/(1+3.104Q^2+1.428Q^4+0.1112Q^6-0.006981Q^8+0.0003705Q^{10}-0.7063E\text{-}5Q^{12})$$

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

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

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

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

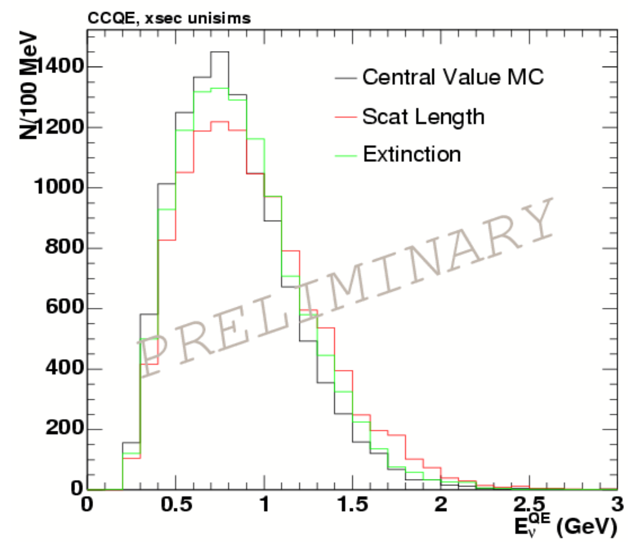


Bodek, Budd, Arrington BBA-2003 fit values (hep-ex/0308005)

Systematic Error Calculation

Estimate uncertainties by constructing an error matrix from MC to calculate 1^{st} 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
   - $F_i^A = [\, N_i(\lambda_A + \delta\lambda_A) - N_i(\lambda_A)\,] / \delta\lambda_A$
   - $F_i^S = [\, N_i(\lambda_S + \delta\lambda_S) - N_i(\lambda_S)\,] / \delta\lambda_S$

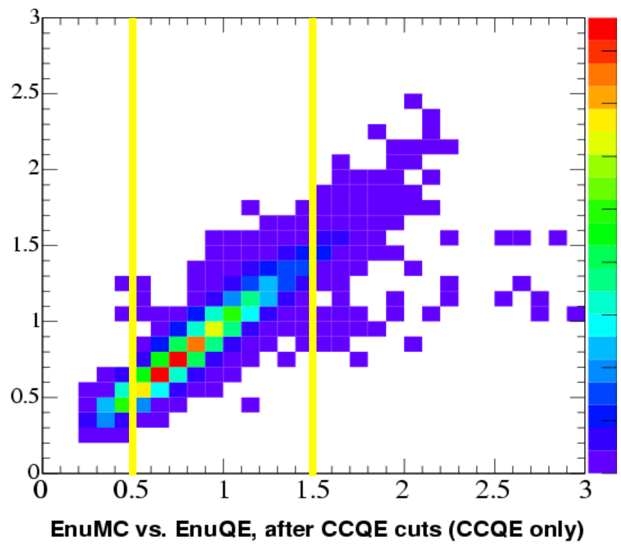
3. construct first derivative matrix $F_{i,j}$
   - i indexes energy hins, j indexes systematic error parameters

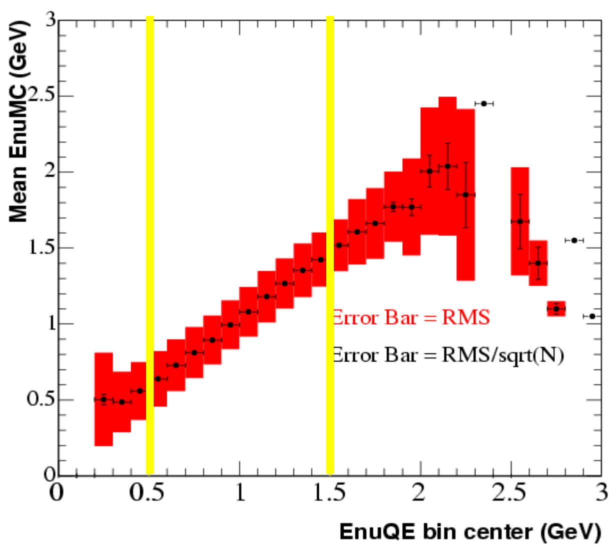
4. construct error matrix $M_{i,l}$ from parameter correlation matrix $P_{j,k}$ and $F_{i,j}$
   - $M_{i,l} = (F_{i,j})^T \; P_{j,k} \; F_{i,j}$

Energy Scale Uncertainty

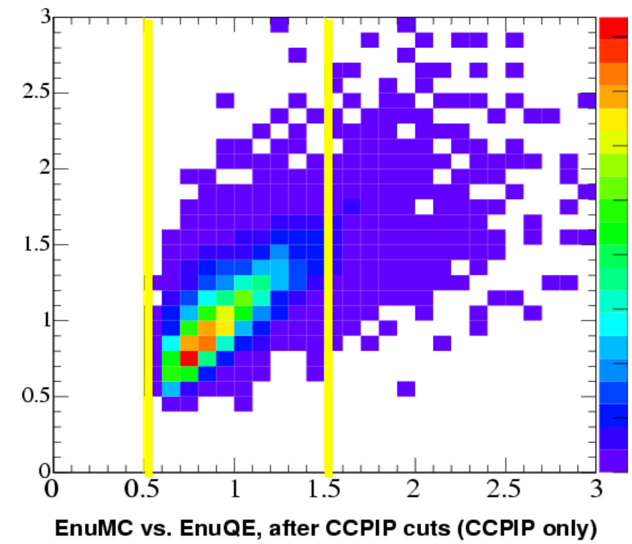
Energy scale uncertainty comes from difference performance between CCPiP and CCQE neutrino energy reconstruction.

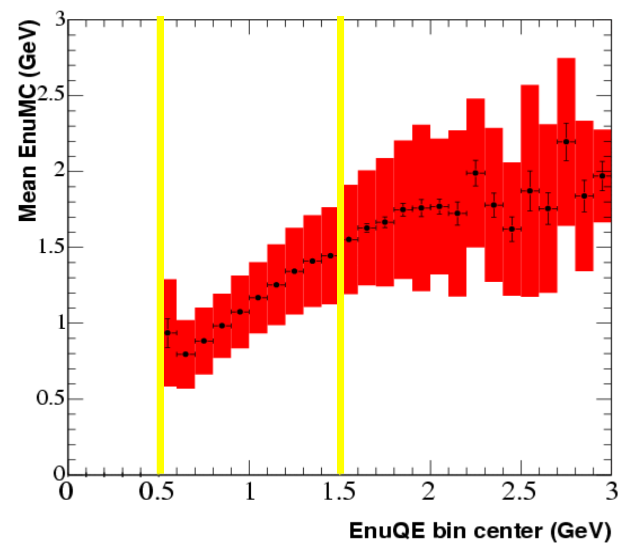
- CCQE





- CCPiP





CCQE ``Golden Mode'' : MC Comparisons

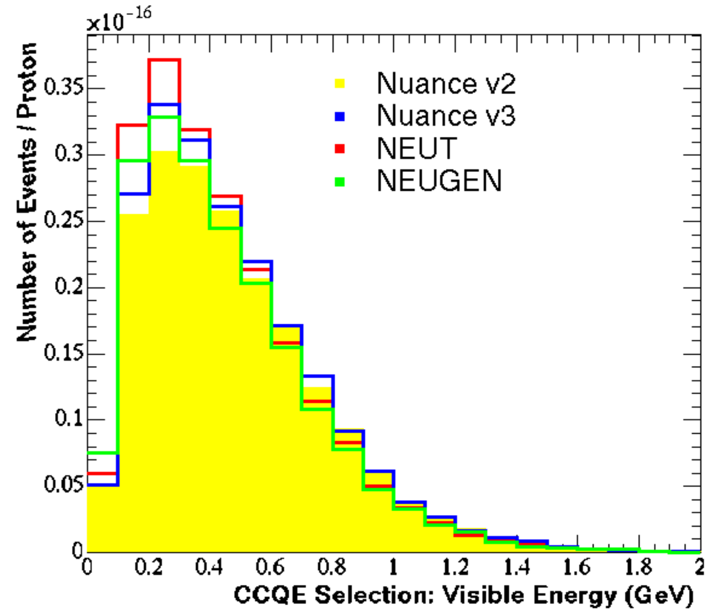
Same CCQE cuts, different Monte Carlos ...

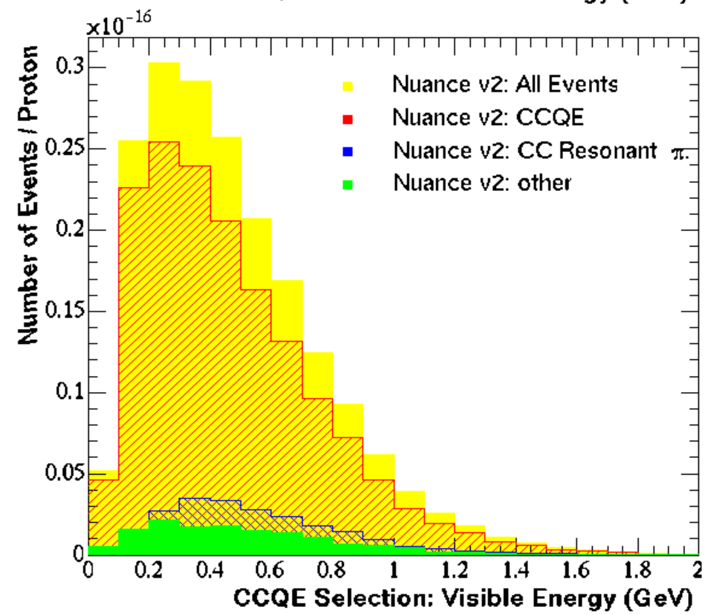
- Absolute normalization

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

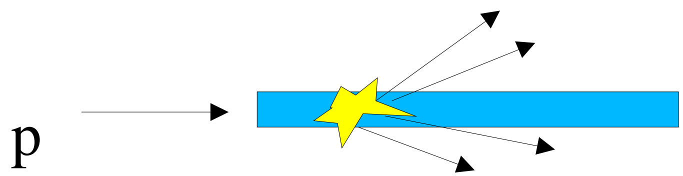
- After CCQE event selection: signal purity

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





External Prediction for ν_μ Flux



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

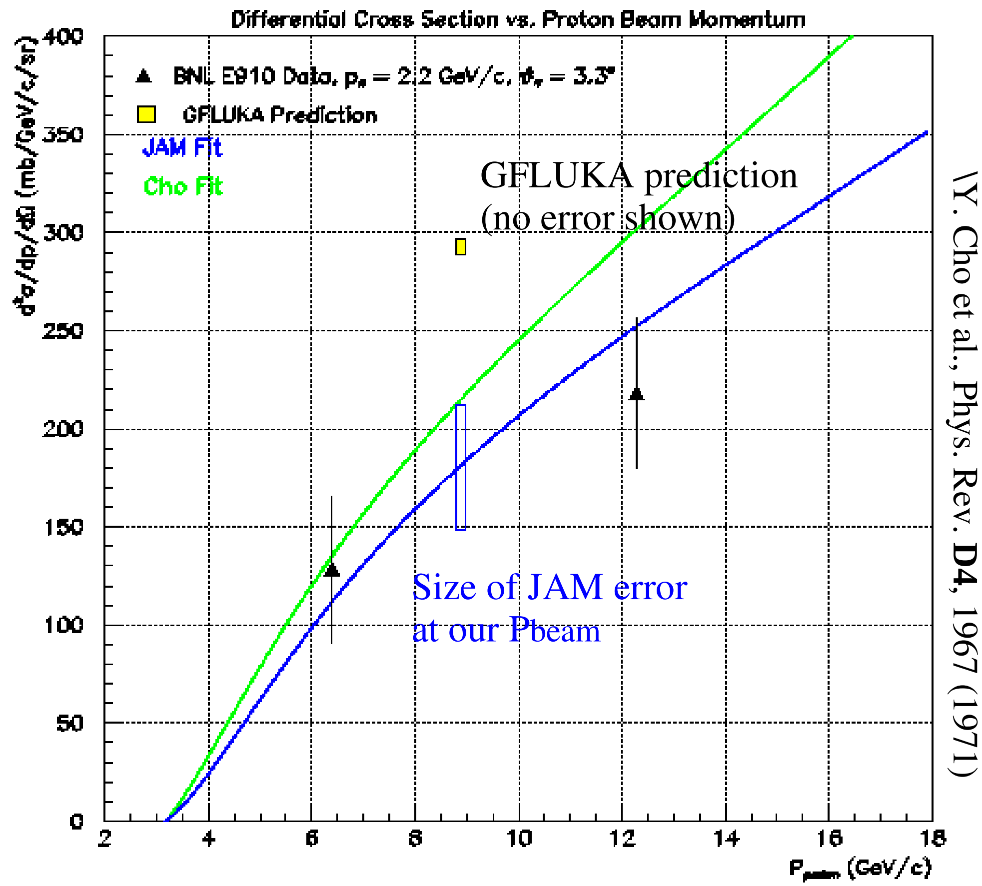
Production of secondaries in Be target:

- 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 → π^+ X) at 8 GeV at HARP with high statistics and MiniBooNE target

Calibrating CC Interactions at MiniBooNE

- Hodoscope + 7 Scintillator-Filled Cubes Track Cosmic Rays