MiniBooNE ν_μ CCπ^+/CCQE σ Ratio

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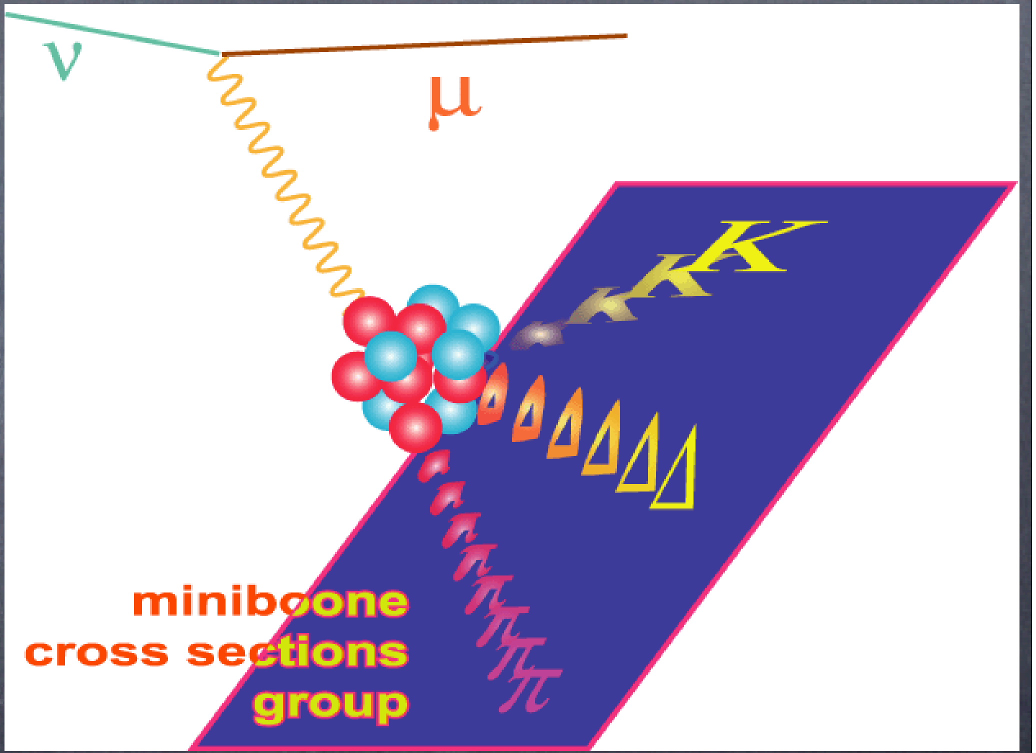
- CC interactions
  - Quasi-Elastic (CCQE)
  - Inclusive Single π^+ Production (CCPiP)
- Measuring CC Interactions
- Modelling CC Interactions
- (CCPiP / CCQE) σ Ratio

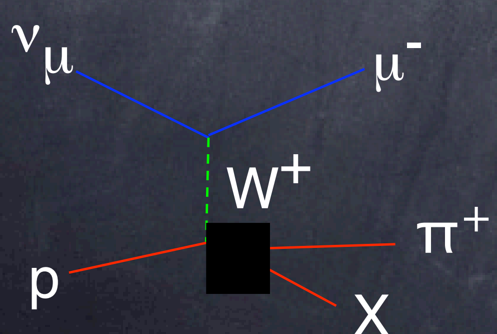


Analysis performed under the auspices of the MiniBooNE Cross Sections Working Group

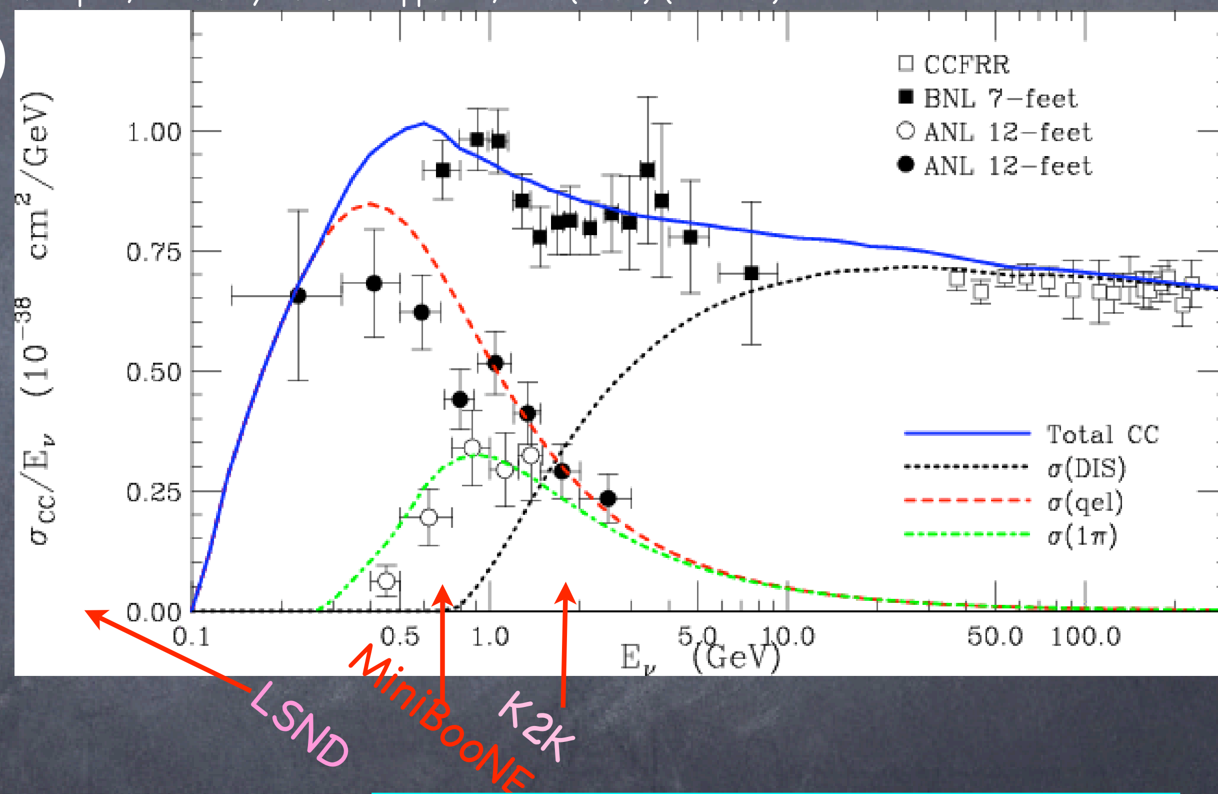
Charged Current Interactions

- Quasi-Elastic (CCQE)

- Single π+ (CCPiP) (Inclusive)



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



Super-K atmospheric νs

Range of NuMI Possibilities

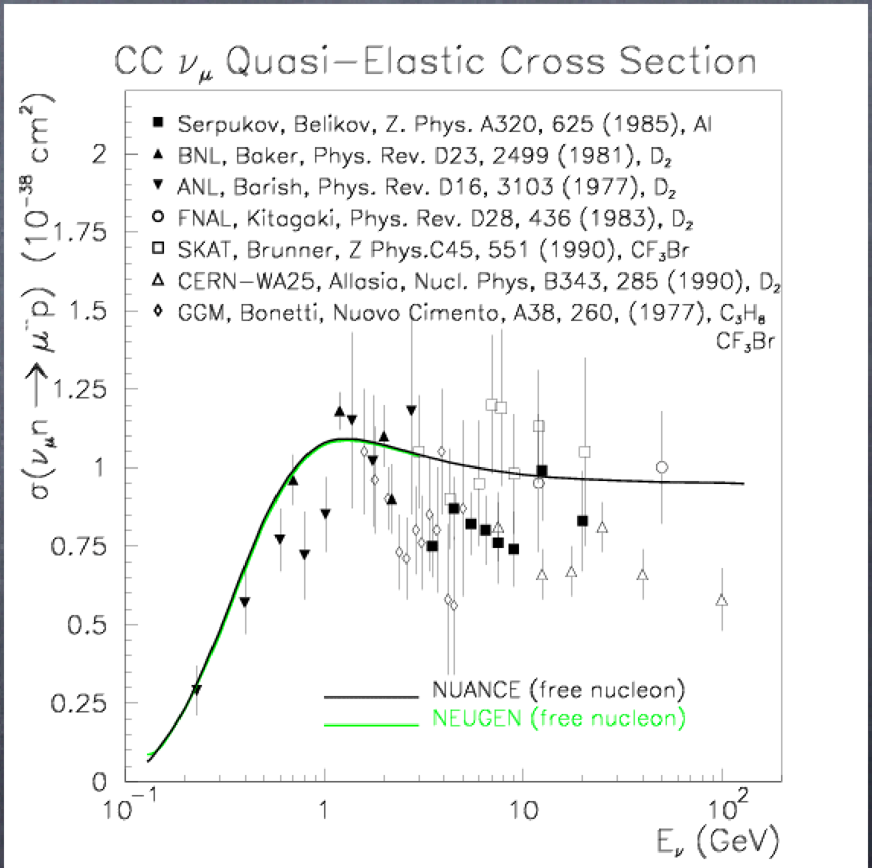
Charged Current Quasi-Elastic Interactions

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

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

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

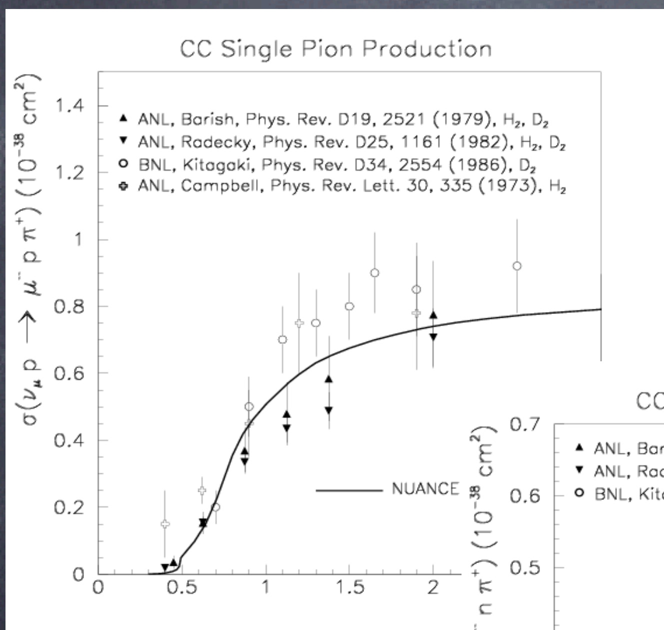
- Past data:
  - not much below ~few GeV
  - only light targets

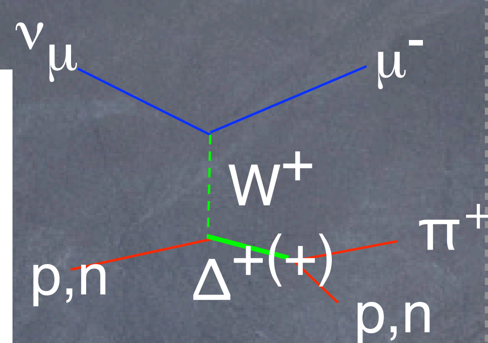


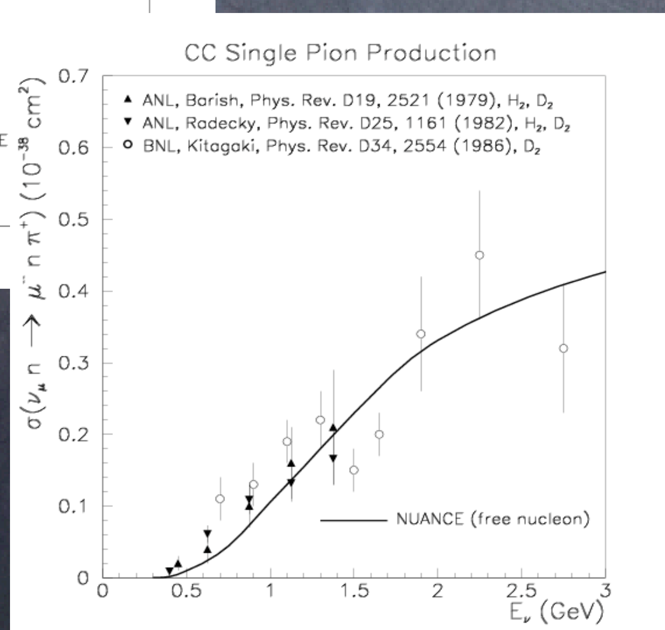
Charged Current Single π^+ Interactions

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

Resonant Production

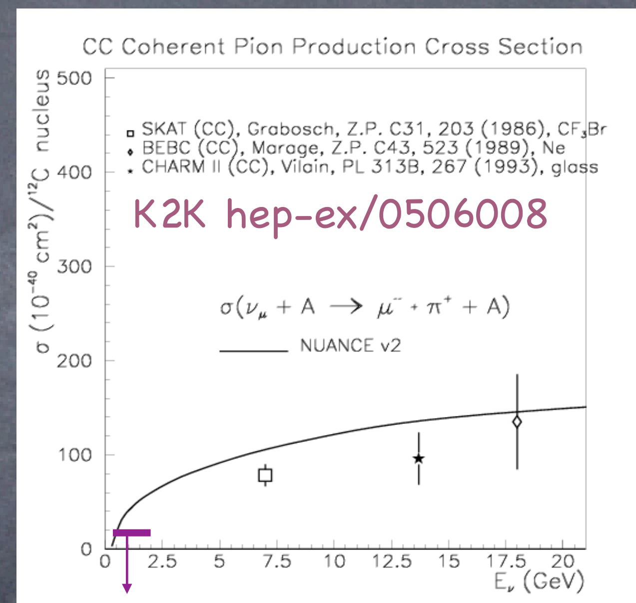


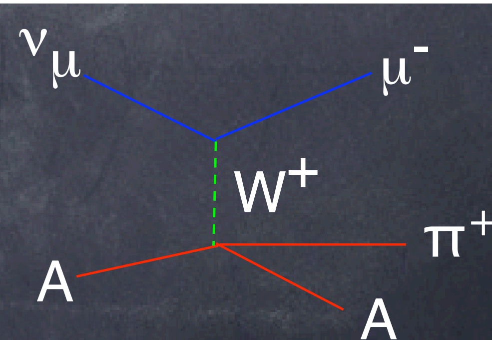




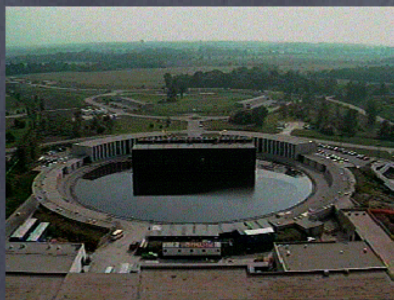
- no heavy target data below 3 GeV

Coherent Production



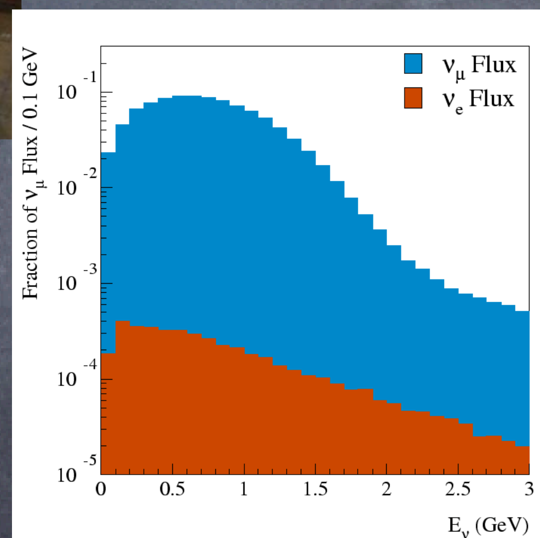


MiniBooNE Overview

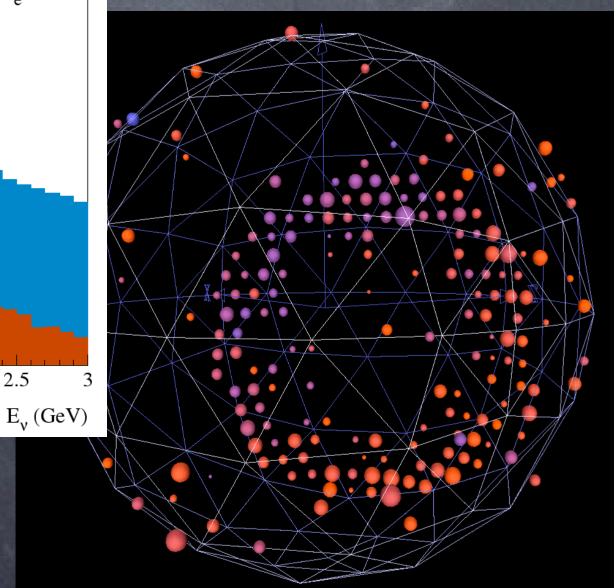


- 8 GeV KE protons from Fermilab Booster Accelerator
- 1.7 λ beryllium target (HARP results coming soon!)

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



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



Measuring CC Interactions at MiniBooNE

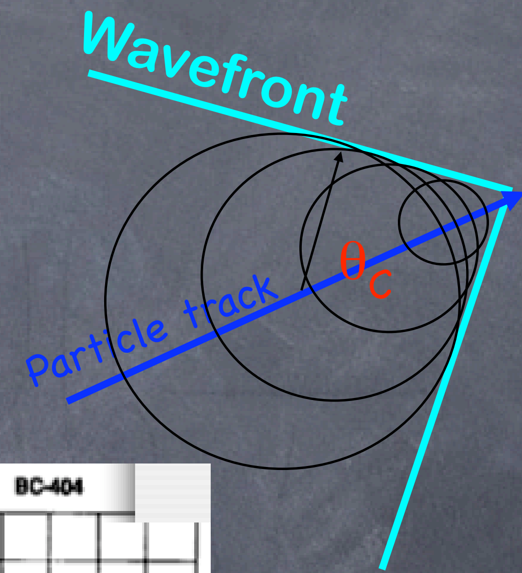
We measure visible light produced by charged final state particles in mineral oil

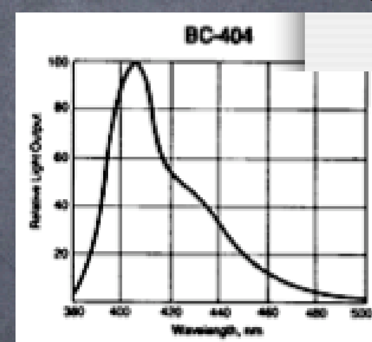
Cherenkov radiation

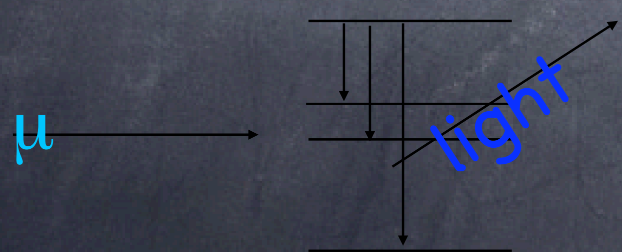
- Light emitted by oil if particle v > c / n
- forward and prompt in time

Scintillation

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





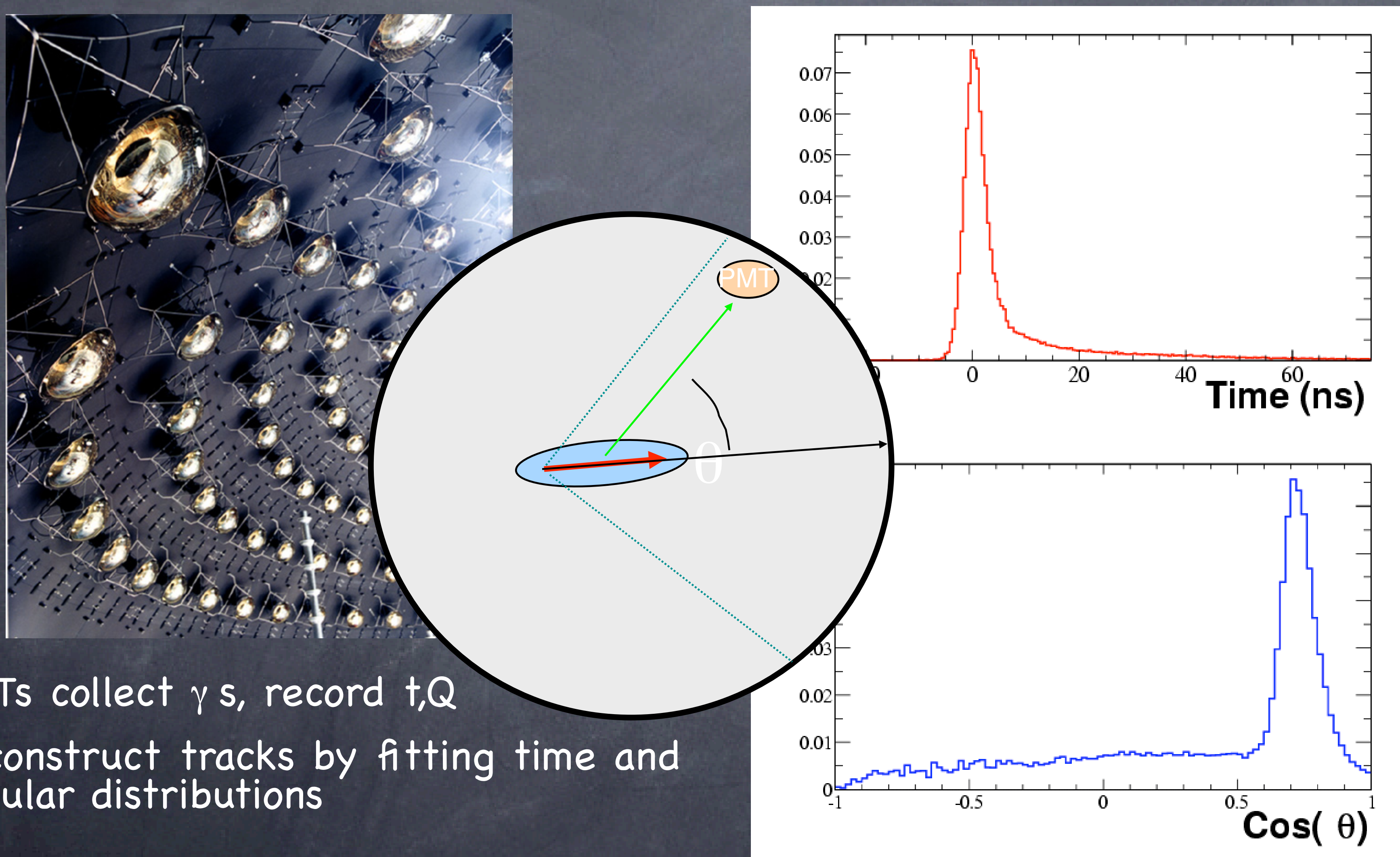


Molecular energy levels of oil

... after the γ s travel to edge of detector

- Flourescence
- Scattering (Rayleigh, Raman)
- Absorption

Reconstructing CC Interactions at MiniBooNE

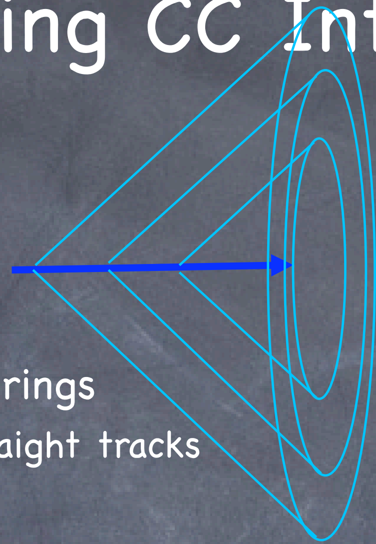


PMTs collect γ s, record t,Q

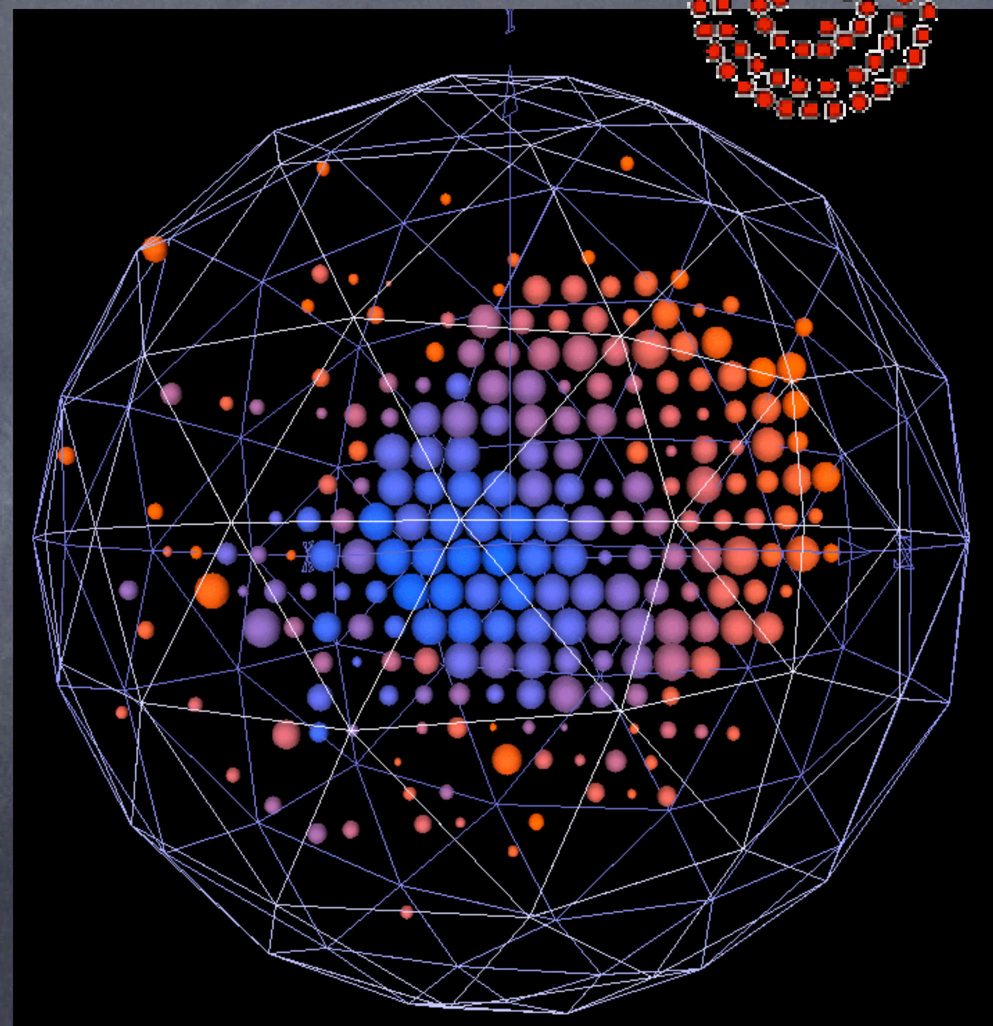
Reconstruct tracks by fitting time and angular distributions

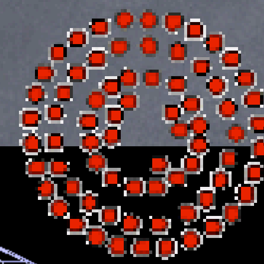
Identifying CC Interactions at MiniBooNE

- 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



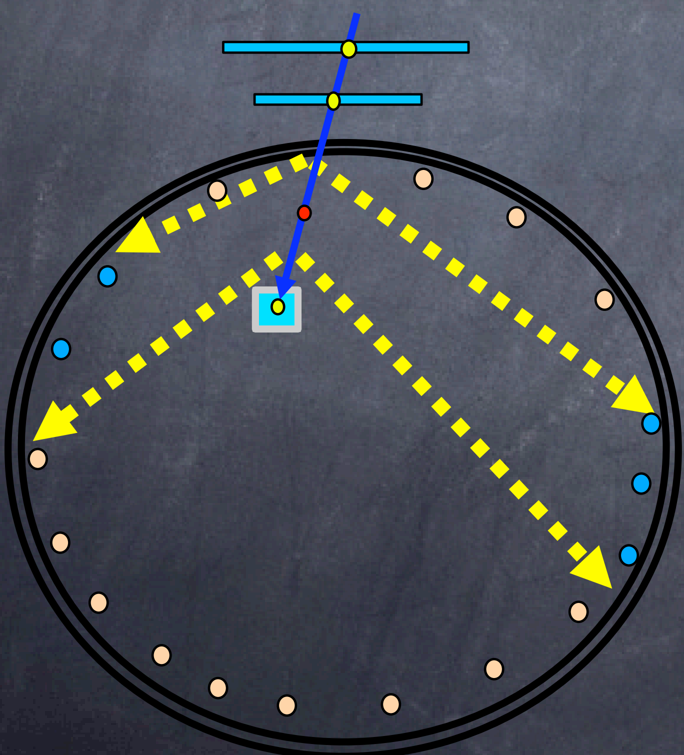


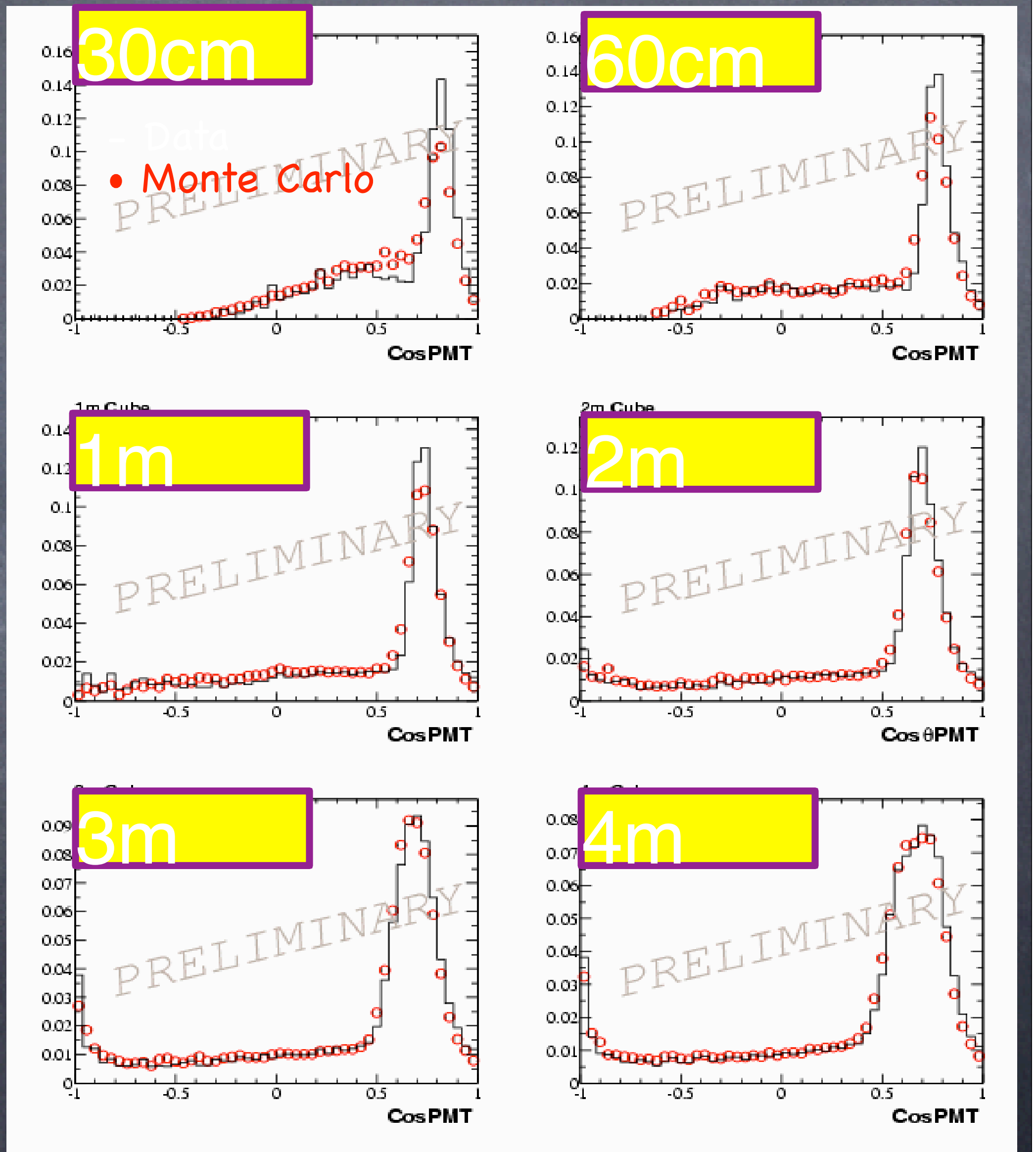
Calibrating CC Interactions at MiniBooNE

Use muon tracker system to determine the event parameters (x, t, u)

Assemble corrected times, angles using known track center

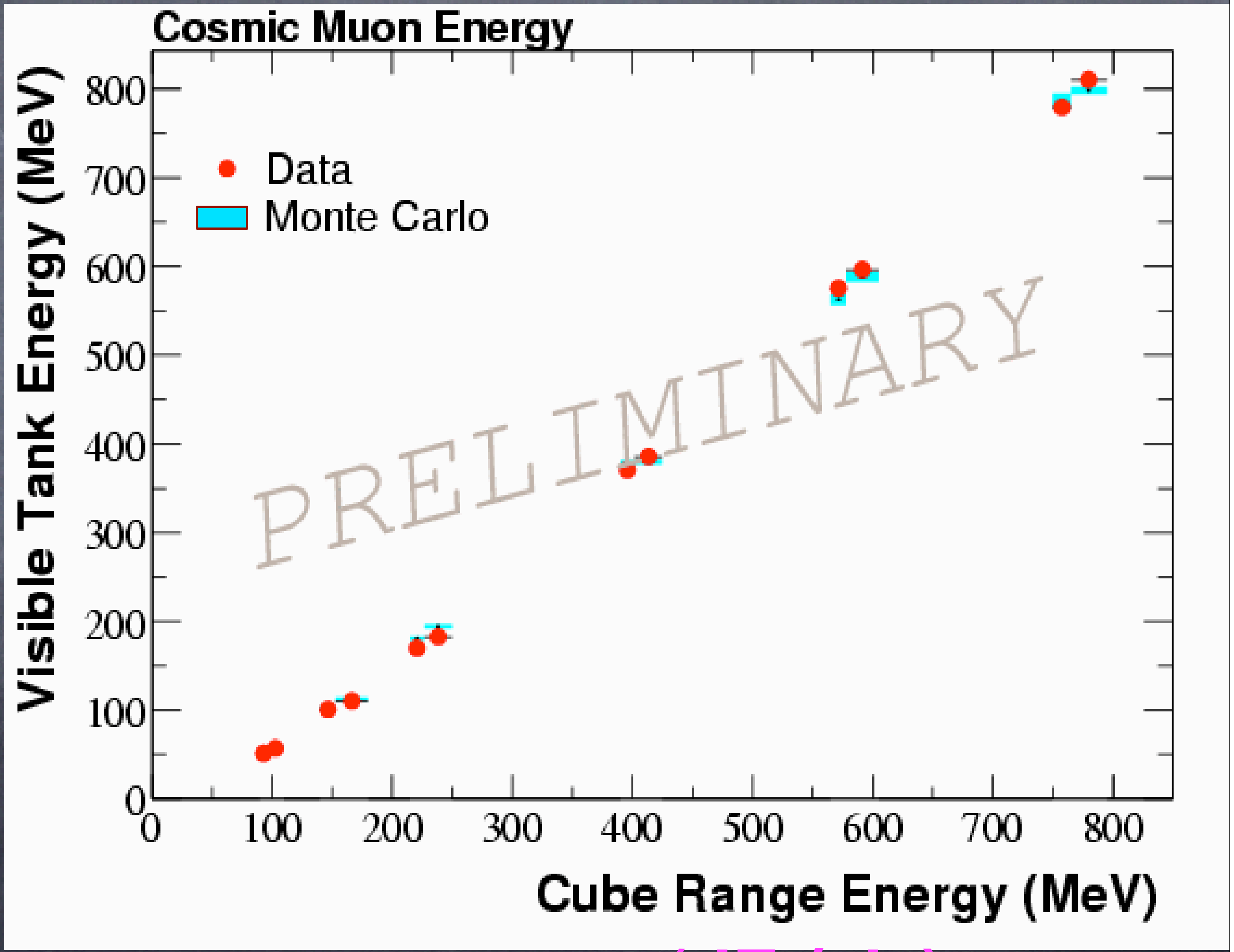
Find Cherenkov rings and time peaks, isotropic and delayed emission





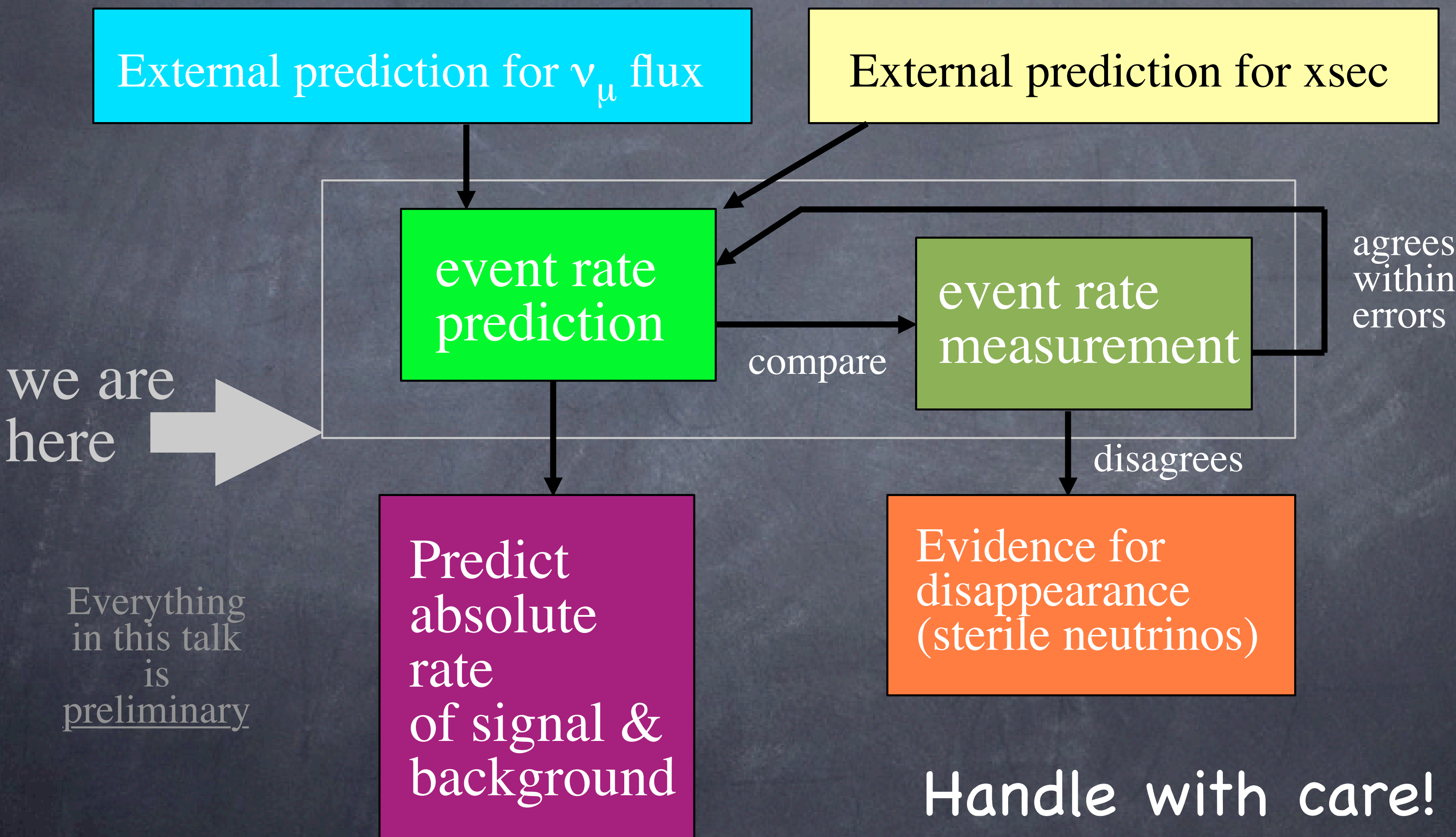
Calibrating CC Interactions at MiniBooNE

- 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)



(dE / dx)

Modelling CC Interactions at MiniBooNE



Everything in this talk is preliminary

Handle with care!

External Prediction for $\sigma\nu$

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

Theoretical inputs

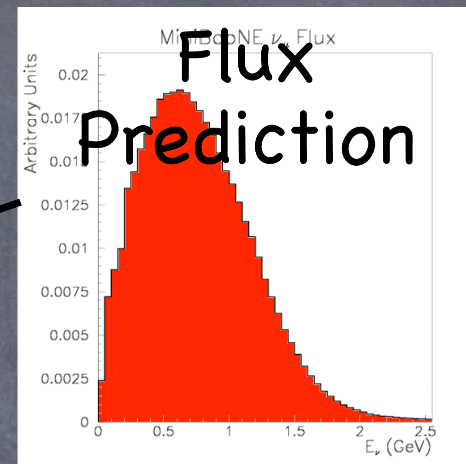
- Llewellyn Smith free nucleon QE xsec
- non-dipole BBA03 vector form factors
- m_A = 1.03 GeV

- 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

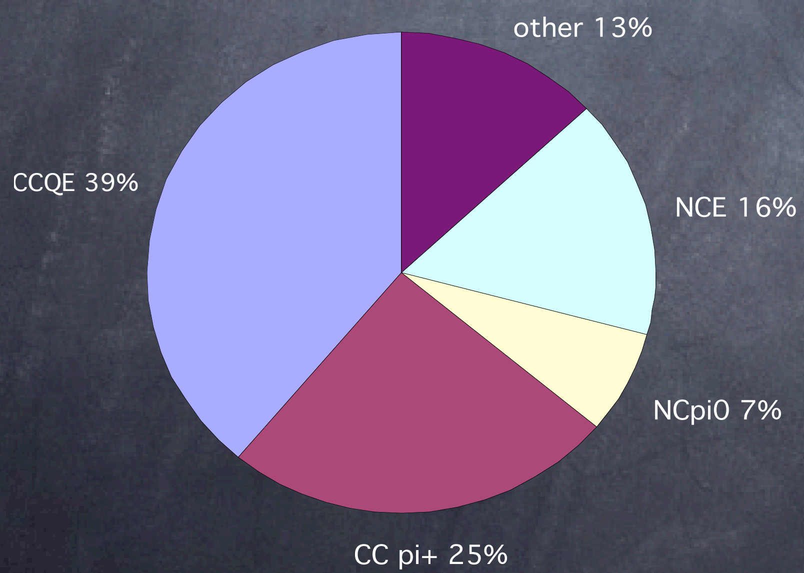
MiniBooNE Detector Monte Carlo (Geant3.21)

MiniBooNE Analysis Framework (reconstruction, etc.)

Compare with Data

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 ...

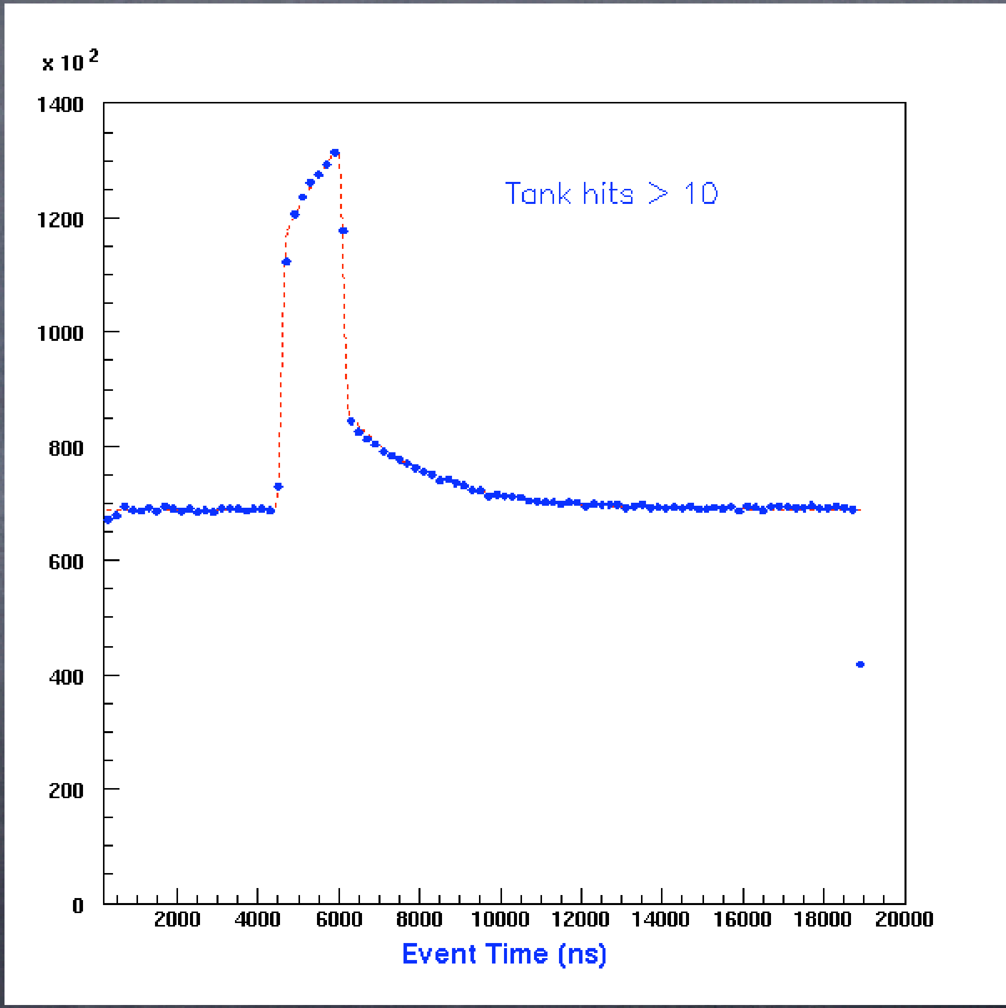
This Analysis:

- 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 ...

Simple Neutrino Event Cuts

- Times of hit-clusters (sub-events)
- Beam spill (1.6μs) is clearly evident
  - simple cuts eliminate cosmic backgrounds
- Neutrino Candidate Cuts
  - <6 veto PMT hits
    - Gets rid of muons
  - >200 tank PMT hits
    - Gets rid of Michels



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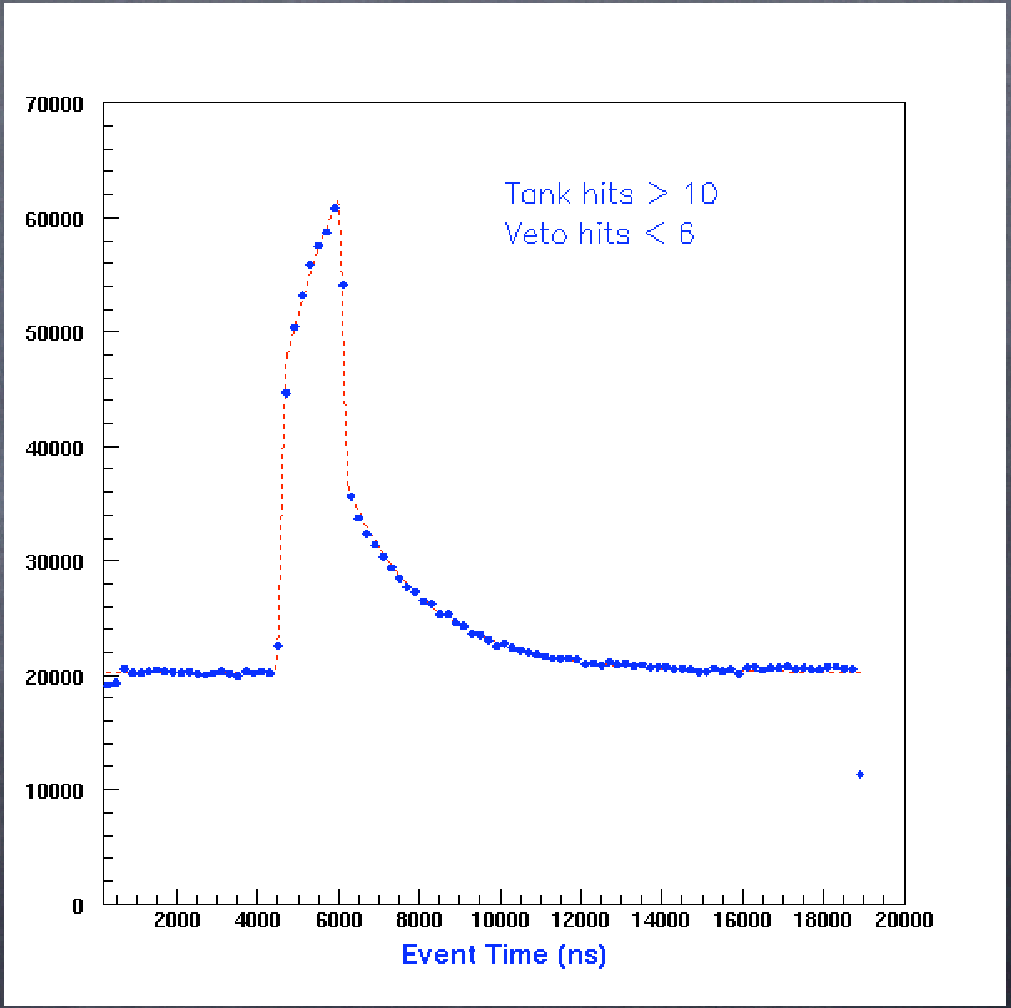

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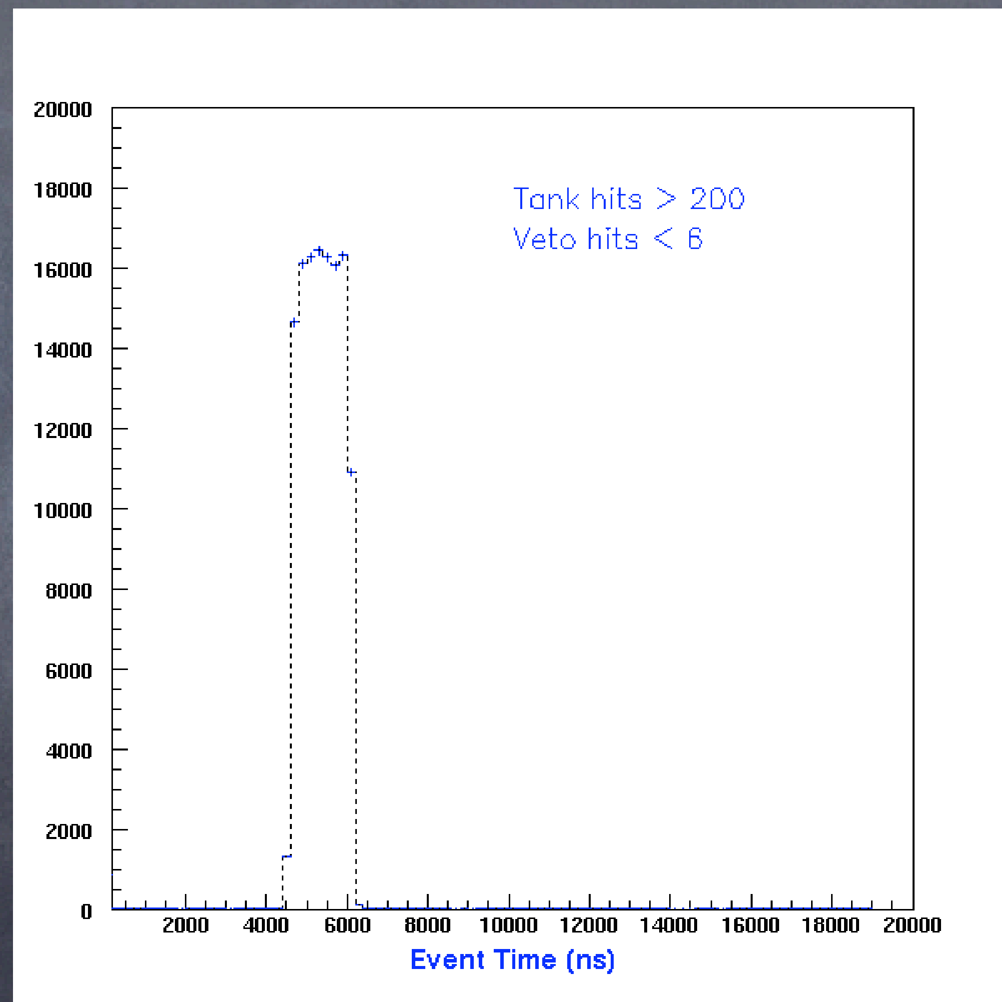


CCQE Event Selection

First Level of Cuts:

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

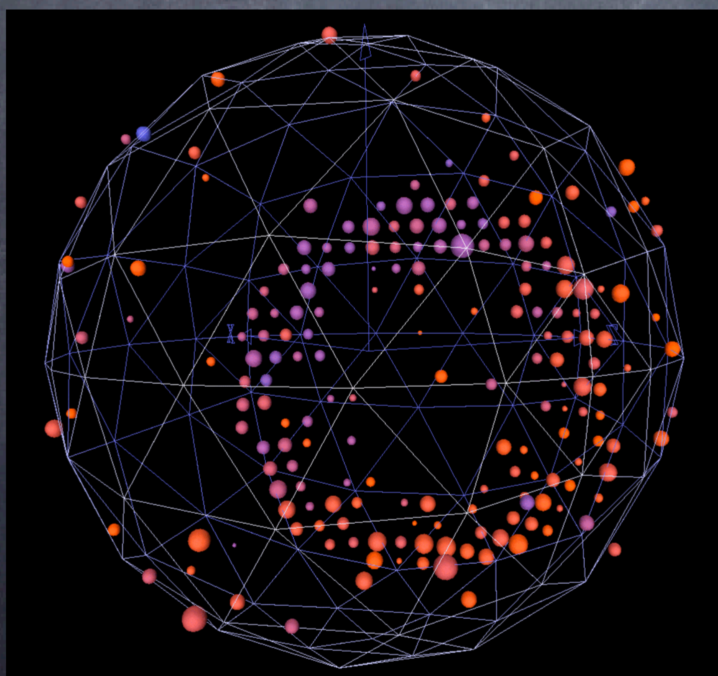
    (allows 0 or 1 Michels ($20<N_{PMT}<200$))

Signal:

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

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

$\mu^- \rightarrow e^-\ \nu_\mu\ \bar{\nu}_e$

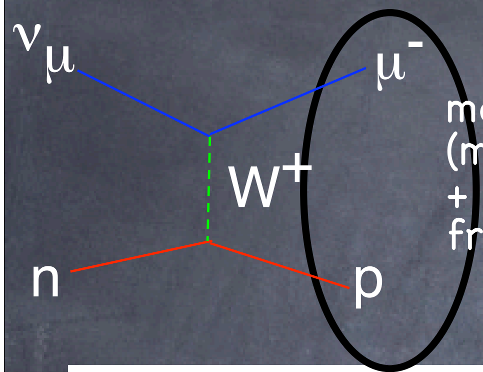


Second Level Cuts: Final State ID

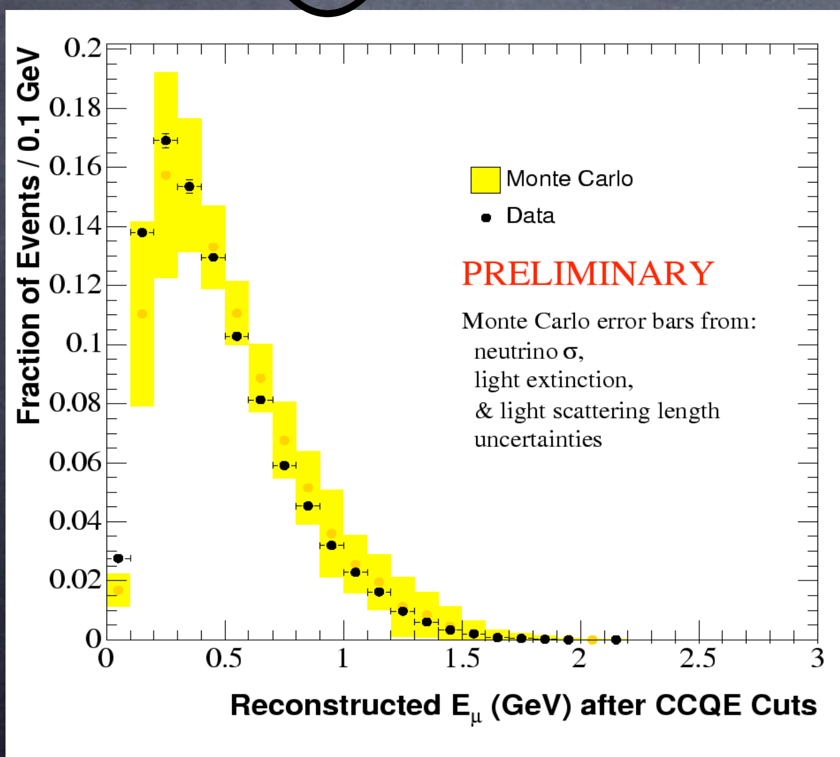
- event topology
- fraction of on- vs. off- ring light
- PMT hit timing
- fraction of prompt vs. late light
- μ-like energy loss
- given E, is track length consistent with μ?
- 10 variable Fisher discriminant

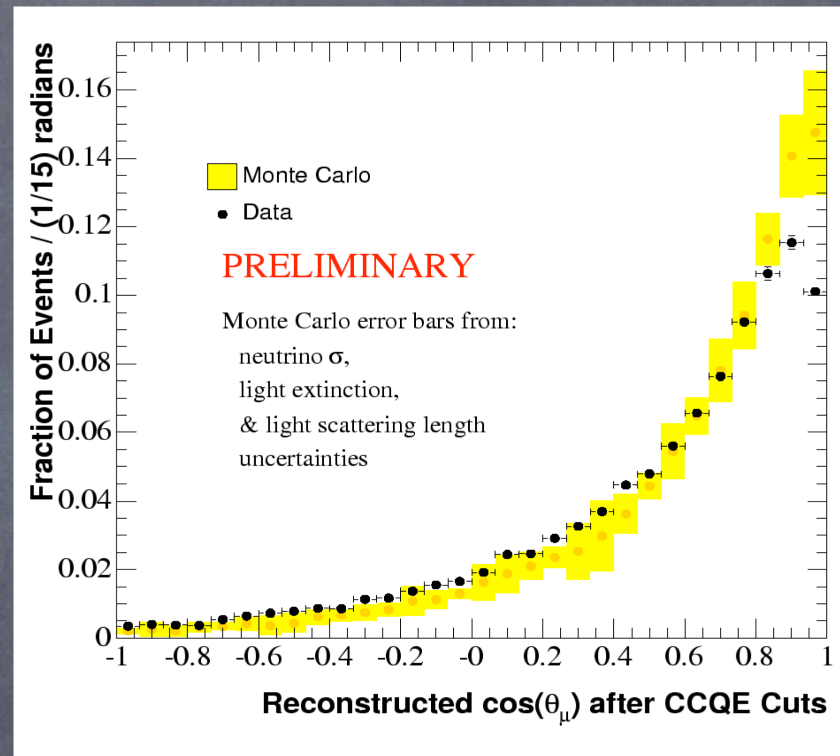
- Result: 86% CCQE purity
- most of background from CCPiP
- more pure than in past presentations

CCQE Data



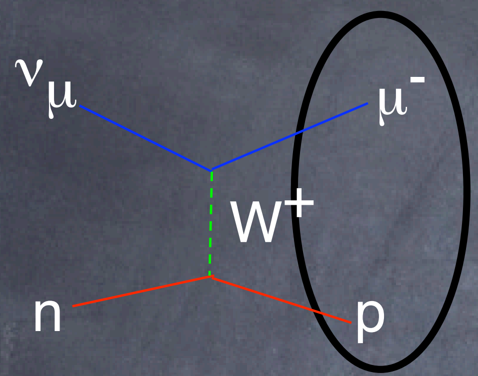
measure visible energy (mostly Cherenkov from μ, + a little scintillation light from proton)





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

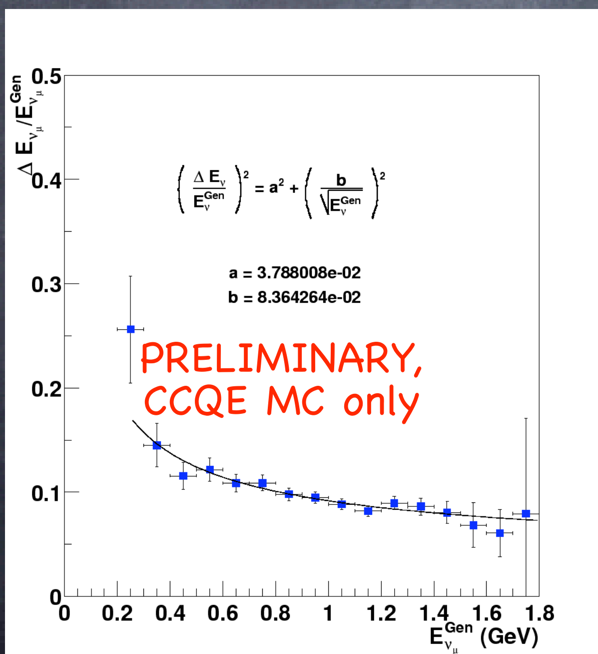
CCQE Data

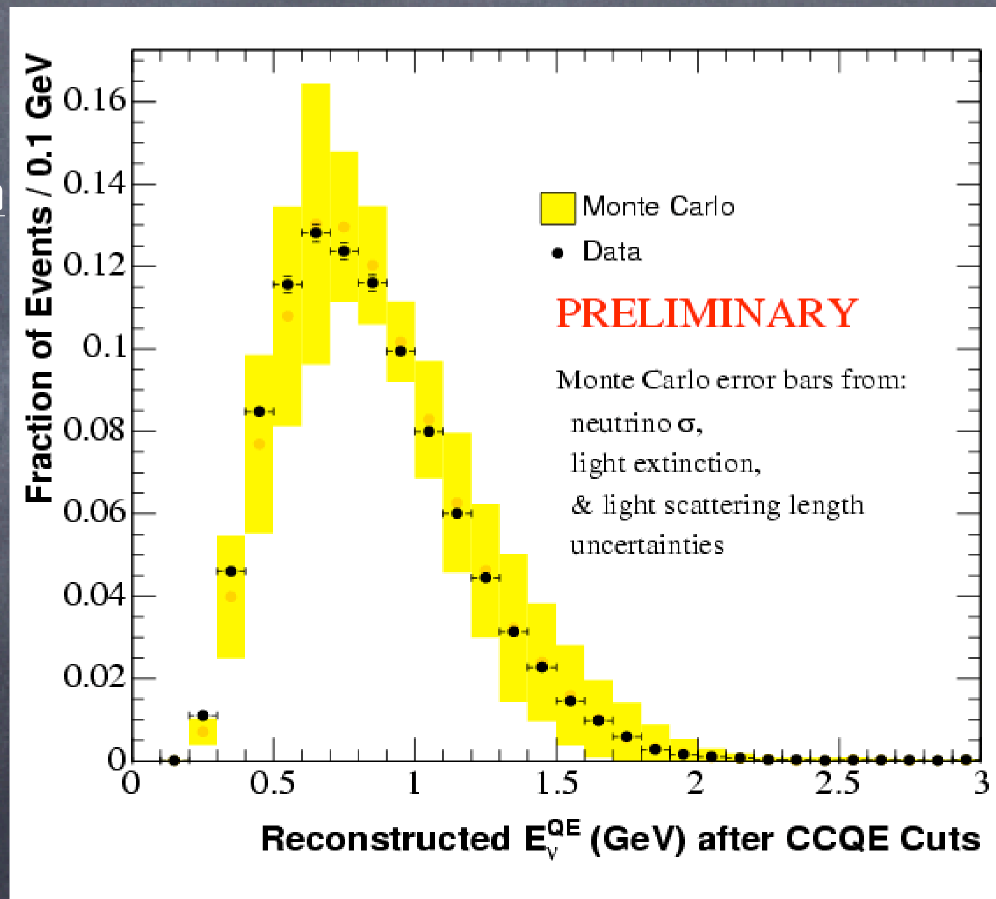


use measured μ visible energy and angle to reconstruct E_ν^{QE}

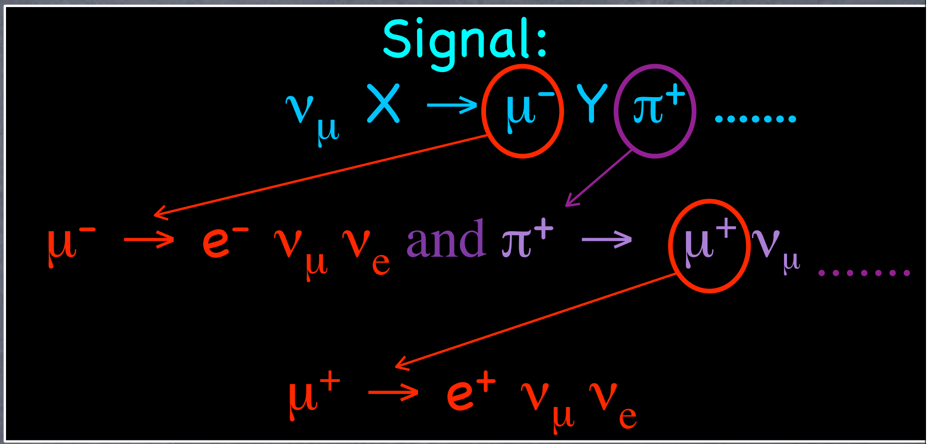
$$E_\nu^{QE} = \frac{1}{2}\frac{2M_p E_\mu - m_\mu^2}{M_p - E_\mu + \cos\theta_\mu \sqrt{E_\mu^2 - m_\mu^2}}$$

Neutrino Energy Reconstruction



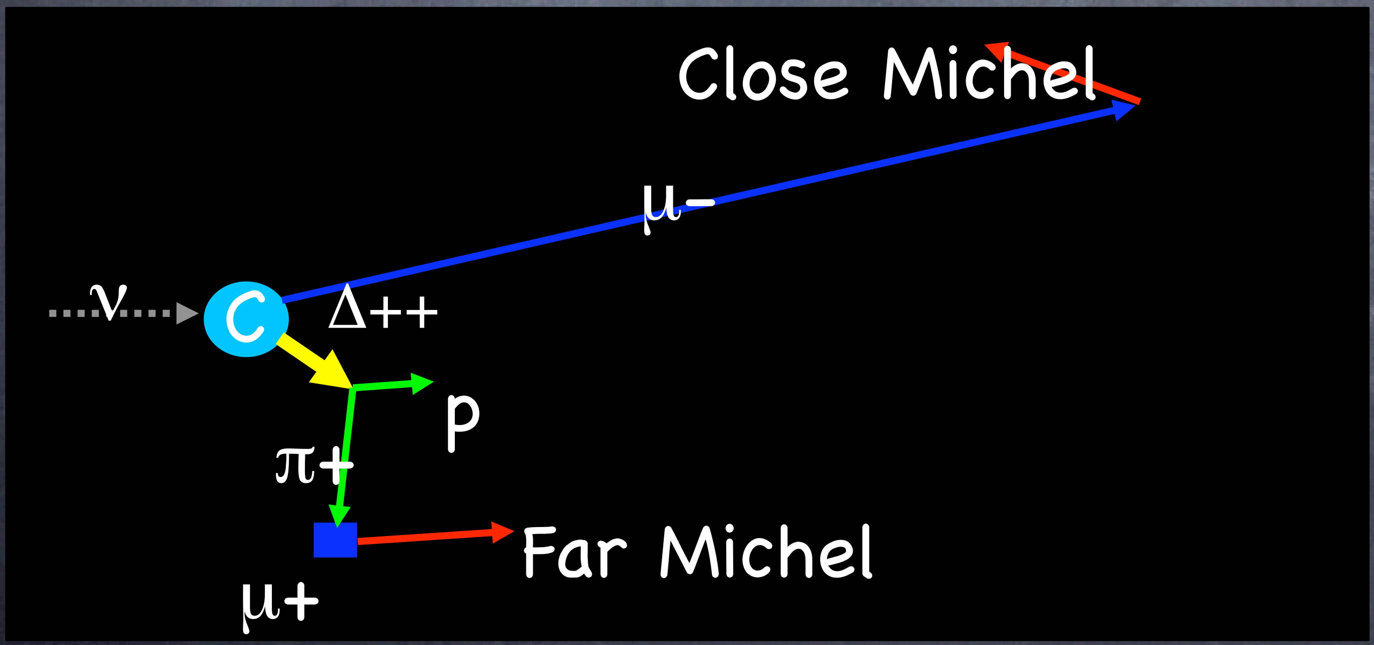


CCPiP Event Selection



First Level of Cuts:

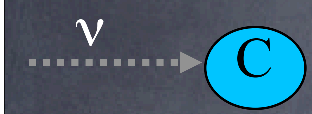
- Neutrino-Induced Event Selection Cuts
- exactly 3 sub-events
- 2nd 2 sub-events consistent with Michel e^- ($20 < N_{PMT} < 200$)



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

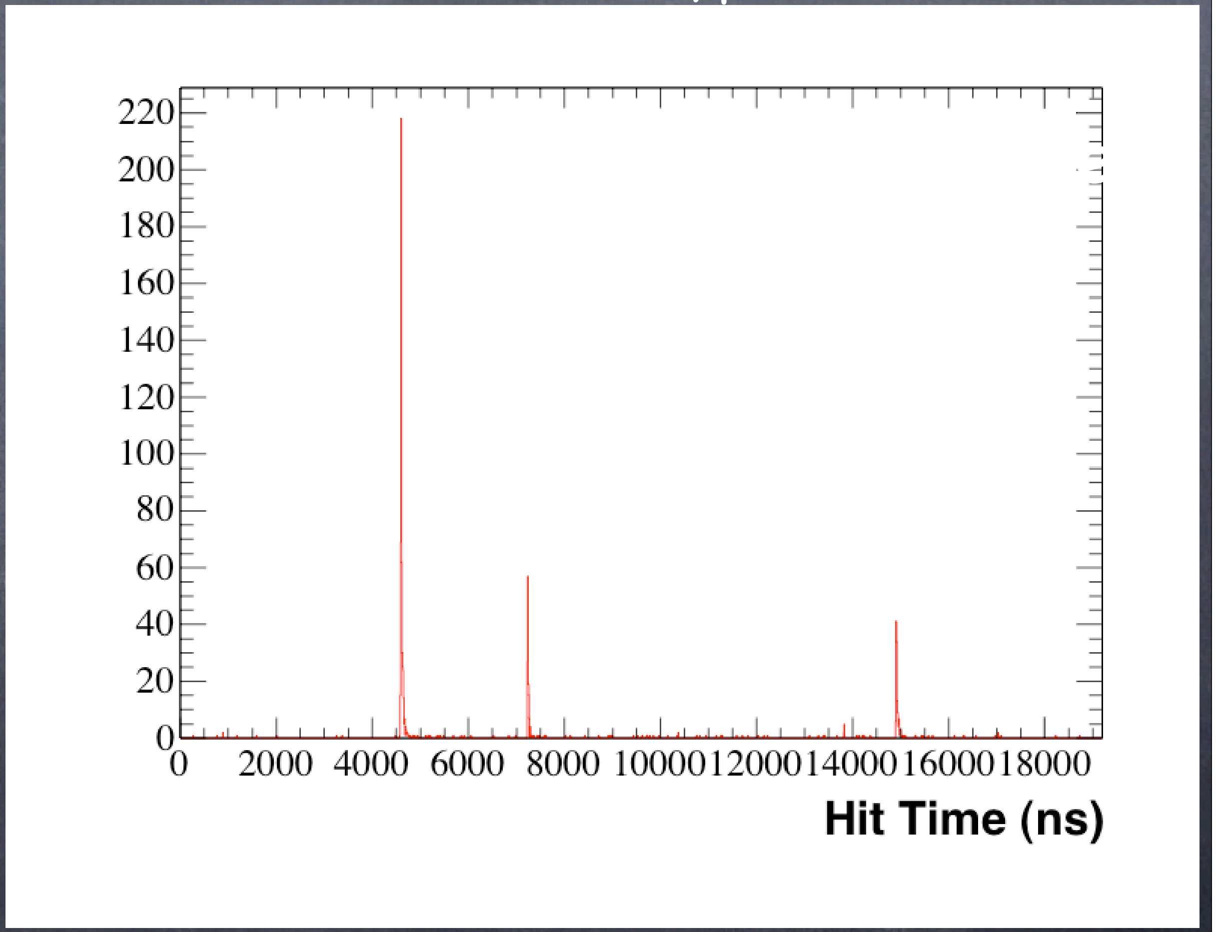
84% purity with 1st level cuts, bgnd from Nπ and QE

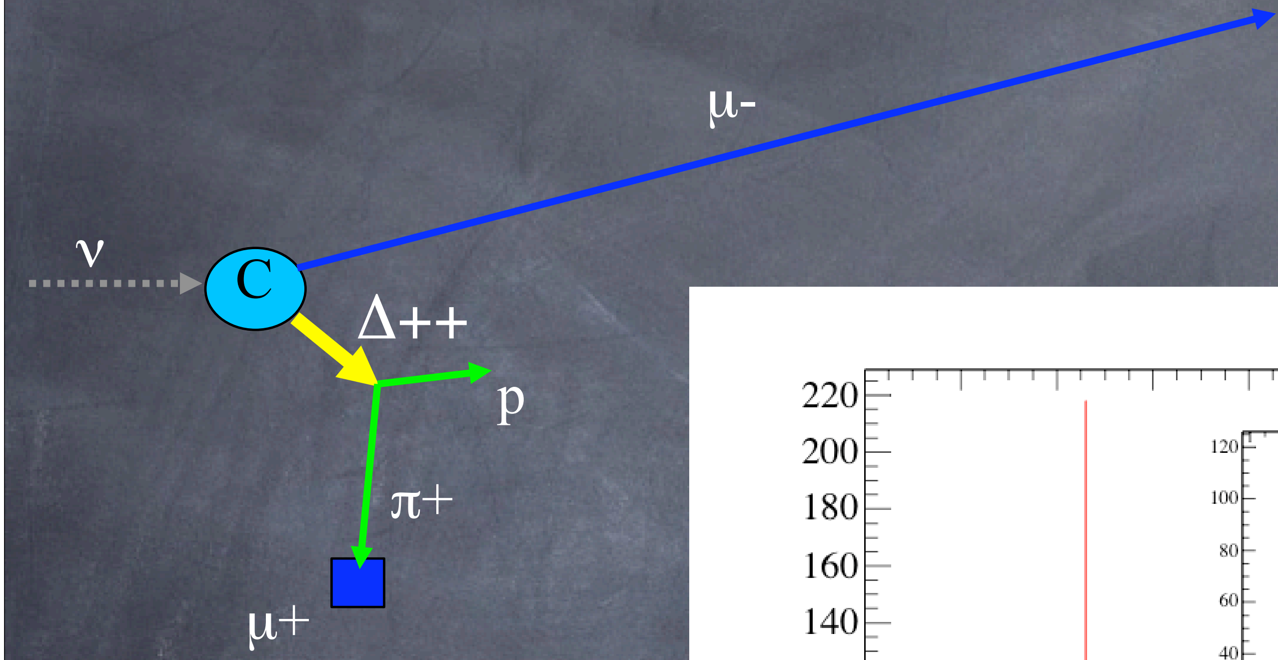
CCPIP Event Selection: Chain of (Sub)Events

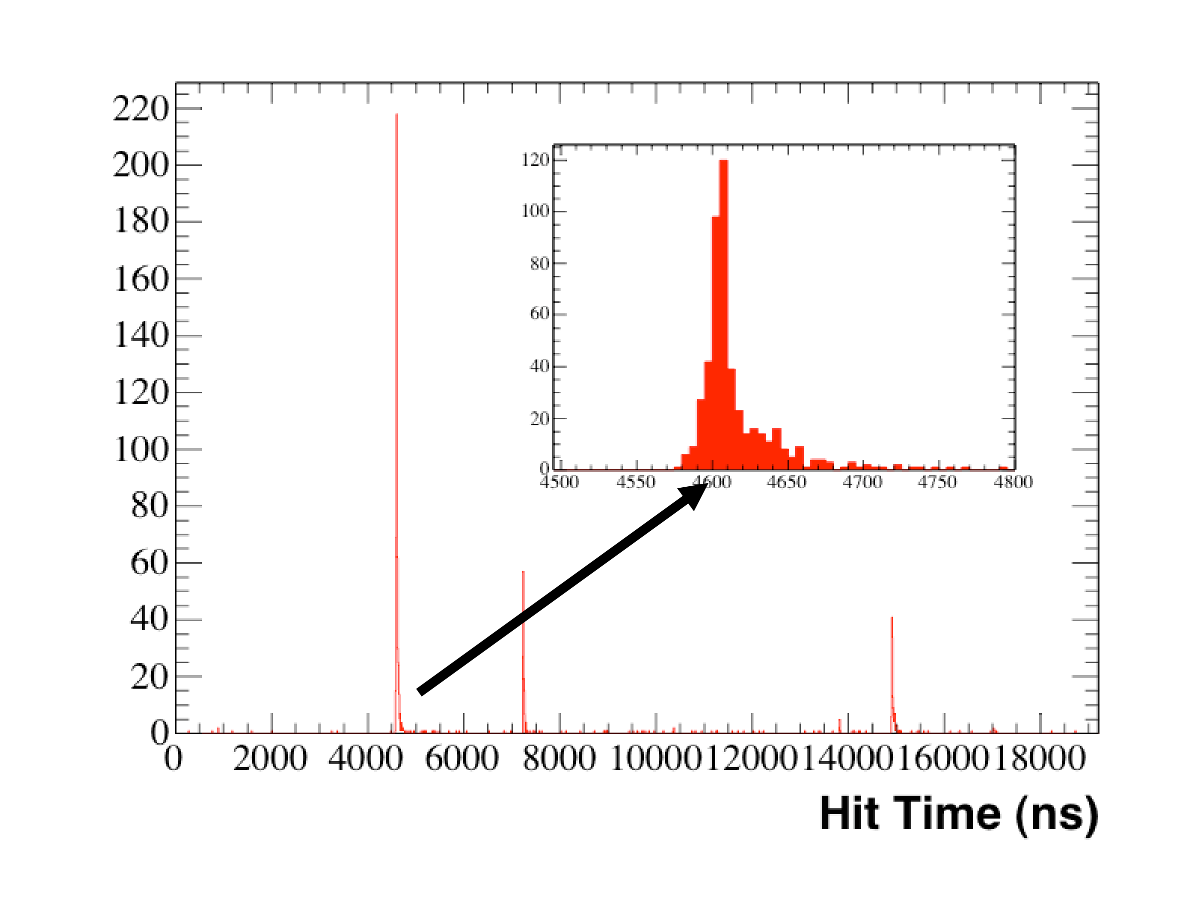


Neutrino interacts with carbon nucleus

Distribution of hits in a typical CCPIP event



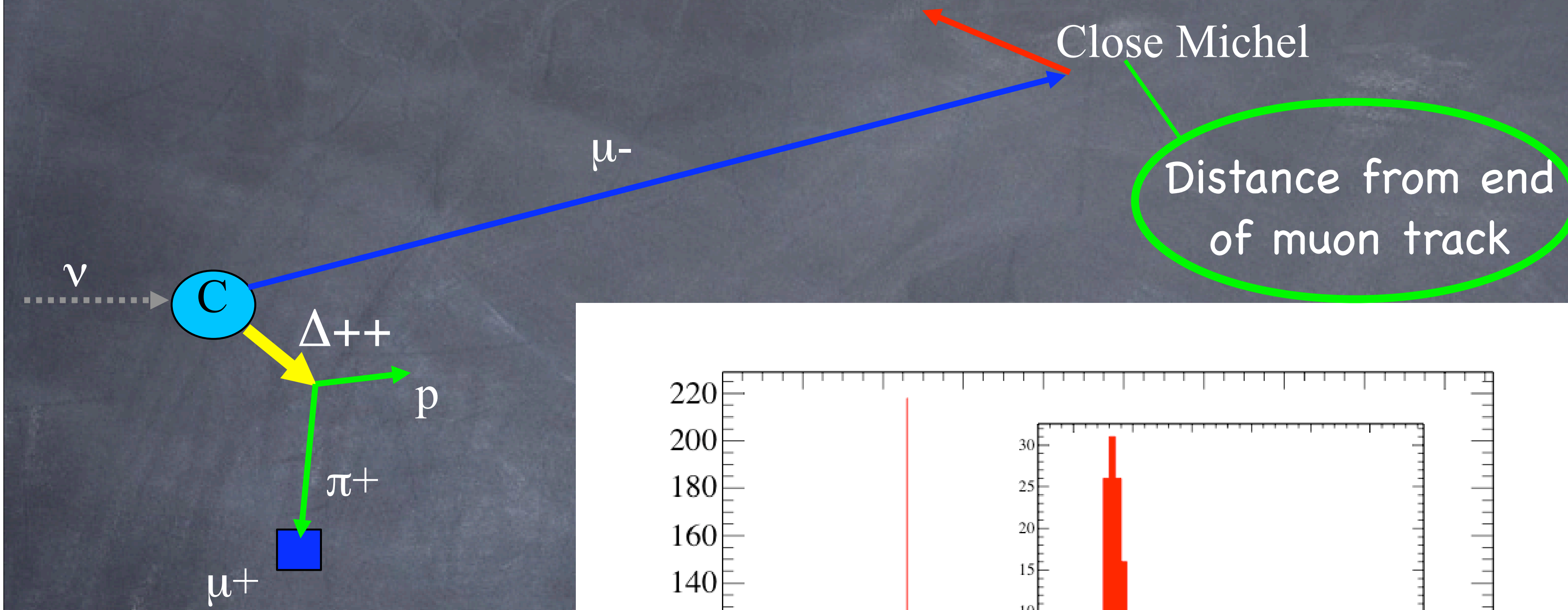


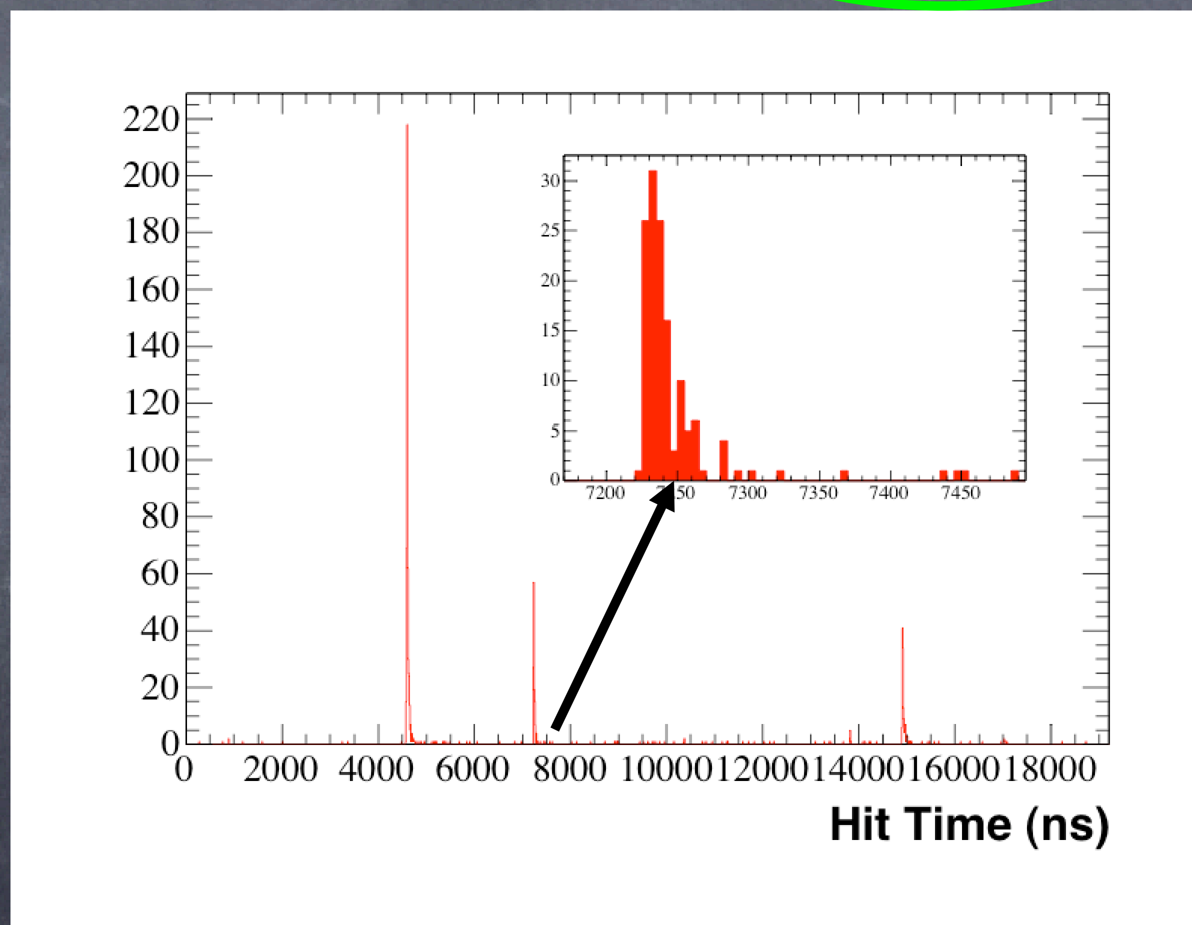


Neutrino subevent

Use these hits to reconstruct neutrino properties

Fit for muon Cherenkov ring

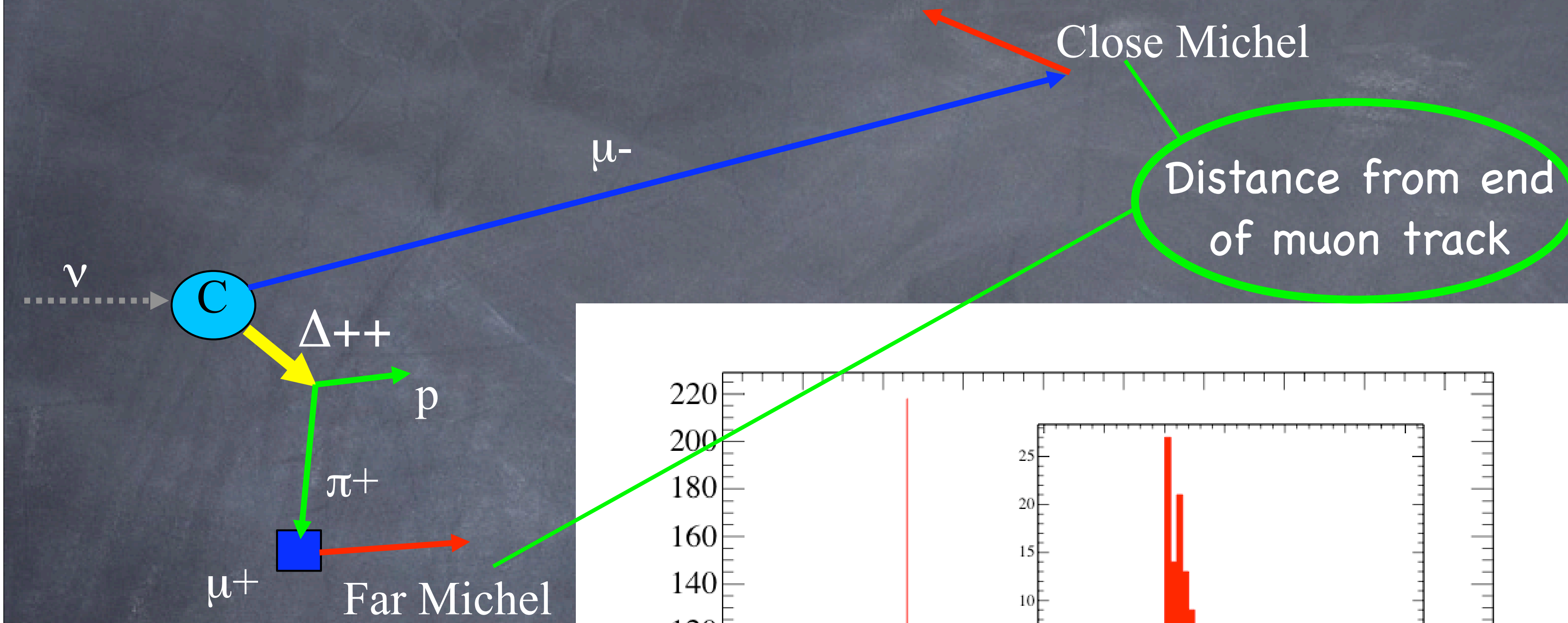


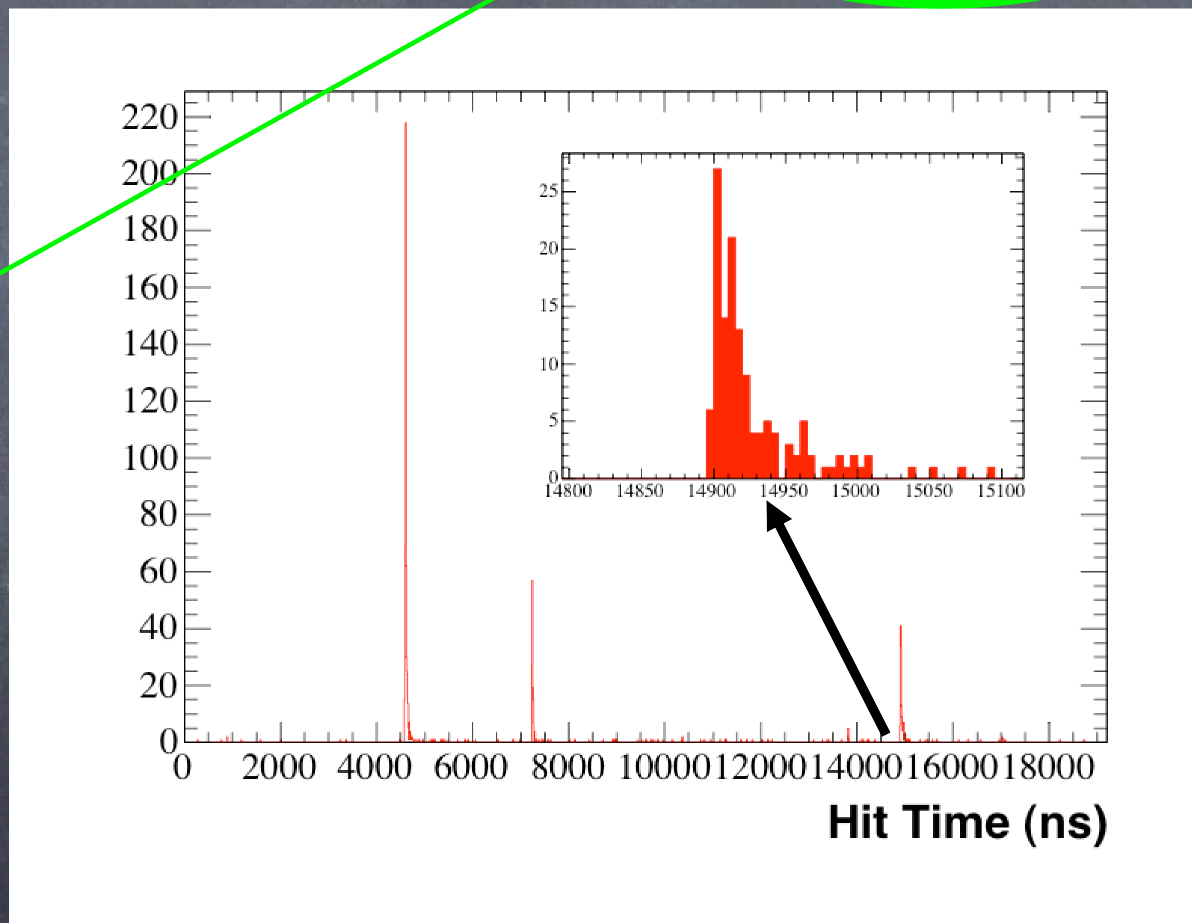


1^{st} Michel $e^{\pm}$ subevent

Could be from μ- or π+(μ+) decay

In this case, I've drawn it as e-





2^{nd} Michel $e^{\pm}$ subevent

Can use Michel subevents to help understand the neutrino subevent

CCPiP Event Selection Validation

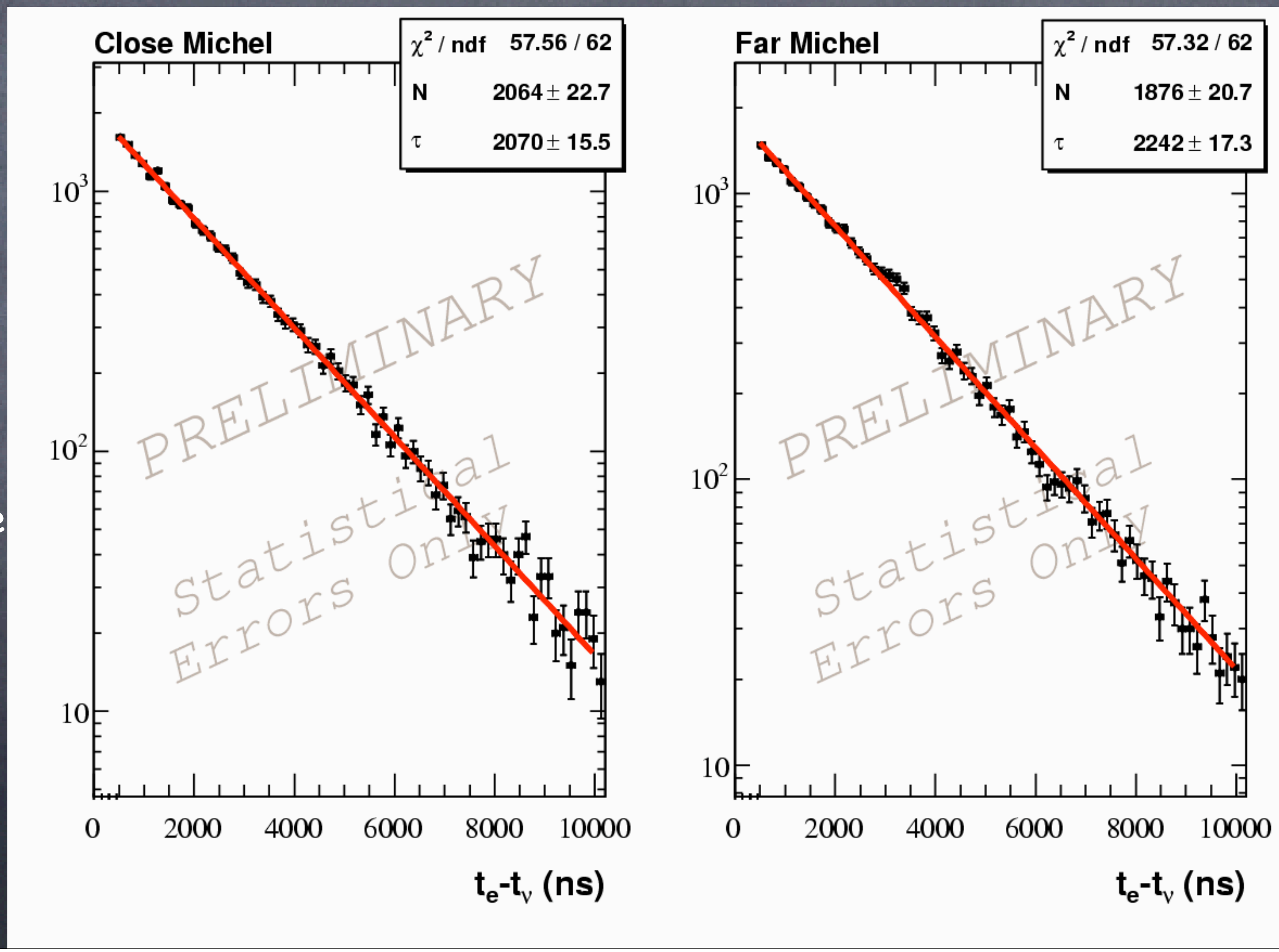
- validate CCPiP event selection with μ^+ and $\mu-$ lifetime measurement
- separated Michels from μ^+ and μ^- by distance to μ^- track

- close:
  $\mu-$ capture (8%)

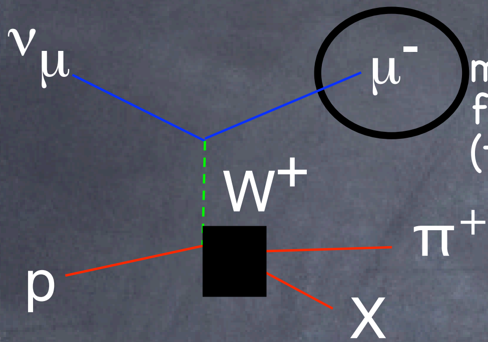
  expect
  τ=2026±1.5 ns
  measure
  τ=2070±15.5 ns

- far:
  $\mu+$: do not capture

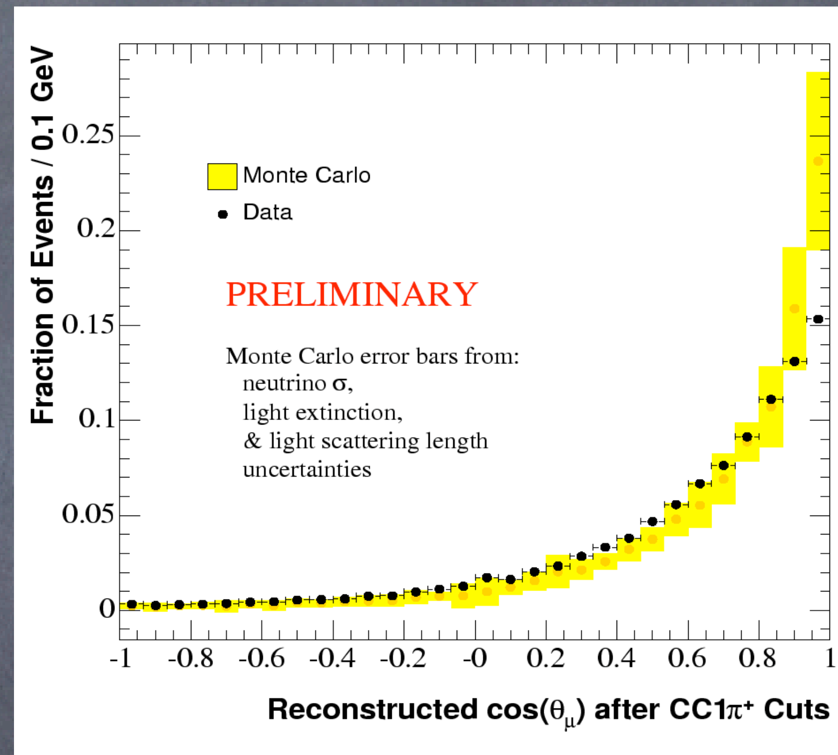
  expect
  τ=2197.03±0.04 ns
  measure
  τ=2242±17.3 ns

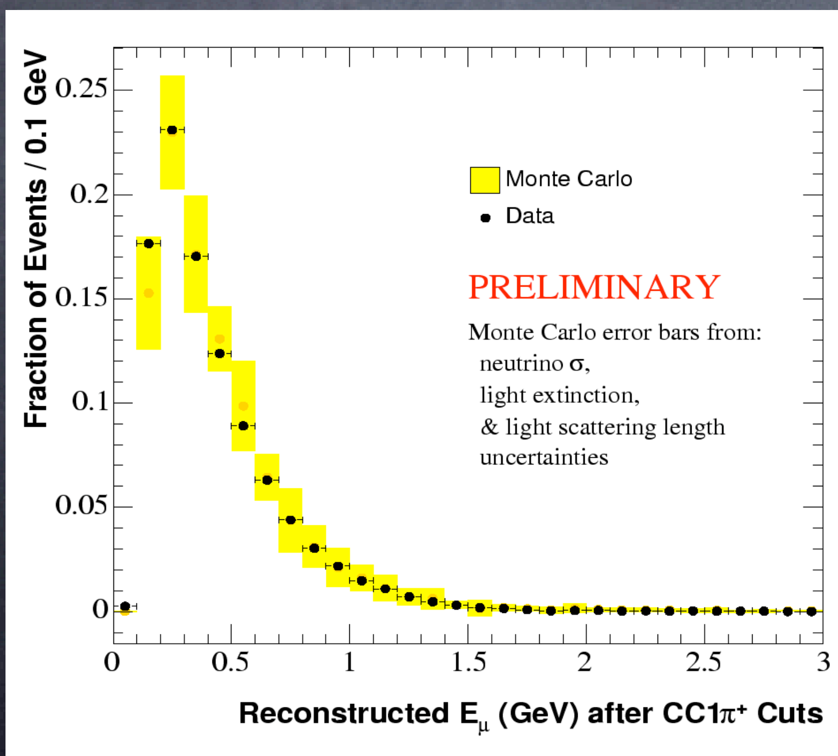


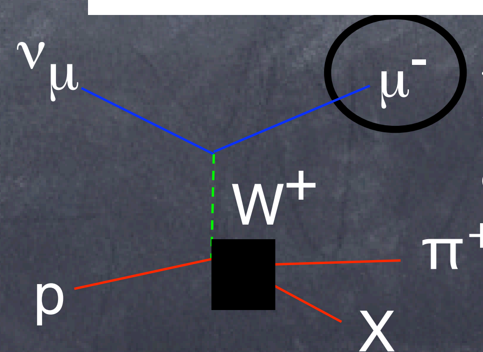
CCPiP Data



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

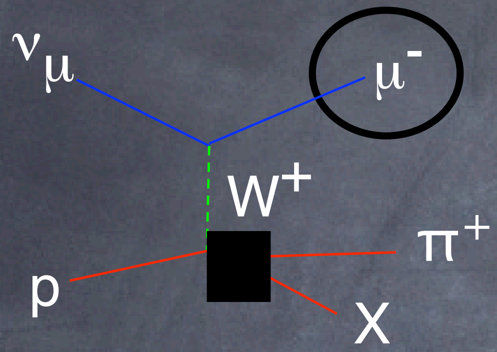






reconstruct μ direction
from Cherenkov light,
$\cos(\theta) = 1$ ~ low Q^2

CCPiP Data

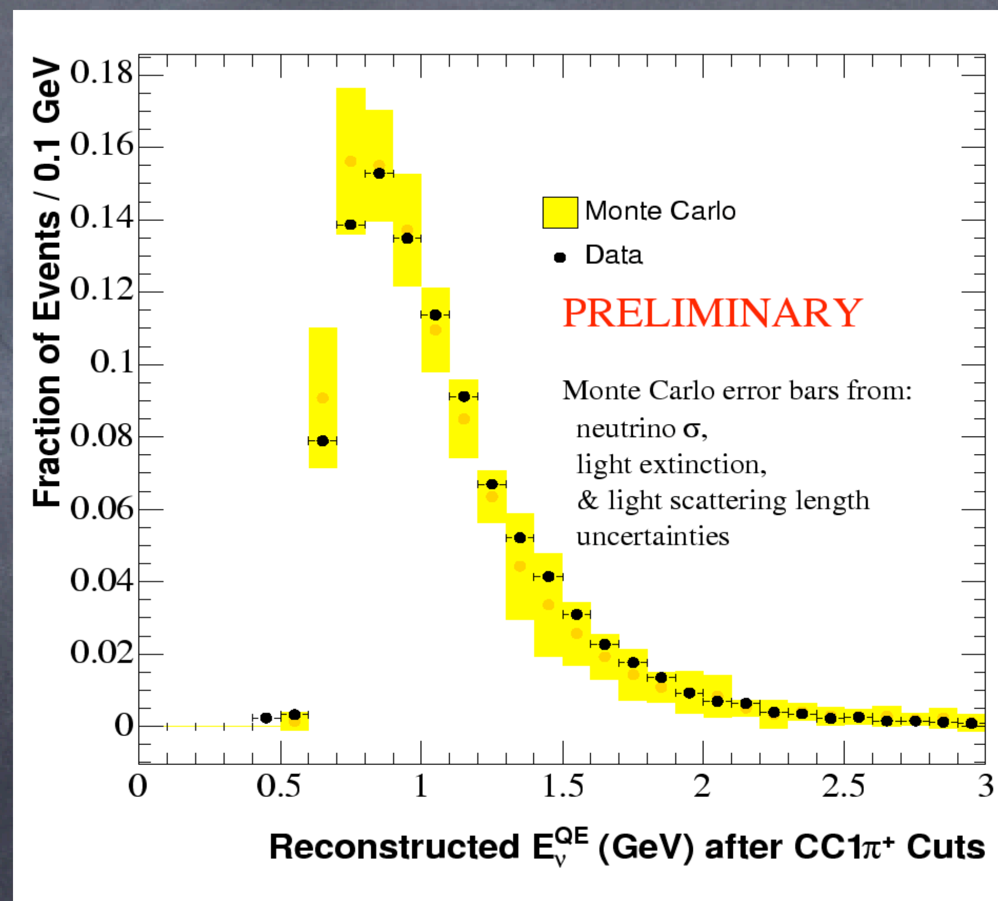


use measured μ visible energy and angle to reconstruct E_ν^{QE}

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

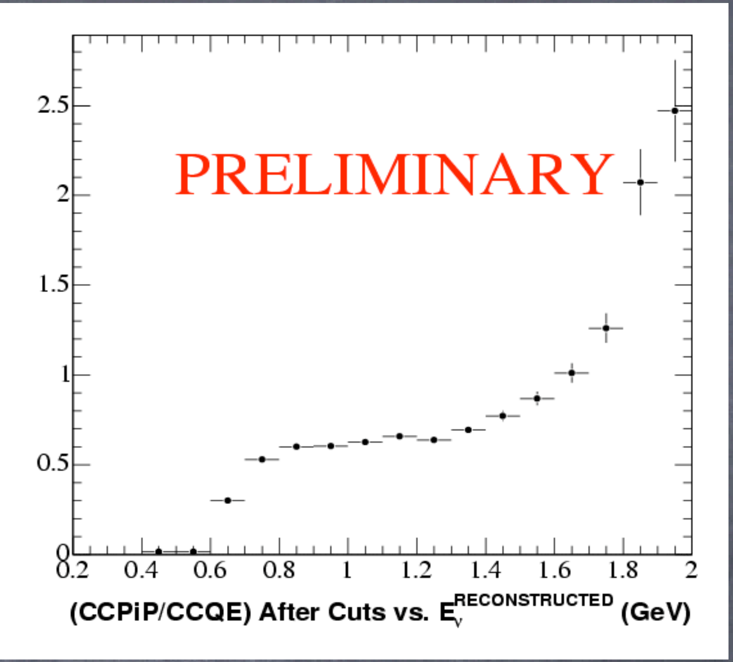
Neutrino Energy Reconstruction

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



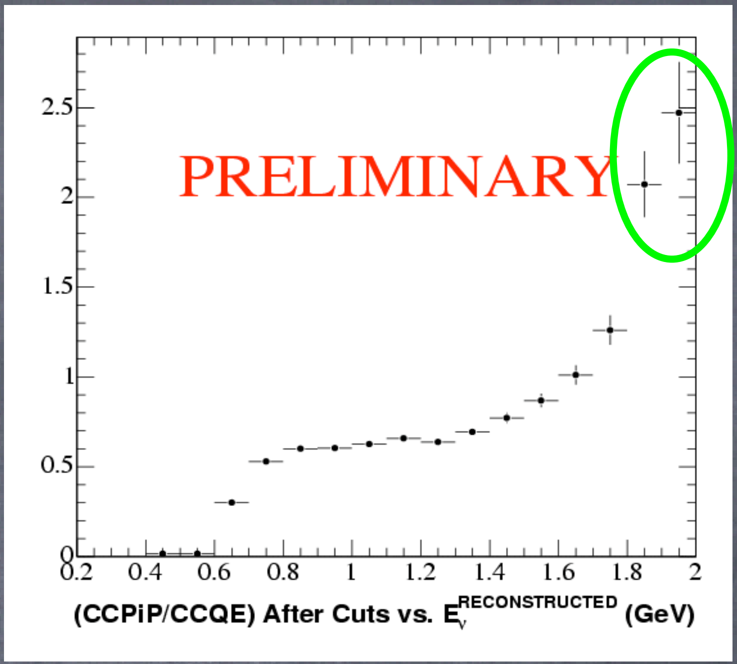
CCPiP/CCQE Ratio

- 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



CCPiP/CCQE Ratio

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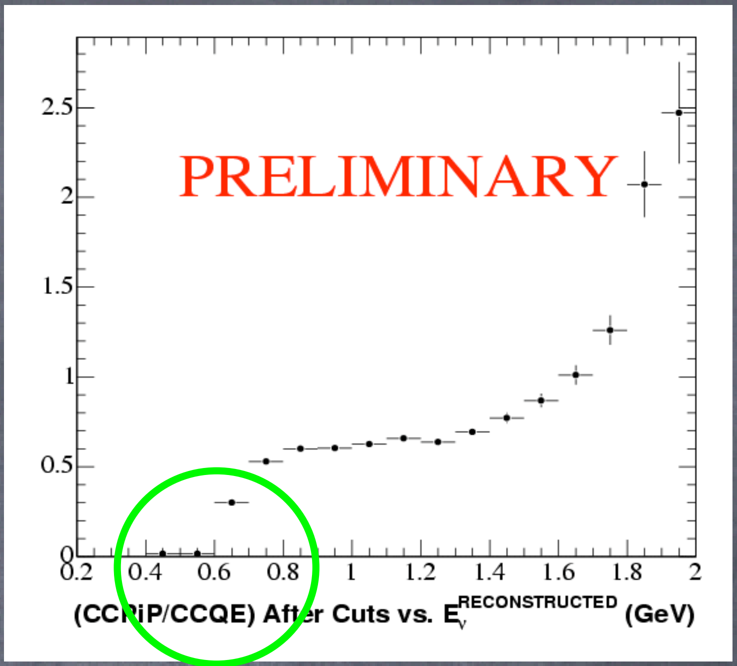
- CCPiP threshold > CCQE



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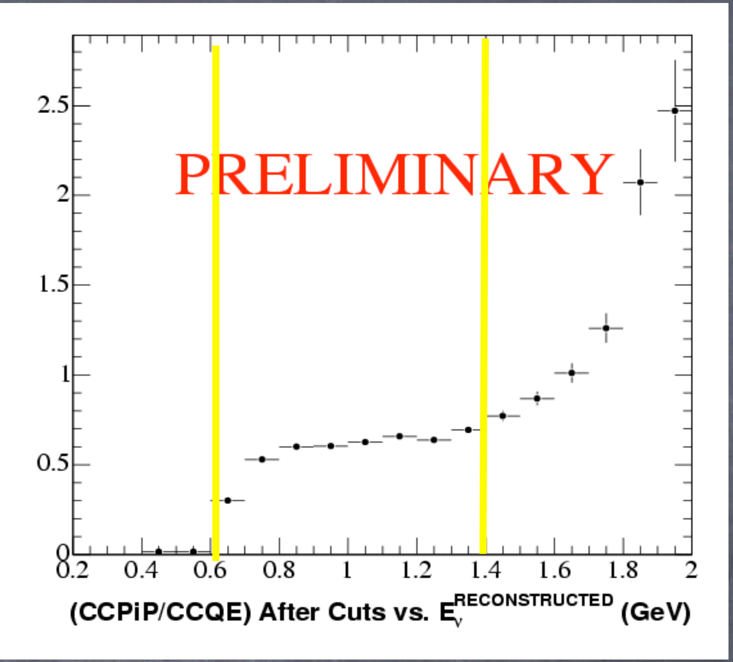
- possibility of ν_μ disappearance
- like branching ratio measurements, normalize to ``golden mode'' in our own data
- CCQE is the ``golden mode'' of low E ν σs



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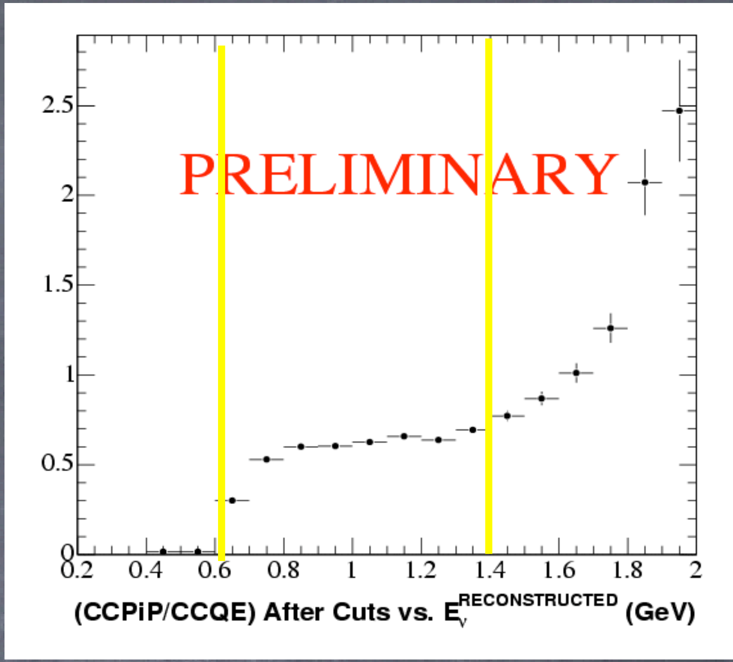
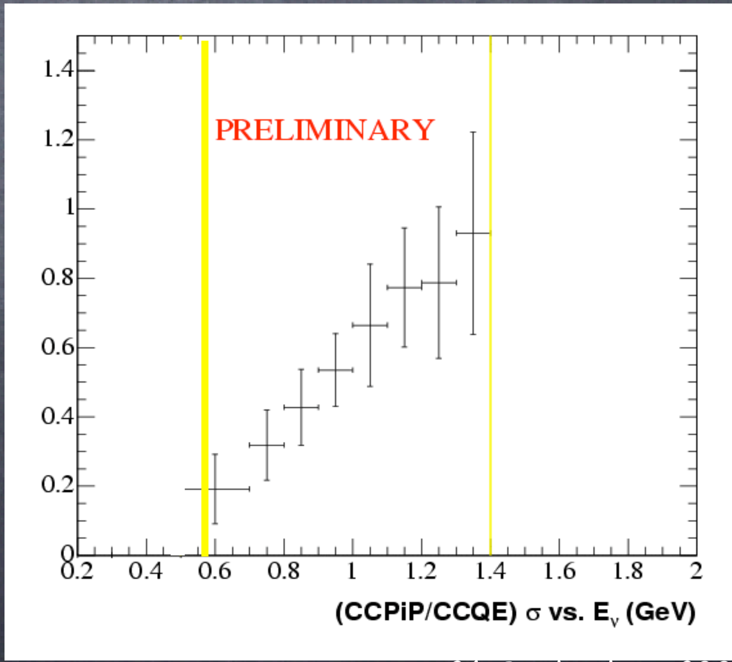
- possibility of ν_μ disappearance
- like branching ratio measurements normalize to "golden mode" in our own data
- CCQE is the "golden mode" of low E ν σs

- Efficiency corrected ratio measurement:
- estimate efficiency correction in MC
- systematic errors: ν cross sections (~15%), γ extinction and scattering 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:

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

PRELIMINARY

Sources of Uncertainty

γ propagation in detector oil (optical model) uncertainties:

parameter varied	*variation amount*
extlen(460nm)	+33%
Rayleigh A & B	-16%
Raman	-16%

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- incomplete list

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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)
- (HARP results expected to improve flux uncertainties)

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PRELIMINARY

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- (HARP results expected to improve flux uncertainties)

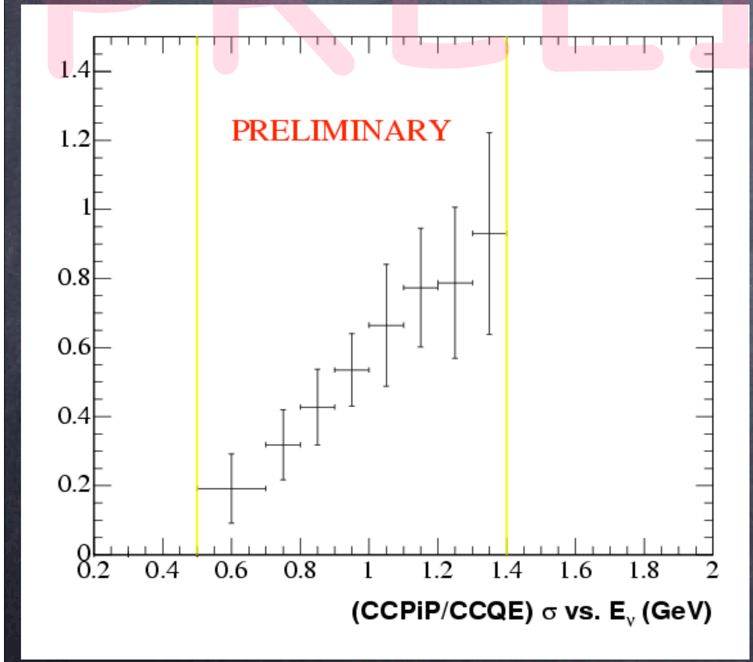
Preliminary → Final:

- estimate / measure parameter (anti-)correlations
- reduce detector optical model uncertainties with continued analysis of calibration data
- reduce $\nu\,\sigma$ uncertainties with analysis of electron scattering data
- consistent π interaction uncertainties in NUANCE and detector Monte Carlo

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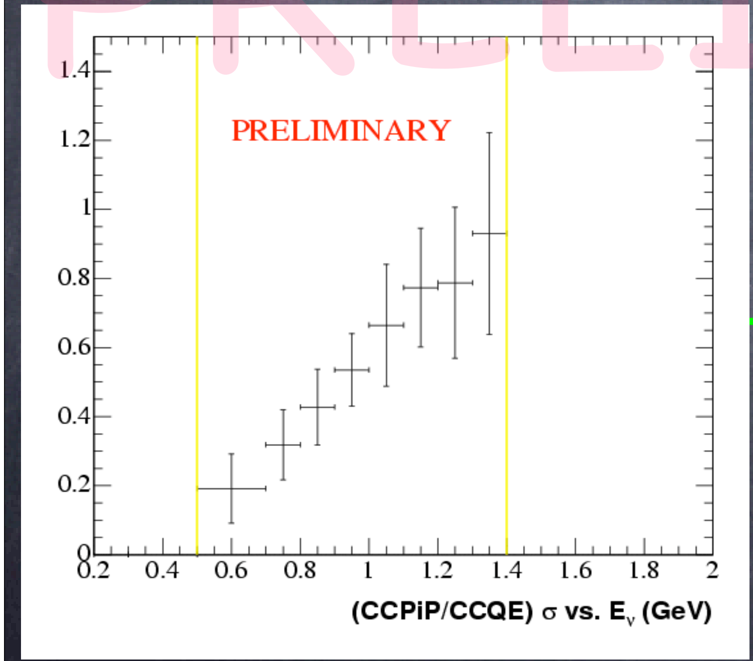
- use ``golden mode" to convert to σ(CCPiP):

$$\sigma(CCPIP) = R_{Measured} \times \sigma_{NUANCE}$$

PRELIMINARY



Multiply by NUANCE MC σ CCQE

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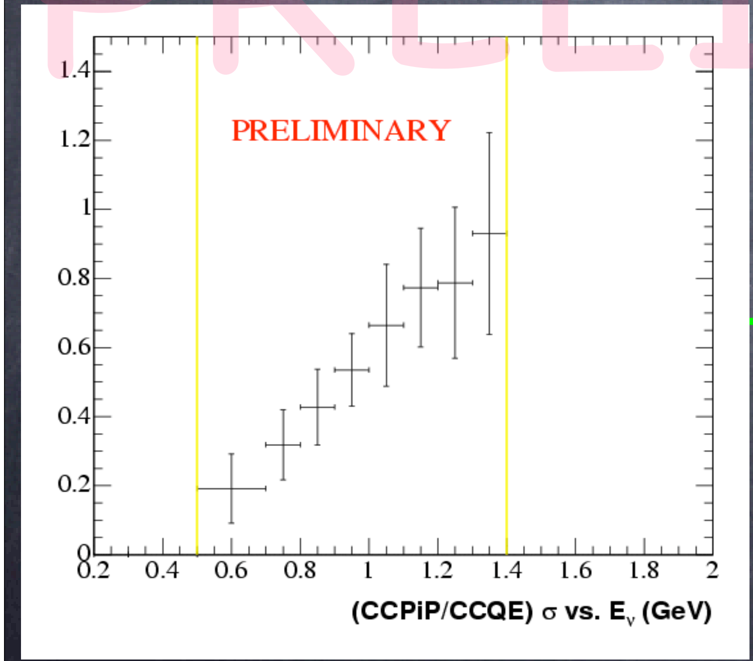
PRELIMINARY



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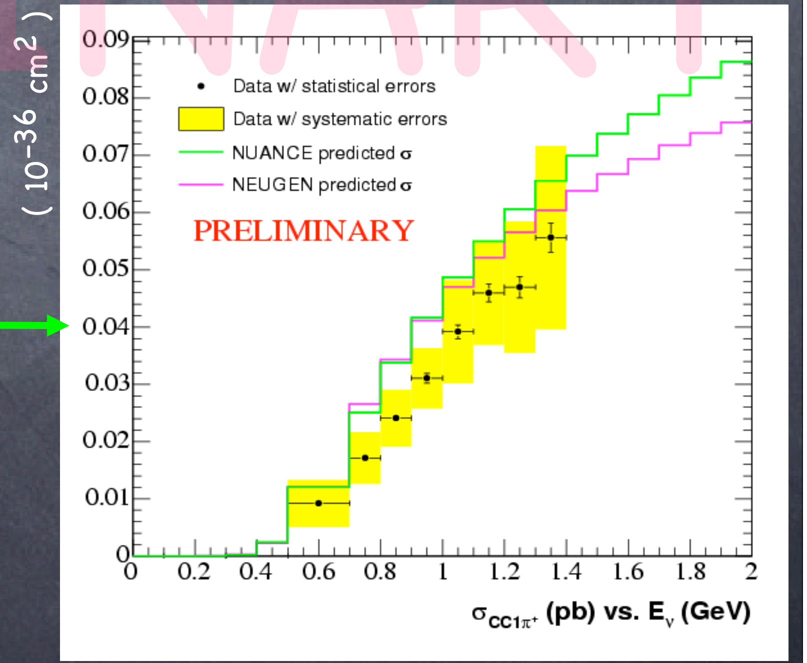
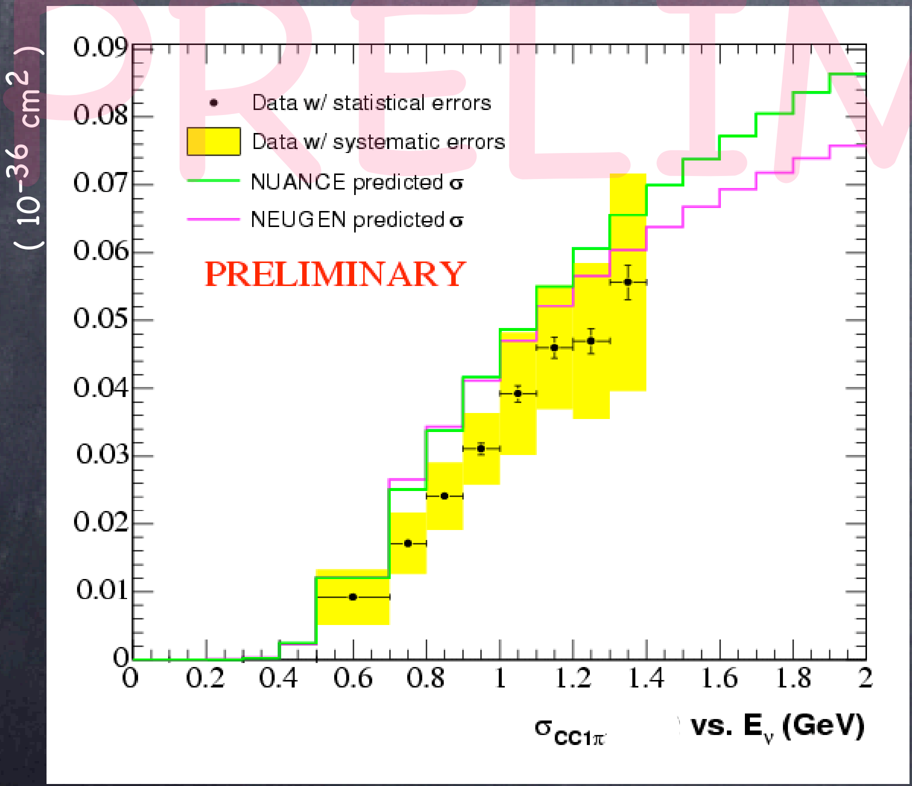
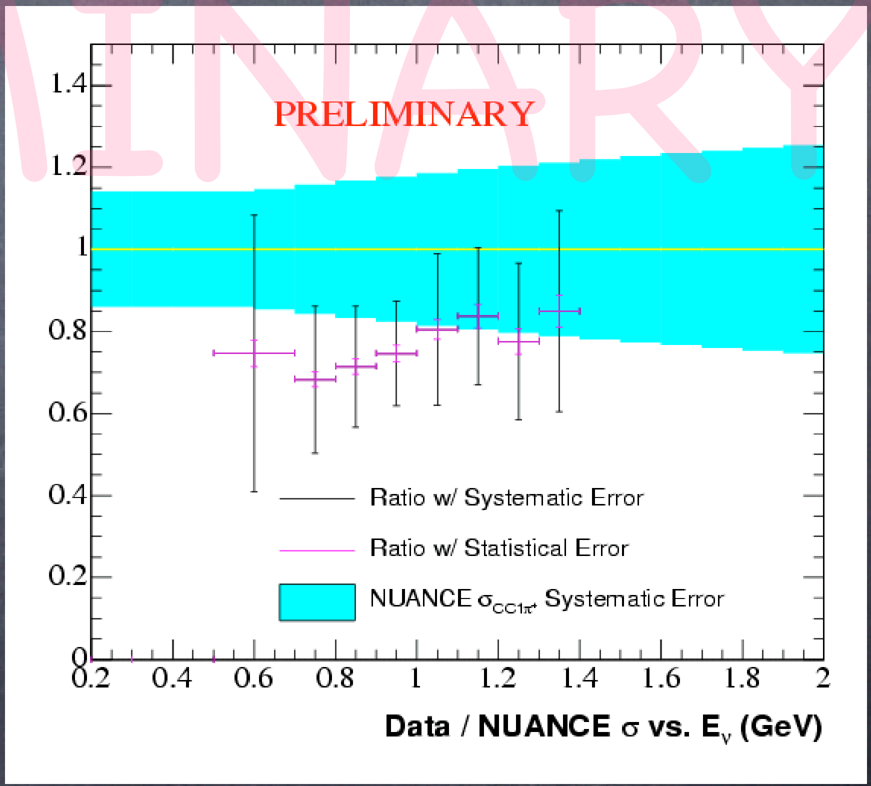


CCPiP/CCQE Ratio

- 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)



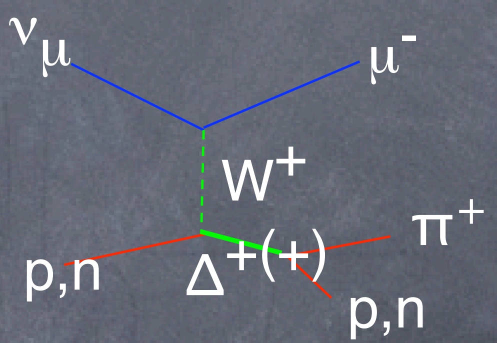


effective CCPiP/CCQE Ratio

- 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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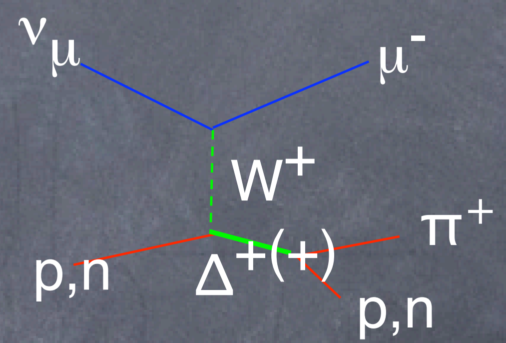

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- MiniBooNE can also measure ``effective'' σ(CCPiP)
- define numerator of MC efficiency correction as anything CCPiP-like, not just $\nu_\mu p \rightarrow \mu^- p \pi^+$, $\nu_\mu n \rightarrow \mu^- n \pi^+$, and $\nu_\mu A \rightarrow \mu^- A \pi^+$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

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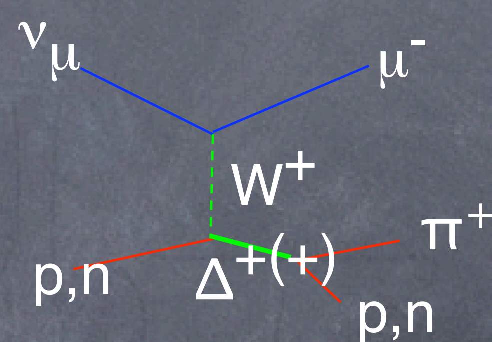

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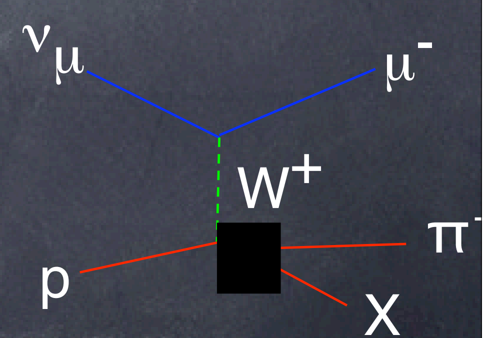
- CCPiP-like = 1 μ^- and 1 π^+ in final state (before particles decay)

- 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



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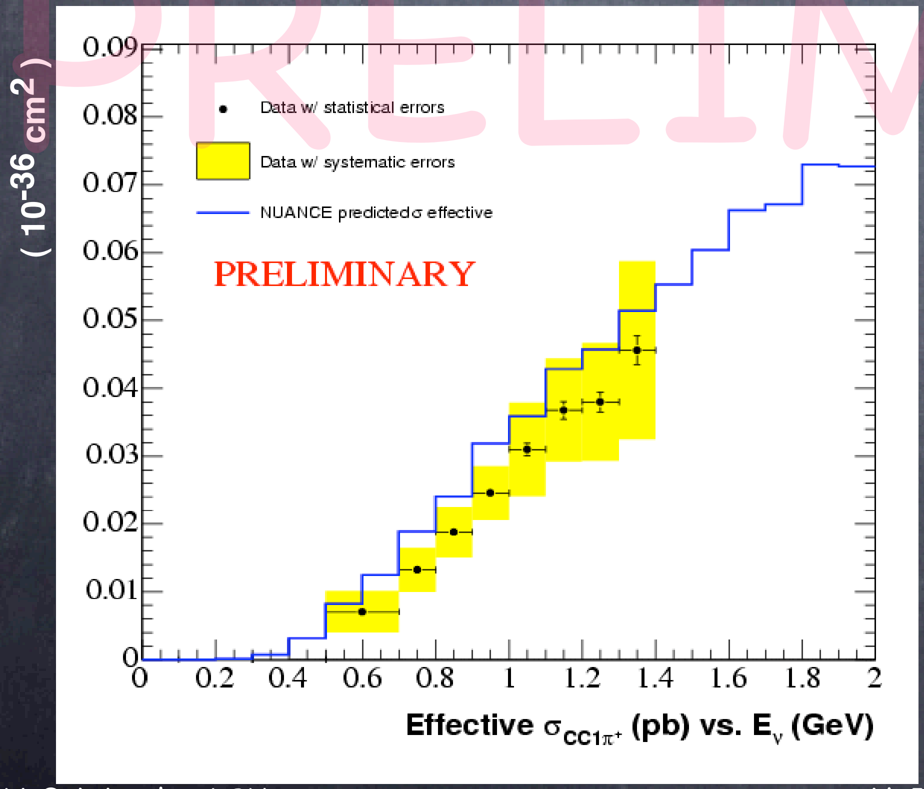
- efficiency corrected ratio measurement as a function of ν energy:

$$R^{Effective}_{Measured} = \frac{N_{CCPIP}}{N_{CCQE}} = \frac{\sigma_{CCPIP}}{\sigma_{CCQE}}$$

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

PRELIMINARY

$\sigma_{EFFECTIVE}$



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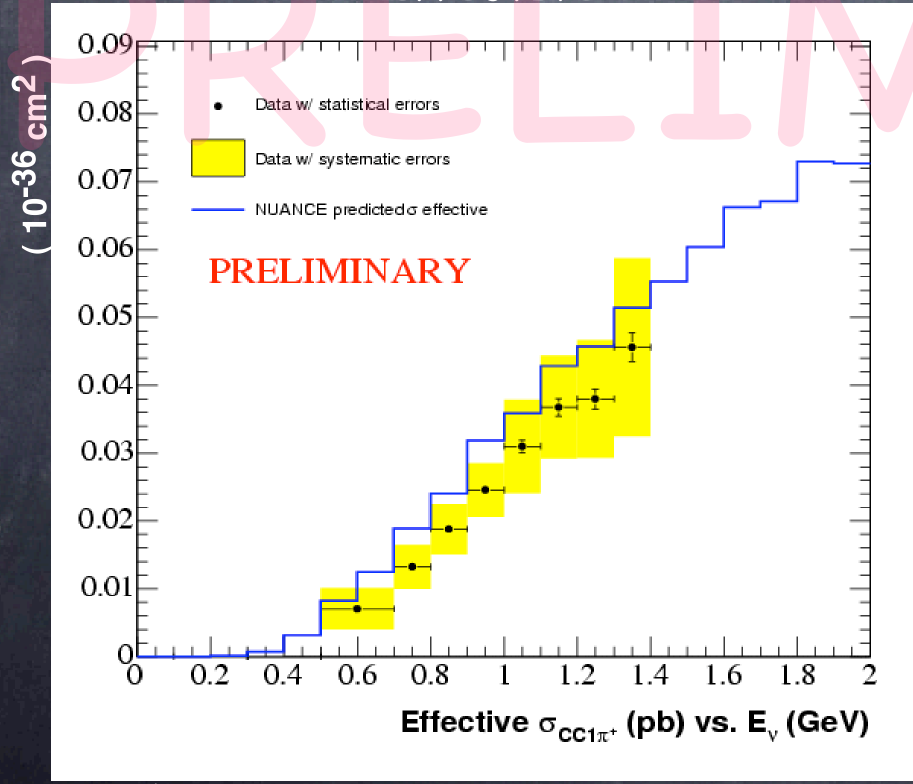
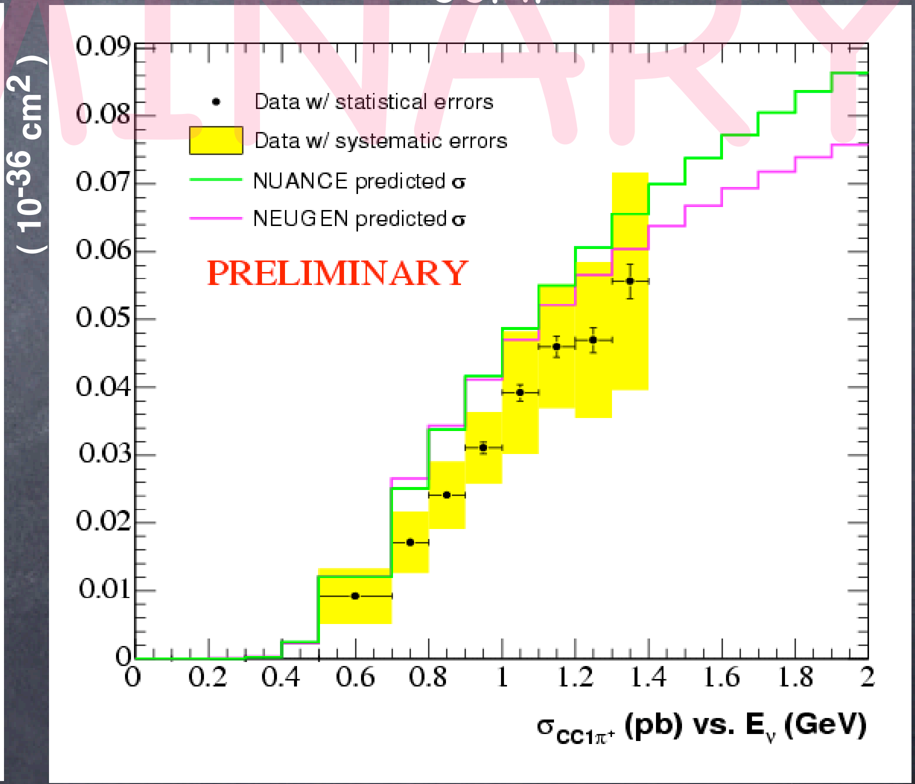
- use ``golden mode'' to convert to σ(CCPiP-like), compare σ(CCPiP)

PRELIMINARY

$\sigma_{EFFECTIVE}$



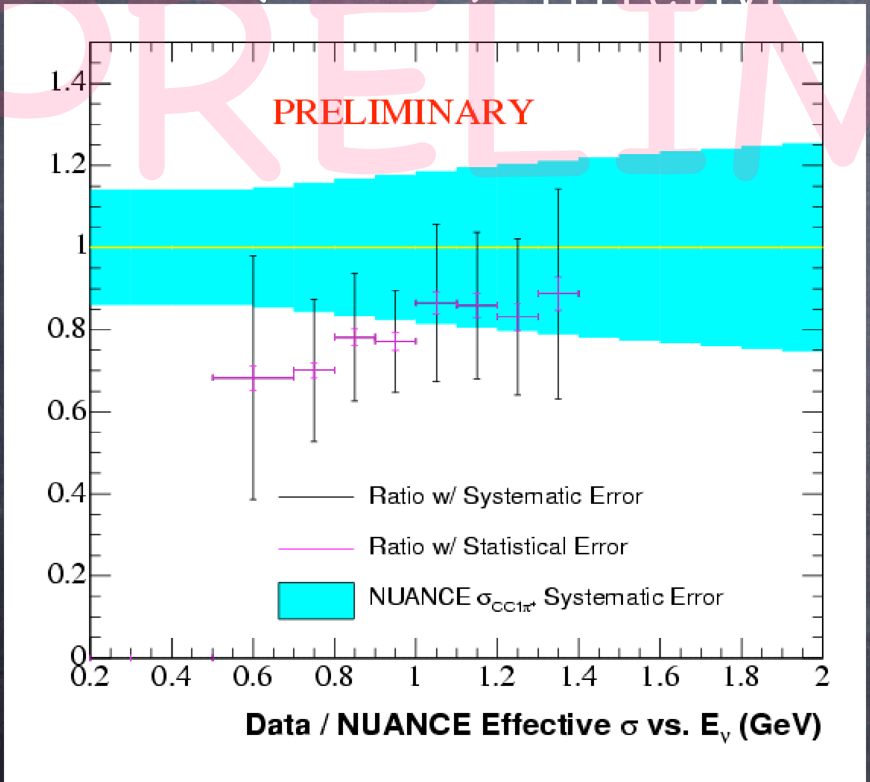
σ_{CCPiP}



effective CCPiP/CCQE Ratio

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

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



PRELIMINARY

effective CCPiP/CCQE Ratio

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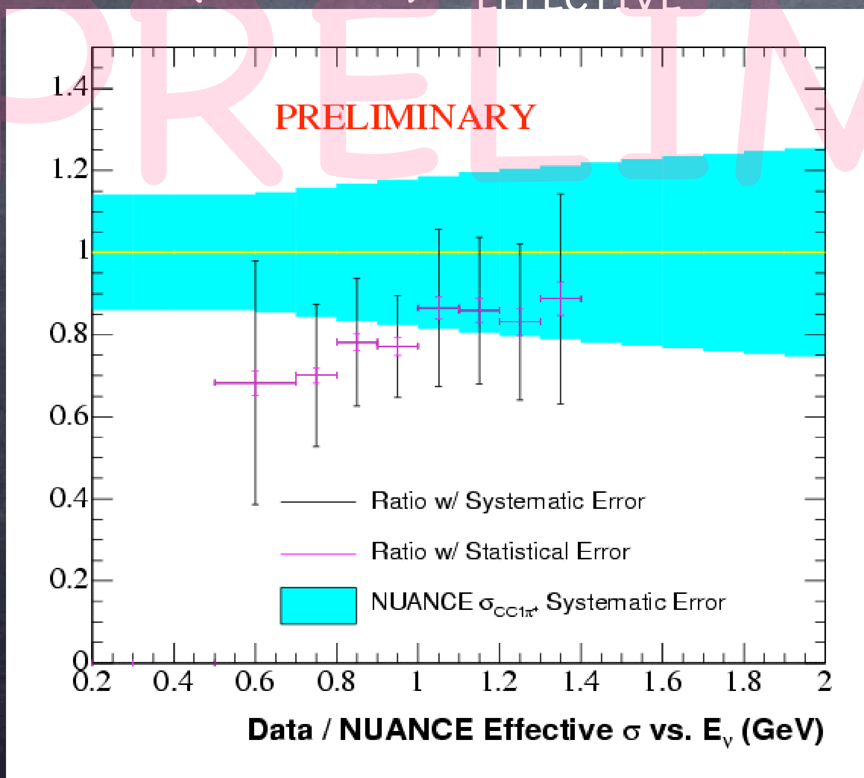
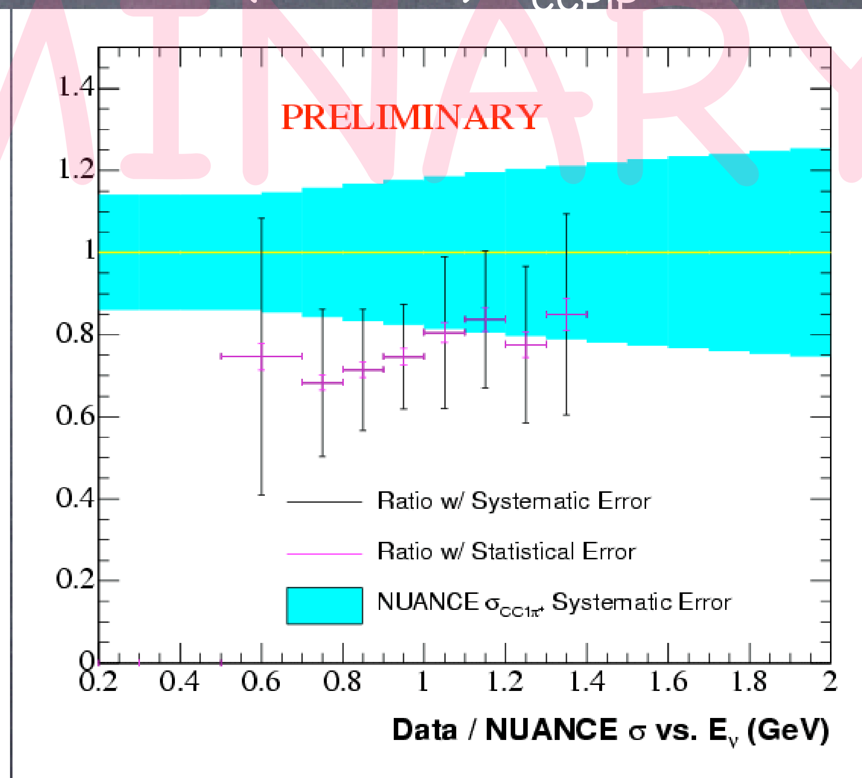
(Data/MC) $\sigma_{EFFECTIVE}$



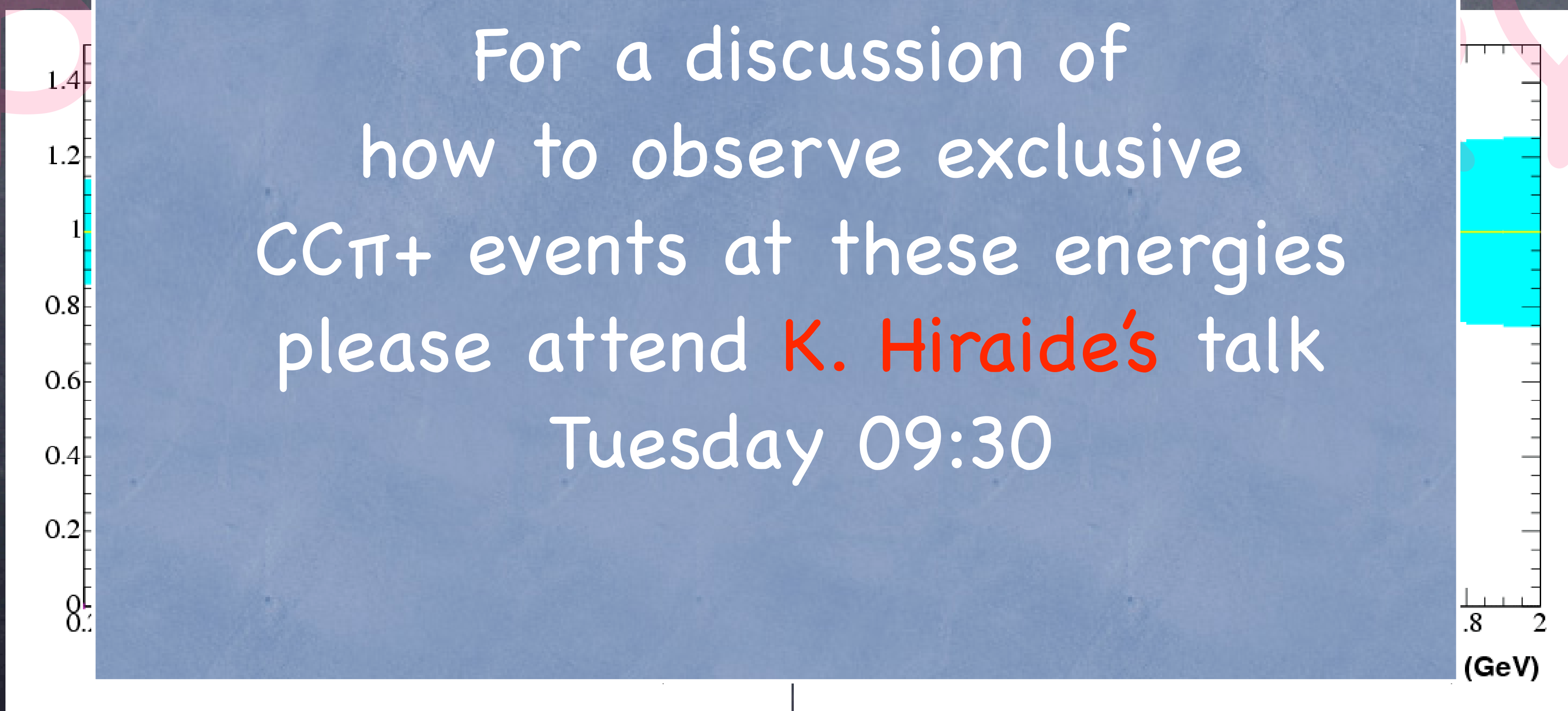
(Data/MC) σ_{CCPiP}



PRELIMINARY

effective CCPiP/CCQE Ratio

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



For a discussion of
how to observe exclusive
CCπ+ events at these energies
please attend K. Hiraide's talk
Tuesday 09:30

Outlook and Conclusions

CCPiP Analysis Plan:

- Extract coherent vs. resonant fractions with 2D fits to kinematic distributions
- reconstruct π information, feed back into ν 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:

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

Oscillations
- ν_e appearance result: not before end of 2005

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Thanks to the organizers
for the invitation
and support!

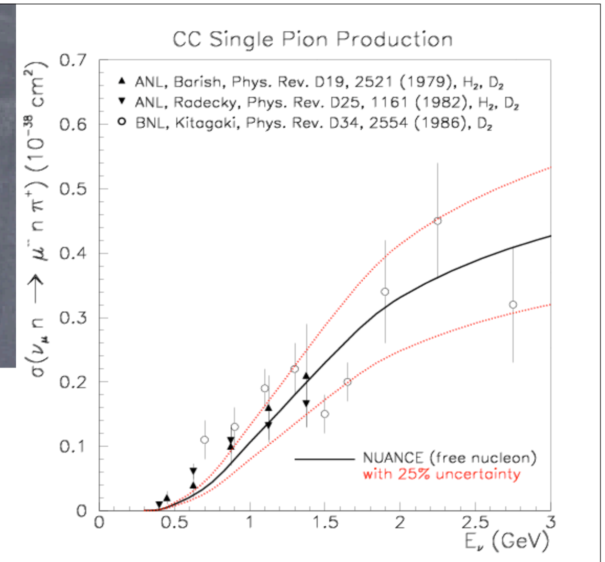
Backup Slides

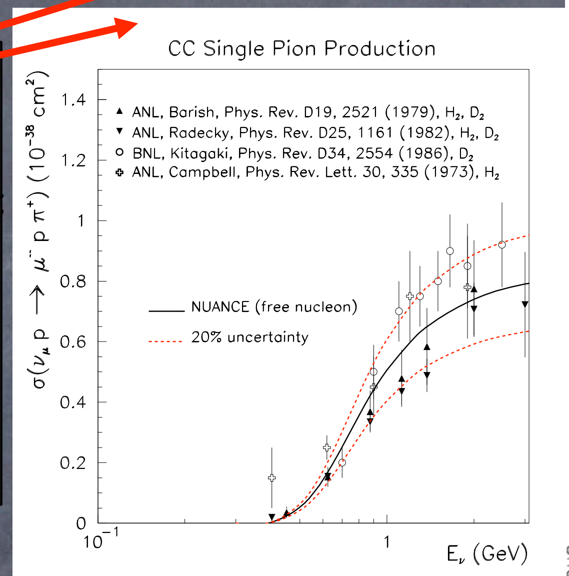
CCPiP σ Errors

CCPiP cross section uncertainties:

Resonant Production

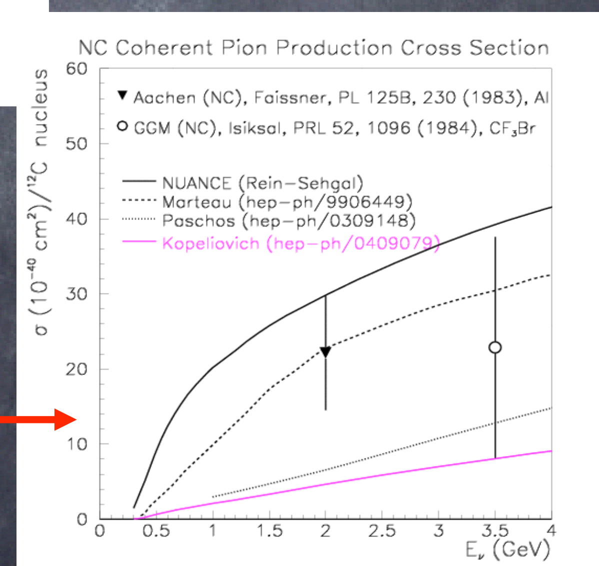
- 25% uncertainty on $m_A^{1\pi}$
- derived from external data
- size of error driven by difference between ANL and BNL measurements





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

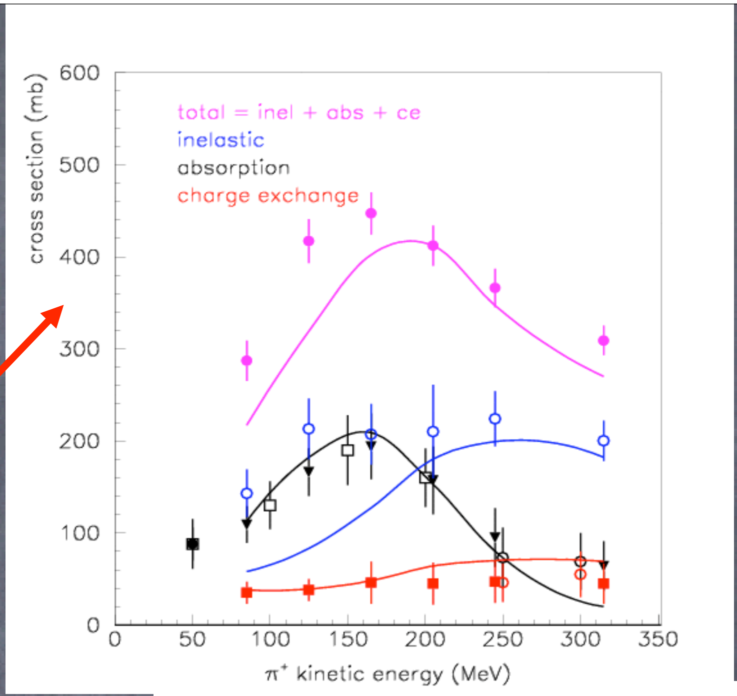


effective CCPiP σ Errors

Final state interaction uncertainties:

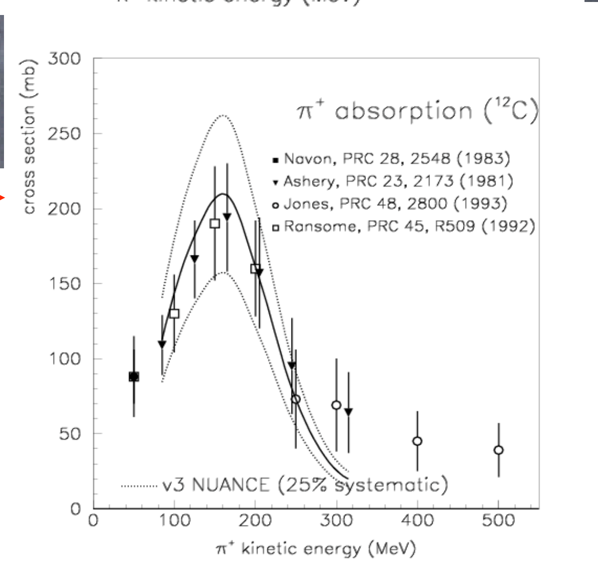
NUANCE FSI model tuned to reproduce external π scattering data

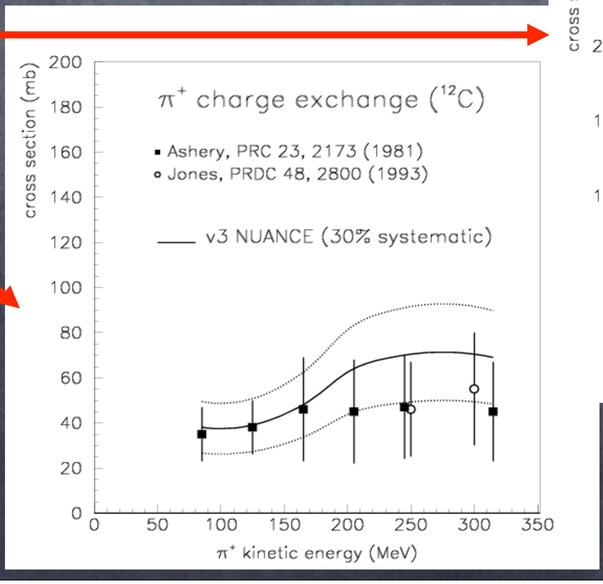
- Comparison between NUANCE and data



Uncertainties on NUANCE compared with external data

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



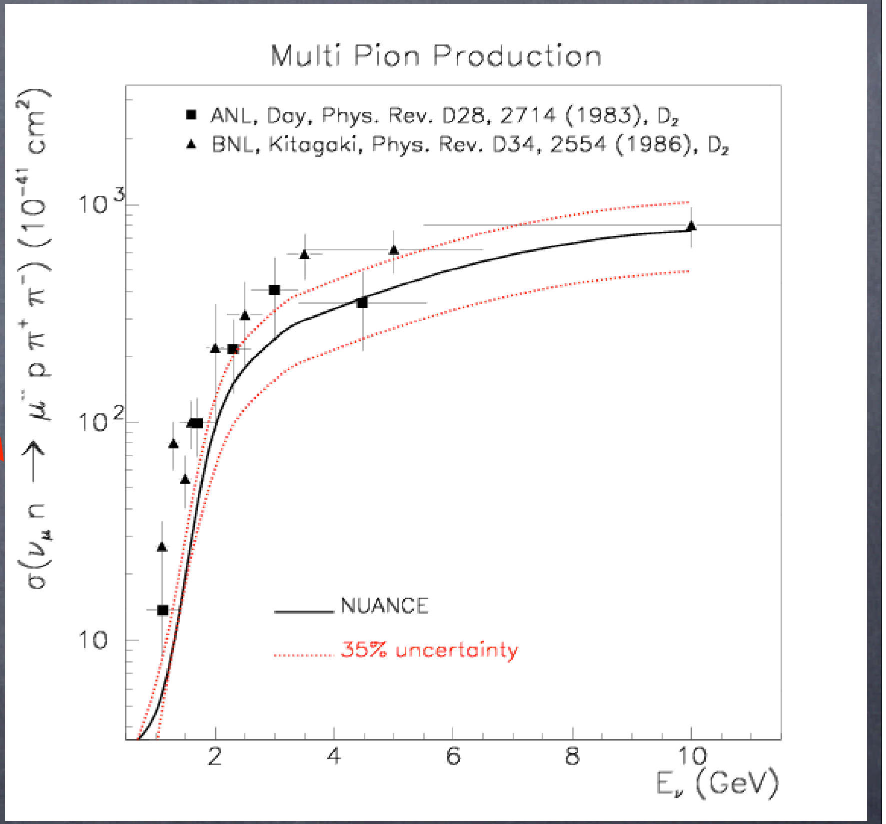


effective CCPiP σ Errors

Uncertainties on CCPIP-like processes:

Multi-Pion Production

- Comparison between NUANCE and external data
- 35% uncertainty on m_A^{Np}



Uncertainties from PDG

- Δ decay width
- 4% uncertainty

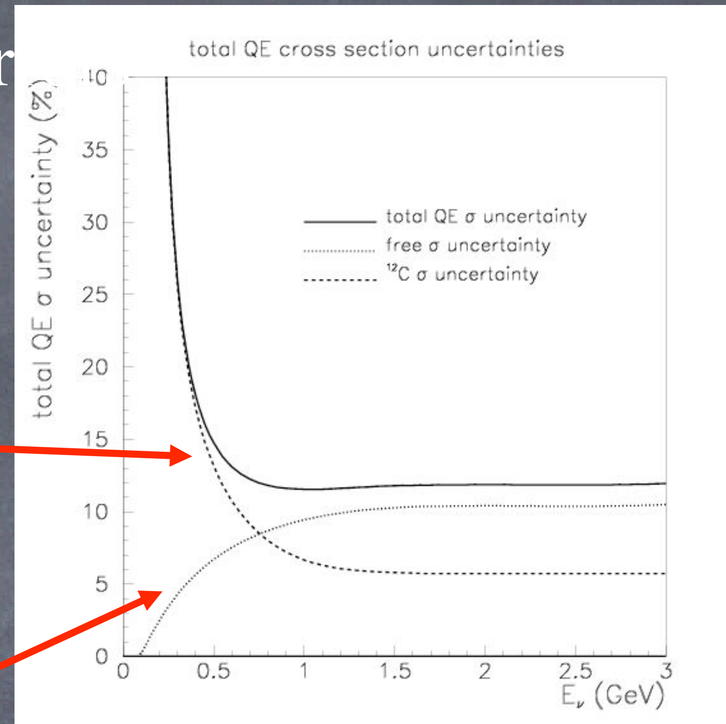
Conservative Guess

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

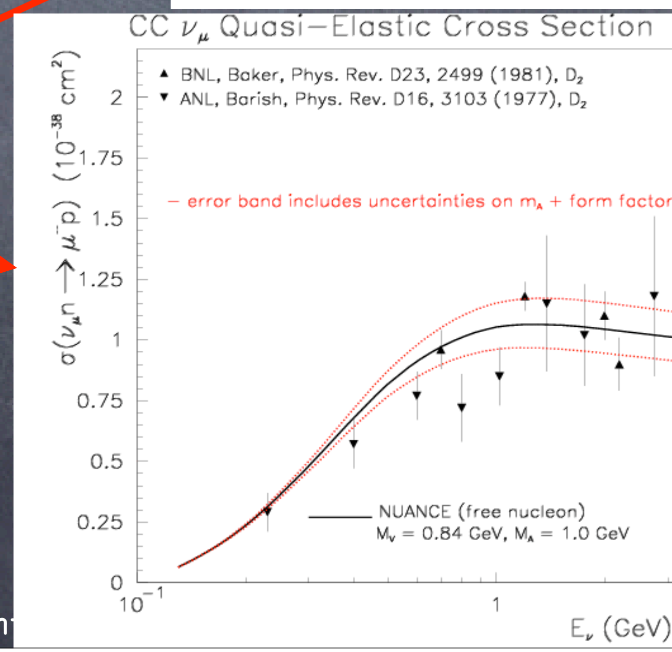
CCQE σ Er

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 s_{QE} at low energy



- 10% uncertainty in m_A to cover range in m_A from light vs. heavy target n 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 ...

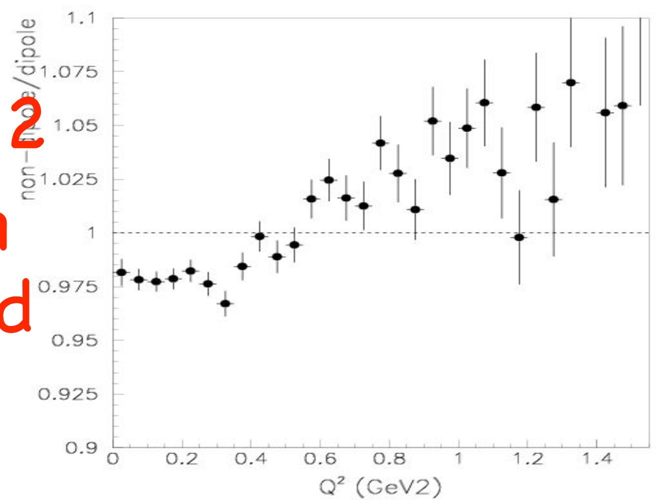
$$G_M^p(Q^2) = \mu_p/(1+0.35Q+2.44Q^2+0.5Q^3+1.04Q^4+0.34Q^5)$$

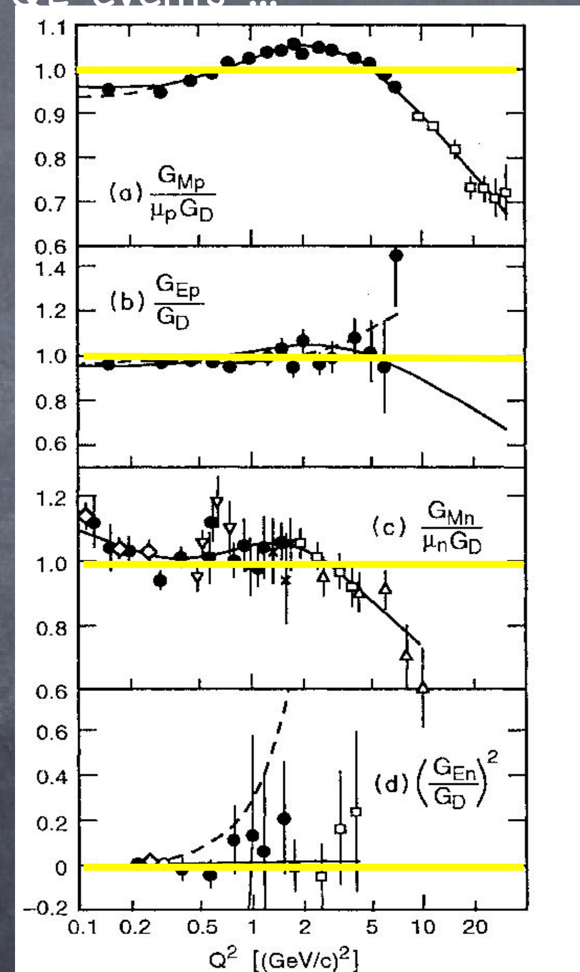
$$G_E^p(Q^2) = 1/(1+0.62Q+0.68Q^2+2.8Q^3+0.83Q^4)$$

$$G_M^n(Q^2) = \mu_n/(1-1.74Q+9.29Q^2-7.63Q^3+4.63Q^4)$$

$$G_E^n(Q^2) = -1.25\mu_n\tau/(1+18.3\tau)(1+Q^2/0.71)^2 \quad , \tau=Q^2/4M^2$$

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:

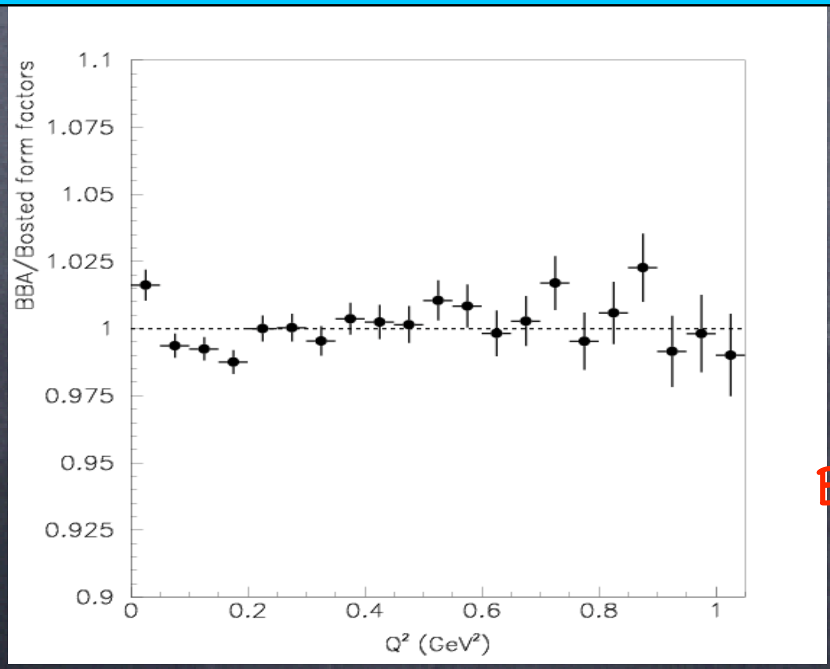
$G_M^p(Q^2) = \mu_p/(1+3.104Q^2+1.428Q^4+0.1112Q^6-0.006981Q^8+0.0003705Q^{10}-0.7063E\text{-}5Q^{12})$

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

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

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

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



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

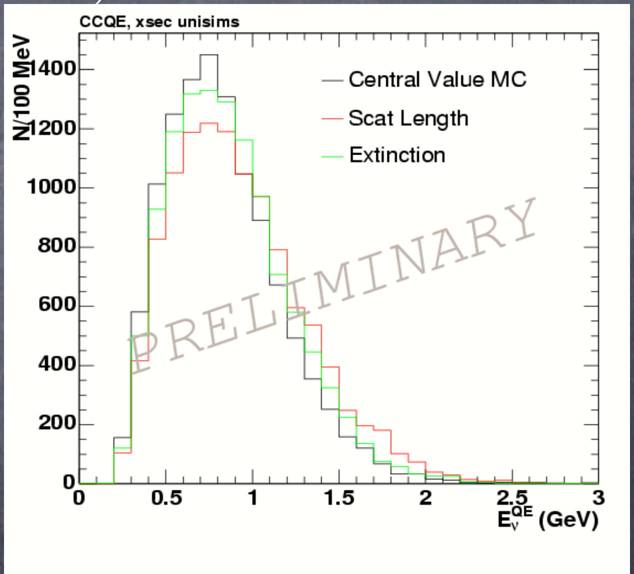
Systematic Error Calculation

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

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

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: energy bins, j: systematic error parameters



4. construct error matrix $M_{i,l}$ from parameter correlation matrix $P_{j,k}$ and $F_{i,j}$

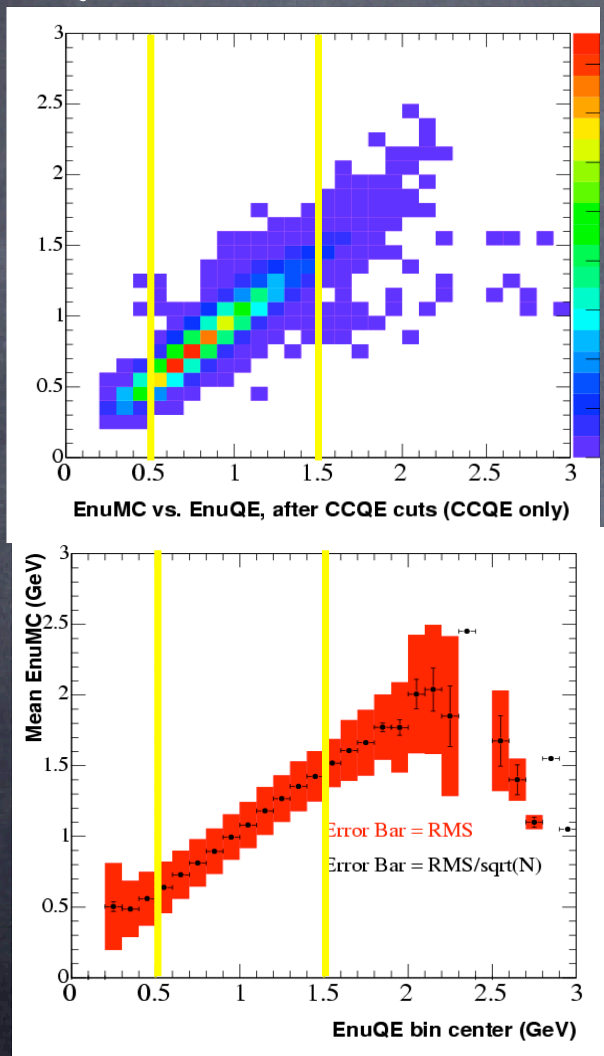
$$\mathcal{M}(E_\nu) = \mathcal{F}^T(E_\nu)\mathcal{P}\mathcal{F}(E_\nu)$$

$$m_{i,j} = f_{i,k}\, p_{k,l}\, f_{l,j}$$

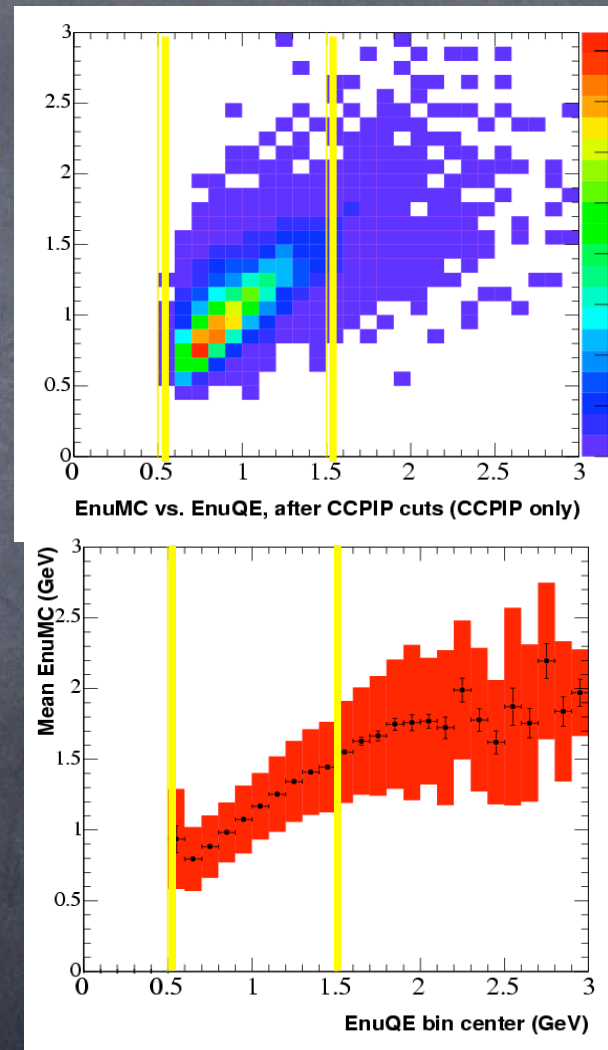
Energy Scale Uncertainty

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

- CCQE



- CCPiP



CCQE ``Golden Mode'' : MC Comparisons

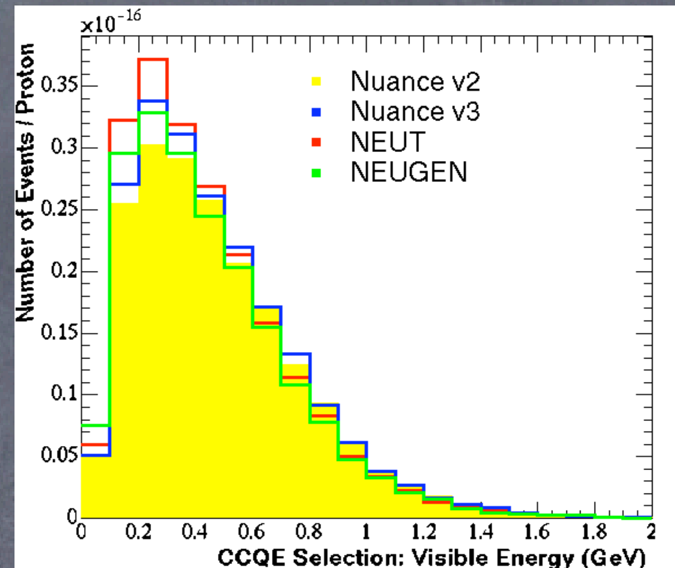
Same CCQE cuts, different Monte Carlos ...

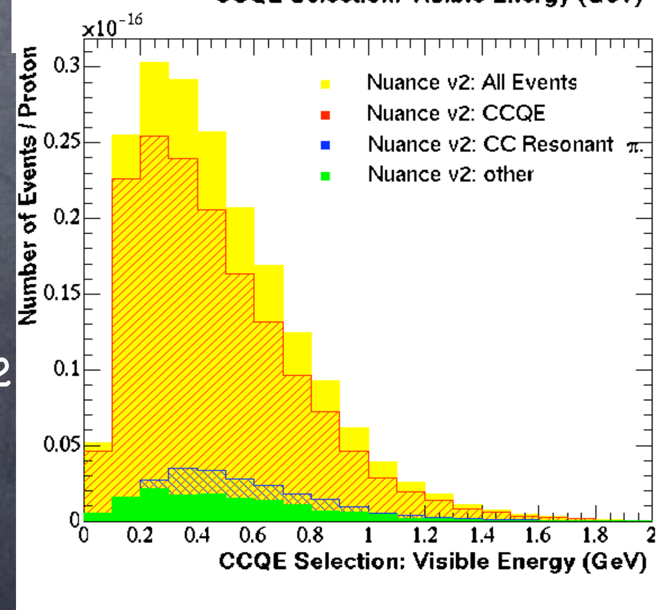
- Absolute normalization

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

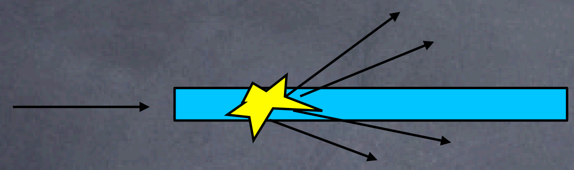
- After CCQE event selection: signal purity

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 νμ Flux



p

Production of secondaries in Be target:

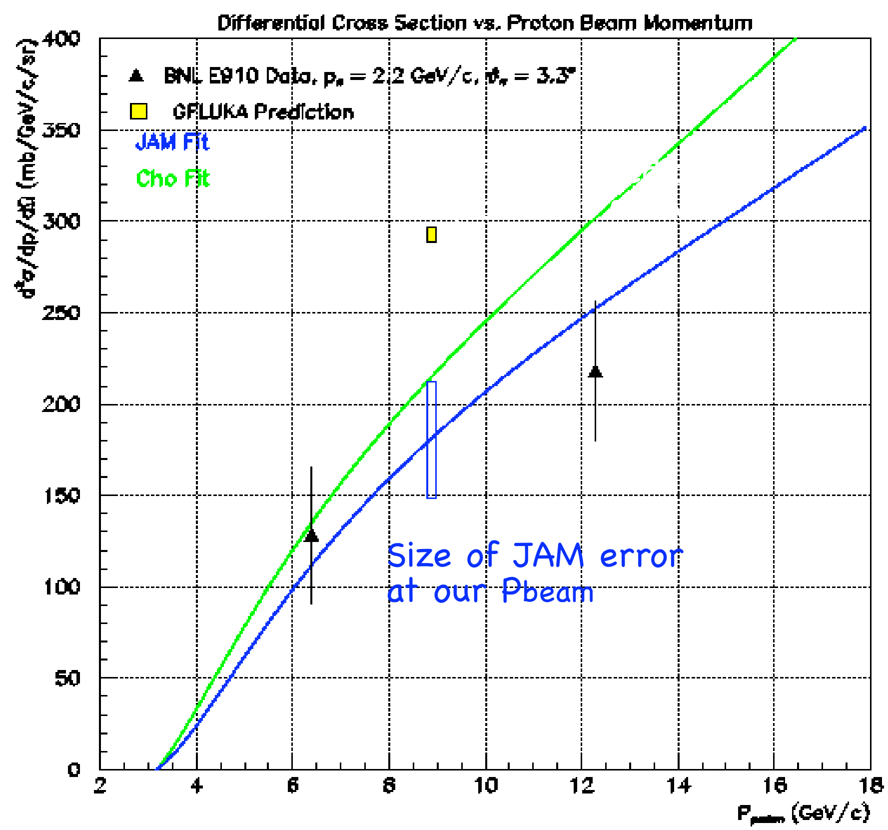
- Geant4 Secondary Beam Monte Carlo
- GFLUKA or MARS (p, n)
- Sanford-Wang parametrization (p,K)

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

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

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

$K^+ / K^0_L \to \pi\, e\, \nu_e$



Near future:

- Measure σ (p Be → π^+ X) at 8 GeV at HAR

Calibrating CC Interactions at MiniBooNE

- Hodoscope + 7 Scintillator-Filled Cubes Track Cosmic Rays