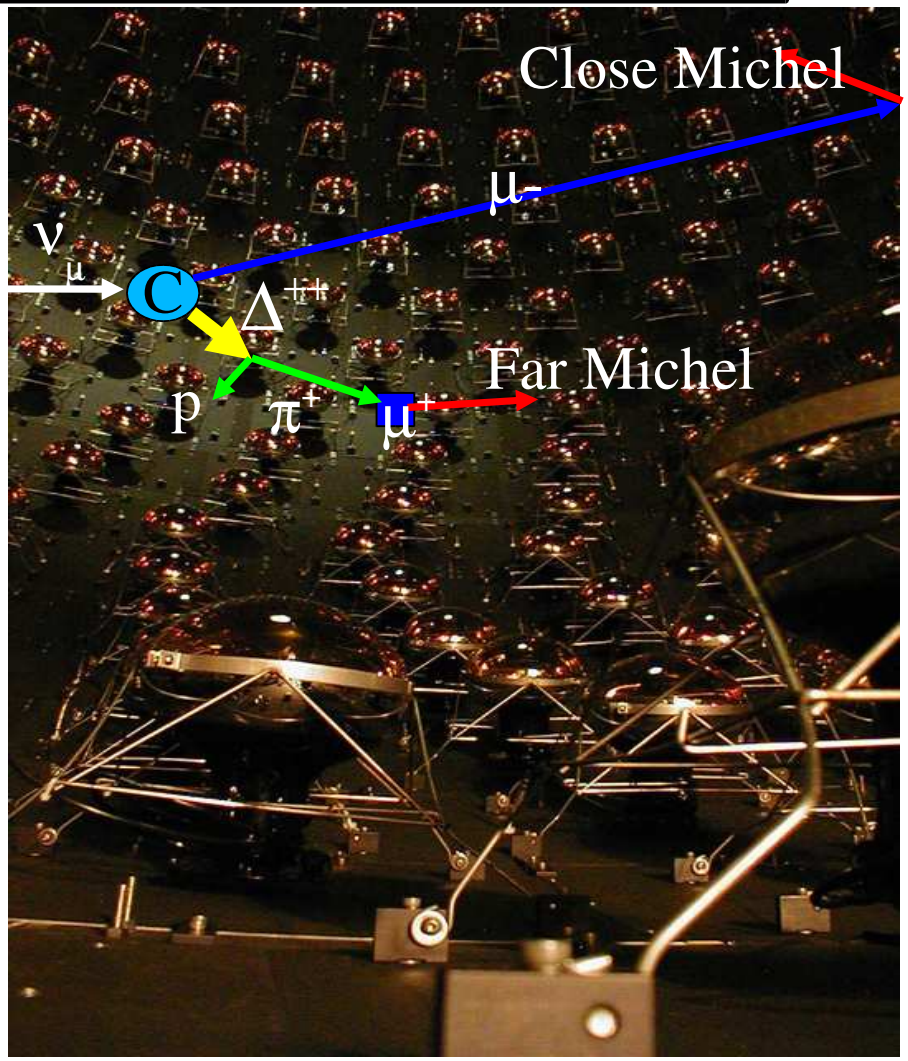
MiniBooNE
ν_μ CC1π^+/CCQE Cross Section Ratio

Morgan Wascko
Louisiana State University



- ν_μ CC interactions
  - Quasi-Elastic (CCQE)
  - Single π^+ Production (CC1π^+)
- Measuring CC Interactions
- Modeling CC Interactions
- (CC1π^+ / CCQE) σ Ratio

MiniBooNE Collaboration

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T. Hart, R. Nelson, M. Wilking, E.D. Zimmerman *Colorado*

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D. C. Cox, T. Katori, H.-O. Meyer, C. Polly, R. Tayloe *Indiana*

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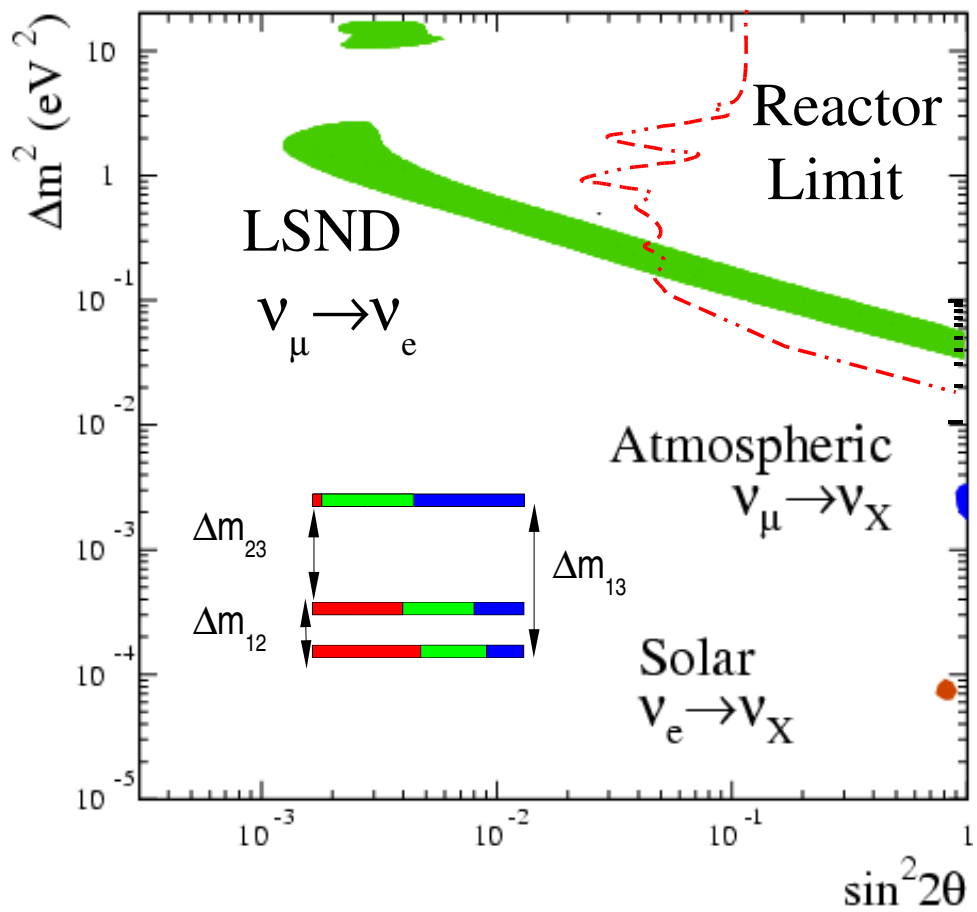
Introduction to MiniBooNE

- MiniBooNE is a ν oscillation experiment
- Goal: confirm or rule out the LSND $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance result
  - 3 Δm^2 regions
  - antineutrinos
- First, search for oscillations in neutrinos
  - Appearance of ν_e in ν_μ beam
- Appearance result will not be released before the end of 2005



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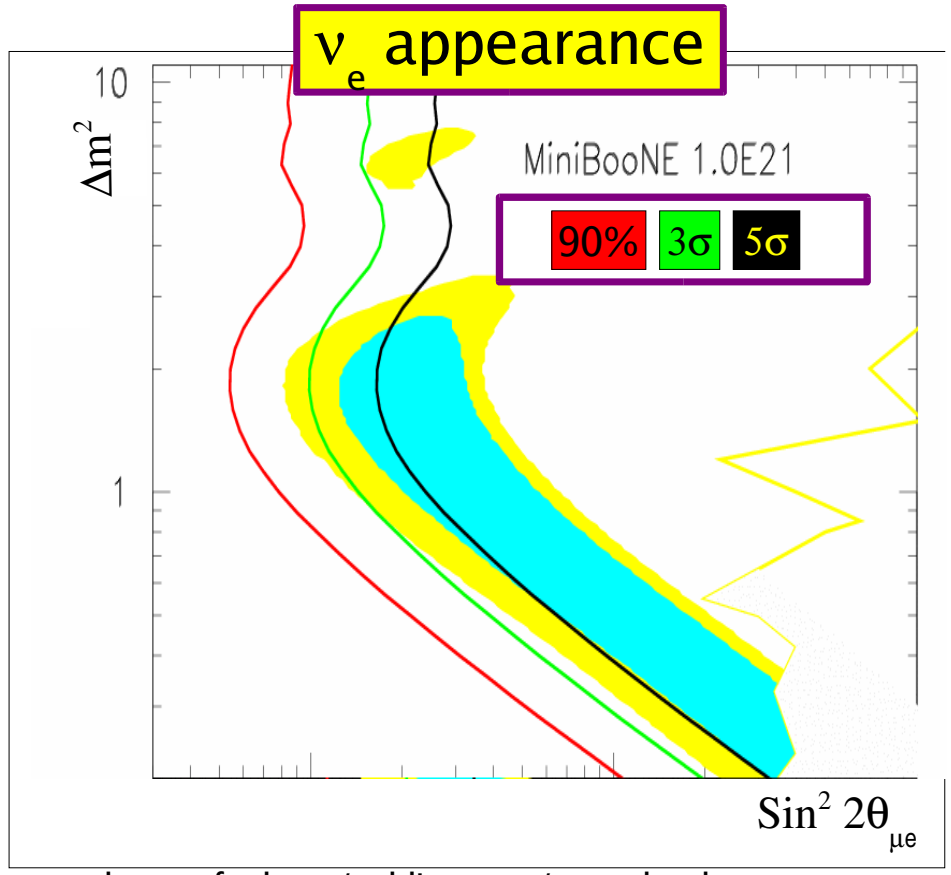


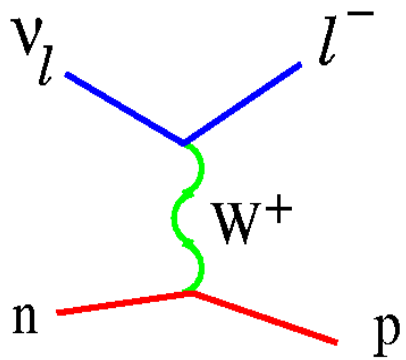
www-boone.fnal.gov/publicpages/news.html

Perspective: why start with cross sections?

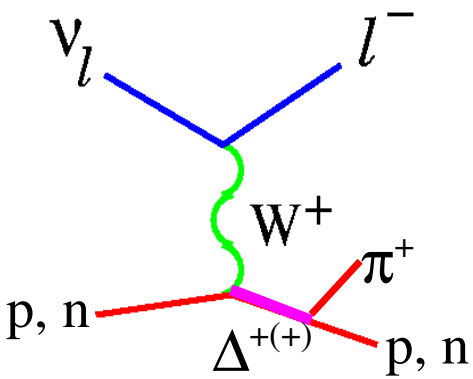
- CCQE and CC1π^+ events are ~79% of the total observed rate
  - Demonstrate understanding of 79% of our events before analyzing the ν_e events, which are <1% of the total rate
- Connections between CC1π^+ events and oscillations
  - Major background to CCQE events at MiniBooNE energies
  - NC resonant processes account for two major ν_e mis-ID backgrounds
    - NCπ^0 production
    - Radiative Δ decay
- ν physics is making a phase transition
  - Hope to measure CP violation in νs in the coming decade (NOνA,T2K)
  - Must improve understanding of ν-nucleus interactions in the ~few GeV region first

ν_μ Charged Current Cross Sections

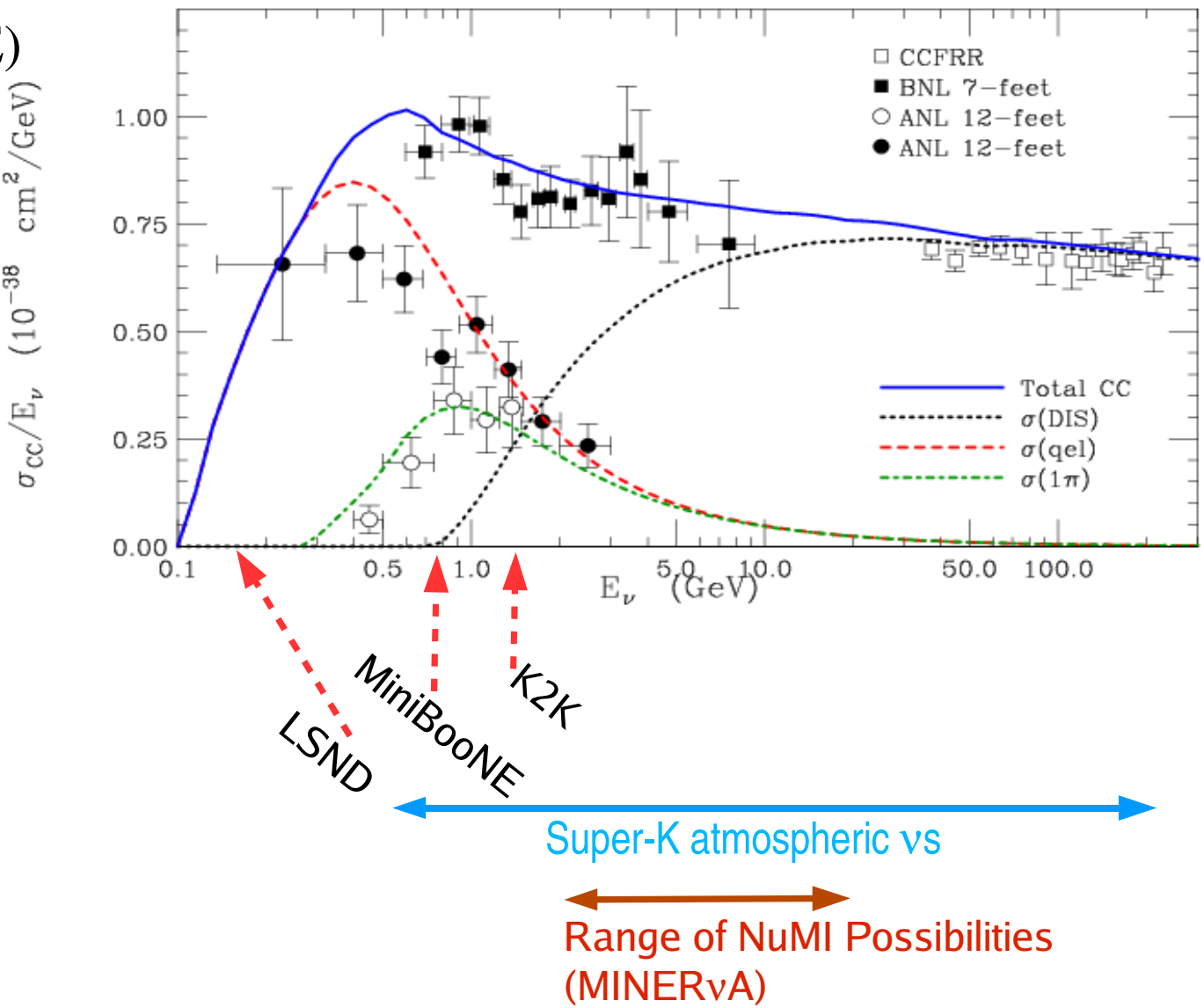
- Quasi-Elastic (CCQE)



- Single π^+ (CC1π^+)



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



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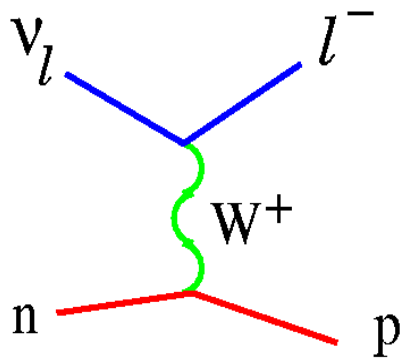

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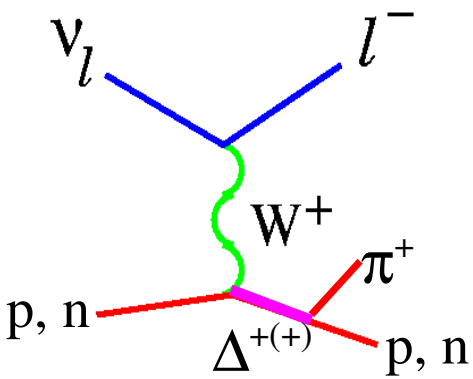

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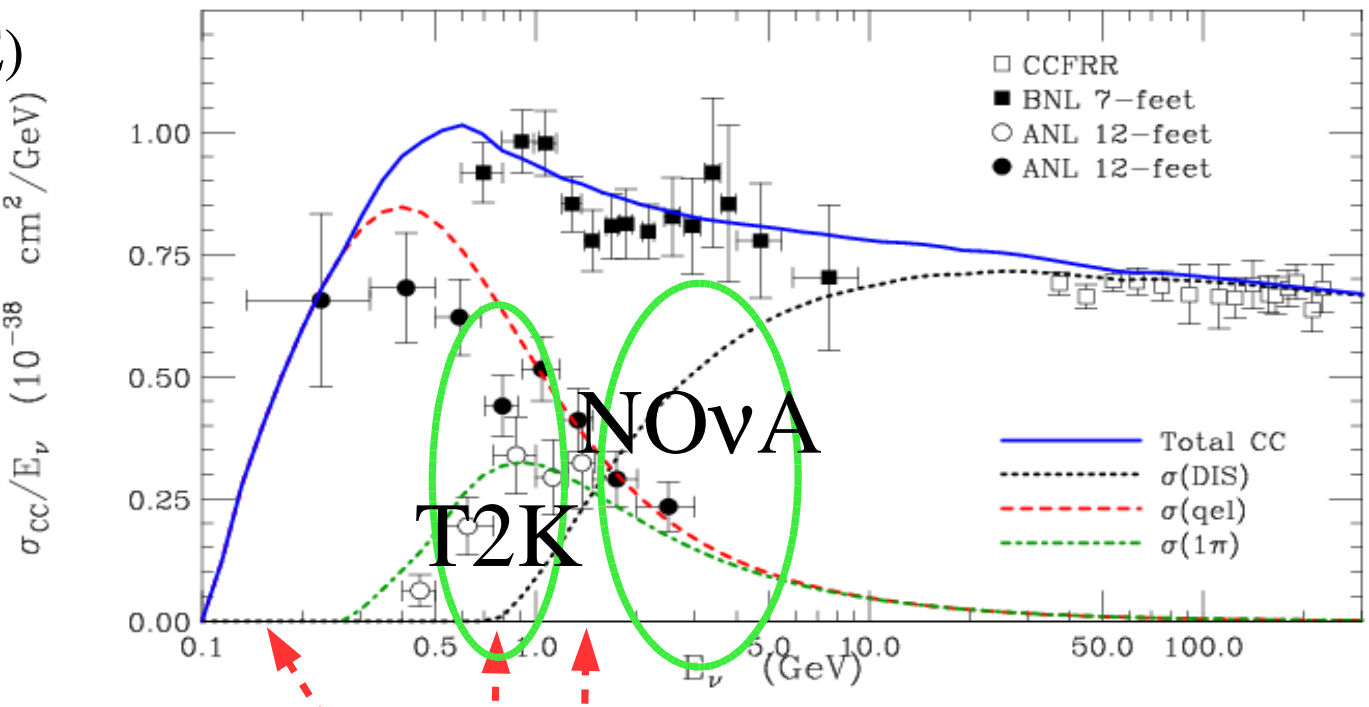


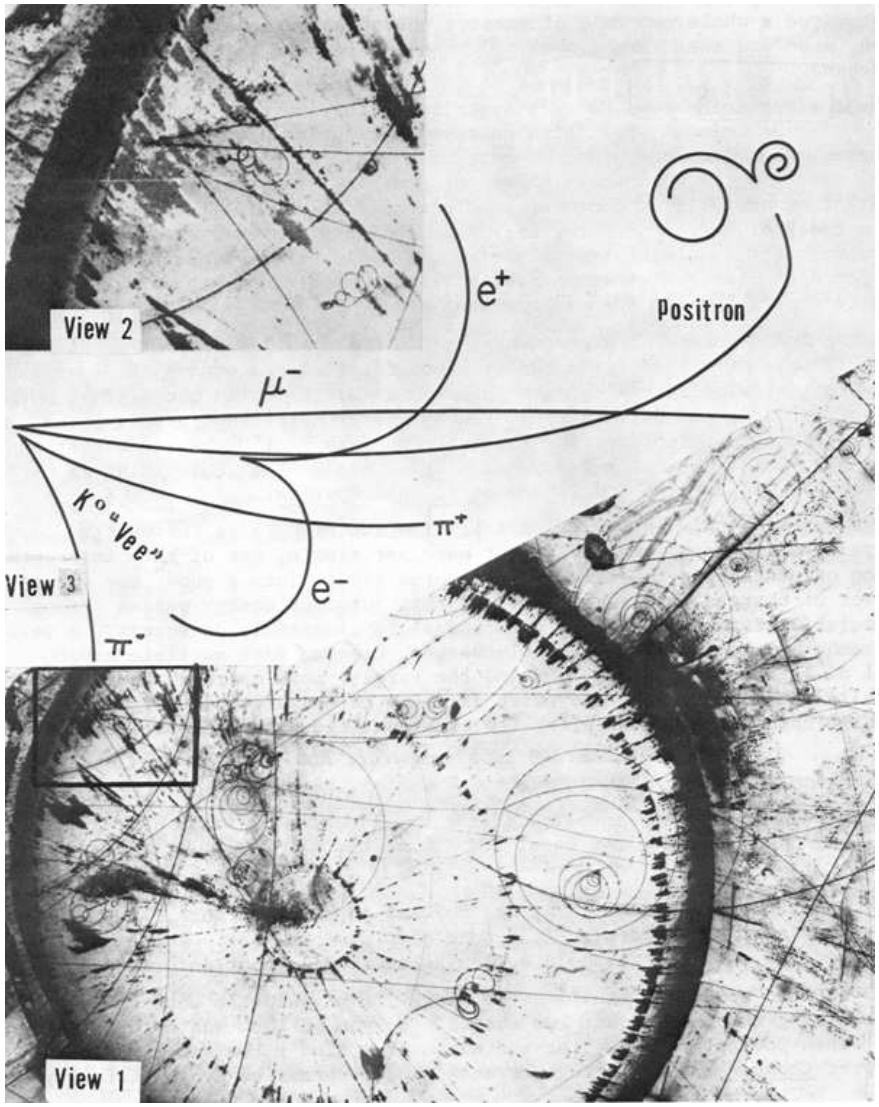
Super-K atmospheric νs

Range of NuMI Possibilities (MINERνA)

- Before final state interactions (FSI=hadrons in nucleus)
- Oscillation expts use "heavy" nuclear targets (C,O,Fe)

A Word on Neutrino Detectors

- Neutrino cross sections around 1 GeV are extremely small: $<10^{-38}\text{cm}^2$
- Need large detectors to observe them
- Trade-off: size vs. resolution
- Bubble chambers
  - great tracking capabilities
  - low target mass
    - few interactions
- Cherenkov calorimeters
  - large mass (10^{30} ^{12}C in MB)
    - many interactions!
  - poorer track resolution than bubble chambers, especially multiple tracks
  - no tracks below Cherenkov thresh.



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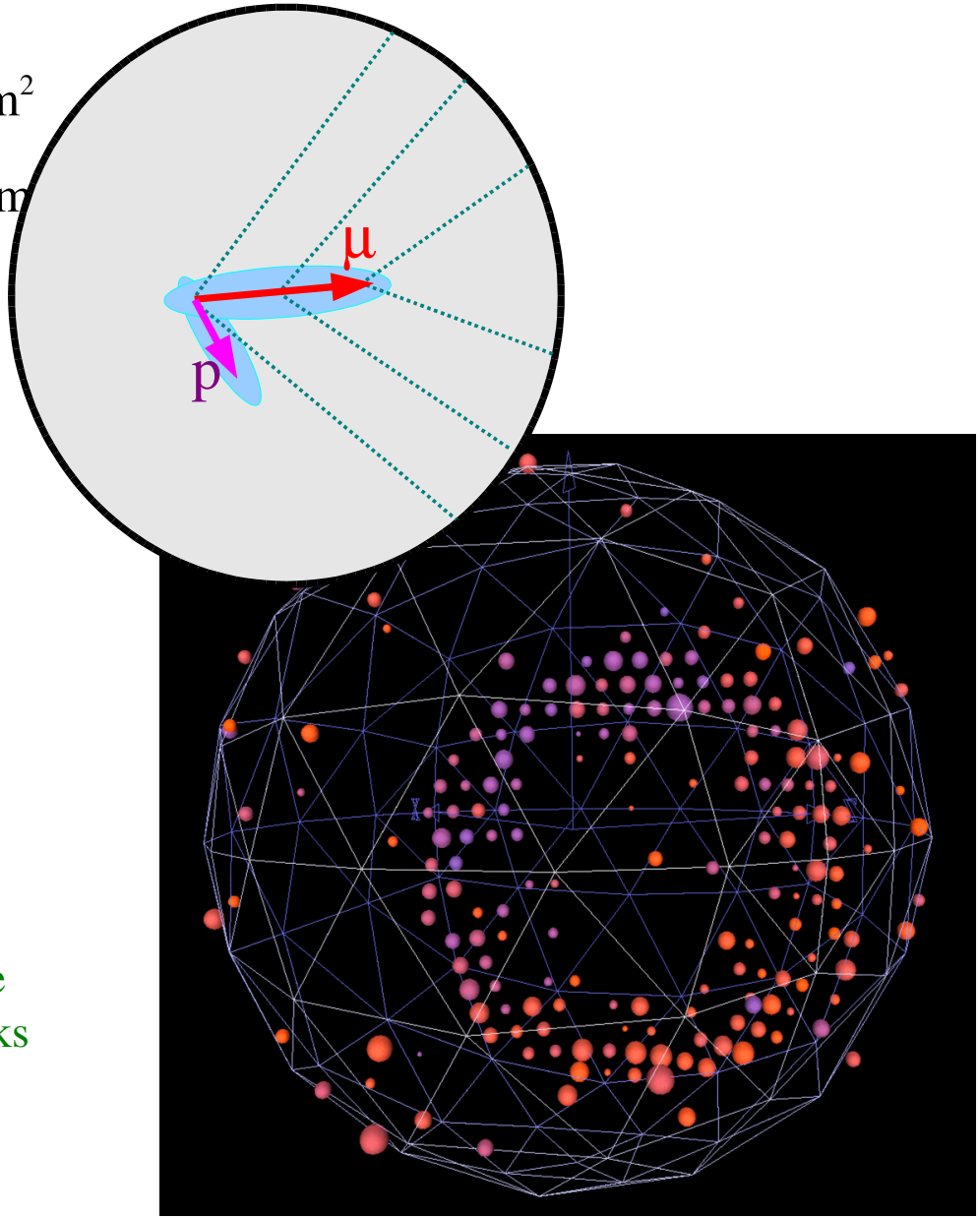
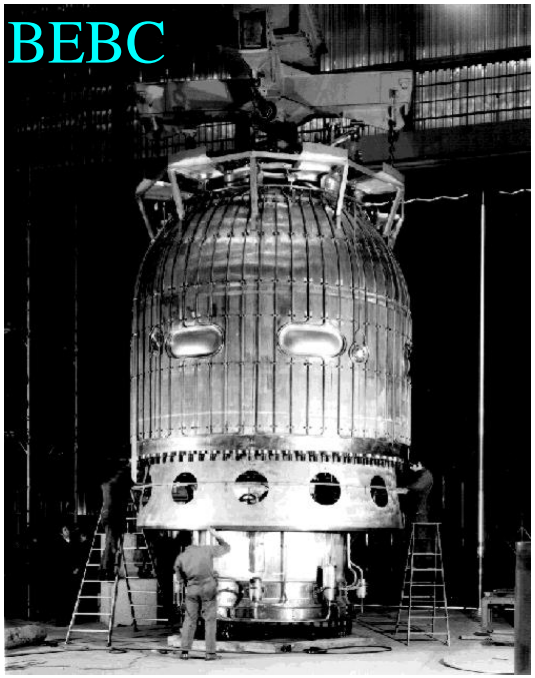
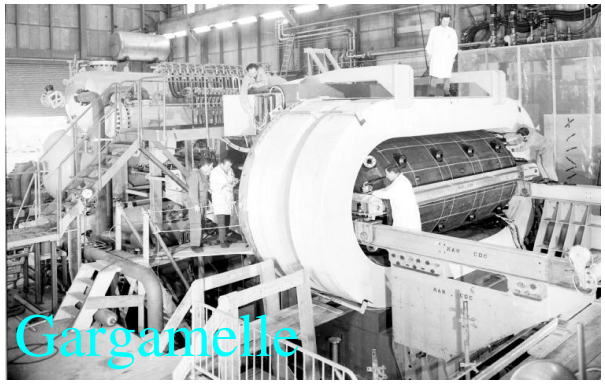


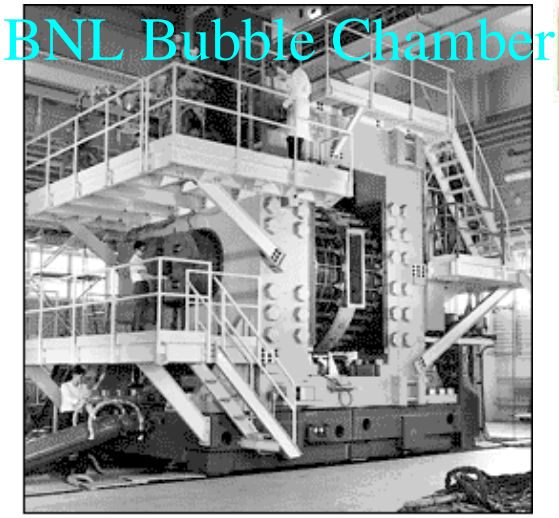
Past ν_μ CC1π^+ Measurements

- E<1 GeV, light targets
  - ANL
  - BNL
- Heavy targets, E > 1GeV
  - SKAT
- E > 1 GeV, light targets
  - FNAL
  - Gargamelle
  - BEBC
- For oscillations, want E~1 GeV, heavy nuclear target
  - Past measurements are not ideal for MBoonE or K2K





BNL Bubble Chamber

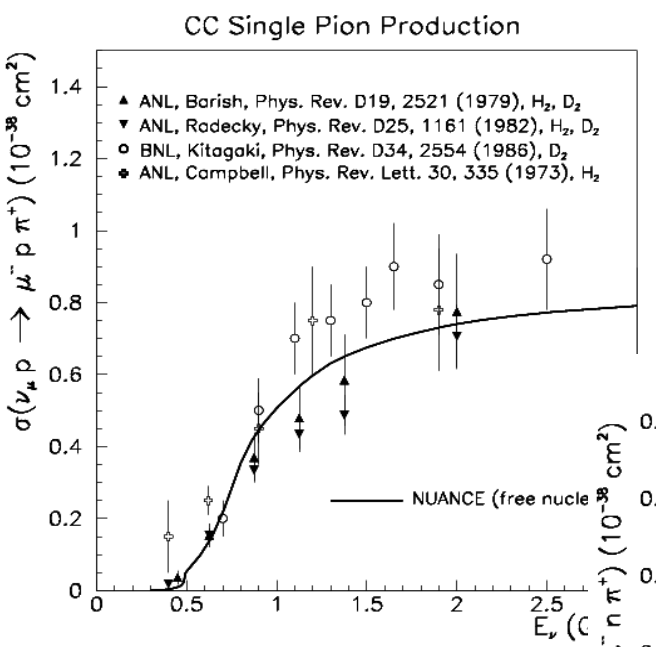


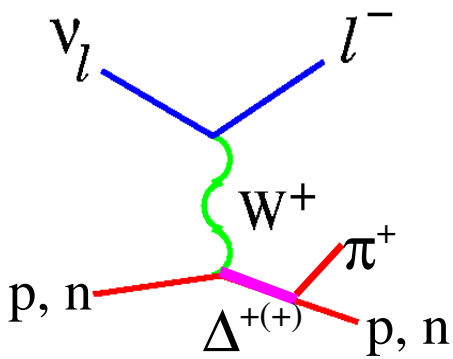
The 80-inch Bubble Chamber

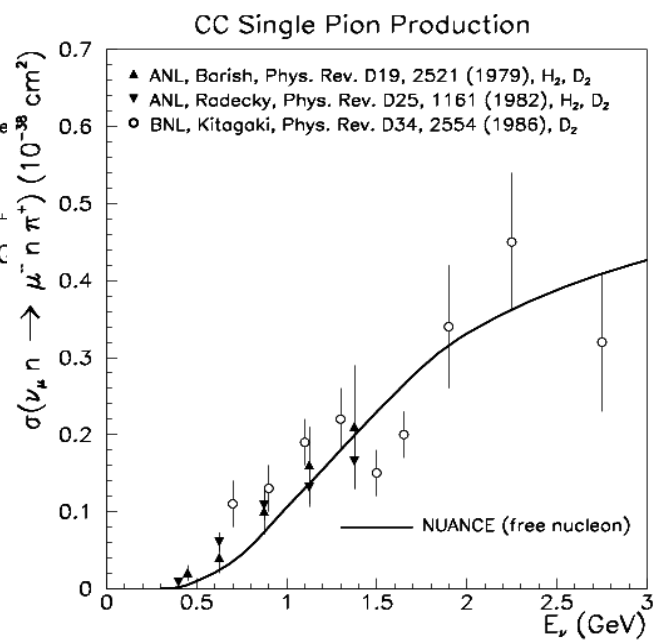
Charged Current Single π^+ Interactions

- Complex final state: π^+ and μ^- exiting nucleus (also a recoil nucleon)

Resonant Production

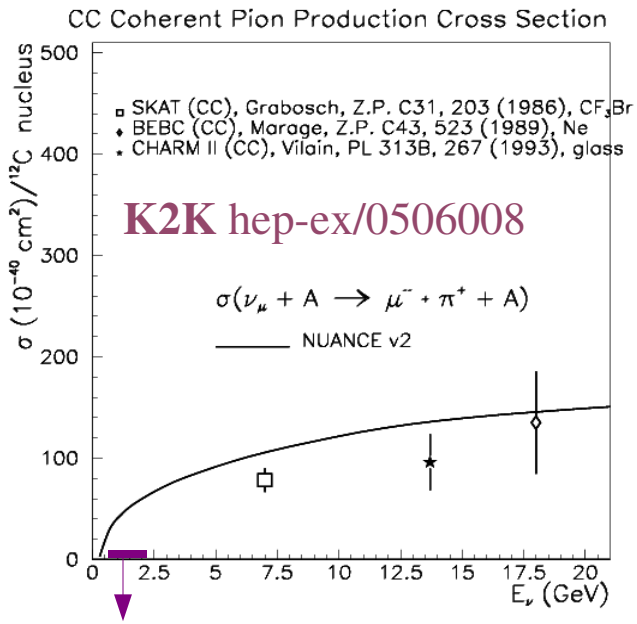


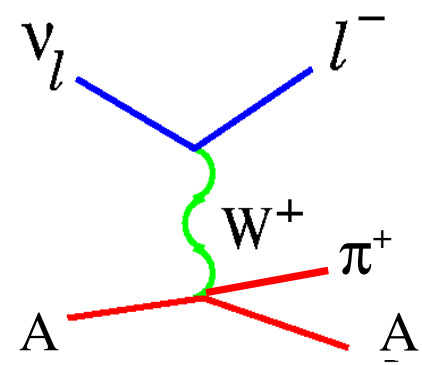




- no heavy target data below 2 GeV
- Exclusive final states

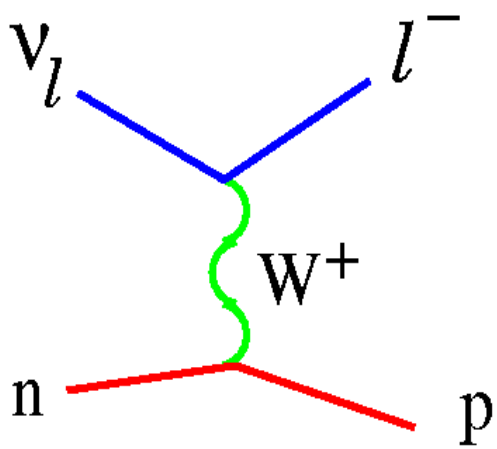
Coherent Production





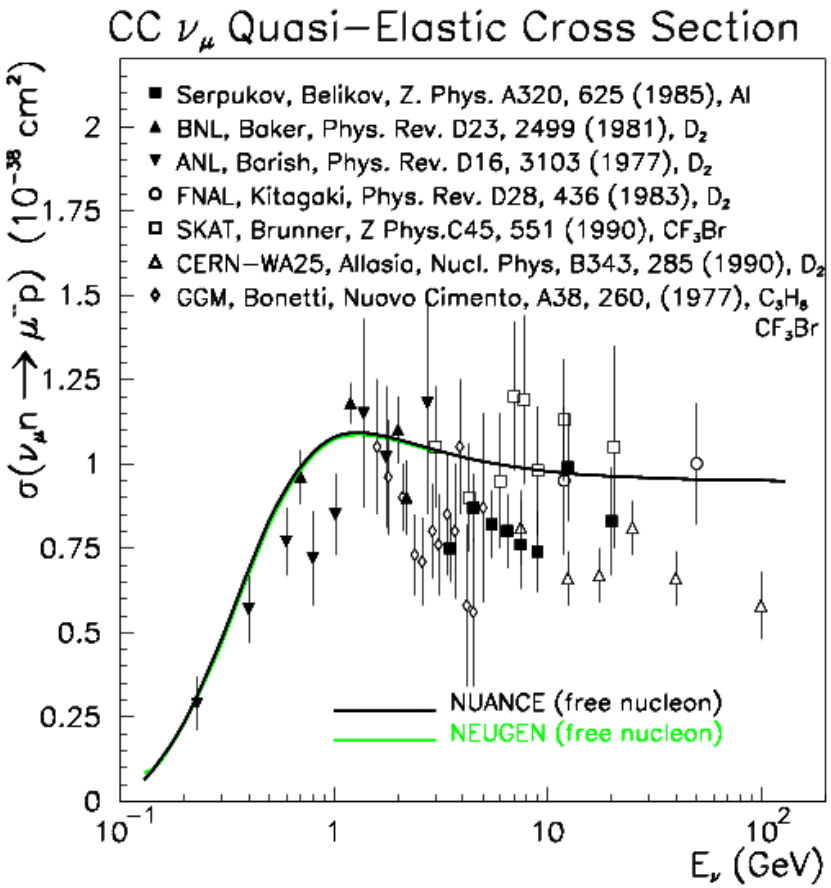
Charged Current Quasi-Elastic Interactions

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



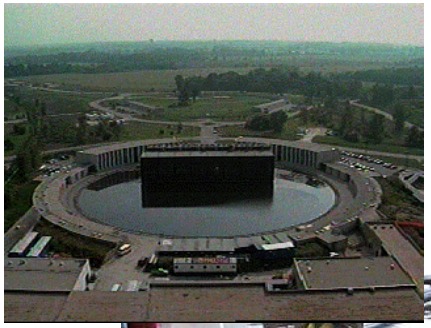
- Fairly well known σ at low ν energy
  - important error contribution to oscillation searches

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

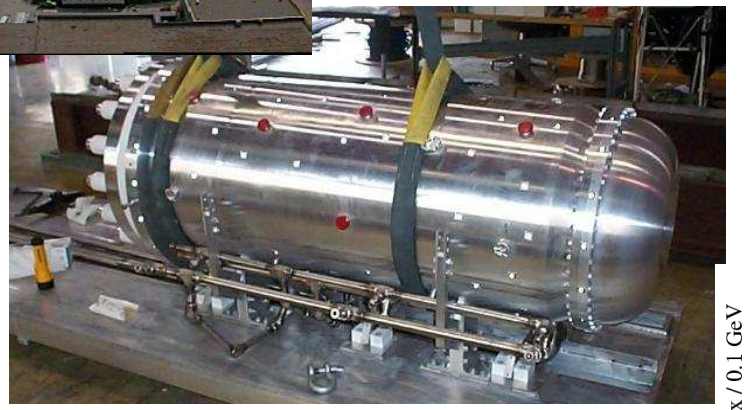


That's the past ν_μ CC σ data...

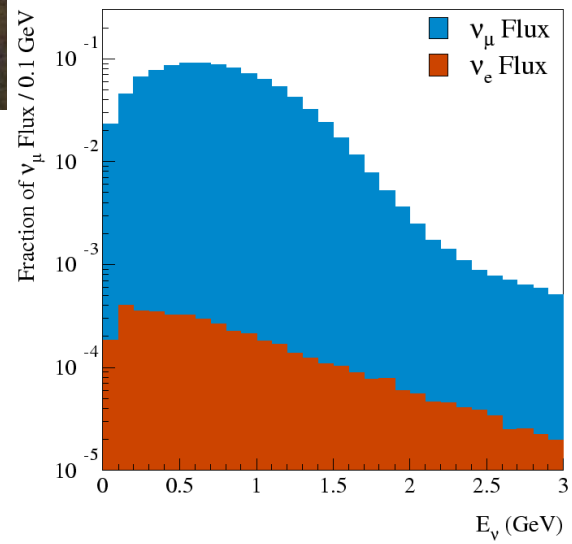
MiniBooNE Overview

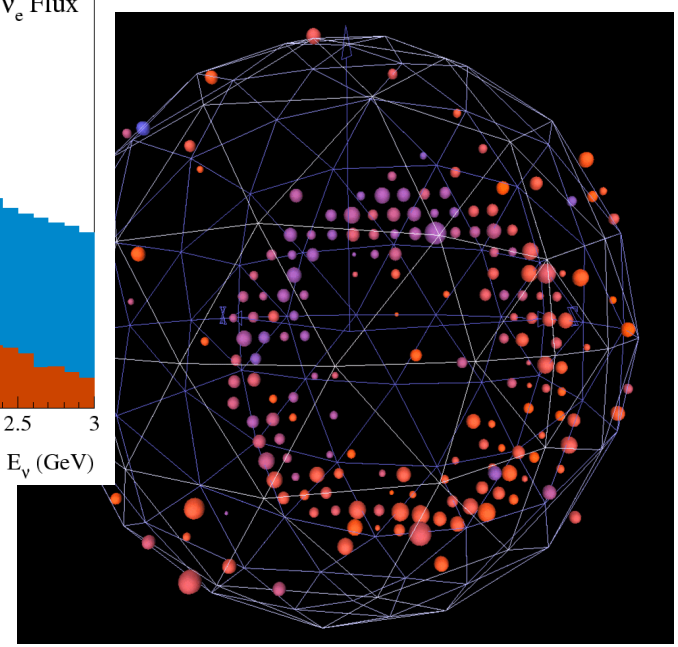


- 8 GeV KE protons from Fermilab Booster Accelerator
- 1.7 λ beryllium target (HARP results coming soon!)



- horn currently focuses π^+ and K^+
- Can reverse polarity (anti-ν beam)

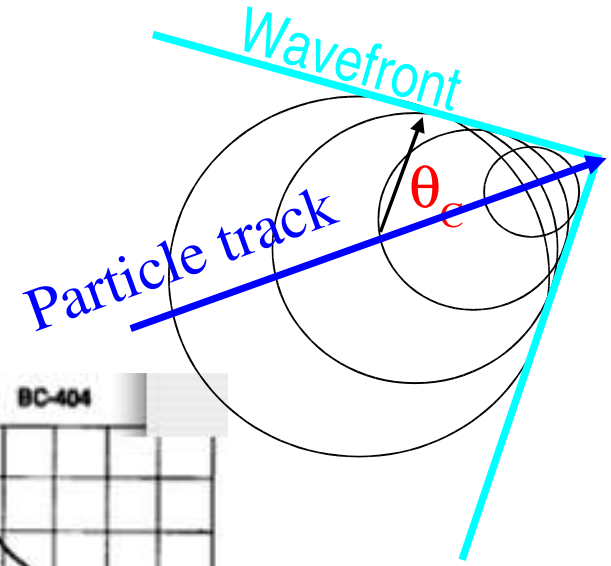




- 50 m decay region
- >99% pure ν_μ flavor beam
- 490 m dirt berm
- 800 ton CH_2 detector
- 1520 PMTs
  - 1280 + 240 in veto

ν_μ CC Interactions in MiniBooNE: All About μ

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

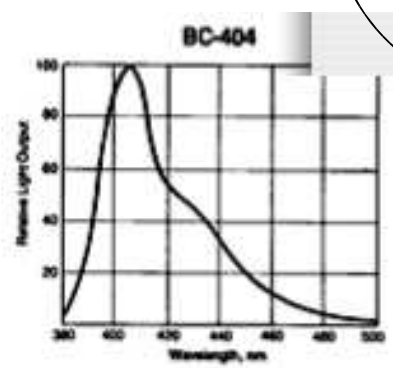


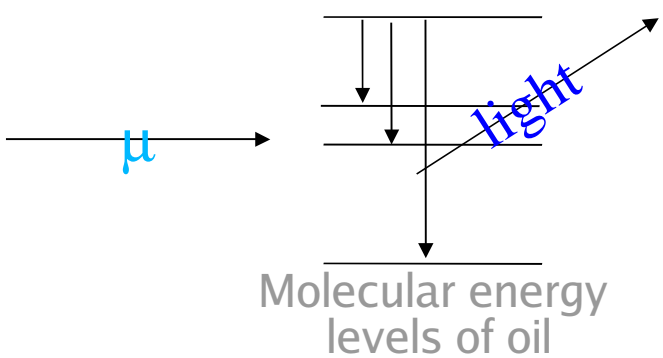
Cherenkov radiation

- Light emitted by oil if particle v > c / n
- Prompt Cherenkov cone

Scintillation

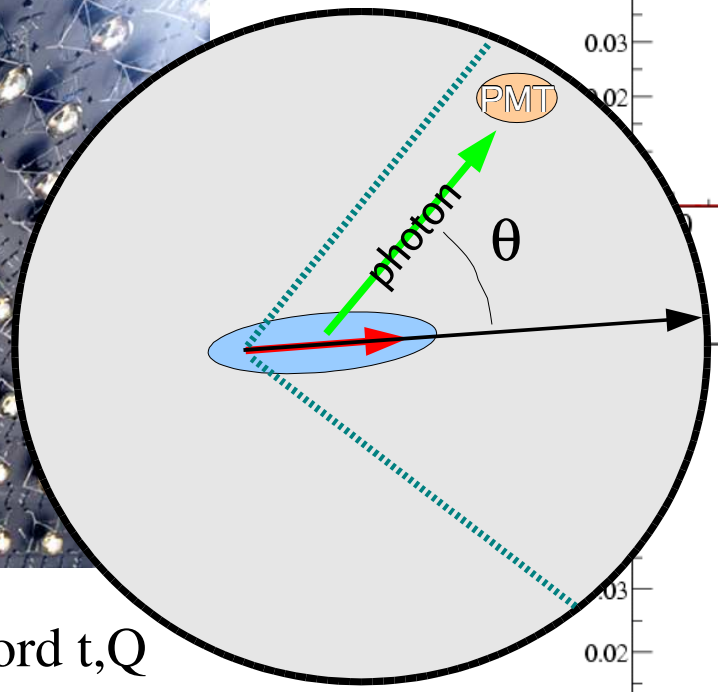
- Excited/ionized molecules emit light when electrons drop to lower E levels
- isotropic and late in time

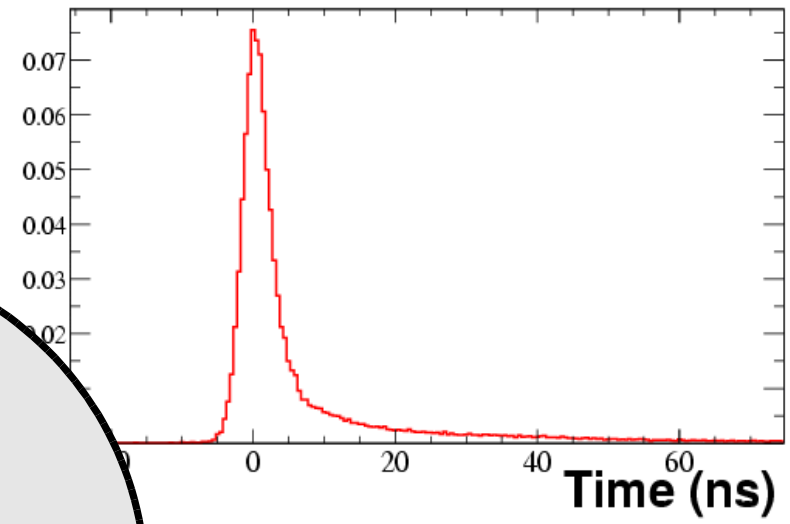


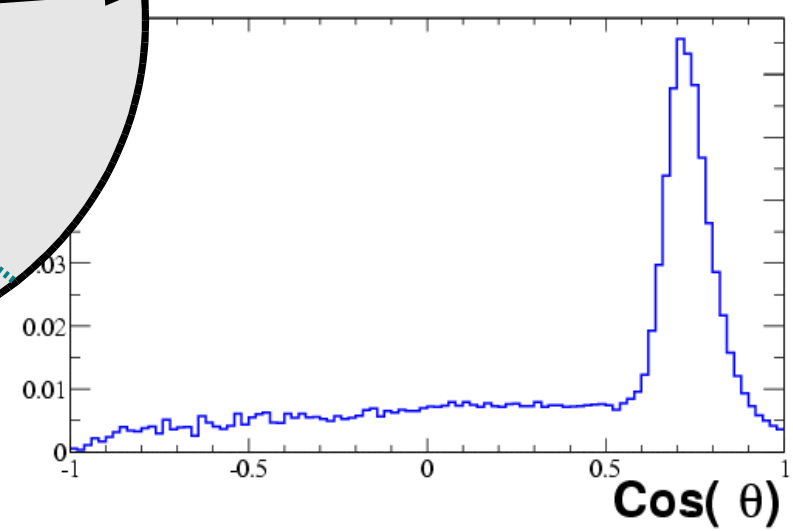


- en route to PMTs, photons are modified by
  - Fluorescence
  - Scattering (Rayleigh and Raman)
  - Absorption
- Measure and constrain these processes with a suite of external and *in-situ* measurements

Reconstructing Muons in MiniBooNE

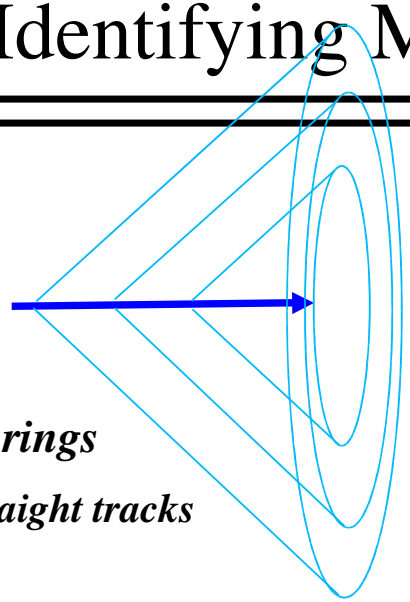




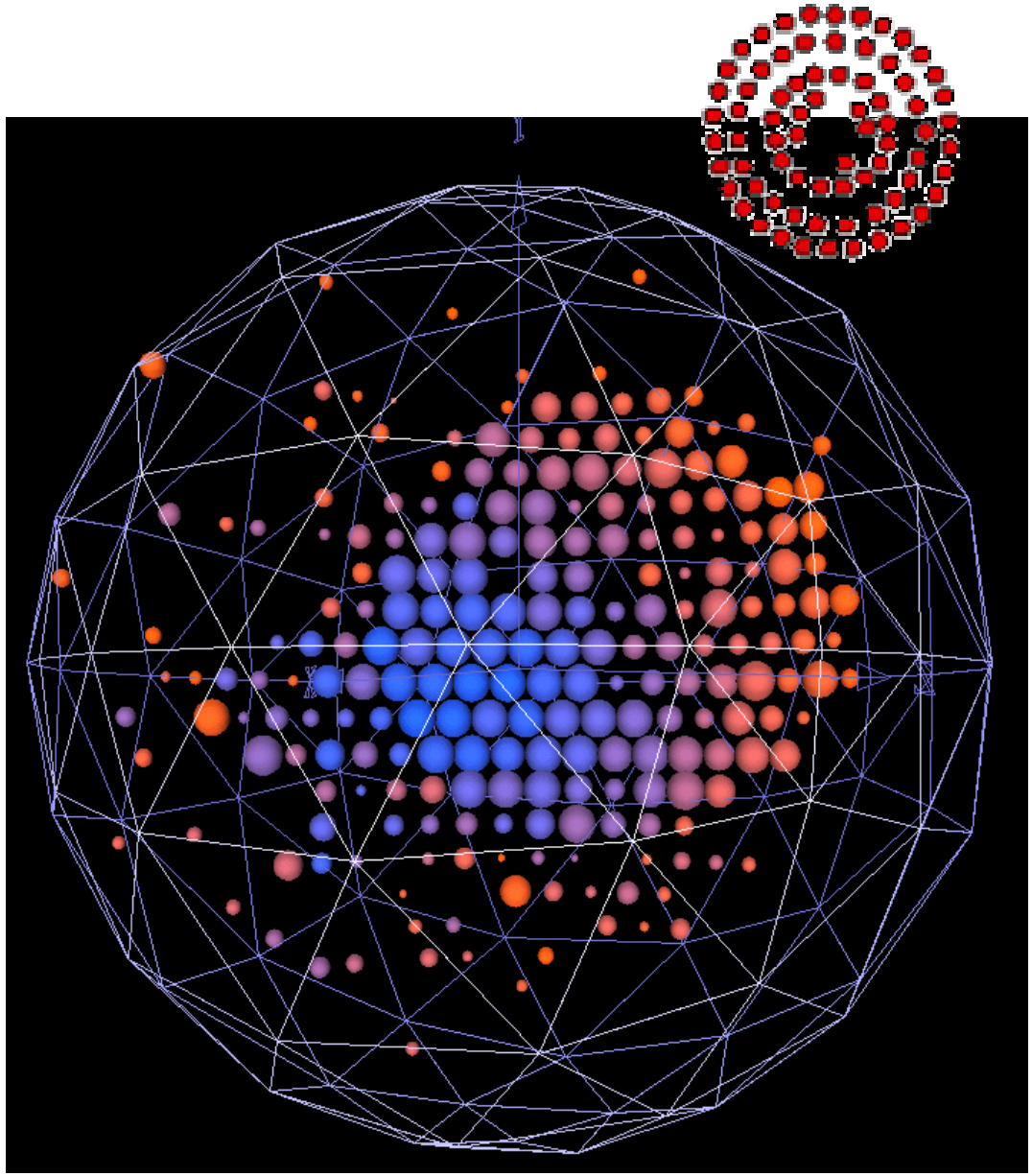


- PMTs collect γ s, record t,Q
- Reconstruct tracks by fitting time and angular distributions

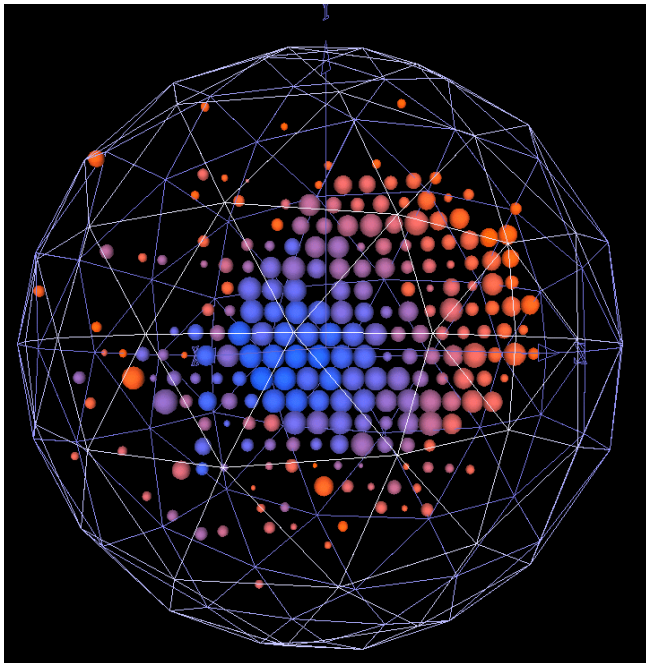
Identifying Muons in MiniBooNE

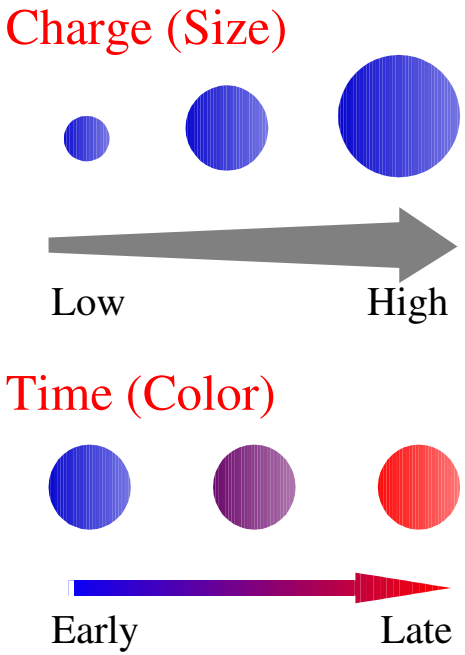


- ***Muons***
  - ***Sharp, clear rings***
    - ***Long, straight tracks***
- Electrons
  - Scattered rings
    - Multiple scattering
    - Radiative processes
- Neutral Pions
  - Double rings
    - Decays to two photons
    - Photons pair produce

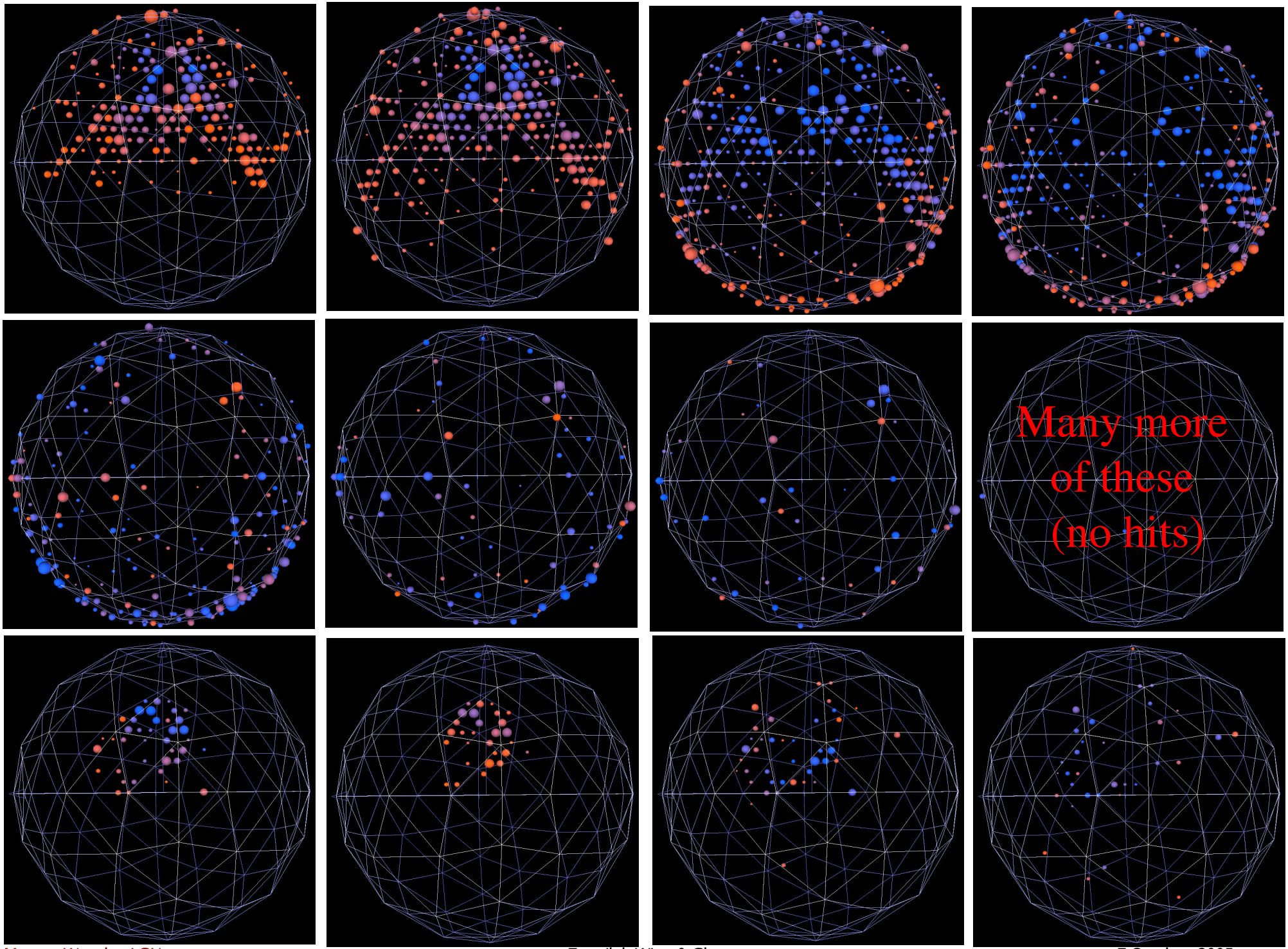


Muon Decay in MiniBooNE



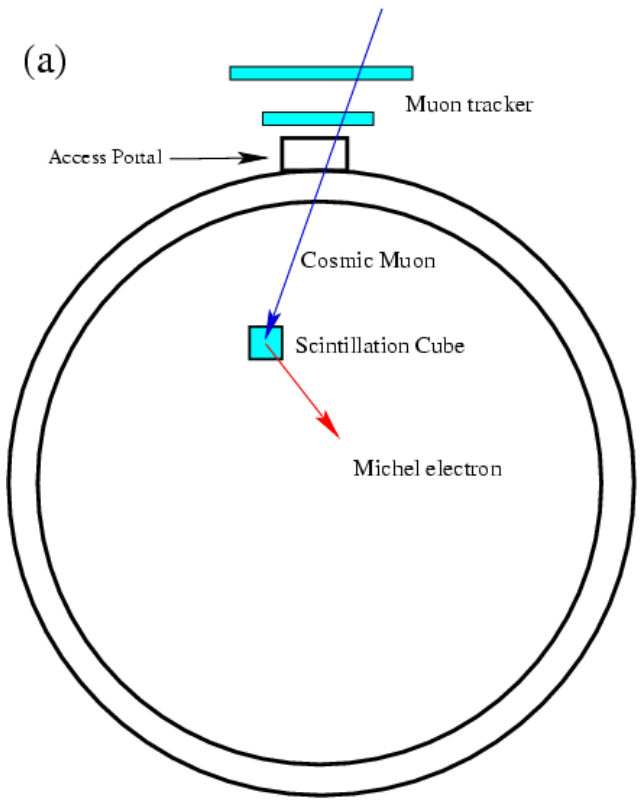


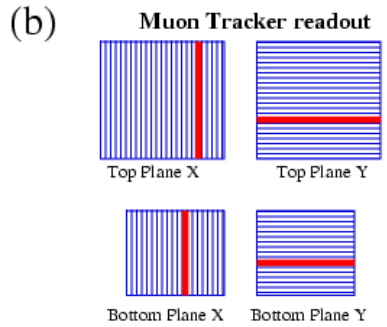
- Muon decay signature is a muon-like ring followed closely in time by an electron-like ring
  - $\mu^- \rightarrow \nu_\mu \; \bar{\nu}_e e^-$ ($\tau \sim 2\ \mu s$)

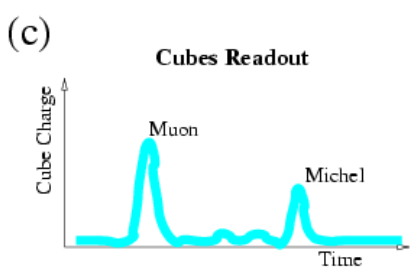

Many more
of these
(no hits)

Calibrating Muons in MiniBooNE

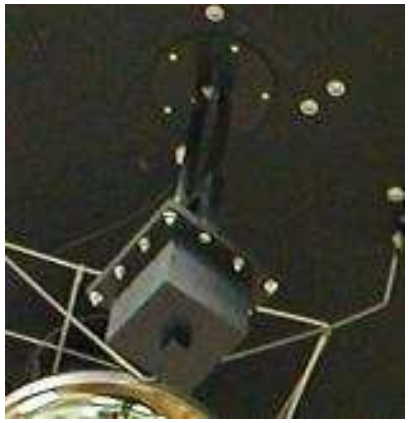
- Hodoscope + 7 scintillator cubes track cosmic rays muons entering the tank







Muon Tracker

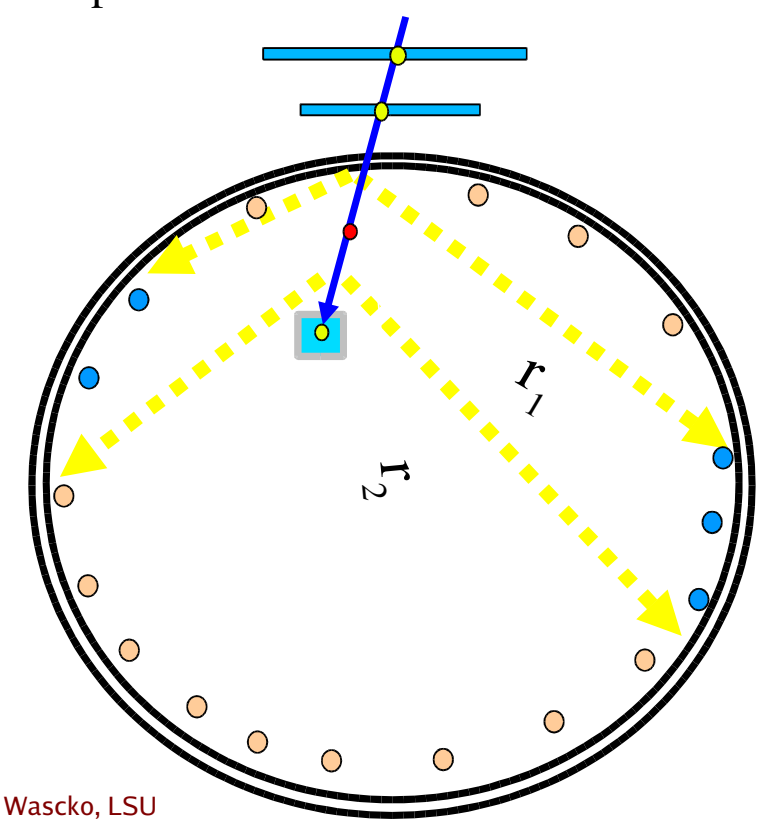


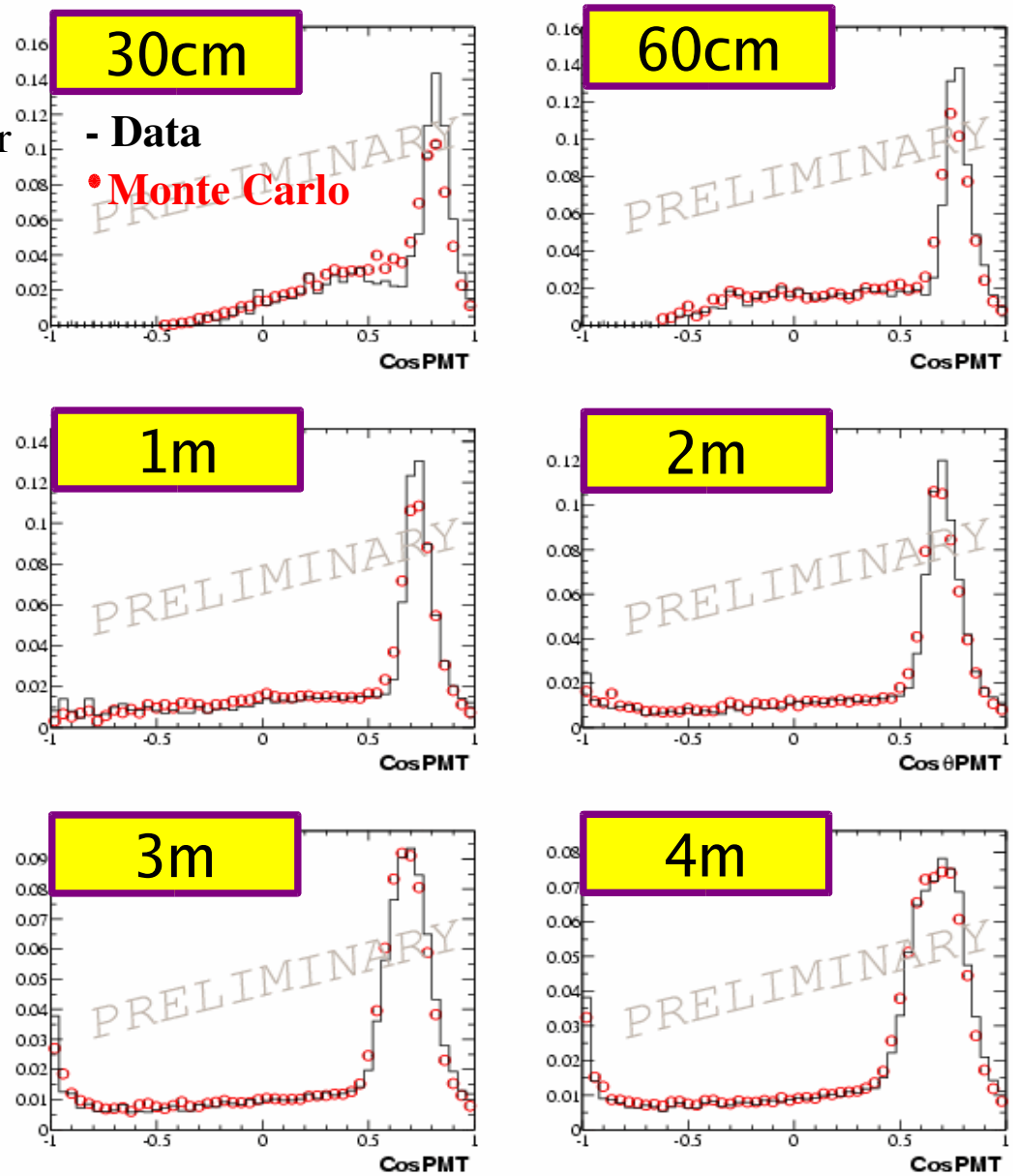
Scintillation cube

- Trigger: match tank subevents with cube hits

Calibrating Muons in MiniBooNE

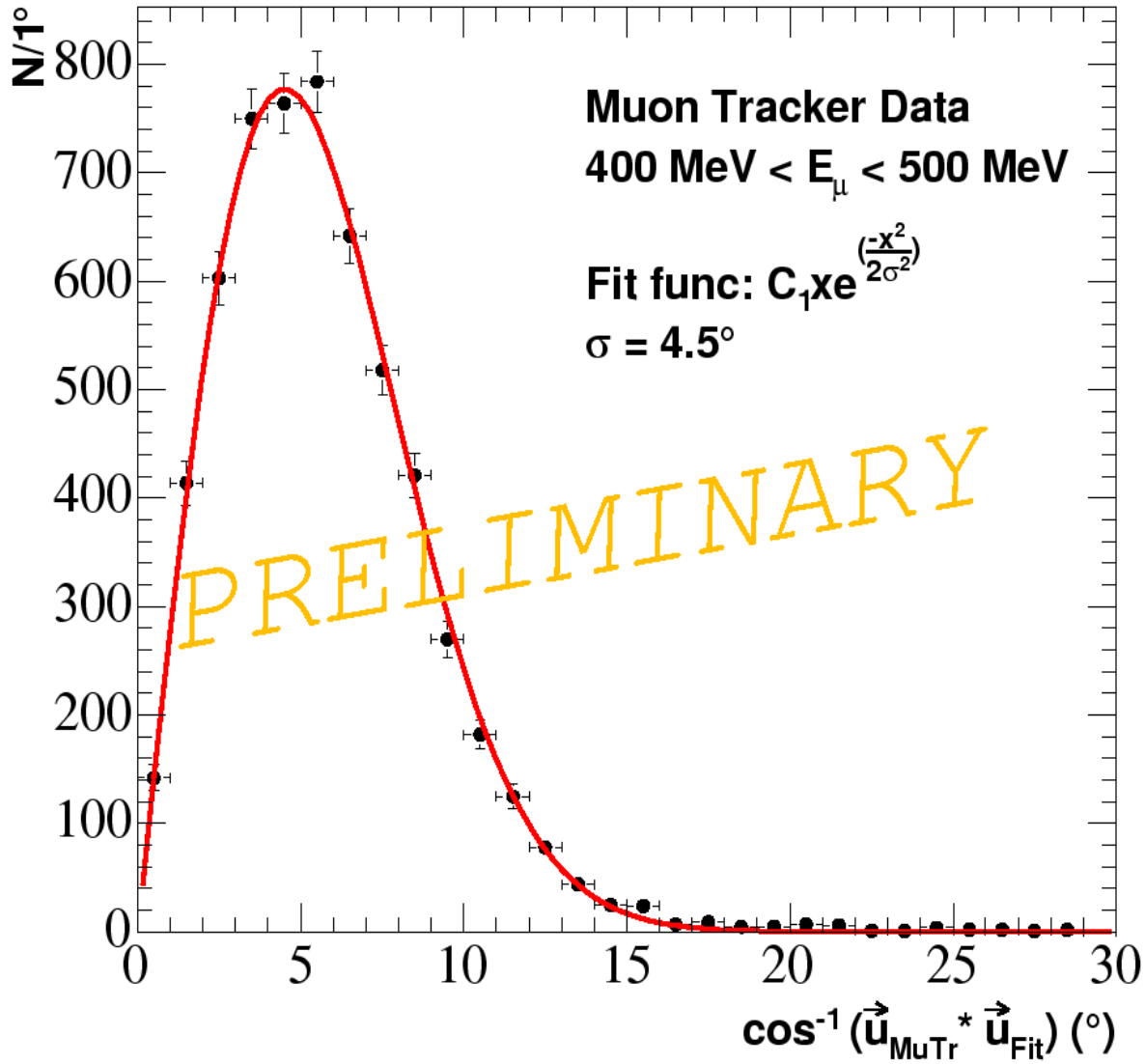
- Muon tracker determines event pars (x, t, u)
- Corrected times,angles w/ known track center
- Cherenkov rings and time peaks; isotropic and delayed emission
- Use cube data for optical model studies
  - separate scintillation and fluorescence





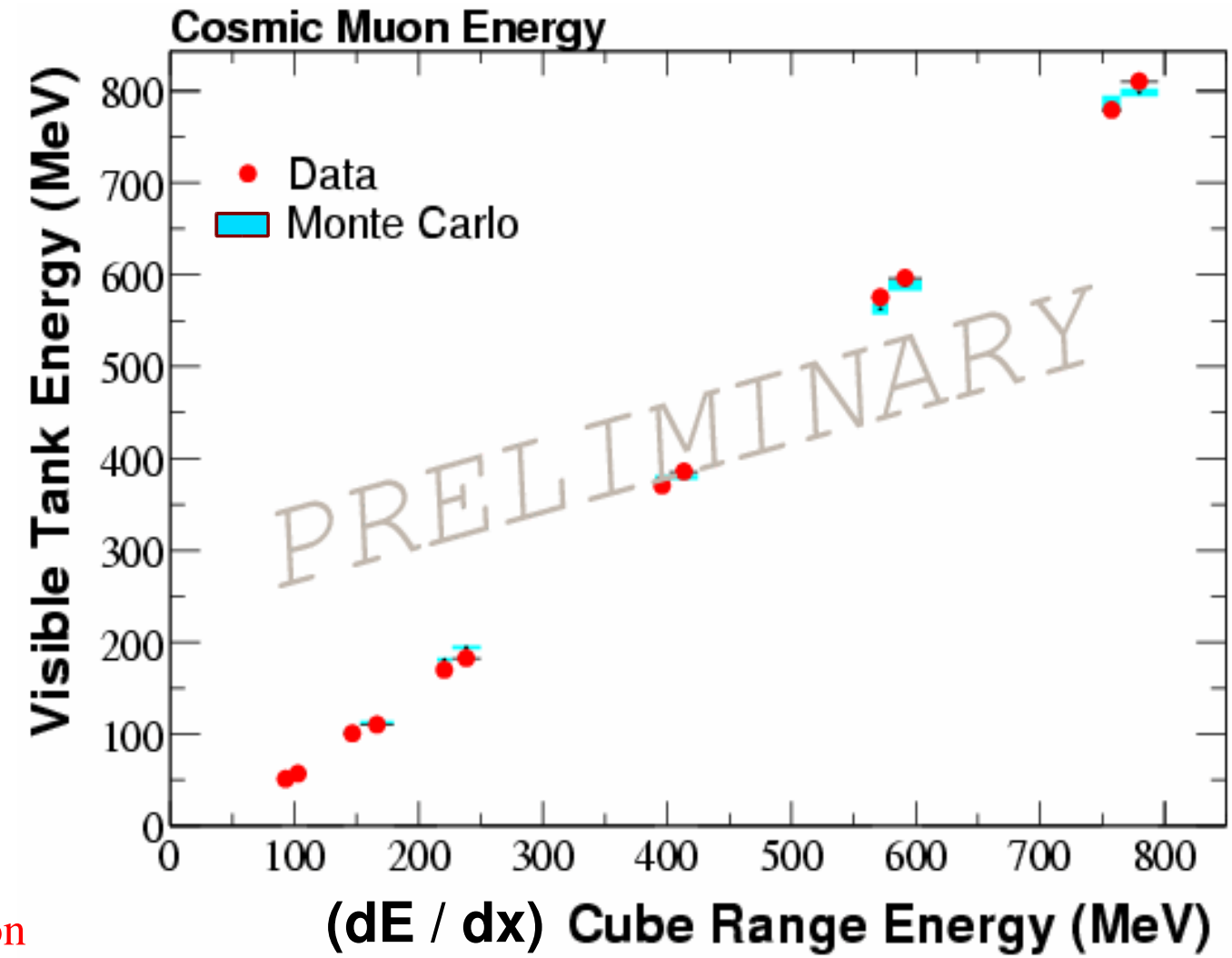
Calibrating Muons in MiniBooNE

- Compare muon directions from muon tracker and tank event fitter
- Fit $\cos^{-1}(u_{MT} \cdot u_{Fit})$ to function $x\exp(-x^2/2\sigma^2)$
  - projection of 2D Gaussian onto 1D
- Extract angular resolution
  - Correct for intrinsic resolution of muon tracker (2°)
  - Angular resolution ~4° at 500MeV
  - Typical muon energy for these analyses



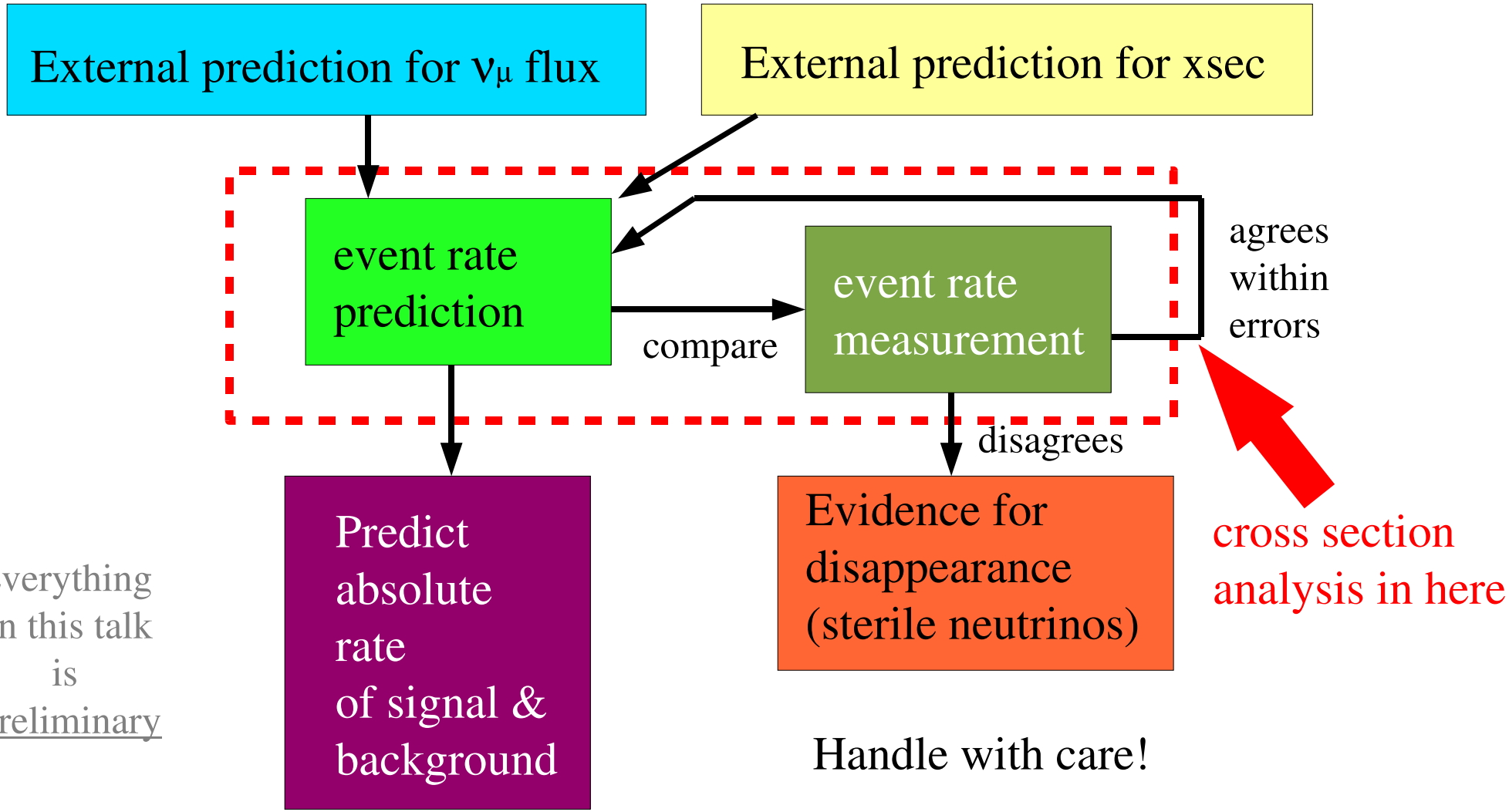
Calibrating Muons in MiniBooNE

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



NIM article on cosmic muon calibration in preparation

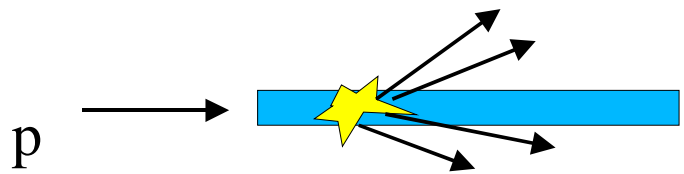
MiniBooNE Analysis Strategy



Everything in this talk is preliminary

Handle with care!

External Prediction for ν_μ Flux



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

- **Production of secondaries in Be target:**
  - Geant4 Secondary Beam Monte Carlo
  - MARS (p, n)
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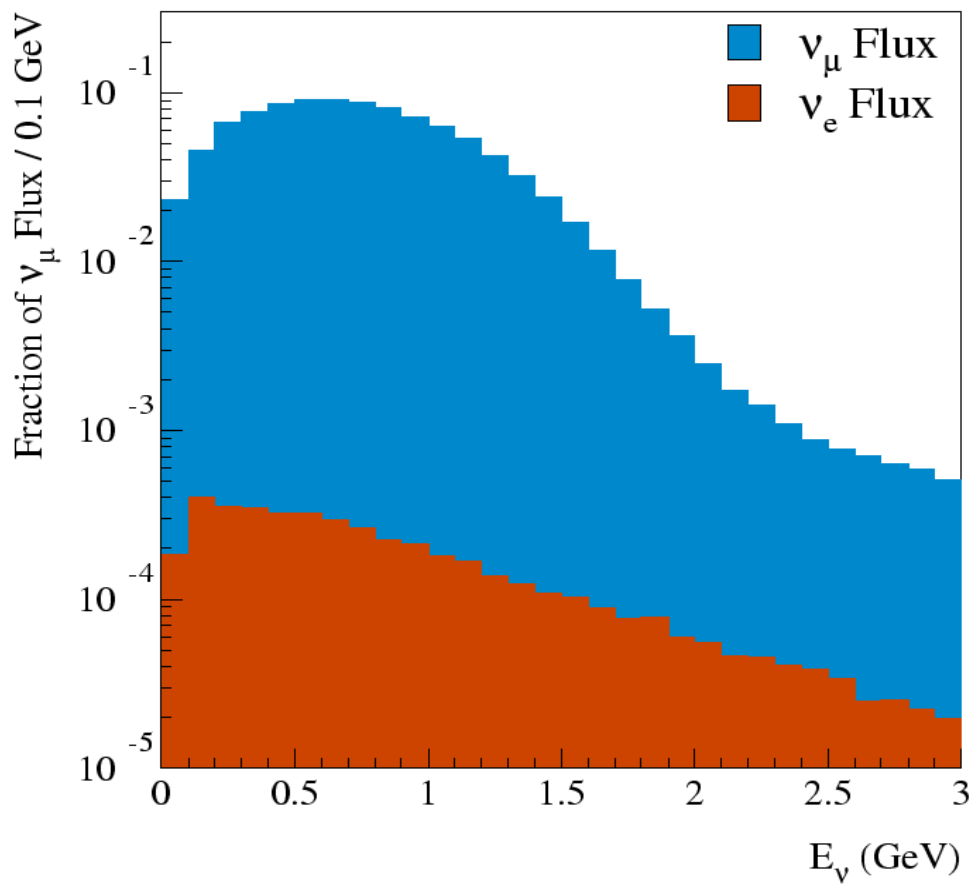
  - Publication in preparation *(J. Link, et al.)*



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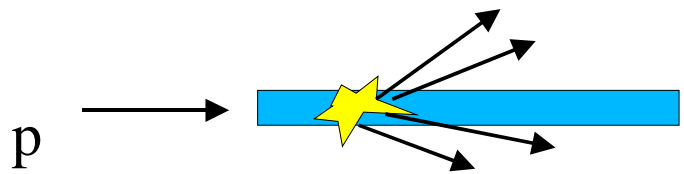

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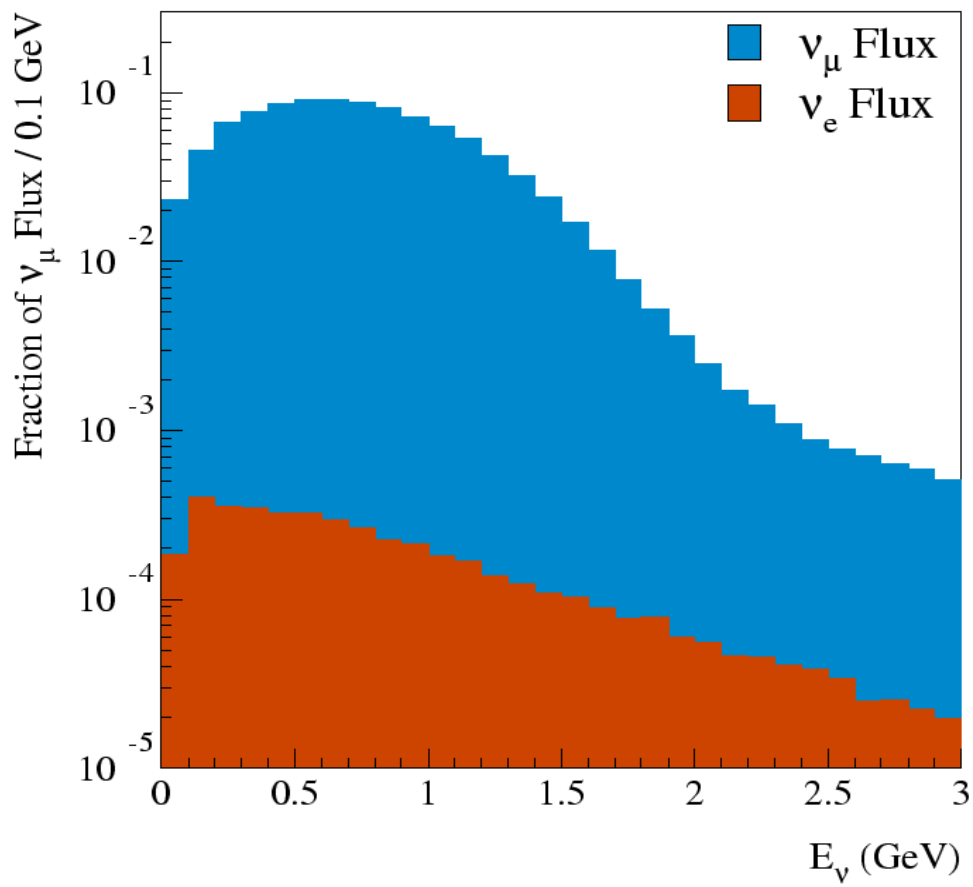
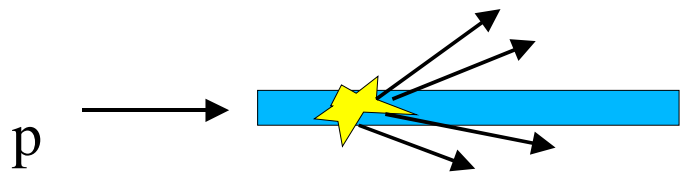
  - Propagates mesons to decay,
  - Keeps neutrinos pointed toward detector



Near future:

- Constrain σ (p Be $\rightarrow \pi^+ X$) at 8 GeV at HARP with MiniBooNE target, ~5% error

External Prediction for ν_μ Flux



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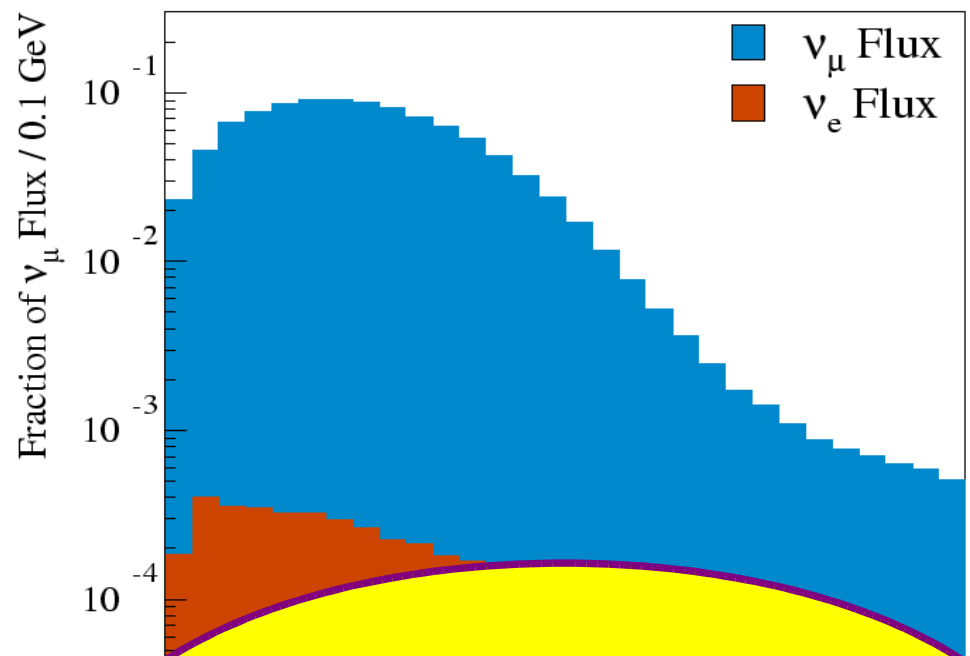


Please see next week's Wine & Cheese for a HARP update by Geoff Mills

Near future:

- Constrain σ (p Be $\rightarrow \pi^+$ X) at 8 GeV at HAR

External Prediction for σ_ν

σ Calculations: NUANCE v3 Monte Carlo

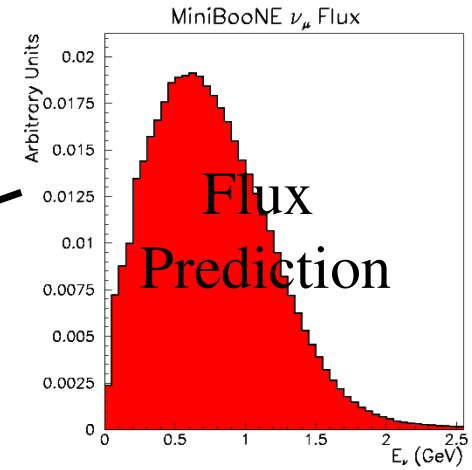
- open source code
- widely used by many experiments
- predicts event rates and kinematics

(have also used NEUGEN, NEUT)

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
- Final State Interaction (FSI) model rescatters nucleons

Analysis Chain



NUANCE v3

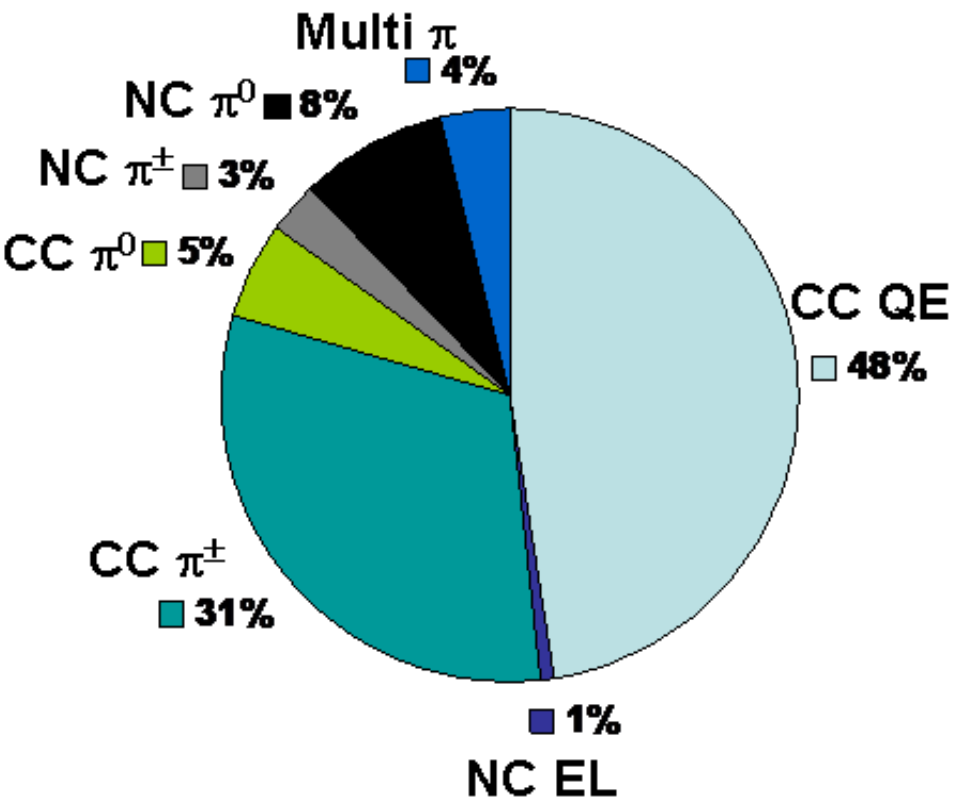
MiniBooNE Detector Monte Carlo (Geant3.21)

MiniBooNE Analysis Framework (reconstruction, etc.)

→ **Compare with Data!**

Event Rate Prediction

- 48% CCQE
- 31% CC1π+
- 1% NC Elastic
- 8% NC π^0
- 12% Other



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

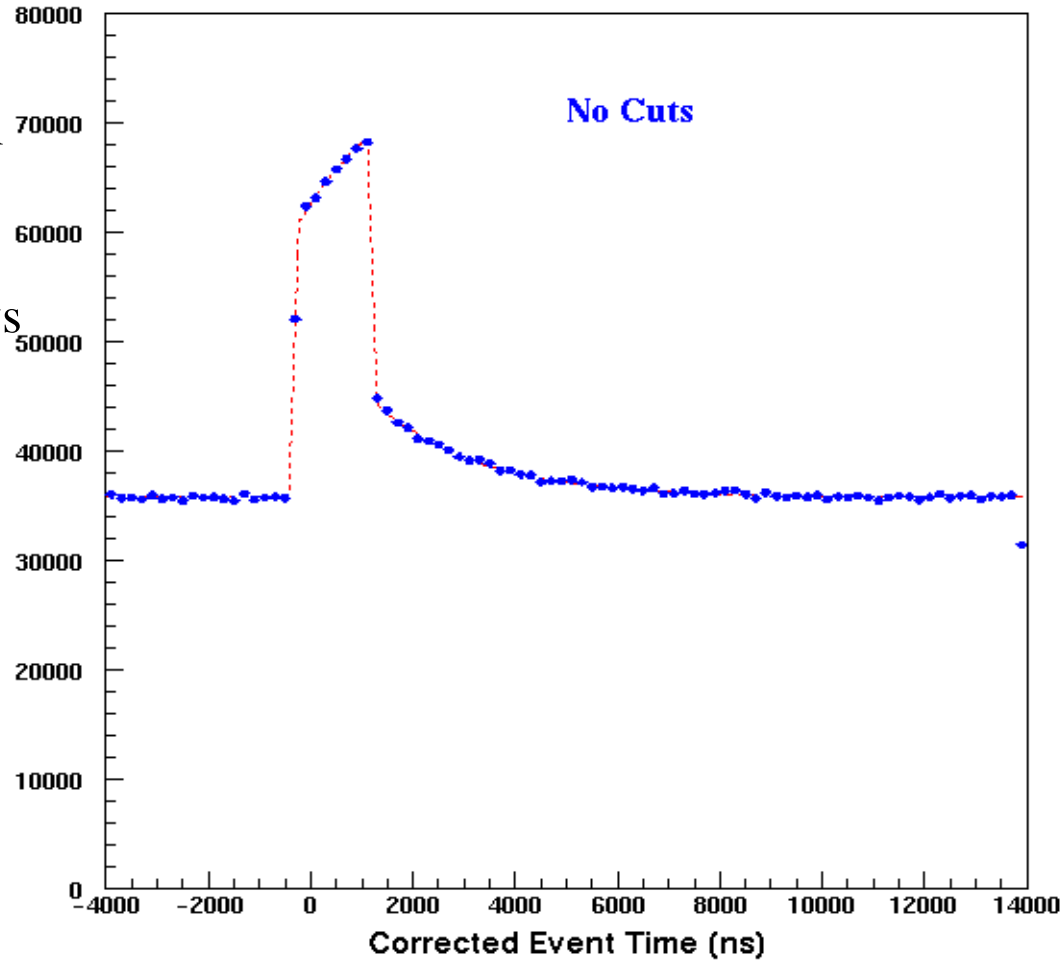
... use Monte Carlo to correct for cut efficiencies ...

This Analysis:

- 3.2E20 protons on target
  - 60k CCQE events (after selection cuts)
  - 40k CC1π+ events (after selection cuts)
- ~ half of current data set

Neutrino-Induced Event Selection

- Times of PMT hit clusters (Subevents)
- Beam window (1.6 μs) evident
- In addition to neutrinos, events contain
  - Cosmic Rays
  - Electrons from Stopped CR Decays (Michel Electrons)
  - Beam-Induced Background
  - Need cuts to eliminate these BGs
- No cuts
  - Fit function includes Michel electrons from beam-induced muons
- Veto Hits < 6
- Tank Hits > 200



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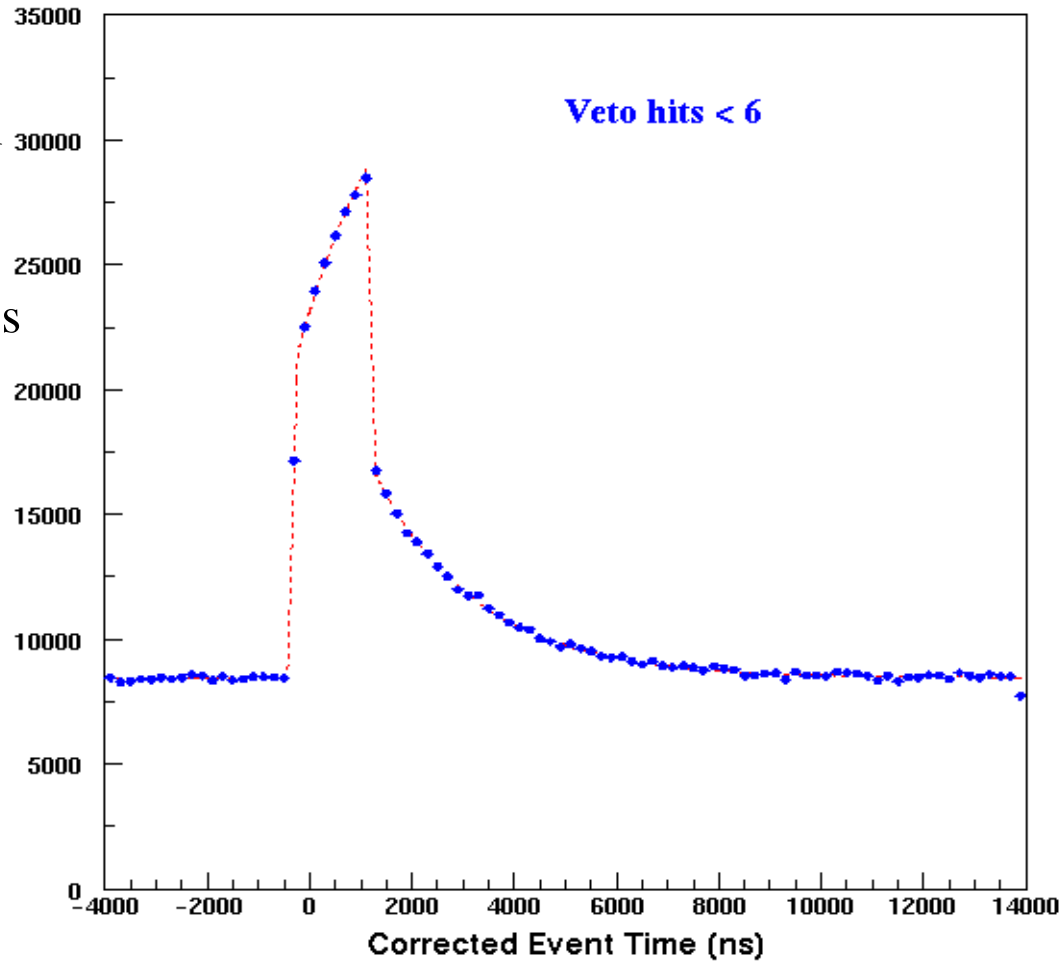
- Tank Hits > 200



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- Veto Hits < 6
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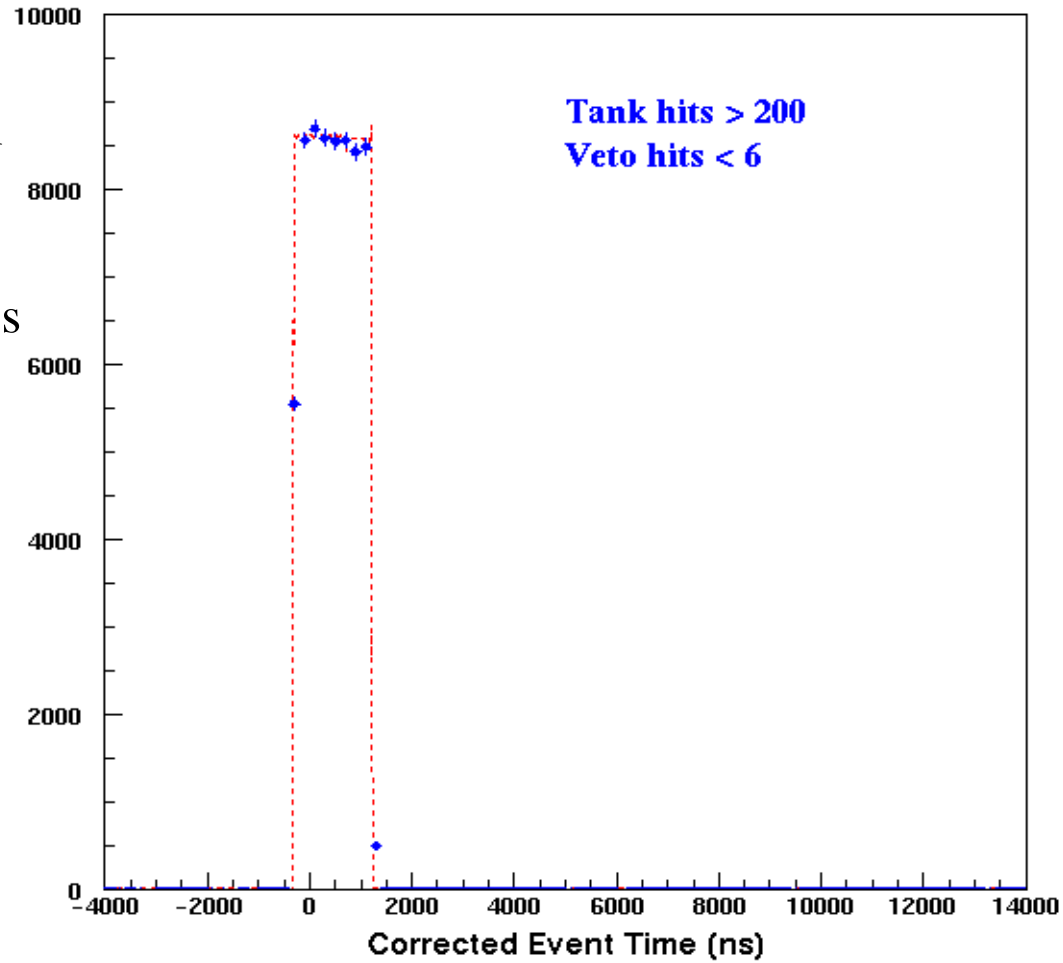
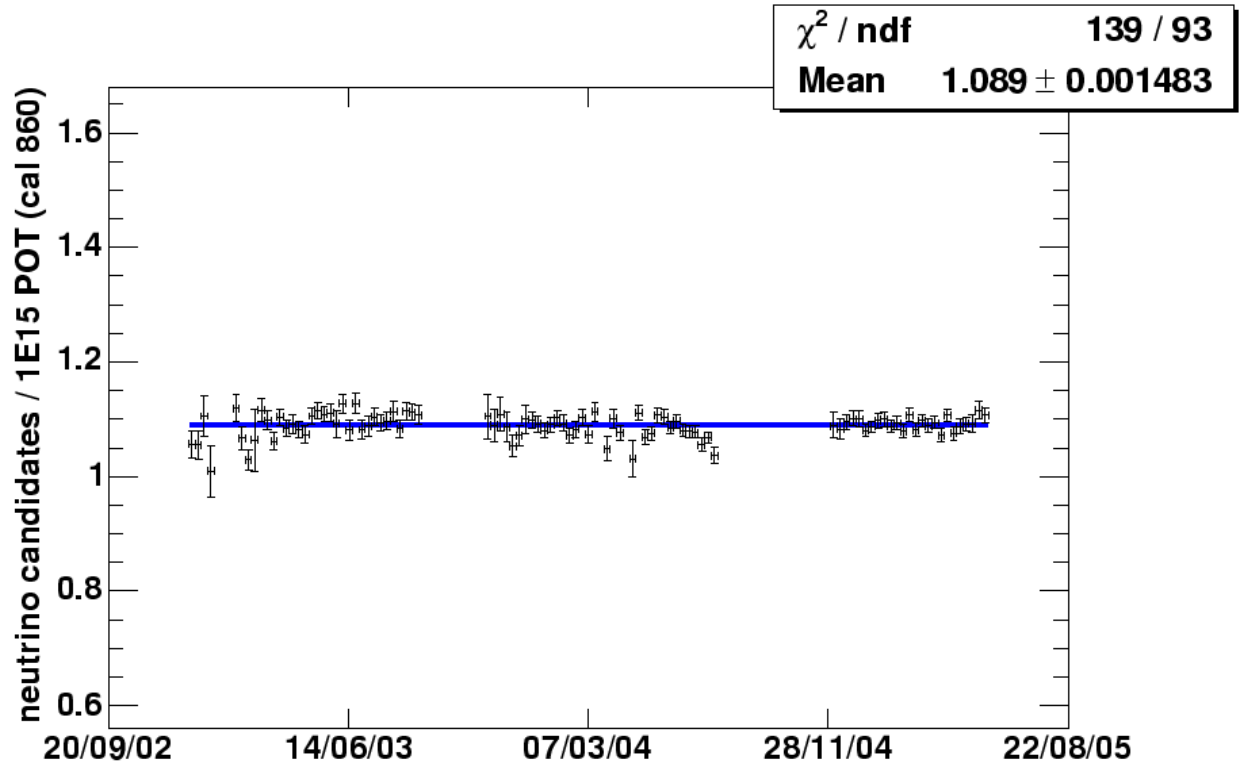
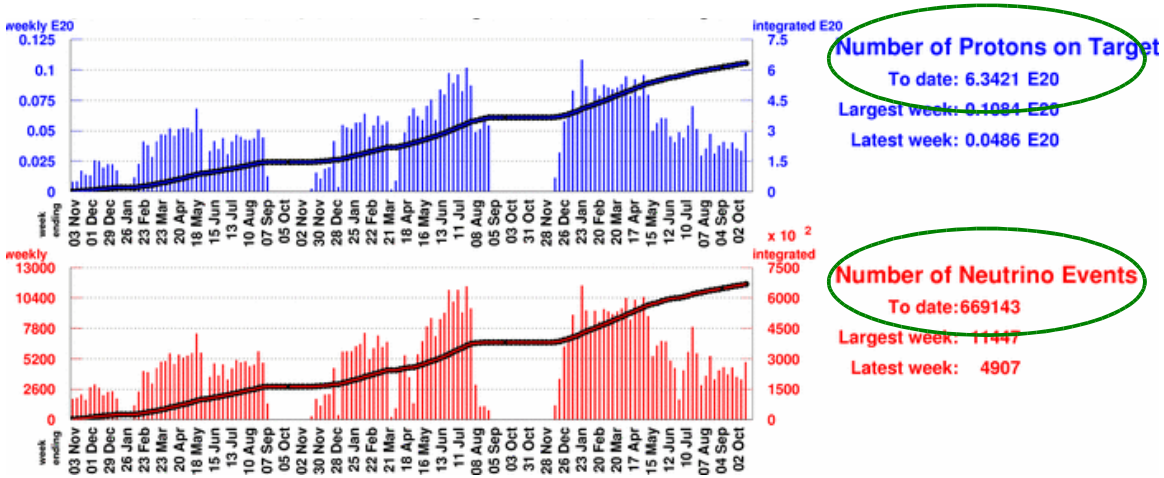
  - Eliminates Michel electrons
- Background rejection about 5000:1



Event Rates vs. Time

- Using simple ν cuts
- ν/POT vs. time
  - rate is constant!
  - spans two shutdowns,
  - two horns





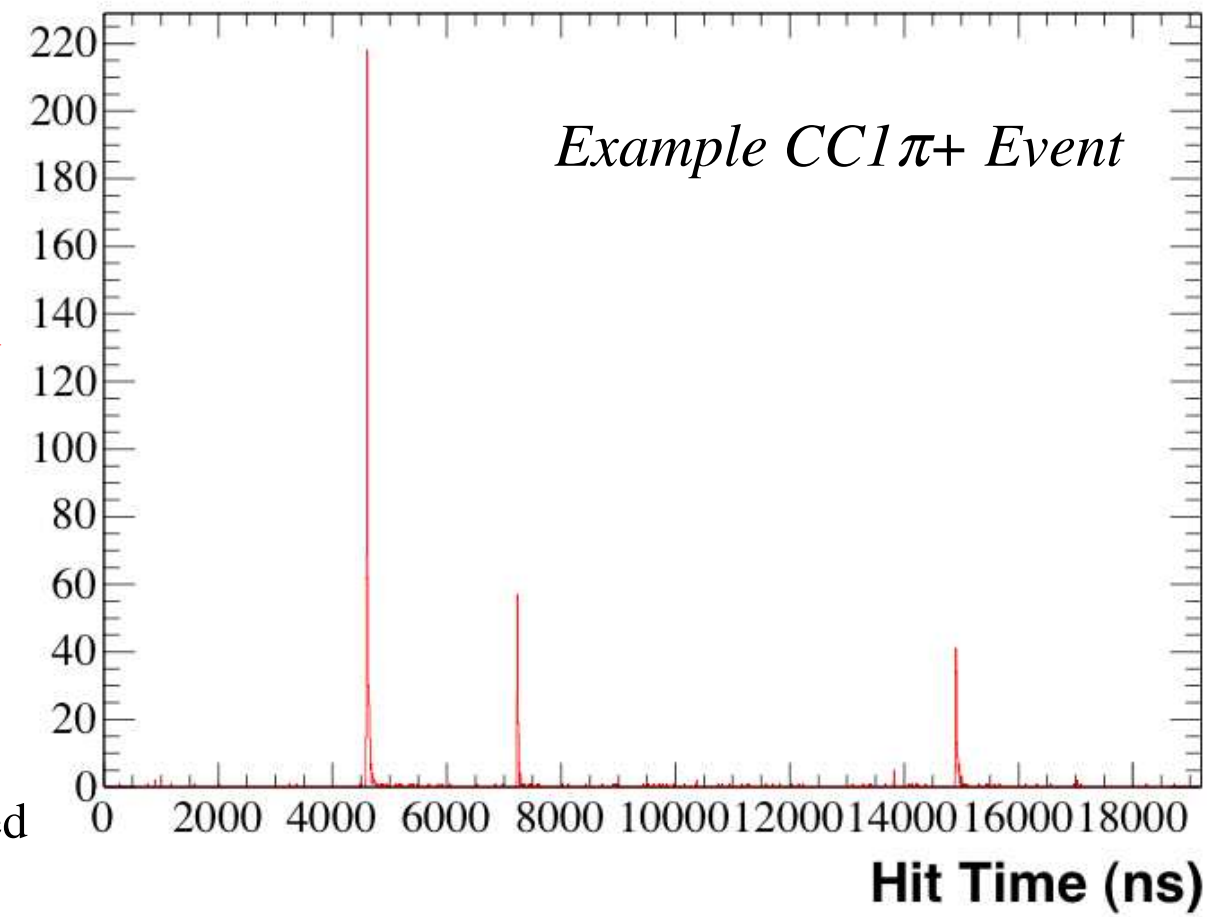
- Total data set to date:
- >6.3E20 POT
  - >670k events!

Charged Current Event Selection

- Use Muon Decay to Identify Charged Current Event Candidates

Distribution of Tank PMT Hits

in Time w.r.t. Beam Trigger Window start (clusters ≡ subevents)



- Counting Michel electrons is a powerful and simple cut!

- First subevent used to reconstruct final state particle tracks

- Michel electrons tell us where tracks stopped

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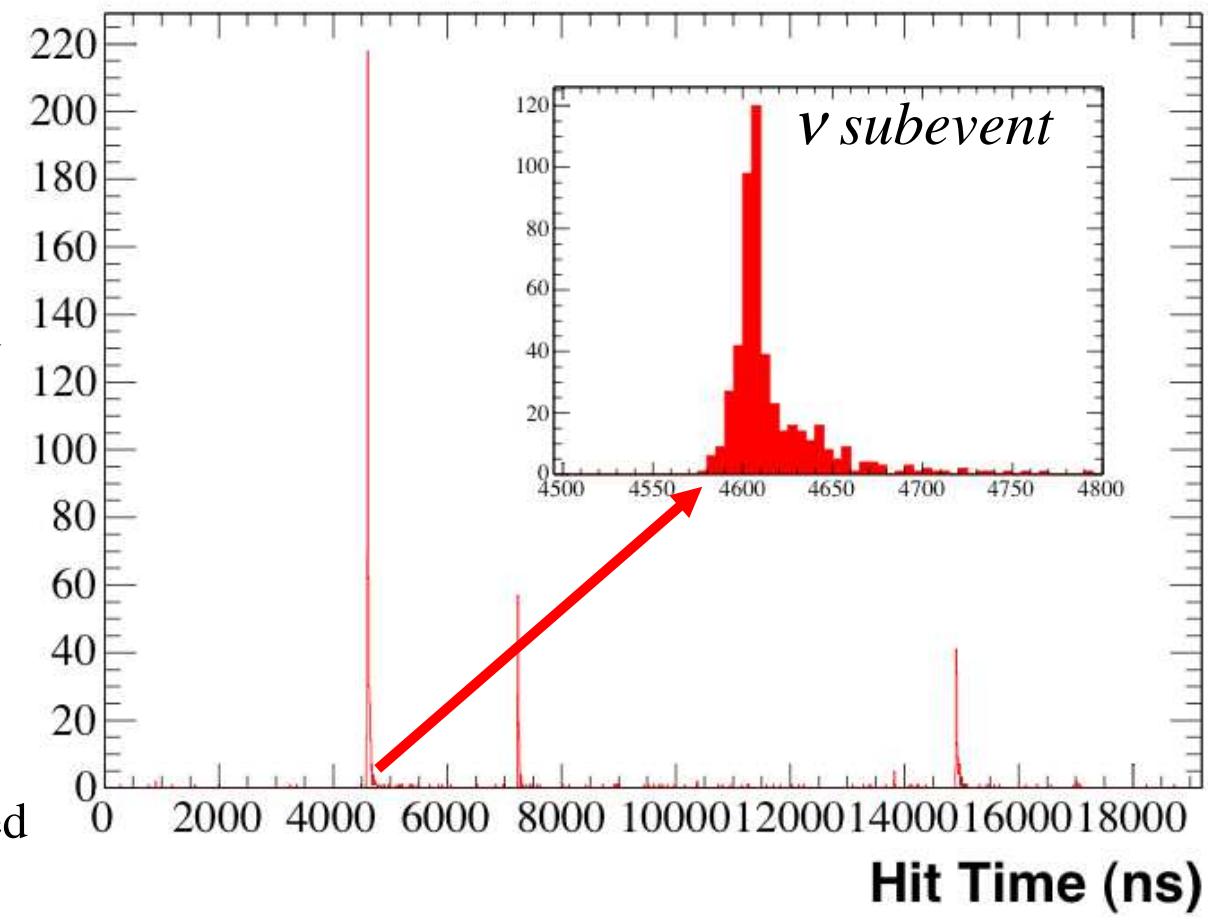

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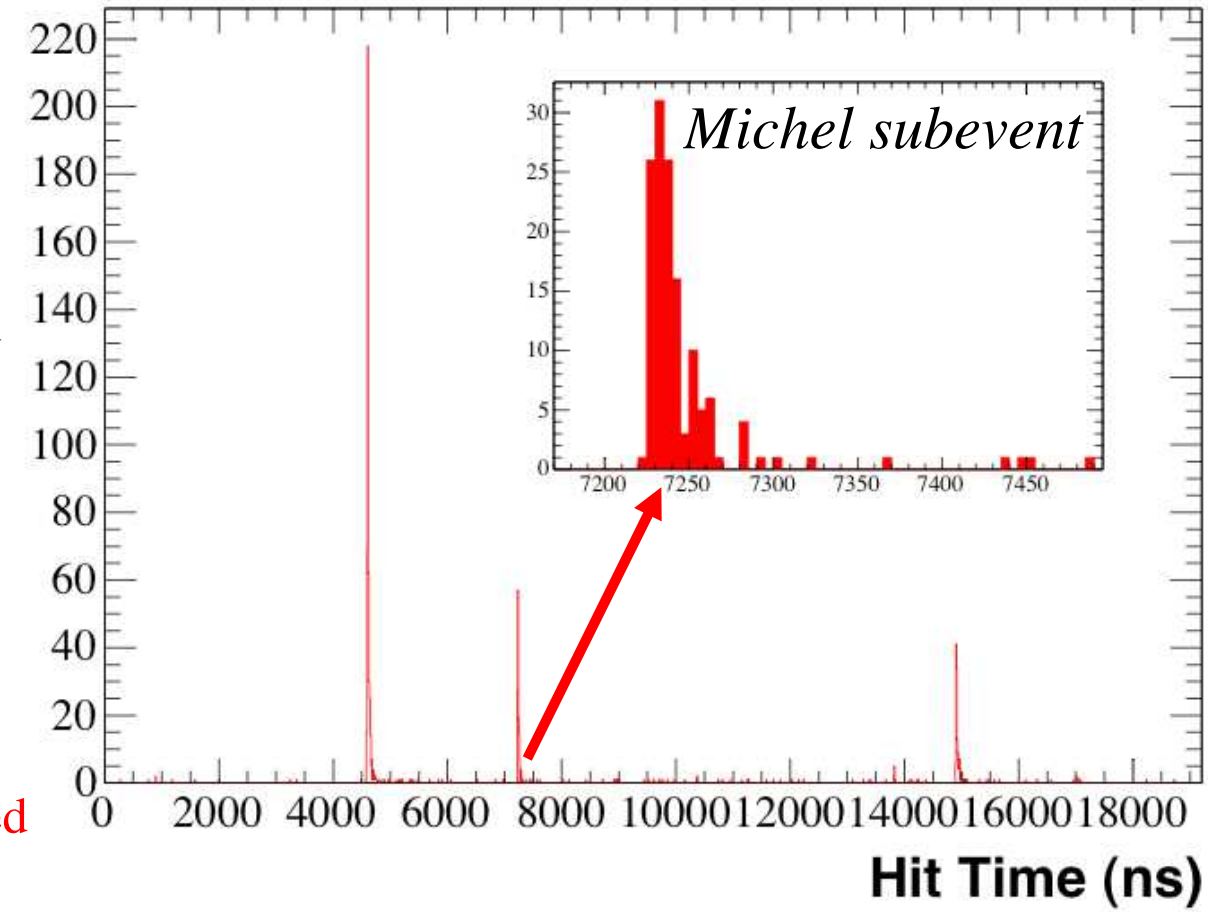


CCQE Event Selection

First Level of Cuts:

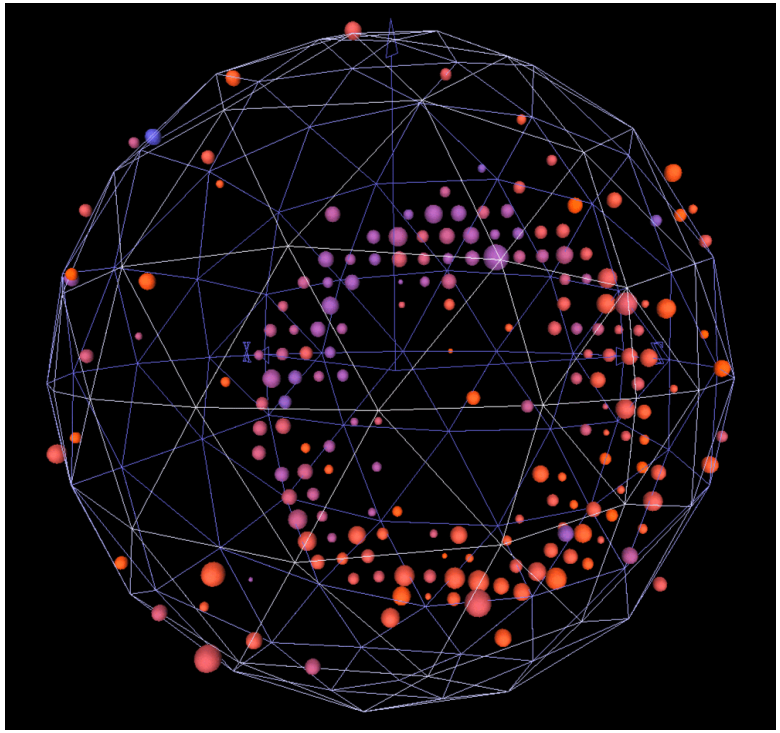
- Neutrino-Induced Event Selection Cuts
- CC Selection Cut
  - < 3 sub-events

Signal:

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

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

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

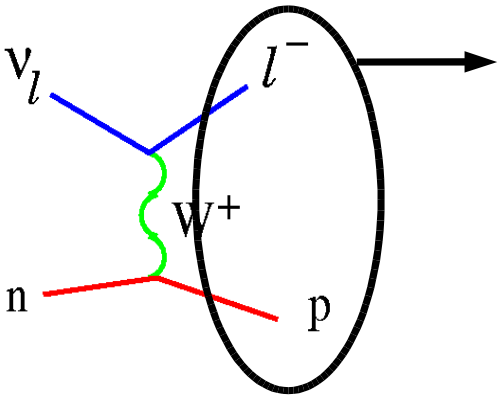


Second Level Cuts: Final State ID

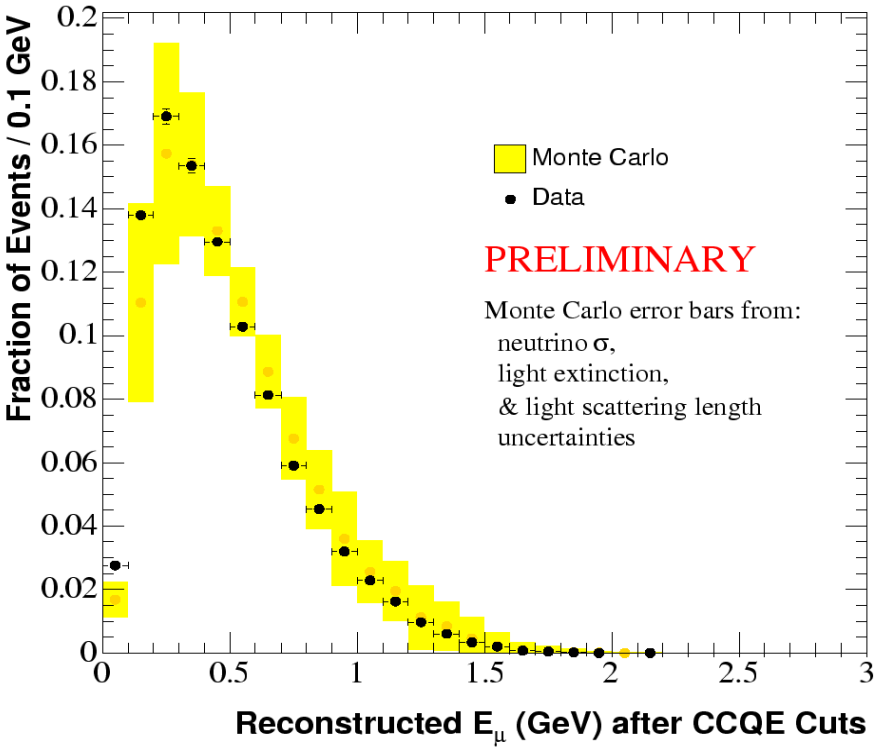
- event topology
  - fraction of on- vs. off- ring light
- PMT hit timing
  - fraction of prompt vs. late light
- μ-like energy loss
  - given E, is track length consistent with μ?
- 10 variable Fisher discriminant

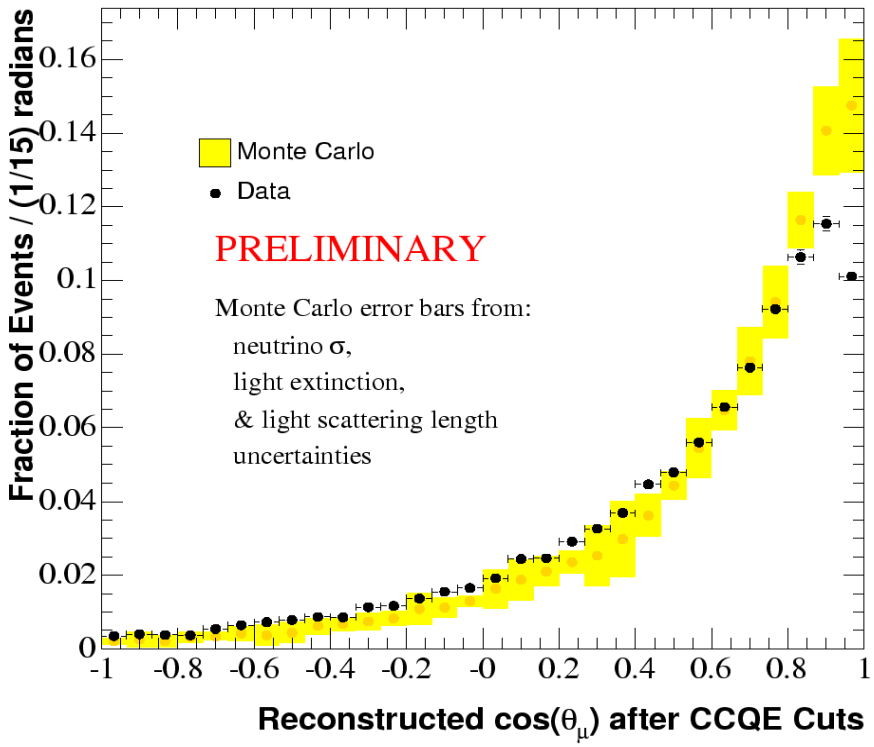
- Result: 86% CCQE purity
  - most of background from CC1π+ (due to π absorption in nucleus)

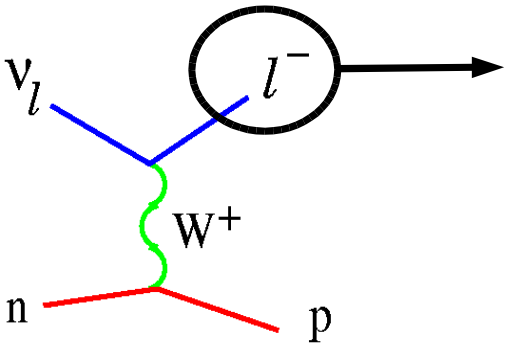
CCQE Data



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

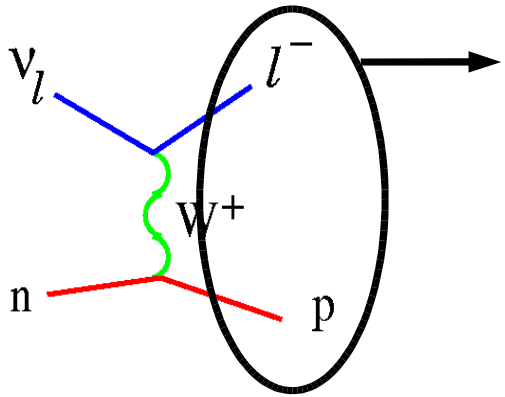






reconstruct μ^- direction from Cherenkov light, $\cos(\theta) = 1 \sim$ low Q^2

CCQE Data



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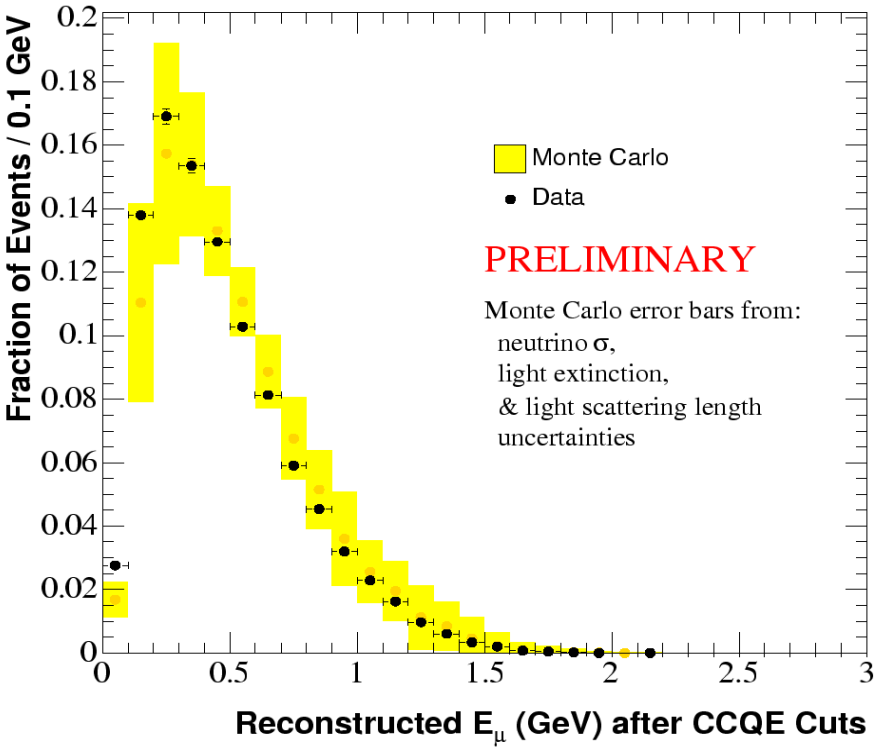
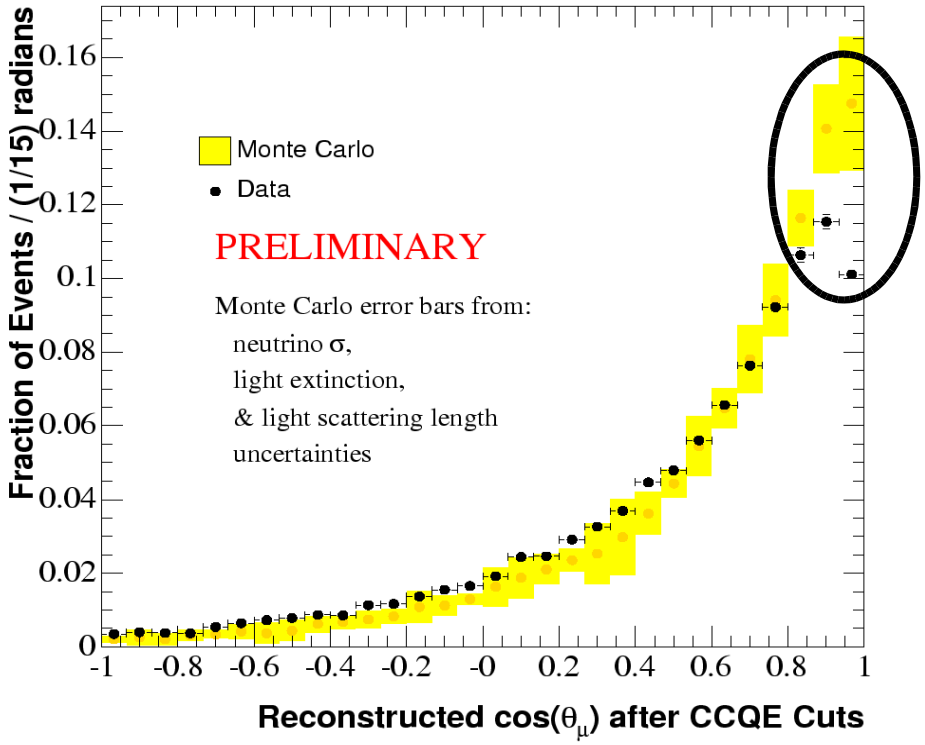
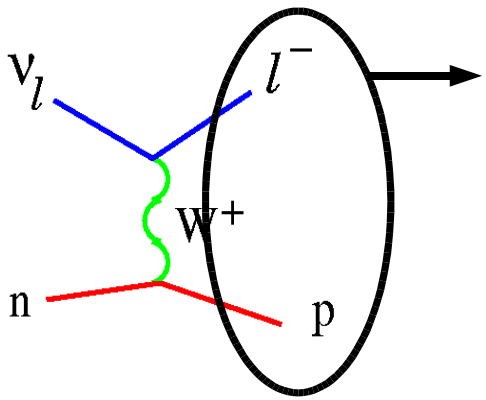




- Deficit of forward angle muons (low Q2 region) also seen by K2K
- Interesting physics?
- Working on understanding this feature

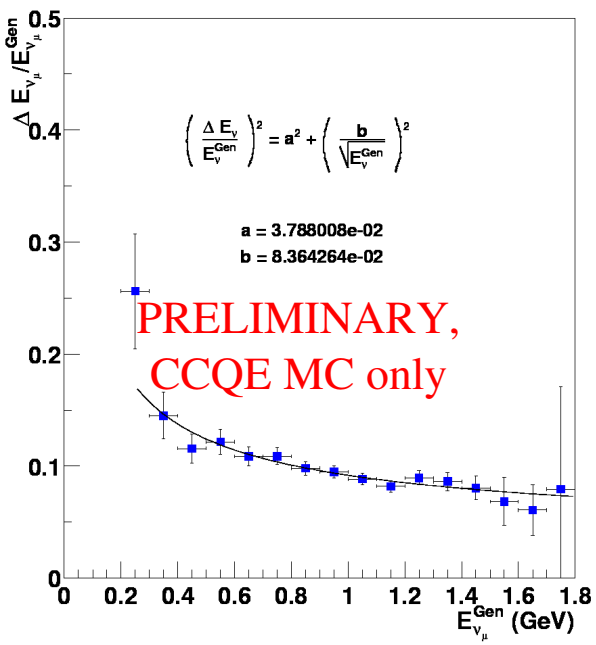
CCQE Data

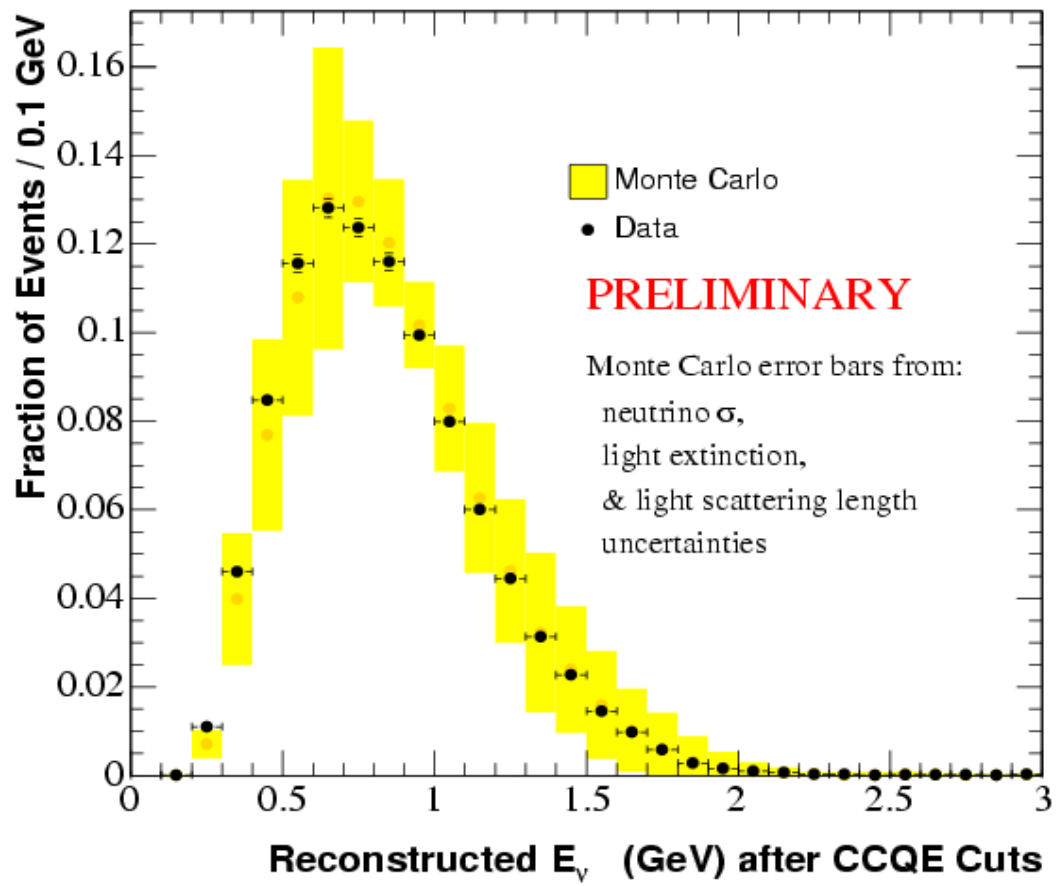


use measured μ^- visible energy and angle to reconstruct E_ν^{QE}

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

Neutrino Energy Reconstruction





Energy distribution used for the cross section measurement

CC1π^+ Event Selection

First Level of Cuts:

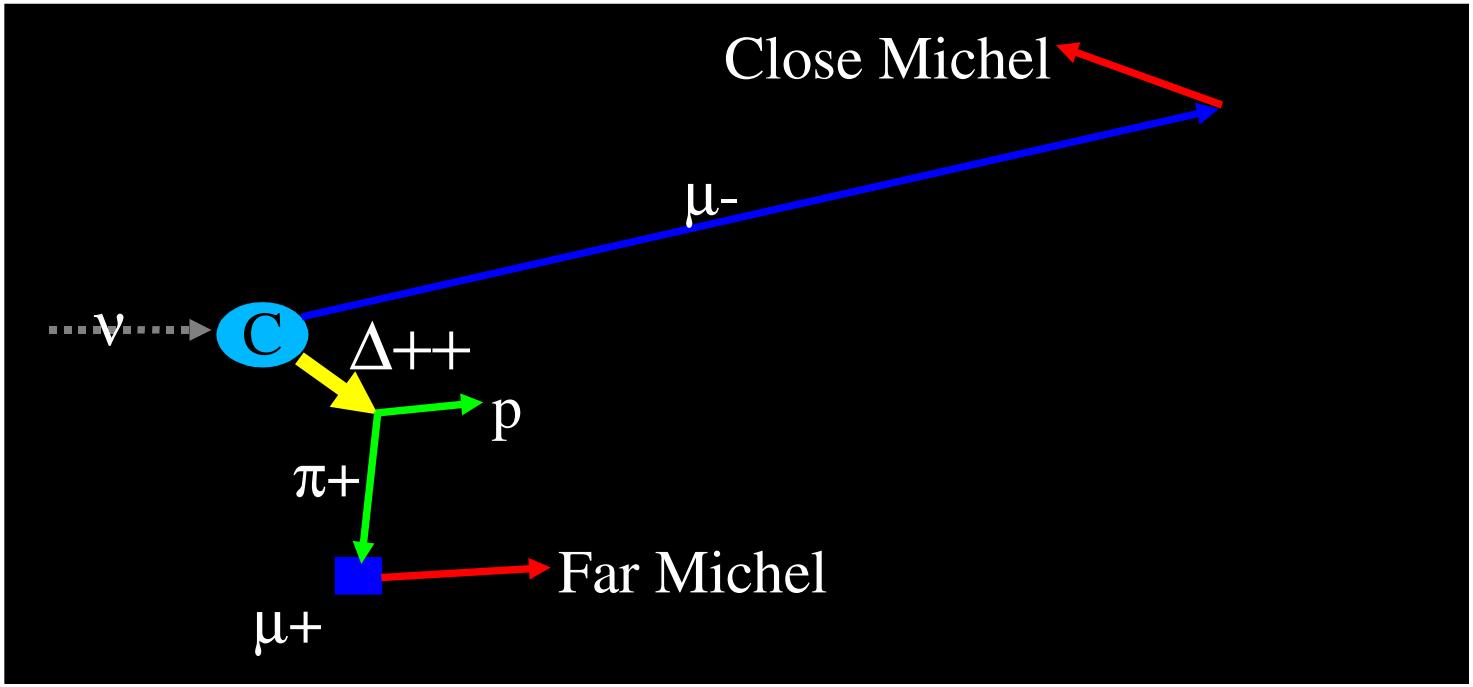
- Neutrino-Induced Event Selection Cuts
- CC Selection Cut
  - exactly 3 sub-events
  - 2nd 2 sub-events consistent with Michel e^- ($20 < N_{PMT} < 200$)

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:

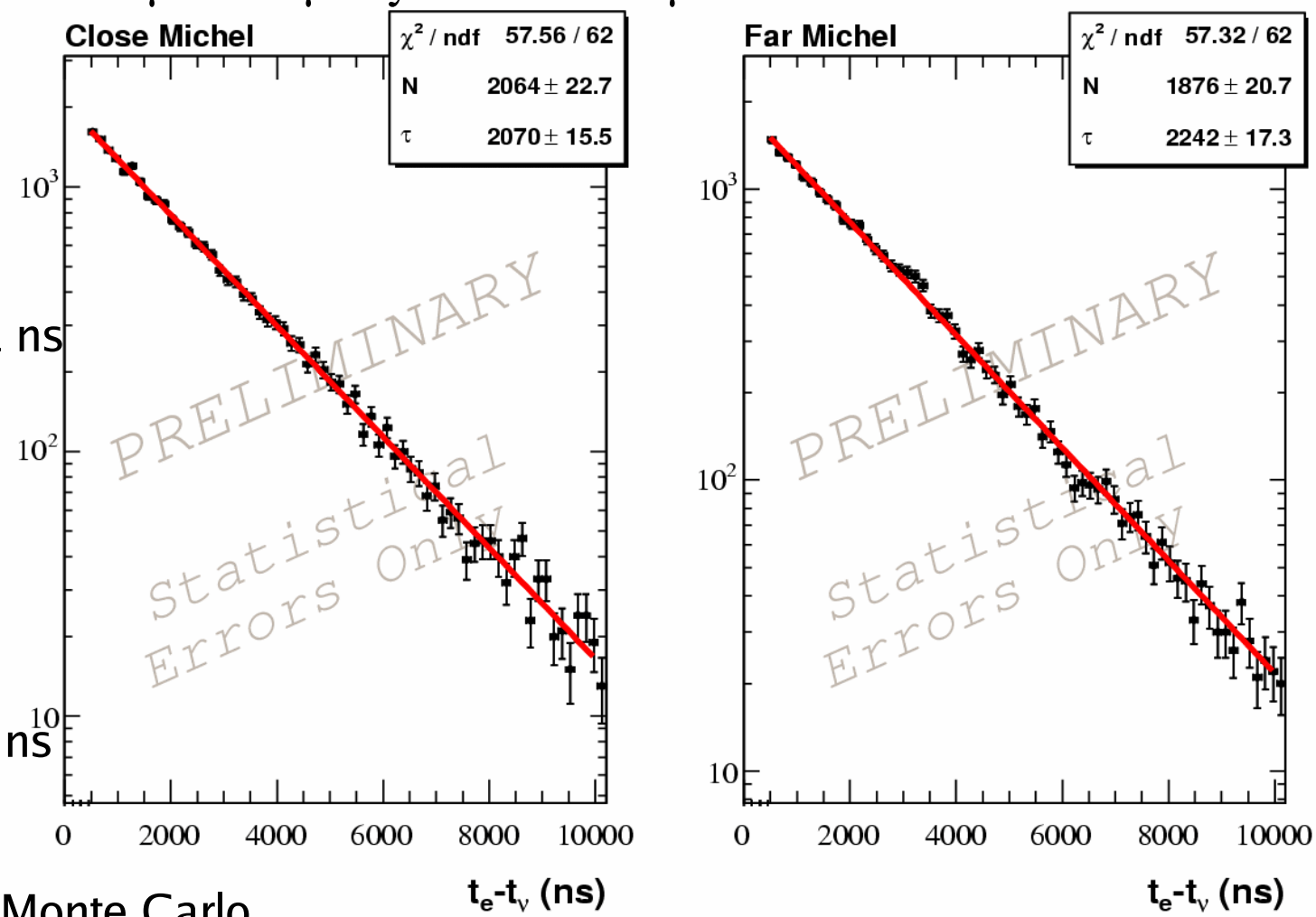
84% purity!

Main Backgrounds: Nπ and QE

Inclusive final states

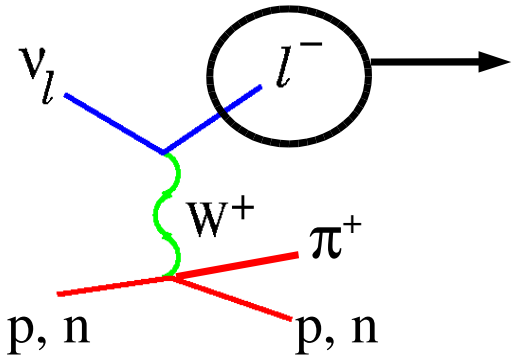
CC1π^+ Event Selection Validation

- validate CC1π+ 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±18.1 ns
- far:
  μ^+ do not capture
  expect
  τ=2197.03±0.04 ns
  measure
  τ=2242±17.3±30.0 ns

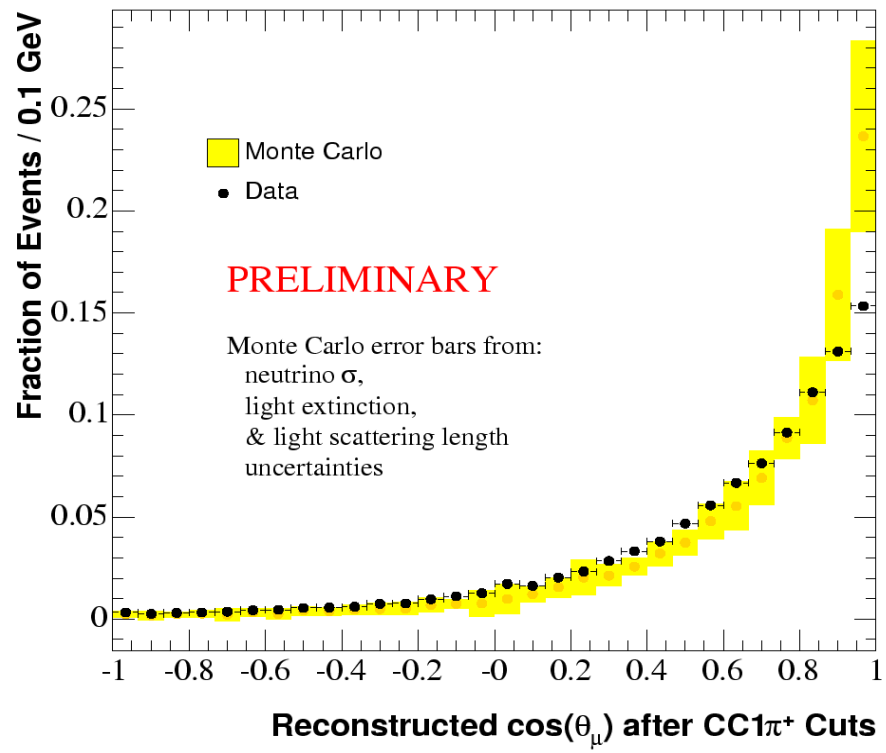


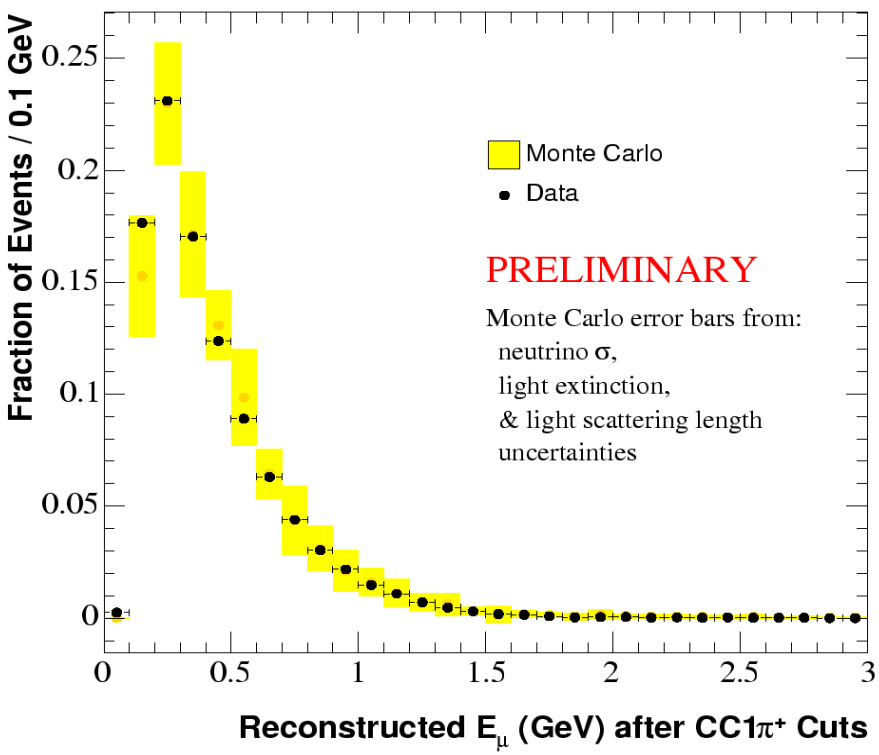
- Same separation in Monte Carlo

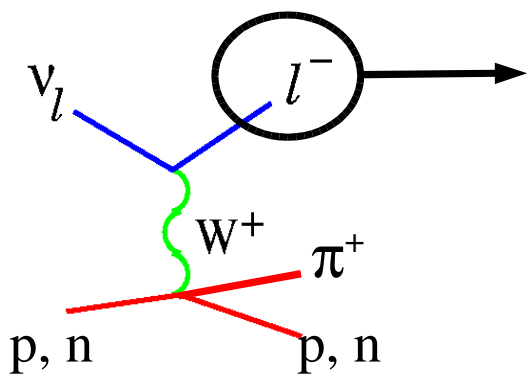
CC1π^+ Data



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

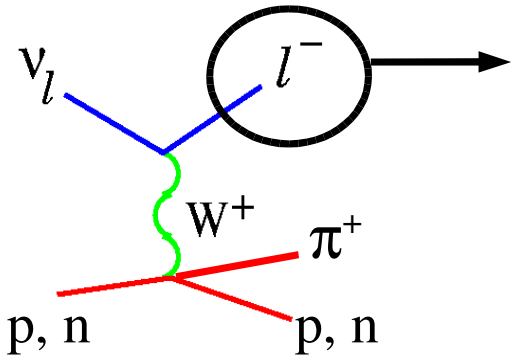






reconstruct μ^- direction from Cherenkov light, $\cos(\theta) = 1 \sim$ low Q^2

CC1π^+ Data



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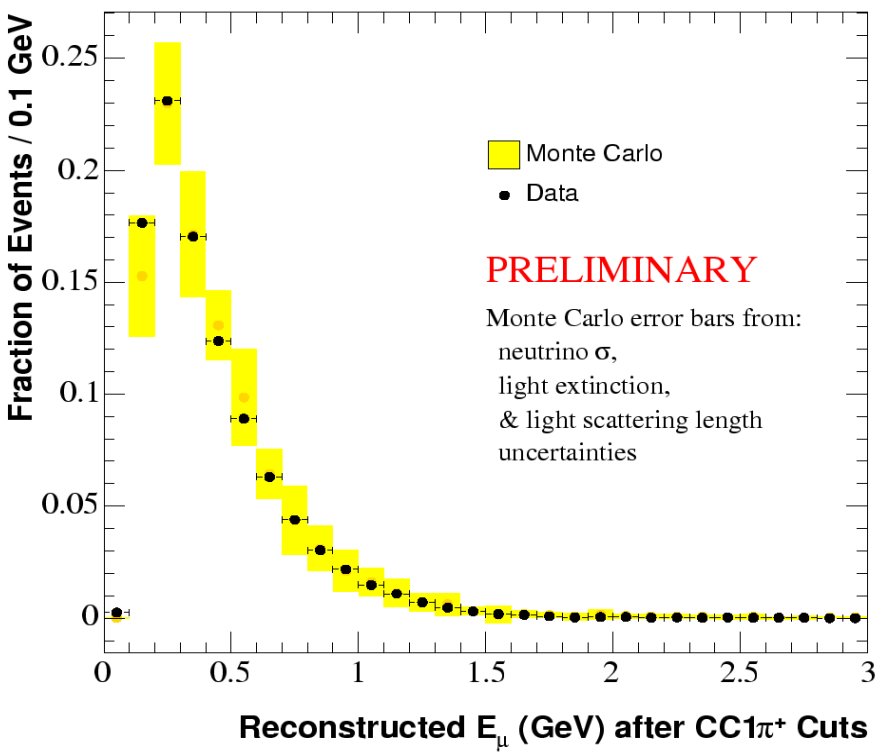
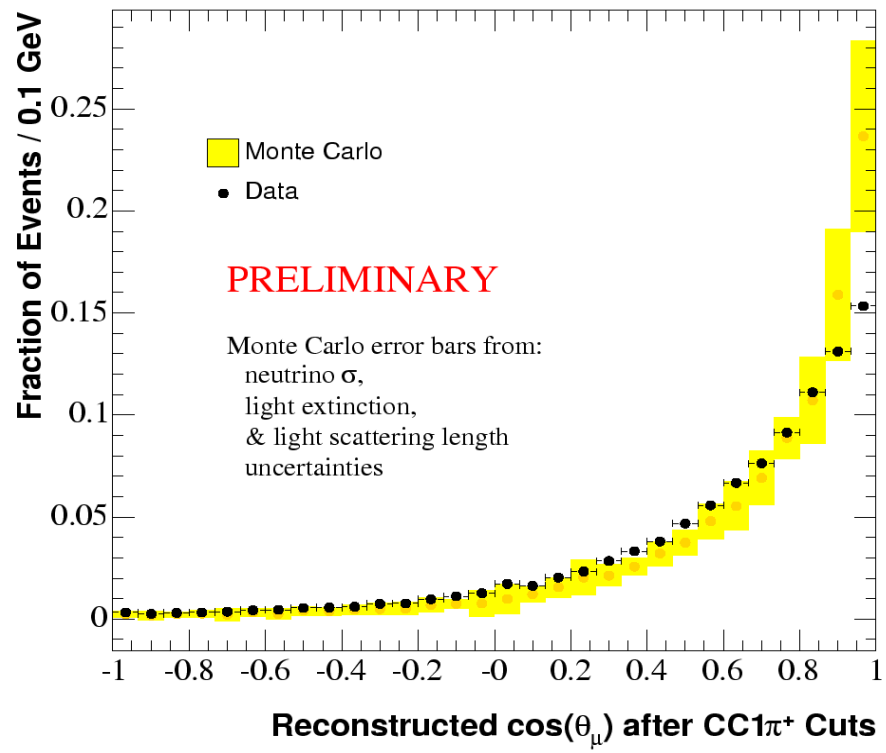
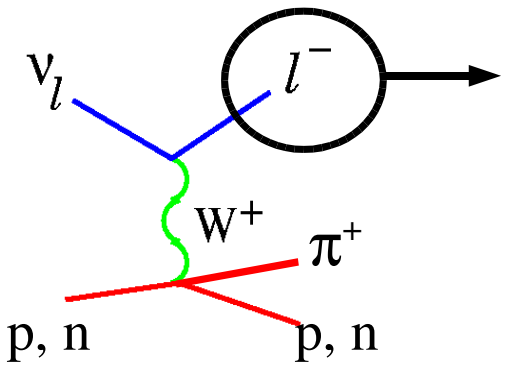




- Similar deficit of forward angle muons
- Deficit larger than CCQE sample: clue to interesting physics?
- Working on understanding this feature

CC1π^+ Data

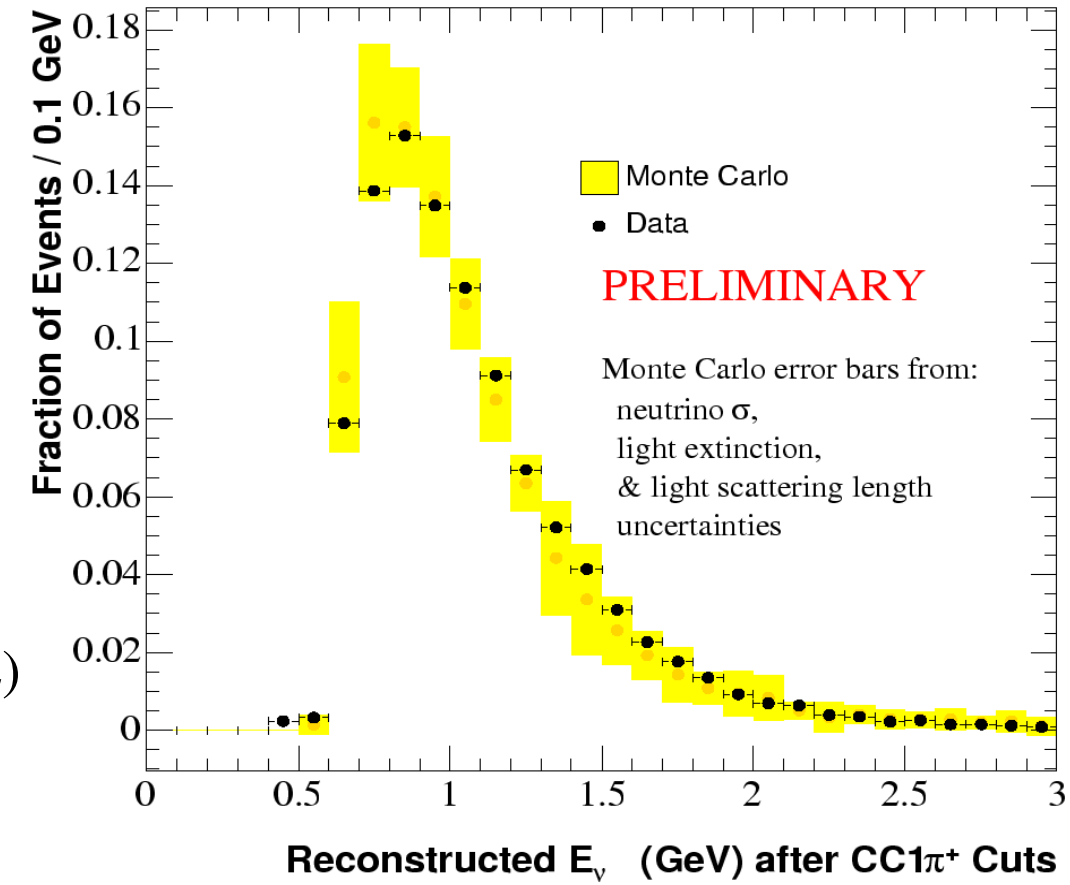


use measured μ^- visible energy and angle to reconstruct E_ν^{QE}

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

Neutrino Energy Reconstruction

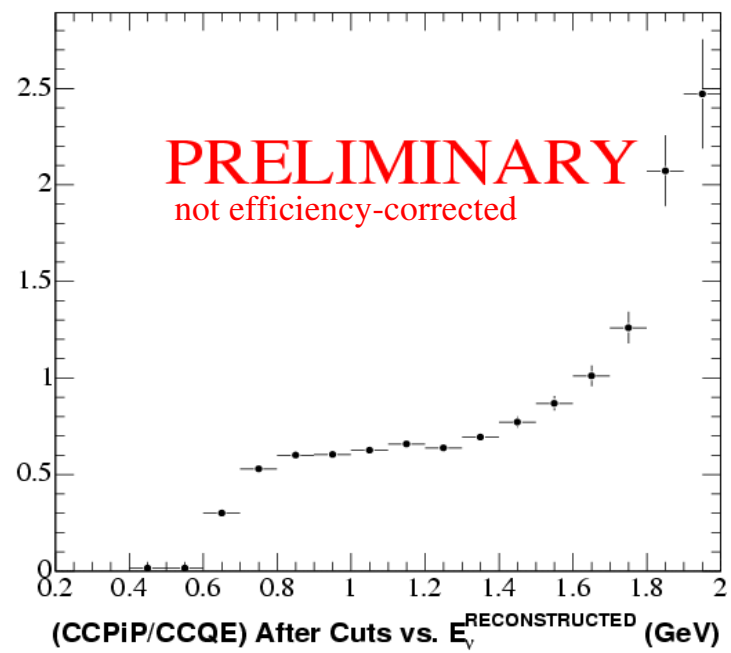
- Assume 2 body kinematics (as in CCQE)
- Assume $\Delta(1232)$ in final state (instead of a proton as in CCQE)
- ~20% resolution



Energy distribution used for the cross section measurement

$CC1\pi^+/CCQE$ Ratio

- Without cut efficiency corrections:
  - measured $N(CC1\pi^+)/N(CCQE)$ vs. E_ν^{QE}



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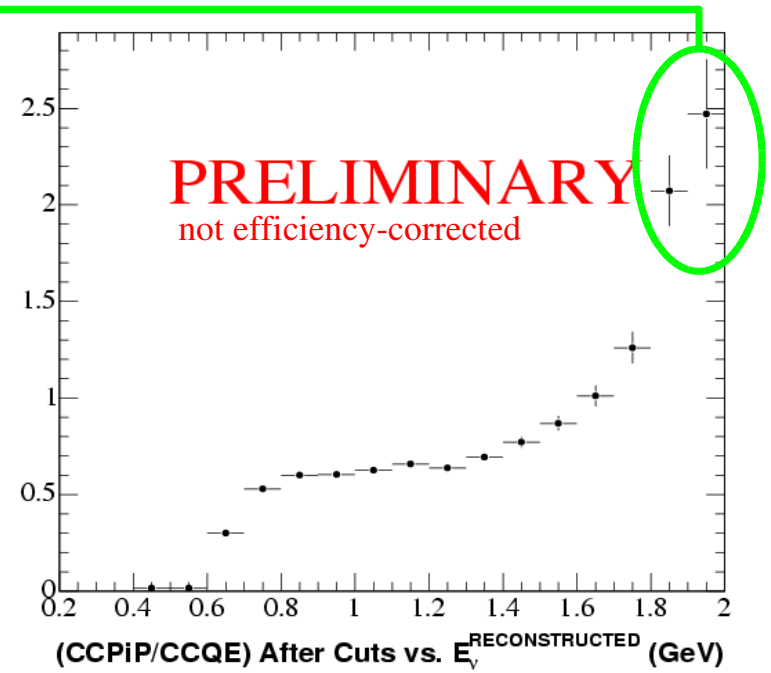

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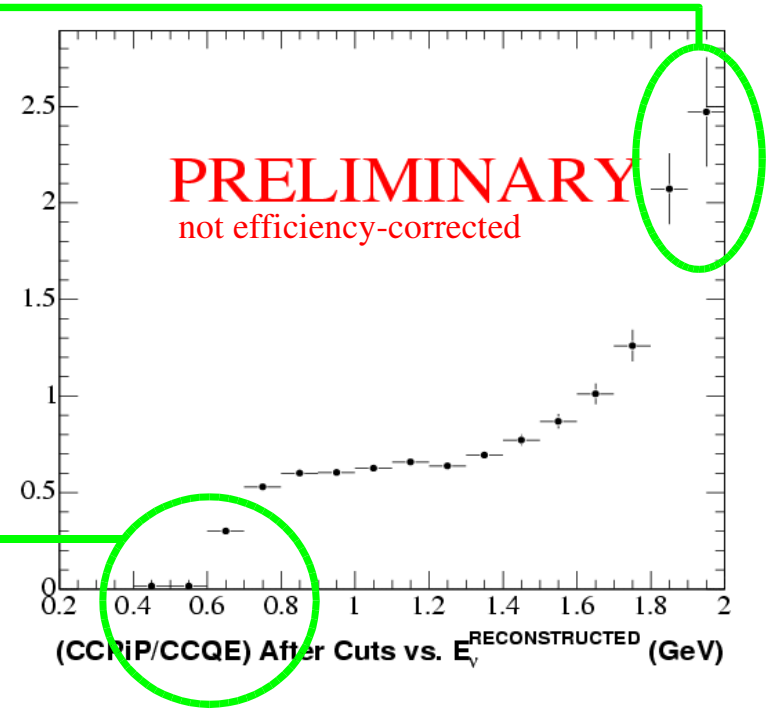

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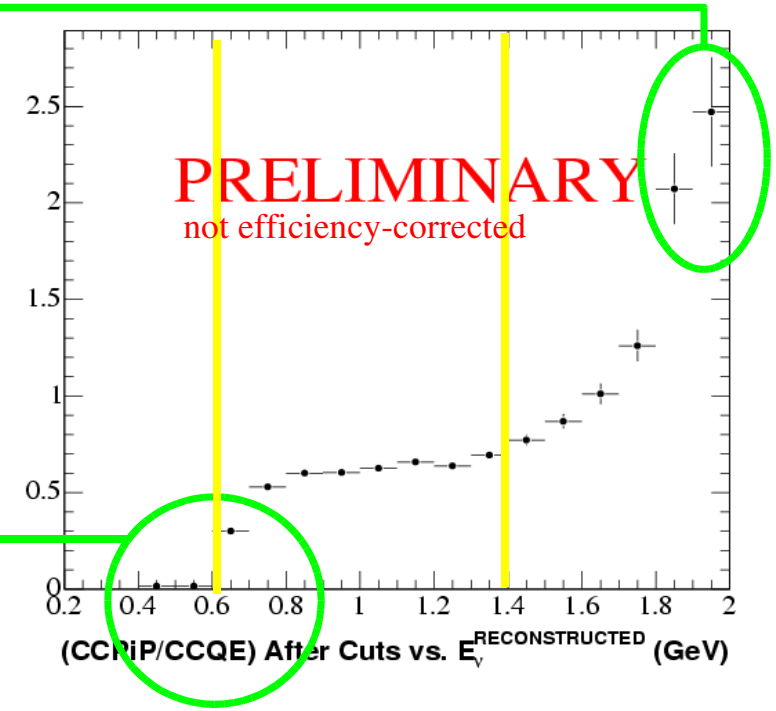

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  - possibility of ν_μ disappearance
  - like branching ratio measurements, normalize to ``golden mode'' in data
  - CCQE is the ``golden mode'' of low E ν σs

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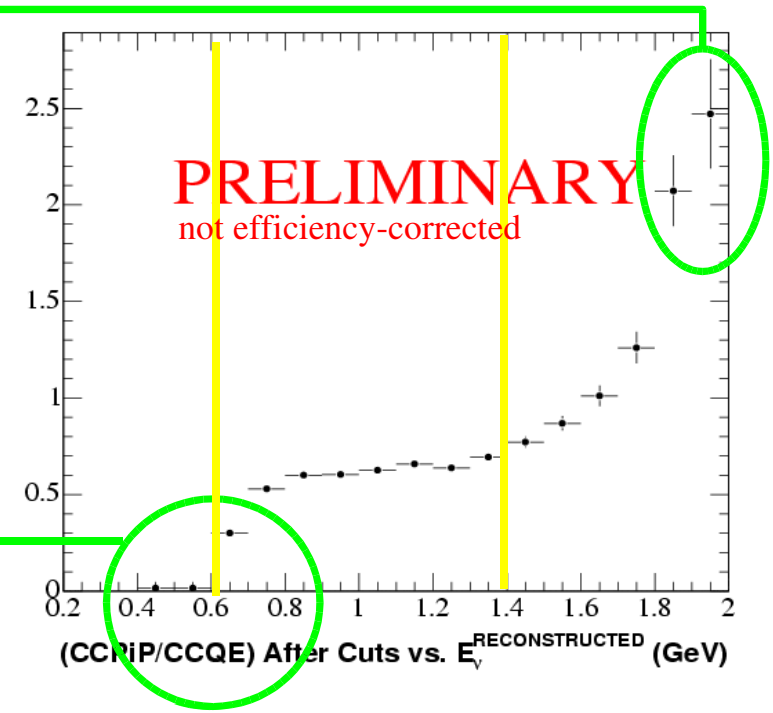

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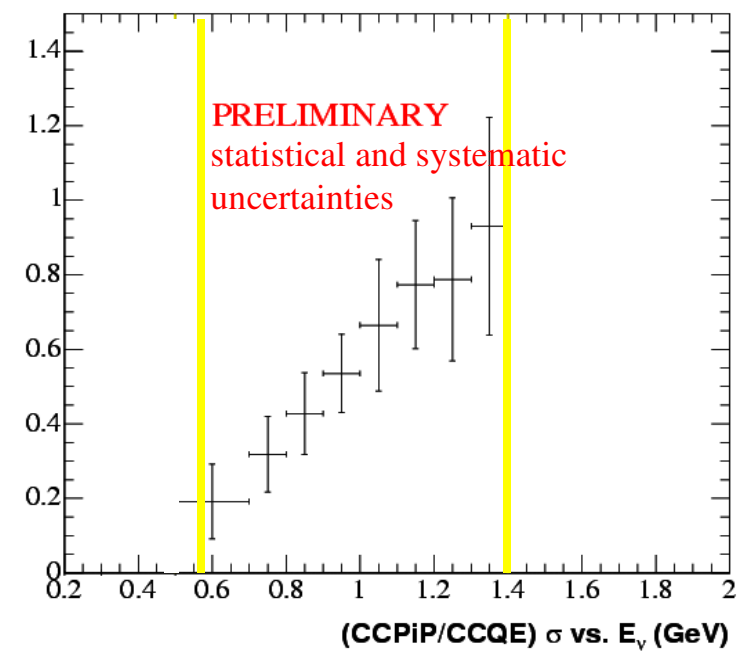
  - possibility of ν_μ disappearance
  - like branching ratio measurements, normalize to ``golden mode'' in data
  - CCQE is the ``golden mode'' of low E ν σs

- Efficiency corrected ratio measurement:
  - estimate efficiency correction in MC
  - systematic errors due to ν cross sections (~15%), photon atten. and scatt. lengths in oil (~20%), energy scale (~10%)



Sources of Uncertainty

ν cross section uncertainties:

- 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

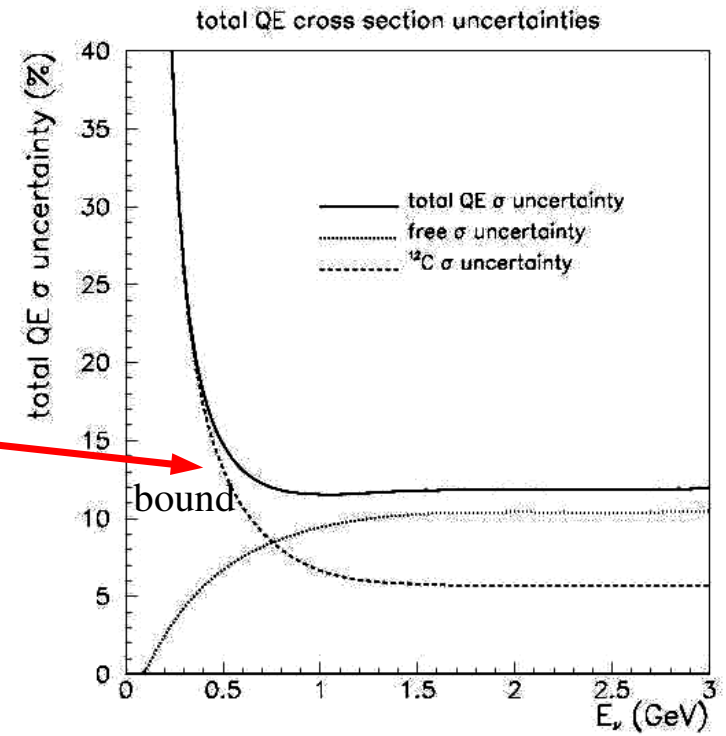
Systematic	Parameter variation	Effect on $\sigma_{CC1\pi}$ ratio

PRELIMINARY

CCQE σ Errors

CCQE cross section uncertainties

- Fermi Gas Model uncertainties
  - 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



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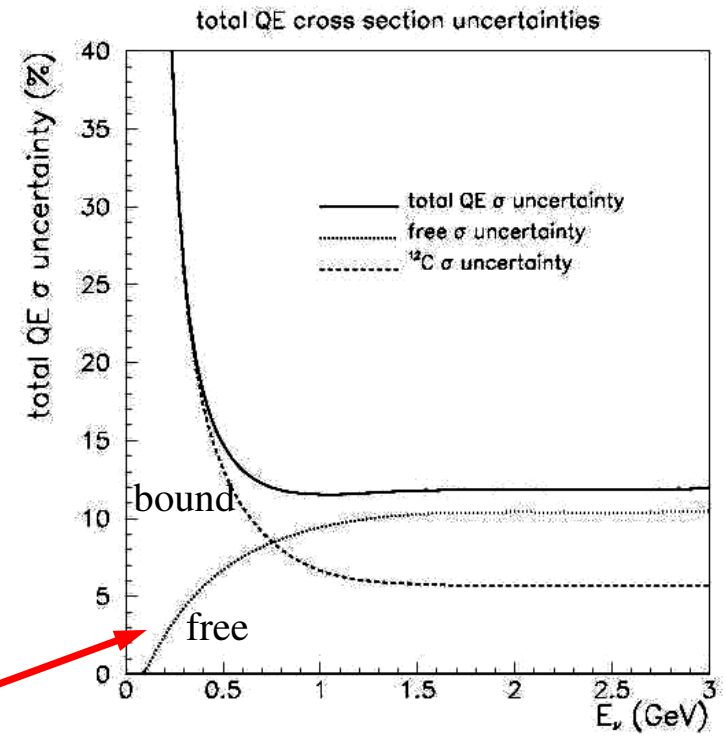
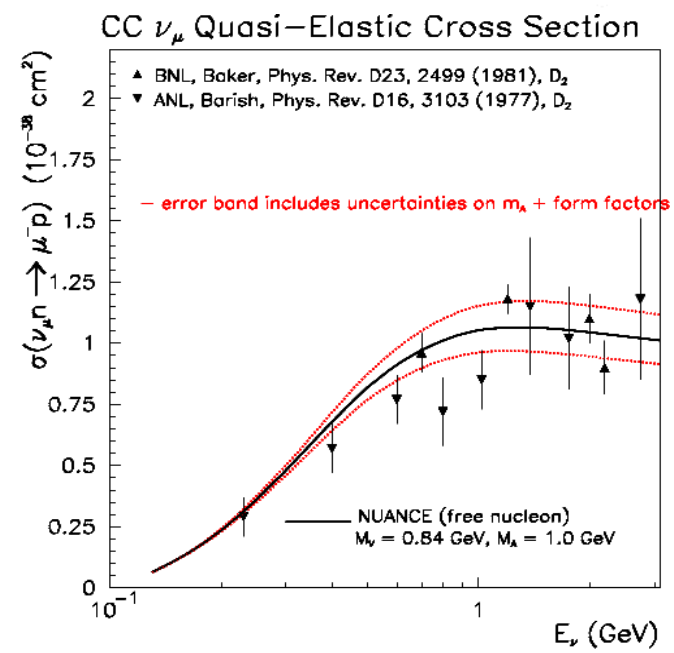
- 10% uncertainty in m_A^{QE} to cover range in m_A^{QE} from light vs. heavy target ν data fits, as well as K2K choice

- 7%,5% uncertainty on cross section ratio





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Systematic	Parameter variation	Effect on $\sigma_{CC1\pi}$ ratio
Fermi Gas Model (E_B,p_F)	100%,14%	7%
M_A^{QE}	10%	5%

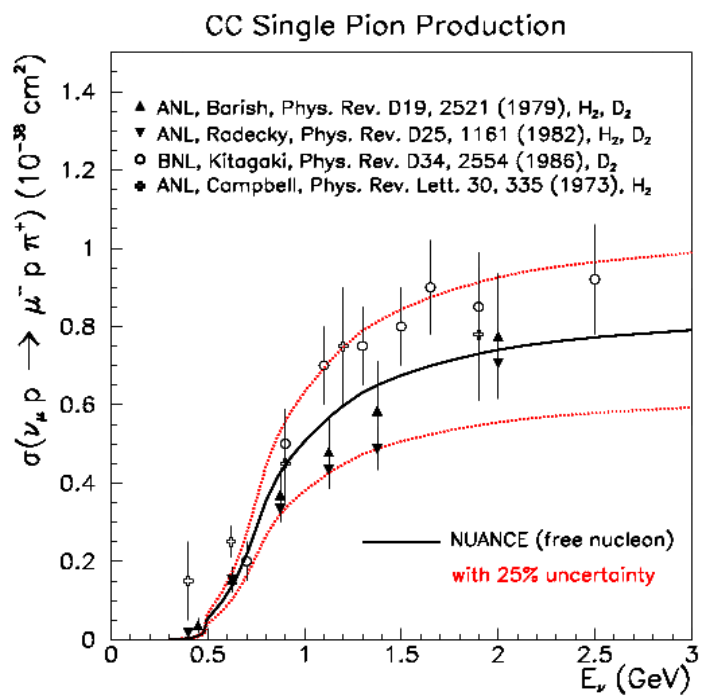
PRELIMINARY

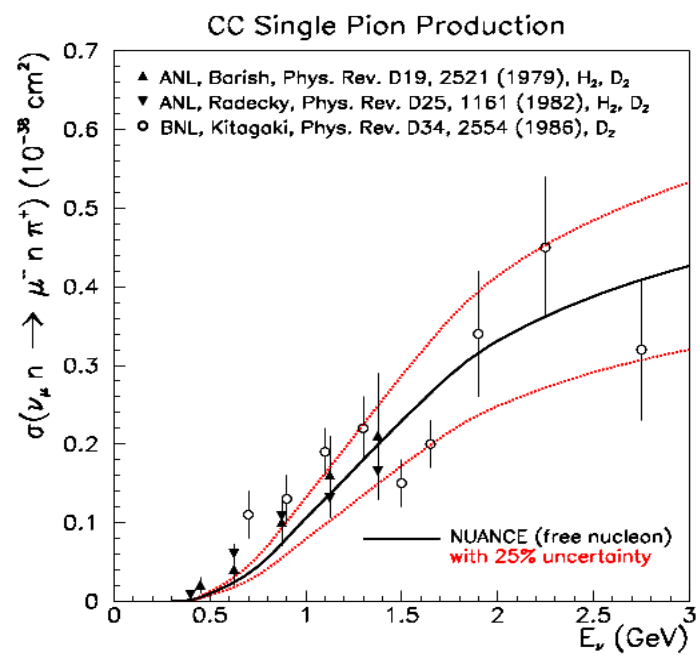
CC1π+ σ Errors

CC1π+ 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





- Contributes to error on the $CC1\pi^+$ BG

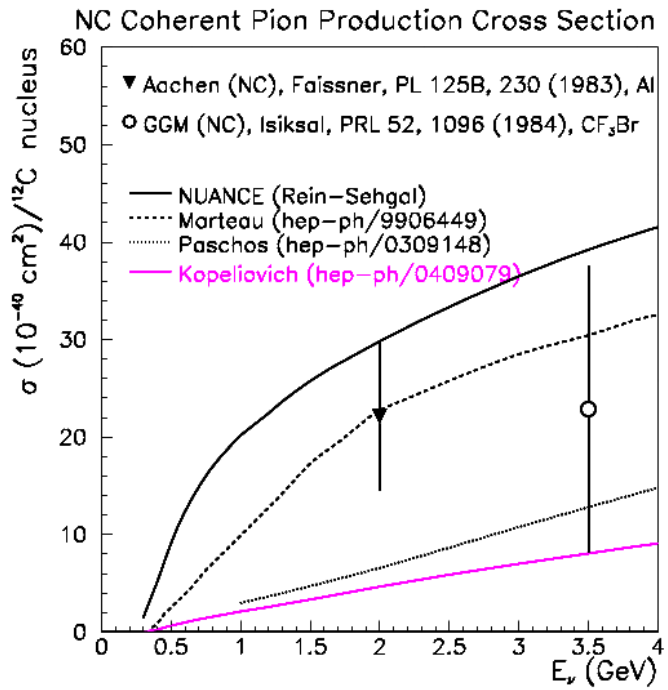
- 2% uncertainty on cross section ratio

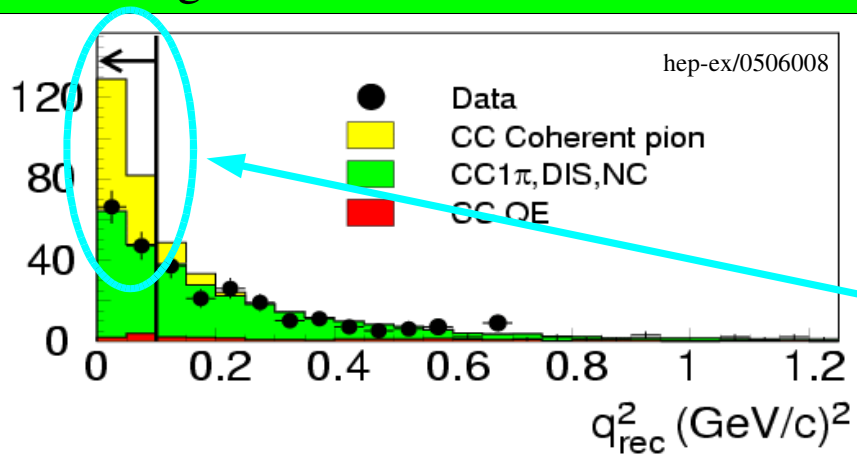
CC1π+ σ Errors

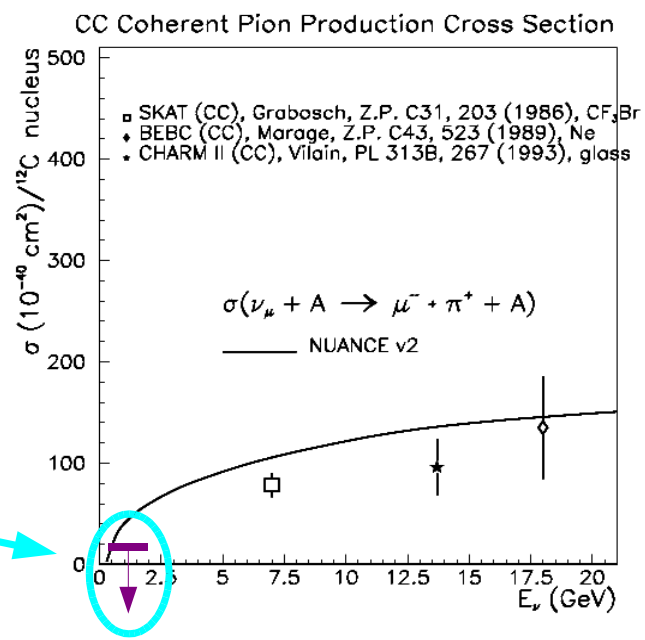
CC1π+ cross section uncertainties:

Coherent Production

- 100% uncertainty on σ
- lower energy NC coherent data exist
  - wide range of theoretical predictions for size of σ
- no CC data below 7 GeV
  - K2K sets limit (1.3 GeV)
  - Deviation from expectation in low Q^2 region of SciBar data







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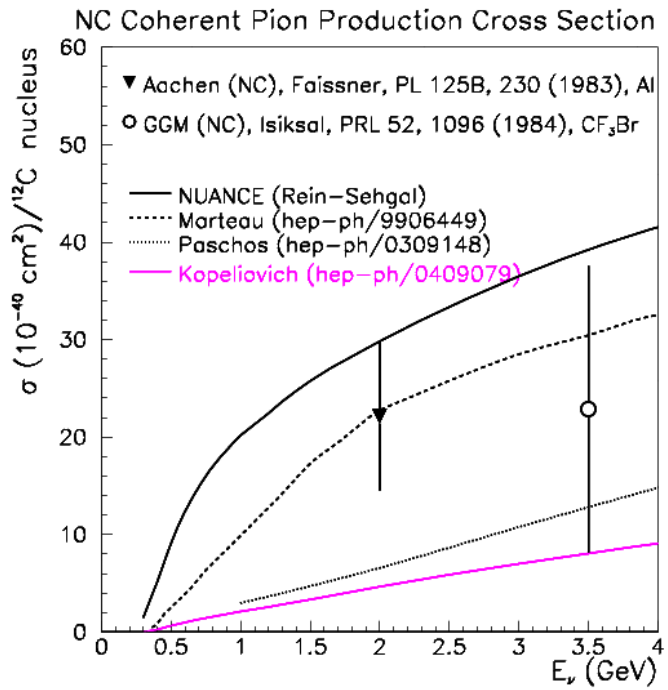

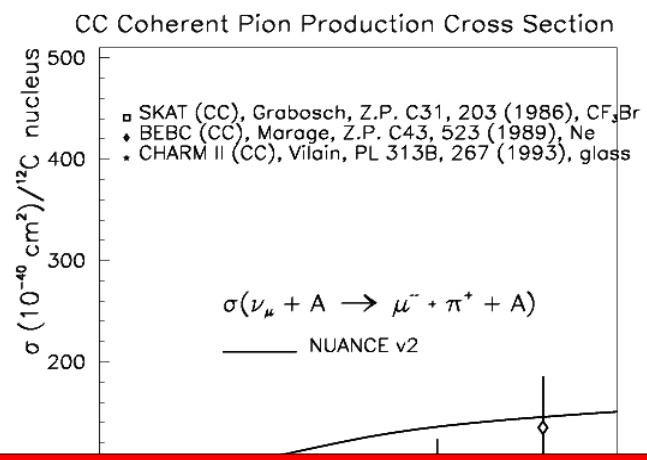

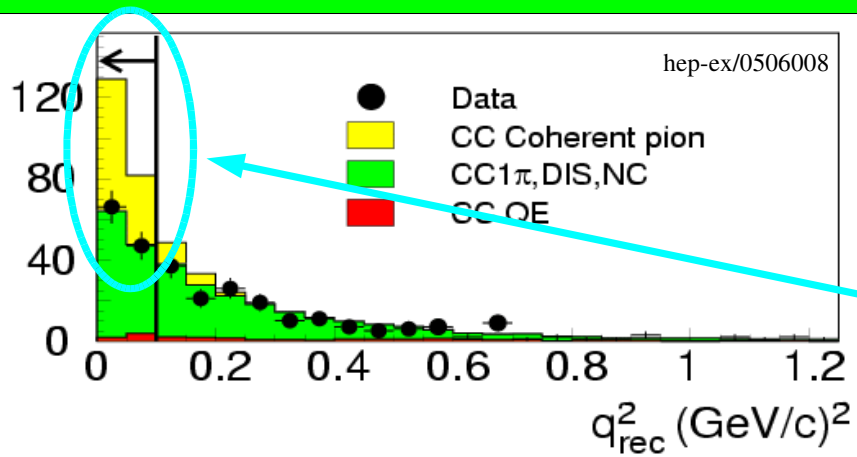

- 4% uncertainty on cross section ratio

Sources of Uncertainty

ν cross section uncertainties:

- assessed inside the nucleus (in the NUANCE Monte Carlo)
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Systematic	Parameter variation	Effect on $\sigma_{CC1\pi}$ ratio
Fermi Gas Model (E_B,p_F)	100%,14%	7%
M_A^{QE}	10%	5%
coherent π production	100%	4%
$M_A^{1\pi}$	20%	2%

PRELIMINARY

CC1π+ σ Errors

Uncertainties on CC1π^+-like processes:

Multi-Pion Production

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

5% on σ ratio

Uncertainties from PDG

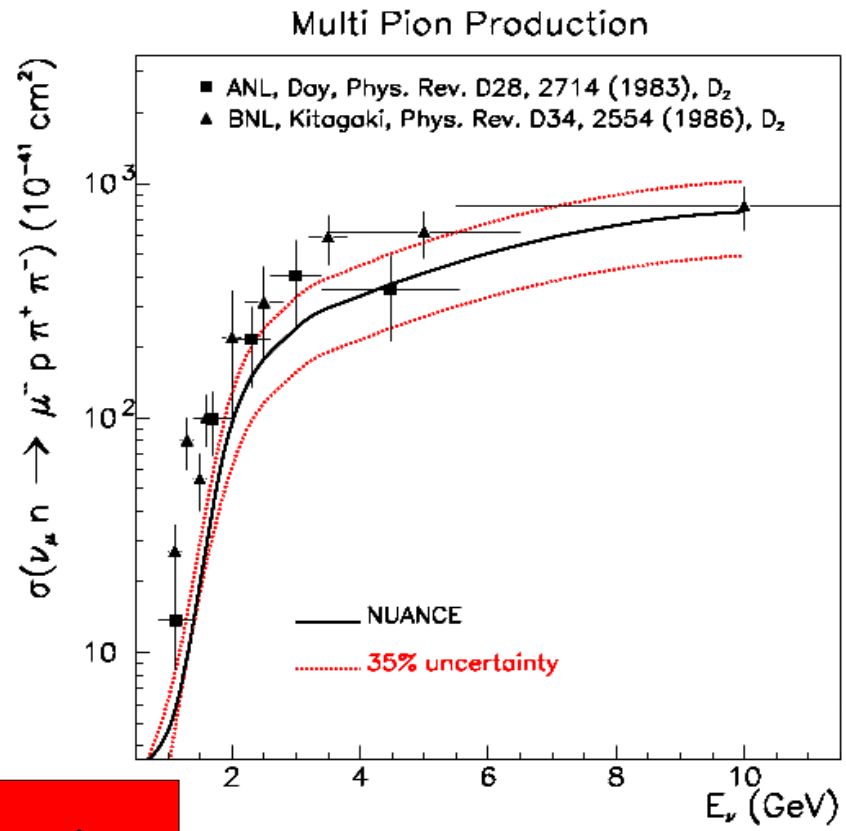
- Δ decay width
  - 4% uncertainty

3% on σ ratio

5% on σ ratio

Conservative Guess

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



CC1π+ σ Errors

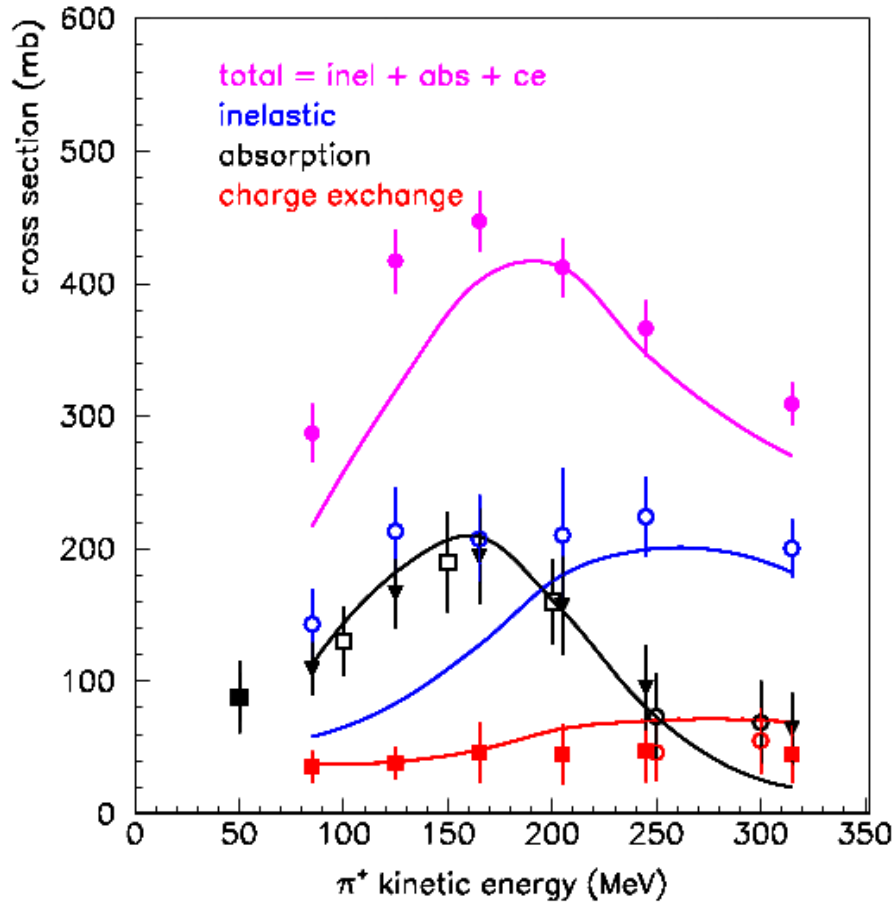
Final state interactions:

- NUANCE FSI model tuned to reproduce external $\pi-^{12}C$ scattering data

- Comparison between NUANCE and data

Uncertainties on NUANCE compared with external data

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



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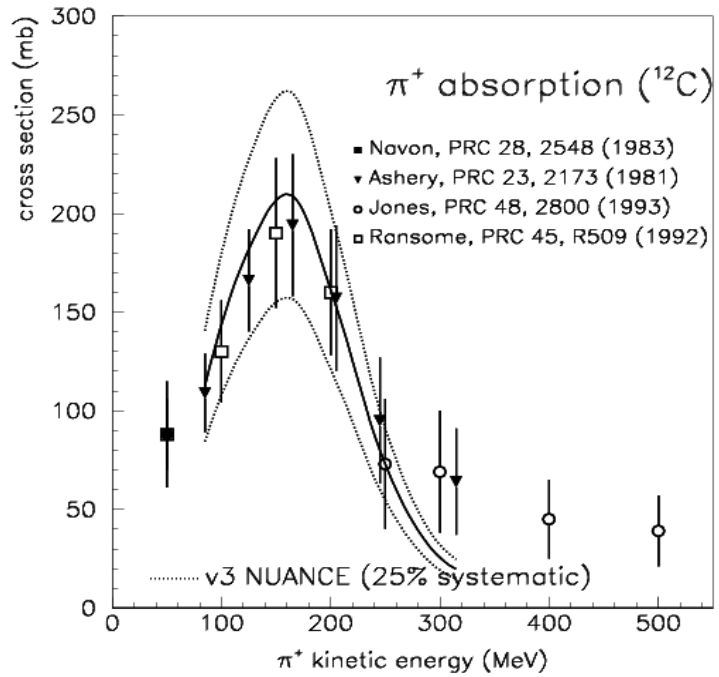
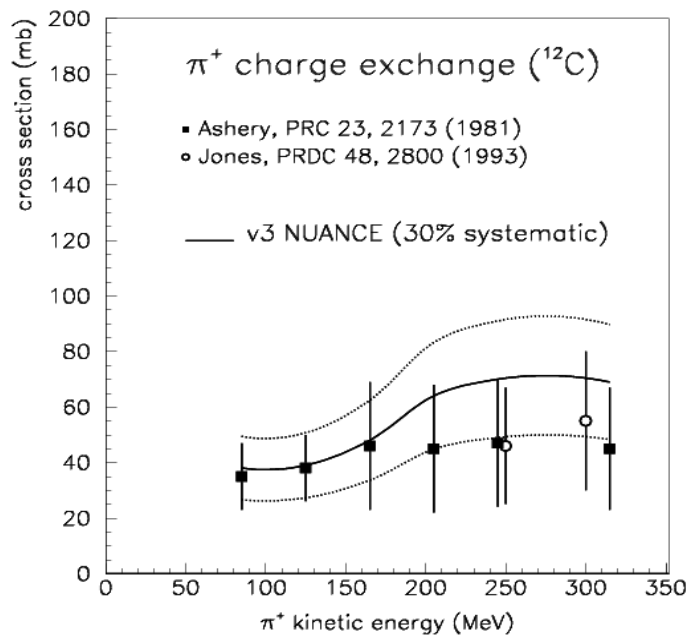
5% on σ ratio

3% on σ ratio





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M_A^{QE}	10%	5%
coherent π production	100%	4%
$M_A^{1\pi}$	20%	2%
$M_A^{n\pi}$	35%	5%
Δ re-interaction	50%	5%
π absorption	25%	4%
Δ width	4%	3%
π CE	30%	3%

- systematic errors due to ν cross sections (~15%),
- $\delta^{SYS}_{\nu\sigma}(E_\nu)$ ~15%, $\delta^{STAT}(E_\nu)$ ~ 5 to 6%

PRELIMINARY

Sources of Uncertainty

Photon propagation in detector oil (optical model) uncertainties:

- 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
  - in reality they are *anti-correlated* (only dominant uncertainties shown)

Systematic	Parameter variation	Effect on $\sigma_{CC1\pi}$ ratio
attenuation length	33%	17%
scattering lengths	16%	8%

- $\delta^{SYS}_{opticalModel}(E_\nu) \sim 20\%$, $\delta^{STAT}(E_\nu) \sim 5$ to 6%

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ν Flux Uncertainties

- do not enter here because we normalize to ``golden mode'' in our own data

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Preliminary → Final Result

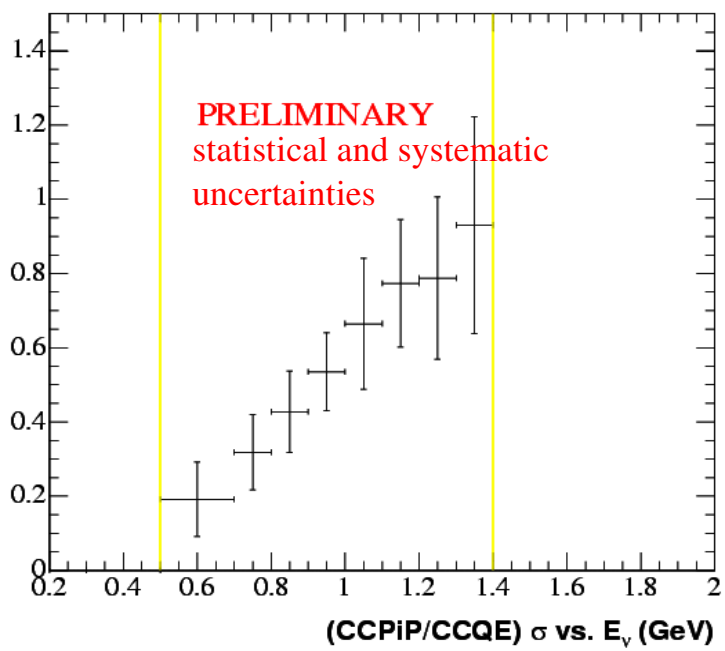
- Estimate/measure MC parameter correlations
- Reduce detector optical model uncertainties with continued analysis of calib data
- Reduce ν σ errors with analysis of e^- data (JUPITER @ JLab)

PRELIMINARY

$CC1\pi^+/CCQE\ \sigma$ Ratio on CH_2

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

$$R_{MEASURED} = \frac{N(CC1\pi)}{N(CCQE)} = \frac{\sigma(CC1\pi)}{\sigma(CCQE)}$$



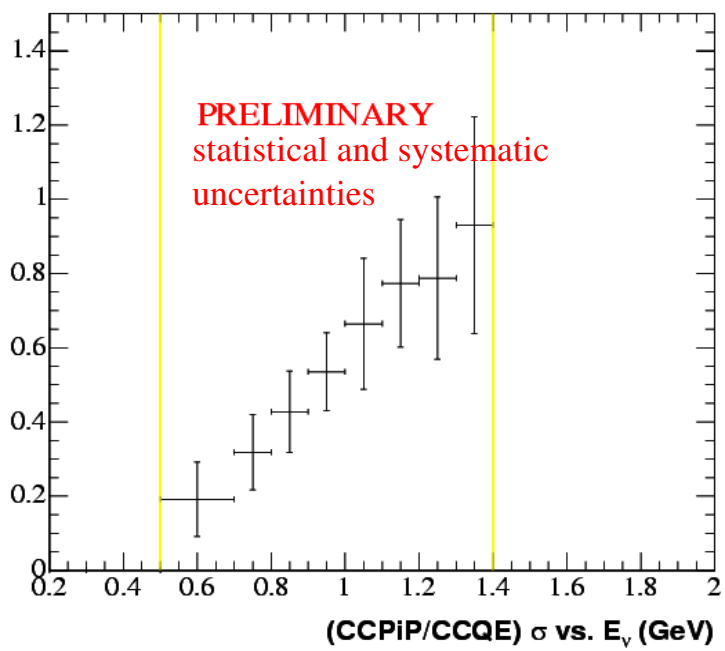
$CC1\pi^+$ σ on CH_2

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

$$R_{MEASURED} = \frac{N(CC1\pi)}{N(CCQE)} = \frac{\sigma(CC1\pi)}{\sigma(CCQE)}$$

- use ``golden mode'' to convert to σ(CC1π+):

$$\sigma(CC1\pi) = R_{MEASURED} \times \sigma_{NUANCE}(CCQE)$$



Multiply by
NUANCE MC
σ CCQE
m_A=1.03

$CC1\pi^+$ σ on CH_2

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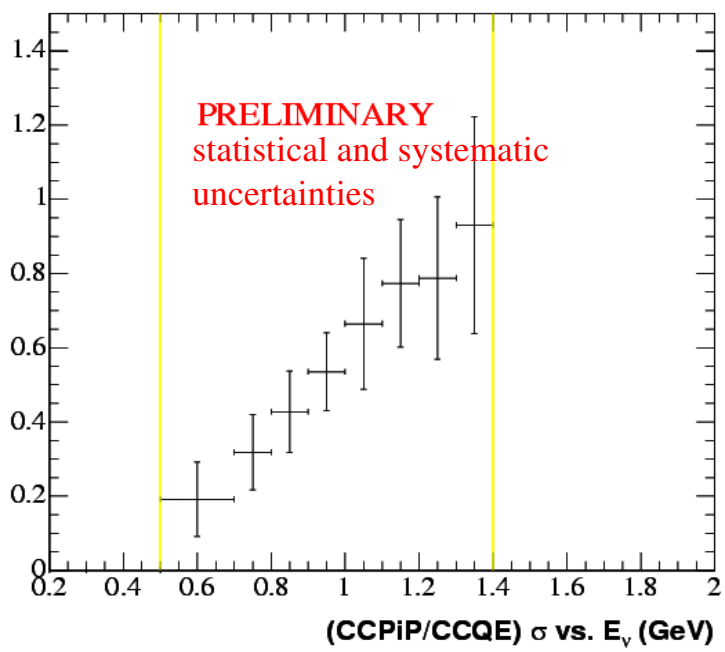
- use ``golden mode'' to convert to $\sigma(CC1\pi^+)$:

$$\sigma(CC1\pi) = R_{MEASURED} \times \sigma_{NUANCE}(CCQE)$$



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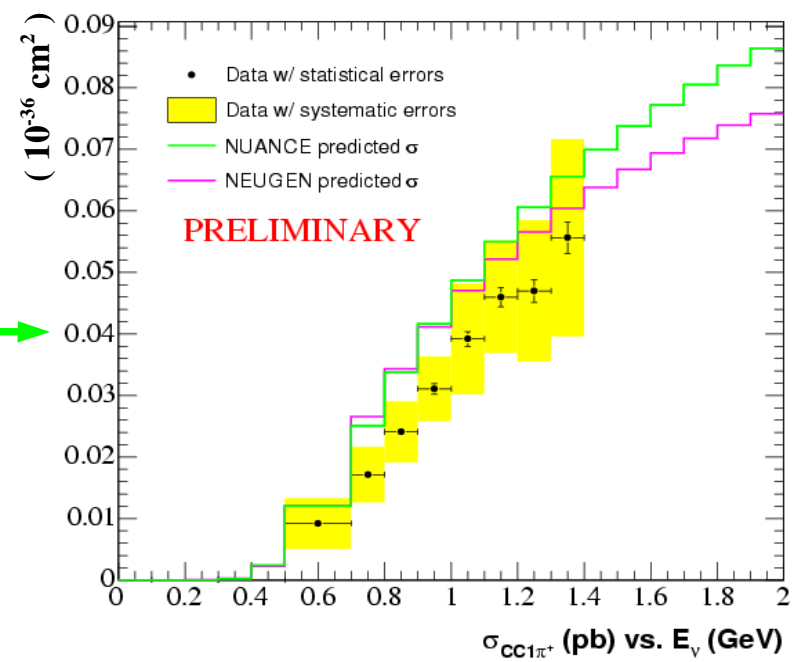
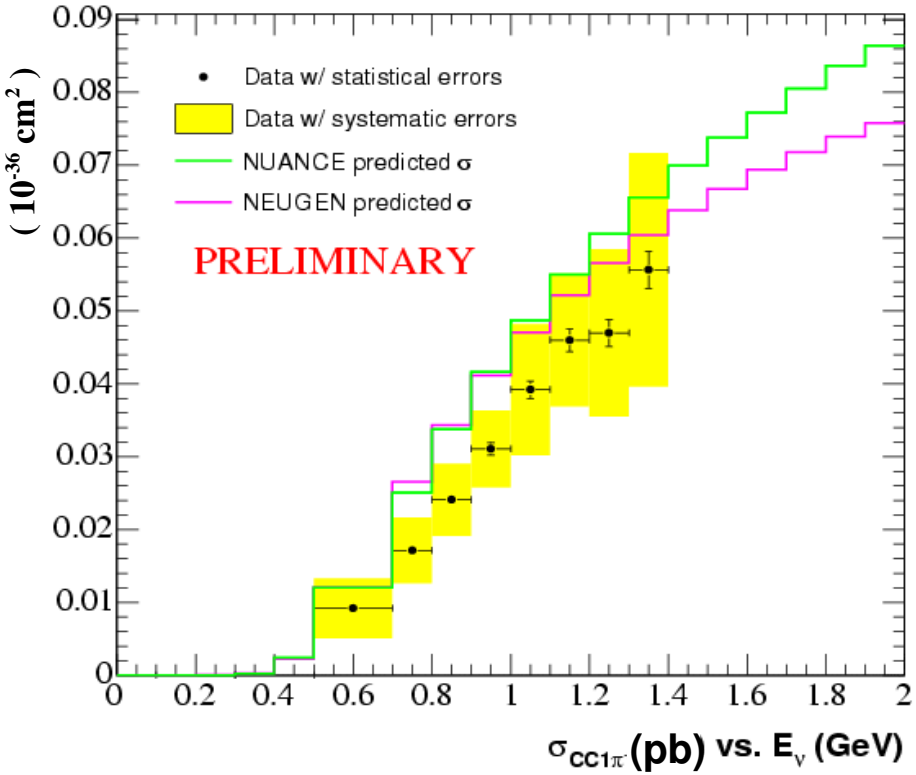
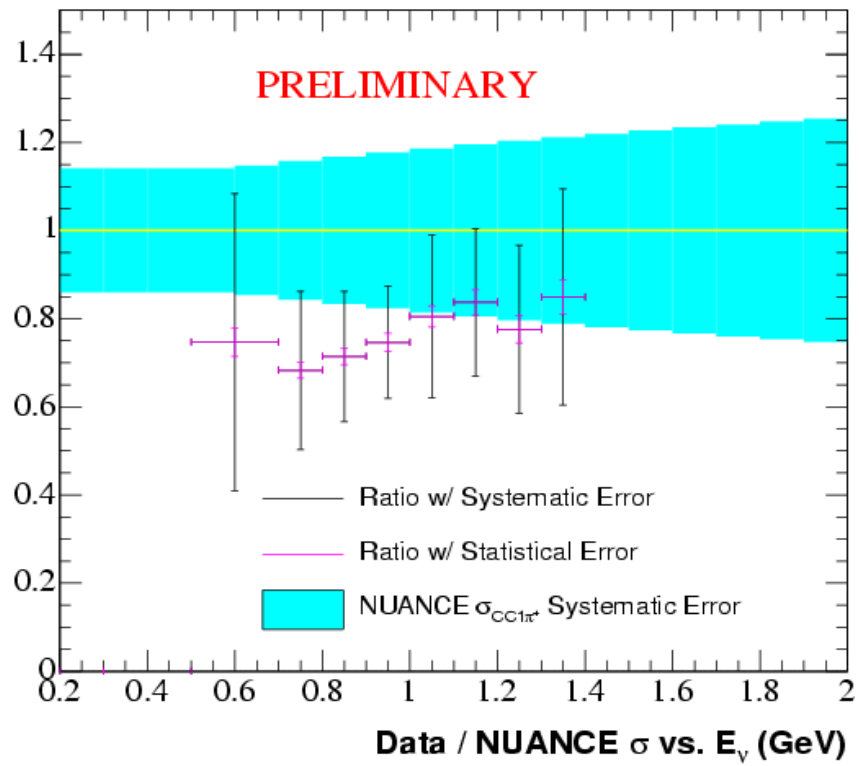


$CC1\pi^+$ σ on CH_2

- Compare with NUANCE MC prediction
- Inclusive $\sigma(CC1\pi^+)$: $\nu_\mu\, p \rightarrow \mu^-\, p\, \pi^+$ and $\nu_\mu\, n \rightarrow \mu^-\, n\, \pi^+$ and $\nu_\mu\, A \rightarrow \mu^-\, A\, \pi^+$
- Ratio to predicted $\sigma_{NUANCE}(CC1\pi^+)$ is ~75%, but ~within $\delta\sigma_{NUANCE}(CC1\pi^+)$
- NUANCE error band comes from $M_A^{1\pi}$ and coherent production

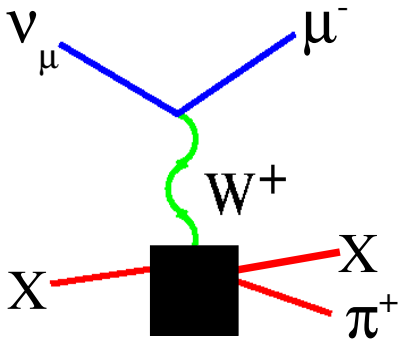




effective $CC1\pi^+$ σ on CH_2

- MiniBooNE can also measure ``effective'' $\sigma(CC1\pi^+)$
  - Final state is "$CC1\pi^+$-like" $\equiv$ 1 μ^- and 1 π^+ (before particles decay)
  - define numerator of MC efficiency correction as anything $CC1\pi^+$-like, not just $\nu_\mu\ p \rightarrow \mu^-\ p\ \pi^+$, $\nu_\mu\ n \rightarrow \mu^-\ n\ \pi^+$, and $\nu_\mu\ A \rightarrow \mu^-\ A\ \pi^+$

- MC efficiency correction includes NUANCE MC FSI model since we use MC to correct back to generated CC1π+ events
- Test of NUANCE FSI model



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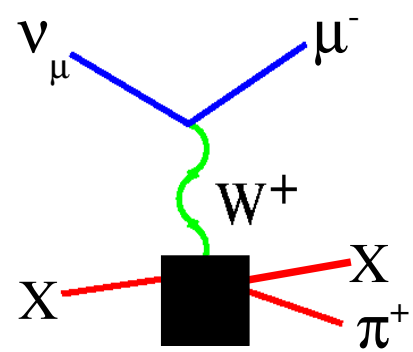

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- Test of NUANCE FSI model

Final State Interactions (with uncertainty):

- σ pion absorption (δ_{NUANCE} = 25%)
- σ charge exchange (δ_{NUANCE} = 30%)
- $P(\Delta N \rightarrow NN)$ (Δ-reinteraction) (δ_{NUANCE} = 50%)

- from MC: N ($CC1\pi^+$-like) / N (true $CC1\pi^+$) = 0.8
  - 24% true $CC1\pi^+$ are not $CC1\pi^+$-like (π^+ absorption)
  - 7% true non-$CC1\pi^+$ are $CC1\pi^+$-like

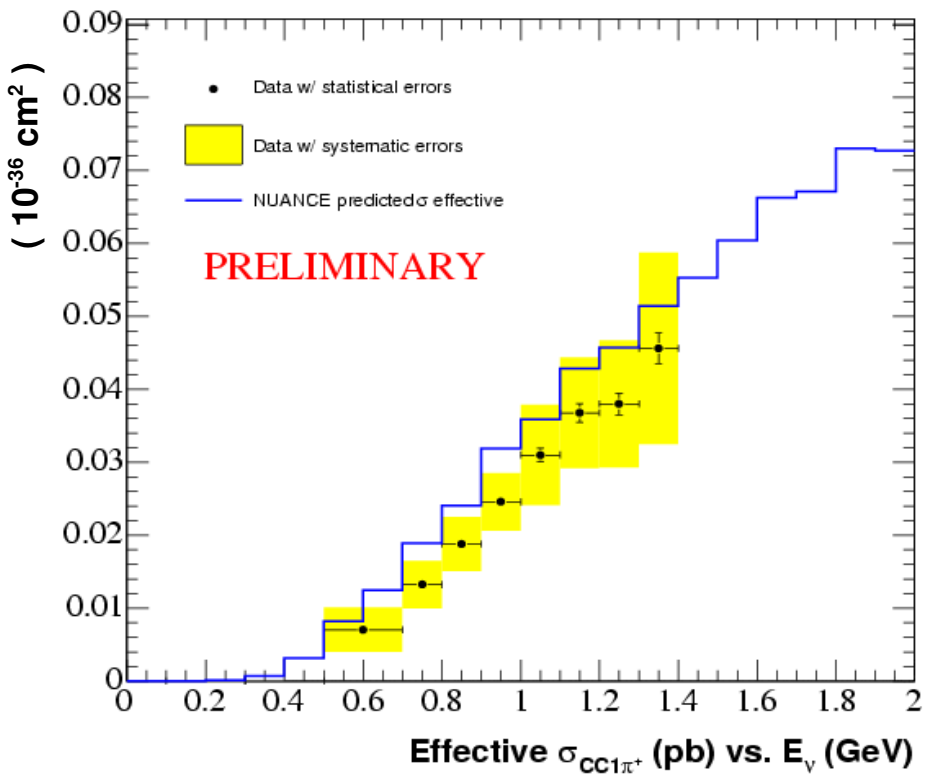
effective $CC1\pi^+$ σ on CH_2

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

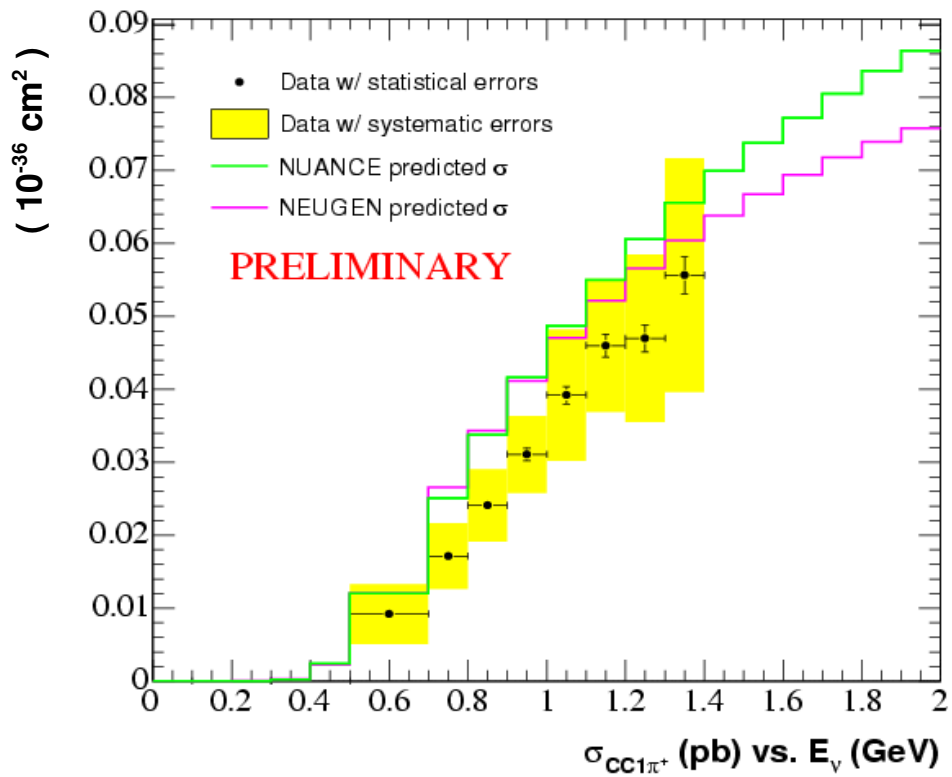
$$R^{EFFECTIVE}_{MEASURED} = \frac{N(CC1\pi-like)}{N(CCQE)} = \frac{\sigma(CC1\pi-like)}{\sigma(CCQE)}$$

- use ``golden mode'' to convert to $\sigma(CC1\pi^+\text{-like})$ and compare with $\sigma(CC1\pi^+)$

$\sigma_{EFFECTIVE}$



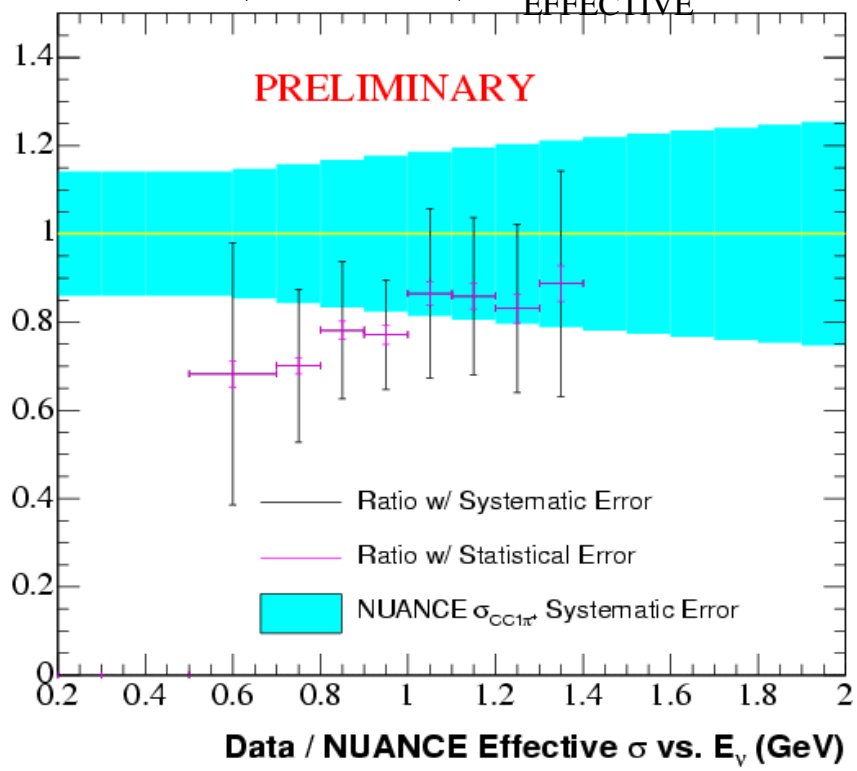
$\sigma_{CC1\pi+}$



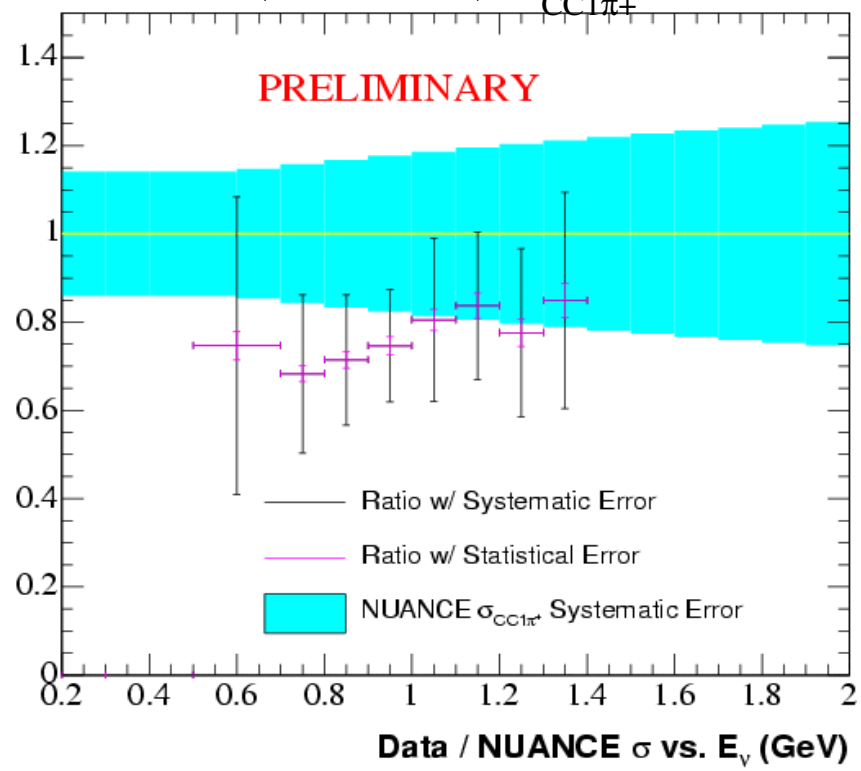
effective $CC1\pi^+$ σ on CH_2

- Cross check NUANCE FSI by comparing (Data/MC) $\sigma_{EFFECTIVE}$ to (Data/MC) $\sigma_{CC1\pi+}$
- Ratio to predicted σ_{NUANCE}($CC1\pi^+$-like) is similar to σ($CC1\pi^+$) result

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



(Data/MC) $\sigma_{CC1\pi+}$



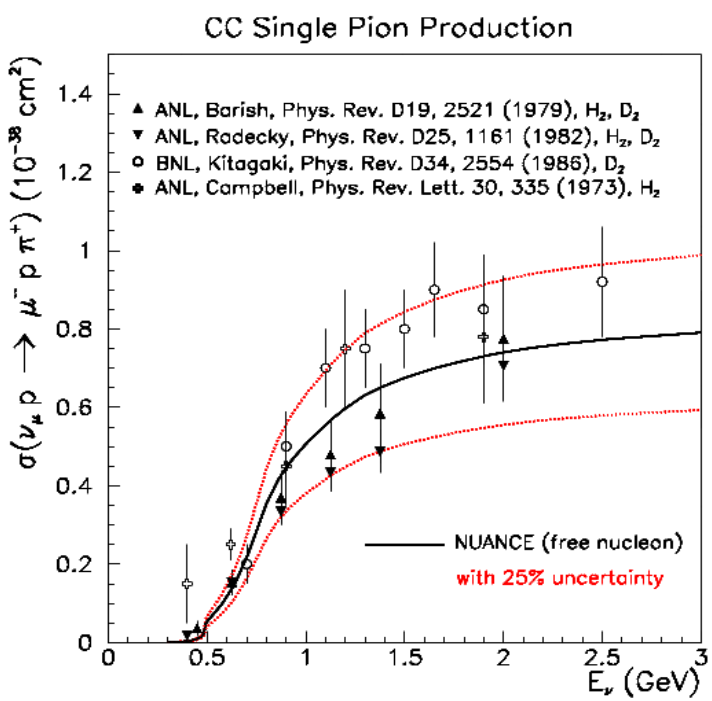
- Implies that low $CC1\pi^+$ rate is not due to FSI model deficiency,

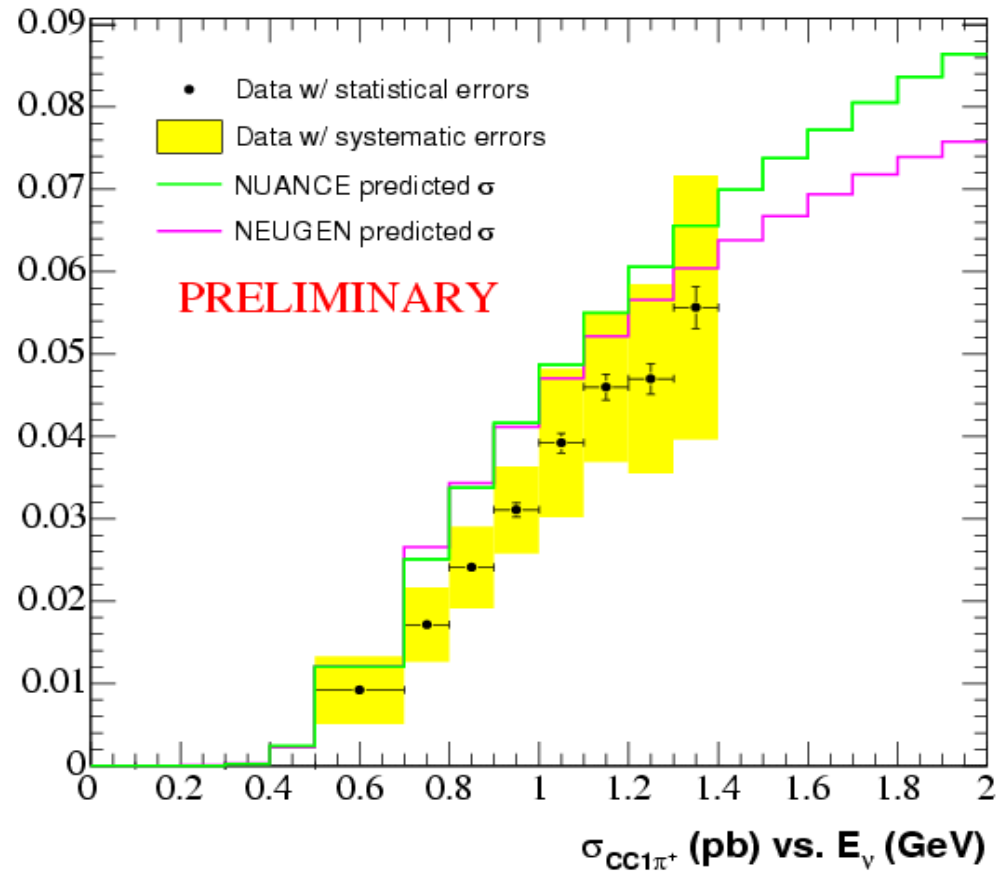
rather, the $\sigma_{CC1\pi+}$ is *truly lower than NUANCE prediction*

Interpretation

What does this result mean?

- ANL and BNL results disagree in normalization
- NUANCE splits the difference
- MiniBooNE result more consistent with ANL

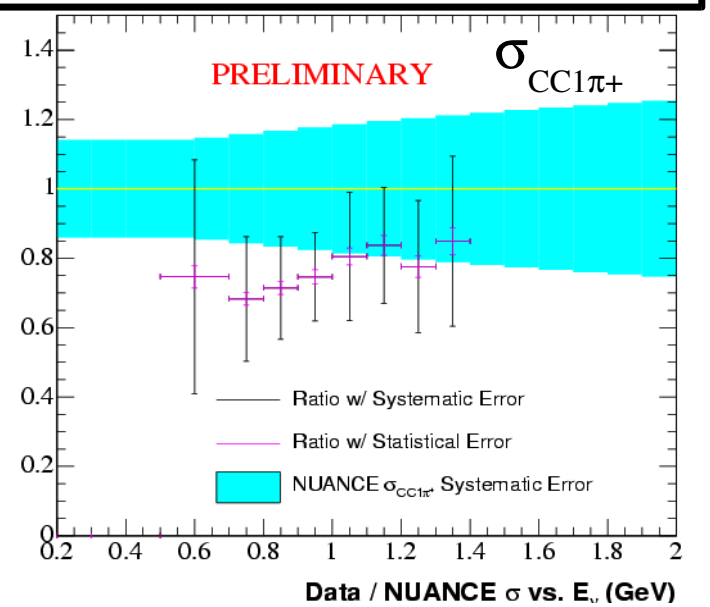


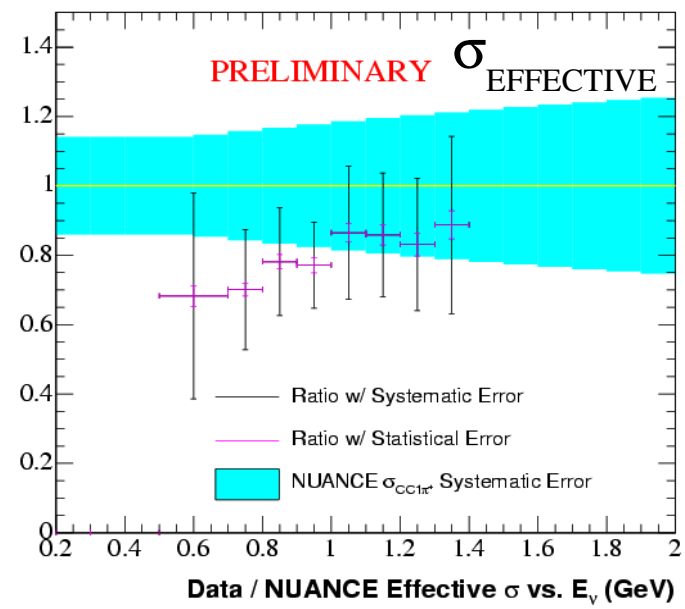


Implications for Oscillations

What does this result mean?

- ν_e appearance oscillation search
  - $CC1\pi^+$ reduction constrains resonant backgrounds
- ν_μ disappearance oscillation search
  - effective $CC1\pi^+$ constrains non-QE contamination
    - Improves energy resolution
    - Important for Super-K and K2K
- Agreement between data/MC in true $CC1\pi^+$ and effective cross section measurements demonstrates NUANCE modeling of FSI is reasonable
  - Good nuclear models important for ν physics phase transition





How do we use this result?

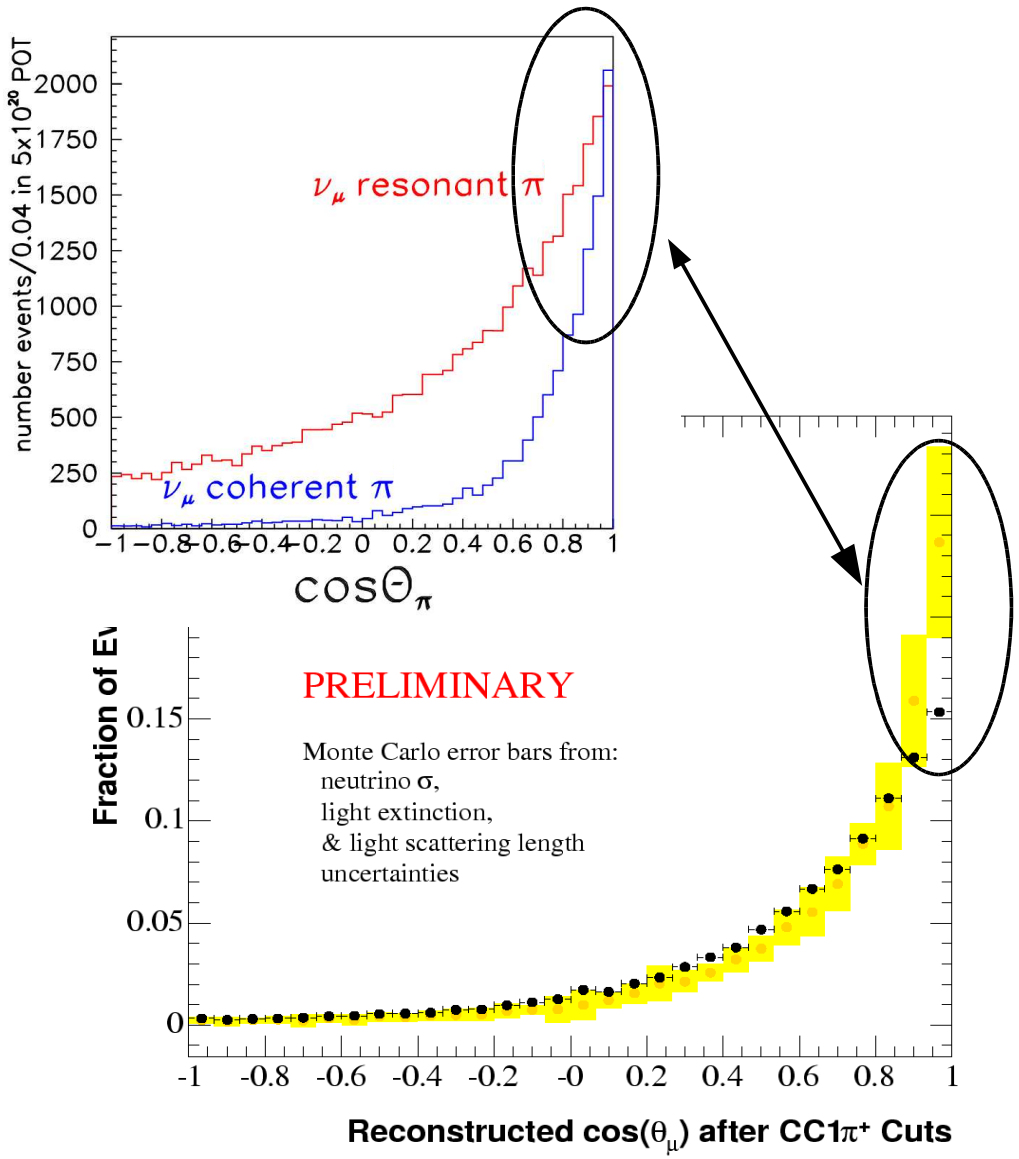
Future Directions

At MiniBooNE

- Extract resonant and coherent fractions
- Understand source of low Q^2 deficit
- Tune NUANCE to match MiniBooNE measurement

SciBooNE

- New collaboration formed to bring SciBar detector from K2K to FNAL
- Fine grained detector
- Excellent final state reconstruction
  - track PID (dE/dx)
  - multiple track
- Improved event kinematic reconstruction for this and many other processes



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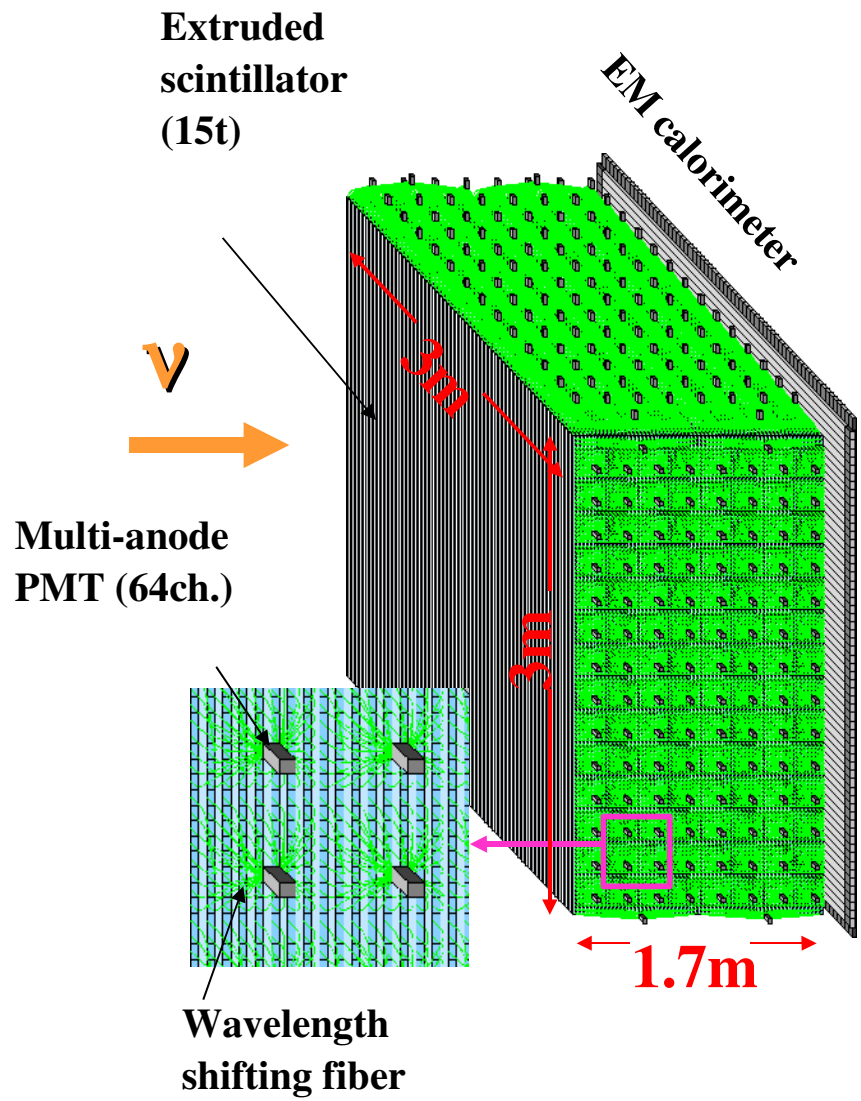

http://home.fnal.gov/~wascko/scibar.pdf

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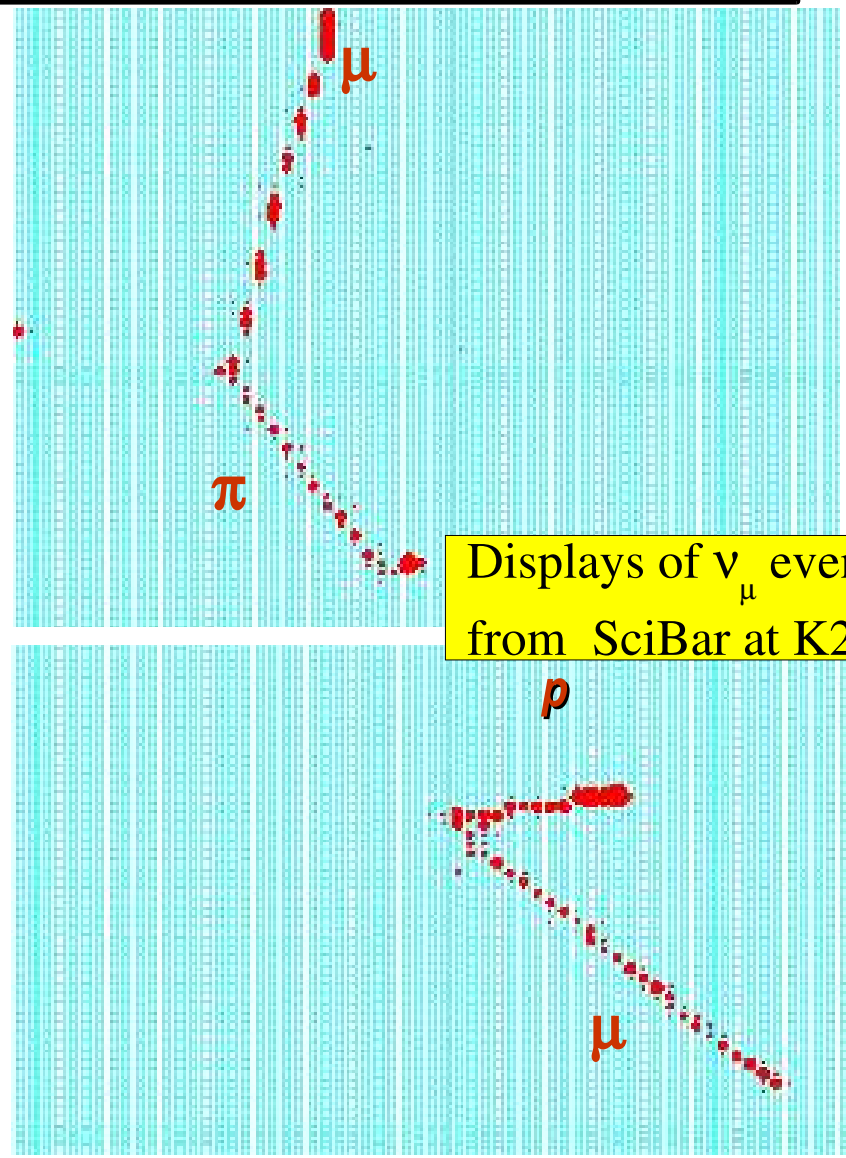

Displays of ν_μ events from SciBar at K2K

http://home.fnal.gov/~wascko/scibar.pdf

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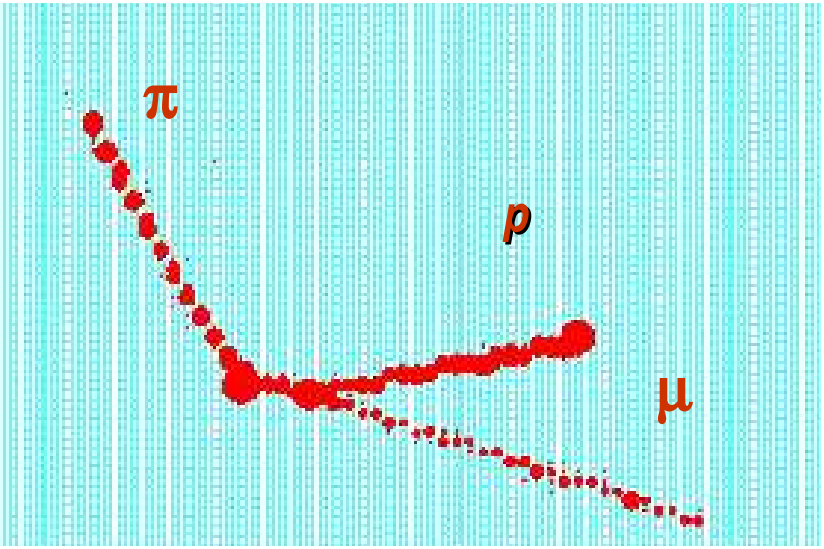
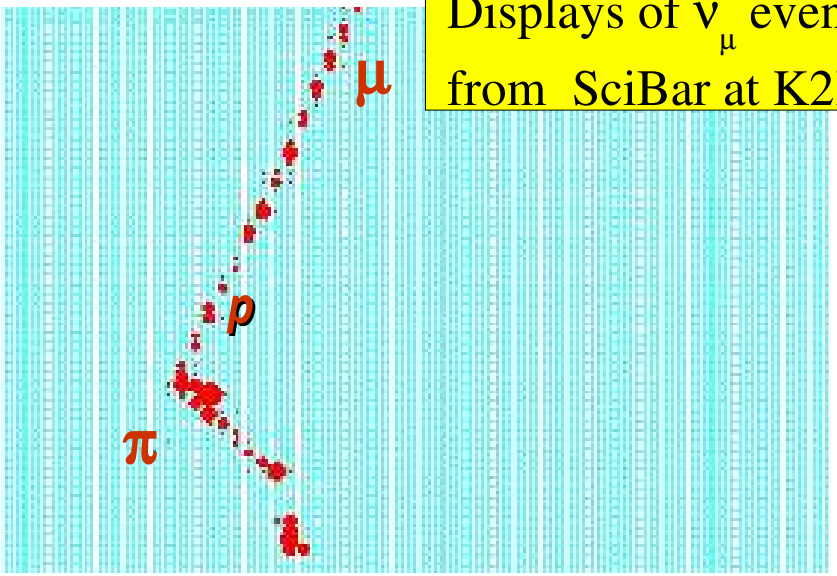




Displays of ν_μ events from SciBar at K2K

http://home.fnal.gov/~wascko/scibar.pdf

Conclusion

First measurement of CC1π^+ cross section on a nuclear target at these energies

STAY TUNED!

MiniBooNE Outlook:

- Late '05:
  - CC1π^+ paper
  - NC π^0 σ measurement
  - HARP 8 GeV Be results
- After the end of 2005:
  - CCQE ν_e appearance result
  - CCQE ν_μ disappearance result

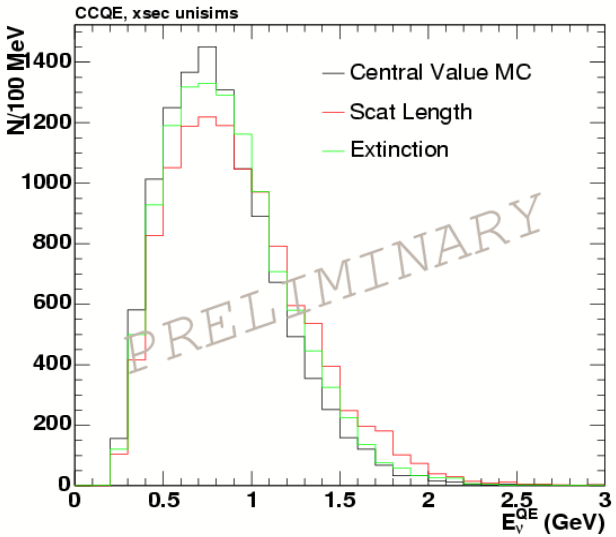
Many thanks to
my MiniBooNE collegaues and
Fermilab, esp. Accelerator Division!

Backup Slides

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: energy bins, j: systematic error parameters

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

Systematic Error Estimator

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

Total errors estimated by summing absolute values of fractional errors in each bin:

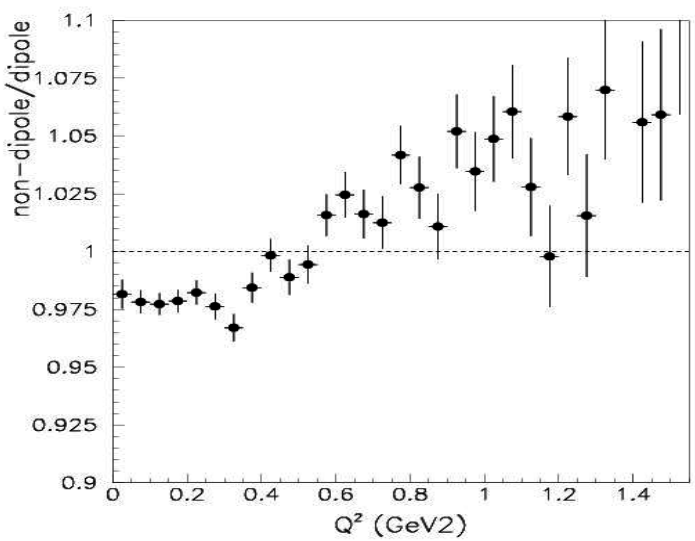
$$ErrEst = \frac{\sum \left| \delta N_i \right|}{\sum N_i}$$

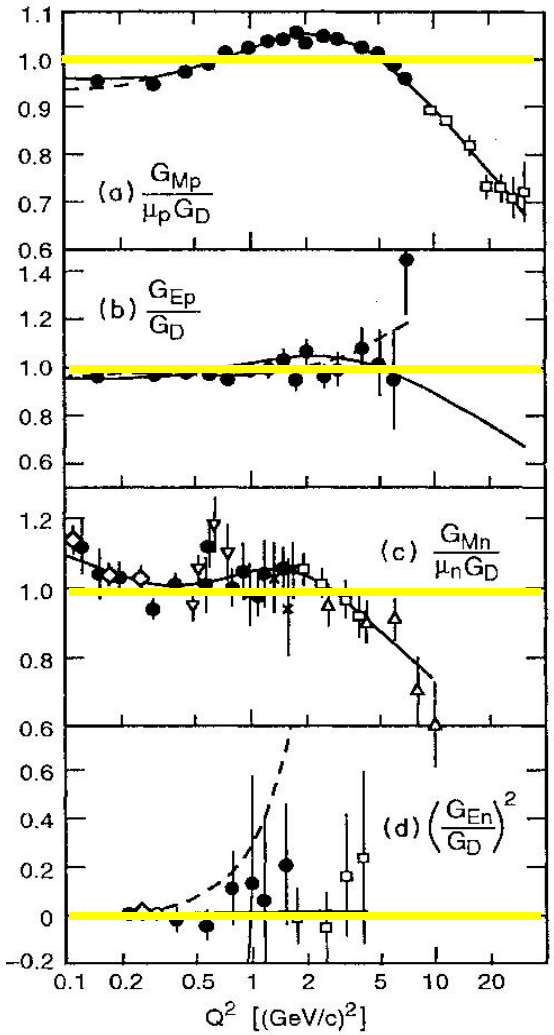
Non-Dipole Vector Form Factors (NUANCE v3)

- 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:

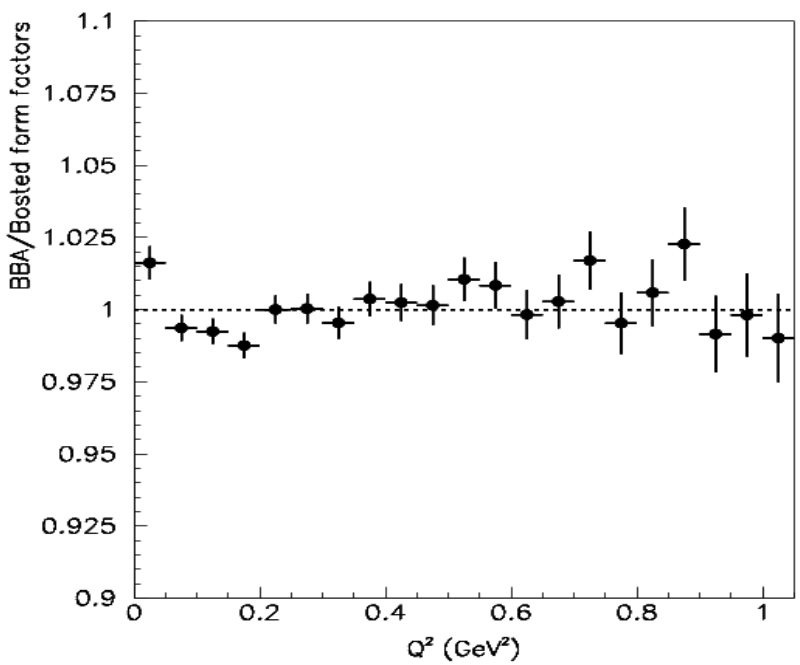
$$G_M^p(Q^2) = \mu_p/(1+3.104Q^2+1.428Q^4+0.1112Q^6-0.006981Q^8+0.0003705Q^{10}-0.7063E\text{-}5Q^{12})$$

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

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

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

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

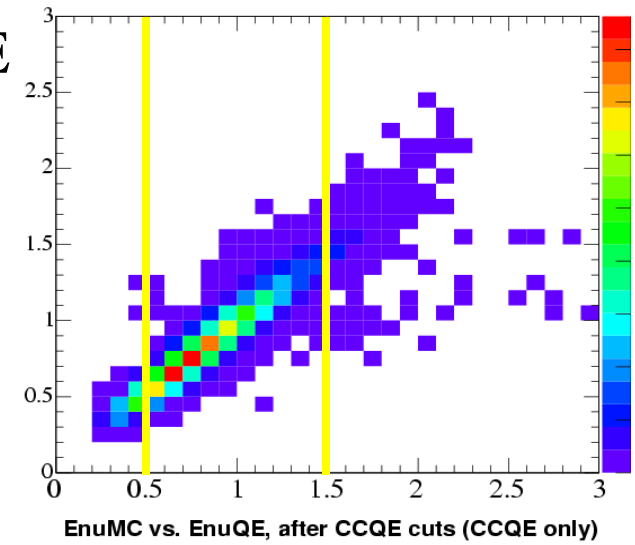


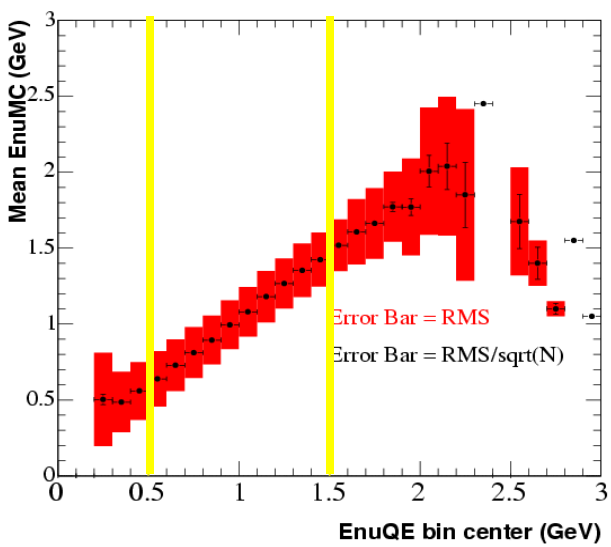
Bodek, Budd, Arrington BBA-2003 fit values (hep-ex/0308005)

Energy Scale Uncertainty

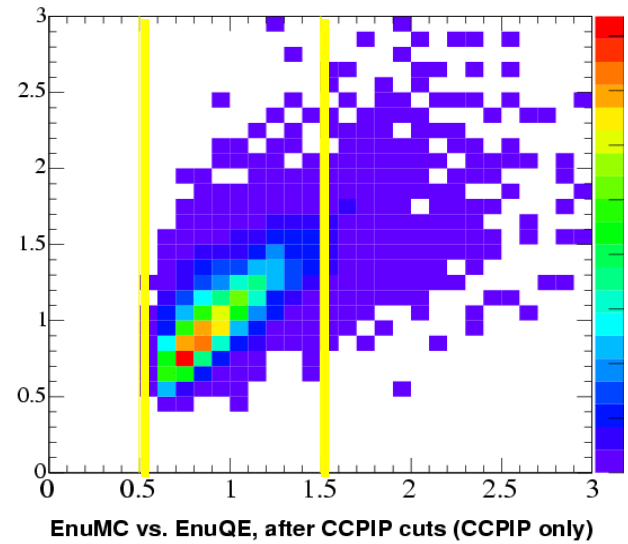
Energy scale uncertainty comes from different performance between $CC1\pi^+$ and CCQE neutrino energy reconstruction.

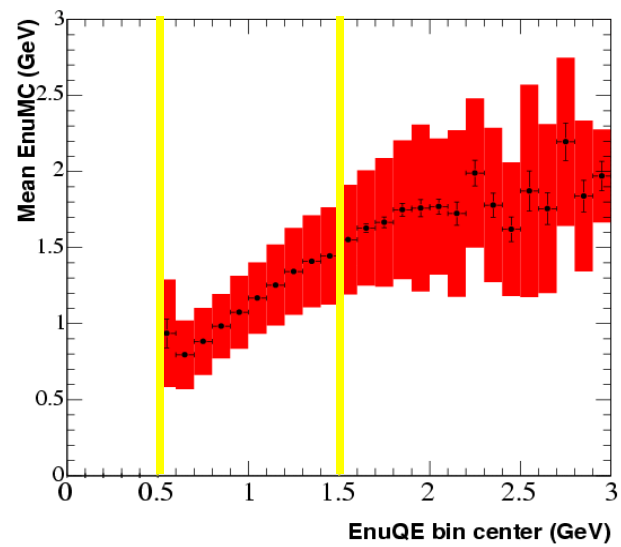
- CCQE





- $CC1\pi^+$





CCQE ``Golden Mode'' : MC Comparisons

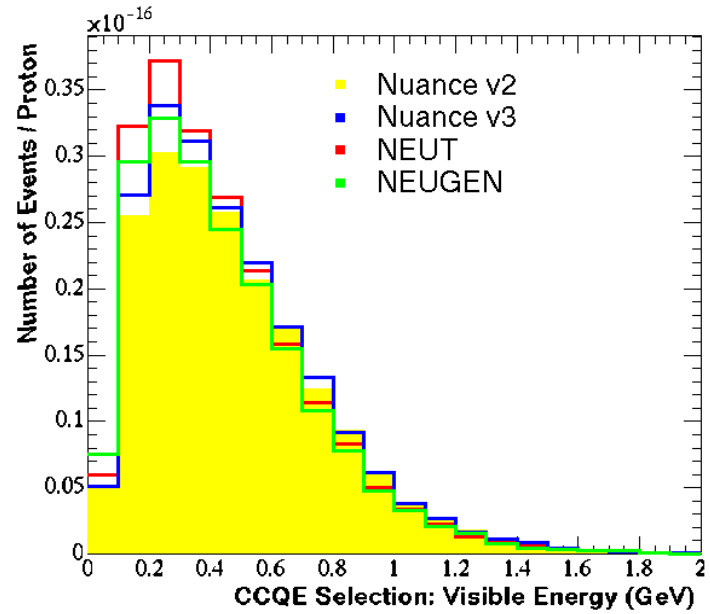
Same CCQE cuts, different Monte Carlos ...

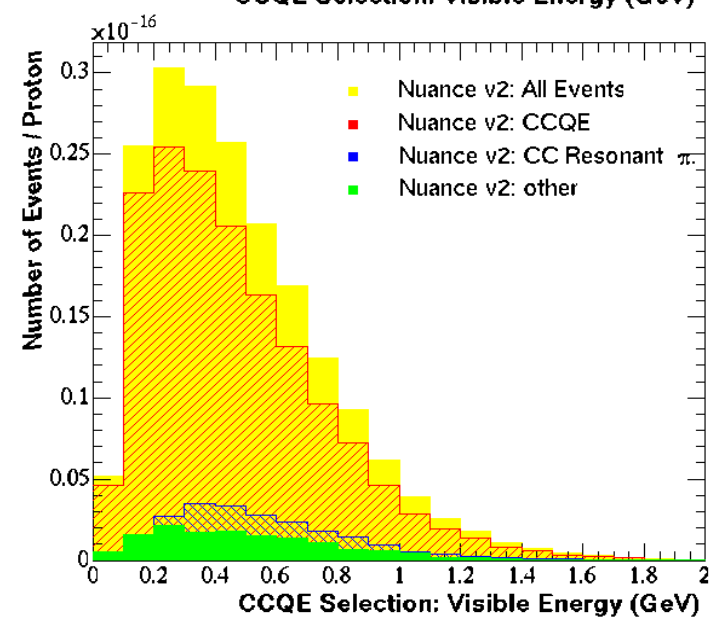
- Absolute normalization

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

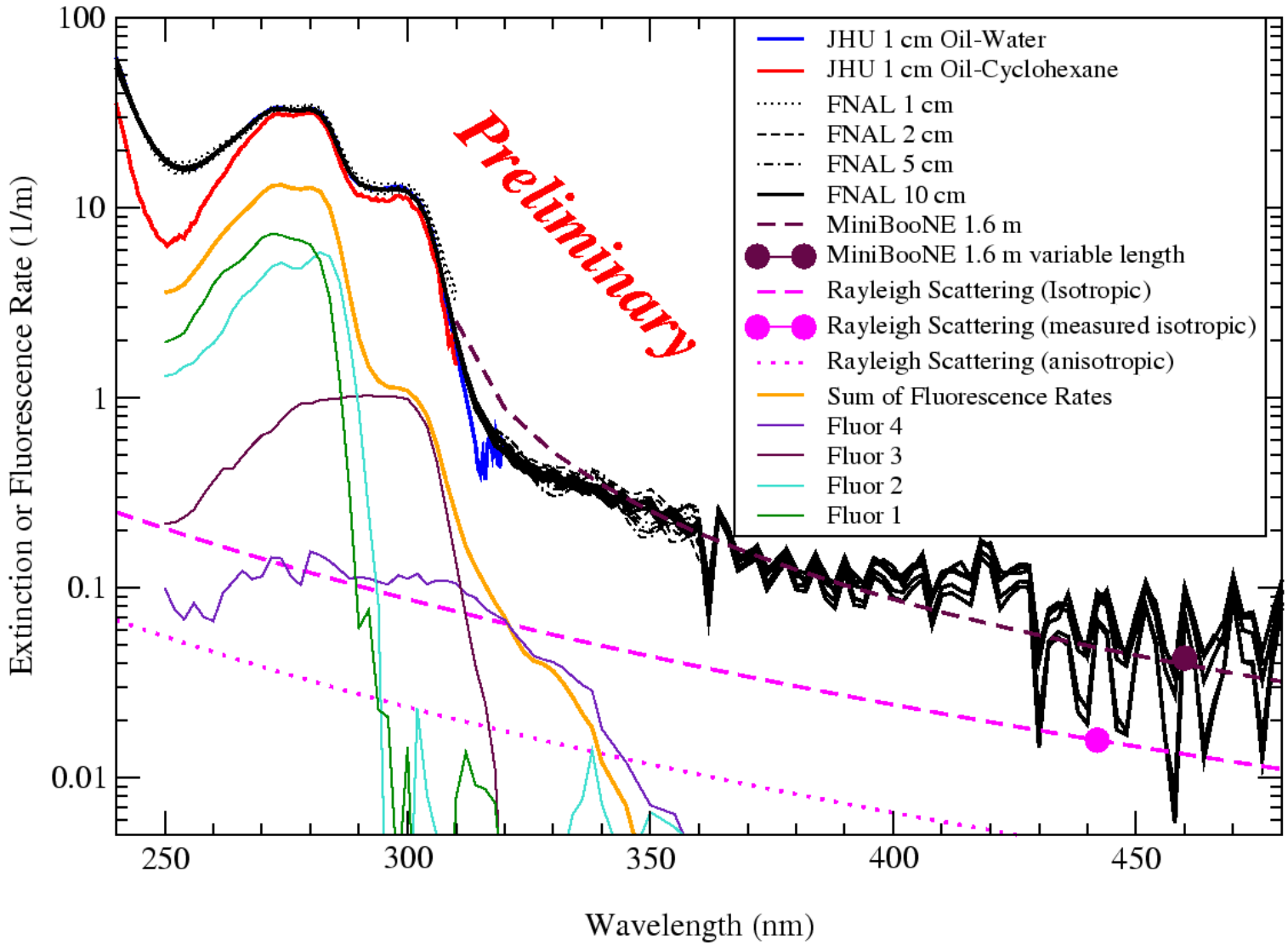
- After CCQE event selection: signal purity

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



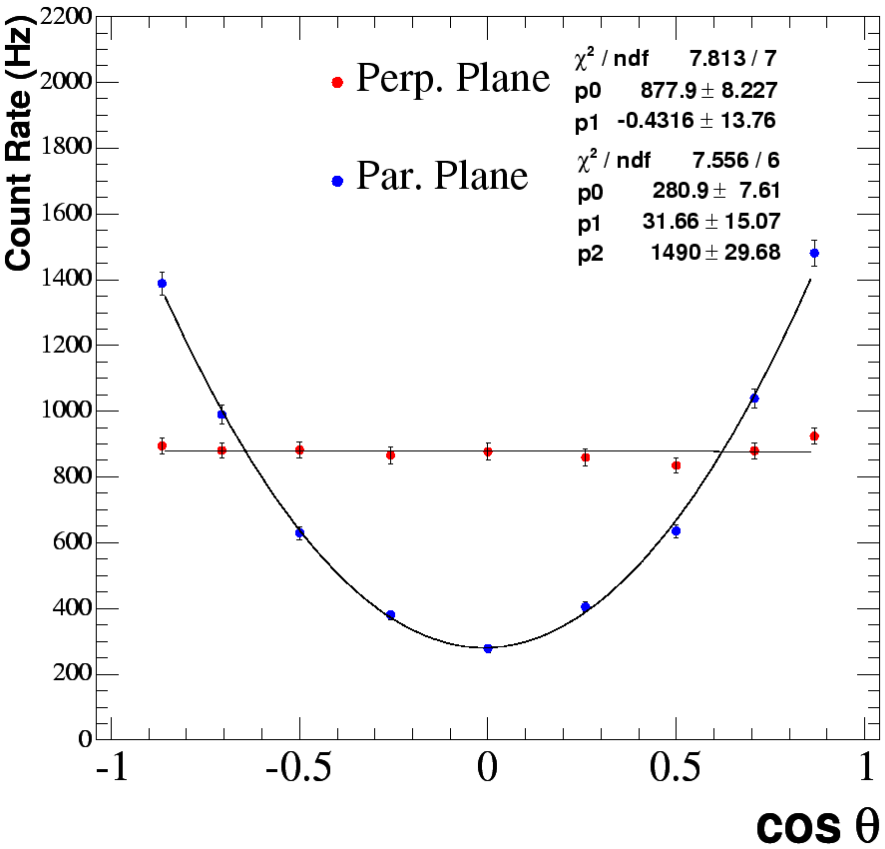


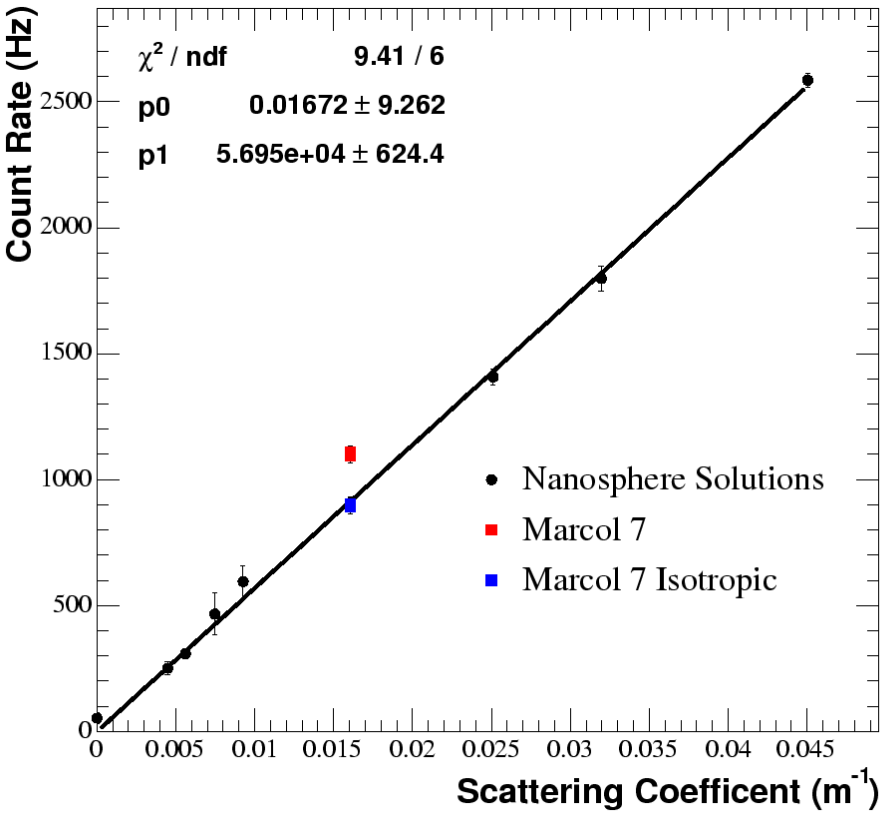
Extinction Rate for MiniBooNE Marcol 7 Mineral Oil



- Measurements of the transmission of light in samples of Marcol 7 oil drawn from the MiniBooNE detector; shown is the extinction rate (inverse of extinction length) over a range of wavelengths.

Optical Model: Rayleigh Scattering





- L: Angular distribution measured with goniometer at 442 nm. The distributions are consistent with Rayleigh scattering off isotropic density perturbations in the mineral oil with an additional contribution from non-isotropic fluctuations.

- R: Scattering in perp plane to the incident polarization. Black points correspond to different concentrations of nanospheres, Red point is the total observed scattering in Marcol 7, blue point is due to isotropic density fluctuations, isolated using the measured angular distributions. These points are at the scattering coefficient predicted by the Einstein-Smoluchowski equation.

Optical Model: Fluorescence

- Additional information: All data were taken in 1 cm fused-silica cells using the Hitachi fluorimeter in Lab 6. The sample of Marcol 7 used in the study was extracted from the tank. Corrections applied: 1. Inner filter corrections, obtained using transmission measurements with the HP spectrophotometer at Lab 6. 2. Removal of noise and scattering peaks: Rayleigh and Raman scattering contributions were parameterized as Gaussian distributions and subtracted. A flat contribution of noise was also subtracted. The data are compared to the results of the singular value decomposition (SVD) described in JHU Report no. 7 on independent data taken at Johns Hopkins using Marcol 7.

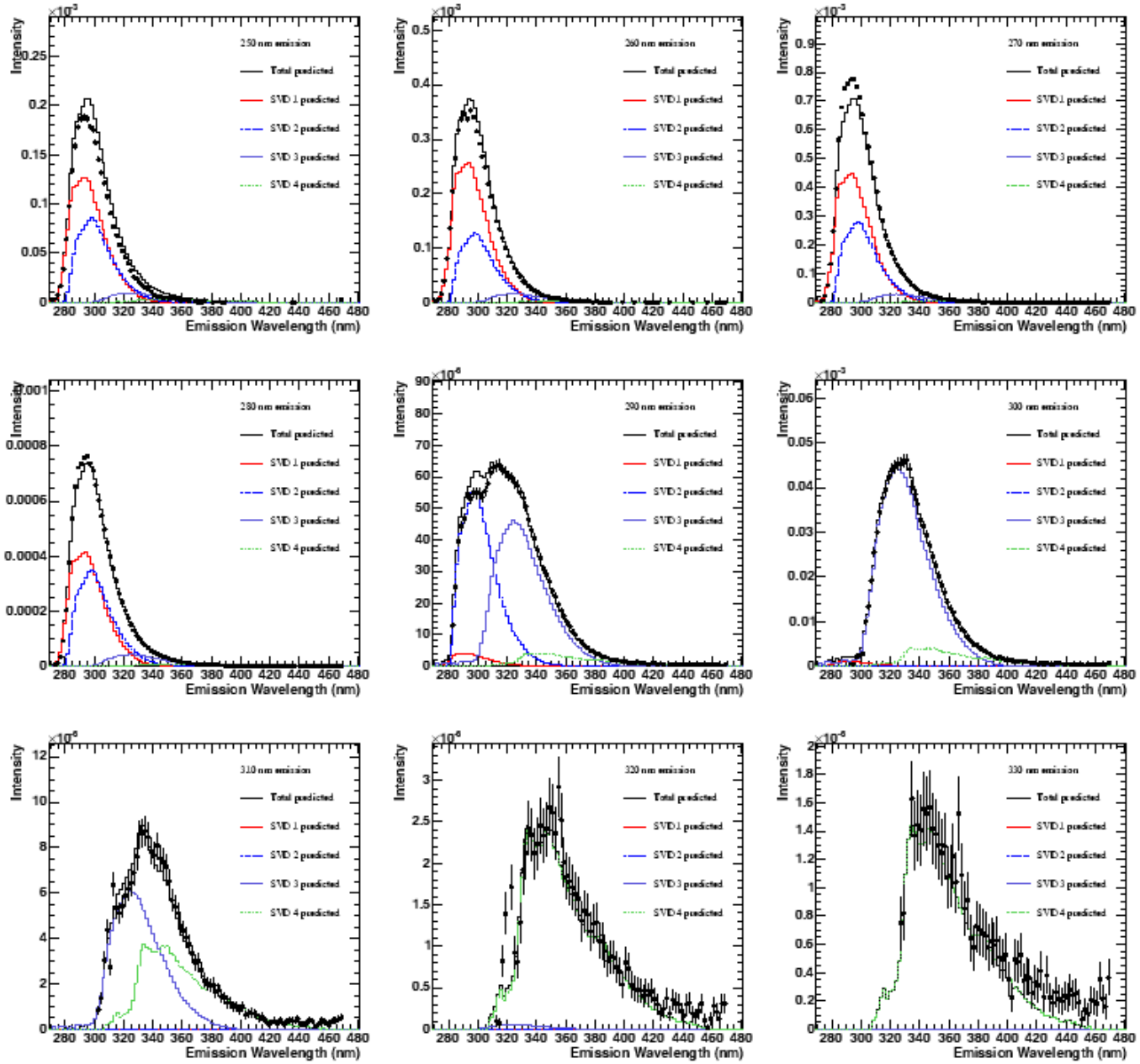


Figure 10: Comparison of background and scattering-subtracted emission curves (black points) with emission predicted by the SVD analysis (black line). The expected contribution from each fluorophore is shown by the colored lines (red, blue, violet and green for fluorophores 1,2,3 and 4, respectively).