Neutrino and Antineutrino Cross Sections at MiniBooNE

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(for the MiniBooNE collaboration)

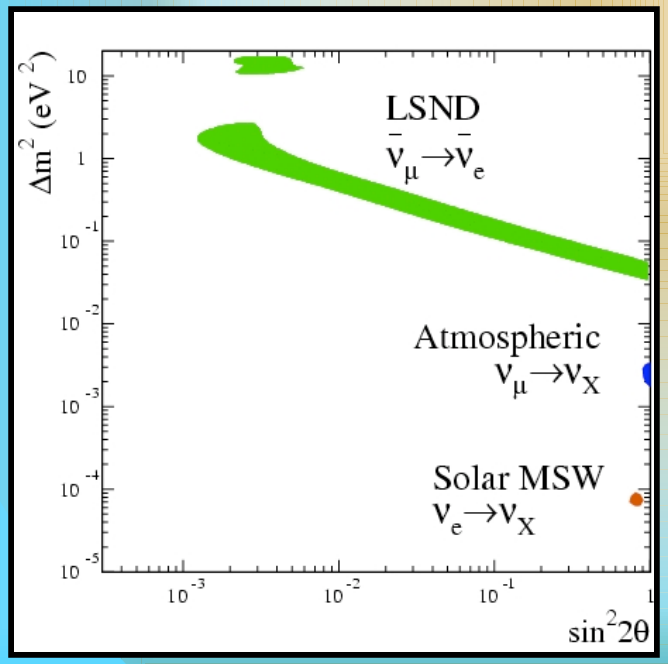
NO-VE Workshop
February 7, 2006

- our 1st ν cross section results (CC π^+/QE)

- future directions in MiniBooNE σ_ν program

MiniBooNE is a ν Oscillation Experiment

- main goal: confirm or rule out $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ LSND results
- search for $\nu_\mu \rightarrow \nu_e$ oscillations



- not going to be showing oscillation results
- working hard on performing a very careful ν_e appearance analysis …
- you'll have to stay tuned

MiniBooNE On the Way

- while designed for $\nu_\mu \rightarrow \nu_e$ oscillation search …

MiniBooNE is a dynamic experiment

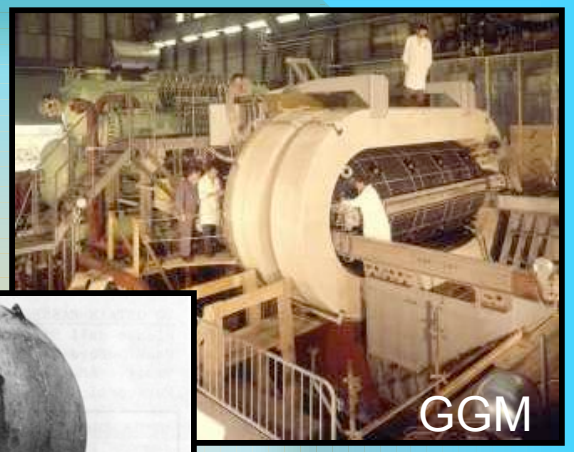
* well-suited for low E ν cross section physics
  - useful to the community
  - important for oscillation analysis
  - will tell you about

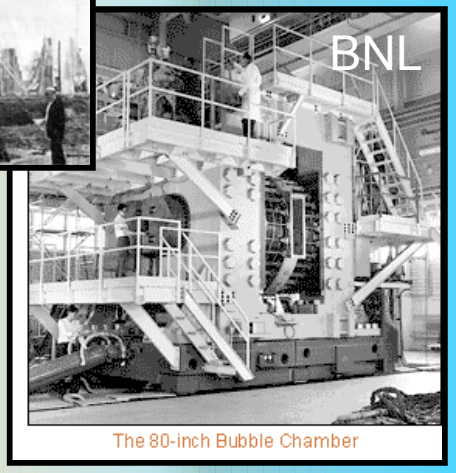
updating σ_ν is important

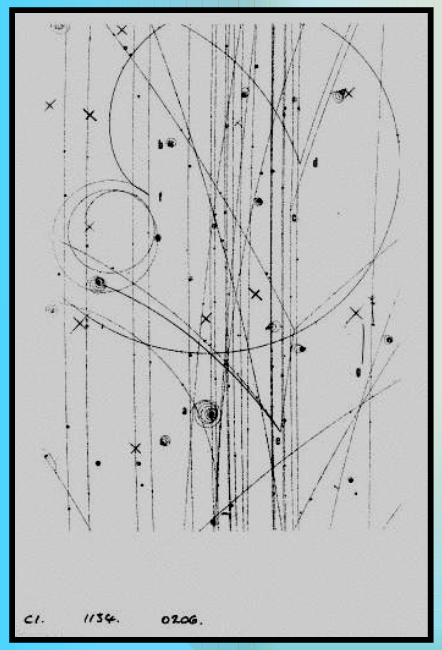
* plus some new opportunities (mention at end)
  - antineutrino data! (big change for us)

Previous Measurements

- most of present low energy ν σ knowledge comes from bubble chamber exps
- early experiments at ANL, BNL, FNAL, CERN, Serpukhov, etc.

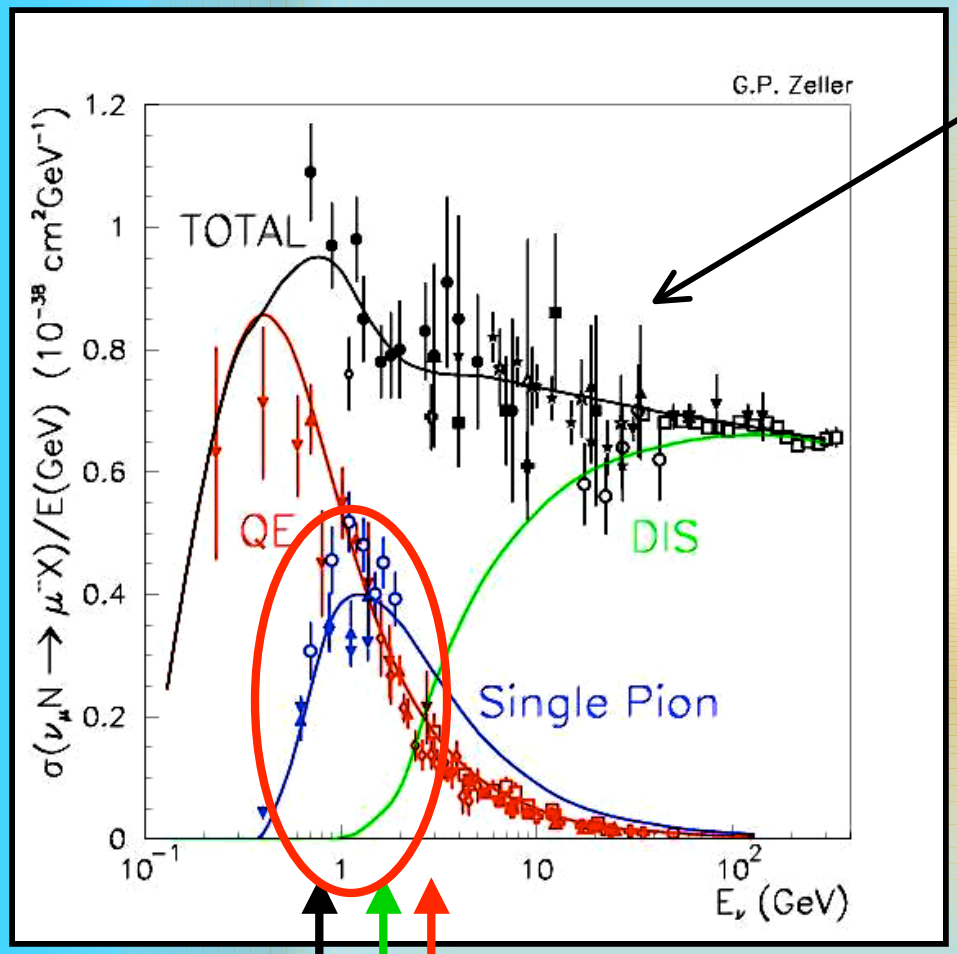






- 20-100% errors due to:
  - low statistics (100's of events)
  - uncertainties in ν flux
- in addition to large errors, results often conflicting (some care in interpreting)
- data useful to constrain our MCs
- idea of caliber of past data …

Low Energy ν Cross Sections

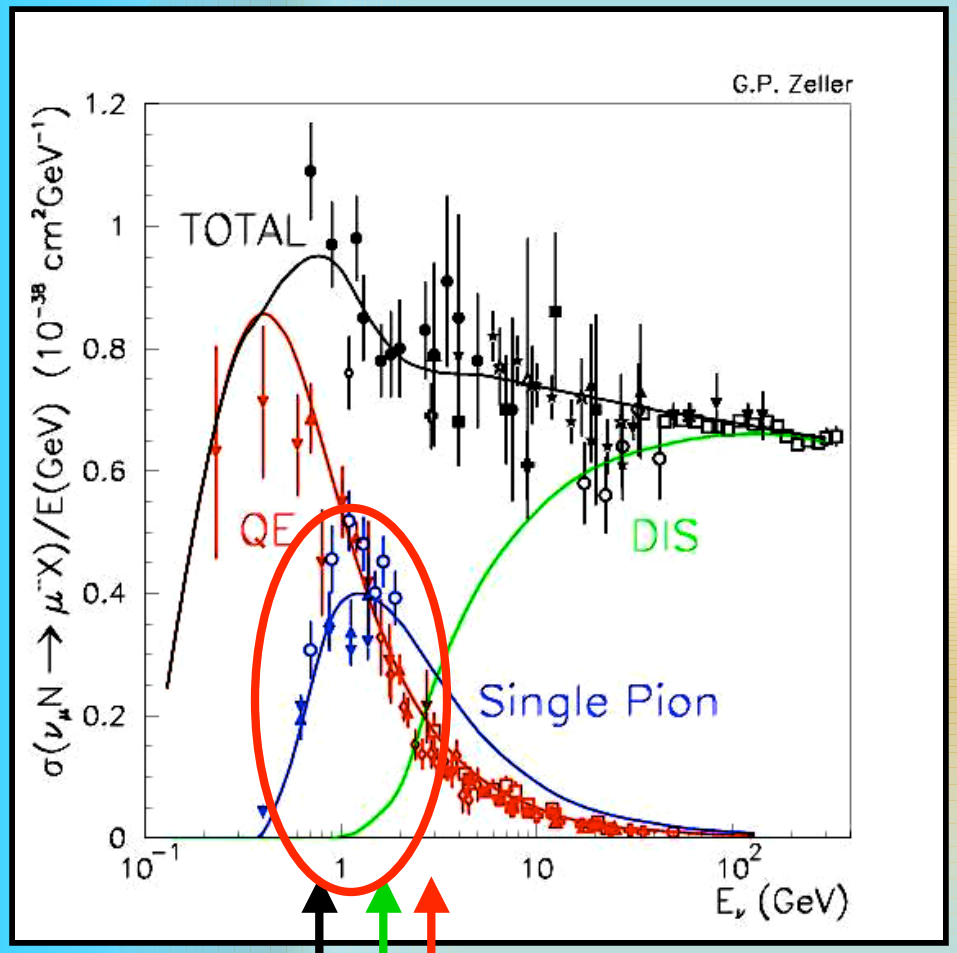


predictions from NUANCE

- MC which MBooNE uses
- open source code
- supported & maintained by D. Casper (UC Irvine)

- standard inputs
  (common ingredients - osc exps)
  - Smith-Moniz Fermi Gas
  - Rein-Sehgal 1π
  - Bodek-Yang DIS

Low Energy ν Cross Sections



- imperative to precisely predict signal & bkgd rates for future oscillation exps
  - will be more sensitive to sources of syst error
  - nuclear targets! (most past data on H_2, D_2)
- further motivates need for new measurements
- new data adding new info; revealing interesting features

  K2K, NOMAD, MiniBooNE

MiniBooNE Beamline

- >700,000 contained ν events
- providing a valuable sample to study low E ν cross sections

FNAL 8 GeV Booster

decay region:
$\pi \rightarrow \mu\nu_\mu$, $K \rightarrow \mu\nu_\mu$

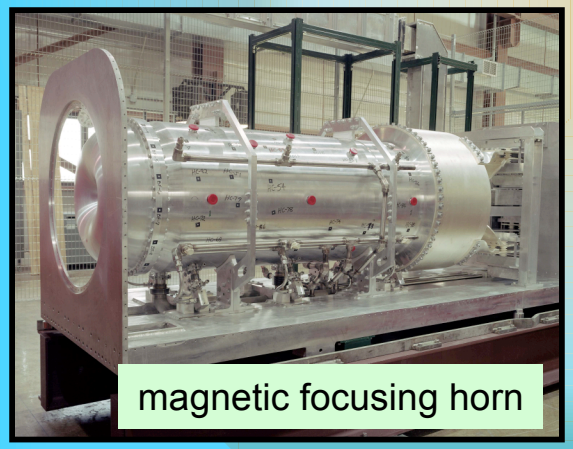
"LMC"
measure K flux in-situ

magnetic horn:
meson focusing

MiniBooNE detector (CH_2)

450 m earth berm: ν

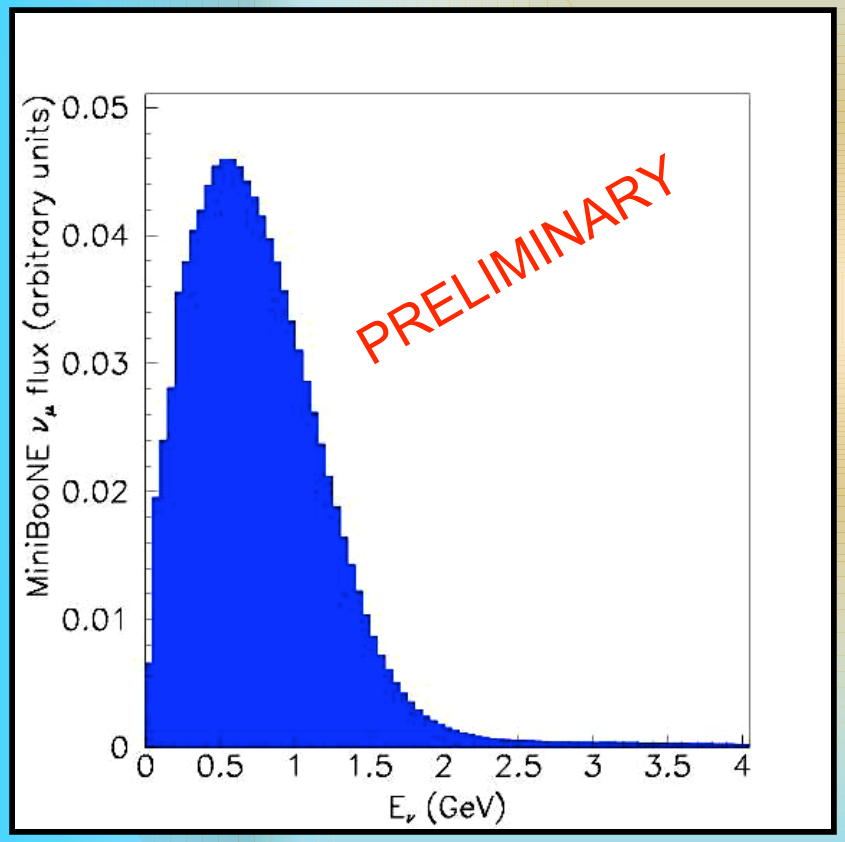
movable absorber:
stops muons, undecayed mesons



magnetic focusing horn

ν_μ Flux at MiniBooNE Detector

- incident on detector: high purity beam (>99% ν_μ flavor)



MC predicted ν energy spectrum

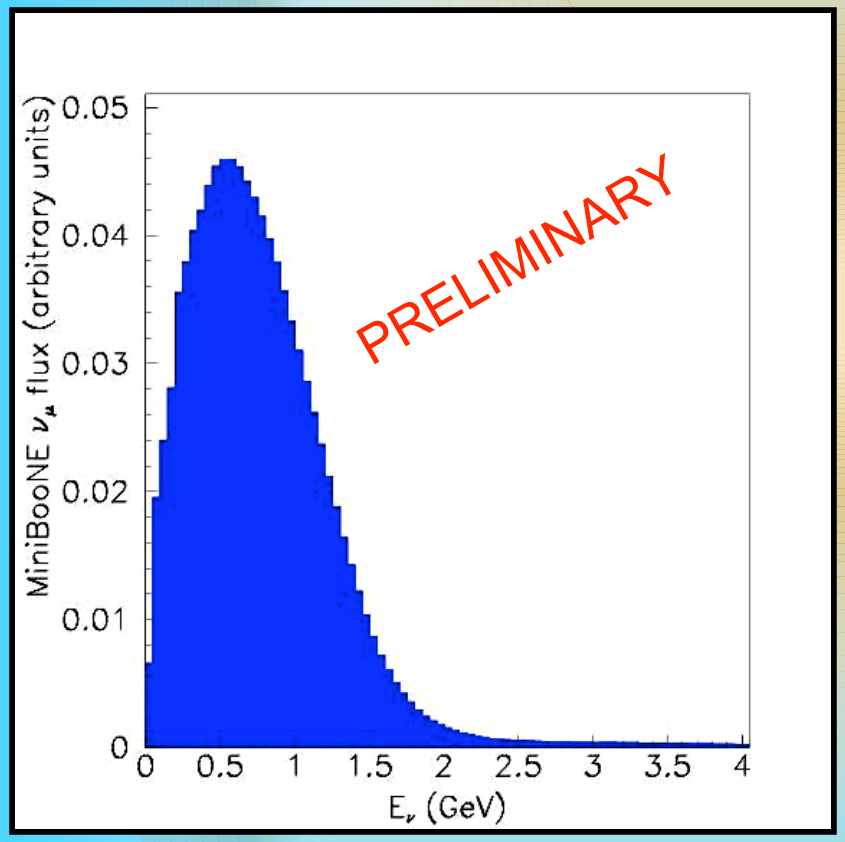
– ν_μ mainly from $\pi^+ \rightarrow \mu^+ \nu_\mu$

– π production constrained by global π data & E910 …

- eventually HARP

- really advance knowledge of low E hadroproduction (see Gibin's talk)

ν_μ Flux at MiniBooNE Detector



MC predicted ν energy spectrum

- $\langle E_\nu \rangle^{MBooNE} \sim 0.7$ GeV

- well-suited for low energy ν cross section studies

  - small tail; enjoy smaller backgrounds from higher multiplicity ν interactions

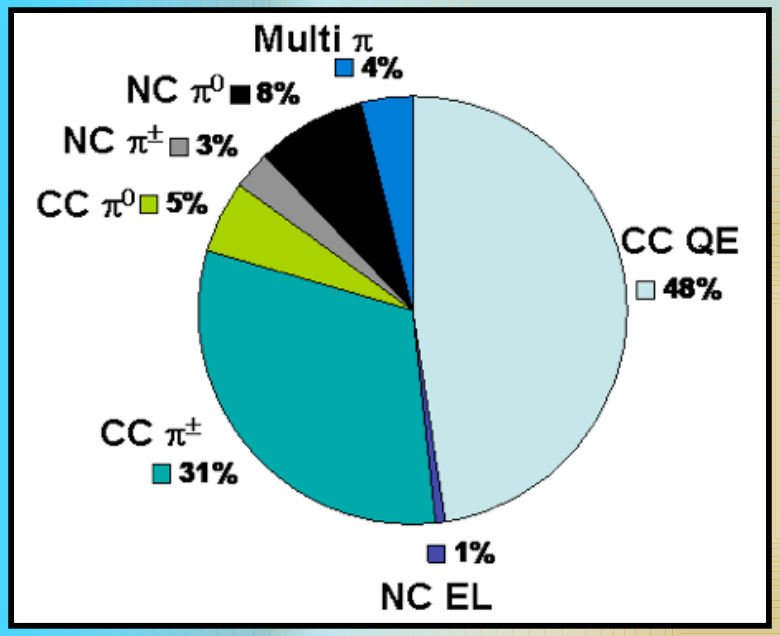
- complementary to other σ_ν experiments

$\langle E_\nu^{K2K} \rangle \sim 1.3$ GeV

$\langle E_\nu^{NuMI} \rangle \sim 10$ GeV

$\langle E_\nu^{NOMAD} \rangle \sim 24$ GeV

Event Fractions at MiniBooNE



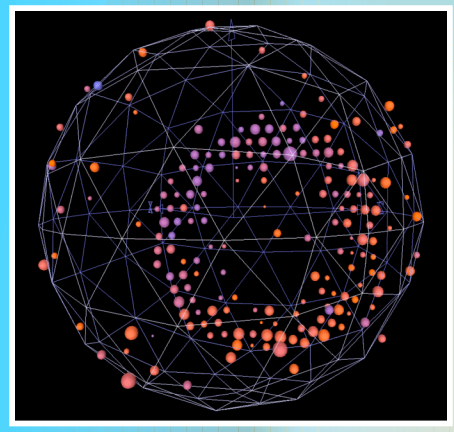
MiniBooNE flux-averaged event compositions
(N_{TANK}>200, N_{VETO}<6)

this flux spectrum dictates what type of ν interactions we see …

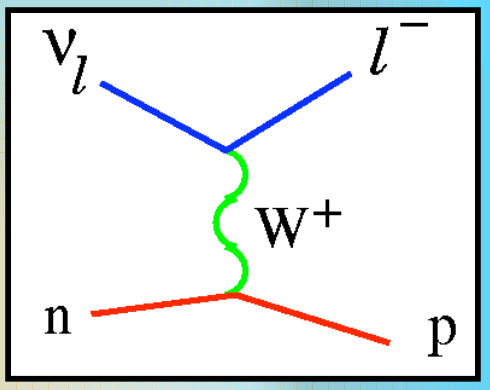
- **48% CC QE**
- **31% CC π^+**
- **8% NC π^0**
- **5% CC π^0**
- **3% NC $\pi^{+/-}$**
- **4% multi-π**
- **1% NC elastic**

demonstrate understanding of 79% of events before analyzing ν_e (<1% of total)

Quasi-Elastic Scattering



Why important?



ν_μ n → μ^- p

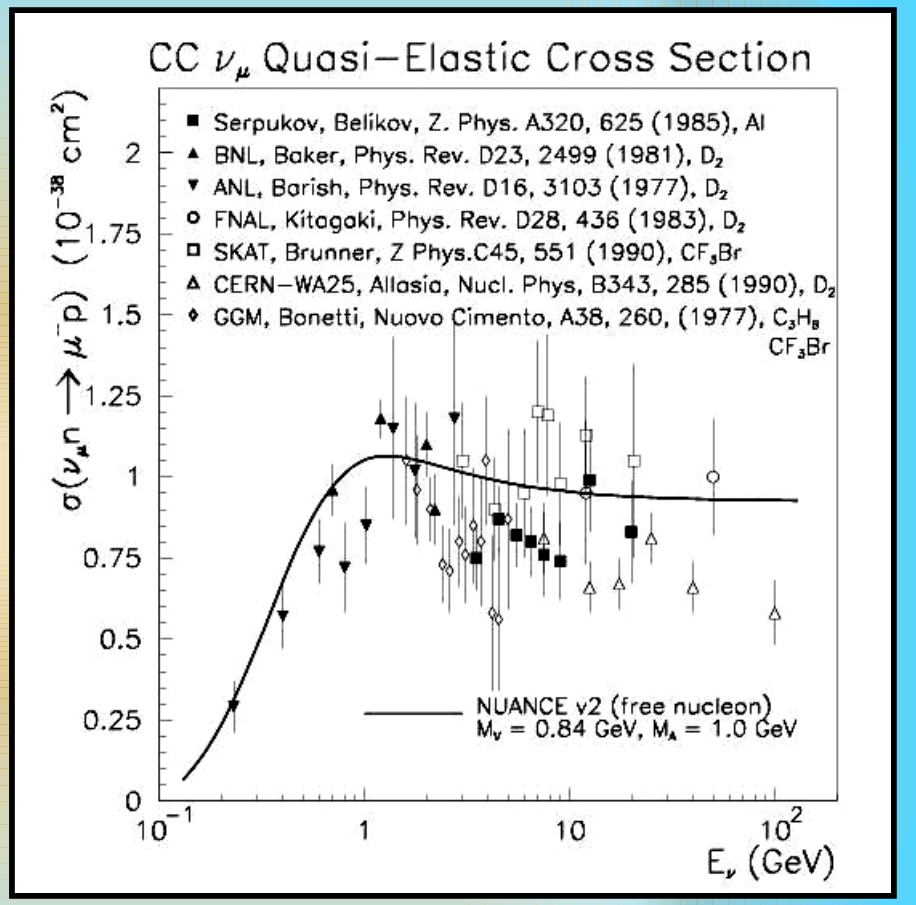
- ν_μ QE σ necessary to accurately predict signal rates in oscillation experiments (including our own)
  - * ν_e QE are main signal for ν_μ → ν_e appearance searches; have similar kinematics & σ
- channel used as "golden mode" to normalize other cross section samples - lots of events, well known σ

(common practice that we will also adopt for now)

Quasi-Elastic Scattering

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

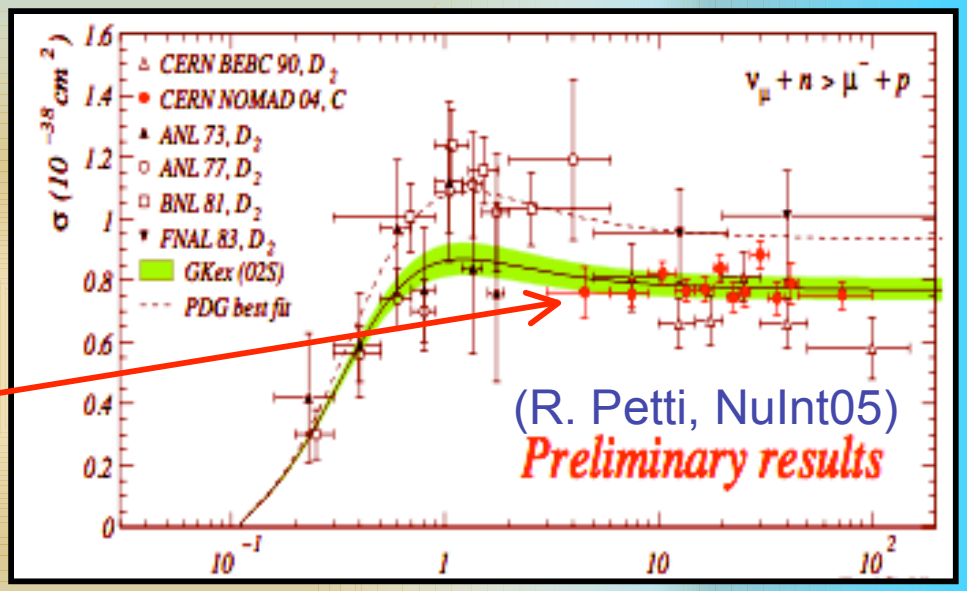
- highest statistics **~2500 events**
- low E data on D_2



Quasi-Elastic Scattering

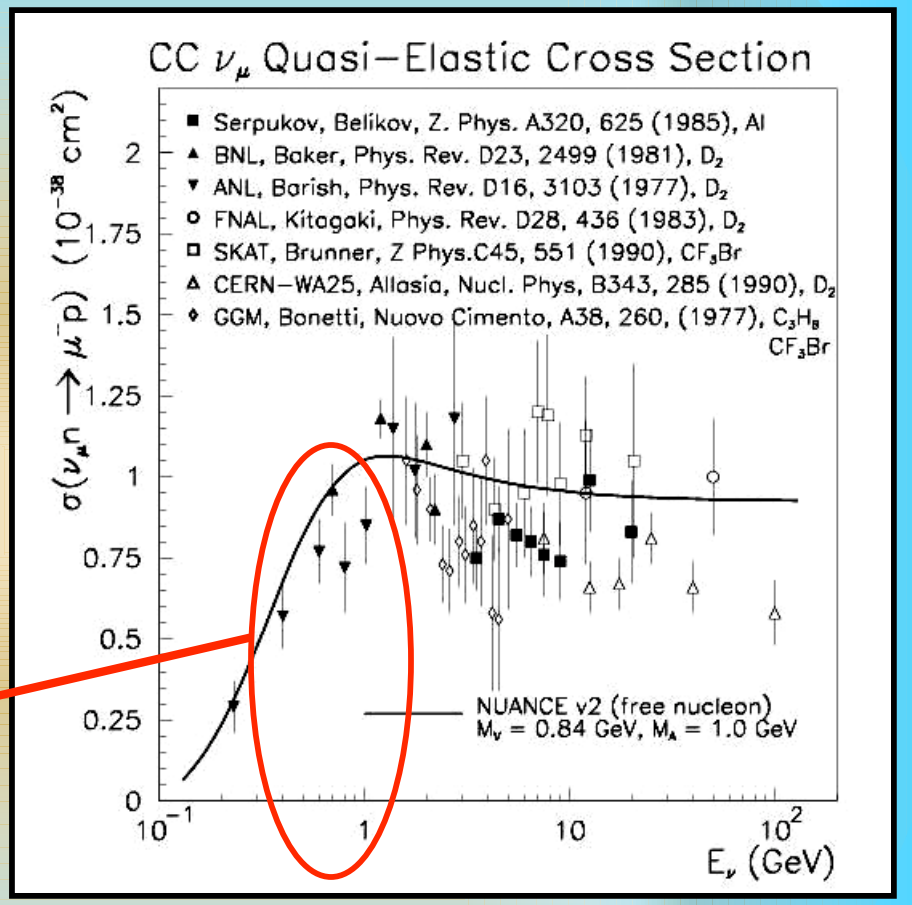
$\nu_\mu n \rightarrow \mu^- p$

- new information already coming in (NOMAD, ^{12}C)



Quasi-Elastic Scattering

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

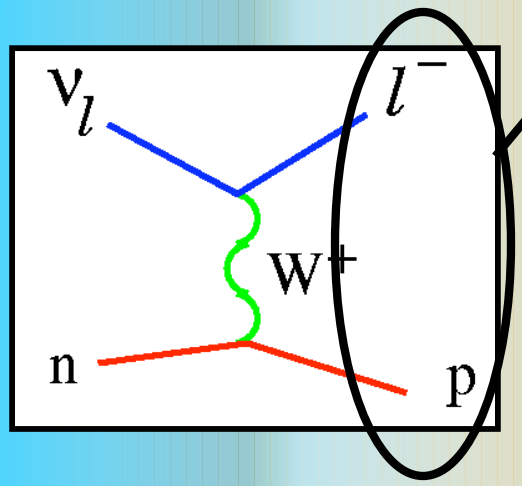


- **MiniBooNE:**
  - ^{12}C (valuable for osc exps)
  - this analysis: **60k events** (3.2×10^{20} POT)
    (already more data than all previous exps combined)
  - can select 86% pure QE sample

MiniBooNE QE Data

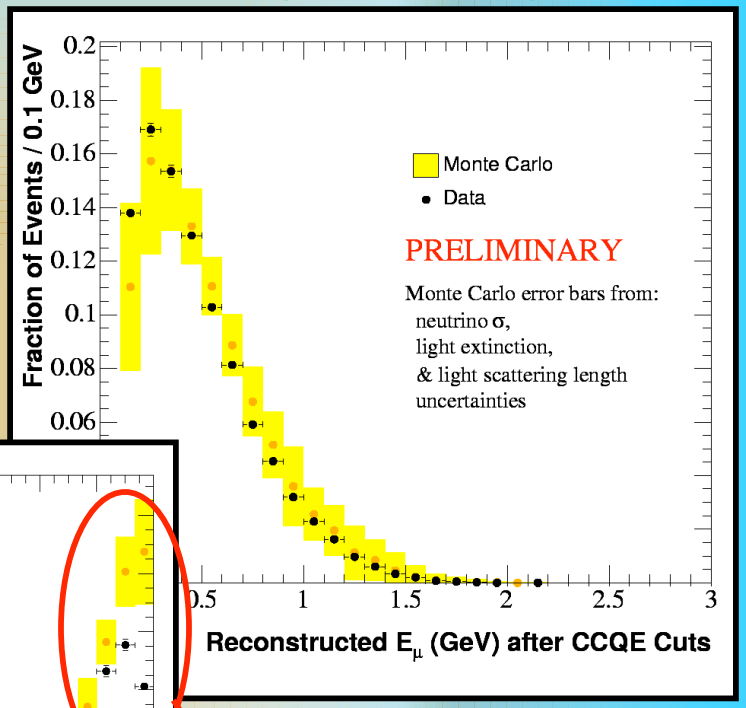
- most copious events at MiniBooNE
- also simplest: two body kinematics

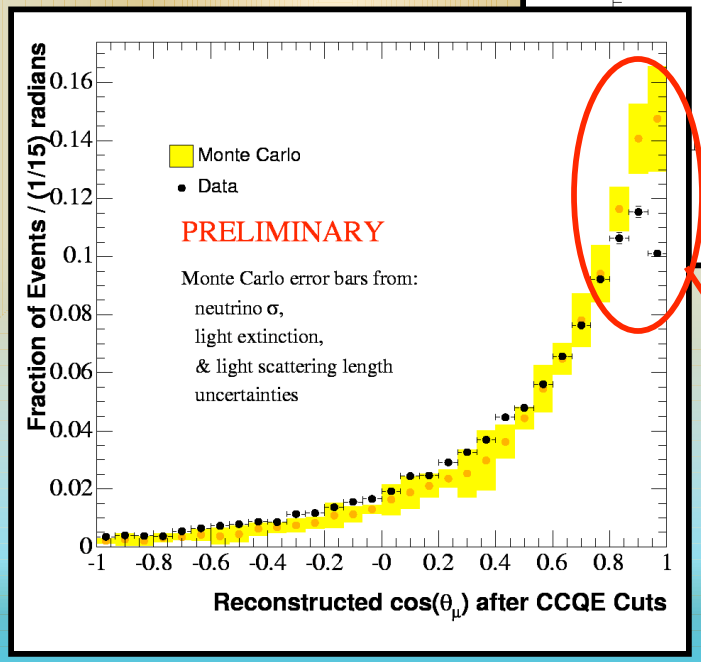
(J. Monroe)



measure visible E and θ_μ from mostly Čerenkov (μ) + some scintillation light (p)

ν_μ n $\rightarrow$ μ^- p

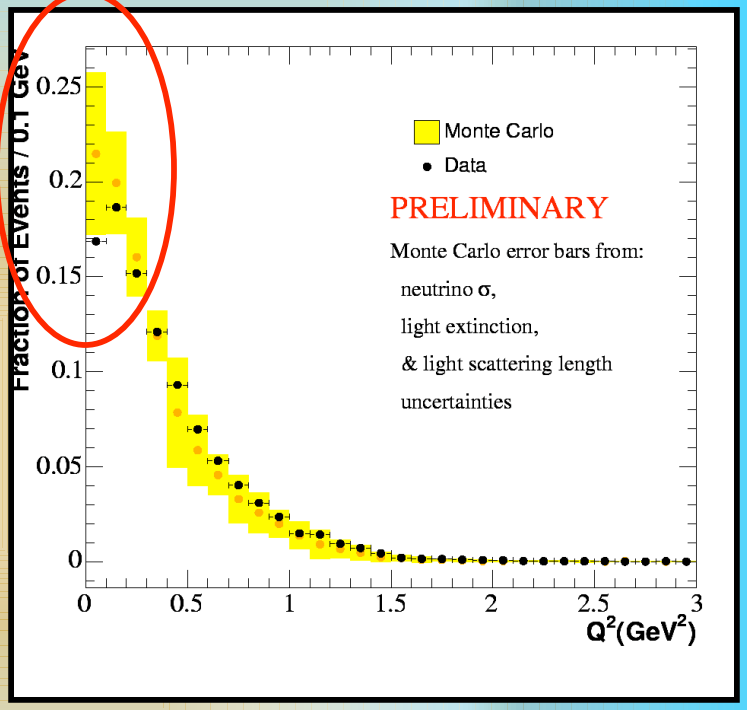




forward muons corresponds to low Q^2 …

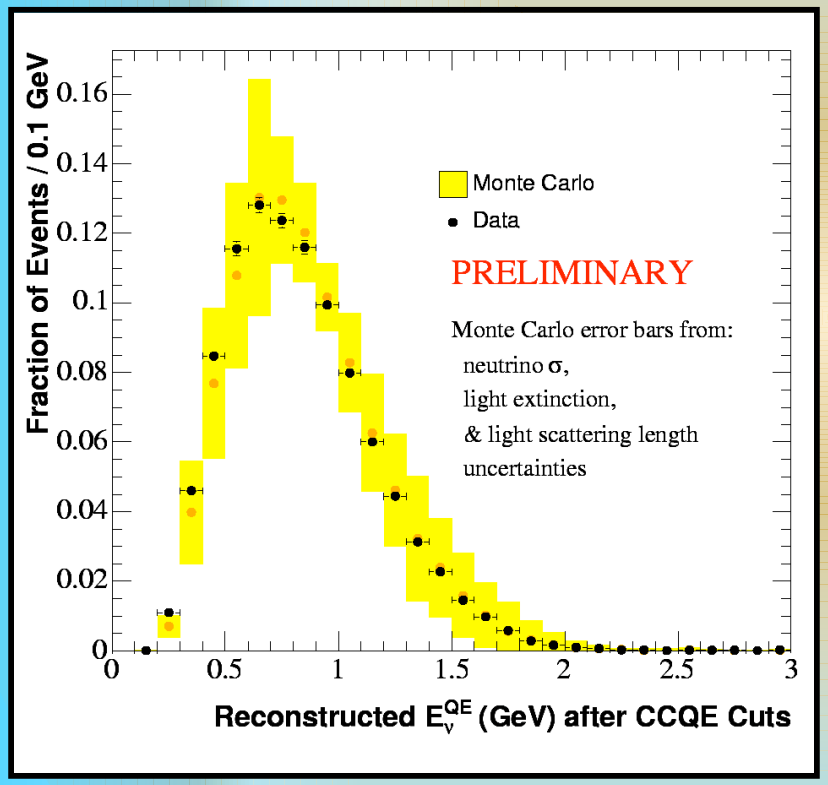
MiniBooNE QE Data

- similar effect seen by K2K
- working on understanding these features in our data …
- to improve data, MC agreement performing shape fits for: (J. Monroe)
  - axial form factor (M_A) &
  - nuclear model pars (E_B,p_F)
- incorporating new nuclear models (R. Tayloe) (that are constrained by modern electron scattering data)



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

MiniBooNE QE Data



(J. Monroe)

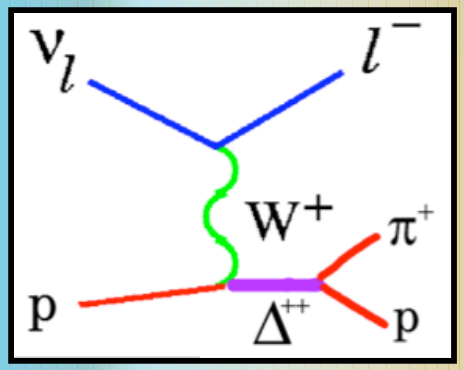
- making use of E_μ, θ_μ …

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

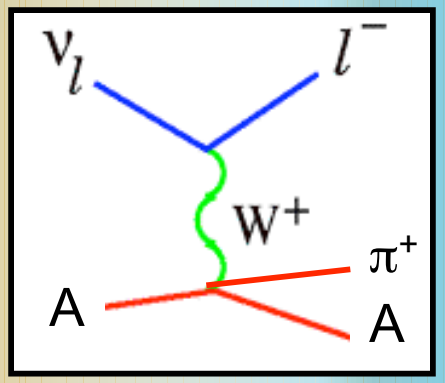
- energy distribution that will be used for CC π^+/QE cross section measurement
- next, numerator (CC π^+) …

CC $1\pi^+$ Production

resonant π^+ production (dominant)



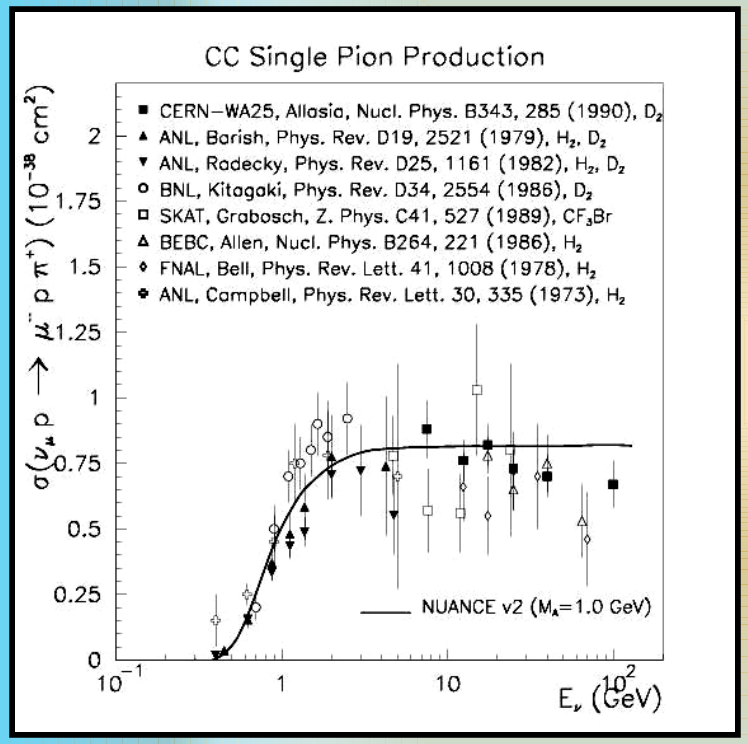
coherent π^+ production



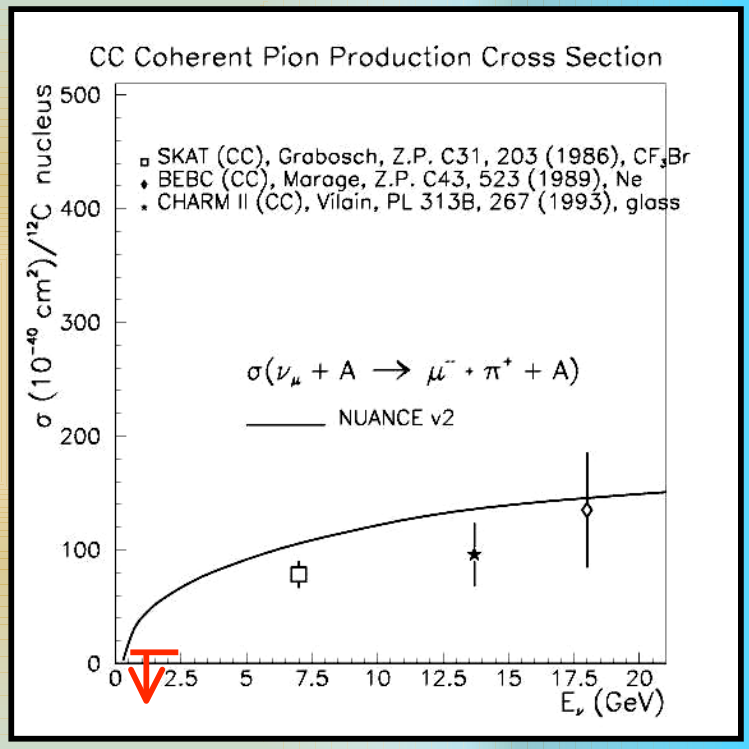
- forward emitted π
- low Q^2

CC $1\pi^+$ Production

resonant π^+ production (dominant)

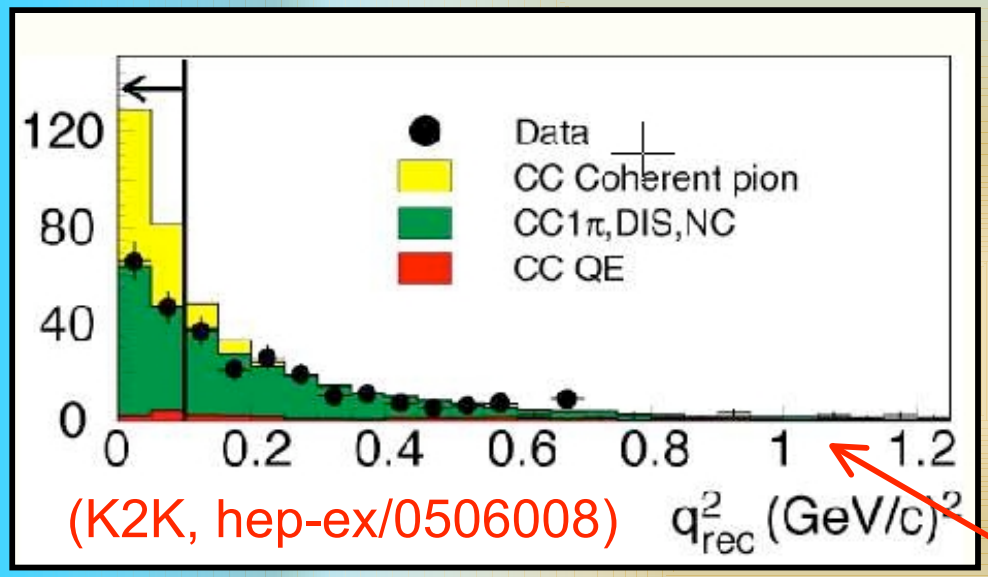


coherent π^+ production

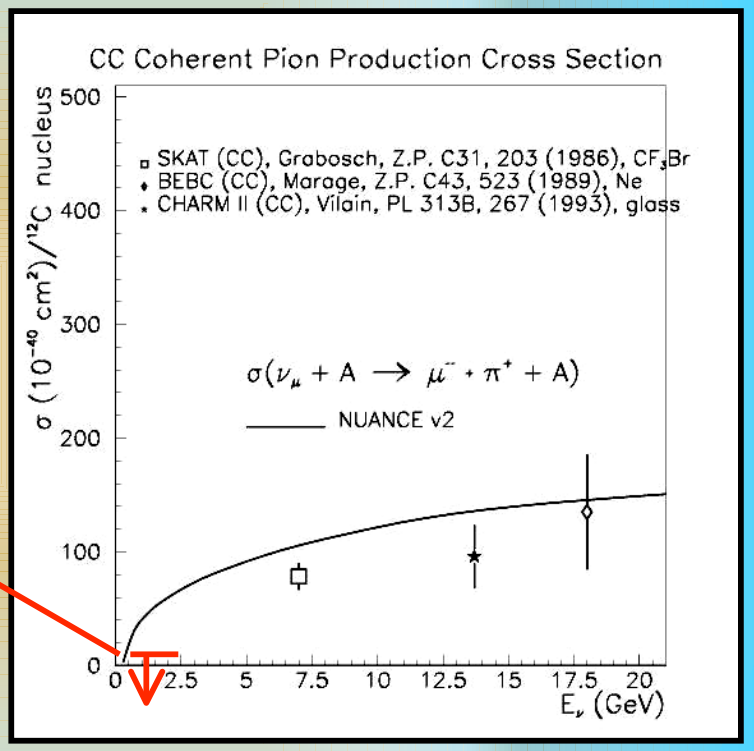


CC $1\pi^+$ Production

resonant π^+ production (dominant)



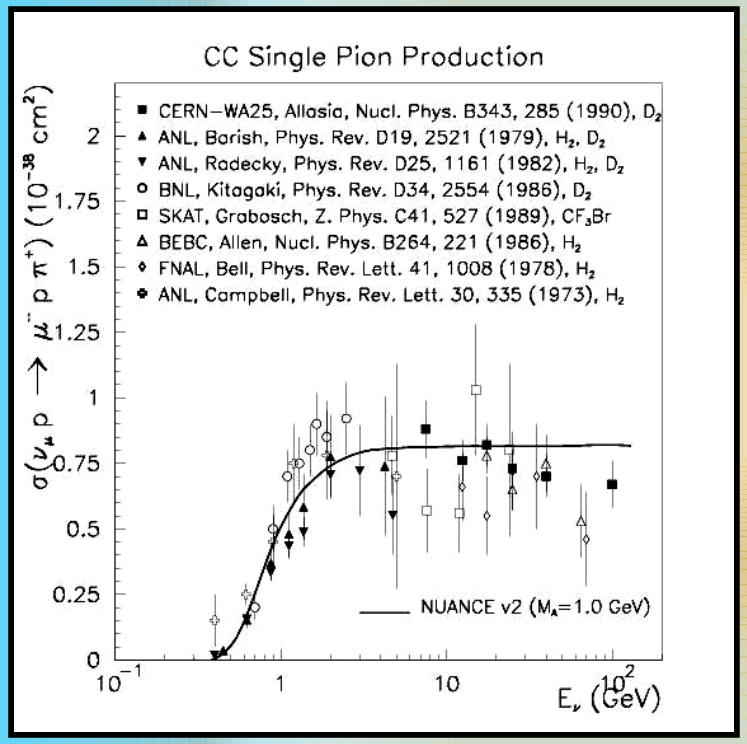
coherent π^+ production



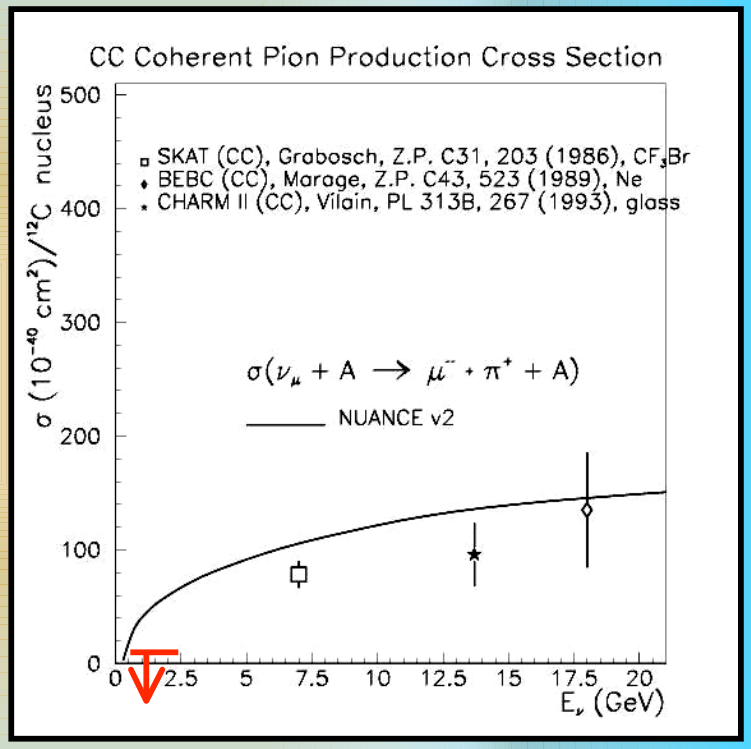
- K2K: 1st search for coh π^+ prod at low E
- somewhat surprising results …
- see no evidence for coh π^+ production!

CC $1\pi^+$ Production

resonant π^+ production (dominant)



coherent π^+ production

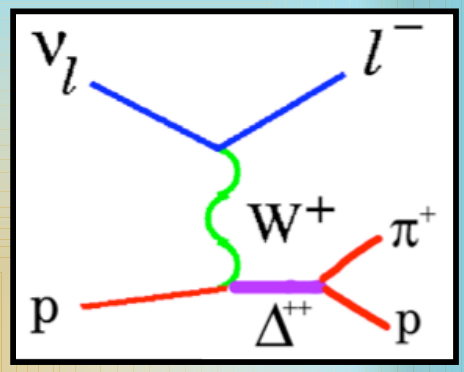


- **MiniBooNE:**- inclusive measurement, CH_2

  - this analysis: **40k events** (3.2×10^{20} POT)
    (5x more than previous bubble chamber data combined)

CC π^+ Production

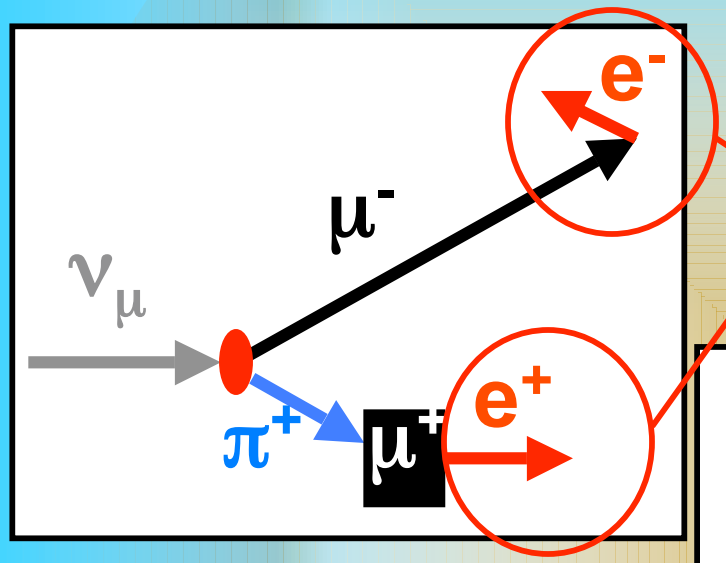
Why important?



$\nu_\mu N \rightarrow \mu^- N \pi^+$

- poses largest background to ν_μ QE samples (large σ & π^+ can be absorbed in nucleus)
- useful for understanding Δ production in CH_2 ($\Delta \rightarrow N \gamma$ a background to $\nu_\mu \rightarrow \nu_e$ search)
- possibility for CC π^+ oscillation search
- useful in understanding our event reconstruction

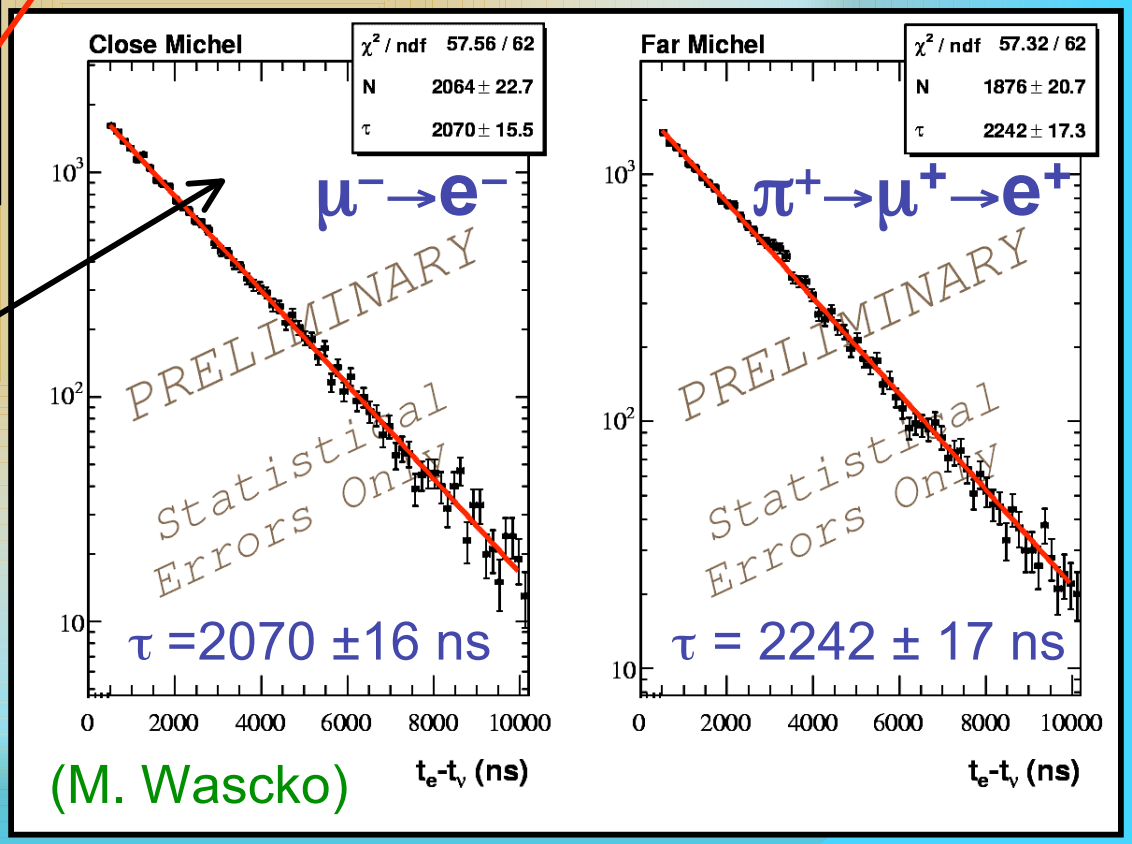
MiniBooNE CC π^+ Selection



- very simple selection:
  - events with 2 decay electrons
  - unique, results in 84% purity

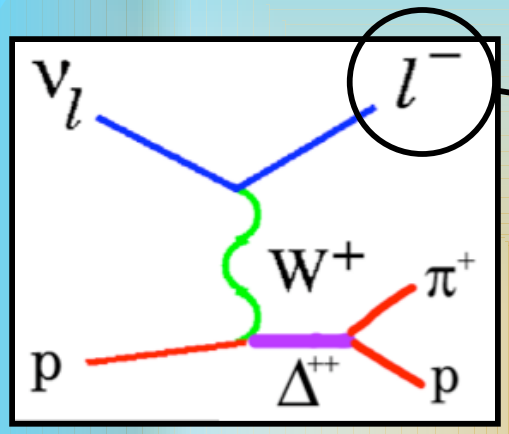
- expect μ^- to have shorter lifetime from μ^- capture (8% in ^{12}C)

- will also make use of this later

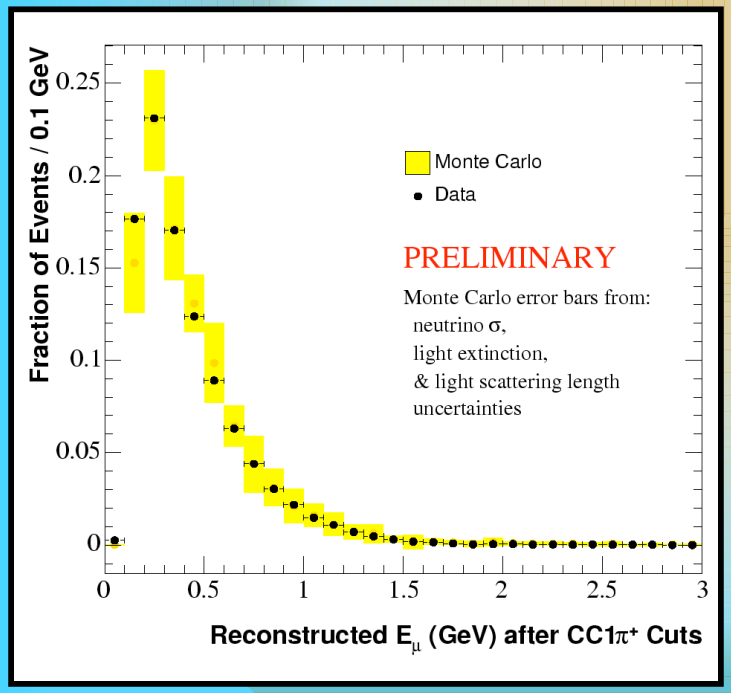


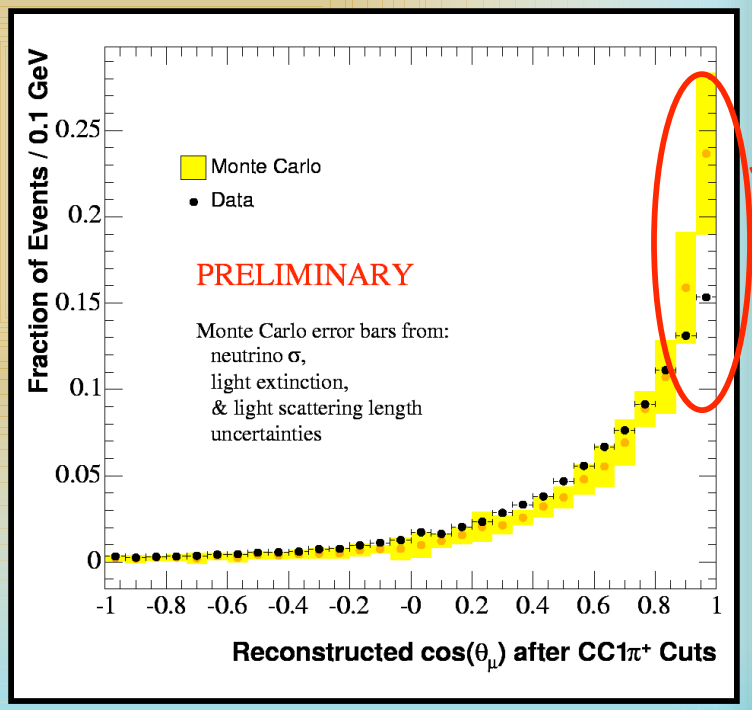
(M. Wascko)

MiniBooNE CC π^+ Reconstruction



measure Čerenkov light from muon (to avoid light from π^+)





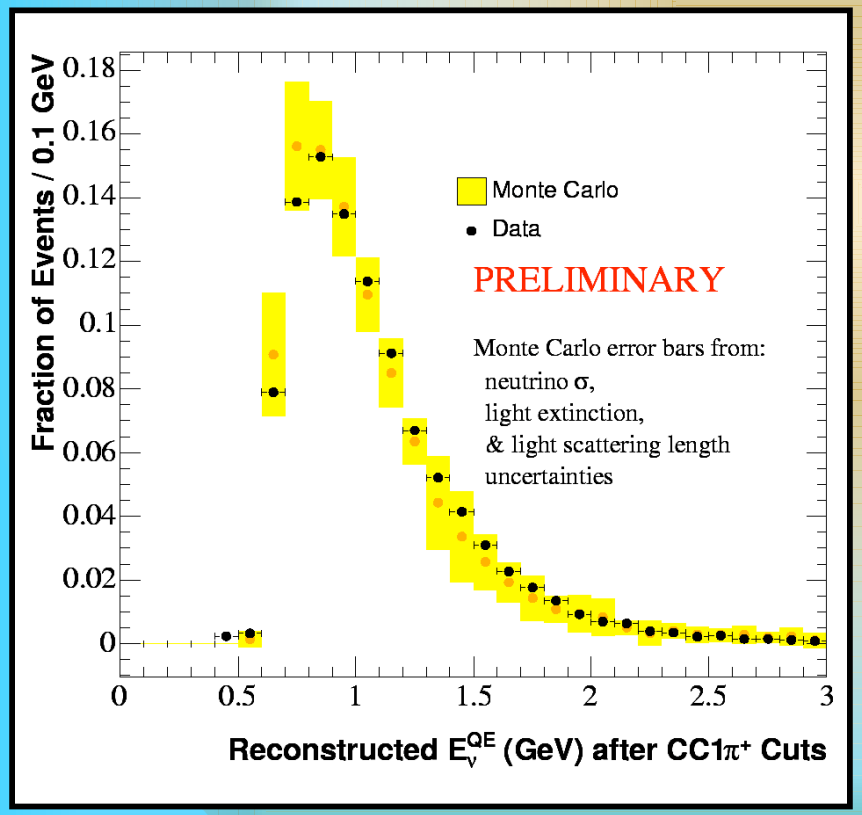
see larger deficit in forward μ (low Q^2) than in QE data

(M. Wascko)

MiniBooNE CC π^+ Data

$$\text{“}E_\nu^{QE}\text{”} = \frac{2M_pE_\mu - m_\mu^2 + (m_\Delta^2 - M_p^2)}{2(M_p - E_\mu + p_\mu \cos\Theta_\mu)}$$

(M. Wascko)

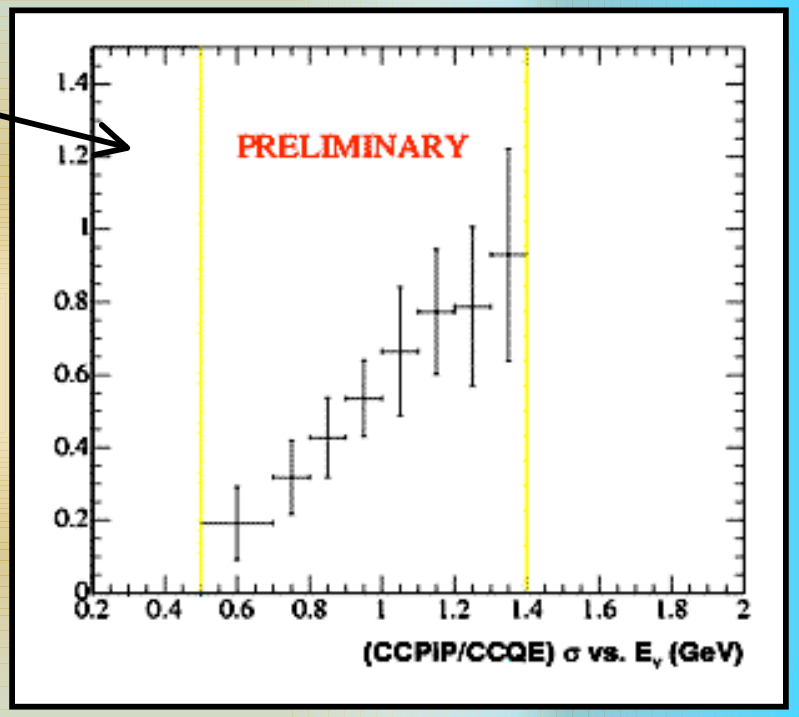


- use 2 body (QE) kinematics
- assume $\Delta(1232)$ in final state (instead of p in QE case)
- energy distribution that will be used for CC π^+/QE cross section measurement

MiniBooNE CC π^+/QE Ratio

(J. Monroe, M. Wascko)

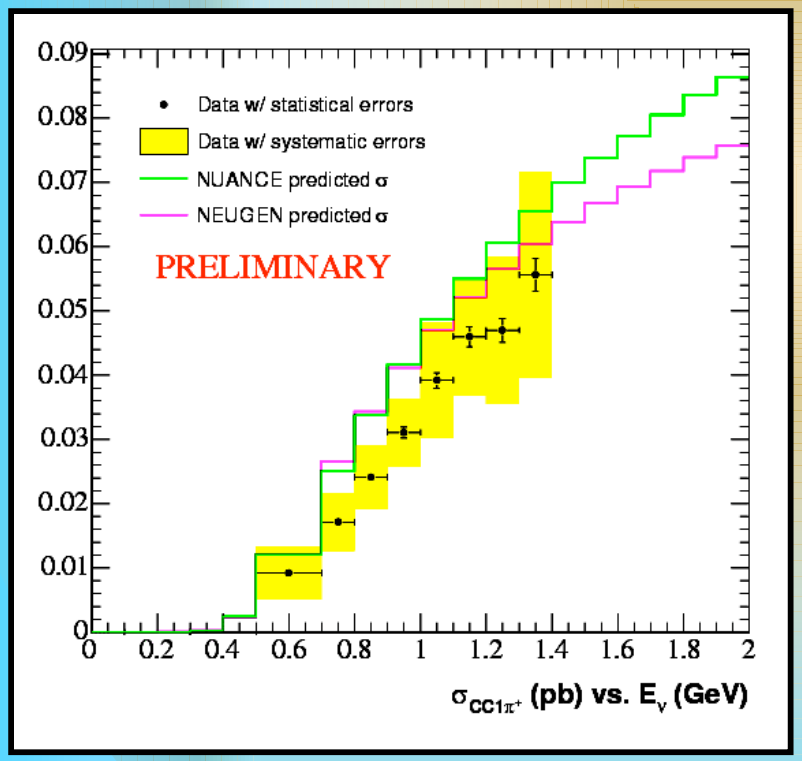
- efficiency corrected CC π^+/QE σ ratio meas on CH_2
- eff corrections from MC
- ample statistics → can perform a binned measurement
- <u>current systematics estimate:</u>
  - light propagation in oil: ~20%
  - ν cross sections: ~15%
  - energy scale: ~10%
  - statistics: ~5%

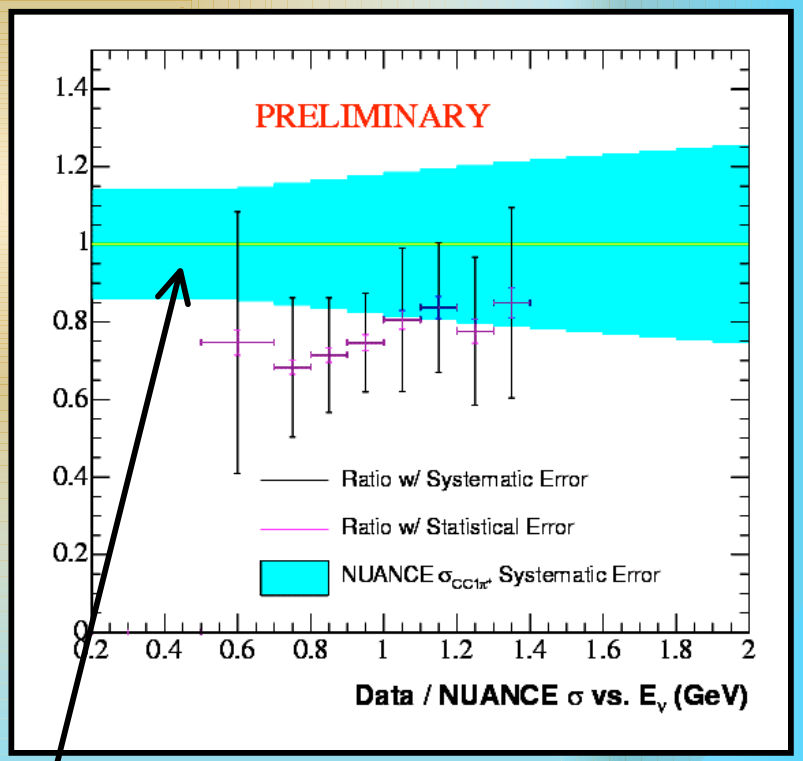


first measurement of this cross section ratio on a nuclear target at low energy!

MiniBooNE CC π^+ Cross Section

- multiplying measured CC π^+/QE ratio by QE σ prediction
  (σ_{QE} with M_A=1.03 GeV, BBA non-dipole vector form factors)
- ~25% lower than prediction, but within errors



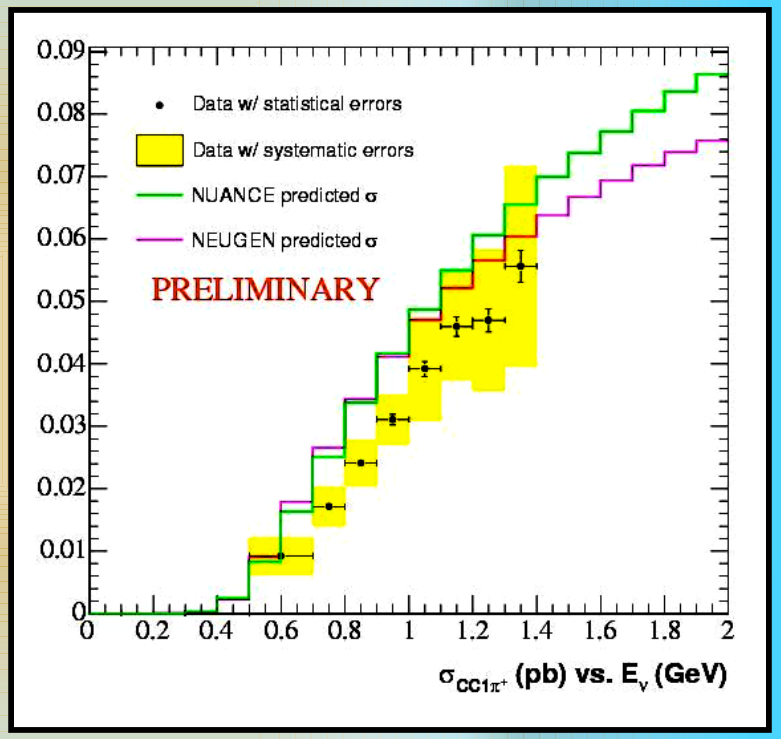


(J. Monroe, M. Wascko)

- MC error band from external ν data constraints

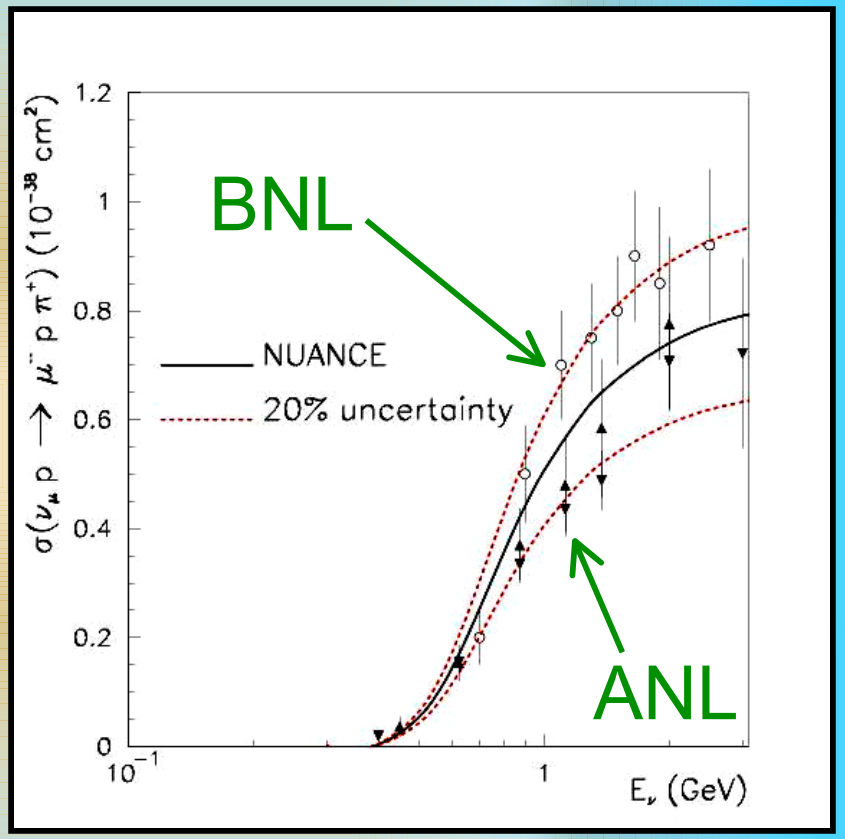
Plausible Interpretation

- since MiniBooNE 1st meas on nuclear target at these E's
- at 1st glance, one might think this is pointing to a potential problem with nuclear corrs



Plausible Interpretation

- since MiniBooNE 1st meas on nuclear target at these E's
- at 1st glance, one might think this is pointing to a potential problem with nuclear corrs
- but free nucleon σ's disagree!
- MC prediction splits difference



- MiniBooNE results more consistent with ANL than BNL
  - new data helping to decide between 2 disparate σ meas
  - once final, type of info that can feed back into open source MC

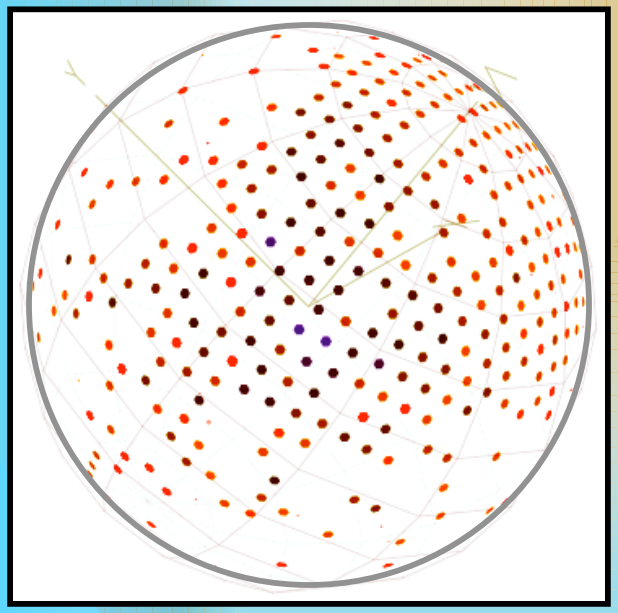
New σ_ν Directions at MiniBooNE

- new antineutrino data!
- observing ν events from NuMI
- coming soon: new fine-grained new detector to this beamline

  (comparisons to MiniBooNEwill be interesting)

MiniBooNE Antineutrino Running

- just started antineutrino running (January 19th)
  - ~1,000 $\overline{\nu}$ events/week
  - will have world's largest low E $\overline{\nu}$ data set in a few weeks!



1st MiniBooNE antineutrino event

- goals are two-fold:
  - check LSND $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ signal
    (longer program, not yet approved)
  - measure $\overline{\nu}$ cross sections
    - systematic check of ν analyses
    - low Q^2 investigations
    - coherent π production

Need for $\overline{\nu}$ σ Measurements

- $\overline{\nu}$ σ data even less abundant

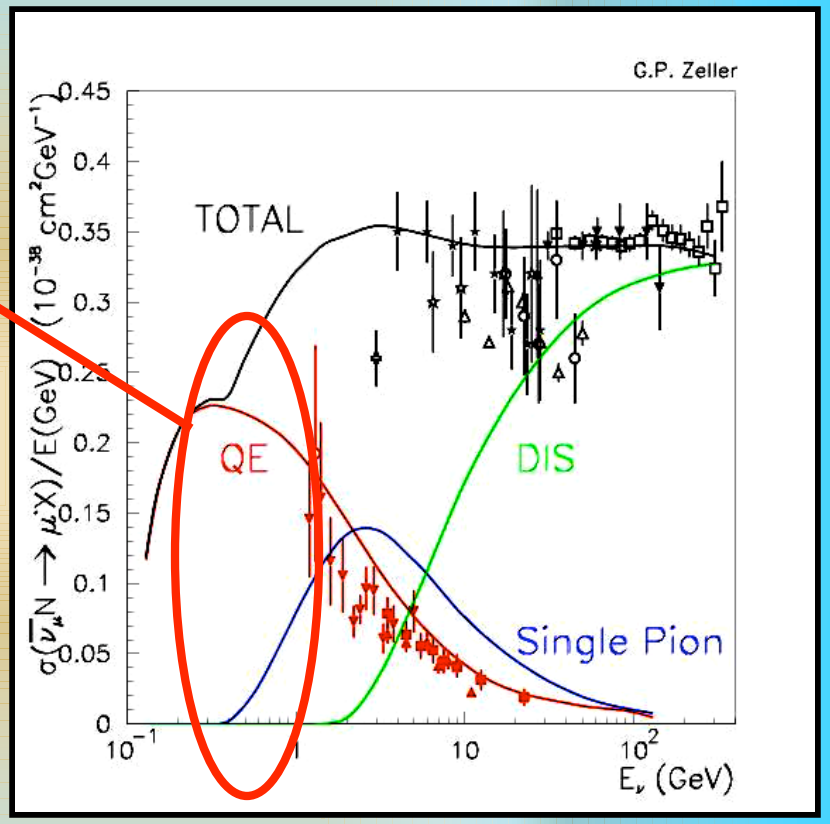
- MiniBooNE will make world's 1st meas of $\overline{\nu}$ σ in this E range

  - expect ~10k $\overline{\nu}_\mu$ QE in 1 year (after cuts)

- provide valuable input for future CP violation searches

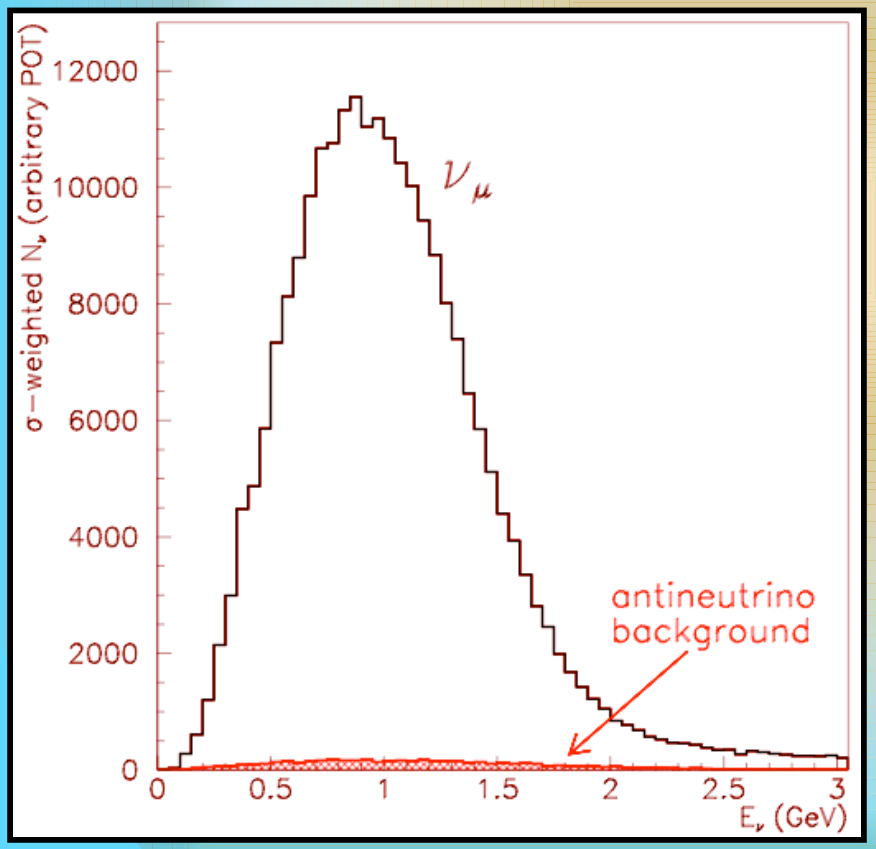
  $P(\nu_\mu \rightarrow \nu_e) \neq P(\overline{\nu}_\mu \rightarrow \overline{\nu}_e)$

- prefer not to rely on extrapolation of models into regions where no data



Added Difficulty with $\overline{\nu}$ Beams

- contending with "wrong sign" backgrounds (ν in $\overline{\nu}$ beam)
  - MiniBooNE beam is no exception …



- in **neutrino mode**, antineutrinos are ~2% of total events

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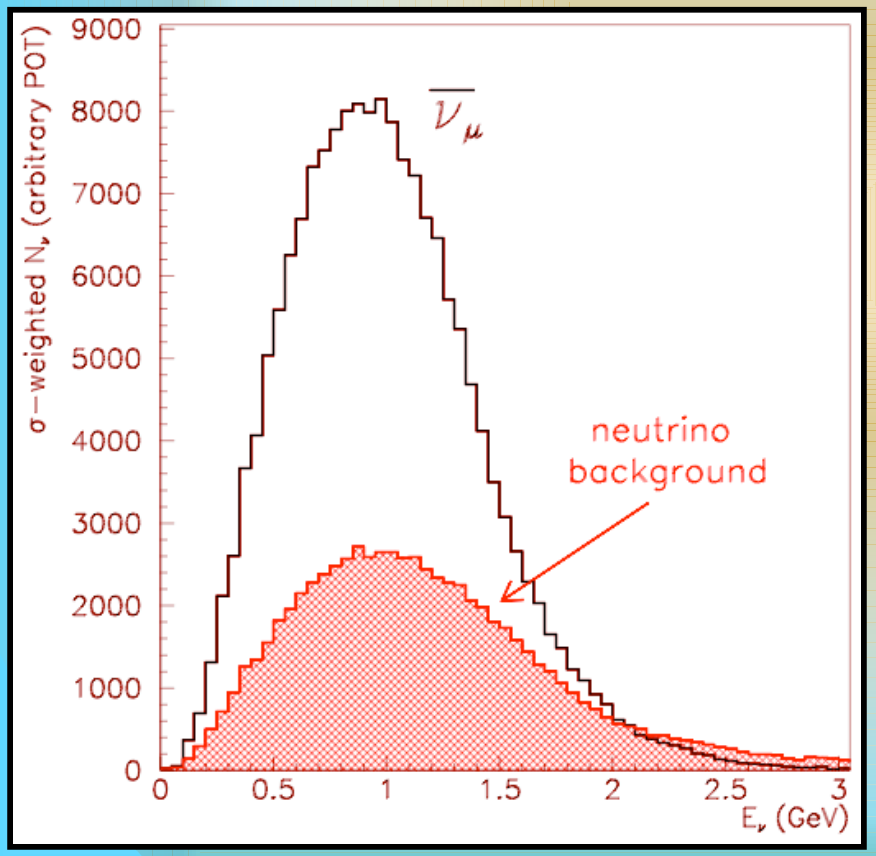


- in **antineutrino mode**, neutrinos are ~30% of total events

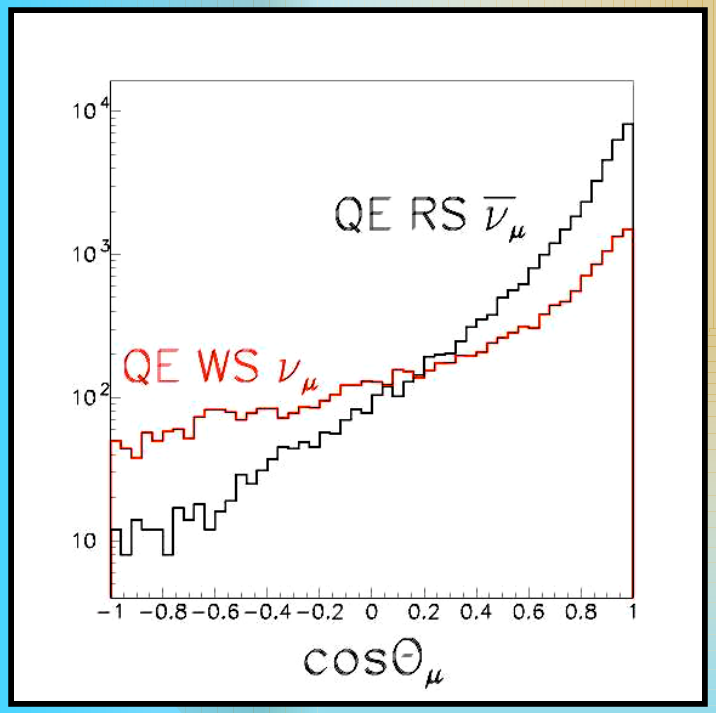
  "$\overline{\nu}$-enhanced beam"

- need a way to constrain ν backgrounds in $\overline{\nu}$ data

- Čerenkov detectors cannot distinguish μ^-, μ^+ event-by-event (no magnetic field)

Constraining ν Backgrounds in $\overline{\nu}$ Data

- needed to be more clever
- developed several novel techniques to measure from data



- 1st and most powerful …
- makes use of fact that QE ν & $\overline{\nu}$ have different angular distributions
- large angle QE's as means of measuring ν content in $\overline{\nu}$ data

("poor man's sign-selection")

Three Independent Constraints

redundant checks

1. QE **angular distributions** provide best "wrong-sign" constraint, but also …

   7% constraint

2. add'l constraint from **CC π^+ events** in $\bar{\nu}$ mode data

   (come entirely from ν interactions as $\bar{\nu}$'s produce a π^- in final state)

   - higher E constraint

   15% constraint

3. also **muon lifetimes** (μ^- vs. μ^+ to distinguish ν vs. $\bar{\nu}$)

   - μ^- and μ^+ have different lifetimes due to μ^- capture probability in oil

   - not as precise a constraint, but indep of kinematics & recon

   30% constraint

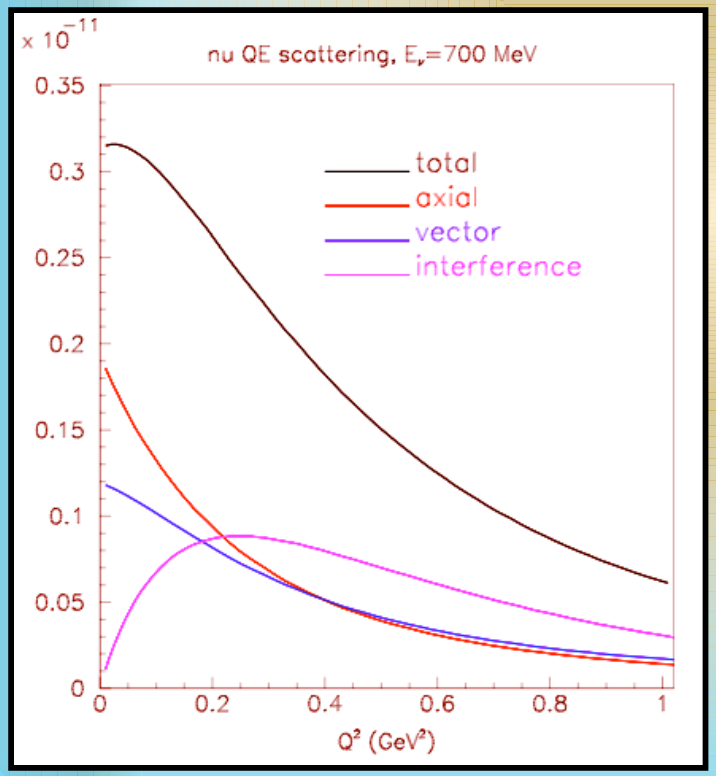
→ allows precise antineutrino σ measurements

(once have a handle on ν backgrounds)

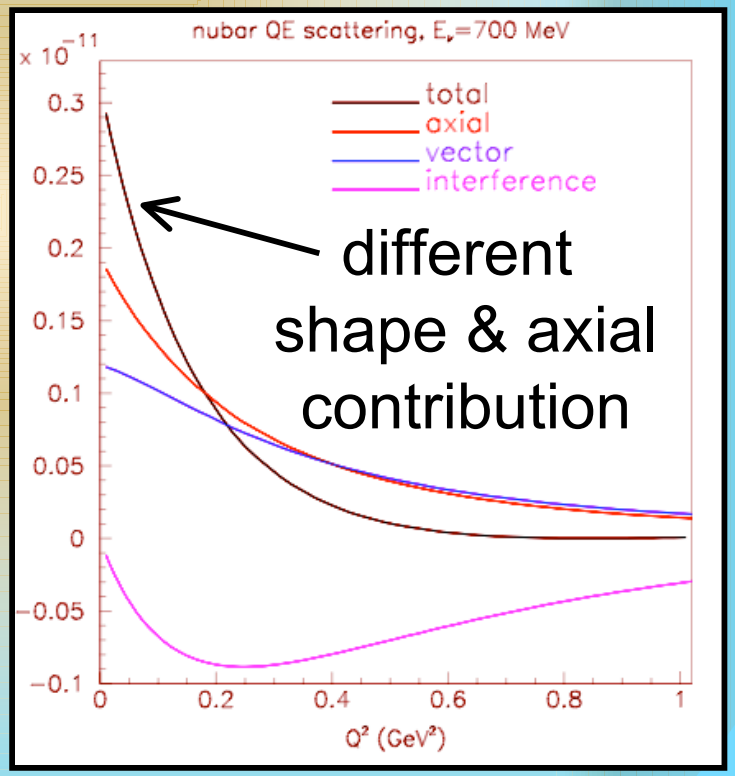
Antineutrino σ Measurements

- can add new info by mere fact that $\overline{\nu}$ scattering is different

ν_μ QE



$\overline{\nu_\mu}$ QE



difference isolates interference term - directly α to axial FF

Antineutrino σ Measurements

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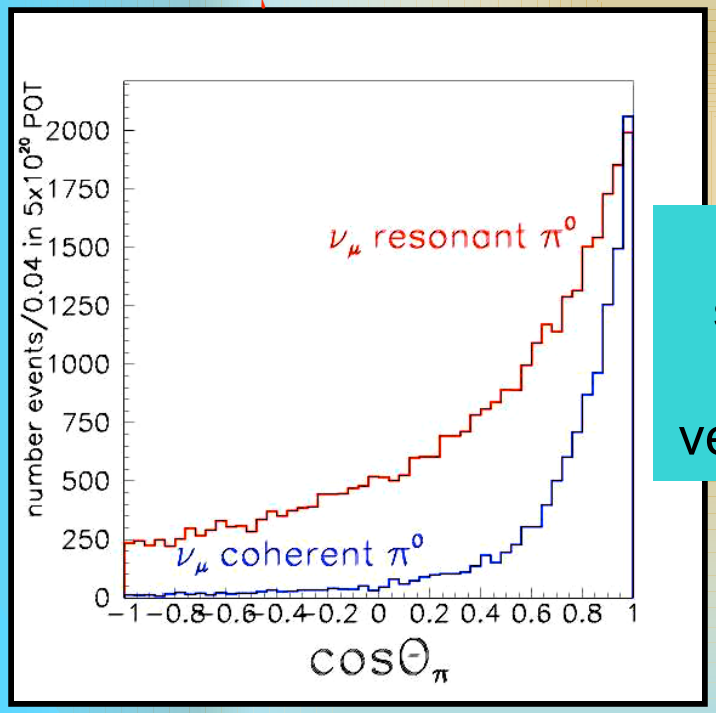
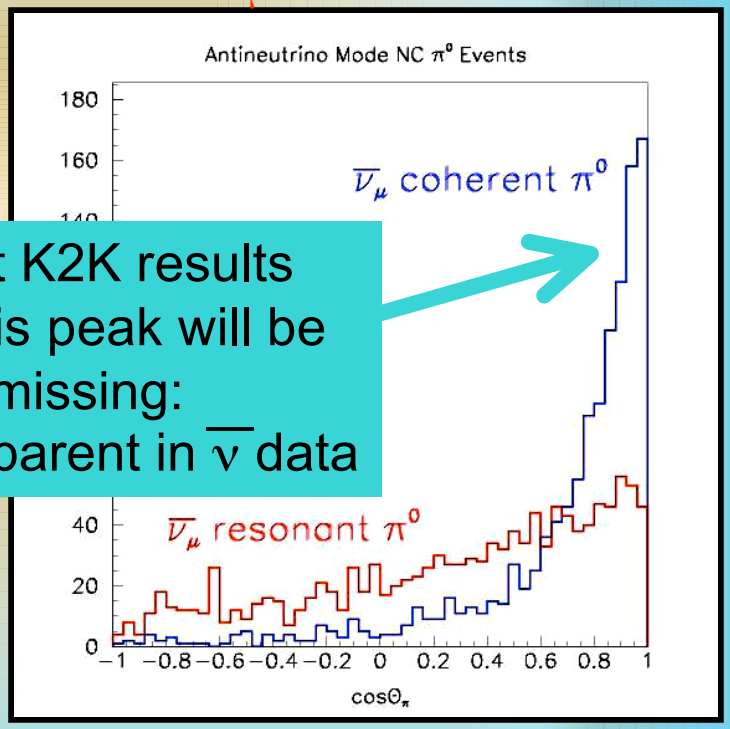
ν_μ NC π^0



- 20% is coherent production

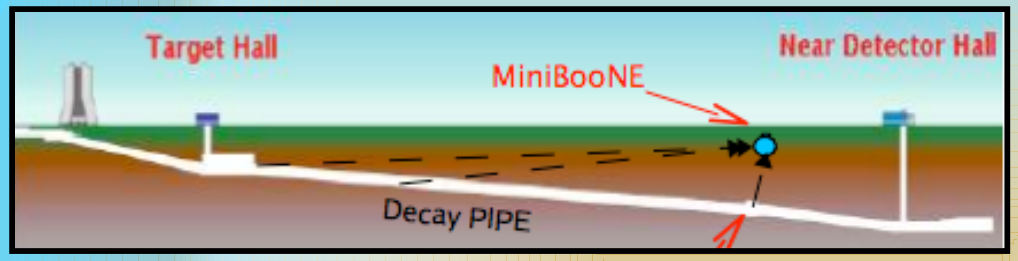
$\overline{\nu}_\mu$ NC π^0



latest K2K results say this peak will be missing: very apparent in $\overline{\nu}$ data

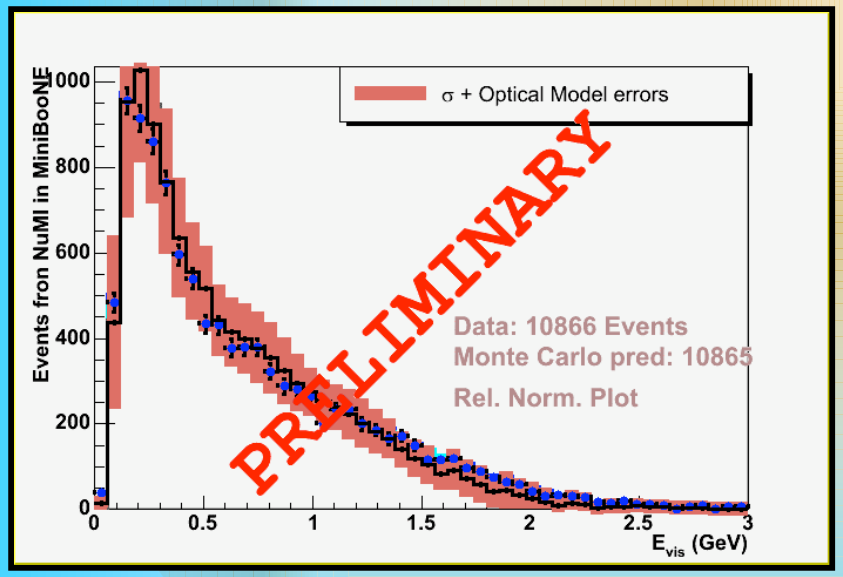
- 40% is coherent production
- "enhanced" coherent sample

Can Detect ν's from NuMI !



- neighbor's beam
- first off-axis neutrino beam!

(A. Aquilar-Arevalo)

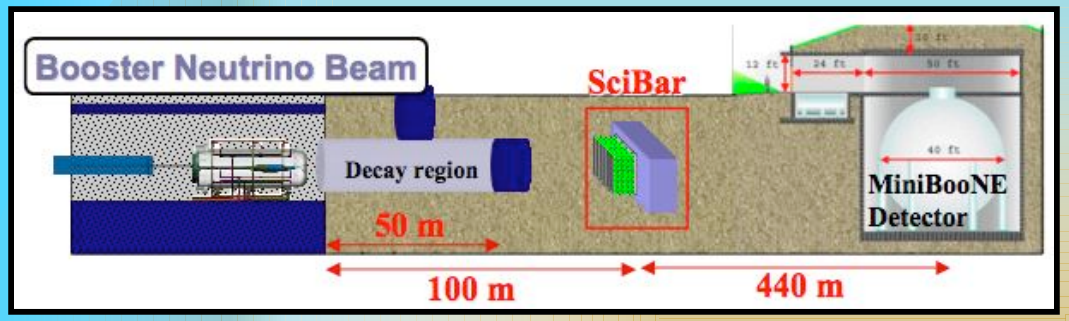


NuMI ν events in MiniBooNE detector

- ~10,000 ν events so far
- 100's of ν_e events (calibration)
- also opened up possibility to use this sample for σ_ν meas (slightly diff beam spectrum)

- MINOS also sees MiniBooNE neutrinos in their detector

SciBooNE (E954)



- new Int'l collaboration

- couple well-understood, fine-grained detector with high rate beam
- unique, low risk opportunity

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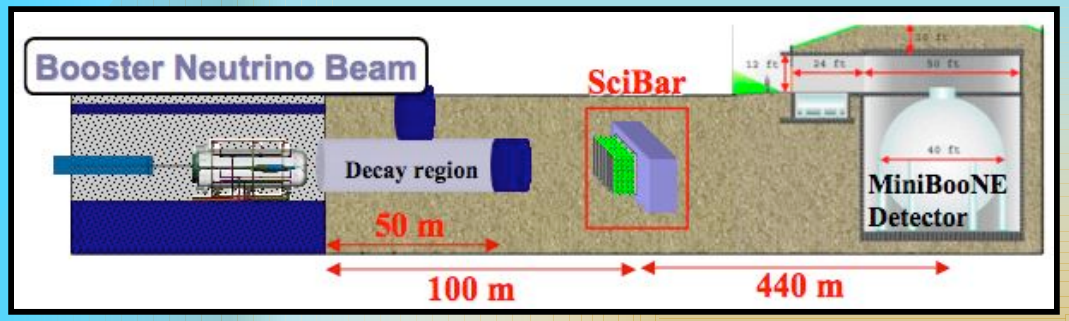

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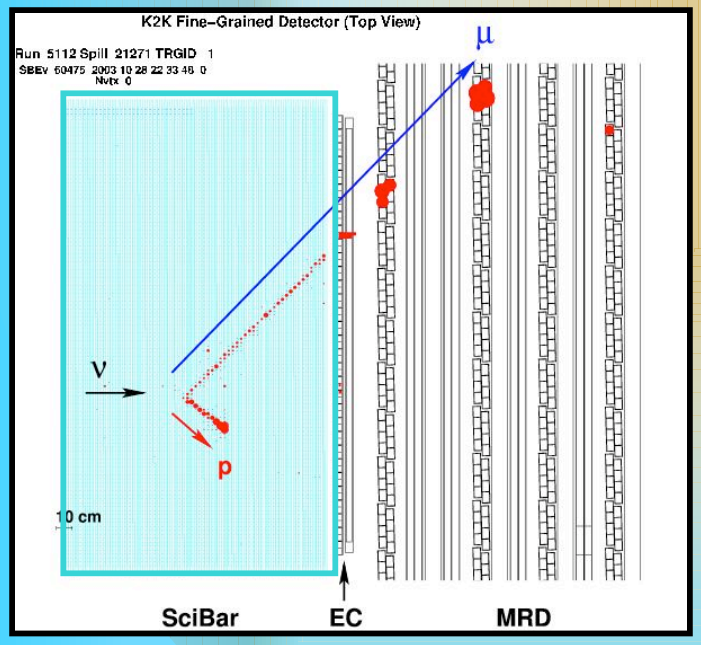

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- excellent final state resolution
- improve on MiniBooNE $\nu, \overline{\nu}\ \sigma$ studies

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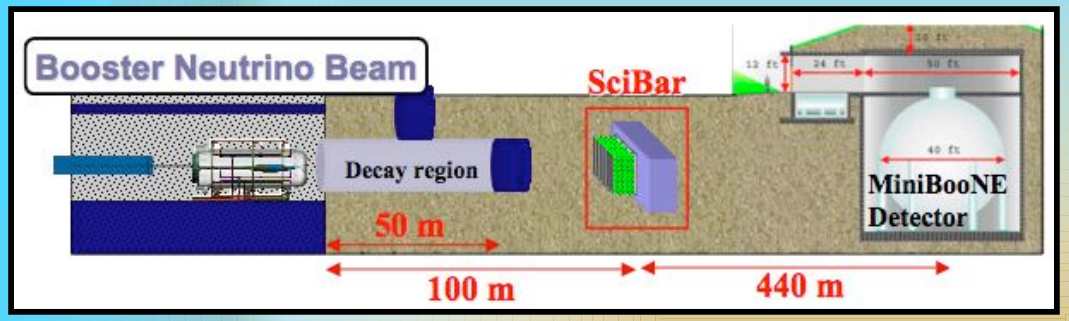

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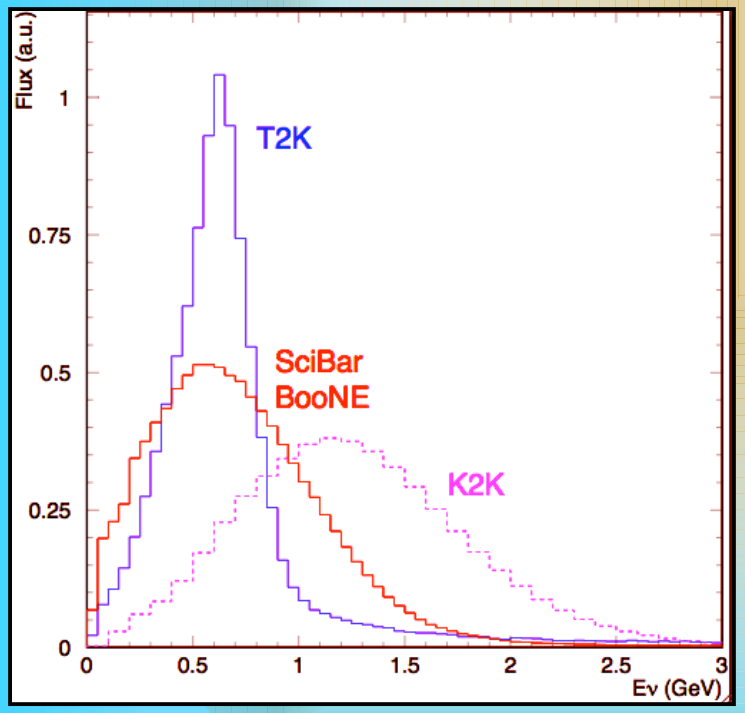

- couple well-understood, fine-grained detector with high rate beam
- unique, low risk opportunity
- excellent final state resolution
  - improve on MiniBooNE $\nu, \overline{\nu}$ σ studies
  - σ_ν measurements for T2K

- just received Stage 1 approval (Dec '05) rapid schedule: begin data taking this Fall
- www-sciboone.fnal.gov

Conclusions

- **collected > 700k neutrino (> 1k antineutrino) events (7 x 10^{20} POT)**
  - amassed the world's largest ν sample in 1 GeV range
  - already an order of magnitude more data than previous bubble chamber based measurements
  - part of effort to help improve our current understanding of low E σ_ν
  - 1st results on MiniBooNE CC π^+/QE cross section
- **coming soon …**
  - ν_μ CC QE cross section results
  - NC π^0 cross sections

  } ν cross sections

  - HARP results (8 GeV, Be, thick target) → ν flux
- **stay tuned for $\nu_\mu \rightarrow \nu_e$ oscillation results**