Recent Neutrino Interaction Measurements

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TRIUMF
PIC Conference, 3-Sept-2010

Neutrinos: more than just missing E_T...

ν Interactions and Oscillations

- Neutrino oscillation experiments have now moved into the realm of precision physics
- Cross section uncertainties are now becoming an important factor in interpreting oscillation data
- The next generation of accelerator-based neutrino experiments all take place at the ~1 GeV neutrino energy scale
- In the last few years, several new cross section measurements have been reported at these energies

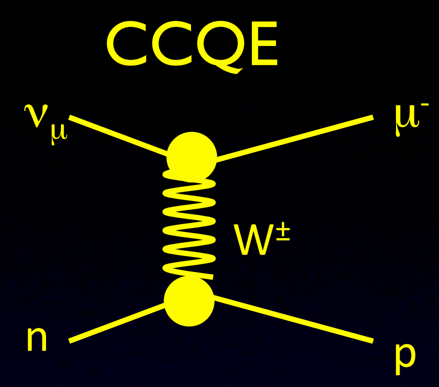
MiniBooNE ν_e Appearance Systematic Uncertainties

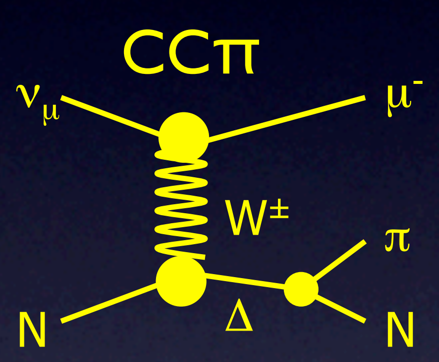
Source	Error (%)
Flux from π^+/μ^+ decay	6.2
Flux from K+ decay	3.3
Flux from K0 decay	1.5
Target and beam models	2.8
ν cross sections	**12.3**
NC π^0 yield	1.8
External interactions ("Dirt")	0.8
Optical model	6.1
DAQ electronics model	7.5

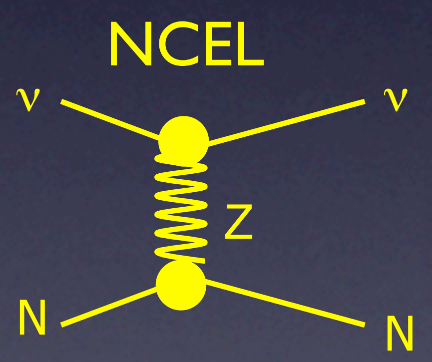
Conrad & Lewis, FNAL Wine and Cheese, Apr 11, 2007
Information from Phys. Rev. Lett. 98 231801 (2007)

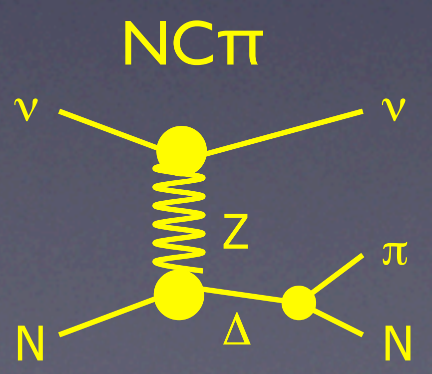
ν Interactions at the GeV Scale

- The simplest charged current interaction converts a neutron to a proton
  - Charged Current Quasi-Elastic (CCQE)
- If the $W^{\pm}$ excites the target nucleon into a resonance state, it can produce a nucleon and a pion
  - Charged Current Pion Production ($CC\pi^{+,0}$)





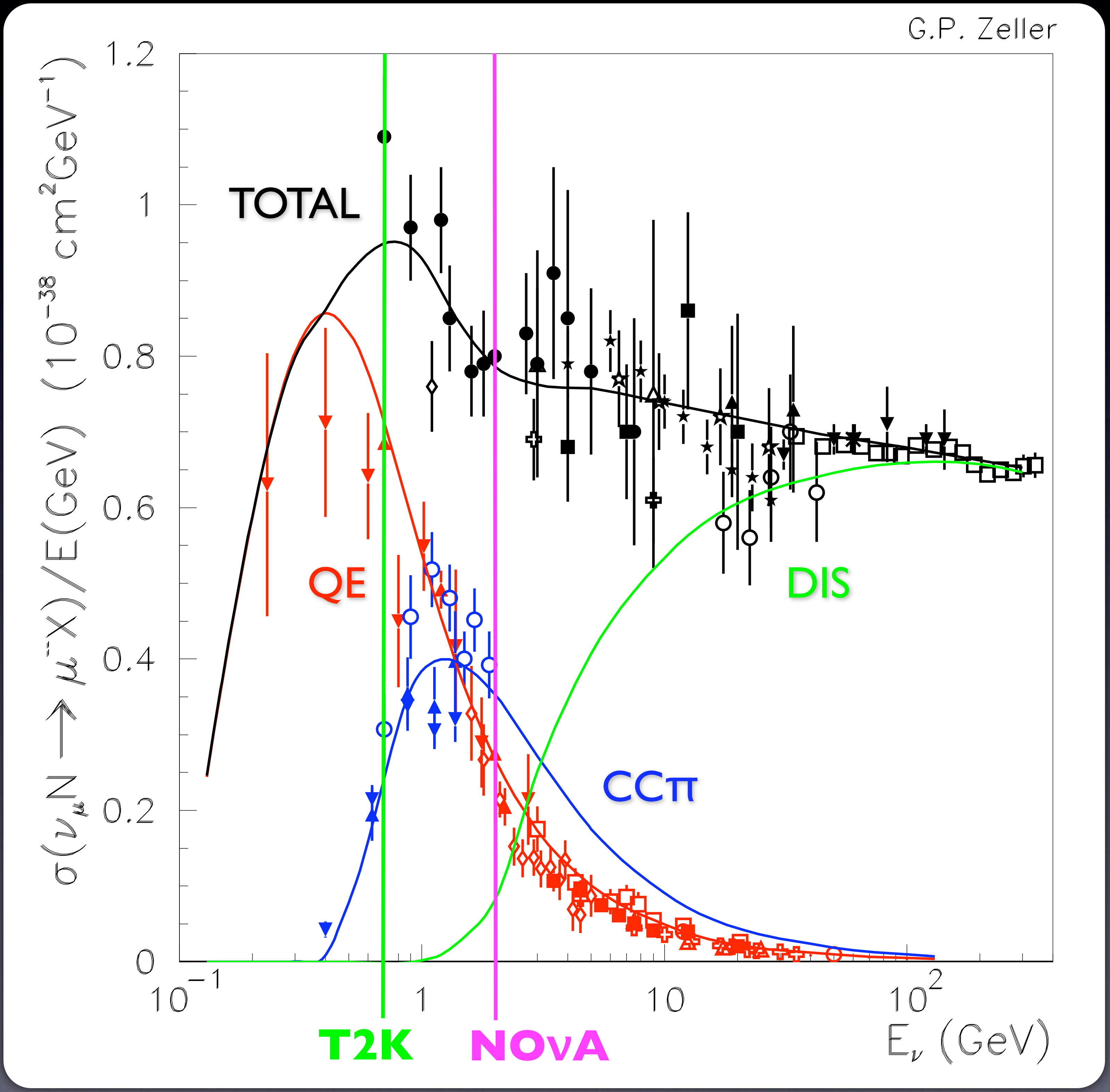




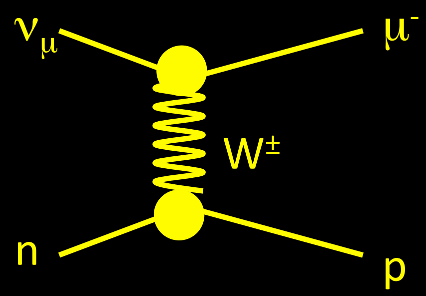
- A neutral current interaction can result only in the ejection of a target nucleon
  - Neutral Current Elastic (NCEL)
- Pions can be produced via neutral currents as well
  - Neutral Current Pion Production ($NC\pi$)
- Other higher-mass hadronic states are possible, but are suppressed at the ~1 GeV scale

Charge Current Interactions (circa 2006)

- The new generation of neutrino oscillation experiments will take place at the GeV scale
- ν_μ and ν_e CCQE interactions are the signal modes for these experiments
  - Simple, single lepton reconstruction
  - Allows for flavor tagging the neutrino
- The largest charged current background (or additional signal?) is $CC\pi^+$
- Recent experimental results in neutrino cross sections have focused on CCQE and $CC\pi$



CCQE Interactions



- The differential cross section contains 3 terms that contain all of the complexity of the hadronic current:

$$\frac{d\sigma}{dQ^2} = \frac{M^2 {G_F}^2 cos^2\theta_c}{8\pi {E_\nu}^2} \left\{ A(Q^2) \pm B(Q^2)\frac{(s-u)}{M^2} + C(Q^2)\frac{(s-u)^2}{M^4} \right\}$$

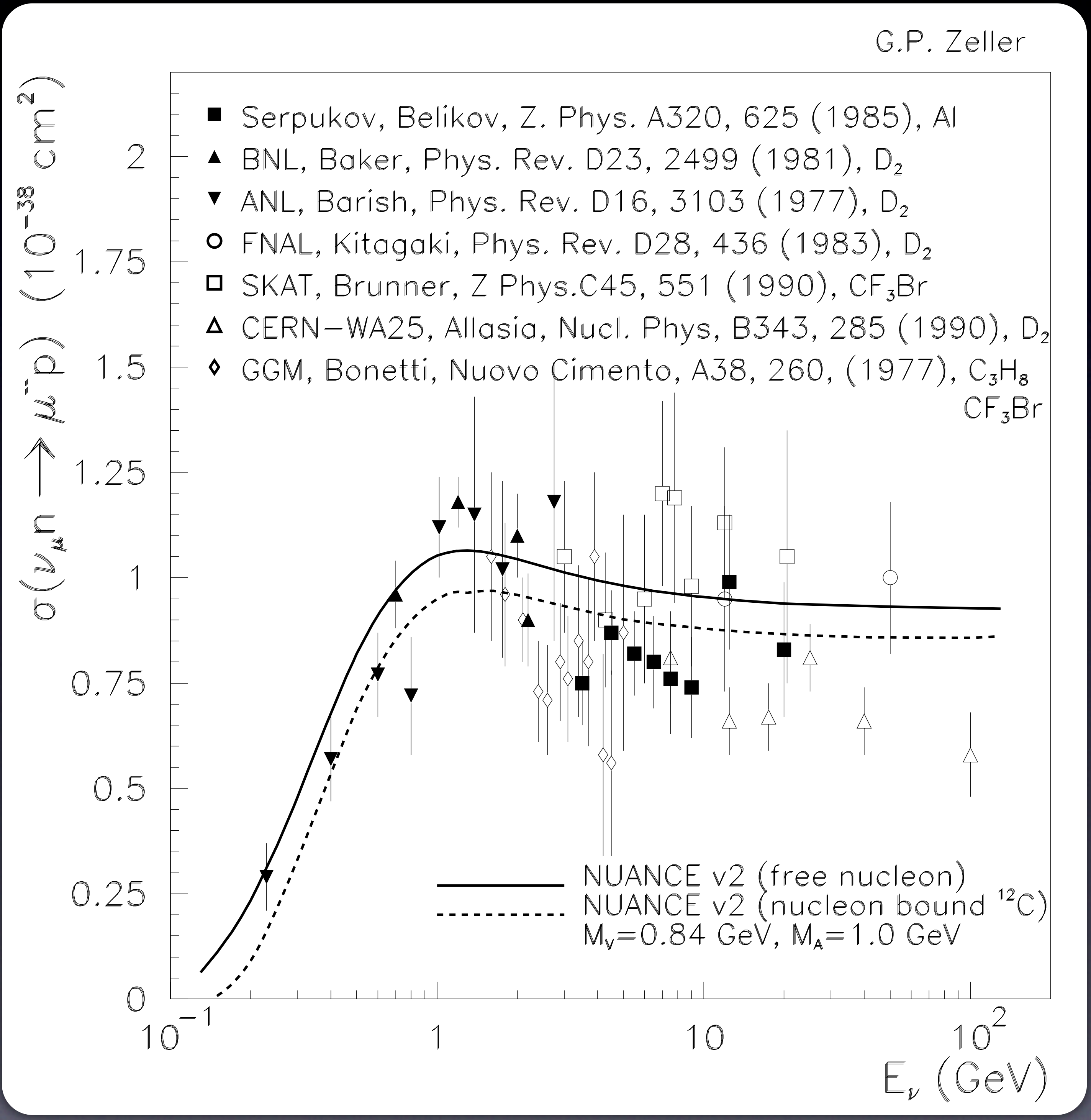
- Each term is parametrized by 3 form factors
  - 2 vector form factors; well determined from electron scattering
  - 1 axial-vector form factor assumed to have a dipole form:

$$F_A(Q^2) \quad = \quad -\frac{g_A}{\left(1+\frac{Q^2}{M_A^2}\right)^2}$$

- g_A is precisely determined in neutron beta decay experiments
- Only remaining free parameter is the axial mass, M_A
  - Accessible only via weak interactions (not via electron scattering)
- M_A can be measured via the shape of the Q^2 distribution, or the value of the total cross section

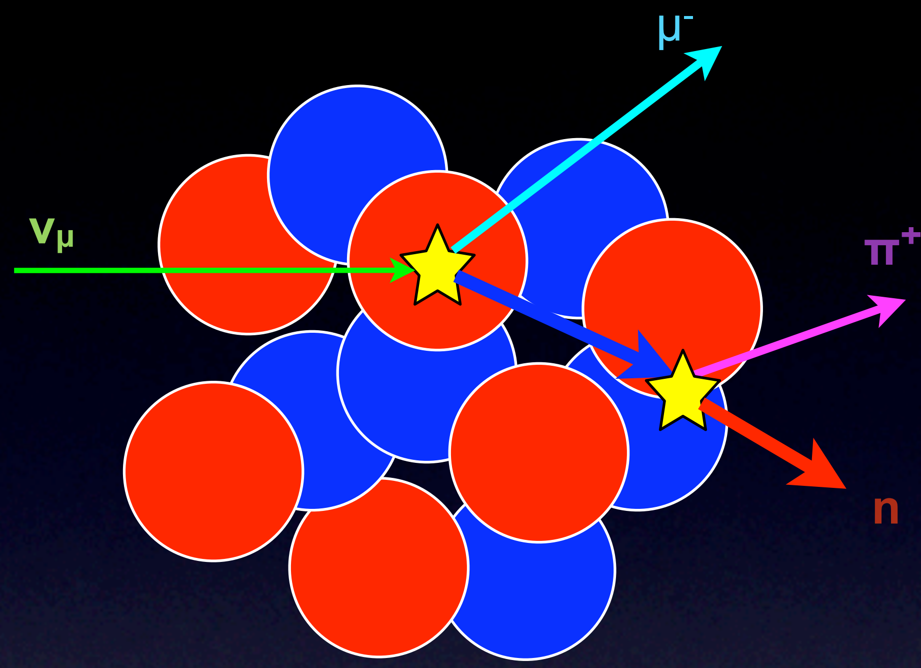
Previous CCQE Measurements

- At low energies (~1 GeV), measurements were provided by bubble chamber experiments (D_2)
- Typically O(1,000) events per experiment
- Often large uncertainties from flux determination and background contamination
- World average from these experiments: $M_A = 1.026 \pm 0.021$ GeV

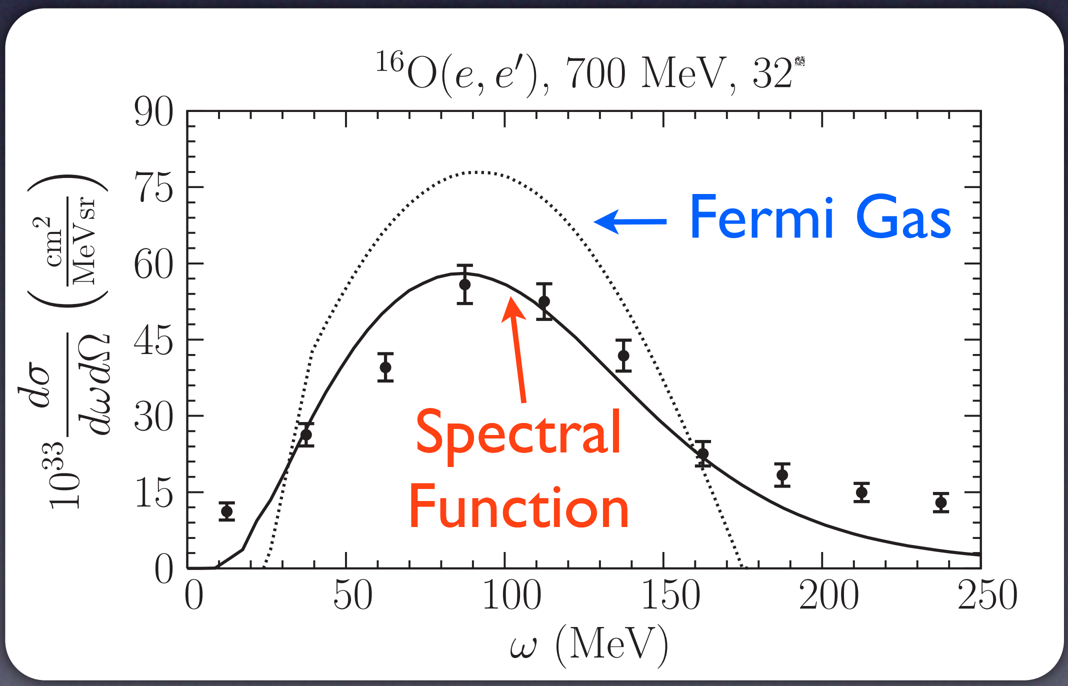


Nuclear Effects

- The new generation of oscillation experiments all use nuclear targets
- Introduces more physics to worry about
  - Event generators used by experimentalists typically describe nucleus as a **relativistic Fermi gas**
    - Theorists typically use more sophisticated models (e.g. spectral functions)
  - Final states containing a nucleon below the Fermi momentum are **Pauli-blocked**
  - Nucleons must overcome a **binding energy** before being freed from the nucleus
  - Target nucleons and resulting resonances are **off-shell**
- After the initial interaction takes place, final state particles must traverse the nuclear medium before being observed
  - **Pion absorption and charge exchange** can alter the observed interaction channel
- Event generators use **impulse approximation**
  - Neutrinos assumed to interact with a single nucleon
  - Not a good approximation in all regions of phase space

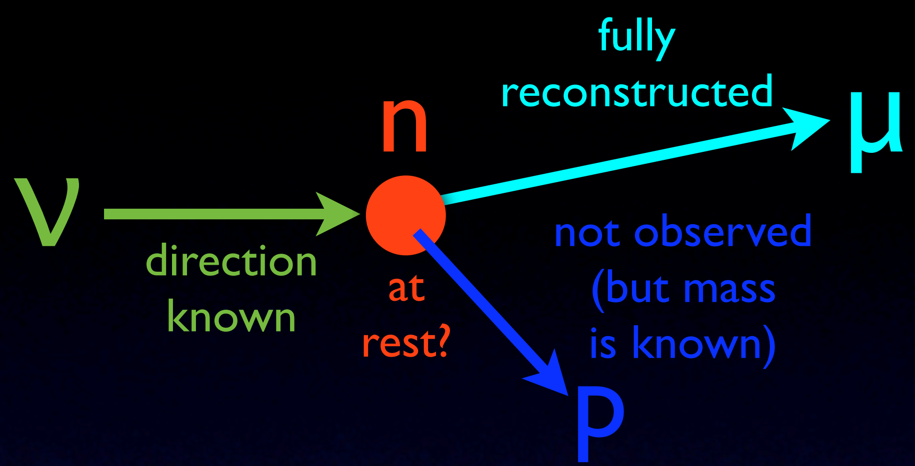


Fermi Gas vs Spectral Function in Electron Scattering on ^{16}O



A. Ankowski & J. Sobczyk
PRC 77, 044311 (2008)

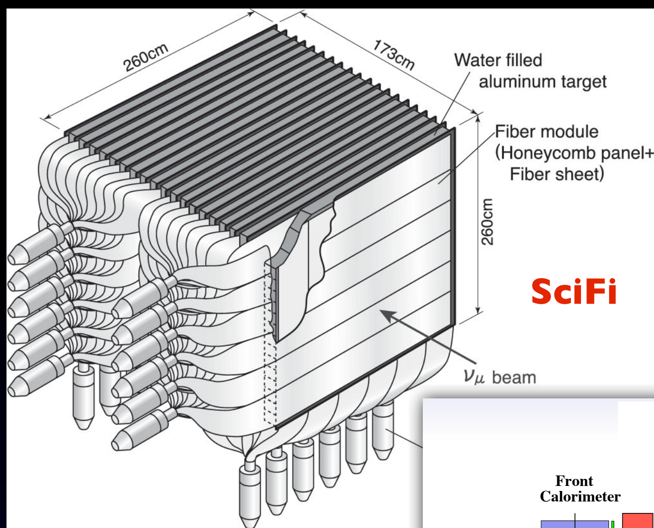
Measuring E_ν^{CCQE}

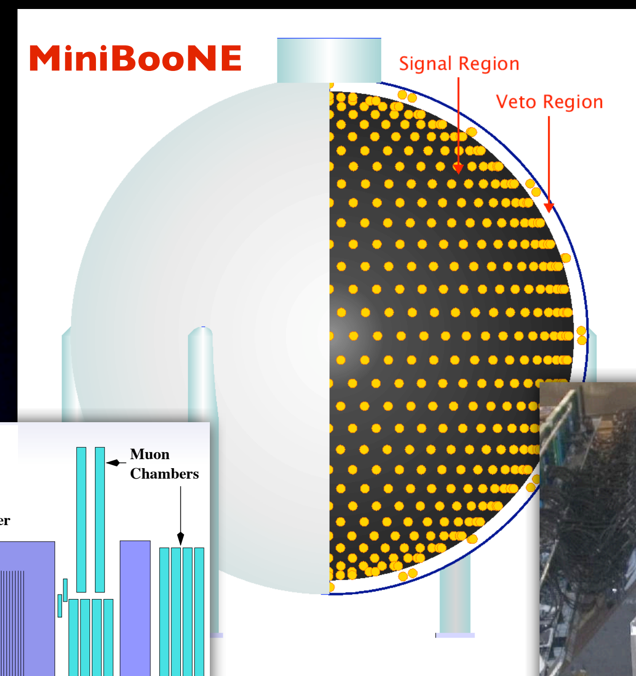


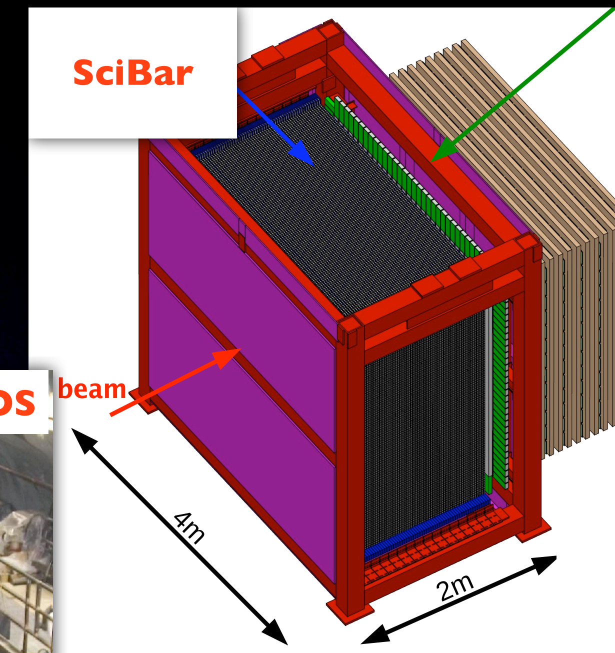
$$E_\nu^{QE} = \frac{2(M_n')E_\mu - ((M_n')^2 + m_\mu^2 - M_p^2)}{2 \cdot [(M_n') - E_\mu + \sqrt{E_\mu^2 - m_\mu^2} \cos\theta_\mu]}$$

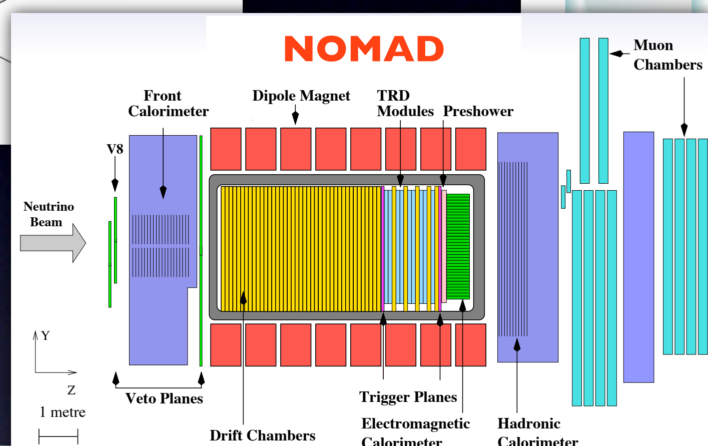
- The neutrino energy is determined from the final state particle kinematics
- If only the outgoing muon 4-momentum is measured, Eν is determined assuming:
  - **The neutrino direction is known (good assumption)**
    - Detectors are far from the beam source
  - **The recoiling nucleon mass is known (good assumption)**
    - Warning: this is only valid when the impulse approximation is valid (e.g. multi-nucleon interactions are reconstructed with a bias in E_ν)
  - **The target nucleon is at rest (not a very good assumption)**
    - Adds an irreducible smearing to the neutrino energy resolution
- In some cases, both the muon and proton kinematics are measured
  - Above assumptions can be relaxed

Recent M_A Measurements





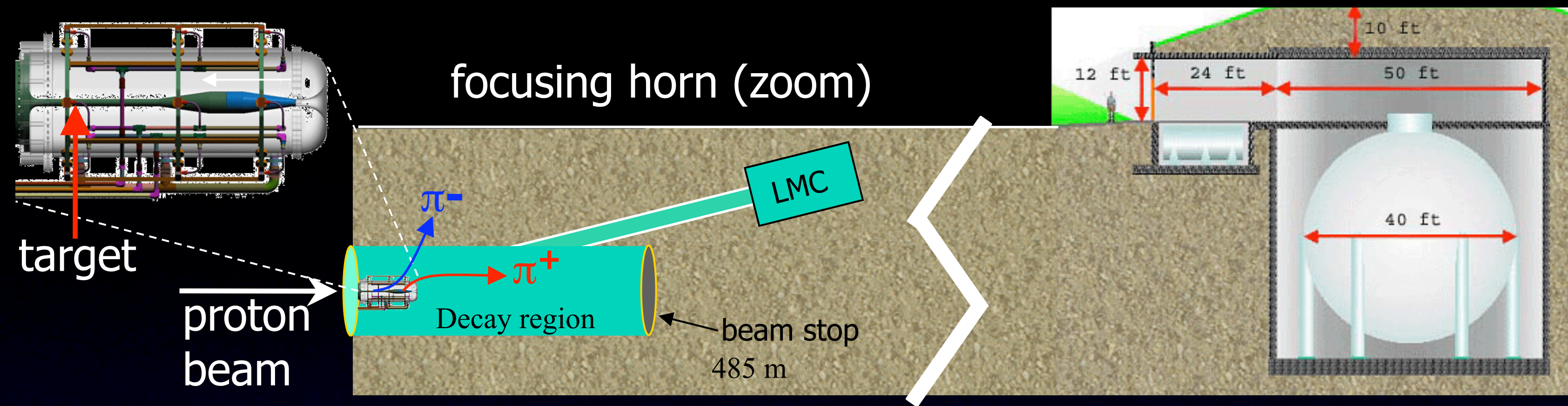




Experiment	Detector	Target	peak E_ν
K2K-SciFi	Scintillating Fiber + MRD	O	1.2 GeV
MiniBooNE	Oil Cherenkov	C	0.7 GeV
MINOS	Scintillating Bars	Fe	3, 6, 9 GeV
NOMAD	DCs + TRD + ECAL + MRD	C	12 GeV
SciBar	Scintillating Bars + MRD	C	0.7, 1.2 GeV

Neutrino Flux Predictions

Beamline for MiniBooNE & SciBooNE

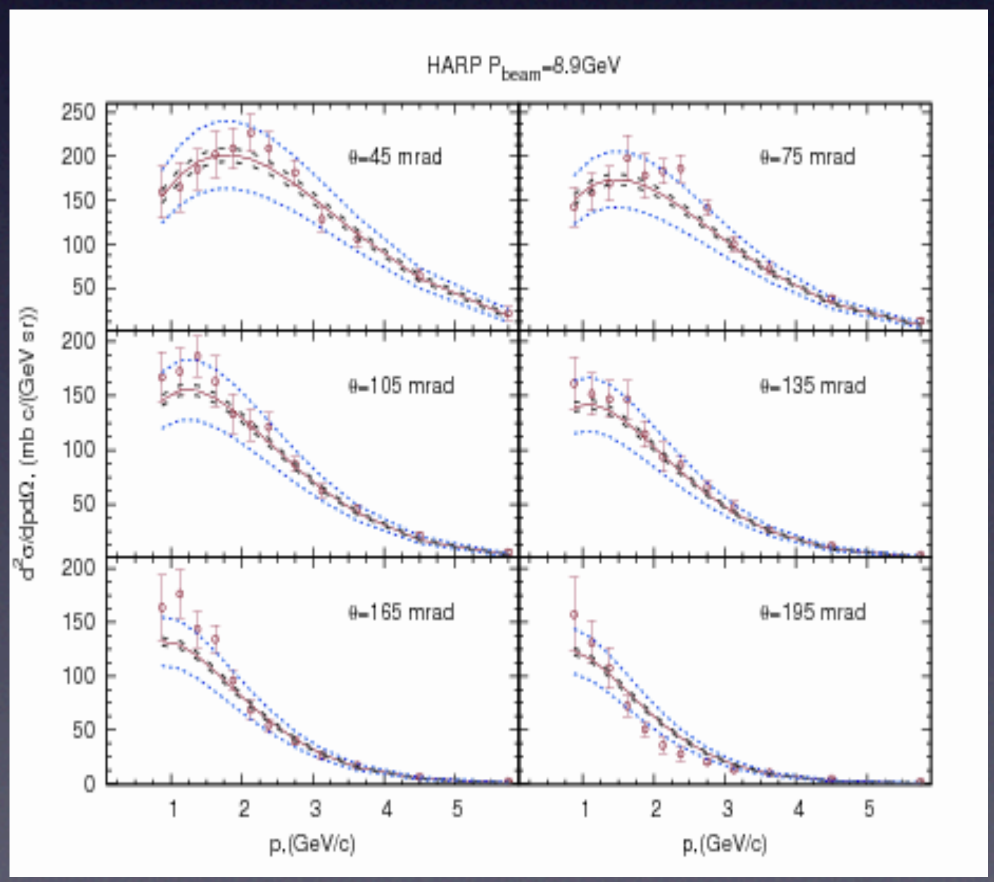


- To measure a neutrino cross section, must understand the neutrino flux, Φ (i.e. energy spectrum + normalization)

$$\sigma = N_{interactions}/\Phi$$

- Protons → target interactions → pion production → horn focusing → pion decay to neutrinos
- Dominant uncertainty is in pion production (in momentum and angle bins)
- Dedicated experiments measure pion production on replica targets (e.g. HARP for K2K & BooNEs; MIPP for NuMI)

HARP pion momentum spectra in 6 angular bins

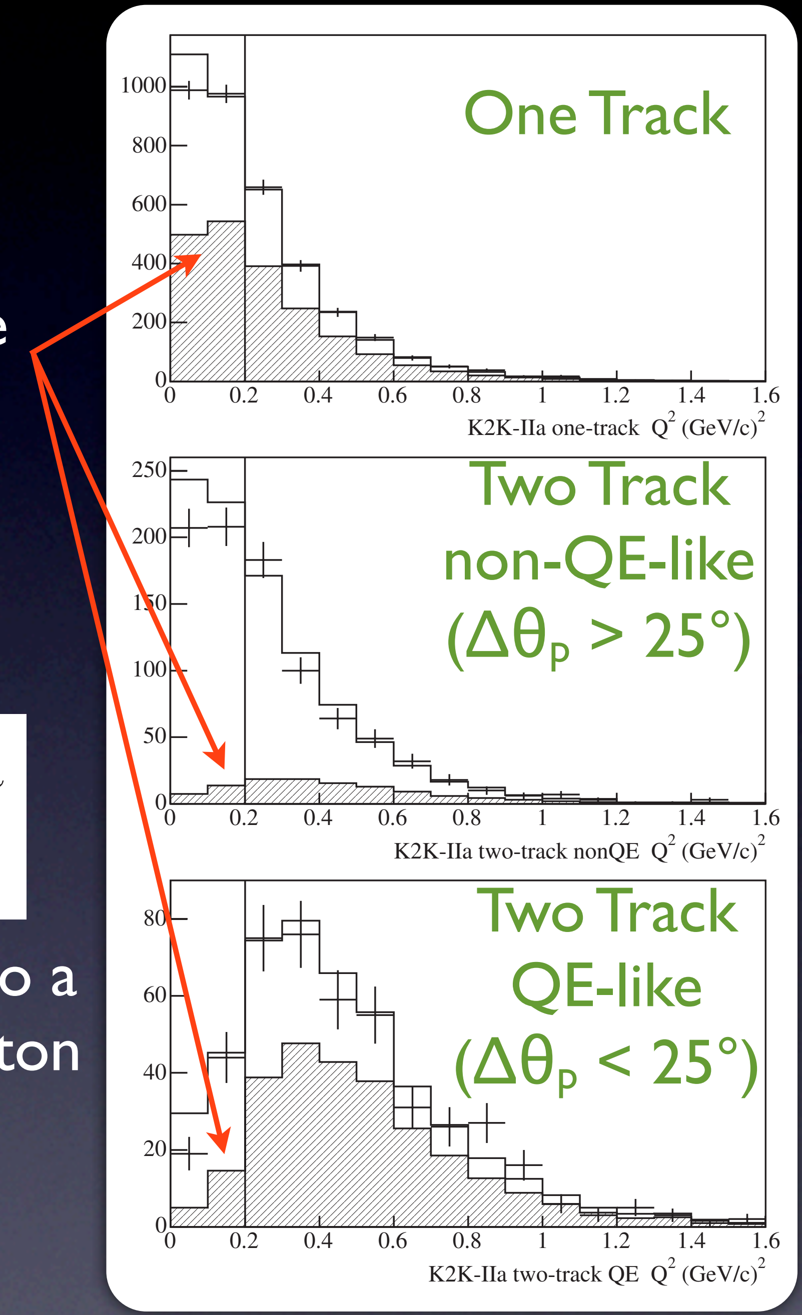


K2K-SciFi CCQE

- CCQE appears as one track (muon only) or two tracks (muon + proton)
- Two track sample contains CCπ^+ background
  - Since CCQE is a two-body scattering process, can separate CCπ^+ using expected proton angle
- Fit Q^2 shape for M_A
  - Only fit above 0.2 GeV^2 to avoid poorly modeled region
  - Notice the excess of simulated events in the lowest bin
  - **Measured M_A value is significantly higher than previous world average**

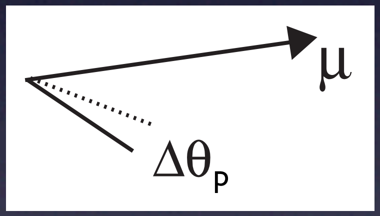
Q^2 (data & Best Fit MC)

MC true CCQE



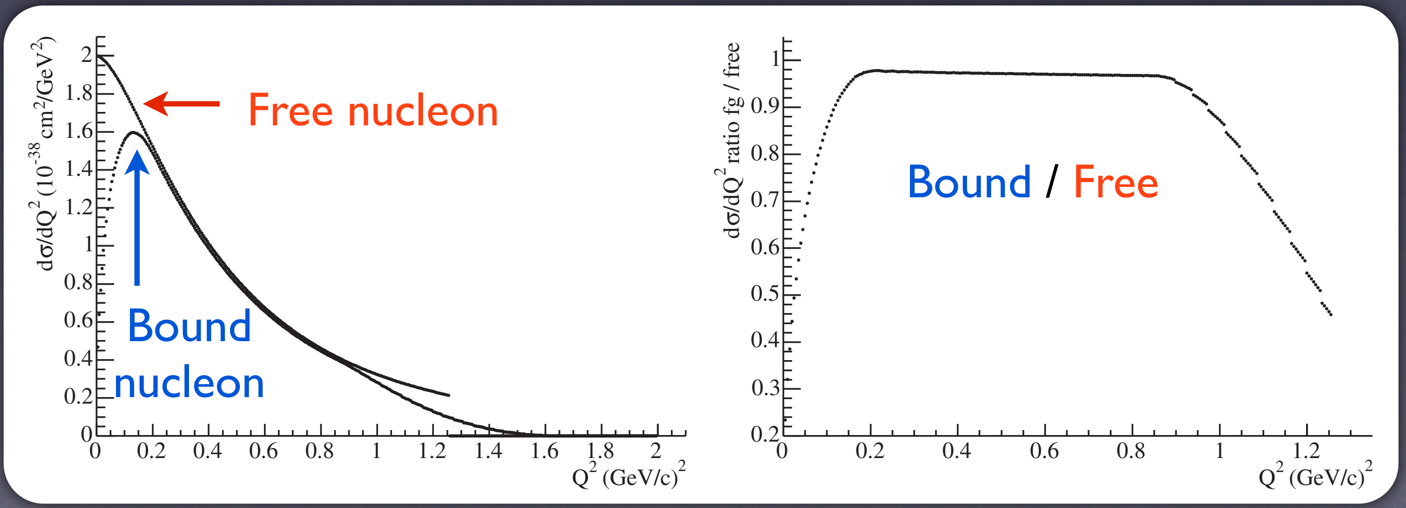
Phys. Rev. D74 052002 (2006)

CCQE $\Delta\theta_P$



Angle relative to a CCQE-like proton

Effect of target nucleon momentum

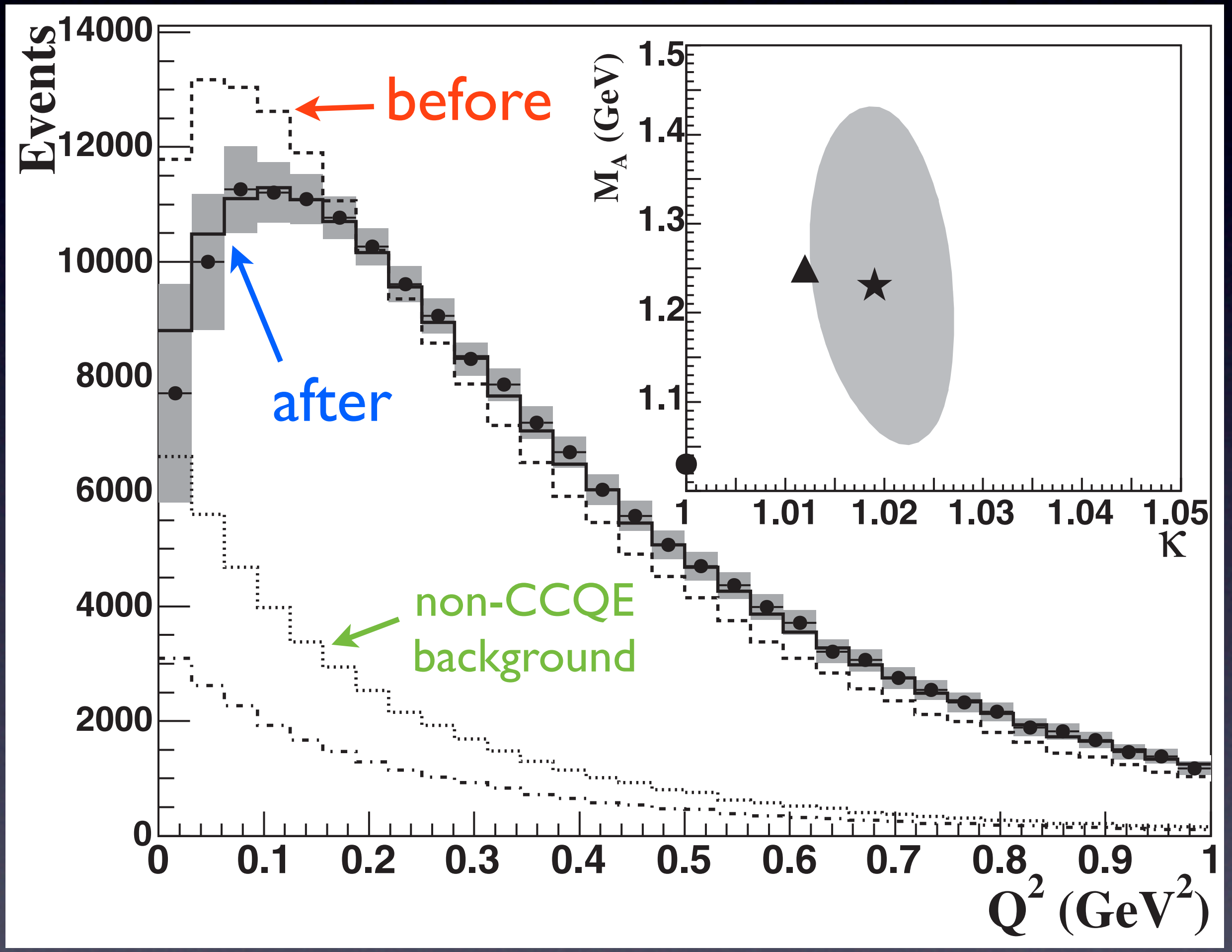


Measured M_A=1.20 +/- 0.12

MiniBooNE (2008)

- All CCQE events are one track
  - The proton is almost always below Cherenkov threshold
- Same low-Q^2 data deficit seen by K2K
- Introduce a new parameter, κ, that increases Pauli blocking at low Q^2
  - Effective parameter used only to compensate for inadequate modeling
  - Still does not completely fix low Q^2 disagreement
- Fit Q^2 shape for M_A
  - Result is 20% higher than world average: **<u>same as K2K</u>**

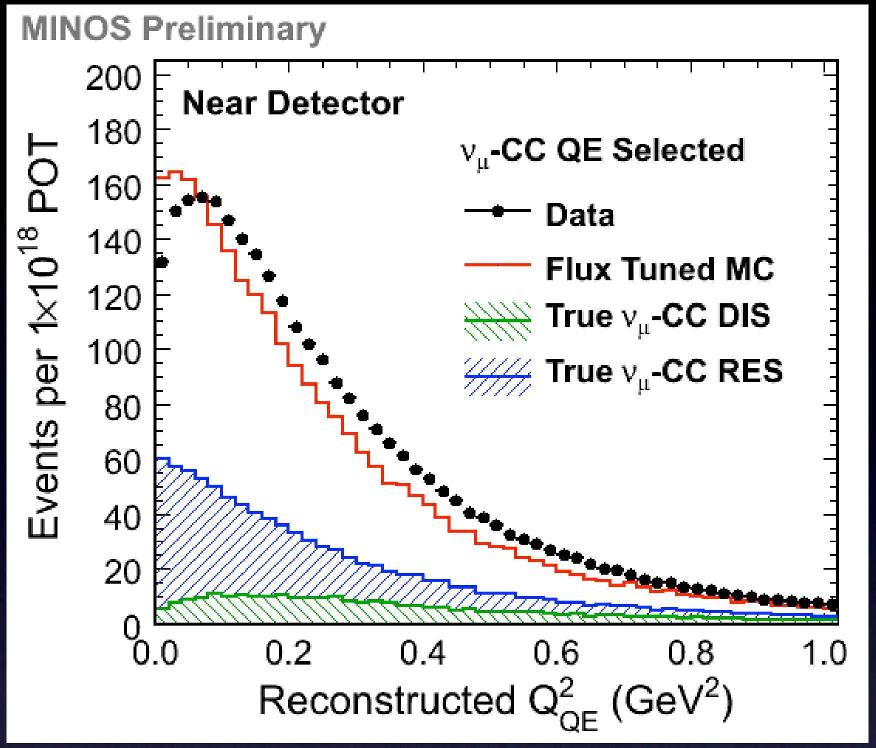
Data / MC Comparison Before and After Fit

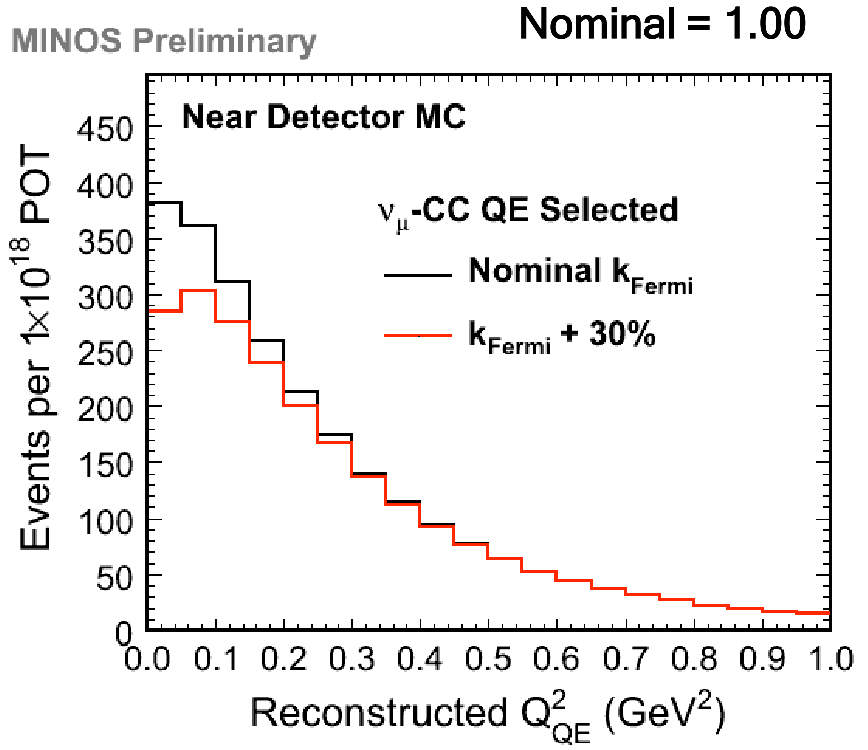


Measured M_A=1.23 +/- 0.12

MINOS Preliminary M_A

- Neutrino interactions on an iron target
- Events are selected with one muon track and low hadronic shower energy
- Once again, strong suppression in the data at low Q^2
- Once again, Pauli blocking is modified to account for the difference
- Two fits are performed (fit parameters: M_A^{CCQE}, $M_A^{CC\pi+}$, E_μ scale):
  - Fit above 0.3 GeV2 with k_{Fermi} fixed to 1
  - Fit entire range including k_{Fermi} parameter
- Both fits give results consistent with K2K and MiniBooNE





Q^2 > 0.3 GeV^2 Fit

Parameter	M_A^{QE} (GeV)	E_μ-Scale	$M_A^{CC\pi+}$ (GeV)
Best Fit	1.256	0.988	1.065

Effective M_A^{QE}

$1.26^{+0.12}_{-0.10}$ (fit) $^{+0.08}_{-0.12}$ (syst) GeV

Fit to Full Q^2 Range

Parameter	M_A^{QE} (GeV)	E_μ-Scale	$M_A^{CC\pi+}$ (GeV)	k_{Fermi}-Scale
Best Fit	1.192	0.988	1.112	1.284

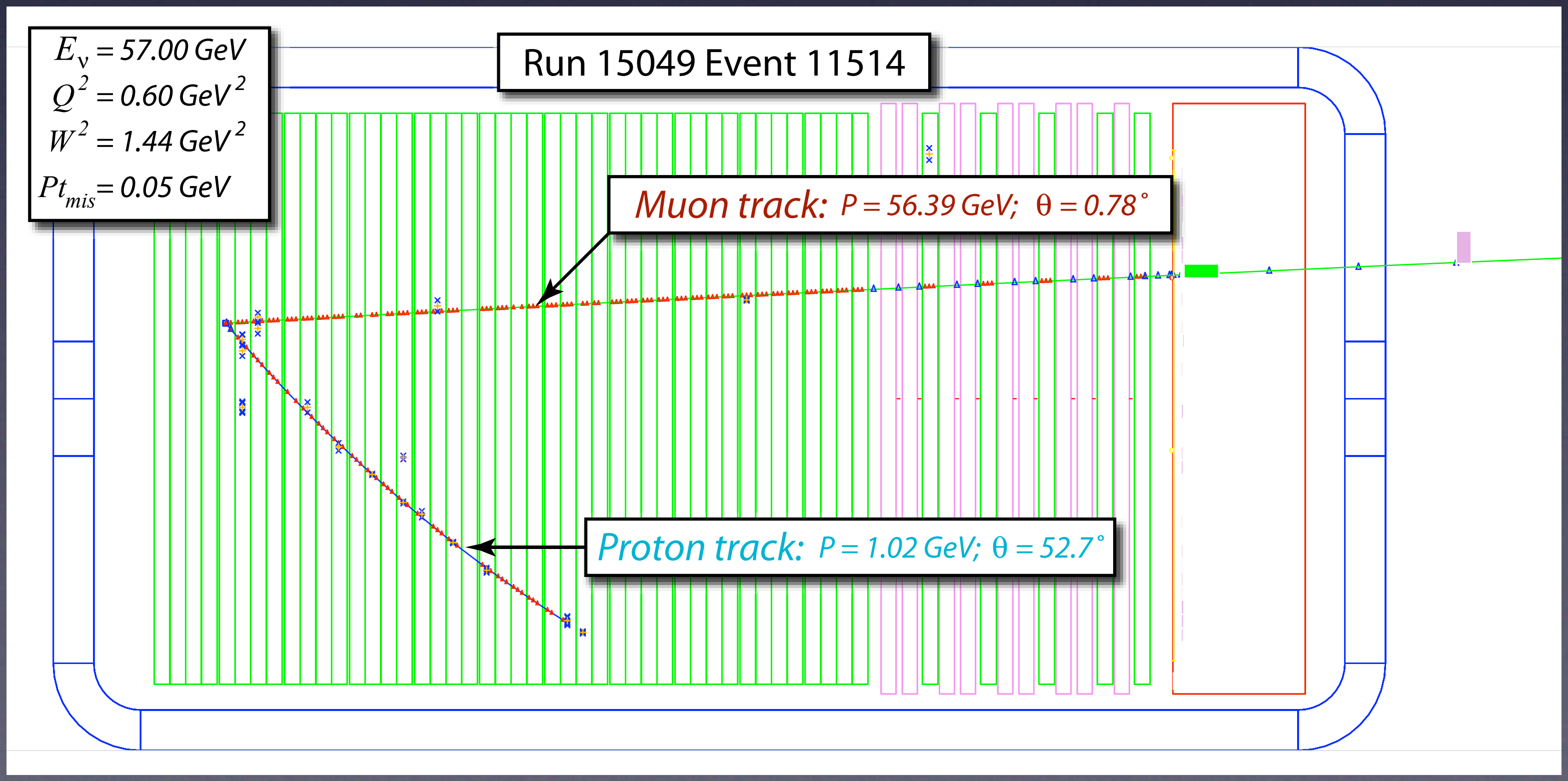
Effective M_A^{QE}

$1.19^{+0.09}_{-0.10}$ (fit) $^{+0.12}_{-0.14}$ (syst) GeV

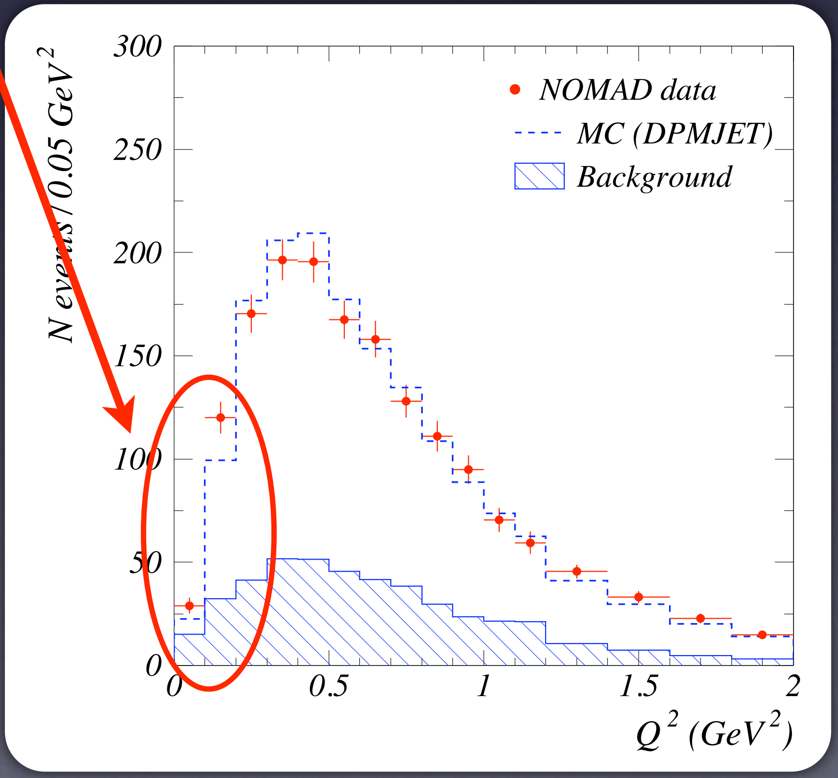
M. Dorman, NuInt 2009

NOMAD CCQE

- Higher neutrino energy (peak: ~12 GeV)
- Magnetic field allows for sign separation of final state particles
- Used known DIS cross section to normalize flux
- No low Q^2 deficit in data (as was seen in K2K, MiniBooNE, and SciBooNE)
- M_A consistent with previous world average
  $M_A = 1.05 \pm 0.06$ GeV
- Measurements are consistent for both neutrinos and anti-neutrinos

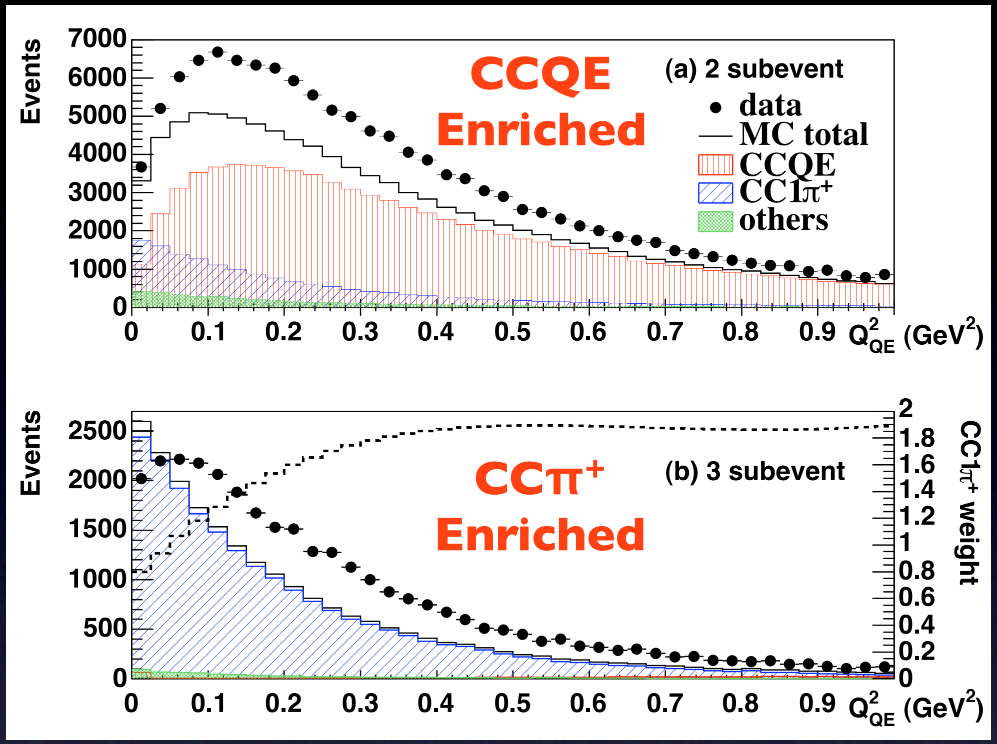


Eur. Phys. J. C63, 355 (2009)

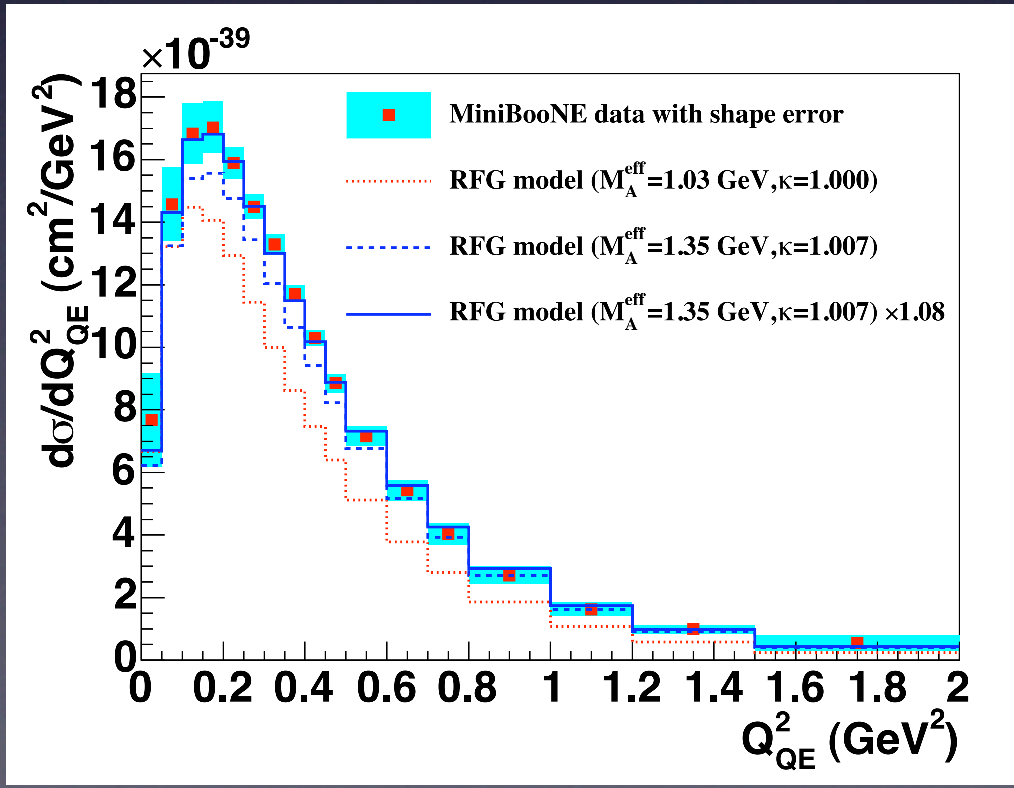


MiniBooNE Revisited (2010)

- Uncertainties in the M_A/κ fit included varying the $CC\pi^+$ background
  - This was accomplished by varying $M_A^{CC\pi}$ within existing experimental limits
  - Only works if the $CC\pi^+$ model is correct
- At low Q^2, the simulation of $CC\pi^+$ disagrees strongly with the data (revisted in a few slides)
- MiniBooNE can isolate a $CC\pi^+$ enhanced sample by selecting events with a stopped muon decay AND a stopped pion decay
- The Q^2 shape of the $CC\pi^+$ sample is extracted from data to correct the CCQE background subtraction
  - Resulting fit gives κ consistent with 1
  - Fit M_A value is even higher than before: $M_A = 1.35 \pm 0.17$
- After fitting for M_A, the simulated normalization disagrees by 8%
  - The interaction model is still not perfect



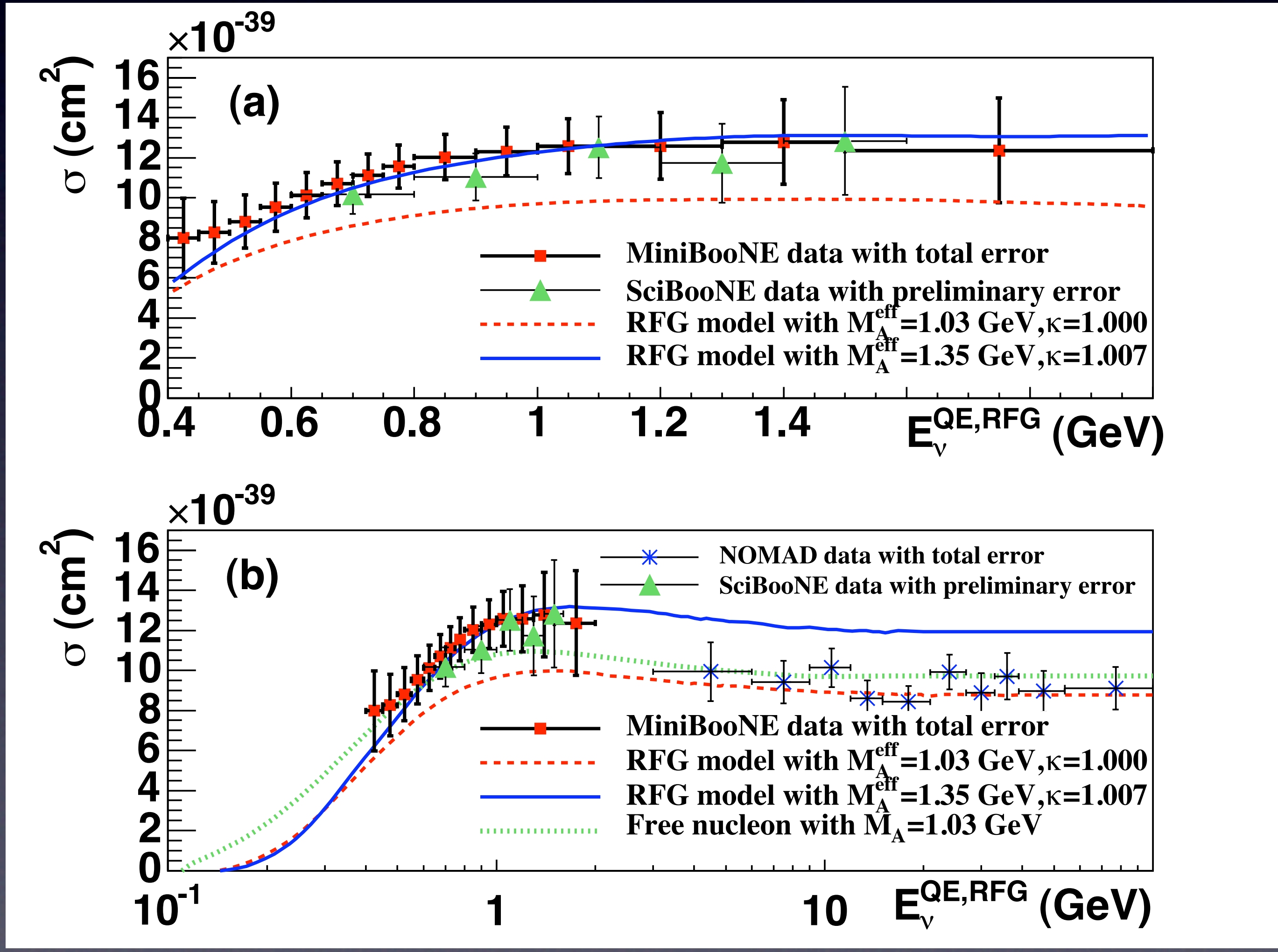
Phys. Rev. D81, 092005 (2010)



SciBooNE CCQE

- Measurement of the total cross section vs E_ν
- From normalization alone, data appear to be consistent with higher M_A
  - Recall, M_A determines both the Q^2 shape and the total cross section
- Q^2 fit results have not yet been released

MiniBooNE, SciBooNE, and NOMAD Total CCQE Cross Section Results

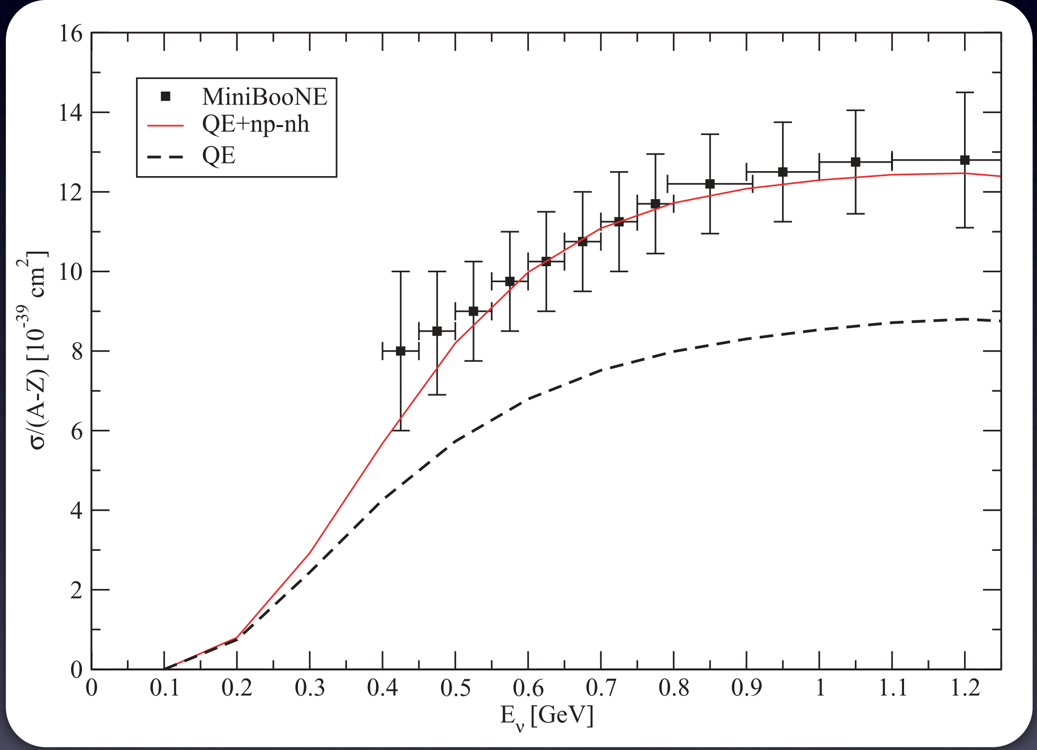


Plot by T. Katori

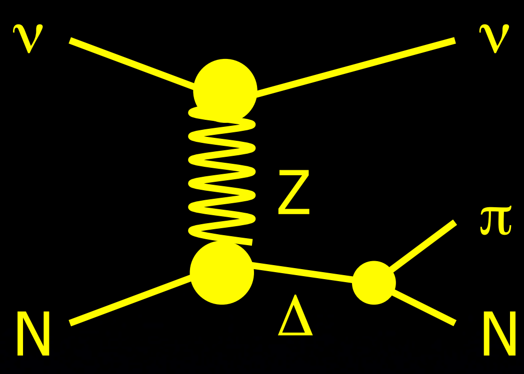
Nuclear Effects to the Rescue?

- Martini et. al. use a random-phase approximation (RPA) model to account for multi-nucleon interactions
    - Neutrino can simultaneously eject several nucleons from the nucleus
- The additional 2- and 3-nucleon contributions to the total cross section are large
    - The model can explain the MiniBooNE CCQE excess while maintaining an M_A of 1.032 GeV
    - Much smaller effect in deuterium → effect is small on older bubble chamber data
- Can this model also explain the NOMAD data?
- If true, this model has implications for neutrino energy reconstruction
    - Recoiling nucleon mass assumption is no longer valid

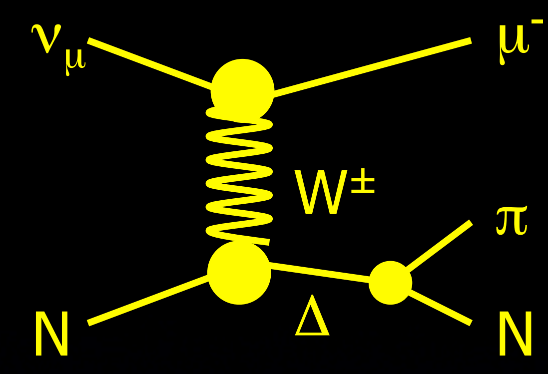
MiniBooNE Data compared to
- RFG with M_A = 1.03 (dashed)
- RPA with M_A = 1.03 (red line)



Phys. Rev. C80, 065501 (2009)



π Production Interactions

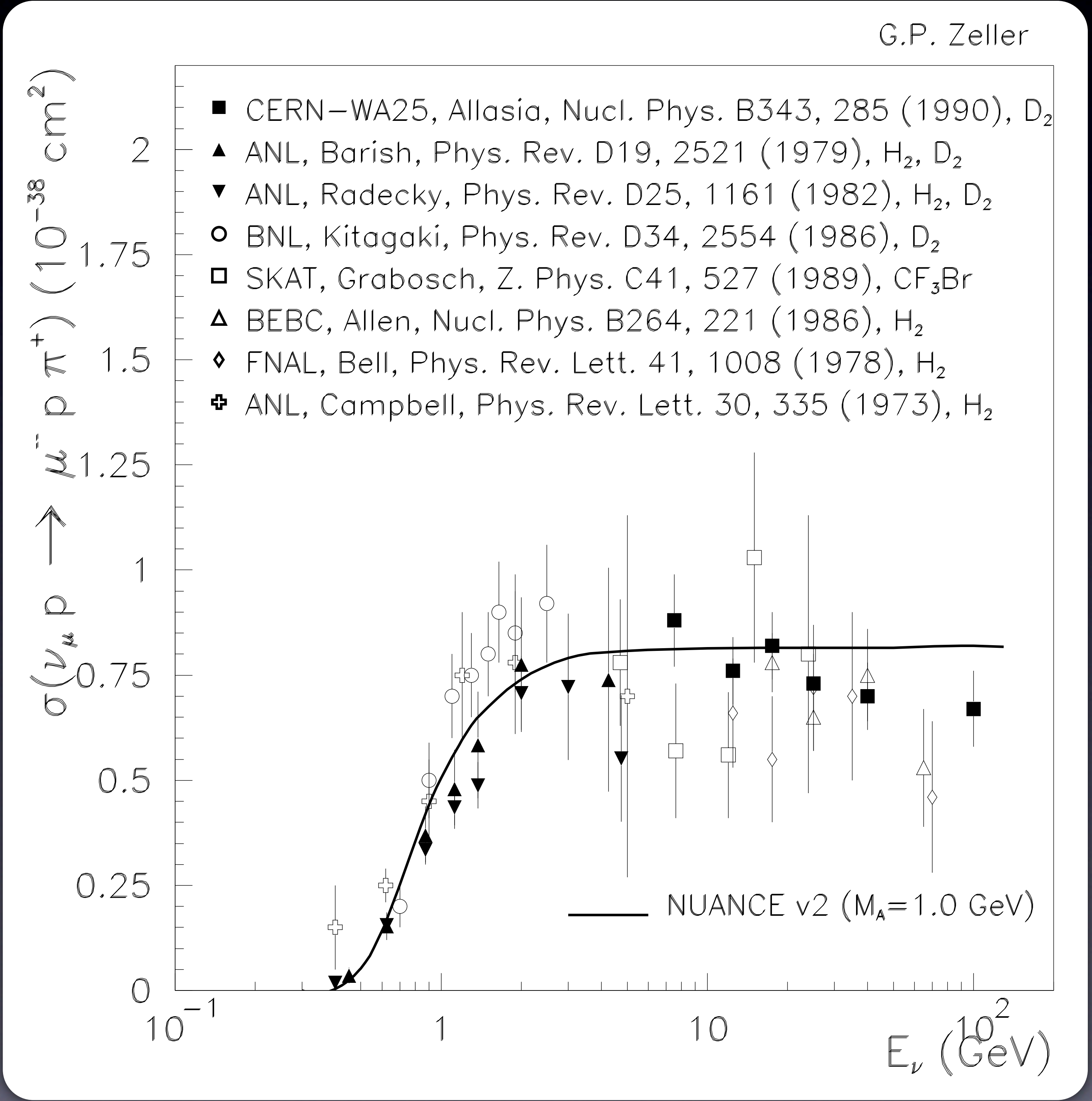


- All CC and NC pion production channels are described by the Rein-Sehgal model
  - Target nucleon is excited into a resonance state that decays to a nucleon and a pion
  - All 18 resonances below 2 GeV in mass are included in the calculation
- Axial form factor is again parametrized by M_A
- Final state interactions play a much larger role for pion production processes
  - Pion absorption and charge exchange interactions alter the observed final state

Previous CCπ Measurements

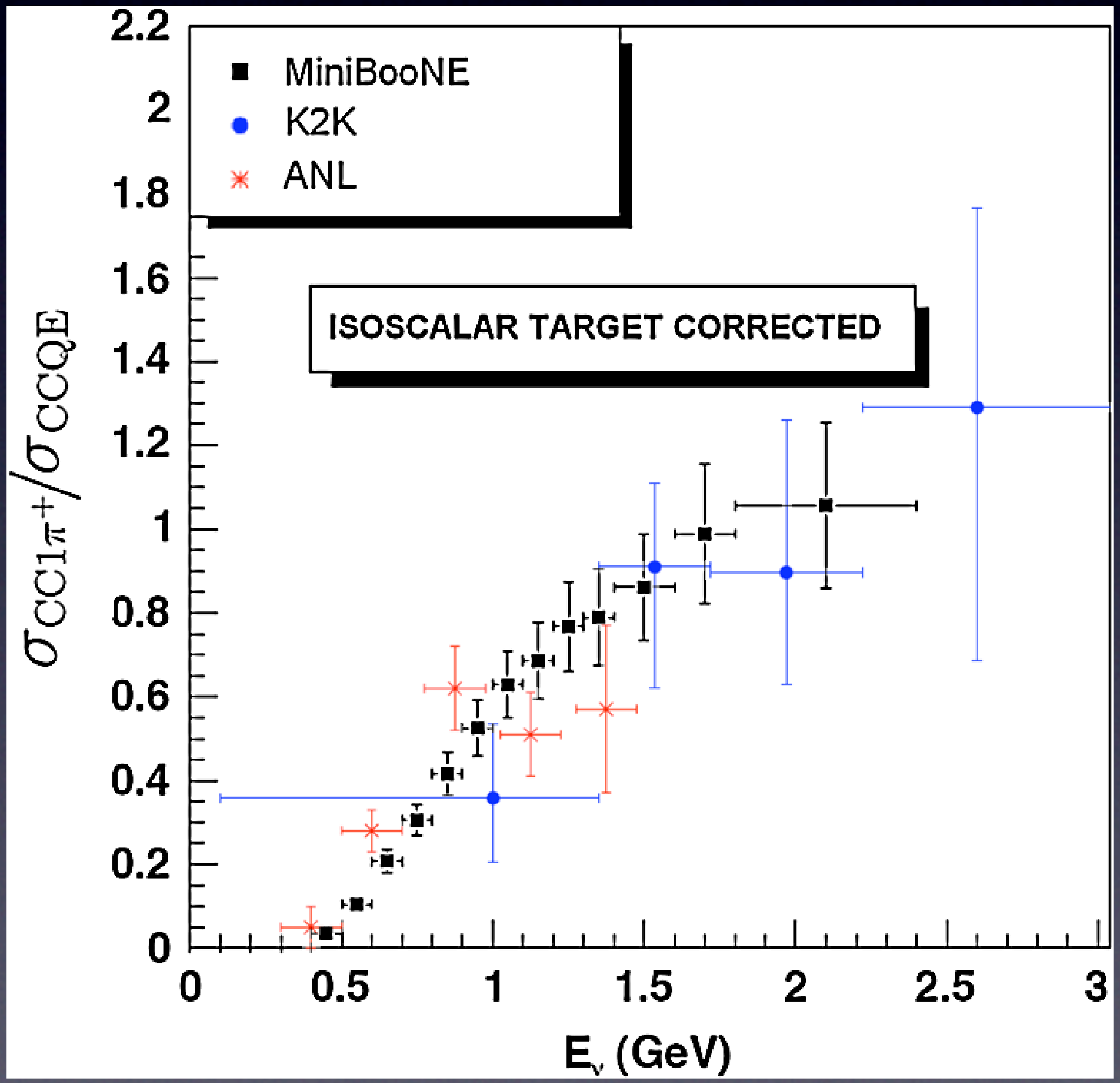
- The plot shows previous CCπ^+ measurements
- At low energies, only data from BNL and ANL bubble chambers
  - Less than 4,000 signal events combined
  - These same experiments are responsible for all the previous CCπ^0 data as well
- Significant disagreement is evident between the BNL and ANL results
- Interactions containing pions are much more sensitive to final state interactions (e.g. pion absorption and charge exchange)
  - Comparisons between H_2/D_2 data and heavier nuclei are not straightforward

Previous CCπ^+ Measurements



CCπ⁺/CCQE Ratio Measurements

- Measuring the ratio to CCQE significantly reduces the neutrino flux uncertainties
- Measurements from all 3 experiments agree with one another
  - Also consistent with Rein Sehgal predictions
- No information on final state kinematic distributions

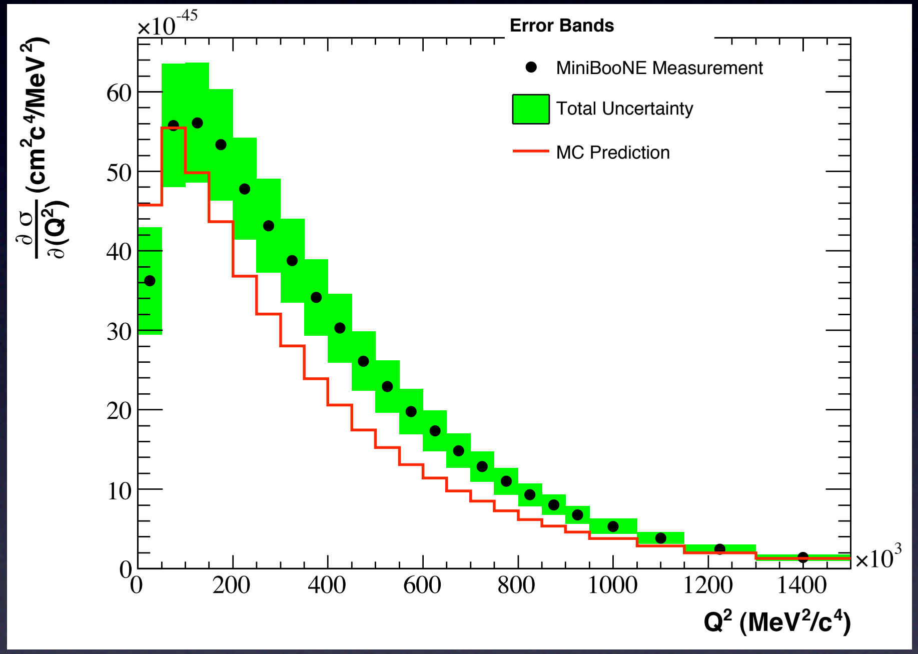


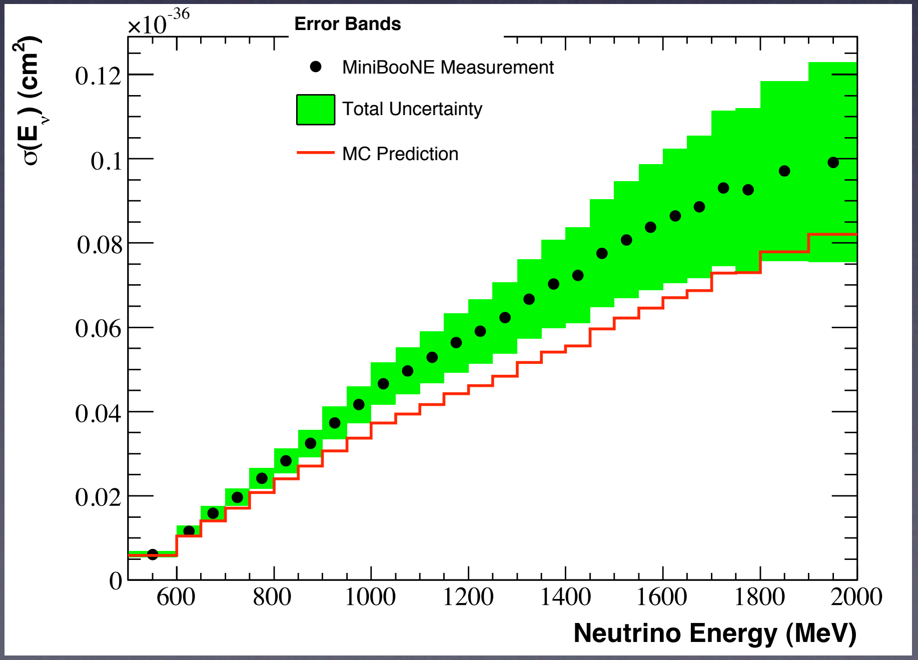
Phys. Rev. Lett. 103, 081801 (2009)

MiniBooNE CCπ^+

$$E_\nu = \frac{m_\mu^2 + m_\pi^2 - 2m_N(E_\mu + E_\pi) + 2p_\mu \cdot p_\pi}{2\left(E_\mu + E_\pi - |\mathbf{p}_\mu|\cos\theta_{\nu,\mu} - |\mathbf{p}_\pi|\cos\theta_{\nu,\pi} - m_N\right)}$$

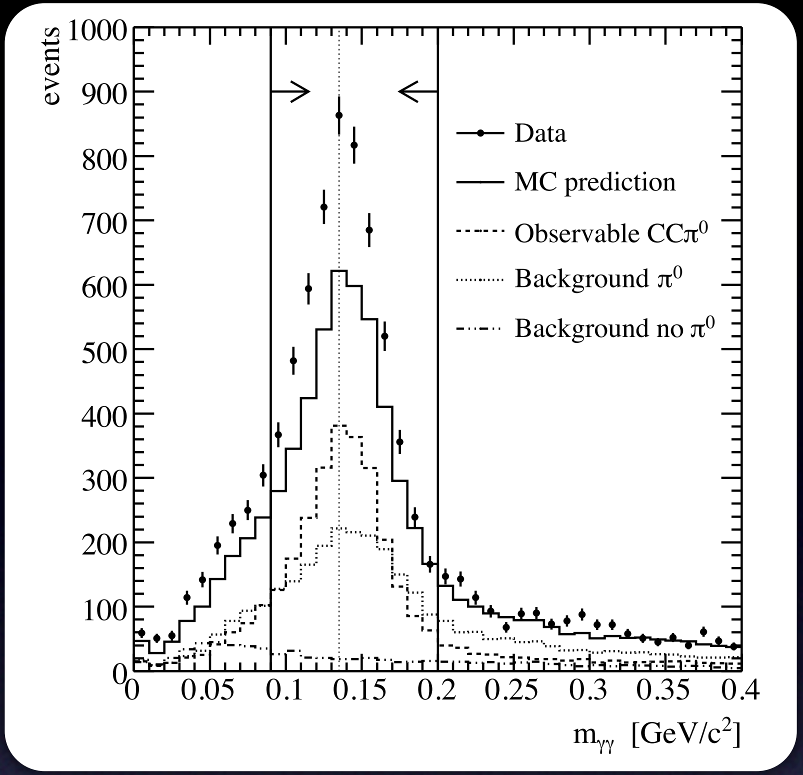
- Both the muon and the pion are reconstructed
  - No need to assume a recoiling, on-shell Δ mass (necessary for single track reconstruction)
- Low Q^2 deficit in data relative to MC, as expected
- Excess of ~20% relative to the Rein-Sehgal prediction (with MA = 1.1 GeV)
  - Fermi gas model assumed



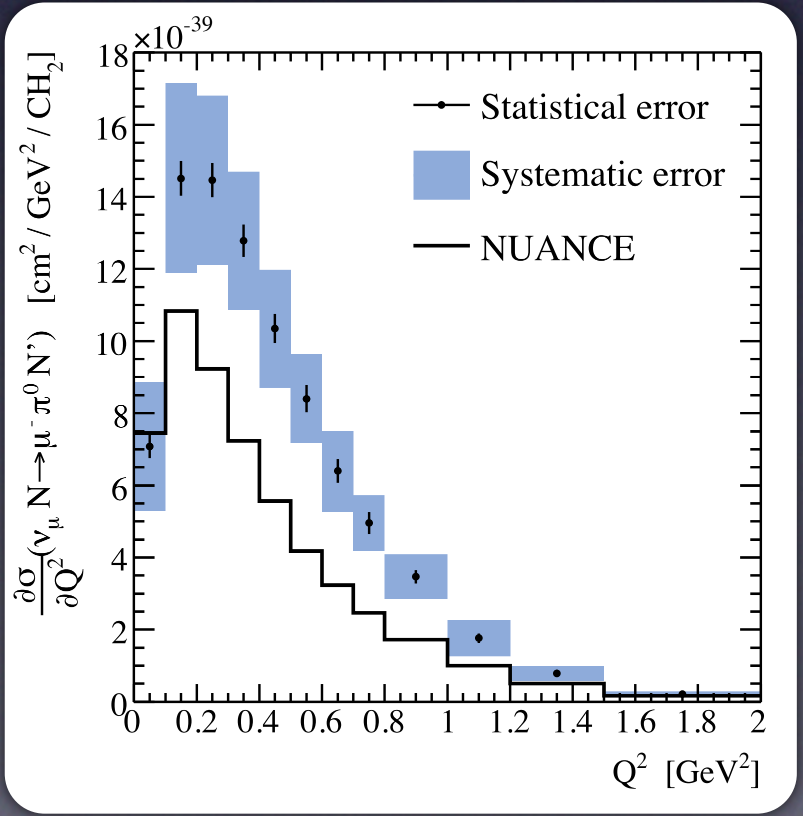


MiniBooNE CCπ^0

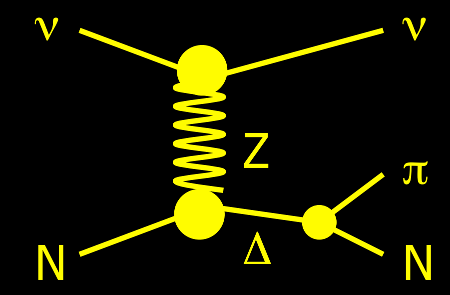
- Three ring reconstruction (μ, γ, γ) in an 11m diameter Cherenkov detector (1280 PMTs)
- The two photons form a π^0 mass, and (N,γ,γ) system gives the Δ mass
- Data excess above the Rein-Sehgal prediction (M_A=1.1 GeV) is 56%
  - Much larger than other single pion channels
- Shape comparison shows same effects at low Q^2 as seen in CCπ^+
- Recent preliminary result from K2K also reports excess of CCπ^0 over expected value: (49 ± 16)%
(C. Mariani, NuInt09)



R. Nelson, NuInt09

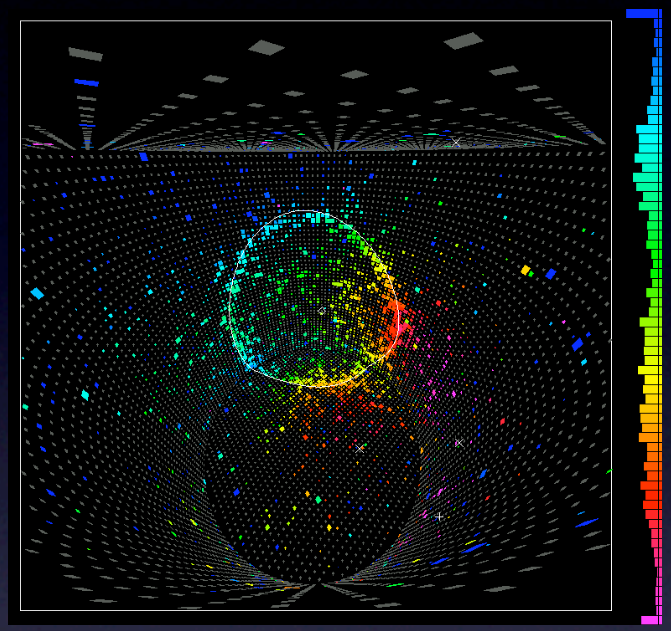


$NC\pi^0$ Overview

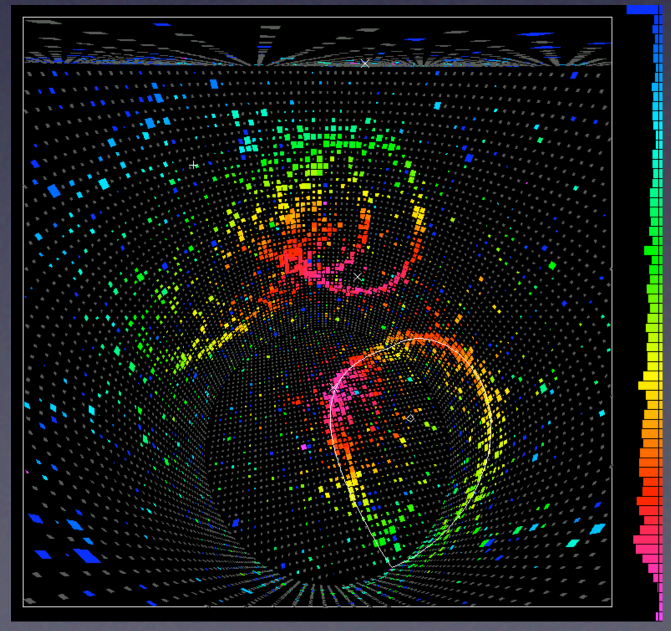


- Significant background to ν_e appearance searches
  - $\pi^0 \rightarrow \gamma\gamma$: if one γ is lost, looks just like an electron in a Cherenkov detector
- Can't measure neutrino energy as is done in CC interactions
- Instead, the total cross section is often reported
  - A differential cross section in pion momentum can also be measured
- Therefore, results are flux integrated
  - Hard to apply measurements from one experiment to other experiments
  - Desirable to measure the rate in-situ or via near detector

Super-K ν_e-CCQE Event

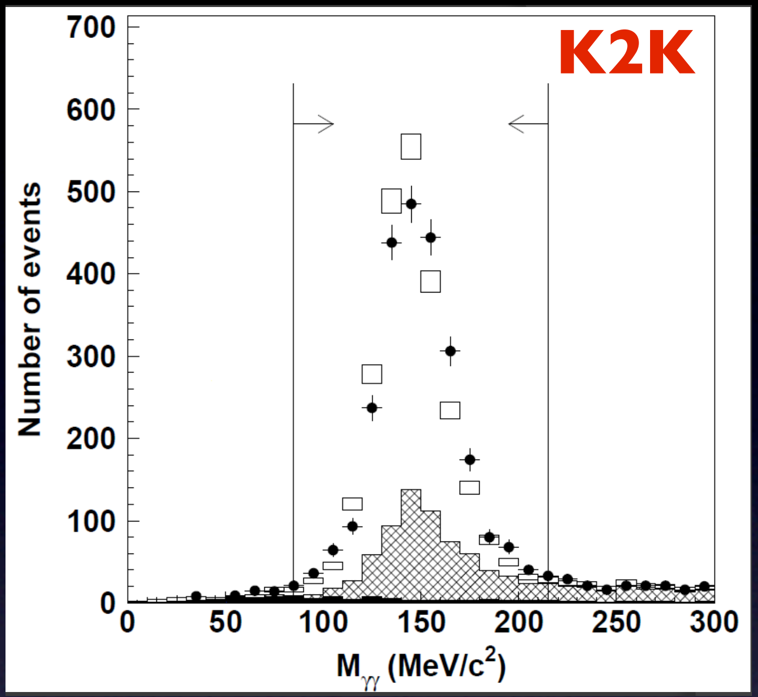


Super-K $NC\pi^0$ Event



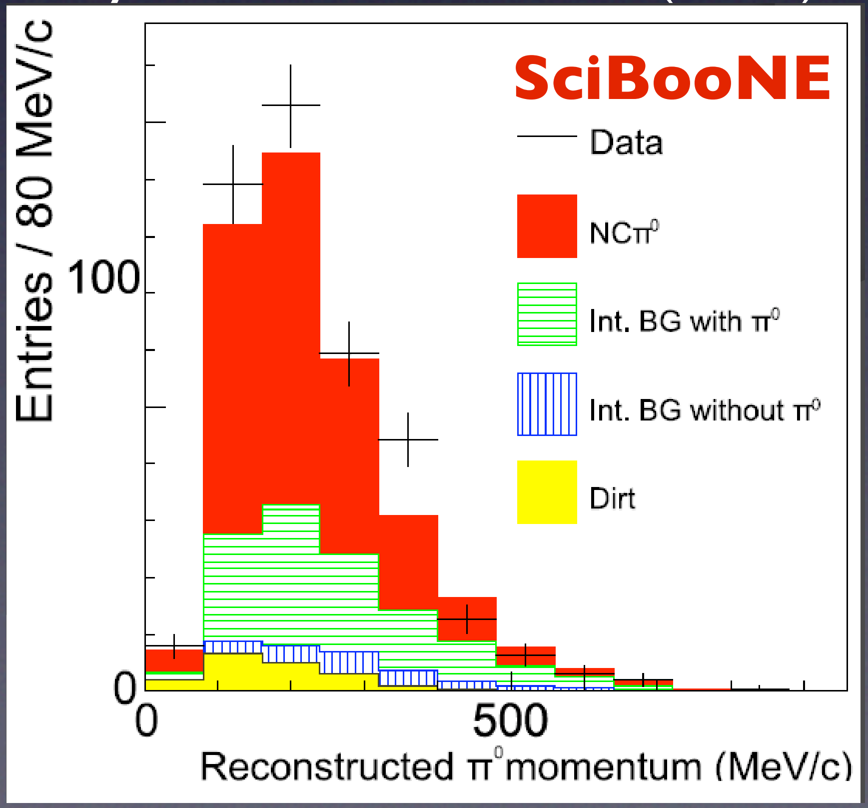
K2K and SciBooNE NCπ^0/CC

- Cherenkov detectors are well suited to measure NCπ^0 interactions
  - Both photons will usually produce electrons with rings that point back to the interaction vertex
- $\sigma_{NC\pi 0}/\sigma_{CC} = 0.064 \pm 0.001_{stat} \pm 0.007_{syst}$
- Reasonable agreement with Rein Sehgal model using M_A = 1.1 GeV



Phys. Lett. B619, 255 (2005)

Phys. Rev. D81, 033004 (2009)

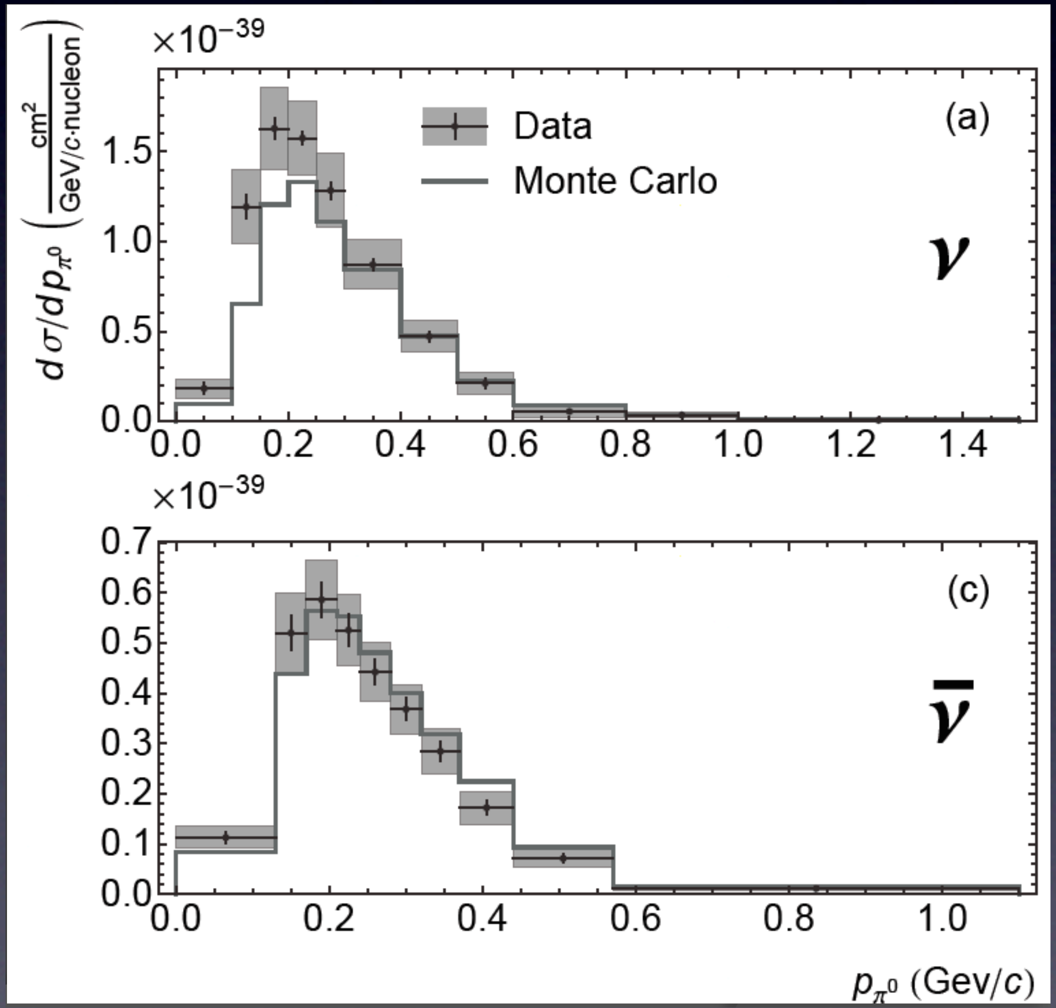


- Both photons must convert in either SciBar or the downstream energy calorimeter
  - Limited acceptance
- $\sigma_{NC\pi 0}/\sigma_{CC} = 0.077 \pm 0.005_{stat} \pm 0.005_{syst}$
- Consistent with K2K result

MiniBooNE NCπ^0

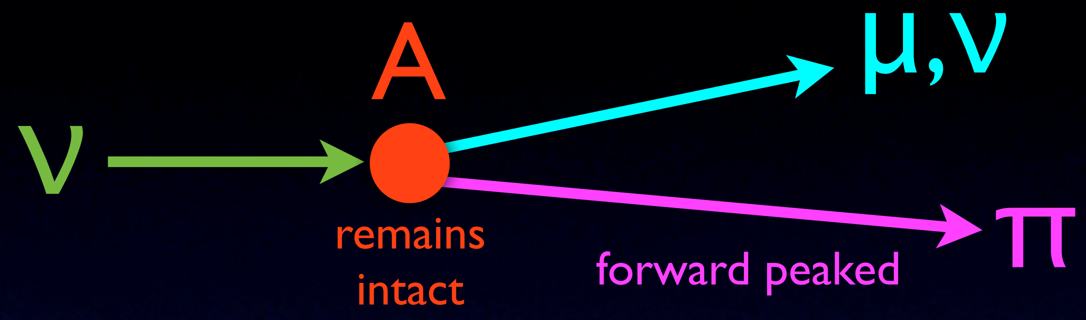
- 4π detector coverage
- 21,375 ν events with 73% purity (2,789 anti-ν events with 58% purity)
- First inclusive differential cross section for both neutrinos and anti-neutrinos
- Better agreement with RS model (M_A = 1.1 GeV) than other single pion modes
  - No 20-50% normalization differences as seen in CCπ
  - Data spectrum is softer

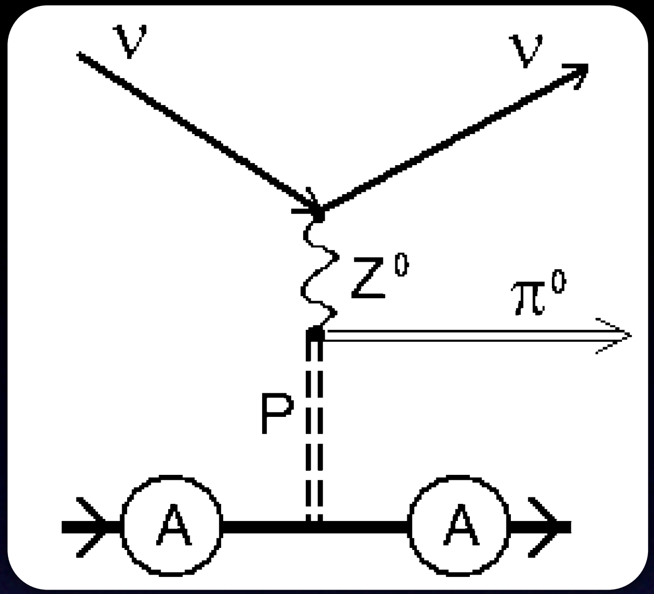
$d\sigma/dp_{\pi 0}$



Phys. Rev. D81, 013005

Coherent Pion Production

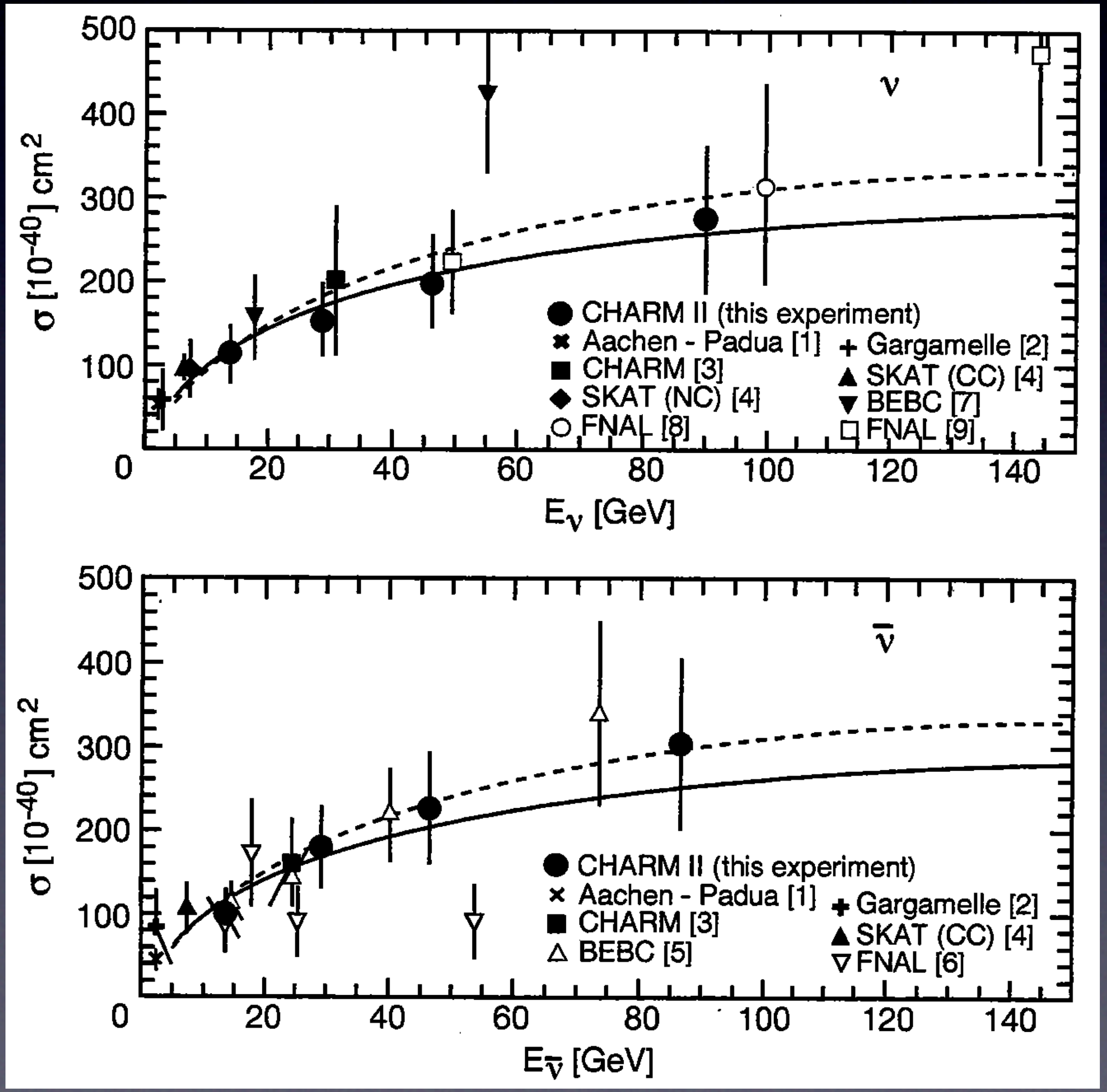




- In addition to interactions with a single nucleon, pion production can interact with the nucleus as a whole
  - From charge conservation: only NCπ^0 and CCπ^+
- Require low-Q^2 to keep the nucleus intact
  - Muon direction is very forward peaked
  - No other final state particles
- Various theoretical descriptions; older results were checked with Rein and Sehgal

Previous Coherent Measurements

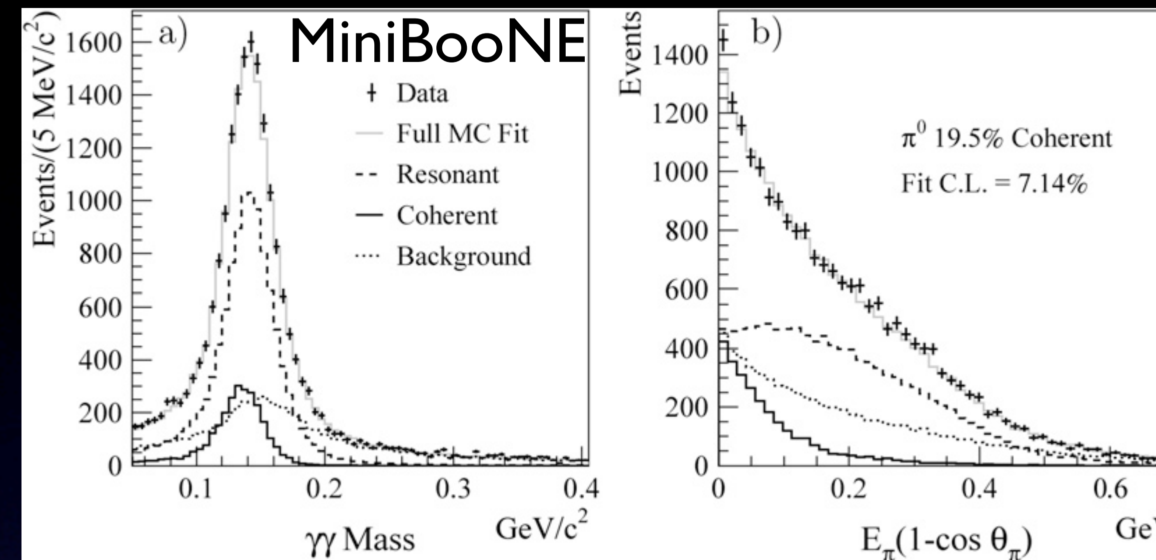
- All previous data are compiled in a single figure
  - Cross sections are scaled by $A^{1/3}$ to account for different target masses
  - NC data has been multiplied by two (R-S prediction)
- Once again, older experiments generally agree with R-S predictions (M_A = 1.3 GeV) for both CC and NC coherent production

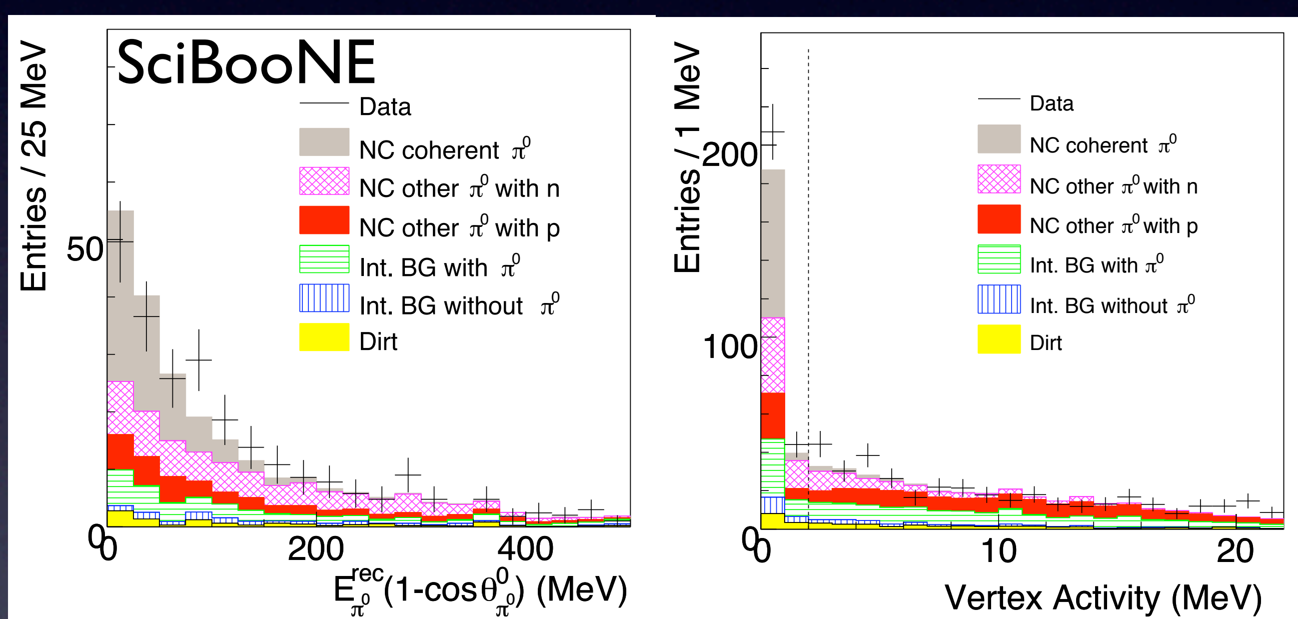


Phys. Lett. B313, 267 (1993)

Recent Coherent π^0 Results

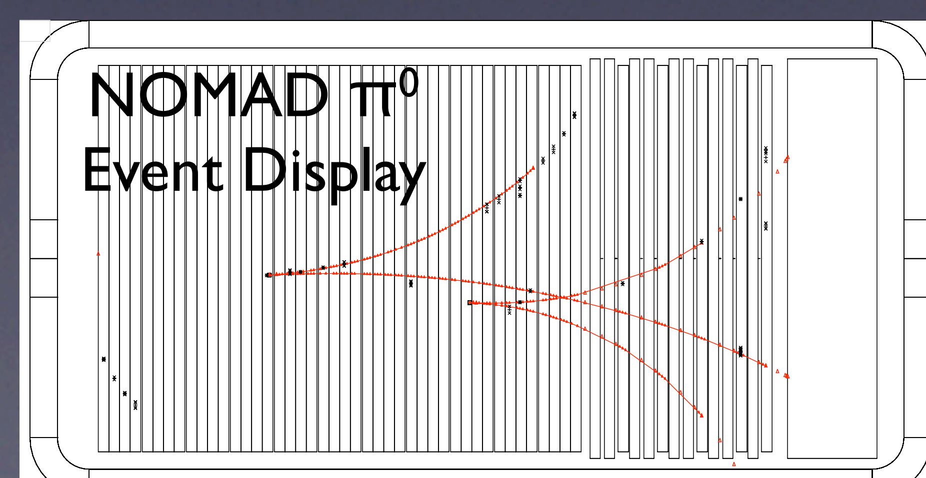
- MiniBooNE searches for an excess of forward peaked π^0 events
- Coherent π^0 / Total π^0 = $(19.5 \pm 1.1_{stat} \pm 2.5_{syst})\%$
- Rein Sehgal prediction = 30%

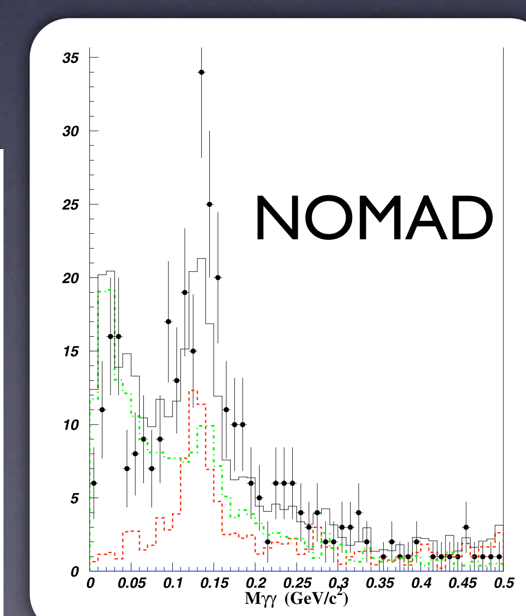




- SciBooNE can also look for energy deposits consistent with nuclear breakup at the event vertex
- $\sigma_{CCcoh\pi}/\sigma_{CC} = (1.16 \pm 0.24) * 10^{-2}$
- Rein Sehgal prediction = $1.21 * 10^{-2}$

- NOMAD can reconstruct the e^+/e^- separation from photon conversions
- Fit for the normalization of coherent π^0 relative to RS prediction
- $\sigma = (72.6 \pm 8.1_{stat} \pm 6.9_{syst}) * 10^{-40}$ cm/N
- $\sigma_{RS} =\sim 78 * 10^{-40}$ cm/N

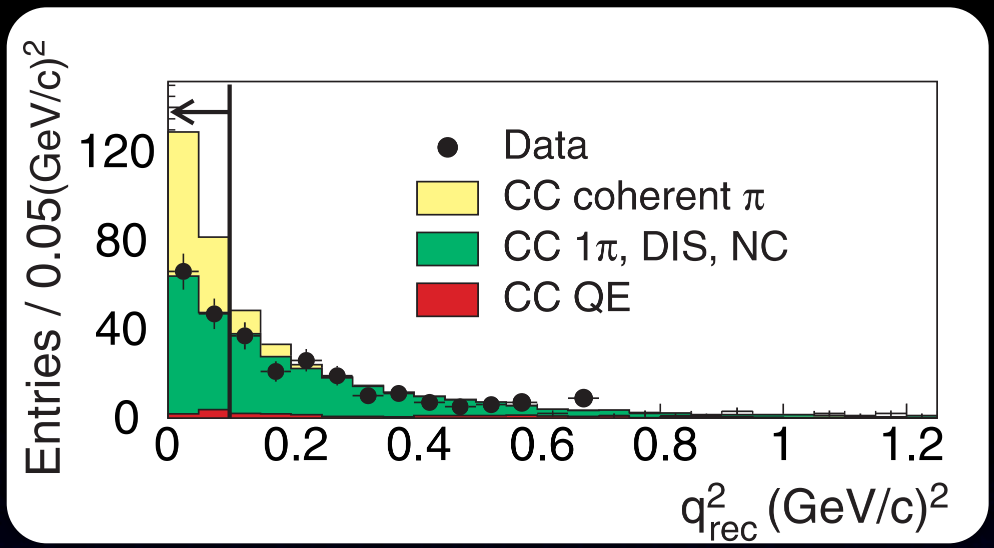




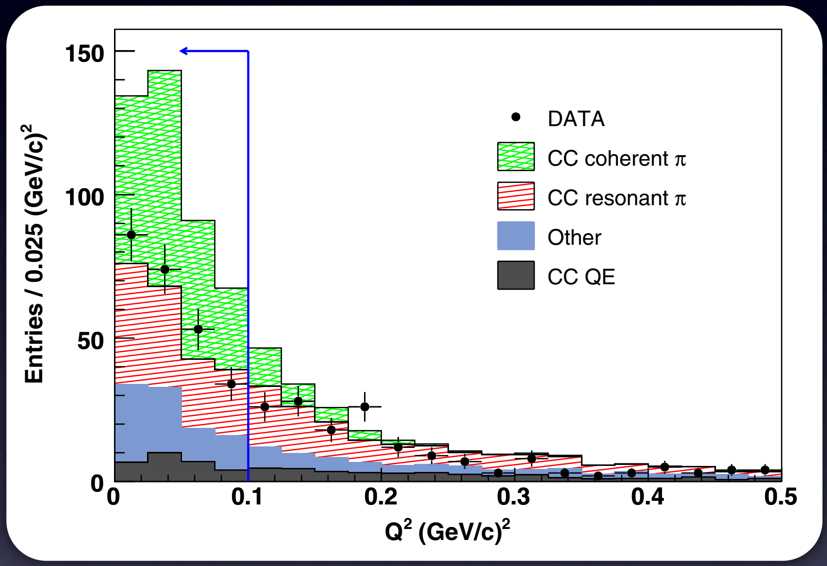
Coherent π^+

- Measured at K2K and SciBooNE (both using the SciBar detector)
- Once again, select coherent enriched sample by requiring little vertex activity
- Search for coherent events at low Q^2
- **No evidence seen for coherent π^+**
- SciBooNE coherent $CC\pi^+/CC\pi^0 = 0.14^{+0.30}_{-0.28}$
- Most theoretical models predict $CC\pi^+/CC\pi^0$ = 1-2

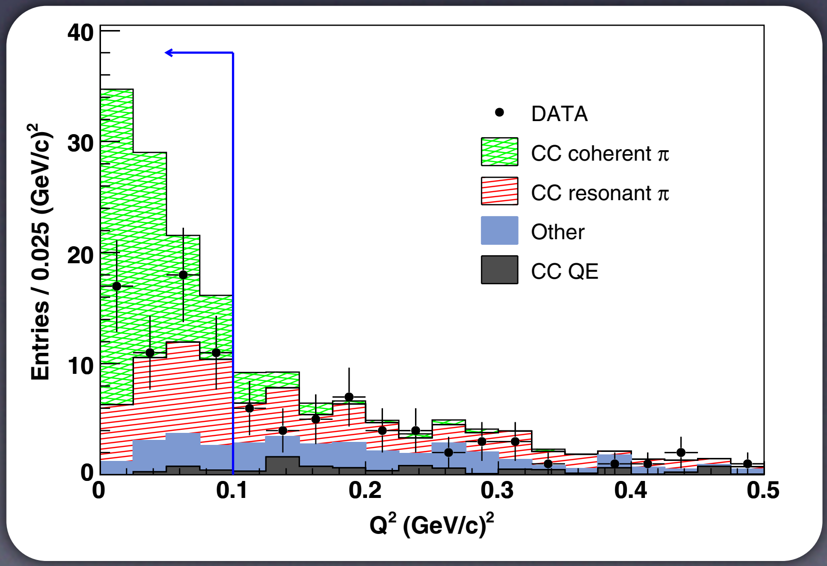
K2K



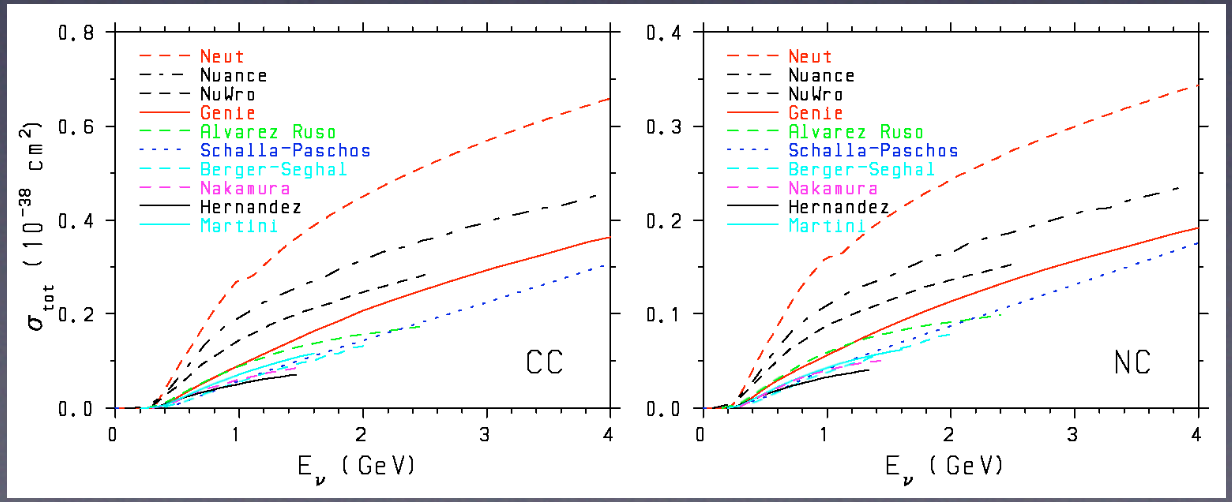
SciBooNE Low E



SciBooNE High E

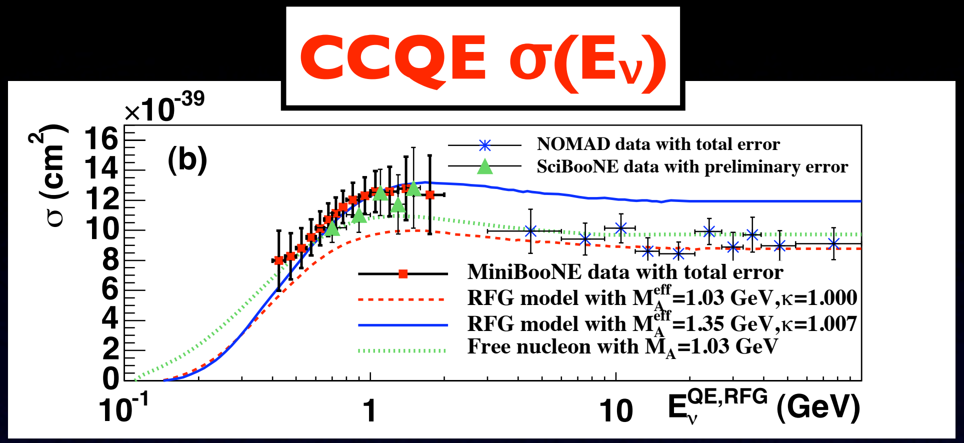


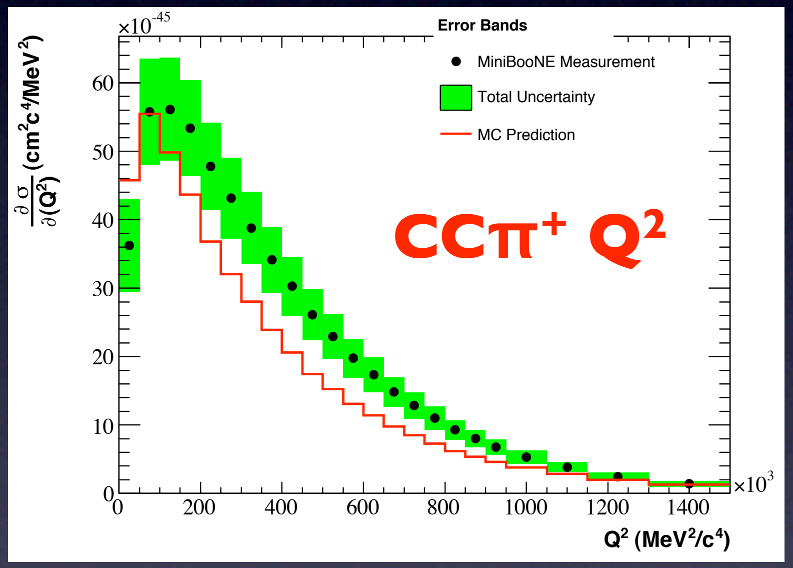
Various theory and ν-generator values for coherent CC and NC pion production

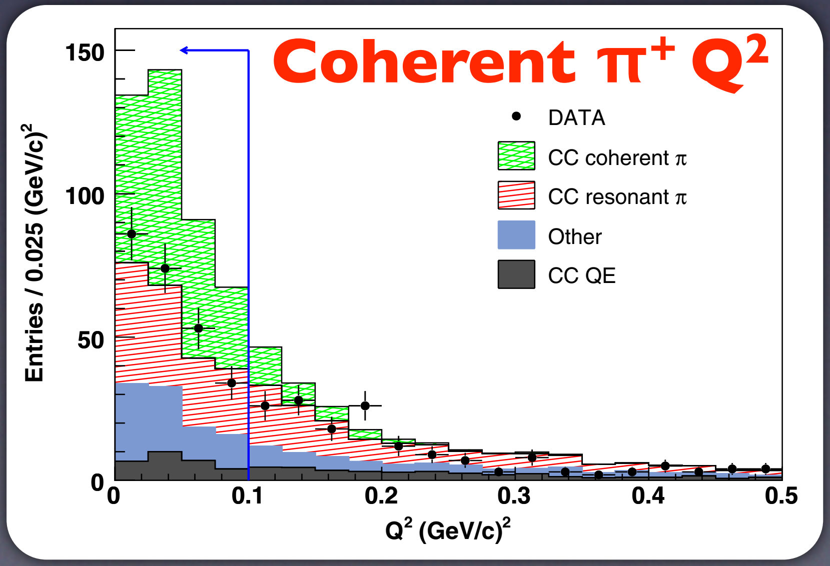


Experimental Summary

- Recent experiments are shedding light on the low Q^2 mystery in CCQE interactions
  - Much of the burden has been shifted to $CC\pi^+$ interactions
- At low energies, M_A values are higher than previous world average
  - At higher energies, NOMAD has reported a very precise measurement that agrees with the previous average
- $CC\pi$ measurements all show an excess over prediction as well as a faster-than-expected falloff at low Q^2
  - Data excess is significantly larger for $CC\pi^0$ interactions
- Coherent π^0 production is reasonably consistent with expectations
- Coherent π^+ production has not been observed in recent experiments
  - Upper limit on coherent π^+/π^0 ratio is ~3σ lower than prediction
- Additional cross sections have also been measured
  - MiniBooNE NCEL: arXiv:1007.4730
  - MINOS CC Inclusive: Phys.Rev.D 81, 072002 (2010)



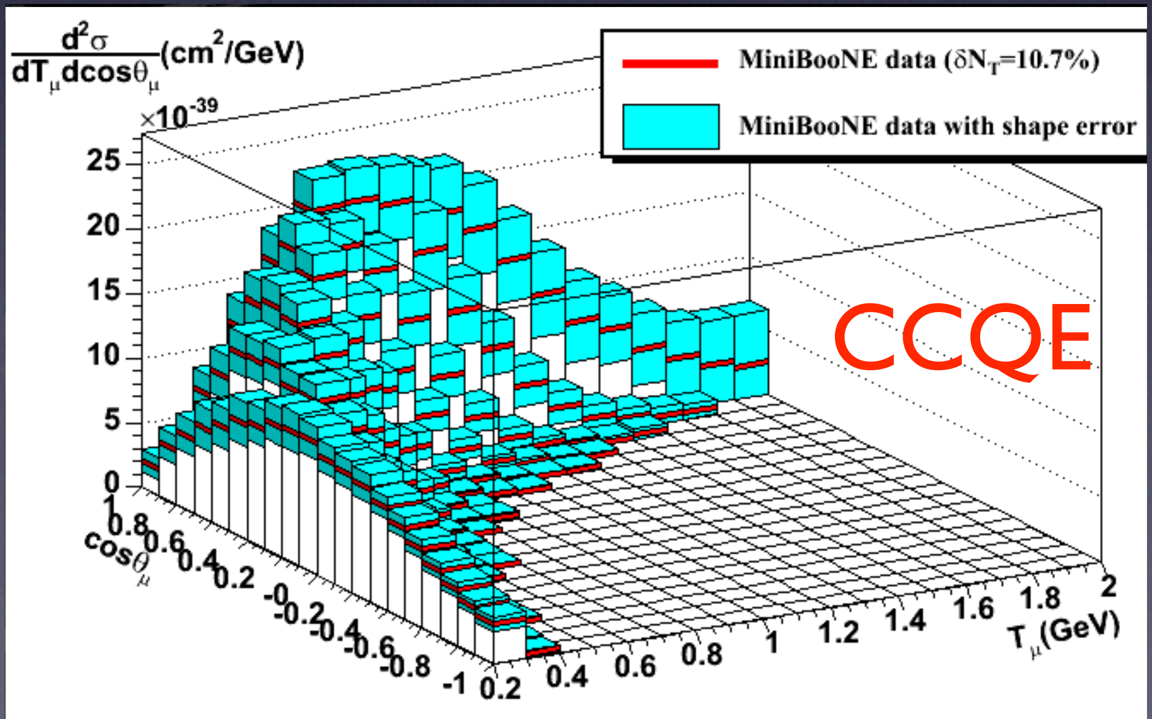


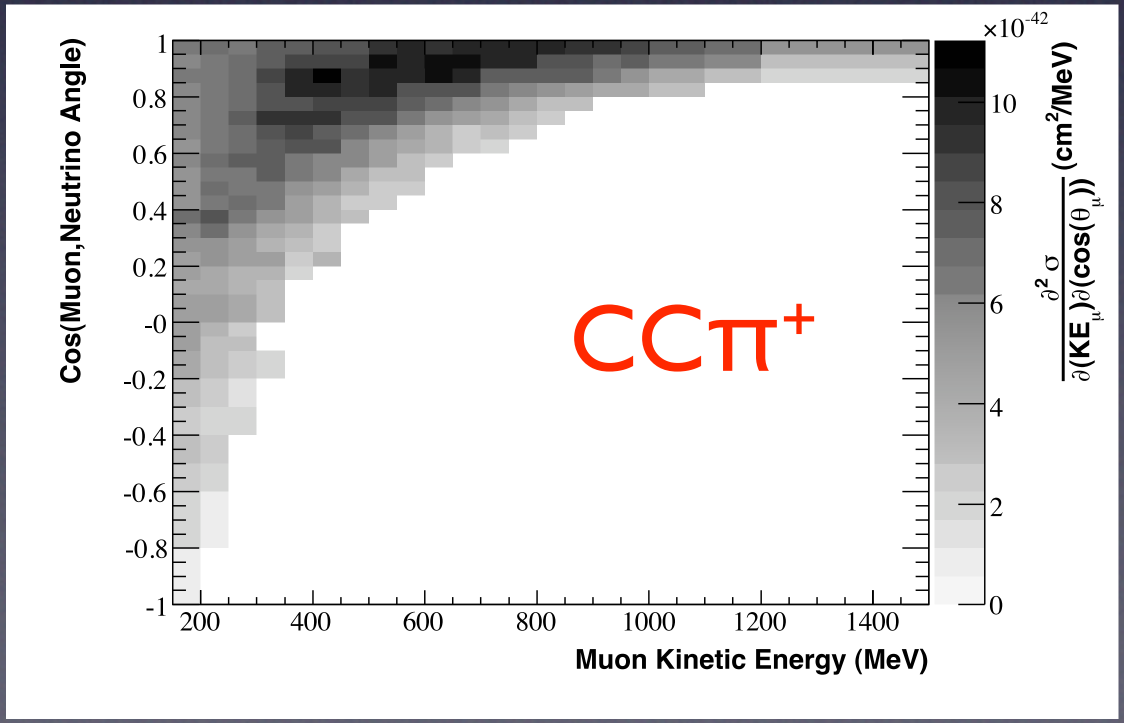


The Path Forward

- From an experimental point of view, we need model-independent measurements of final state particle kinematics
  - Fits to M_A and model-dependent nuclear corrections are more difficult to interpret as inputs to neutrino event generators
- Input from the theory community
  - Need help to explain observed anomalies
  - Still need to extrapolate observations to unmeasured regions of phase space

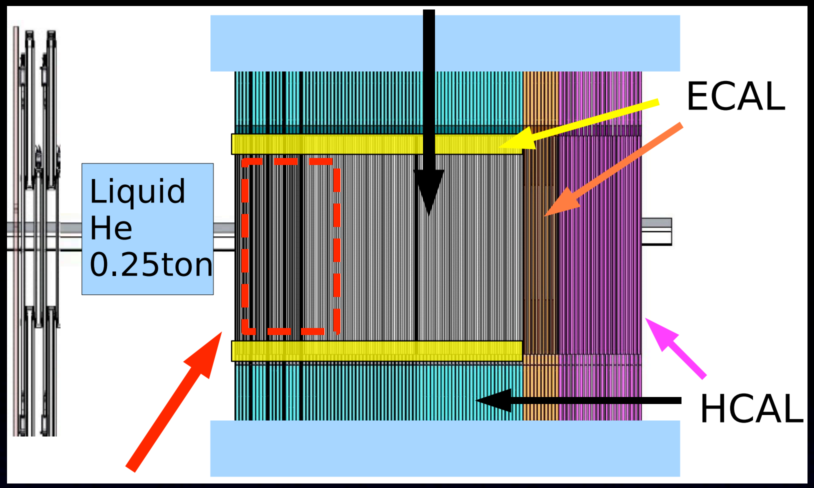
Absolutely normalized double-differential cross sections in muon energy and angle

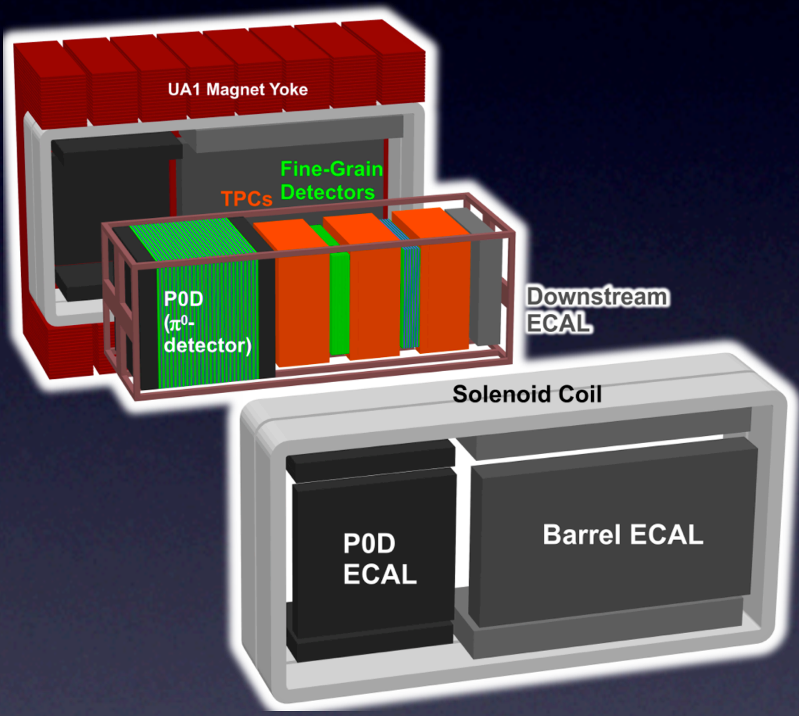


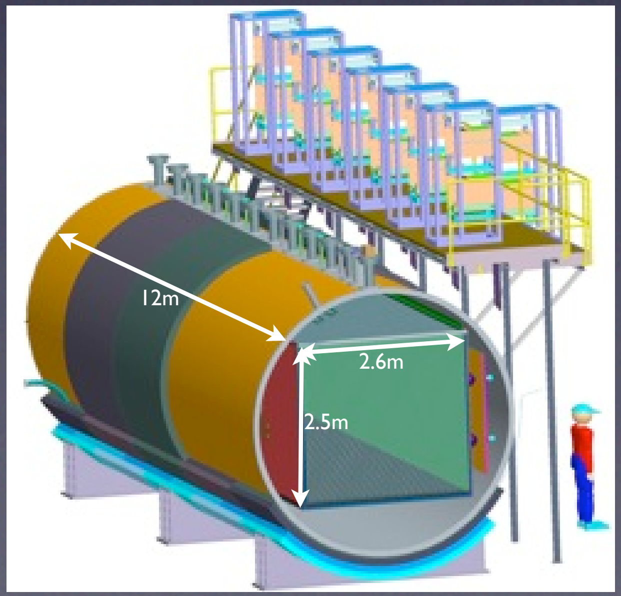


Future Experiments

- Minerνa (FNAL)
  - Finely segmented, fully active scintillator tracker
  - Surrounded by calorimeters to detect escaping photons
  - Variety of targets: He, C, Fe, Pb
  - Wide range in neutrino energy: 0.7 - 30 GeV
- T2K ND280 (J-PARC)
  - Thin, active, scintillator target
  - Time projection chambers immediately upstream and downstream provide precise momentum and particle identification measurements
  - Also surrounded by energy calorimeters
- MicroBooNE (FNAL)
  - Liquid argon time projection chambers
  - Single electrons are distinguishable from photon conversions
    - NCπ^0 backgrounds are eliminated







Conclusion

- Interest in neutrino interaction cross sections has increased dramatically in the last few years
  - Becoming a limiting factor in interpreting neutrino oscillation data
- Although useful for oscillation experiments (to achieve sensitivity to $\Delta m223$), neutrino cross sections at the ~1 GeV energy scale is particularly difficult to understand
- Fortunately, there are now large improvements in experimental precision
  - From 10^3 events/experiment to 10^5
- New puzzles have been uncovered
  - M_A non-universality?
  - $CC\pi^+$ discrepancy at low Q^2?
  - Where are the coherent $CC\pi^+$ events at low E_ν?
- Exciting time in neutrino interaction physics
  - Many new experiments are beginning to take data
  - An active and engaged theory community is making quick progress