Impact of Neutrino Cross Section Knowledge on Oscillation Measurements

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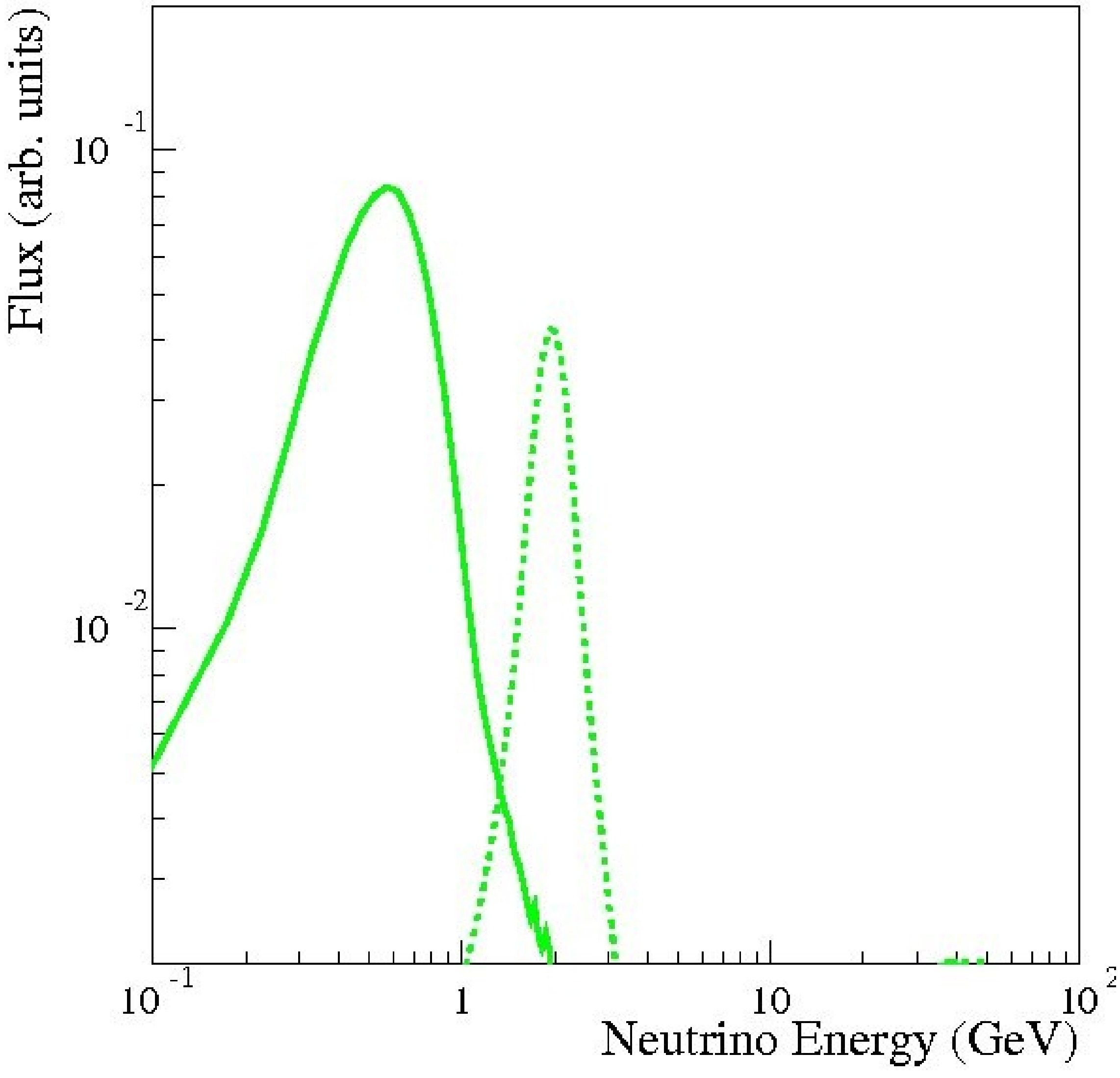
IDS-NF, RAL, Jan 16-17 2008

Neutrino Cross Sections: At What Energies Needed?

Superbeams:

- Solid: T2K
- Dashed: NovA



Neutrino Cross Sections: At What Energies Needed?

Superbeams:
- Solid: T2K
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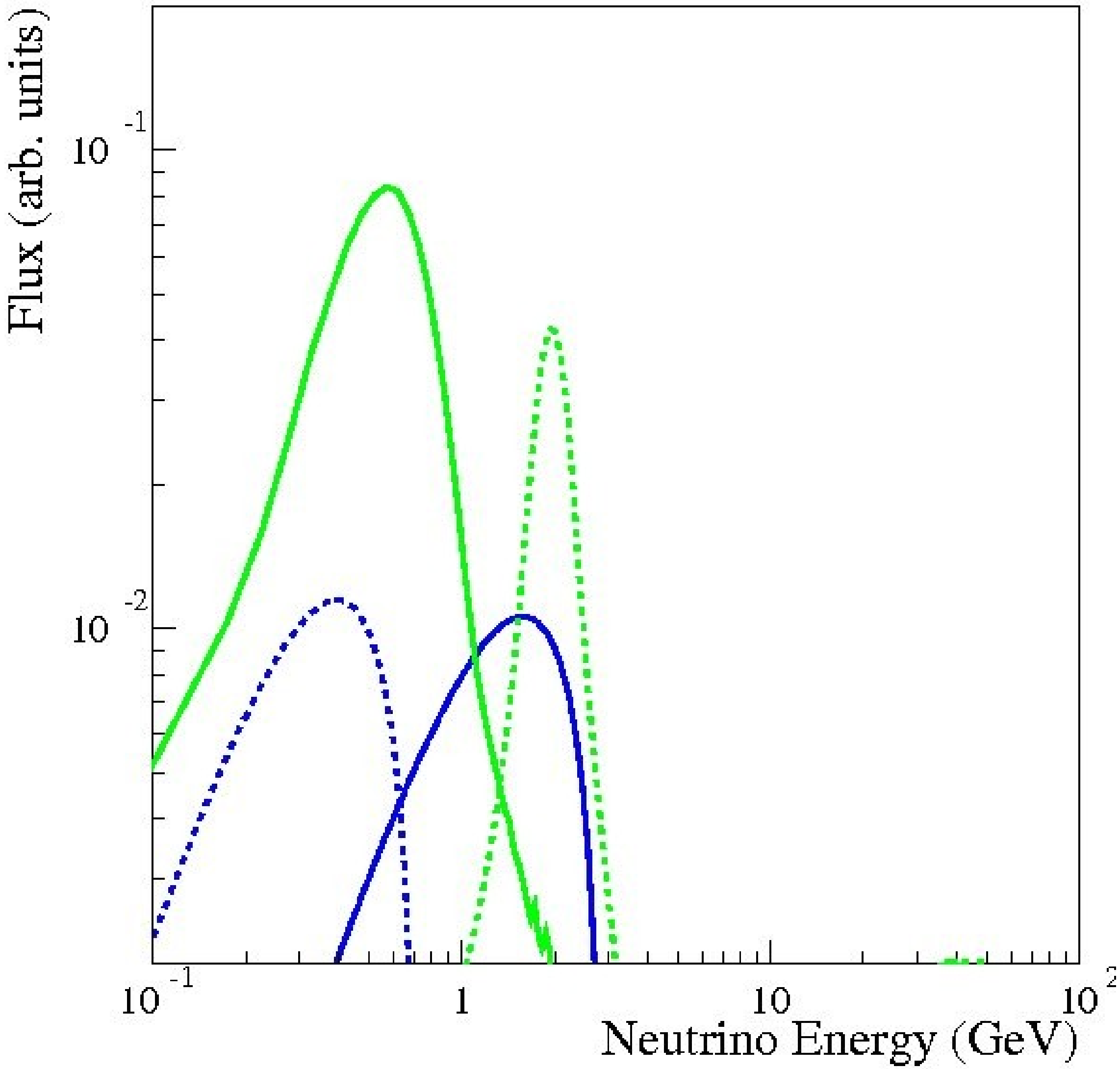
Beta Beams:
- Solid: ^{6}He, γ = 400
- Dashed: ^{6}He, γ = 100



Neutrino Cross Sections: At What Energies Needed?

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- Solid: T2K
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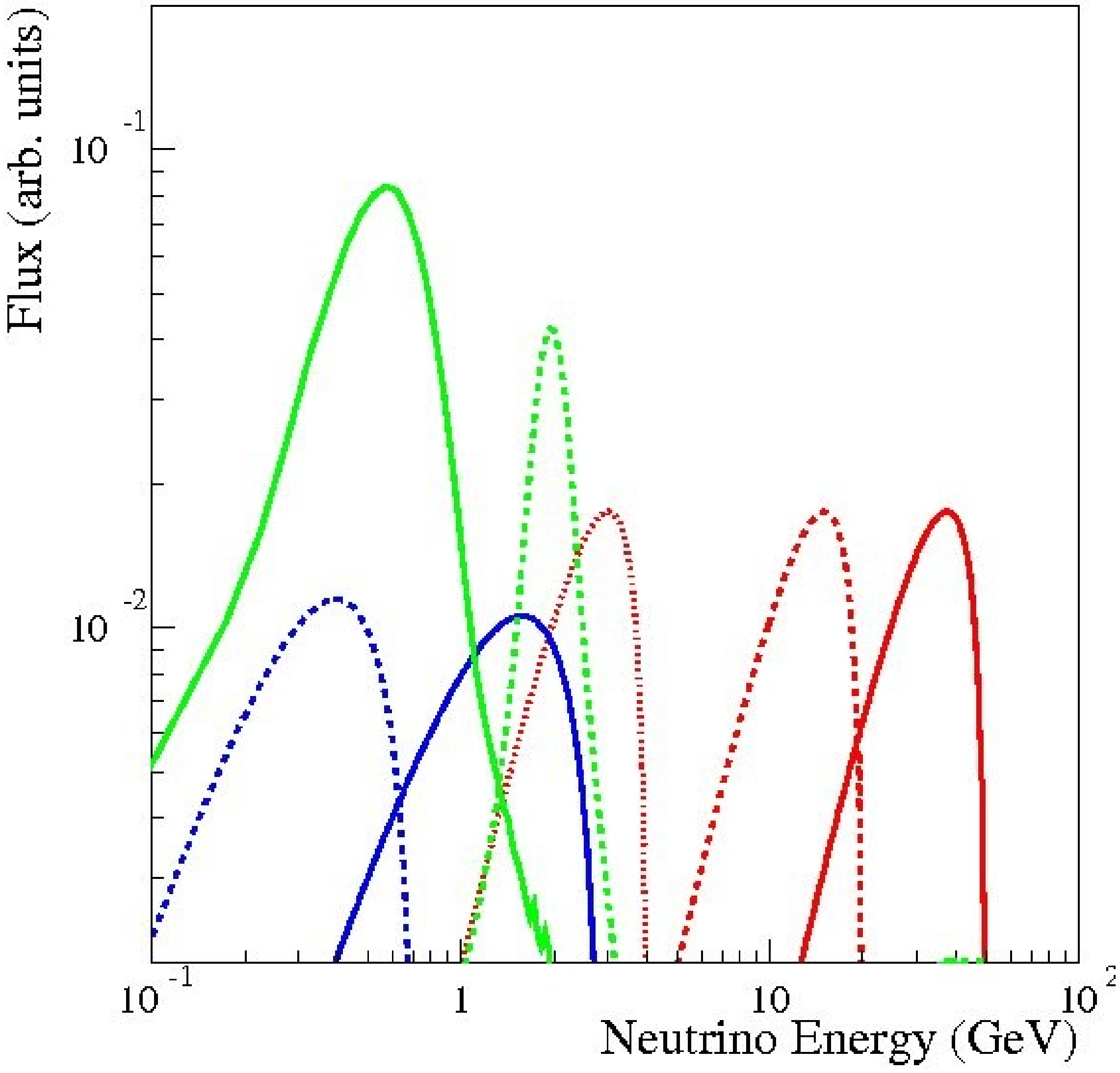
Beta Beams:

- Solid: ^{6}He, γ = 400
- Dashed: ^{6}He, γ = 100

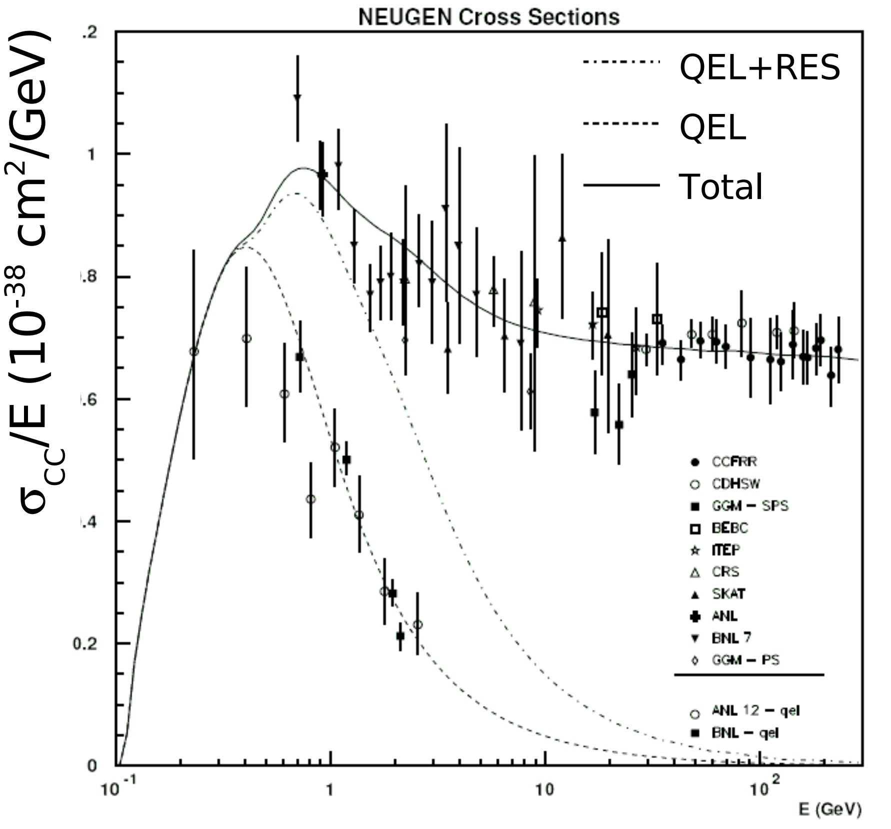
Neutrino Factories:

- Solid: E_{μ} = 50 GeV
- Dashed: E_{μ} = 20 GeV
- Dotted: E_{μ} = 4 GeV

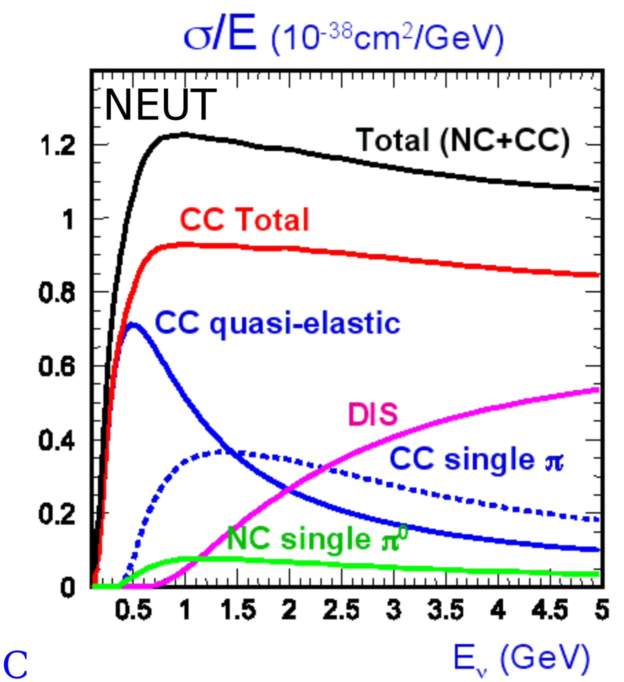
• Cross Sections needed by future oscillation experiments across wide energy range: $0.3 < E_{\nu} < 50$ GeV



Neutrino Cross Sections: Status Until Recently



- Relatively precise measurements at high energies, E_ν > 20 GeV, where deep inelastic scattering dominates
- Less precise measurements in few-GeV region, where many processes contribute
- Scarce antineutrino cross section data
- Effects from nuclear targets important at all energies, especially low energies



Two Scenarios For Measuring θ_{13}

"Superbeam scenario":

- E_ν <~ 2 GeV
- S/B <~1

-> both background and signal cross section uncertainties important to extract oscillation probability

- Signal: electron neutrino CCQE on nuclei
- Background: single pion production on nuclei (NC π^0), beam ν_e CCQE on nuclei
- Interaction rate measurements at near detectors (numu and nue) can help reduce cross-section uncertainties

"Neutrino factory scenario":

- E_ν >~ 2 GeV
- S/B >> 1 (for $\sin^2 2\theta_{13} >> 10^{-4}$)

-> signal cross section uncertainty dominates

- Signal: deep inelastic scattering (DIS) on nuclei
- Muon neutrino "right-sign" interaction rate measurements can help reduce cross-section uncertainties

Outline

- Will discuss recent progress and near-future expectations for:
  - Charged current quasi elastic scattering (CCQE)
  - Neutrino-induced single pion production (mostly RES)
  - Deep inelastic scattering (DIS)
  - Nuclear effects

Neutrino Scattering Experiments

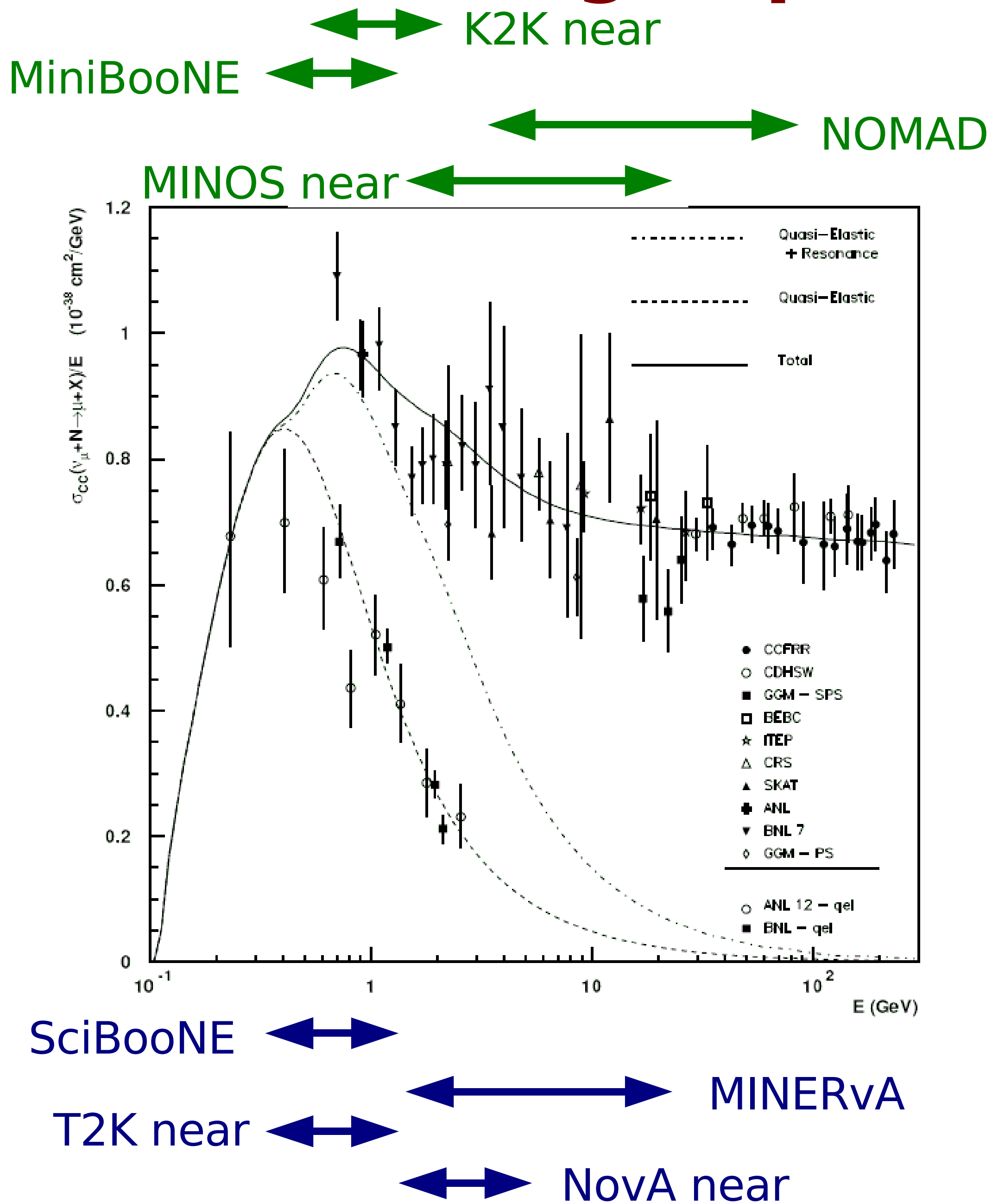
Reporting recent progress:

- *K2K near*:
  - *1KT* (Cherenkov detector, water target, ~10^5 interactions)
  - *SciFi* (segmented tracker, water, ~10^4 interactions)
  - *SciBar* (segmented tracker, carbon, ~10^4 interactions)
- *MiniBooNE* (Cherenkov, mineral oil, ~10^6 interactions)
- *NOMAD* (spectrometer/calorimeter, carbon, ~10^6 interactions)
- *MINOS near* (magnetized tracking calorimeter, iron, ~10^6 interactions)

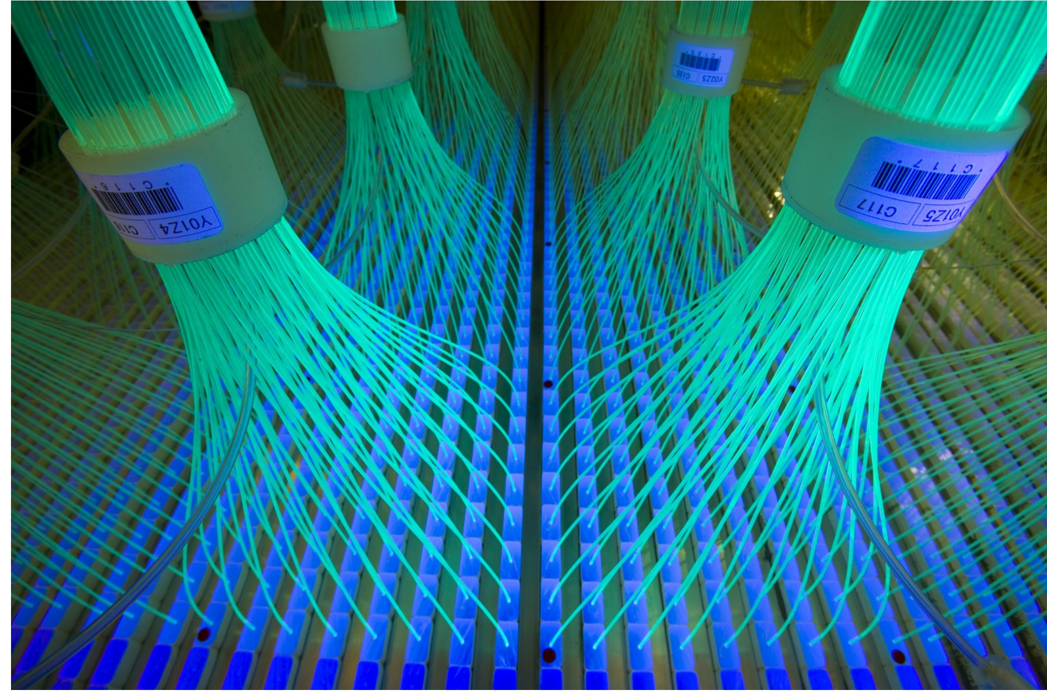
Results expected soon:

- SciBooNE (segmented tracker, carbon, ~10^5 interactions)
- MINERvA (segmented tracker, He/C/Fe/Pb, ~10^6 interactions)
- T2K, NOvA near detectors

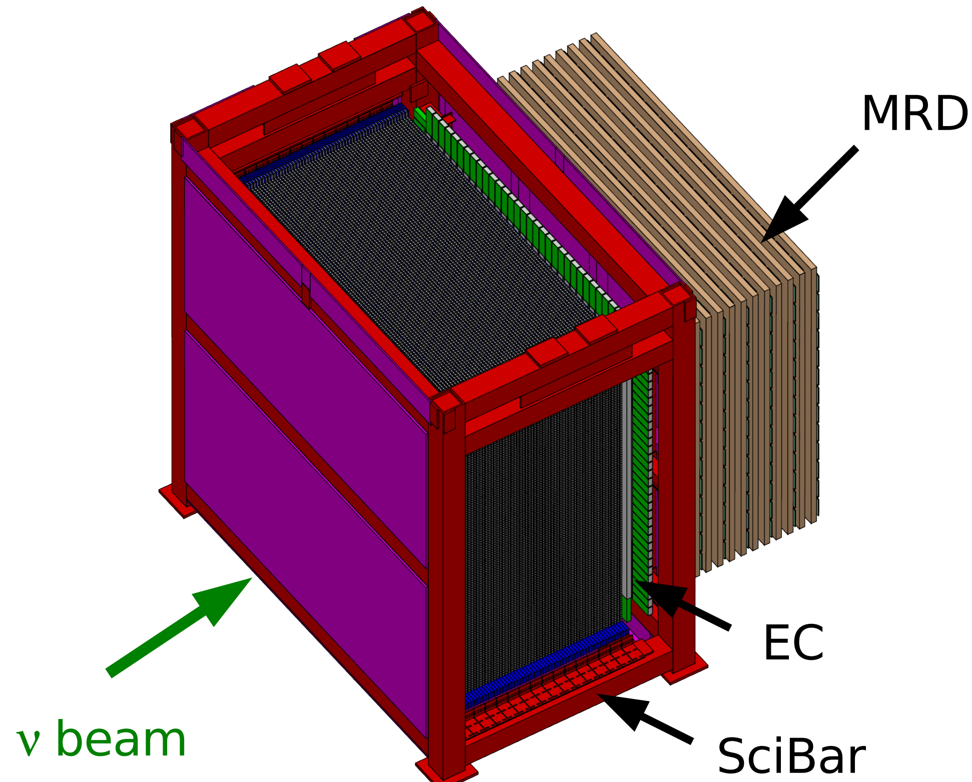
Neutrino Scattering Experiments



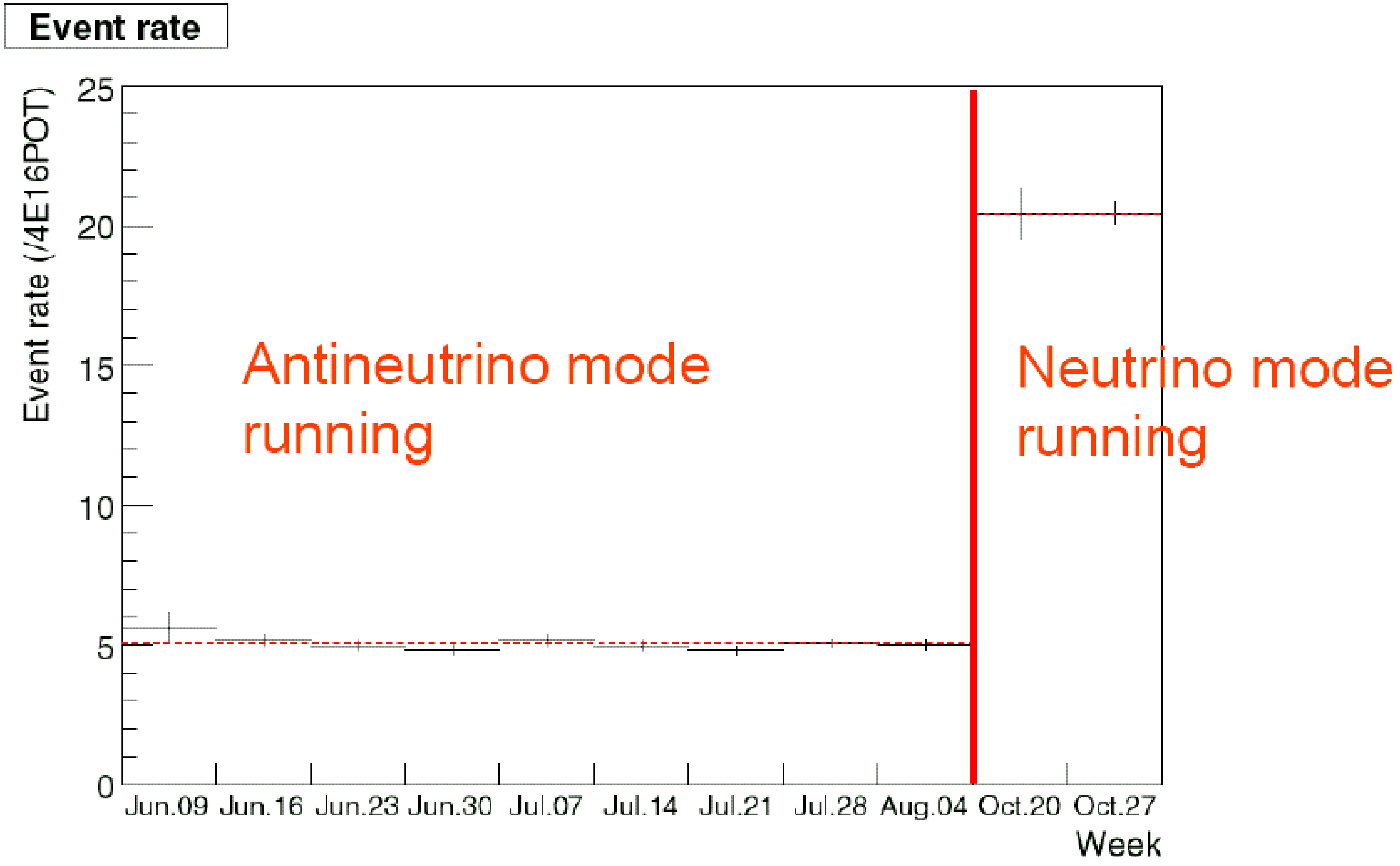
SciBooNE



- New neutrino experiment at Fermilab (data-taking start: June '07)
- Near detector in Booster Neutrino Beamline serving also MiniBooNE
- Precision muon neutrino and muon antineutrino cross-section measurements at 1 GeV
- Detector:
  - SciBar: neutrino target + tracker
  - EC: electromagnetic calorimeter
  - MRD: muon range detector

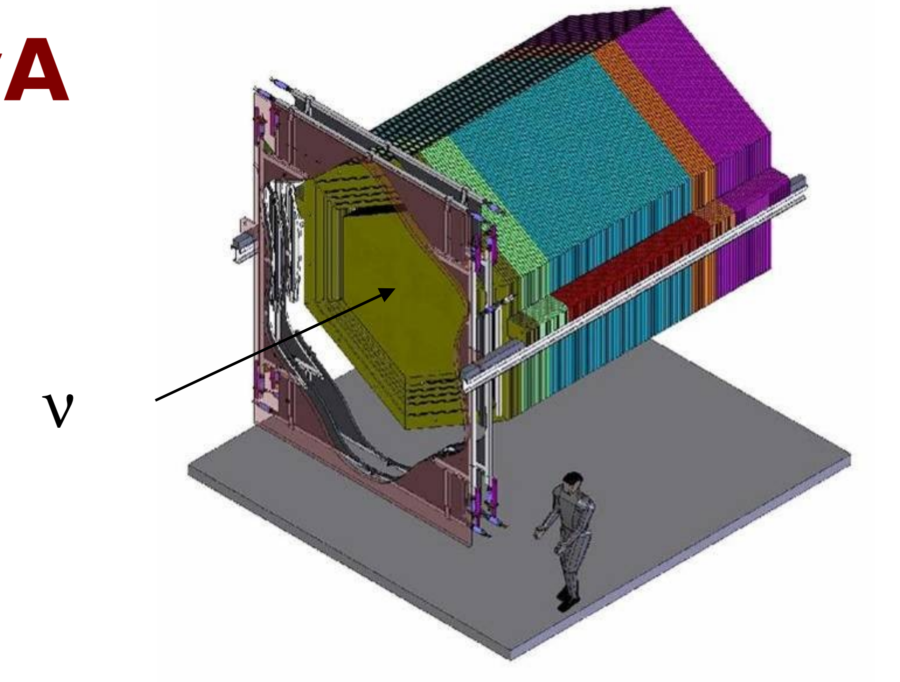


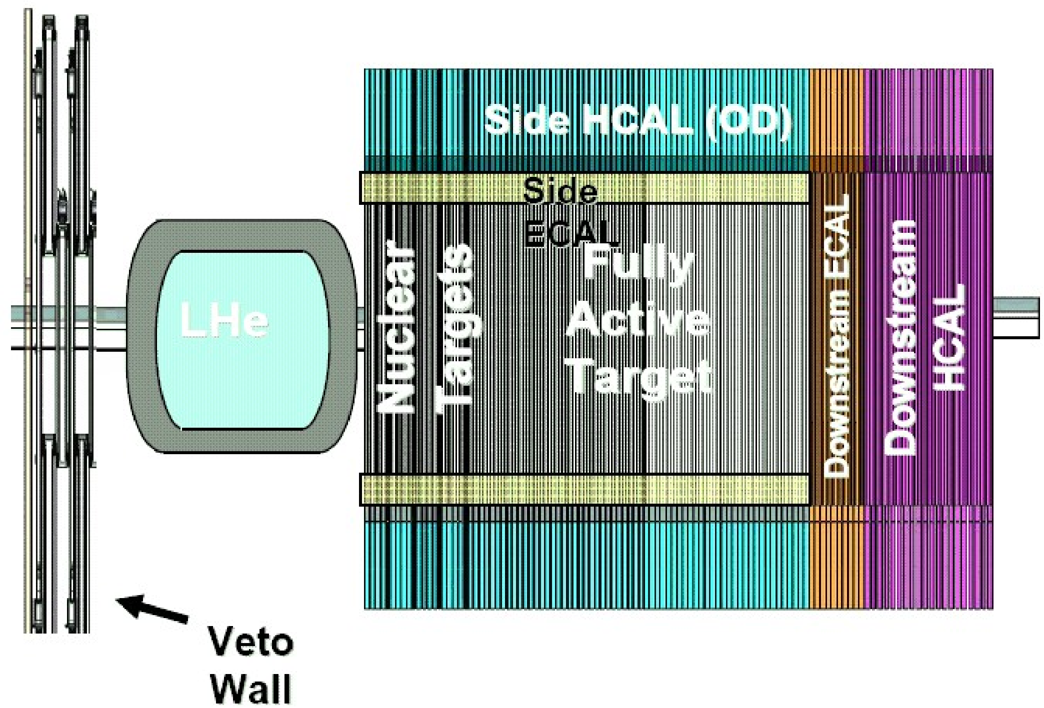
SciBooNE Event Rates



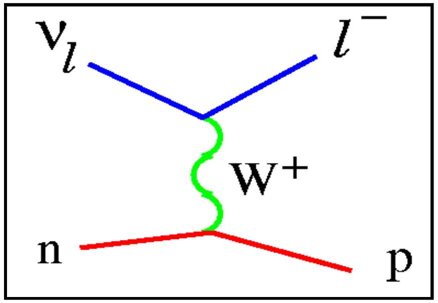
MINERvA

- Proposed neutrino experiment at Fermilab (expected start: 2009)
- Located on-axis in NuMI beamline, upstream of MINOS near detector
- Precision measurements of muon neutrino cross-sections and nuclear effects in the 1-20 GeV range
- Detector:
  - Active target made of solid scintillator bars
  - Other nuclear targets: He/Fe/Pb
  - Electromagnetic and hadronic calorimeters surrounding active detector
  - MINOS near as muon catcher





Quasi-Elastic Scattering



- Llewellyn Smith formalism:

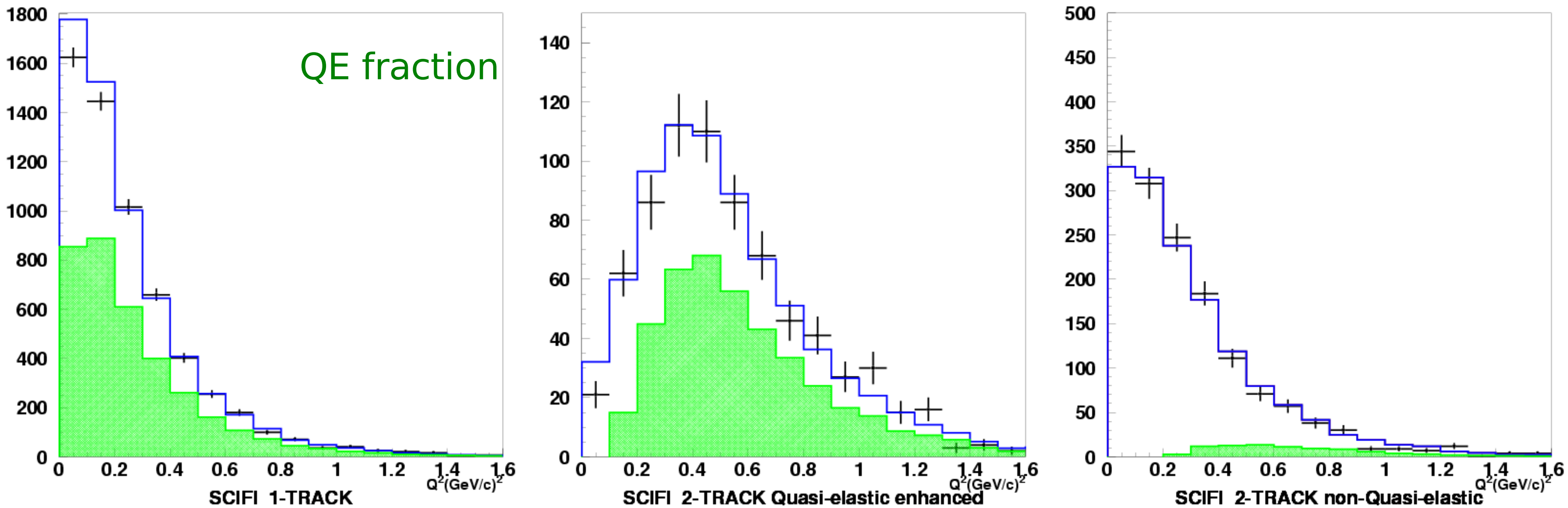
$$\frac{d\sigma}{dQ^2} = \frac{m_N^2 G_F^2 |V_{ud}|^2}{8\pi(\hbar c)^4 E_\nu^2}\left[A(Q^2) \pm B(Q^2)\frac{(s-u)}{m_N^2} + \frac{C(Q^2)(s-u)^2}{m_N^4}\right]$$

- $(s\text{-}u) \sim 4m_N E_\nu - Q^2$
- + for neutrinos, - for antineutrinos
- A,B,C depend on two vector (f_1, f_2) and one axial vector (g_1) form factors
- Q^2 dependence of axial vector form factor assumed to have dipole form:

$$g_1(Q^2) \approx \frac{1.25}{(1+Q^2/m_A^2)^2}, \quad m_A\text{: axial mass}$$

- Vector form factors: few % deviations from dipole form from electron scattering data, causing few % differences in CCQE cross section and axial mass extraction in recent analyses
- Axial for factor: given current accuracy, dipole approximation seems OK

CCQE at K2K



Source: K2K Coll., PRD 74, 052002 (2006)

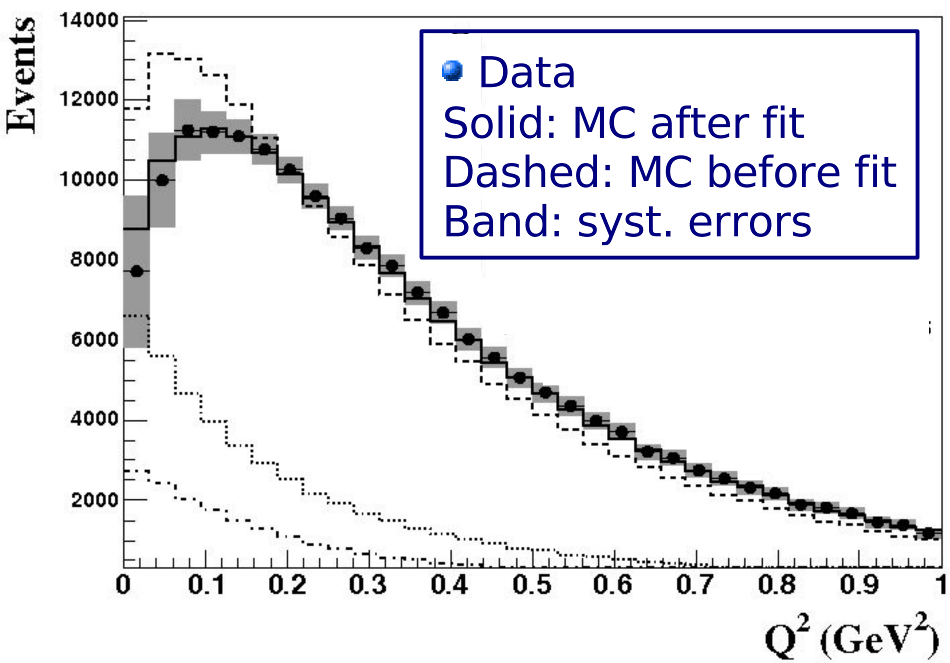
- Fit Q^2 shape in 1 track and 2 track QE CC samples in SciFi near detector
- Constrain nonQE background and flux prediction with 2 track nonQE CC sample and Q^2 fit in separate E_ν bins. $Q^2 > 0.2$ GeV^2 to reduce nuclear effects uncertainties
- Axial mass result (oxygen target): **M_A = (1.20 ± 0.12) GeV**
- Similar analysis with SciBar near detector (carbon): **M_A = (1.14 ± 0.11) GeV**

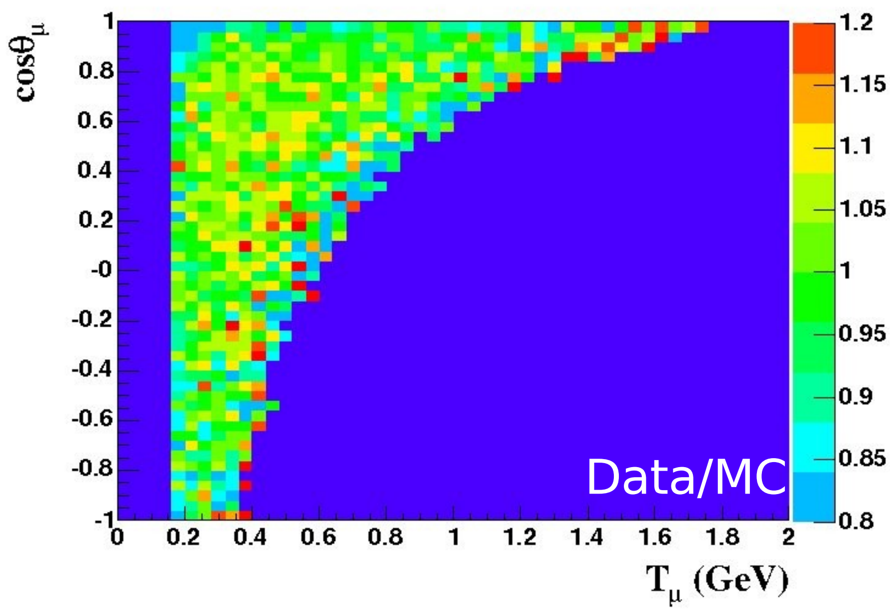
Source: X. Espinal and F. Sanchez, AIP Conf. Proc. 967 (2007)

CCQE at MiniBooNE

- Fit shape of Q^2 distribution, to measure both:
  - Axial mass
  - Parameter controlling strength of Pauli suppression in relativistic Fermi gas model
- Use sample of 200,000 events with ~74% estimated CCQE purity
- Axial mass result (carbon target): **M_A = (1.23 ± 0.20) GeV**
- Achieve good data/MC agreement in CCQE kinematic distributions after tuning these two parameters in MC

Source: MiniBooNE Coll., 0706.0926 [hep-ex], to appear in Phys. Rev. Lett.



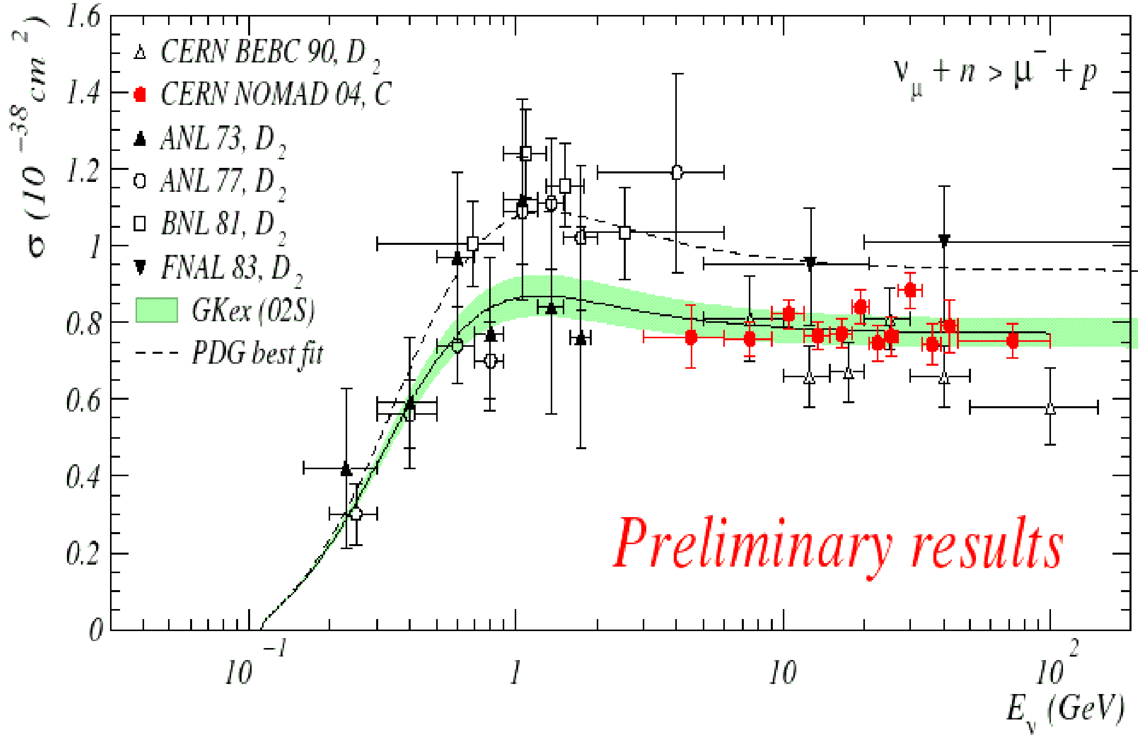


CCQE at NOMAD

- ~8,000 events selected in $3 < E_\nu < 100$ GeV, with 71% estimated CCQE purity
- Normalization via DIS sample in $40 < E_\nu < 200$ GeV, whose cross section is taken as $\sigma / E_\nu = 0.677 \cdot 10^{-38}$ cm^2 / GeV
- Preliminary CCQE cross section (stat.-only error quoted):

$\sigma(\nu_\mu n \to \mu^- p) = (0.72 \pm 0.01)\ 10^{-38}$ cm^2

- Systematic uncertainty evaluation underway, expected to be dominated by nuclear effects
- Measured cross section is ~20% smaller than the world average of previous bubble chamber experiments, and ~40% smaller than K2K's and MiniBooNE's
- Experimental biases, or MA parameter is not “universal”?

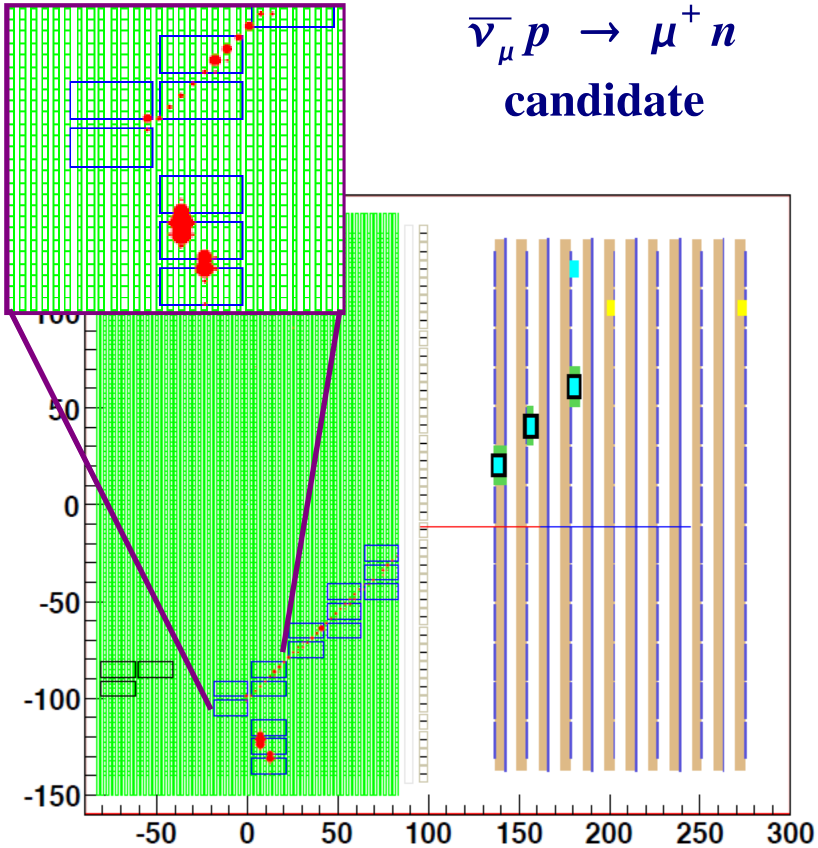


Sources: R. Petti, Nuint05; V. Lyubushkin and B. Popov, Phys. Atomic Nucl. 69, 1876 (2006)

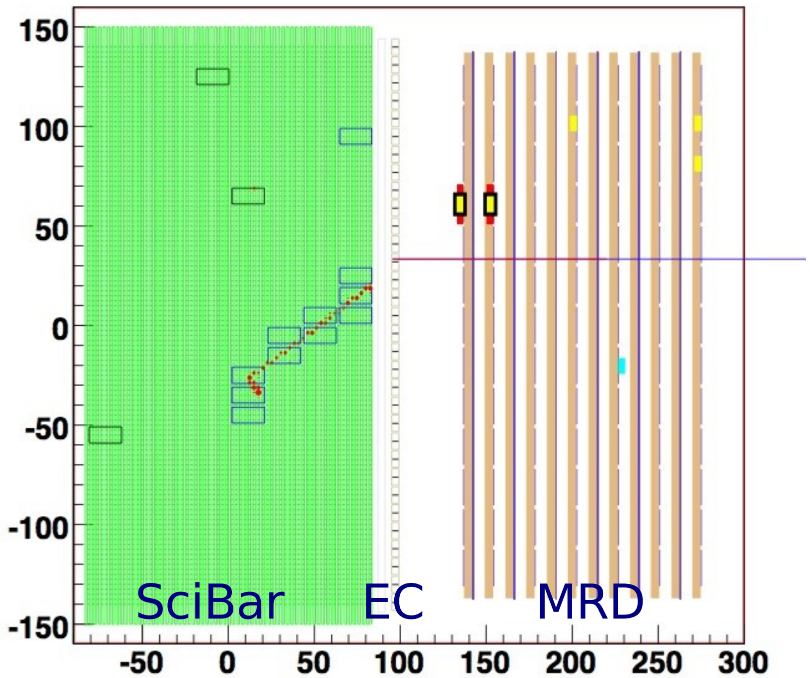
CCQE at SciBooNE

- Cross-check MiniBooNE's CCQE measurement with same beam and with better proton detection capability
- Measure both neutrino and antineutrino CCQE cross-sections, important for future leptonic CP violation measurements
- Expected SciBooNE statistics: ~50,000 numu CCQE, ~10,000 numubar CCQE

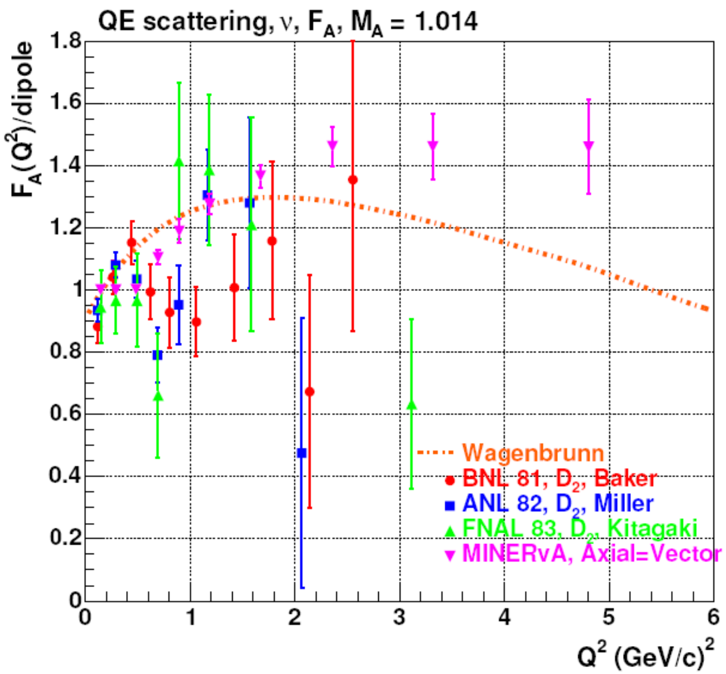
$\bar{\nu}_\mu p \rightarrow \mu^+ n$
candidate



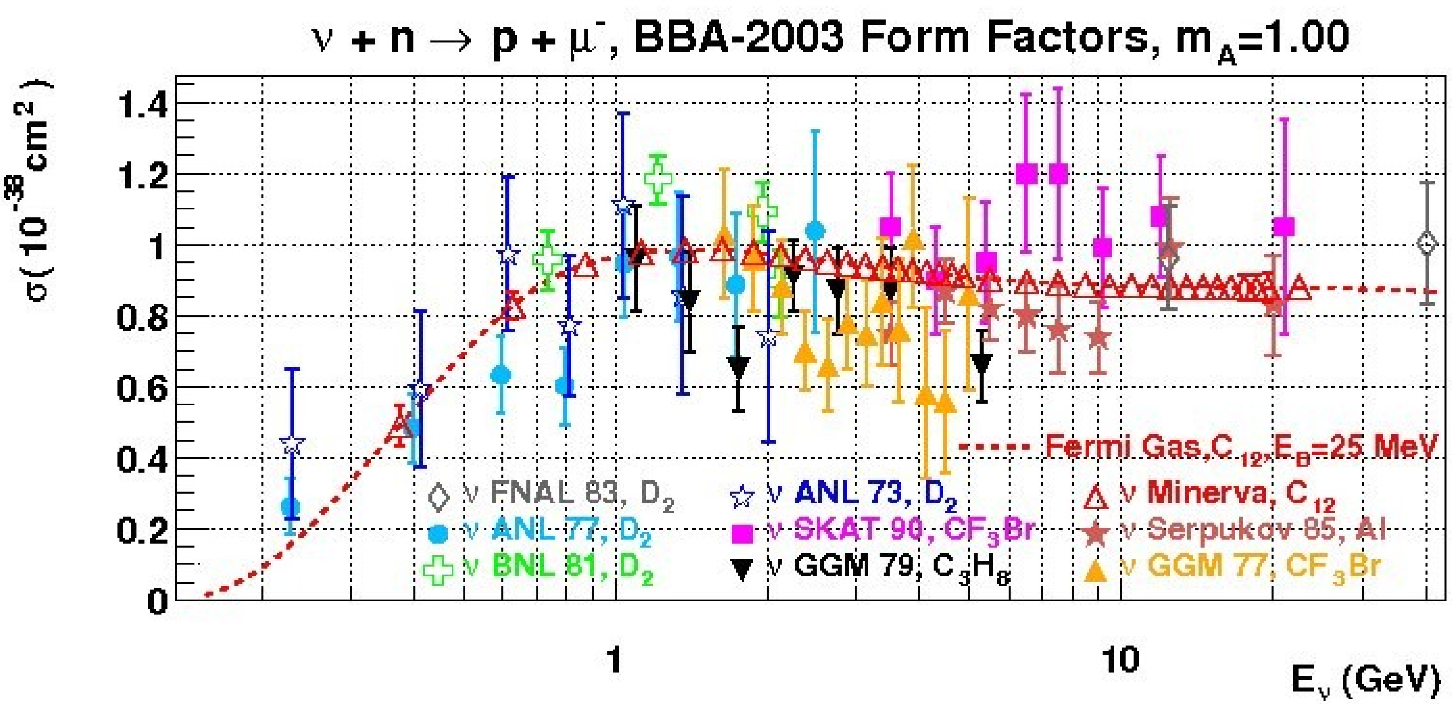
$\nu_\mu n \rightarrow \mu^- p$
candidate



CCQE at MINERvA

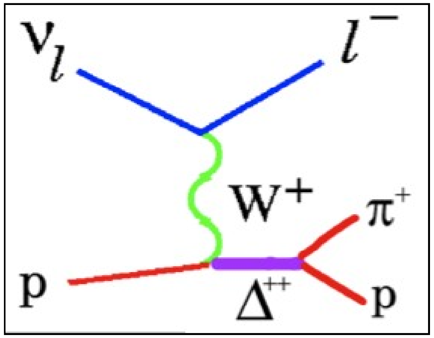


- Measure possible deviations from non-dipole axial vector form factor across wide Q^2 range (0-5 GeV^2)
- Measure cross section across wide energy range (0.5-20 GeV)
- Expected statistics: ~10^6 CCQE events



Sources: MINERvA Coll., CDR

Single Pion Production



- Dominant mechanism is resonant pion production: excitation, and subsequent decay, of resonances of hadronic masses 1.08 < W (GeV) < 1.4-2.0
- 14 final states overall (6 CC, 8 NC) for resonant process:

CC

$$\nu_\mu p \to \mu^- \Delta^{++} \qquad \Delta^{++} \to p\pi^+$$
$$\nu_\mu n \to \mu^- \Delta^{+} \qquad \Delta^{+} \to p\pi^0,\ \Delta^{+} \to n\pi^+$$
$$\overline{\nu}_\mu p \to \mu^+ \Delta^{0} \qquad \Delta^{0} \to n\pi^0,\ \Delta^{0} \to p\pi^-$$
$$\overline{\nu}_\mu n \to \mu^+ \Delta^{-} \qquad \Delta^{-} \to n\pi^-$$

NC

$$\nu_\mu p \to \nu_\mu \Delta^{+} \qquad \Delta^{+} \to p\pi^0,\ \Delta^{+} \to n\pi^+$$
$$\nu_\mu n \to \nu_\mu \Delta^{0} \qquad \Delta^{0} \to n\pi^0,\ \Delta^{0} \to p\pi^-$$
$$\overline{\nu}_\mu p \to \overline{\nu}_\mu \Delta^{+} \qquad \Delta^{+} \to p\pi^0,\ \Delta^{0} \to n\pi^+$$
$$\overline{\nu}_\mu n \to \overline{\nu}_\mu \Delta^{0} \qquad \Delta^{0} \to n\pi^0,\ \Delta^{0} \to p\pi^-$$

- Rein and Sehgal formalism. Resonance production and decay matrix elements computed according to FKR model and resonance decay experimental input
- Other mechanisms contributing to single pion production: coherent and deep inelastic scattering

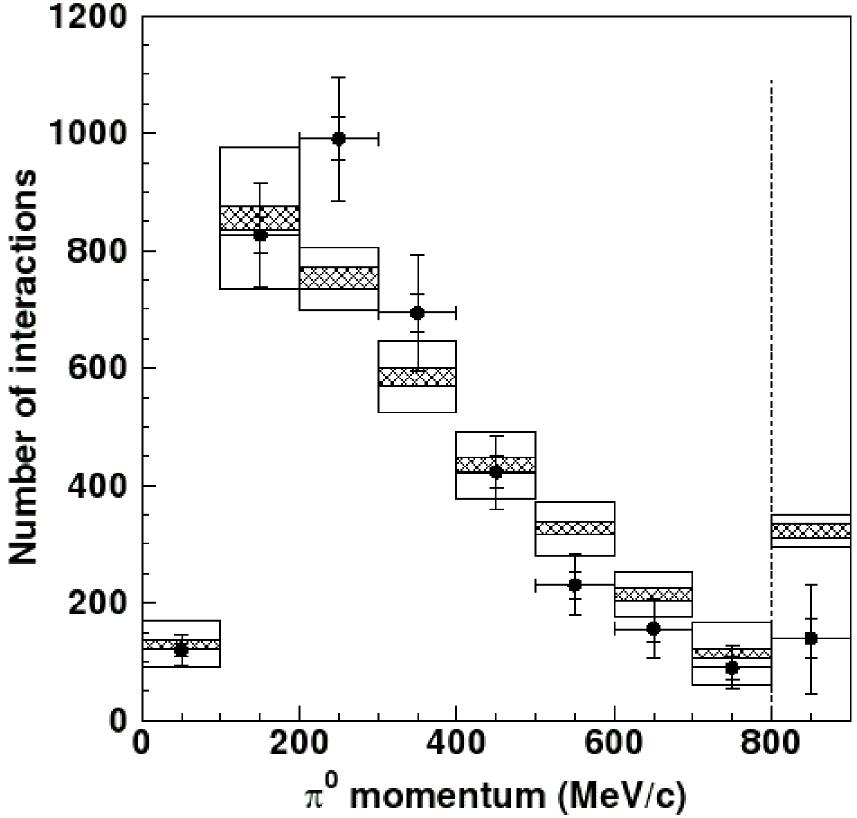
Single Pion Production at K2K

- **NC 1π^0 production in K2K-1KT:**

• σ(NC 1π^0)/σ(CC) = (6.4 ± 0.1 ± 0.7)%

• Good agreement with expectations, also for π^0 momentum distribution

Source: K2K Coll., Phys. Lett. B619 (2005)



- **CC inclusive π^0 production in K2K-SciBar:**

• σ(CC π^0)/σ(CCQE) = (30.6 ± 2.3 ± 2.5)%

• (39 ± 15)% excess wrt expectations

Source: C. Mariani, AIP Conf. Proc. 967 (2007)

- **CC 1π^+ production in K2K-SciBar:**

• σ(CC 1π^+)/σ(CCQE) = (74 ± 23)%

• Good agreement with expectations, also for energy dependence of xsec ratio

Source: A. Rodriguez, L. Whitehead, AIP Conf. Proc. 967 (2007)

- **CC coherent π^+ production in K2K-SciBar:**

• σ(CC coh π^+)/σ(CC) < 0.60% at 90% CL

• No coherent production seen, tension with some models + NC coherent exp. data

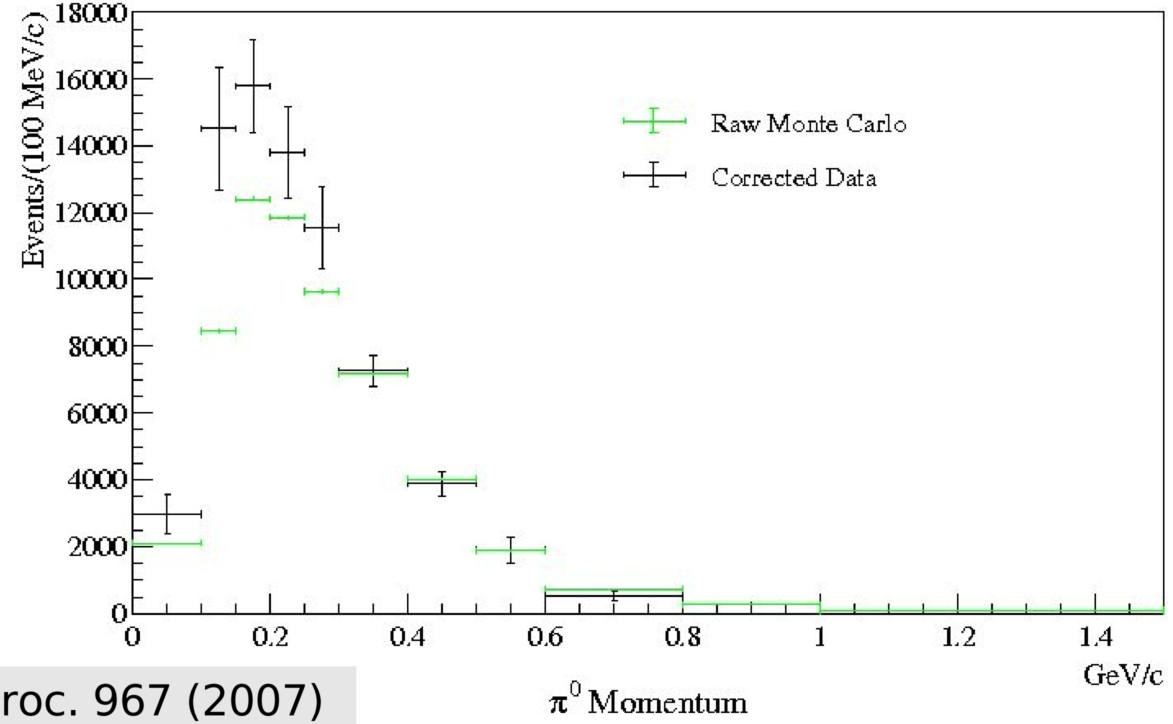
Source: K2K Coll., Phys. Rev. Lett. 95 (2005)

Single Pion Production at MiniBooNE

- **NC 1π^0 production:**

• Measure higher production rate wrt predictions at low π^0 momenta

Source: J. Link, AIP Conf. Proc. 967 (2007)



- **NC coherent π^0 production:**

• N(NC coh π^0)/N(NC 1π^0) = (19.5 ± 1.1 ± 2.5)%

• Measured ratio is ~2/3 expectation

• Antineutrino data also suggest non-zero coherent contribution

Source: J. Link and V. Nguyen, AIP Conf. Proc. 967 (2007)

- **CC 1π^+ production:**

• σ(CC 1π^+)/σ(CCQE) measured over E_ν = 0.6 – 1.4 GeV range

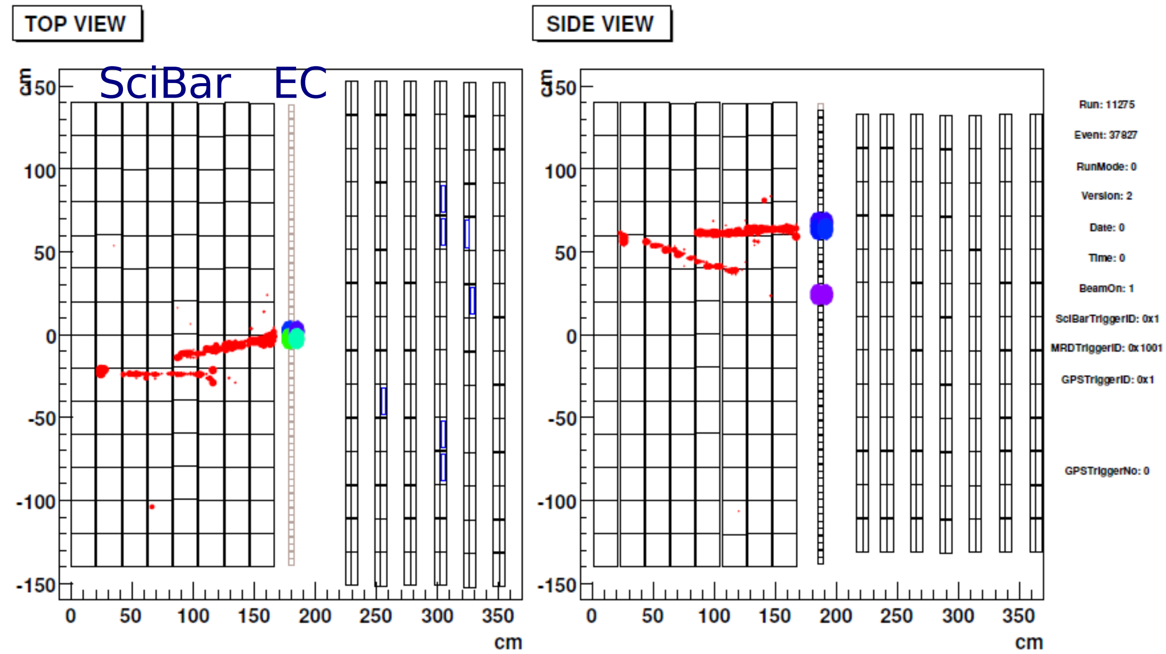
• Ratio ~25% lower than predictions, energy dependence agrees well

Source: M. Wascko, Nucl. Phys. Proc. Suppl. 159 (2006)

- **K2K+MiniBooNE:** High statistics samples allow us to test in detail for the first time pion production kinematics. Current modeling seems OK at the ~20% level

Pion Production at SciBooNE

$\nu_\mu N \rightarrow \nu_\mu N \pi^0, \ \pi^0 \rightarrow \gamma\gamma$
candidate

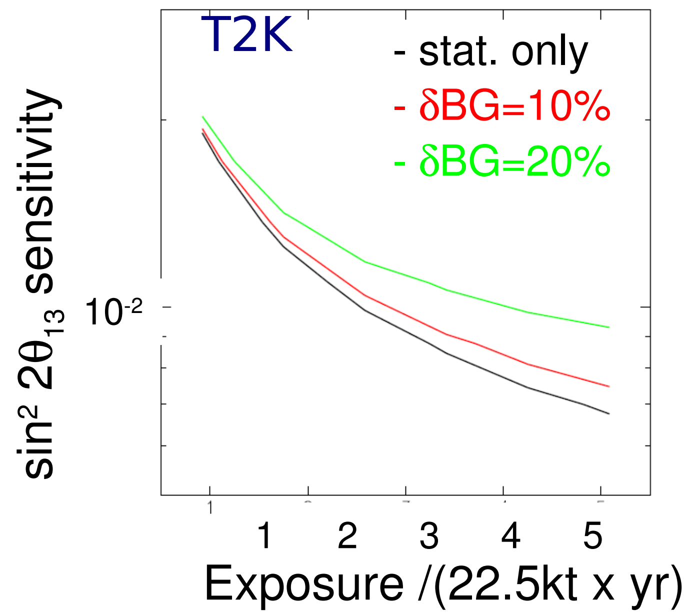


- Expected single pion production statistics at SciBooNE (nu + nubar, CC + NC): ~40,000 events
- SciBooNE+MiniBooNE should be able to meet goals for T2K oscillation physics:
- ν_μ -> ν_e appearance:

Reduce NC π^0 cross-section uncertainty at T2K energies from ~25% to <~10%

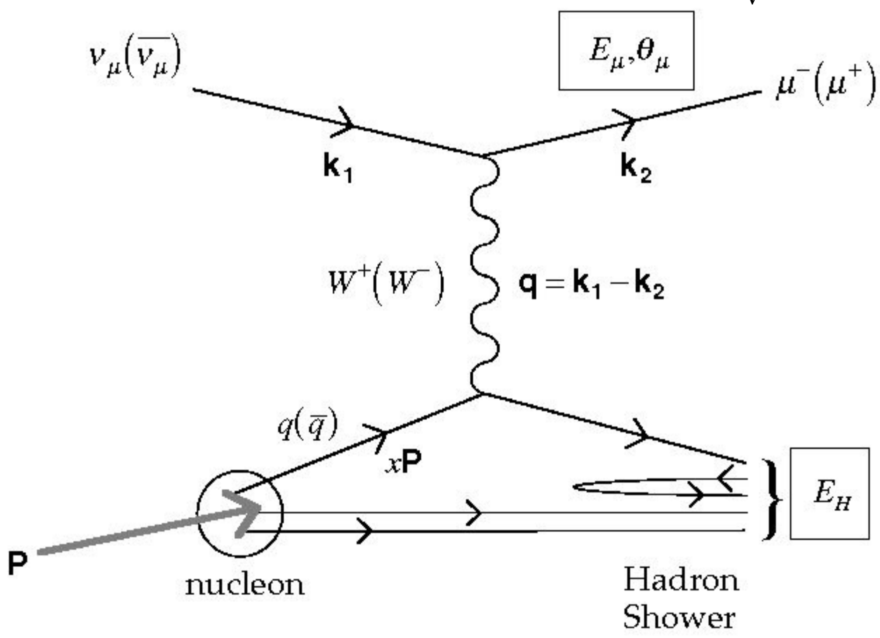
- ν_μ disappearance:

Reduce CC π^+ cross-section uncertainty at T2K energies from ~25% to <~10%



From Resonance Region to Deep Inelastic Scattering

- DIS: dominant process for E_ν>3 GeV. Allows to probe nucleon structure



- Measure E_μ, θ_μ, E_H. Infer:
- *Neutrino energy:* $E_\nu = E_\mu + E_H$
- *Momentum transfer*: $Q^2 = 4E_\nu E_\mu \sin^2(\theta_\mu/2)$
- *Bjorken scaling variable:* $x = Q^2 / (2ME_H)$
- *Inelasticity:* $y = (E_H\text{-}M) / E_\nu$
- *Hadronic mass:* $W^2 = M^2+2ME_H\text{-}Q^2$

- Differential neutrino cross sections $d^2\sigma/(dxdy)$ can be expressed in terms of structure functions $F_2(x,Q^2)$, $xF_3(x,Q^2)$, and $R_L(x,Q^2)$
- Smooth transition from resonance production to DIS regime
- Neutrino generators simulate low multiplicity hadronic final states up to some W~1.4-2 GeV with resonance formalism, turn to DIS formalism for higher W

DIS at MINOS Near

- Large data sample of DIS (W>2 GeV) and transition region (1.4<W<2 GeV) events

ν DIS sample:

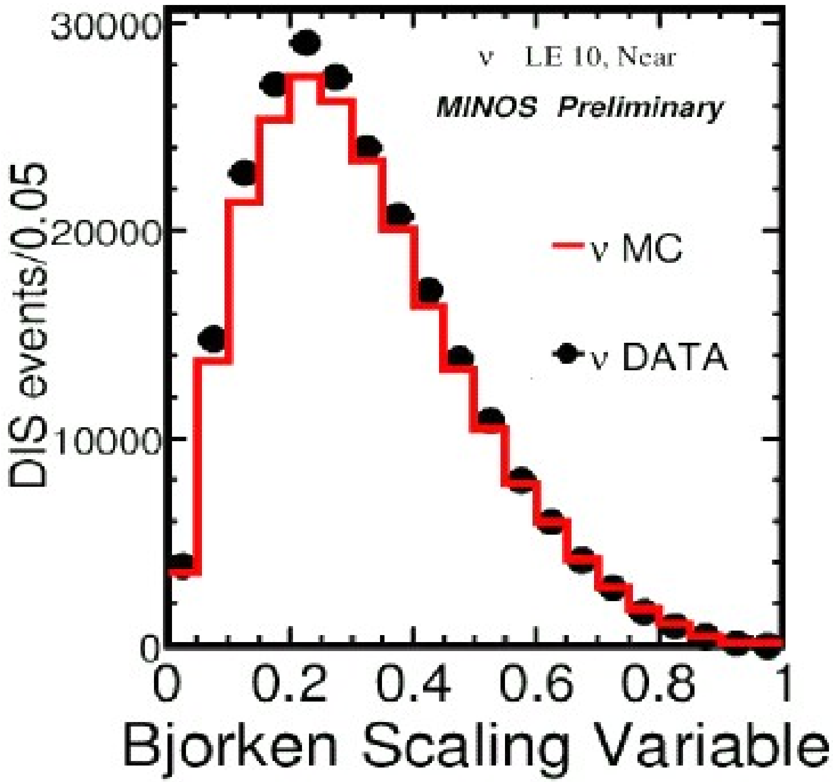
(1E20 POT LE-10)

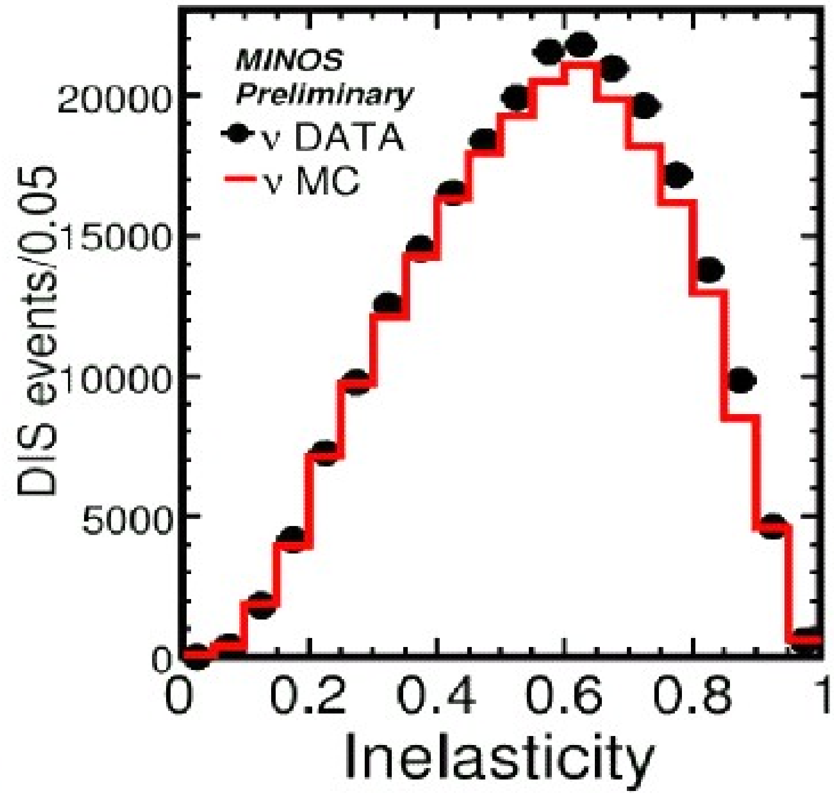
MC: Low-ν flux rewt.

$W > 2\,\mathrm{GeV}$

$Q^2 > 1\,\mathrm{GeV}^2$

$E_\nu > 5\,\mathrm{GeV}$





Source: D. Naples, APS-DPF 2006

- Require $E_H = \nu < 1$ GeV, and extract flux for $E_\nu > 5$ GeV
- From flux and event distributions, get $d^2\sigma/(dxdy)$ for neutrinos and antineutrinos

-> *extract F2 and xF3 in neutrino-iron scattering*

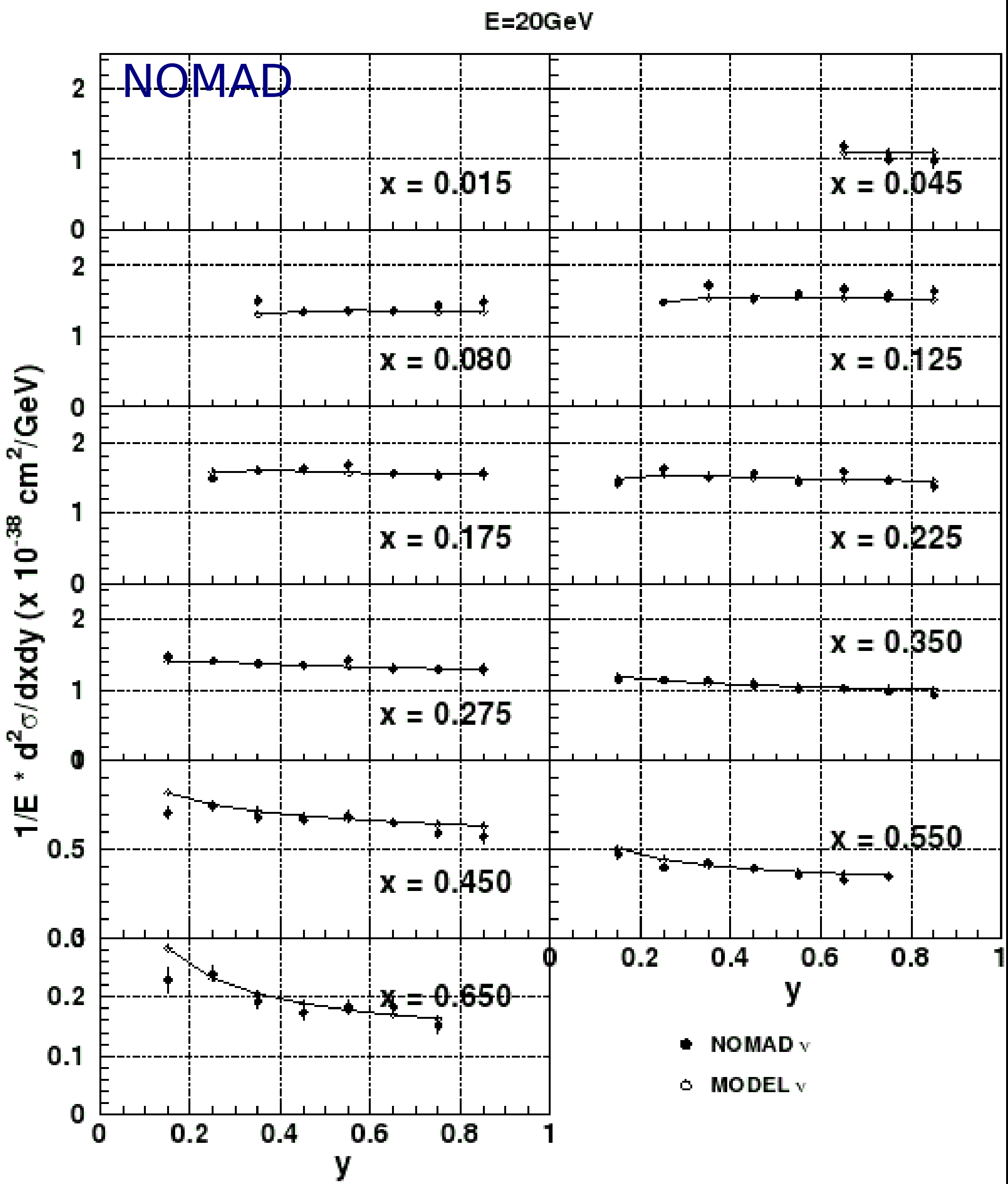
DIS at Higher Energies: NOMAD/NuTeV

- NOMAD: first measurement of inelastic CC cross section on a carbon target and large Q^2 (~13 GeV^2)
- Absolute xsec normalization from world average in 40 < E_ν < 200 GeV
- Measurement in (E_ν,x,y) bins. Energy range: 6<E_ν<300 GeV

Source: R. Petti, NuInt05

- At even higher energies: recent NuTeV precision structure functions measurements, with neutrinos and antineutrinos on Fe

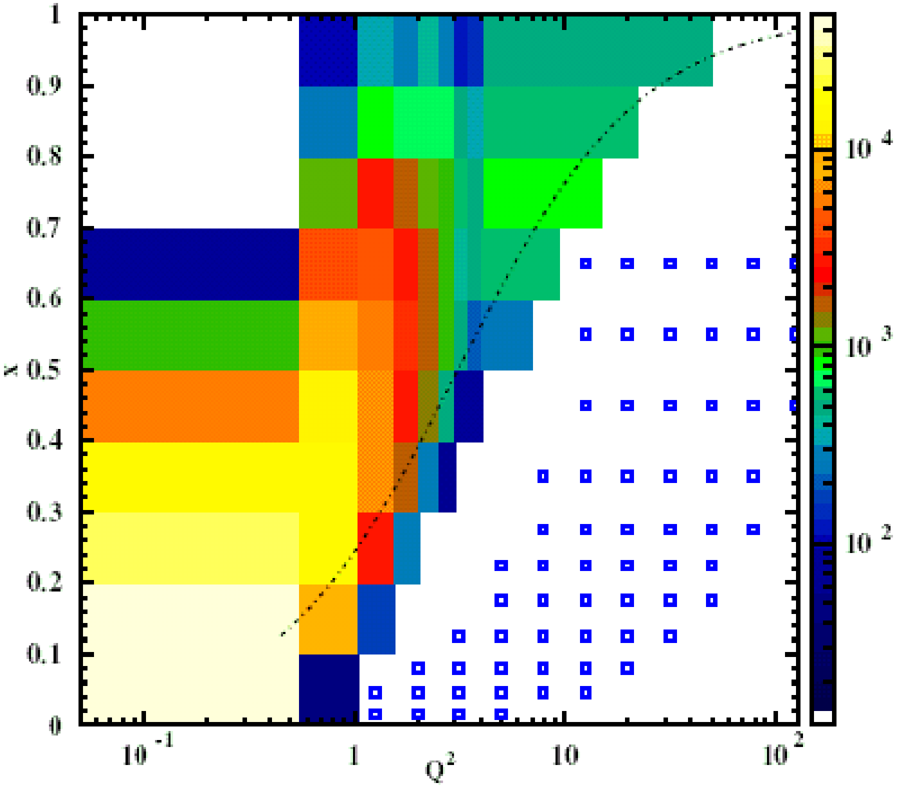
Source: M. Tzanov, NuFact06



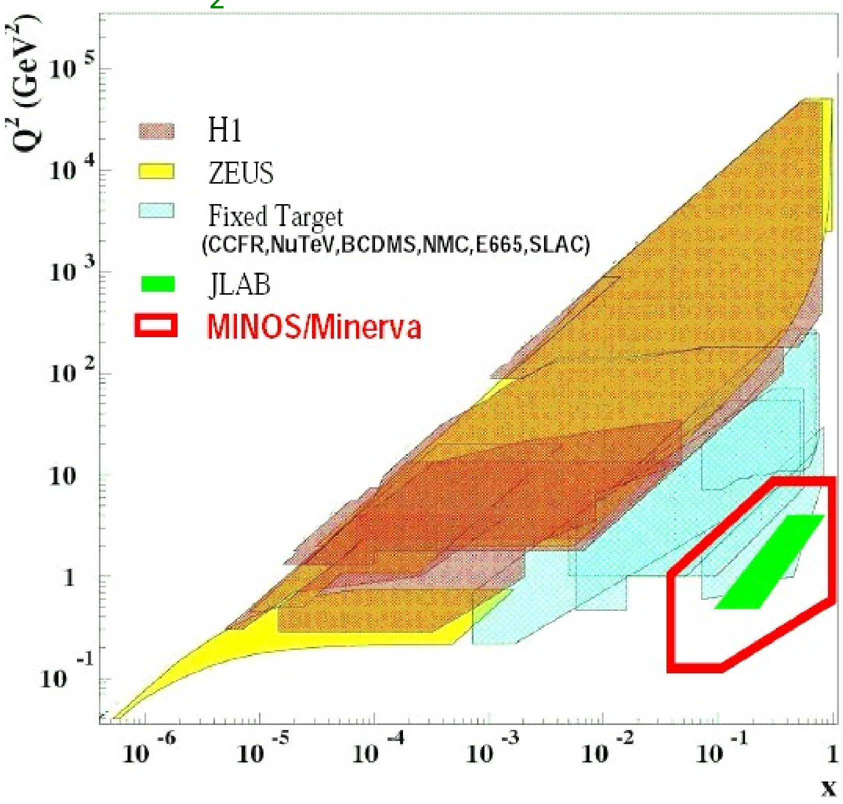
Resonance-to-DIS at MINERvA

- Able to cover regions of phase space (high x, low/medium Q^2) for structure functions measurements that are complementary to charged lepton scattering and beyond past neutrino scattering experiments
- Relevant for relatively low energy neutrino beams and for understanding RES-to-DIS transition

Available xF_3 data and MINERvA reach

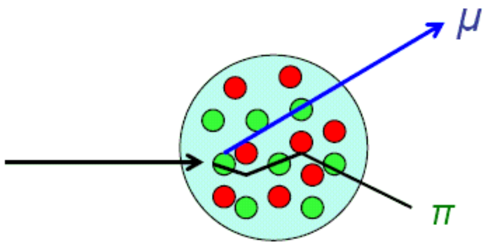


Available F_2 data and MINERvA reach



Sources: MINERvA Coll., CDR; D. Naples, NuInt07

Nuclear Effects

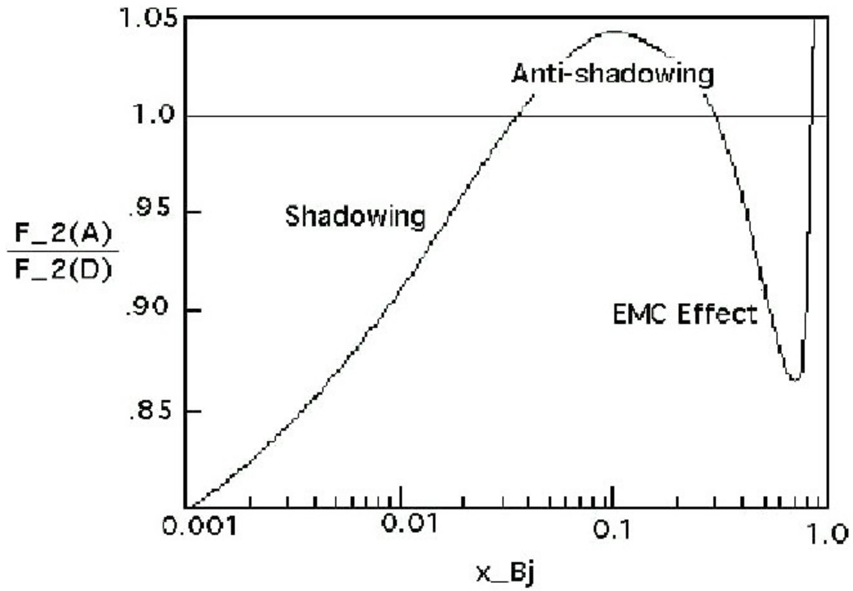


Few-GeV neutrino energies and below:

- *Fermi motion and binding energy of target nucleons*
-> changes interaction kinematics

- *Pauli suppression of the phase space available to final state nucleons*
-> causes Q^2-dependent suppression of the cross-sections, compared to free nucleon ones

- *Final state interactions (FSI) inside the nucleus, such as proton re-scattering or pion absorption*
-> can change composition and kinematics of the hadronic part of the final state



Higher energies:

- Shadowing, anti-shadowing, EMC effects
-> causes x-dependent variation of the cross-sections, compared to free nucleon ones

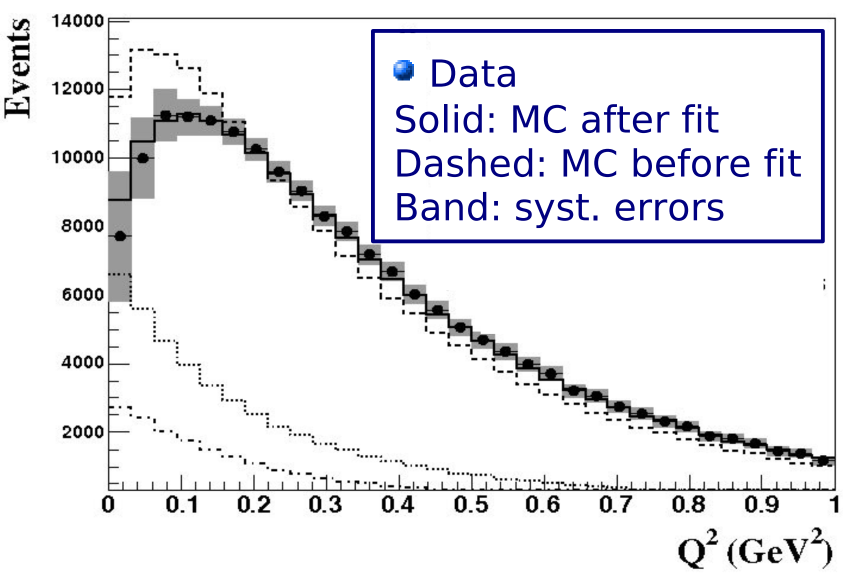
Nuclear Effects at MiniBooNE and K2K

- Low-Q^2 interactions: ones mostly affected by nuclear effects
  -> important for low-energy neutrinos (eg, superbeams)

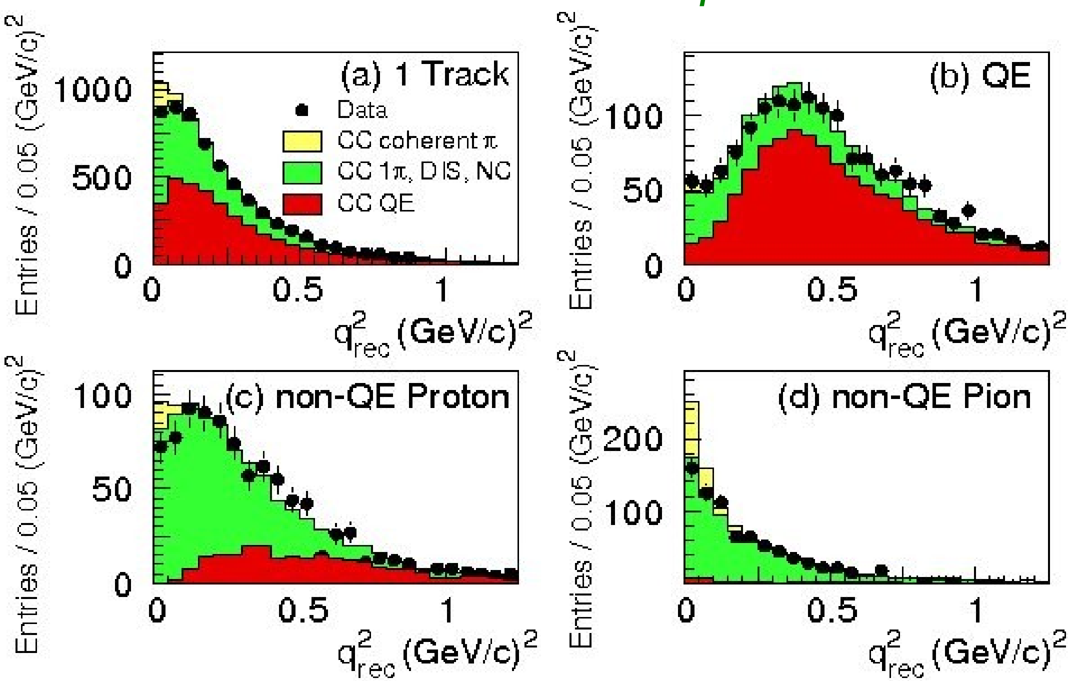
- Early analyses of low-Q^2 samples showed a deficit with respect to predictions for $Q^2 < 0.2$ GeV^2 . Distinct approaches to tune low-Q^2 predictions:

- *MiniBooNE:* extra degree of freedom in nuclear model to set Pauli suppression
  -> nuclear physics explanation

- *K2K*: most (if not all) of the discrepancy gone assuming no coherent pion prod.
  -> neutrino interaction explanation



Source: MiniBooNE Coll., 0706.0926 [hep-ex], to appear in Phys. Rev. Lett.



Source: Phys. Rev.Lett. 95, 252301 (2005)

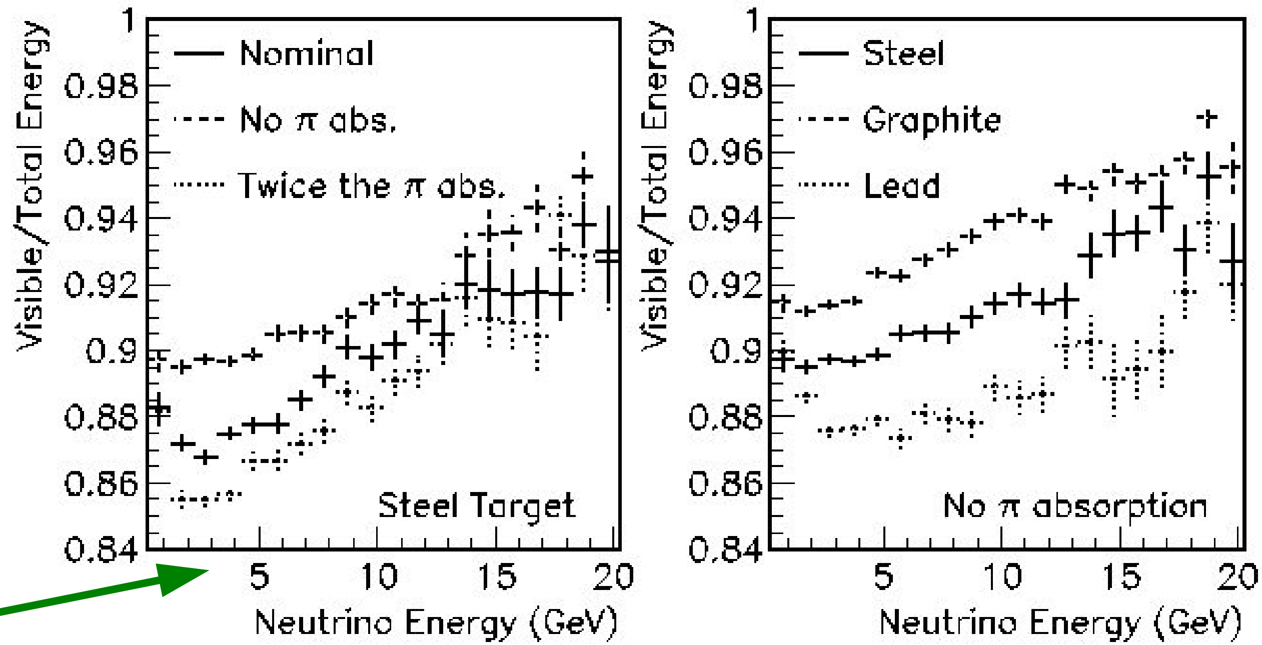
- SciBooNE will check

Nuclear Effects at MINERvA

- Final state multiplicities, and hence pion absorption probabilities, as a function of nuclear target A

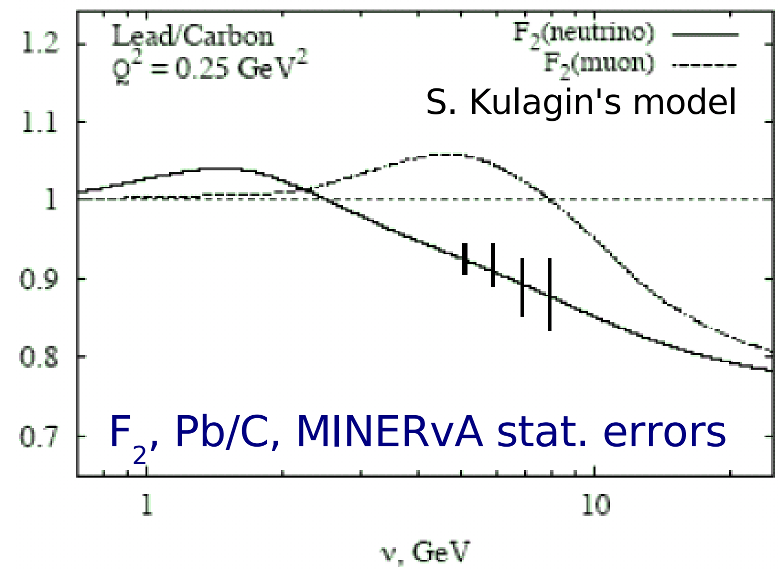
- Visible hadron energy distribution as a function of target to determine relative energy loss due to FSI

-> Important for calorimetric neutrino energy reconstruction in oscillation experiments



Source: MINERvA Coll., hep-ex/0410005

- σ(x) for each nuclear target to compare x-dependent effects with neutrino and charged lepton



Source: K. McFarland, NuInt05

Summary

Neutrino cross sections for oscillation measurements:

- Better known at high energy (-> neutrino factory) than low (-> superbeam)
- Cross sections on medium/heavy nuclei needed over wide energy range, $0.3 < E_\nu < 50$ GeV, spanning all relevant channels (CCQE, RES, COH, DIS)

Recent progress in neutrino scattering measurements:

- Several new cross section results, including study of nuclear effects with neutrinos. Higher statistics samples allowing to study differential cross-sections
- Large (~10-30%) error bars may be deceiving, but represent more accurately current systematic uncertainties, with respect to what was done in the past
- Results not always consistent, pointing to either non-understood experimental biases, or deficiencies in the models used to analyze the data. Need to solve this to get to the needed precision era (~5%) in few-GeV neutrino-nucleus scattering

The future is bright:

- SciBooNE, MINERvA, MINOS/NovA/T2K Near
- Synergies established with nuclear physics and charged lepton DIS communities