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Neutrino Scattering Measurements with MiniBooNE

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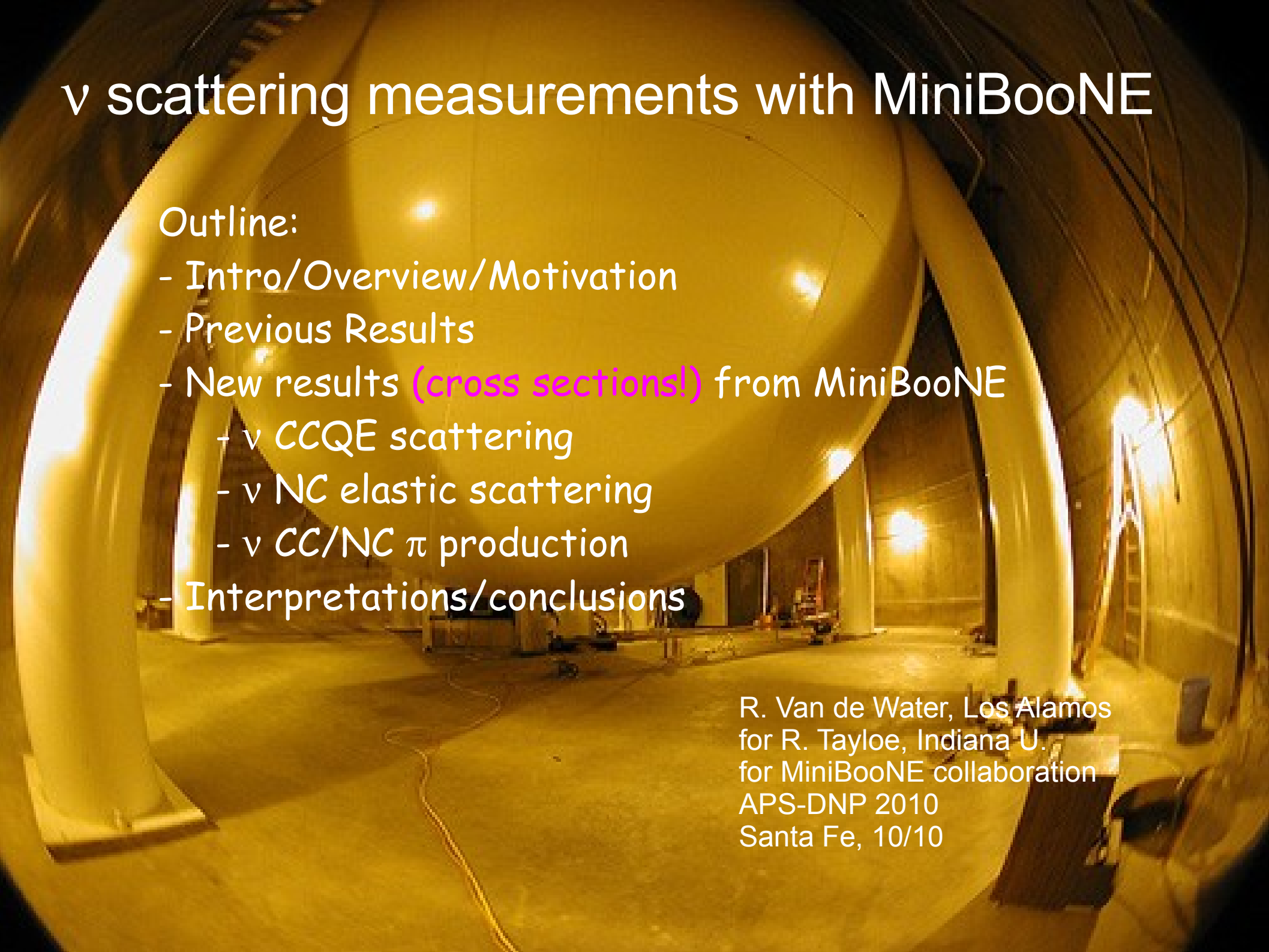
— The MiniBooNE experiment at Fermilab has collected the world's largest sample of neutrino and antineutrino scattering events in the 1 GeV energy region. The sample includes charged- and neutral-current interactions from quasielastic and resonant channels. Recent results are confronting existing models for neutrino scattering on light nuclei. These results will be presented along with the latest interpretations.

ν scattering measurements with MiniBooNE



Outline:

- Intro/Overview/Motivation
- Previous Results
- New results (cross sections!) from MiniBooNE
  - ν CCQE scattering
  - ν NC elastic scattering
  - ν CC/NC π production
- Interpretations/conclusions

R. Van de Water, Los Alamos
for R. Tayloe, Indiana U.,
for MiniBooNE collaboration
APS-DNP 2010
Santa Fe, 10/10

ν scattering measurements and oscillations

In order to understand ν oscillations, it is crucial to understand the detailed physics of ν scattering (at 1-10 GeV)

- for MiniBooNE, both signal and backgrounds
- and for others (T2K, NOvA, DUSEL etc)
- especially for *precision* (e.g. 1%) measurements.

Requires: Precise measurements to enable a complete theory valid over wide range of variables (reaction channel, energy, final state kinematics, nucleus, etc)

A significant challenge with neutrino experiments:

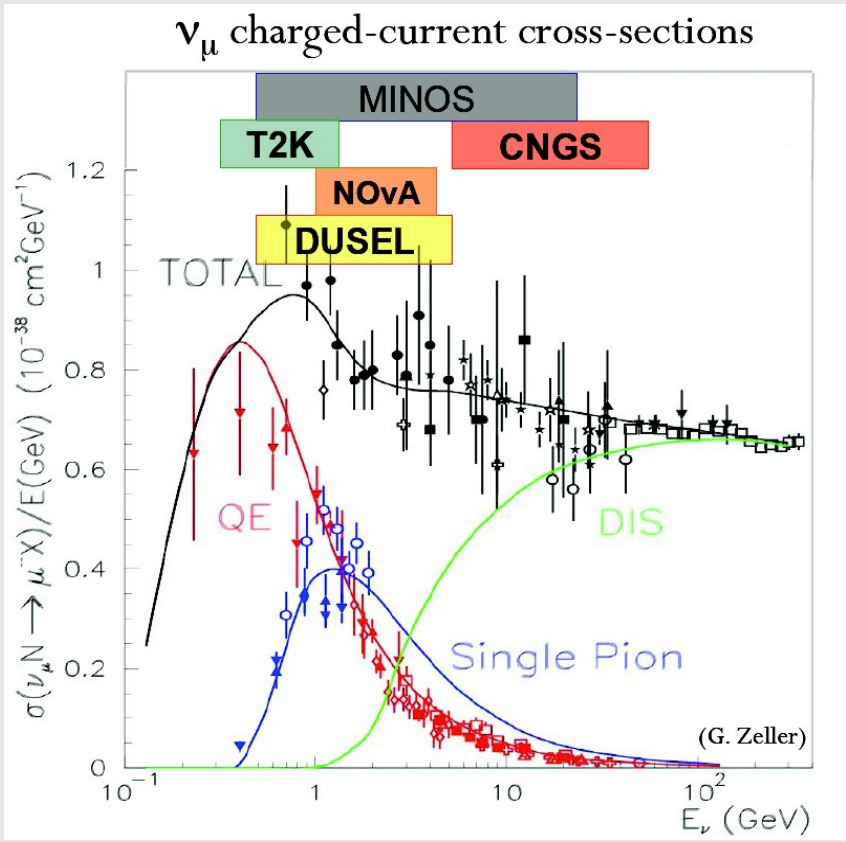
- non-monoenergetic beams
- large backgrounds
- nuclear scattering (bound nucleons)

New measurements are appearing and guiding the models:

- SciBooNE, MINOS (currently)
- MINERvA, T2K, μBooNE, NOvA (soon)

- and MiniBooNE....
  and some surprises have surfaced...

before MiniBooNE ~2000



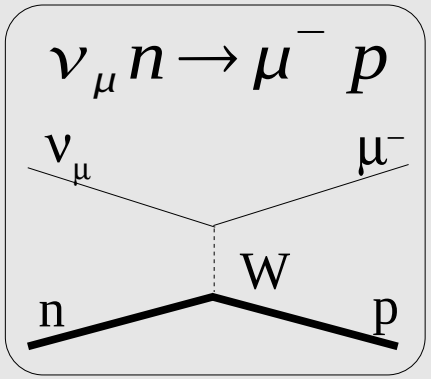
D. Schmitz, nufact'09

ν scattering measurements and nuclear physics

- MiniBooNE observes several ν scattering processes on carbon at E_ν~800MeV teaching us about axial structure of the nucleon.

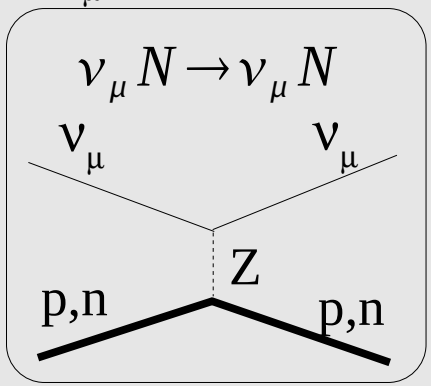
- For example, the charged- and neutral-current "elastic" processes:

ν_μ CCQE



ν_μ charged-current quasielastic (CCQE)

ν_μ NC elastic



ν_μ neutral-current elastic (NCel)

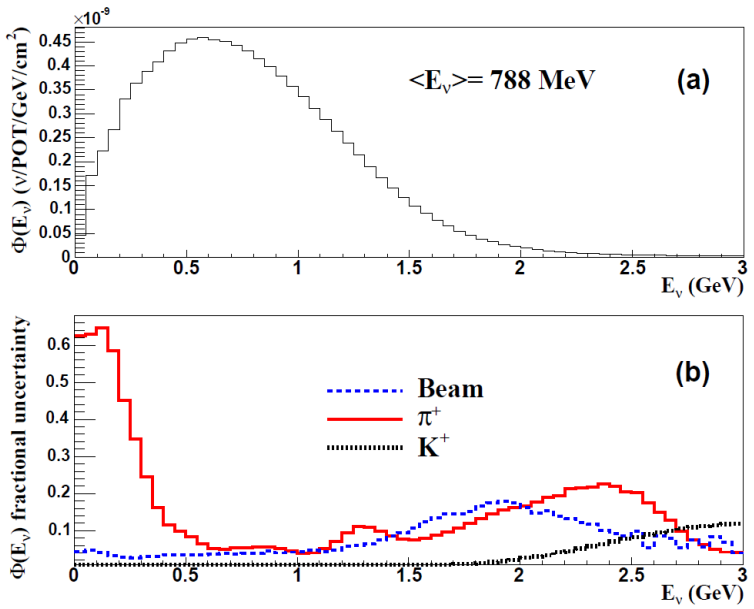


FIG. 2: (color online) Predicted ν_μ flux at the MiniBooNE detector (a) along with the fractional uncertainties grouped into various contributions (b). The integrated flux is 5.16×10^{-10} ν_μ/POT/cm^2 ($0 < E_\nu < 3$ GeV) with a mean energy of 788 MeV. Numerical values corresponding to the top plot are provided in Table V in the Appendix.

- However, the nucleons are bound in carbon.
- Is the (typical) impulse approximation with a Fermi Gas nuclear model adequate?
- perhaps not... as recent MiniBooNE data indicates

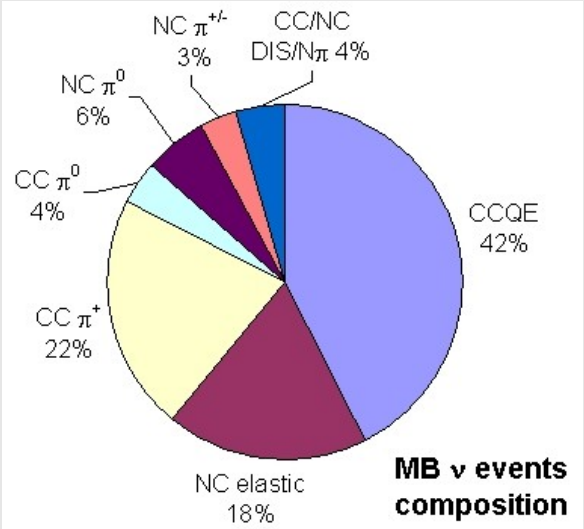
MiniBooNE ν scattering measurements

MiniBooNE has published results on these ν_μ scattering processes in last 2 years

(see http://www-boone.fnal.gov/publications/ for full list, including detector and neutrino flux descriptions)

- ν_μ charged-current (CC) quasielastic (CCQE)
  - detection and normalization signal for oscillations
  - charged-current axial formfactor
- ν_μ neutral-current (NC) elastic (NCel)
  - predicted from CCQE excepting NC contributions to axial form factor (strange quarks)
- ν_μ CC production of π^+, π^0
  - insight into models of neutrino pion production via nucleon resonances
- ν_μ NC production of neutral pions
  - very important oscillation background
  - sizeable coherent production?

- Results include absolutely normalized differential cross sections...
  - flux-averaged quantities at $\langle E_\nu \rangle \sim 800$ MeV
  - normalization known (neutrino flux) to ~10%
  - reported results are as model independent as possible
  - for most channels both "observed" and "final-state corrected" observables reported

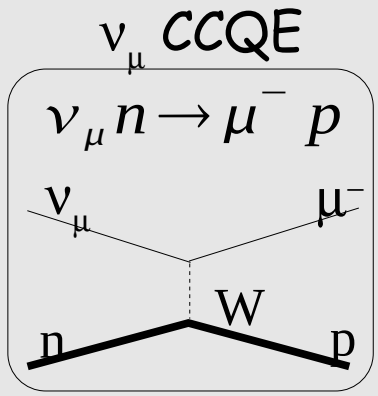


MiniBooNE CCQE scattering

- Phys. Rev. D81, 092005 (2010), thesis T. Katori, Indiana U.
- CCQE experimental defintion: 1 μ^- , no π
- Requires id of stopping μ^- and 1 decay e^- (2 "subevents")

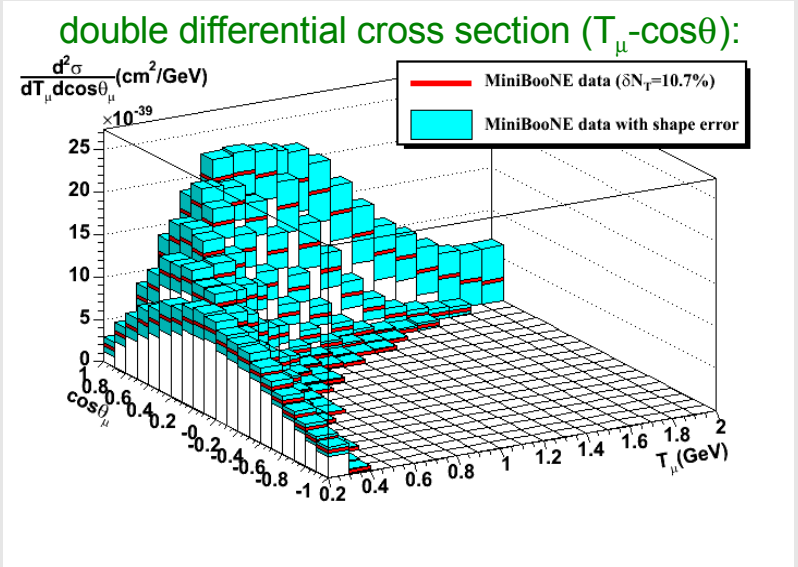
$$\nu_\mu + n \rightarrow \mu^- + p$$
$$\hookrightarrow \nu_\mu + \nu_e + e^- \quad (\tau \sim 2\mu s)$$

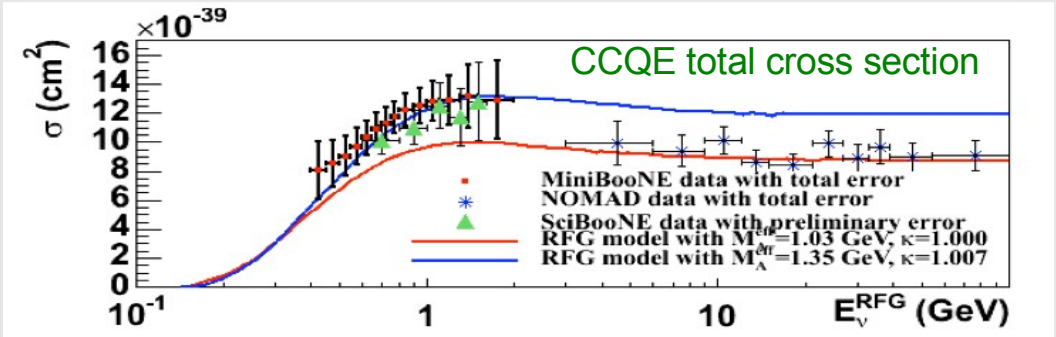
- Largest background, CCπ^+ , measured from MB data



Results:

- first ever double diff. cross section for this process
- more strength at high-momentum-transfer than expected, extracted axial mass, M_A =1.35 ± 0.17GeV
- total cross section also larger than expected.
- rel. fermi-gas (RFG) plus impulse approximation model correct for total cross section with larger M_A
- consistent with SciBooNE prelim. results
- However, NOMAD exp. w/carbon target, but at higher E_ν , consistent with world average M_A





MiniBooNE CCQE scattering

- perhaps multi-nucleon correlations are contributing significantly .
(Martini et al PRC80, 065501, '09)

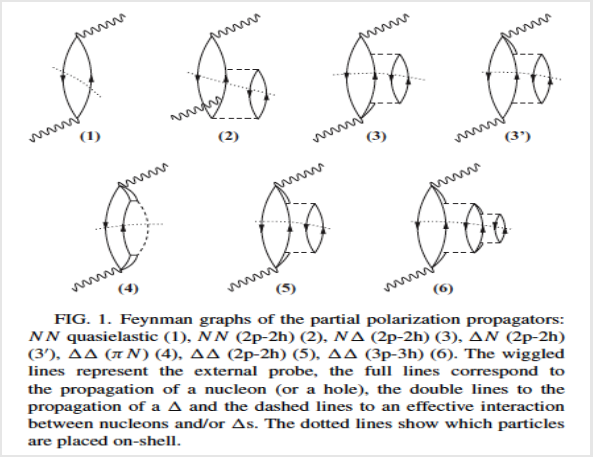
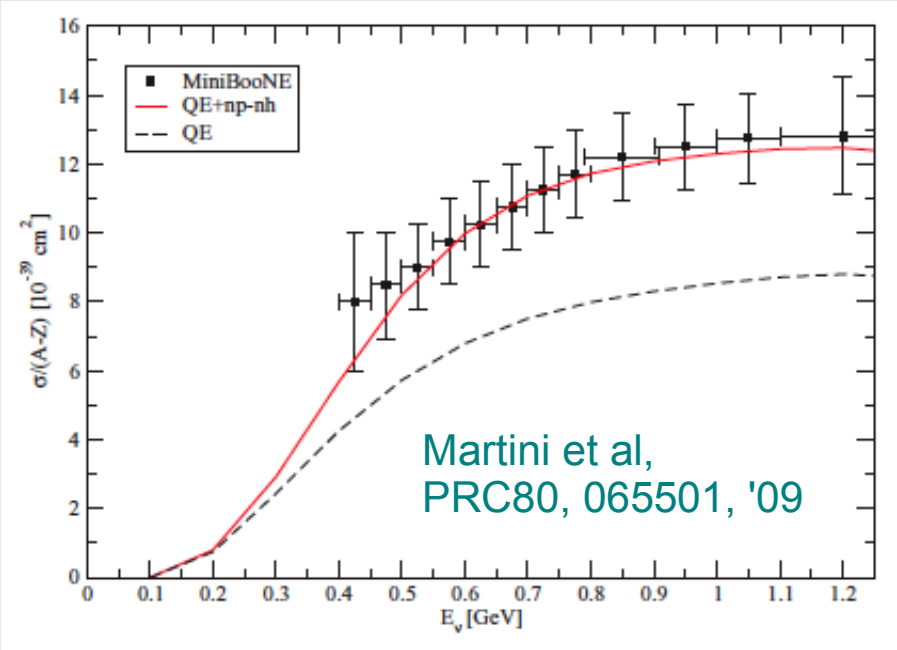


FIG. 1. Feynman graphs of the partial polarization propagators: NN quasielastic (1), NN (2p-2h) (2), $N\Delta$ (2p-2h) (3), ΔN (2p-2h) (3′), $\Delta\Delta$ (πN) (4), $\Delta\Delta$ (2p-2h) (5), $\Delta\Delta$ (3p-3h) (6). The wiggled lines represent the external probe, the full lines correspond to the propagation of a nucleon (or a hole), the double lines to the propagation of a Δ and the dashed lines to an effective interaction between nucleons and/or Δs. The dotted lines show which particles are placed on-shell.

CCQE total cross section



- related to neglected “transverse” response in noted in electron scattering?
- in superscaling model $f_L = f_T$ (“0-th kind scaling”) ,
(Amaro et al Phys. Rev. C 71 , 015501 (2005))
- also, Carlson etal, PRC65, 024002, '02)
- Expected with nucleon short range correlations (SRC) and 2-body exchange currents

- recent results from e-scattering suggest 20% of nucleons in carbon are in a “SRC state”
(K. S. Egiyan et al., PRL 96, 082501 (2006), PR C68, 014313 (2003).)

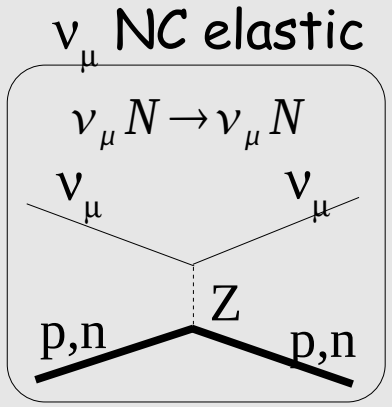
This channel needs further investigation via more exclusive final states
(recoil nucleons observed) in different ν beam (e.g. MINERvA, SciNOvA)

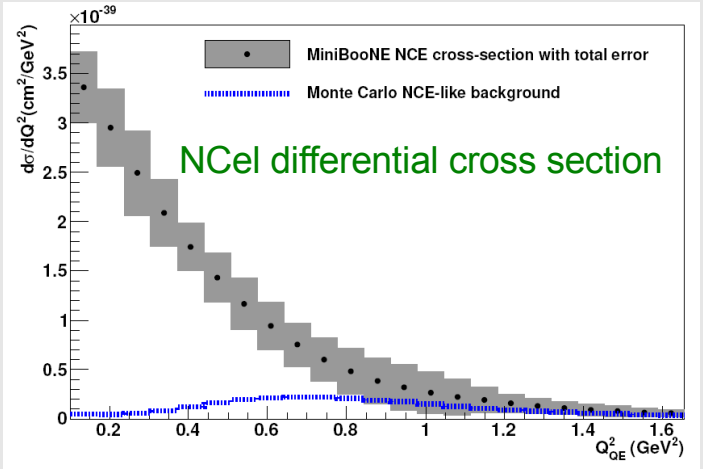
MiniBooNE ν NC elastic scattering

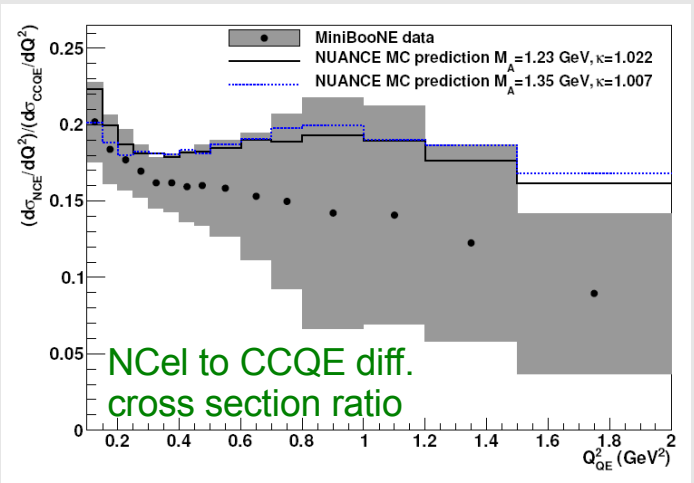
- arXiv:1007.4730 [hep-ex], to appear, Phys. Rev. D , thesis D. Perevalov, U. Alabama.
- NCel experimental definition: 1 p/n , no μ^- , π (1 subevent)
- below Cerenkov threshold, p/n separation not possible, p/n recon'd via small amount of scintillation
- Largest background, NCπ

- Results:
  - NCel differential cross section vs squared four-momentum transfer (Q^2)
  - extracted M_A consistent with MiniBooNE CCQE (M_A = 1.39 ± 0.11 GeV)
  - cross section (diff and total) consistent with CCQE (using fermi-gas plus impulse approximation model and M_A =1.35 GeV)
  - so, "extra-strength" present in NCel as well
  - isoscalar part of axial form factor extracted from p/p+n yields for protons above cerenkov threshold (plots not shown) => $\Delta s = 0.08 \pm 0.26$

  Not precise enough to compete with DIS experiments, need scint. tracking detector







MiniBooNE ν CC pion production

$$\nu_\mu + p(n) \rightarrow \mu + \Delta^{+(+)} \rightarrow \mu + p(n) + \pi^+$$
$$\nu_\mu + A \rightarrow \mu + A + \pi^+$$

- CCπ⁺/CCQE ratio measured
- Phys. Rev. Lett. 103, 081801 (2009), Thesis S. Linden, Yale U.
- experimental definition: 1 μ^- ,1 π^+ (3 subevents)

Results:

- CCπ⁺/CCQE ratio in agreement with model. So CCπ⁺ rate (cross section) is also larger than expected. True in both FSI corrected/uncorrected samples

CCπ⁺ /CCQE ratio, FSI corrected

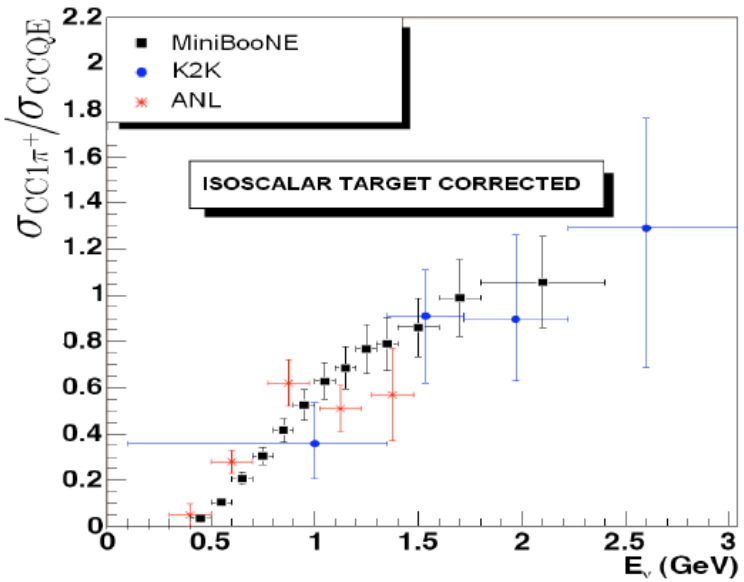


FIG. 2: FSI-corrected CC1π^+ to CCQE cross section ratio on CH_2 compared with results from ANL (D_2) [1] and K2K (C_8H_8) [3]. The data have been corrected for final state interactions and re-scaled for an isoscalar target.

CCπ⁺ /CCQE ratio, no FSI corrections

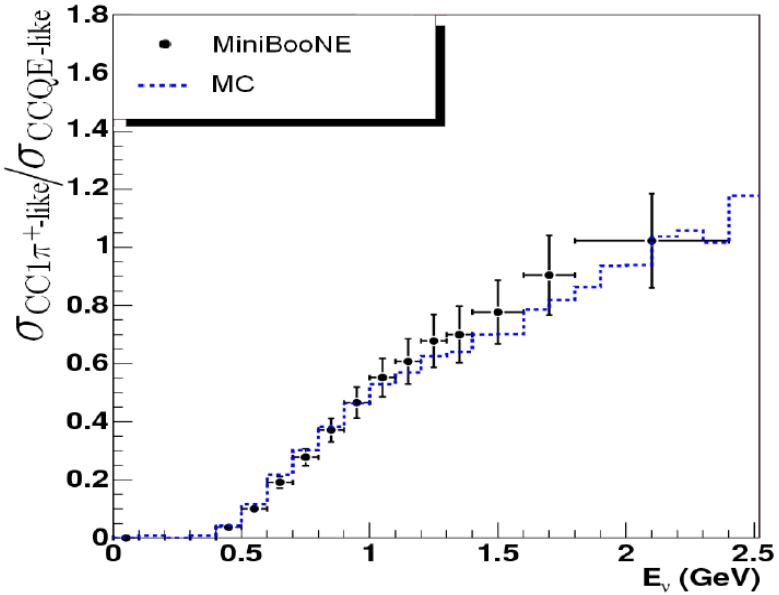


FIG. 1: Observed CC1π^+-like/CCQE-like cross section ratio on CH_2, including both statistical and systematic uncertainties, compared with the MC prediction [6]. The data have not been corrected for hadronic re-interactions.

MiniBooNE ν CC pion production (cont)

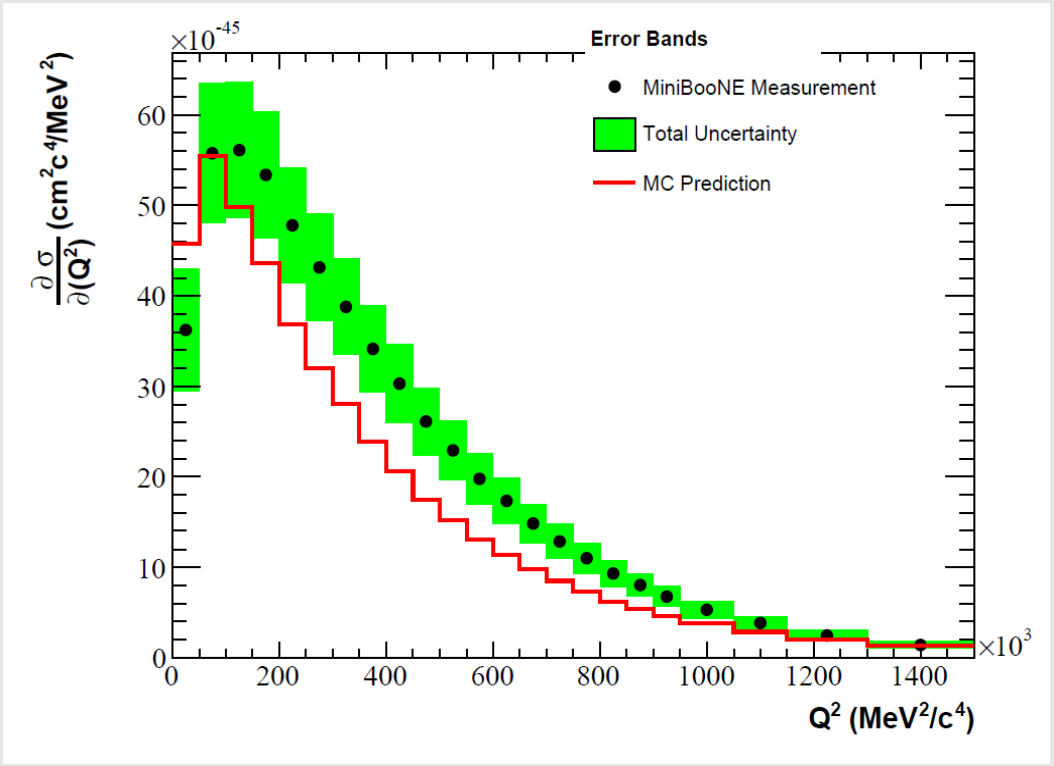
- CCπ⁺ and CCπ⁰ differential cross sections:
- papers in prep, Theses M. Wilking, R. Nelson, U. Colorado
- experimental definition: 1 μ^- ,1 π^+/π^0 (3/2 subevents)

$$\nu_\mu + p(n) \rightarrow \mu + \Delta^{+(+)} \rightarrow \mu + p(n) + \pi^+$$
$$\nu_\mu + A \rightarrow \mu + A + \pi^+$$

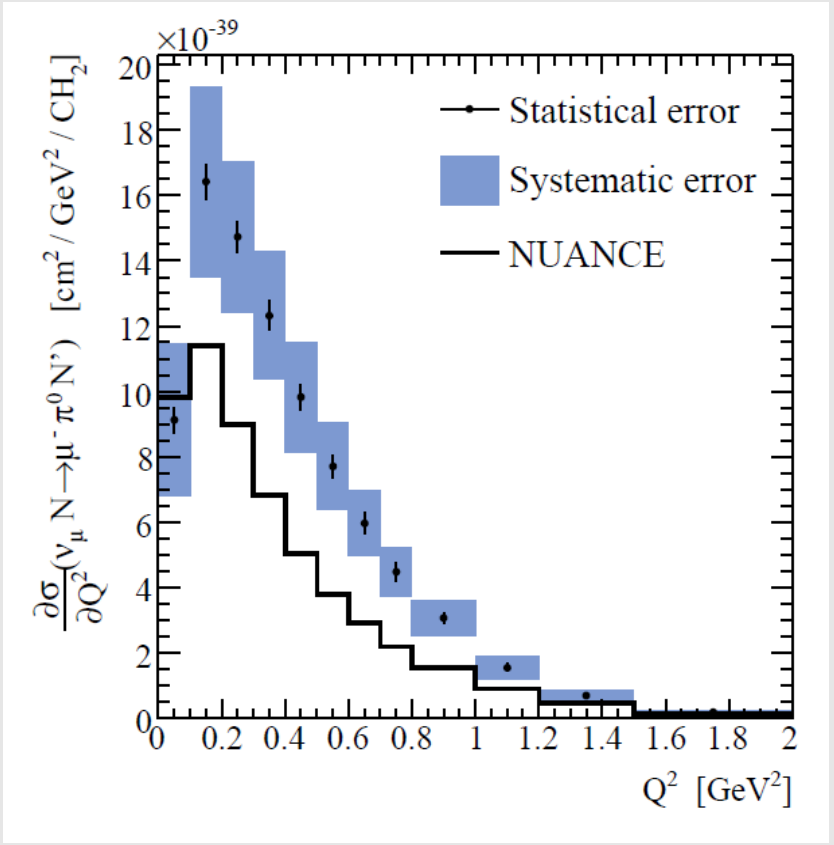
$$\nu_\mu + n \rightarrow \mu + \Delta^+ \rightarrow \mu + p + \pi^o$$

Results:
- differential cross sections (flux-averaged) reported in multiple kinematic variables
- cross sections consistently high compared to (event generator) neutrino models
- data now confronting state-of-art calculations

CCπ⁺ diff. cross section (Q^2)



CCπ⁰ diff. cross section (Q^2)

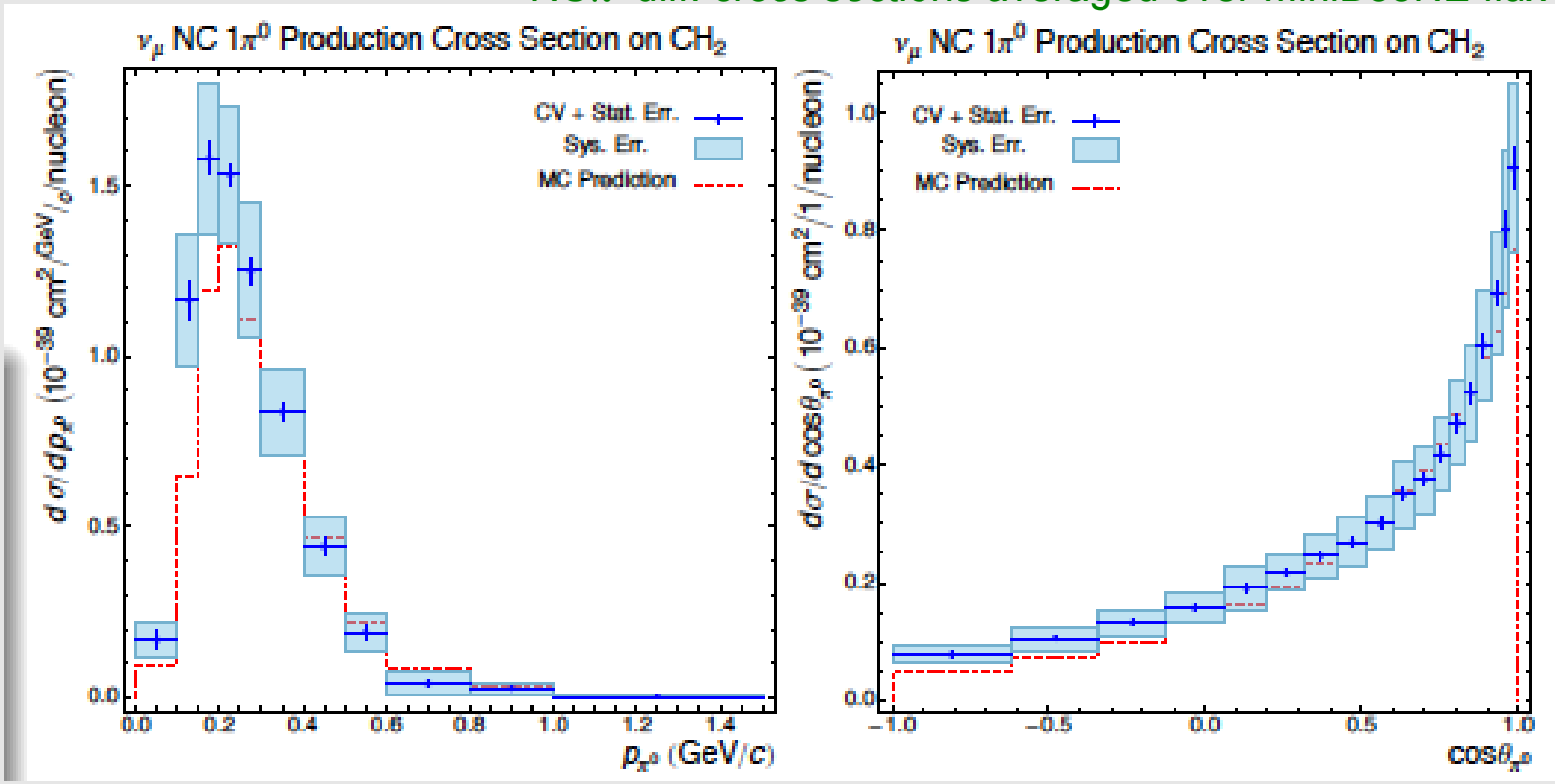


MiniBooNE ν NC π^0 production

$$\nu_\mu + N \rightarrow \nu_\mu + \Delta^o \rightarrow \nu_\mu + N + \pi^o$$
$$\nu_\mu + A \rightarrow \nu_\mu + A + \pi^o$$

- NC π^0 production:
- an important background for ν_e appearance searches
- Phys. Rev. D81, 013005 (2010), Thesis C. Anderson, Yale U.
- NCπ^+ experimental definition: 1 π^0 (1 subevent)
- Results:
  - diff. (in π^0 momentum, angle) cross sections extracted in both neutrino, antineutrino
  - non-zero coherent fraction of cross section measured, ~35% smaller than model.

NCπ^0 diff. cross sections averaged over MiniBooNE flux



Conclusions

- MiniBooNE has produced absolutely normalized, model-independent, differential cross sections for a variety of neutrino scattering processes (CCQE, NC elastic, CC/NC π) important at O(1 GeV).

- These results show cross sections ~30% high compared to state-of-art neutrino generators and are now confronting the models.

- Antineutrino results coming soon for CCQE, NCel.. Important as vector/axial vector interference terms change sign, will constrain explanations of neutrinos results