neutrino scattering results from MiniBooNE

Outline:
- Intro/Overview/Motivation
- Previous Results
- New results on neutrino CCQE scattering
- Other MB scattering results
- Interpretations/Ideas

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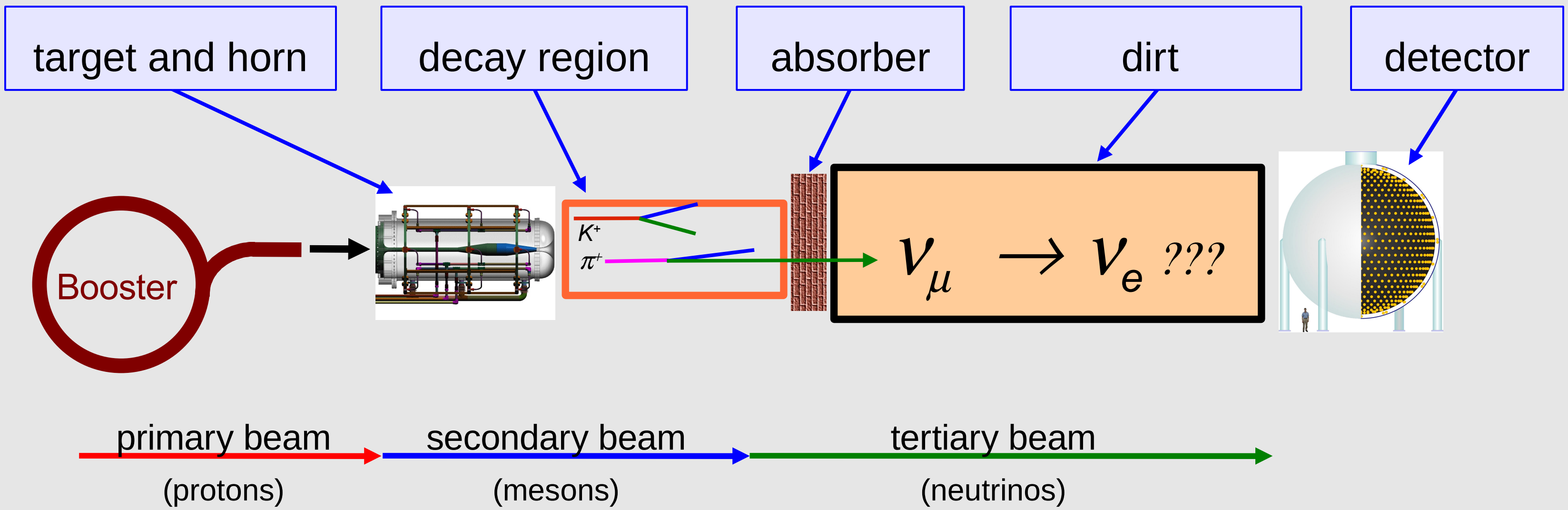
IU nuc phys seminar
03/2010

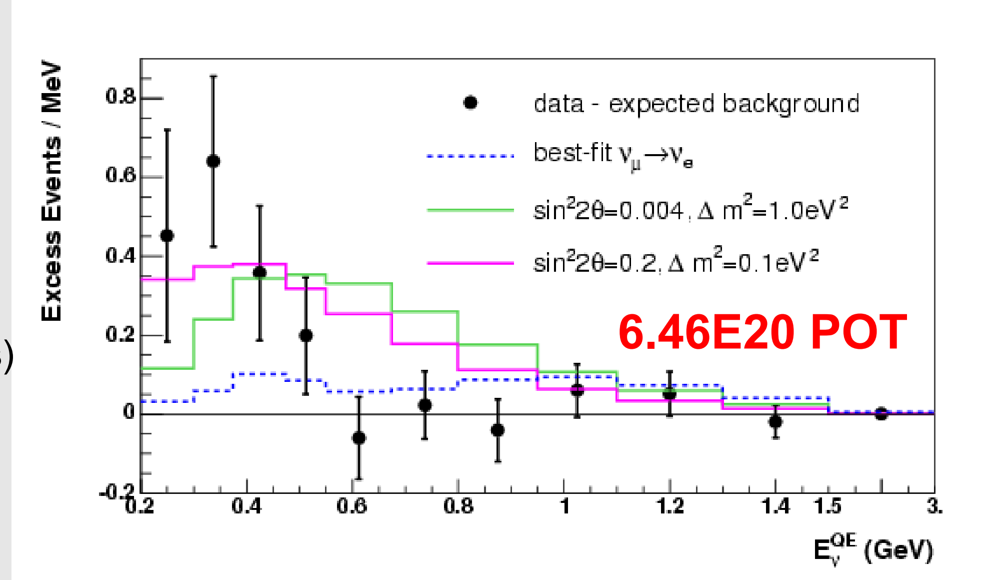
MiniBooNE experiment:

- Designed and built (at FNAL) to test the LSND observation of ν oscillations via $\nu_\mu \rightarrow \nu_e$ (and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$) appearance.
- Currently running. 2002-2005,2007 in ν_μ mode, 2005-2006,2008-2012 $\bar{\nu}_\mu$ mode.
- 15 papers published (so far, on oscillations, scattering, details) See http://www-boone.fnal.gov/publications/ (including theses)



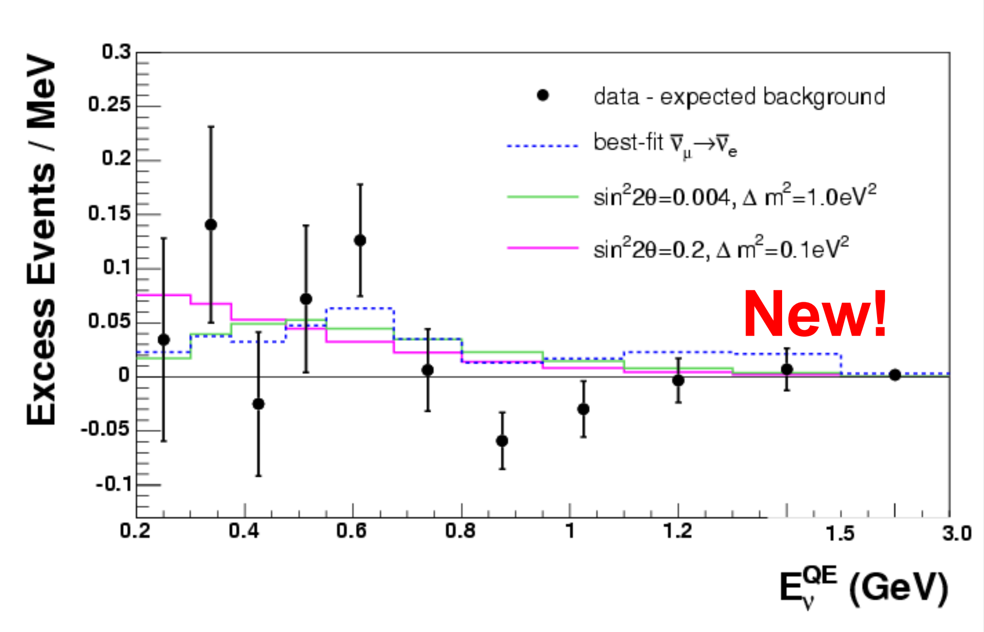
Quick review/status of MB oscillation results:

Energy distributions of background-subtracted oscillation candidate events:



neutrino mode ($\nu_\mu \rightarrow \nu_e$):

- Ruled out "standard osc model" interpretation of LSND
- however, low-E excess observed
  (Excess from 200-475 MeV = 128.8+-20.4+-38.3 events)
- A.A. Aguilar-Arevalo et al., PRL 102, 101802 (2009)



antineutrino mode ($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$):

- Preliminary results for 4.863E20 POT (~50% increase in POT):
- Still not definitive wrt LSND
- low-E excess not large
  (Excess from 200-475 MeV = **11.4 ± 9.4 ± 11.2** events)
- A.A. Aguilar-Arevalo et al., PRL. 103, 111801 (2009) (from 3.4E20 POT)

"POT" = protons on target (provides normalization of neutrino flux

neutrino scattering measurements

In order to understand ν oscillation measurements, it is crucial to understand the detailed physics of neutrino scattering (at few-GeV)

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

(And it is interesting nuclear physics!)

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

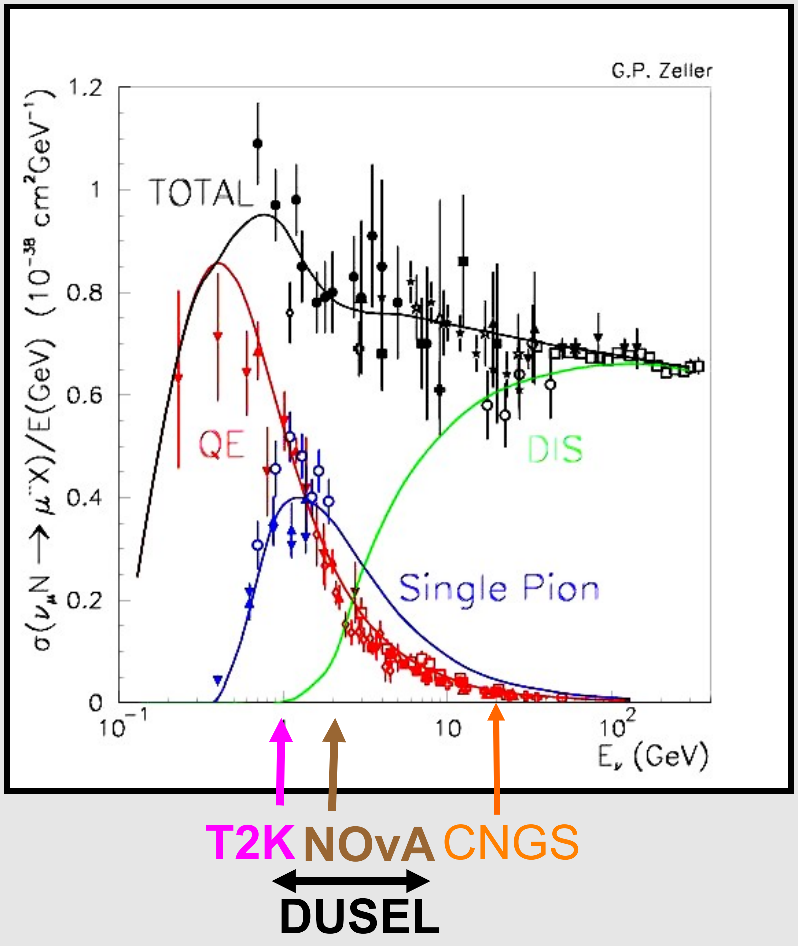
A significant challenge with neutrino experiments:

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

New measurements are forthcoming:
- MiniBooNE, SciBooNE (publications appearing)
- MINERvA, μBooNE, T2K,   (coming soon)

And likely to require even more input...
- from more theoretical work
- dedicated experiments.

nu cross section data



CCQE scattering

Charged-current quasielastic scattering (CCQE):

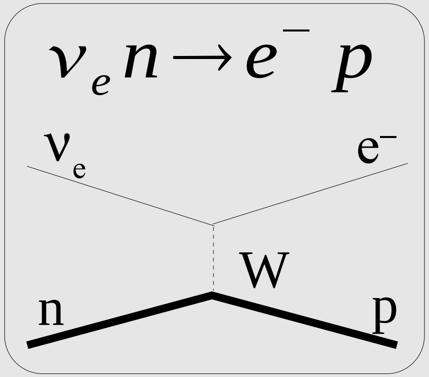
- crucial process to understand as it is... (in MiniBooNE)
  - most common process in ~1 GeV energy region
  - detection signal for $\nu_\mu \to \nu_e$
  - normalization signal for ν_μ flux
  - details are slightly different for experiments with near/far detectors (but CCQE still important channel)

- so CCQE scattering must be measured (using ν_μ)

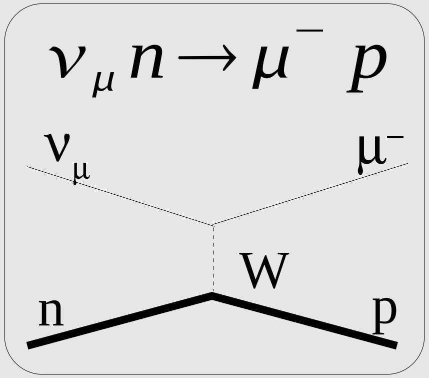
- challenging
  - non-monoenergetic beams
  - different detection details between exps. (recoil nucleon detected?)
  - backgrounds (some "irreducible", eg CCπ w/π absorption)
  - bound nucleons

- but should be simple process to model...

ν_e CCQE



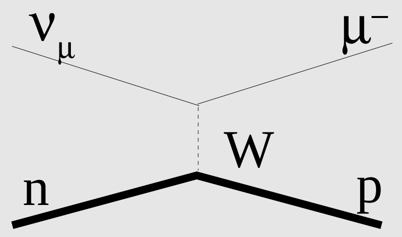
ν_μ CCQE



CCQE models

ν_μ CCQE

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



The canonical model for the CCQE process is straightforward, and well-constrained. It looks something like this:

- Llewellyn-Smith formalism for diff cross section

$$\frac{d\sigma}{dQ^2}\left(\begin{array}{c}\nu_l + n \rightarrow l^- + p\\ \bar{\nu}_l + p \rightarrow l^+ + n\end{array}\right) = \frac{M^2 {G_F}^2 cos^2\theta_c}{8\pi {E_\nu}^2}\left\{A(Q^2) \pm B(Q^2)\frac{(s-u)}{M^2} + C(Q^2)\frac{(s-u)^2}{M^4}\right\}$$

- Q^2 = 4-momentum transfer
- lepton vertex well-known
- nucleon structure parameterized with 2 vector formfactors (F_1,F_2), and 1-axial vector (F_A). These are functions of Q^2 and contained in A,B,C.

- To apply:
  - bound nucleons, use a Relativistic Fermi Gas (RFG) model (typically Smith-Moniz version), with parameters known from e-scattering
  - F_1,F_2 from e scattering measurements
  - F_A is large(st) contribution, not well known from e scattering
  - F_A (Q^2=0) = g_A.. known from beta-decay , assume dipole form, same M_A should cover all experiments.

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

- No unknown parameters, model can be used for prediction of CCQE rates and final state particle distributions.

- Until recently, this approach has seemed adequate (even though more sophisicated approaches exist) and all common neutrino event generators use this.

M_A from CCQE

- M_A measurments, from Lyubushkin, etal (NOMAD collab, arXiv:0812.4543)

- different targets/energies

- world average from Bernard, etal, JPhysG28, 2002: M_A=1.026±0.021 (also, M_A from π photo-production similar)

- However, recent data from some high-stats experiments not well-described with this M_A and/or the canonical model

summary of ν, $\bar{\nu}$ measurements of M_A

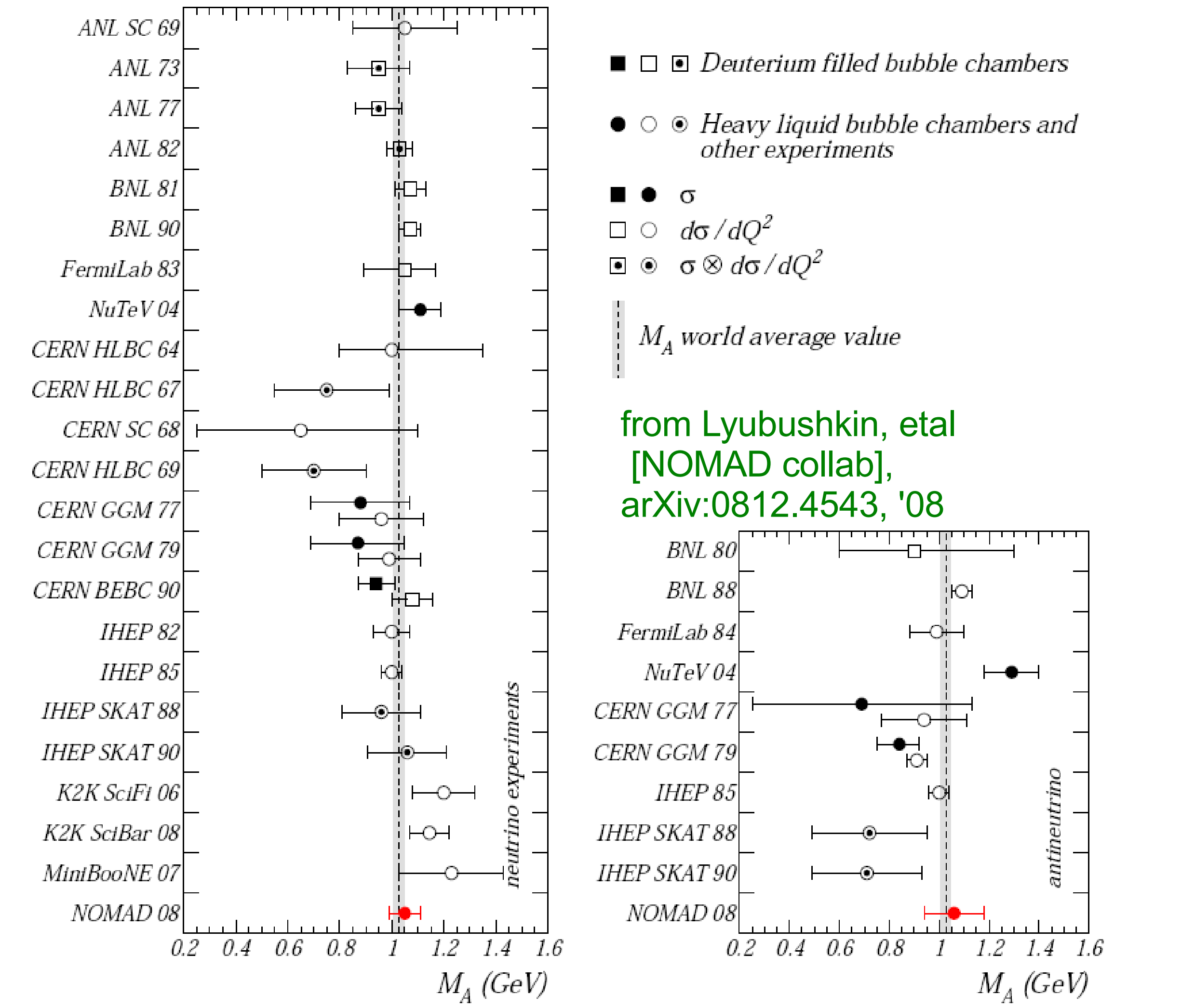


Fig. 18. A summary of existing experimental data: the axial mass M_A as measured in neutrino (left) and antineutrino (right) experiments. Points show results obtained both from deuterium filled BC (squares) and from heavy liquid BC and other experiments (circles). Dashed line corresponds to the so-called world average value $M_A = 1.026 \pm 0.021$ GeV (see review [33]).

Previous CCQE results

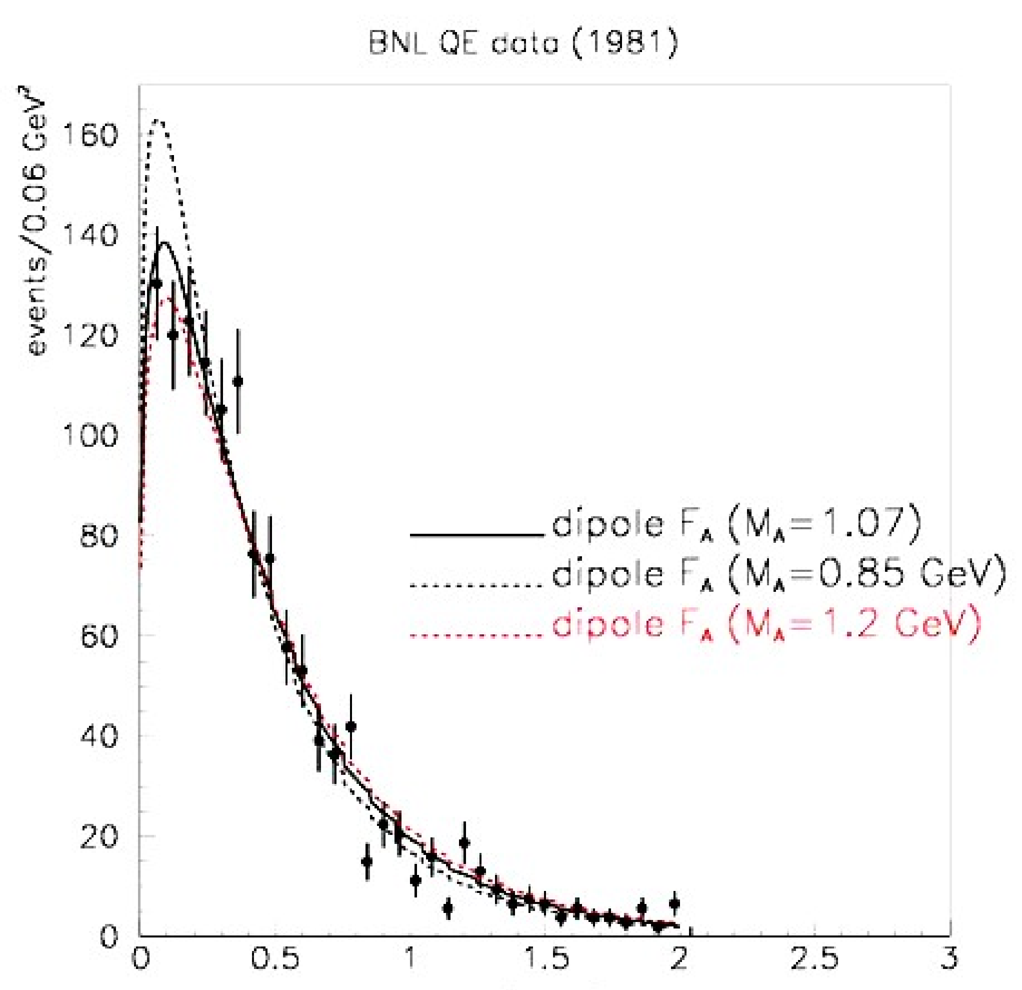
BNL QE data:
- Baker, PRD 23, 2499 (1981)
- data on D_2
- M_A=1.07 +/- 0.06 GeV

1,236 ν_μ QE events

- curves with diff M_A values, relatively norm'd, overlaid.

- M_A extracted from the shape of this data in Q^2

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



from Sam Zeller

Previous CCQE results

- K2K results from scifi (in water) detector (PRD74, 052002, '06)

- Q^2 spectrum: more events at $Q^2 > 0.2$ GeV^2

- also note data deficit $Q^2 < 0.2$ GeV^2

- shape only fit of Q^2 distribution yields $M_A = 1.20 \pm 0.12$

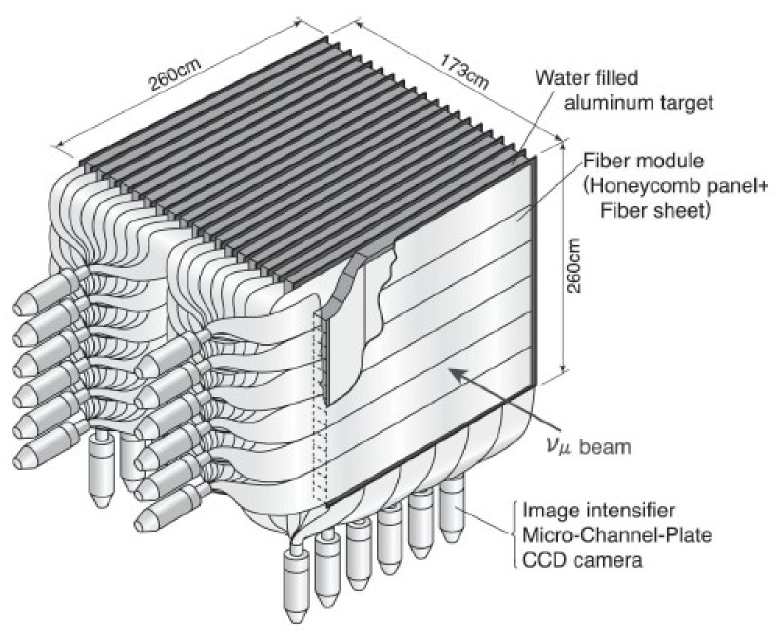
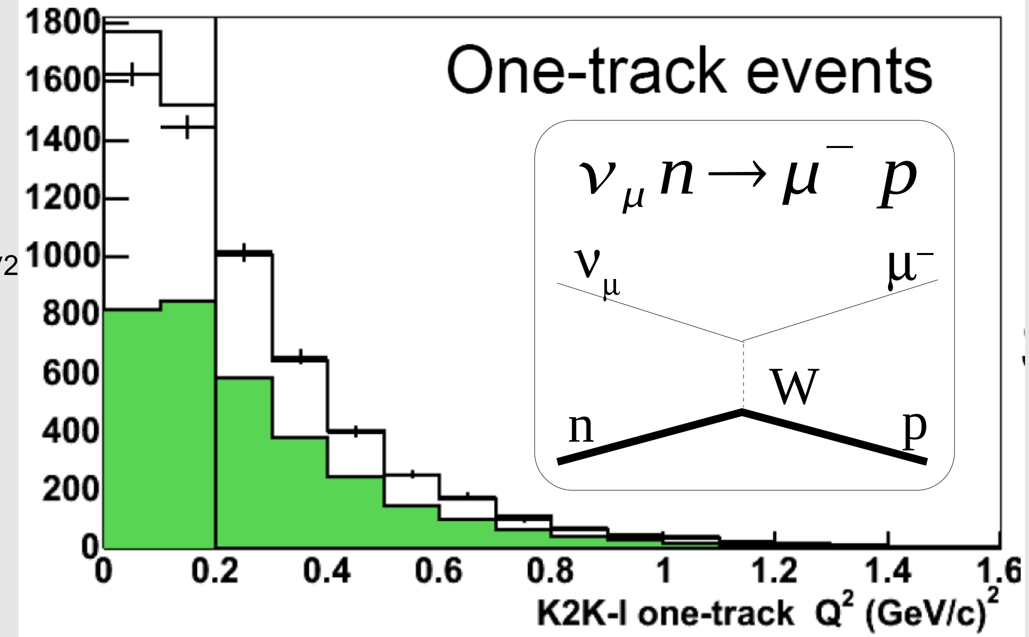
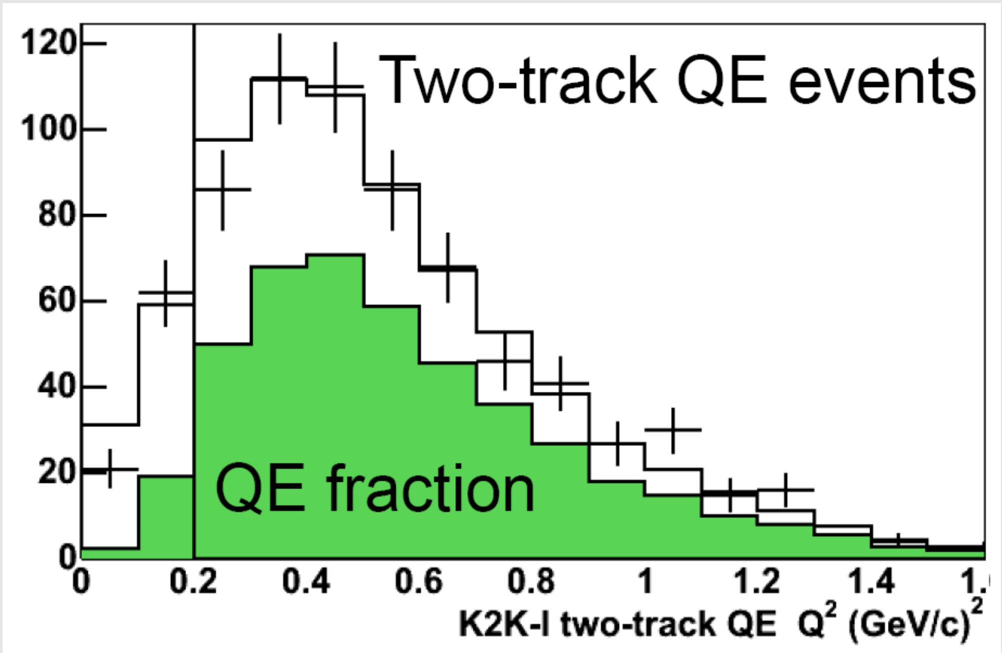


FIG. 2. A schematic diagram of the SciFi detector.





from Rik Gran, Nuint09

Previous CCQE results

- MiniBooNE results (from CH2) (PRL100, 0323021, '08)

- Q^2 spectrum of data, compared to "world average model" (dashed)
  - event excess at $Q^2 > 0.2\ \mathrm{GeV}^2$
  - also event deficit at $Q^2 < 0.2\ \mathrm{GeV}^2$

- could not get satisfactory fit (at low Q^2 with only M_A so had to add new parameter κ that increases Pauli-blocking of outgoing nucleon

- shape-only fit of Q^2 distribution yielded:

$$M_A^{\mathrm{eff}} = 1.23 \pm 0.20\ \mathrm{GeV},$$

$$\kappa = 1.019 \pm 0.011.$$

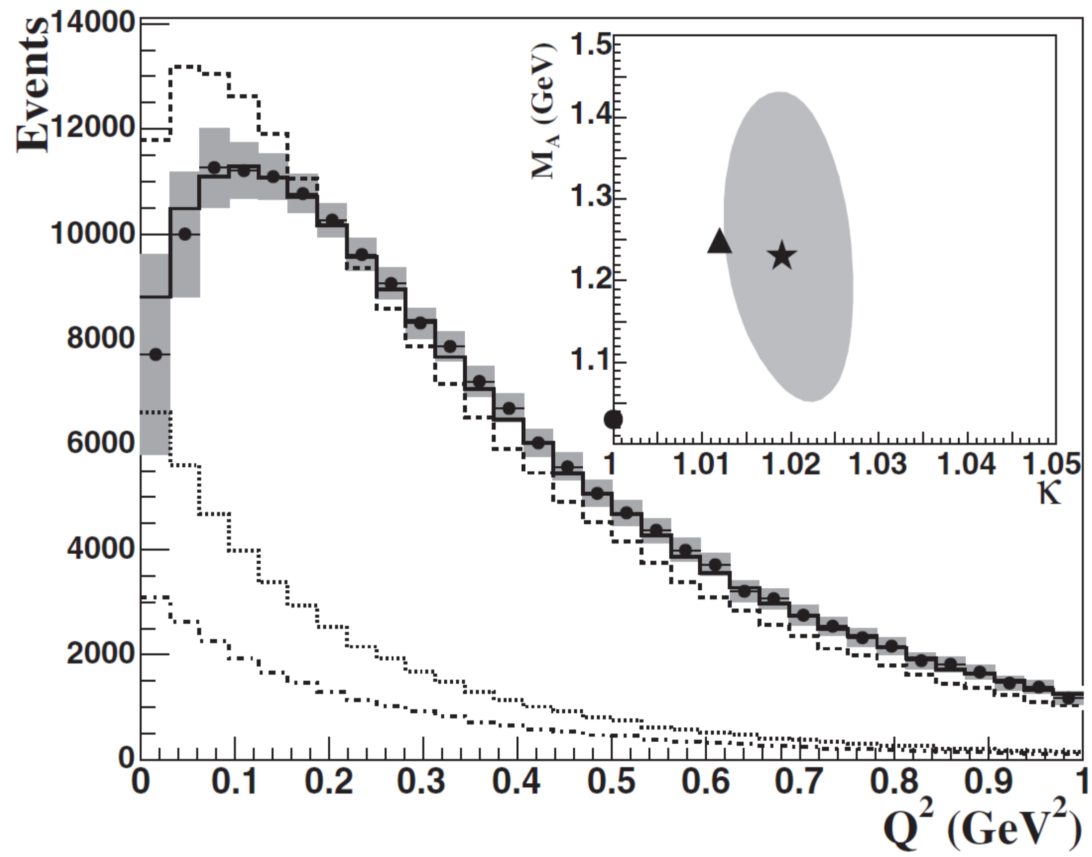


FIG. 2. Reconstructed Q^2 for ν_μ CCQE events including systematic errors. The simulation, before (dashed curve) and after (solid curve) the fit, is normalized to data. The dotted curve (dot-dashed curve) shows backgrounds that are not CCQE (not "CCQE-like"). The inset shows the 1σ C.L. contour for the best-fit parameters (star), along with the starting values (circle), and fit results after varying the background shape (triangle).

Previous CCQE results

- NOMAD (carbon target) total cross section as func of E_ν

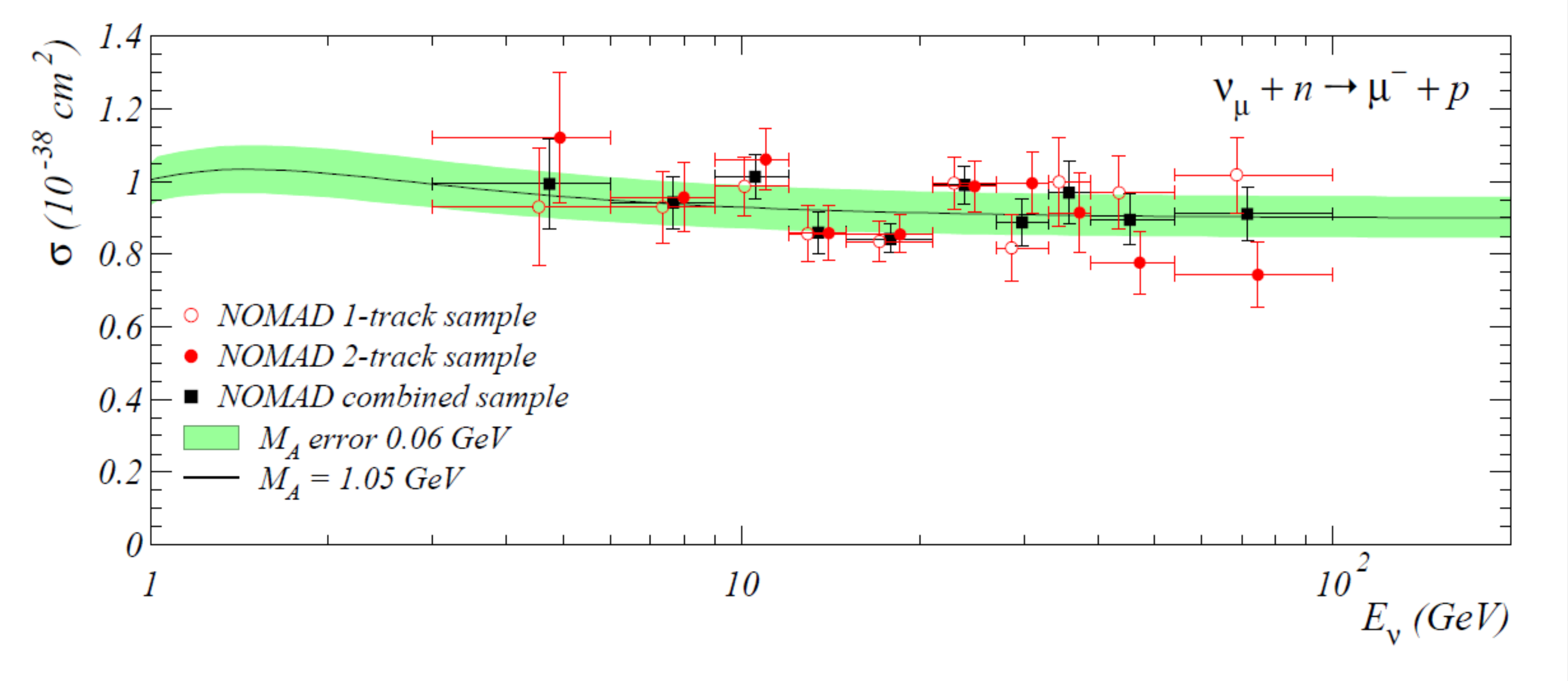
- from Lyubushkin, etal (NOMAD collab, arXiv:0812.4543)

- curve is that predicted with M_A of this NOMAD measurement

- M_A =1.05+-0.02+-0.06 GeV^2

- Q^2 distribution consistent with this M_A

ν cross section



Previous CCQE results

Additional tidbits:

- scibar detector at K2K and at FNAL (sciboone) saw/seeing larger M_A also (~1.20 GeV^2)

- MINOS also (on Fe!)

- so there exists a mystery in CCQE scattering
  - what is M_A ?
  - Different for different nuclei?
  - Inadequate model?

- how much has old (bad?) experimental habits (necessities?) clouded the issue? EG: nu flux tuning based on data.

PHYSICAL REVIEW D VOLUME 23, NUMBER 11 1 JUNE 1981

Quasielastic neutrino scattering: A measurement of the weak nucleon axial-vector form factor

N. J. Baker, A. M. Cnops,* P. L. Connolly, S. A. Kahn, H. G. Kirk, M. J. Murtagh, R. B. Palmer, N. P. Samios, and M. Tanaka
Brookhaven National Laboratory, Upton, New York 11973
(Received 12 February 1981)

BNL QE data, Baker, PRD 23, 2499 (1981)

with the data. Figure 7 shows the relative ν_μ flux spectrum obtained from the observed E_ν distribution of the events after correcting for the deuteron effects and the Q_{min}^2 cut.

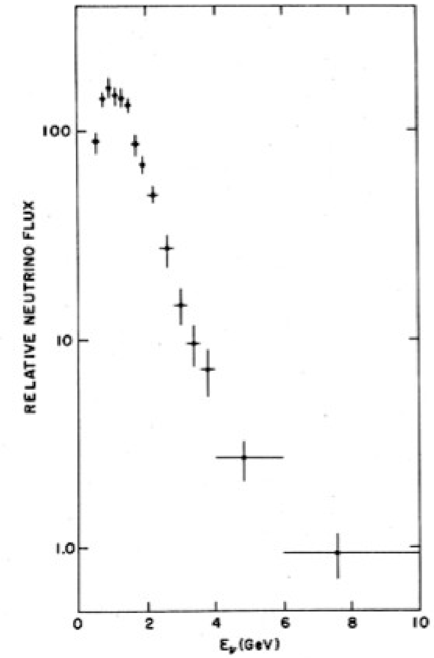


FIG. 7. The relative ν_μ flux spectrum obtained from the observed E_ν distribution of the events with $M_A = 1.07$ GeV.

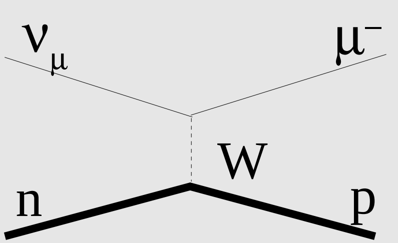
Latest CCQE results from MiniBooNE

- In our latest (and final) analysis of ν CCQE scattering, we have reported model-independent, absolutely normalized (double) differential cross sections.
  arXiv:1002.2680, submitted to PRD.

- thesis work of Teppei Katori, IU PhD 08.

ν_μ CCQE

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



First Measurement of the Muon Neutrino Charged Current Quasielastic Double Differential Cross Section

A. A. Aguilar-Arevalo[13], C. E. Anderson[18], A. O. Bazarko[15], S. J. Brice[7], B. C. Brown[7], L. Bugel[5], J. Cao[14], L. Coney[5], J. M. Conrad[12], D. C. Cox[9], A. Curioni[18], Z. Djurcic[5], D. A. Finley[7], B. T. Fleming[18], R. Ford[7], F. G. Garcia[7], G. T. Garvey[10], J. Grange[8], C. Green[7,10], J. A. Green[9,10], T. L. Hart[4], E. Hawker[3,10], R. Imlay[11], R. A. Johnson[3], G. Karagiorgi[12], P. Kasper[7], T. Katori[9,12], T. Kobilarcik[7], I. Kourbanis[7], S. Koutsoliotas[2], E. M. Laird[15], S. K. Linden[18], J. M. Link[17], Y. Liu[14], Y. Liu[1], W. C. Louis[10], K. B. M. Mahn[5], W. Marsh[7], C. Mauger[10], V. T. McGary[12], G. McGregor[10], W. Metcalf[11], P. D. Meyers[15], F. Mills[7], G. B. Mills[10], J. Monroe[5], C. D. Moore[7], J. Mousseau[8], R. H. Nelson[4], P. Nienaber[16], J. A. Nowak[11], B. Osmanov[8], S. Ouedraogo[11], R. B. Patterson[15], Z. Pavlovic[10], D. Perevalov[1], C. C. Polly[7], E. Prebys[7], J. L. Raaf[3], H. Ray[8,10], B. P. Roe[14], A. D. Russell[7], V. Sandberg[10], R. Schirato[10], D. Schmitz[5], M. H. Shaevitz[5], F. C. Shoemaker[15*], D. Smith[6], M. Soderberg[18], M. Sorel[5†], P. Spentzouris[7], J. Spitz[18], I. Stancu[1], R. J. Stefanski[7], M. Sung[11], H. A. Tanaka[15], R. Tayloe[9], M. Tzanov[4], R. G. Van de Water[10], M. O. Wascko[11‡], D. H. White[10], M. J. Wilking[4], H. J. Yang[14], G. P. Zeller[7], E. D. Zimmerman[4]

(The MiniBooNE Collaboration)

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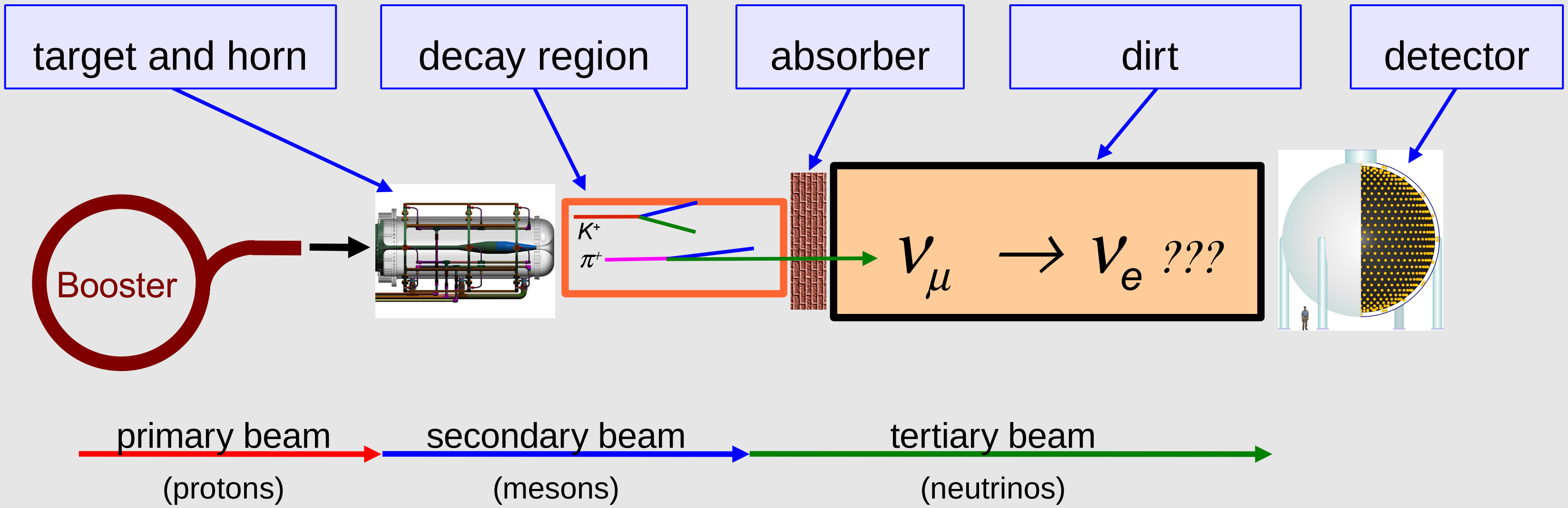
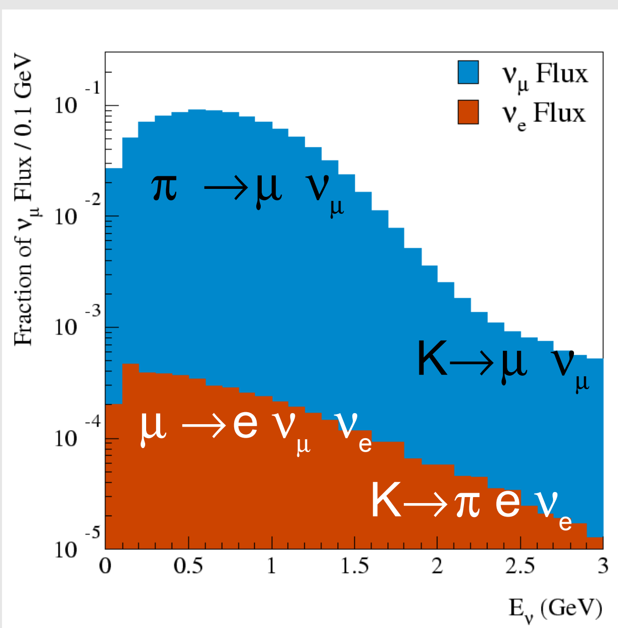
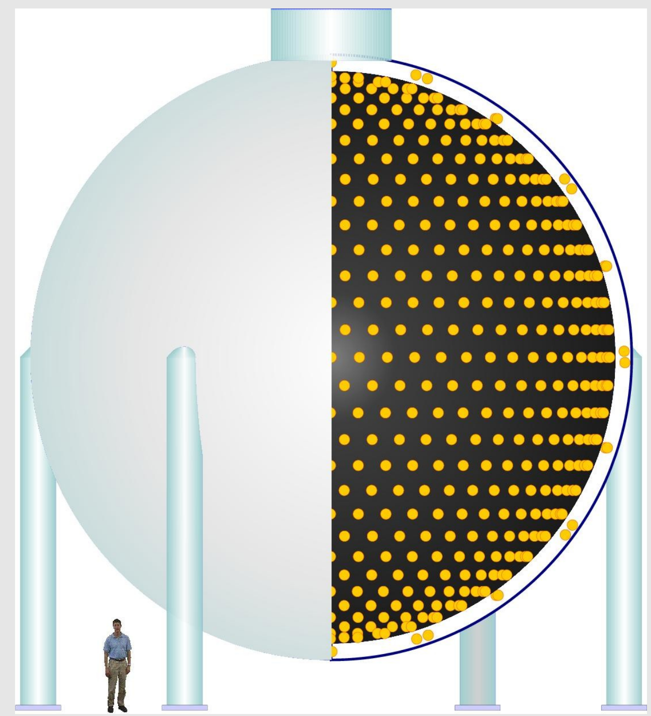
(Dated: February 13, 2010)

A high-statistics sample of charged-current muon neutrino scattering events collected with the MiniBooNE experiment is analyzed to extract the first measurement of the double differential cross section ($\frac{d^2\sigma}{dT_\mu d\cos\theta_\mu}$) for charged-current quasielastic (CCQE) scattering on carbon. This result features minimal model dependence and provides the most complete information on this process to date. With the assumption of CCQE scattering, the absolute cross section as a function of neutrino energy ($\sigma[E_\nu]$) and the single differential cross section ($\frac{d\sigma}{dQ^2}$) are extracted to facilitate comparison with previous measurements. These quantities may be used to characterize an effective axial-vector form factor of the nucleon and to improve the modeling of low-energy neutrino interactions on nuclear targets. The results are relevant for experiments searching for neutrino oscillations.

MiniBooNE experiment, overview







MiniBooNE experiment, ν flux

- predicted nu flux:

- determined from π prod measurements plus MC simulations of target+horn (PRD79(2009)072002)

- no flux tuning based on MB data

- most important π prod measurements from HARP (at CERN) at 8.9 GeV/c beam momentum (as MB), 5% int. length Be target (same material, thinner than MB) (Eur.Phys.J.C52(2007)29)

- error on HARP data (5%) is dominant contribution to flux uncertainty which leads to biggest error on scale error of cross sections.

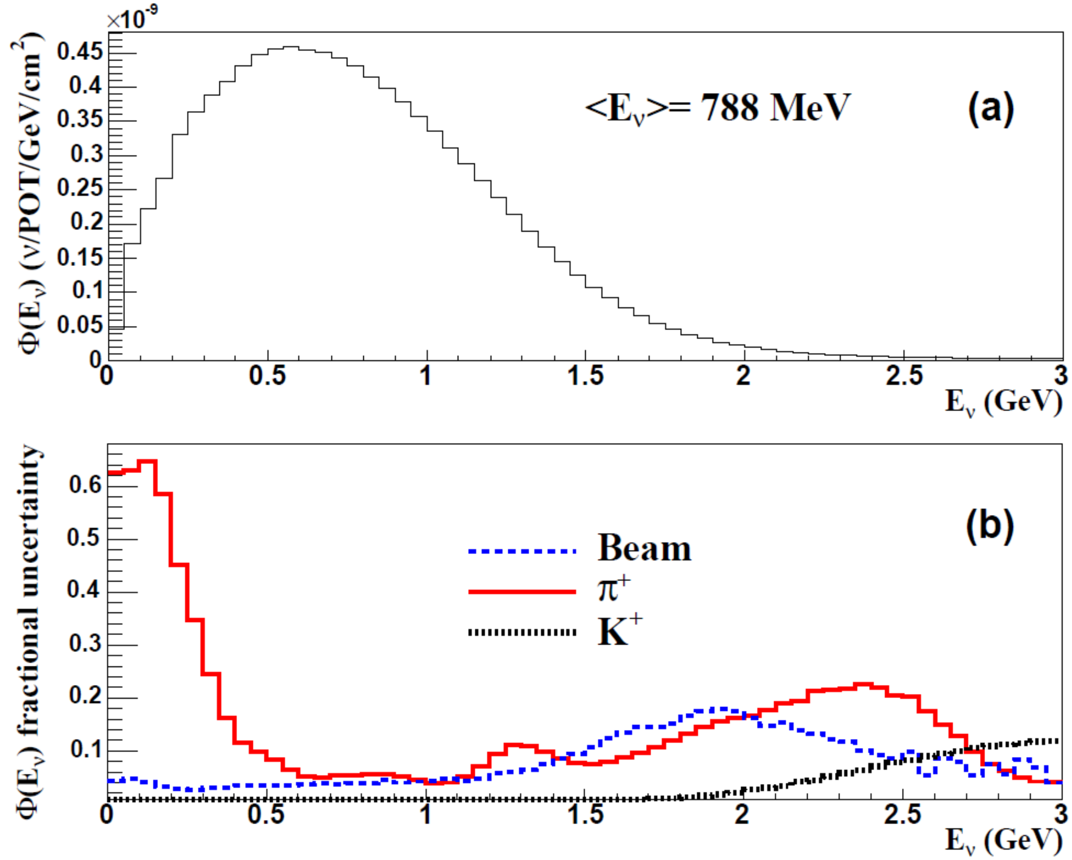
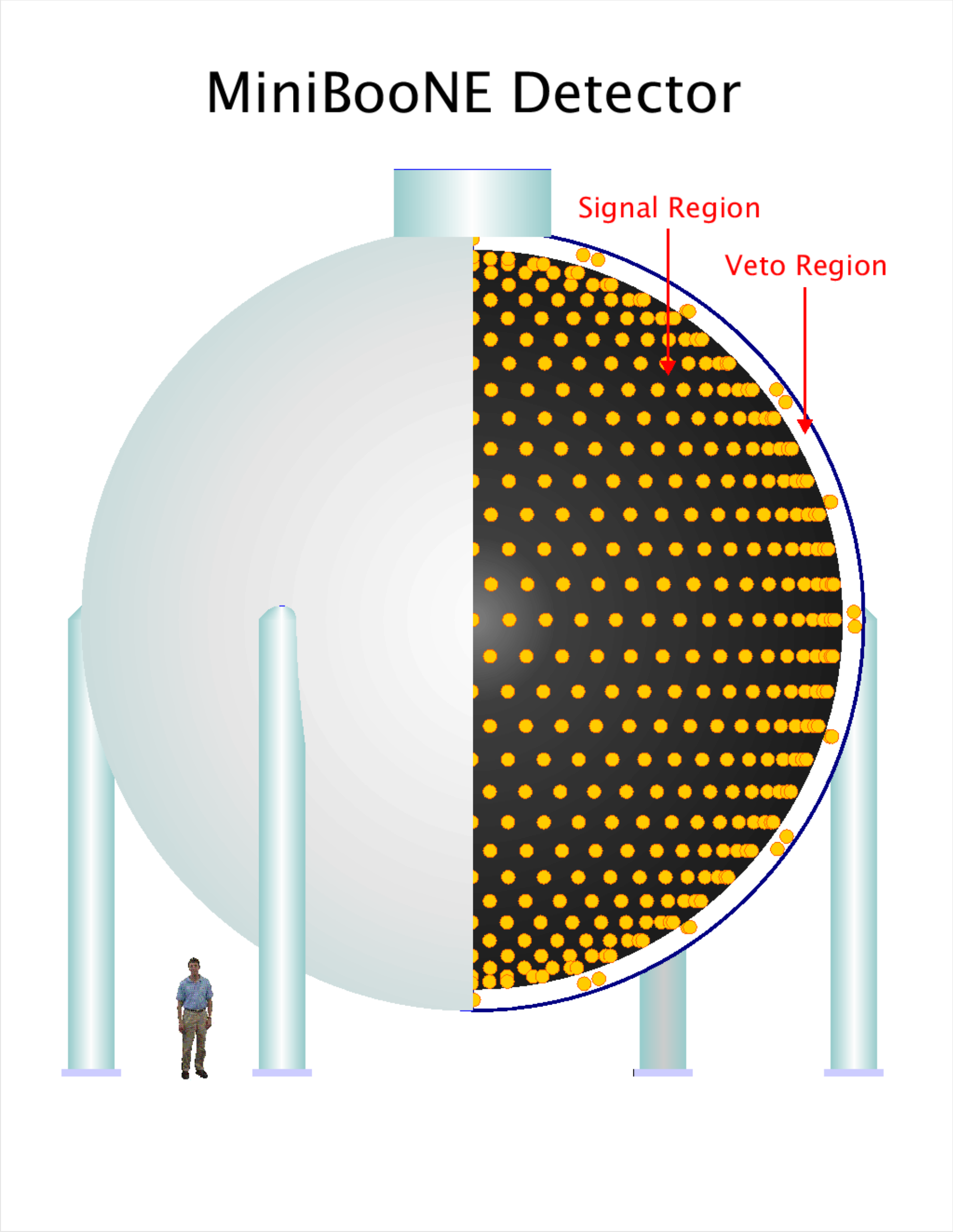


FIG. 2: (color online) Predicted ν_μ flux at the MiniBooNE detector (a) along with the fractional uncertainties grouped into various contributions (b). The integrated flux is 5.16×10^{-10} $\nu_\mu/\mathrm{POT/cm}^2$ ($0 < E_\nu < 3$ GeV) with a mean energy of 788 MeV. Numerical values corresponding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

MiniBooNE experiment, detector

- 541 meters from target
- 12 meter diameter sphere
- 800 tons mineral oil (CH_2)
- 3 m overburden
- includes 35 cm "veto region"
- viewed by 1280 8" PMTs (10% coverage) + 240 veto
- Simulated with a GEANT3 Monte Carlo program



MiniBooNE experiment, event reconstruction

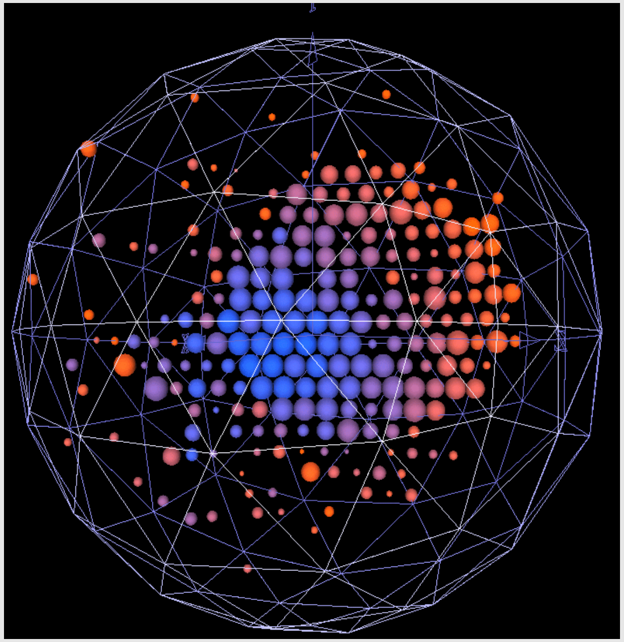
- charged particles in MB create cherenkov (and some scintillation) light

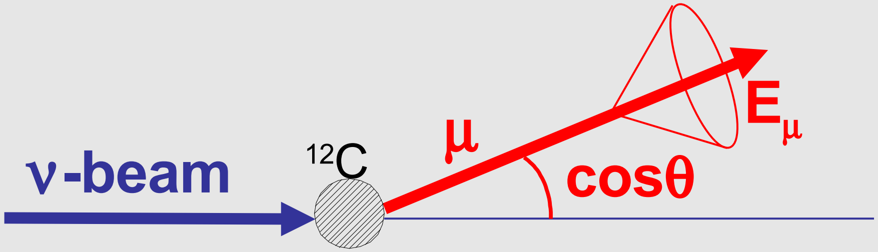
- tracks reconstructed (energy, direction, position) with likelihood method utilizing time, charge of PMT hits (NIM, A 608 (2009), pp. 206-224)

- in addition, muon, pion decays are seen by recording PMT info for 20μs around 2μs beam spill

- In this analysis, all observables are formed from muon energy (E_μ) and muon scattering angle (θ_μ)

- Energy of the neutrino E_ν^{QE} and 4-momentum transfer Q^2_{QE} can be reconstructed by these 2 observables, under the assumption of CCQE interaction with bound neutron at rest (“QE assumption”)





$$E_\nu^{QE} = \frac{2(M_n')E_\mu - ((M_n')^2 + m_\mu^2 - M_p^2)}{2\cdot[(M_n') - E_\mu + \sqrt{E_\mu^2 - m_\mu^2}\cos\theta_\mu]}, \quad (1)$$

$$Q^2_{QE} = -m_\mu^2 + 2E_\nu^{QE}(E_\mu - \sqrt{E_\mu^2 - m_\mu^2}\cos\theta_\mu), \quad (2)$$

MiniBooNE experiment, event types

neutrino process	abbreviation	reaction	fraction (%)
CC quasielastic	CCQE	$\nu_\mu + n \to \mu^- + p$	39
NC elastic	NCE	$\nu_\mu + p(n) \to \nu_\mu + p(n)$	16
CC $1\pi^+$ production	CC$1\pi^+$	$\nu_\mu + p(n) \to \mu^- + \pi^+ + p(n)$	25
CC $1\pi^0$ production	CC$1\pi^0$	$\nu_\mu + n \to \mu^- + \pi^0 + p$	4
NC $1\pi^\pm$ production	NC$1\pi^\pm$	$\nu_\mu + p(n) \to \nu_\mu + \pi^+(\pi^-) + n(p)$	4
NC $1\pi^0$ production	NC$1\pi^0$	$\nu_\mu + p(n) \to \nu_\mu + \pi^0 + p(n)$	8
multi pion production, DIS, etc.	other	$\nu_\mu + p(n) \to \mu^\mp + N\pi^\pm + X$, etc.	4

TABLE I: Event type nomenclature and NUANCE-predicted ν_μ event fractions for MiniBooNE integrated over the predicted flux in neutrino mode before selection cuts. For the pion production channels, indirect production (through resonance states) and direct production (through coherent processes) are included. (CC=charged-current, NC=neutral-current).

- raw (no selection, yet) event fractions
- CCQE process most common
- biggest background to CCQE, CC$1\pi^+$

MiniBooNE CCQE analysis

- CCQE experimental defintion: 1 μ^- , no π
- Requires id of stopping μ^- and 1 decay e^- (2 “subevents”)

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

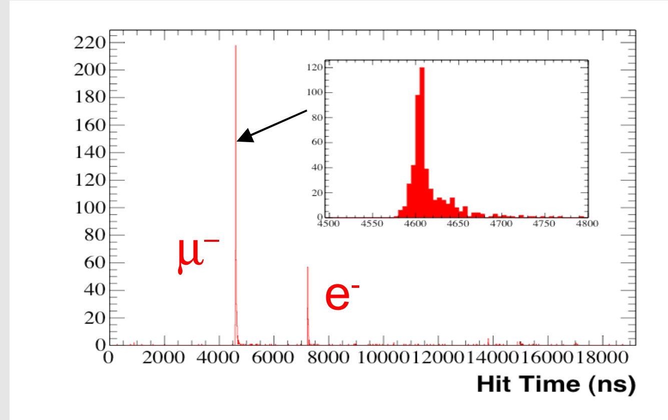
- (No selection on (and ~no sensitivity to) f.s. nucleon)
- CCπ produces 2 decay electrons (3 subevents)

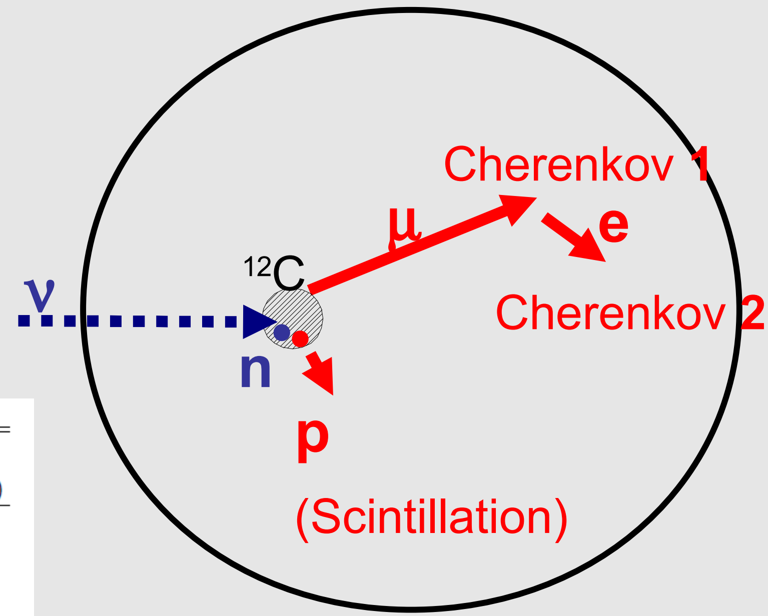
$$\nu_\mu + N \rightarrow \mu^- + N + \pi^+$$
$$\quad \hookrightarrow \mu^+ \rightarrow \nu_\mu + \nu_e + e^+ \quad (\tau \sim 2\mu s)$$
$$\quad \hookrightarrow \nu_\mu + \nu_e + e^- \quad (\tau \sim 2\mu s)$$

- CCπ^+ is (largest) background,
  (e^{+-} missed because of π absorption, μ^- capture)

- MiniBooNE data used to measure this background

event time dist within (19mus) DAQ window





CCQE cuts

cut #	description	CCQE effic.(%)	CCQE purity(%)
1	all subevents, # of veto hits < 6	54.8	36.8
2	1st subevent, event time window, $4400 < T(\text{ns}) < 6400$	54.3	36.8
3	1st subevent, reconstructed vertex radius < 500 cm	45.0	37.4
4	1st subevent, kinetic energy > 200 MeV	39.7	46.3
5	1st subevent, μ/e log-likelihood ratio > 0.0	36.0	62.3
6	# total subevents $= 2$ for CCQE ($= 3$ for CC$1\pi^+$)	29.1	71.0
7	(CCQE-only) 1st subevent, $\mu - e$ vertex distance > 100 cm and $\mu - e$ vertex distance $> (500 \times T_\mu(\text{GeV}) - 100)$ cm	26.6	77.0

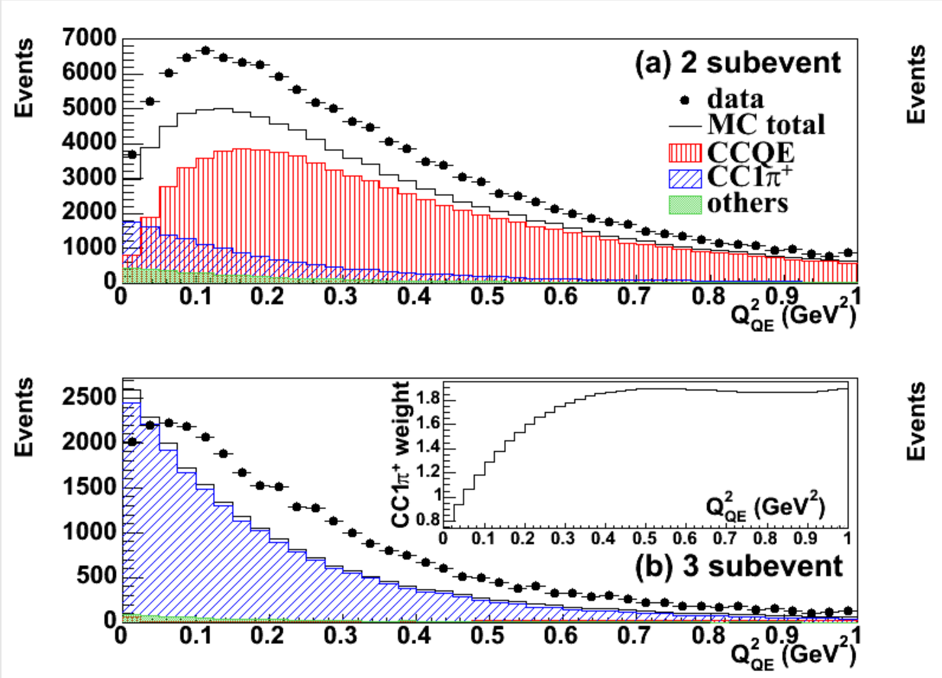
MiniBooNE CCQE analysis

CCπ (absolute) background measurement:

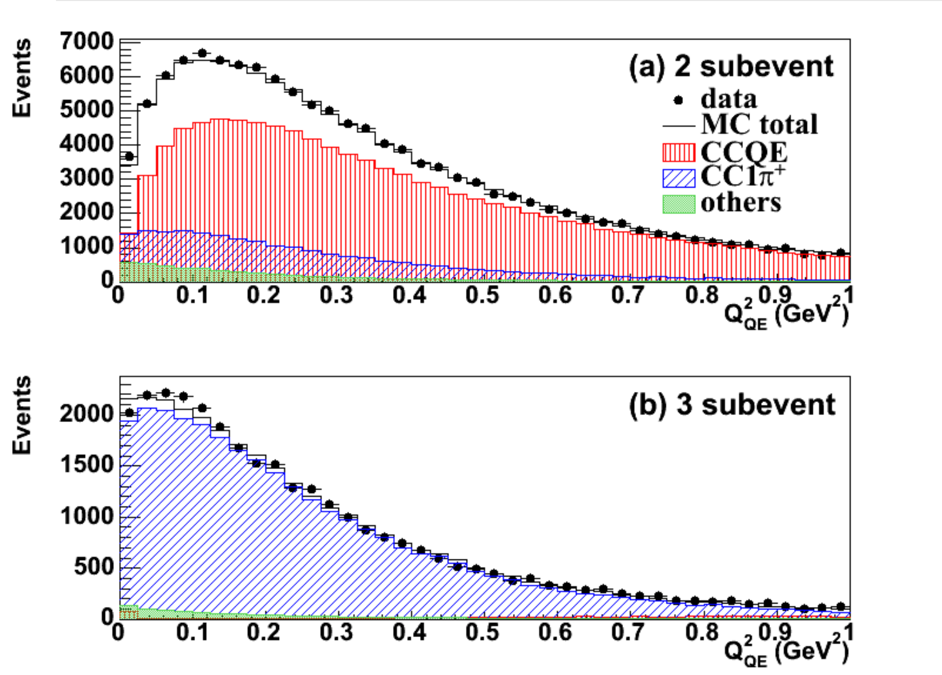
- Use events with 2 observed μ decays to measure $CC\pi^{+}$ (3 subevents)

- Determine weighting function to apply to MC to better describe CCπ

before CCπ measurement



after CCπ measurement



Getting CCπ correct is very important in CCQE measurement as it is large background ~20%

MiniBooNE CCQE analysis

- M_A, κ fit results:

- at this stage we fit (shape-only) for M_A, κ
(but, not main result of analysis and has no effect on cross section results).

M_A^{eff} = 1.35 ± 0.17 GeV (stat+sys)

$\kappa = 1.007^{+0.007}_{-\infty}$ (stat+sys)

χ^2/ndf = 47.0/38

Compared to prev result:

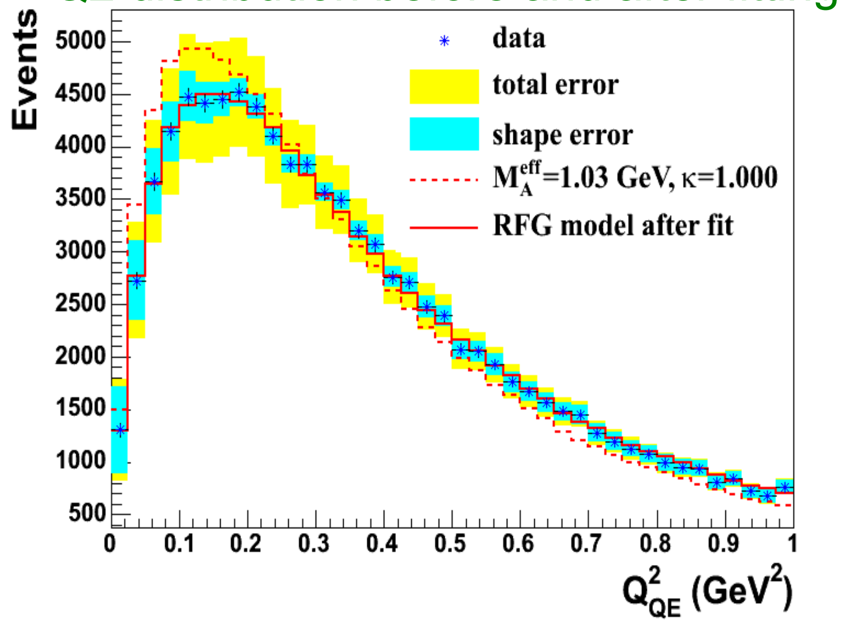
- M_A^{eff} goes up slightly, this is related to our new background subtraction.

- κ goes down due to the shape change of the background. Now κ is consistent with 1. κ doesn't affect cross section below ~0.995.

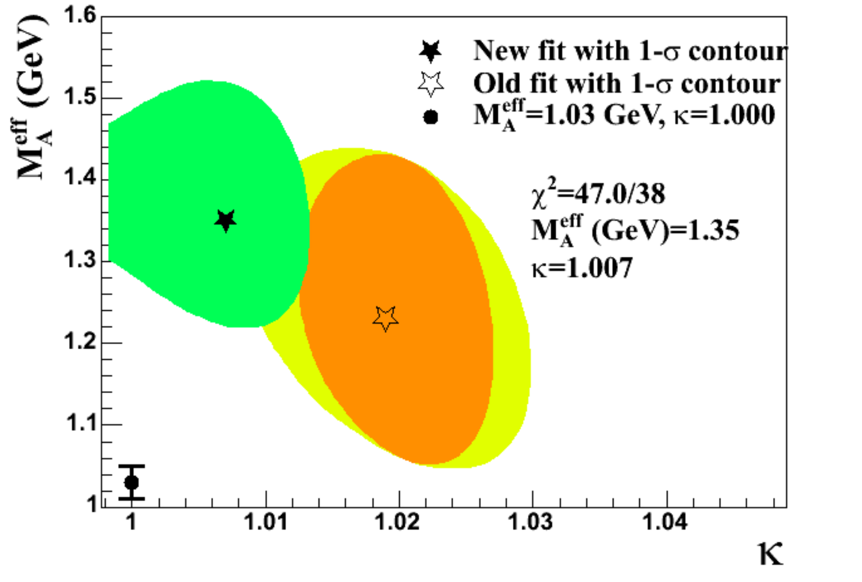
- with world-average M_A and κ = 1.0
χ^2/ndf = 67.5/40 (0.5% prob)

- M_A^{eff} only fit
M_A^{eff} = 1.37 ± 0.12 GeV
χ^2/ndf = 48.6/39

Q2 distribution before and after fitting



M_A^{eff} - κ shape-only fit result



MiniBooNE CCQE analysis

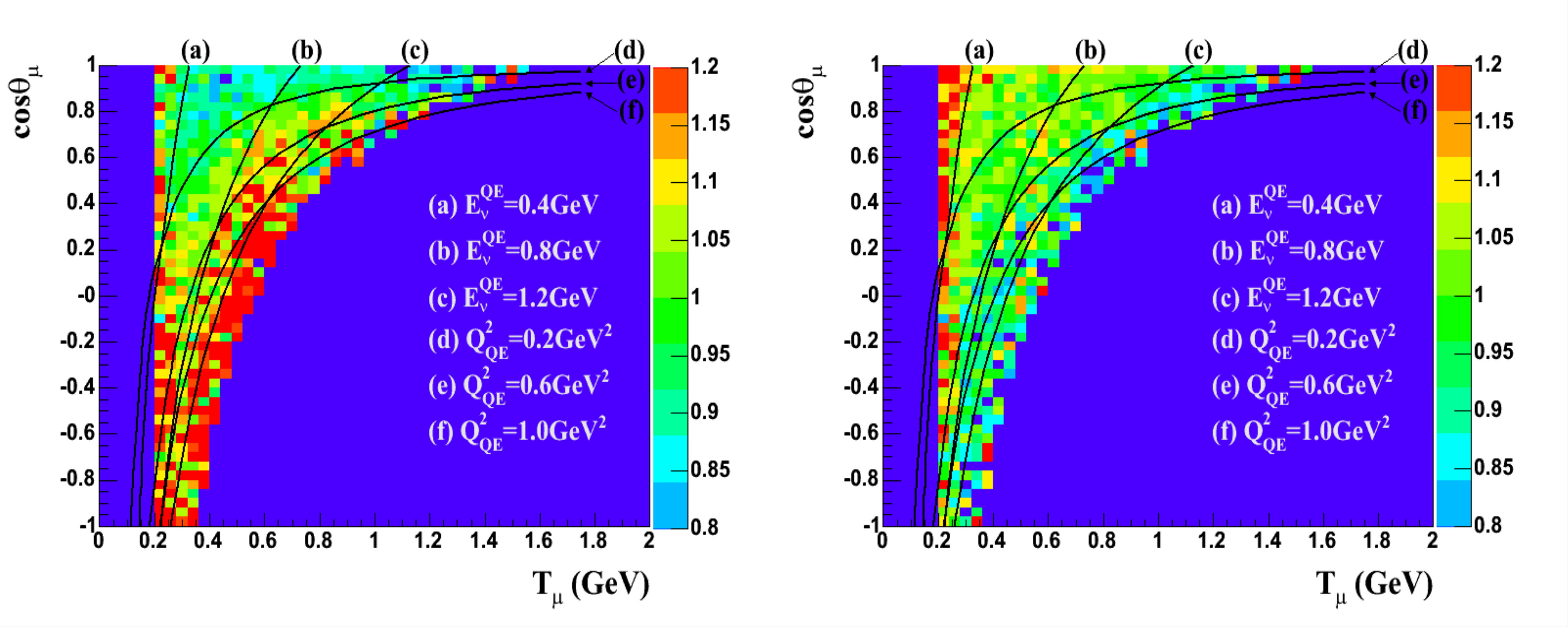
Muon energy, angle distributions:

- Good description of data in muon energy/angle (2d) space after background adjustment, fit

- important check as adjustments to model depend only on Q^2

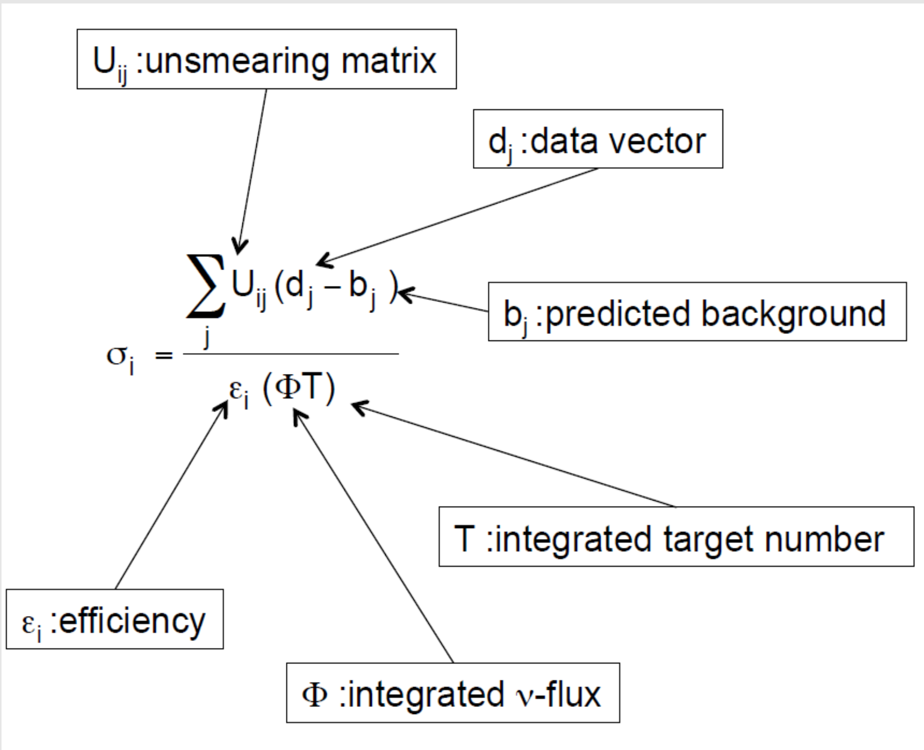
before CCQE fit w/ world-average RFG model, M_A^{eff} = 1.03, κ = 1.000

after fit



MiniBooNE CCQE analysis

Now extract differential cross sections for particular true bin i, from measured bin j:



integrated protons on target		5.58×10^{20}
energy-integrated ν_μ flux		2.90×10^{11} ν_μ/cm^2
CCQE candidate events		146070
CCQE efficiency ($R < 550$ cm)		26.6%
background channel	events	fraction
NCE	45	< 0.1%
CC1π^+	26866	18.4%
CC1π^0	3762	2.6%
NC1$\pi^\pm$	535	0.4%
NC1π^0	43	< 0.1%
other ν_μ	328	0.2%
all non-ν_μ	1977	1.4%
total background	33556	23.0%

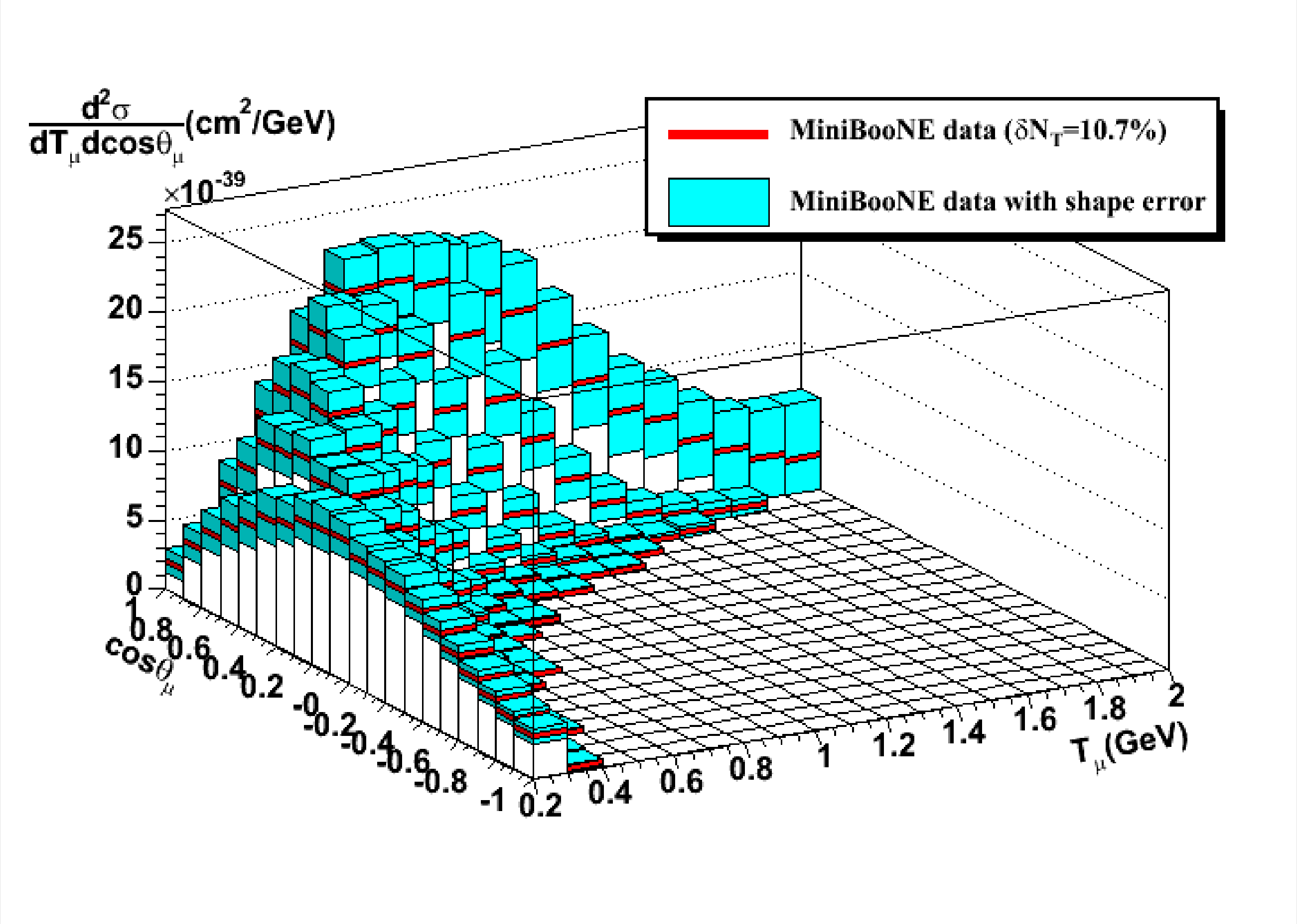
TABLE III: Summary of the final CCQE event sample including a breakdown of the estimated backgrounds from individual channels. The fraction is relative to the total measured sample. The channel nomenclature is defined in Table I.

- unsmearing corrects for detector "smearing" effects in differential cross sections. Not nuclear model effects. (excepting total cross section, come back to this)

MiniBooNE CCQE results

- maximum information possible on CCQE process from MB (using muon only)
- model-independent
- normalization (scale) error is 10.7% (not shown)
- error bars is remaining (shape) error

Flux-integrated double differential cross section (T_μ-cosθ):



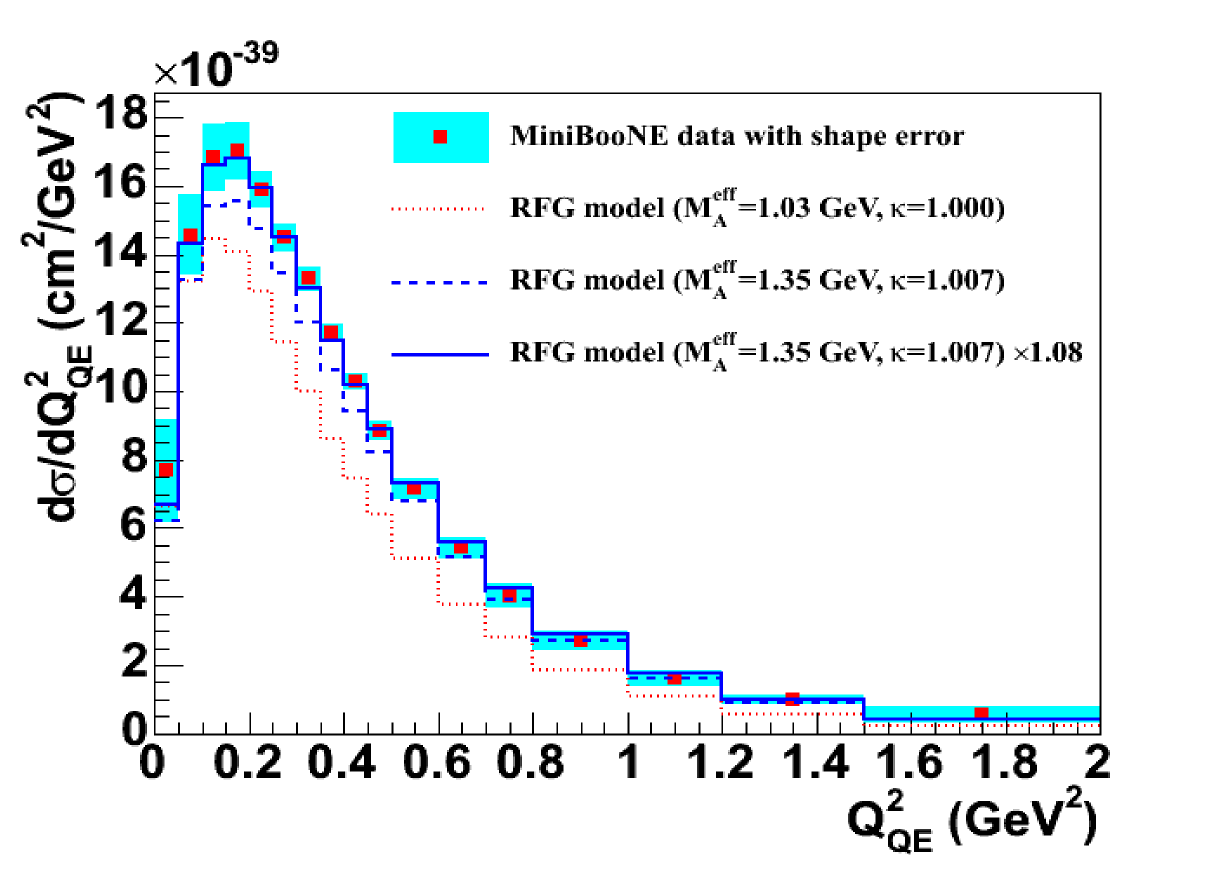
MiniBooNE CCQE results

- data is compared with CCQE (RFG) model with various parameter values

- Compared to the world-averaged CCQE model (red), our CCQE data is 30% high

- model with our CCQE parameters (extracted from *shape-only* fit) agrees well with over normalization (to within normalization error).

Flux-integrated single differential cross section (Q^2_{QE}):



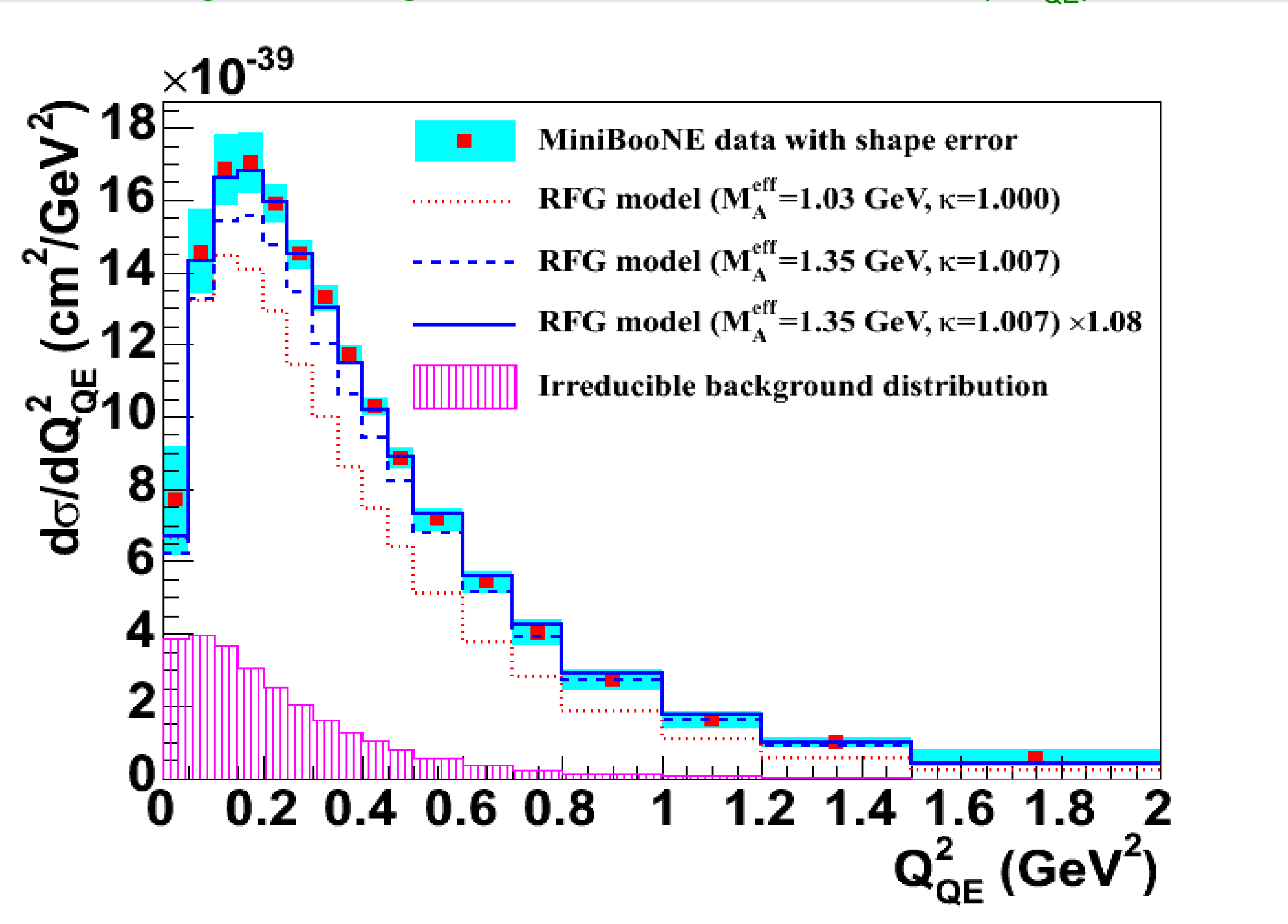
MiniBooNE CCQE results

- same plot as previous but with "irreducible" background overlaid.

- this background is subtracted, but may be undone (if desired) to produce "CCQE-like" sample

- also report this for double-diff xsection

Flux-integrated single differential cross section (Q^2_{QE}):



MiniBooNE CCQE results

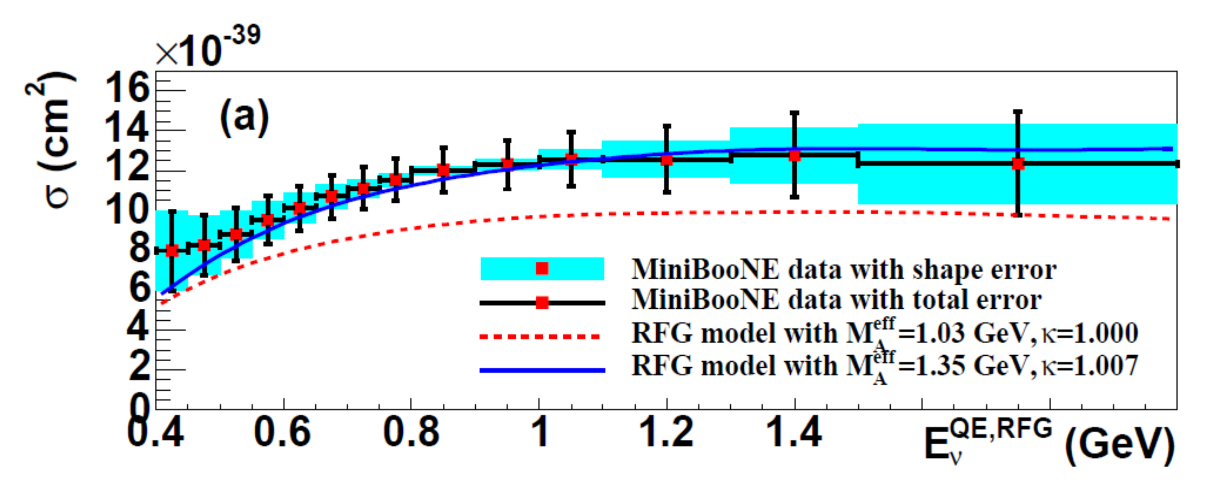
- total cross section is extracted by binning in "true" neutrino energy bins.

- Caution, model dependent

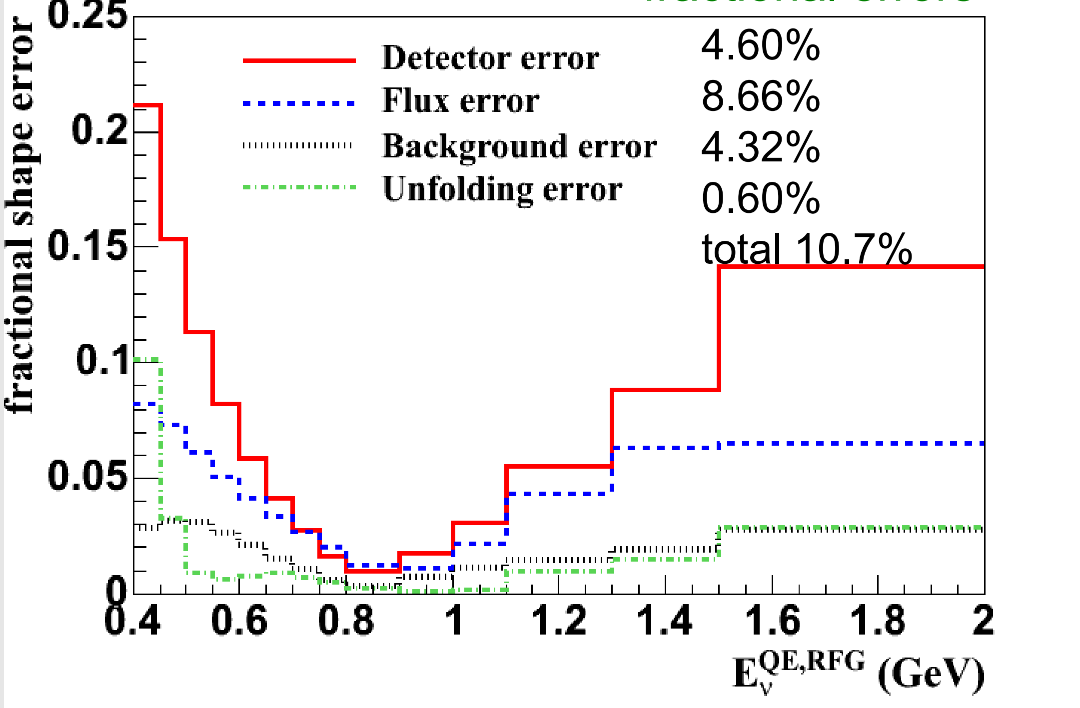
- again, total cross section value well-reproduced from extracted CCQE model parameters

- fractional errors (as function of neutrino energy) and overall normalization errors reported

Flux-unfolded total cross section ($E_\nu^{QE,RFG}$)



fractional errors

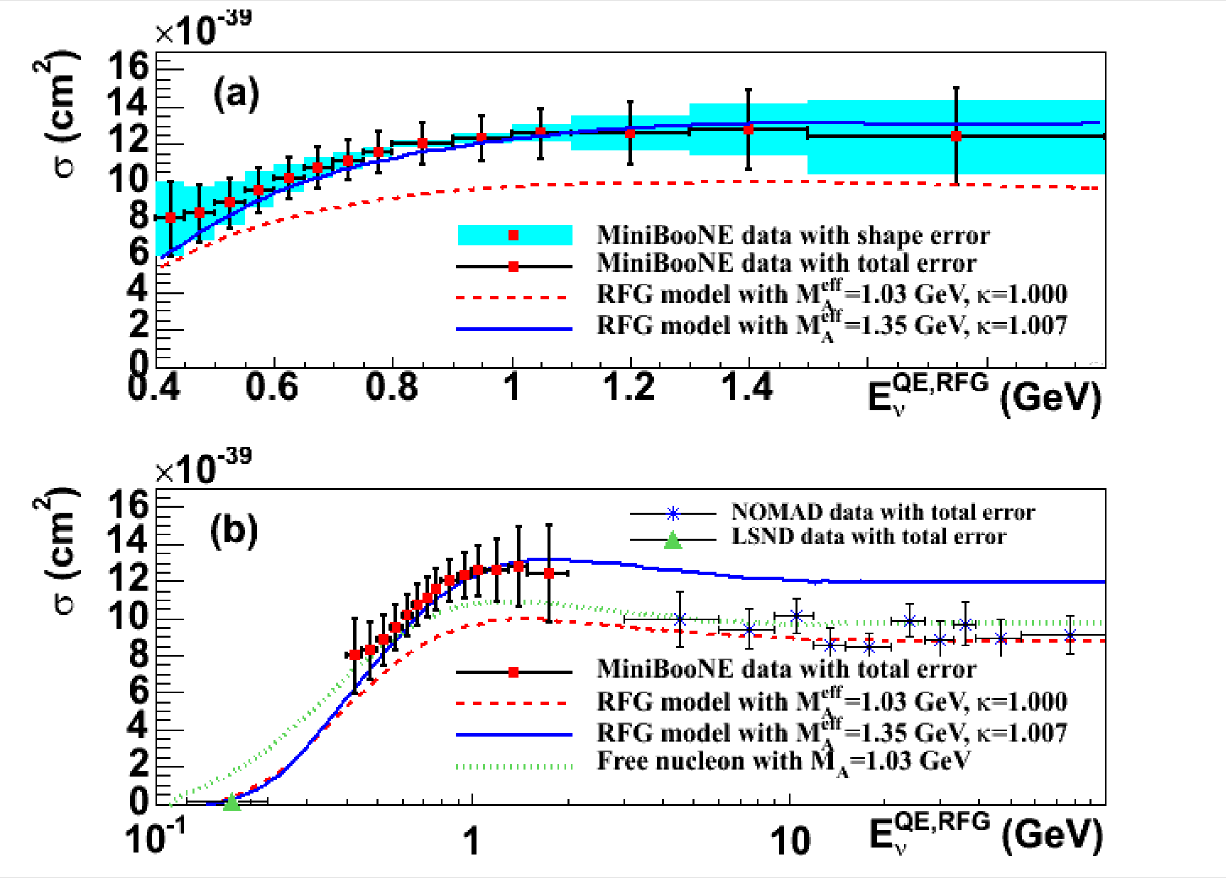


MiniBooNE CCQE results

- MiniBooNE cross section at 0.5-2 GeV is 30% higher than NOMAD at 5-100 GeV

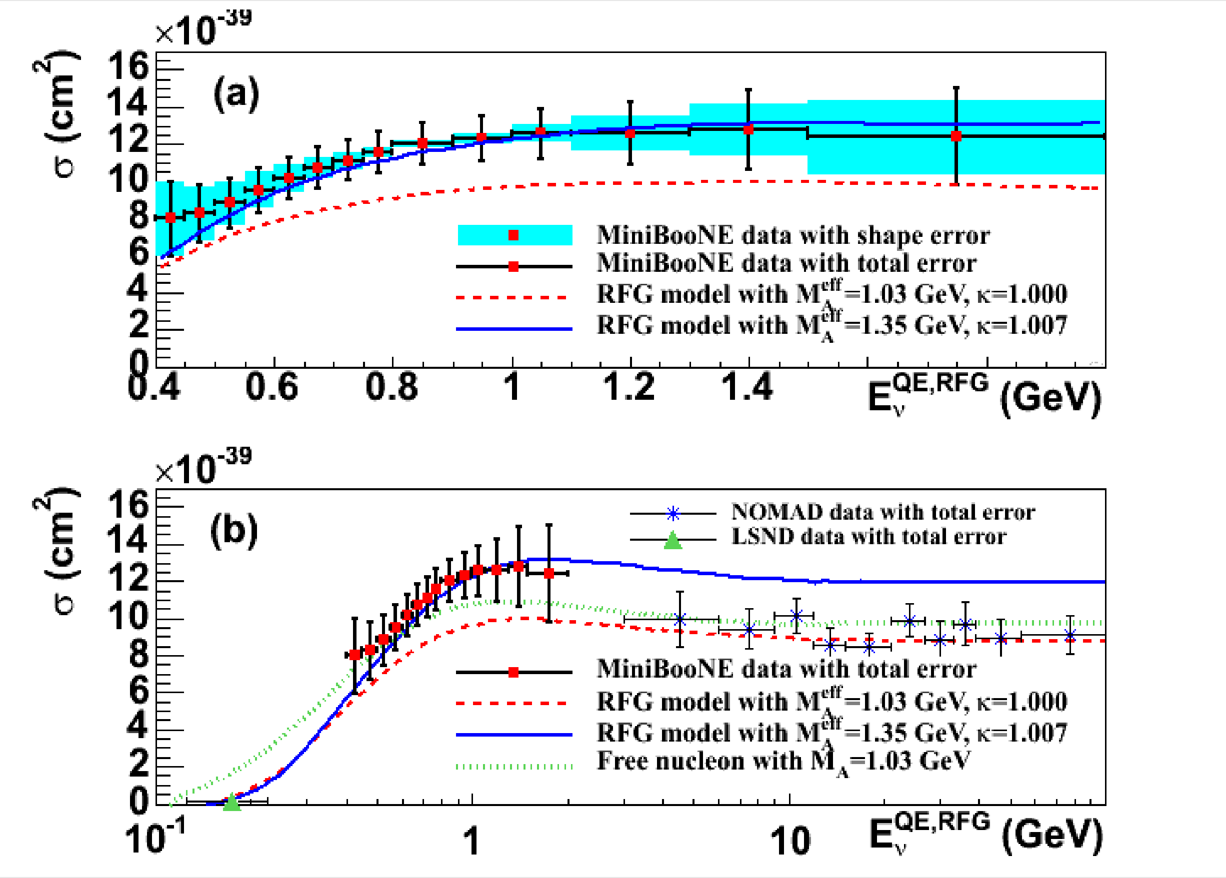
- physics? or something else?

Flux-unfolded total cross section ($E_\nu^{QE,RFG}$)



MiniBooNE CCQE results

Flux-unfolded total cross section ($E_\nu^{QE,RFG}$)



MB neutrino CCQE summary:

- first measurement of double differential cross section
- single, total cross section, M_A , also reported

- data indicates a larger M_A (or "stonger" Q^2 distribution) than previous (world average) in both shape and overall rate.

- these are separate experimental observations. Coincidence?

- Can larger M_A be attributed to nuclear effects (in carbon)? But at odds with NOMAD.

CCQE models

Much recent theory work on CCQE scattering and the “high-MA” puzzle:

J. E. Amaro et al. ,
Phys. Rev. C 71 , 015501 (2005);
Phys. Rev. C 75 , 034613 (2007);
T. Leitner et al. ,
Phys. Rev. C 73 , 065502 (2006);
Phys. Rev. C 79 , 065502 (2006);
O. Benhar et al. ,
Phys. Rev. D 72 , 053005 (2005);
arXiv:0903.2329 [hep-ph];
A. Butkevich et al. ,
Phys. Rev. C 76 , 045502 (2007);
Phys. Rev. C 80 , 014610 (2009);
S. K. Singh et al. ,
arXiv:0808.2103 [nucl-th];
J. Nieves et al. ,
Phys. Rev. C 73 , 025504 (2006);
N. Jachowicz et al. ,
Phys. Rev. C 73 , 024607 (2006);
A. M. Ankowski et al. ,
Phys. Rev. C 77 , 044311 (2008);
A. Meucci et al. ,
Nucl. Phys. A 739 , 277 (2004).

predicted differential cross section

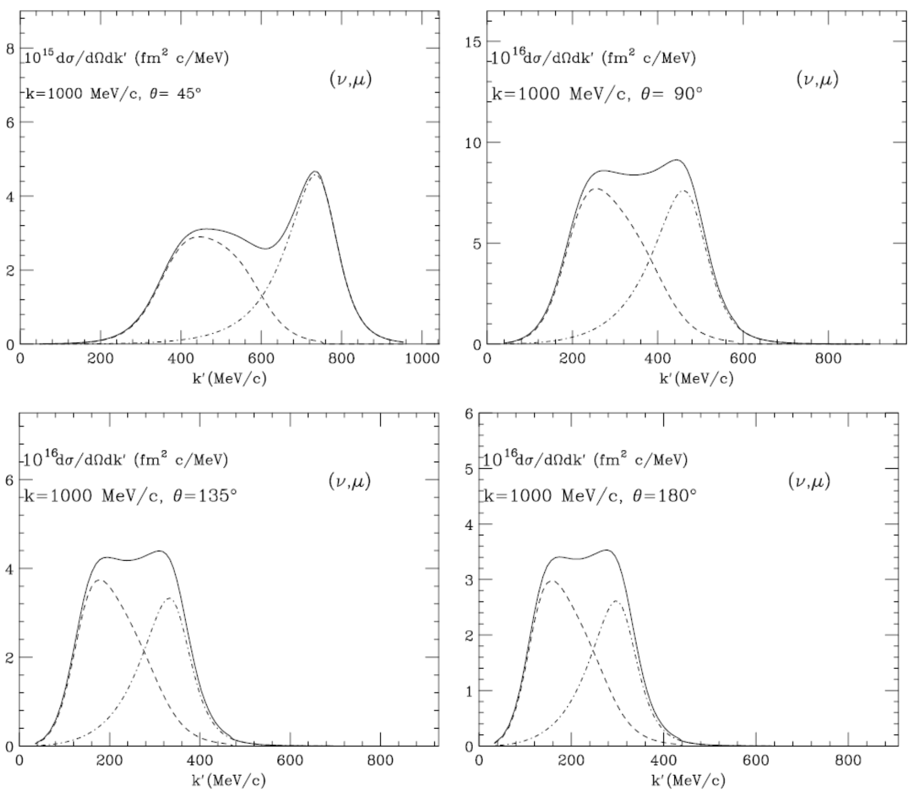


FIG. 6. Charge-changing neutrino reactions (ν_μ, μ^-) on ^{12}C for 1 GeV neutrinos and neutrino-muon scattering angles of 45, 90, 135, and 180 degrees. The cross sections are plotted versus the final-state muon momentum k'. The dash-dotted curve gives the QE contribution, the dashed curve the Δ contribution, and the solid curve the total. As discussed in the text, results for values of k' lying below the Δ peak (higher excitation energies than that of the Δ) must be viewed with caution.

- No solution has yet emerged, except perhaps...

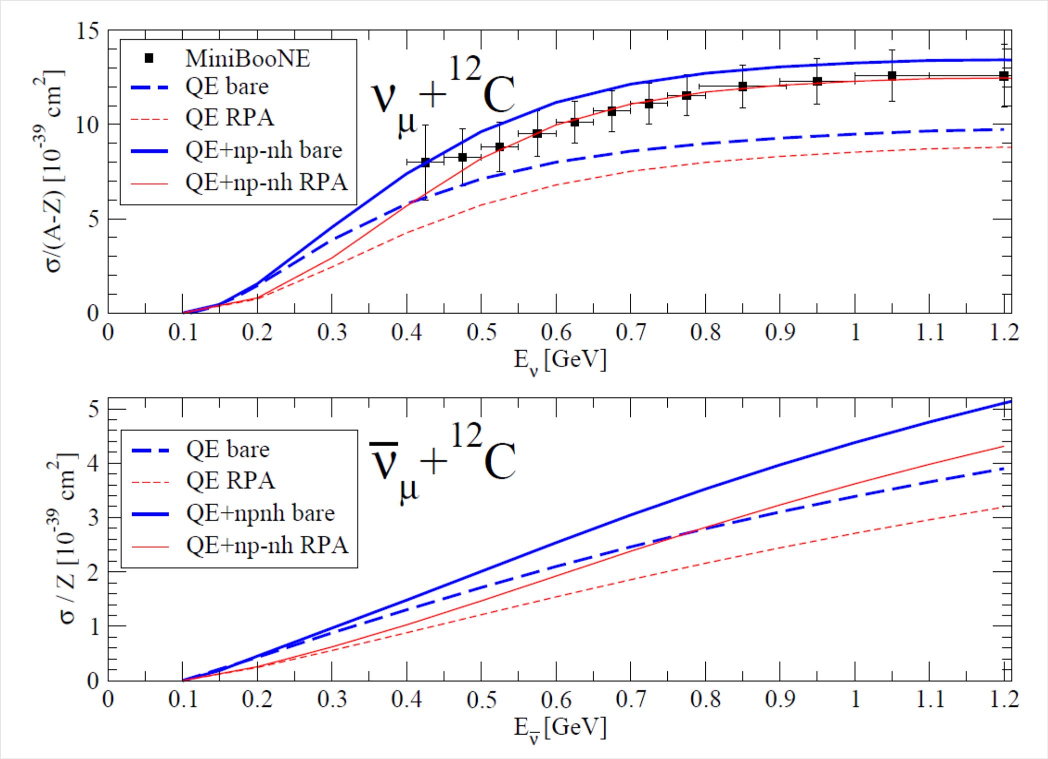
PHYSICAL REVIEW C **71**, 015501 (2005)

CCQE models

- ... a recent work by Martini et al (arXiv:1002.4538v1) proposes a model that reproduces larger CCQE cross section.

- Involves multinucleon excitations, tensor correlations.

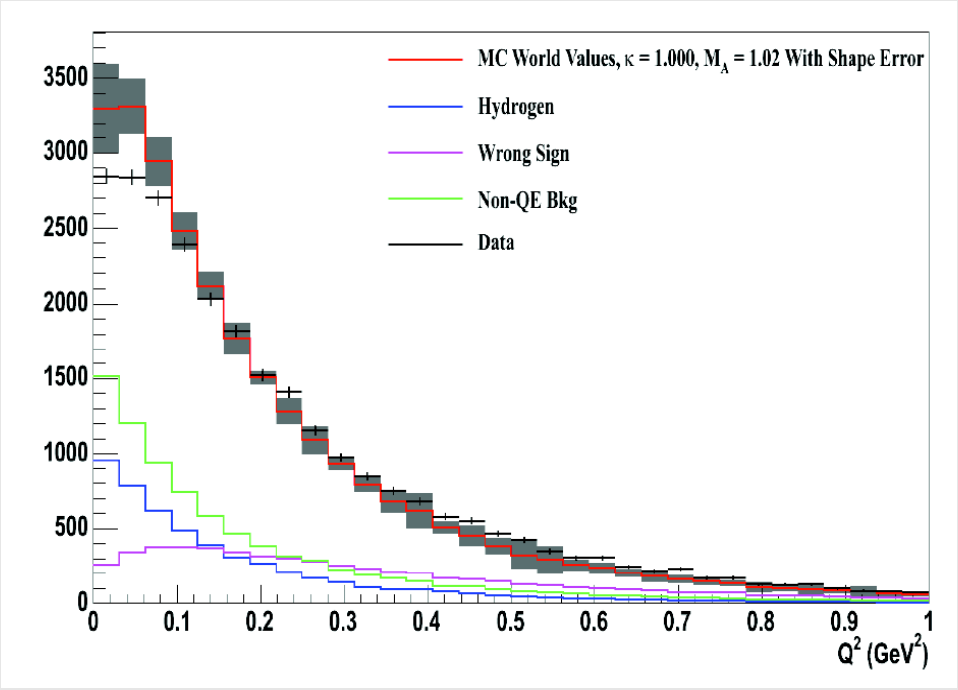
$$\begin{aligned}\frac{\partial^2\sigma}{\partial\Omega\,\partial k'} = & \frac{G_F^2\,\cos^2\theta_c\,(\boldsymbol{k}')^2}{2\,\pi^2}\,\cos^2\frac{\theta}{2}\,\Big\{G_E^2\,(\frac{q_\mu^2}{\boldsymbol{q}^2})^2\,R_\tau^{NN} \\ & + G_A^2\,\frac{(M_\Delta - M)^2}{2\,\boldsymbol{q}^2}\,R^{N\Delta}_{\sigma\tau(L)} + G_A^2\,\frac{(M_\Delta - M)^2}{\boldsymbol{q}^2} \\ & \times R^{\Delta\Delta}_{\sigma\tau(L)} + \left(G_M^2\,\frac{\omega^2}{\boldsymbol{q}^2} + G_A^2\right)\left(-\frac{q_\mu^2}{\boldsymbol{q}^2} + 2\tan^2\frac{\theta}{2}\right) \\ & \times \left[R^{NN}_{\sigma\tau(T)} + 2R^{N\Delta}_{\sigma\tau(T)} + R^{\Delta\Delta}_{\sigma\tau(T)}\right] \pm 2G_A G_M \frac{k+k'}{M} \\ & \times \tan^2\frac{\theta}{2}\,\left[R^{NN}_{\sigma\tau(T)} + 2R^{N\Delta}_{\sigma\tau(T)} + R^{\Delta\Delta}_{\sigma\tau(T)}\right]\Big\} \qquad (1)\end{aligned}$$

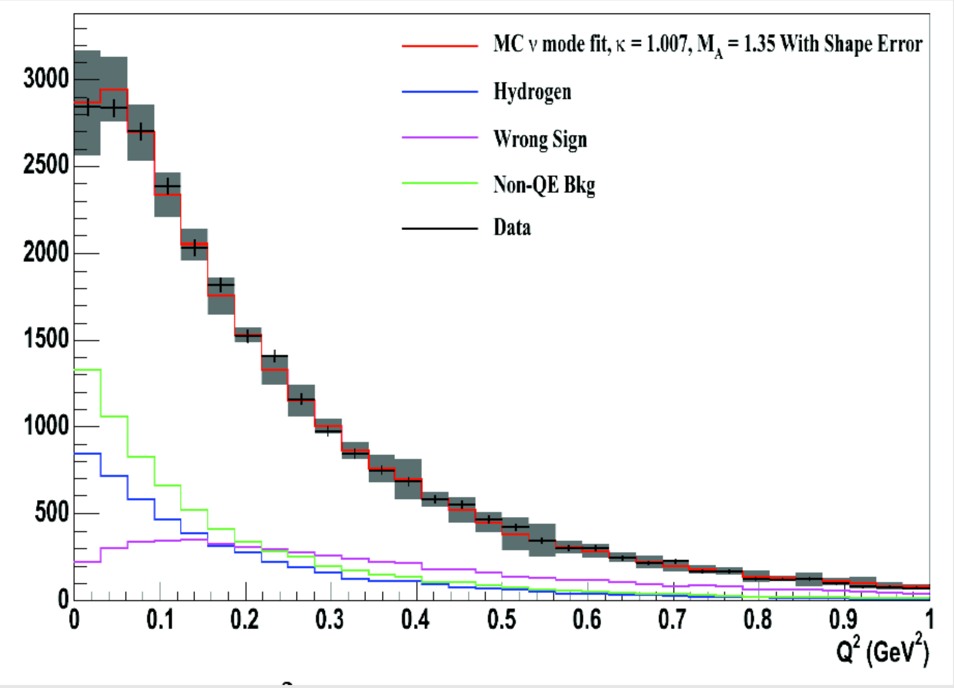


Other MiniBooNE scattering results

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

anti-neutrino CCQE scattering NC:
- preliminary results presented (arXiv:0910.1802)
- results consistent with neutrino mode CCQE scattering (higher M_A prefered)



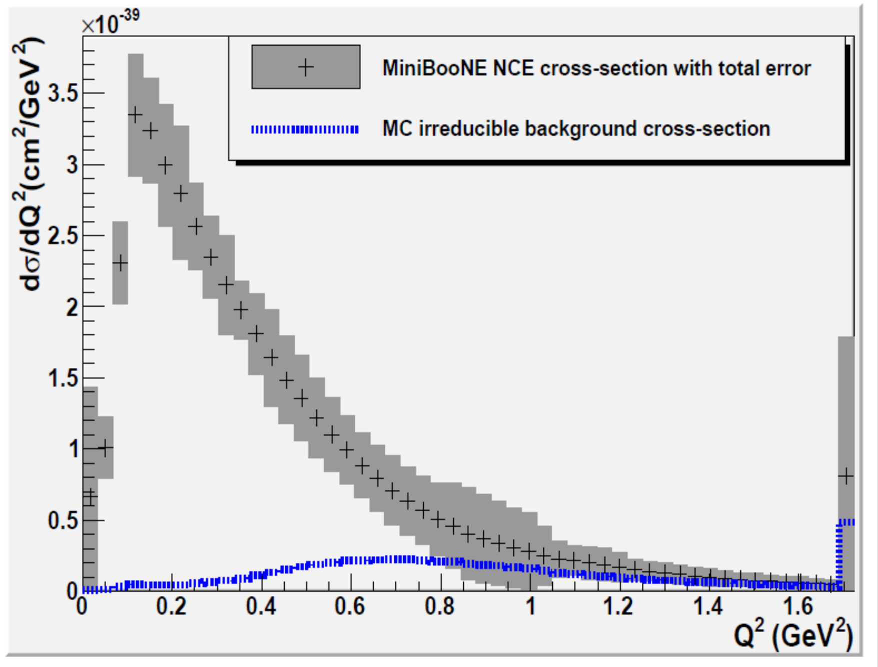


Other MiniBooNE scattering results

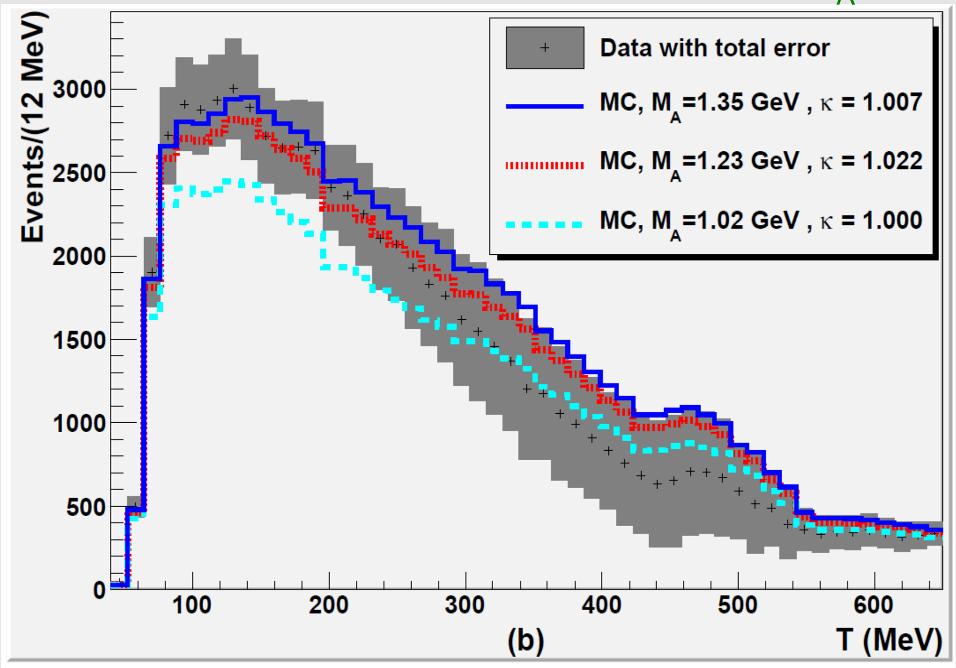
$$\nu_\mu + p \rightarrow \nu_\mu + p$$
$$\nu_\mu + n \rightarrow \nu_\mu + n$$

NC elastic scattering:
- differential cross section (arXiv:0909.4617v1)
- M_A consistent with CCQE scattering
- very little Δs sensitivity
- full publication in preparation (will include NC/CCQE ratios)

NC elastic differential cross section



NC elastic M_A fits



Other MiniBooNE scattering results

CC pion production:

- $CC\pi^+/CCQE$ ratio measured

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

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

- $CC\pi^+/CCQE$ ratio in agreement with expectations. So $CC\pi^+$ rate (cross section) is also larger than expected. True in both FSI corrected/uncorrected samples

$CC\pi^+$ /CCQE ratio, FSI corrected

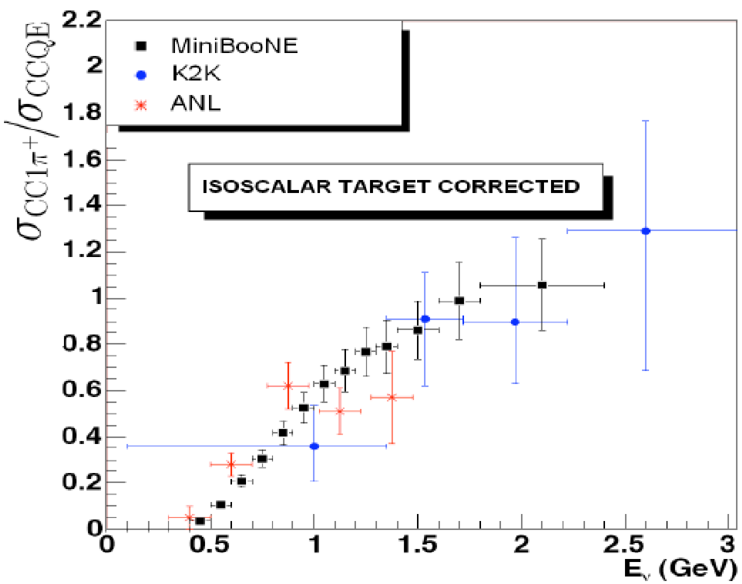


FIG. 2: FSI-corrected $CC1\pi^+$ to CCQE cross section ratio on CH_2 compared with results from ANL (D_2) [1] and K2K (C_8H_8) [3]. The data have been corrected for final state interactions and re-scaled for an isoscalar target.

$CC\pi^+$ /CCQE ratio, no FSI corrections

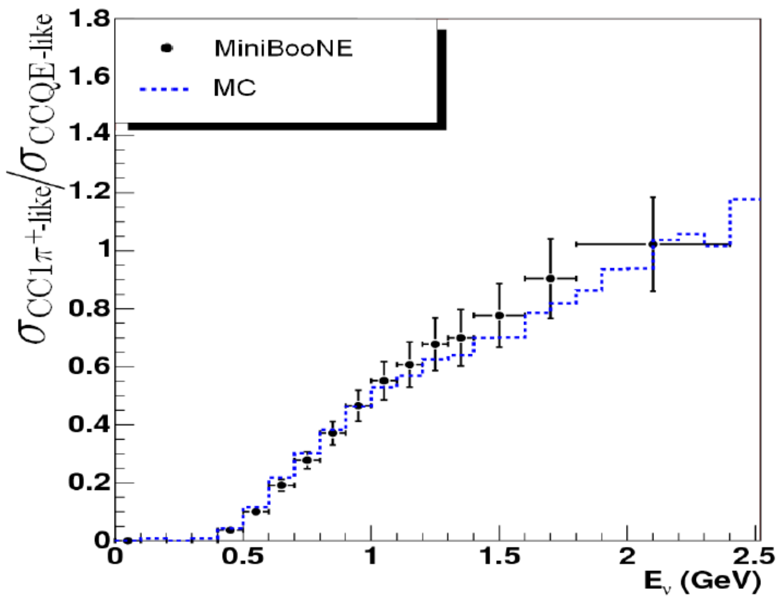


FIG. 1: Observed $CC1\pi^+$-like/CCQE-like cross section ratio on CH_2, including both statistical and systematic uncertainties, compared with the MC prediction [6]. The data have not been corrected for hadronic re-interactions.

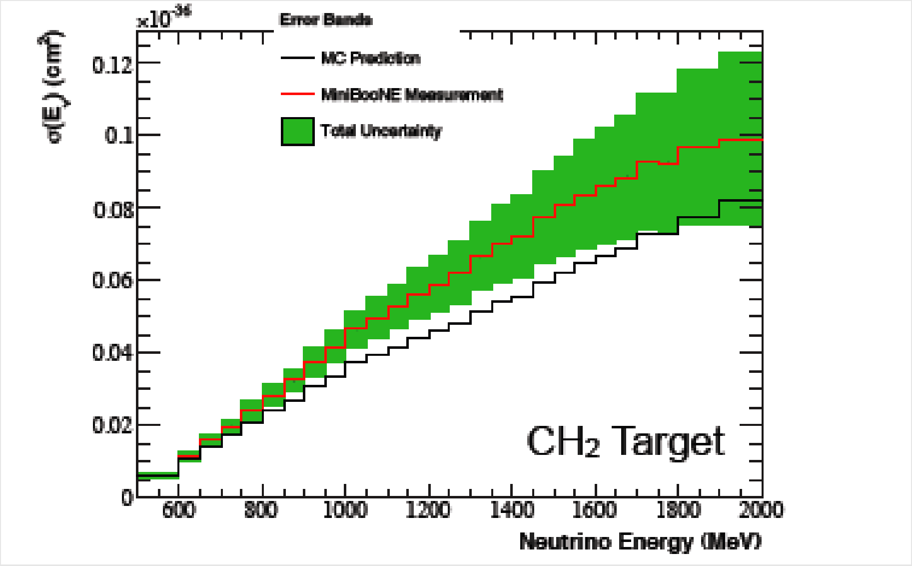
Other MiniBooNE scattering results

CC pion production:

- $CC\pi^+$ differential cross sections to appear (article in preparation)
- $CC\pi^+$ cross section larger than expected

- $CC\pi^0$ in the works also

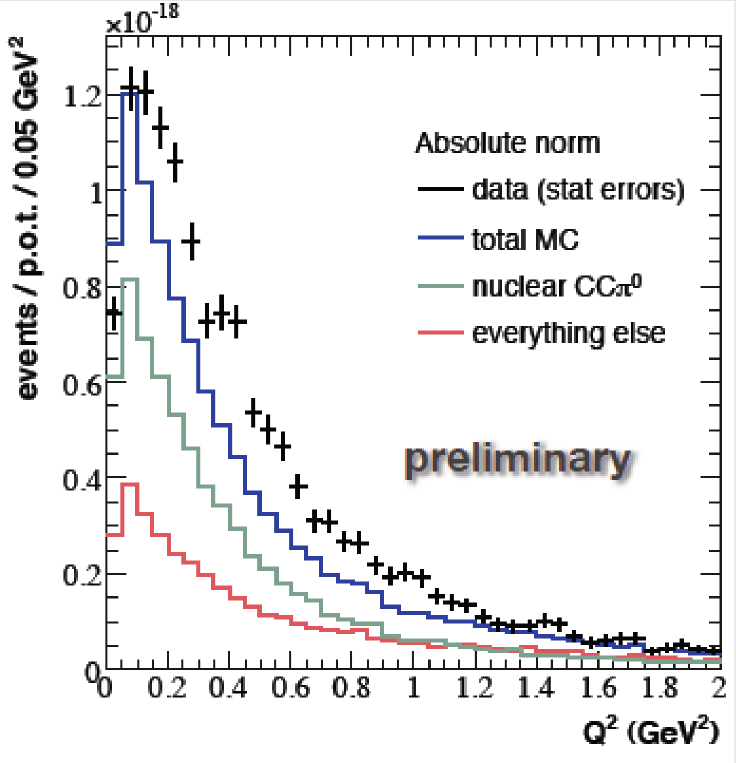
$CC\pi^+$ total cross section



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

$$\nu_\mu + A \rightarrow \mu + A + \pi^+$$

$CC\pi^0$ event distribution

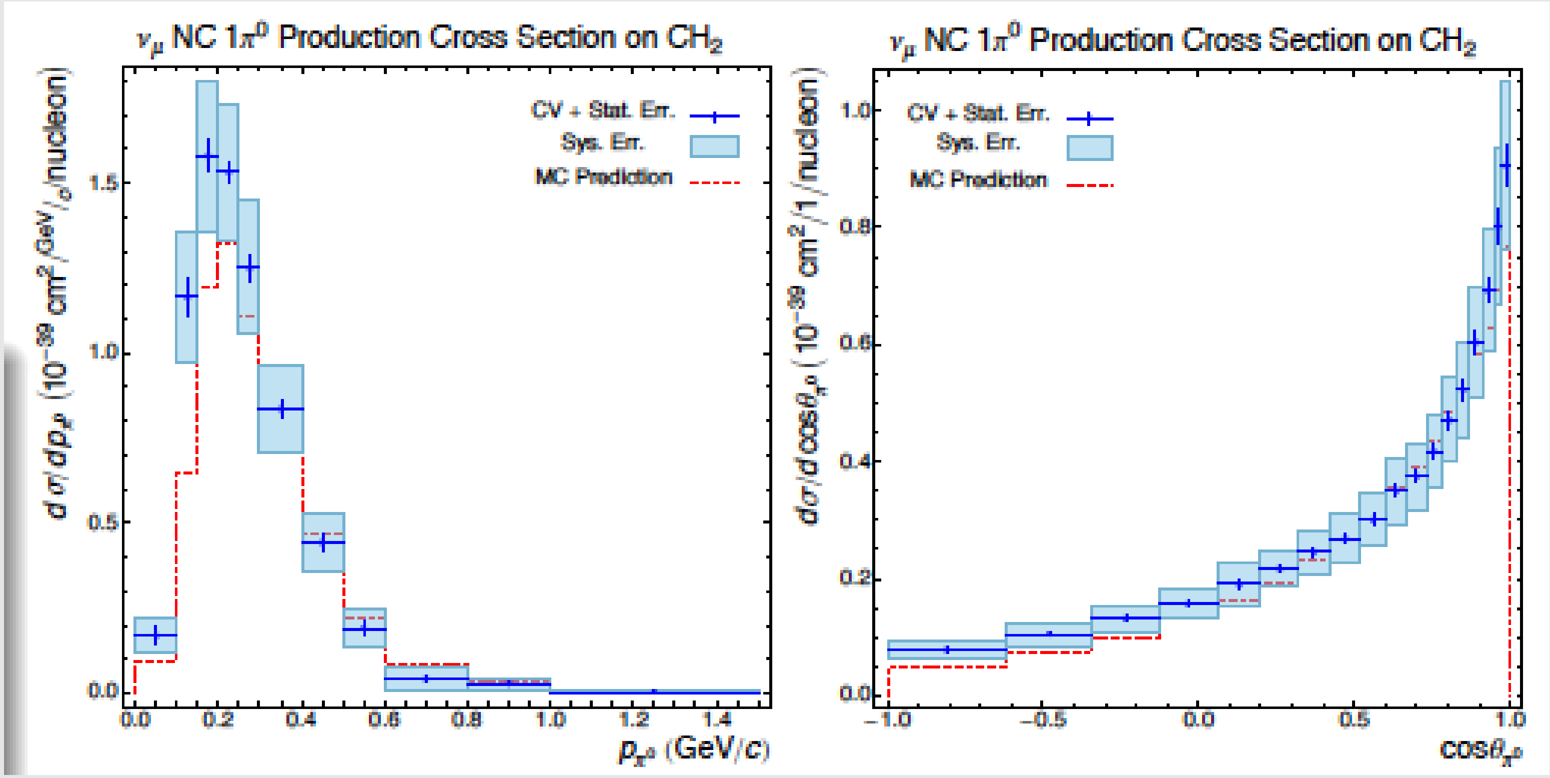


$$\nu_\mu + n \rightarrow \mu + \Delta^+ \rightarrow \mu + p + \pi^o$$

Other MiniBooNE scattering results

NCπ^0 pion production:
- differential cross sections in both neutrino and antineutrino modes
(Phys. Rev. D81, 013005 (2010))
- coherent fraction extracted

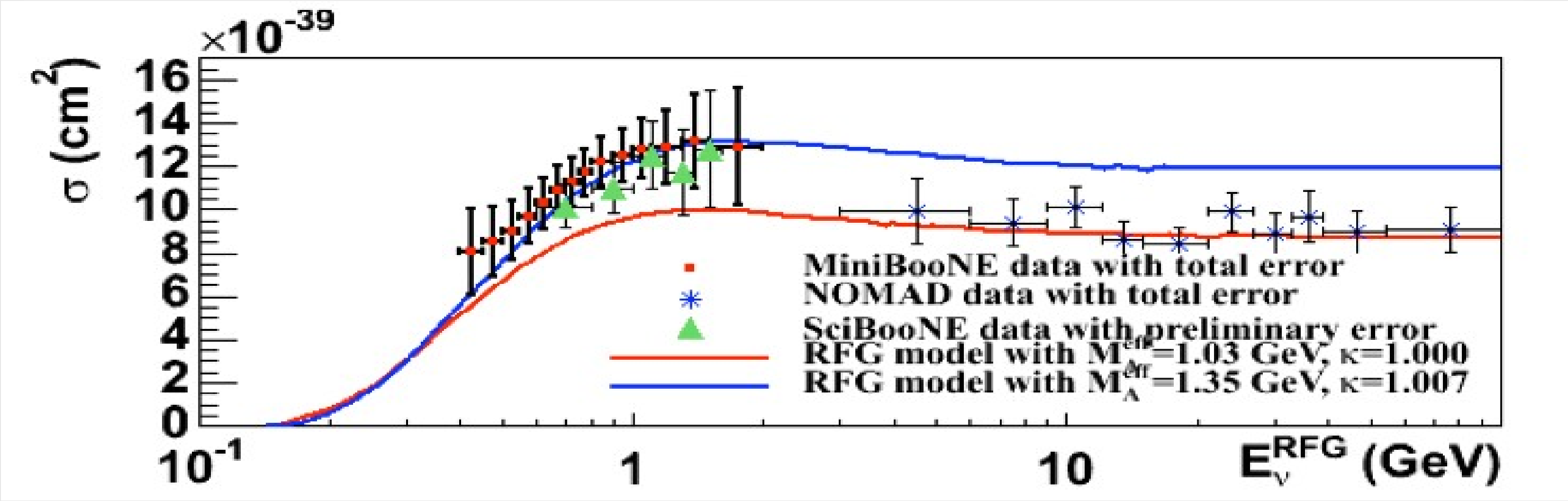
$$\nu_\mu + N \rightarrow \nu_\mu + \Delta^o \rightarrow \nu_\mu + N + \pi^o$$
$$\nu_\mu + A \rightarrow \nu_\mu + A + \pi^o$$



SciBooNE CCQE results

CCQE results:

- SciBooNE: (highly segmented) scibar in Booster nu beam at FNAL (as MiniBooNE)
- (preliminary) results indicated higher cross section as seen by MiniBooNE (arXiv:0909.5647)
- final results soon and (hopefully) differential cross sections

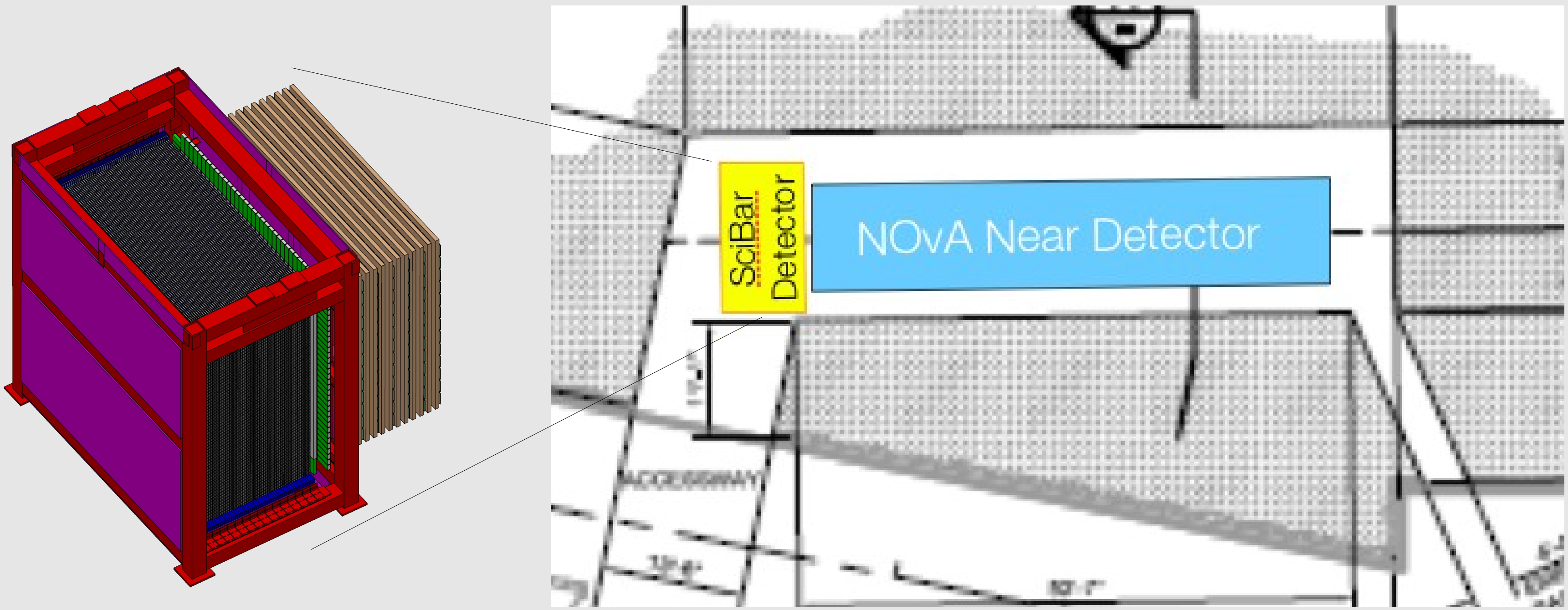


- (near) future experiments such as MINERvA, T2K will also provide CCQE results

- and there is another possibility... SciNOvA..

SciNOvA

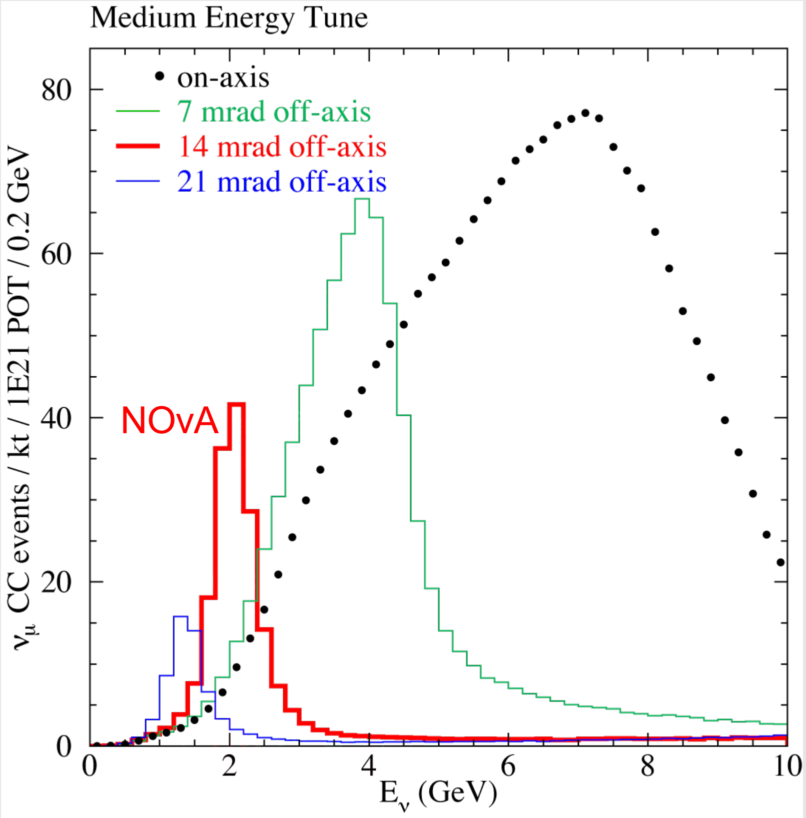
A proposal to reinstrument the existing SciBar detector and deploy in front of the NOvA near detector in the NuMI (off-axis) 2 GeV narrow-band beam.   A fine-grained detector such as SciBar in this location enables important and unique ν scattering measurements and enhances the NOvA ν oscillation measurements.



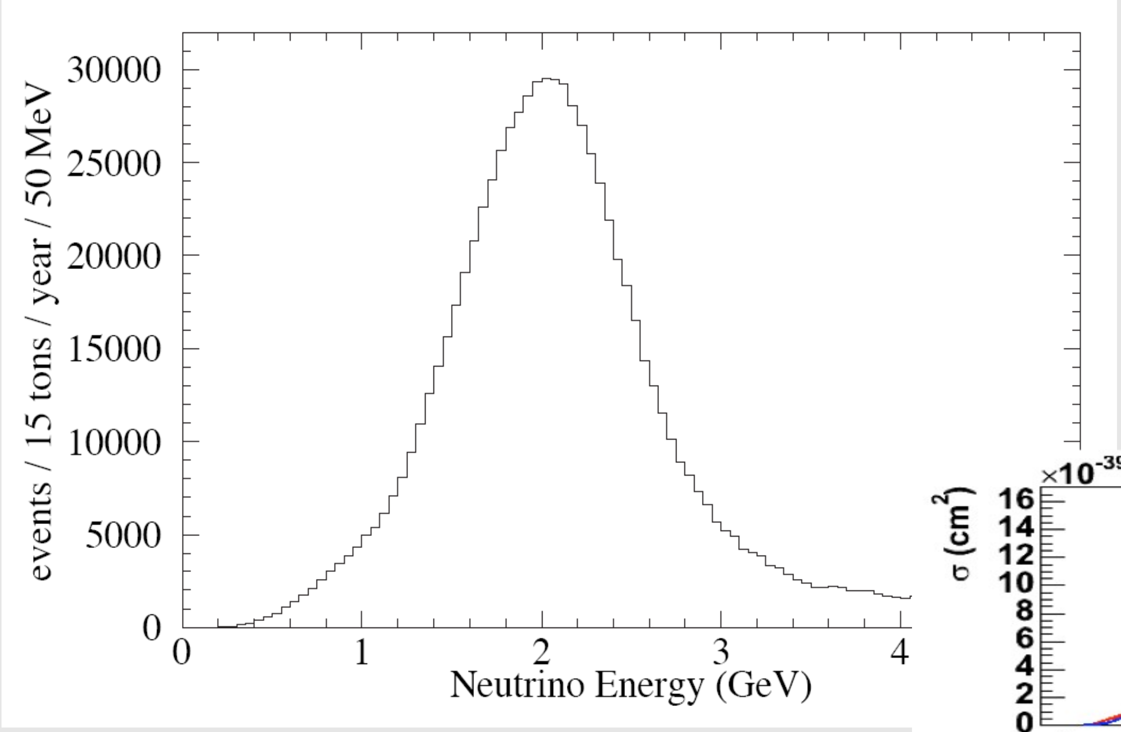
CCQE scattering with SciNOvA

- A measurement with the SciBar detector (which has produced CCQE measurements in SciBooNE/K2K)...
- in the narrow-band 2 GeV ν, $\bar{\nu}$ beam, where CCQE vs CCpi kinematics, are more easily separated..
- will be invaluable in testing/guiding future CCQE models

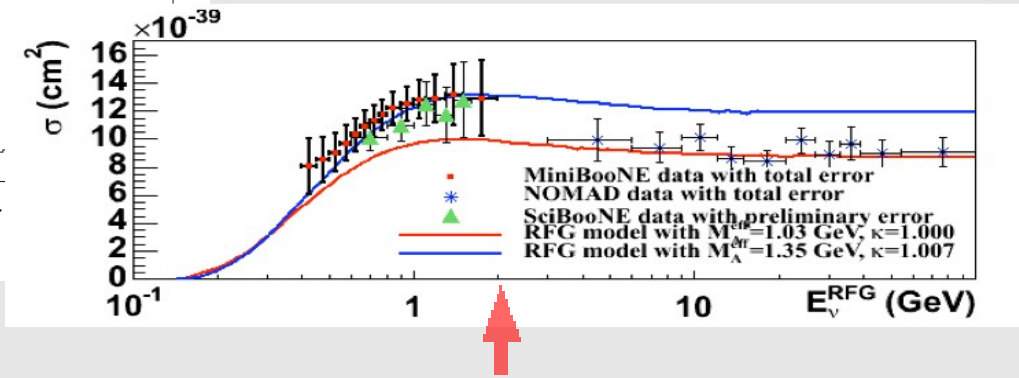
event rate from NuMI near locations



neutrino event rate at NOvA near location



MiniBooNE & others CCQE data



SciNOvA experimental plan

Reinstrumenting the SciBar detector for SciNOvA:

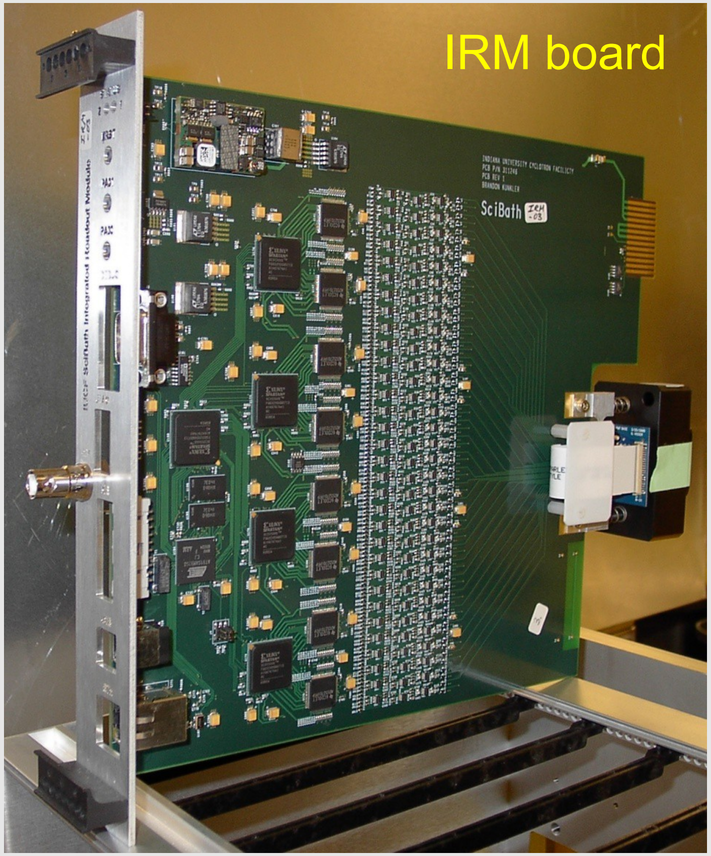
- PMTs/readout electronics removed from SciBar after SciBooNE completed

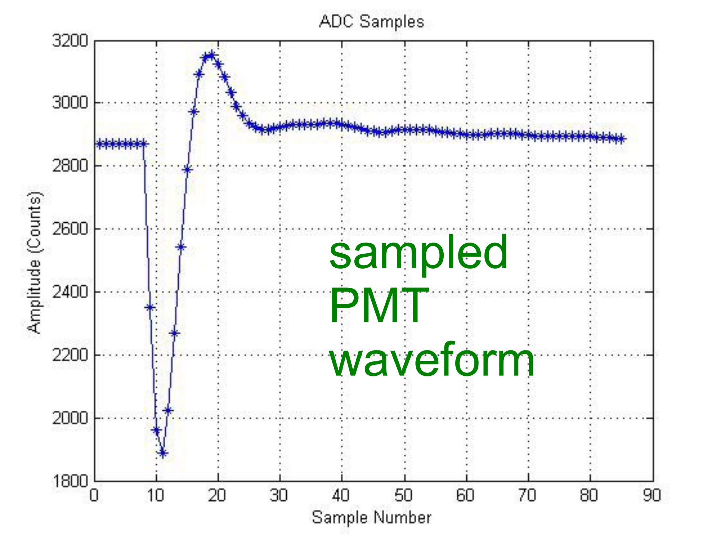
- At Indiana U. , a system has been developed (with support from Indiana U. and NSF) for WLS-fiber readout of "scibath" detector

- 15 "IRM" boards built and running!

- Integrated readout of (64-channel) PMT with flash ADC of "ringing integrator" front-end circuit for charge, time info with one-ADC channel.

- Cost:
  - $50/channel for readout (including mechanical)
  - $25/channel for PMT





SciNOvA status

- “expression of interest” presented to FNAL PAC in 11/09:

- FNAL PAC was “intrigued”, asked for more information on a few issues and to verify availability of detector

- A Japanese group wants to use scibar detector for cosmic neutron experiment in Mexico. Funding situation for that will be more clear in April...

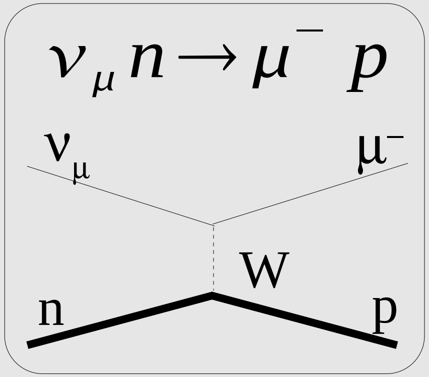
- ... next steps on SciNOvA

SciNOvA: A Measurement of Neutrino-Nucleus Scattering in a Narrow-Band Beam

D. Harris, R. Tesarek
FNAL
G. Feldman
Harvard
C. Bower, L. Corwin, M.D. Messier, N. Mayer, J. Musser, J. Paley, R. Tayloe, J. Urheim
Indiana U.
M. Sanchez
Iowa State U.
K. Heller
U. of Minnesota
S. Mishra, X. Tian
U. of South Carolina
H. Meyer
Wichita State U.
P. Vahle
William and Mary

Conclusions

ν_μ CCQE

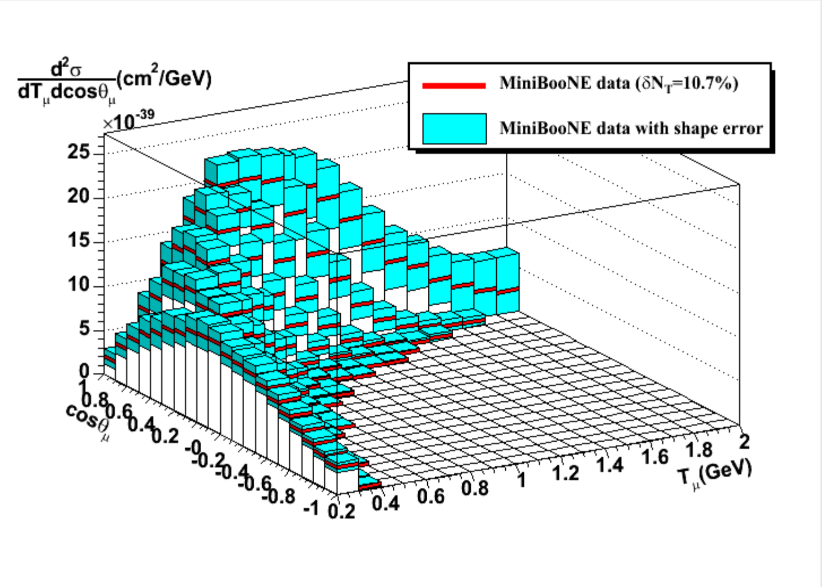


- Important to understand the CCQE process as it is a fundamental process, required for measuring neutrino oscillations as well as independently interesting.

- Recent results from measurments on carbon, oxygen, Fe, dont agree with what we thought we knew about CCQE, ~10 years ago.

- Need to dig into problem and sort this out with:
    - unbiased, cross section (model-independent) measurements
    - complementary measurements with different (but understood) flux
    - detailed work modeling, understanding data (including backgrounds)

- Recent MB results are a step in this direction.



backups

CCQE scattering

Charged-current quasielastic scattering (CCQE):

- crucial process to understand as it is... (in MiniBooNE)
  - detection signal for $\nu_\mu \rightarrow \nu_e$
  - normalization signal for ν_μ flux
- Thought to be a simple process....
  - Llewellyn-Smith formalism for diff cross section:

$$\frac{d\sigma}{dQ^2}\left(\begin{array}{c}\nu_l + n \rightarrow l^- + p \\ \bar{\nu}_l + p \rightarrow l^+ + n\end{array}\right) = \frac{M^2 G_F{}^2 cos^2\theta_c}{8\pi E_\nu{}^2}\left\{A(Q^2) \pm B(Q^2)\frac{(s-u)}{M^2} + C(Q^2)\frac{(s-u)^2}{M^4}\right\}$$

  - combined with model of nucleus (eg for Carbon)

- with only one unknown parameter, M_A (via axial form factor, F_A):

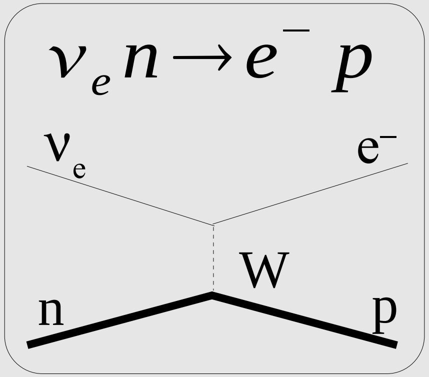
$$F_A(Q^2) = -\frac{g_A}{\left(1+\frac{Q^2}{M_A^2}\right)^2}$$

- and measuring ν_μ CCQE process (has been) thought of as extraction of M_A.

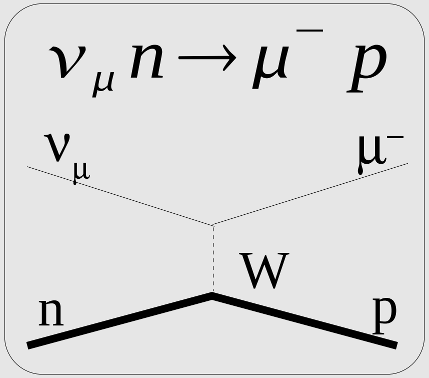
- However:
  - non-monoenergetic beams
  - different detection details between exps. (recoil nucleon detected?)
  - backgrounds (some "irreducible", eg CCπ w/π absorption)
  - bound nucleons

- and a puzzle has emerged (with newer data over last few years)....

ν_e CCQE

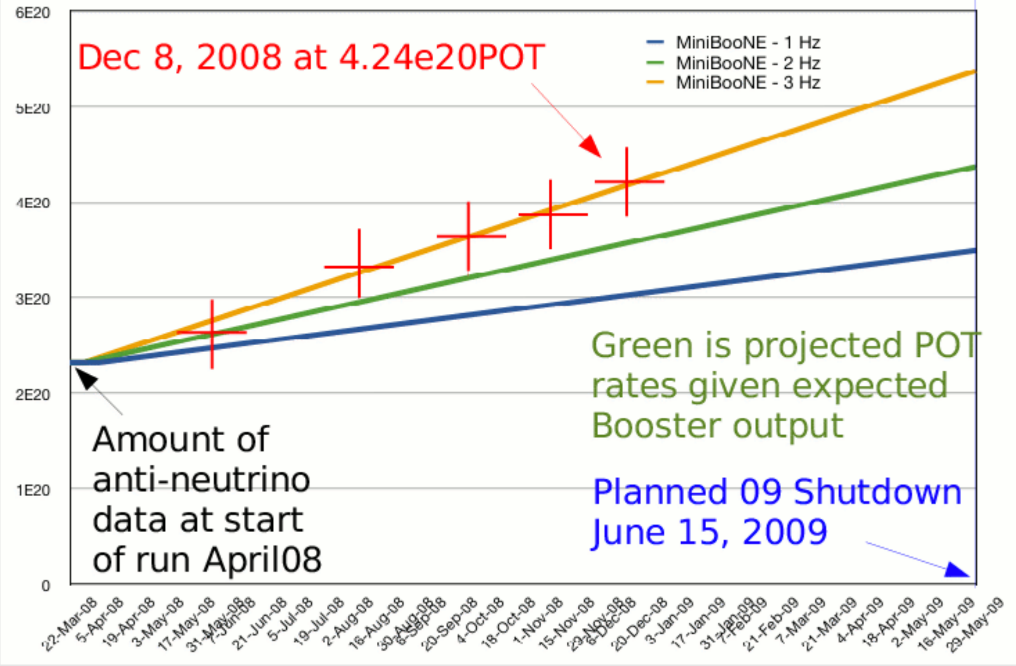


ν_μ CCQE



MiniBooNE: continuing to collect data...

- Have collected both neutrino and antineutrino data
- 2002-2005, ν mode, 5.5E20POT, published oscillation data
- 2005-2007, $\bar{\nu}$ mode, 2.3E20POT, first SciBooNE data
- 2007-present, ν mode, 1.0E20POT, for SciBooNE
- 2008-2009, $\bar{\nu}$ mode, ~3E20POT,
  to collect ~5E20POT in $\bar{\nu}$ mode, for MB $\bar{\nu}$ oscillation search
- *POT=protons on target



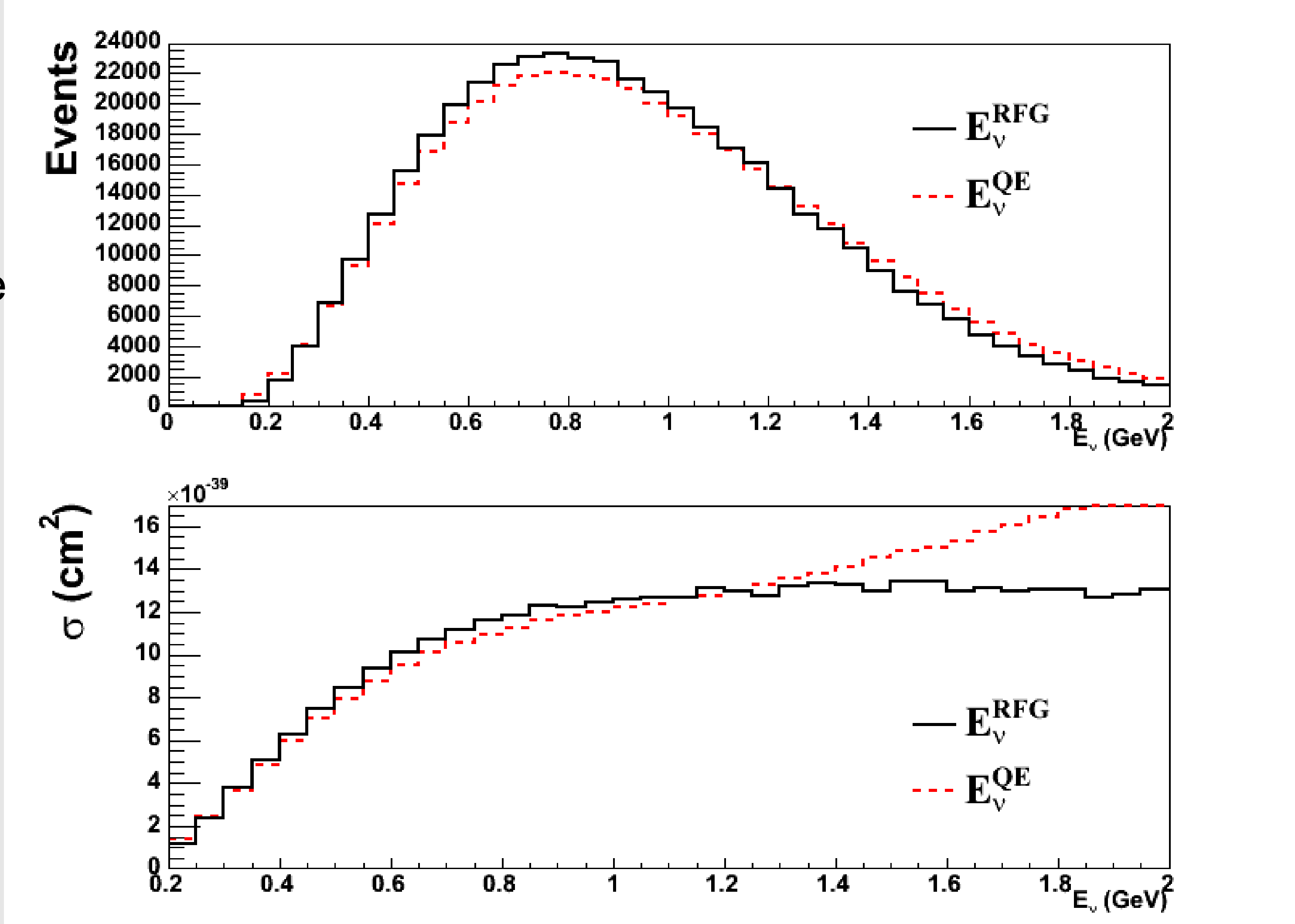
6. CCQE total cross section model dependence

Flux-unfolded total cross section (E_ν^{RFG})

Unfortunately, flux unfolded cross section is model dependent.

Reconstruction bias due to "QE" assumption is corrected under "RFG" model assumption.

One should be careful when comparing flux-unfolded data from different experiments.

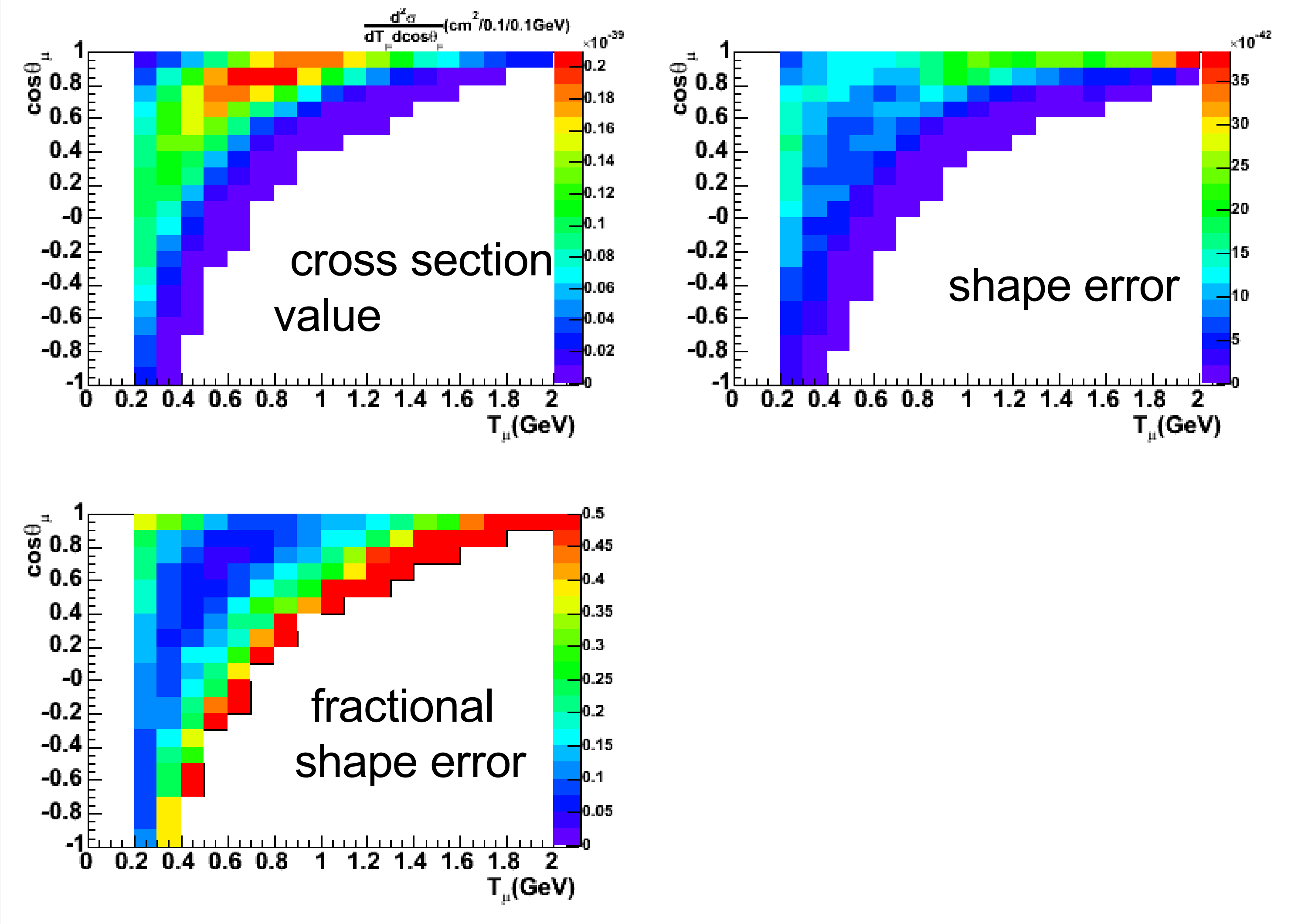


6. CCQE double differential cross section

Flux-integrated double differential cross section (T_μ-cosθ)

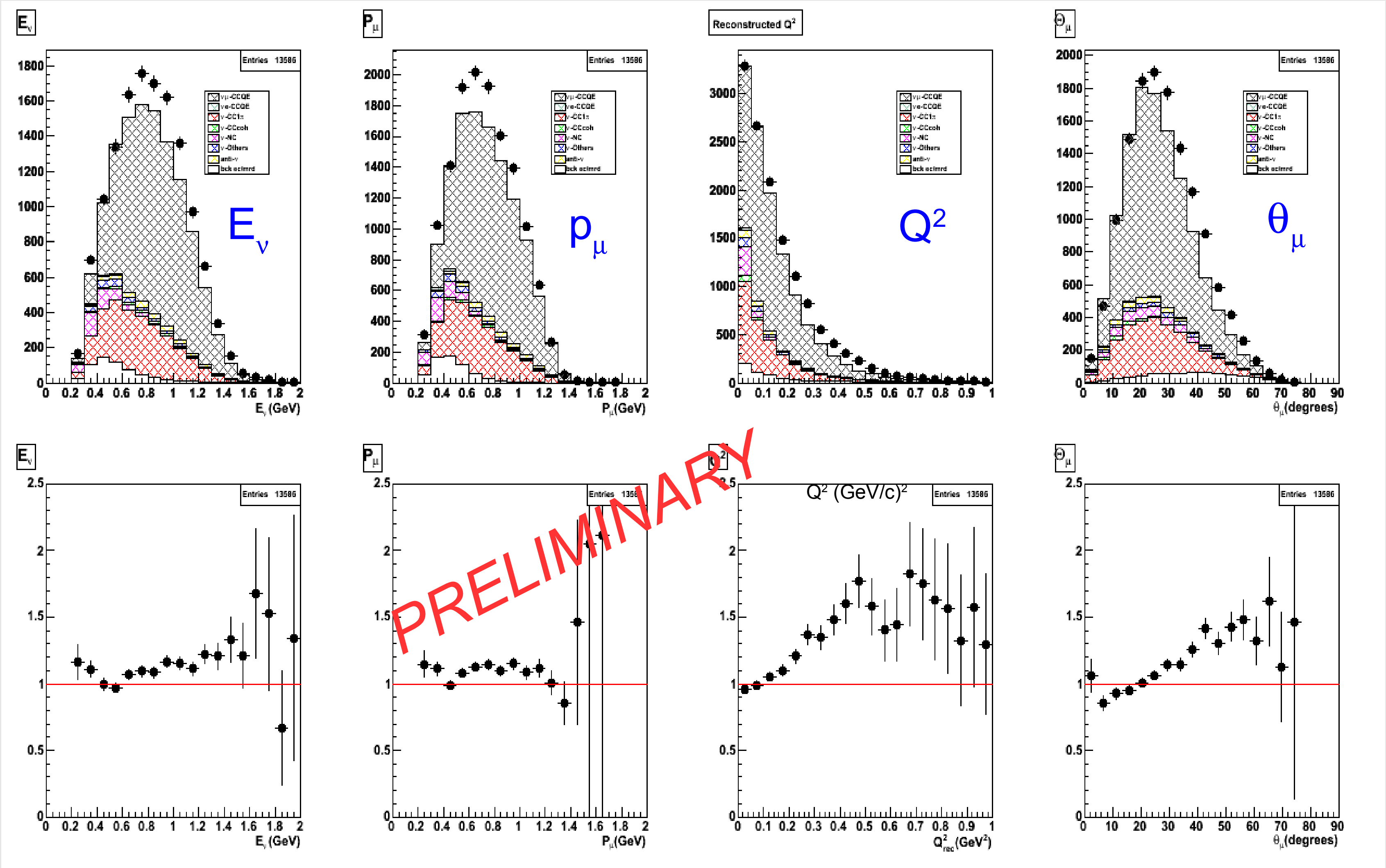
This is the most complete information about neutrino cross section based on muon kinematic measurement.

The error shown here is shape error, a total normalization error (δN_T=10.7%) is separated.



Preliminary CCQE results from SciBooNE

- 1 track (μ) MRD-stopped sample



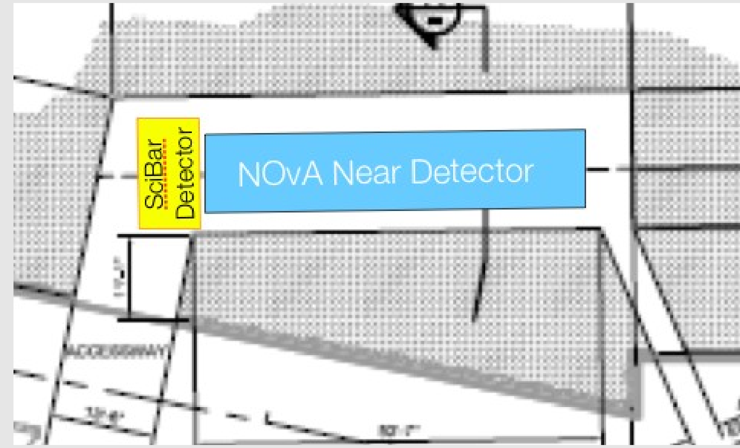
- total measured rate data in excess compared to Neut MC (M_A=1.2GeV)
- excess of data at Q^2>0.2 GeV^2
- both are (qualitatively) similar to MiniBooNE observations

costs and schedule

Estimated costs:

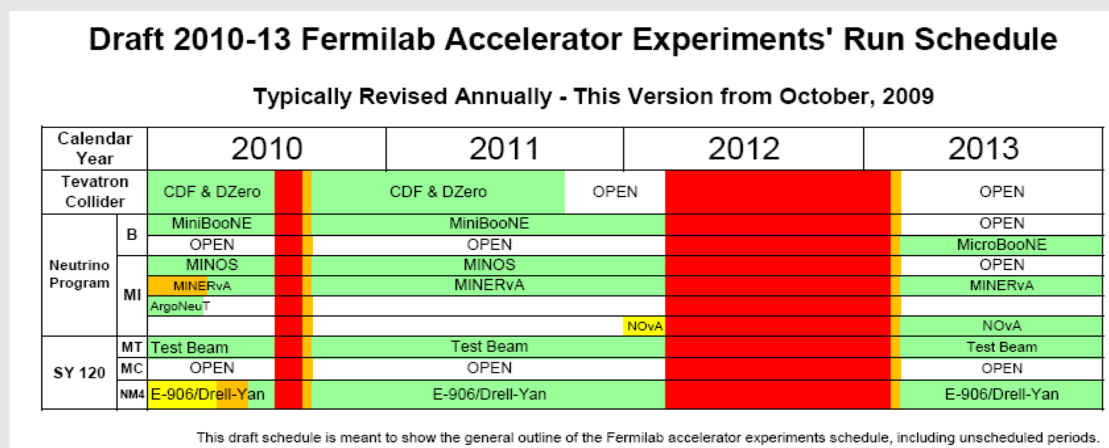
- readout system, equipment: $1.255M
    boards: $775k
    PMTs: 400k
    misc: 80k
- readout system, personnel: $290k
- readout total (w/overhead) $1.75M

- costs of moving detector and associated, TBD.



Schedule:

- 11/09 FNAL support agreed (details TBD)
- 01/10 NSF MRI submission
- 08/10-12/11 PMT/readout procurement/fabrication
- 08/10-12/11 scibar detector move planning, support fabrication
- 01/12-06/12 commissioning, substructure assembly
- 07/12 ready for installation at NOvA near location

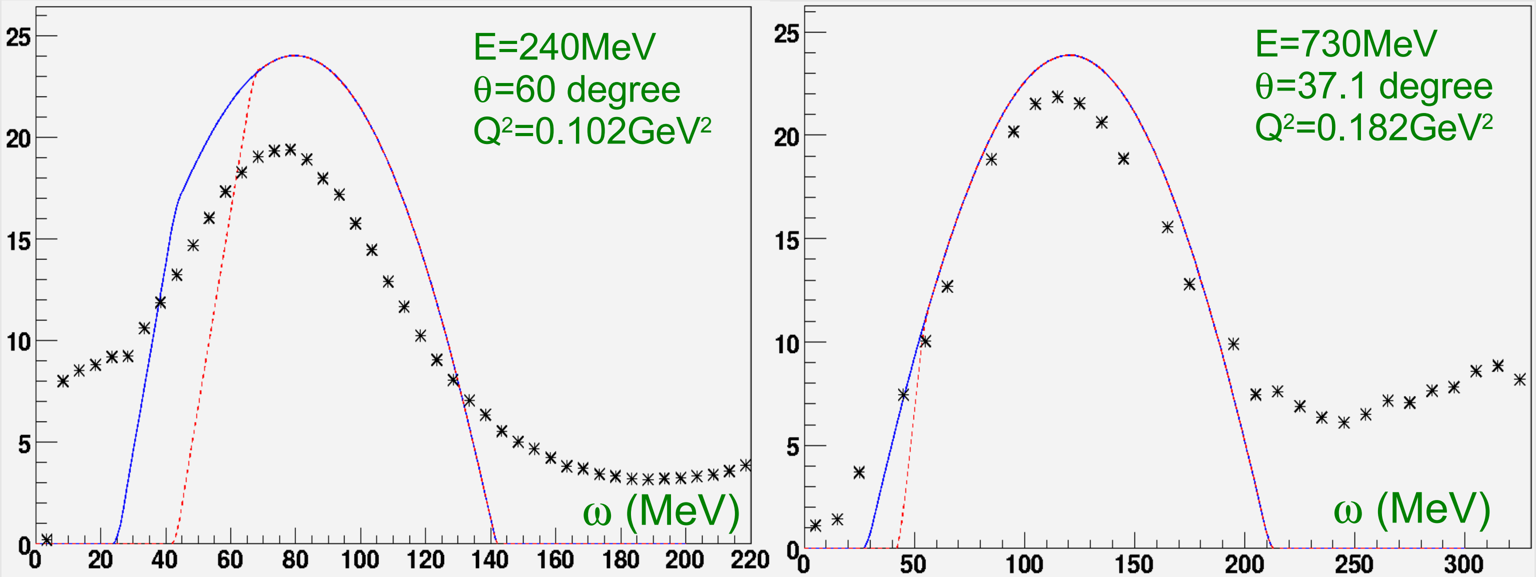


4. Kappa and (e,e') experiments

In low |q|, The RFG model systematically over predicts cross section for electron scattering experiments at low |q| (~low Q^2)

We had investigated the effect of Pauli blocking parameter "κ" in (e,e') data. κ cannot fix the shape mismatching of (e,e') data for each angle and energy, but it can fix integral of each cross section data, which is the observables for neutrino experiments. We conclude κ is consistent with (e,e') data.

black: (e,e') energy transfer data
red: RFG model with kappa (=1.019)
blue: RFG model without kappa



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RFG prediction-(e,e') data ratio in Q^2 (GeV^2)