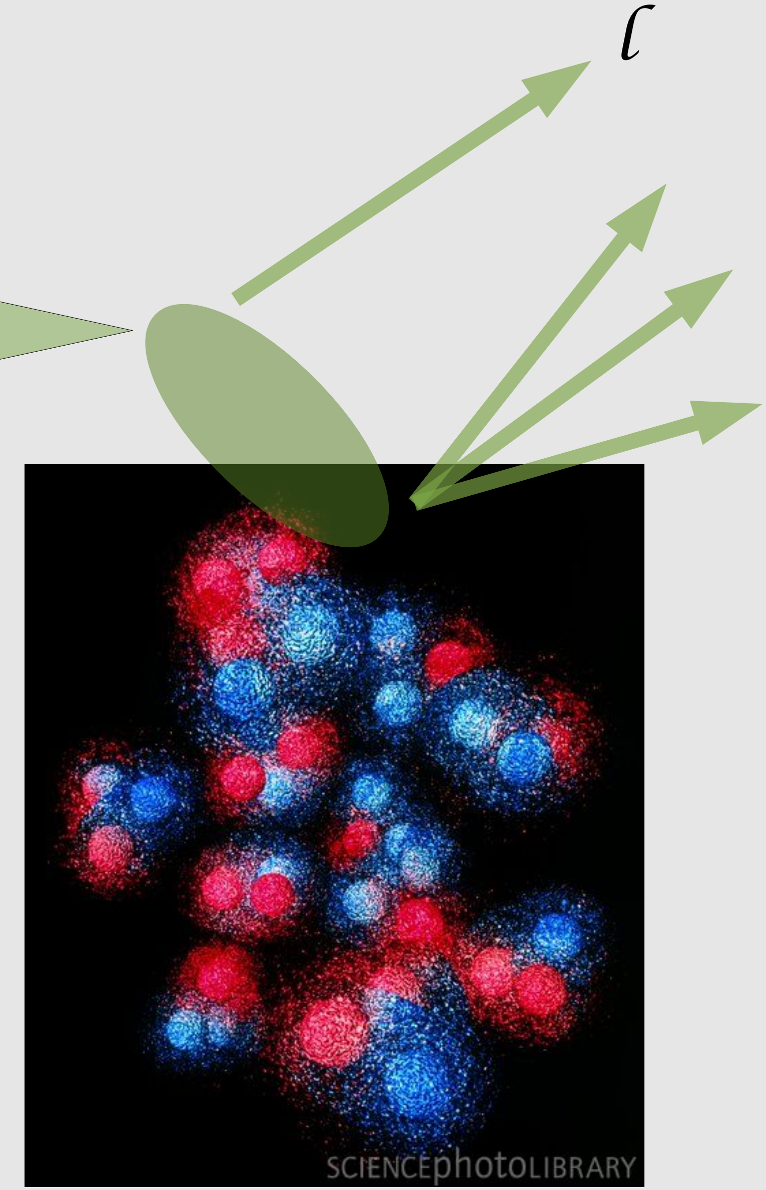
ν–Nucleus scattering: An overview



Outline:
- introduction, motivation
- ν nucleus scattering channels
- past, current, future results
  with interpretations, models
- summary

R. Tayloe, Indiana U.
APS-DPF 2011
Providence, RI, 8/11

Neutrino scattering measurements

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

- for current and future oscillation experiments:
  MINOS, MiniBooNE, T2K, NOvA, LBNE
- especially for *precision* (e.g. 1%) measurements and/or small oscillation probabilities (e.g. 0.1%)

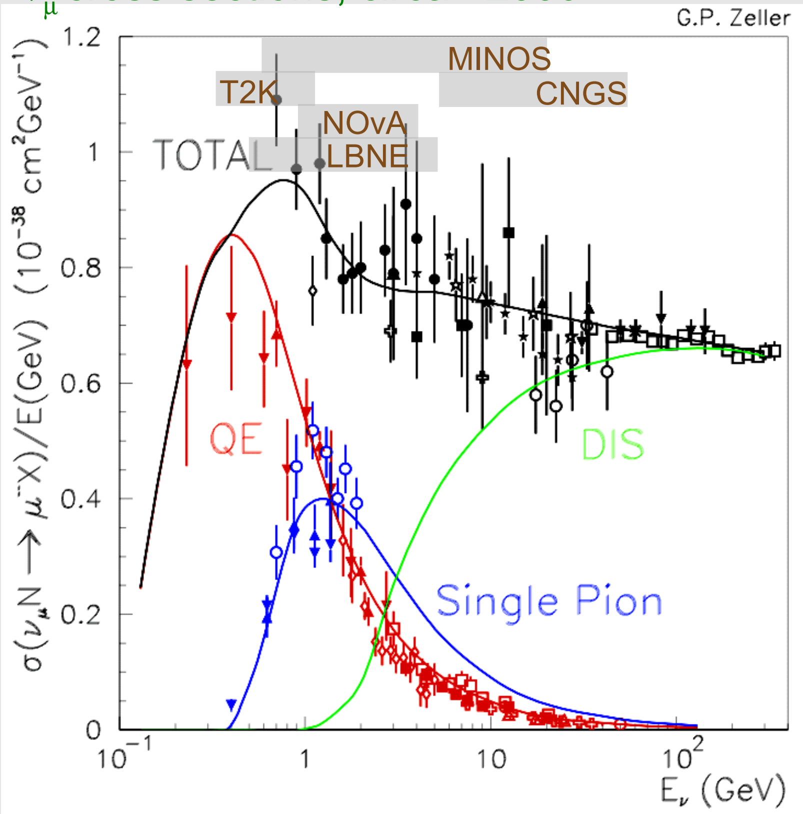
Requires: Precise measurements to enable a complete theory valid over wide range of variables (reaction channel, energy, final state kinematics, nucleus, etc)

A significant challenge with neutrino experiments:

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

Also, there is some interesting physics (independent of oscillations) in these measurements.

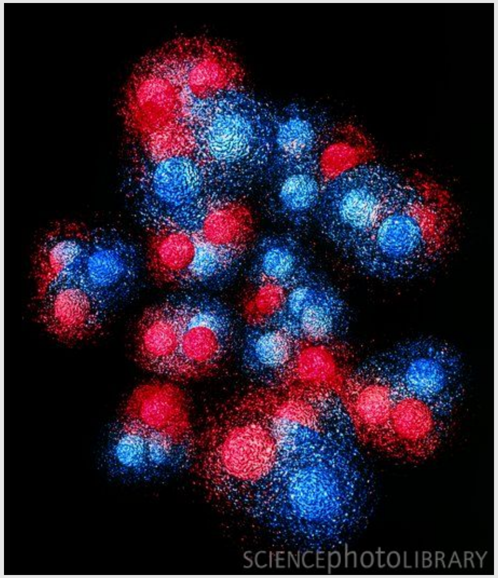
ν_μ cross sections, circa ~2000



Neutrino-*nucleus* scattering

Current and forseen future ν oscillation experiments will use nuclear targets: eg: C, O, Ar

exhibit A: carbon



So an understanding of ν nucleus interactions is crucial.

Recent results seem to be showing that these nuclei are not just a bag of independent nucleons for neutrino scattering...

and are revealing some interesting physics.

These experiments are in the O(1-10GeV) range,
so will focus there.

Neutrino-*nucleus* scattering

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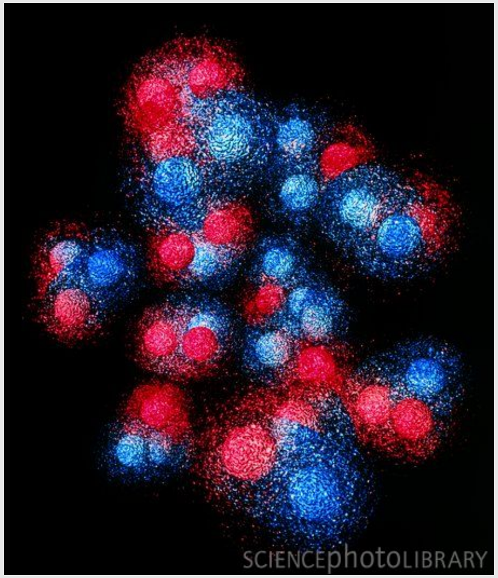

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and are revealing some interesting physics.

These experiments are in the O(1-10GeV) range, so will focus there.

Disclaimers:
1) This is not to say that there is not interesting physics outside of that range:
- on bare nucleons,
- at higher/lower energies

But outside of scope of this talk.

2) In addition, I am on MiniBooNE, SciBooNE, SciNOvA experiments...

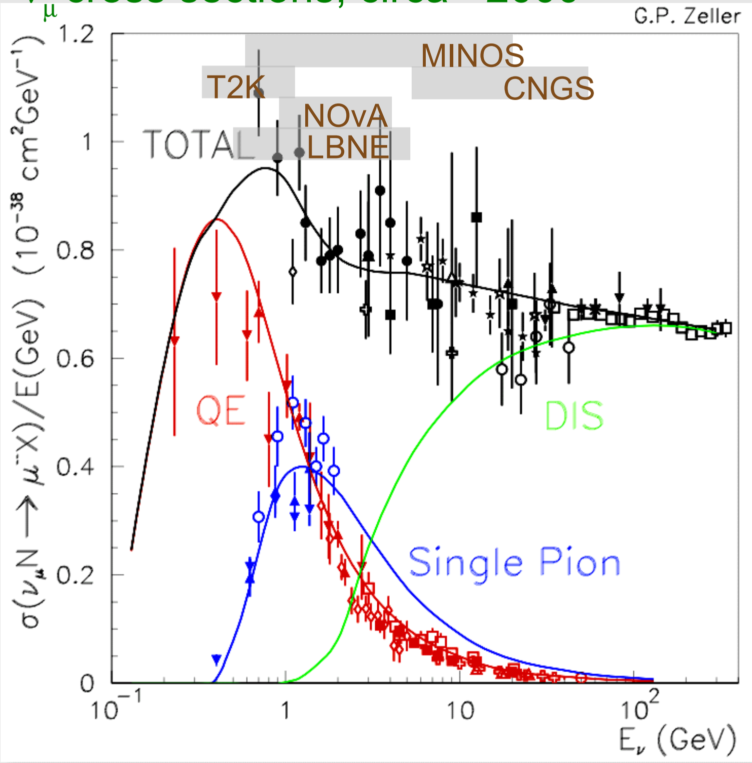
3) Experimental details will be/have been covered in other talks

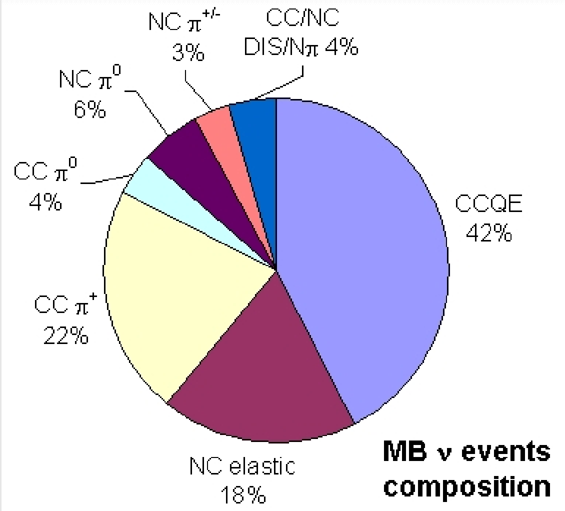
MiniBooNE oscillations Z. Pavlovic friday am

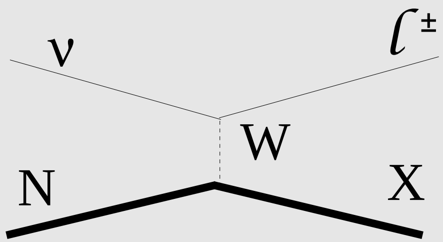
νN interaction channels of interest

- ν charged-current (CC) quasielastic (CCQE)
  - detection and normalization signal for oscillations
  - charged-current axial formfactor
- ν neutral-current (NC) elastic (NCel)
  - predicted from CCQE excepting NC contributions to axial form factor (strange quarks)
- ν CC production of π^+ , π^0
  - background (and perhaps signal) for oscillations
  - insight into models of neutrino pion production via nucleon resonances and via coherent production
- ν CC inclusive scattering
  - should be understood together with exclusive channels
  - ~independent of final state details
- ν NC production of neutral pions
  - very important oscillation background
  - complementary to CC pion production
- ν NC production of photons
  - a possible oscillation background

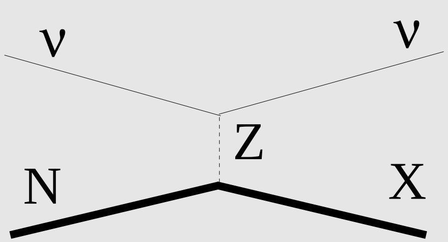
ν_μ cross sections, circa ~2000







"CC":
charged-current



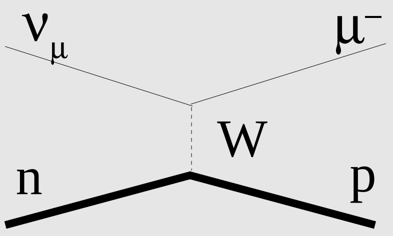
"NC":
neutral-current

CCQE

- ν_μ charged-current (CC) quasielastic (CCQE)
    - most fundamental scattering process in ~1GeV range
    - detection and normalization signal for oscillations
    - charged-current axial formfactor

ν_μ CCQE

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



- Historically, "quasielastic" in "CCQE" comes from high-energy ν experiments where muon mass is negligible.

- But has evolved to mean quasielastic scatting from bare nucleons (lightly?) bound in nucleus. How true is this?

- Careful! Can also imply a final state selection for experiments. Important to consider.
    - eg: in MiniBooNE, QE = muon and no pions, no selection on outgoing nucleons
    - in K2K, QE=muon + proton with QE kinematics

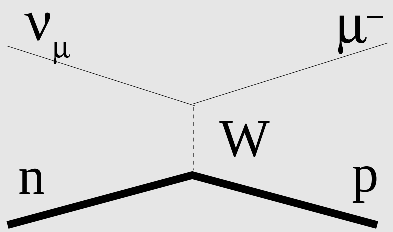
  Can result in different measurements.

If quasielastic is good approximation, should(?) be well-modeled with a relativistic fermi gas model...

modeling ν QE scattering

ν_μ CCQE

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



The canonical model for the ν QE process is fairly simple.
Based on impulse-approximation (IA) with relativistic Fermi gas (RFG).

- start with Llewellyn-Smith formalism for differential cross section:

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

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

- To apply (for a nucleus, such as carbon)
  - assume bound but independent nucleons (IA)
  - use Rel. Fermi Gas (RFG) model (typically Smith-Moniz), with params from e-scattering
  - F_1,F_2 also from e-scattering measurements
  - F_A is largest contribution, not well known from e scattering, but
  - F_A (Q^2=0) = g_A known from beta-decay and
  - 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 (1 parameter if you want to fit for M_A)

- can be used for prediction of CCQE rates and final state particle distributions (eg: Q^2)

- Until fairly recently, this approach has appeared adequate and all common (current) neutrino event generators use a model like this..

Summary of M_A from CCQE scattering

- M_A values extracted from various experiments

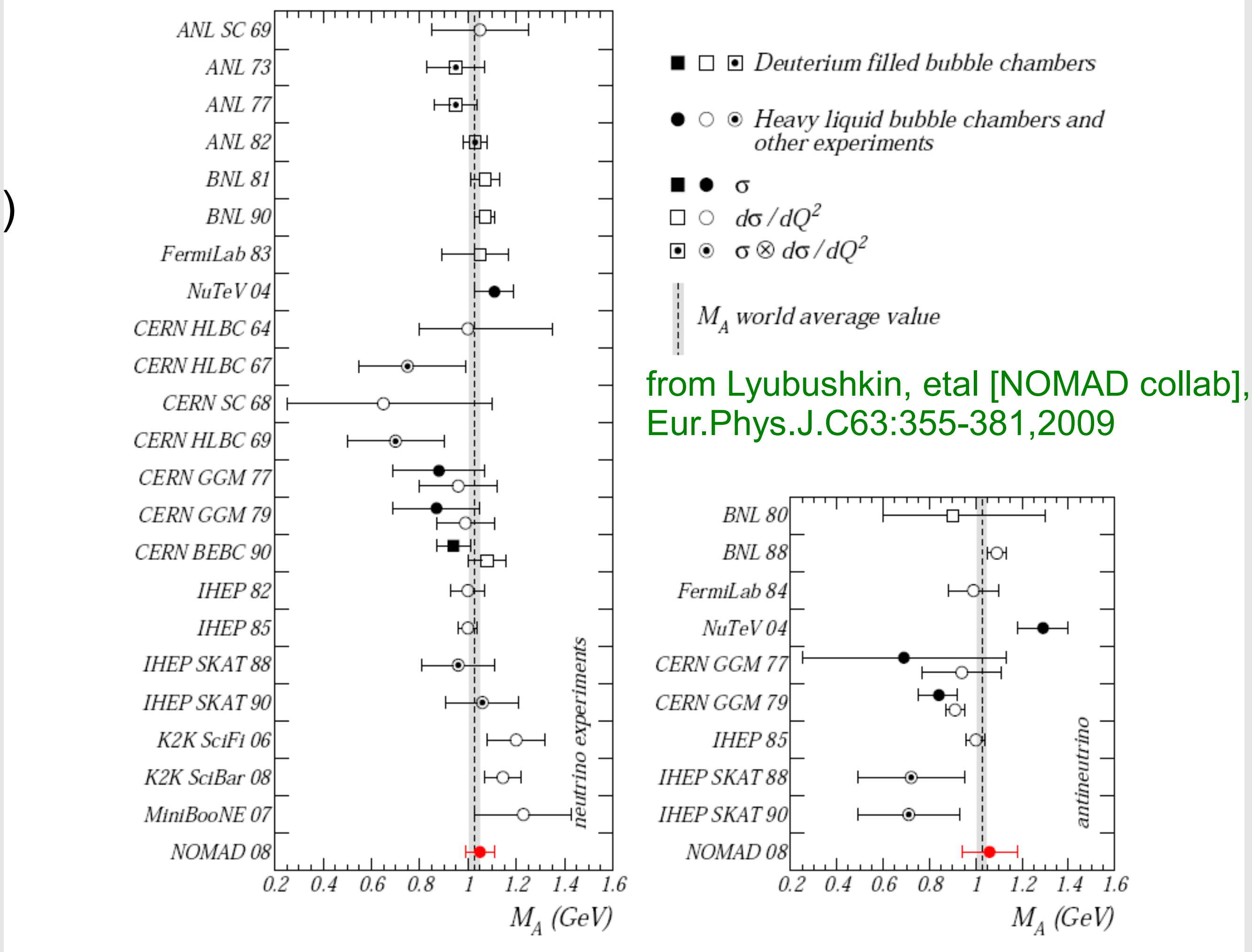
- different targets/energies, fit strategies

- world average (as of 2002)
  M_A=1.026±0.021 GeV
  (Bernard, etal, JPhysG28, 2002)

- Also, M_A from π electro-production similar

- However, recent data from some high-stats experiments (on nuclear targets) not well-described with this M_A . (or perhaps... the physics model).

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



from Lyubushkin, etal [NOMAD collab], Eur.Phys.J.C63:355-381,2009

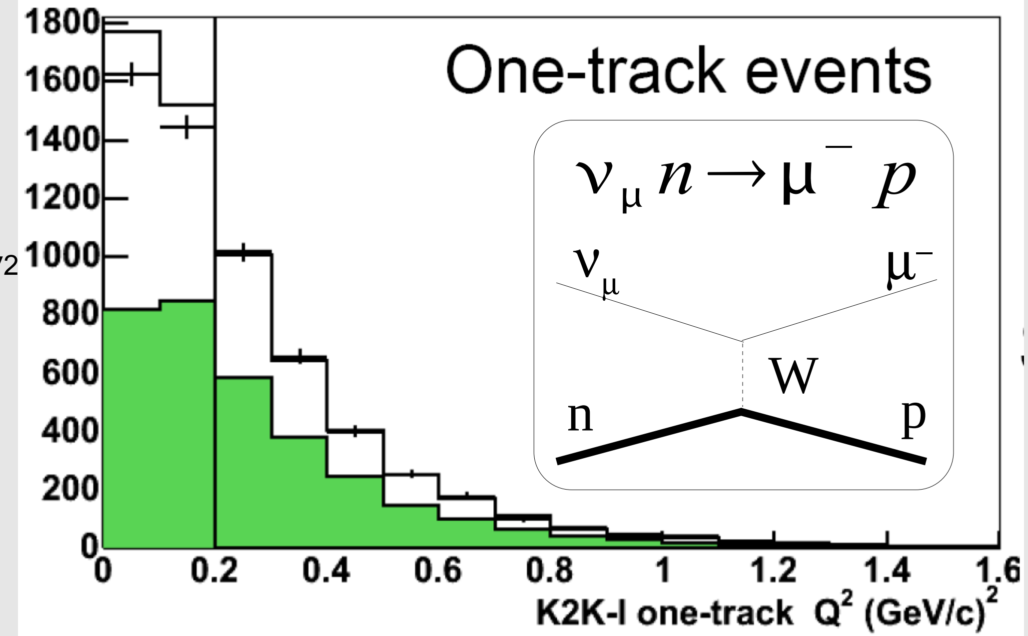
Fig. 18. A summary of existing experimental data: the axial mass M_A as measured in neutrino (left) and antineutrino (right) experiments. Points show results obtained both from deuterium filled BC (squares) and from heavy liquid BC and other experiments (circles). Dashed line corresponds to the so-called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

K2K CCQE results

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

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

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



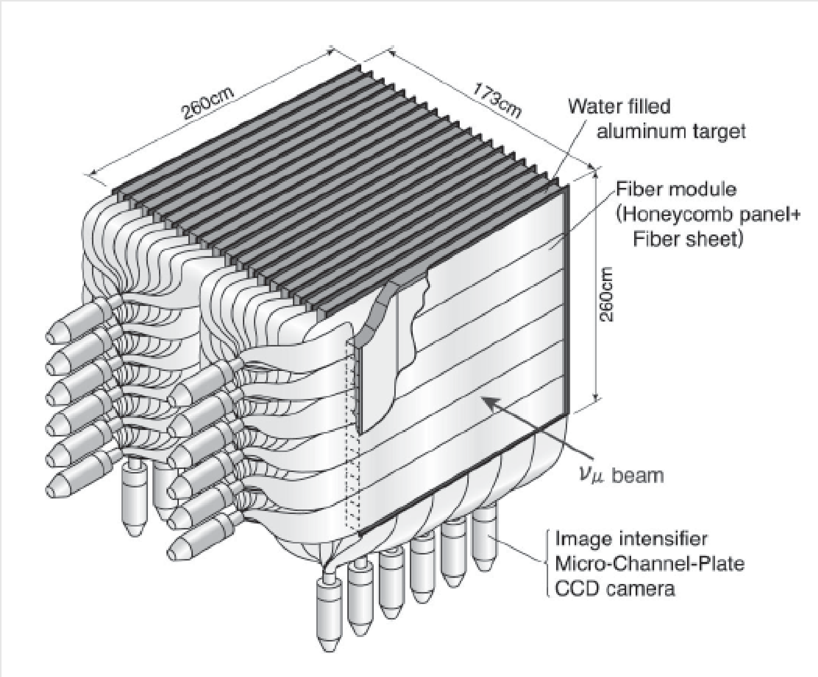
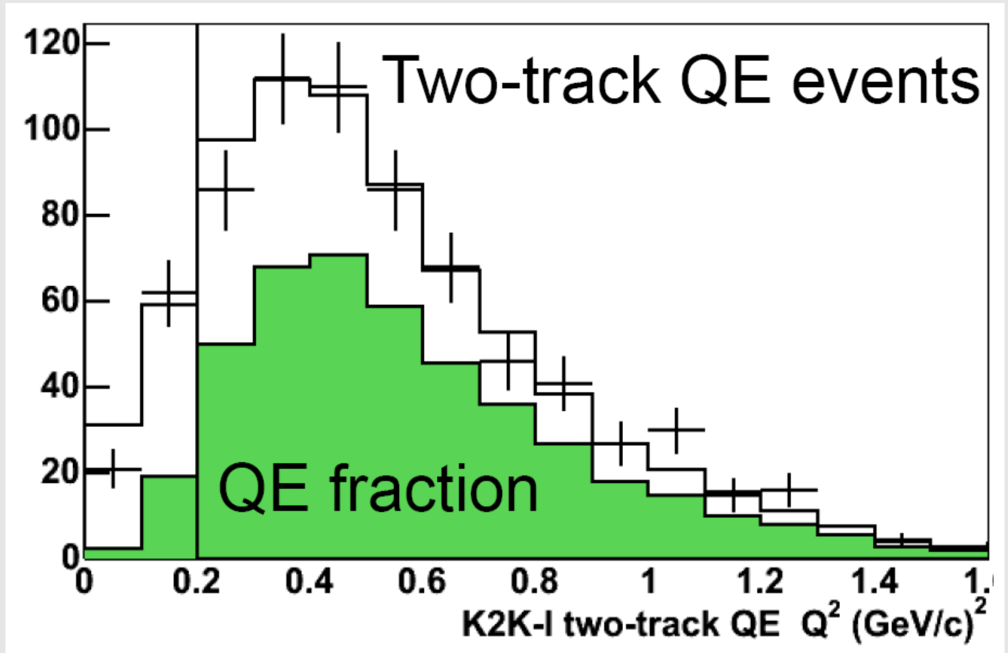


FIG. 2. A schematic diagram of the SciFi detector.

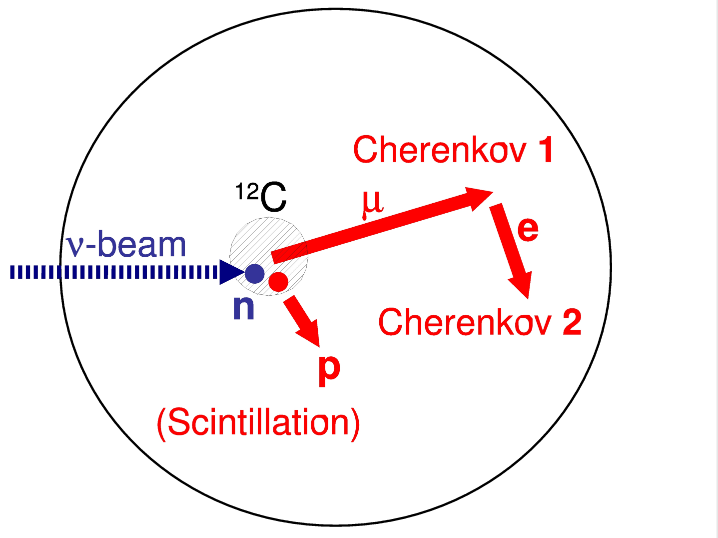


from Rik Gran, Nuint09

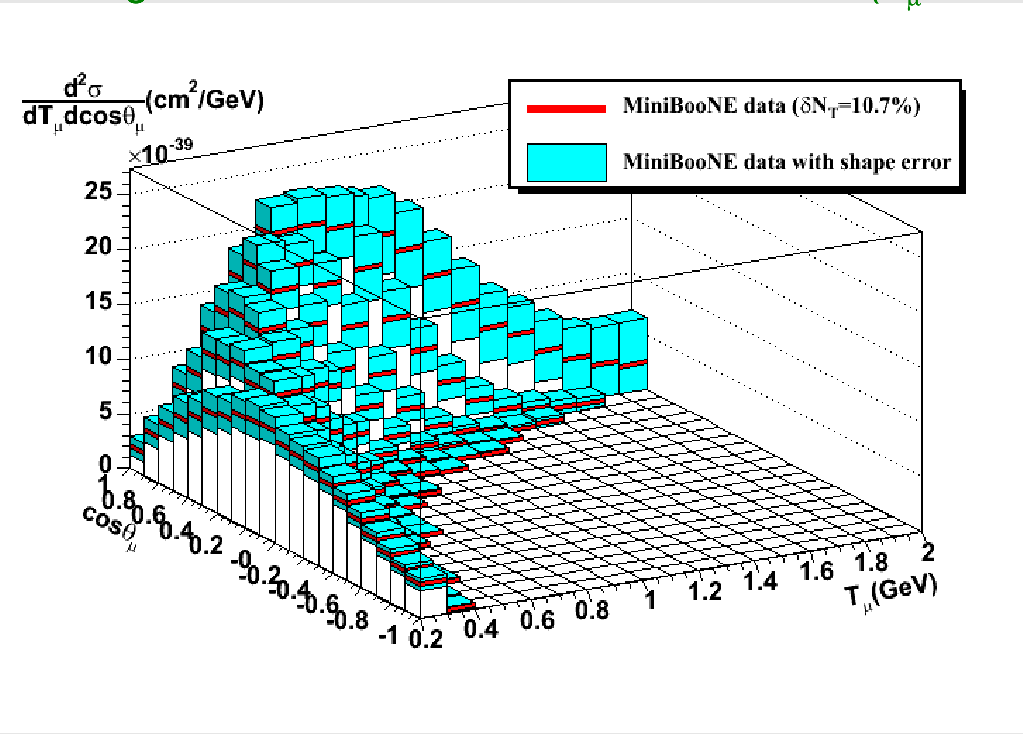
MiniBooNE CCQE results

- CCQE scattering from carbon (in CH_2)
- experimental definition: 1 μ^- , no π
    - μ used for all observables
    - practically no sensitivity to recoil nucleons
- first results showed larger M_A (=1.25±0.12 GeV)
  (PRL100, 0323021, '08)
- full analysis reports absolutely norm'd, model-independent differential cross sections
  (T. Katori thesis, PRD81, 092005, '10)

CCQE in MiniBooNE



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



MiniBooNE ν flux

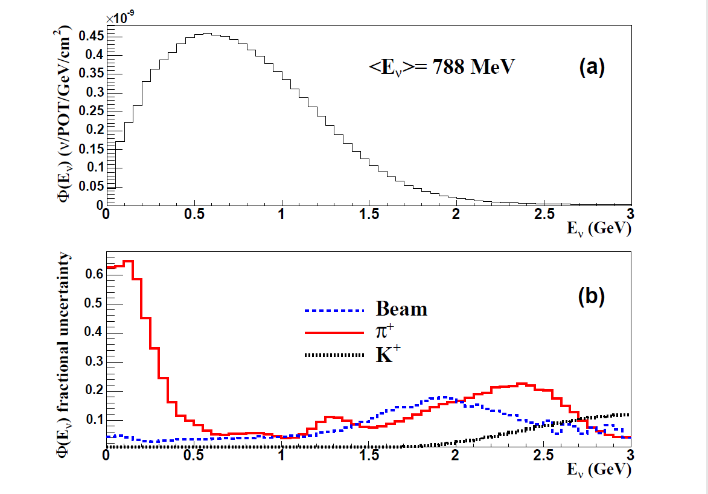


FIG. 2: (color online) Predicted ν_μ flux at the MiniBooNE detector (a) along with the fractional uncertainties grouped into various contributions (b). The integrated flux is 5.16×10^{-10} ν_μ/POT/cm^2 ($0 < E_\nu < 3$ GeV) with a mean energy of 788 MeV. Numerical values corresponding to the top plot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

MiniBooNE CCQE results

More cross sections:

- M_A from shape fit
  M_A= 1.35 ± 0.17 GeV

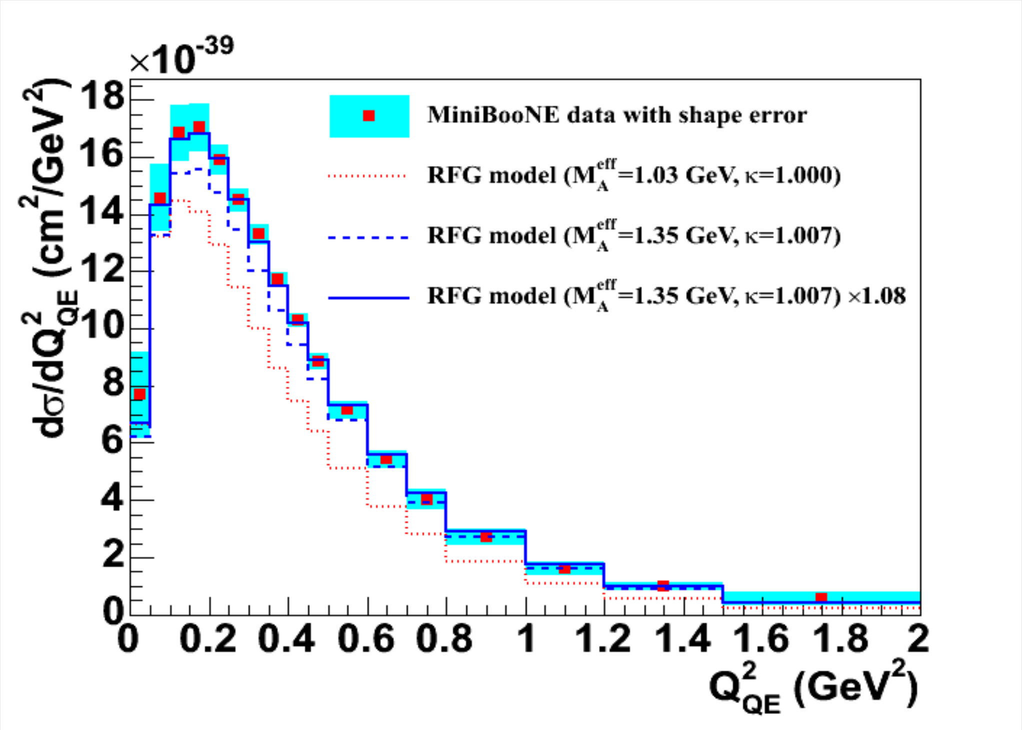
- data is compared (absolutely) with CCQE (RFG) model with various parameter values

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

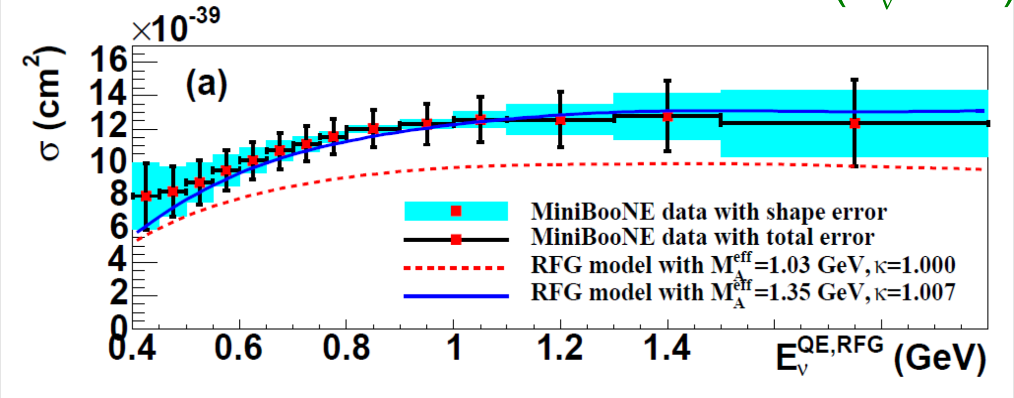
- model with our CCQE parameters (extracted from *shape-only* fit) agrees well with over normalization (to within normalization error).

- M_A~1.35 GeV descibes data in both Q^2 shape and total cross section (within RFG model), coincidence?

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



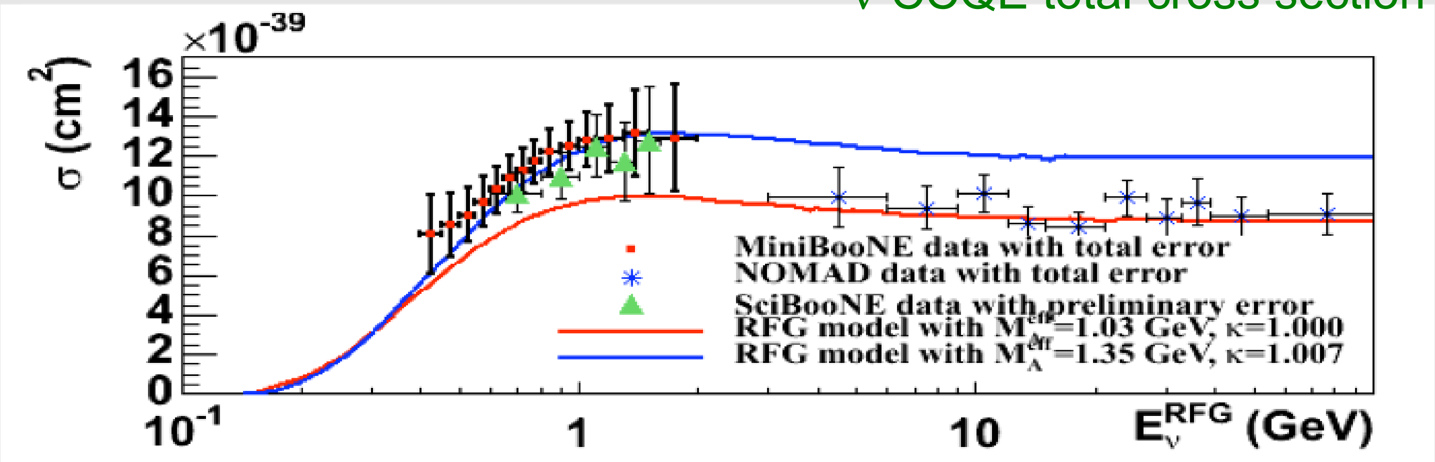
Flux-unfolded total cross section ($E_\nu^{QE,RFG}$)



more CCQE results

- SciBooNE:
  - (M. Wascko, thursday am)
  - fine-grained scintillator detector in FNAL booster neutrino beam (as MiniBooNE)
  - results agree with MiniBooNE

ν CCQE total cross section



- NOMAD:
  - wire chamber detector at CERN, mostly carbon target, 3-100 GeV
  - in agreement with "world-average" M_A …. !??
- MINOS:
  - Fe target, ~5GeV
  - yields larger M_A (~1.2 ± 0.1 ± 0.1 GeV) consistent with MiniBooNE, SciBooNE, K2K

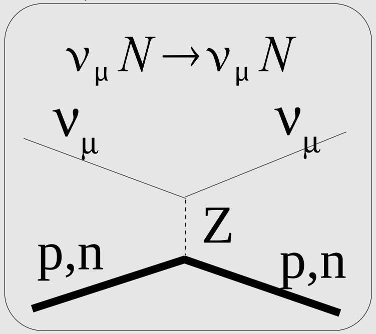
MiniBooNE NC elastic results

differential cross section:

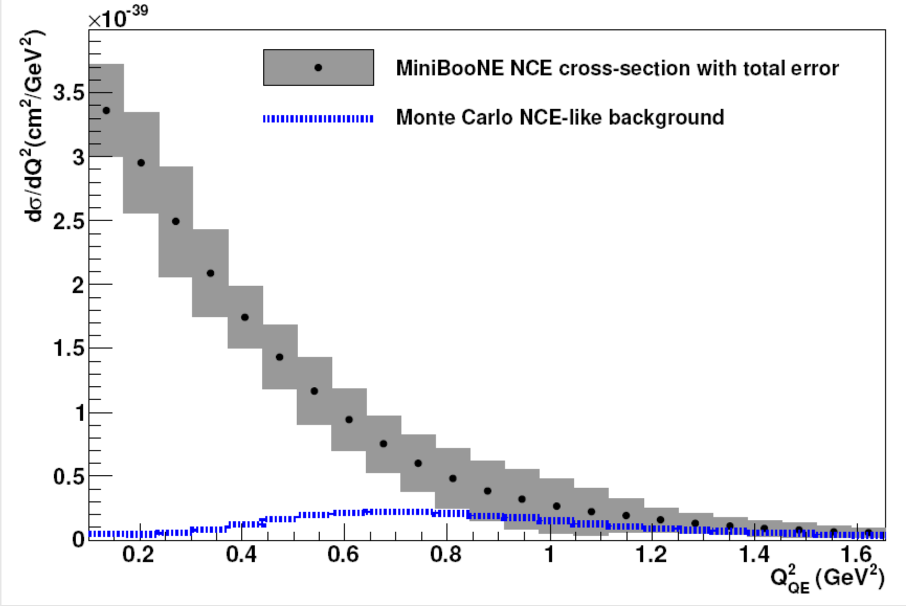
- from an absolute fit to proton KE distribution

- $M_A = 1.39 \pm 0.11$ GeV

ν_μ NC elastic



NCel differential cross section

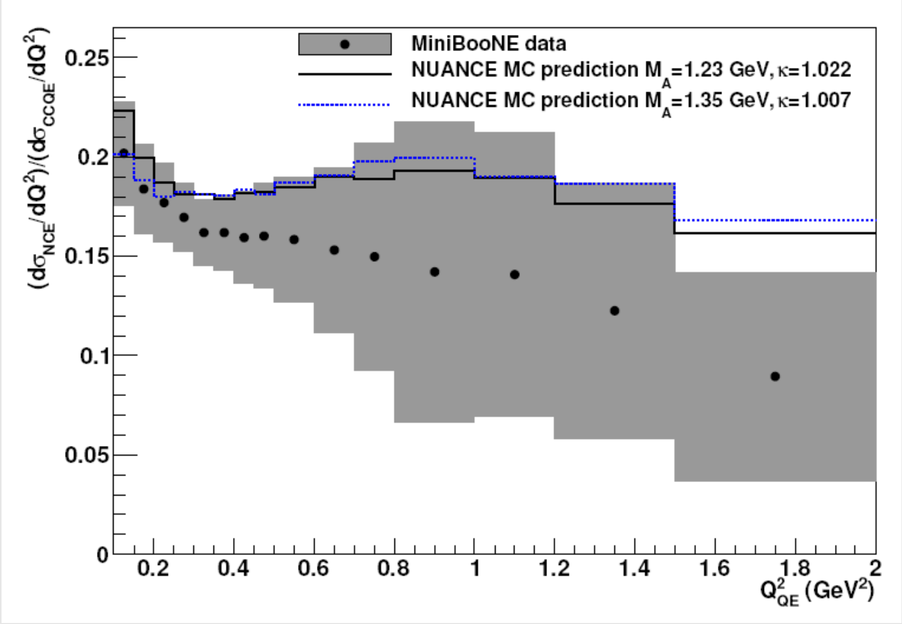


NCel to CCQE differential cross section ratio:

- flux error cancels between the 2 channels

- ratio is consistent with RFG model. So no discrepency in NCel compared to CCQE

NCel to CCQE differential cross section ratio



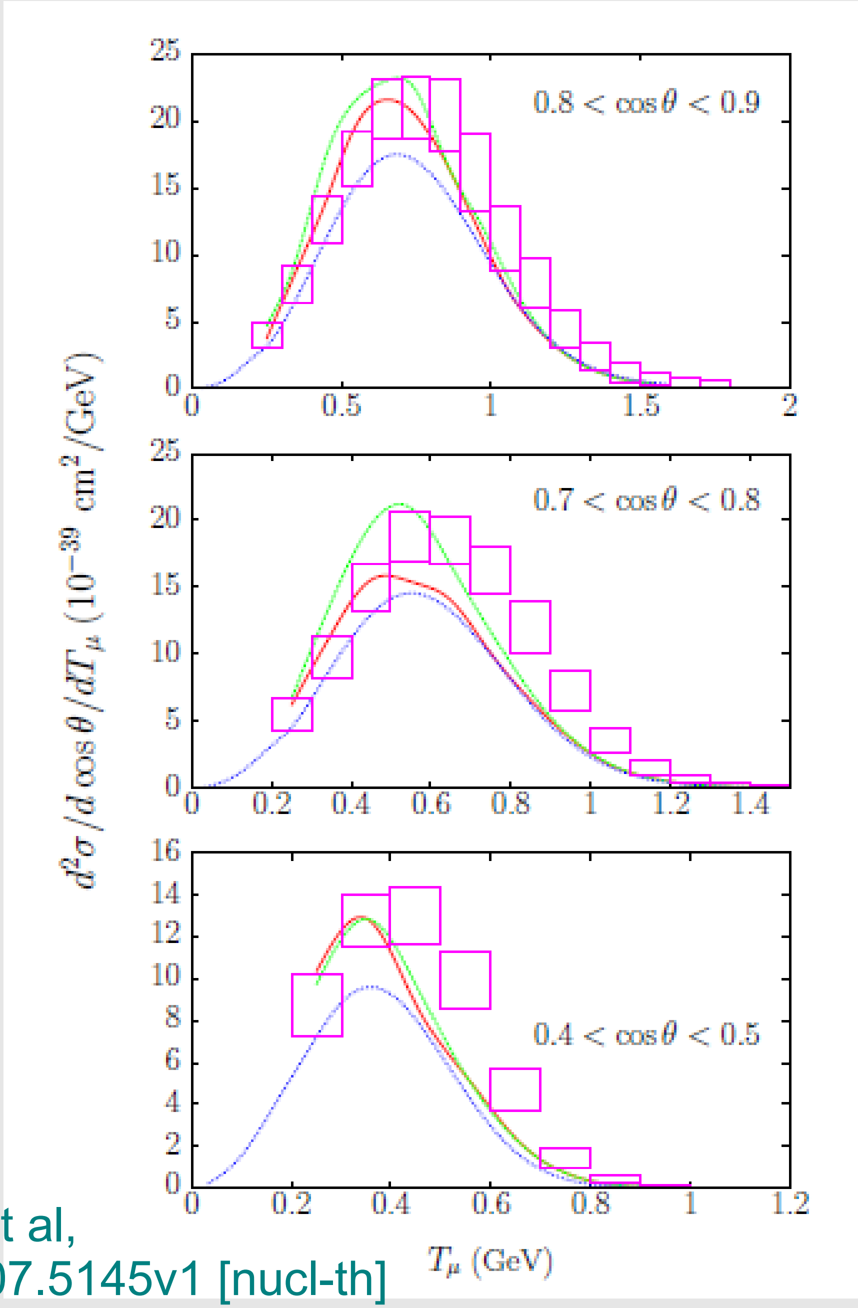
models for ν QE scattering

These interesting new results have generated much theoretical interest recently:

Nieves et al., arXiv:1106.5374 [hep-ph]
Bodek et al., arXiv:1106.0340 [hep-ph]
Amaro, et al., arXiv:1104.5446 [nucl-th]
Antonov, et al., arXiv:1104.0125
Benhar, et al., arXiv:1103.0987 [nucl-th]
Meucci, et al., Phys. Rev. C83, 064614 (2011)
Ankowski, et al., Phys. Rev. C83, 054616 (2011)
Nieves, et al., Phys. Rev. C83, 045501 (2011)
Amaro, et al., arXiv:1012.4265 [hep-ex]
Alvarez-Ruso, arXiv:1012.3871[nucl-th]
Benhar, arXiv:1012.2032 [nucl-th]
Martinez, et al., Phys. Lett B697, 477 (2011)
Amaro, et al., Phys. Lett B696, 151 (2011)
Martini, et al., Phys. Rev C81, 045502 (2010)

- for example

model comparison to MiniBooNE CCQE

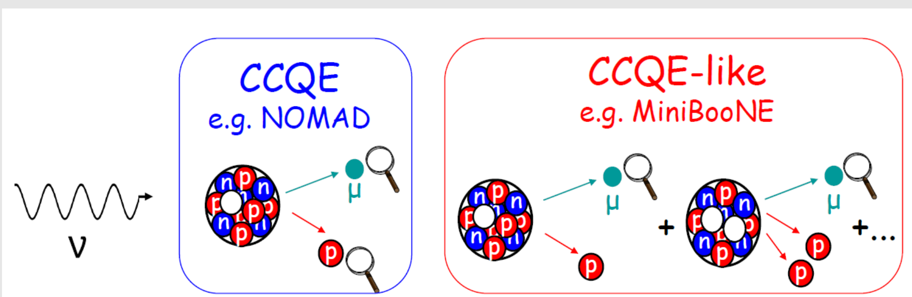


Meucci et al, arXiv:1107.5145v1 [nucl-th]

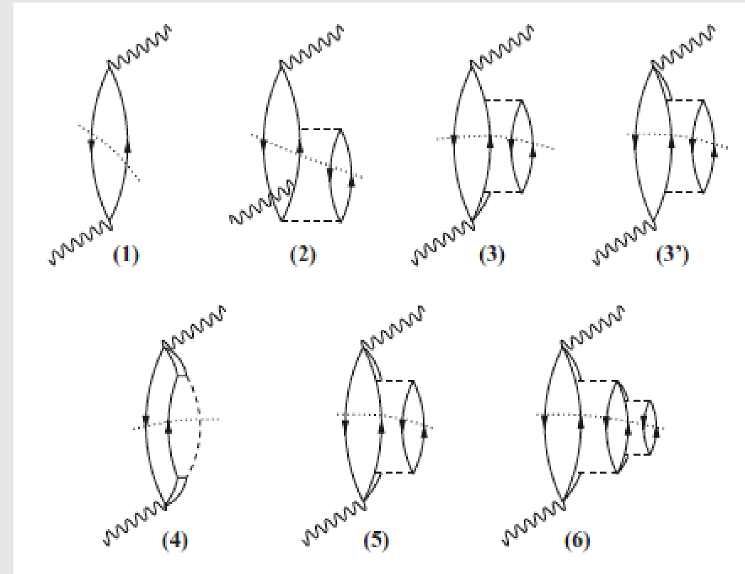
models for ν QE scattering

An interesting idea has emerged...

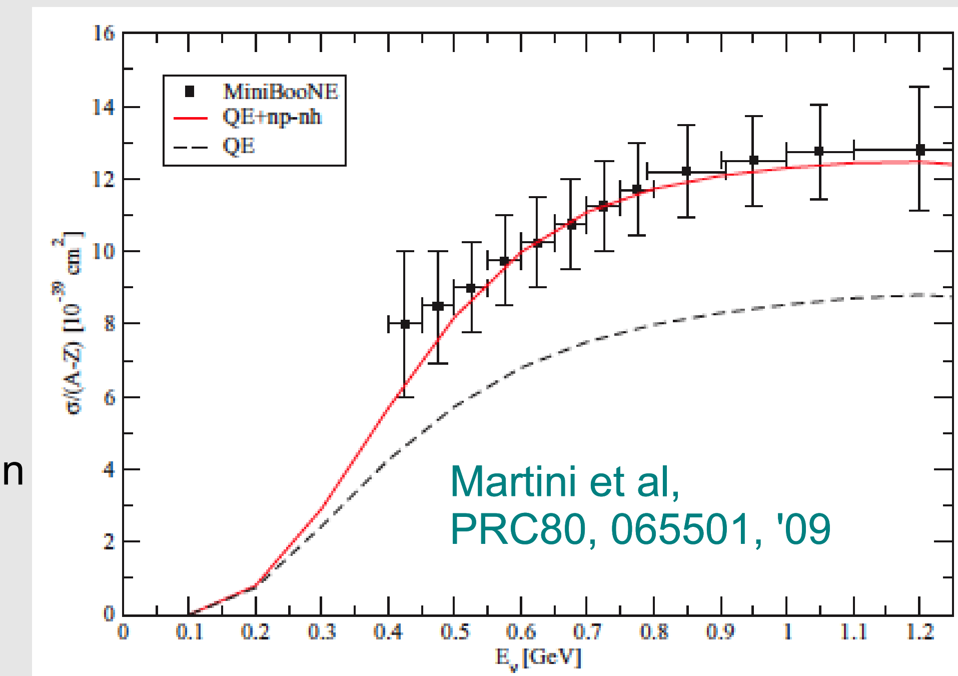
- Perhaps extra "strength" in CCQE from multi-nucleon correlations within carbon (Martini et al PRC80, 065501, '09)
- Related to neglected "transverse" response in noted in electron scattering? (Carlson etal, PRC65, 024002, '02)
- Expected with nucleon short range correlations (SRC) and 2-body exchange currents
- and perhaps related to different CCQE selections, eg:



- Note: may effect neutrino energy reconstruction in oscillation experiments!



CCQE total cross section

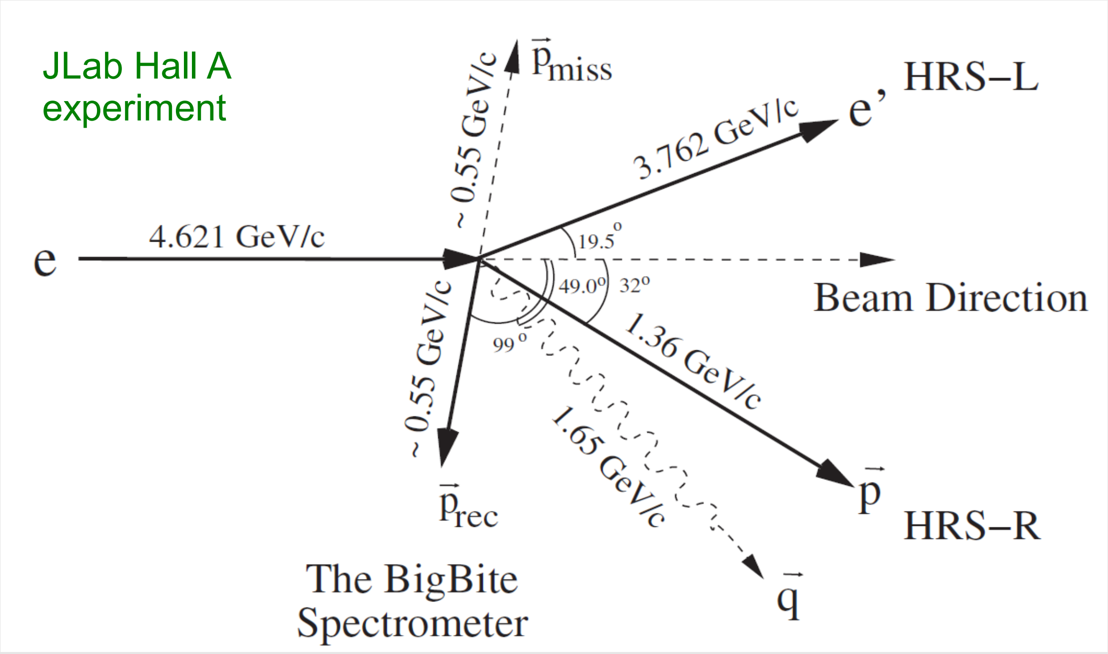


CCQE scattering and 2-N correlations

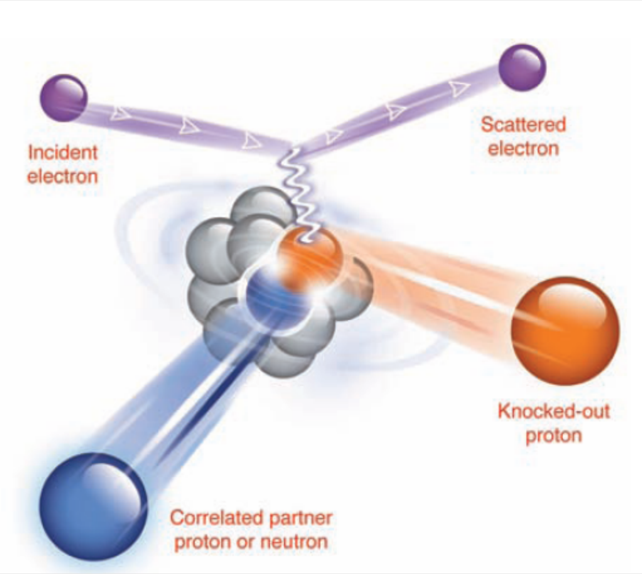
- Recent results from e-scattering suggest 20% of nucleons in carbon are in a "SRC state"
(R. Subedi etal, Science, 320, 1476 (2008))

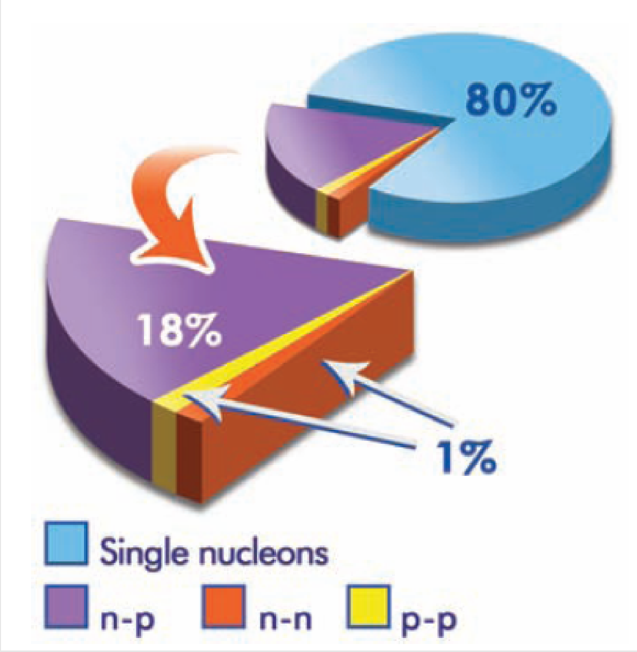
- This effect should result in distinguishable final states of multiple recoil nucleons.

- Can/should be experimentally tested, ala e-scattering:



(see SciNOvA talk, X. Tian, thurs am).





CCQE scattering outlook: 2-N correlations

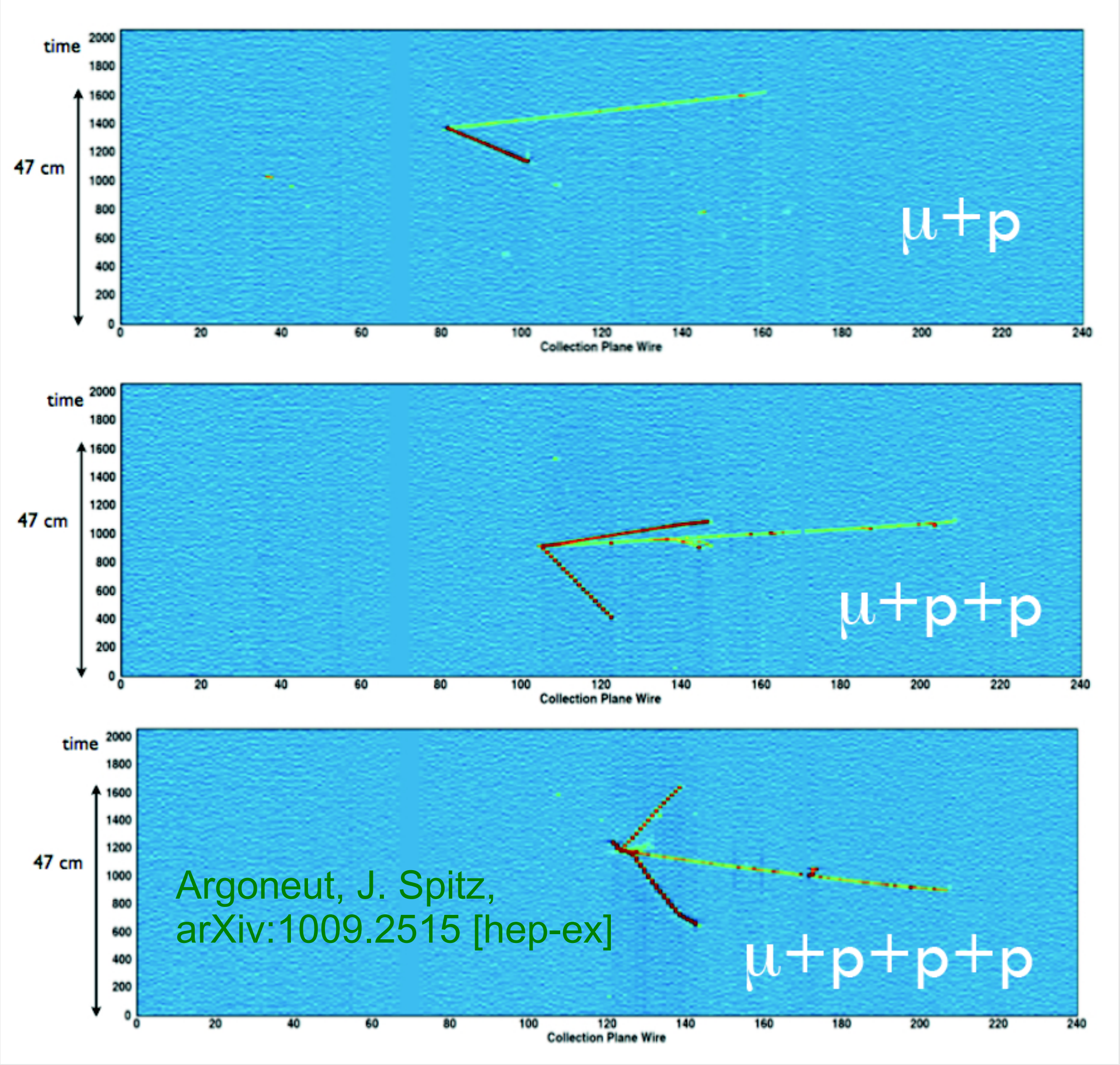
- 2N correlations deserve further experimental work..

- microBooNE should be able to observe on argon

- as should a number of fine-grained detectors, eg: MINERvA, T2K, SciNOvA

- more on
  ArgoNeut:
  R. Guenette, friday pm;
  MicroBooNE:
  C. Ignarra, friday pm.

Argoneut event displays



Argoneut, J. Spitz, arXiv:1009.2515 [hep-ex]

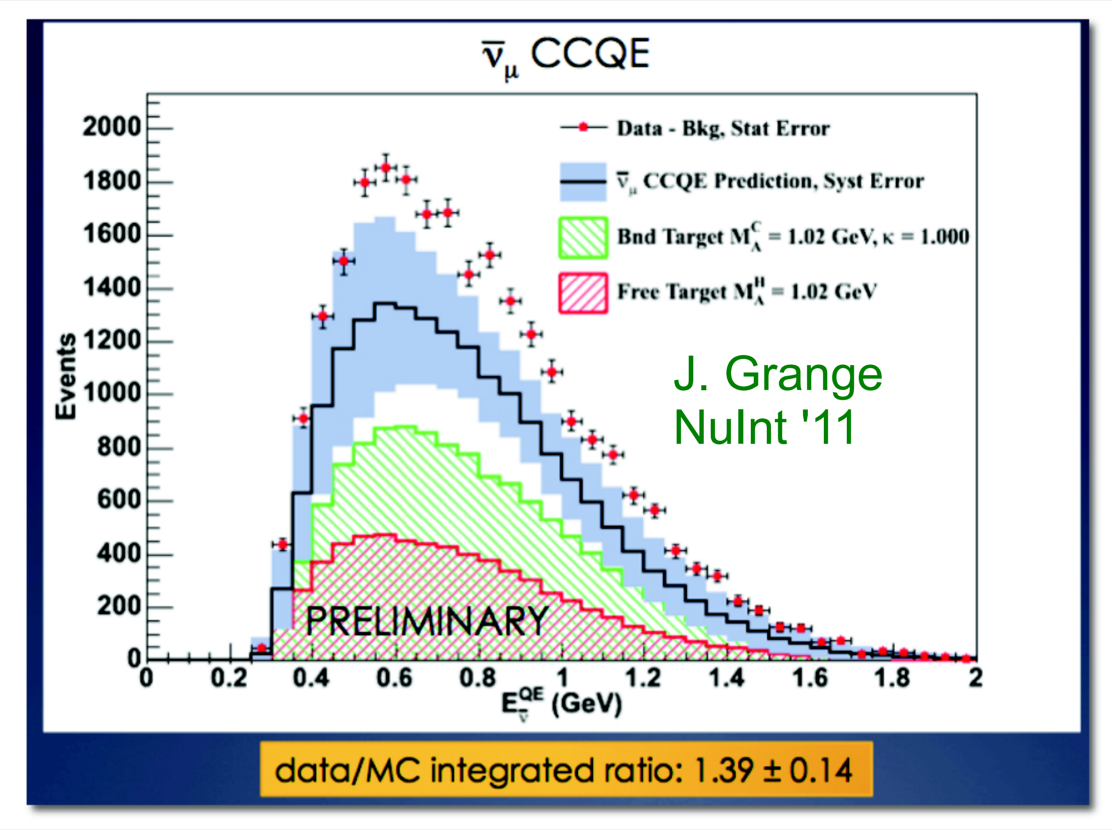
CCQE outlook: $\bar{\nu}$ CCQE

If 2N final states are distinguishable, then interference of amplitudes will be different than that predicted by RFG:

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

Study of $\bar{\nu}$ CCQE may show this.

MiniBooNE $\bar{\nu}$ CCQE and NCel coming soon..



CCQE outlook: $\bar{\nu}$ CCQE

MINERVA: $\bar{\nu}$ CCQE

MINERvA will also (soon!) produce CCQE results to add further info

- and T2K

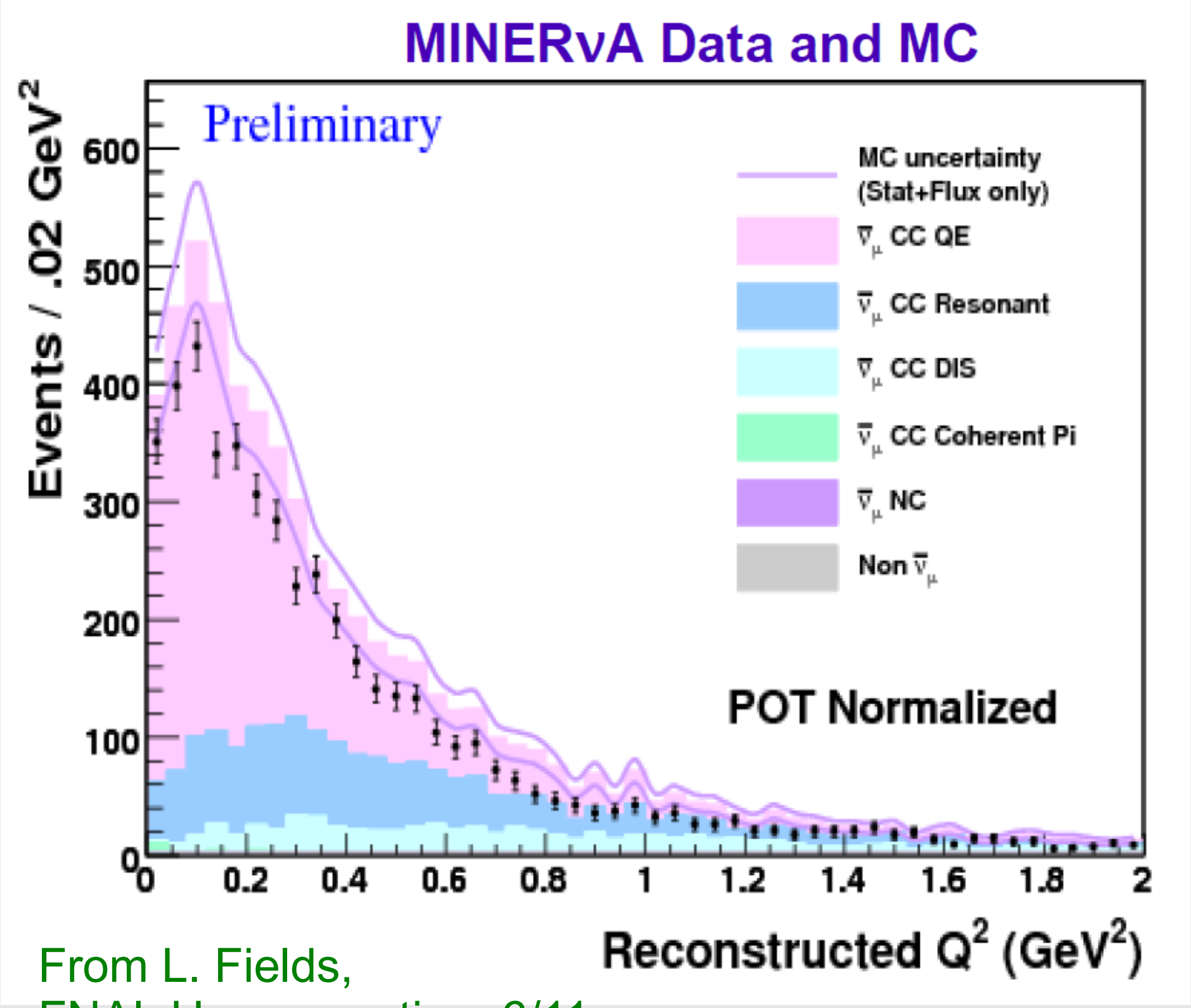
- In different beam (than MiniBooNE/ SciBooNE)

- with fine-grained detector

- in model-independent, absolutely normed, differential cross sections (hopefully!)

- more from MINERvA:
  A. Mcgowan,B. Osmanov, wed pm.

- and T2K:
  B. Kirby, D. Beznosko, wed pm.



From L. Fields,
FNAL Users meeting, 6/11

CCπ production

– ν CC production of π^+, π^0

- background (and perhaps signal) for oscillations
- insight into models of neutrino pion production via nucleon resonances and via coherent production
- may also feed into "CCQE-like" events

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

- $CC\pi^+$/CCQE ratio measured in MiniBooNE (Phys. Rev. Lett. 103, 081801 (2009))

- $CC\pi^+$/CCQE ratio in agreement with model.

- So $CC\pi^+$ rate (cross section) is also larger than expected.

- In both FSI corrected/uncorrected samples

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

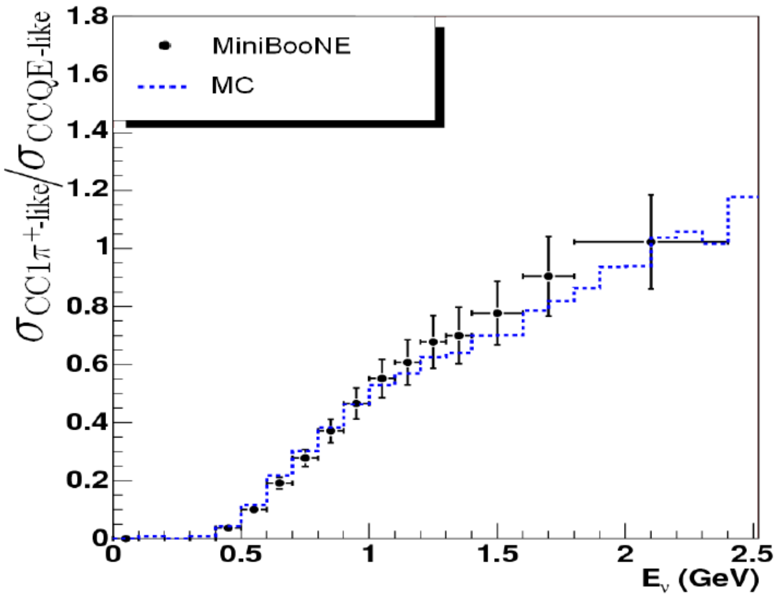


FIG. 1: Observed $CC1\pi^+$-like/CCQE-like cross section ratio on CH_2, including both statistical and systematic uncertainties, compared with the MC prediction [6]. The data have not been corrected for hadronic re-interactions.

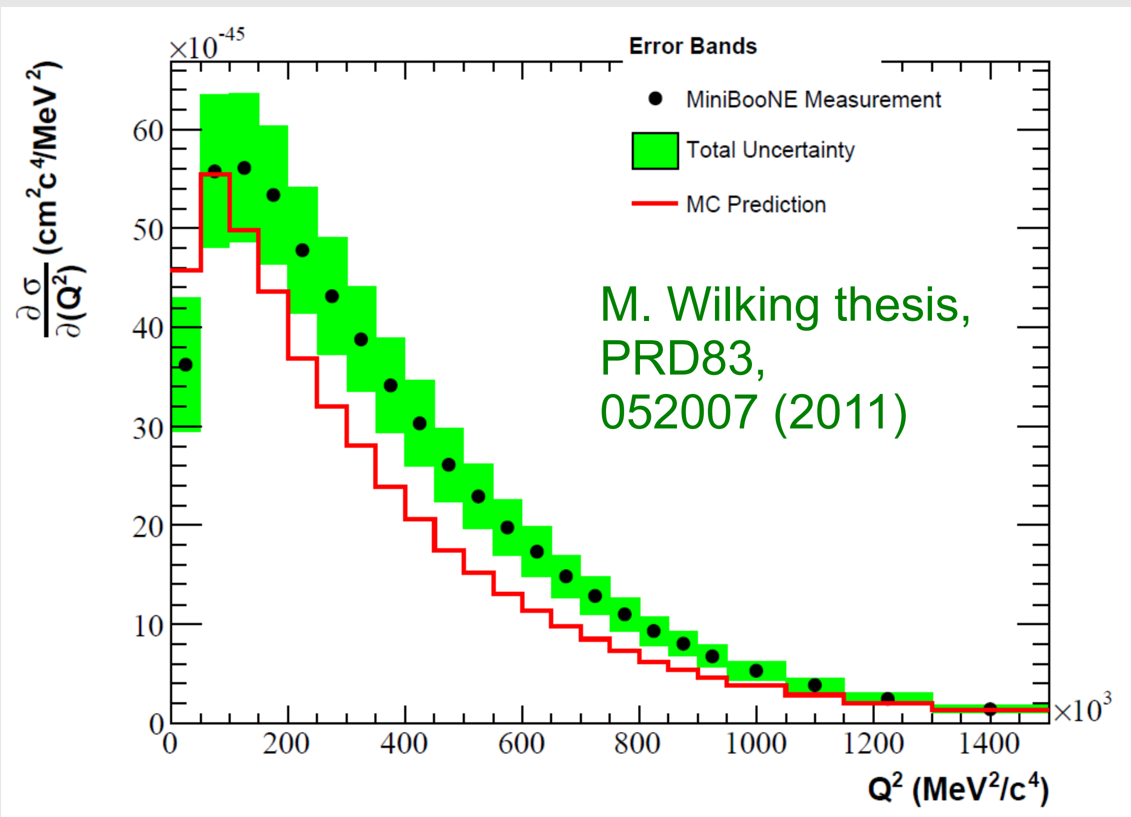
CCπ production

$CC\pi^+$, π^0 differential cross sections from MiniBooNE:

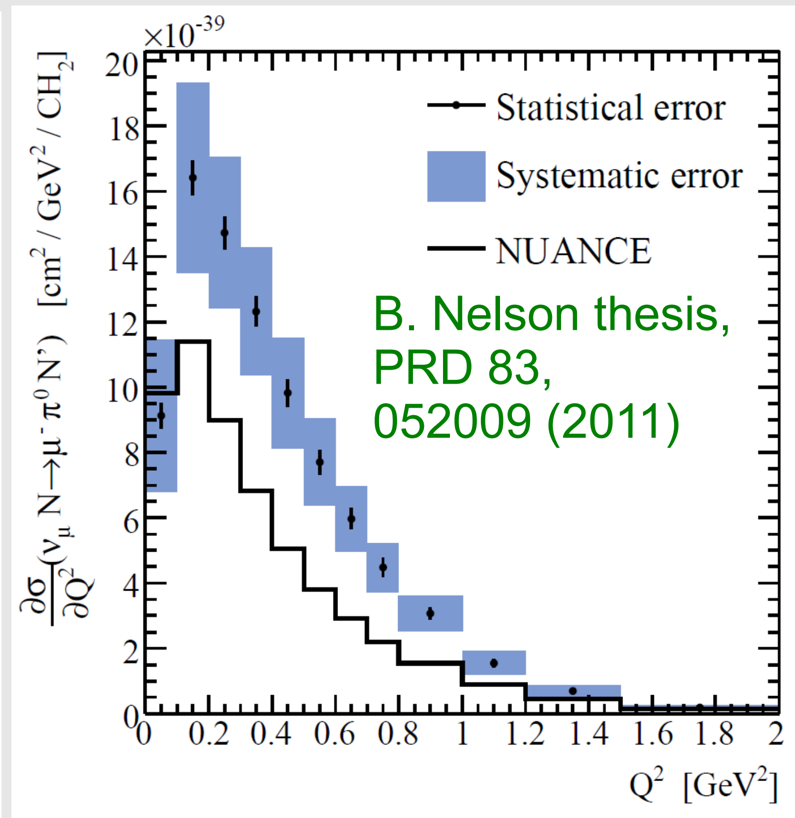
$$\nu_\mu + p(n) \rightarrow \mu + \Delta^{+(+)} \rightarrow \mu + p(n) + \pi^+$$
$$\nu_\mu + A \rightarrow \mu + A + \pi^+$$

- in a variety of kinematic variables
- model independent, absolutely norm'd
- will guide models of pion production including coherent piece (also from SciBooNE, see Waskco talk)

$CC\pi^+$ differential cross sections



$CC\pi^0$ differential cross section

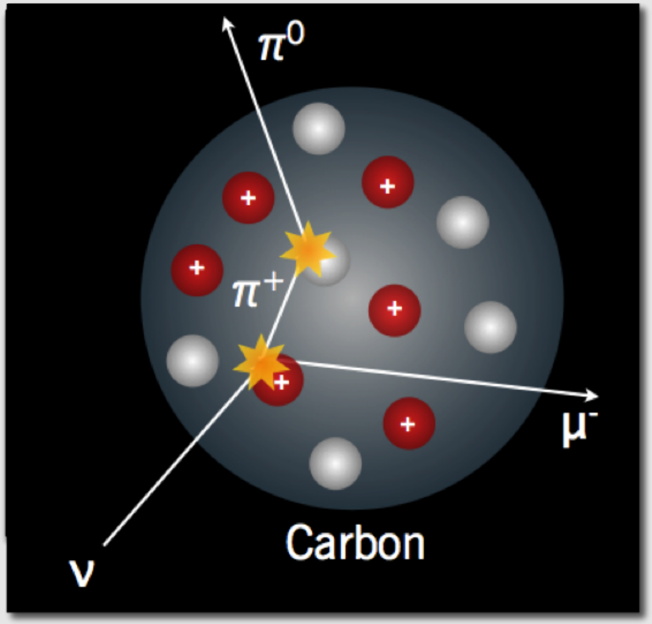


CCπ production

CCπ^+ coherent production results from SciBooNE:
- *Phys.Rev.D78, 112004 (2008)*
- more from Wascko, thurs

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

Outlook:
- upcoming results from : MINERvA, T2K, MicroBooNE
- fine-grained detectors should be able to say more about coherent/non-coherent/FSI pieces with information on event vertex



CC inclusive

$$\nu_\mu N \rightarrow \mu^- X$$

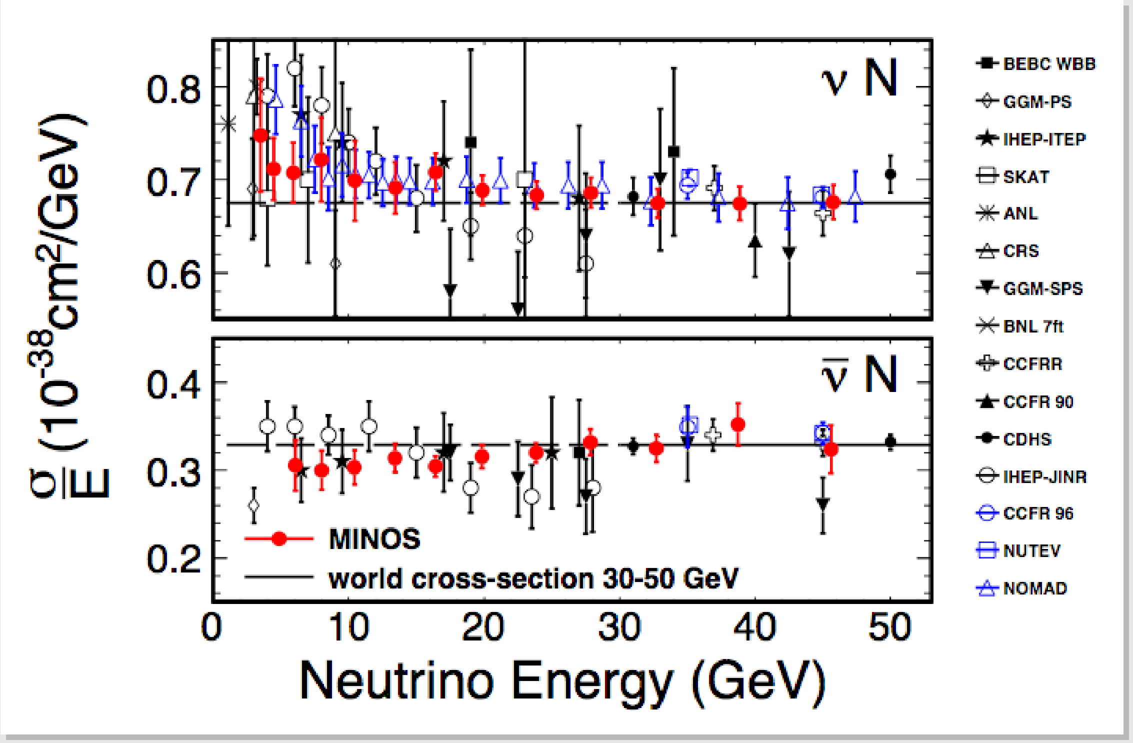
– ν CC inclusive scattering
    - should be understood together with exclusive channels
    - ~independent of final state details

- includes DIS channel, more important at higher energies (>5 GeV).

- recent SciBooNE result (see SciBooNE talk)

- recent MINOS, NOMAD data have increased data quality in this energy region

ν CC inclusive cross section



NOMAD: (ν 12C), 4.5<Eν<230 GeV, PLB 660 19 (2008)
MINOS: (ν,ν 56Fe), 3.5<Eν<45 GeV, PRD 81, 072002 (2010)

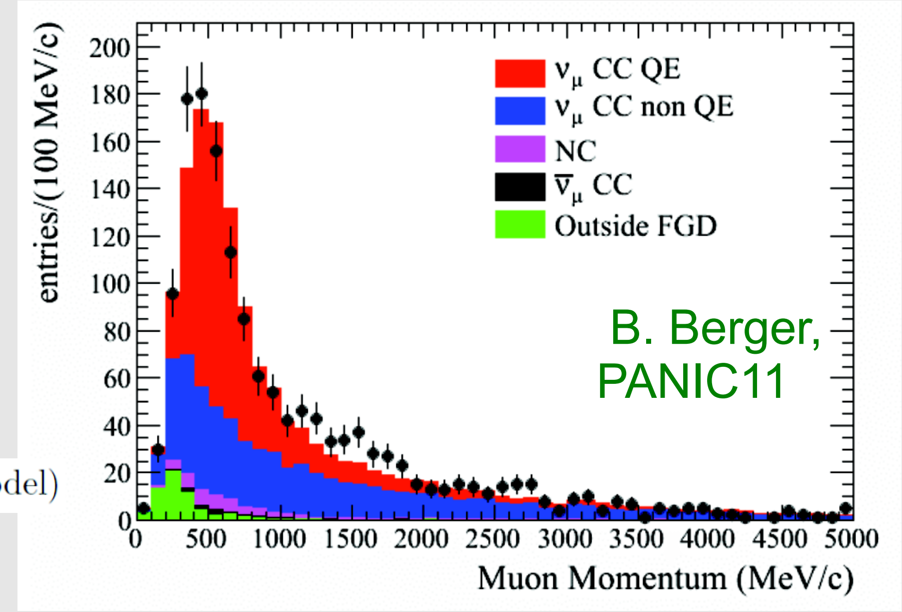
CC inclusive: outlook

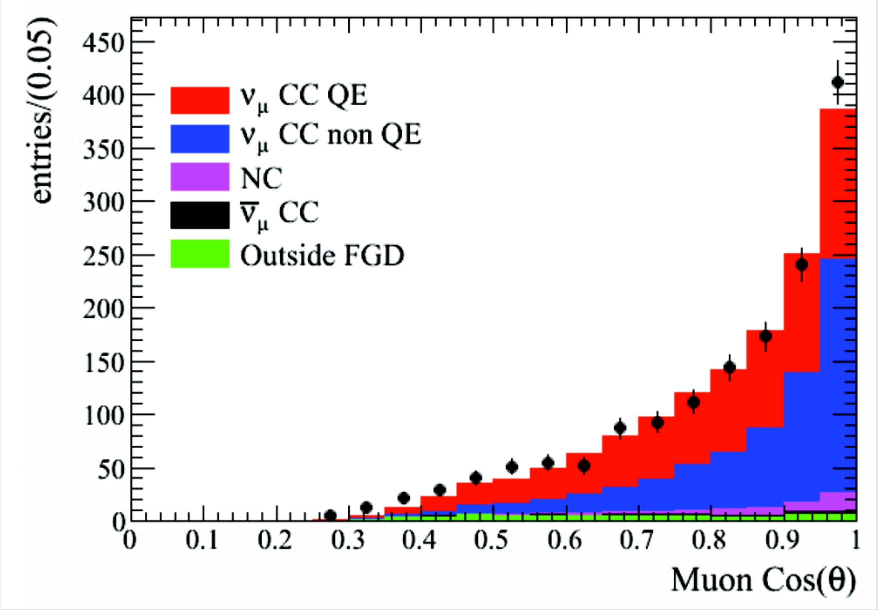
T2K CC inclusive distributions

- upcoming results from T2K on carbon, oxygen

- reported data/MC ratio show that data understood (as well as flux)

$$R_{\mathrm{data/MC}} = 1.036 \pm 0.028(\mathrm{stat.})^{+0.044}_{-0.037}(\mathrm{det.\ sys.}) \pm 0.038\ (\mathrm{phys.\ model})$$





- also MINERvA results on C, Pb, Fe will lead to scaling laws with nucleus

NCπ^0 production

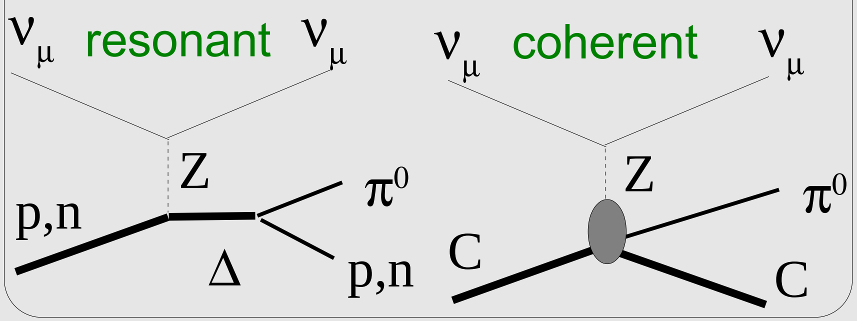
- ν NC production of neutral pions
  - very important oscillation background
  - complementary to CC pion production
  - sizable coherent piece

- MiniBooNE has produced differential cross section on NCπ^0 production, used to constrain oscillation search background

- and SciBooNE results (see SciBooNE talk)

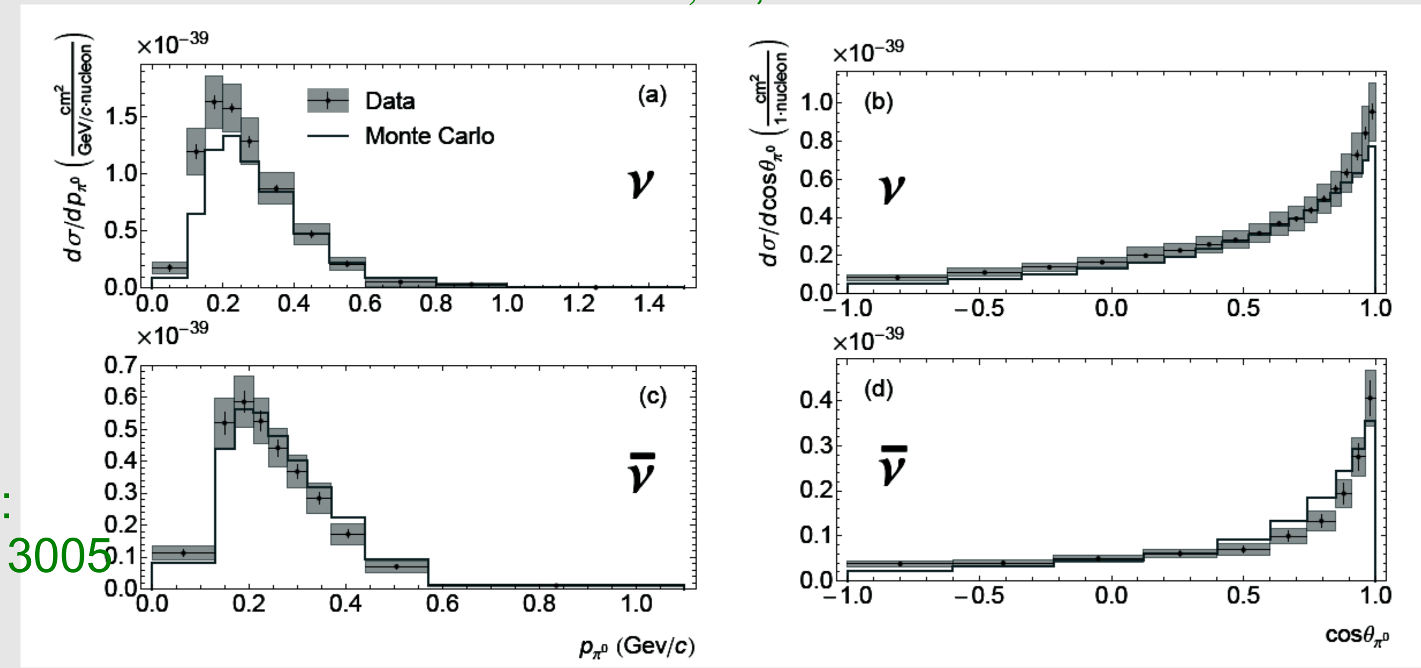
- outlook:
  - results from T2K, MINERvA, SciNOvA

$$\nu_\mu(p,n)\rightarrow\nu_\mu(p,n)\pi^0,\ \pi^0\rightarrow\gamma\gamma$$



NCπ^0 production

ν, $\bar{\nu}$, NC $\pi0$ differential cross sections

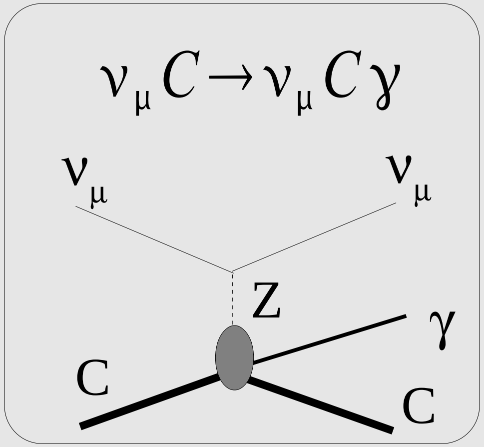


C. Anderson thesis: Phys. Rev. D81, 013005 (2010)

NC γ production

- ν NC production of photons
    - a possible oscillation background

- MiniBooNE low-energy excess has spurred work on a possible background: NCγ production
- important background for ν_e appearance searches
- eg: R. Hill, Phys. Rev. D 81, 013008 (2010) and e-Print: arXiv:1002.4215 [hep-ph]



NC γ production

TABLE I: Single photon and other backgrounds for MiniBooNE ν-mode in ranges of $E_{\rm QE}$. Ranges in square brackets are the result of applying a $20-30\%$ efficiency correction.

process	200-300	300-475	475-1250
1γ, non-Δ	$85[17-26]$	$151[30, 45]$	$159[32, 48]$
$\Delta \rightarrow N\gamma$	$170[34-51]$	$394[79-118]$	$285[57-86]$
$\nu_\mu e \rightarrow \nu_\mu e$	$14[2.7-4.1]$	$20[4.0-5.9]$	$40[7.9-12]$
$\nu_e n \rightarrow ep$	$100[20-30]$	$303[61-91]$	$1392[278-418]$
MB excess	45.2 ± 26.0	83.7 ± 24.5	22.1 ± 35.7
MB $\Delta \rightarrow N\gamma$	19.5	47.5	19.4
MB $\nu_\mu e \rightarrow \nu_\mu e$	6.1	4.3	6.4
MB $\nu_e n \rightarrow ep$	19	62	249

NC γ production

- more and recent work on this:
"Weak Pion and Photon Production off Nucleons in a Chiral Effective Field Theory", B. Serot, X. Zhang, arXiv:1011.5913 [nucl-th]

- related to and constrained by π production

- ultimately must understand this process together with pion production in all modes: resonant/non, coherent/non

- may be background for ~1% oscillation probabilities

- outlook: should search/meas this process.
May be possible in SciNOvA (see X. Tian SciNOvA talk)

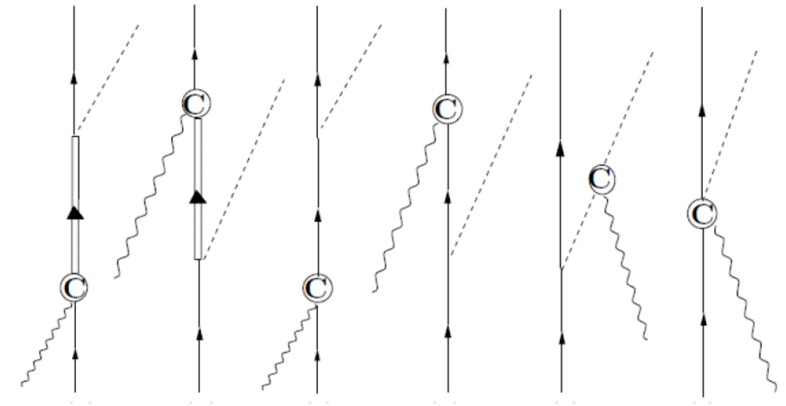


Fig.1: Feymann diagrams for pion production. Change the outgoing pion line to photon line for photon production. C indicates both vector and axial vector currents.

E_{QE}(GeV)	[0.2 , 0.3]	[0.3 , 0.475]	[0.475 , 1.25]
coh	3.1	10.37	5.59
incoh	$6 \times (1.01 + 1.01)$	$6 \times (3.64 + 3.62)$	$6 \times (2.90 + 2.88)$
total	15.22	53.93	40.27
MiniBN	19.5	47.5	19.4

preliminary

Tab.1: NC photon production event's EQE distribution in MiniBooNE for neutrino scattering.

Summary/Conclusions/Outlook

- Recent results on ν nucleus scattering have greatly improved the quality of data over that from 10 years ago:
  - from MiniBooNE, SciBooNE, NOMAD, K2K
  - better-statistical precision
  - more model-independent
  - absolutely normalized
  - more recoil particle information

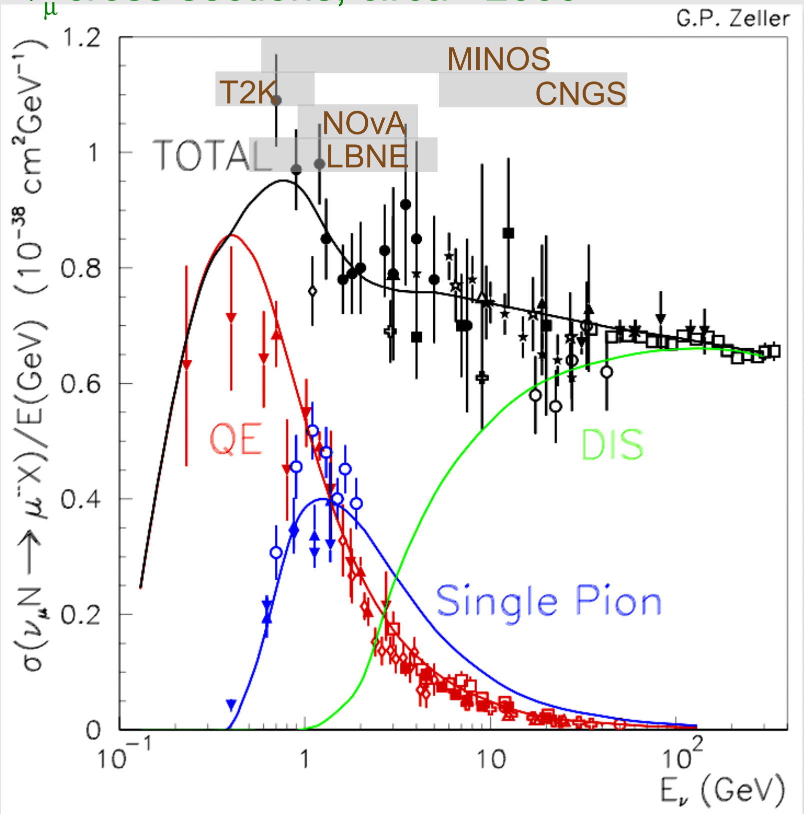
- But has also uncovered some mysteries.

- Outlook is good to continue to improve data with upcoming experiments:
  - MINERvA
  - T2K
  - microBooNE
  - NOvA, SciNOvA
- and hopefully resolve the mysteries.

- Should continue recent theoretical activity to support the efforts with models and predictions.

- Important for oscillation program.

ν_μ cross sections, circa ~2000



backup slides

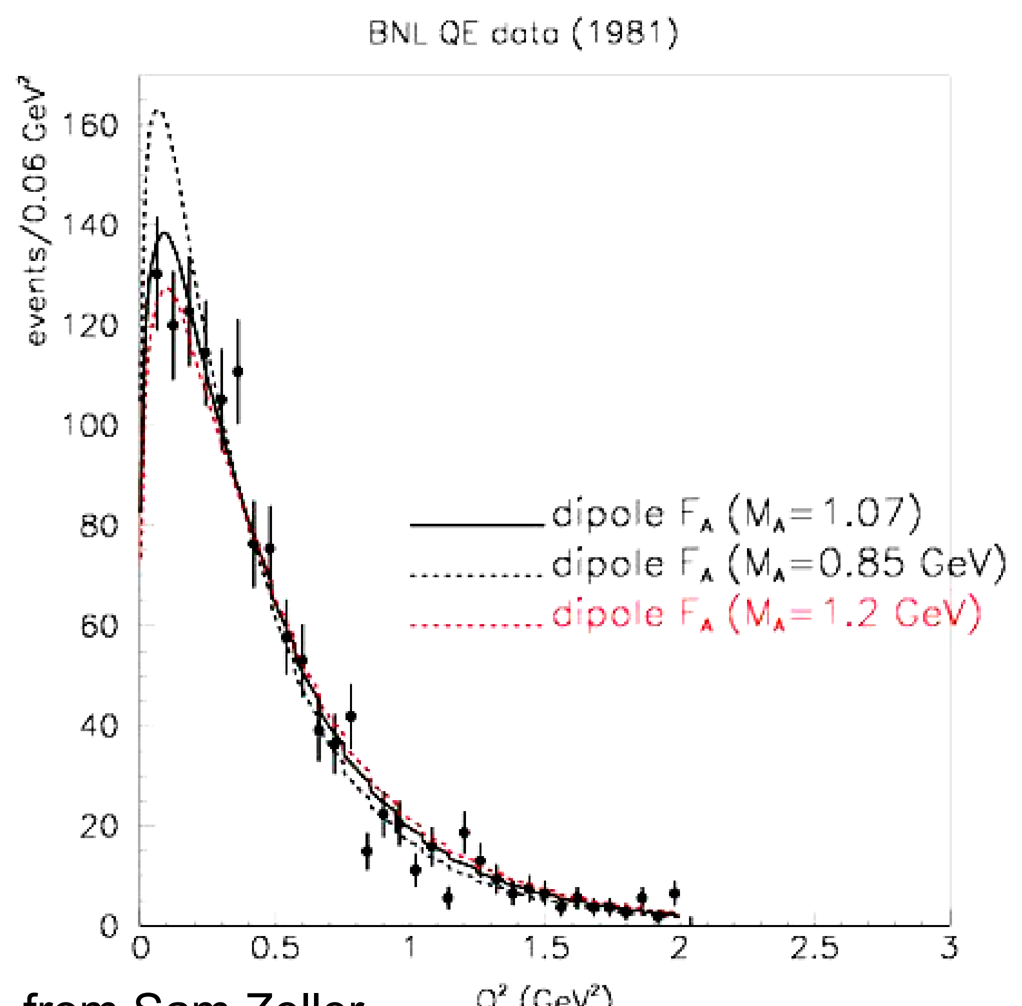
Early CCQE results

For example, BNL CCQE data:
- Baker, PRD 23, 2499 (1981)
- data on D_2
- 1,236 ν_μ QE events
- M_A=1.07 +/- 0.06 GeV

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

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

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



from Sam Zeller

modeling ν QE scattering

8.C.2 Nuclear Physics B43 (1972) 605-622. North-Holland Publishing Company

NEUTRINO REACTIONS ON NUCLEAR TARGETS ‡

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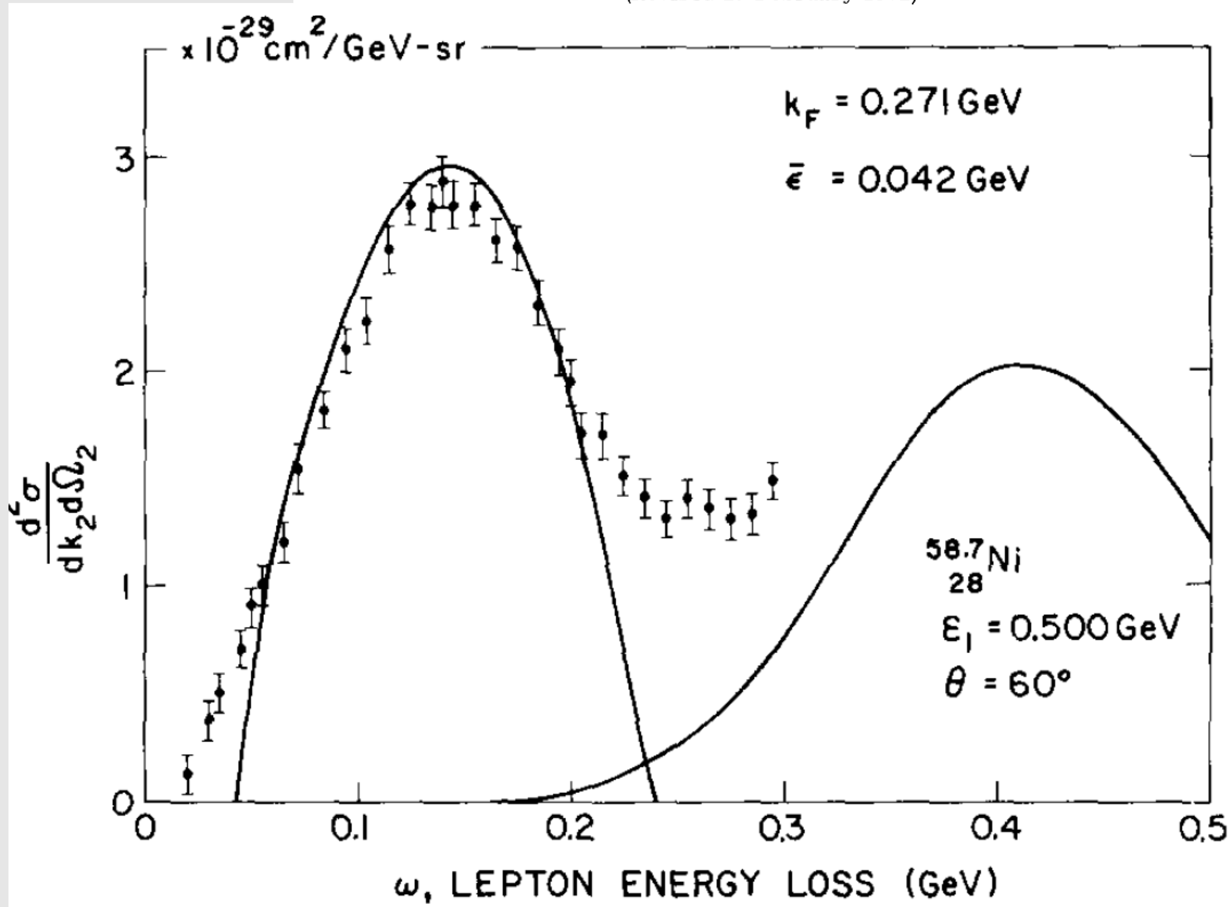
Received 15 December 1971
(Revised 29 February 1972)



MiniBooNE NC elastic results

- M_A extraction:

- from an absolute fit to proton KE distribution

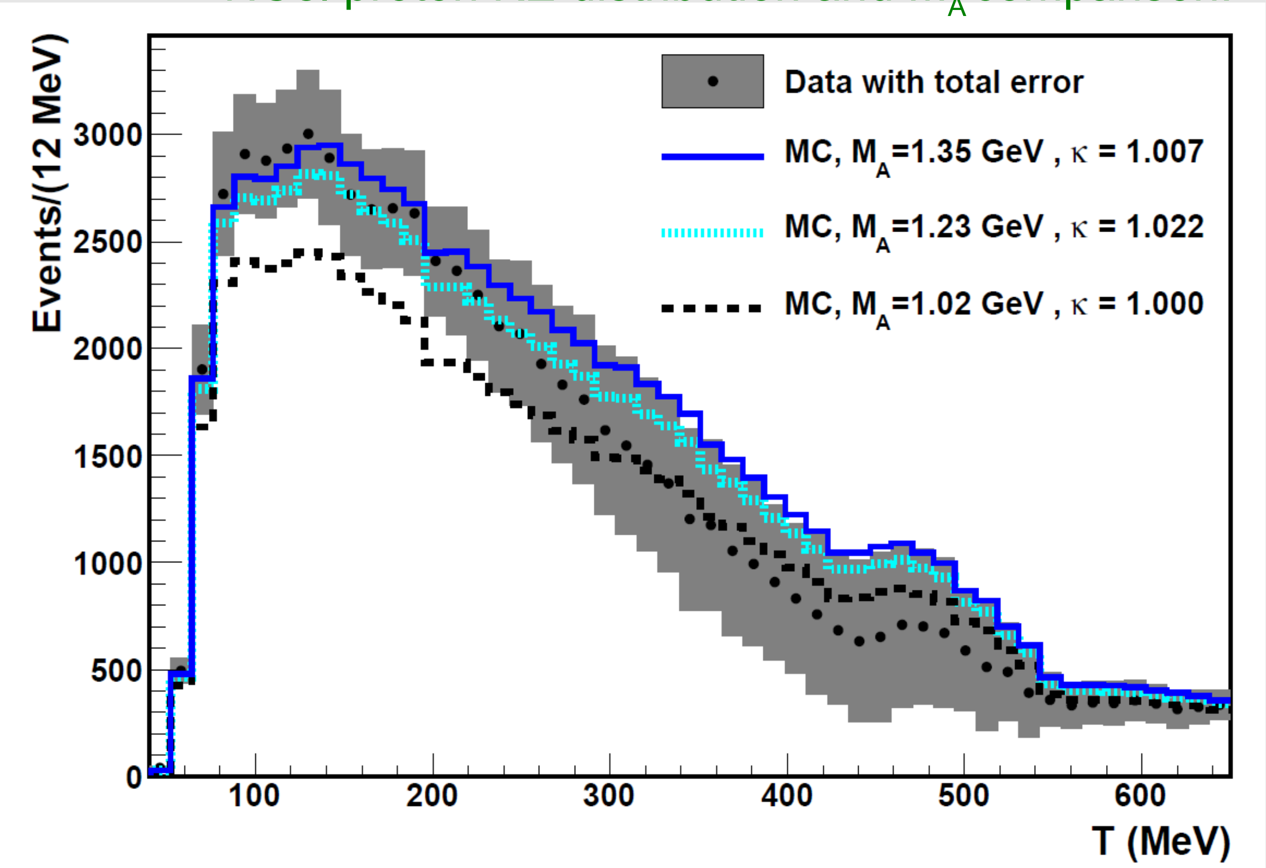
M_A = 1.39 ± 0.11 GeV
χ^2/ndf = 26.9/50

- small sensitivity to Δs, assume Δs = 0.

- negligible sensitivity to κ

- consistent with M_A from CCQE (shape) fit

NCel proton KE distribution and M_A comparison:



NC photon production

- should be possible (at higher rate experiments) and should be pursued
- SciNOvA event rates
- ~ equal to full MiniBooNE neutrino sample (but in 10 tons).
- NCγ cross sections are calculated to be O(10^{-3}) that of CCQE (from Hill or Serot/Zhang)
- resulting in sample of O(100) events in MB (same as 0.1% oscillations)
- SciNOvA will collect O(100) events of this type if calculations are correct
- photon recon down to ~100MeV and comparison with NCπ^0 channel allows a measurement of NCγ
- together with NCπ^0 channel will lend crucial info to ν_e appearance search (NOvA and others)

SciNOvA ν kevent/yr (6E20POT) in 10 ton fiducial vol

	Charged-current	Neutral-current
elastic	220	86
resonant	327	115
DIS	289	96
coherent	8	5
total	845	302
$\nu + A \rightarrow \pi^0 + X$	204	106

photon energy in NCπ^0 event in scibar/SciBooNE

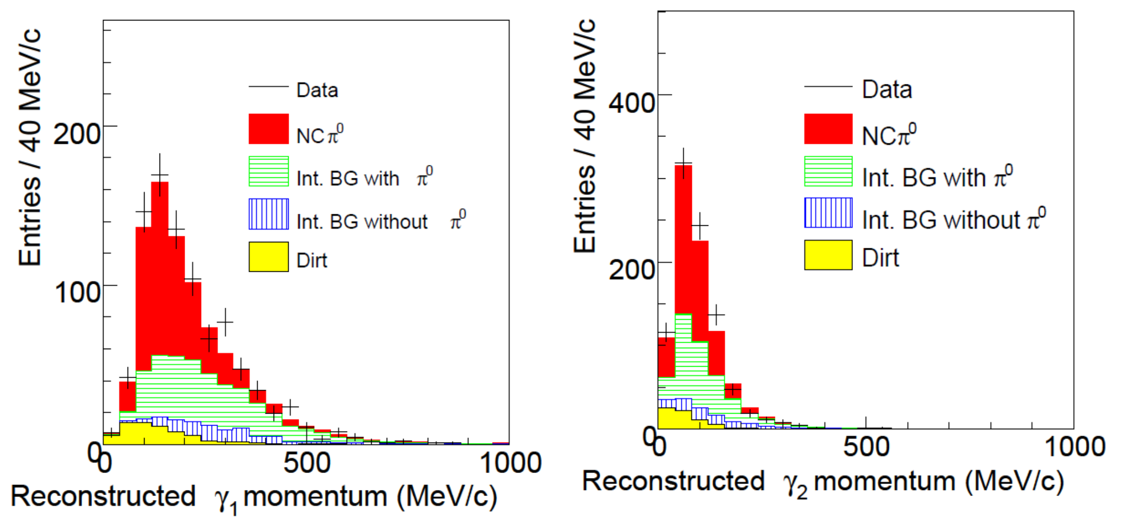
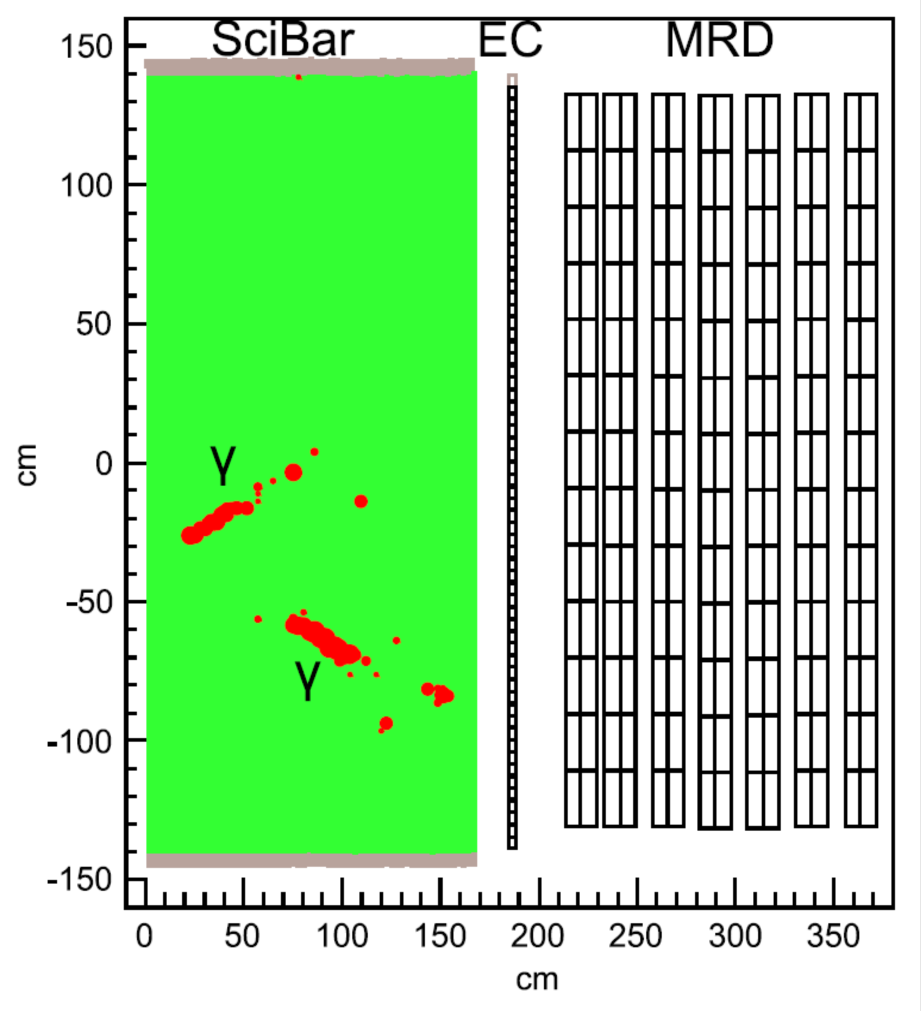


Figure 6.4: $E^{rec}_{\gamma 1}$ and $E^{rec}_{\gamma 2}$ before the π^0 mass cut ($E^{rec}_{\gamma 1} > E^{rec}_{\gamma 2}$)

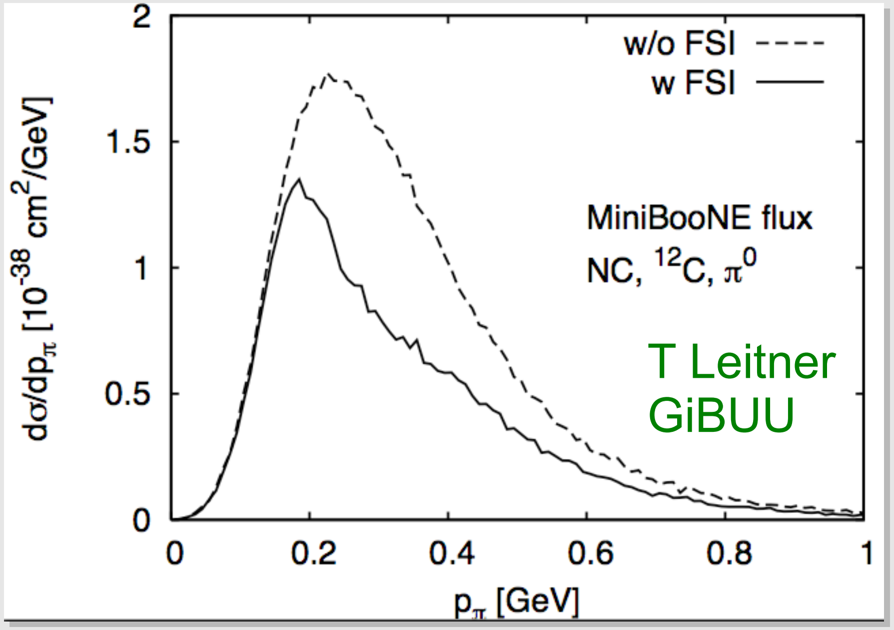
Measuring NC photon production

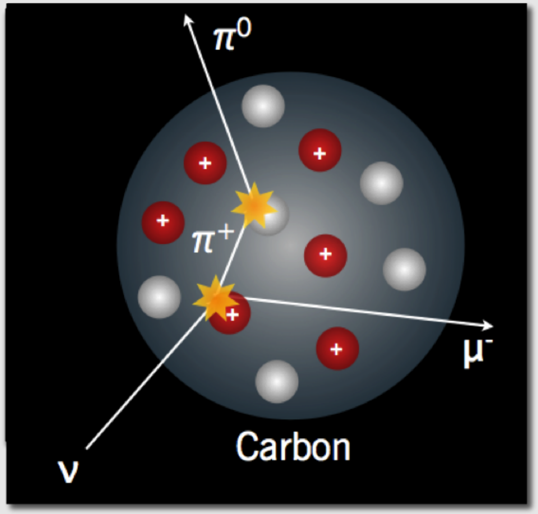


Final State interactions in nN

Might wonder about how FSI in nucleus of nucleons, pions may effect this story.

Good question... as they are not small...





in brief, they are modeled in state-art generators with guidance from theory,
and constrained by nucleon, pion, scattering data,
but had better also understand nu pion production channels..