Detectors : 1980's : Bubble chambers
1990's : Tracking calorimeters at high energy
2000's : Tracking calorimeters at low energy

QE: Introduction
Llwewllyn-Smith
Archaelogical data
Miniboone/NOMAD comparison
Complications at low energy – MEC / RFC vs SF / RPA
Clarity

Single pi : Bare Xsec
FSI
DUET

Multipi :

DIS : Effect of nucleus on structure functions

Coherent : ???

nu_e / numu_bar :

dramatis personae

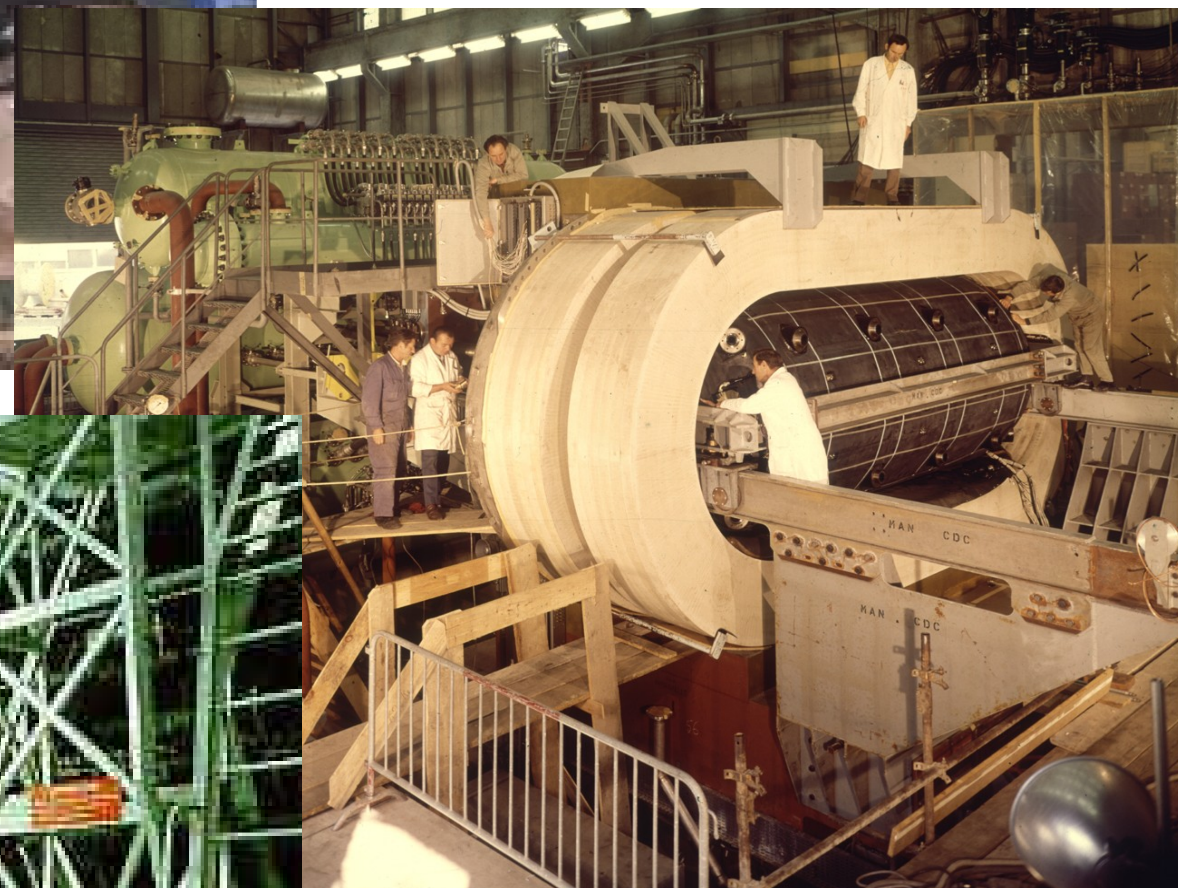
1970's – 1980's

Experiments split between high energy tracking calorimeters studying DIS and medium energy bubble chambers studying axial current physics.

Experiment	Date	Energy	Target
CHARM I/II	1979-1986	20-30	Glass
CDHS	1976-1985	80-200	Iron
Aachen-Padova	1979	2.0	Aluminium
Gargamelle	1970-1976	5.0	Freon/Propane
BNL 7ft	1975-1980	0.0-3.0	D2
ANL 12ft	1970-1975	0.0-6.0	D2/H2
SKAT	1975-1980	3-30	Freon/Bromine
BEBC	1970-1985	5-100	Neon/H2
FNAL 15ft	1975-1985	2-100	D2/H2

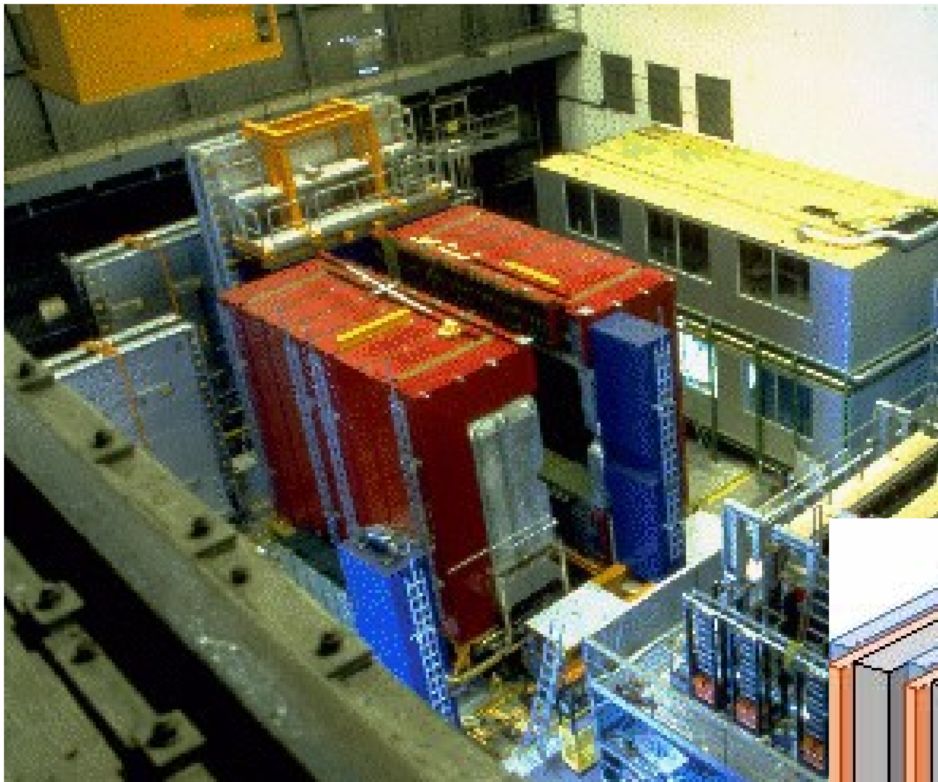
BEBC

GARGAMELLE

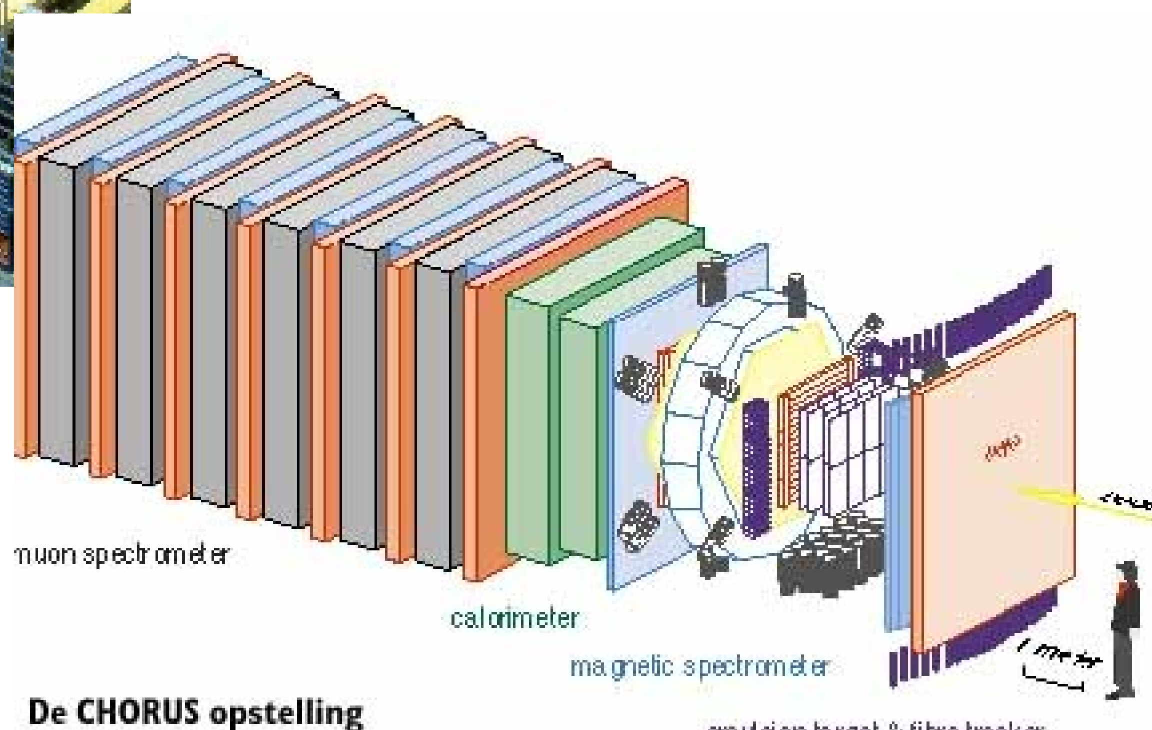


CDHS

1990's



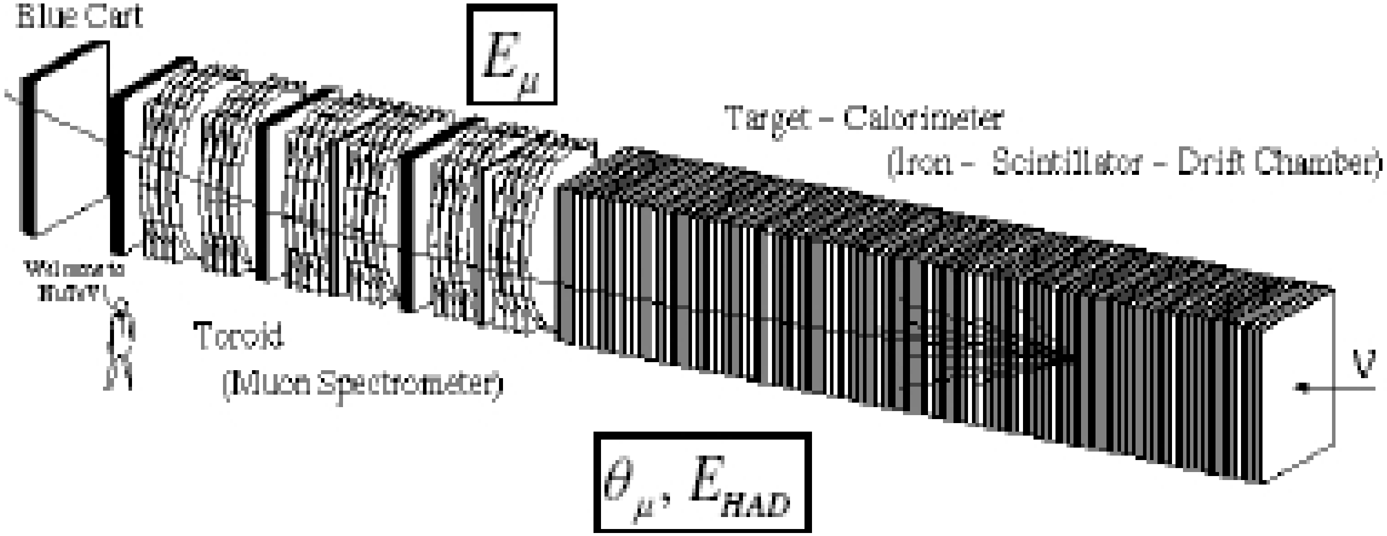
NOMAD tracking detector
E_ν : 5 – 100 GeV
Carbon (mostly) target
1990-1998



CHORUS Emulsion
E_ν : 5 – 100 GeV
Silver target
1990-1998

1990's

NUTEV Tracking Calorimeter
Iron target
30-500 GeV sign-selected beam



2000's

Scattering experiments in the last decade mostly sit at medium energy and use scintillator as the target material. Note that MINERvA can look & compare other target types as well.

Experiment	Date	Energy	Target
MINOS	2005-	0-30 GeV	Iron
MiniBooNE	2002-2012	0-5 GeV	C_nH_m
SciBooNE	2007-2008	0-5 GeV	C_nH_m
MINERvA	2011-	0.0-3.0	C_nH_m,Pb,Fe,C,H_20
T2K ND280	2009-	0.0-5.0	C_nH_m, H_20

$$\nu_\mu$$

Neutrino-Nucleon Interactions

q^2

CC – $W^{\pm}$ exchange

- Quasi-elastic Scattering
  - Target changes but no breakup
  - $\nu_{\mu} + n \rightarrow \mu^{-} + p$
- Coherent/Diffractive production
  - Target unchanged
  - $\nu_{\mu} + n \rightarrow \mu^{-} + n + \pi^{+}$
- Nuclear resonance production
  - Target goes to excited state and decays
  - $\nu_{\mu} + n \rightarrow \mu^{-} + p + \pi^{0}$ (N* or Δ)
  - $n + \pi^{+}$
- Deep Inelastic Scattering
  - Target breaks up
  - ν_{μ} + quark $\rightarrow \mu^{-}$ + quark'

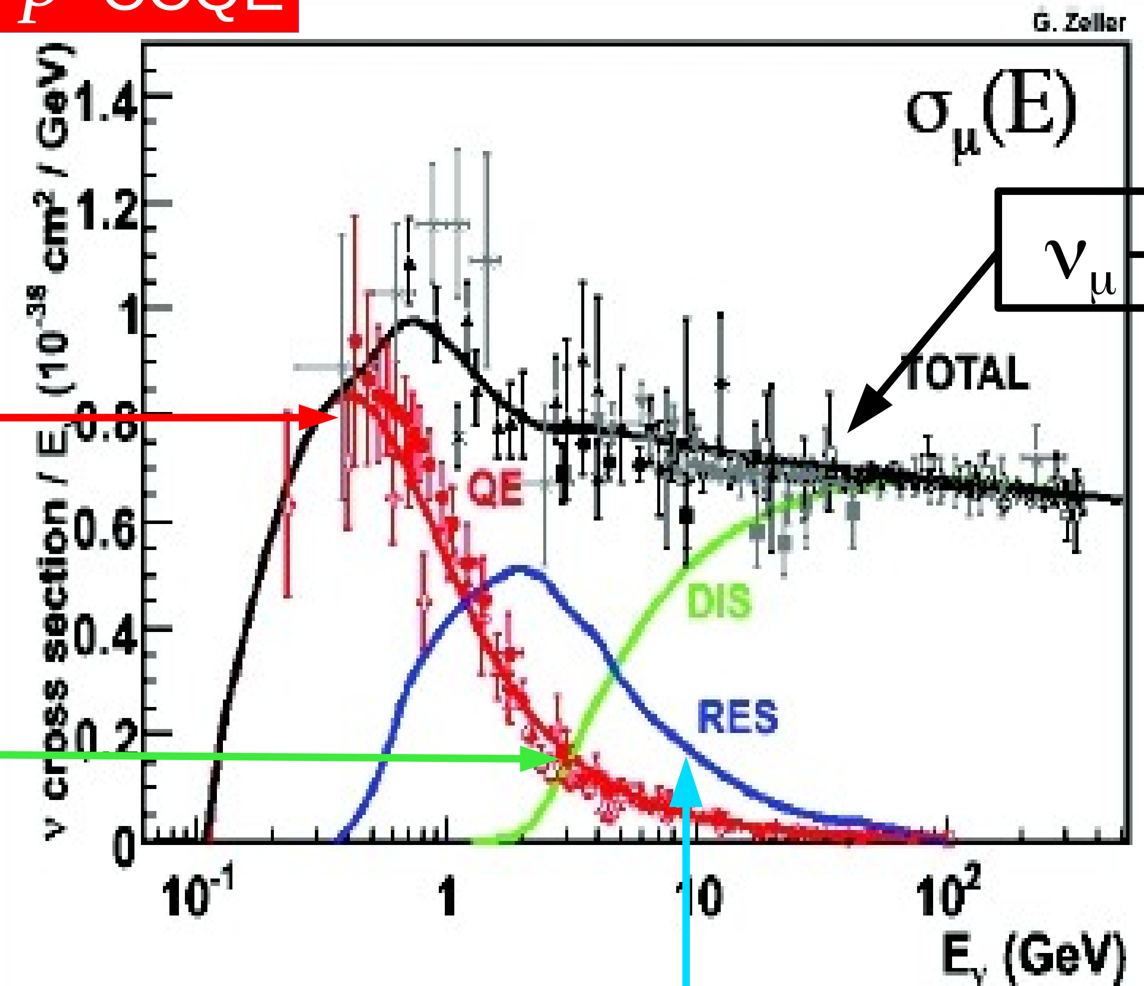
NC – Z^{0} exchange

- Elastic Scattering
  - Target unchanged
  - $\nu_{\mu} + n \rightarrow \nu_{\mu} + n$
- Coherent/Diffractive production
  - Target unchanged
  - $\nu_{\mu} + N \rightarrow \nu_{\mu} + N + \pi^{0}$
- Nuclear resonance production
  - Target goes to excited state and decays
  - $\nu_{\mu} + N \rightarrow \nu_{\mu} + N + \pi$ (N* or Δ)
- Deep Inelastic Scattering
  - Target breaks up
  - ν_{μ} + quark $\rightarrow \nu_{\mu}$ + quark

Cross-sections – current knowledge

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

ν_μ



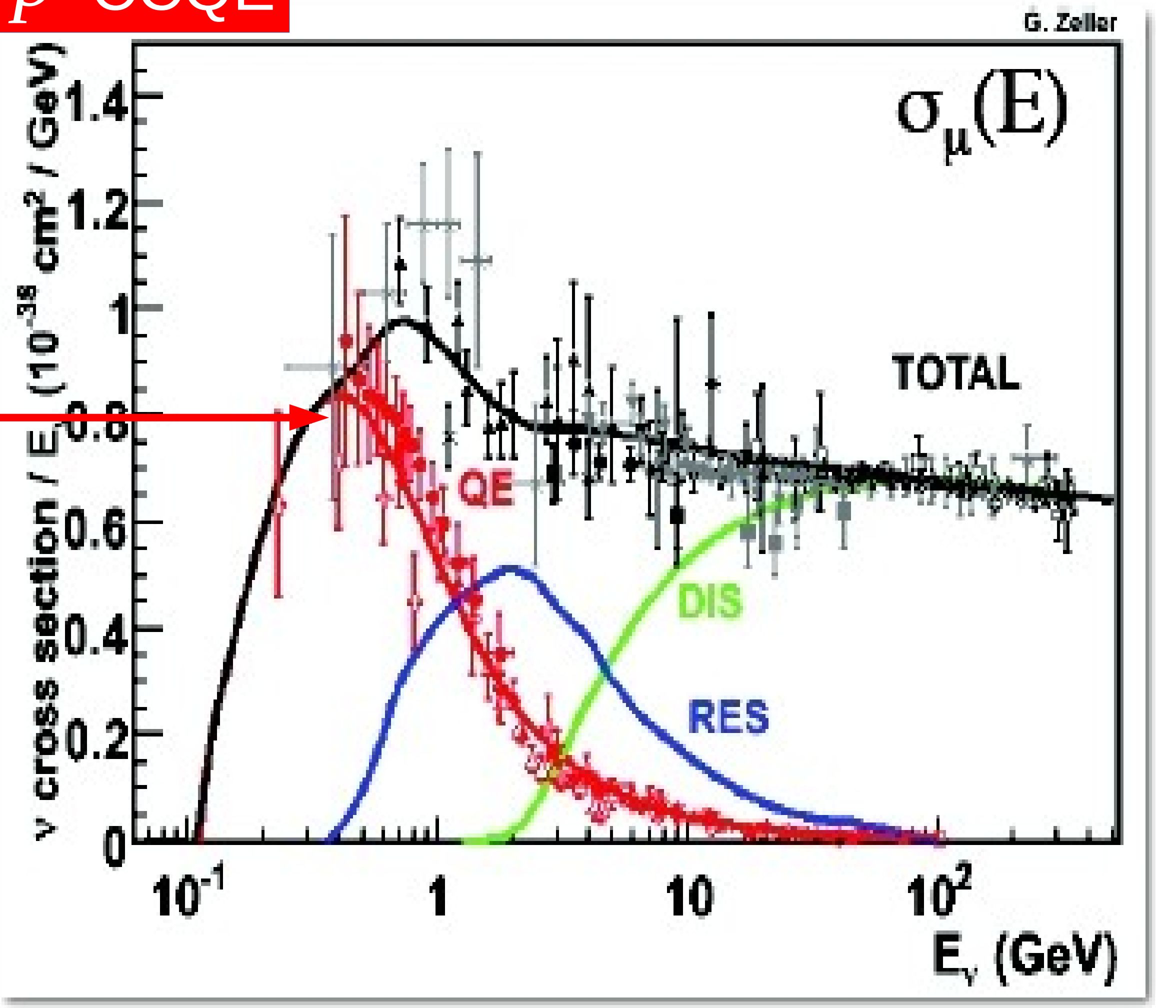
$\nu_\mu + N \rightarrow \mu^- + X$

"Transition Region"

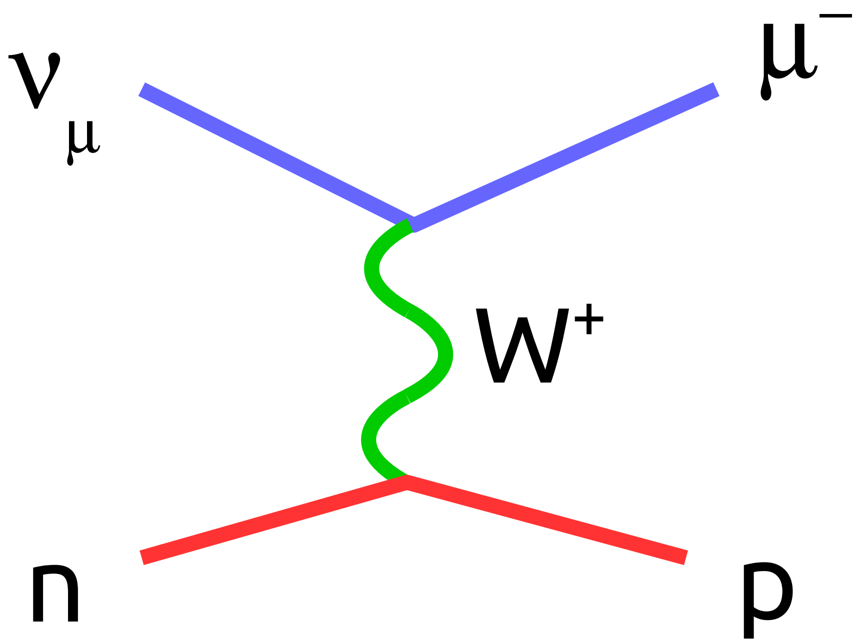
$\nu_\mu + N \rightarrow \mu^- + N' + \pi$ Single pion

Charged Current QE

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



Quasi-Elastic Scattering



- Usually though of as a single nucleon knock-on process
- In the past has been used as a “standard candle” to normalise other cross sections
- Heavily studied in the 1970's and 1980's and considered to be “understood”

Very important for current oscillation experiments as it contributes the most of the total cross section at a few GeV

“Standard” Formalism

Llewellyn-Smith formalism on a free nucleon

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

Contain 6 Q^2 dependent form factors

Most form factors are known from electron scattering except the “axial” form factor

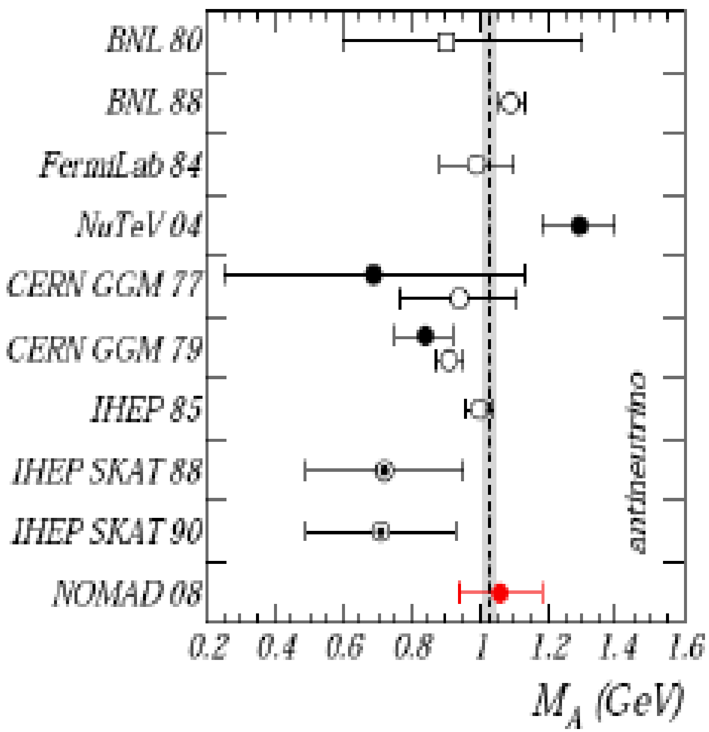
$$F_{Axial}(Q^2) = \frac{F_A(0)}{1 - \frac{Q^2}{m_A^2}}$$

Axial Mass

Dipole parametrisation of axial form factor

$$F_{Axial}(Q^2) = \frac{F_A(0)}{\left(1 - \frac{Q^2}{m_A^2}\right)^2}$$

known from β decay

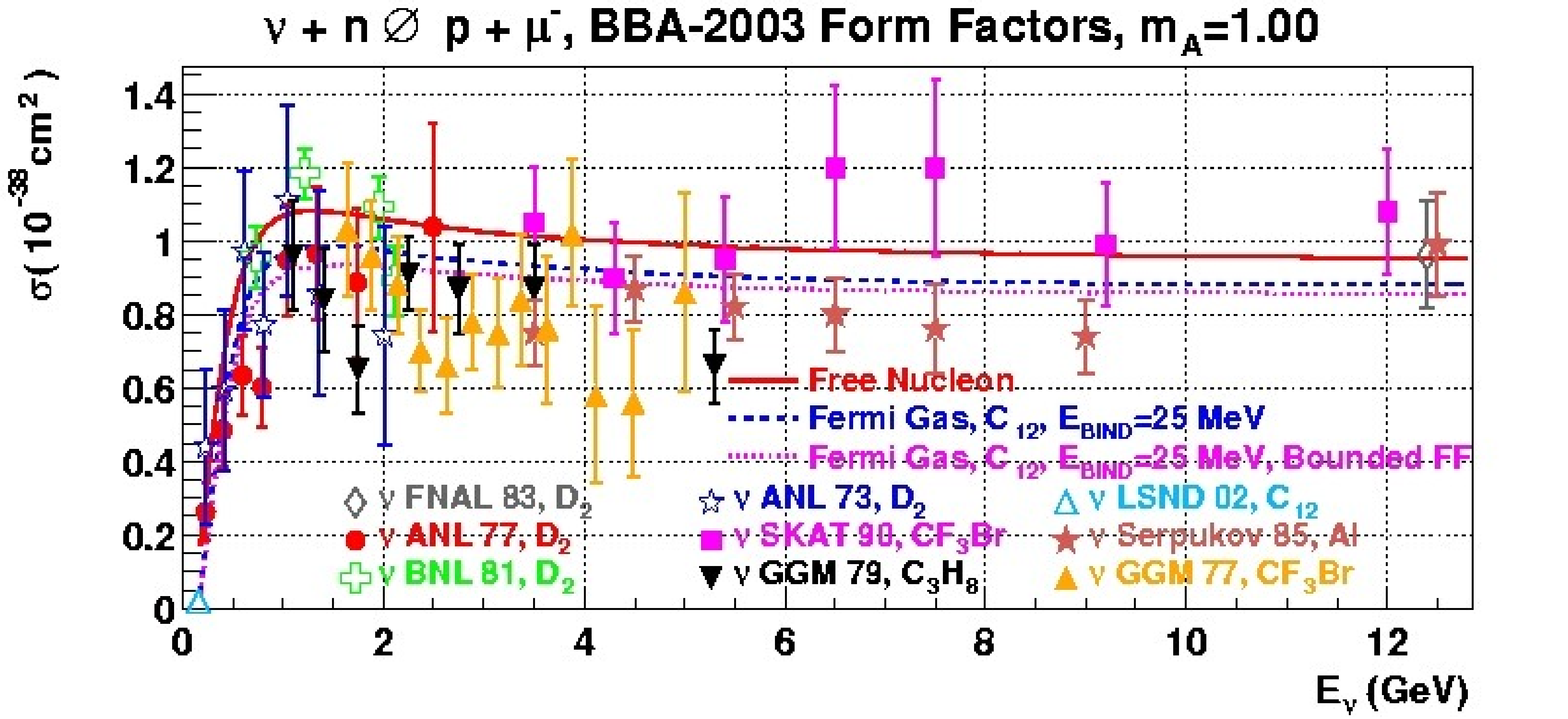


Lyubushkin et al,
Eur. Phys. JC63:355-381

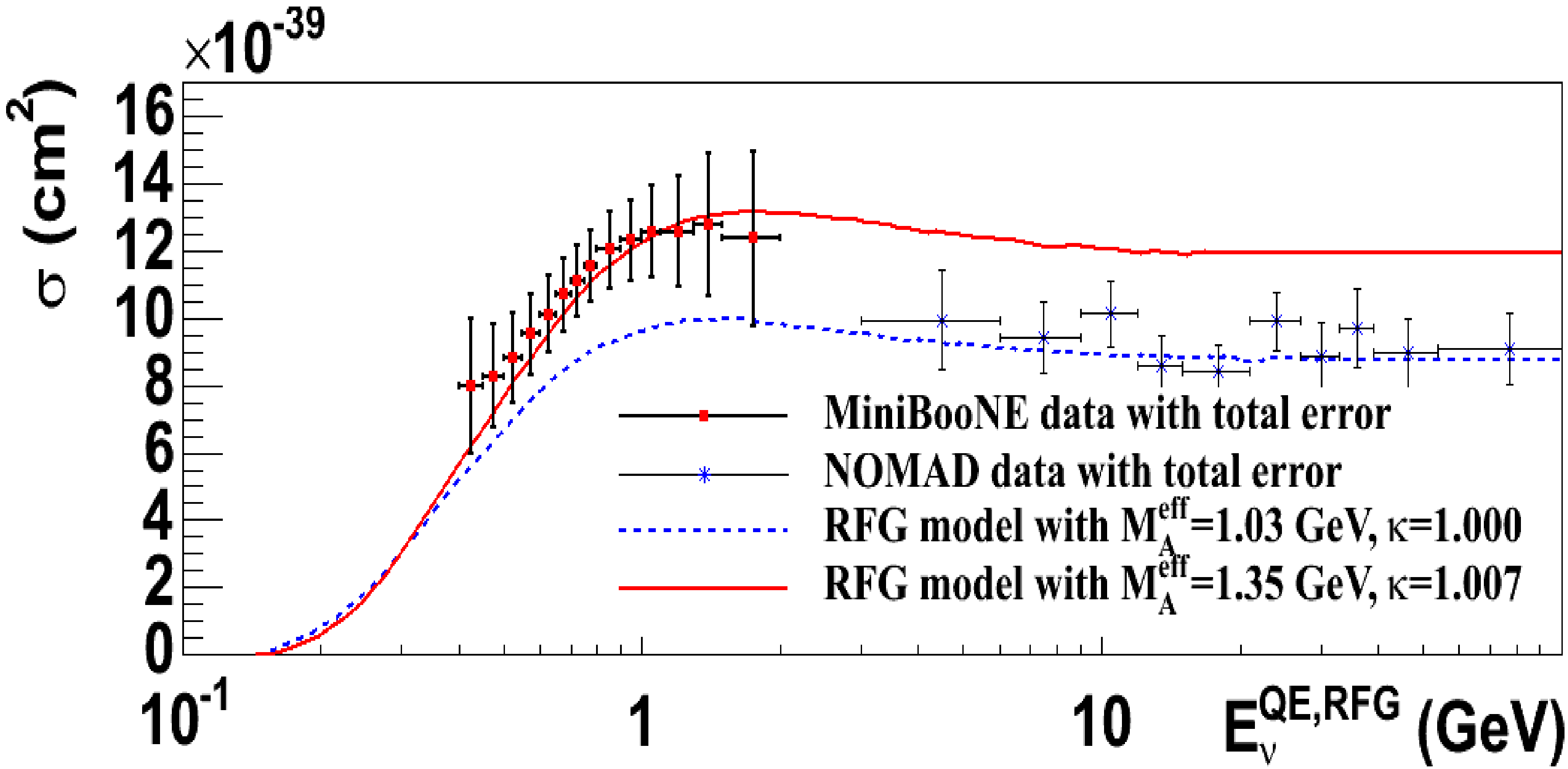
- m_A is the "axial mass"
- this was the "measurement"
- Deuterium bubble chambers and high energy experiements determine m_A = 1.026 ± 0.021 GeV^2
- Low energy experiments on carbon seem to show m_A is ~ 1.3

Dipole form is only a *parametrisation*

Status of data



The current mystery



MiniBooNE and NOMAD both measured this process and there is significant tension……but are we comparing apples with oranges?

What is the signal?

MiniBooNE is a hybrid cerenkov/scintillator experiment

CCQE signal is actually CC-0π

NOMAD is a high energy tracker

CCQE signal : 1 μ track

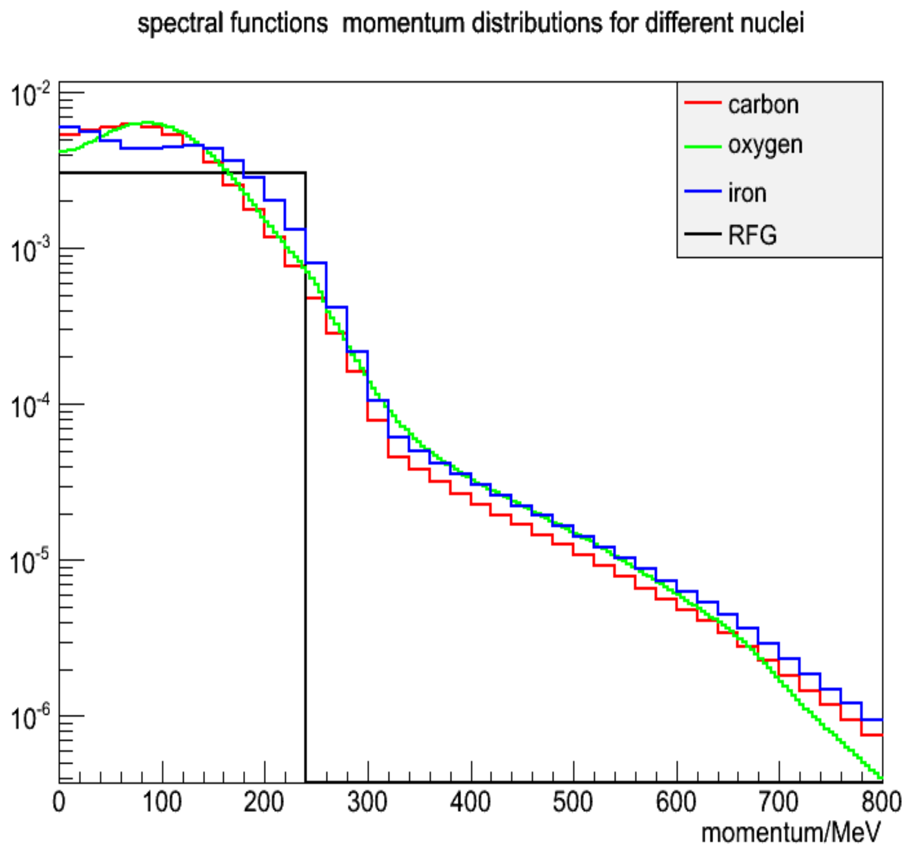
μ / p 2 track

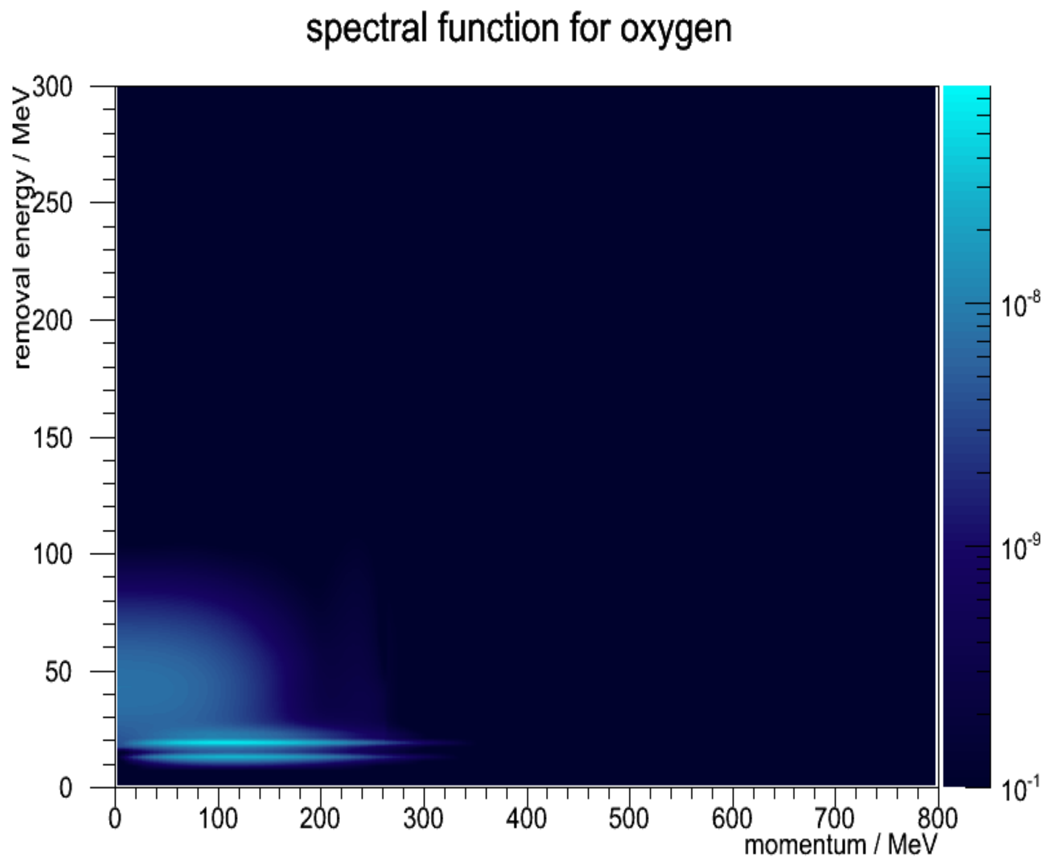
Signals contain different contributions from nuclear and bare processes. Unfolding relies on models. Can we compare the results sensibly?

Initial state model

The model of the target kinematics can affect the cross-section

Spectral function model is known to perform better in describing electron scattering. Is it the same for neutrino scattering?

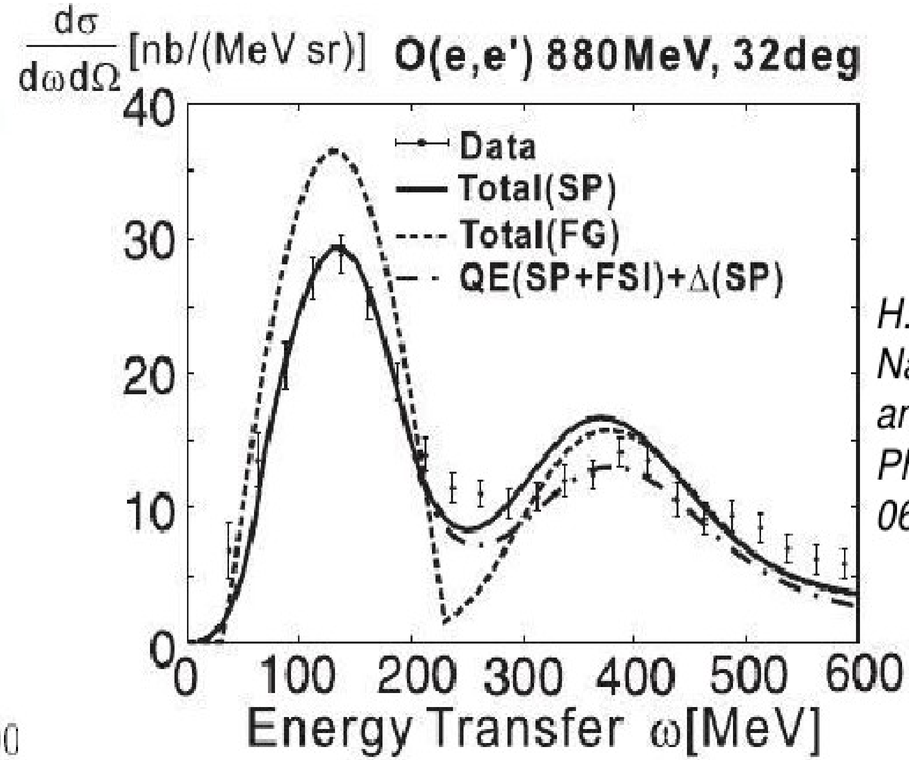




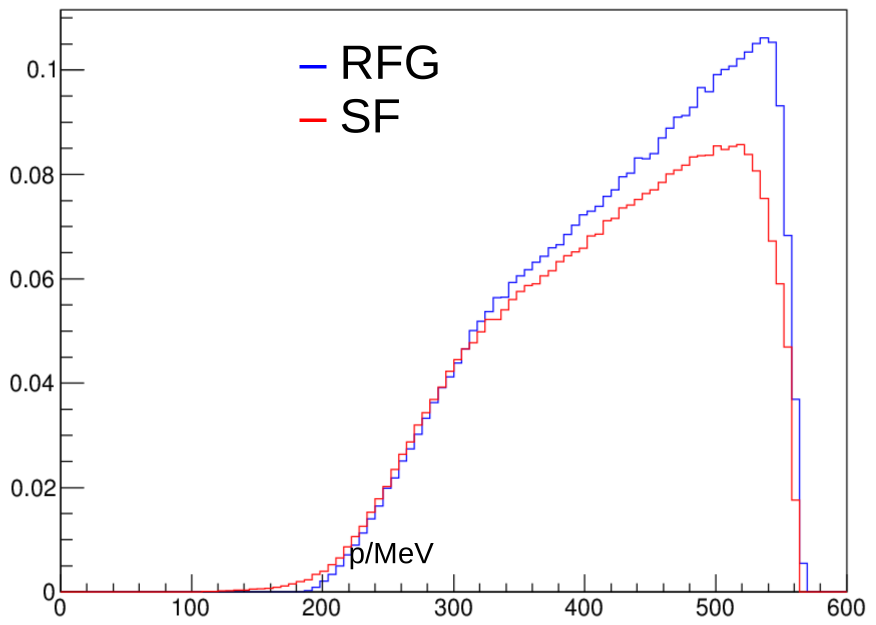
Effect on cross-section

SF can have a large effect on normalisation and shape of the cross-section and is known to perform better than RFG in electron scattering.

SF has to be calculated for each target atom species

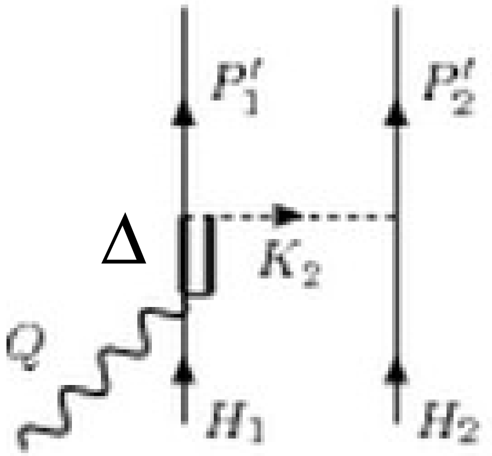


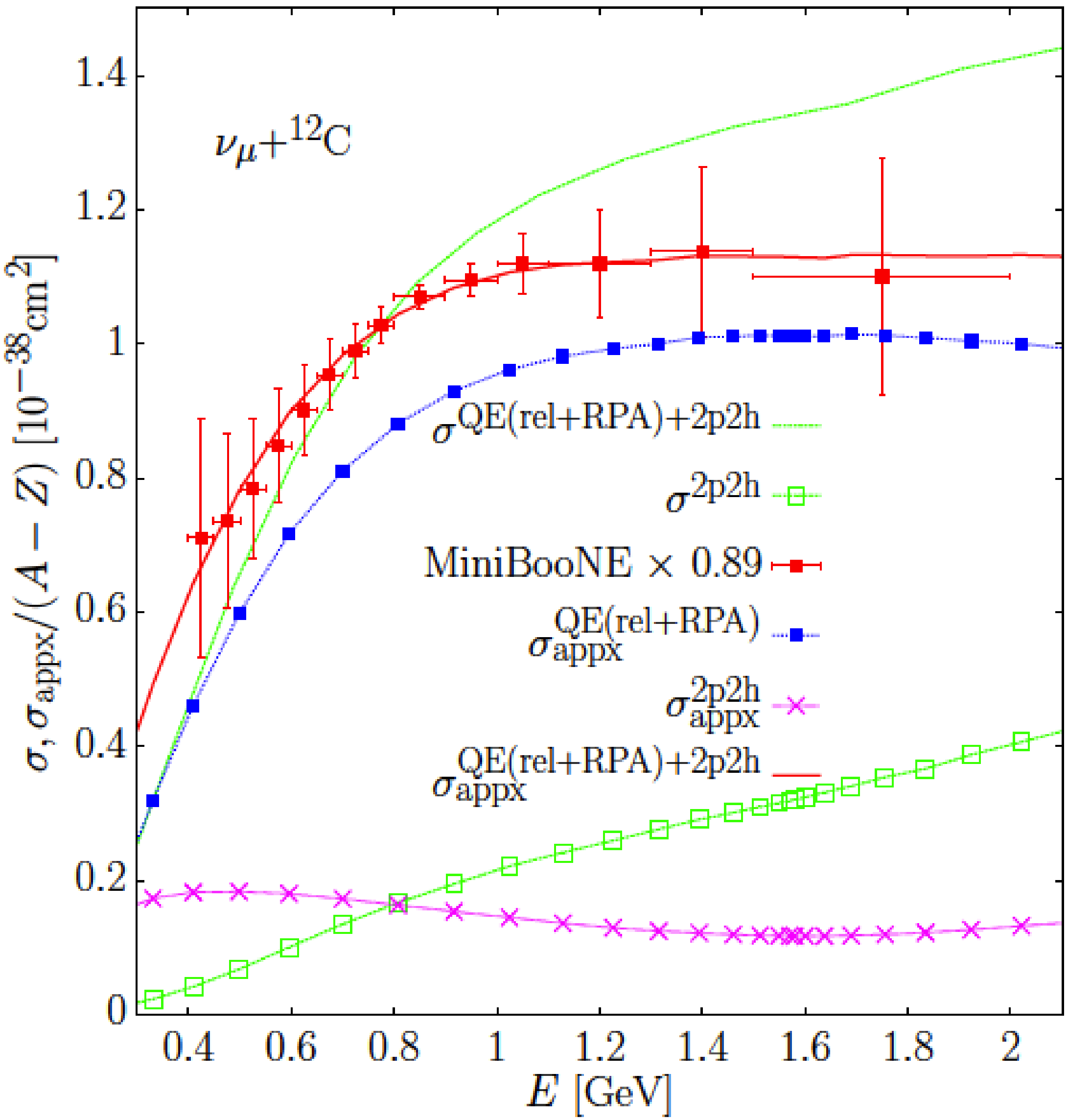
H. Nakamura, T. Nasu, M. Sakuda and Omar Benhar, Phys. Rev. C 76, 065208 (2007)



Cross section as a function of muon momentum for CCQE on carbon at 600MeV

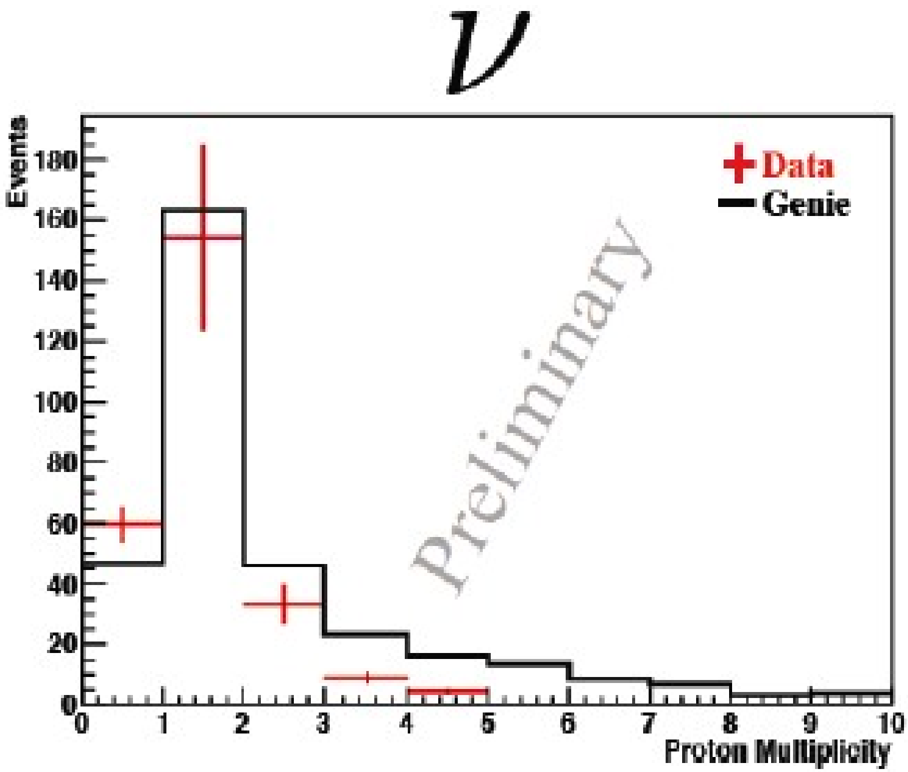
Multinucleon contributions

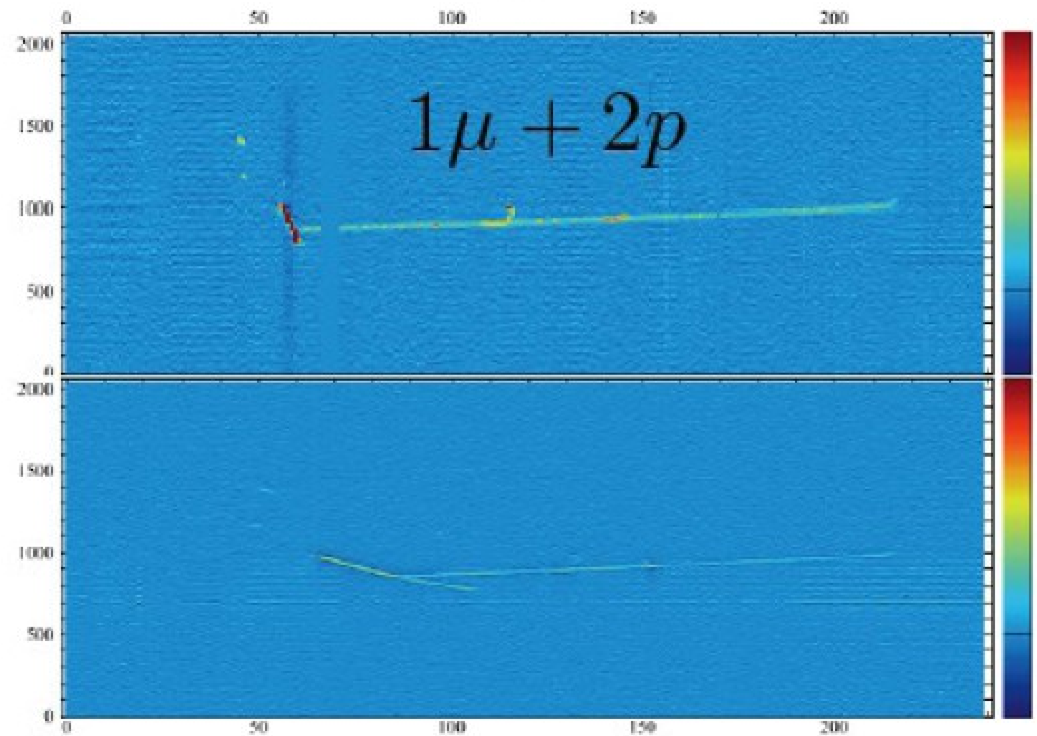




- Extra contribution to observed MiniBooNE signal but less for NOMAD
- Process has not been "conclusively" observed
- Kinematics of the hadronic system are not known

Prospects





Understanding the nuclear issues will require :

- imaging the hadronic system
- high precision data on different nuclei
- data on light nuclei (D?)

LAr data from Argoneut, microBooNE and T2K could help

Differential cross-section

Unravelling all the different effects will require more information than just σ vs E_ν - we need full differential cross sections in observed variables

Cautionary tales

The data underlying our CCQE models come from :

- electron scattering from nuclei (electrons scatter from surface)
- D_2 data from 1970's/1980's

VOLUME 49, NUMBER 2 PHYSICAL REVIEW LETTERS 12 JULY 1982

Neutrino Flux and Total Charged-Current Cross Sections in High-Energy Neutrino-Deuterium Interactions

T. Kitagaki, S. Tanaka, H. Yuta, K. Abe, K. Hasegawa, A. Yamaguc
T. Hayashino, Y. Ohtani, and H. Hayano
Tohoku University, Sendai 980, Japan

To obtain the total cross section from the number of events, the neutrino flux has to be measured on an absolute scale. In this analysis, we determine the neutrino flux using 362 quasielastic events identified in our data[10] and the cross section for reaction (2) derived from the $V-A$ theory.

Theoretical QE Xsec used to measure neutrino flux

and then this flux is used to measure the QE cross section

PHYSICAL REVIEW D VOLUME 28, NUMBER 3 1 AUGUST 1983

High-energy quasielastic $\nu_\mu n \rightarrow \mu^- p$ scattering in deuterium

T. Kitagaki, S. Tanaka, H. Yuta, K. Abe, K. Hasegawa,
A. Yamaguchi, K. Tamai, T. Hayashino, Y. Otani, H. Hayano, and H. Sagawa
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R. A. Burnstein, J. Hanlon, and H. A. Rubin
Illinois Institute of Technology, Chicago, Illinois 60616

C. Y. Chang, S. Kunori, G. A. Snow, D. Son,* P. H. Steinberg, and D. Zieminska†
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State University of New York at Stony Brook, Stony Brook, New York 11974

C. C. Chang,§ W. A. Mann, A. Napier, and J. Schneps
Tufts University, Medford, Massachusetts 02155

(Received 13 December 1982)

We have studied the quasielastic reaction $\nu_\mu n \rightarrow \mu^- p$ in an exposure of the Fermilab deuterium-filled 15-foot bubble chamber to a high-energy wide-band neutrino beam. From an analysis of the Q^2 distribution based on the standard $V-A$ theory, the axial-vector mass in a dipole parametrization of the axial-vector form factor is determined to be $M_A = 1.05$ [illegible] GeV, consistent with the values previously reported from low-energy experiments.

CCQE Summary

- CCQE - the “simple” process - is turning out to be a lot less simple than we thought

- Measured cross sections depend on the definition of the signal in the each experiment, modelling of nuclear effects and, to a lesser extent at the moment, modelling of the bare process

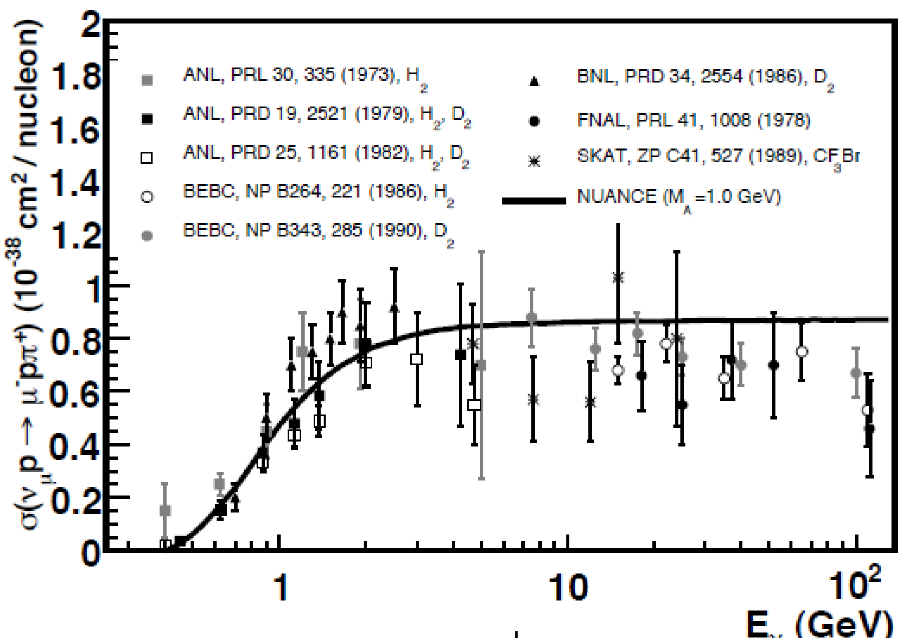
- Better to try to measure final-state cross sections rather than generator mode dependent cross sections

- Need differential cross sections.

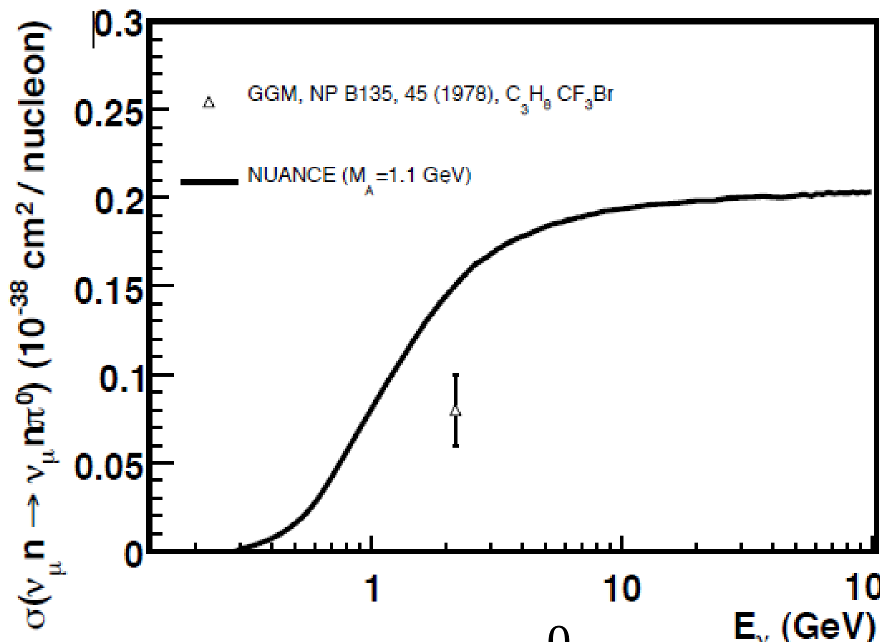
- New high precision data should help unravel the nuclear questions, but the situation at the moment is far from clear.

Single pion production

Light target data is, as with CCQE, dominated by the bubble chamber experiments with the usual precision issues



$\nu_\mu p \rightarrow \mu^- p \pi^+$



$\nu_\mu p \rightarrow \nu_\mu n \pi^0$

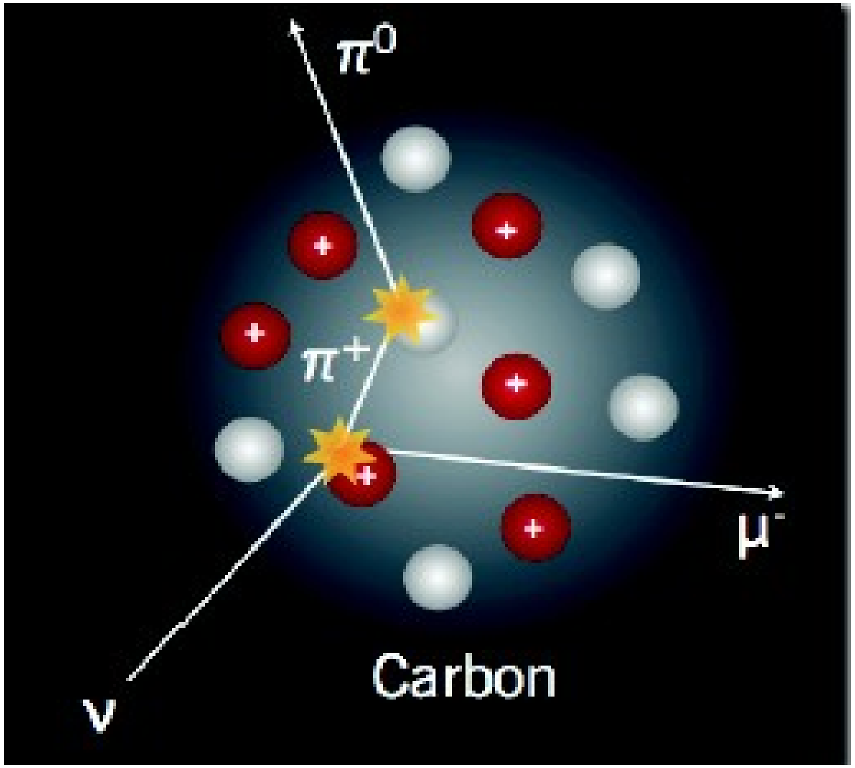
Rein-Seghal resonance model is used in all generators

Model can be modified in nuclear environment : Δ width

Final State Effects

Pions generated in a nuclear potential can

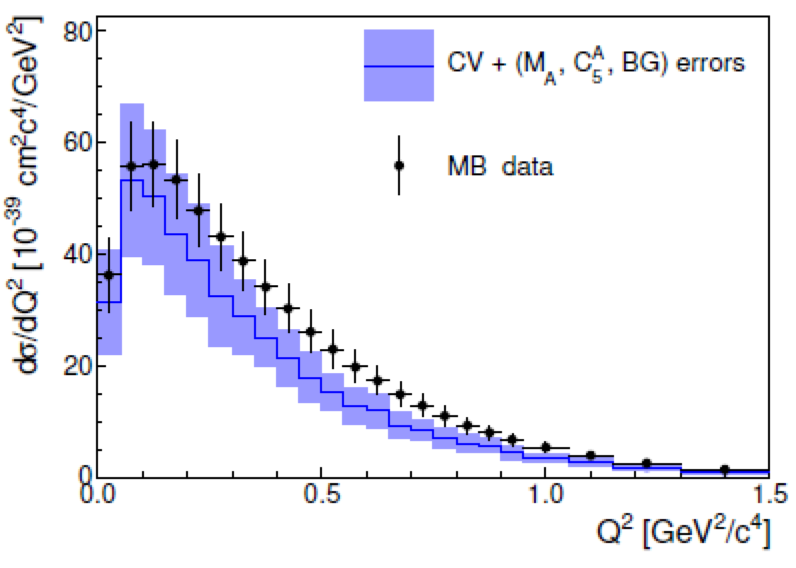
-be absorbed
-be elastically scattered
-undergo charge exchange

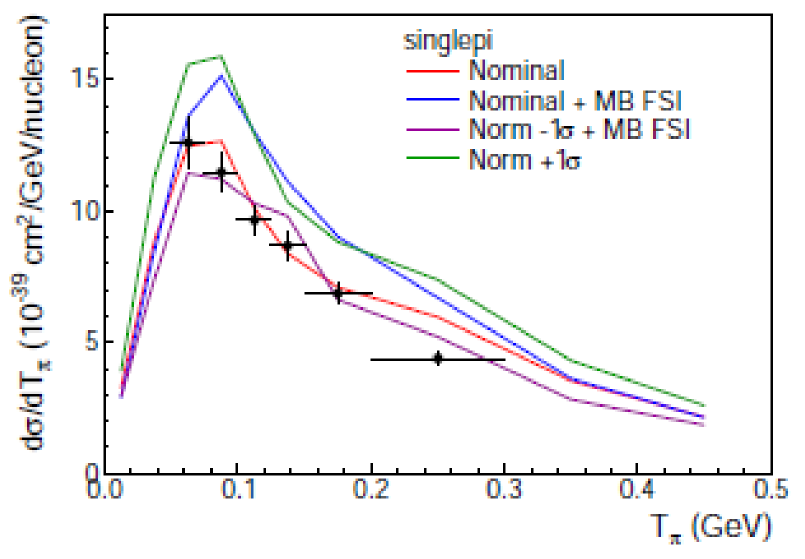


Recent data

MiniBooNE and MINERvA have recently published high statistics differential distributions on single pion production.

The results are....confusing....

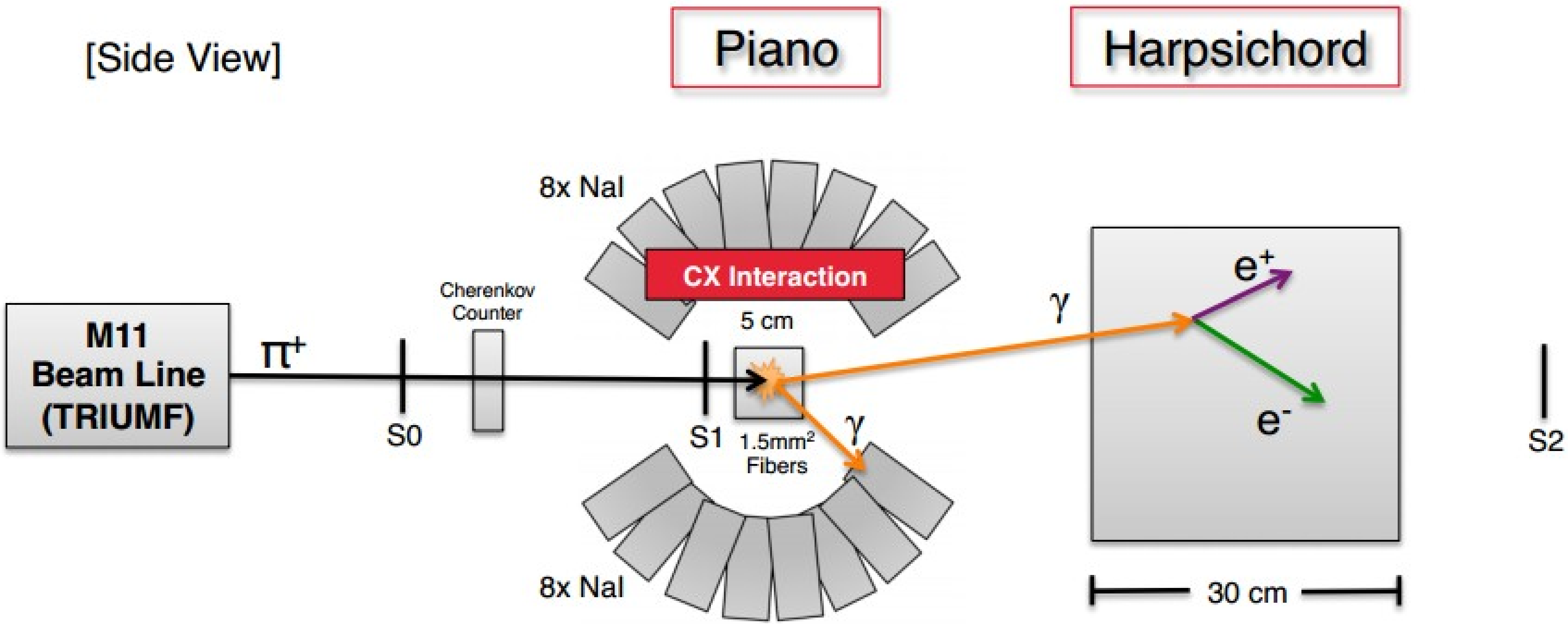




MiniBooNE data does not agree with NEUT+nominal FSI model in either shape of normalisation (in fact, it supports no FSI effects)

MINERvA data prefers nominal FSI model in normalisation but has little sensitivity to shape (yet)

Constraining FSI : Duet

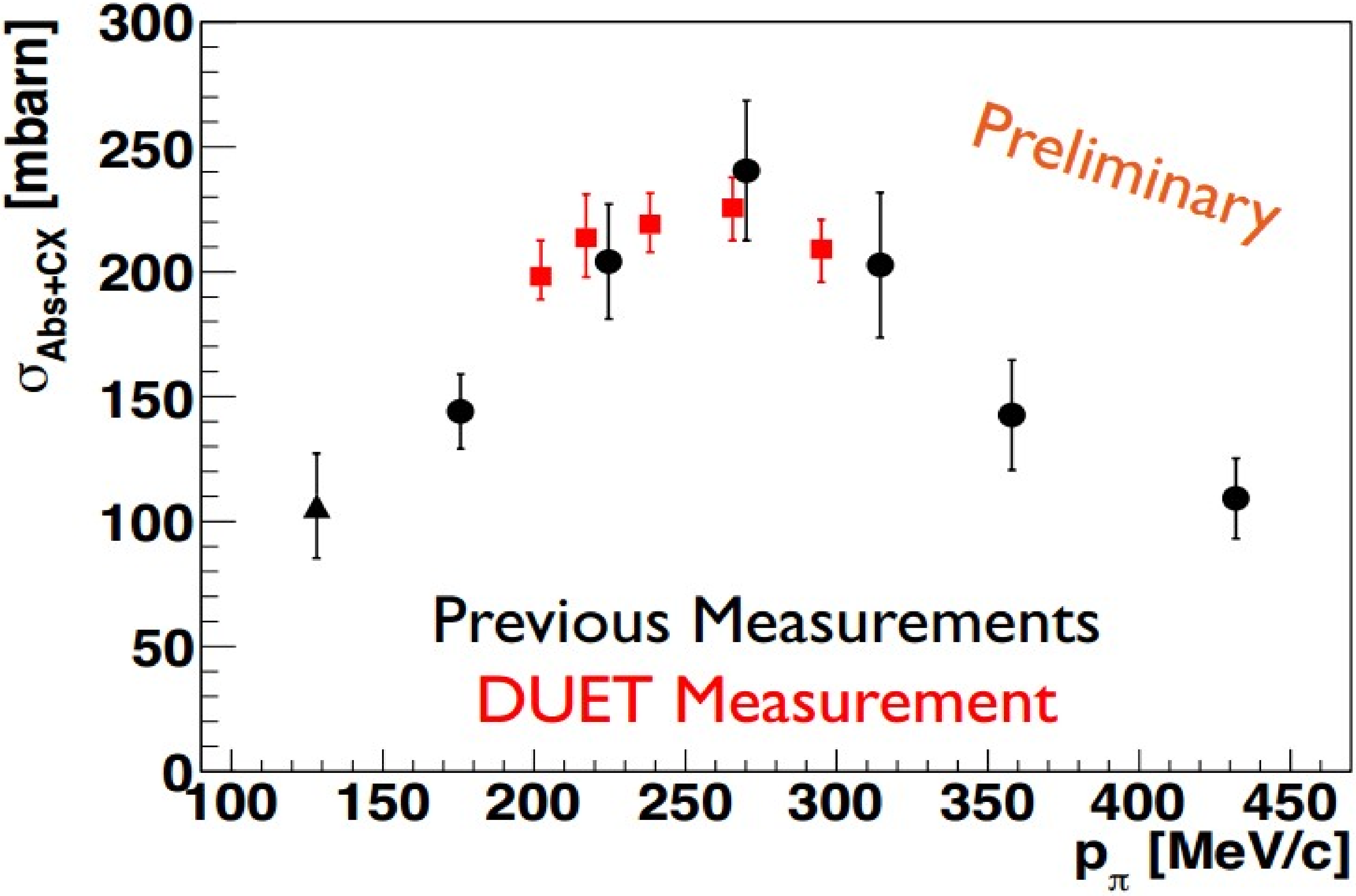


The DUET experiment used the TRIUMF secondary pion beam to study π-N interactions for π energies between 50 and 300 MeV

Goal to measure pion absorption to 10% and charge exchange to 20%

This will be extremely useful for tuning the FSI models we use

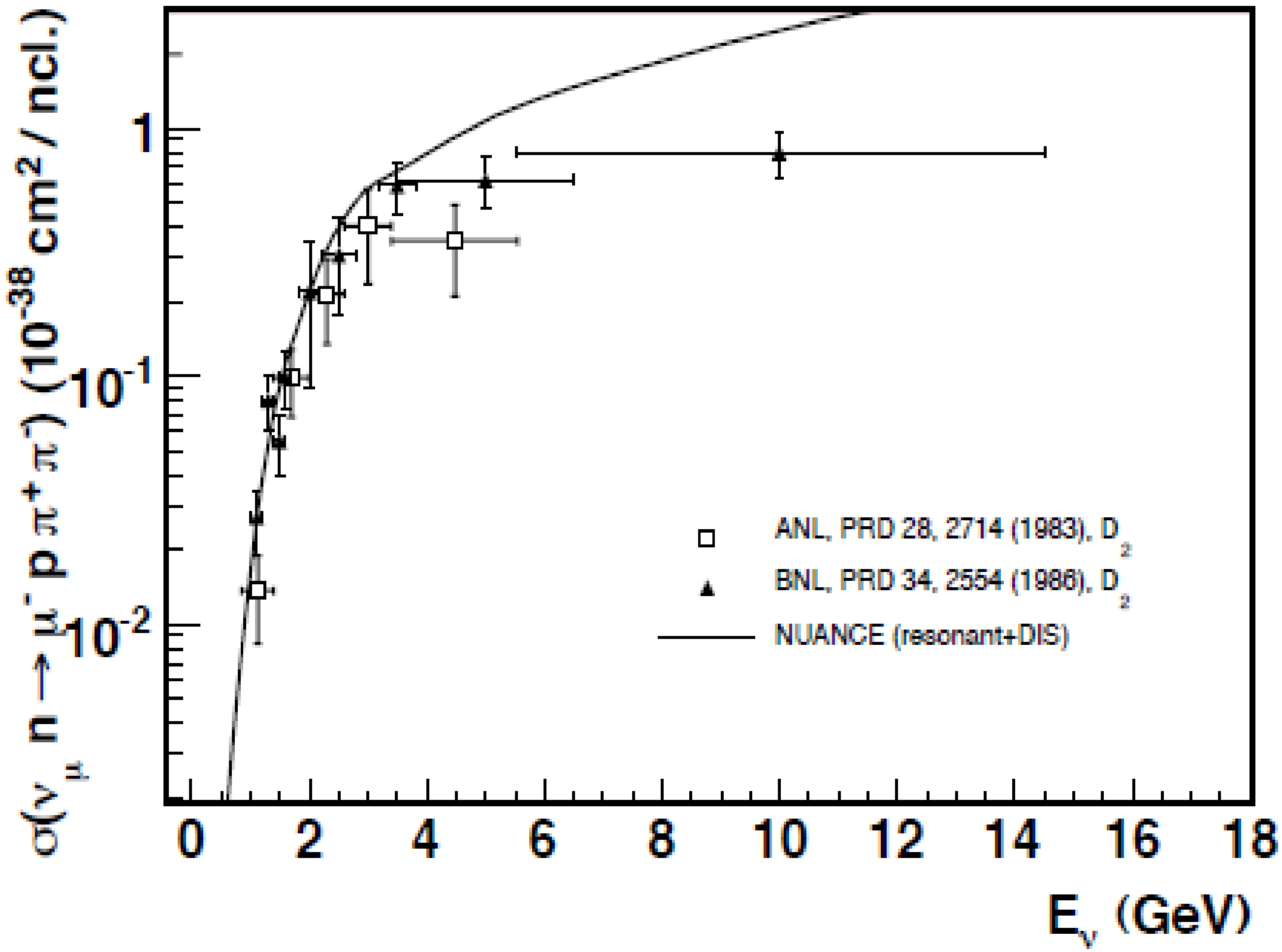
Constraining FSI : Duet



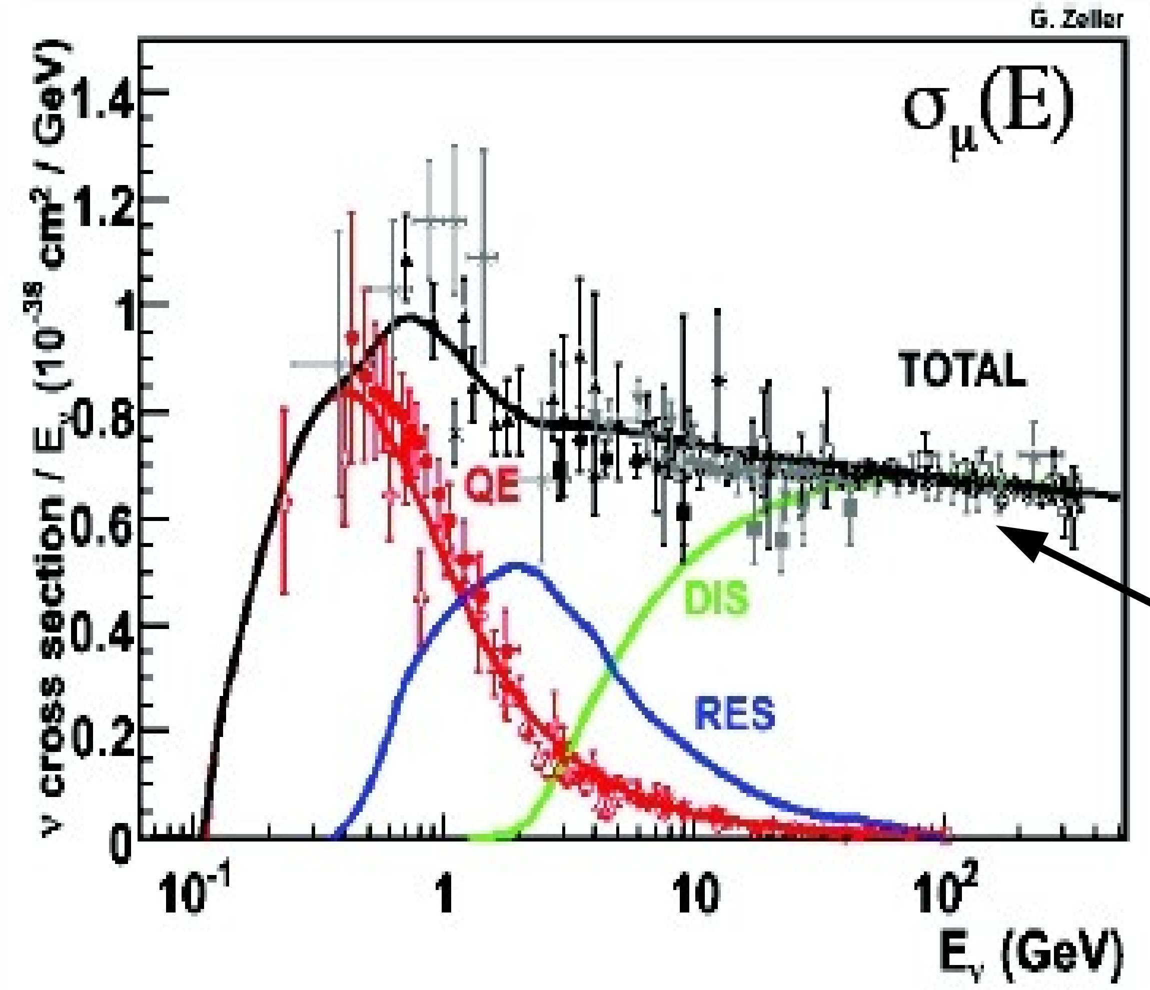
As of NuFact2013

Multipion Production

The so-called Shallow Inelastic region lies around E_ν ~ few GeV and W > 2 GeV. Only light target bubble chamber data exists for this.



Deep Inelastic Scattering



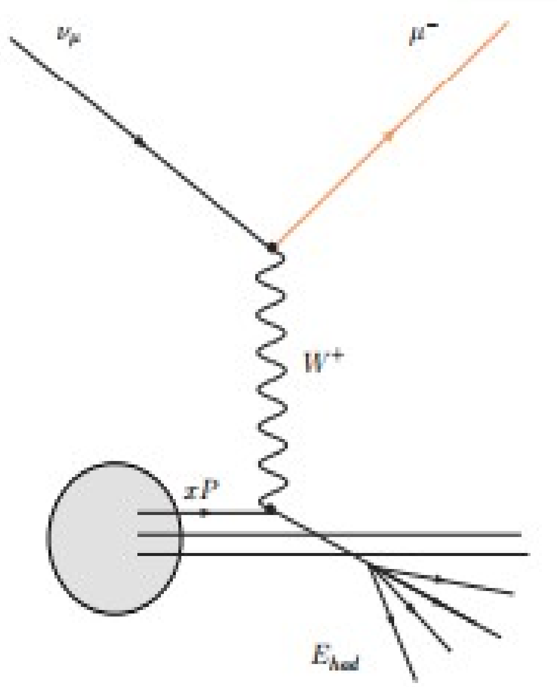
Incoherent scattering off bound quarks, antiquarks and gluons

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

DIS Cross section

Neutrino and antineutrino DIS at high energies has been studied extensively in the 80's and 90's.

$$\frac{d^2\sigma^{\nu(\overline{\nu})}}{dxdy} = \frac{G_F^2 M E_\nu}{\pi(1+\frac{Q^2}{M_W^2})^2}\left[\left(1-y-\frac{Mxy}{2E_\nu}\right)F_2^{\nu(\overline{\nu})} + \frac{y^2}{2}2xF_1^{\nu(\overline{\nu})} \pm y(1-\frac{y}{2})xF_3^{\nu(\overline{\nu})}\right]$$



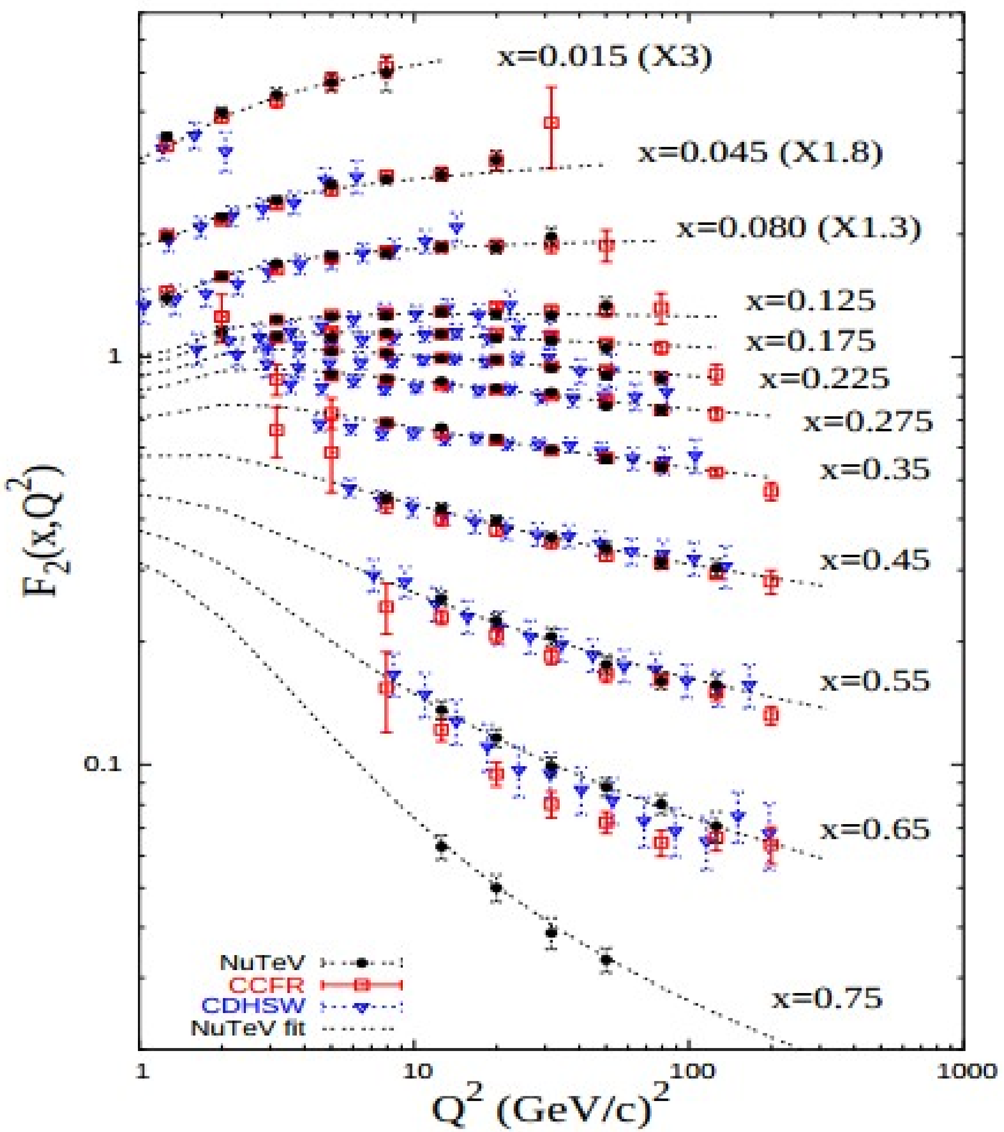
$$2xF_1^{\nu,\bar{\nu}}(x,Q^2)=\sum\left[xq^{\nu,\bar{\nu}}+x\bar{q}^{\nu,\bar{\nu}}\right]$$

$$F_2^{\nu,\bar{\nu}}(x,Q^2)=\sum\left[xq^{\nu,\bar{\nu}}+x\bar{q}^{\nu,\bar{\nu}}+2xk^{\nu,\bar{\nu}}\right]$$

$$F_3^{\nu,\bar{\nu}}(x,Q^2)=\sum\left[xq^{\nu,\bar{\nu}}-x\bar{q}^{\nu,\bar{\nu}}\right]$$

Accessibly only using neutrinos

Data



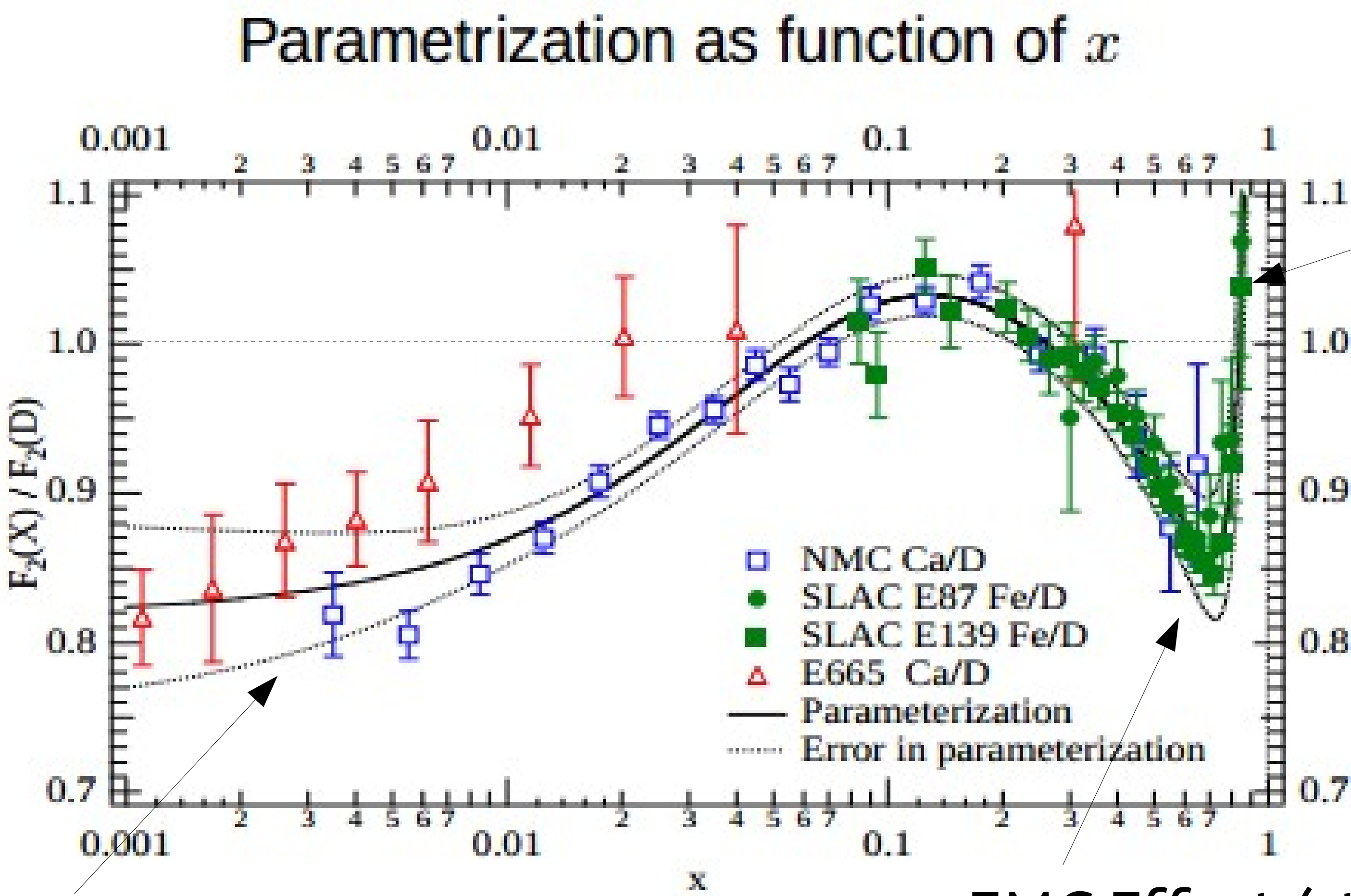
At high energies the data is quite precise

data is corrected from nuclear to nucleon model

(NuTEV,2008)

Nuclear corrections

Electron-Nucleus data is used in electron scattering to study DIS.

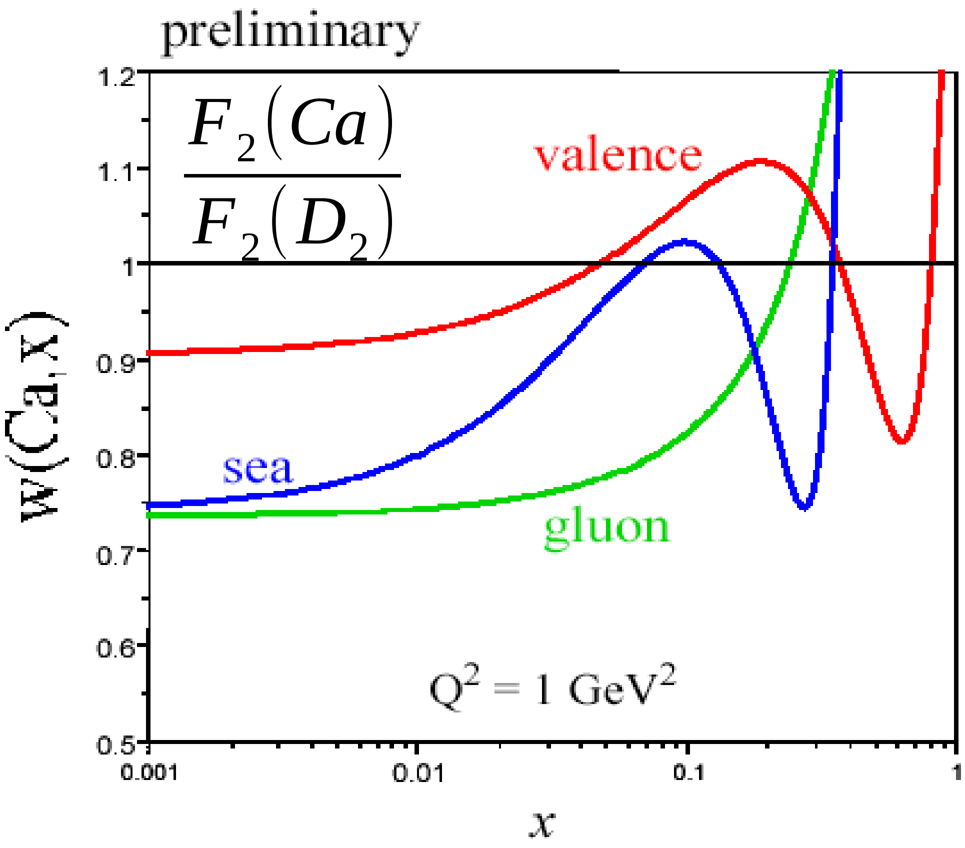


Fermi motion

Shadowing

EMC Effect (still not understood)

Nuclear effects are different in ν



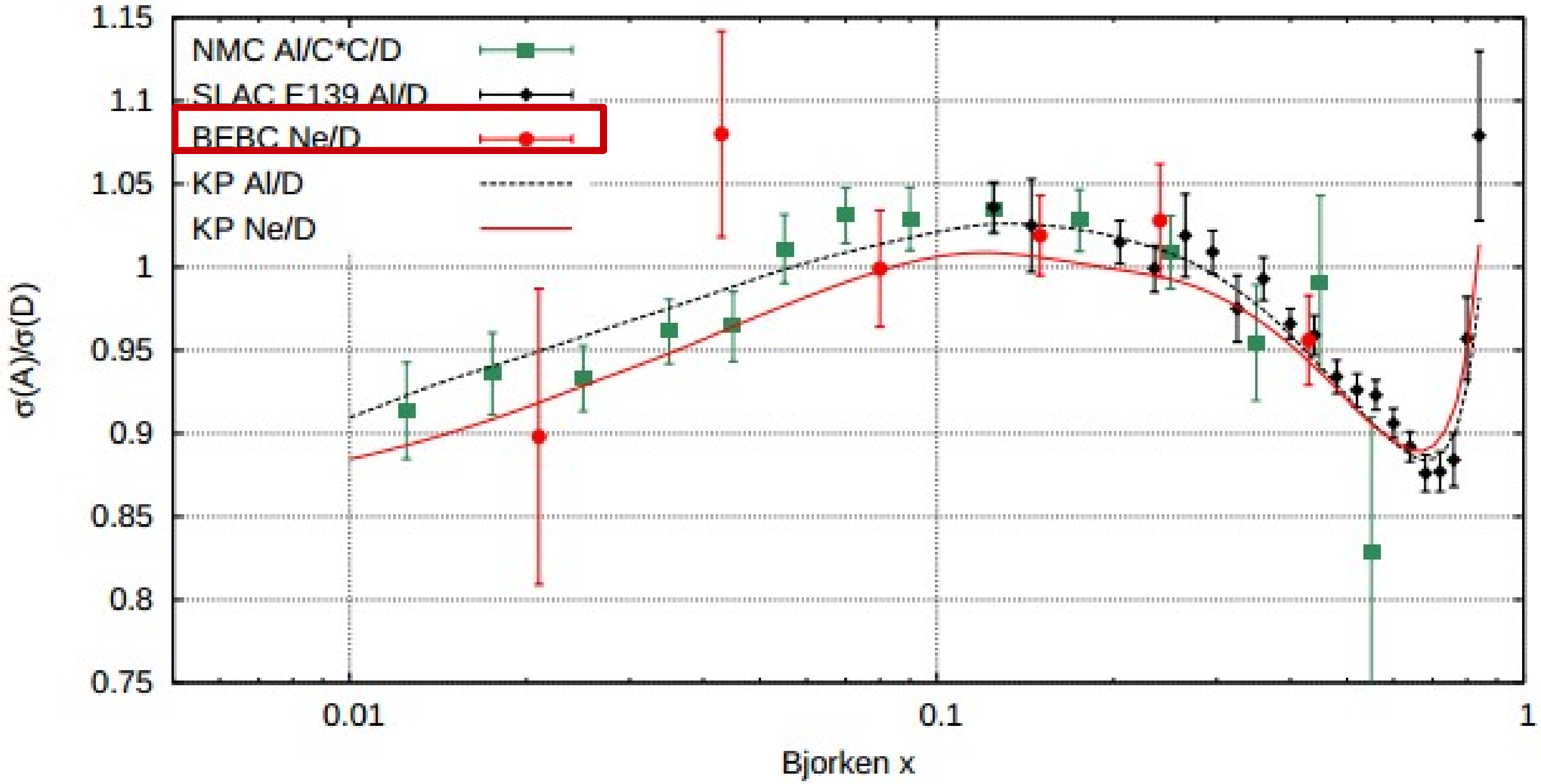
Recent calculations seem to show that the nuclear effects for neutrinos in DIS are significantly different

Presence of the axial current

Nuclear effects for F_2 and xF_3 could also be different

Very little data

BEBC Data



MINERvA will study ν and $\overline{\nu}$ DIS on different nuclear targets

$$\overline{\nu_{\mu}}$$

ν_e