Status of Quasi-elastic Scattering after NuInt11

Jan T. Sobczyk

Institute for Theoretical Physics
Wrocław University

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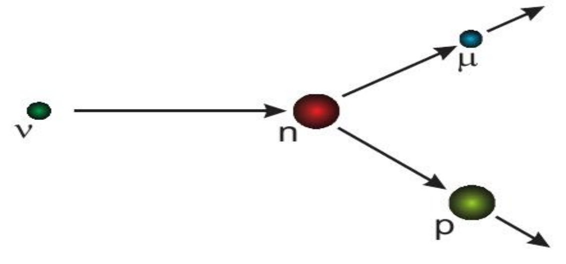
Outline

What is CCQE?

Quasielastic charge current reaction on a free nucleon target

$$\nu_l + n \longrightarrow l^- + p,$$

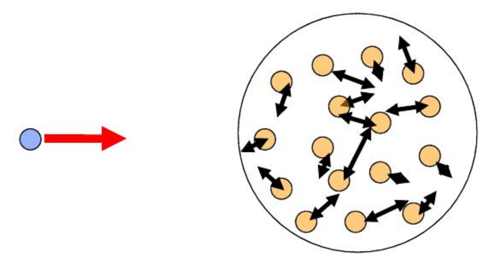
$$\bar{\nu}_l + p \longrightarrow l^+ + n.$$



QE reaction on nuclear targets

The fundamental questions are:

- how reliable is the picture of (quasi-)free nucleons (think about Fermi gas model)?



- what do experimentalists actually measure? which quantities are theorists expected to compute?

QE reaction on nuclear target - MiniBooNE

- only 2 subevents (Cherenkov light from muon and then from electron)
- no assumptions about proton

QE reaction on nuclear target - NOMAD

- 1- and 2-track events (muons and protons with $p > 300$ MeV/c)
- discussion of an impact of *formation zone* effects which modify predictions for the events multiplicities

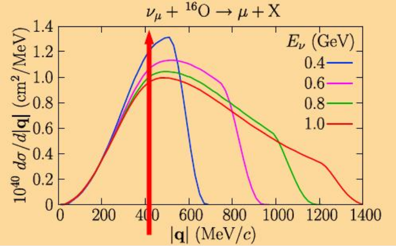
Do MiniBooNE and NOMAD measure the same?!...

Nuclear target: Impulse Approximation

- nucleus composed from individual quasi-free nucleons. How well is this assumption justified?...
- de Broglie wave length of a virtual vector bosons should be at least $\frac{1}{|\vec{q}|} \sim 1$ fermi.
- experience from electron scattering: momentum transfer should be $|\vec{q}| \geq 300 - 500$ MeV/c.

Nuclear target: Impulse Approximation

In neutrino inclusive experimental data there is always a large contribution from low momentum transfers. Below: results obtained within IA.

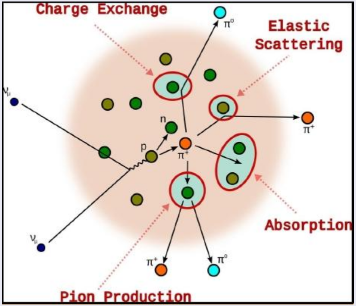


$|\vec{q}| > \omega$ (momentum and energy transfers), $Q^2 = \vec{q}^2 - \omega^2$.

It follows that the region $Q^2 <\sim 0.2$ GeV^2 is subject to large uncertainty.

We can continue with a picture of individual nucleons but at low Q^2 problems are expected.

Nuclear target: FSI effects



Experimentalists distinguish:

- QE-like events (no pions in the final state)
- 1π -like events (a single pion in the final state)
- etc

Pions produced in the primary interaction are subject to: absorption, charge exchange reactions, inelastic reactions (if they only have enough kinetic energy).
FSI effects introduce a lot of uncertainty.

CCQE and CCQE-like

- it is a good idea that experimentalists report results for CCQE-like events
- everybody can apply its own FSI model

but after all ...

- we need also predictions for parameters describing **free** CCQE because they are universal

Basic theory

$$< p(p')|J^\alpha|n(p) >= \cos\theta_C N_{p'} N_p \bar{u}(p')\Gamma^\alpha u(p)$$

$$\Gamma^\alpha = \gamma^\alpha F_V(Q^2) + i\sigma^{\alpha\beta} q_\beta \frac{F_M(Q^2)}{2M} + \gamma^\alpha\gamma_5 F_A(Q^2) + q^\alpha \gamma_5 F_P(Q^2),$$

CVC and PCAC are to be used.
Electromagnetic FF are assumed to be well known.

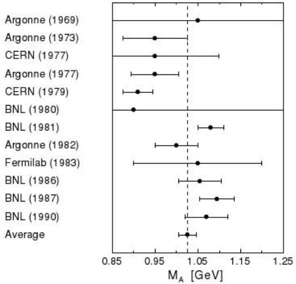
$$F_A(Q^2) = \frac{G_A}{\left(1 + \frac{Q^2}{M_A^2}\right)^2}.$$

Axial mass

- the only unknown quantity is axial mass M_A,
- its value must be determined experimentally,
- M_A determines both the overall integrated cross section and the shape of $\frac{d\sigma}{dQ^2}$,
- because of large flux uncertainty the shape analysis is a preferable way to get the value of M_A.
- current experiment are not precise enough to address a question of a deviation from the dipole form

CCQE axial mass puzzle

Until few years ago it seemed that the measurements converge to a value of the order $M_A \sim 1.03$ GeV.
There is a disagreement between old, mainly deuterium (left), and recent (right) M_A measurements.

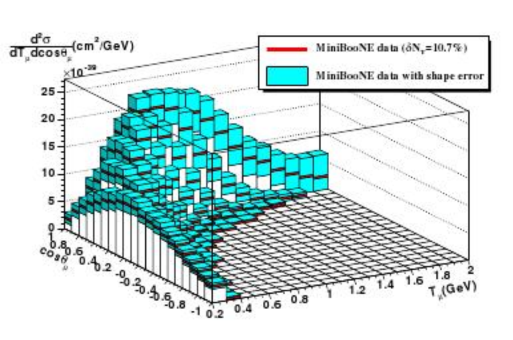


[from Bernard, Elouadrhiri, Meissner]

Experiment	Target	Cut in Q^2 [GeV^2]	M_A[GeV]
K2K[5]	oxygen	$Q^2 > 0.2$	1.2 ± 0.12
K2K[6]	carbon	$Q^2 > 0.2$	1.14 ± 0.11
MINOS[7]	iron	no cut	1.19 ± 0.17
MINOS[7]	iron	$Q^2 > 0.2$	1.26 ± 0.17
MiniBooNE[1]	carbon	no cut	1.35 ± 0.17
MiniBooNE[1]	carbon	$Q^2 > 0.25$	1.27 ± 0.14
NOMAD[8]	carbon	no cut	1.07 ± 0.07

MiniBooNE double differential cross section data

The data is available in the form of double differential cross section in muon kinetic energy and production angle:



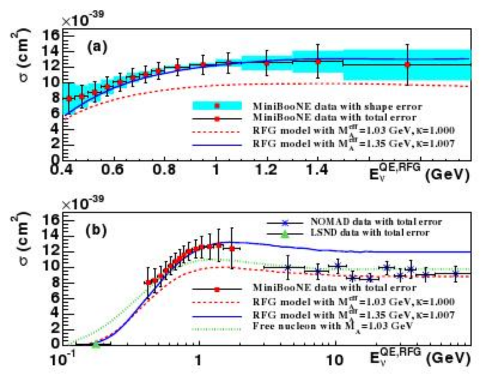
A.A. Aguilar-Arevalo et al.,[MiniBooNE collaboration] Phys. Rev. D81, 092005 (2010)

The best fit value is $M_A^{eff} = 1.35 \pm 0.17$ GeV, $\kappa = 1.007 \pm 0.012$ (see later).

Similar values of M_A^{eff} were obtained both for shape only and for normalized cross section analysis.

MiniBooNE CCQE cross section data

Hypothesis: a large value of M_A^{eff} accounts for other dynamical mechanisms which contribute to the MB's CCQE sample.



If the value of M_A is raised from 1.03 to 1.37, the total CCQE cross section is increased by $\sim 30\%$, the huge effect! NUANCE uses Fermi Gas model...

Theoretical approaches to understand MB data

Basic idea: to remain within the IA regime, but to use nucleus model better than Fermi Gas.

- DPWIA (Distorted Plane Wave Impulse Approximation)

  A.V. Butkevich, Phys. Rev. C82 055501 (2010)

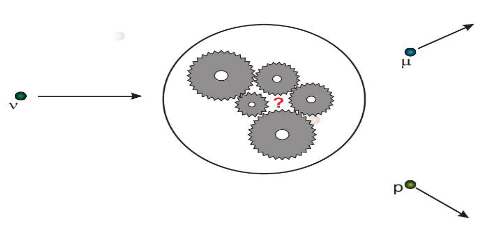
- Spectral Function

  C. Juszczak, JTS, J. Żmuda, Phys. Rev C82 045502 (2010)

In both analyses very similar values of the axial mass were obtained:

- Butkevich: $M_A = 1.37 \pm 0.05$ GeV for RDWIA, and $M_A = 1.36 \pm 0.05$ GeV for FG
- JSŻ: $M_A = 1.34 \pm 0.06$ GeV for SF (with a cut $|\vec{q}| < 500$ MeV/c), and $M_A = 1.35 \pm 0.07$ GeV for FG

What is going on?!



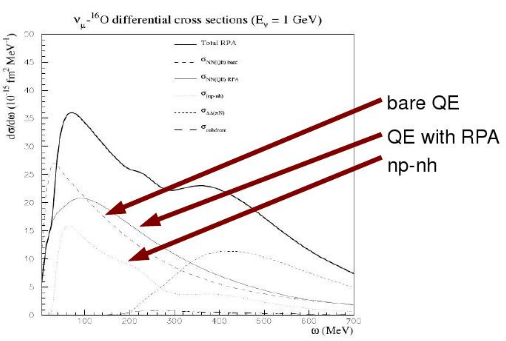
Two body current

The problem of CCQE axial mass leads us to theoretical frameworks going beyond simple theory of CCQE and Impulse Approximation presented before.

- large contribution from two-body current?!
- one of the central themes of NuInt11
- not a new idea in the NuInt community!

Two-body current

The figure below is taken from Jacques Marteau presentation given 10 years ago at ... NuInt01.

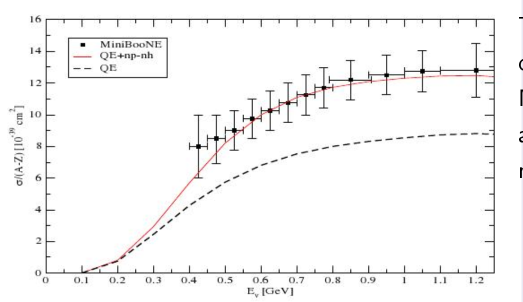


The original idea was put forward by Magda Ericson in 1990: appearance of pion branch, a collective state which decays into a pair of nucleons.
The model (developed by J. Marteau in PhD thesis supervised by J. Delorme) predicts a large contribution from n-particle n-hole excitations

How large?

$\sim$ a half of *bare QE* part!

Martini-Ericson-Chanfray-Marteau model



The anomalous CCQE-like cross section measured by MiniBooNE is explained as a contribution from multinucleon ejection.

M. Martini, M. Ericson, G. Chanfray, J. Marteau, Phys. Rev. **C80** 065501 (2009); ibid **C81** 045502 (2010).

Martini-Ericson-Chanfray-Marteau model

One still needs a comparison with MiniBooNE's double differential cross section.

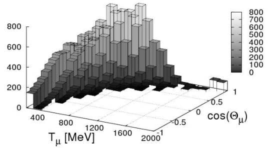


FIG. 7. The difference between the double differential cross section measured by MiniBooNE and prediction from the SF model with $M_A = 1.03$ GeV without rescaling. The units are 10^{-41} cm^2/GeV/nucleon.

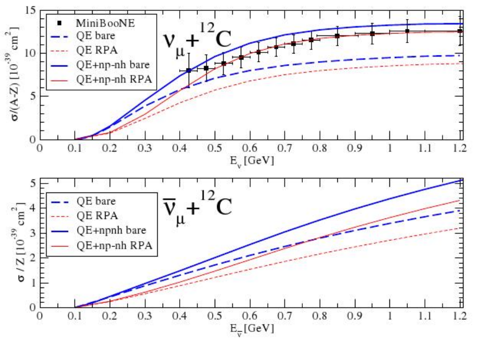
C.J., JTS, J.Żmuda, PRC82 045502 (2010)

A difference between MB measurement and IA predictions with $M_A = 1.03$. np-nh contribution should reproduce this shape. A large fraction of events with backward moving muon!

- in the MEChM model 2p-2h part is not a subject to RPA
- the model is non-relativistic and not reliable for energies larger then ~ 1.2 GeV
- in the MB flux there is a significant component with larger energy...

MEChM model: neutrinos and antineutrinos

The model predicts much smaller effect for antineutrinos:



	ν			$\bar{\nu}$		
	QE	np-nh	QE+np-nh	QE	np-nh	QE+np-nh
bare	7.46	2.77	10.23	2.09	0.52	2.61
RPA	6.40	2.73	9.13	1.60	0.47	2.07

TABLE I: MiniBooNE flux-integrated CC ν_μ-^{12}C and $\bar{\nu}_\mu$-^{12}C total cross sections per neutron and per proton respectively in unit of 10^{-39} cm^2. The experimental CCQE ν_μ-^{12}C value measured by MiniBooNE is 9.429×10^{-39} cm^2 with a total normalization error of 10.7 % [10].

Which is the value of M_A^{eff} from MB $\bar{\nu}_\mu$ CCQE data?!...

Nieves, Ruiz, and Vicente Vacas computations

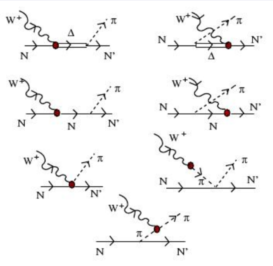
On Feb. 15, 2011 a new paper with 2p-2h contribution to neutrino-nucleus cross section was put on arXive:

J. Nieves, I. Ruiz, and M.J. Vicente Vacas, Phys. Rev. C83 045501 (2011).

The approach is a continuation of works:

A. Gil, J. Nieves and E. Oset, Nucl. Phys. A 627 (1997) 543;

J. Nieves, J. E. Amaro and M. Valverde, Phys. Rev. C 70 (2004) 055503 [Erratum-ibid. C 72 (2005) 019902].

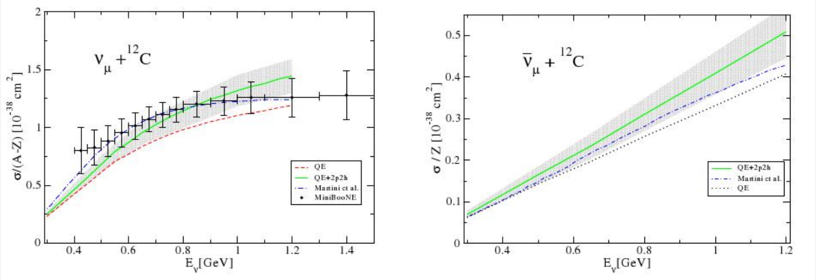


General strategy: calculate W boson self-energy and apply Cutkosky cuts. Contributions from exclusive channels to the inclusive cross section can be evaluated.

On the left: seven vertices used in the computations.

Nieves, Ruiz, and Vicente Vacas computations

Comparison with MiniBooNE $\nu_\mu{}^{12}C$ data and predictions for $\bar{\nu}_\mu{}^{12}C$:



On the left: a difference between *green* and *red* lines. On the right: a difference between *green* and *dotted* lines.

Fractions of 2p-2h contributions in neutrino and antineutrino reactions are of similar size (MEChM model predictions are different).

One could expect a very interesting debate at NuInt11.

New paradigm?...

O. Benhar, P. Coletti, D. Meloni, PRL 105, 132301 (2010)

- within SF approach there is a 2p-2h contribution but not that large
- broad flux average causes problems: CCQE-like events come from different kinematical regions with different reaction mechanisms
- one needs a more flexible model working in the wide kinematical range corresponding to the relevant neutrino energies.

No need for a new paradigm!...

J. Nieves, I. Ruiz, and M.J. Vicente Vacas, arXiv: 1102.2777 [hep-ph]

- SF approach fails to include all the 2p-2h contribution
- the results support the basic picture that emerges from the MEChM model
- MiniBooNE takes np-nh events as CCQE

NuInt11 CCQE experimental talks

MINOS CCQE reactions, N. Mayer (Indiana) 25+5

SciBOONE CCQE reactions, Y. Nakajima (Kyoto) 25+5

Argoneut CCQE reactions, J. Spitz (Yale) 25+5

T2K Charged Current QE Analysis, L. Monfregola (Valencia) 25+5

MiniBooNE CC QE Analysis, J. Grange (Florida) 25+5

MiniBooNE NC/elastic Analysis, R.Dharampalan (BNL) 25+5

MINERVA Charged Current QE Analysis, K. McFarlane (Rochester) 25+5

NuInt11 CCQE theoretical talks

Quasi-Elastic Scattering: A Review, J.S. (Wroclaw) 35+5

Discussion of 2p-2h effects, L. Alvarez-Ruso (Valencia) 20

Nuclear Effects of CC QE Scattering, D. Meloni (Wurzberg) 35+5

Talk and Discussion on New Paradigm for modelling neutrino cross section, O.Benhar (Rome) 40

Unfortunately, the authors of 2p-2h papers were not present.

CCQE at NuInt11

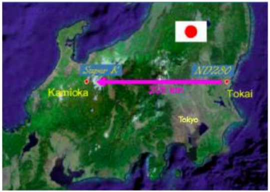
The session was convened by: M. Yokoyama, M. Sorel, D. Schmitz.

In my presentation I will try to focus on new results.

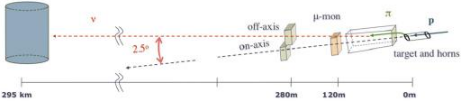
T2K

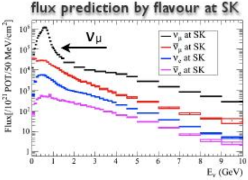
3

T2K (Tokai to Kamioka)



- second generation long baseline experiment
- high intensity off-axis beam from J-PARC to Super-Kamiokande





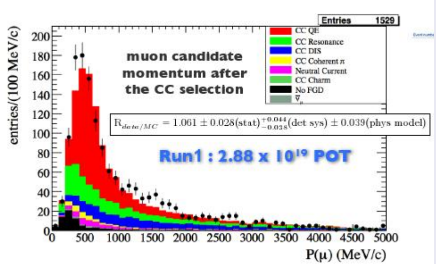
T2K goals:

- measurement of last unknown mixing angle θ_{13} using $\nu_\mu \longrightarrow \nu_e$ appearance
- precise measurement of the atmospheric parameters θ_{23} and Δm_{23}^2 using $\nu_\mu \longrightarrow \nu_\mu$ disappearance

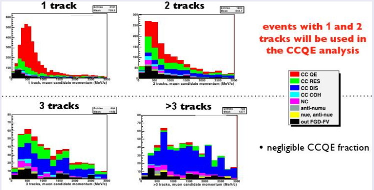
T2K - March 11 quake

T2K - first results

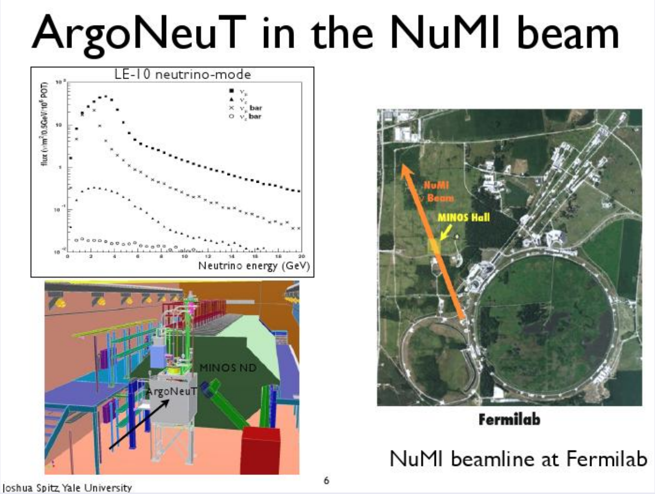
The overall number of ND280 CC events is the only ND280information used in current oscillation analysis.



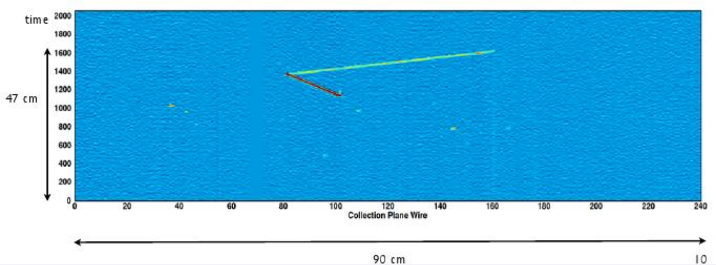
The work on CCQE is under way.



Argoneut


ArgoNeuT in the NuMI beam
LE-10 neutrino-mode
Neutrino energy (GeV)
MINOS ND
ArgoNeuT
NuMI
Beam
MINOS Hall
Fermilab
NuMI beamline at Fermilab
Joshua Spitz, Yale University
6

Argoneut



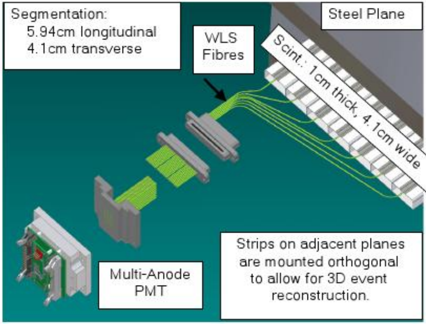
The threshold for reconstructed proton tracks is 50 MeV

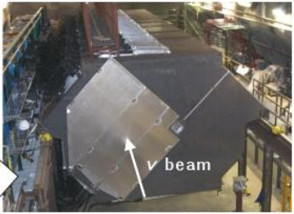
Reaction	#events in AV (~1.35E20 POT)
ν_μ CC	~6600
$\overline{\nu}_\mu$ CC	~4900
ν_μ CCQE	~600
ν_e CC	~130

MINOS

NuInt 2011 Dehradun India

The Near Detector (ND)





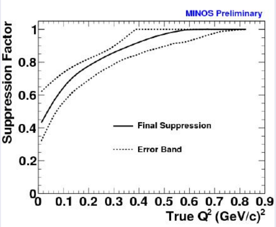
- 1km from target
- 0.98 kton (0.03 kton fiducial)
- 282 steel planes
- Magnetized
  - •P_μ from range and curvature

- High rates so ND is instrumented with deadtime-less QIE electronics.

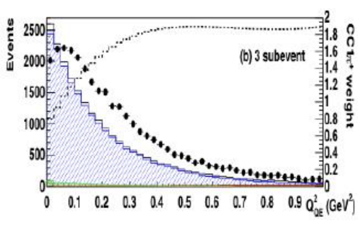
MINOS - RES rescaling function

A lot of work was devoted to estimate a background coming from RES events.

A function rescaling RES MC (NEUGEN) predictions was proposed:

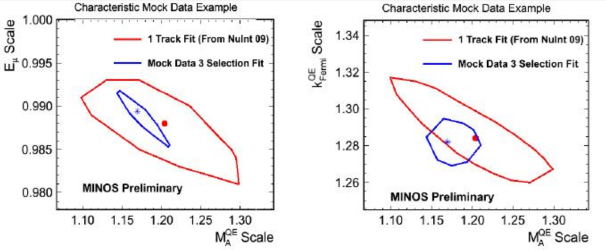


The shape is similar to the function introduced by MiniBooNE:



- But MB corrections make the background much larger!
- MINOS argues that it is only the shape which matters.
- How to understand the very shape of both curves?!...

MINOS - results



- We project a factor of three improvement in the error bar due to the fit when fitting for M_A^{QE}. At NuInt 09 we measured M_A^{QE} to be $M_A^{QE} = 1.19^{+0.09}_{-0.10}$ (fit) from this mock data study we project M_A^{QE} to be $M_A^{QE} = 1.16^{+0.03}_{-0.04}$ (fit) which shows a factor of 3 improvement to the fit part of the error bar.

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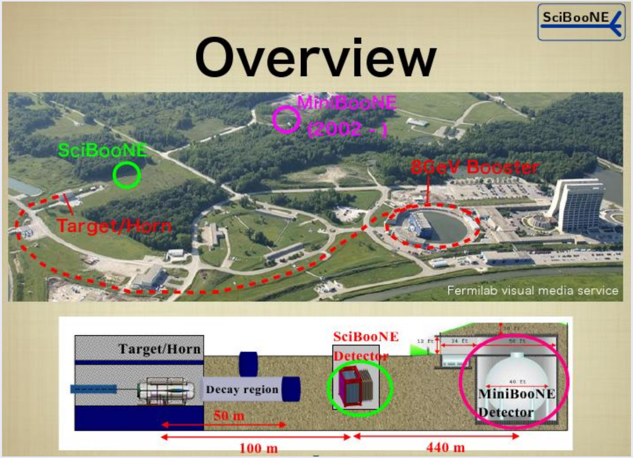
How to estimate an impact of the hypothetical np-nh contribution in the inclusive CC cross section?!...

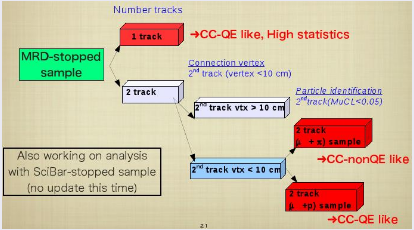
I thank Rik Gran and Nathan Mayer for many clarifications

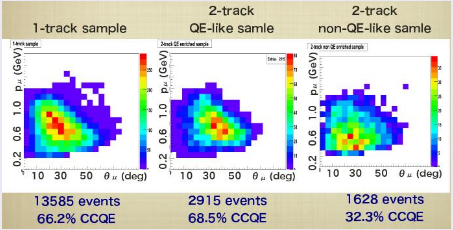
SciBooNE


SciBooNE
Overview
MiniBooNE
(2002 -)
SciBooNE
8GeV Booster
Target/Horn
Fermilab visual media service
Target/Horn
SciBooNE
Detector
Decay region
50 m
MiniBooNE
Detector
100 m
440 m

SciBooNE

CCQE analysis is based on three samples of events





SciBooNE

Fit is done for 13 parameters:

$$N_{ij}^{exp} = F_N \left[\sum_{k}^{n=10} a_k N_{ij}^{QE,k} + a_{bck} N_{ij}^{nonQE} \right]$$

$$N^{nonQE}_{ij,1-track} = (1. - \alpha) \times N^{nonQE}_{ij,1-track},$$

$$N^{nonQE}_{ij,2-track\ QE} = N^{nonQE}_{ij,2-track\ QE} + \alpha \times N^{nonQE}_{ij,1-track}.$$

and the **measured** cross section is equal to

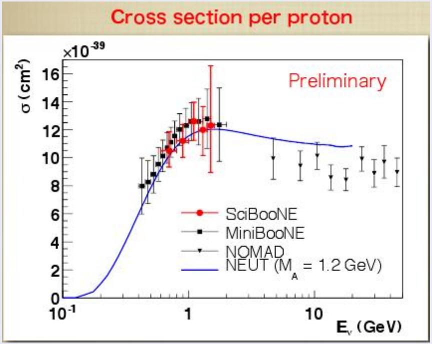
$$\sigma(E_k) = F_N * a_k * \sigma^{MC}(E_k)$$

where $\sigma^{MC}(E_k)$ comes from NEUT ($M_A = 1.21$ GeV).

I thank Morgan Wascko and Yasuhiro Nakajima for clarifications

SciBooNE - results

parameter	value
a(0.6-0.8)	1.01
a(0.8-1.0)	1.00
a(1.0-1.2)	1.09
a(1.2-1.4)	1.01
a(1.4-1.6)	1.04
a_{bck}	1.37
F_N	1.02
α	0.030



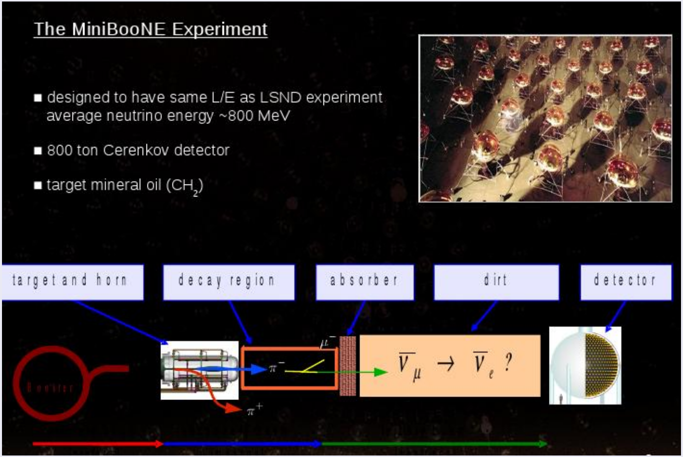
The values of parameters a_k and F_N indicate that SciBooNE measurement can be translated to $M_A \sim 1.25 - 1.3$ GeV.

Anti-neutrino data

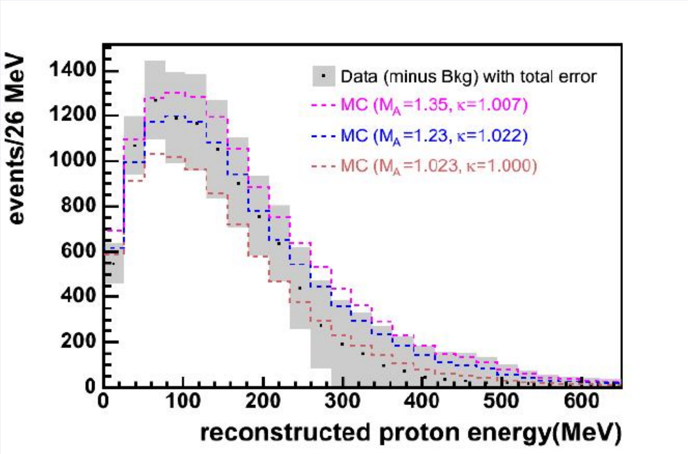
Very important for np-nh hypothesis.

Data from MiniBooNE and from MINERvA (the first MINERvA data ever?).

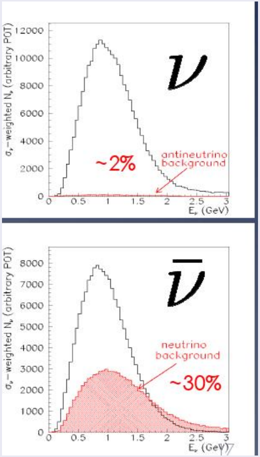
$\bar{\nu}_\mu$ NC El from MiniBooNE



$\bar{\nu}_\mu$ NC El from MiniBooNE



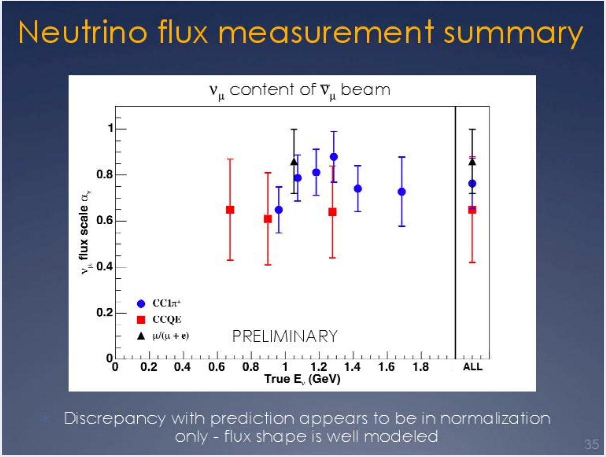
$\bar{\nu}_\mu$ from MiniBooNE



The challange: evaluation of ν_μ contamination.
Three methods:

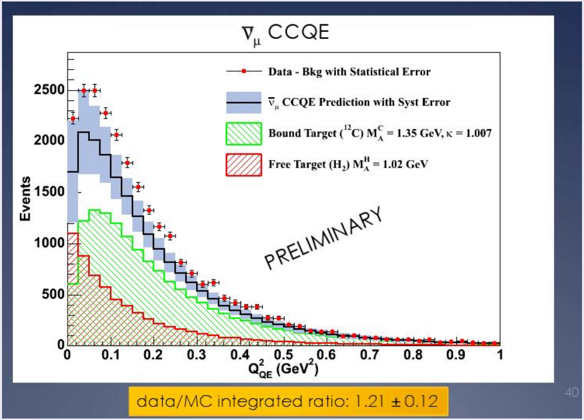
- angular distribution of (anti) muons
- DATA/MC CCπ^+ sample
- μ^- capture

$\bar{\nu}_\mu$ from MiniBooNE



Important consequences: ν_μ flux prediction scaled down by ?∼ 20%; the number of events identified as coming from $\bar{\nu}_\mu$ is automatically increased?...

$\bar{\nu}_\mu$ from MiniBooNE



If we accept an idea of a large contribution from np-nh, in the case of $\bar{\nu}_\mu$ the contribution is even larger !
An argument in favor of Nieves, Ruiz, and Vicente Vacas!

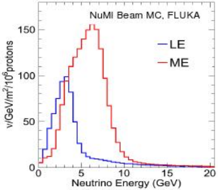
MINERvA

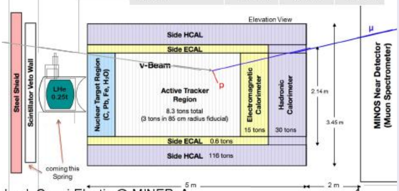
Goals for (Quasi)-Elastic Scattering at MINERvA

- MINERvA was designed in large part to map out features of quasi-elastic cross-sections at moderate energies across a wide range of Q^2
  - Broad range of energies, target nuclei

Fiducial CCQE Interactions/1.2E20 POT

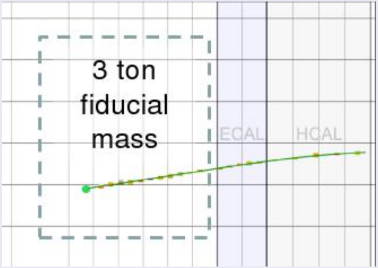
Target	LE ν_μ	LE $\bar{\nu}_\mu$	Mass
Scint. (CH)	58.0K	34.1K	6.4t
Helium	2.6K	1.3K	0.25t
Graphite (C)	1.5K	0.8K	0.17t
Water (H_2O)	3.2K	2.2K	0.4t
Iron (Fe)	9.5K	4.3K	0.97t
Lead	11.4K	3.7K	0.98t



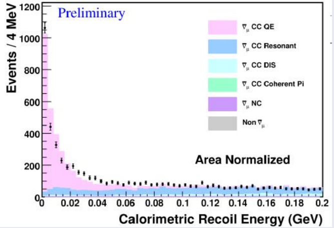


8 March 2011 K. McFarland, Quasi-Elastic @ MINERvA 4

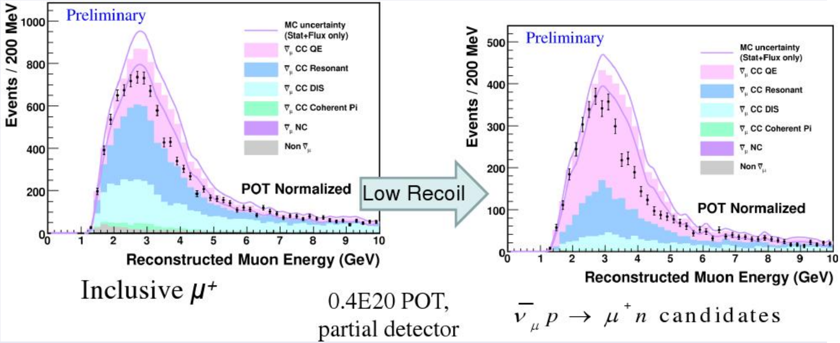
$\bar{\nu}_\mu$ from MINERvA



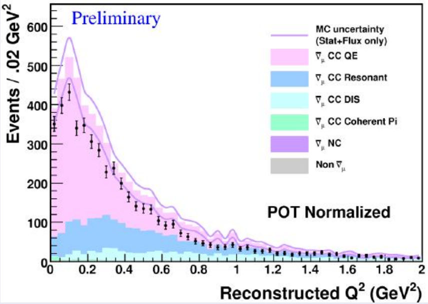
- one (μ^+) track
- no attempt to reconstruct other tracks, only the left energy is summed up
- low recoil energy events are dominated by CCQE



$\bar{\nu}_\mu$ from MINERvA



$\bar{\nu}_\mu$ from MINERvA



Data point are slightly below MC predictions (GENIE with $M_A = 0.99$ GeV)

Hypothetical 2p-2h final states with two low energy neutrons are included in the analysis...

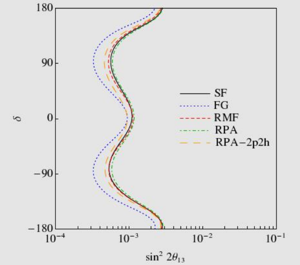
The shapes in Q^2 seem to agree very well...

Unfortunately, **it is impossible to say that there is no access of *CCQE-like* events at large** Q^2. This region is dominated by RES and DIS events.

I thank Kevin McFarland for clarifications

Davide Meloni

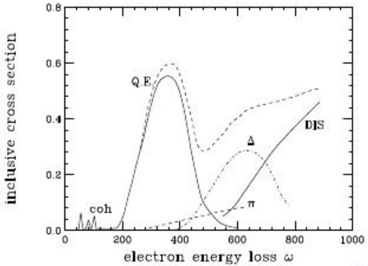
β beam; 5 nucleus models - impact on experimental analysis



- *Summary*
  - *We studied the impact of nuclear effects on the determination of various neutrino parameters*
  - *In particular, we compare the FG results (widely adopted in MonteCarlo codes) with the SF, RMF and RPA approaches*
  - *The different behaviour of the cross sections translates into overestimated sensitivity to* θ_{13} *and* δ_{CP}
  - *Although we focused on Oxygen, the same pattern is observed for other nuclear targets*

Omar Benhar

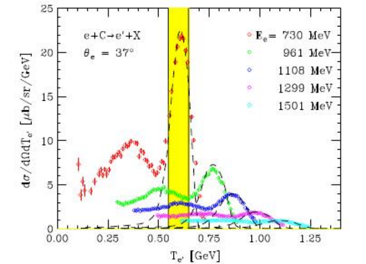
In neutrino interations the lepton kinematics is *not* fully determined. The flux-averaged double differential cross sections picks up contributions iat different neutrino energies, corresponding to a variety of kinematical regimes in which different reaction mechanisms dominate



Omar Benhar - gedanken electron experiment

- Consider the cross section at θ=37° and $550 \leq T_{e'} \leq 650$ MeV (corresponding to the QE peak at 730 MeV)
- Data are available at E_e = 730, 961, 1108, 1299 and 1501 MeV
- Compute the flux averaged cross section using experimental data and assuming that the electron beam energies be distributed according to the MiniBooNE neutrino flux (Σ_{exp})
- Compute the flux averaged cross section using the results of theoretical calculations including QE scattering only (Σ_{th})
- The above procedure yields

$$\frac{\Sigma_{exp}}{\Sigma_{th}} \gtrsim 1.20$$



Explanation: one can see that in the inclusive data there is a contribution from DIP and Δ regions (starting from green curve!).

Omar Benhar - 3 important clarifications

Two particle-two hole final states may be produced through different mechanisms

1. Initial state correlations (taken into account in IA)
2. Final state interactions (not taken into account in IA)
3. Coupling to two-body current (not taken into account in IA)

(*taken into account in IA* means taken into account in spectral function formalism)

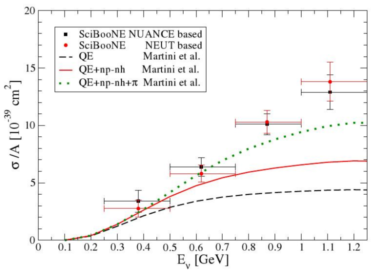
According to the above scheme, Nieves *et al* and Martini *et al* are in fact contributing to the development of a new paradigm

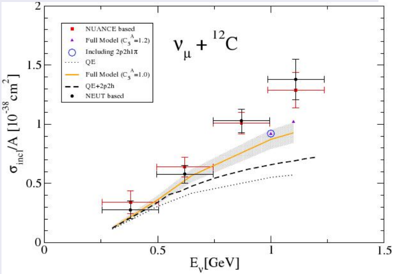
Theoretical predictions must be tested against electron scattering data

(and the electron data should cover the whole interesting kinematical region)

Luis Alvarez-Ruso: 2p2h discussion

Comparison with SciBooNE inclusive $\nu_\mu{}^{12}C$ CC data (left: Nieves et al, right: MChEM model)





Data points include QE, np-nh and π productions. The models give very similar results!

The plots were done by MM and IRS for a purpose of NuInt11 2p-2h discussion!

Luis Alvarez-Ruso: 2p2h or not 2p2h

- (Some) questions:
  - Implications for oscillation measurements:
    - Larger inclusive cross section
    - 2p2h: CCQElike, do they affect Eº reconstruction?
  - Do 2p2h explain MiniBooNE CCQE measurement?
  - If YES, what about NOMAD, MA~1 GeV ???

Outlook

- there are two theoretical computations which predict a large 2p-2h contribution which can mimic CCQE and are able to explain recent large M_A measurements
- the models give different estimations of the size of 2p-2h contribution in the case of anti-neutrino CCQE reaction
- MiniBooNE $\bar{\nu}_\mu$ results seem to support Nieves, Ruiz, Vicente-Vacas approach
- MINERvA $\bar{\nu}_\mu$ analysis is not yet finished.

Altogether...

- WE LIVE IN INTERESTING TIMES!

Thank you!

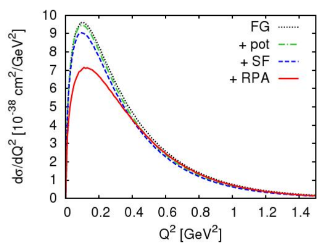
Back-up slides:

Low Q^2 problem

In order to describe low Q^2 deficit of CCQE events modification of Pauli blocking (κ parameter) was proposed.

Typical impact of RPA correlations

Differential cross section in Q^2 for CCQE averaged over MiniBooNE's flux:



FG=Fermi Gas, pot=mean field potential, SF=Spectral Function for outgoing nucleon.

L. Alvarez-Ruso, O. Buss, T. Leitner, U. Mosel, AIP Conf.Proc. 1189 151-156 (2009)

Many-body 2p-2h computations in neutrino scattering

Approach/author	Ground state	Relativistic	Contributions included
SF/Benhar	realistic	no	full hole SF
Marteau/Martini	Local FG	no	only corr diagrams
			RPA for 1p-1h only
Nieves et al	Local FG	no	real part of hole SF
			all 2p-2h diagrams, full RPA
GiBUU/Mosel	Local FG	yes	full particle SF
			real part in hole SF
Amaro et al	FG	yes	MEC, only vector part

MB CCQE data

Technical comments:

- overall flux normalization uncertainty is 10.7%.
- an effective parameter κ is proposed to improve low Q^2 behavior (Pauli blocking effect is made larger)

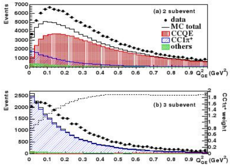


FIG. 7: (color online) Distribution of events in Q^2_{QE} for the (a) 2 and (b) 3 subevent samples *before* the application of the CC1π^+ background correction. Data and MC samples are shown along with the individual MC contributions from CCQE, CC1π^+, and other channels. In (b), the dashed line shows the CC1π^+ reweighting function (with the y-axis scale on the right) as determined from the background fit procedure.

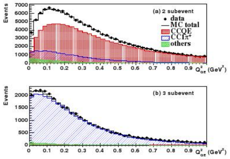


FIG. 8: (color online) Distribution of events in Q^2_{QE} for the (a) 2 and (b) 3 subevent samples *after* the application of the data-based CC1π^+ background constraint and the new CCQE model parameters $M_A^{\rm eff}$ and κ as determined from the CCQE fit procedure described in the text.

- subtracted CCQE-like background is corrected by a function obtained from the 3 subevents data-MC comparison

Do we understand the shape of this function?!...

Short detour: non dipole axial form factor

In early years of neutrino experiments non-dipole axial FF were considered motivated by quark model vector-dominance (QM V-D)

L.M. Sehgal (1979)

$$F_A(Q^2) = \frac{F_A(0)}{1+\frac{Q^2}{M_A^2}} \cdot \exp\left(-\frac{Q^2[GeV^2]}{1+\frac{Q^2}{4M^2}}\right),$$

Various analysis produced the following results for M_A:

Experiment	"Dipole" M_A	"QM V-D" M_A
SKAT (1990)	$1.06 \pm 0.05 \pm 0.14$ (ν)	1.22 ± 0.14
	$0.71 \pm 0.10 \pm 0.20$ ($\bar{\nu}$)	
Serpukhov (1985)	1.00 ± 0.04	1.11 ± 0.10
BNL (1981)	1.07 ± 0.06	1.31 ± 0.16
ANL (1982)	1.00 ± 0.05	1.11 ± 0.16

Comparison of two fits

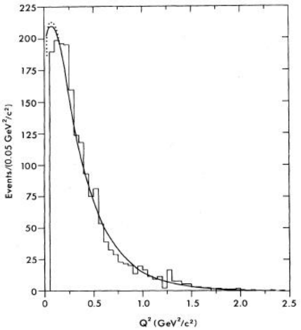


FIG. 4. Weighted Q^2 distribution. The solid curve is from a maximum-likelihood fit to the dipole model ($M_A = 1.00$ GeV/c^2). The dotted curve is from a fit to the AVMD model ($M_A = 1.11$ GeV/c^2).

The QM V-D fit is better by one standard deviation!

ANL

Non dipole axial form factor - references

[SKAT] J. Brunner et al, Z.Phys. C45, 551 (1990)

[Serpukhov] S.V. Belikov et al, Z.Phys. A320, 625 (1985)

[BNL] N.J. Baker et al, Phys. Rev. D23, 2499 (1981)

[ANL] K.L. Miller et al, Phys. Rev D26, 537 (1982)

Non dipole axial form factor

Also monopole and tripole expressions

$$F_A^{monopole}(Q^2) = \frac{F_A(0)}{1 + \frac{Q^2}{M_A^2}}, \quad F_A^{tripole}(Q^2) = \frac{F_A(0)}{(1 + \frac{Q^2}{M_A^2})^3}$$

were confronted with the data:

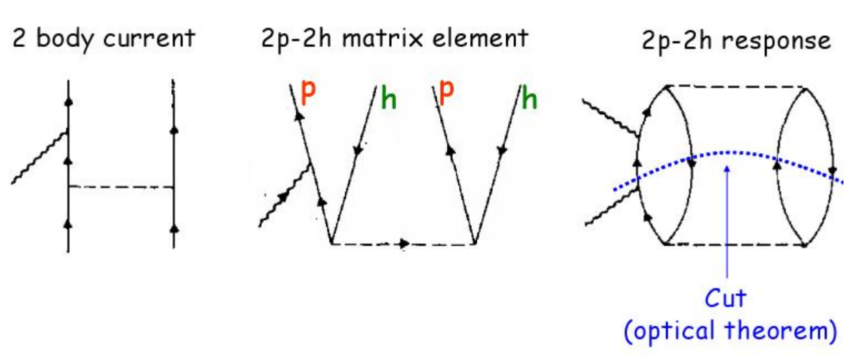
Experiment	"Monopole" M_A	"Tripole" M_A
BNL	0.57 ± 0.05	
ANL	0.54 ± 0.05	1.31 ± 0.07

Both [monopole and tripole] gave worse fits than obtained from the dipole form by at least 1.5 standard deviations

The end of detour

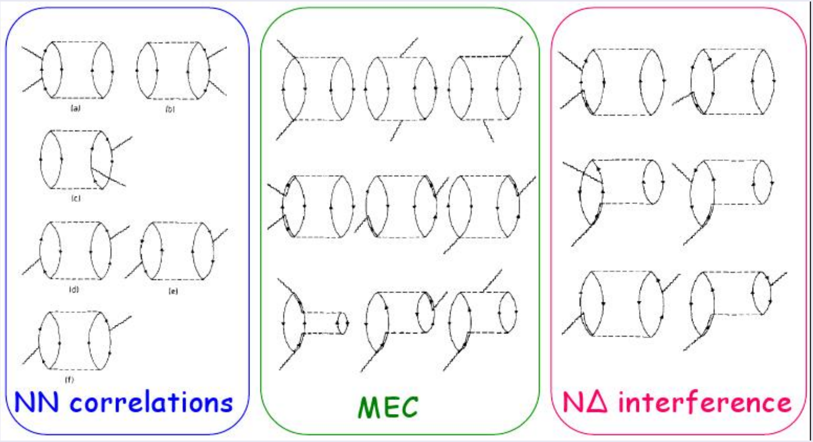
Two-body currents - terminology

There will be a lot of discussions on two-body contribution and it is useful to remind basic concepts and terminology:



from M. Martini talk at Fermilab, Sept. 30, 2010

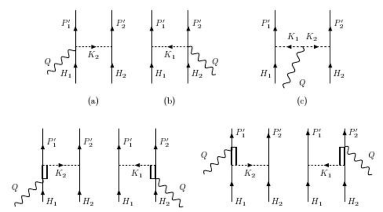
Two-body currents - terminology



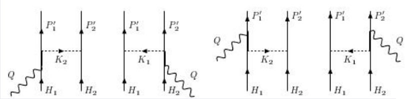
from M. Martini talk at Fermilab, Sept. 30, 2010

Two-body currents - terminology

There will be a lot of discussions on two-body contribution and it is useful to fix terminology:



Meson Exchange Currents (MEC) diagrams



Correlation diagrams

From: J.E. Amaro, C. Maieron, M.B. Barbaro, J.A. Caballero, and T.W. Donnelly, Phys. Rev. C82 044601 (2010)

Spectral Function in action

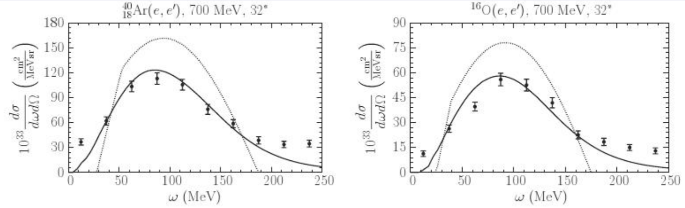


FIG. 7. (Left panel) Comparison of the cross section of GSF (solid line) and the FG model (dotted line) with experimental points for Ar(e, e′) at beam energy 700 MeV and scattering angle 32° [7]. (Right panel) Same but for oxygen. Note that in both cases the similar accuracy is obtained. The value of momentum transfer at the peaks is 371 MeV.

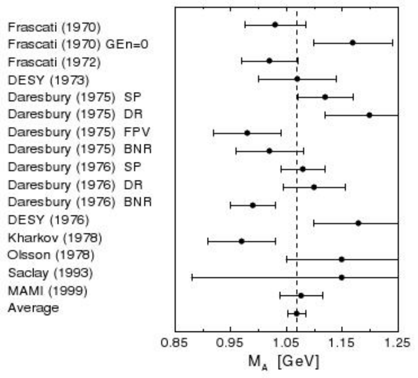
[from: A.M. Ankowski, JTS, Phys. Rev. C 77 044311 (2008)]

Typically, SF based computations reproduce better QE peak. But...

- we compared to inclusive data which include Δ excitation and other dynamics in the DIP region (see later)
- SF computations include effects beyond PWIA which modify the shape of the distribution

Axial mass - pion electroproduction argument

An independent theoretical argument in favour of a low value of M_A coming from PCAC.



The transition amplitude is written in multipole expansion. At the threshold two amplitudes contribute; E_{0+} and L_{0+}. Nambu, Lurie and Shrauner proved the low energy theorem: electric dipole amplitude $E_{0+}^{(-)}$ at the threshold can be expressed in terms of $G_A(Q^2)$.