Theory overview on neutrino-nucleon (-nucleus) scattering

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There is nothing more practical than a good theory (Kurt Lewin)

Outline:

- motivation
- ccqe scattering
- nuclear effects
  - nucleon correlations
- two body current
- pion production
- (neutral current γ production)
- outlook

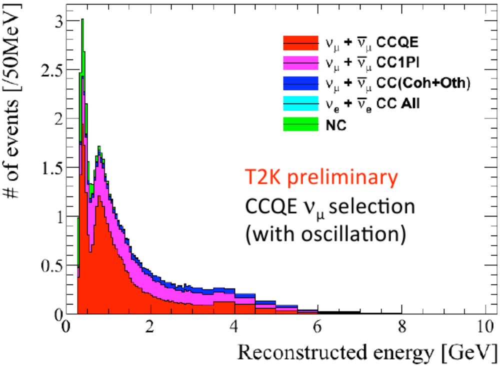
Review articles:

J.A. Formaggio, G.P. Zeller, Rev. Mod. Phys. 84 (2012) 1307

J.G. Morfin, J. Nieves, JTS, Adv. High Energy Phys. 2012 (2012) 934597

A main motivation is to understand correctly the oscillation signal.

Below a T2K example.



Two immediate problems:

- to understand the non-CCQE background
- to translate correctly the *reconstructed energy* into the true *neutrino energy* (the oscillation pattern is a function of E_ν and not of E_{rec}; E_{rec} approximates E_ν using muon information only)

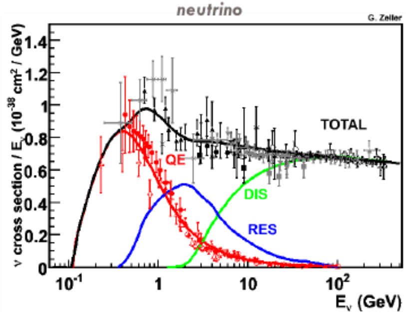
Other specific experimental demands:

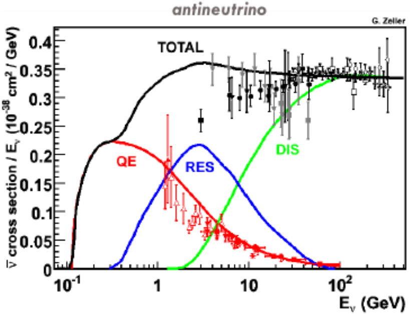
- ν_μ/ν_e cross section ratio
- ^{12}C vrt ^{16}O
- neutral current γ production
- more generally: to improve Monte Carlo generators.

Interest for the hadronic/nuclear physics:

- nucleon strangeness (accessible in NCEl measurements)
- axial form factors of resonances
- validity of Goldberger-Treiman relation
- nucleon-nucleon correlations in nuclei

Vocabulary



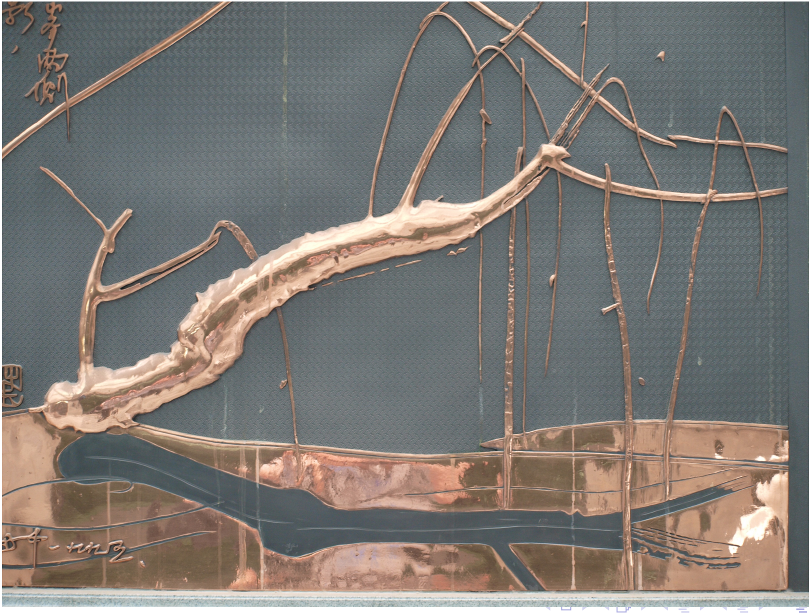


Sam Zeller; based on P. Lipari et al

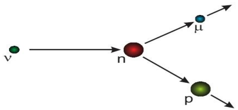
CCQE is $\nu_\mu \; n \to \mu^- \; p$, or $\bar{\nu}_\mu \; p \to \mu^+ \; n$.

RES stands for resonance region e.g. $\nu_\mu \; p \to \mu^- \; \Delta^{++} \to \mu^- \; p \; \pi^+$; one often speaks about SPP - single pion production

DIS stands for: more inelastic than RES.



Charge current quasielastic (CCQE) scattering



$$\nu_l/\bar{\nu}_l(k) \; + N(p) \; \rightarrow l^{\pm}(k') \; + N'(p')$$

$$q^{\mu} \equiv k^{\mu} - k'^{\mu}; \quad Q^2 \equiv -q_{\mu}q^{\mu}.$$

CCQE on free nucleon target

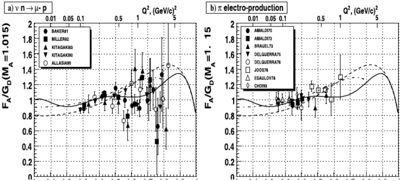
$$< p(p')|J^{\alpha}_{weak}|n(p) >= \bar{u}(p') \left(\gamma^{\alpha} F_V(Q^2) + i\sigma^{\alpha\beta} q_{\beta} \frac{F_M(Q^2)}{2M} - \gamma^{\alpha}\gamma_5 F_A(Q^2) - q^{\alpha}\gamma_5 F_P(Q^2) \right) u(p)$$

- CVC arguments $\Rightarrow$ vector part known from electron scattering
- PCAC arguments $\Rightarrow$ only one independent axial form factor $F_A(Q^2)$
- β decay $\Rightarrow$ $F_A(0) = 1.26$
- analogy with EM and some experimental hints $\Rightarrow$ dipole axial form factor:

$$F_A(Q^2) = \frac{F_A(0)}{(1 + M_A^2/Q^2)^2}$$

- the only unknown quantity is M_A, axial mass.

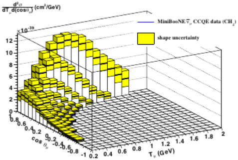
Large CCQE M_A controversy.



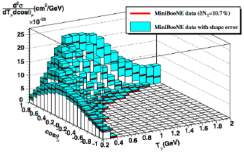
The experimental data is consistent with dipole axial FF and $M_A = 1.015$ GeV.

A. Bodek, S. Avvakumov, R. Bradford, H. Budd

- older M_A measurements indicate the value of about 1.05 GeV
- independent pion production arguments lead to the similar conclusion



$\bar{\nu}_\mu$ CCQE

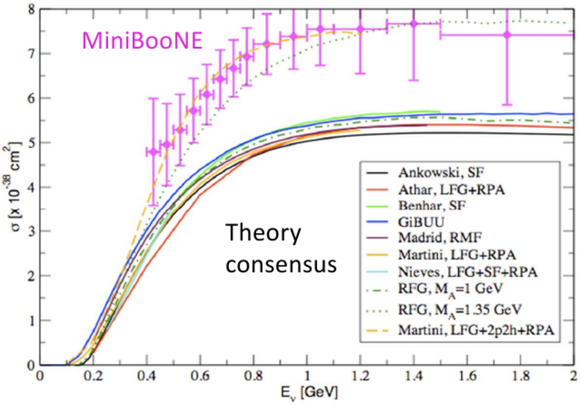


ν_μ CCQE

T. Katori, J. Grange

MiniBooNE reported $M_A \sim 1.35$ GeV.

Large CCQE M_A controversy.



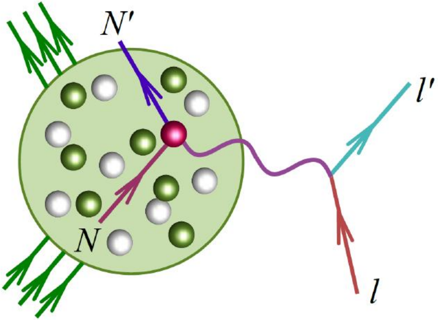
$M_A = 1.35$ GeV translates into much larger cross section than predictions from several theoretical models with a lot of care to cover properly nuclear effects, with $M_A \sim 1.05$ GeV.

G. Garvey


双结生翅成超导
单行苦奔遇阻力
政道先生意
C_{60}

Neutrino-nucleus scattering in the 1 GeV region - a big picture.

Impulse approximation (IA): neutrinos interact with individual bound nucleons.

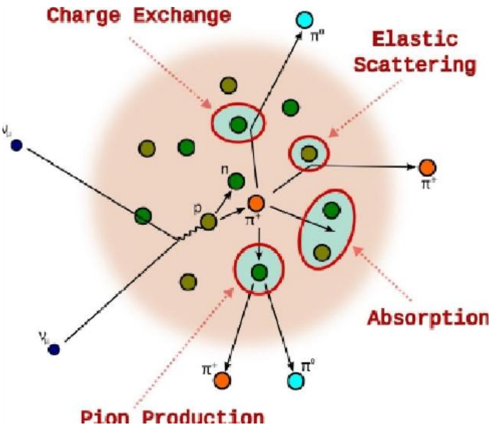


A. Ankowski

Within the IA one needs a joint probability distribution of momenta and binding energies of target nucleons.

ν nucleus interaction is viewed as a two-step process: a primary interaction followed by final state interactions (FSI) effects: before leaving nucleus hadrons undergo reinteractions.

Final state interactions:



T. Golan

Pions...

- can be absorbed
- can be scattered elastically
- (if energetically enough) can produce new pions
- can exchange electic charge with nucleons

There can be two nucleon knock-out events resulting from a primary QE interaction.

Two nucleon knock-out events can also result from pion absorption.

Sophisticated FSI models: FLUKA, GiBUU.

Plane wave impulse approximation (neglecting FSI):

The final state is assumed to be (a nucleon of momentum $\vec{p}'$ is decoupled from the remnant nucleus):

$$|f(p_f)>=|R(p_R)>\otimes|p'>.$$

It can be show that:

$$\frac{d^2\sigma}{d\omega dq}=\frac{G_F^2\cos^2\theta_C q}{4\pi E_\nu^2}L_{\mu\nu}W^{\mu\nu}$$

$$W^{\mu\nu}=\int dE\int d^3p\frac{\delta(\omega+M-E-E_{p'})}{E_pE_{p'}}H^{\mu\nu}(\vec{p}+\vec{q},\vec{p})P(E,\vec{p})$$

$L_{\mu\nu}=2\left(k_\mu k'_\nu+k'_\mu k_\nu-k\cdot k'g_{\mu\nu}-i\varepsilon_{\mu\nu\kappa\lambda}k^\kappa k'^\lambda\right)$, $H^{\mu\nu}$ is the free nucleon hadronic tensor, k^μ, k'^μ are neutrino and charged lepton four-momenta, $q^\mu\equiv k^\mu-k'^\mu=(\omega,\vec{q})$ is four-momentum transfer.

$P(E,\vec{p})$ is spectral function.

$$P(E,\vec{p}) \equiv \sum_R \delta(M_A - E_R - M + E)| < R(\vec{p}_R)|a(\vec{p})|i(M_A) > |^2,$$

$$\frac{1}{A}\int d^3p \int dE \; P(E,\vec{p}) = 1.$$

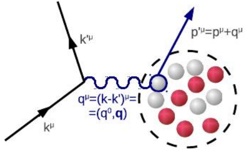
$\frac{1}{A}P(E,\vec{p})$ has a probabilistic interpretation.

- in the Fermi gas model, $P(E,\vec{p})$ is characterized by two parameters: Fermi momentum k_F and binding energy B:

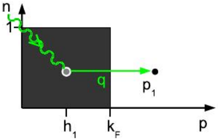
$$P(E,\vec{p}) = \frac{3A}{4k_F^3}\Theta(k_F - |\vec{p}|)\delta(E + \sqrt{M^2 + \vec{p}^2} - B)$$

- $\vec{p}$ is a target nucleon momentum
- typically both k_F and B are fitted to electron scattering data (width and position of the quasielastic peak)
- alternatively one can think that k_F is a function of a (local) nuclear density.

Fermi gas model is a useful first approximation to model nucleus target in the QE region:



Fermi Gas: noninteracting nucleons, all states filled up to k_F



- FG is used in the major MC neutrino event generators (GENIE, NEUT, NUANCE)
- FG fails to reproduce electron-nucleus transverse and longitudinal response functions (corresponding to transverse and longitudinal polarizations of virtual photon).

Nuclear correlations

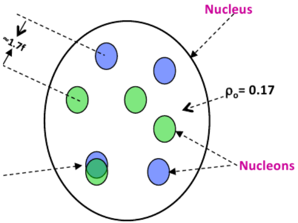
Fermi gas model completely neglects nucleon-nucleon correlations.

From electron scattering experiments we know that $\sim 20\%$ of time nucleons are strongly correlated in pairs with large $\sim$ back to back momenta.

- for $|\vec{p}| \leq\sim 600$ MeV/c corrections are expected to be due to tensorial nuclear force and pairs to be deuteron like with isospin $I = 0$ (proton-neutron only).

A typical distance between nucleon is 1.7 fm

A correlated pair:

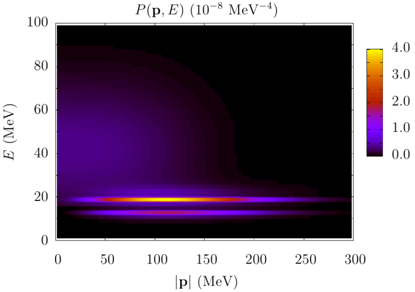


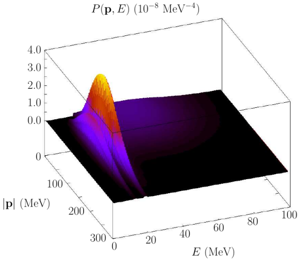
A. Bodek

Three nucleon correlations are very unlikely (0.5%).

Correlations are accounted for in the spectral function (SF) formalism.

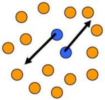
Below, the oxygen SF evaluated by Omar Benhar:





Shell model orbitals are clearly seen.

	$1s_{1/2}$	$1p_{3/2}$	$1p_{1/2}$
E	45	18.44	12.11



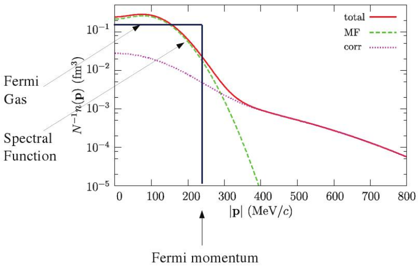
Contribution from correlated large momentum pairs is included.

$P(E, \vec{p})$ contains a lot of information about nucleus:

$$n(\vec{p}) = \int dE \; P(E, \vec{p}) = \sum_R |< R(p_R)|a(\vec{p})|i(M_A) > |^2 =$$

$$= < i(M_A)|a^\dagger(\vec{p})a(\vec{p})|i(M_A) >$$

is nucleon momentum probability distribution.



- mean field (MF) and short range correlation (corr) contributions are shown separately.
- high momentum tail, absent in the FG model, comes from correlated nucleon pairs

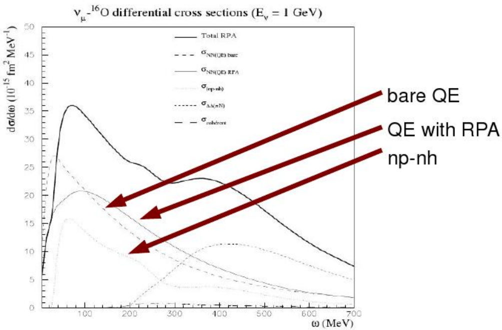
Multinucleon knock-out contribution?

- two-nucleon and one-nucleon knock out events are undistinquishable in the MB detector (typically, nucleons kinetic energy is below the Cherenkov threshold); perhaps there are multinucleon knock-out events in the MB CCQE selection?!
- we recognized two sources of such events:
  - FSI effects
  - SF predicts that there are events with two-nucleon knock out even without FSI effects (one nucleon is merely a spectator)
- both do not resolve the large M_A puzzle, is there something else?
- hypothesis: there are is a large two-body current multinucleon knock out contribution to the neutrino cross section in the scattering of 1 GeV neutrinos on nucleus targets

WARNING: the two body current contribution is basically distinct from SF, but nucleon correlations seem to play a very important role.

Marteau (developed later by M. Martini) model

The figure below is taken from the Jacques Marteau seminar given 12 years ago at NuInt01.



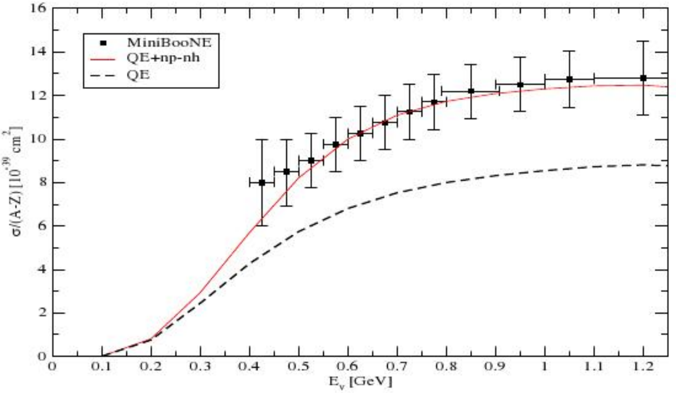
The original idea was put forward by Magda Ericson in 1990: appearance of pion branch, a collective state which decays into a pair of nucleons.

The model developed by J. Marteau in his PhD thesis (1998) supervised by J. Delorme predicts a large contribution from n-particle n-hole excitations.

How large?
$\sim$ a half of *bare QE* part!

The model was almost forgotten for $\sim$ 8 year and reintroduced to the community by Marco Martini.

The solution of the MB large axial mass puzzle?



M. Martini, G. Chanfray, M. Ericson, J. Marteau

Two body current in the electron scattering

- a necessity of the two body current follows from the continuity equation:

$$\vec{q}\cdot\vec{J} = [H, \rho], \qquad H = \sum_j \frac{\vec{p}_j^{\,2}}{2M} + \sum_{j<k} v_{jk} + \sum_{j<k<l} V_{jkl}\,.$$

$$\vec{q}\cdot\vec{J}_j^{(1)} = [\frac{\vec{p}_j^{\,2}}{2M}, \rho_j^{(1)}], \qquad \vec{q}\cdot\vec{J}_{jk}^{(2)} = [v_{jk}, \rho_j^{(1)} + \rho_k^{(1)}].$$

- in the context of electron scattering the problem studied over 40 years
- an example: relativistic computations by M.J. Dekker, P.J. Brussaard, J.A. Tjon, Phys. Rev. C49 (1994) 2650.

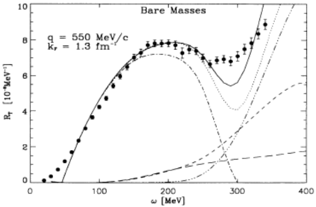
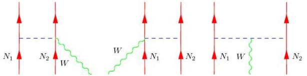


FIG. 15. Comparison of the combined transverse response (solid line) of the quasifree knockout (dash-dotted line), the pion production (dash-triple dotted line) and the full two-body knockout (dashed line) with the data of kinematics I for ^{56}Fe. Also displayed is the static-limit result for the two-body knockout contribution (long-dashed line). Finally, the dotted line shows the combined response one would obtain replacing the full two-body results with the SL two-body results. The data are taken from [5].

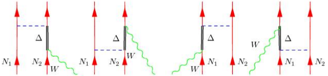
Two body current contributes mostly to the transverse response function

Two body current provides a lot of strength in the dip region between the QE and Δ peaks (dashed line).

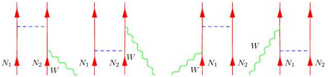
Two body current neutrino computations



Contact and *pion-in-flight* diagrams



Δ-Meson Exchange Current diagrams



Correlation diagrams

- since the pioneer study of Martini et al other groups developed various models (IFIC, superscaling, relativistic Green function)
- microscopic models vary in many details but they are based on (local) Fermi gas model and include contributions from the set (or a subset) of the Feynman diagrams shown on the left
- details: see slides of J. Nieves talk, WG2

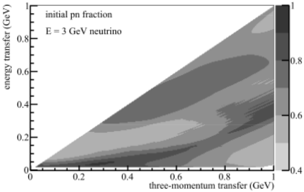
Also effective models were proposed (transverse enhancement (discussed in Dave's talk), GiBUU, GENIE).

Terminology: two body current, MEC, np-nh usually mean the same.

Two body current neutrino computations

- inclusion of the two body current contribution leads to good agreement with the MB CCQE data with $M_A \sim 1.05$ GeV.
- neutrino energy unfolding procedures should be accordingly modified
- difficult to get predictions for final state nucleon momenta (JTS, PRC86, 015504 (2012)), important ArgoNeut data discussed in Dave's talk

Microscopic model prediction for isospin of the initial state nucleons:



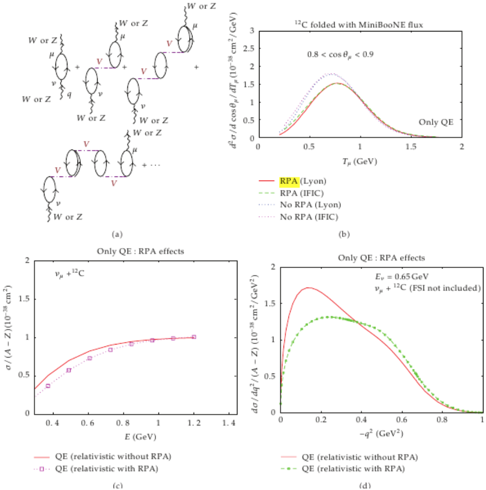
R. Gran, J. Nieves, F. Sanchez, M.J. Vicente-Vacas

The average fraction of p-n pairs is 67%.

Microscopic models can be extended to energies up to 10 GeV (R. Gran, J. Nieves, F. Sanchez, M.J. Vicente-Vacas, arXiv:1307.8105 [hep-ph])

- important role of correlations introduced within the random phase approximation (RPA) approach and 2p-2h contribution
- RPA brings in a strong suppression at $Q^2 \sim 0$ (a factor of 0.6) and some enhancement for $Q^2 \geq 0.4$ GeV^2.

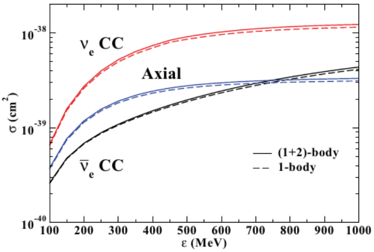
Random phase approximation (RPA)



- RPA accounts for long range correlations treated in the medium polarization like fashion
- an effective ph-ph interaction is used of the Landau-Migdal type
- IFIC (Nieves et al) and Lyon (Martini et al) results are very similar.

Beyond Fermi gas ground state computations

Two body current contribution to neutrino-deuteron scattering:



G. Shen, L.E. Marcucci, J. Carlson, S. Gandolfi, R. Schiavilla

- Smaller than 10% ($\sim 6-7\%$) enhancement due to two-body current contribution.
- plane waves approximation for final state nucleons is very good.

Beyond Fermi gas ground state computations

- results from J. Carlson, J. Jourdan, R. Schiavilla, I. Sick, Phys. Rev. C**65** (2002) 024002 for electron scattering suggest that it is very important to consider a realistic ground state
- non-relativistic computations done for light nuclei: ^{3}H, ^{4}H and ^{6}Li in the language of Euclidean responses and sum rules
    - almost all the enhancement of the strength due to two-body current comes from proton-neutron, and not from proton-proton or neutron-neutron pairs
    - when ground state correlations are neglected (Fermi gas model) the extra strength due to two-body current contributions becomes very small.


核子重如牛對撞生新態

Single pion production (SPP) channels.

In the 1 GeV energy region most of the cross section comes from $\Delta(1232)$ excitation:

$$\nu_l \; N \to l^- \; \Delta \to l^- \; N' \; \pi .$$

The understanding of SPP is surprisingly poor:

- the axial part of the nucleon-$\Delta(1232)$ transition matrix element is not well known

$$\left\langle \Delta^{++}(p') \right| V_\mu \left| N(p) \right\rangle = \sqrt{3}\bar{\Psi}_\lambda(p') \left[g^\lambda_{\ \mu} \left(\frac{C_3^V}{M}\gamma_\nu + \frac{C_4^V}{M^2} p'_\nu + \frac{C_5^V}{M^2} p_\nu \right) q^\nu - q^\lambda \left(\frac{C_3^V}{M}\gamma_\mu + \frac{C_4^V}{M^2} p'_\mu + \frac{C_5^V}{M^2} p_\mu \right) \right] \gamma_5 u(p)$$

$$\left\langle \Delta^{++}(p') \right| A_\mu \left| N(p) \right\rangle = \sqrt{3}\bar{\Psi}_\lambda(p') \left[g^\lambda_{\ \mu} \left(\gamma_\nu \frac{C_3^A}{M} + \frac{C_4^A}{M^2} p'_\nu \right) q^\nu - q^\lambda \left(\frac{C_3^A}{M}\gamma_\mu + \frac{C_4^A}{M^2} p'_\mu \right) + g^\lambda_{\ \mu} C_5^A + \frac{q^\lambda q_\mu}{M^2} C_6^A \right] u(p).$$

$\Psi_\mu(p')$ is the Rarita-Schwinger field, and $u(p)$ is the Dirac spinor.

C_3^V, C_4^V, C_5^V are known from pion electroproduction due to CVC.

Single pion production, the axial current:

- typically one sets $C_3^A(Q^2) = 0$,
- Adler model suggests $C_4^A(Q^2) = -C_5^A(Q^2)/4$,
- PCAC implies $C_6^A(Q^2) = \frac{M^2}{m_\pi^2 + Q^2} C_5^A(Q^2)$,
- typically one assumes $C_5^A(Q^2) = C_5^A(0)\left(1 + \frac{Q^2}{{M_{A,RES}}^2}\right)^{-2}$.
- the value of $C_5^A(0)$ ...
  - is either evaluated from the *off-diagonal Goldberger-Treiman relation*

$$C_5^A(0) = \frac{g_{\pi N\Delta} f_\pi}{\sqrt{6}M} \simeq 1.15,$$

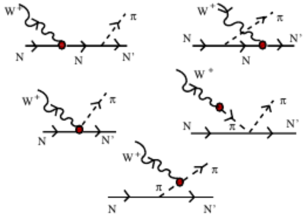
  - or is treated as a free parameter.

Altogether one or two free parameters.

Single pion production: nonresonant background contribution.

In order to compare to the data nonresonant contribution must be included.

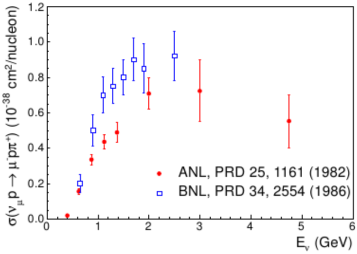
The state of art background model based on chiral field theory:



E. Hernandez, J. Nieves, M. Valverde

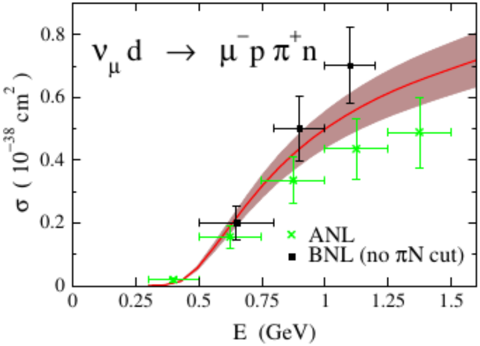
Relative phases of $\Delta(1232)$ and background terms should better be adjusted in order to satisfy the Watson theorem.

The data quality (old ANL and BNL deuteron bubble chamber experiments) is rather poor:



Ph. Rodrigues

Single pion production. Reconciling ANL and BNL data.



E. Hernandez, J. Nieves, M. Valverde

Hernandez et al obtained from the joint ANL and BNL data fit (including also deuteron nuclear effects) $C_5^A(0) = 1.0 \pm 0.11$ and $M_{A,RES} = 0.93 \pm 0.07$ GeV.

Single pion production on nuclear targets

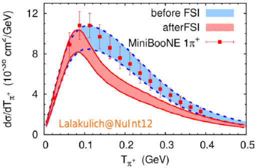
In order to compare with the recent data nuclear effects must be accounted for.

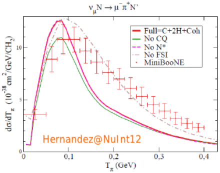
Nuclear effects and larger neutrino energies (beyond $\Delta(1232)$ region) introduce many theoretical complications:

- $\Delta(1232)$ self-energy (Oset-Salcedo model is a common tool)
- pion absorption and charge exchange reactions inside nucleus
- axial form factors for heavier resonances are not known (educated guesses must be done)
- two pion production channels (with a subsequent pion aborption) contribute.

Single pion production on nuclear targets

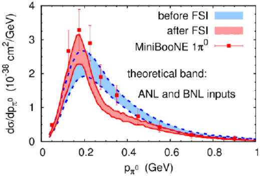
- State of the art calculations describe better the data without FSI



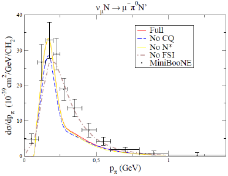


- Transport
- 13 resonances
- Resonance propagation
- contribution from DIS

- Cascade
- 2 resonances
- No resonance propagation
- No DIS



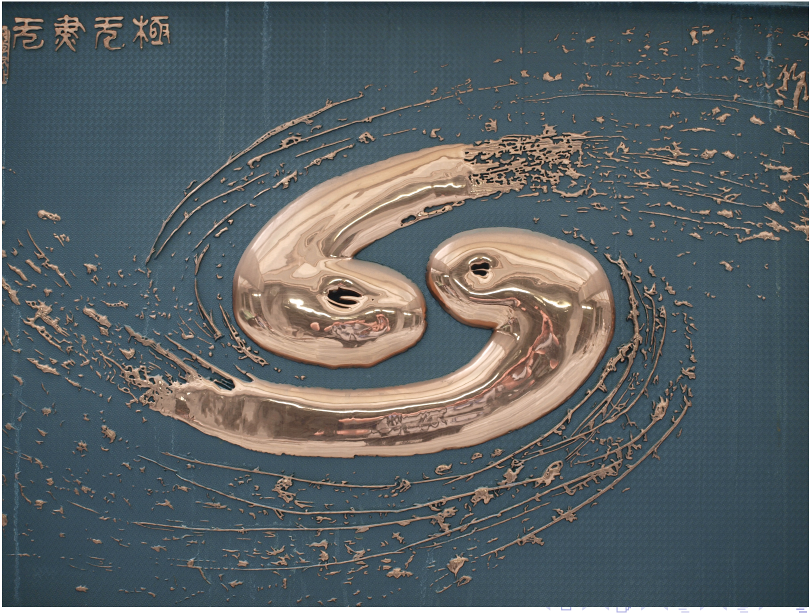
Lalakulich@NuInt12



Hernandez@NuInt12

The data/theoretical models comparison is very puzzling: better agreement is reached without FSI effects.

- ? deficiency of the neutrino-nucleon SPP model
- ? FSI
- ? two body current pion production (correlations again?!)

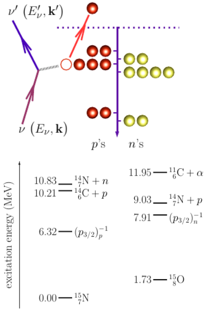


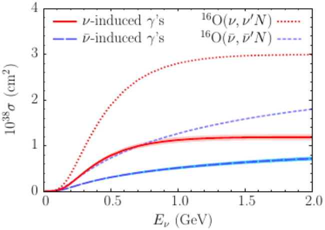
Techniques discussed before can be used in other problems

Neutral current γ production

Spectral function contains a mean field contribution from the proton/neutron orbitals and enables computation of low energy NC γ rays from nucleus deexcitation.

$$\sigma_\gamma = \sigma(\nu + {}^{16}_{8}O \rightarrow \nu + \gamma + Y + N) = \sum_\alpha \sigma(\nu + {}^{16}_{8}O \rightarrow \nu + X_\alpha + N) Br(X_\alpha \rightarrow \gamma + Y).$$

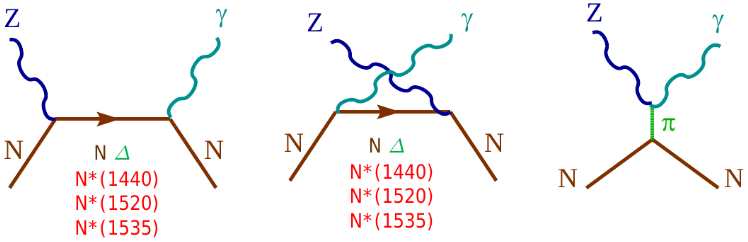




Can be used to estimate NCEl cross section.

A. Ankowski, O. Benhar, T. Mori, R. Yamaguchi, M. Sakuda

NC γ production (larger energies).



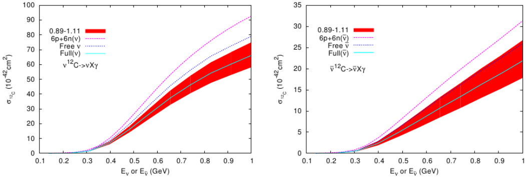
Theoretical framework:

- Relativistic Local Fermi Gas $p_F(r) = [\frac{3}{2}\pi^2\rho(r)]^{1/3}$
- Fermi motion $f(\vec{r},\vec{p}) = \Theta(p_F(r) - |\vec{p}|)$
- Pauli blocking $P_{\text{Pauli}} = 1 - \Theta(p_F(r) - |\vec{p}|)$
- In-medium modification of the $\Delta(1232)$ resonance

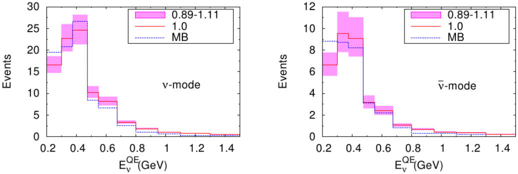
$$\Gamma_\Delta \rightarrow \tilde{\Gamma}_\Delta(\rho) - 2\text{Im}\Sigma_\Delta(\rho)$$

NC γ production (larger energies) (cont.)

Model predictions with error bands:



A possible impact on the MiniBooNE analysis:

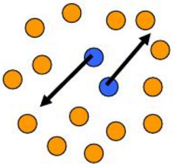


L. Alvarez-Ruso, J. Nieves, E. Wang

Conclusion: NCγ cannot explain the observed excess of low E_{rec} e-like events.

Outlook:

- an improved description of ν interactions requires consideration of nucleon correlations effects, neglected in Fermi gas approach (a common model in Monte Carlo simulation tools)
  - present in the spectral function formalism
  - RPA effects should be included if microscopic (Nieves et al or Martini et al) model is implemented in MC event generator
  - important in more rigorous two-body current computations
  - perhaps relevant also in pion production?

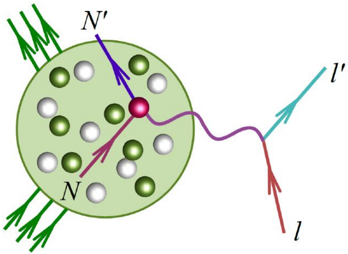


- more precise ν-nucleon cross section measurements (in particular in the $\Delta(1232)$ region) are badly needed.

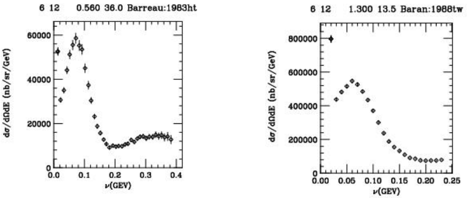
Thank you!

Back-up slides

Impulse Approximation (IA) - limitations.



A. Ankowski



Electron carbon data

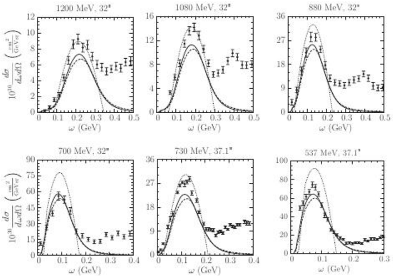
Intuition: intermediate boson as a de Broglie wave (1 fm $\simeq \frac{1}{200 \ MeV}$).

If momentum transfer is 200 MeV/c spatial resolution is 1 fm. If momentum transfer is larger than $\sim$ 300...500 MeV/c IA is justified.

For small energy transfers one can see giant resonances (lowest energy transfer points on above figures).

A difference between electron and neutrino scattering experiments.

For electron scattering one knows momenta of initial and final electrons and thus energy and momentum transfer. It is possible to analyze QE region, Δ excitation region, ... separately.



Electron oxygen scattering.

Format: fixed incident electron energy and scattering angle. On the figures: differential cross section in energy transfer.

A.M. Ankowski, JTS

Similar precision for neutrino scattering is an utopia; the flux is always a kind of wide band – even with the off-axis trick!

Universality of the correlated contribution

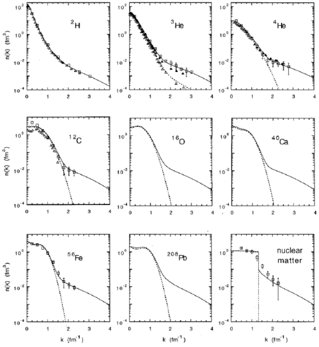


Figure 1: Nucleon momentum distributions $n(k)$ (solid lines) along with the momentum distribution for nucleons in an average potential (dotted lines) for various nuclei are shown.

J. Arrington, D.W. Higinbotham, G. Rosner, M. Sargasian

$$\mathcal{P}^{N_1}_{0(1)}(k_1^{\pm}) = 4\,\pi \int_{k_1^-}^{k_1^+} n^{N_1}_{0(1)}(\boldsymbol{k}_1)k_1^2\,d\,k_1$$

$k_1^+ = \infty$

$\mathcal{P}_0$ and $\mathcal{P}_1$ are probabilities to find a mean field or correlated nucleon in a range $|\vec{p}| \geq k_1^-$.

	^2H	^{3}He(n)	^{3}He(p)		^{4}He		^{16}O		^{40}Ca	
k_1^- [fm^{-1}]	$\mathcal{P}$	$\mathcal{P}_1$	$\mathcal{P}_0$	$\mathcal{P}_1$	$\mathcal{P}_0$	$\mathcal{P}_1$	$\mathcal{P}_0$	$\mathcal{P}_1$	$\mathcal{P}_0$	$\mathcal{P}_1$
0.00	1.000	0.999	0.677	0.323	0.84621	0.15285	0.79999	0.20016	0.80	0.19321
0.50	0.3078	0.568	0.277	0.201	0.53643	0.14032	0.66972	0.19635	0.69997	0.18301
1.00	0.081	0.163	0.038	0.0723	0.10479	0.1045	0.17588	0.14794	0.24706	0.13771
1.50	0.0366	0.067	0.0049	0.036	0.0079	0.0791	0.00792	0.09417	0.01022	0.10143
2.00	0.0221	0.041	0.0015	0.024	$6.9512\ 10^{-4}$	0.06156	$5.9\ 10^{-5}$	0.06344	$3.28\ 10^{-4}$	0.07124

M. Alvioli, C. Ciofi degli Atti, L.P. Kaptari, C.B. Mezzetti, H. Morita

A very small difference between ^{16}O and ^{40}Ca.

A progress in understanding ν interactions is rather slow:

- ν flux is known with an accuracy not better than $\sim 10\%$ of normalization and $\sim 7\%$ bin-to-bin shape
- recent cross section measurements are done on nuclear targets and it is difficult to disentangle nuclear effects

Example: MiniBooNE NC $1\pi^0$ measurement ($1\pi^0$ in the final state, the target is CH_2):

- $1\pi^0 \rightarrow 1\pi^0 \Longleftrightarrow 88.3\%$
- $0\pi \rightarrow 1\pi^0 \Longleftrightarrow 2.4\%$
- $2\pi \rightarrow 1\pi^0 \Longleftrightarrow 3.5\%$
- $\pi^{\pm} \rightarrow 1\pi^0 \Longleftrightarrow 5.8\%$

based on NuWro simulations, T. Golan, C. Juszczak, JTS, Phys. Rev. C86 (2012) 015505

It is not easy to compare theoretical models to the data!