Neutrino interactions – 2

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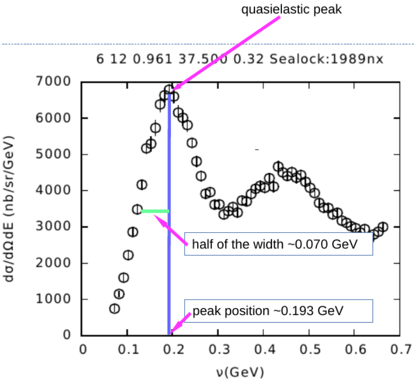
Outline of lecture 2:

- QE/CCQE peak region.
- Importance of CCQE scattering.
- Theory of CCQE ν-nucleon scattering.
  - Form factors.
  - Axial mass.
- CCQE in ν-nucleus scattering (in Impulse Approximation)
  - Plane Wave Impulse Approximation.
  - Fermi gas model.
  - Spectral function.
  - Two-body currents.
  - Neutrino energy reconstruction.
  - Basic intuition.
  - Two body current in electron scattering.
  - Nucleon-nucleon correlations.
  - Two body current in neutrino scattering.
  - Experimental search for two body current contribution in neutrino scattering.
- Message to take home.

Quasi-elastic peak

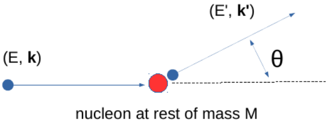
Consider electron scattering.

Example: carbon; $E = 961$ MeV, $\theta = 37.5°$; inclusive (only final state electron is measured) differential cross section in energy transfer $\omega = E - E'$.



http://faculty.virginia.edu/qes-archive/

Suppose the elementary process is $eN \rightarrow eN$.



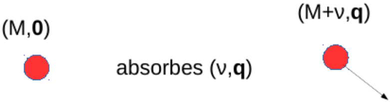
If target nucleon is at rest scattering angle θ determines energy transfer ω.

What is *quasi-elastic peak*?

k^μ, k'^μ are four-momenta of initial and final electrons,
$q^\mu = k^\mu - k'^\mu \equiv (\omega, \vec{q})$ is four-momentum transfer.
Electron mass is neglected.

$$0 < Q^2 \equiv -q_\mu q^\mu = -(k^2 + k'^2 - 2kk') = 2k \cdot k' = 2(EE' - |\vec{k}||\vec{k}'|\cos\theta)$$

$$Q^2 = 2(EE' - EE'\cos\theta) = 2EE'(1 - \cos\theta) = 4EE'\sin^2\frac{\theta}{2}.$$



Knocked-out nucleon must be on-shell i.e.

$$(M+\omega)^2 - \vec{q}^2 = M^2 \quad \Rightarrow Q^2 = \vec{q}^2 - \omega^2 = 2M\omega.$$

What is *quasi-elastic peak*?

Two equations can be solved for ω:

$$\omega = \frac{4E^2 \sin^2\frac{\theta}{2}}{2M + 4E\sin^2\frac{\theta}{2}} \Rightarrow \omega = 167\mathrm{MeV}$$

Great, almost OK! What about a small difference?

Suppose the target nucleon is bound. Knocked-out nucleon four-momentum is $(M + \omega - B, \vec{q})$. $B \approx \text{const}$ is called *binding energy*.

Slightly modified equation for ω:

$$\omega = \frac{4E^2 \sin^2\frac{\theta}{2} + 2MB - B^2}{2M - 2B + 4E\sin^2\frac{\theta}{2}}$$

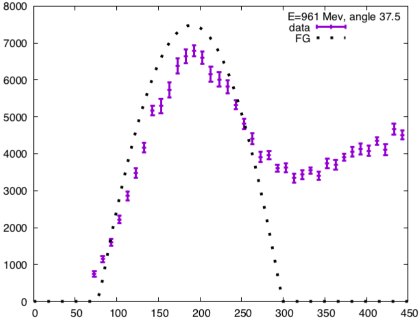
Take $B = 25$ MeV $\Rightarrow \omega = 192\mathrm{MeV}$!

We understand the peak position!

What is *quasi-elastic peak*?

What about the peak's width?

- It arises due to Fermi motion (nucleons inside nucleus are moving).
    - Peak's width tells us about the Fermi momentum.
- Try Fermi gas model to reproduce this data (for details see later).

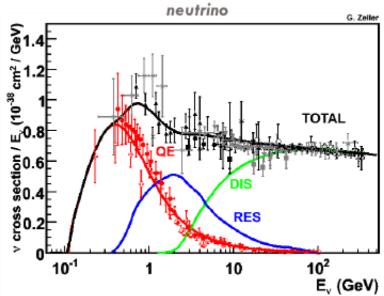


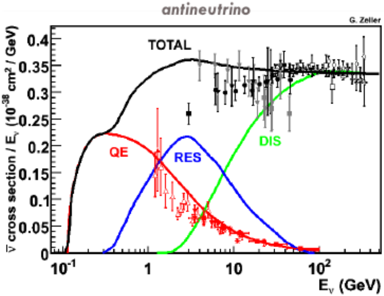
QE peak arises due to scattering on individual nucleons (like CCQE).

We need a model to describe precisely QE peak.

Fermi gas model is OK up to $\sim 10\%$ (at least in this example!).

Importance of CCQE

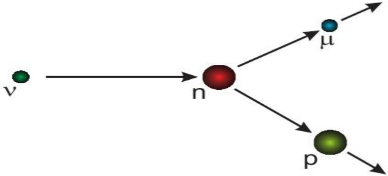




- In experiments like T2K, MicroBooNE most of events are CCQE.
- Theoretical models must be able to reproduce QE peak measured in electron scattering.

CCQE (charge current quasi-elastic)

$$\nu_l(k) + n(p) \to l^-(k') + p(p')$$



Experimental signal is clear: muon and proton in the final state

In the 1 GeV energy range:

$$Q^2 << M_W^2$$
$$\Downarrow$$
$$\mathcal{H}_{int} = \frac{G_F}{\sqrt{2}} J_\alpha^{lep} \mathbb{J}^\alpha + h.c.$$

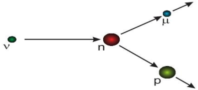
$$< \mu(k')|J_\alpha^{lep}|\nu_\mu(k) >= \bar{u}(k')\gamma_\alpha(1-\gamma_5)u(k), \quad \mathbb{J}^\alpha = \cos\theta_C(\mathbb{V}^\alpha - \mathbb{A}^\alpha).$$

$\mathbb{J}^\alpha$ acts in the hadronic Hilbert space only.

CCQE on free nucleon target

A chain of arguments (and simplifications!) leads to a conclusion:

everything that is not known is a value of *axial mass* parameter.



$$\nu_l/\bar{\nu}_l(k) + N(p) \to l^{\pm}(k') + N'(p')$$
$$q^{\mu} \equiv k^{\mu} - k'^{\mu}; \quad Q^2 \equiv -q_{\mu}q^{\mu}.$$

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

- The structure follows from Lorentz symmetry, no 2nd class currents.
- $F_V(Q^2)$, $F_M(Q^2)$ are vector form factors
- $F_A(Q^2)$, $F_P(Q^2)$ are axial form factors
- They are scalar functions.
- In the static limit F_V determined by charge distribution inside nucleon.

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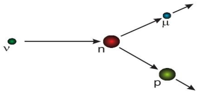


$$\nu_l/\bar{\nu}_l(k) \; + N(p) \; \to l^{\pm}(k') \; + N'(p')$$
$$q^\mu \equiv k^\mu - k'^\mu; \quad Q^2 \equiv -q_\mu q^\mu.$$

- CVC arguments $\Rightarrow$ vector part known from electron scattering
- PCAC arguments $\Rightarrow$ only one independent axial form factor $F_A(Q^2)$
- β decay $\Rightarrow$ $F_A(0) \simeq 1.26$
- 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.

Electromagnetic form-factors

A convenient language of Sachs electric and magnetic form-factors (G_E , G_M)

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \frac{\epsilon(G_E)^2 + \tau(G_M)^2}{\epsilon(1+\tau)},$$

$$\epsilon = [1 + 2(1+\tau)\tan^2(\frac{\theta}{2})]^{-1},$$

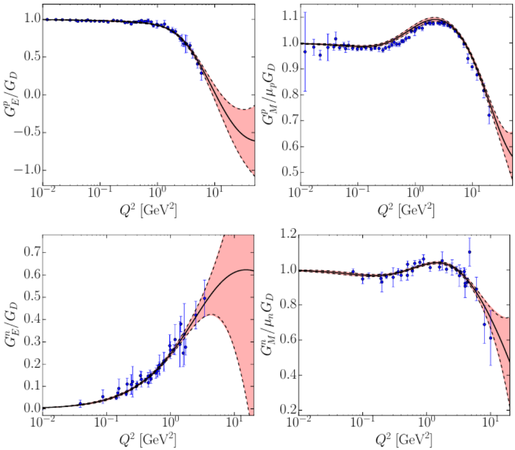
$\tau = Q^2/4M^2$.

Studied by many authors ... Alberico, Bilenky, Giunti, Graczyk, ...
A very recent fit done by Ye, Arrington, Hill, Lee

Results shown as ratios wrt dipole expression:

$$G_D(Q^2) = \frac{1}{1 + \frac{Q^2}{M_D^2}}, \qquad M_D^2 = 0.71 \text{ GeV}^2.$$

Electromagnetic form-factors

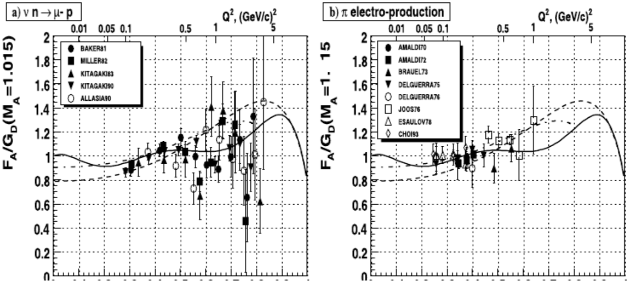


$G_E^n(Q^2)$ has different shape because $G_E^n(0) = 0$ (neutron has no electric charge).

For remaining FF for $Q^2 < 1$ GeV^2 dipole approximation is ok.

Ye, Arrington, Hill, Lee

Axial mass



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

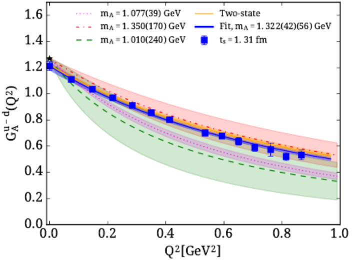
- Notice a dramatic difference in data precision!
- Old deuteron bubble chamber M_A measurements indicate the value of about 1.015 GeV and are consistent with the dipole form of F_A
- independent pion production arguments lead to similar conclusions: $M_A = 1.077 \pm 0.039$ GeV.

Further progress in determination of axial FF.

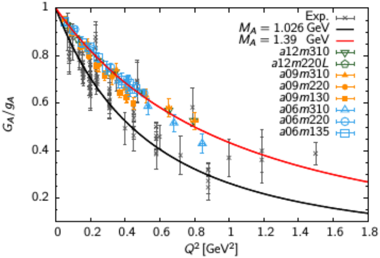
Because of nuclear effects (see later) hydrogen or deuteron bubble chamber experiments are needed.

- Severe safety issues.

Another option: lattice QCD computations. Recent results:



Alexandrou et al



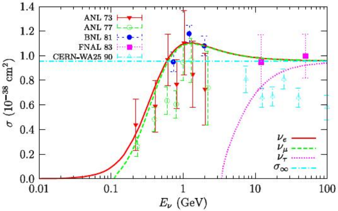
Gupta et al

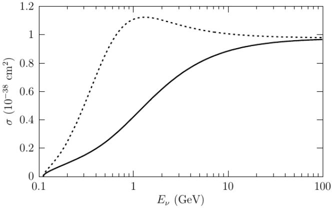
Lattice computations suggest $M_A \sim 1.32..1.39$ GeV.

This sounds like a joke !!! (see later).

CCQE cross section

The E dependence is shown below ($M_A = 1.05$ GeV).



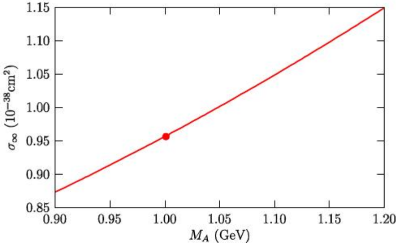


- Large experimental uncertainty
- Most recent data are not included
- At large energy cross section saturates

On the left: comparison of CCQE for ν_μ and $\bar{\nu}_\mu$.
A difference comes from V-A intereference term which comes with different signs for ν_μ and $\bar{\nu}_\mu$.

$E \to \infty$ limit

Assuming dipole vector and axial FFs:



[A.M. Ankowski, Act. Phys. Pol. B37 (2005) 377]

- $\sigma_\infty(E)$ dependence on M_A is in the relevant region almost linear.
- It may seem surprising that there is a controversy if $M_A = 1.05$ GeV or rather $M_A = 1.35$ GeV.
  - The difference translates into $25 - 30\%$ difference in the number of events!

CCQE on nuclear target in IA

Theoretical issues:

- Target nucleon is not free and is moving.
- Off-shell matrix elements.
- Outgoing nucleon *feels* nuclear environment.

Experimental issues:

- For neutrinos one cannot seperate CCQE on event by event basis.
- Other dynamical mechanisms contribute as a background.
- The best one can do is to measure CCQE-like (no pions in the final state) cross section.

Impulse Approximation still leaves a lot of freedom.

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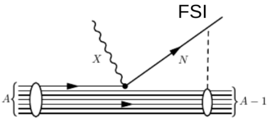
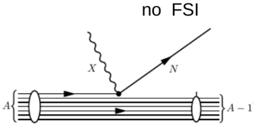
Assume that final nucleon does not interact with nucleus: Plane Wave Impulse Approximation





Plane Wave Impulse Approximation (PWIA)

The simplest way to calculate quasi-elastic neutrino-nucleus cross section is to assume PWIA:

- Nucleon resulting from CCQE leaves nucleus as it is.
- A useful starting point.
- FSI effects are neglected.
- Incoherent sum of contributions from individual nucleons.
- Cross section can be calculated in a straightforward way.
- One needs a distribution of target nucleon momenta and binding energies.
- A technical problem: how to deal with off-shell matrix elements (de Forest prescription, restoring gauge invariance, ...)

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):

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

Neglecting negative energy states it can be shown that

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

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

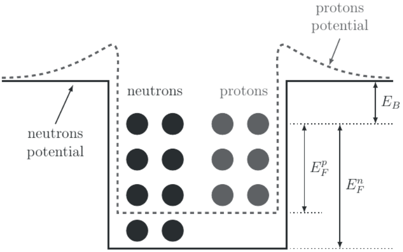
$L_{\mu\nu}=2\left(k_\mu k'_\nu+k'_\mu k_\nu-k\cdot k' g_{\mu\nu}-i\varepsilon_{\mu\nu\kappa\lambda}k^\kappa k'^\lambda\right)$, $H^{\mu\nu}$ is the free nucleon hadronic tensor, k^μ, k'^μ are neutrino and charged lepton four-momenta, $q^\mu\equiv k^\mu-k'^\mu=(\omega,\vec{q})$ is four-momentum transfer.

All information about nucleus is encoded in $P(E,\vec{p})$.

Fermi gas model

FG is a convenient first approximation to model nucleus target.

- Free nucleons in the potential well.
- In a finite well momenta are quantized and we make it infinite!
- Momentum levels filled, up to p_F (Fermi momentum).
- A useful relation between p_F and nucleon density n: $n = \frac{p_F^3}{3\pi^2}$.



from Tomasz Golan

- Its MC implementation is easy
- FG fails to reproduce electron-nucleus transverse and longitudinal response functions (corresponding to transverse and longitudinal polarizations of virtual photon).

Fermi gas model

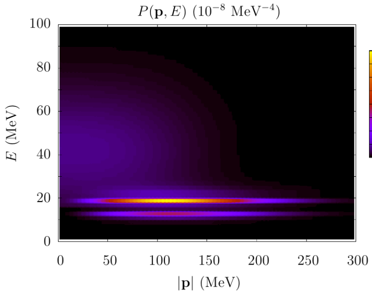
- In the FG model, $P(E,\vec{p})$ is characterized by two parameters: Fermi momentum k_F and binding energy B:

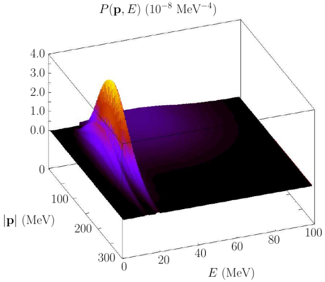
$$P(E,\vec{p}) = \frac{3A}{4k_F^3}\Theta(k_F - |\vec{p}|)\delta(E + \sqrt{M^2+\vec{p}^2} - B)$$

- $\vec{p}$ is a target nucleon momentum.
- Both k_F and B can be 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 (this defines *local Fermi gas model* – LFG)
- Easy to implement in Monte Carlo generators.

Hole Spectral function (SF)

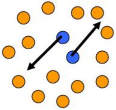
Much better choice is hole spectral function (SF). Below oxygen hole SF calculated by Omar Benhar.





Shell model orbitals are clearly seen.

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



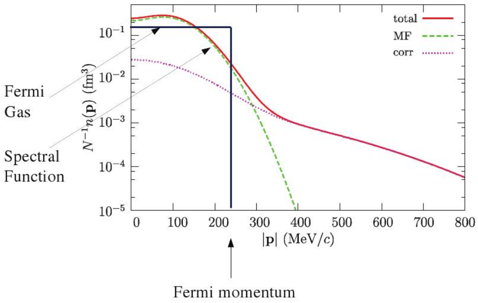
Hole spectral function

Hole SF 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.

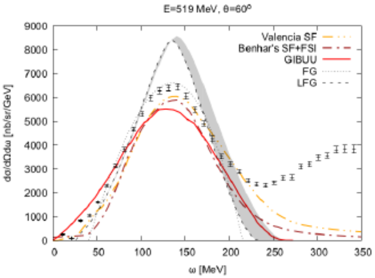


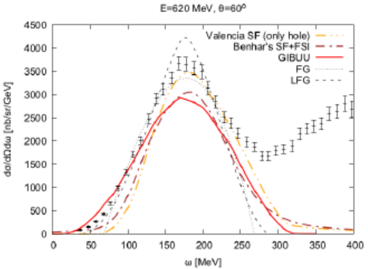
- mean field (MF) and SRC (corr) contributions are shown separately.
- high momentum tail, absent in the FG model, comes from correlated nucleon pairs (see later).

Other theoretical models

Hole SF in PWIA is only a beginning of the story.

- Other nuclear effects must be added.
- Outgoing nucleon *feels* nuclear environment.
- Many approaches to describe QE peak region.



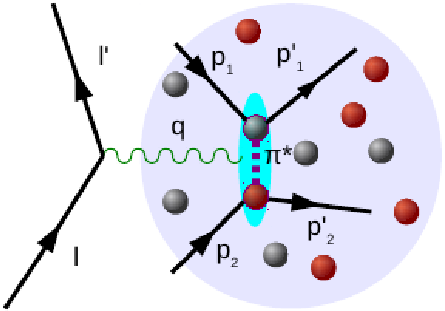


J.E. Sobczyk

Valencia, Benhar SF, GiBUU models reproduce the data quite well.

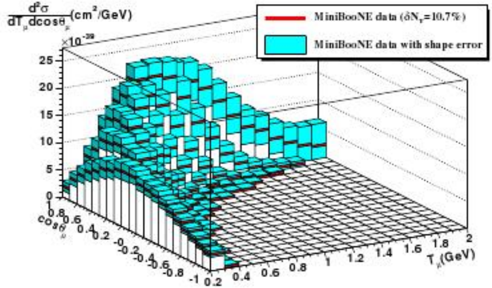
Some strength is perhaps missing – see later.

Two-body current contribution.



Large axial mass puzzle

MiniBooNE CCQE double (muon kinetic energy and production angle) differential cross section results.



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

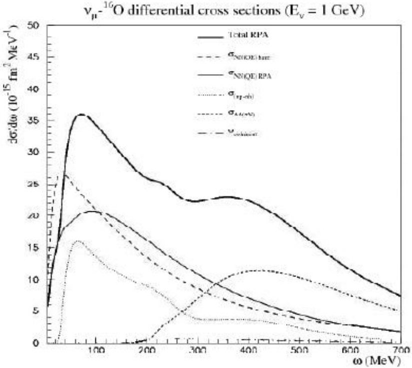
The best fit value is $M_A^{eff} = 1.35 \pm 0.17$ GeV.

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

Much more than previous measurements $M_A \sim 1.05$ GeV.

Two-body current contribution.

The figure below is taken from Jacques Marteau presentation given in 2001 at NuInt01.

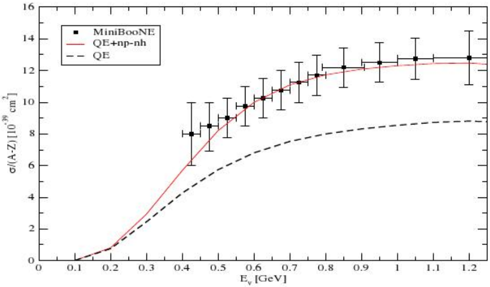


The model (developed by J. Marteau in his PhD thesis supervised by J. Delorme and W. Ericsson) predicts a large contribution from n-particle n-hole excitations

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

Two-body current contribution.

Marteau model was used by Marco Martini et al to explain the MiniBooNE results.



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

- np-nh events are a part of a signal (pion absorption contribution was estimated and subtracted).
- pionless Δ decays were also subtracted.

It is why recent LQCD results are so puzzling!

Why should we care about np-nh contribution?

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Is that relevant if an interaction was CCQE or np-nh?

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Is that relevant if an interaction was CCQE or np-nh?

YES!

CCQE ν_μ reconstructed energy

We need to know interaction neutrino energy!

Assume that:

- Only final state muon is detected
- The interaction was CCQE
- Target neutron was a (bound) neutron at rest.

CCQE ν_μ reconstructed energy

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- Target neutron was a (bound) neutron at rest.

Notation:
four-vectors of ν, μ^-, neutron and proton are denoted as: $k^\mu = (E_\nu, \vec{k})$, $k'^\mu = (E', \vec{k}')$, $p^\mu = (M, \vec{0})$, $p'^\mu = (E_{p'}, \vec{p}')$.

Energy and momentum conservation (B is a binding energy) reads:

$$E_\nu + M - B = E' + E_{p'}$$
$$\vec{k} = \vec{k}' + \vec{p}'$$

CCQE ν_μ reconstructed energy

$$E_\nu + M - B = E' + E_{p'}$$
$$\vec{k} = \vec{k}' + \vec{p}'$$

imply:

$$E_{p'}^2 = M^2 + \vec{p}'^2 = M^2 + (\vec{k} - \vec{k}')^2 = M^2 + E_\nu^2 + \vec{k}'^2 - 2E_\nu|\vec{k}'|\cos\theta.$$

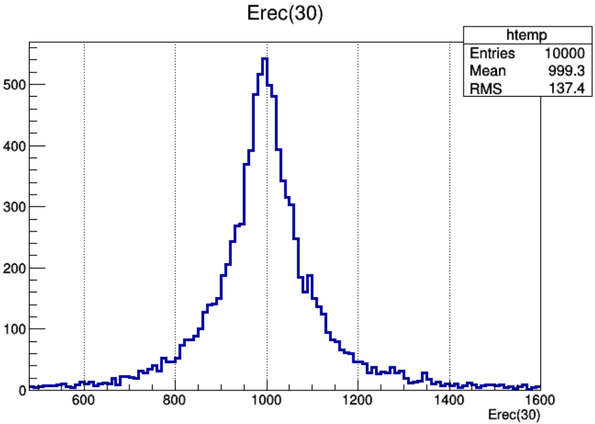
$$E_{p'}^2 = (E_\nu - E' + M - B)^2.$$

Neglecting a difference between proton and neuton mass we obtain:

$$E_\nu = \frac{E'(M-B) + B(M-B/2) - m^2/2}{M - B - E' + k'\cos\theta} = E_{CCQE}^{rec}.$$

We need only information about final state muon.

CCQE ν_μ reconstructed energy



CCQE events, $E_\nu = 1000$ MeV, carbon target, Spectral Function.

E_ν is reconstructed based on final state muon (formula from the previous slide with $B = 30$ MeV).

Neutrino energy reconstruction – a case study

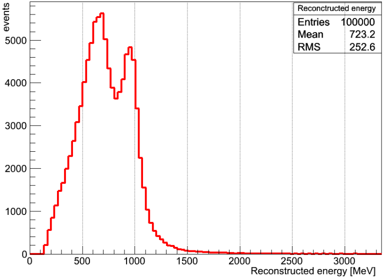
Consider 100 000 random two body current events generated with Nieves et al model. $E_\nu^{TRUE} = 1000$ MeV.

Using the formula

$$E^{rec}_{CCQE} = \frac{E'(M-B) + B(M-B/2) - m^2/2}{M - B - E' + k' \cos\theta}$$

with $B = 25$ MeV one gets – see on the right.

On average ν energy is underestimated by ~ 280 MeV. Understanding of oscillation maximum may be strongly biased.



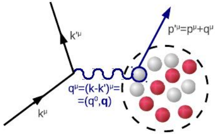
obtained with NuWro MC event generator

It is critical that MC event generators have reliable implementation of two body contribution.

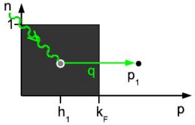
Two-body current – basic intuition.

One-body current operator:

$$J^\alpha = \cos\theta_C (V^\alpha - A^\alpha) = \cos\theta_C \bar{\psi}(p')\Gamma^\alpha_V \psi(p)$$



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



from J. Żmuda

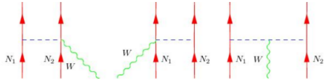
In the second quantization language J^α

- annihilates (removes from the Fermi see, producing a hole) a nucleon with momentum p
- creates (above the Fermi level) a nucleon with momentum p'
- altogether gives rise to 1p-1h (one particle, one hole state)

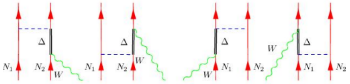
$$\boxed{J^\alpha_{1body} \sim a^\dagger(p')a(p)}$$

Two-body current – basic intuition

Think about more complicated Feynman diagrams:



Contact and *pion-in-flight* diagrams



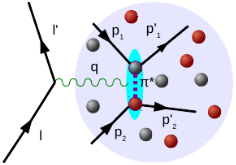
Δ-Meson Exchange Current diagrams

J. Morfin, JTS

Transferred energy and momentum are shared between two nucleons.

$$\boxed{J^{\alpha}_{2body} \sim a^{\dagger}(p_1')a^{\dagger}(p_2')a(p_1)a(p_2)}$$

can create two particles and two holes (2p-2h) states



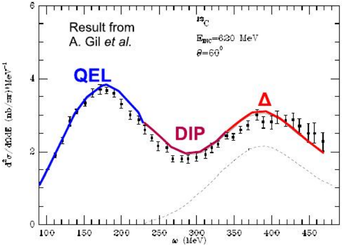
from J. Żmuda

Two body current in electron scattering

Do we see two-body current contribution in electron scattering?

Two body current in electron scattering

- In the context of electron scattering the problem has been studied for over 40 years.
- An increase of cross section in the DIP region between QE and Δ peaks



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

- The extra strength is believed to come from the two-body current mechanism.

A suitable language is that of R_T and R_L nuclear response functions.

Ab initio computations

It is only recently that results from *ab initio* state-of-art computations (electron scattering) of nuclear response functions R_T and R_L are available.

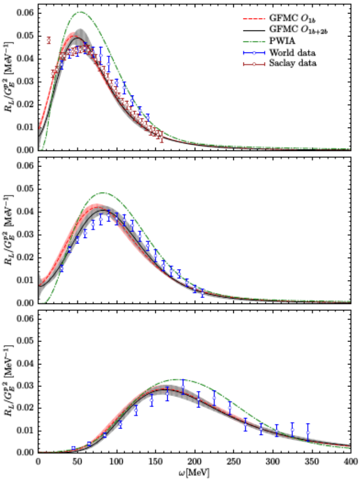
- Computations are non-relativistic.
- For a moment only light nuclei, up to carbon.
- Pion production is not included.
- Green function Monte Carlo (GFMC) technique.

Altogether a rather restricted phase space (values of momentum and energy transfer).

$$H = \sum_j \frac{\vec{p}_j^{\,2}}{2M} + \sum_{j<k} V_{jk} + \sum_{j<k<l} V_{jkl}.$$

Argonne v18 potential fitted to the NN scattering data.

GFMC and electromagnetic response functions

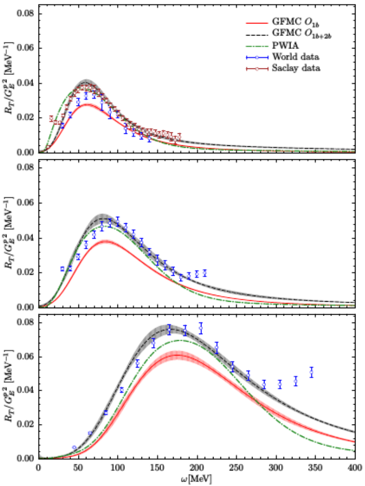


R_L for carbon.
$q = 300, 380, 570$ MeV/c.

- An impact of two-body current is negligible.
- Very good agreement with the data.

Lovato et al

GFMC and electromagnetic response functions



Lovato et al

R_T for carbon.
$q = 300, 380, 570$ MeV/c.

> Both one- and two-body currents are needed to reproduce QE peak in R_T.

- One body and two body current interference is important.
- Too much strength on the right from the the peak?
  - Problems with non-relativistic kinematics.

Important lessons from R_T/R_L separation

R_T/R_L separation is more useful than one might expect.

- QE (in IA) is the only mechanism that contributes to R_L.
- The experimental data for R_L can be used to test CCQE models (IA).
- A little paradoxical conclusion:

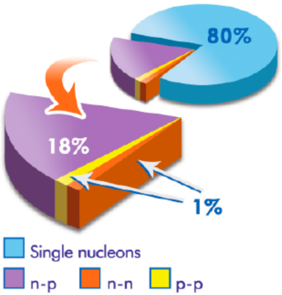
CCQE is not enough to describe CCQE/QE peak region!

- In order to describe CCQE/QE peak we need both one- and two-body current contributions in a consistent theoretical frame.
- Amount of R_L and R_T contributions at the peak depend on kinematics.
- If R_L dominates CCQE mechanism is enough.

Nucleon-nucleon correlations

^{12}C From (e,e'), (e,e'p), and (e,e'pN) Results

- 80 +/- 5% single particles moving in an average potential
  - 60 – 70% independent single particle in a shell model potential
  - 10 – 20% shell model long range correlations
- 20 +/- 5% two-nucleon short-range correlations
  - 18% np pairs (quasi-deuteron)
  - 1% pp pairs
  - 1% nn pairs (from isospin symmetry)
- Less than 1% multi-nucleon correlations

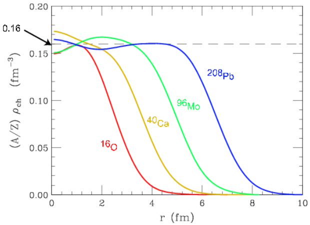


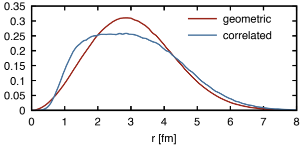
INT Workshop 4 December 2013

Jefferson Lab

from Higinbotham

Nucleon-nucleon correlations





"Correlated" show GFMC results for proton-neutron pairs.

Repulsion at smallest r and attraction at $\sim 1 - 1.5$ fm.

Individual nucleons are distributed in nucleus according to nuclear density profile $\rho(\vec{r})$ (top).

$$\int \rho(\vec{r}) d^3 r = A.$$

$\rho(\vec{r}_1, \vec{r}_2)$ is a joint probability to find nucleons at $\vec{r}_1$ and $\vec{r}_2$.

$$\rho(\vec{r}_1, \vec{r}_2) \neq \rho(\vec{r}_1) \cdot \rho(\vec{r}_2) \equiv \rho_{geom}(\vec{r}_1, \vec{r}_2).$$

On the left we show

$$\rho^{(2)}(|\vec{r}_1 - \vec{r}_2|) \equiv \int d^3 R_{12} \rho(\vec{r}_1, \vec{r}_2), \quad \vec{R}_{12} \equiv \frac{1}{2}(\vec{r}_1 + \vec{r}_2)$$

for $\rho(\vec{r}_1, \vec{r}_2)$ and $\rho_{geom}(\vec{r}_1, \vec{r}_2)$.

Large nucleon momentum tail

Another ("dual") manifestantion of correlations is high momentum tail in nucleon momentum distribution.

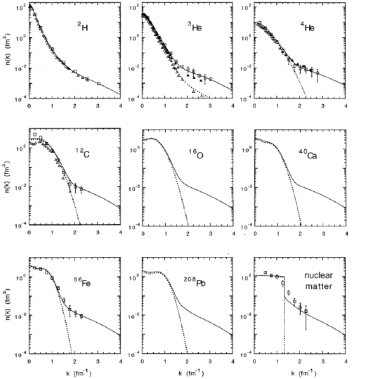
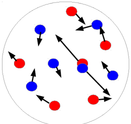


Figure 1: Nucleon momentum distributions $n(k)$ (solid lines) along with the momentum distribution for nucleons in an average potential (dotted lines) for various nuclei are shown.

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

- In the Fermi gas model the distribution is a step function, nucleon momenta are smaller than $k_F \sim 225$ MeV/c
- For carbon $\sim 20\%$ of nucleon have higher momenta carrying $\sim 60\%$ of kinetic energy
- The tails are similar for variety of nuclei.
- The same physics is behind.

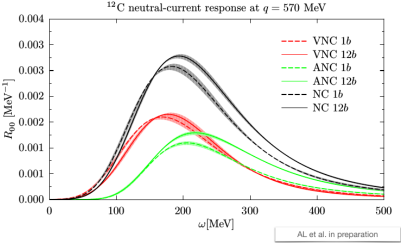


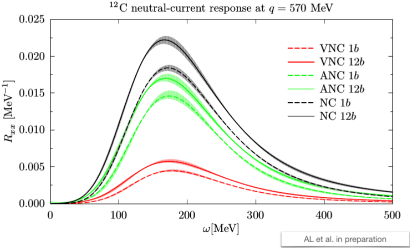
From electrons back to neutrinos

Two body current in neutrino interactions

Ab initio methods are not enough.

- There are only a few (very recent) results.





A. Lovato, NuInt17

- Restricted phase space.
- Very useful to understand physics and as a benchmark for approximations.
- A clear enhancement.

Two body current in neutrino interactions

A variety of models, approximations, approaches.

- Nieves et al (implemented in most MC event generators)
- Martini et al
- Ghent model
- Superscaling approach
- GiBUU model
- ...

It is difficult to understand model similarities and differences.

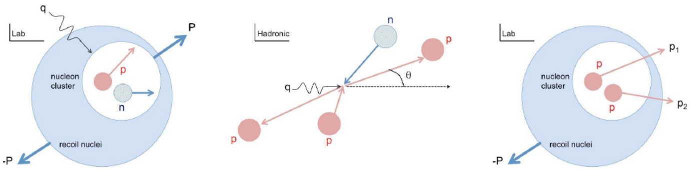
- Each model is based on its own simplifications.

It seems necessary to look for two-body current contribution experimentally.

Two body current in neutrino interactions

A common limitation is that typically there are no predictions for final state nucleons.

A way out is *phase space model*.



from T. Katori

As we will see:

- It is not enough to see at final state muon only.
- Predictions for final state proton/protons are very uncertain.

Experimental search for 2p-2h events

It is important to know the size of the two body current contribution to the muon inclusive cross section.

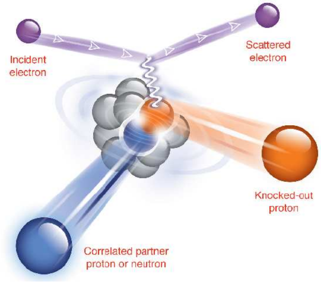
Problem: many sources of multinucleon knock out events

- Genuine two body current events
  - It is not known how transferred momentum is shared between both nucleons
- Real pion production and absorption
- CCQE and FSI effects.
- One body current events on correlated pairs
  - Included in SF formalism.

A big challenge.

Correlations in two nucleon knock-out

- Typical signature of two body current events is two nucleon knock-out (W^+ absorbed on p-n pair).
- But there are other sources of such events:
- CCQE on correlated nucleon-nucleon pairs



Subedi et al

- The other nucleon is a spectator.
- Correlated nucleons are most often p-n with large back-to-back momenta.

Experimental search for 2p-2h events

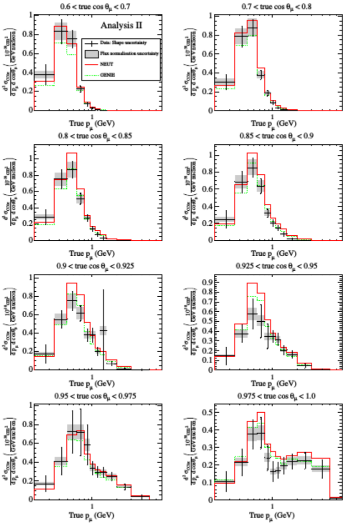
There are three directions

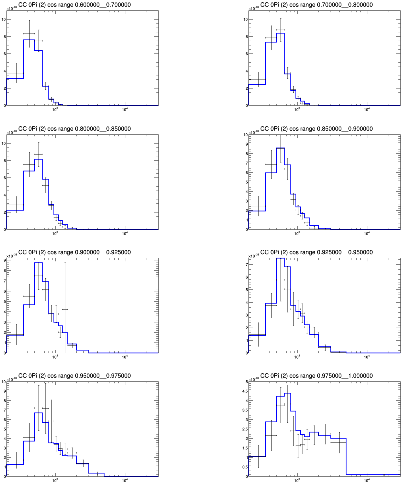
- Look for inclusive results i.e. for CC0π events.
    - Experimentally the simplest option.
    - In the case of electron scattering it required a very good control of kinematics - hard to achieve for neutrinos.
- Look for a subsample of CC0π events with 1μ 1proton.
    - Important to have low momentum reconstruction threshold.
    - Most promising liquid argon technique.
- Look for a subsample of CC0π events with 1μ 2protons.
    - A hope to find correlated nucleons.

There is a lot of activity with no clear conclusions yet.

On next slides some examples.

T2K – CC0π





NuWro results (with Nieves model).

Difficult to draw conclusions.

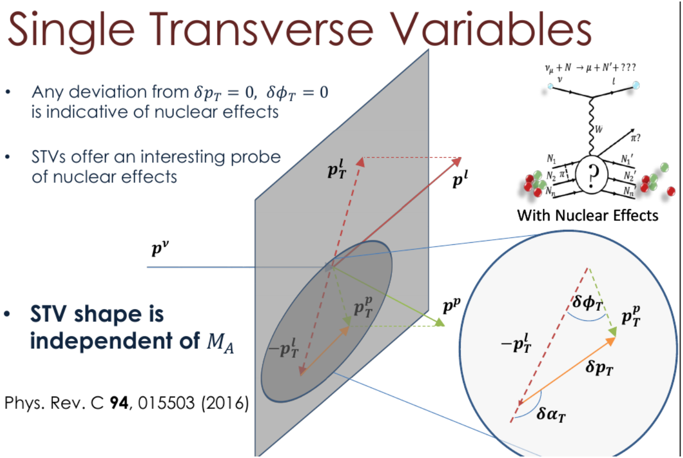
CC differential cross section in transverse variables

Motivation: looking for MEC events and validation of nucleon FSI.
Selection:

- $CC0\pi$
- muon momentum > 250 MeV/c
- cosine of muon angle > -0.6
- leading proton momentum $\in (450, 1000)$ MeV/c
- cosine of leading proton angle > 0.4.

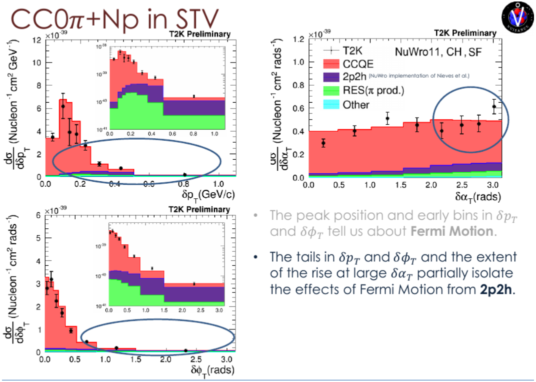
CC differential cross section in transverse variables

Definition of transverse (wrt neutrino flux) variables.



from Stephen Dolan presentation at NuInt17

Transverse kinematics – results

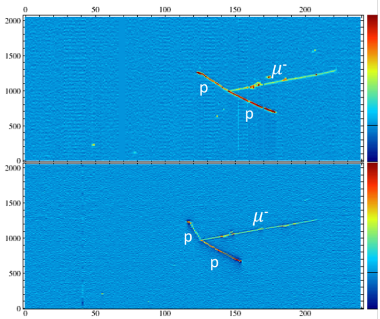


from Stephen Dolan presentation at NuInt17

It is difficult to separate CCQE, pion production and absorption and two body current contributions.

Two-proton events in the ArgoNeut experiment

R. Acciarri, et al [ArgoNeuT], Phys. Rev. D90 (2014) 012008



- Very low proton reconstruction threshold $P_{thr} \sim 200$ MeV/c, below Fermi momentum.
- Four *hammer* events in the LAB frame with almost back-to-back momenta.
- Attempt to reproduce initial two nucleon state (if there is one).
- An increase of reconstructed pairs in back-to-back state.

Two recent studies

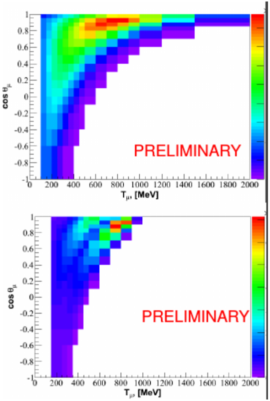
K. Niewczas, JTS, Phys. Rev. C93 (2016) 035502

L.B. Weinstein, O. Hen, E. Piasetzky, Phys.Rev. C94 (2016) 045501

Better statistics results from MicroBooNE should come soon.

Attempts to resolve kinematics

If one is able to measure energy carried by outgoing hadrons, it is possible to calculate both energy and momentum transfer. A dream: to have the precision comparable with electron scattering studies.

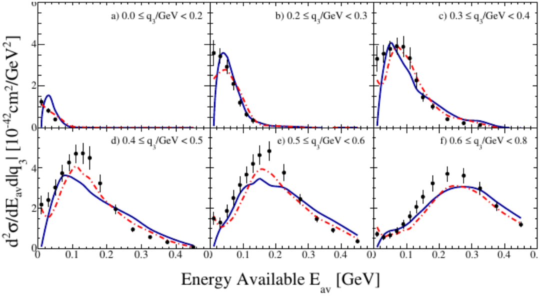


- In MiniBooNE E_ν may be reconstructed from scintillation light.
- From E_ν one can calculate ω, $\vec{q}$
- Unfortunately, the study has not been completed.

On the left: extracted differential cross section at $E_\nu = 1$ GeV.

Martin Tzanov, NuFact12

Attempts to resolve kinematics



Experimental results from MINERvA; MC study by Patrick Stowell: red is NuWro, blue is NEUT

$$E_{av} = \sum_{i=p,\pi^+,\pi^-} T_i^{Kinetic} + \sum_{j=e^\pm,\gamma,\pi^0} E_j^{Total}$$

- In MINERvA energy transfer ω is estimated using Monte Carlo (GENIE) predictions.
- From ω one can calculate both E_ν and $\vec{q}$.

Message to take home

- CCQE is the most important process in ~ 1 GeV energy region.
- Nucleon-nucleon axial form factor is not well known. New measurements and/or more reliable LQCD computations are required.
- Inclusion of two-body current contribution is necessary to reproduce correctly QE peak.
- A knowledge how large is two body current contribution is required for a correct understanding of interacting neutrino energy and neutrino oscillation signal.
- There is a lot of experimental activity with a goal to measure two body current contribution in neutrino scattering.