Neutrino interactions

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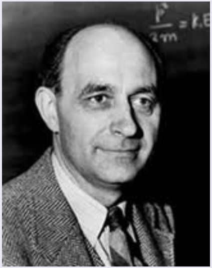
Outline of part I:

- Introduction, vocabulary.
- Motivations:
  - systematic errors in ν oscillation experiments.
  - hadronic and nuclear physics.
- Neutrinos in the Standard Model.
- Neutrino-nucleus scattering; impulse approximation.
- Final state interactions.
- Response functions.
- Monte Carlo generators.
- Message to take home.

Part II: Quasi-elastic peak region.

The lectures are intended to be really elementary.

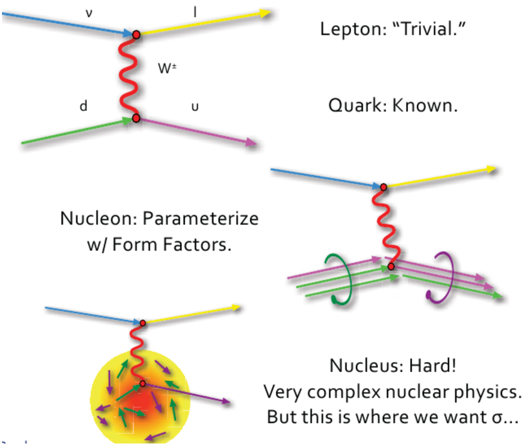
For experts:



Enrico Fermi:

Never underestimate the joy people derive from hearing something they already know.

Neutrino interactions – big picture – targets.



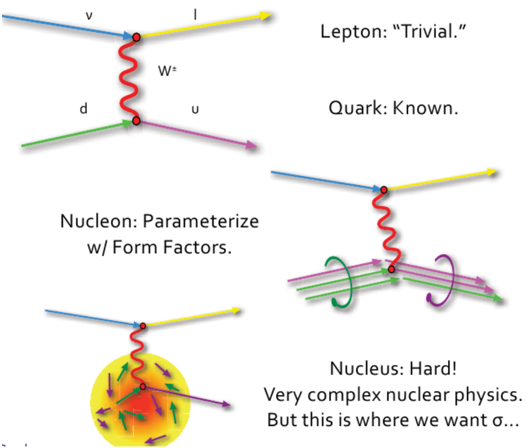
(from Gabe Purdue)

Purely leptonic ν interactions are fully understood (in oscillation experiments a tiny fraction of the cross section).

Hadronic degrees of freedom can be: quarks, nucleons, nuclei.

Only standard neutrino interactions will be discussed. Non-standard interactions (an interesting topic) are left apart.

Neutrino interactions – big picture



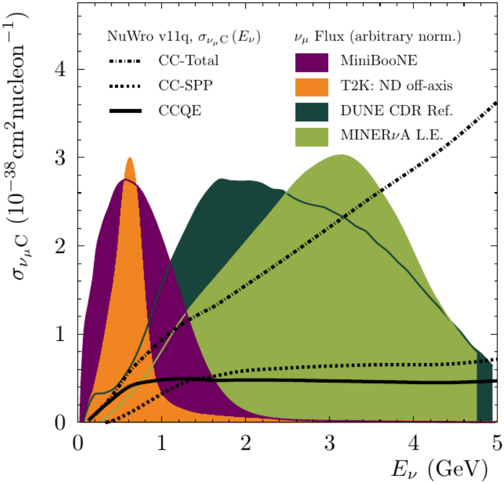
(from Gabe Purdue)

A context for the lectures: neutrino short- and long baseline experiments (MicroBooNE, T2K, NOvA, HK, DUNE).

Most of interactions occur on bound states (nucleons, nuclei) with many theoretical complications.

These lectures will be about ν interactions in ~ 1 GeV energy region.

Typical energies in many ν oscillation experiments.



Basic interaction modes in neutrino-nucleon scattering

In the community slang we distinguish three *dynamics*:

i) Quasi-elastic (QE)

$$\nu_l \; n \to l^- \; p, \quad \bar{\nu}_l \; p \to l^+ \; n, \quad l \in \{e, \mu, \tau\},$$

for neutral current *elastic*:

$$\nu_l \; N \to \nu_l \; N$$

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ii) Resonance excitation (RES) (often called *single pion production)*

$$\nu_l \; p \to l^- \; \Delta^{++} \to l^- \; p \; \pi^+$$

and analogous processes with heavier resonances.

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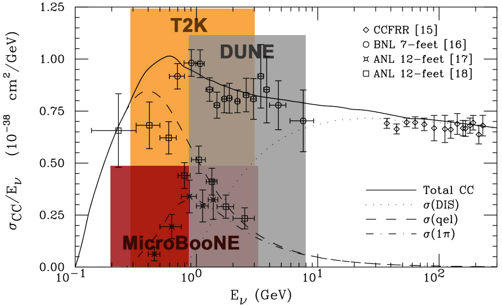
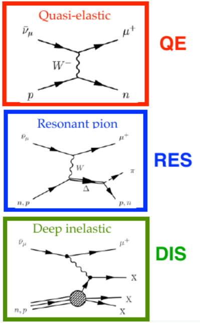
iii) Deep inelastic scattering (DIS, a very confusing name as it stands here only for *more inelastic channels*

Basic interaction modes in neutrino-nucleon scattering





(based on P. Lipari et al, Phys. Rev. Lett. **74** (1995) 4384)

(from Minerba Betancourt)

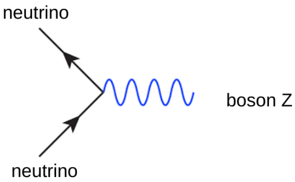
- As neutrino energy grows, more inelastic channels open.
- For $E > 10$ GeV $\sigma \sim E$ and $\frac{\sigma}{E} \approx$ const.
- For $E \in (1, 10)$ GeV all *dynamics* are important.

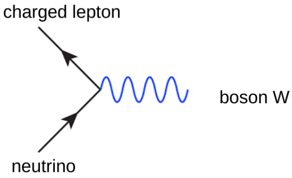
Vocabulary: charged current, neutral current events.

→ SAMOIL BILENKY lectures

Before going into details...

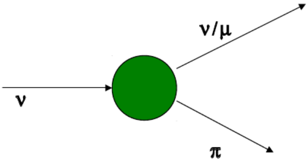
- In the Standard Model neutrinos participates in two kind of weak processes.
- Interaction mechanism is exchange of either Z^0 or $W^\pm$ intermediate boson.
- Z^0 is electrically neutral and process is called neutral current.
- $W^\pm$ carries electric charge and process is called charged current.





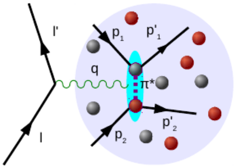
ν-nucleus scattering – new interaction modes

- Coherent pion production (nucleus remains in the ground state).



Can be both CC and NC.

- Two body current (interaction on nucleon pairs).

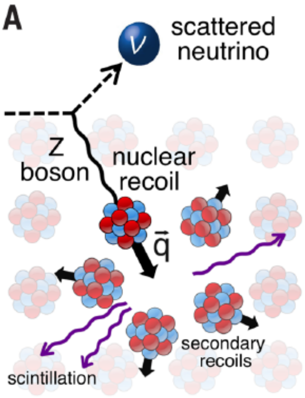


Sometimes called meson exchange current (MEC) or 2p-2h.

from J. Żmuda

ν-nucleus scattering – new interaction modes

Coherent elastic neutrino-nucleus scattering.



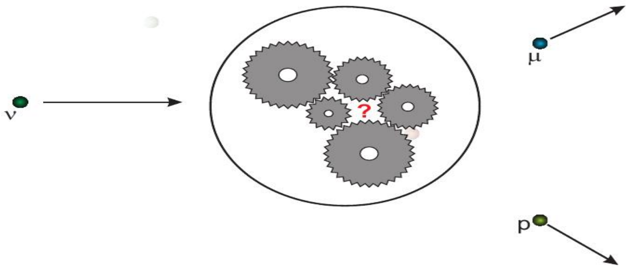
- It took many years to observe this process.
- The only signal is low energy ($\sim$ keV) nuclear recoil.

[COHERENT], Science, 57 (2017) 1123-1126.

$\rightarrow$ HENRY WONG lectures

Do we need a theory?

- Experimental groups need reliable Monte Carlo generators.
- Do MCs need a theory?... Perhaps the ultimate goal is just to parameterize the data?!
- Do we need to understand what is going on?



from T. Golan

Kurt Lewin

There is nothing so practical as a good theory

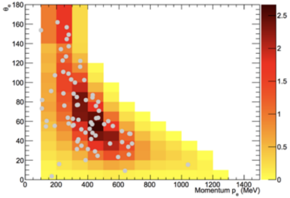
In these lectures I will combine theoretical and experimental arguments.

Recommended review articles

- J.A. Formaggio, G.P. Zeller, Rev. Mod. Phys. **84** (2012) 1307.
- J.G. Morfin, J. Nieves, and JTS, *Recent Developments in Neutrino/Antineutrino - Nucleus Interactions*, Adv.High Energy Phys. 2012 (2012) 934597.
- L. Alvarez-Ruso, Y. Hayato, and J. Nieves, *Progress and open questions in the physics of neutrino cross sections at intermediate energies*, New J.Phys. 16 (2014) 075015.
- U. Mosel, *Neutrino Interactions with Nucleons and Nuclei: Importance for Long-Baseline Experiments*, Ann. Rev. Nucl. Part. Sci. 66 (2016) 171.
- T. Katori, M. Martini, *Neutrino-Nucleus Cross Sections for Oscillation Experiments*, J.Phys. G45 (2018) 013001.
- L. Alvarez-Ruso et al, *NuSTEC White Paper: Status and Challenges of Neutrino-Nucleus Scattering*, Prog.Part.Nucl.Phys. 100 (2018) 1-68.

Motivations – neutrino oscillations

- Interacting neutrino energy is not known.
- Pattern of ν oscillations is energy dependent.
- It is often claimed that ν energy must be *reconstructed* based on detected particles; more precisely we must understand patterns of observed final state particles in terms of oscillation parameters.
- In the T2K mostly CCQE events are studied and a distribution of final state muons is investigated (recently a sample of π^+ production events is also explored).



The goal of T2K analysis is to understand this distribution in terms of oscillation parameters.

On the left SK electron events in the T2K experiment (in color MC predictions).

Modeling ν interactions has become a very important topic.

Motivations from hadronic and nuclear physics

- Nucleon and nucleon-resonance axial form factors.
- Strangeness content of nucleon:
  - relevant for supernova,
  - accessible in ν NC elastic scattering.
- Complementary information about nucleon correlations, meson exchange current, giant resonances, ...

Standard Model – generalities

→ SAMOIL BILENKY lectures

After gauge symmetry group $SU(2) \times U(1)$ is broken to $U(1)_{em}$ we get the following interaction Lagrangian

$$\mathcal{L}_{EW} = -e\mathcal{J}^{\mu}_{em}A_{\mu} - \frac{g}{2\cos\theta_W}\mathcal{J}^{\mu}_{nc}Z_{\mu} - \frac{g}{2\sqrt{2}}\mathcal{J}^{\mu}_{cc}W^{\dagger}_{\mu} + h.c.$$

where

$$\sin\theta_W = \frac{e}{g}, \quad \cos\theta_W = \frac{M_W}{M_Z}, \quad \frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2}.$$

θ_W is Weinberg angle.

$\mathcal{J}^{\alpha}$ consists of two parts: leptonic and quark.

$$\mathcal{J}^{\alpha} = J^{\alpha} + \mathbb{J}^{\alpha}.$$

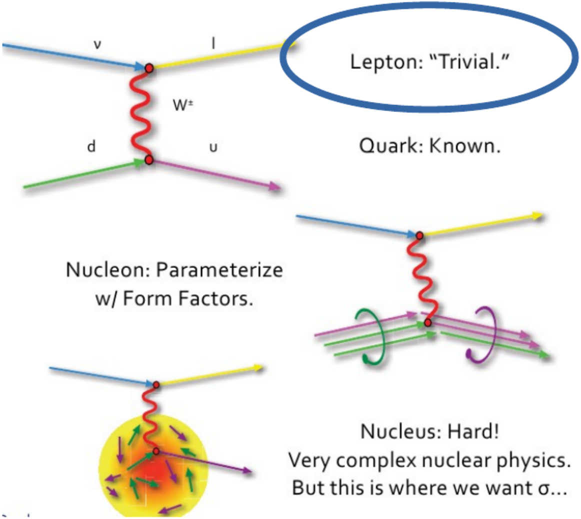
Vocabulary: *vector*, *axial vector*.

→ SAMOIL BILENKY and BORIS KAYSER lectures

- Neutrinos, charged leptons, quarks are all spin $\frac{1}{2}$ particles described by Dirac spinors.
- Algebra of γ matrices
$$\{\gamma^\mu, \gamma^\nu\} = 2g^{\mu\nu}$$
with many important properties.
- A special role is played by $\gamma_5 \equiv i\gamma^0\gamma^1\gamma^2\gamma^3$
- With γ_5 one can build objects transforming as pseudo-scalar, pseudo-vector, etc.
- Examples:
  - $\bar{\Psi}(x)\gamma^\mu\Psi(x)$ transforms like vector
  - $\bar{\Psi}(x)\gamma^\mu\gamma_5\Psi(x)$ transforms like pseudo-vector (axial-vector).

Chirality and helicity. As $m \to 0$

$$\frac{1-\gamma_5}{2}\Psi_p \approx \frac{1-\frac{\vec{\Sigma}\cdot\vec{p}}{|\vec{p}|}}{2}\Psi_p.$$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Very complex nuclear physics.
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Standard Model – generalities

→ SAMOIL BILENKY lectures

In the leptonic sector

$$J^{\alpha}_{em} = \sum_j \bar{l}_j \gamma^{\alpha} l_j,$$

$$J^{\alpha}_{cc} = \sum_j \bar{l}_j \gamma^{\alpha} (1 - \gamma_5) \nu_j,$$

$$J^{\alpha}_{nc} = \frac{1}{2} \sum_j \bar{\nu}_j \gamma^{\alpha} (1 - \gamma_5) \nu_j + \frac{1}{2} \sum_j \bar{l}_j \gamma^{\alpha} (g_V - g_A \gamma_5) l_j$$

and this defines elementary vertices.

$j \in \{e, \mu, \tau\}$, $g_A = -1$, $g_V = 4 \sin^2 \theta_W - 1$.

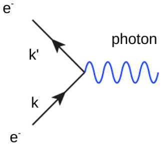
$|g_V| \approx 0.04 << g_A$.

Convention:

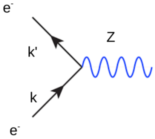
$$\bar{l}_j \gamma^{\alpha} l_j \equiv \overline{\Psi_{l_j}} \gamma^{\alpha} \Psi_{l_j}, \quad etc.$$

Standard Model – generalities

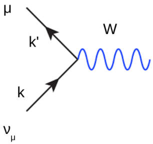
Formulas in the previous slide can be expressed in terms of *Feynman rules* and then used in computations.



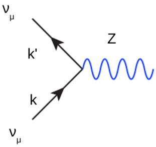
$$e\overline{\Psi(k')}\gamma^\mu\Psi(x)$$



$$\frac{g}{4\cos\theta_W}\overline{\Psi(k')}\gamma^\mu(g_V-\gamma_5 g_A)\Psi(x)$$



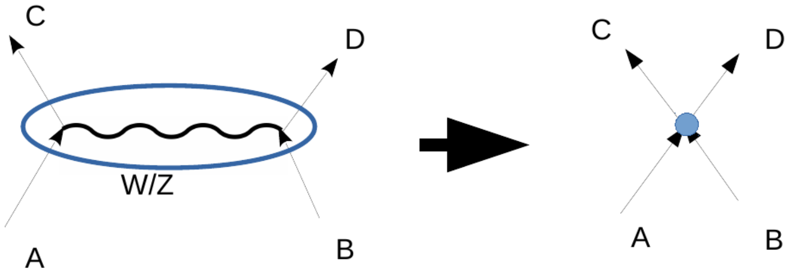
$$\frac{g}{2\sqrt{2}}\overline{\Psi(k')}\gamma^\mu(1-\gamma_5)\Psi(x)$$



$$\frac{g}{4\cos\theta_W}\overline{\Psi(k')}\gamma^\mu(1-\gamma_5)\Psi(x)$$

From Standard Model back to Fermi theory.

For a few GeV (and below) neutrinos a further simplification can be done.



$Q^2 << M_Z^2, M_W^2$ and one arrives at the Fermi-like theory with effective four-fermion interaction.

Cross sections

- When we speak about interactions we think about *cross sections*:
  - there are standard theoretical tools how to calculate them,
  - experimentalists know how to measure them,
  - there is common ground.

Vocabulary.

- *Inclusive* cross section: some outgoing particles are not measured. Often, only outgoing charged lepton is measured.
- *Exclusive* cross section: specific outgoing particles are measured.
- Inclusive cross section is a sum of exclusive cross sections.
- *Differential* cross section: outgoing particles are in specific states (three momentum, spin)

  Example: $\frac{d\sigma}{dE' d\Omega'}(e^- + N \to e^- + X)$,

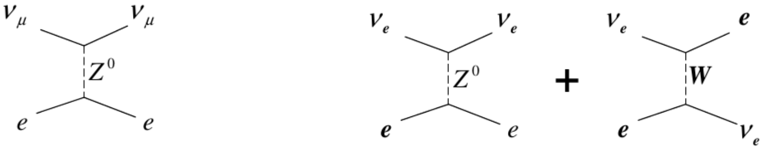
  E', Ω' are final electron energy, spherical angle.

Example: neutrino interactions and solar neutrinos.

Suppose, the measurement is done based on $\nu_l\ e \to \nu_l\ e$ reaction (e.g. in SuperKamiokande or in Sudbery Neutrino Observatory).

An interesting fact is that ν_e and $\nu_{\mu,\tau}$ cross section at $E_\nu \sim 1$ .. 5 MeV are quite different.

It is not a GeV example, but elementary and instructive.



For $\nu_{\mu,\tau}$ it is a neutral current scattering. For ν_e charged current Feynman diagram contributes as well.

Example: neutrino interactions and solar neutrinos.

It is an elementary exercise. For ν_e two amplitudes must be summed up. Dirac algebra must be done. The final results are:

$$\sigma(\nu_l \; e \to \nu_l \; e) = \frac{G_F^2}{\pi} \frac{(s - m^2)^2}{s} \{g_L^2 - g_L g_R \frac{m^2}{s} + \frac{g_R^2}{12}(4s^2 + 4m^4 + 4sm^2)\}$$

where m - electron mass, G_F - Fermi constant, $s = m^2 + 2mE_\nu$.

$$g_L = \begin{cases} \sin^2\theta_W - \frac{1}{2} & \text{for } \nu_{\mu,\tau} \\ \sin^2\theta_W + \frac{1}{2} & \text{for } \nu_e \end{cases} \qquad g_R = \begin{cases} \sin^2\theta_W & \text{for } \nu_{\mu,\tau} \\ \sin^2\theta_W & \text{for } \nu_e \end{cases}$$

θ_W - Weinberg angle, $\sin^2\theta_W \approx 0.23$.

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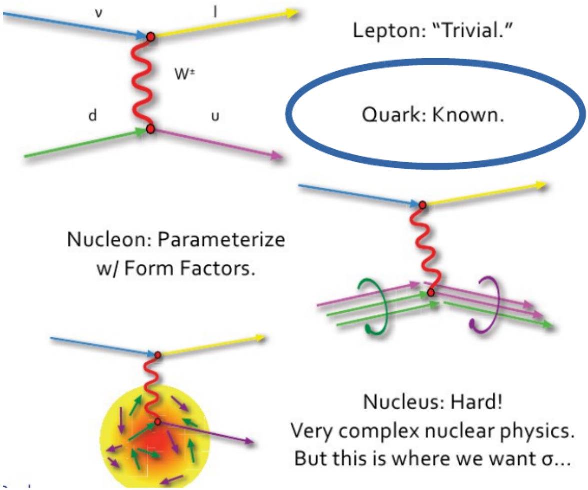
For $E_\nu > 5$ MeV one can neglect m^2/s terms ($m \approx 0.5$ MeV, $m^2/s < 0.1$). Cross sections ratio is

$$\frac{\sigma(\nu_e\ e)}{\sigma(\nu_{\mu,\tau}\ e)} \approx \frac{(\sin^2\theta_W + \frac{1}{2})^2 + \frac{1}{3}\sin^4\theta_W}{(\sin^2\theta_W - \frac{1}{2})^2 + \frac{1}{3}\sin^4\theta_W} \approx 6.0$$

$\nu_{\mu,\tau}$ cross section is much lower and one observes a “deficit” of solar neutrinos expressed in terms of a lower than expected number of reactions.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Very complex nuclear physics.
But this is where we want σ...

Standard Model – quark sector

→ BORIS KAYSER lectures

Quark vertices are also elementary and provided by the SM.

$$\mathbb{J}^{\alpha}_{em} = \sum_k Q_k \bar{q}_k \gamma^{\alpha} q_k$$

with $k \in (u, d, s, c, t, b)$, $Q_k = \frac{2}{3}, -\frac{1}{3}, \ldots$

$$\mathbb{J}^{\alpha}_{cc} = (\bar{q}_u, \bar{q}_c, \bar{q}_t)\gamma^{\alpha}(1-\gamma_5)U \begin{pmatrix} q_d \\ q_s \\ q_b \end{pmatrix}$$

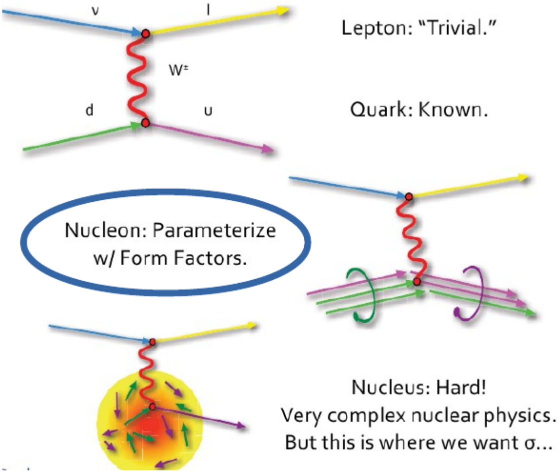
U is Cabibbo-Kobayashi-Maskawa matrix.

In the two-family case

$$U = \begin{pmatrix} \cos\theta_c & \sin\theta_C \\ -\sin\theta_C & \cos\theta_C \end{pmatrix}, \qquad \theta_c \approx 13^o.$$

$$\mathbb{J}^{\alpha}_{nc} = \bar{q}_u\gamma^{\alpha}(C_V + C_A\gamma_5)q_u + \ldots + \bar{q}_d\gamma^{\alpha}(\tilde{C}_V + \tilde{C}_A\gamma_5)q_d + \ldots$$

where $C_V = \frac{1}{2} - \frac{4}{3}\sin^2\theta_W$, $\tilde{C}_V = -\frac{1}{2} + \frac{2}{3}\sin^2\theta_W$, $C_A = -\tilde{C}_A = -\frac{1}{2}$.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From quarks to nucleons

QCD Lagrangian for quarks

$$\mathcal{L}_{QCD} = \sum_k \bar{q}_k (i\gamma^\mu D_\mu - m_k) q_k .$$

If $m_u \approx m_d \approx 0 \Rightarrow$ chiral $SU(2) \times SU(2)$ symmetry.

Conserved currents:

$$V_j^\alpha = (\bar{u}, \bar{d})\gamma^\alpha \frac{\sigma^j}{2} \begin{pmatrix} u \\ d \end{pmatrix}, \quad A_j^\alpha = (\bar{u}, \bar{d})\gamma^\alpha \gamma_5 \frac{\sigma^j}{2} \begin{pmatrix} u \\ d \end{pmatrix}.$$

$$\partial_\alpha V_j^\alpha = \partial_\alpha A_j^\alpha = 0.$$

More exactly $m_u \approx m_d \neq 0$. In this limit it is still true that $\partial_\alpha V_j^\alpha = 0$ (isospin symmetry), but $0 \neq \partial_\alpha A_j^\alpha \sim m_\pi$. Conserved vector current, partially conserved axial current.

From quarks to nucleons.

- We need (for CCQE)

$$< p|\mathbb{J}^{\alpha}_{cc}|n >=< p|\mathbb{V}^{\alpha}_{cc} - \mathbb{A}^{\alpha}_{cc}|n > .$$

- Electromagnetic current can be expressed in terms of V^{α}_{j}:

$$\mathbb{J}^{\alpha}_{em} = \frac{1}{6}(\bar{u}, \bar{d})\gamma^{\alpha} \left(\begin{array}{c} u \\ d \end{array} \right) + V^{\alpha}_{3},$$

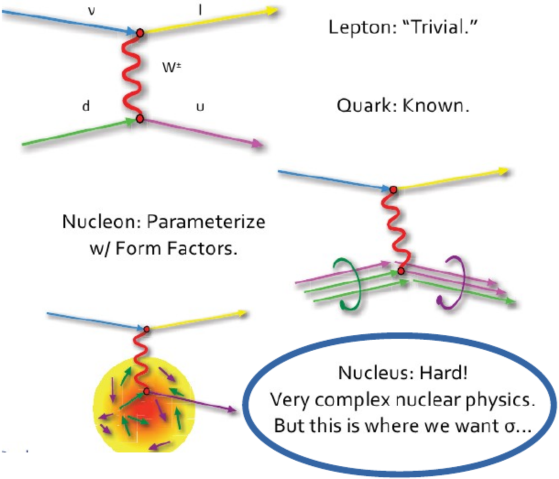
- Conservation of V^{α}_{j} allows to express

$$< p|\mathbb{V}^{\alpha}_{cc}|n >=< p|V^{\alpha}_{1} + iV^{\alpha}_{2}|n >$$

  by well known electromagnetic one.

- *Partial* conservation of A^{α}_{j} allows for simplifications in

$$< p|\mathbb{A}^{\alpha}_{cc}|n > .$$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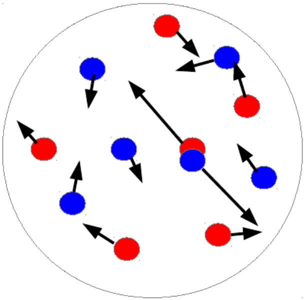
Nuclear effects

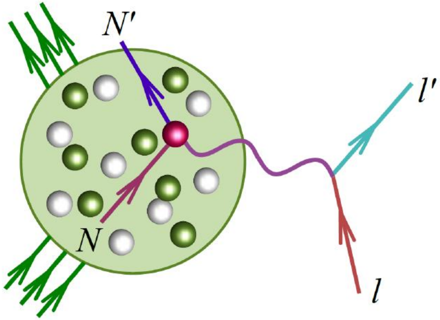


~ 20% of nucleons are in strongly correlated (mostly proton-neutron) pairs with large back to back momenta

Nucleons are moving inside nucleus and are bound (*off-shell*).

Basic theoretical frame: impulse approximation

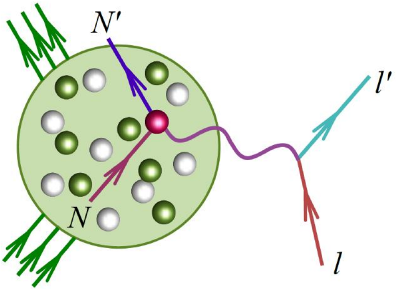
In the ~ 1 GeV energy region one relies on the impulse approximation (IA) picture: ν's interact with individual bound nucleons



from A. Ankowski

- ν_l-nucleus interaction is modeled as a two-step process: a primary interaction followed by hadron reinteractions (final state interactions (FSI) effects)
- Within the IA one needs a joint probability distribution of momenta and binding energies of target nucleons.

Impulse approximation (IA) - limitations.



A. Ankowski

Vocabulary:

momentum transfer is momentum absorbed by nucleus (a difference between initial and final lepton momentum vectors).

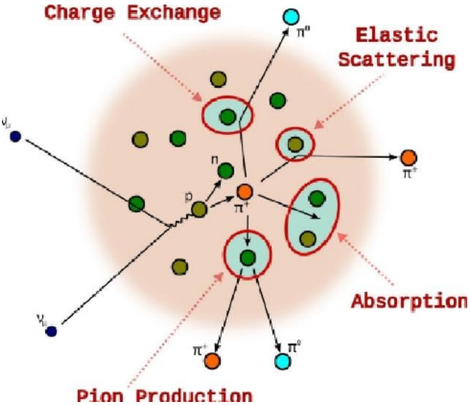
Intuition: intermediate boson as a de Broglie wave (1 fm $\simeq \frac{1}{200\ MeV}$).

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.

The simplest check if impulse approximation picture is correct is to look at the electron scattering data (part 2)

Final state interactions:

What is observed are particles in the final state.



T. Golan

Pions...

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

A similar picture can be drawn for nucleons.

Final state interactions

FSI introduce a lot of complications in understanding neutrino interactions.

Example 1

How to define CCQE on neutrino-nucleus scattering level? Muon and perhaps proton (if energetic enough) in a final state?

- Such events can result from RES reaction with pion production and its subsequent absorption.
- If proton resulting from CCQE is energetic enough it can produce pion.
- As a result of FSI two protons can be knocked out after CCQE interaction.
- ...

Conclusion: there is no unambiguous definition of CCQE in neutrino-nucleus scattering.

Instead, one usually defines CCQE-like (CC0π) cross section. Signal: no π in the final state.

Final state interactions

Example 2

How to interpret CC π^+ production cross section? Muon and π^+ in a final state?

- π^+ can arise from FSIs after CCQE interaction.
- π^+ can arise from π^0 production followed by pion charge exchange FSI.
- π^+ can arise from two pion production process, with one pion being absorbed due to FSI.
- ...

Conclusion: interpretation of a measurement of CC $1\pi^+$ production in neutrino-nucleus scattering requires inclusion of many processes and also FSI effects.

Electron and neutrino response functions

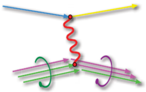
A formalism of nuclear *response functions* (structure functions) for inclusive scaterring data.

- Experimentally: only final state lepton is detected.

Notation:

- initial lepton 4-vector $k^{\alpha} = (E, \vec{k})$
- final lepton 4-momentum $k'^{\alpha} = (E', \vec{k}')$,
- 4-momentum transfer $q^{\alpha} = k^{\alpha} - k'^{\alpha} = (\omega, \vec{q})$, $Q^2 = -q_{\alpha} q^{\alpha} > 0$,
- target nucleon 4-momentum p^{α}, mass M

One boson exchange is



assumed.

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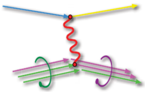
One boson exchange is  assumed.

Lepton inclusive cross section can be written up in a form:

$$\boxed{\frac{d^3\sigma}{d\Omega' dE'} = F_l(Q^2)\frac{|\vec{k}'|}{\sqrt{(k\cdot p)^2}} L_{\mu\nu} W^{\mu\nu},}$$

$$F_l(Q^2) = \begin{cases} 2\frac{\alpha^2}{Q^4} & \text{for } e \\ \frac{G_F^2 \cos\theta_C^2}{2\pi^2} & \text{for } \nu \end{cases} \qquad L_{\mu\nu} = \begin{cases} k_\mu k'_\nu + k'_\mu k_\nu - g_{\mu\nu} k\cdot k' & \text{for } e \\ k_\mu k'_\nu + k'_\mu k_\nu - g_{\mu\nu} k\cdot k' \mp i\varepsilon_{\mu\nu\kappa\lambda} k^\kappa k'^\lambda & \text{for } \nu\ \bar{\nu} \end{cases}$$

$W^{\mu\nu}$ a *hadronic tensor* is a function of two variables e.g. ω, q.

Electron and neutrino response functions

For electron scattering current conservation implies

$$q_\mu W^{\mu\nu}_{em} = W^{\mu\nu}_{em} q_\nu = 0$$

so that

$$W^{\mu\nu}_{em} = W_1(\omega, q)\left(\frac{q^\mu q^\nu}{q\cdot q} - g^{\mu\nu}\right) + \frac{W_2(\omega, q)}{M_T^2}\left(p^\mu - q^\mu \frac{p\cdot q}{q\cdot q}\right)\left(p^\nu - q^\nu \frac{p\cdot q}{q\cdot q}\right).$$

Only two independent functions.

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Only two independent functions. More natural choice

$$W_1 = \frac{1}{2}R_T\,, \quad W_2 = \frac{Q^4}{q^4}R_L + \frac{1}{2}\frac{Q^2}{q^2}R_T$$

$$\frac{d^3\sigma}{d\Omega' dE'} = \frac{\alpha^2\cos^2\frac{\theta}{2}}{4E\sin^4\frac{\theta}{2}}\left(\frac{Q^4}{q^4}R_L + (\tan^2(\frac{\theta}{2} + \frac{1}{2}\frac{Q^2}{q^2})R_T\right).$$

Electron-nucleus inclusive cross section is a sum of contributions from exchange of longitudinally and transversely polarized photon.

In principle, R_L, R_T can be measured separately (Rosenbluth separation).

Inclusive neutrino cross section

For neutrino there is no conservation constraint and a general form of hadronic tensor is:

$$W_{\mu\nu} = -g_{\mu\nu} W_1 + \frac{p_\mu p_\nu}{M^2} W_2 - i \frac{\varepsilon_{\mu\nu\kappa\lambda} p^\kappa q^\lambda}{2M^2} W_3 + \frac{q_\mu q_\nu}{M^2} W_4 + \frac{p_\mu q_\nu + p_\nu q_\mu}{2M^2} W_5 + i \frac{p_\mu q_\nu - p_\nu q_\mu}{2M^2} W_6 .$$

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The contraction of tensors gives:

$$L_{\mu\nu} W^{\mu\nu} = (Q^2 + m^2) W_1 + \left(2E(E-\omega) - \frac{m^2 + Q^2}{2} \right) W_2 +$$

$$\pm \left(EQ^2 - \frac{\omega}{2}(m^2 + Q^2) \right) \frac{W_3}{M} + \left(\frac{1}{2} Q^2 m^2 + \frac{1}{2} m^4 \right) \frac{W_4}{M^2} - \frac{m^2 E}{M} W_5 .$$

Plus sign at W_3 for neutrinos and minus sign for antineutrinos.

At large neutrino energy, m containing terms can be neglected and

$$\boxed{\frac{d^3\sigma}{dE' d\Omega'} \approx \frac{G_F^2 |\vec{k}'|}{(2\pi)^2 E_k} \left(Q^2 W_1 + \left(2E(E-\omega) - \frac{Q^2}{2} \right) W_2 \pm Q^2 \left(E - \frac{\omega}{2} \right) \frac{W_3}{M} \right)}$$

Three structure functions are really relevant.

Why did we spend so much time on response functions?

Response functions

A convenient language in neutrino interactions studies.

Advantages

- A very economic language, functions of two variables only.
- W_j can be represented as sums of contributions from exclusive (no interference between them) channels:

$$W_j = W_j^{0\pi} + W_j^{1\pi} + \ldots$$

- For DIS a starting point for scaling studies.

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Limitations

- Suitable mostly for inclusive cross section.
- Generalization to exclusive channels is complicated (a lot of responses, many independent arguments).
- Final state hadrons are often modeled with a factorization picture which is only a rough approximation.

Monte Carlo event generators

(from C. Andreopoulos)

ν oscillation measurements rely on MC event generators

- What is seen experimentally is flux averaged and includes nuclear effects.
- Recent experimental results are typically reported as including nuclear effects
  - Comparison of theoretical models to the data is not straightforward.
- A central topic of NuInt workshops and many NuSTEC collaboration activities.
  - http://nustec.fnal.gov/

Monte Carlo event generators

Degrees of freedom for a simple process (neglectin spins):

$$\nu_l \; X \to l^- \; p \; X'.$$

- Three particles in the final state, two are on shell but nucleus X' is in unknown excited state:

$$3 + 3 + 4 = 10$$

- Four energy-momentum conservation laws

$$10 - 4 = 6$$

- Rotation symmetry around neutrino momentum vector

$$6 - 1 = 5$$

For a complete information we need e.g. $\dfrac{d^5\sigma}{dp_l d\cos(\theta_l) d^3 p_p}$. If there is an extra pion in the final state we need $\dfrac{d^8\sigma}{dp_l d\cos(\theta_l) d^3 p_p d^3 p_\pi}$.

Approximations are necessary.

Message to take home (part 1):

- Correct understanding of neutrino interactions is important for precise identification of the oscillation signal and for CP violation measurement.
- Most difficult is to account for nuclear effects.
- In a few GeV region the basic picture is that of impulse approximation.
- Many complications come from final state interactions inside nuclei.
- There is the important language of structure/response functions describing lepton inclusive cross section.

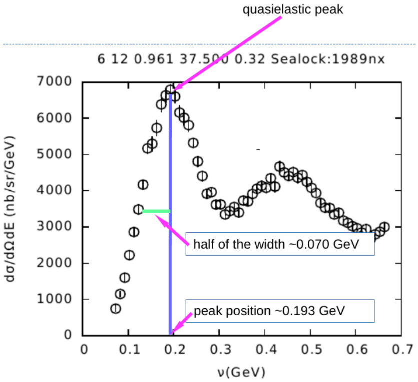
Outline of part 2:

- QE/CCQE peak region.
- Importance of CCQE scattering.
- Theory of CCQE ν-nucleon scattering.
  - Form factors and axial mass
- Two-body currents
  - Ab initio computations of R_T and R_L responses.
  - Basic intuition.
  - Neutrino energy reconstruction.
- Search for np-nh events.
  - Theoretical models.
  - CC0π measurements.
  - Proton measurements.
  - Liquid argon proton pairs measurement.
- Message to take home.

Quasielastic peak

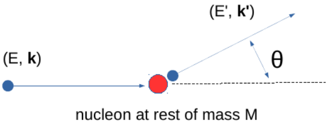
Consider electron scattering.

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



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

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



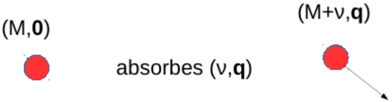
If target nucleon is at rest scattering angle θ determines energy transfer ω.

What is *quasielastic 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 can be neglected.

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

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



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 *quasielastic peak*?

Two equations can be solved for ω:

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

Almost OK! What about a small difference?

We forgot that the target nucleon is bound and it costs energy to take it out of nucleus. Knocked-out nucleon four-momentum is $(M + \omega - B, \vec{q})$. B is called *binding energy*, here we assume that B is a constant.

Slightly modified equation for ω:

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

How large is B? Roughly $B = 8$ MeV$+E_{Fermi}$.

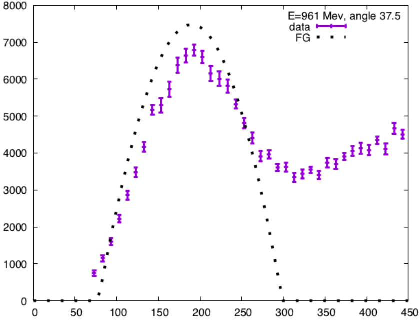
Take $B = 25$ MeV $\Rightarrow \omega = 192\mathrm{MeV}$!

$\boxed{\text{We understand the peak position!}}$

What is *quasielastic peak*?

What about the peak's width?

- It arises because of Fermi motion (nucleons move inside nucleus),
  - peak's width tells us about Fermi momentum.
- The simplest nuclear model is Fermi model.
- It is a reasonable first approximation (in the discussed example the precision $\sim 10\%$).



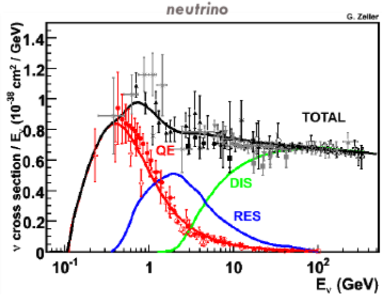
QE peak arises due to scattering on individual moving nucleons.

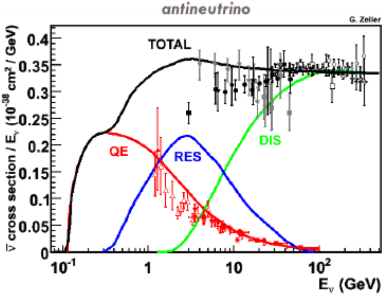
Impulse approximation seems to be reliable.

Importance of CCQE

In weak interactions the analog of QE scattering is usually called CCQE (charged current quasi elastic)

$$\nu_l + n \to l^- + p, \qquad \bar{\nu}_l + p \to l^+ + n$$

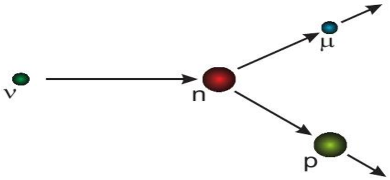




- In experiments like T2K, MicroBooNE most of events are CCQE.
- Theoretical models should be able to reproduce QE peak measured in electron scattering.

CCQE

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



Muon and proton in the final state

In the 1 GeV energy range:

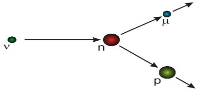
$$Q^2 << M_W^2$$
$$\Downarrow$$
$$\mathcal{H}_{int} = \frac{G_F}{\sqrt{2}} J_\alpha^{lep} \mathbb{J}^\alpha + h.c.$$
$$< \mu(k')|J_\alpha^{lep}|\nu_\mu(k) >= \bar{u}(k')\gamma_\alpha(1-\gamma_5)u(k), \quad \mathbb{J}^\alpha = \cos\theta_C(\mathbb{V}^\alpha - \mathbb{A}^\alpha).$$

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

CCQE on free nucleon target

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

In the simplest model the only unknown is a value of *axial mass*.



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

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

- The structure follows from Lorentz symmetry, no 2^{nd} 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 all functions of Q^2.

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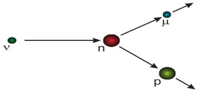


$$\nu_l/\bar{\nu}_l(k) \; + N(p) \; \rightarrow l^{\pm}(k') \; + N'(p')$$
$$q^{\mu} \equiv k^{\mu} - k'^{\mu}; \quad Q^2 \equiv -q_{\mu}q^{\mu}.$$

- CVC (conserved vector current) $\Rightarrow$ vector part ($F_V(Q^2)$, $F_M(Q^2)$) is known from electron scattering
- PCAC (partially conserved axial current) $\Rightarrow$ only one independent axial form factor $F_A(Q^2)$; β decay $\Rightarrow$ $F_A(0) \simeq 1.26$
- Analogy with EM, experimental hints and simplicity $\Rightarrow$ dipole axial form factor:
$$F_A(Q^2) = \frac{F_A(0)}{(1 + M_A^2/Q^2)^2}$$
with one unknown quantity is M_A, axial mass.
- Other expressions (e.g. coming from neural network techniques) are also investigated

L. Alvarez-Ruso, K. M. Graczyk, E. Saul-Sala.

Electromagnetic form factors

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

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

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

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

Fits to available data have been studied by many authors

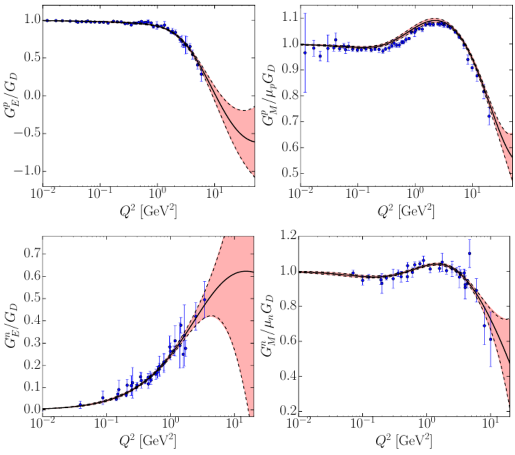
... W. Alberico, S. Bilenky, C. Giunti, K. M. Graczyk, ...

- An important topic here is two photon exchange contribution.

Results usually shown as ratios wrt standard dipole expression:

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

Electromagnetic form-factors

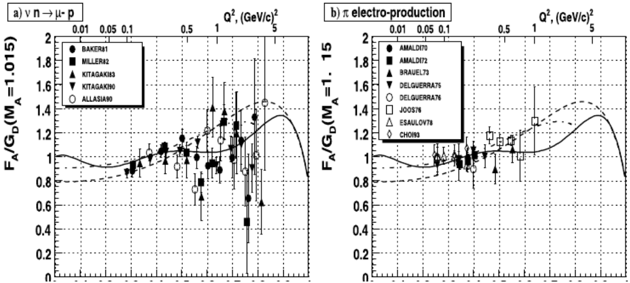


$G_E^n(Q^2)$ has different shape because $G_E^n(0) = 0$ (neutron has no electric charge).

For remaining FFs in the region $Q^2 < 1$ GeV^2 dipole approximation is ok.

(Ye, Arrington, Hill, Lee)

Axial mass

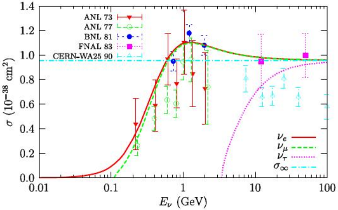


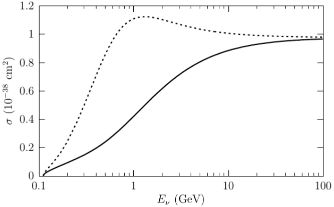
(A. Bodek, S. Avvakumov, R. Bradford, H. Budd)

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

CCQE cross section

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





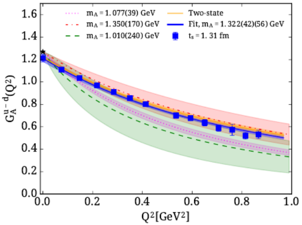
- Large experimental uncertainty
- Most recent data are not included
- At large energy cross section saturates

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

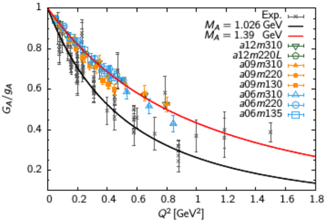
Further progress in determination of axial FF

The situation is not satisfactory.

- On the experimental side problems comes from
  - poor understanding of neutrino flux,
  - no new hydrogen/deuteron target experiments,
  - ambiguities in defining CCQE in heavier target experiments (see later).
- Theory cannot help much:
  - lattice QCD computations are not mature enough.



(Alexandrou et al)



(Gupta et al)

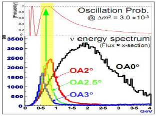
Electron versus neutrino scattering

Electron

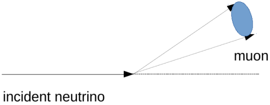
- Monoenergetic beam.
- Fixed scattering angle.
- Distribution of final electron kinetic energies

Neutrino

- Off-axis beam, here T2K



- In order to have good statistics one must collect muons from much larger piece of spherical angle.



- Distribution of final muon kinetic energies.

Electron scattering data

There are large samples of electron scattering data.

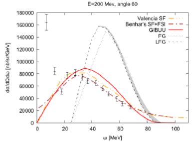
- Mono-energetic electron flux.
- Various nuclear targets.
- Focus on the inclusive data in a format: fixed scattering angle and a distribution of events as a function of outgoing electron energy (or energy transfer).
- Radiative corrections typically corrected for.
- http://faculty.virginia.edu/qes-archive/

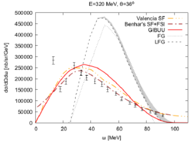
Electron scattering data

We will show some comparisons of various models predictions predictions based on impulse approximation.

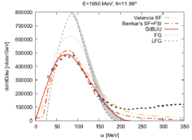
- Important: the data is for the inclusive cross section.
- The theoretical models are for $eN \to eN$ scattering only.
    - They describe the first pronounced peak seen in the data (details: part 2).
- Disagreement on the right of the first peak is here irrelevant.

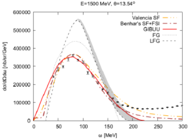
Electron scattering data



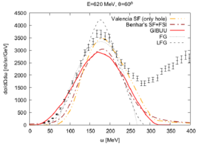


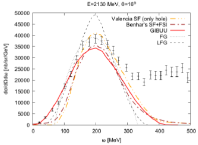
Momentum transfer (at the peak) is 182 and 189 MeV/c.





Momentum transfer (at the peak) is 345 and 353 MeV/c.





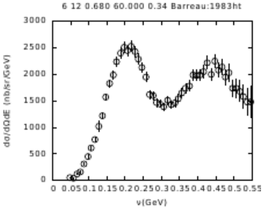
Momentum transfer (at the peak) is 555 and 595 MeV/c.

- Predictions from Fermi gas model and three theoretical models popular in neutrino community: Benhar's spectral function, Valencia, GiBUU.
- For larger momentum transfer agreement is better.

Altogether: reasonable agreement.

Electron scattering

For electron scattering one knows momenta of initial and final electrons and thus energy and momentum transfer on event by event basis.



It is possible to analyze QE, RES, ... regions separately.

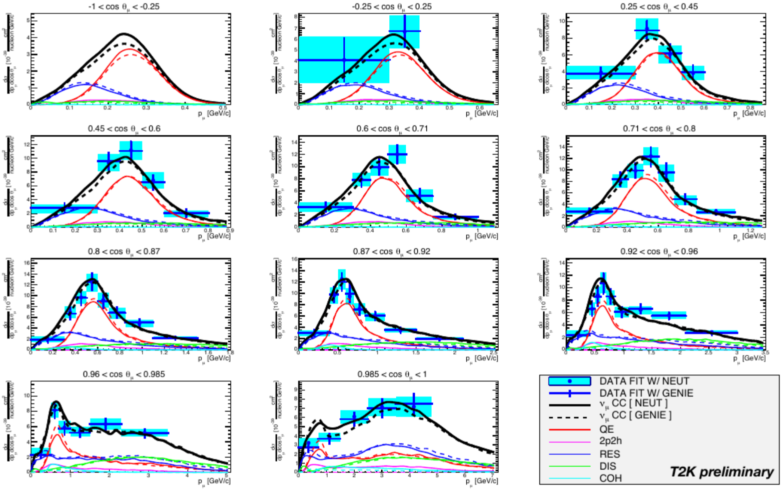
QE and RES regions are clearly separated (see later).

Similar precision for neutrino scattering is utopia; the flux is always smeared out – even with the off-axis trick!

In neutrino experiments one cannot separate *dynamics*, they superimpose each other; data analysis is much more involved.

Electron versus neutrino scattering

T2K example (flux averaged).



Electron versus neutrino scattering

- One can clearly see *QE peak*, great!.
- It is dominated by *true* CCQE mechanism
- However, there is a large (20-30%) contamination from other dynamical mechanism.

What we established so far?

- QE peak in lepton-nucleus scattering seems to originate from the simple binary reaction ($e + N \rightarrow e + N$ for electrons) on bound nucleons
- Its precise understanding requires good control of nuclear physics.
- In the case of neutrino scattering, precise input to description of CCQE process on free nucleons is still missing (axial FF).

Is there anything else missing in the picture?

- Use the most precise tool in nuclear physics: *ab initio* computations.
- Apply it to calculate R_L, R_T response functions (see part 1).

Ab initio computations

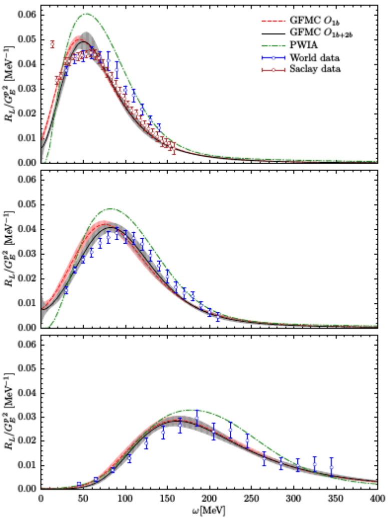
It is only recently that results from *ab initio* state-of-art computations (electron scattering) of nuclear response functions R_T and R_L are available.

- Computations are non-relativistic.
  - Only a restricted phase space (values of momentum and energy transfer) is covered.
- For a moment only light nuclei, up to carbon.
- Pion production is not included.
- Green function Monte Carlo (GFMC) technique.

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

Argonne v18 potential fitted to the NN scattering data.

GFMC and electromagnetic response functions



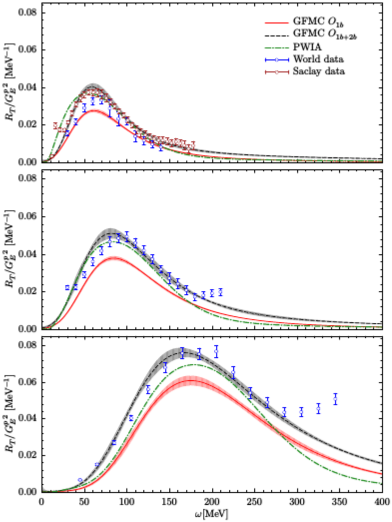
Lovato et al

R_L for carbon.

$q = 300,\ 380,\ 570$ MeV/c.

- Very good agreement with the data (look at red curve).

GFMC and electromagnetic response functions



Lovato et al

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

- Red curve is below the data.
- Another contribution ("two body current") is important!

Two-body current is needed to reproduce QE peak in R_T.

Important lessons from R_T/R_L separation and *ab initio* computations

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).

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

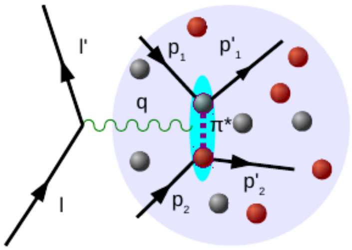
In order to describe CCQE/QE peak we need both one- and two-body current contributions in a consistent theoretical frame.

- Amount of R_L and R_T contributions at the peak depend on kinematics.
- If R_L dominates CCQE mechanism is enough.
- Another conclusion is that it is important to have a realistic description of the nucleus ground state, including nucleon-nucleon correlations.

Unfortunately, the data with R_T, R_L separation is scarse.

Two body current contribution

Neutrino interacts at once with two correlated nucleons:



from J. Żmuda

Something obvious from the theoretical perspective:

Consider electromagnetic interactions

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

$$\vec{J} = \vec{J}_j^{(1)} + \vec{J}_{jk}^{(2)} + \dots$$

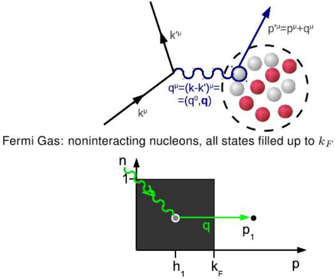
$$\vec{q}\cdot\vec{J}_j^{(1)} = [\frac{\vec{p}_j^{\,2}}{2M}, \rho_j^{(1)}], \qquad \vec{q}\cdot\vec{J}_{jk}^{(2)} = [V_{jk}, \rho_j^{(1)} + \rho_k^{(1)}].$$

Presence of two-body current part in the electromagnetic current is required by the current conservation.

Two-body current – basic intuition.

One-body current operator:

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



from J. Żmuda

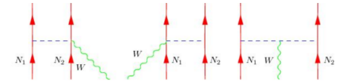
In the second quantization language J^α

- 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)

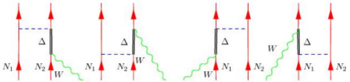
$$\boxed{J^\alpha_{1body} \sim a^\dagger(p')a(p)}$$

Two-body current – basic intuition

Think about more complicated Feynman diagrams:



Contact and *pion-in-flight* diagrams



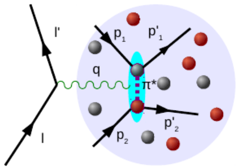
Δ-Meson Exchange Current diagrams

J. Morfin, JTS

Transferred energy and momentum are shared between two nucleons.

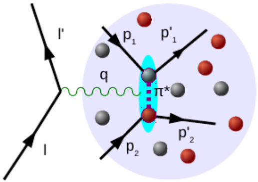
$$\boxed{J^{\alpha}_{2body} \sim a^{\dagger}(p_1')a^{\dagger}(p_2')a(p_1)a(p_2)}$$

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



from J. Żmuda

Why should we care about np-nh contribution?



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

YES!

CCQE ν_μ reconstructed energy

We need to know interaction neutrino energy.

A pattern of neutrino oscillations is energy dependent!

Assume that:

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

CCQE ν_μ reconstructed energy

We need to know interaction neutrino energy.

A pattern of neutrino oscillations is energy dependent!

Assume that:

- Only final state muon is detected (e.g. SuperKamiokande)
- The interaction was CCQE
- 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:

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

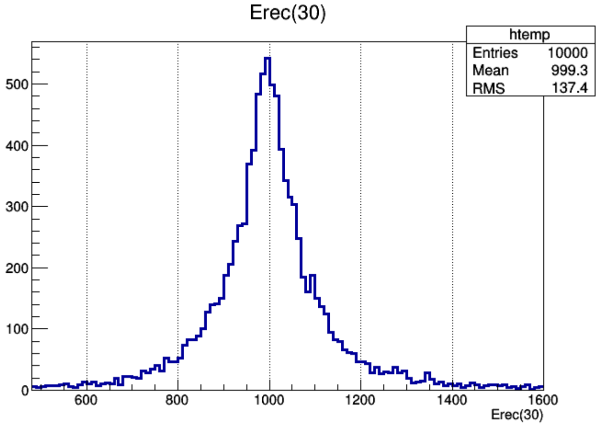
$$E_{p'}^2 = (E_\nu - E' + M - B)^2.$$

Neglecting a difference between proton and neuton mass we obtain:

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

In the above derivation we used only information about final state muon.

CCQE ν_μ reconstructed energy



CCQE events, $E_\nu = 1000$ MeV, carbon target, hole 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

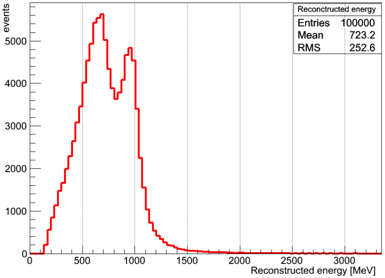
Consider 100 000 random two body current events generated with Nieves et al model. $E_\nu^{TRUE} = 1000$ MeV.

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.



Nieves model implemented in NuWro MC event generator

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

Search for np-nh contribution in neutrino scattering

Theory: a variety of approaches and approximations.

- Ab initio (Lovato, Schiavilla, Gandolfi, Carlson, ...) – nonrelativistic computations covering a tiny fraction of the phase space .
- Marteau, Martini et al – the first model pointing to a large np-nh contribution.
- Valencia model (Nieves, Ruiz-Simo, Vicente Vacas) – implemented in most MC event generators
- Ghent model (Jachowicz, Niewczas, Van Cuyck, ...) – under development
- SuSav2 approach (Megias, Donnelly, Barbaro, Caballero, ...) – based on scaling
- Benhar, Rocco spectral function approach.

It is not easy to understand model similarities and differences.

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

Experimental search for np-nh contribution

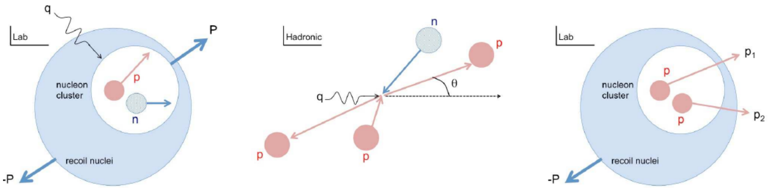
Two basic approaches:

- Study CC0π events
  - a relatively simple measurement
  - usually a large statistics of events, only systematic errors matter.
- Look at final state protons
  - detectors are not opimized to measure protons
  - neutrons are often not seen at all
  - a lot of uncertainty from nucleon FSI effects
  - the best option is liquid argon detector with a low proton reconstruction threshold
  - theoretical predictions for final state protons are uncertain.

Two body current in neutrino interactions

A common limitation of np-nh models is that there are no predictions for final state nucleons.

A way out is *phase space model* typically implemented in MC generators.



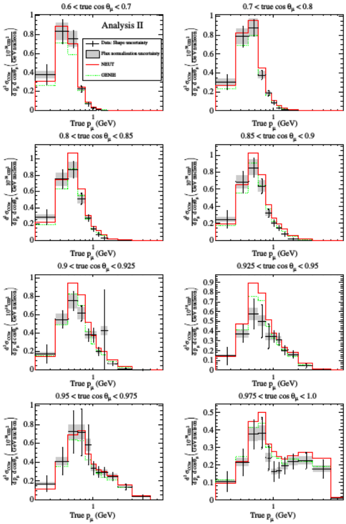
(T. Katori, based on JTS)

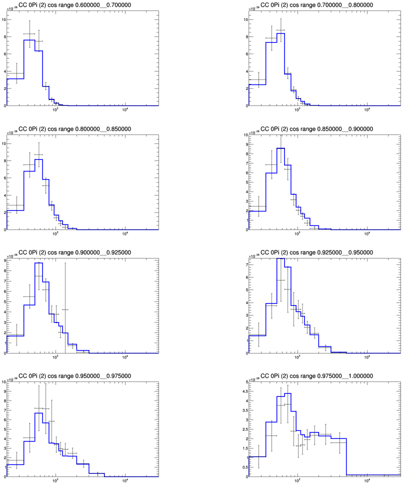
CC0π measurements

Several CC0π cross section measurements were done in recent years:

- MiniBooNE
  - CH_2 target
  - both ν_μ and $\bar{\nu}_\mu$
- T2K
  - CH and water targets
  - both ν_μ and $\bar{\nu}_\mu$, their sum and difference
- MINERvA
  - CH target
  - low energy beam
  - both ν_μ and $\bar{\nu}_\mu$

Example: T2K – CC0π





NuWro results (with Nieves model).

Difficult to draw conclusions.

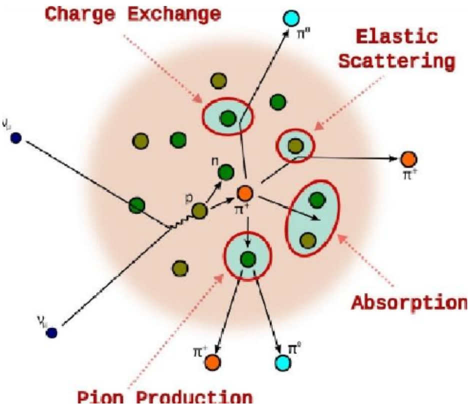
Protons as “window” to measure np-nh

There are several sources of CC0π events (see the discussion of FSI in part 1)

- genuine np-nh
- real pion production and absorption
- CCQE on correlated nucleon-nucleon pairs
- “standard” CCQE with FSI leading to multinucleon knock-out

In order to identify contributions to sample of CC0π events we need proton measurements together with precise theoretical predictions and reliable estmation of remaining background events.

FSI as a source of multinucleon knock-out events



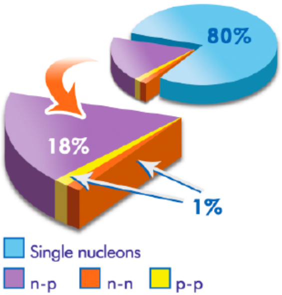
T. Golan

- Real pion production and absorption (shown on the left).
- Nucleon rescattering after CCQE interaction.

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

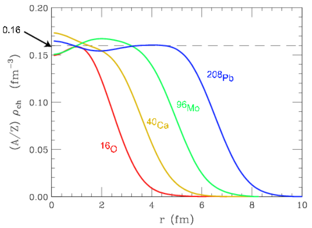


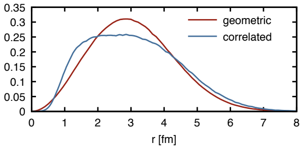
INT Workshop 4 December 2013

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.

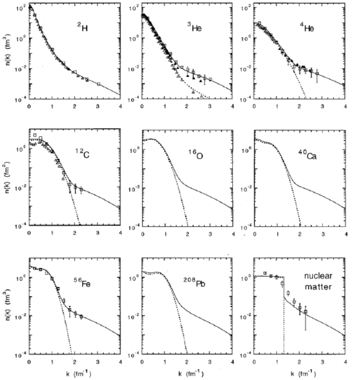
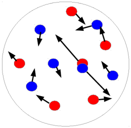


Figure 1: Nucleon momentum distributions $n(k)$ (solid lines) along with the momentum distribution for nucleons in an average potential (dotted lines) for various nuclei are shown.

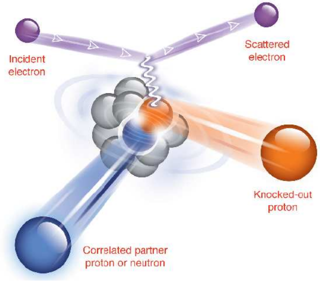
from J. Arrington, D.W. Higinbotham, G. Rosner, M. Sargasian

- 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.



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.

A trendy topic: proton measurements

A general strategy seems to be performing of simple proton measurements, with reduced number of degrees of freedom. Already those present a challenge to understand what is going on.

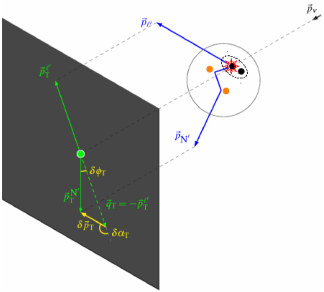
- single transverse variables
- reconstructed neutron momentum
- proton number multiplicity

More "global" measurements were also done

- CC0π without proton (above a detection threshold, of course)
- $1\pi 1p$ differential cross section
- "inferred proton kinematics"

Probably the most interesting: proton pairs in liquid argon detectors.

Transverse kinematic imbalances
– *a neutrino shadow play*



Nuclear target

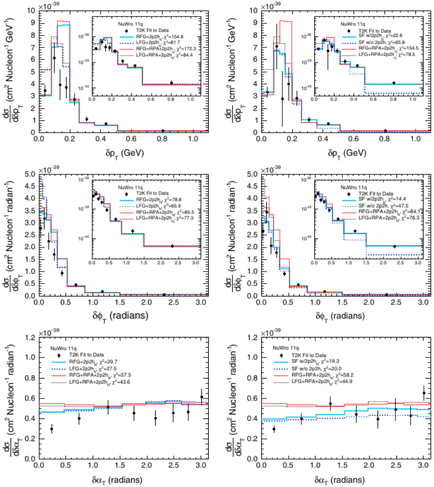
Xianguo Lu, Oxford

Source: http://zhejiangpiying.sokutu.com/tupian.html

To make *Neutrino Shadow Play*, we need
- ✓ beam of light ⟶ accelerator
- ✓ screen ⟶ transverse plane

Transverse kinematics

Measurements done by both T2K and MINERvA collaborations

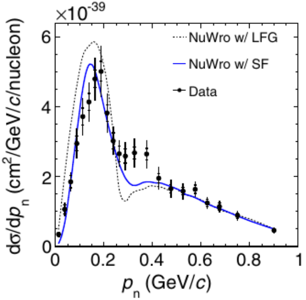


T2K collaboration, Phys. Rev. D 98, 032003 (2018)

Transverse kinematics plus

With information about longitudinal components of muon and proton momentum assuming CCQE mechanism one can reconstruct target neutron momentum vector.

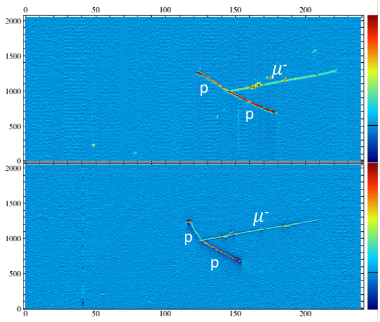
A measurement done by MINERvA:



MINERvA collaboration, Phys. Rev. Lett. 121, 022504 (2018), based on A. Furmanski, JTS, Phys. Rev. C95 (2017) 065501

- A peak at $\sim$ 200 MeV/c comes from CCQE events where proton did not suffer from FSI.
- The structure at $\sim$ 350 MeV/c and the tail come from CCQE events with FSI, np-nh, pion absorption, ...
- Both measurements can be used to validate nuclear models used in MCs.

Two proton events: ArgoNeut experiment



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

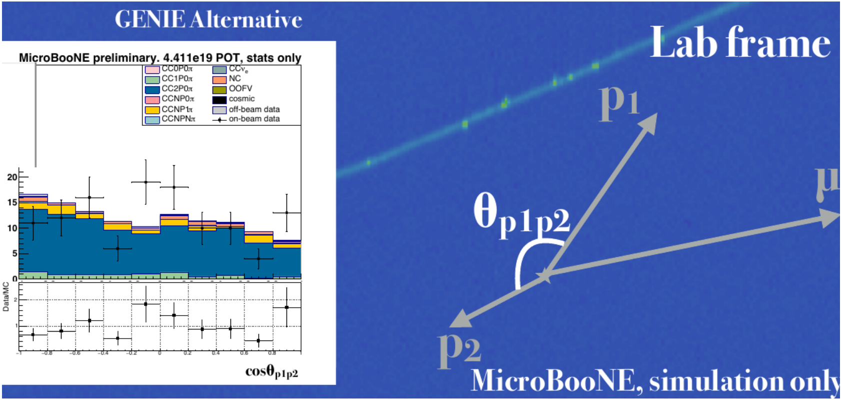
Theoretical studies

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

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

- Very low proton reconstruction threshold $P_{thr} \sim 200$ MeV/c (below Fermi momentum!).
- Excess of *hammer* events in the LAB frame with almost back-to-back momenta (on the left).
- Correlated nucleon-nucleon pairs??.
- Kajetan Niewczas, JTS: correlated back-to back configuration are only in the initial state; what is seen is most likely a fluctuation.

MicroBooNE two-proton study



Raquel Castillo-Fernandez, NuInt2018

No excess of back-to-back proton-proton configurations.

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 the 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.