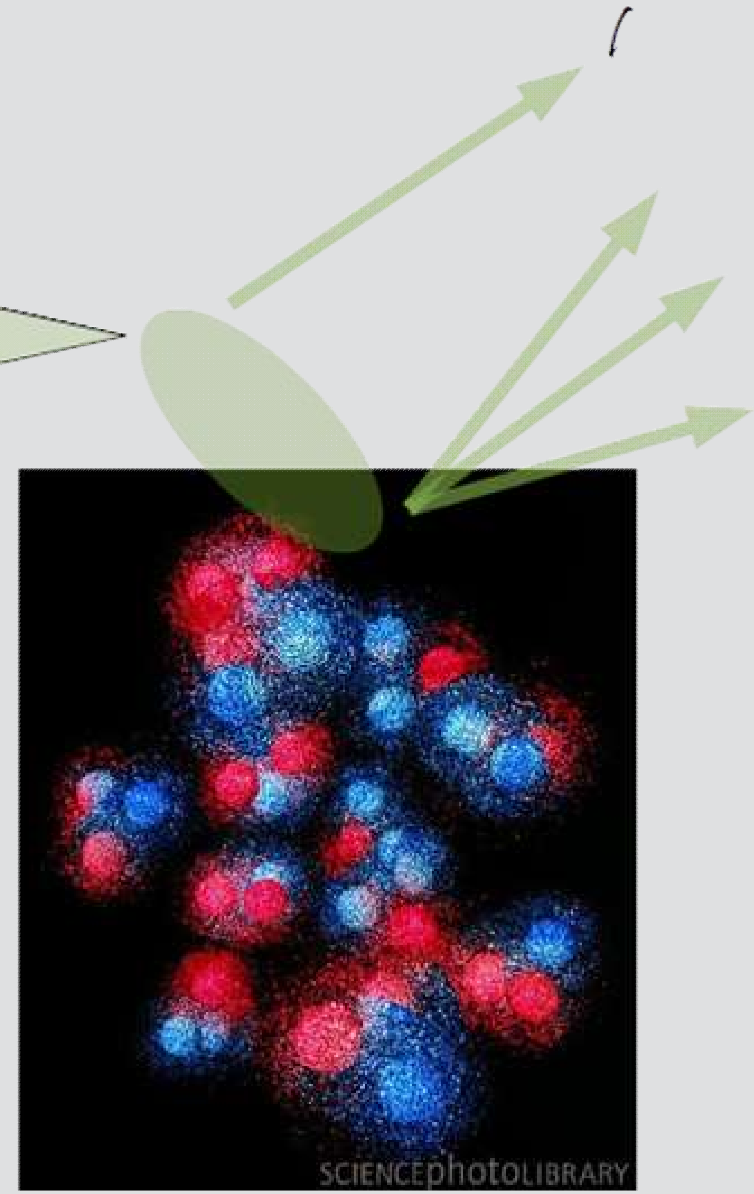
Neutrinos and Nuclear Physics

- Nuclear Physics (NP) in general
- NP and neutrinos, techniques/overview
- ν NP topics



R. Tayloe, Indiana U.
Fermilab ν Summer Lecture
07/16/15

ν and nuclear physics

Why couple nuclear physics and neutrinos?

$$\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = \begin{pmatrix}\cos\theta & \sin\theta\\ -\sin\theta & \cos\theta\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\end{pmatrix}$$

$$|\nu_\mu(t)\rangle = -\sin\theta\,\exp[-i(E_1/\hbar)t]|\nu_1\rangle + \cos\theta\,\exp[-i(E_2/\hbar)t]|\nu_2\rangle$$

$$P(\nu_\mu\rightarrow\nu_e) = \sin^2 2\theta\,\sin^2(\frac{\pi x}{\lambda_{osc}})$$

$$\lambda_{osc} = 2.5E_\nu/\Delta m^2$$

1) Because we must. The atmospheric oscillation $\Delta m^2 \sim 10^{-3}$ eV, necessitates Enu~1GeV and our impatience dictates nuclear targets A >1-2.

ν and nuclear physics

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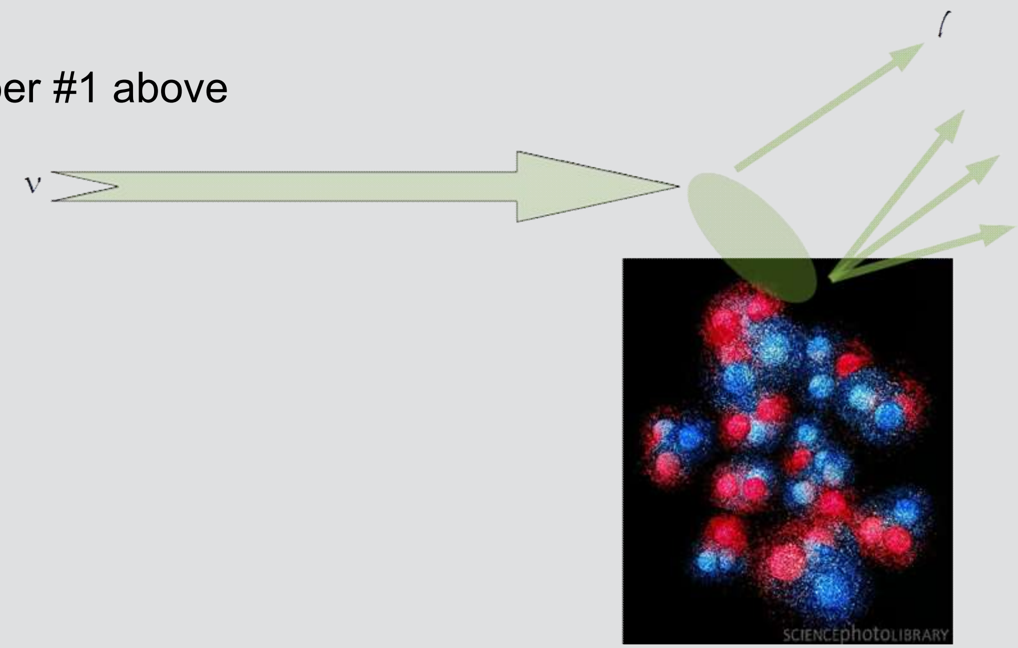
1) Because we must. The atmospheric oscillation $\Delta m^2 \sim 10^{-3}$ eV, necessitates Enu~1GeV and our impatience dictates nuclear targets A >1-2.

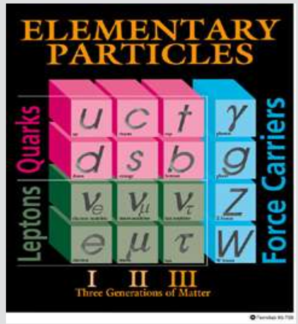
2) Because it is interesting. Number #1 above has provided opportunity to study the structure of the nucleus with ν

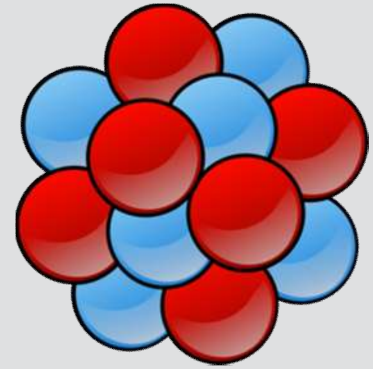


ν and nuclear physics: some definitions

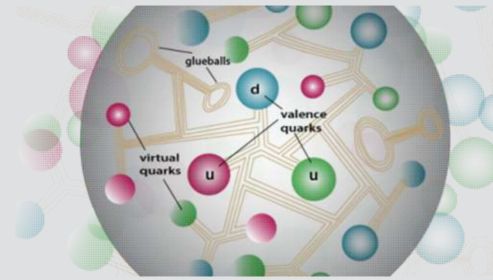
Definitions:

ν:



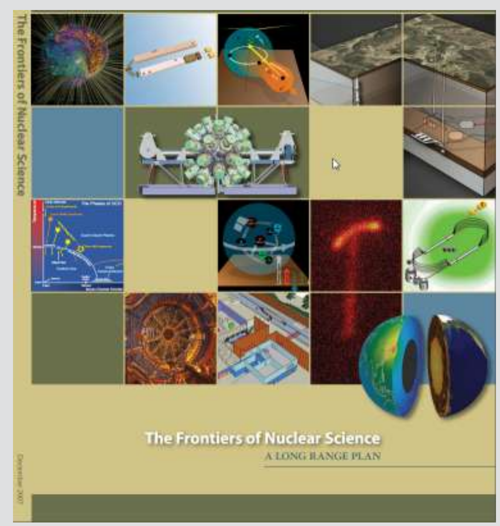


"nuclear physics": physics of … the atomic nucleus, the protons and neutrons and their interactions inside the nucleus.



Also includes physics of:

- Bare (unbound) protons and neutrons
- (0ν) double-beta decay
- Ultimately, whatever the field (and funding agencies!) decide is an exciting and appropriate topic to pursue



How do we see inside a nucleus?

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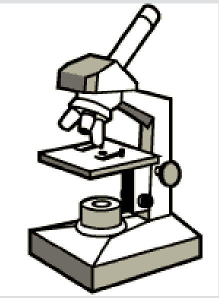
How do we see inside a nucleus?



With a microscope, dummy!

.... one with the appropriate wavelength.

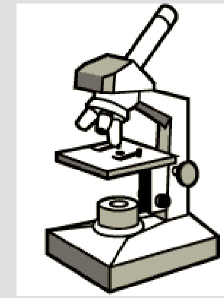
What is right wavelength? Somewhere around:

- O(size of C nucleus)~ (1.3 fm x $A^{1/3}$) ~ 4 fm ,
- O(size of proton) ~ 1 fm

$\Rightarrow$ 1/E ~ R/$\hbar$c ~ 1-4 fm/(200 MeV fm) $\Rightarrow$ E ~0.1-1 GeV *

[*Actually, the size of object probed is dictated by momentum transfer, q]

How do we see inside a nucleus?



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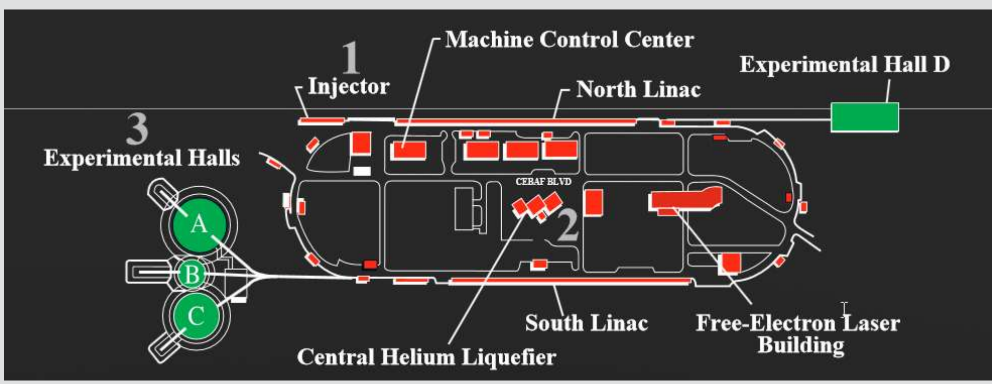
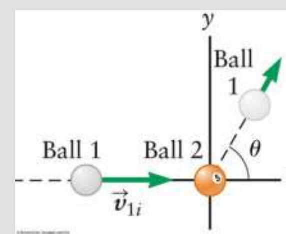
How about an ~1 GeV electron beam. Like at JLAB?

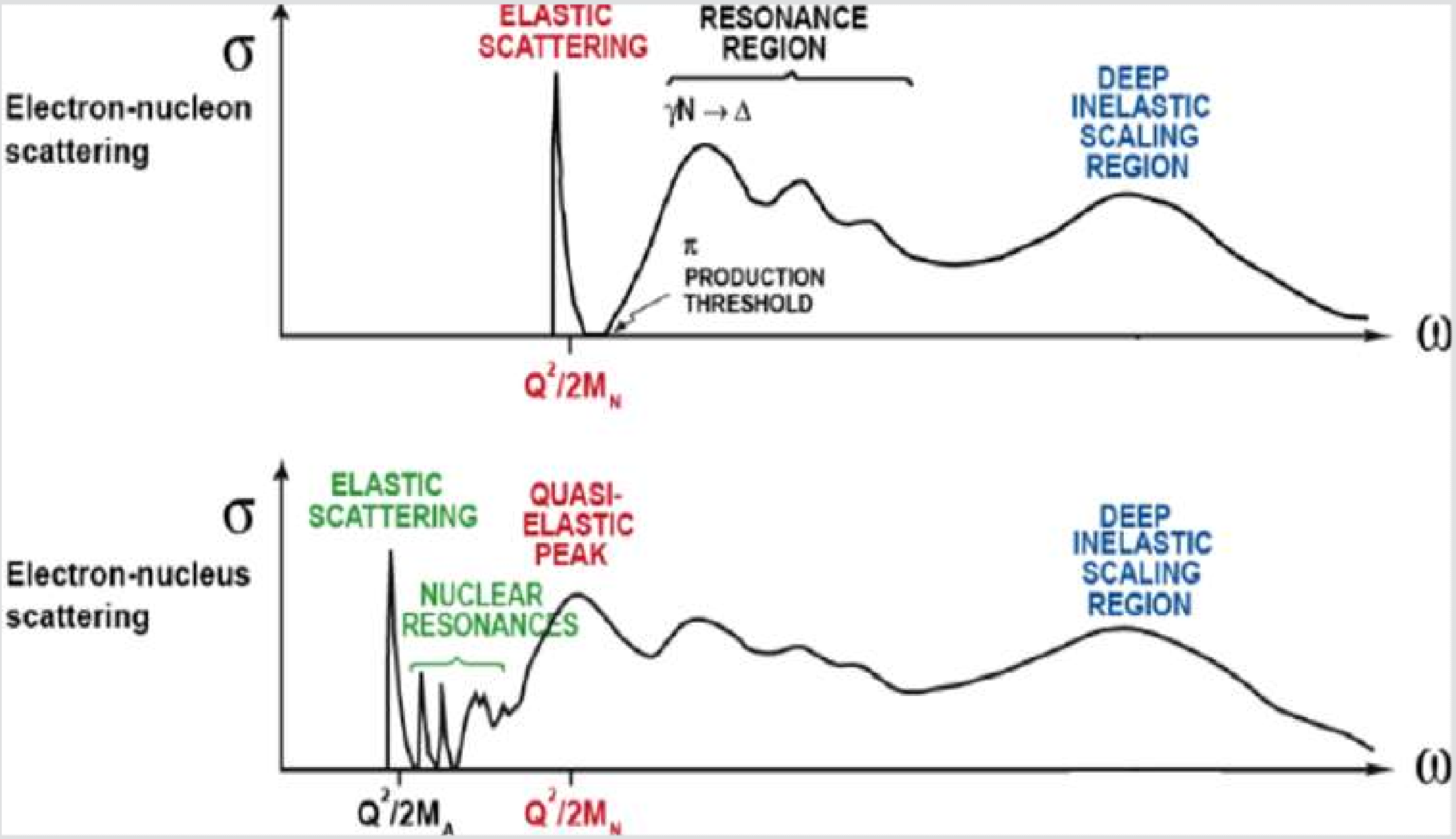




Shoot electrons at nucleus, do the kinematics, plot mass of target…

How do we see inside a nucleus?

and *voila*….the structure of the nucleus is revealed:



Aside: some kinematics

Kinematics

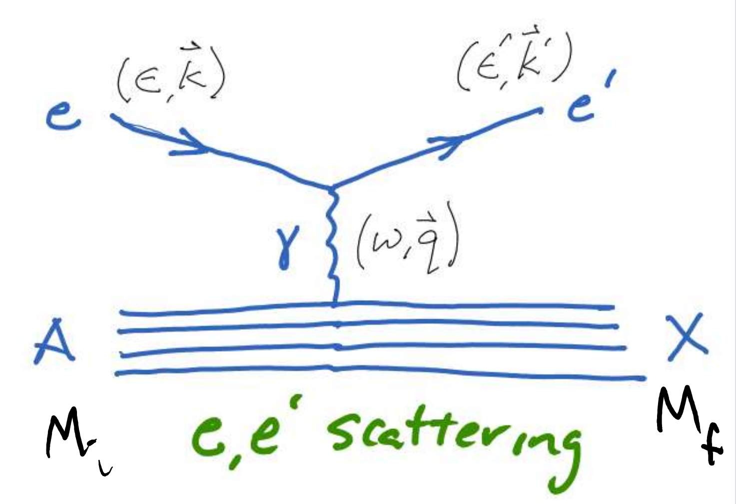
Much physics revealed with understanding of the kinematics!

(I highly recommend working through it for your particular interest)

electron scattering:

$$\epsilon = \sqrt{m^2 + k^2},$$
$$\epsilon' = \sqrt{m'^2 + k'^2},$$

$$\omega = \epsilon - \epsilon',$$
$$\mathbf{q} = \mathbf{k} - \mathbf{k}',$$



$$\omega_0 \equiv \frac{1}{2M_i}\left(M_f^2 - M_i^2\right) \geqslant 0.$$

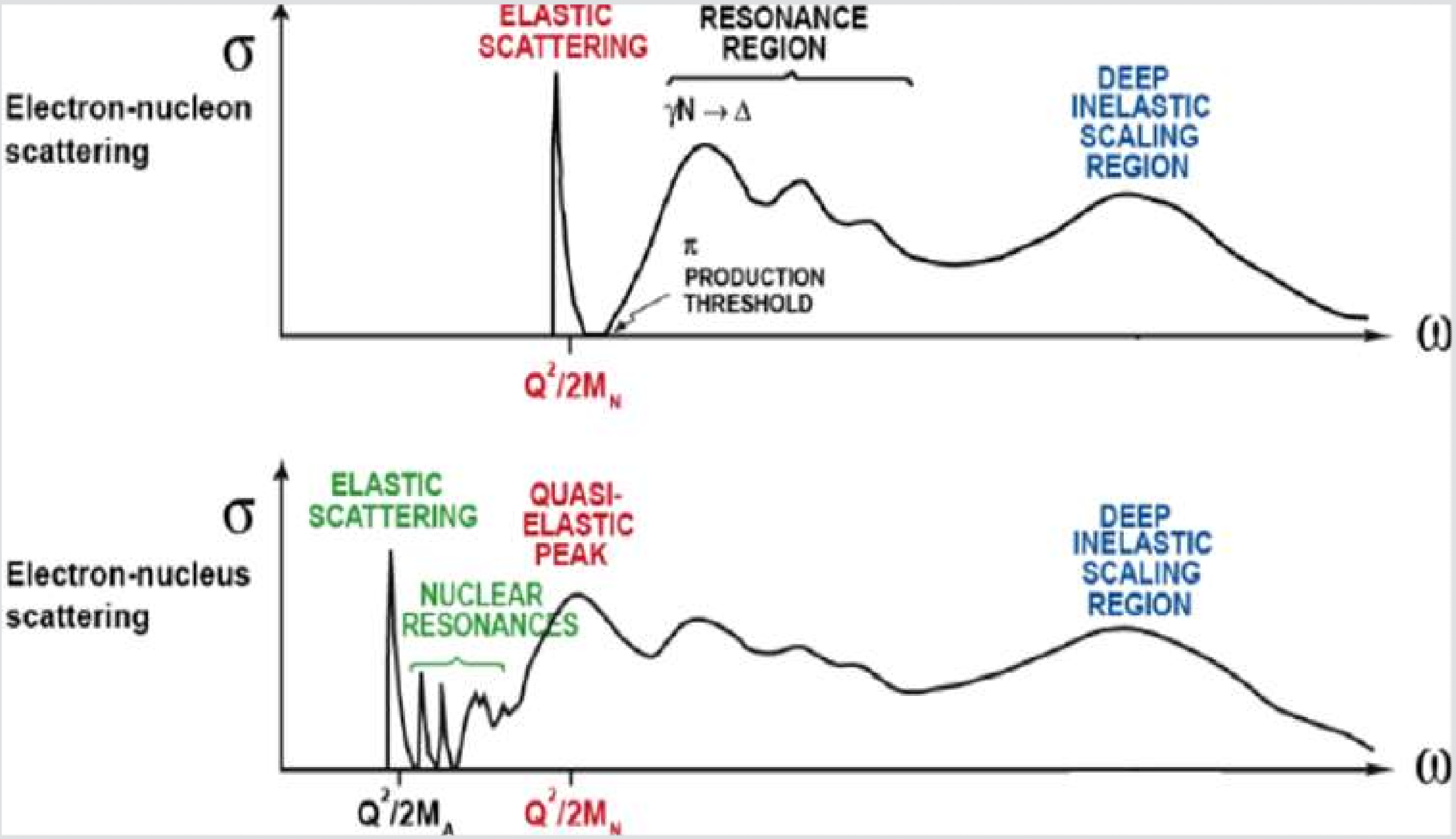
excitation energy

then

$$\omega = \omega_0 + \frac{|Q^2|}{2M_i}.$$

And for QE scattering ($M_f = M_i$), $\omega = Q^2/2M$

How do we see inside a nucleus?

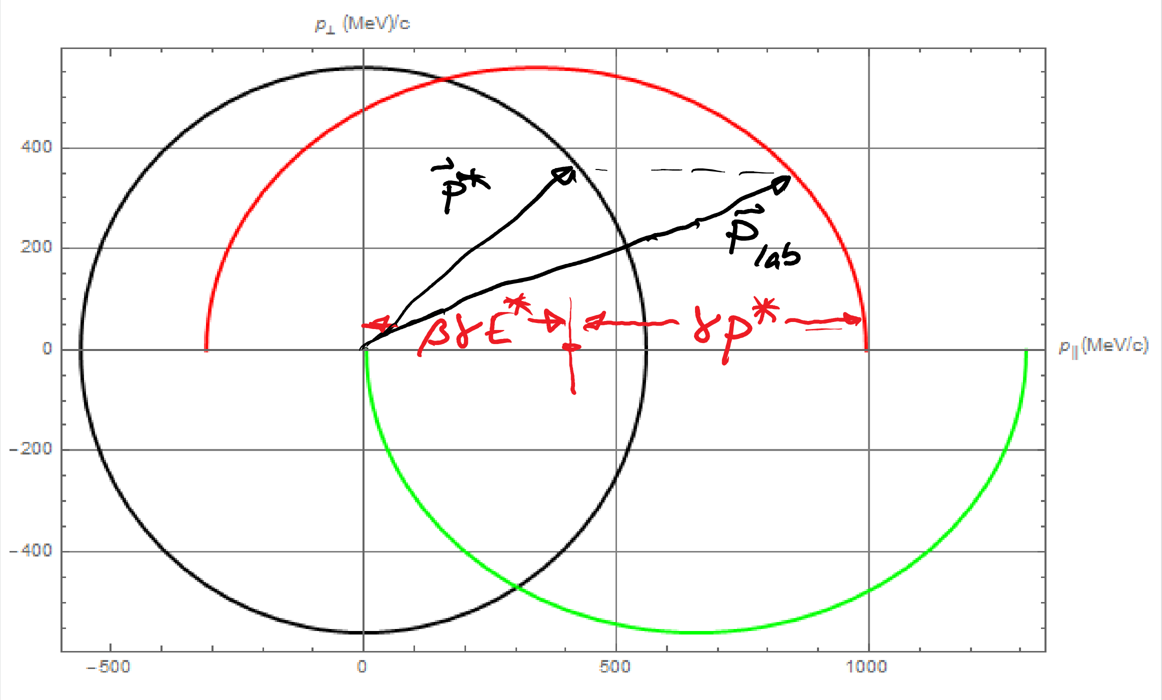


Kinematics (cont)

For ν scattering , the lepton is typically detected over range of angles..

Recommend kinematic ellipse technique to get feel for 2-body kinematics.

Example: $\nu\, n \longrightarrow \mu\, p$



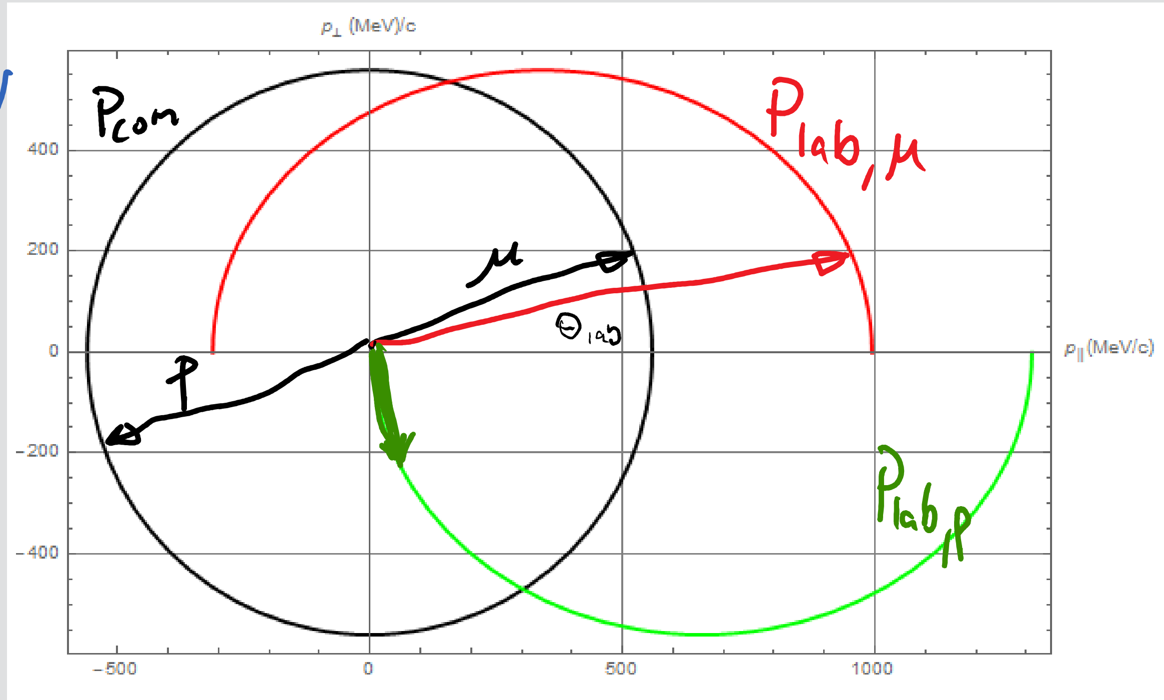
Kinematics (cont)

For ν scattering , the lepton is typically detected over range of angles..

Recommend kinematic ellipse technique to get feel for 2-body kinematics.

Example: $\nu\, n \;\longrightarrow \mu\, p$

$E_\nu = 1000$ MeV



Can graphically see

- p: θ_{max} = 90° of 90deg
- $p_{\mu,min}$ ~ 300MeV/c
- etc,

Kinematics (cont)

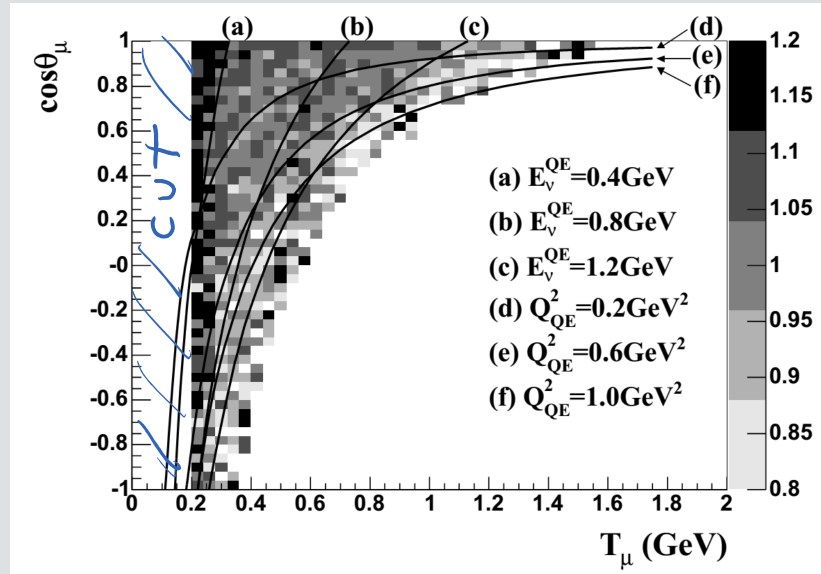
More about kinematics of $\nu\, n \;\longrightarrow \mu\, p$

If you don't observe recoil nucleon,

Only observable is energy, angle of muon.

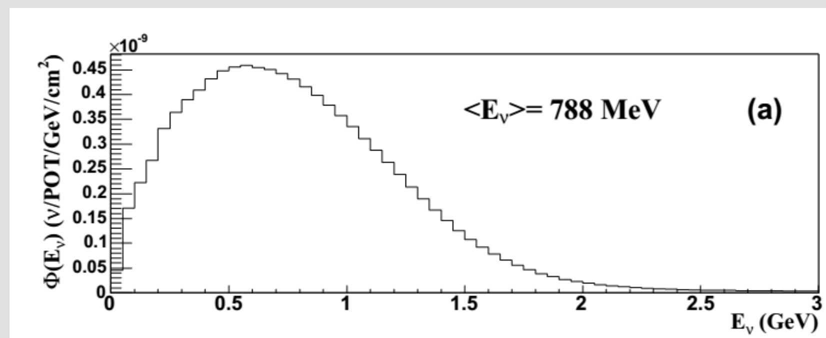
What do data distributions look like?

(for MiniBooNE):



$$E_\nu^{QE} = \frac{2(M_n')E_\mu - ((M_n')^2 + m_\mu^2 - M_p^2)}{2\cdot[(M_n') - E_\mu + \sqrt{E_\mu^2 - m_\mu^2}\cos\theta_\mu]},$$

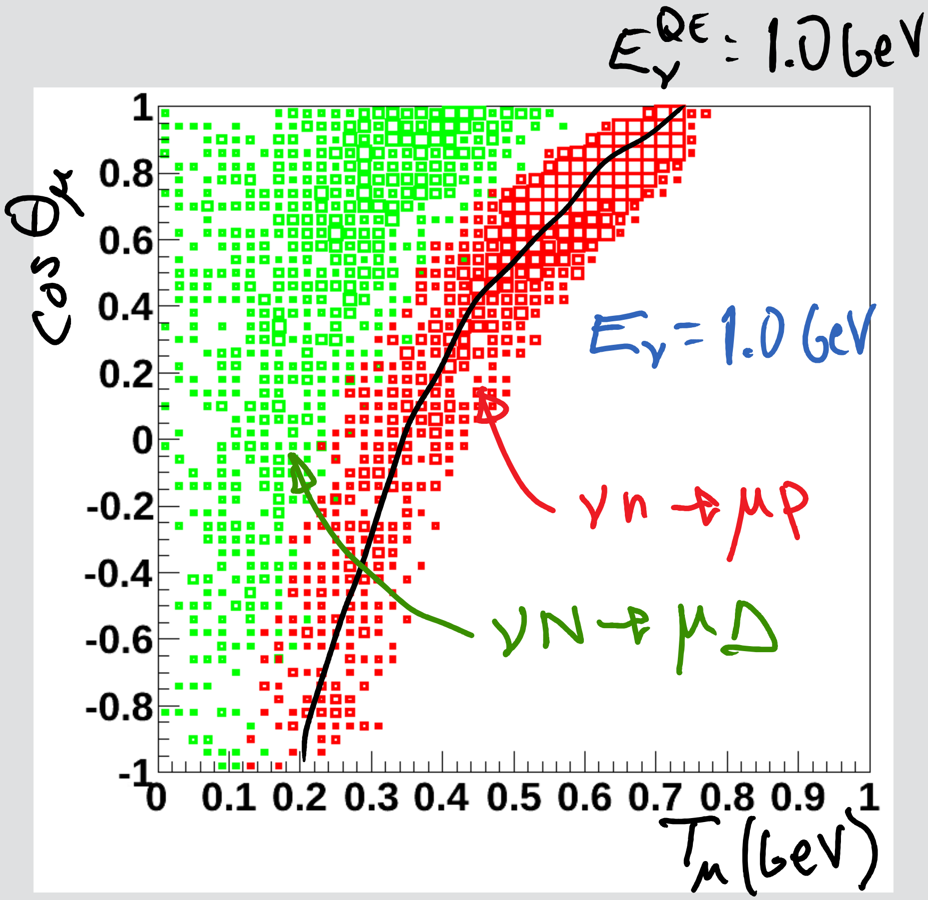
$$Q^2_{QE} = -m_\mu^2 + 2E_\nu^{QE}(E_\mu - \sqrt{E_\mu^2 - m_\mu^2}\cos\theta_\mu),$$



First Measurement of the Muon Neutrino Charged Current Quasielastic Double Differential Cross Section
MiniBooNE Collaboration (A.A. Aguilar-Arevalo (Mexico U., CEN) *et al.*). Feb 2010. 21 pp.
Published in **Phys.Rev. D81 (2010) 092005**

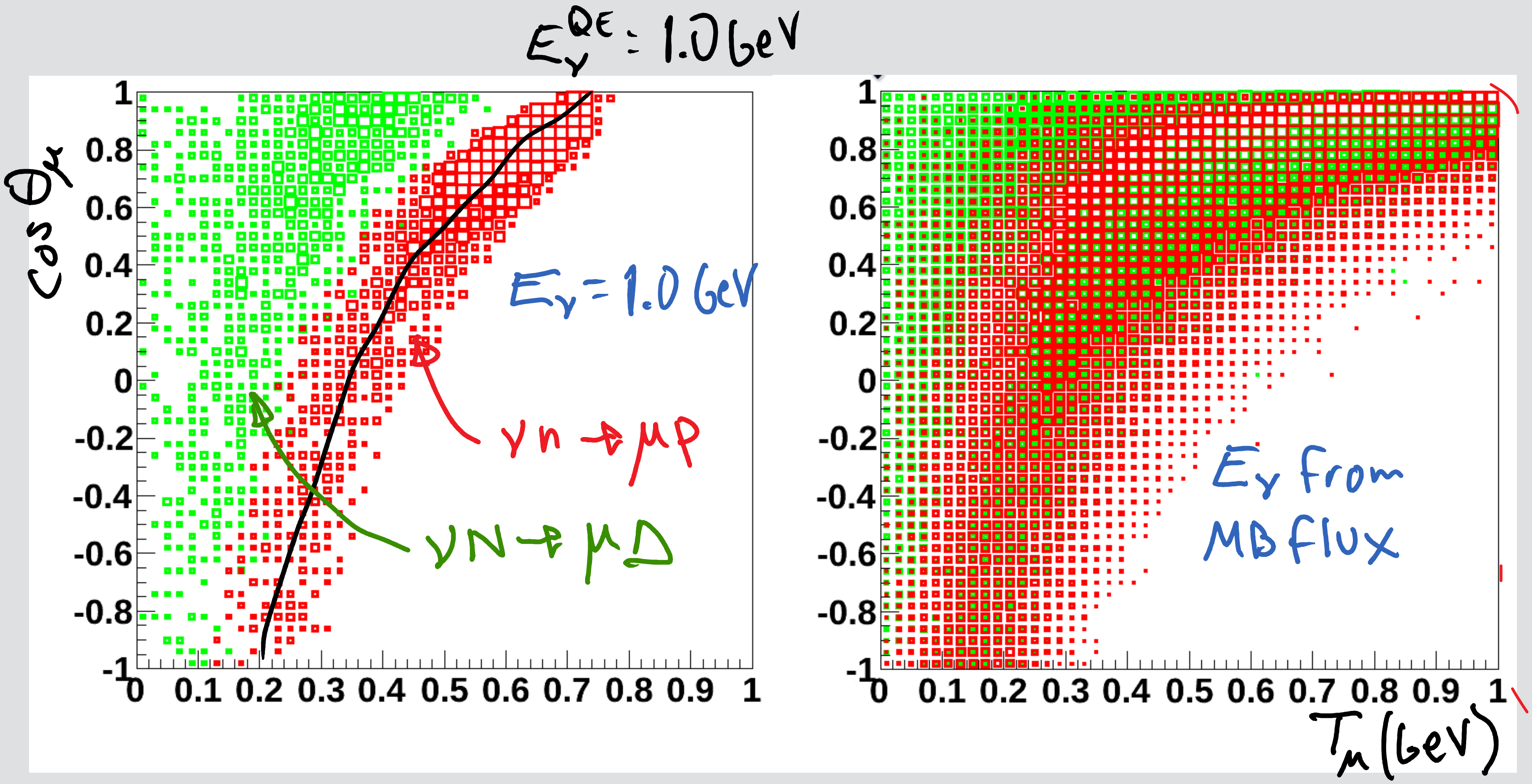
Kinematics (cont)

From (NUANCE) simulations



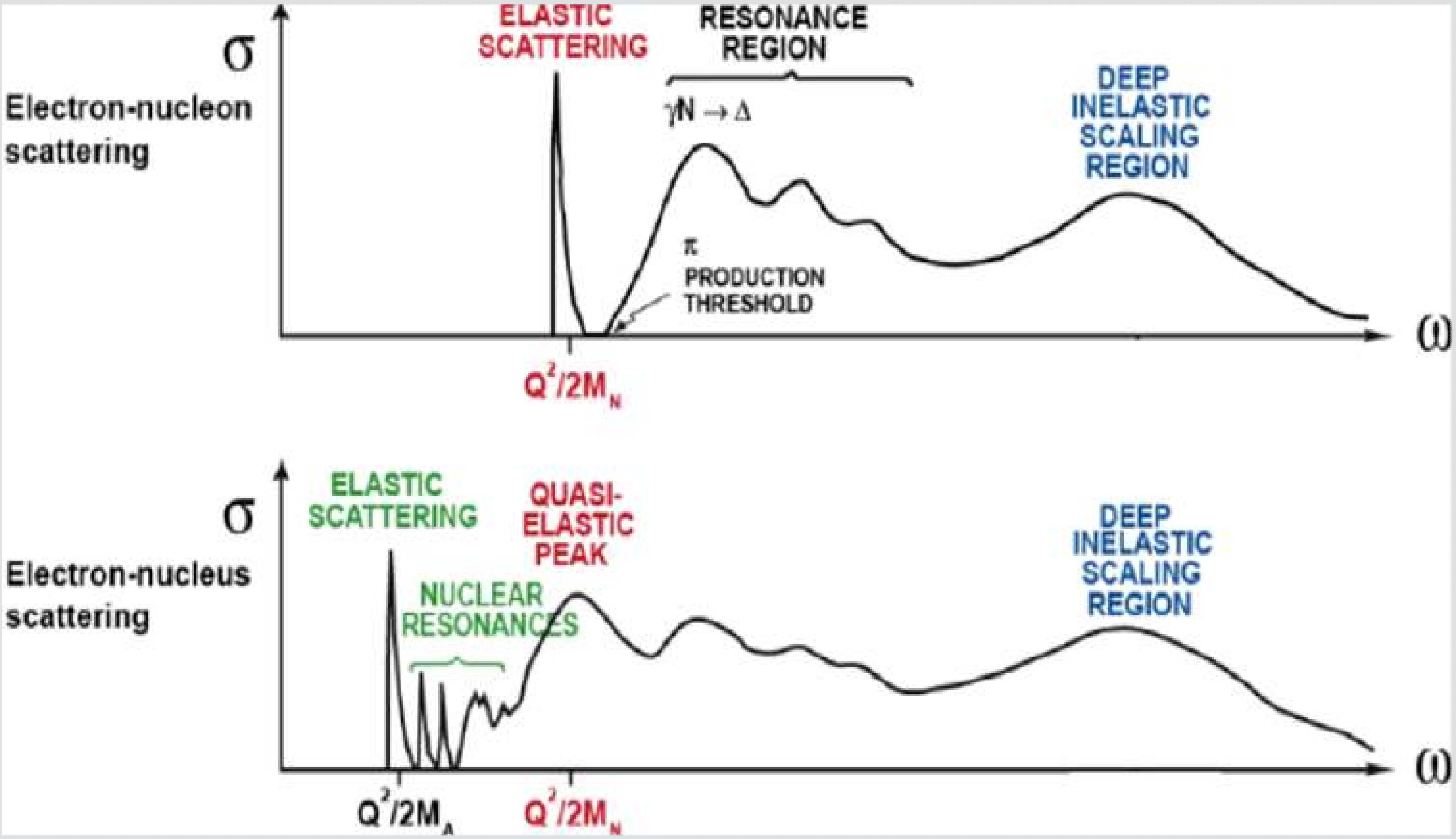
Kinematics (cont)

From (NUANCE) simulations



The non-monoenergetic ν beam makes the nuclear physics more challenging

How do we see inside a nucleus?



cross section

Scattering cross section, experimental definition :

Number of scattering events is prop. to flux of incoming particles x number of scattering nuclei.

Constant of prop. has unit of A^2,
thus name cross section
experimentally defined as:

$$N = \sigma \phi N_s$$

Then, $\sigma = N / \phi N_s$

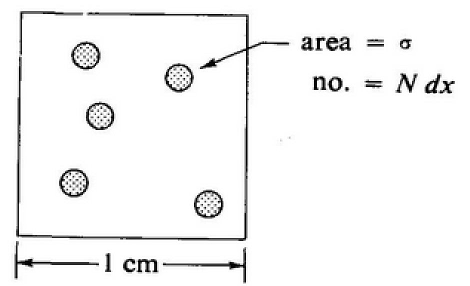


Figure 1-7 Five nuclei, each of cross section σ, are shown in a target of unit area. The probability that a particle crossing the unit area will hit a nucleus is $N^* \sigma$, where N^* is the number of nuclei per unit area and σ is the nuclear cross section; N^* = (number of nuclei per unit volume) × (thickness of target).

Nuclei and Particles

An Introduction to Nuclear and Subnuclear Physics

SECOND EDITION
Completely revised, reset, enlarged

EMILIO SEGRÈ
Professor of Physics (Emeritus)
University of California, Berkeley

cross section

Scattering cross section, calculation:

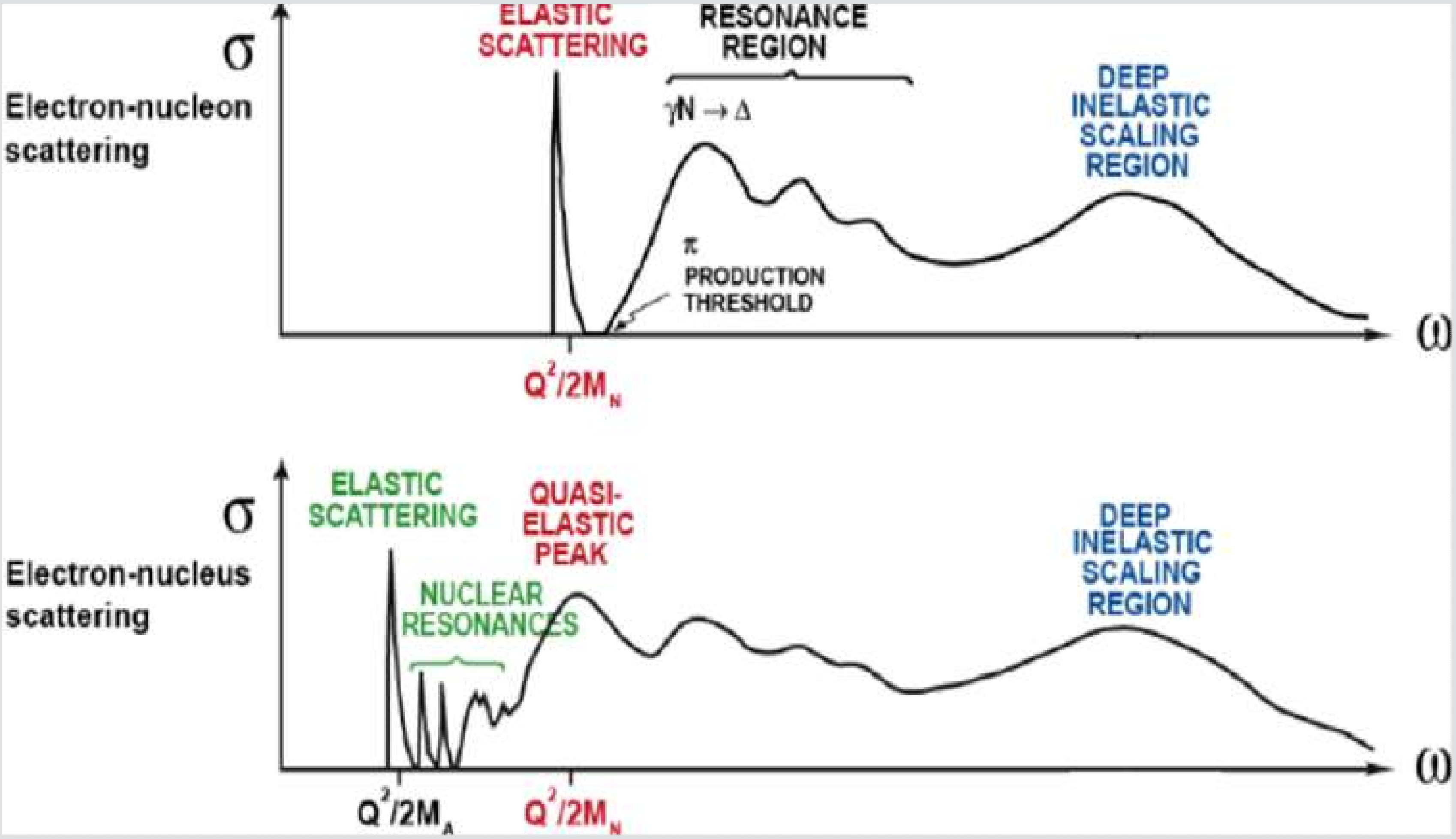
$$\sigma_{A \to B} = \frac{1}{\pi \hbar^4} \langle | \mathcal{H}_{if} |^2 \rangle \frac{p_b^2}{v_a v_b}$$

(Fermi's Golden Rule)

- matrix element with prob of initial->final transition
- includes energy conservation (eg: between states of different masses/binding energies)
- and overall coupling (eg: to electric or weak charge) and
- form factors (q-dependence of coupling)

How do we see inside a nucleus?

Turns out, with ~1GeV neutrino beams on nucleus the quasi-elastic peak and above are most relevant.

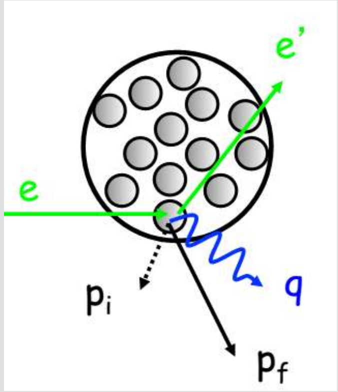


A simple model: The Fermi Gas

For neutrino quasi-elastic (QE) scattering, the Fermi Gas model does a pretty good job of explaining the data.

- Nucleons confined in a nucleus obey Fermi statistics
- Confinement implies a non-zero "Fermi momentum/energy" / p_F, E_F
- Also need a binding energy, E_B
- and a model for scattering from individual nucleons (form-factors)

This model explains the electron scattering QE data fairly well over a range of A



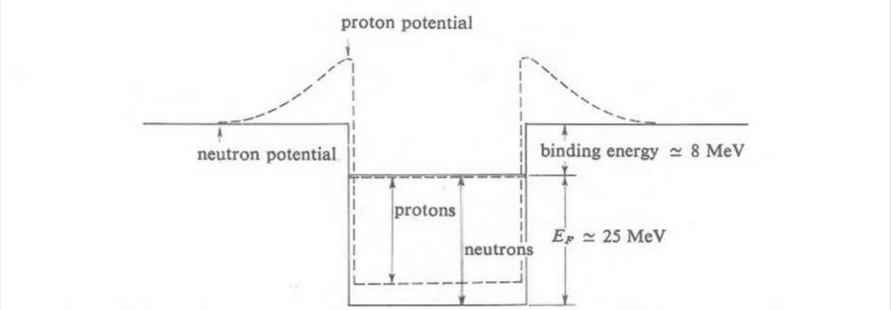
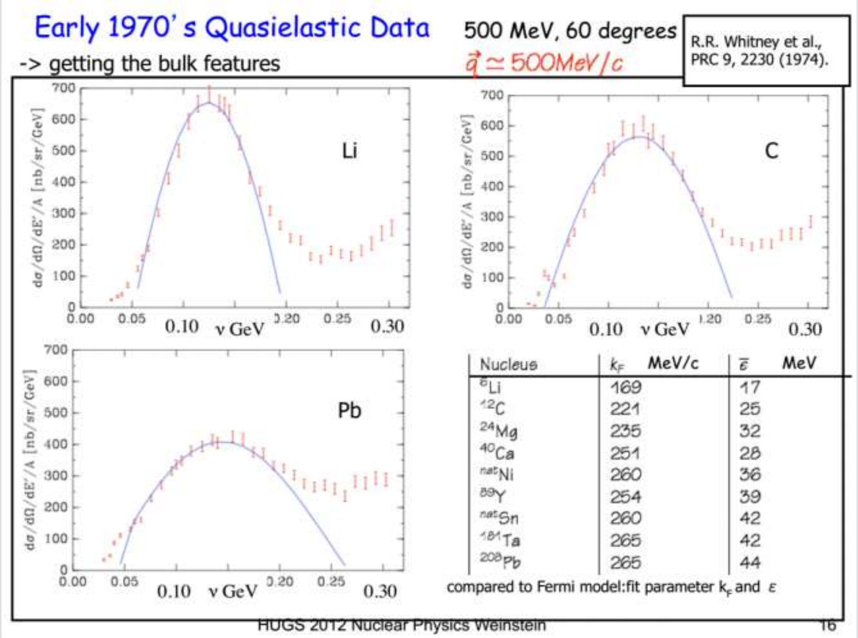


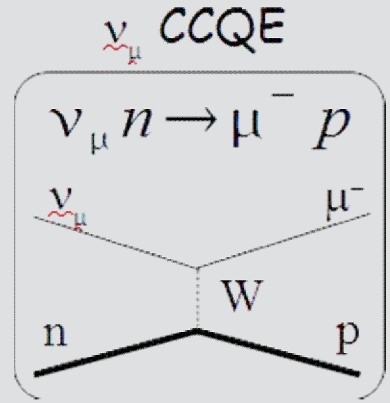
Figure 11-25 Potential well for neutrons and protons in a heavy nucleus, showing the Fermi level. Note the difference between neutron and proton wells.



Nucleus	k_F MeV/c	$\bar{\varepsilon}$ MeV
^{6}Li	169	17
^{12}C	221	25
^{24}Mg	235	32
^{40}Ca	251	28
^{nat}Ni	260	36
^{89}Y	254	39
^{nat}Sn	260	42
^{181}Ta	265	42
^{208}Pb	265	44

Fermi Gas for ν QE scattering

Apply the FG model for the nucleus (as e-scatting)
with changes to handle the νN vertex



- νN scattering, Llewellyn-Smith formalism:

$$\frac{d\sigma}{dQ^2}\begin{pmatrix} \nu_l + n \rightarrow l^- + p \\ \bar{\nu}_l + p \rightarrow l^+ + n \end{pmatrix} = \frac{M^2 {G_F}^2 cos^2\theta_c}{8\pi {E_\nu}^2}\left\{A(Q^2) \pm B(Q^2)\frac{(s-u)}{M^2} + C(Q^2)\frac{(s-u)^2}{M^4}\right\}$$

- lepton vertex well-known
- nucleon vertex parameterized with 2 vector formfactors (F_1,F_2), and 1 axial-vector (F_A)
    - F_1, F_2, F_A (inside of A,B,C) are functions of Q^2 = 4-momentum transfer

To apply (for a nucleus, such as carbon)
- assume bound but independent nucleons (Impulse Aproximation)
- use Rel. Fermi Gas (RFG) model (typically Smith-Moniz), with (mostly known) params
- F_1,F_2 also from e-scattering measurements
- F_A is largest contribution, not well known from e scattering, but
- F_A (Q^2=0) = g_A known from beta-decay and
- assume dipole form, same M_A should cover all experiments.

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

- No unknown parameters (1 parameter if you want to fit for M_A)
- can be used for prediction of CCQE rates and final state particle distributions (eg: Q^2)
- Until fairly recently, this approach has appeared adequate and all common (current) neutrino event generators use a model like this..

Fermi Gas for ν QE scattering

NEUTRINO REACTIONS ON NUCLEAR TARGETS.‡

R. A. SMITH ‡‡ and E. J. MONIZ ‡‡‡
Institute of Theoretical Physics, Department of Physics,
Stanford University, Stanford, California 94305

Received 15 December 1971
(Revised 29 February 1972)

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Fermi Gas Model

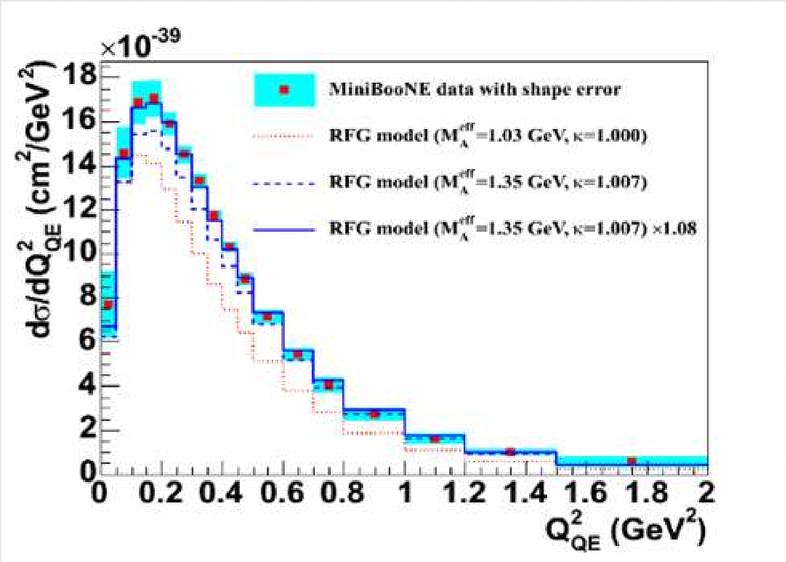
RFG applied to MiniBooNE data

- M_A from shape fit
  $M_A = 1.35 \pm 0.17$ GeV

- data is compared (absolutely) with CCQE (RFG) model with various parameter values

- Compared to the world- averaged CCQE model (red), MB CCQE data is 30% high

Flux-integrated single differential cross section (Q^2_{QE}):



- RFG was sufficient for describing the data, but likely missing some important physics especially for new experiments with different nuclei, finer-grained tracking etc.

Fermi Gas for ν QE scattering

Shortcomings to this approach:

- uses "impulse approximation"
- and initial-, final-state effects are added in later
- ignores correlations between nucleons….

Electron- and neutrino-nucleus scattering in the impulse approximation regime

Omar Benhar[1,2], Nicola Farina[2], Hiroki Nakamura[3], Makoto Sakuda[4], and Ryoichi Seki[5,6]

B. The impulse approximation

The main assumptions underlying the impulse approximation (IA) scheme are that i) as the spatial resolution of a probe delivering momentum **q** is $\sim 1/|\mathbf{q}|$, at large enough $|\mathbf{q}|$ the target nucleus is seen by the probe as a collection of individual nucleons and ii) the particles produced at the interaction vertex and the recoiling (A − 1)-nucleon system evolve indipendently of one another, which amounts to neglecting *both* statistical correlations due to Pauli blocking and dynamical Final State Interactions (FSI), i.e. rescattering processes driven by strong interactions.

In the IA regime the scattering process off a nuclear target reduces to the incoherent sum of elementary processes involving only one nucleon, as schematically illustrated in Fig. 1.

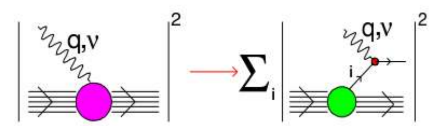


FIG. 1: (Color online) Pictorial representation of the IA scheme, in which the nuclear cross section is replaced by the incoherent sum of cross sections describing scattering off individual bound nucleons, the recoiling (A − 1)-nucleon system acting as a spectator.

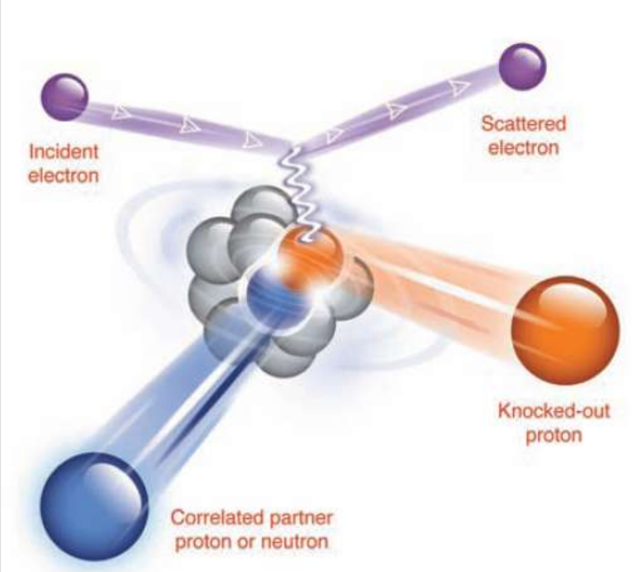
Phys.Rev. D72 (2005) 053005

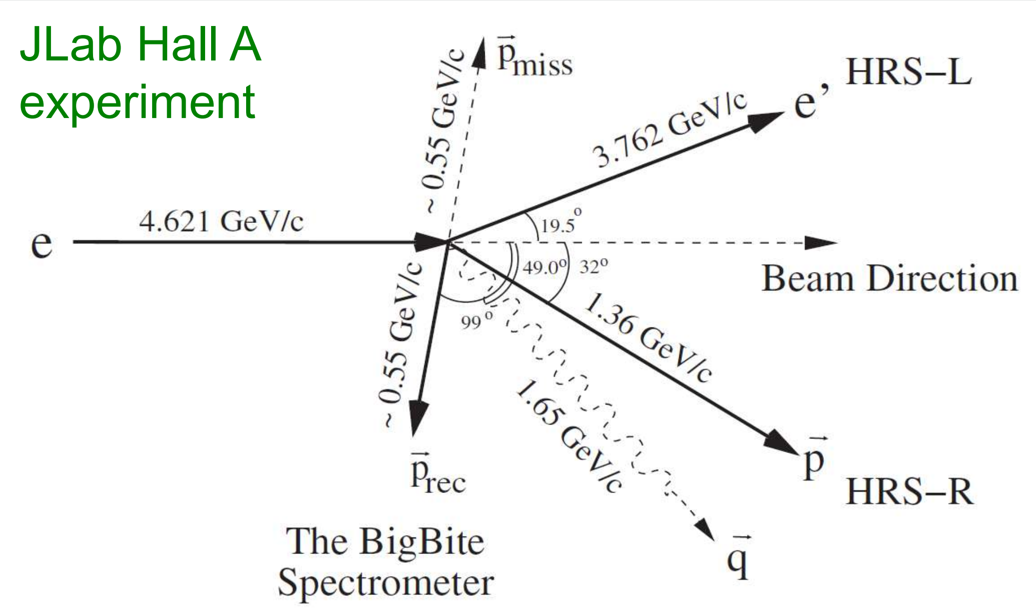
New models

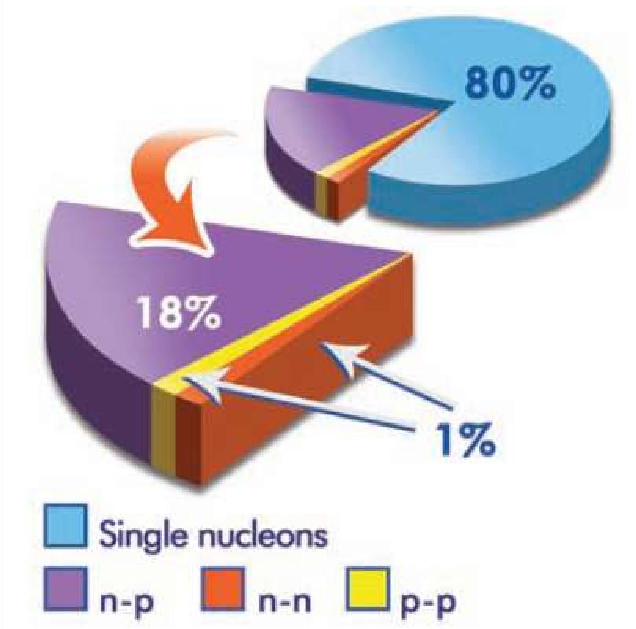
Evidence for nucleon correlations:

Fairly recent results from e-scattering suggest 20% of nucleons in carbon are in a correlated state

(R. Subedi etal, Science, 320, 1476 (2008))







New Models

Argoneut "hammer events", evidence for 2N correlations or FSI effects?

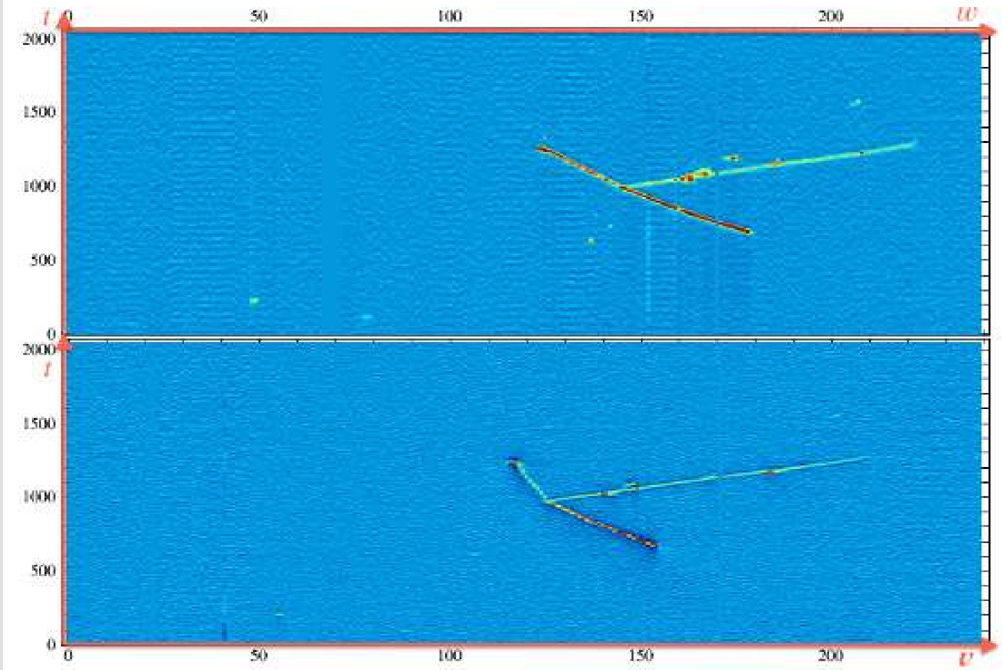


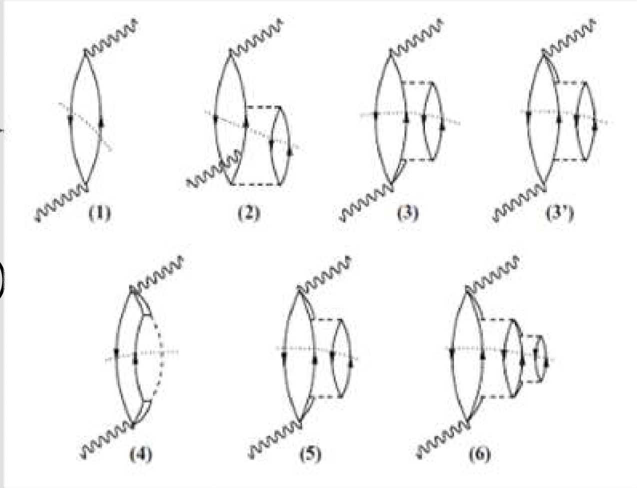
FIG. 4. 2D views of one of the four "hammer events", with a forward going muon and a back-to-back proton pair ($p_{p1} = 552$ MeV/c, $p_{p2} = 500$ MeV/c). Transformations from the TPC wire-planes coordinates (w,t "Collection plane" [Top], v,t "Induction plane" [Bottom]) into Lab coordinates are given in [13].

Phys.Rev. D90 (2014) 1, 012008

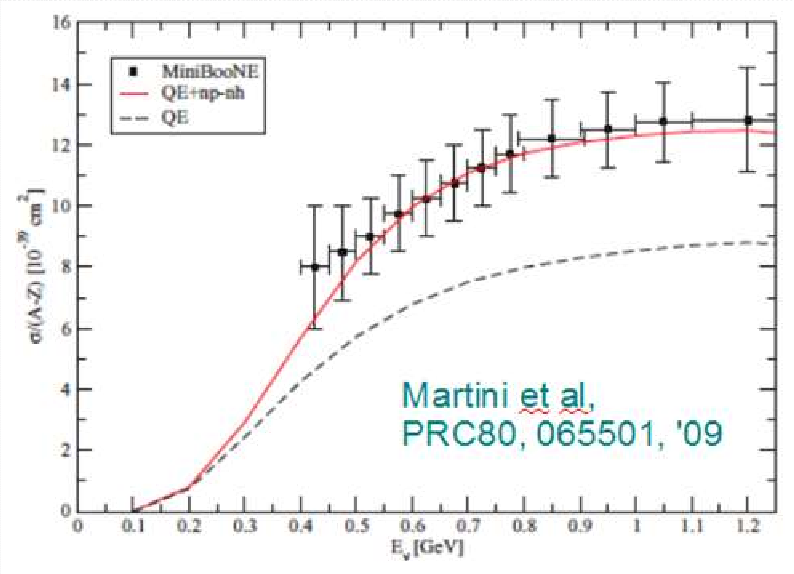
New Models

2-N correlations in ν scattering?

- Perhaps extra “strength” in CCQE from multi-nucleon correlations within carbon (Martini et al PRC80, 065501, '09)
- Related to neglected “transverse” response in noted in electron scattering? (Carlson etal, PRC65, 024002, '02)
- Expected with nucleon short range correlations (SRC) and 2-body exchange currents



CCQE total cross section



Other ν- nuclear physics topics

- NC photon production
- MiniBooNE low-energy excess has spurred work on a possible background: NCg production
  important background for ν_e appearance searches
  eg: R. Hill, Phys. Rev. D 81, 013008 (2010) and
  e-Print: arXiv:1002.4215 [hep-ph]

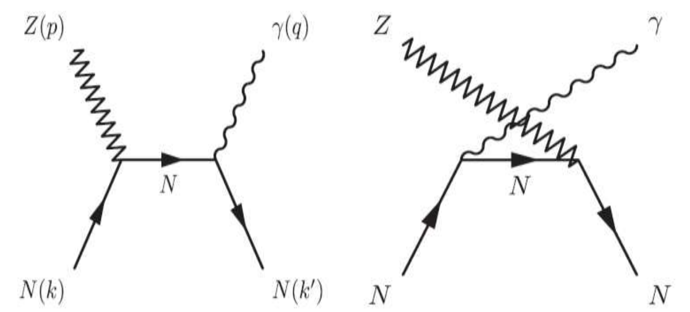


FIG. 1. Generalized Compton scattering.

”Weak Pion and Photon Production off Nucleons in a Chiral Effective Field Theory”,
B. Serot, X. Zhang, arXiv:1011.5913 [nucl-th]

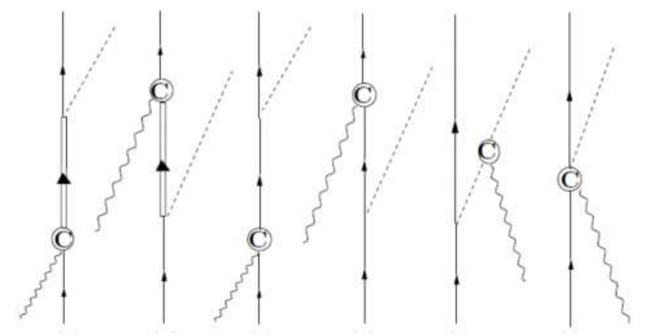
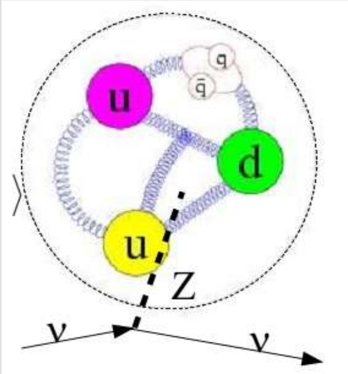


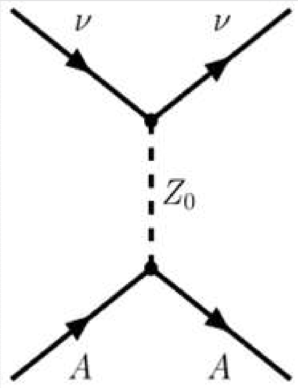
Fig.1: Feymann diagrams for pion production. Change the outgoing pion line to photon line for photon production. C indicates both vector and axial vector currents.

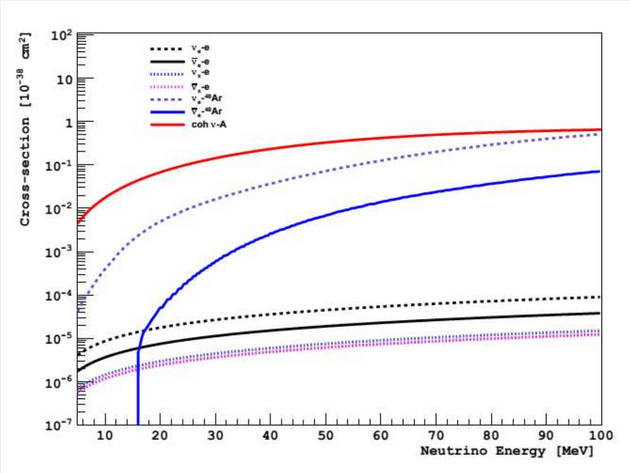
Other ν- nuclear physics topics

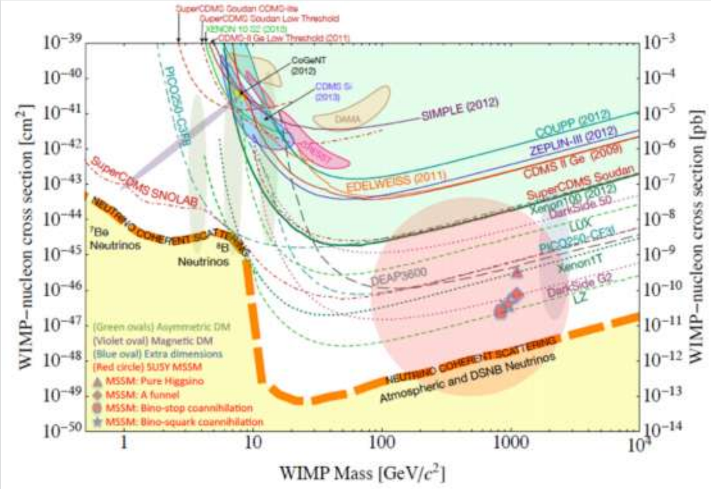
- Strange-quark contribution to spin of nucleon Δs (microBooNE, perhaps)



- Coherent νN elastic scattering (CEvENS)







- And others from MINERvA, ANNIE, etal…

Summary

- Nuclear physics is important part of neutrino physics
- Understanding kinematics and simple nuclear models can yield much insight to data
- More work to do on many nuclear physics topics related to neutrinos

Additional references:

- Segre, “Nuclei and Particles”, (available online)
- Hagedorn, “Relativistic Kinematics”.
- Larry Weinstein, ODU, Talk at **HUGS 2012, Jefferson Lab,** https://www.jlab.org/hugs/archive/Schedule2012/program.html