Nuclear Effects in Neutrino-Nucleus Scattering

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JLAB Users Group Meeting
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Outline

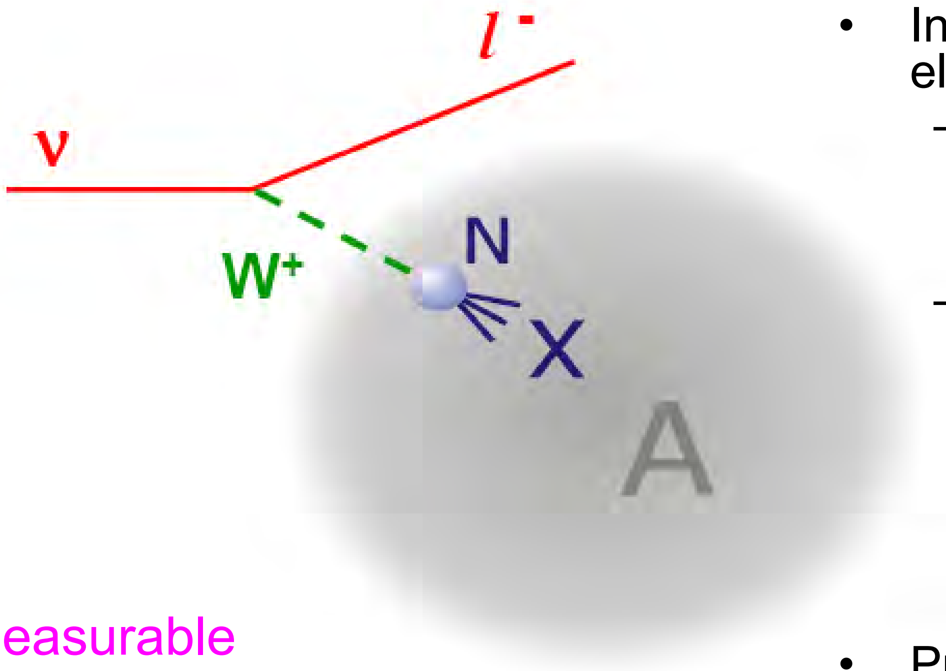
- Why should nuclear effects be different between neutrinos and electrons?
- What do the theories say?
- Why are the experiments different between neutrinos and electrons?
- How can you possibly measure this?
  - Neutrino Beamline: need high intensity
  - Neutrino Detector: need fine granularity
- Who else wants to know about nuclear effects?
  - Oscillation experiments
    - T2K experiment: form factor modification example
    - MINOS experiment: intra-nuclear rescattering
- What are we doing about it…MINERvA

Differences between e^- and ν

- Electrons
  - Neutral current exchange (γ,Z)
  - Vector Form Factors
  - Initial state radiation effects
  - Sensitive to $q+\bar{q}$

- Neutrinos
  - Charged current exchange (W)
  - Vector and Axial-Vector form factors
  - No Initial state radiation
  - Valence and Sea available separately
  - Proton and Neutron effects available separately for QE (by comparing ν versus $\bar{\nu}$)
  - Strange Sea measurements possible

Nuclear Effect Categories



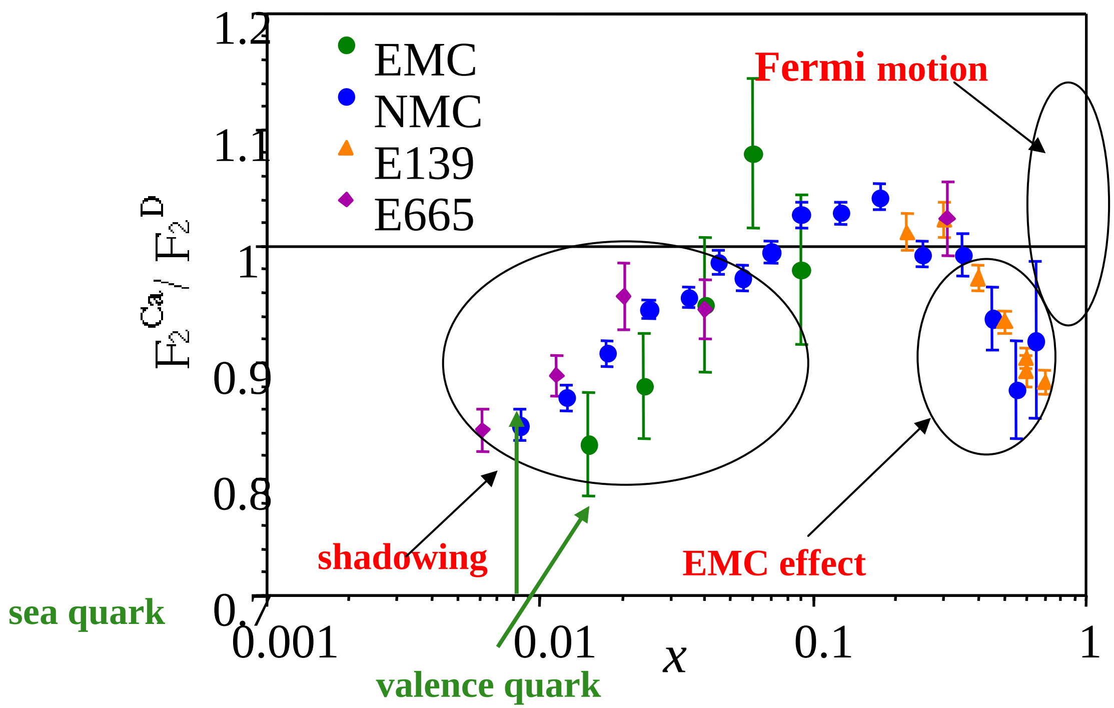
- In-medium modifications of elementary cross sections
  - Small x_{Bj}: fluctuation into qqbar pair can happen for long enough that the pair sees more than one nucleon
  - Large x_{Bj}: boson scatters incoherently off bound protons and neutrons
    - Fermi Motion
    - Nuclear binding
    - Off-shell modifications of nucleon structure functions

Measurable final states are convolution of BOTH these effects…

- Propagation of final state particles
  - Re-scattering and Absorption
  - Produces large changes in energy that leaves the nucleus

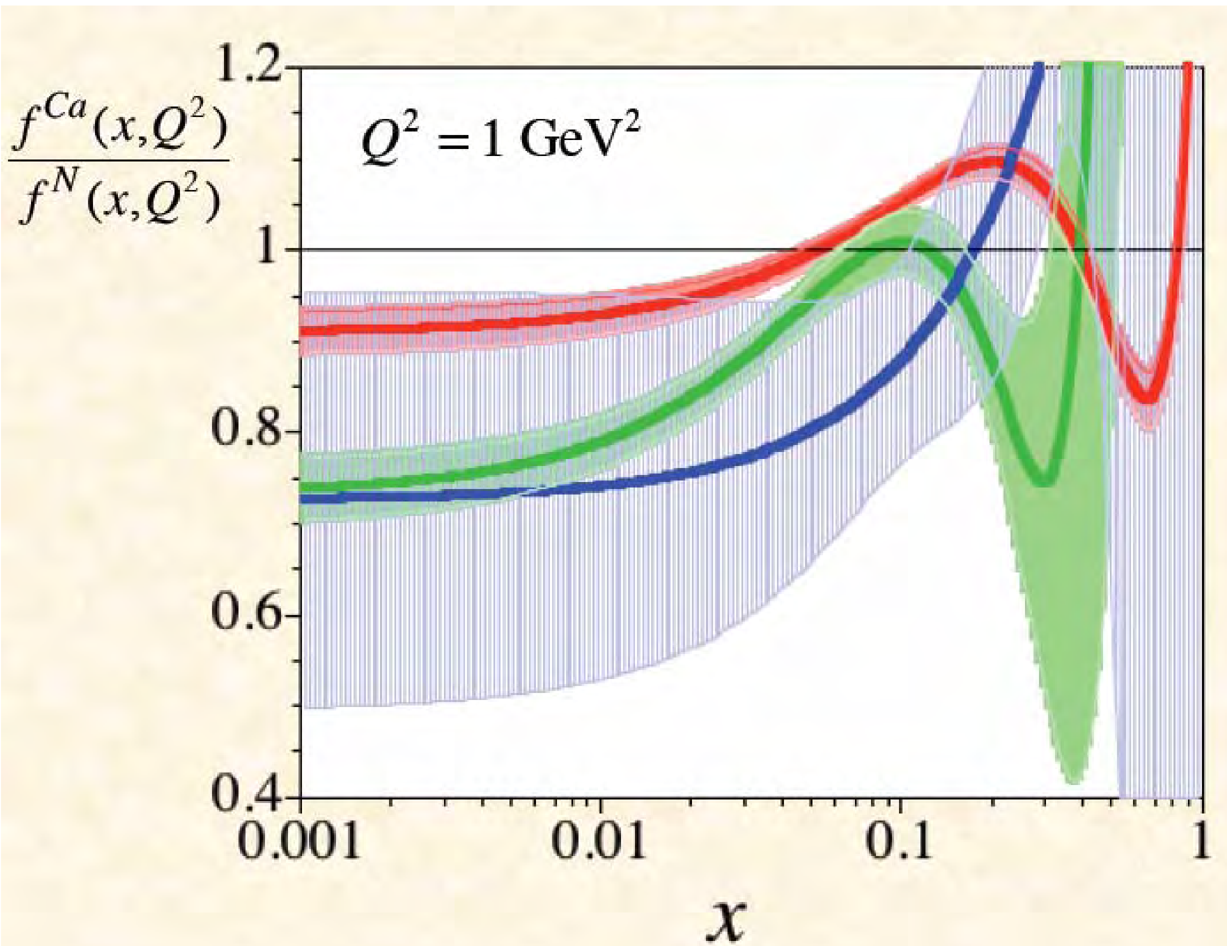
Focus in this talk on Shadowing and Form Factor differences
Many good talks available at Intersections Workshop on other effects

Shadowing: how would ν be different from e?



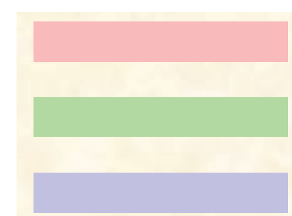
- F_2 / nucleon changes as a function of A. Measured in μ/e – A <u>**not in ν**</u>
- <u>**Good reason to consider nuclear effects are DIFFERENT in ν - A**</u>.
  - **Presence of axial-vector current.**
- **Is there stronger shadowing for ν -A but weaker "EMC" effect?**
- **Is there Different nuclear effects for valence and sea ?**
- **Different nuclear effects for d and u quarks?**

Quarks in the nuclear environment…



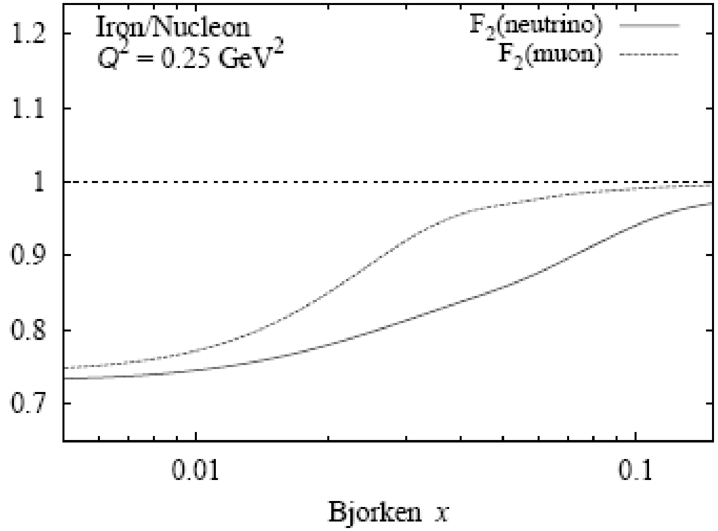
Valence Quark
Anti-Quark
Gluon

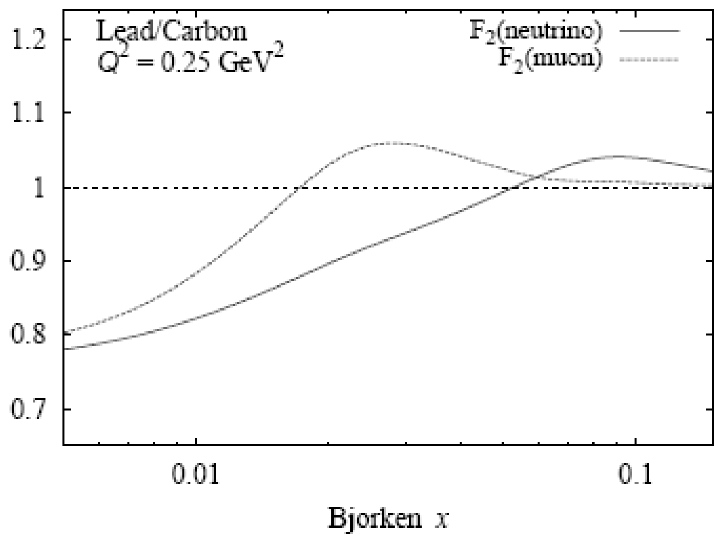
PDF Uncertainties:



From Kumano, S, Intersections Conference, May 2006

Nuclear Effects in F_2, e compared to ν

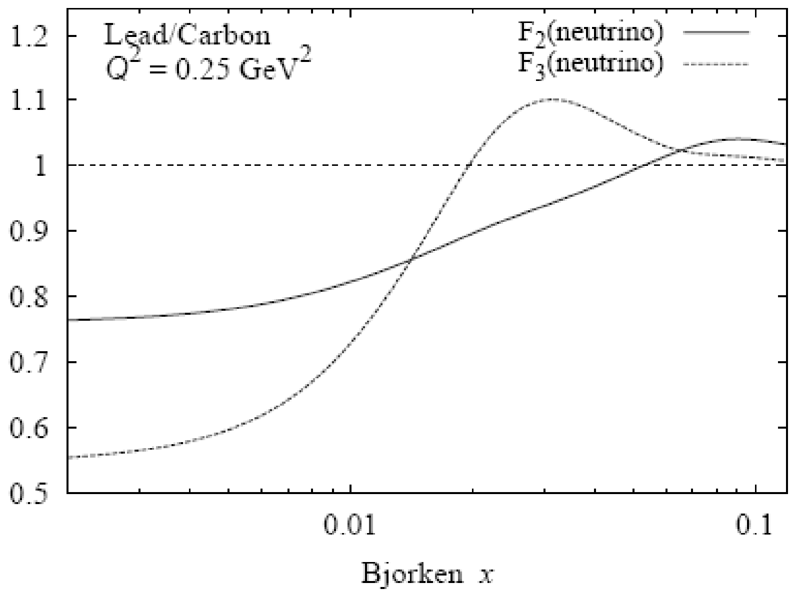


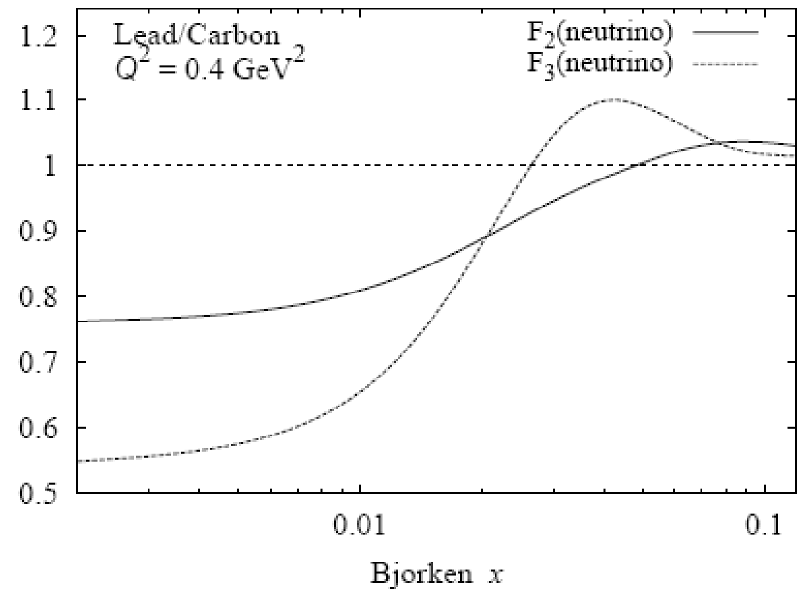


- Muon Ratios: Calculated using VMD approach
- Neutrino Ratios: Calculated using VMD plus PCAC for axial current
- Predictions:
  - ➢Shadowing for neutrinos sets in at larger x
  - ➢X shape is different between x=0.01 and x=0.1
- Difference in correlation lengths of hadronic fluctuations: vector versus axial-vector currents

Sergey Kulagin,
hep-ex/0405002

Shadowing in F_2 versus xF_3



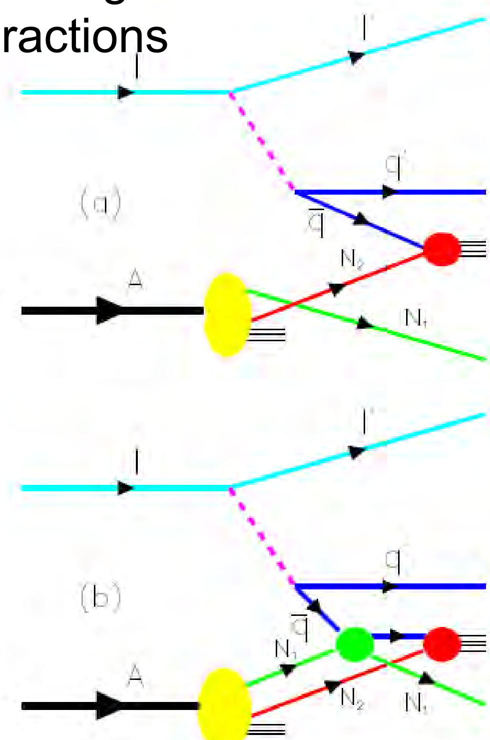


- Shadowing for xF3: visible only in neutrinos
- Much larger effect predicted by VMD combined with PCAC model
- Very different from electron nuclear effects: shadowing at small x

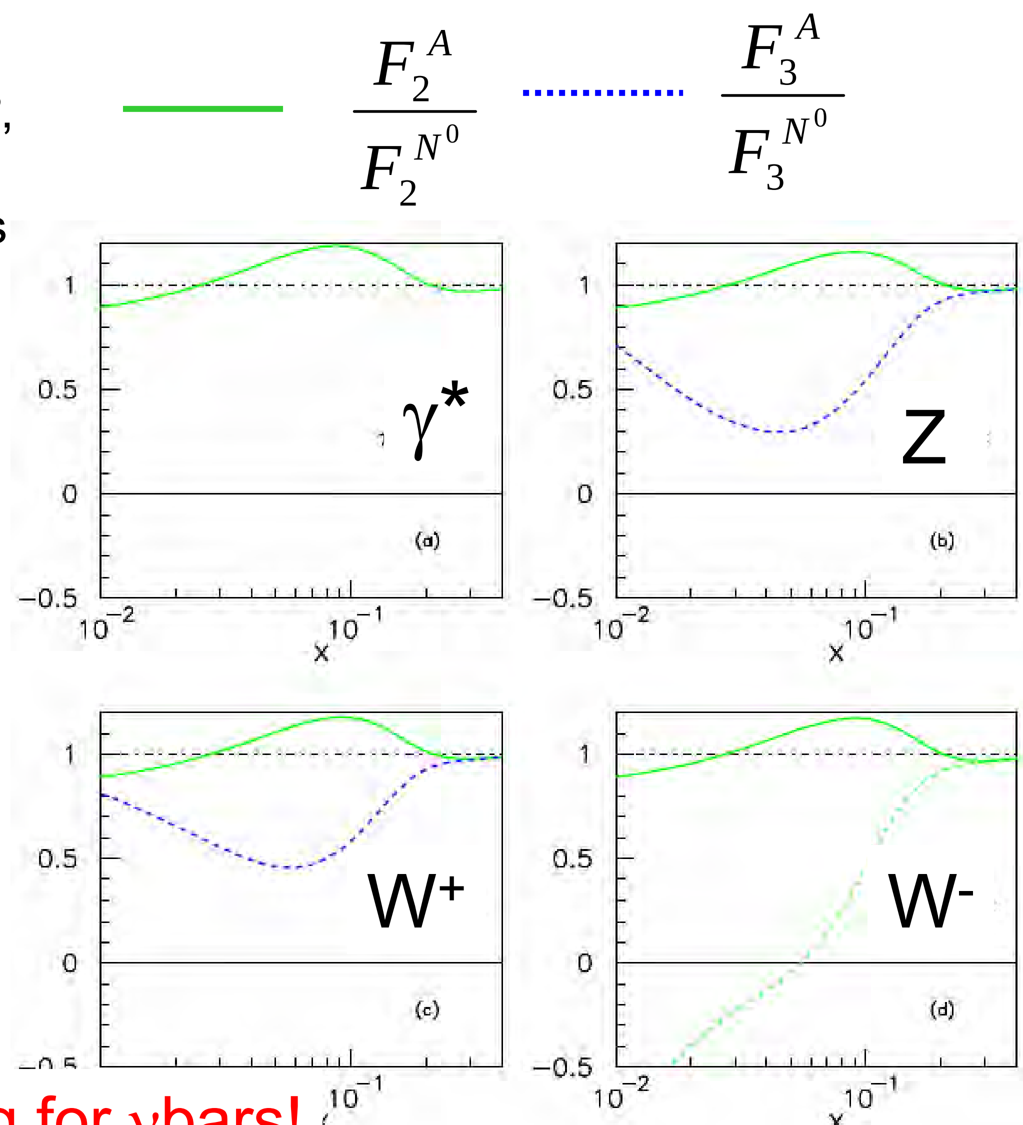
Sergey Kulagin, hep-ex/0405002

Shadowing for ν's: NC versus CC

- Inspired by NuTeV anomalous $\sin^2\theta_W$ measurement (Ref: *PRL* ***88***, 2002), Brodsky et al have investigated ν shadowing in terms of looking at NC versus CC interactions



Brodsky et al, PRD70, 2004



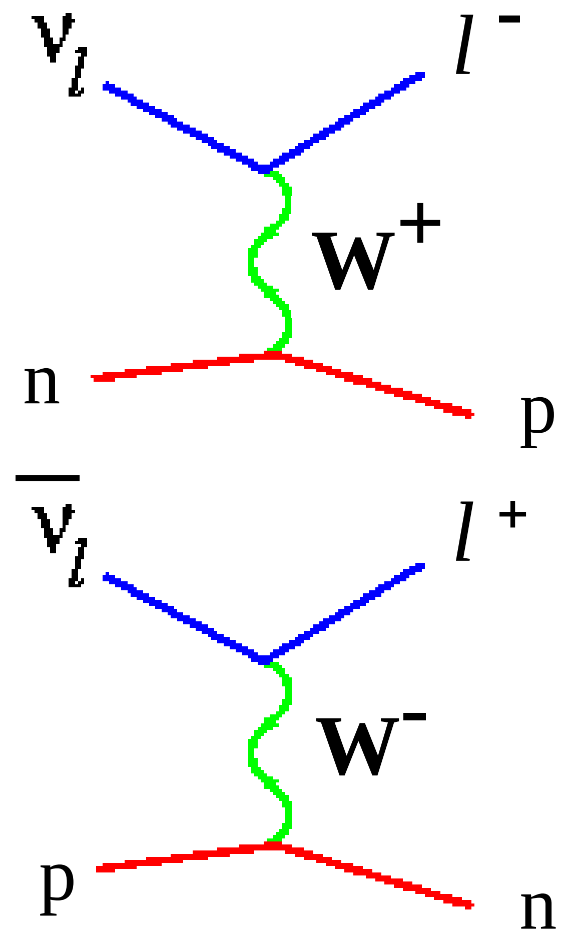
Predicts different shadowing for νbars!

Quasi-elastic Scattering

$$\sigma_{QE} = \sigma_V + \sigma_A$$

σ_V parameterized by elastic form factors (G_V^E, G_V^M)

σ_A parameterized by axial form factors (G_A or F_A)



With neutrinos and antineutrinos, able to access n and p separately, and perhaps to measure form factors separately!

See B. Bradford, Parallel session X tomorrow 1:35

→ ν scattering, with help from e^- scattering, can access F_A.

Why particle physicists are worrying about form factors and nuclear effects…

- Next big challenge in neutrino physics:
  - Measurements of flavor oscillations
    - $\nu_\mu \rightarrow \nu_x$ (disappearance versus ν energy)
    - $\nu_\mu \rightarrow \nu_e$ and $\nu_\mu \rightarrow \nu_e$
  - Oscillation Probability: $\sin^2 2\theta \sin^2(\Delta m^2 L/E)$
  - Experiments of 300km/E (GeV) are key
  - Quasi-elastic events are cleanest signature of neutrino flavor: nothing else “muddies the waters”

But…we assume (qe)

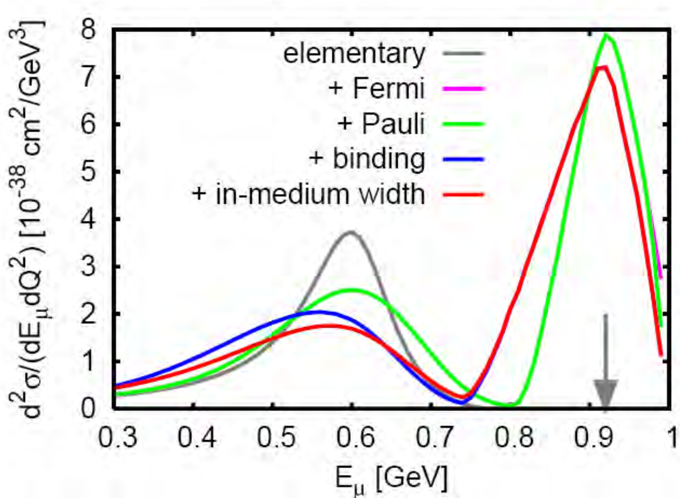
$$E_\nu = \frac{m_N E_\mu - m_\mu^2/2}{m_N - E_\mu + p_\mu \cos\theta_\mu}$$

Form Factor Modification

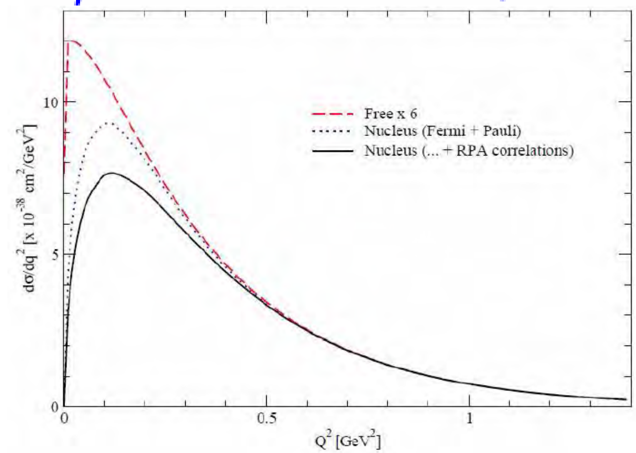
$$\nu_\mu {}^{56}\mathrm{Fe} \to \mu^- X$$

$$E_\nu = 1\,\mathrm{GeV}$$

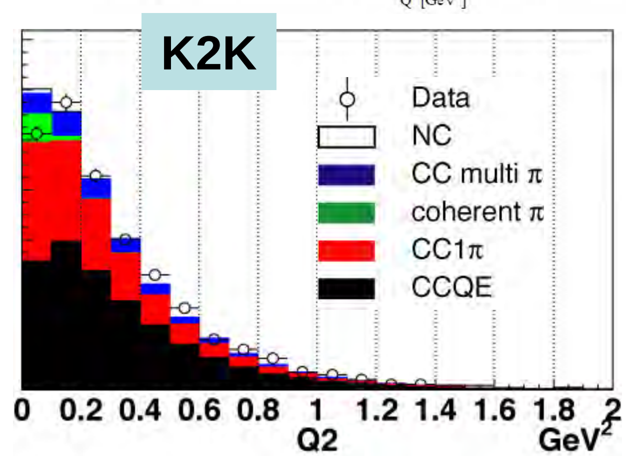
$$Q^2 = 0.15\,\mathrm{GeV}^2$$

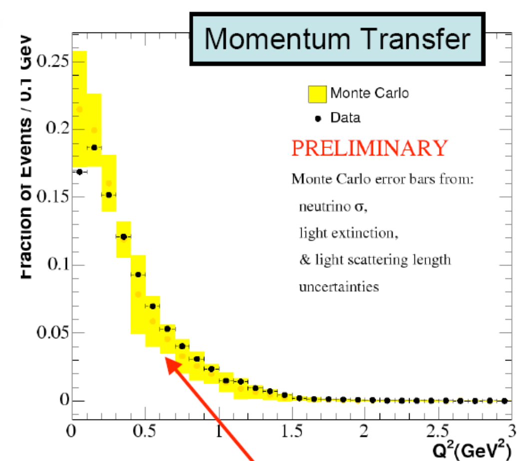


$$\nu_\mu + {}^{12}C \to \mu^- + X$$



May be seeing hints of this already!





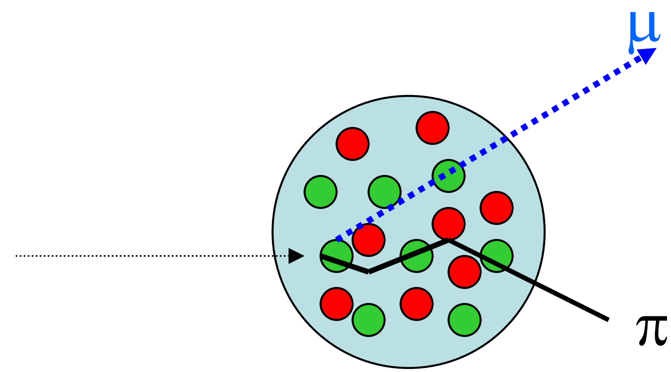
Larger than expected rollover at low Q^2

Dec 2005 Fermilab PAC

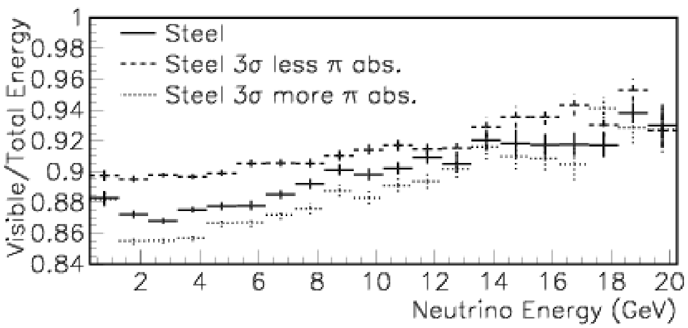
Alvarez Intersections Workshop at JLAB

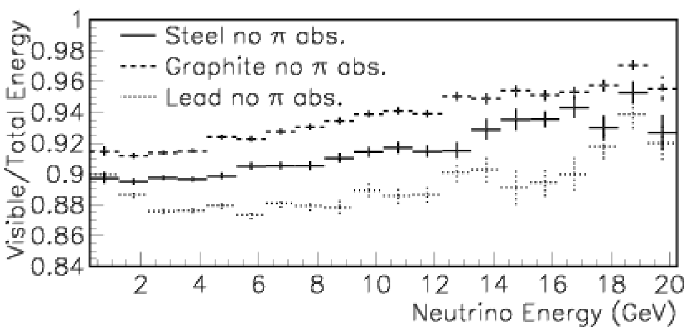
Nuclear effects at MINOS

- Visible Energy in Calorimeter is NOT ν energy!
  - π absorption, rescattering
  - final state rest mass

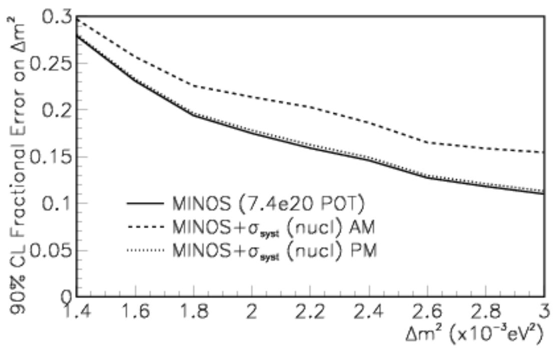


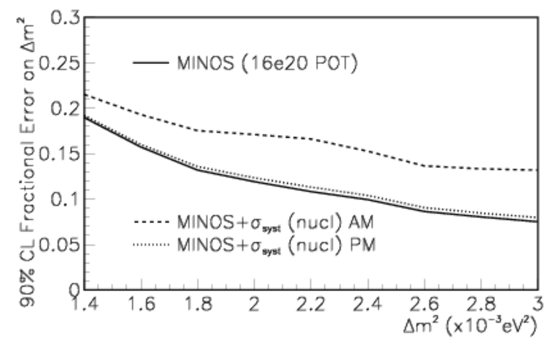
Toy MC analysis:





Nuclear Effects Studied in Charged Lepton Scattering, from Deuterium to Lead, at High energies, but nuclear corrections may be different between e/μ and ν scattering



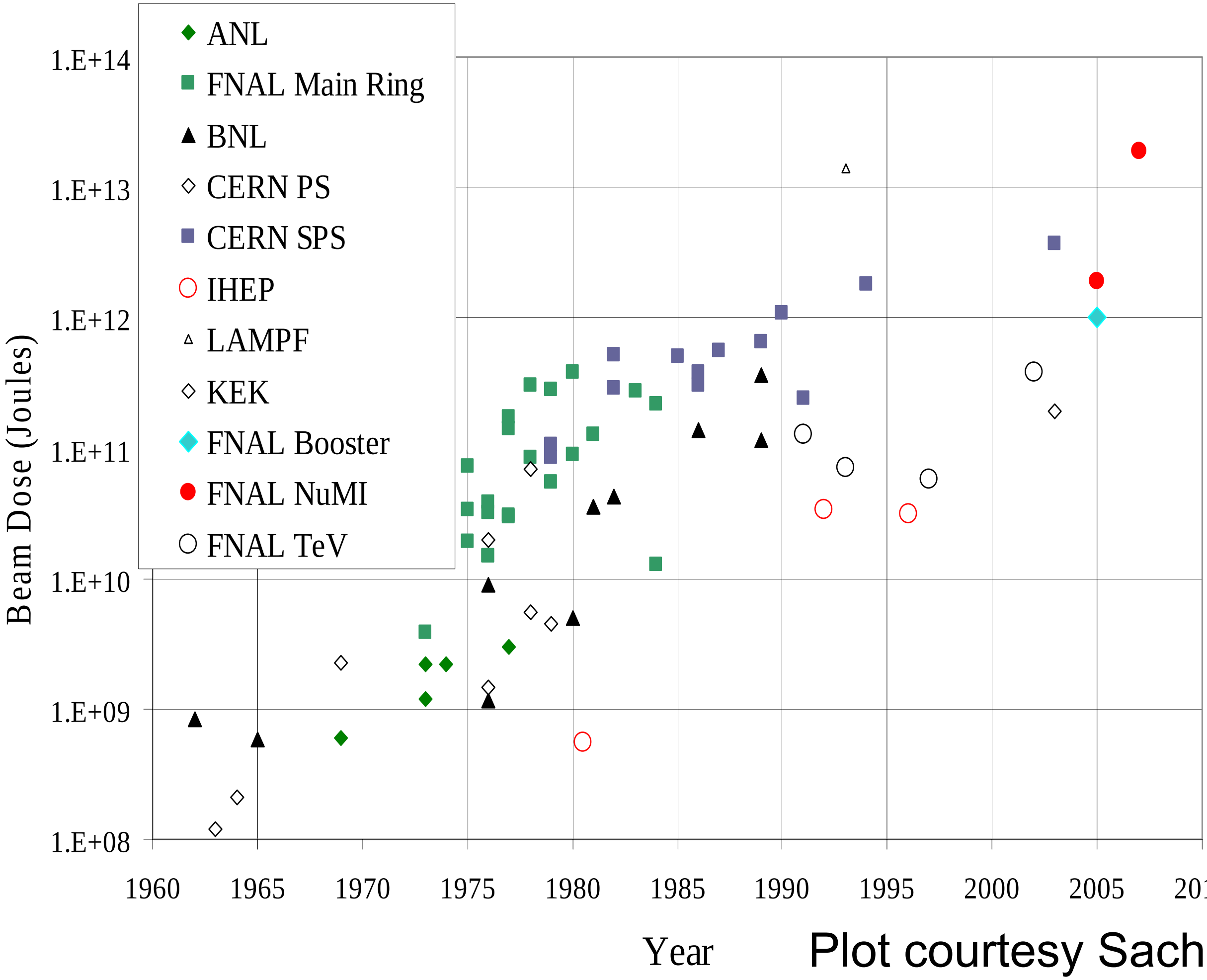


Experimental Differences between e^- and ν

- Electrons
  - Can measure initial and final e momentum very precisely
  - Can scatter off D or H by itself…go all the way up to Pb207
  - Polarized targets available
  - Statistics plentiful

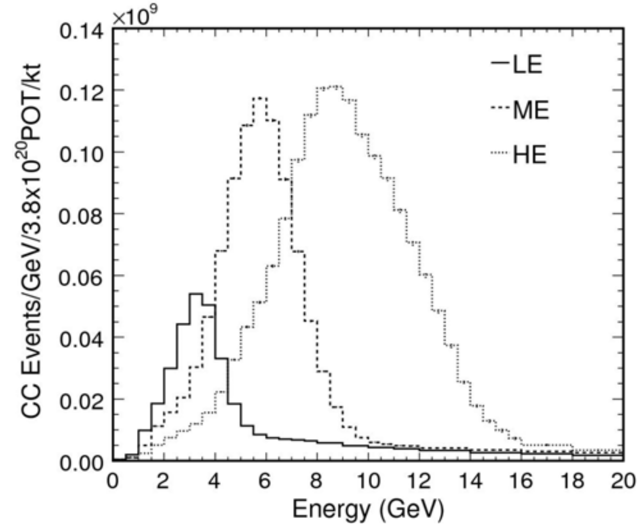
- Neutrinos
  - Can only measure outgoing particles
  - Range in A that has been covered: H_2 Bubble Chambers to Lead, but not in systematic way
  - Statistics hard to come by: means most neutrino events have been collected on steel.

But Neutrino Beam Intensity is Increasing…



Plot courtesy Sacha Kopp

To get events at long baselines, beams are being made at higher and higher intensities…

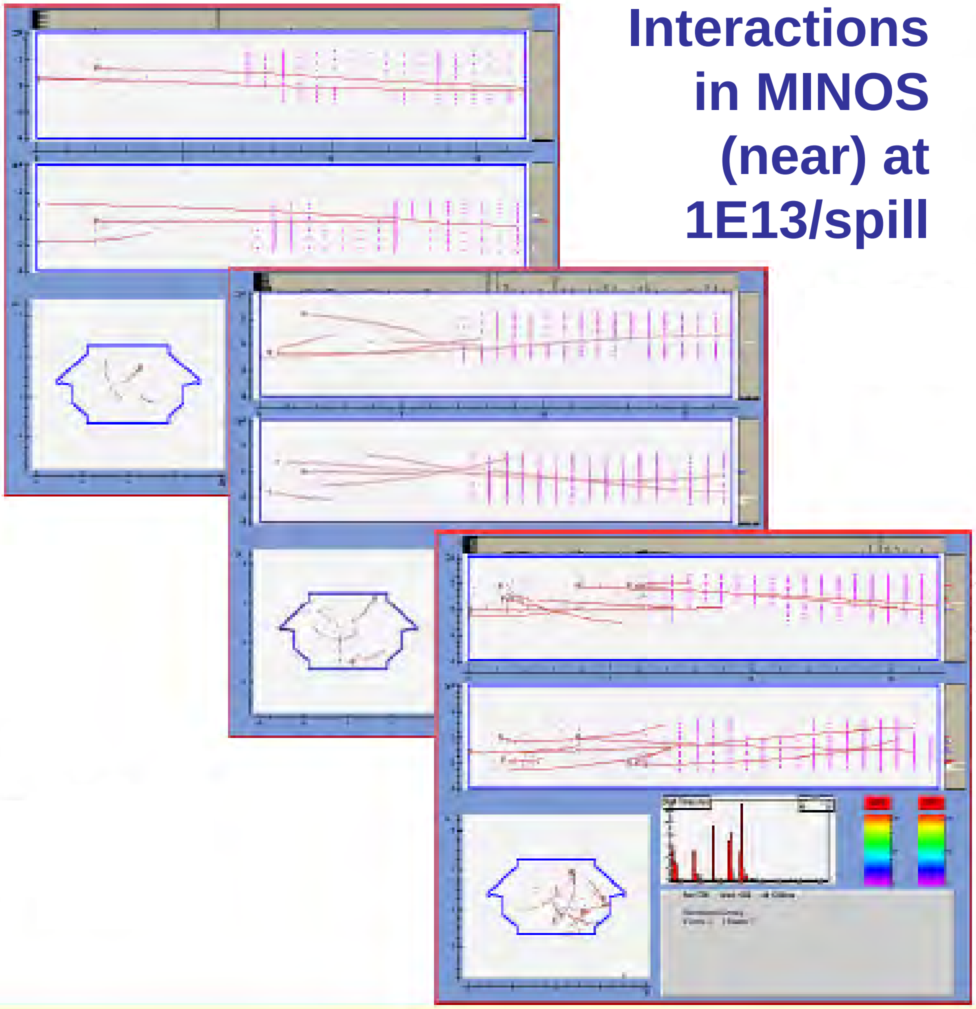


NuMI Spectra (at 1km, not 730km)

NuMI Beam Intensity (Near)

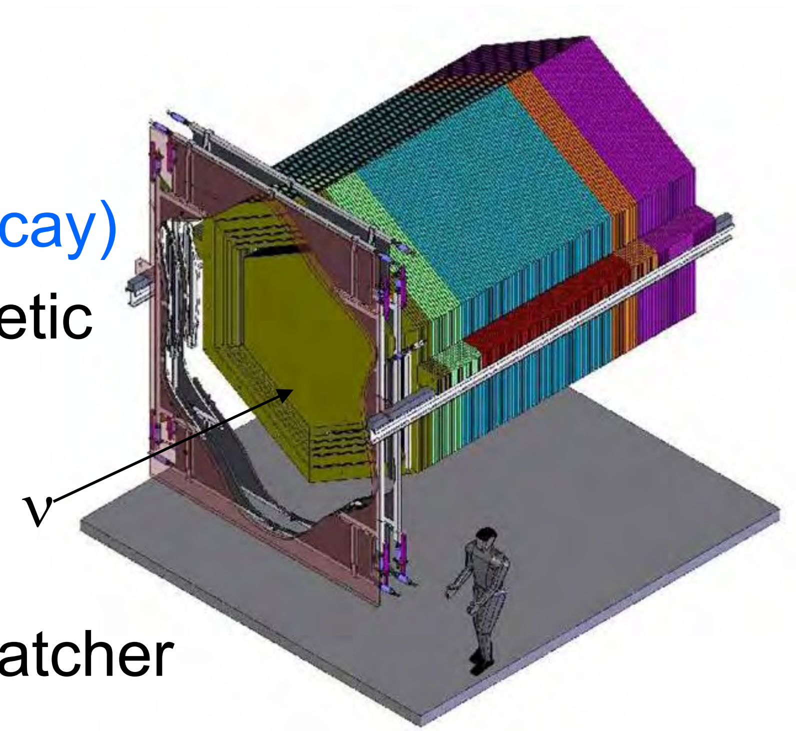
- LE-configuration: **Events-** (E_μ >0.35 GeV) E_{peak} = 3.0 GeV, $<E_\nu>$ = 10.2 GeV, rate = **60 K events/ton - 10^{20} pot**
- ME-configuration: **Events-** E_{peak} = 7.0 GeV, $<E_\nu>$ = 8.0 GeV, rate = **230 K events/ton - 10^{20} pot**
- HE-configuration: **Events-** E_{peak} = 12.0 GeV, $<E_\nu>$ = 14.0 GeV, rate = **525 K events/ton - 10^{20} pot**

Multiple Interactions in MINOS (near) at 1E13/spill



But we need a detector…MINERνA

- MINERνA is a low-risk detector with simple, well-understood technology
- Active core is segmented solid scintillator
  - Tracking (including low momentum recoil protons)
  - Particle identification
  - <3 ns (RMS) per hit timing (track direction, stopped $K^{\pm}$ decay)
- Core surrounded by electromagnetic and hadronic calorimeters
  - Photon (π^0) & hadron energy measurement
- MINOS Near Detector as muon catcher



MINERνA Detector Performance in Pictures

MINERvA: exclusive final state reconstruction, muon charge ID from MINOS

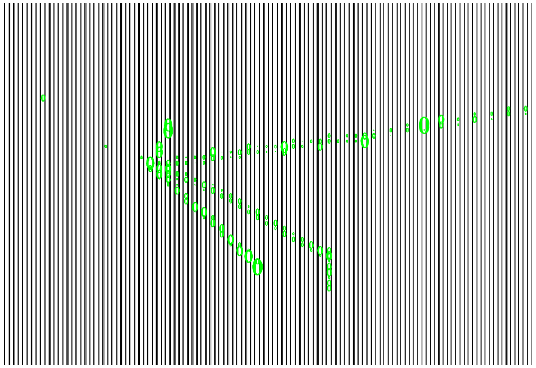
$$E_\nu = p_\mu + E_{\rm had} ,$$

$$y = \frac{E_{\rm had}}{E_\nu} ,$$

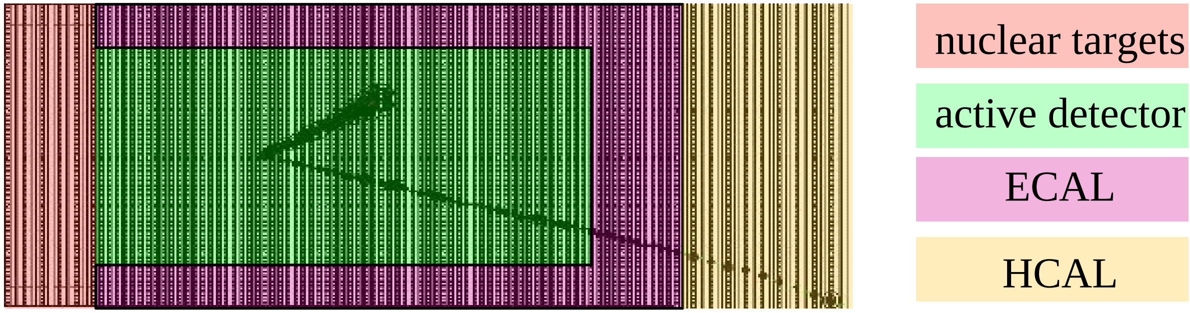
$$Q^2 = 4 E_\nu p_\mu \sin^2(\frac{\theta_\mu}{2})$$

$$x = \frac{Q^2}{2 M_{\rm N} E_{\rm had}} ,$$

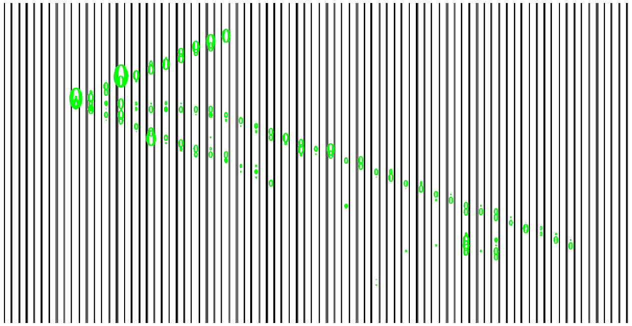
ν_μ+p→ μ 2$\pi^\pm$ p



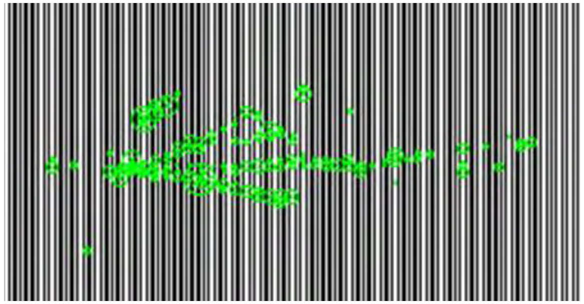
ν_μ+n→ μ^- p



ν_e+p→ e^- π^+ p

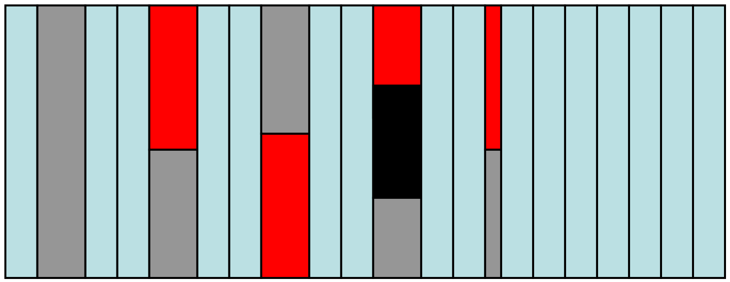


ν_e+n→ ν_e p π^- π^0

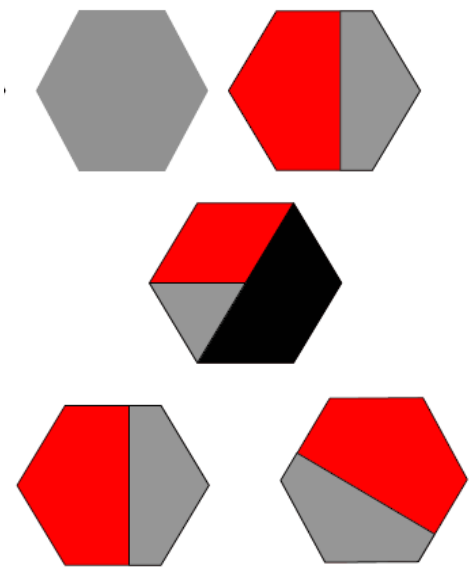


Area of circle proportional to energy deposition

MINERνA Nuclear Target Design



- 2 upstream targets – about 230 kg each of Pb and Fe (areal coverage – 60% Fe, 40% Pb)
  - Total mass – 460 kg of each target
  - Total events – 1 million each
- Middle target – about 110 kg of Pb/Fe and 140 kg C
  - About 300 K events in C, 250 K in Pb/Fe
  - Areal coverage 50% C, 30% Fe, 20% Pb
- Downstream target – about 115 kg each of Pb and Fe
  - About 250 K events in each target



Conclusions

- Neutrino Scattering Measurements can provide stringent tests of underlying theories of nuclear structure
- Many more examples of effects described at JLAB workshop in May 2006

  http://conferences.jlab.org/neutrino/
- Beamlines are becoming intense enough that precise measurements are possible
- Detector Development Underway

  …measurements to come in 2009!