Nuclear Effects for Electron and Neutrino Inelastic Scattering

Sergey Kulagin

Institute for Nuclear Research, Moscow

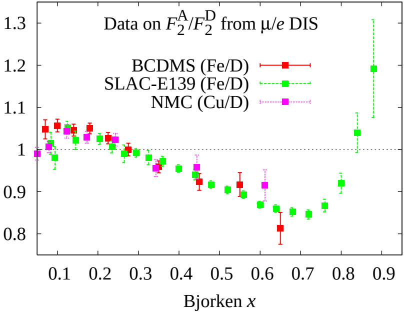
Talk at the LBNE collaboration meeting
Fermilab, Feb 3, 2014

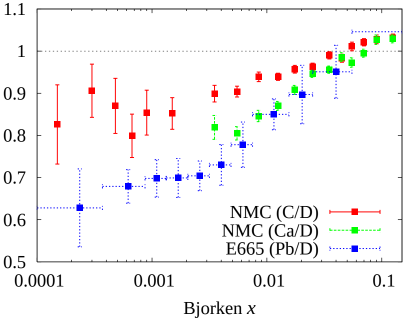
Motivation of the talk

Future precision measurements at LBNE clearly need to address nuclear effects in DIS/Resonance region.

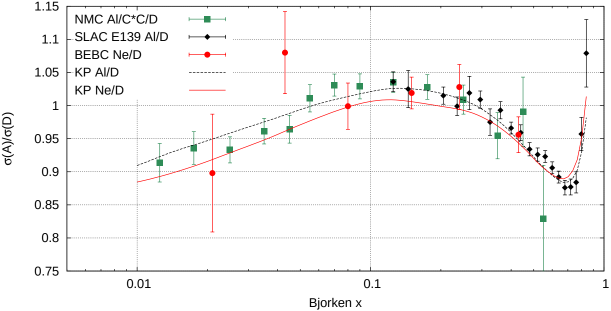
Data on the nuclear ratios of the struct. fns. $\mathcal{R}(A/D)$ show pronounced A dependence and a weak Q^2 dependence of nuclear effects. Characteristic nuclear effects vs. the Bjorken x – structure function strength oscillation

- Suppression (shadowing) at small x ($x < 0.05$).
- Enhancement (antishadowing) at $0.1 < x < 0.25$.
- A well with a minimum at $x \sim 0.6 \div 0.75$ (EMC effect).
- Enhancement at large values of $x > 0.75 \div 0.8$ (Fermi motion region).





Classical BEBC measurement



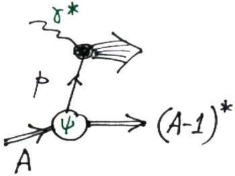
- So far the only DIRECT measurement of nuclear effects in $\nu(\bar{\nu})$ DIS from ratio ^{20}Ne/D by *BEBC Coll., ZPC 36 (1987) 337; PLB 232 (1989) 417*
  - Consistent with shadowing at small x_{Bj} but large uncertainties;
  - Consistent with the EMC effect measured from e, μ DIS.
- Differences with respect to e, μ DIS at small x mainly due to the axial-vector current.

Modelling nuclear effects

A good starting point is impulse approximation:

$$F_2^A(x,Q^2) = \int \mathrm{d}^4p\, \mathcal{P}_A(p) \left(1+\frac{p_z}{M}\right) F_2^N(x',Q^2,p^2),$$

$$x = \frac{Q^2}{2Mq_0}, \quad x' = \frac{Q^2}{2p\cdot q} \approx \frac{M\,x}{p_0+p_z}$$



In IA the basic corrections are due to the nucleon momentum distribution and its energy spectrum which are driven by nuclear spectral function

$$\mathcal{P}_A(p) = \sum_{(A-1)_n} \left|\langle (A-1)_n, -\boldsymbol{p}|\psi(0)|A\rangle\right|^2 \delta(\varepsilon + E_n(A-1) - E_0(A)).$$

Nuclear spectral function

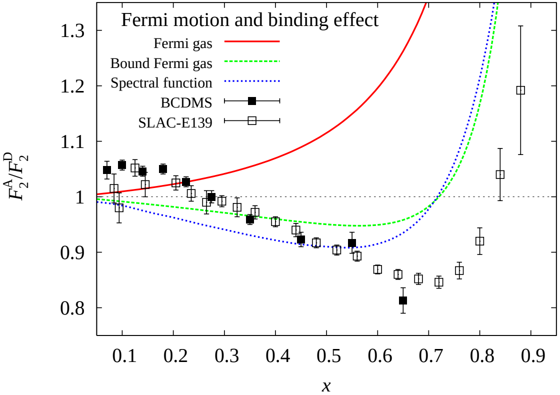
- The nuclear spectral function describes probability to find a bound nucleon with momentum $\boldsymbol{p}$ and energy $p_0 = M + \varepsilon$:
- The nuclear spectral function determines the rate of nucleon removal reactions such as $(e, e'p)$. At low energy and momentum, $|\varepsilon| < 50\,\mathrm{MeV}$, $p < 300\,\mathrm{MeV/c}$, the observed spectrum is described by mean-fild model:

$$\mathcal{P}_{\mathrm{MF}}(\varepsilon, \boldsymbol{p}) = \sum_{\lambda<\lambda_F} n_\lambda |\phi_\lambda(\boldsymbol{p})|^2 \delta(\varepsilon - \varepsilon_\lambda)$$

- At high-energy and momentum $p < 300\,\mathrm{MeV/c}$ the mean field fails. The spectrum is driven by $(A-1)^*$ excited states with one or more nucleons in the continuum, which are due to correlation effects in nuclear ground state as witnessed by numerous studies.
- Two-component model $\mathcal{P} = \mathcal{P}_{\mathrm{MF}} + \mathcal{P}_{\mathrm{cor}}$.

EMC effect in impulse approximation

- Fermi motion qualitatively describes the trend of data at $x > 0.7$.
- Binding correction is important and brings the calculation closer to data in the dip region.
- However, even realistic nuclear spectral function fails to explain the slope and the position of the minimum.



Impulse Approximation should be corrected for a number of effects.

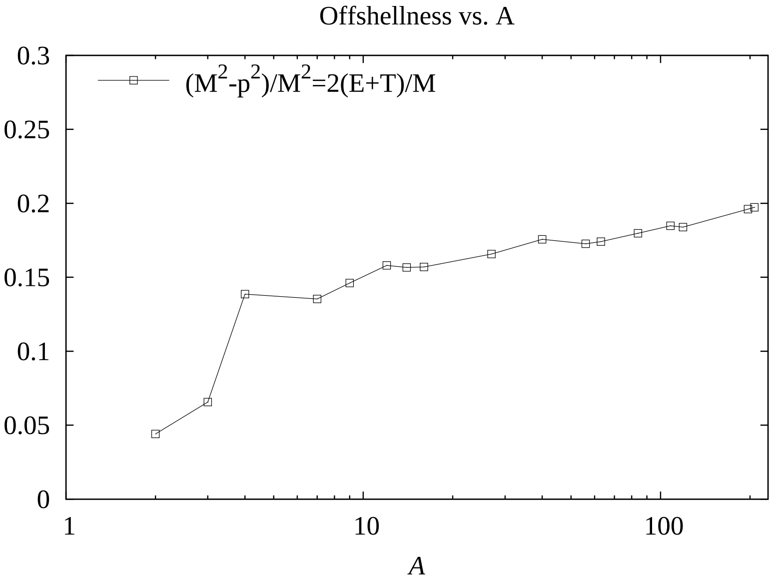
Nucleon off-shell effect

Bound nucleons are off-mass-shell $p^2 = (M+\varepsilon)^2 - \boldsymbol{p}^2 < M^2$. In off-shell region nucleon structure functions depend on additional variable $F_2(x, Q^2, p^2)$.
The nucleon virtuality parameter $v = (p^2 - M^2)/M^2$ is small (average virtuality $v \sim -0.15$ for ^{56}Fe). Expand $F_2(x, Q^2, p^2)$ in series in v:

$$F_2^N(x, Q^2, p^2) = F_2^N(x, Q^2)\big(1 + \delta f(x, Q^2)(p^2 - M^2)/M^2\big)$$

- $\delta f(x, Q^2)$ is a new structure function that describes modification of the off-shell nucleon PDFs in the vicinity of the mass shell.
- Off-shell correction is closely related to modification of the nucleon PDFs in nuclear environment.

Average virtuality (offshellness) of a bound nucleon



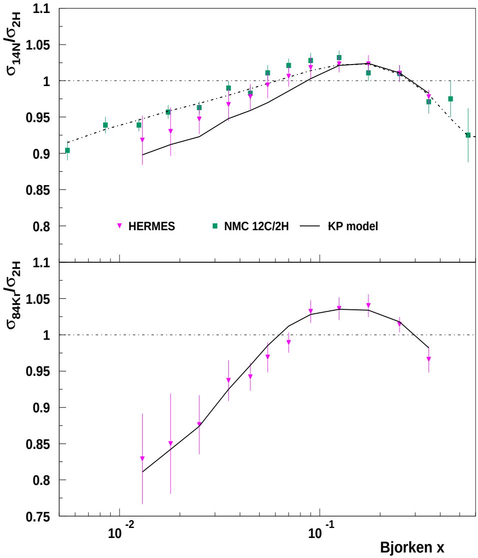
Model *S.K. & R.Petti, Nucl. Phys. A765 (2006) 126*

A quantitative model for nuclear structure functions

$$F_i^A = F_i^{p/A} + F_i^{n/A} + \delta_\pi F_i + \delta_{\mathsf{coh}} F_i$$

- $F_i^{p/A}$ and $F_i^{n/A}$ are bound proton and neutron structure functions with Fermi motion, binding and off-shell effects calculated using realistic nuclear spectral function.
- $\delta_\pi F_i^A$ and $\delta_{\mathsf{coh}} F_i^A$ are nuclear pion and shadowing corrections.

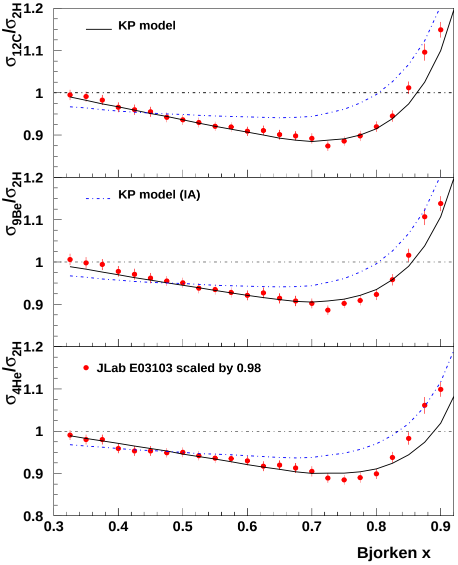
Prediction for HERMES *S.K. & R.Petti, PRC82 (2010) 054614*



- A good agreement of our predictions with HERMES data for $^{14}\mathrm{N/D}$ and $^{84}\mathrm{Kr/D}$ with $\chi^2/d.o.f. = 14.7/24$
- A comparison with NMC data for $^{12}\mathrm{C/D}$ shows a significant Q^2 dependence at small x in the shadowing region related to the cross-section for scattering of hadronic states off the bound nucleons nucleons.

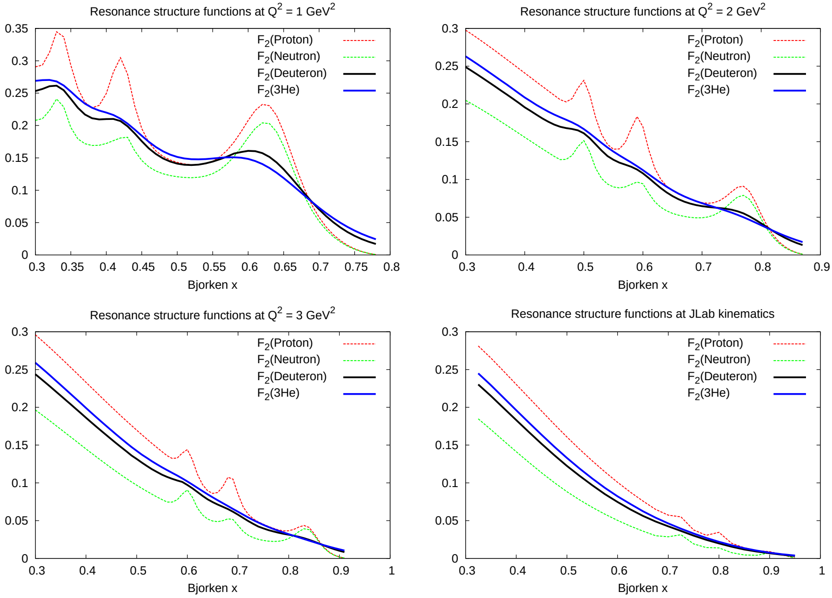
  The model correctly describes the observed x and Q^2 dependence.

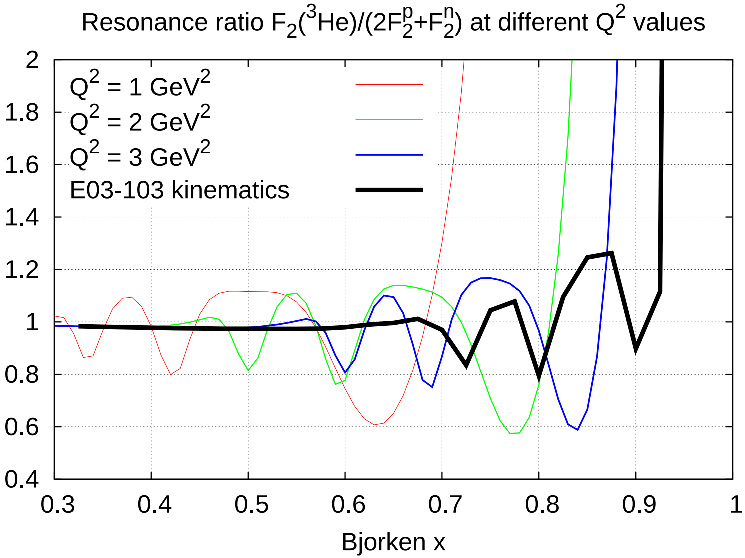
Prediction for JLab *S.K. & R.Petti, PRC82 (2010) 054614*

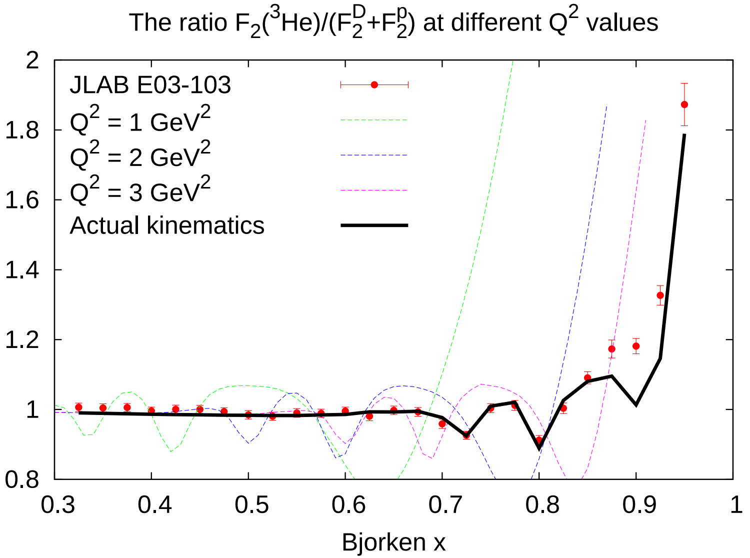


- Very good agreement of our predictions with JLab E03-103 for all nuclear targets: $\chi^2/d.o.f. = 26.3/60$ for $W^2 > 2$ GeV^2
- Nuclear corrections at large x is driven by nuclear spectral function, the off-shell function $\delta f(x)$ was fixed from previous studies.
- A comparison with the Impulse Approximation (shown in blue) demonstrates that the off-shell correction is crucial to describe the data leading to both modification of the slope and position of the minimum of the EMC ratios.

Structure functions in the resonance region




Resonance ratio $F_2(^3He)/(2F_2^p+F_2^n)$ at different Q^2 values
Q^2 = 1 GeV^2
Q^2 = 2 GeV^2
Q^2 = 3 GeV^2
E03-103 kinematics
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Bjorken x



The ratio $F_2(^3He)/(F_2^D+F_2^p)$ at different Q^2 values
JLAB E03-103
Q^2 = 1 GeV^2
Q^2 = 2 GeV^2
Q^2 = 3 GeV^2
Actual kinematics
2
1.8
1.6
1.4
1.2
1
0.8
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Bjorken x

Application to neutrino scattering

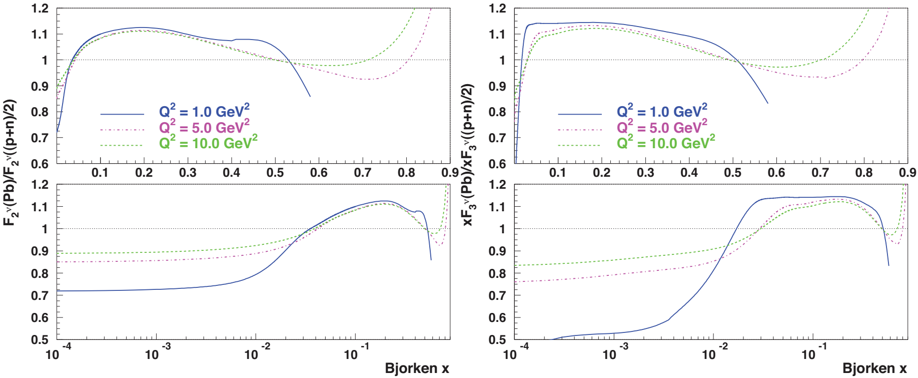
Neutrino scattering is affected by both vector (V) and axial-vector (A) currents.

$$VV, AA \quad \Longrightarrow \quad F_{1,2} \quad (\text{or } F_L,\ F_T)$$
$$VA \quad \Longrightarrow \quad F_3 \text{ (not present for CL scattering)}$$

(Anti)neutrino differential cross sections in terms of Bjorken x and inelasticity y:

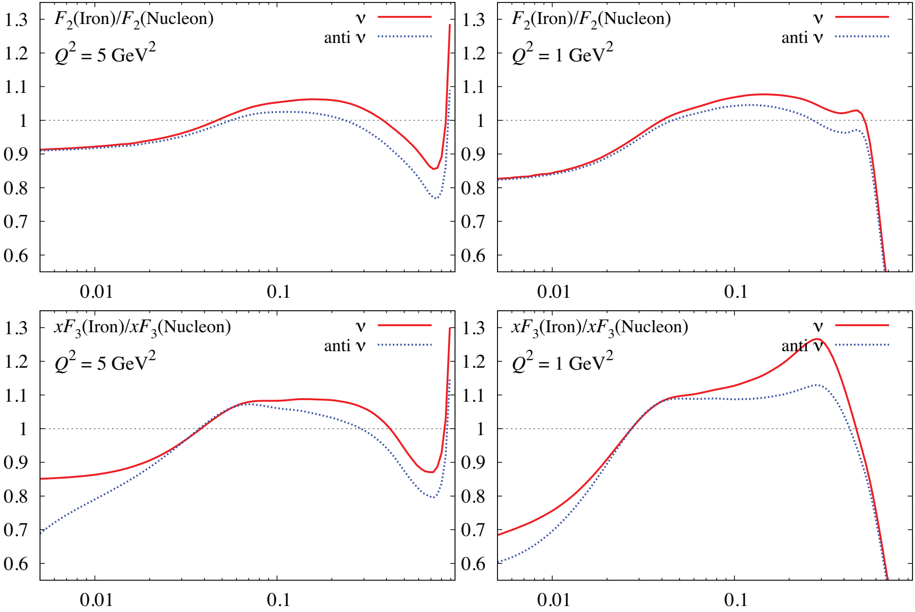
$$\frac{\mathrm{d}^2\sigma_{\mathrm{CC}}^{(\nu,\bar\nu)}}{\mathrm{d}x\mathrm{d}y} = \frac{G_F^2 M E}{\pi(1+Q^2/M_W^2)^2}\left[Y_+ F_2^{\nu,\bar\nu} - y^2 x F_L^{\nu,\bar\nu} \pm Y_- x F_3^{\nu,\bar\nu}\right],$$
$$Y_+ = \frac{1}{2}\left[1+(1-y)^2\right] + M^2x^2y^2/Q^2, \quad Y_- = \frac{1}{2}\left[1-(1-y)^2\right].$$

Nuclear effects for F_2 vs. xF_3

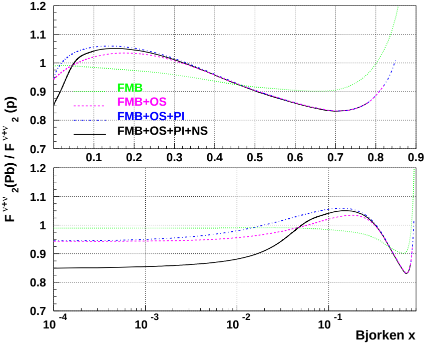


Ratio of Charged Current structure functions on ^{207}Pb and isoscalar nucleon $(p+n)/2$

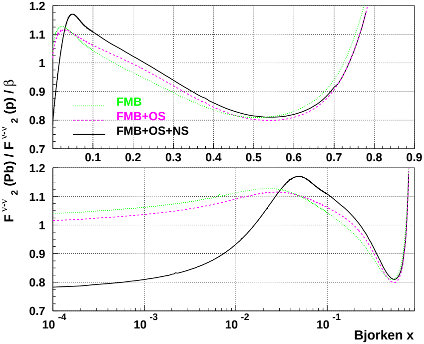
Nuclear effects for ν vs. $\bar{\nu}$



Isoscalar vs. isovector nuclear effects

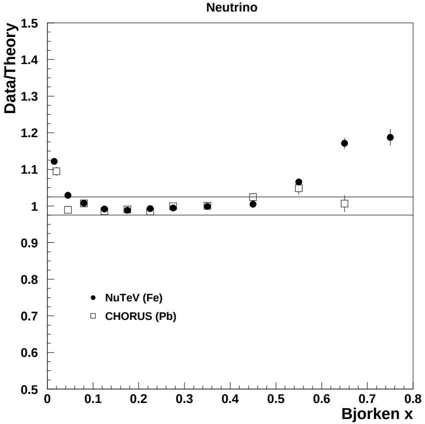


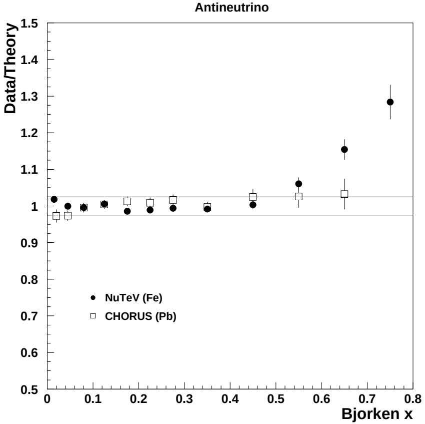
The ratio $\frac{1}{A}F_2^{(\nu+\bar{\nu})A}/F_2^{(\nu+\bar{\nu})p}$ calculated for ^{207}Pb at $Q^2 = 5$ GeV^2. The labels on the curves correspond to effects due to Fermi motion and nuclear binding (FMB), off-shell correction (OS), nuclear pion excess (PI) and coherent nuclear processes (NS).



The ratio $\frac{1}{A}F_2^{(\nu-\bar{\nu})A}/(\beta F_2^{(\nu-\bar{\nu})p})$ calculated for ^{207}Pb at $Q^2 = 5$ GeV^2. The labels on the curves correspond to effects due to Fermi motion and nuclear binding (FMB), off-shell correction (OS) and coherent nuclear processes (NS).

Comparison with CHORUS and NuTeV cross sections





Data/model predictions by *S.K. and R.Petti, NPA 765 (2006) 126; PRD 76 (2007) 094023*. The x-point is the weighted average over available E and y. The solid horizontal lines indicate a $\pm 2.5\%$ band.

Main observations from this comparison

- The model provides reasonably accurate predictions for nuclear cross sections (not the ratios!).
- Good agreement with CHORUS differential cross section data for $^{208}\mathrm{Pb}$ in the whole kinematical range.
- Good agreement with NuTeV cross sections for $^{56}\mathrm{Fe}$ for $0.015 < x < 0.55$.
- Excess of data/theory for NuTeV cross sections at large $x > 0.5$ for both ν and $\bar{\nu}$. No such excess for CHORUS(Pb) (and also NOMAD(Fe) data – *Roberto Petti, private communication*).
- Excess of data over theory for both, NuTeV and CHORUS data at small x ($0.015 - 0.025$) (also supported by preliminary NOMAD(Fe) data – *Roberto Petti, private communication*).

Summary

- A detailed semi-microscopic model of nuclear DIS was developed which includes the QCD treatment of nucleon structure function and addresses a number of nuclear effects such as shadowing, Fermi motion and nuclear binding, nuclear pion and off-shell corrections to bound nucleon structure functions
- Note the importance of the nuclear binding along with the off-shell corrections. The magnitude of the off-shell correction is similar to that od binding in the EMC effect.
- Good agreement of our predictions with the data from JLab E03-103 and HERMES experiments. Good agreement with the Drell-Yan data from E772 and E866 experiments.
- The nuclear corrections depend on the type of the structure function (F_2 vs xF_3). They are also different for the isoscalar $F_2^{\nu+\bar{\nu}}$ and the isovector $F_2^{\nu-\bar{\nu}}$ combinations.
- Predictions for neutrino cross sections are in a good agreement (within $\pm 2.5\%$ band) with the CHORUS $^{208}\mathrm{Pb}$ data in the whole kinematical region of x and Q^2. We also observe a good agreement with the NuTeV $^{56}\mathrm{Fe}$ data in the region $0.15 < x < 0.55$.
- We observe systematic excess of data/theory for the NuTeV data at large $x > 0.5$ for both the neutrino and antineutrino. Note also about 10% data/theory excess for small $x = 0.015$ for neutrino scattering for both $^{208}\mathrm{Pb}$ and $^{56}\mathrm{Fe}$ data.

Plan/directions for future studies relevant for LBNE

- Detailed studies of nuclear effects for $^{40}Ar_{18}$ and $^{40}Ca_{20}$ and $^{12}C_6$ nuclei with LBNE spectrum in ND.
- Clarify/refine the description of non-isoscalar (isovector) nuclear effects. This is relevant for calculation of $\nu - \bar{\nu}$ asymmetries in the cross sections.
- Extension of the model to the resonance region. More efforts are needed to understand nuclear effects in resonance production in heavy targets and neutrino scattering for both CC and NC.
- Refine the model of nuclear spectral function.
- Refinement/improvement of description of small x (shadowing) region.
- Clarify dicreapancies between predictions for the neutrino and the charged-lepton DIS at large $x > 0.65$ and in the shadowing region of small $x < 0.01$.
- Incorporate QE mechanism in the model.