Recent Results on Nuclear Structure Functions

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OUTLINE

I *A Quantitative Model of Nuclear Structure Functions*

- *Incoherent Nuclear Scattering;*
- *Nuclear Pion Correction;*
- *Coherent Nuclear Effects;*
- *The Off-shell Correction.*

II *Comparison with Recent Charged Lepton Data*

- *Consistency of Measurements from Different Experiments;*
- *Comparison with JLab E03-103 and HERMES Data;*
- *The ^{3}He Data and the Ratio F_2^n/F_2^p.*

III *Comparison with Neutrino Data*

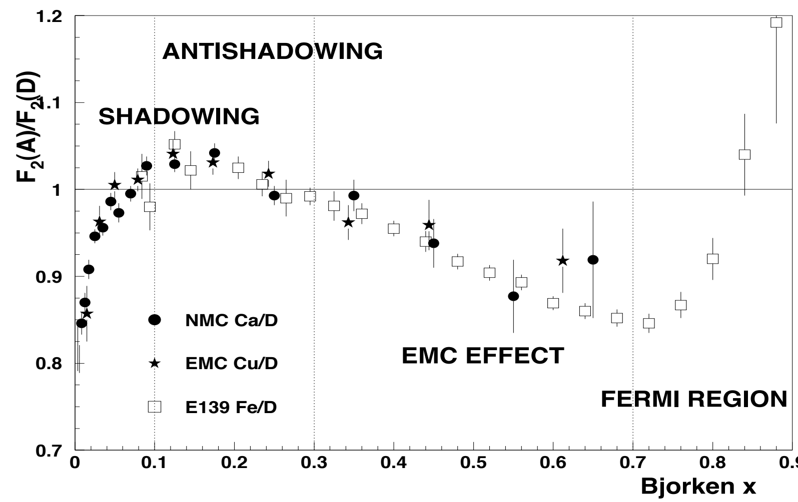
- *Effects of the Axial-Vector Current;*
- *Isospin and C Dependence;*
- *Comparison with NuTeV and CHORUS Data;*

IV *Summary*

NUCLEAR STRUCTURE FUNCTIONS

✦ GLOBAL APPROACH *aiming to obtain quantitative calculations covering the complete range of x and Q^2 available (S. Kulagin and R.P., NPA 765 (2006) 126-187):*

- *Scale controlling nuclear processes* $L_I = (Mx)^{-1}$
  Distance between nucleons $d = (3/4\pi\rho)^{1/3} \sim 1.2 Fm$
- $L_I < d$
  For $x > 0.2$ *nuclear DIS* $\sim$ *incoherent sum of contributions from bound nucleons*
- $L_I \gg d$
  For $x \ll 0.2$ *coherent effects of interactions with few nucleons are important*



✦ DIFFERENT EFFECTS *on structure functions (SF) are taken into account:*

$$F_i^A = F_i^{p/A} + F_i^{n/A} + F_i^{\pi/A} + \delta F_i^{\rm coh}$$

- $F_i^{p(n)/A}$ *bound proton(neutron) SF with Fermi Motion, Binding (FMB) and Off-Shell effect (OS)*
- $F_i^{\pi/A}$ *nuclear Pion excess correction (PI)*
- $\delta F_i^{\rm coh}$ *contribution from coherent nuclear interactions: Nuclear Shadowing (NS)*

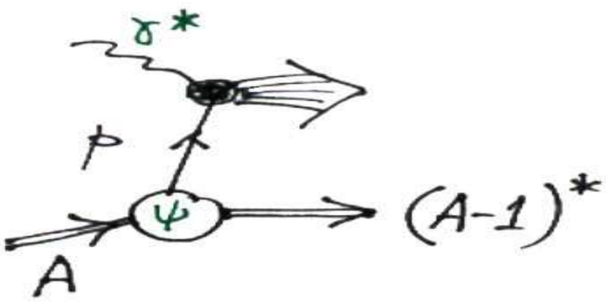
INCOHERENT NUCLEAR SCATTERING

✦ FERMI MOTION AND BINDING *in nuclear structure functions can be calculated from the convolution of nuclear spectral function and (bound) nucleon SFs:*

$$F_2^A(x, Q^2) = F_2^{p/A} + F_2^{n/A}$$

$$F_2^{p/A} = \int \mathrm{d}\varepsilon\, \mathrm{d}^3\mathbf{k}\, \mathcal{P}_p(\varepsilon, \mathbf{k}) \left(1 + \frac{k_z}{M}\right) F_2^p(x', Q^2, k^2)$$

where $x' = Q^2/(2k \cdot q)$ *and* $k = (M + \varepsilon, \mathbf{k})$.



✦ *Since bound nucleons are* OFF-MASS-SHELL *there appears dependence on the nucleon virtuality* $k^2 = (M + \varepsilon)^2 - \mathbf{k}^2$*:*

$$F_2(x, Q^2, k^2) = F_2(x, Q^2) \left(1 + \delta f_2(x)(k^2 - M^2)/M^2\right) .$$

where we have introduced an off-shell structure function $\delta f_2(x)$

✦ *Hadronic/nuclear input:*

- *Proton/neutron SFs computed in NNLO pQCD + TMC + HT from fits to DIS data*
- *Two-component nuclear spectral function (mean-field + correlated part) based on Ciofi & Simula*

THE OFF-SHELL FUNCTION

- *Universal off-shell structure function $\delta f(x)$ describing the modification of the bound nucleon in the nuclear medium*

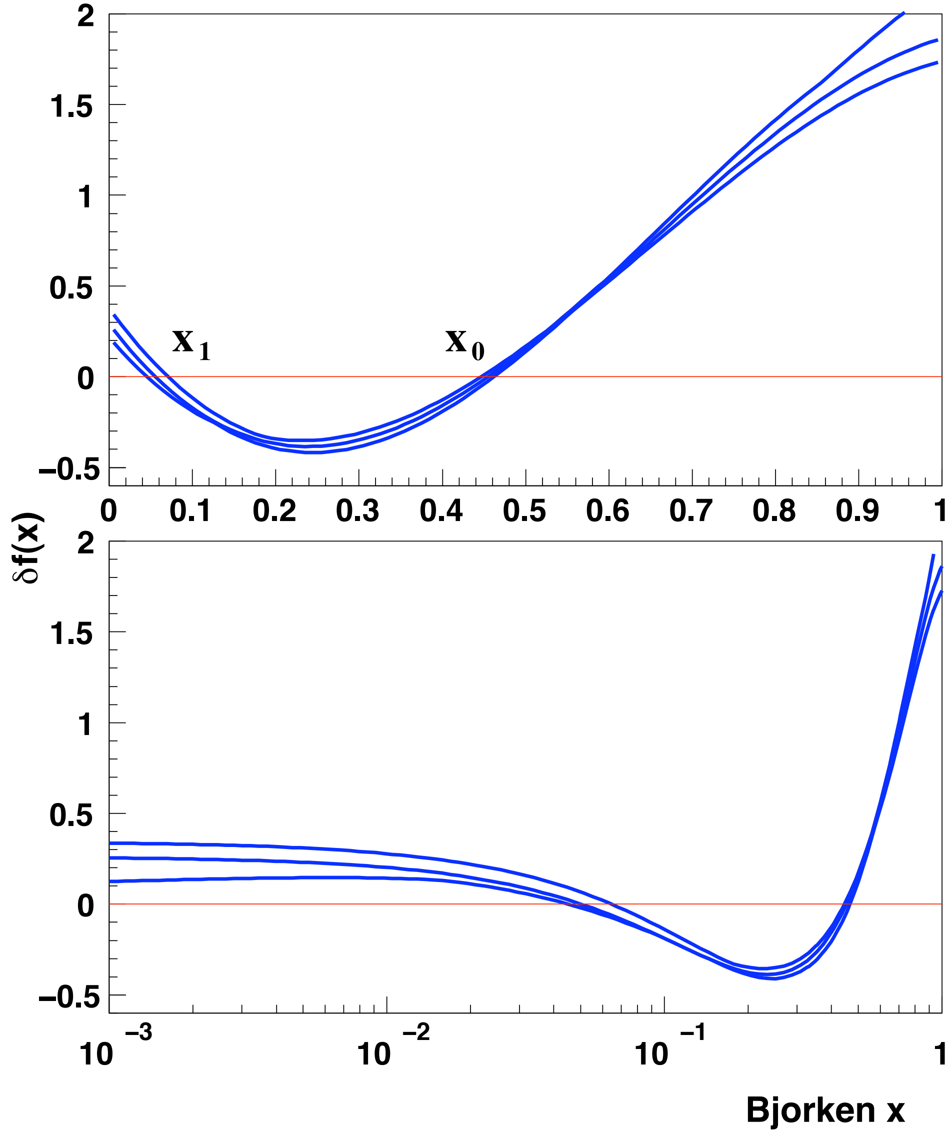
  $\Longrightarrow$ *Response to the local nuclear environment (from spectral function)*

- *Parameterization of $\delta f(x)$ extracted phenomenologically from nuclear DIS data:*

  $$C_N(x-x_0)(x-x_1)(1+x_0-x)$$

  $\Longrightarrow$ *x_0 and the slope $\delta f'(x_0)$ suggest an increase of the radius of nucleon valence region by $\sim 10\%$ in Fe*

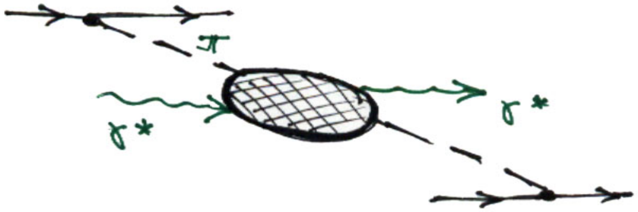
- *Interesting to check the universality of δf for all partons, which was suggested by normalization of nuclear valence number*



NUCLEAR PION CORRECTION

✦ *Leptons can scatter off mesons which mediate interactions among bound nucleons:*

$$F_i^{\pi/A}(x,Q^2) = \int_x \mathrm{d}y\, f_{\pi/A}(y) F_i^{\pi}(x/y,Q^2)$$



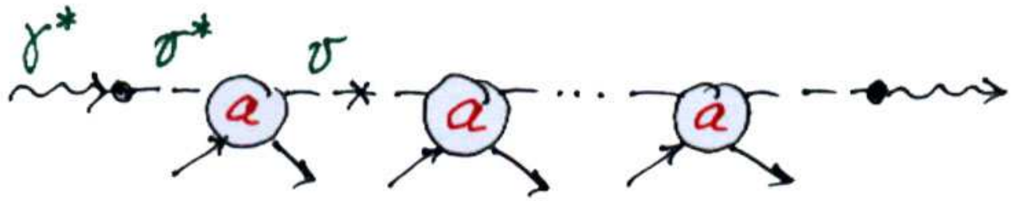
✦ *Contribution from nuclear pions (mesons) to balance nuclear light cone momentum* $\langle y\rangle_\pi + \langle y\rangle_N = M_A/(A\,M)$. *The pion distribution function is localized at* $y \leq p_F/M \sim 0.3$ *so that the pion contribution is at* $x < 0.3$. *The correction is driven by the average number of "pion excess"* $n_\pi = \int \mathrm{d}y\, f_\pi(y)$ *and* $n_\pi/A \sim 0.1$ *for heavy nuclei. It modifies the nuclear sea quark distributions, but not the valence quarks.*

✦ *Hadronic/nuclear input:*

- *Pion Parton Density Functions from fits to Drell-Yan data by Gluck, Reya & Schienbein*
- $f_{\pi/A}(y)$ *calculated using constraints of light-cone momentum conservation and equations of motion for pion-nucleon system*

COHERENT NUCLEAR EFFECTS

✦ SHADOWING *correction comes from multiple interactions of the hadronic component of virtual photon during the propagation through matter. This is described following the Glauber-Gribov approach:*



$$\delta\mathcal{R} = \frac{\delta F_2^{\rm coh}}{F_2^N} \approx \frac{\delta\sigma^{\rm coh}}{\sigma}; \quad \delta\sigma^{\rm coh} = 2\,{\rm Im}\left(ia^2\mathcal{C}_2^A(a)\right)$$

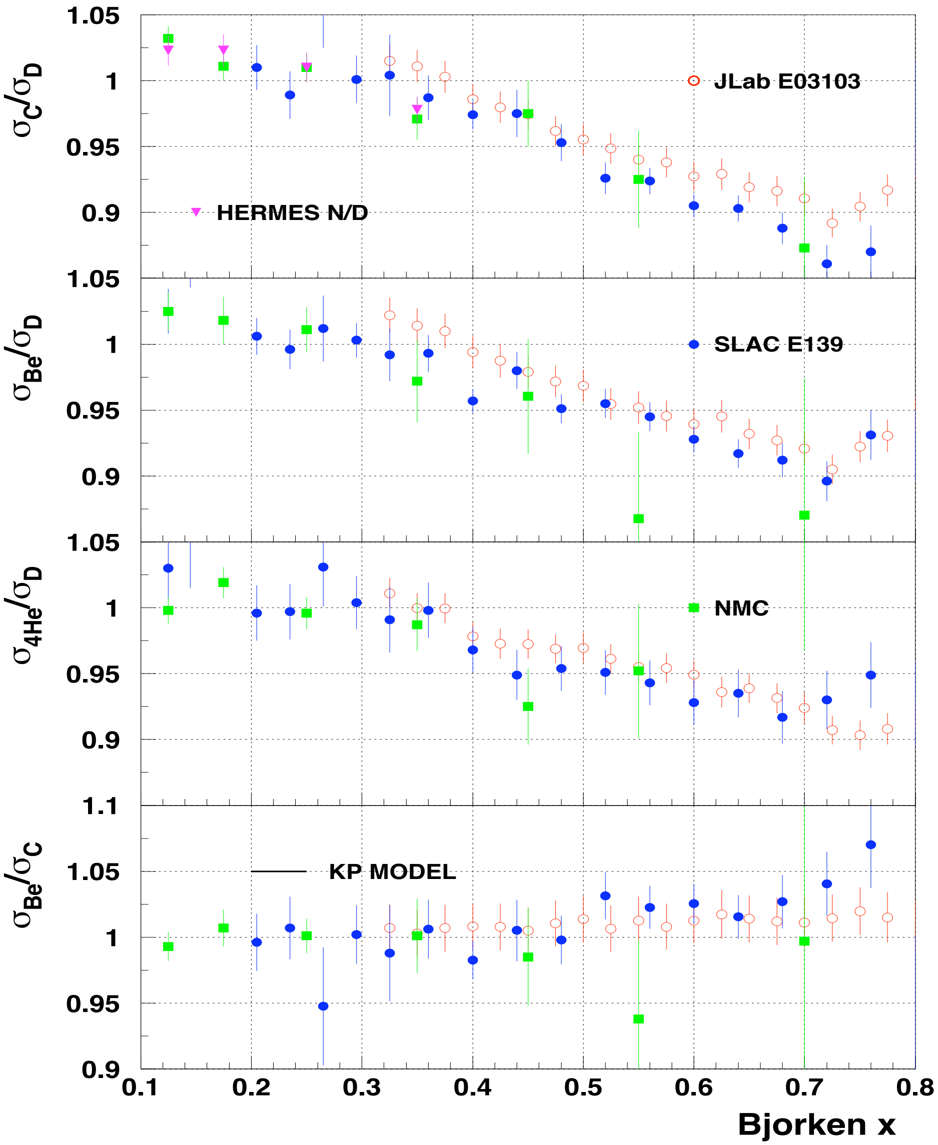
$$\mathcal{C}_2^A(a) = \int_{z_1<z_2} {\rm d}^2\mathbf{b}\,{\rm d}z_1{\rm d}z_2\,\rho_A(\mathbf{b},z_1)\rho_A(\mathbf{b},z_2)\exp\left[i\int_{z_1}^{z_2}{\rm d}z'\,(a\,\rho_A(\mathbf{b},z')-k_L)\right]$$

$a = \sigma(i+\alpha)/2$ *is the (effective) scattering amplitude* ($\alpha = {\rm Re}\,a/{\rm Im}\,a$) *in forward direction,* $k_L = Mx(1+m_v^2/Q^2)$ *is longitudinal momentum transfer in the process* $v^* \to v$ *(accounts for finite life time of virtual hadronic configuration).*

✦ *Hadronic/nuclear input:*

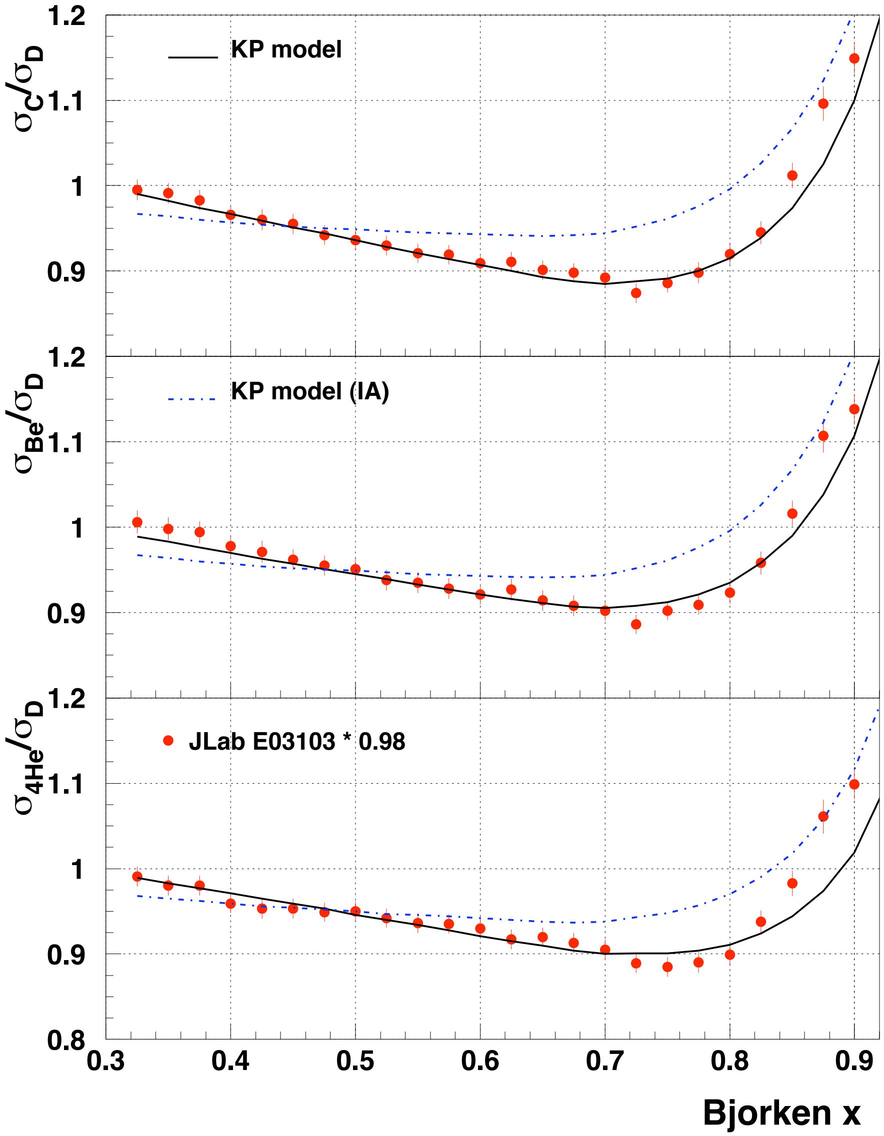
- *Nuclear number densities* $\rho_A(r)$ *from parameterizations based on elastic electron scattering data*

CONSISTENCY OF DIFFERENT EXPERIMENTS



- *Shapes of all nuclear cross-section ratios are consistent*
- *Evaluate χ^2 for each pair of experiments in coarse x-bins within the overlap region of the data sets*
- *Consistent overall normalization for SLAC E139, NMC and HERMES data sets;*
- *The new JLab E03-103 data is systematically above previous measurements resulting in a $\chi^2/d.o.f. = 42.7/12$ with respect to SLAC E139 data on the same targets*
- *An overall normalization* **factor 0.98** *for all JLab points improves the statistical consistency with SLAC E139* data to $\chi^2/d.o.f. = 8.8/12$

PREDICTIONS FOR JLAB E03-103



- *Apply overall normalization factor 0.98 to JLab data on ^{4}He/D, ^{9}Be/D and ^{12}C/D*

  $\Longrightarrow$ *Offset statistically consistent with quoted normalization uncertainties*

- *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}

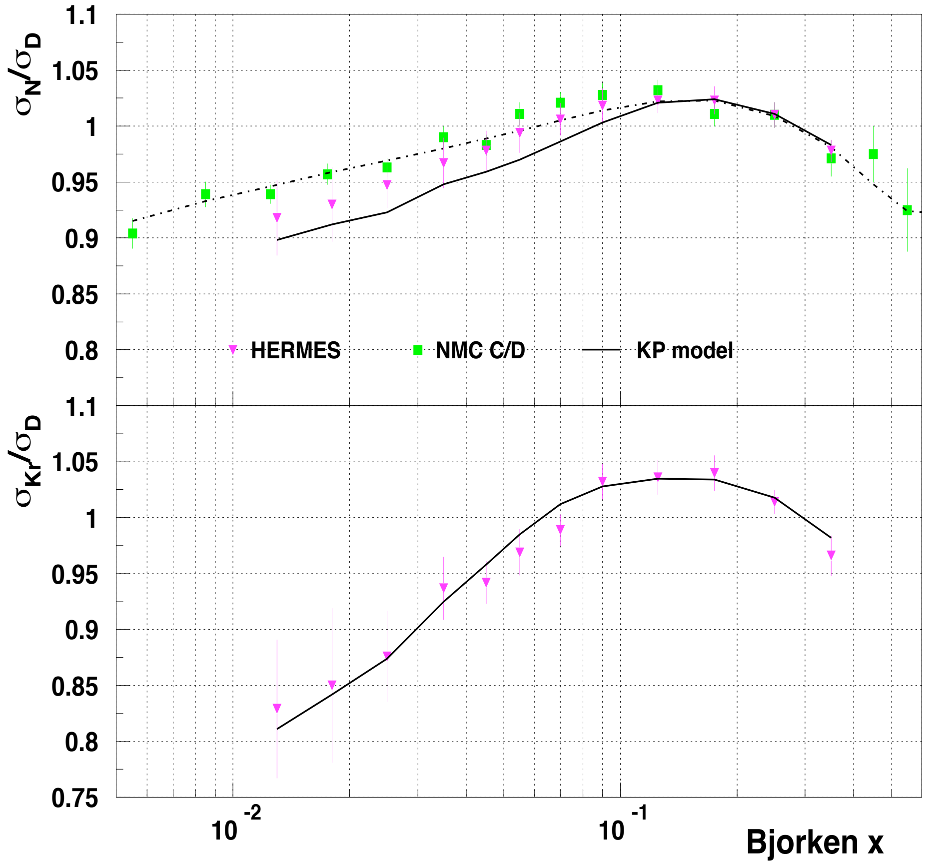
  S. Kulagin and R.P., arXiv:1004.3062 [hep-ph]

- *No free parameter in the model since the description of the nucler target is incorporated into the spectral function*

- *A comparison with the Impulse Approximation demonstrates the off-shell correction is crucial to describe the data*

  $\Longrightarrow$ *Mechanism for modification of bound nucleon parton structure in nuclei*

PREDICTIONS FOR HERMES

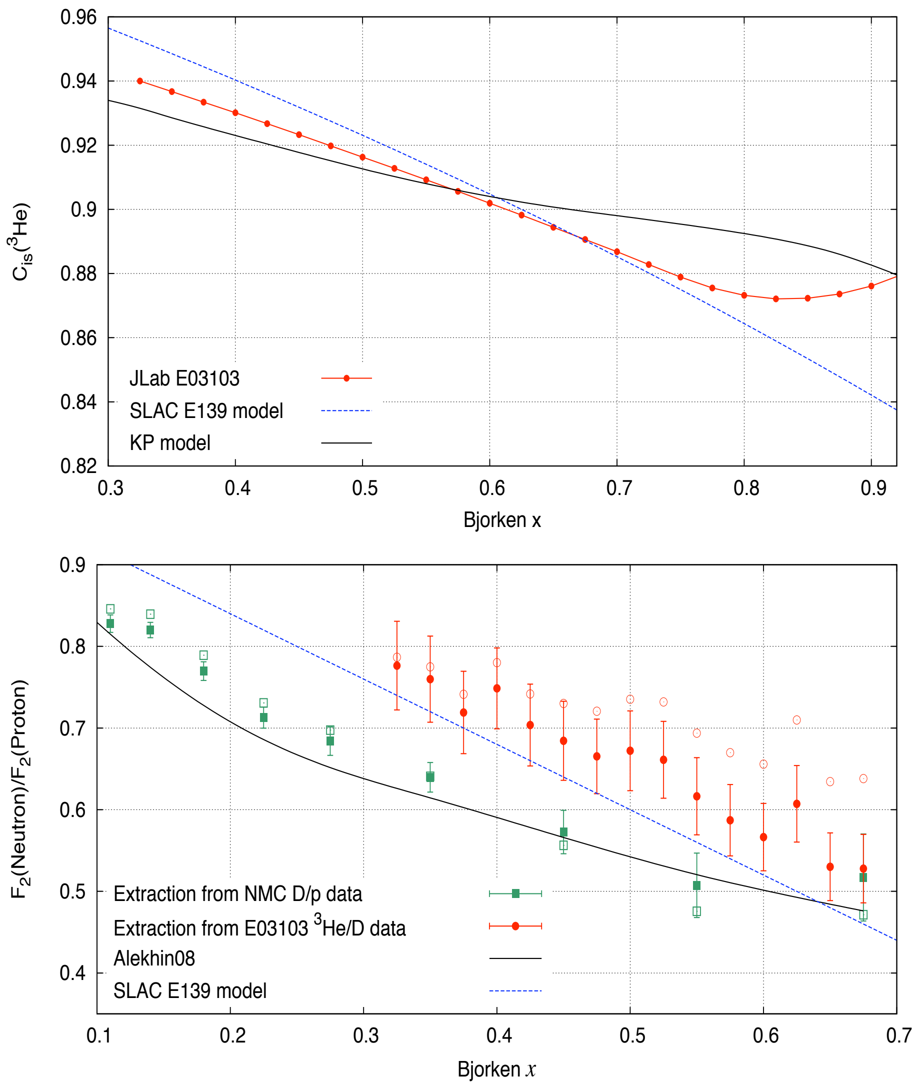


- *Very good agreement of our predictions with HERMES data* for ^{14}N/D and ^{84}Kr/D with $\chi^2/d.o.f. = 14.7/24$

- *A comparison with NMC data for ^{12}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*

  $\Longrightarrow$ *The model correctly describes the observed x and Q^2 dependence*

THE ^{3}He/D DATA AND F_2^n/F_2^p



- The proton excess in ^{3}He implies a large non-isoscalarity correction:

$$C_{\rm is} \equiv \frac{AF_2^{(p+n)/2}}{ZF_2^p + NF_2^n}$$

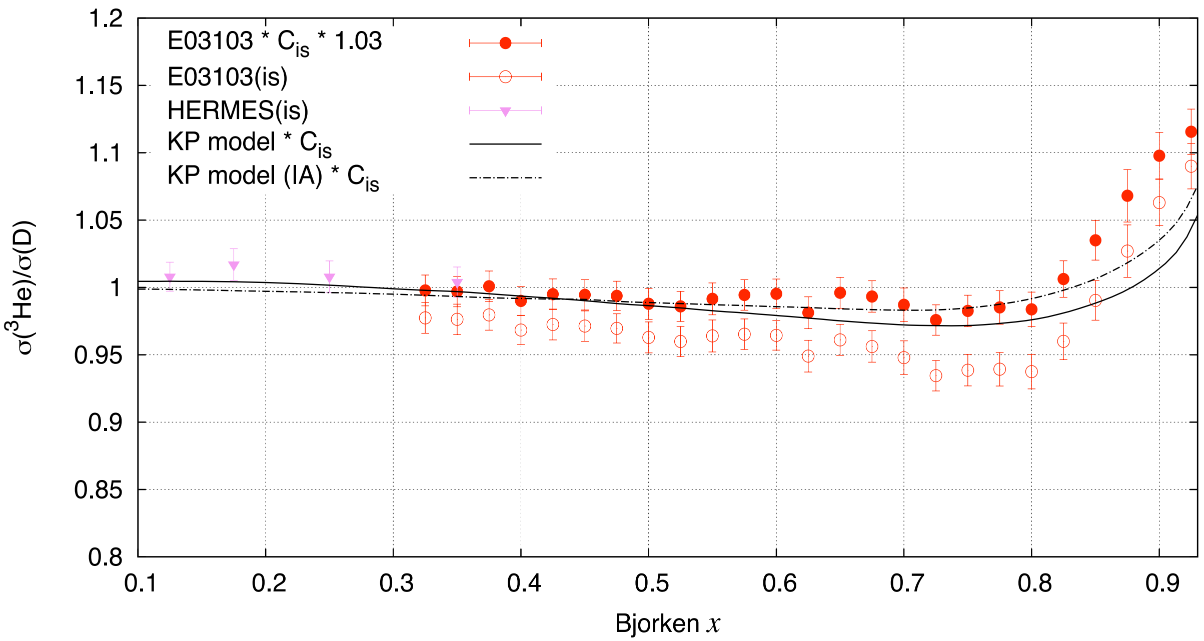
$\Longrightarrow$ Verify different assumptions for $C_{\rm is}$

- Extract the ratio F_2^n/F_2^p from both JLab E03-103 raw data on ^{3}He/D and from the NMC data on D/p

- At $x \sim 0.35$, where nuclear corrections are negligible, the ratio F_2^n/F_2^p from JLab is 15% higher than the one from NMC

$\Longrightarrow$ Overall normalization **factor 1.03** for JLab ^{3}He/D

PREDICTIONS FOR ^{3}He/D



- *Apply normalization factor from F_2^n/F_2^p and our $C_{\rm is}$ correction to JLab raw data*
  $\Longrightarrow$ *Consistent normalization with HERMES measurement of (isoscalar) ^{3}He/D*

- *Use ^{3}He spectral function with terms for bound pn deuteron intermediate state, pn continuum scattering states ($\mathcal{P}^p$) and pp continuum scattering states ($\mathcal{P}^n$)*
  R. Schulze and P. Sauer, Phys. Rev. C 48 (1993) 38

- *Good agreement of our predictions with both JLab and HERMES ^{3}He/D data*

APPLICATION TO NEUTRINO SCATTERING

✦ AXIAL-VECTOR CURRENT *(V-A)*:

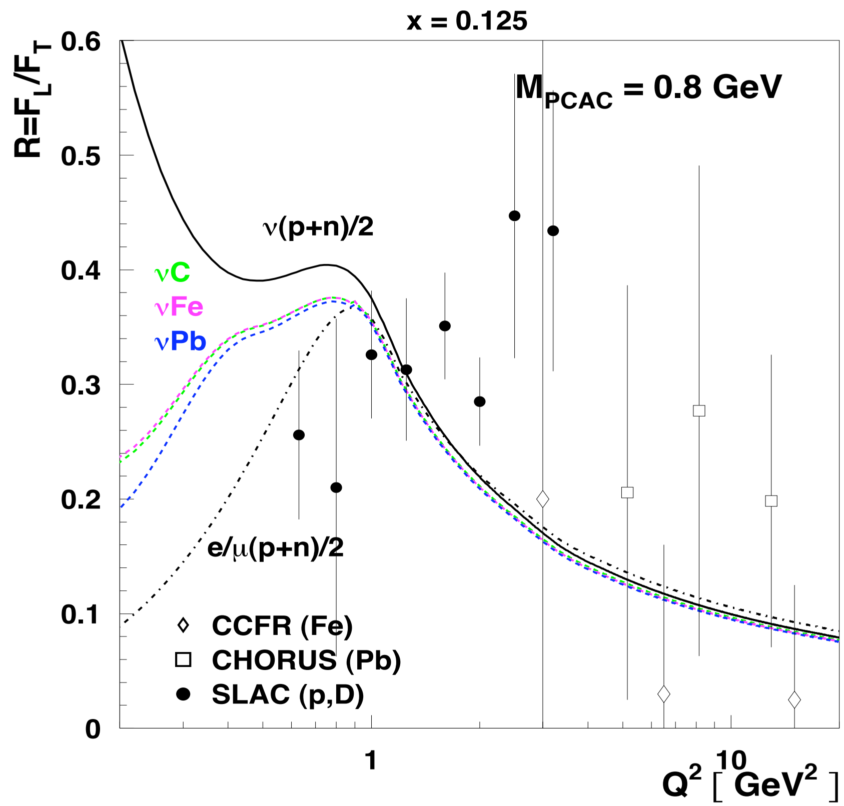
$$VV, AA \implies F_{1,2} \quad (or\ F_L,\ F_T)$$
$$VA \implies F_3$$

✦ *Conservation of Vector Current (CVC), in analogy to the charged leptons, implies:*

$$F_2, F_T \sim Q^2 \qquad F_L \sim Q^4 \qquad for \quad Q^2 \to 0$$

✦ *Axial Current is only Partially Conserved (PCAC) and dominates SFs at low Q^2:*

$$F_L = \frac{f_\pi^2 \sigma_\pi}{\pi}(1+Q^2/M^2_{\rm PCAC})^{-2} + \widetilde{F}_L \qquad \widetilde{F}_L \propto Q^4$$

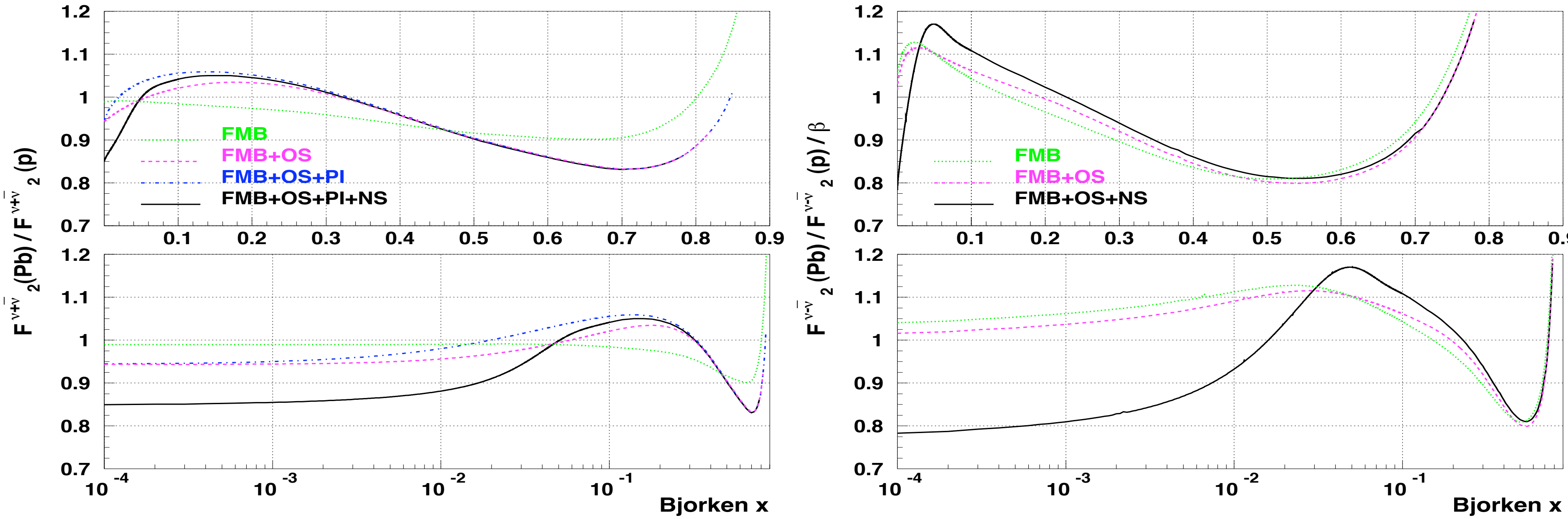


✦ *Transition scale between low and high Q^2 is NOT m_π^2 but rather $m_a \sim 1\ GeV^2$. Due to the PCAC contribution* $R = \sigma_L/\sigma_T$ *does not vanish for $Q^2 \to 0$*

S. Kulagin and R.P., Phys. Rev. D 76 (2007) 094023

$\implies$ *Substantial difference with respect to charged lepton scattering.*

C-PARITY AND ISOSPIN DEPENDENCE



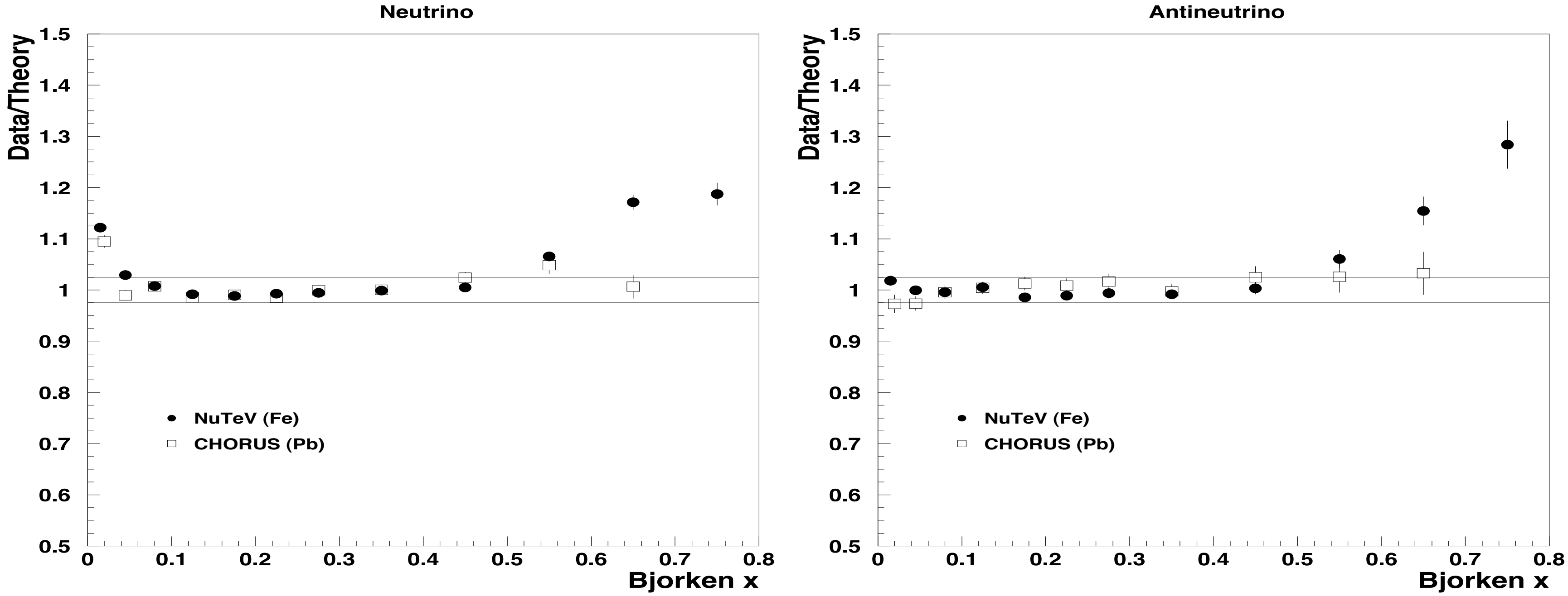
✦ *The effective amplitude for coherent scattering,* $\boxed{a_h^{(I,C)}}$*, depends on the helicity of the boson* h*, on the isospin* I *of the target and on the* C*-parity:*

- γ^* *only* C*-even while* W *both* C*-even and* C*-odd;*
- *Differences between neutrinos and anti-neutrinos;*
- *Nuclear isovector corrections beyond trivial isospin violations in nucleon SFs (heavy quark production, strange sea asymmetry etc.)*

✦ *Isoscalar and Isovector spectral functions,* $\boxed{\mathcal{P}_0 \text{ and } \mathcal{P}_1}$*, enter nuclear convolution*

$$F_2^A/A = \langle \frac{F_2^p + F_2^n}{2} \rangle_0 + \frac{\beta}{2} \langle F_2^p - F_2^n \rangle_1 \qquad \beta = (Z - N)/A$$

PREDICTIONS FOR CHORUS AND NuTeV



- *Calculate weighted average (over E_ν and y) of data pulls as a function of x*
- *Our predictions for (anti)neutrino scattering consistent with NuTeV (Fe) and CHORUS (Pb) cross-section data over main kinematic range (band in plots $\pm 2.5\%$).*
- *Systematic excess observed for $x > 0.5$ in both ν and $\bar{\nu}$ NuTeV data on Fe*
  - *Known problem and discrepancy between NuTeV and old CCFR data at large x on Fe target;*
  - *CHORUS data on Pb target consistent with predictions at large x;*
  - *Preliminary NOMAD data on carbon target seem to indicate no significant excess at large x.*

Cut	# of points Neutrino	# of points Antineutrino	χ^2/dof Neutrino	χ^2/dof Antineutrino
NuTeV (Fe)				
No cut	*1423*	*1195*	*1.36*	*1.10*
$x > 0.015$	*1324*	*1100*	*1.15*	*1.08*
$x < 0.55$	*738*	*671*	*1.16*	*1.02*
$0.015 < x < 0.55$	**686**	**620**	**0.97**	**1.01**
CHORUS (Pb)				
No cut	**607**	**607**	**0.68**	**0.84**
$x > 0.02$	*550*	*546*	*0.55*	*0.83*
$x < 0.55$	*506*	*507*	*0.74*	*0.83*
$0.02 < x < 0.55$	*449*	*447*	*0.60*	*0.83*

$\Longrightarrow$ *Fully independent model PREDICTIONS, NOT FIT!*

- *Good agreement of our predictions with the CHORUS differential cross-sections on Pb in the whole kinematic range*

- *Good agreement of our predictions with the NuTeV differential cross-sections on Fe in the main kinematic region* $0.015 < x < 0.55$

SUMMARY

- *Detailed semi-microscopic model including Fermi motion and binding energy, off-shell effect of bound nucleons, nuclear pion excess and shadowing correction*

  $\Longrightarrow$ *All parameters were fixed from independent studies*

- *New JLab E03-103 nuclear data consistent with previous measurements after applying overall normalization factors of 0.98 for ^{4}He/D, ^{9}Be/D and ^{12}C/D and 1.03 for ^{3}He/D*

- *Our predictions are in good agreement with the new nuclear data from both JLab E03-103 and HERMES for ^{3}He/D, ^{4}He/D, ^{9}Be/D and ^{12}C/D*

- *Our predictions for neutrino scattering off nuclei are in good agreement with cross-section data from CHORUS (Pb) in the whole kinematic region and from NuTeV (Fe) in the region $0.15 < x < 0.55$*