The nuclear EMC effect in the DIS and the resonance region (work in progress)

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Motivations

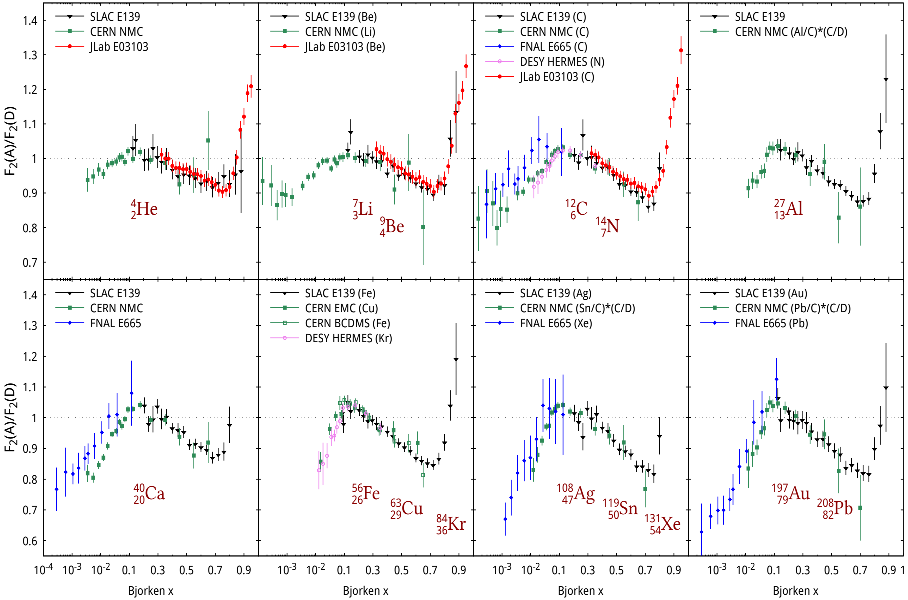
Nuclear DIS probes nuclei at quark-gluon level. However, recent measurements from JLab at large Bjorken x fall into a resonance or DIS transition region with center-of-mass energy $W < 2$ GeV.

The purpose of this talk is to address this region in the context of nuclear effects with particular emphasis on light nuclei, the deuteron and $^3\mathrm{He}$.

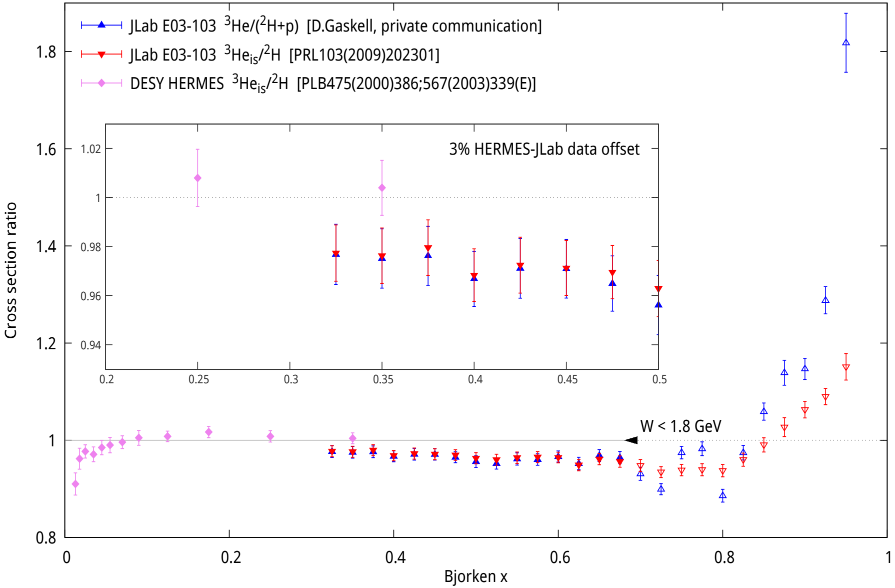
Outline

- Data overview on the nuclear EMC effect (DIS).
- Computing nuclear structure functions with particular emphasis on large Bjorken x.
  - Structure functions in DIS regime
  - Structure functions in the resonance region
  - Combined RES+DIS model for the proton and neutron
  - Calculation of nuclear structure functions
- Comparison with JLab BONuS (Hall B) and E03103 (Hall C) measurements on $^2\mathrm{H}$ and $^3\mathrm{He}$ structure functions.

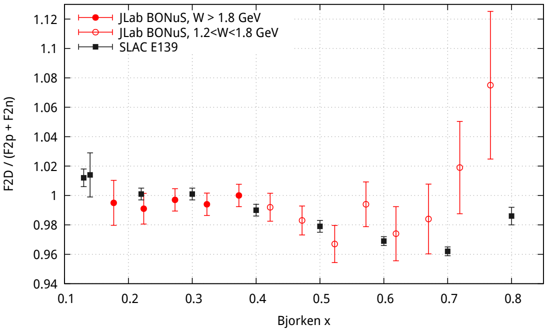
Summary of data on nuclear ratios from DIS experiments

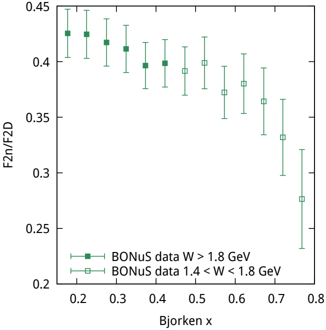


HERMES and JLab measurements on $^3\mathrm{He}$



SLAC E139 and JLab BONUS results on ^{2}H





- SLAC E139 [*PRD49(1994)4348*] obtains $R_D = F_2^D/(F_2^p + F_2^n)$ by extrapolating data on $R_A = F_2^A/F_2^D$ with $A \geq 4$ assuming $R_A - 1$ scales as nuclear density.
- BONuS [*PRC92(2015)015211*] obtains R_D from a direct measurement of F_2^n/F_2^D [*PRC89(2014)045206*] using world data on F_2^D/F_2^p.

Remarks

- Nuclear effects show oscilating behavior with a common shape for all nuclei.
- Different kinematical regions are driven by different mechanisms:
  - Shadowing, i.e. a negative correction at small $x < 0.05$, can be understood in terms of multiple scattering effect on the total nuclear cross section (*Glauber, Gribov 1970s* and many papers followed).
  - Antishadowing at $x \sim 0.1$ is a combination of a few contributions (meson-exchange currents, modification of the nucleon meson cloud in nuclear environment, off-shell correction, . . . *Llewellyn-Smith, A.Thomas, M.Ericson, 1983; Akulinichev,SK,Vagradov, 1985; SK & Petti, 2004*)
  - The "EMC effect" region can be understood as a combination of nuclear binding, off-shell correction together with the effect of momentum distribution *Akulinichev,SK,Vagradov, 1985; SK,Piller,Weise, 1994; SK & Petti, 2004*
- A significant part of new data from JLab at large x is below the DIS regime. Typically $W < 2$ GeV for $x > 0.5 - 0.6$. In this talk we develop a phenomenological model aiming to combine the DIS and the resonance regions and then study the nuclear ratios.

Structure functions in the DIS region

If Q^2 is large compared the nucleon mass, the operator product expansion in QCD produces power series:

$$F_2(x,Q^2) = F_2^{LT,TMC}(x,Q^2) + \frac{H_2(x,Q)}{Q^2} + \cdots$$

The leading term is given in terms of PDFs convoluted with coefficient functions:

$$F_2^{LT} = \left[1 + \frac{\alpha_S}{2\pi} C_q^{(1)}\right] \otimes x \sum_q e_q^2 (q + \bar{q}) + \frac{\alpha_S}{2\pi} C_g^{(1)} \otimes xg + \mathcal{O}(\alpha_S^2)$$

The HT terms involve interaction between quarks and gluons and lack simple probabilistic interpretation.
In the region of high Bjorken x and/or low Q^2 (small W^2) one has to account for the target mass correction *Georgi & Politzer, 1976*

$$F_2^{LT,TMC}(x,Q^2) = \frac{x^2}{\xi^2\gamma^2} F_2^{LT}(\xi,Q^2) + \frac{6x^3M^2}{Q^2\gamma^4} \int_\xi^1 \frac{\mathrm{d}z}{z^2} F_2^{LT}(z,Q^2) + \mathcal{O}(Q^{-4})$$

$\xi = 2x/(1+\gamma)$ is the Nachtmann variable and $\gamma^2 = 1 + 4x^2M^2/Q^2$

In this work we use the results of the PDF global analysis performed to QCD NNLO approximation (i.e. to order α_S^2) and which includes the proton (and deuteron) data sets from DIS, DY and collider data. Kinematical range $0.8 < Q^2 < 10^5$ GeV^2 and $10^{-6} < x < 1$ with the cut $W > 1.8$ GeV.

S.Alekhin, K.Melnikov, F.Petriello, 2007

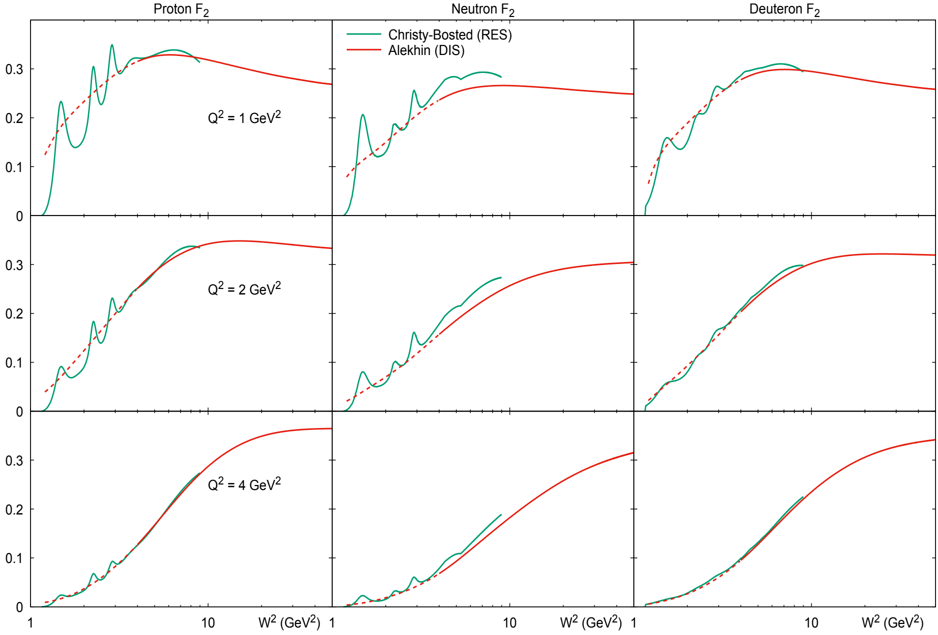
S.Alekhin, S.K., R.Petti, 2007

Structure functions in the resonance region

Empirical model of *M.E. Christy & P.E. Bosted, 2010* includes a Breit-Wiegner parametrization of 7 resonance contributions and a phenomenological nonresonance background.

$$\sigma_{T,L} = \sigma_{T,L}^{\mathsf{RES}} + \sigma_{T,L}^{\mathsf{NR}},$$

The resonance parameters and form-factors are tuned to describe electron scattering data and photoproduction in the kinematical range $0 < Q^2 < 8$ GeV^2 and $1.1 < W < 3.1$ GeV. Data sets included about 1900 JLab data points and about 300 SLAC data points.


Proton F2
Neutron F2
Deuteron F2
Christy-Bosted (RES)
Alekhin (DIS)
Q2 = 1 GeV2
Q2 = 2 GeV2
Q2 = 4 GeV2
0.3
0.2
0.1
0
1
10
W2 (GeV2)

Duality

DIS and RES structure functions are dual in the integral sense *Bloom & Gilman, 1970*:

$$\int_{W_{\rm th}^2}^{W_0^2} \mathrm{d}W^2\, F_2^{\rm DIS}(W^2, Q^2) = \int_{W_{\rm th}^2}^{W_0^2} \mathrm{d}W^2\, F_2^{\rm RES}(W^2, Q^2)$$

$W_{\rm th} = M_p + m_\pi$ the pion production threshold energy and $W_0 = 2$ GeV the boundary of the resonance region.

Comparing CB (RES) and Alekhin (DIS) analyses we observe:

- For the proton the error of the duality relation is better than 5% for $1 \le Q^2 < 10$ GeV^2.
- For the neutron the error is larger $\sim 5 - 10\%$. This could be related to a different treatment of the deuteron correction in Alekhin and CB fits.

Combined model for the proton

A good matching between RES and DIS models in overlap region of $1.8 < W < 3$ GeV motivates us to use a combined model in a wide region of W and Q^2:

$$F_2 = \begin{cases} F_2^{\mathsf{RES}}(W^2), & W \le W_1, \\ F_2^{\mathsf{RES}}(W_1^2) + \dfrac{W^2 - W_1^2}{W_2^2 - W_1^2}\left(F_2^{\mathsf{DIS}}(W_2^2) - F_2^{\mathsf{RES}}(W_1^2)\right), & W_1 < W < W_2, \\ F_2^{\mathsf{DIS}}(W^2), & W \ge W_2 \end{cases}$$

Here $W_1 = 1.8$ GeV and $W_2 = 2$ GeV.

Combined model for the neutron

- For the neutron, the matching between RES and DIS models is somewhat worse than for the proton. As the neutron is extracted from the deutron – proton difference, a significant part of disagreement could arise from a different treatment of the deuteron correction (discussed below).
- We compute neutron F_2^n in the resonance region using the RES model for the proton and the ratio $R_{np} = F_2^n / F_2^p$ from the DIS model.
- Special care has to be taken in the $\Delta(1232)$ region and near threshold. We assume equal contribution to the proton and the neutron from the Δ resonace $= F_2^{\Delta}$ (supported by analysis *Bosted & Christy, 2010*).

$$F_2^{n(\mathsf{RES})} = R_{np} \left(F_2^{p(\mathsf{RES})} - F_2^{\Delta} \right) + F_2^{\Delta}$$

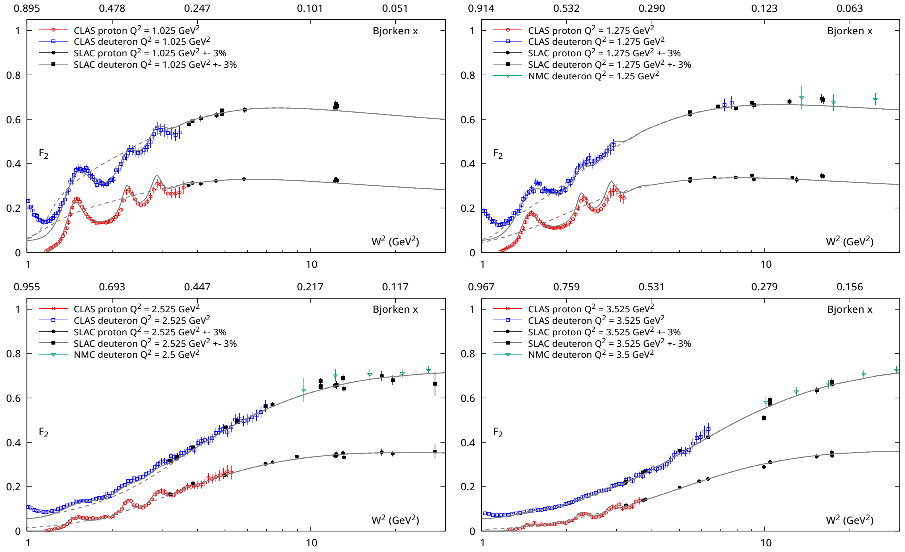
Computing the deuteron structure functions

A good starting point is to treat nuclear scattering as incoherent scattering off bound protons and neutrons [for more detail see Alekhin,S.K.,Liuti, 2002 and S.K. & Petti, 2004]

$$F_2^D = \int \mathrm{d}\boldsymbol{p}\, |\Psi_D(\boldsymbol{p})|^2\, K\, (F_2^p + F_2^n)$$

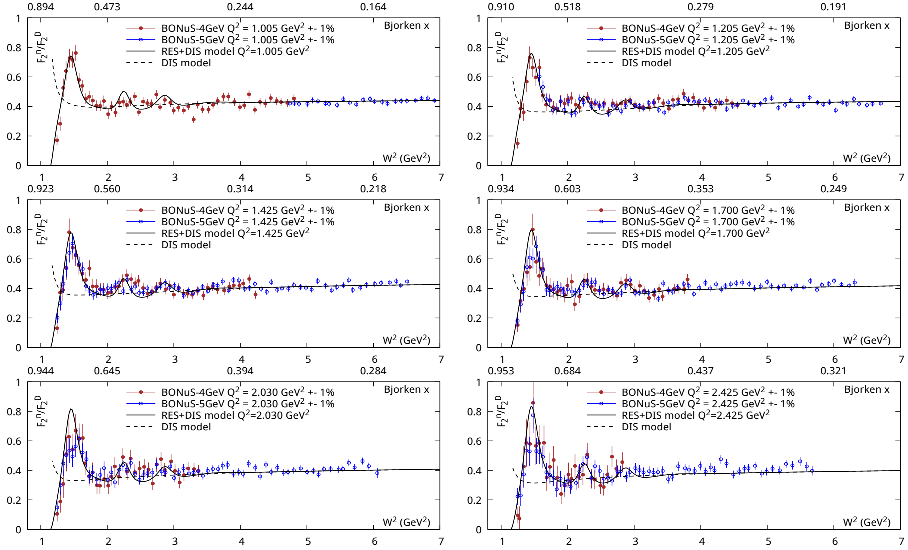
- $\Psi_D(\boldsymbol{p})$ is the deuteron wave function normalized as $\int \mathrm{d}\boldsymbol{p}\, |\Psi_D(\boldsymbol{p})|^2 = 1$.
- The four-momentum of bound proton (neutron) $p = (M_D - \sqrt{M^2 + \boldsymbol{p}^2}, \boldsymbol{p})$, and $M_D = 2M + \varepsilon_D$ with $\varepsilon_D = -2.2\,\mathrm{MeV}$ the deuteron binding energy.
- The bound proton/neutron structure functions depend on $W^2 = (p+q)^2$, the scale Q^2, and the nucleon invariant mass squared p^2.
- Kinematical factor $K = \left(1 + \frac{\gamma p_z}{M}\right)\left(1 + \frac{6x'^2 \boldsymbol{p}_\perp^2 + 4x'^2 p^2}{Q^2}\right)/\gamma^2$ with $\gamma^2 = 1 + \frac{4M^2 x^2}{Q^2}$ and $x = \frac{Q^2}{2Mq_0}$ and $x' = \frac{Q^2}{Q^2 + W^2 - p^2}$ the Bjorken variable for the on-shell and off-shell nucleon, respectively.

Predictions for proton and deuteron vs. data

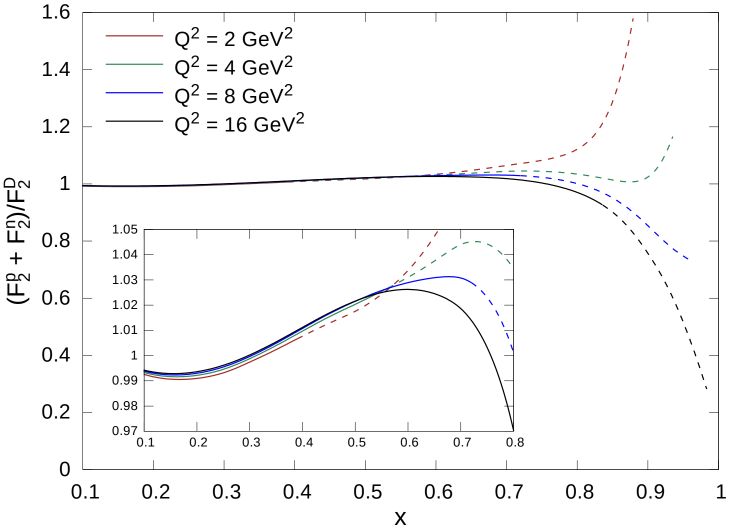


Proton and deuteron F_2 computed at $Q^2 = 1.025,\ 1.275,\ 2.525,\ 3.525$ GeV^2 in a combined RES-DIS model. Data from SLAC Whitlow,1991 and JLab-CLAS Osipenko,2003,2005 and NMC,1997.

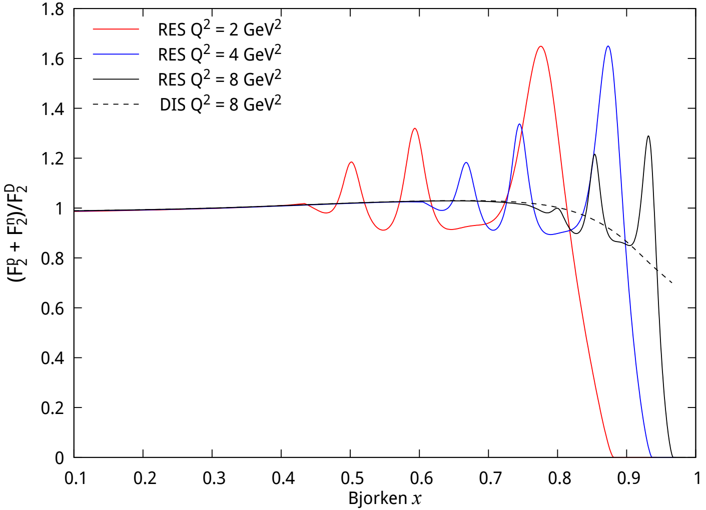
Comparison with BONuS data F_2^n/F_2^D



The ratio $(F_2^p + F_2^n)/F_2^D$ in the DIS model



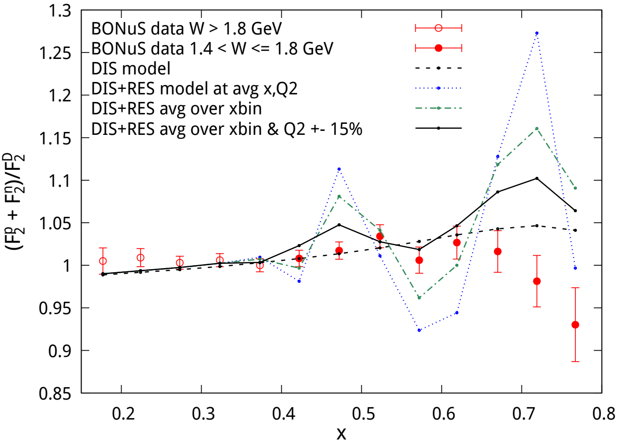
The ratio $(F_2^p + F_2^n)/F_2^D$ in the RES model



Remarks

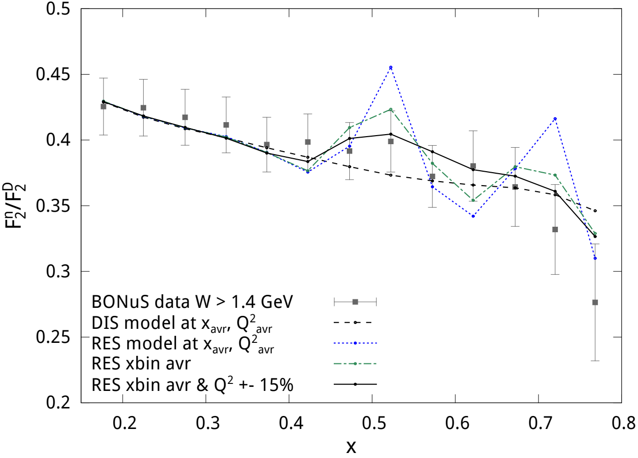
- The linear behavior of the ratio $R_D = (F_2^p + F_2^n)/F_2^D$ for $0.2 < x < 0.6$ is due to $R_D''(x \sim 0.4) = 0$. The slope of R_D is driven by the binding (separation) energy as well as off-shell correction S.K. & Petti, 2004.
- The threshold behavior of $F_2^{p,n}$ in the DIS regime is violated by the target mass corrections of Georgi & Politzer, 1976 leading to nonzero values of $F_2(x = x_{\rm th} \sim 1)$. This in turn leads to unphysical behavior of the ratio R_D at very large x.
- In the resonance region, the resonances in nuclei are smeared and damped by momentum distribution. For this reason the ratio R_D strongly oscillates in this region.

Comparison with BONuS measurement of $(F_2^p + F_2^n)/F_2^D$



K.Griffioen et.al., 2015 BONuS experiment measurement compared with model predictions. The dashed (dotted-blue) line shows the DIS (RES) results at average x and Q^2 for each x-bin. The dash-dotted green line is the result of averaging over x within each x-bin. The solid line is the result of additional smearing over Q^2.

Comparison with BONuS F_2^n/F_2^D



Tkachenko et.al., 2014 BONuS experiment measurement compared with model predictions. The notations are similar to those of $(F_2^p + F_2^n)/F_2^D$ figure.

Computing the $^3\mathrm{He}$ structure functions

Assuming again the incoherent scattering from bound proton and neutron we have [S.K. & Melnitchouk, 2007 and SK & Petti, 2010]

$$F_2^A = \int \mathrm{d}\boldsymbol{k}\mathrm{d}\varepsilon\, K \left(\mathcal{P}^p(\varepsilon,\boldsymbol{k})F_2^p + \mathcal{P}^n(\varepsilon,\boldsymbol{k})F_2^n\right)$$

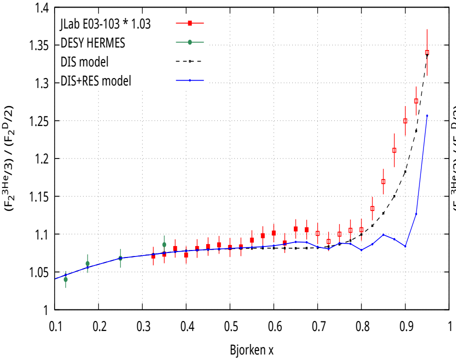
- $\mathcal{P}^{p,n}(\varepsilon,\boldsymbol{k})$ is the proton(neutron) spectral function of $^3\mathrm{He}$ normalized to the proton(neutron) number.
- The four-momentum of bound proton (neutron) $p = (M+\varepsilon,\boldsymbol{k})$
- The bound proton (neutron) structure functions depend on 3 variables, $F_2^{p,n} = F_2^{p,n}(W^2,Q^2,p^2)$. Note the nucleon virtuality p^2 is additional variable for off-shell nucleon.
- Kinematical factor $K = \left(1+\frac{\gamma k_z}{M}\right)\left(1+\frac{6x'^2\boldsymbol{k}_\perp^2+4x'^2p^2}{Q^2}\right)/\gamma^2$ with $\gamma^2 = 1+\frac{4M^2x^2}{Q^2}$ and $x = \frac{Q^2}{2Mq_0}$ and $x' = \frac{Q^2}{Q^2+W^2-p^2}$ the Bjorken variable for the on-shell and off-shell nucleon, respectively.

Spectral function

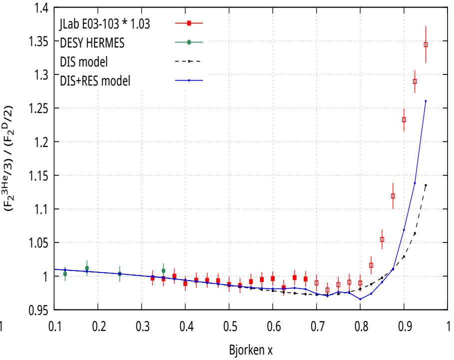
$$\mathcal{P}^p(\varepsilon, \boldsymbol{k}) = \sum_f \left|\langle (A-1)_{f,-\boldsymbol{k}} | a^p(\boldsymbol{k}) | A\rangle\right|^2 \delta(E_3 - E_f(-\boldsymbol{k}) - \varepsilon)$$
$$= d(k)\delta(E_3 - E_D(-\boldsymbol{k}) - \varepsilon) + c^p(\varepsilon, k).$$
$$\mathcal{P}^n(\varepsilon, \boldsymbol{k}) = \sum_f \left|\langle (A-1)_{f,-\boldsymbol{k}} | a^n(\boldsymbol{k}) | A\rangle\right|^2 \delta(E_3 - E_f(-\boldsymbol{k}) - \varepsilon)$$
$$= c^n(\varepsilon, k).$$

Note that integrating $\mathcal{P}(\varepsilon, \boldsymbol{k})$ over the energy we get momentum distribution. In numerical analysis we use the proton/neutron spectral function of $^3\mathrm{He}$ by G.Salme et.al. computed with AV18(2-body)+UIX(3-body) nucleon-nucleon potential.

Comparison with JLab E03103 measurement of $^3\mathrm{He}/D$

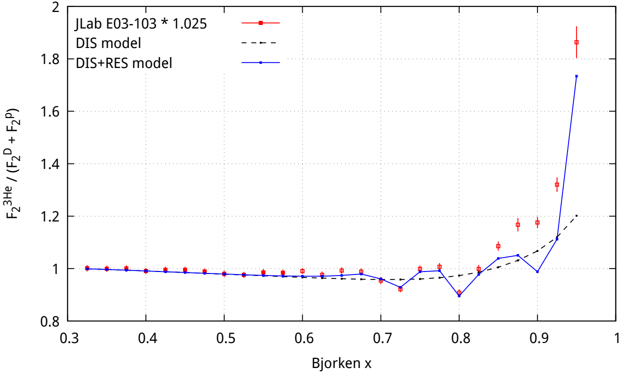


Data on $F_2^{3\mathrm{He}}/F_2^D$ from JLab Hall C Seely et.al., 2009 and DESY HERMES measurement compared with model predictions. The dashe line – DIS model, the solid line – combined DIS+RES model. No isoscalarity correction.



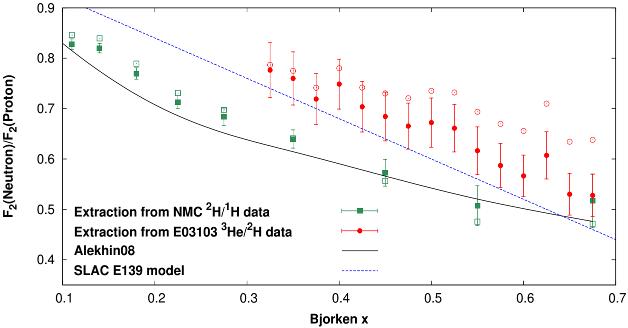
Same as left panel but with the nonisoscalarity correction factor $C_{is} = \frac{(Z+N)(F_2^p+F_2^n)/2}{ZF_2^p+NF_2^n}$ with $N(Z)$ the neutron (proton) number. The notations are similar to those of left panel.

Isoscalar ratio $^3\mathrm{He}/(D+p)$



The isoscalar ratio $F_2^{3\mathrm{He}}/(F_2^D + F_2^p)$ from JLab E03103 experiment (D.Gaskell, private communication) compared with model predictions. The dashe line – DIS model, the solid line – combined DIS+RES model.

Using F_2^n/F_2^p as a consistency test of nuclear data



Extraction of F_2^n/F_2^p from F_2^p/F_2^D (NMC) and $F_2^{^3\mathrm{He}}/F_2^D$ (JLab) with account of nuclear effect (full symbols) and also with no nuclear effects (open symbols).

- Significant mismatch in F_2^n/F_2^p extracted from different experiments. At $x \sim 0.35$, where nuclear corrections are negligible, the ratio F_2^n/F_2^p from JLab E03-103 is 15% bigger than that from NMC.
- Normalization of F_2^n/F_2^p is directly related to the normalization of $^3\mathrm{He/D}$. Requiring F_2^n/F_2^p from JLab to match NMC, we obtain a renormalization factor of $1.03^{+0.006}_{-0.008}$ for the central values of JLab $^3\mathrm{He/D}$ measurement.

Summary

- We discussed a phenomenological model of the proton and the neutron structure functions, which incorporates the resonance structure at low values of W and provides a smooth transistion to the DIS regime. The model shows a good performance in comparison with the structure function data.
- This model was applied to study the nuclear EMC effect with particular emphasis at large Bjorken x. We found that the resonance structure shows up in the EMC effect of JLab data for $x > 0.6$ even after a proper averaging over x and Q^2 bins.
- The region $x < 0.5$ corresponds to $W > 2$ GeV for recent JLab measurements. The ratio $R_D = F_2^D/F_2^N$ is nearly a linear function of x for $0.25 < x < 0.55$ because $\partial_x^2 F_2^N(x \sim 0.4) = 0$. The slope of R_D is explained by nuclear binding and off-shell correction.
- We also discussed how to use the ratio F_2^n/F_2^p as a tool to test consistency of different nuclear ratios.