Nuclear Medium Effects on the Structure Functions

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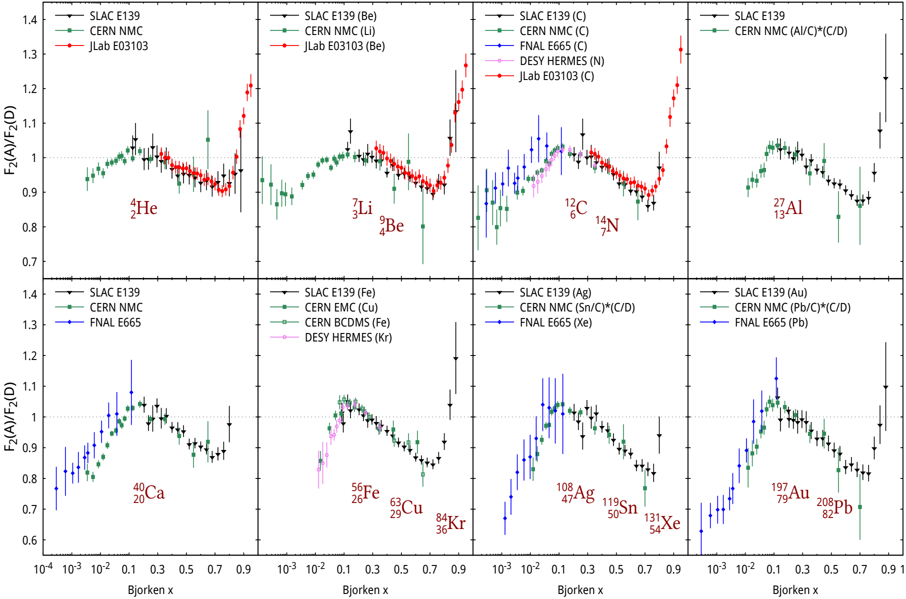
Outline

- Experimental observations on modification of partonic structure of nuclei
- Understanding and modelling nuclear corrections in DIS region
  - Sketch of basic mechanisms of nuclear DIS in different kinematic regions.
  - Brief review of our efforts to build a quantitative model of nuclear structure functions.
- Extend the model into the resonance region. Discuss the ratios $D/(p+n)$ and $^3\text{He}/D$ and $^3\text{He}/(D+p)$ in comparison with JLab *BONuS, 2015* and *Hall C, 2009* measurements.
- Summary/Conclusions

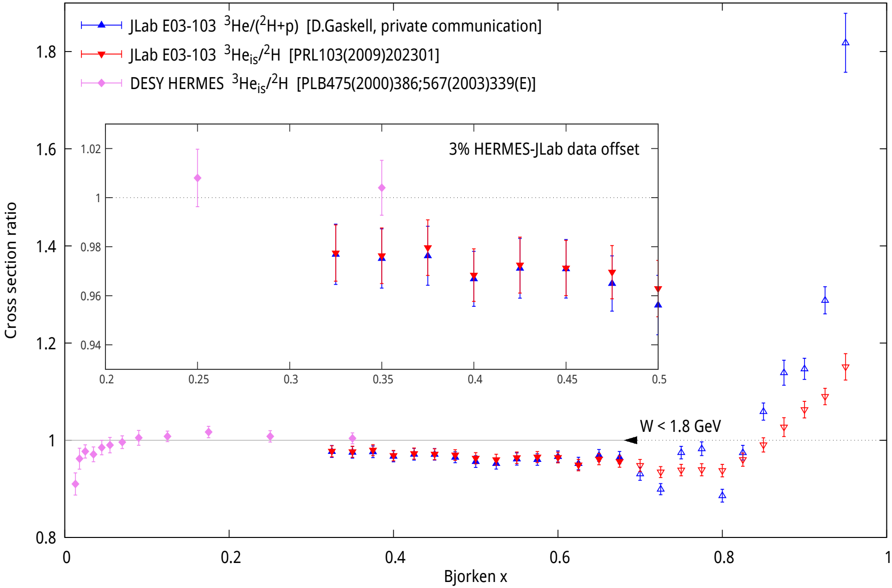
Data summary on nuclear effects on the parton level

- Nuclear ratios $\mathcal{R}(A/B) = \sigma_A(x, Q^2)/\sigma_B(x, Q^2)$ or F_2^A/F_2^B from DIS experiments
- Data for nuclear targets from $^2\mathrm{H}$ to $^{208}\mathrm{Pb}$
  - Fixed-target experiments with e/μ:
    - Muon beam at CERN (EMC, BCDMS, NMC) and FNAL (E665).
    - Electron beam at SLAC (E139, E140), HERA (HERMES), JLab (E03-103).
  - Kinematics and statistics:
    Data covers the region $10^{-4} < x < 1.5$ and $0 < Q^2 < 150$ GeV^2. About 800 data points for the nuclear ratios $\mathcal{R}(A/B)$ with $Q^2 > 1$ GeV^2.
- Nuclear effects for antiquarks have been probed by Drell-Yan experiments at FNAL (E772, E866).
- Nuclear cross sections from high-energy measurements with neutrino BEBC ($^2\mathrm{H}$ and $^{20}\mathrm{Ne}$), NOMAD ($^{12}\mathrm{C}$ and $^{56}\mathrm{Fe}$) CDHS, CCFR and NuTeV ($^{56}\mathrm{Fe}$) CHORUS ($^{207}\mathrm{Pb}$). Nuclear cross section ratios $\mathrm{Fe/CH}$ and $\mathrm{Fe/CH}$ from MINERvA in the region of low Q^2.

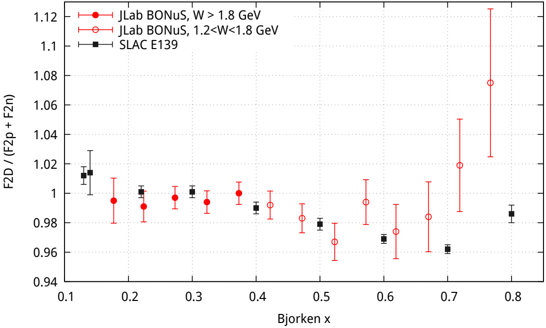
Nuclear ratios from DIS experiments

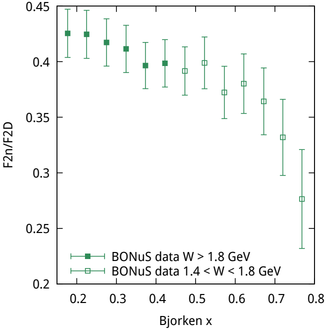


HERMES and JLab measurements on $^3\mathrm{He}$



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.

Why nuclear corrections survive at DIS?

Space-time scales in DIS

$$W_{\mu\nu} = \int \mathrm{d}^4x \exp(iq\cdot x)\langle p|[J_\mu(x), J_\nu(0)]|p\rangle$$

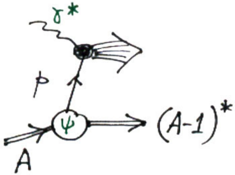
$$q\cdot x = q_0 t - |\boldsymbol{q}|z = q_0 t - \sqrt{q_0^2 + Q^2}z \simeq q_0(t-z) - \frac{Q^2}{2q_0}\,z$$

- DIS proceeds near the light cone: $|t-z| \sim 1/q_0$ and $t^2 - z^2 \sim Q^{-2}$.
- In the TARGET REST frame the characteristic time and longitudinal distance are NOT small at all: $t \sim z \sim 2q_0/Q^2 = 1/Mx_{\mathrm{Bj}}$. DIS proceeds at the distance ~ 1 Fm at $x_{\mathrm{Bj}} \sim 0.2$ and at the distance ~ 20 Fm at $x_{\mathrm{Bj}} \sim 0.01$.
- Two different regions in nuclei from comparison of coherence length (Ioffe time) $L = 1/Mx_{\mathrm{Bj}}$ with average distance between bound nucleons r_{NN}:
  - $L < r_{\mathrm{NN}}$ (or $x > 0.2$) $\Rightarrow$ Nuclear DIS $\approx$ incoherent sum of contributions from bound nucleons. Nuclear corrections $\sim EL$ and $\sim |\boldsymbol{p}|^2L^2$ where $E(p)$ typical energy (momentum) in the nuclear ground state.
  - $L \gg r_{\mathrm{NN}}$ (or $x \ll 0.2$) $\Rightarrow$ Coherent effects of interactions with a few nucleons are important.

Incoherent nuclear scattering

A good starting point is incoherent scattering off bound protons and neutrons

$$F_2^A = \int \mathrm{d}^4p\, K\,(\mathcal{P}^p F_2^p + \mathcal{P}^n F_2^n)$$



- The four-momentum of the bound proton (neutron) $p = (M + \varepsilon, \boldsymbol{p})$
- $\mathcal{P}^{p,n}(\varepsilon, \boldsymbol{p})$ the proton (neutron) nuclear spectral function, which is normalized to the nucleon number $\int \mathrm{d}\varepsilon \mathrm{d}\boldsymbol{p} \mathcal{P}^p = Z$ and describes probability to find a bound nucleon with momentum $\boldsymbol{p}$ and energy $p_0 = M + \varepsilon$.
- The bound nucleon structure functions depend on 3 independent variables $F_2^{p,n} = F_2^{p,n}(x', p^2, Q^2)$, $x' = Q^2/2p\cdot q$ is the Bjorken variable of a nucleon with four-momentum p. Note the nucleon virtuality p^2 is additional variable for off-shell nucleon.
- Kinematical factor $K = (1 + p_z/M)\left(1 + \mathcal{O}(\boldsymbol{p}^2/|\boldsymbol{q}|^2)\right)$.

Nuclear spectral function

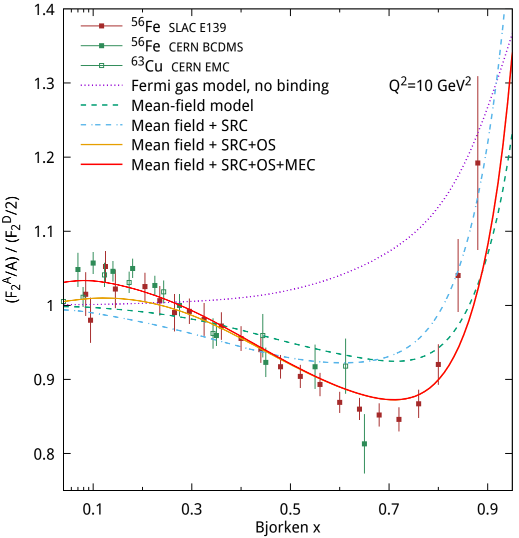
The nuclear spectral function describes probability to find a bound nucleon with momentum $\boldsymbol{p}$ and energy $p_0 = M + \varepsilon$:

$$\mathcal{P}(\varepsilon, \boldsymbol{p}) = \int \mathrm{d}t\, e^{-i\varepsilon t} \langle \psi^\dagger(\boldsymbol{p}, t)\psi(\boldsymbol{p}, 0)\rangle$$
$$= \sum_i |\langle (A-1)_i, -\boldsymbol{p}|\psi(0)|A\rangle|^2\, 2\pi\delta\left(\varepsilon + E_i^{A-1}(\boldsymbol{p}) - E_0^A\right)$$

- The sum runs over all possible states of the spectrum of $A-1$ residual system.
- The nuclear spectral function determines the rate of nucleon removal reactions such as $(e, e'p)$. For low separation energies and momenta, $|\varepsilon| < 50\,\mathrm{MeV}$, $p < 250\,\mathrm{MeV/c}$, the observed spectrum is dominated by bound states $A-1$ similar to those predicted by the mean-field model.
- High-energy and high-momentum components of nuclear spectrum is not described by the mean-field model and driven by correlation effects in nuclear ground state (short-range correlations, or SRC). We combine the mean-field together with SRC contributions and consider a two-component model $\mathcal{P} = \mathcal{P}_{\mathrm{MF}} + \mathcal{P}_{\mathrm{cor}}$ *Ciofi degli Atti & Simula, 1995 S.K. & Sidorov, 2000 S.K. & Petti, 2004*

EMC effect in impulse approximation (IA)

- Impulse approximation: $F_2(x', Q^2, p^2) = F_2(x', Q^2, M^2)$
- Momentum distribution (Fermi motion) leads to a rise at large Bjorken x *Atwood & West, 1970s*.
- Nuclear binding correction is important and results in a "dip" at $x \sim 0.6 - 0.7$ *Akulinichev, Vagradov & S.K., 1984*.
- However, even realistic nuclear spectral function fails to accurately explain the slope and the position of the minimum in IA. Corrections to IA are needed!



Nucleon off-shell effect (OS)

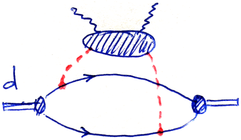
Bound nucleons are off-mass-shell, $p^2 < M^2$. The treatment of p^2 dependence can greatly be simplified in the vicinity of the mass shell. If the virtuality parameter $v = (p^2 - M^2)/M^2$ is small (e.g. average virtuality $v \sim -0.15$ for ^{56}Fe) then expand $q(x, Q^2, p^2)$ in series in v

$$F_2^N(x, Q^2, p^2) \approx F_2^N(x, Q^2) \left(1 + \delta f(x, Q^2)\, v\right)$$

- $\delta f(x, Q^2)$ is a special structure function describing the 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 size in nuclear environment *S.K. & R.Petti, 2004*.

Nuclear meson-exchange current effect (MEC)

Leptons can scatter on nuclear meson field which mediate interaction between bound nucleons. This process generate a MEC correction to nuclear sea quark distribution

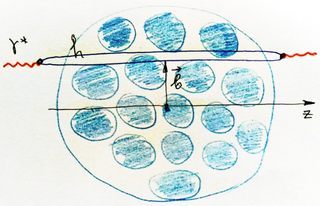


$$\delta F_2^{\mathsf{MEC}}(x, Q^2) = \int_x \mathrm{d}y f_{\pi/A}(y) F_2^{\pi}(\frac{x}{y}, Q^2)$$

- Contribution from nuclear pions (mesons) is important to balance nuclear light-cone momentum $\langle y \rangle_\pi + \langle y \rangle_N = 1$.
- The nuclear pion distribution function is localized in a region $y < p_F/M \sim 0.3$. For this reason the MEC correction to nuclear (anti)quark distributions is localized at $x < 0.3$.
- The magnitude of the correction is driven by average number of "nuclear pion excess" $n_\pi = \int \mathrm{d}y\, f_{\pi/A}(y)$ and $n_\pi/A \sim 0.1$ for a heavy nucleus like ${}^{56}\mathrm{Fe}$.

Nuclear shadowing

Coherent nuclear correction is due to propagation of intermediate state $\gamma^* \to h$ in nuclear environment, which can be described in the multiple scattering theory *Glauber, Gribov 1970s*.



$$\frac{\delta F_{2A}^{\mathsf{coh}}}{F_{2N}} = \frac{\operatorname{Im}\delta\mathcal{A}}{\operatorname{Im} a}$$

$$\delta\mathcal{A} = \delta\mathcal{A}^{(2)} + \delta\mathcal{A}^{(3)} + \dots$$

$$\delta\mathcal{A}^{(2)} = ia^2 \int_{z_1<z_2} \mathrm{d}^2\boldsymbol{b}\,\mathrm{d}z_1\mathrm{d}z_2\,\rho(\boldsymbol{b}, z_1)\rho(\boldsymbol{b}, z_2)\,e^{i\frac{z_1-z_2}{L}}$$

- $\rho(\boldsymbol{r})$ is the nuclear number density, $\int \mathrm{d}^3\boldsymbol{r}\rho(\boldsymbol{r}) = A$
- $a = \frac{\sigma}{2}(i+\alpha)$ is the (effective) forward scattering amplitude of intermediate state h off the nucleon
- L is the coherence length of intermediate state which accounts finite life time of intermediate state, $1/L = Mx(1 + m_h^2/Q^2)$. Its presence suppresses the coherence effect in the region of large x.

Modelling the nuclear corrections

Assemble everything together and confront model to data

S.K. & R.Petti, NPA765(2006)126; PRC82(2010)054614; PRC90(2014)045204

$$F_2^A = Z \langle F_2^p \rangle + N \langle F_2^n \rangle + \delta F_2^{\mathrm{MEC}} + \delta F_2^{\mathrm{coh}}$$

Strategy of the analysis:

- Compute the proton and neutron structure functions in terms of free proton PDF with relevant perturbative QCD corrections, TMC, as well as HT correction.
- Using $F_2^{p,n}$ compute nuclear structure functions/cross sections with accurate treatment of nuclear spectral function effects (Fermi-motion and nuclear binding), MEC and nuclear shadowing correction.
- Treat the off-shell function $\delta f(x)$ and effective amplitude a as unknown and parametrize them. Study the data on the nuclear DIS in terms of the ratios F_2^A/F_2^B and determine $\delta f(x)$ together with the amplitude a from data.
- Use the normalization conditions and the DIS sum rules (GLS, Adler) to determine the amplitude a (responsible for nuclear shadowing) in the region of high Q^2, which is not constrained by data.
- Verify the model by comparing the calculations with data not used in analysis.

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:

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

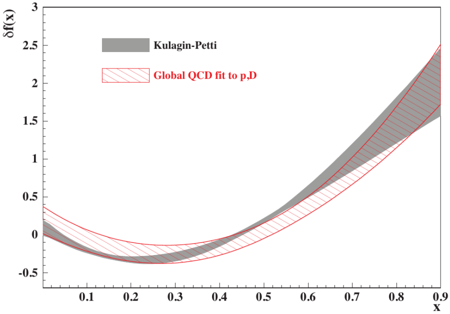
The HT terms involve interaction between quarks and gluons and lack simple probabilistic interpretation. In the region of high Bjorken x and/or low Q^2 (small W^2) one has to account for the target mass correction *Georgi & Politzer, 1976*

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

$\xi = 2x/(1+\gamma)$ 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*

Determination of the off-shell function $\delta f(x)$

- Analysis of A/D and A/C ratios with a model $\delta f(x) = C_N(x-x_1)(x-x_0)(1+x_0-x)$ gives a good fit to all studied nuclei from ^{4}He to ^{208}Pb with χ^2/d.o.f. $= 459/556$ *S.K. & R.Petti, 2006*.
- A different approach: global QCD analysis using deuteron data and a model $\delta f(x) = Ax^2 + Bx + C$ *Alekhin, S.K., Petti, 2017*.

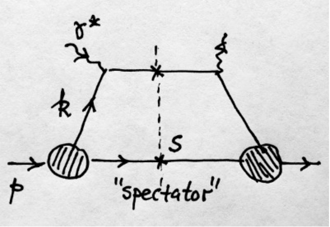


- The function $\delta f(x)$ provides a measure of the modification of the quark distributions in a bound nucleon.
- The slope of $\delta f(x)$ in a single-scale nucleon model is related to the change of the radius of the nucleon in the nuclear environment *S.K. & R.Petti, 2006*. The observed slope suggests an increase in the bound nucleon radius in the iron by about 10% and in the deuteron by about 2%.

Off-shell effect and the modification of the bound nucleon radius

The valence quark distribution in a (off-shell) nucleon

Kulagin, Piller & Weise, PRC50(1994)1154



$$q_{\text{val}}(x,p^2) = \int^{k^2_{\text{max}}} \mathrm{d}k^2 \Phi(k^2,p^2)$$

$$k^2_{\text{max}} = x\left(p^2 - s/(1-x)\right)$$

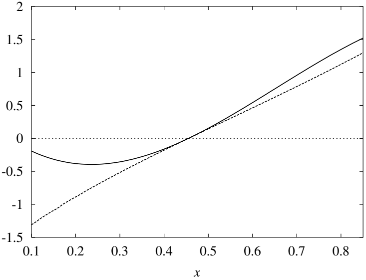
- A one-scale model of quark k^2 distribution: $\Phi(k^2) = C\phi(k^2/\Lambda^2)/\Lambda^2$, where C and ϕ are dimensionless and Λ is the scale.
- Off-shell: $C \to C(p^2),\ \Lambda \to \Lambda(p^2)$
- The derivatives $\partial_x q_{\text{val}}$ and $\partial_{p^2} q_{\text{val}}$ are related

$$\delta f(x) = \frac{\partial \ln q_{\text{val}}}{\partial \ln p^2} = c + \frac{\mathrm{d}q_{\text{val}}(x)}{\mathrm{d}x} x(1-x)h(x)$$

$$h(x) = \frac{(1-\lambda)(1-x) + \lambda s/M^2}{(1-x)^2 - s/M^2}$$

$$c = \frac{\partial \ln C}{\partial \ln p^2},\quad \lambda = \frac{\partial \ln \Lambda^2}{\partial \ln p^2}$$

- A simple pole model $\phi(y) = (1-y)^{-n}$ (note that $y < 0$ so we do not run into singularity) provides a resonable description of the nucleon valence distribution for $x > 0.2$ and large Q^2 ($s = 2.1$ GeV^2, $\Lambda^2 = 1.2$ GeV^2, $n = 4.4$ at $Q^2 = 15 \div 30$ GeV^2).
- The size of the valence quark confinement region $R_c \sim \Lambda^{-1}$ (nucleon core radius).
- Off-shell corection is independent of specific choice of profile $\phi(y)$ and is given by $(\ln q_{\mathsf{val}}(x))'$.
- Fix c and λ to reproduce $\delta f(x_0) = 0$ and the slope $\delta f'(x_0)$. We obtain $\lambda \approx 1$ and $c \approx -2.3$. The positive parameter λ suggests decreasing the scale Λ in nuclear environment (swelling of a bound nucleon)



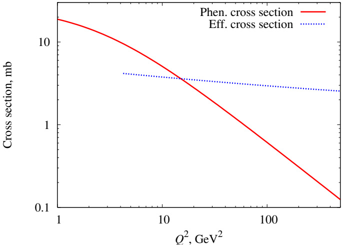
$$\frac{\delta R_c}{R_c} \sim -\frac{1}{2}\frac{\delta\Lambda^2}{\Lambda^2} = -\frac{1}{2}\lambda\frac{\langle p^2 - M^2\rangle}{M^2}$$

^{56}Fe : $\delta R_c/R_c \sim 9\%$

^{2}H : $\delta R_c/R_c \sim 2\%$

Determination of effective cross section

- The monopole form $\sigma = \sigma_0/(1 + Q^2/Q_0^2)$ for the effective cross section of C-even $q + \bar{q}$ combination provides a good fit to data on DIS nuclear shadowing for $Q^2 < 15\ \text{GeV}^2$ with $\sigma_0 = 27\,\text{mb}$ and $Q_0^2 = 1.43 \pm 0.06 \pm 0.195\ \text{GeV}^2$. Note σ_0 is fixed from $Q^2 \to 0$ limit by the vector meson dominance model. Also we assume $\mathrm{Re}\, a/\,\mathrm{Im}\, a$ for C-even amplitude to be given by VMD at all energies.

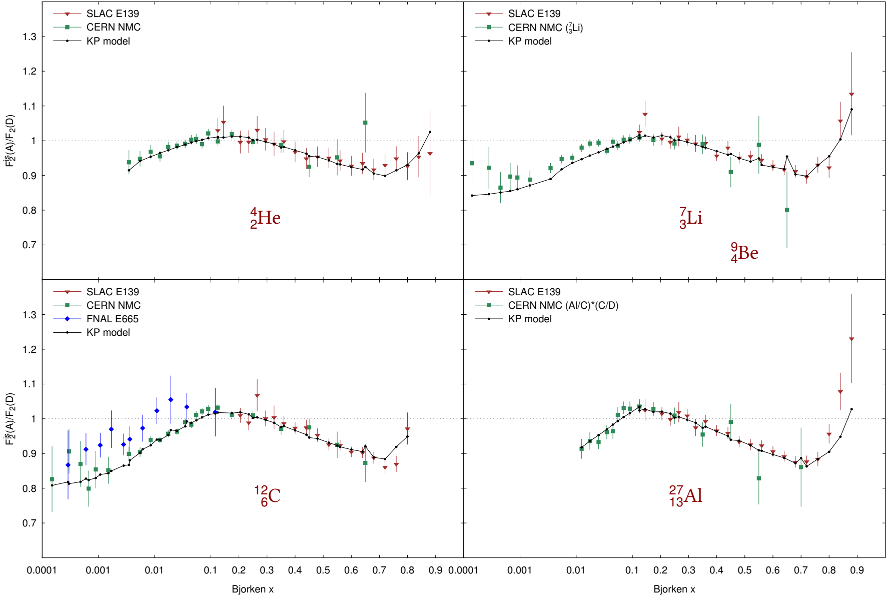


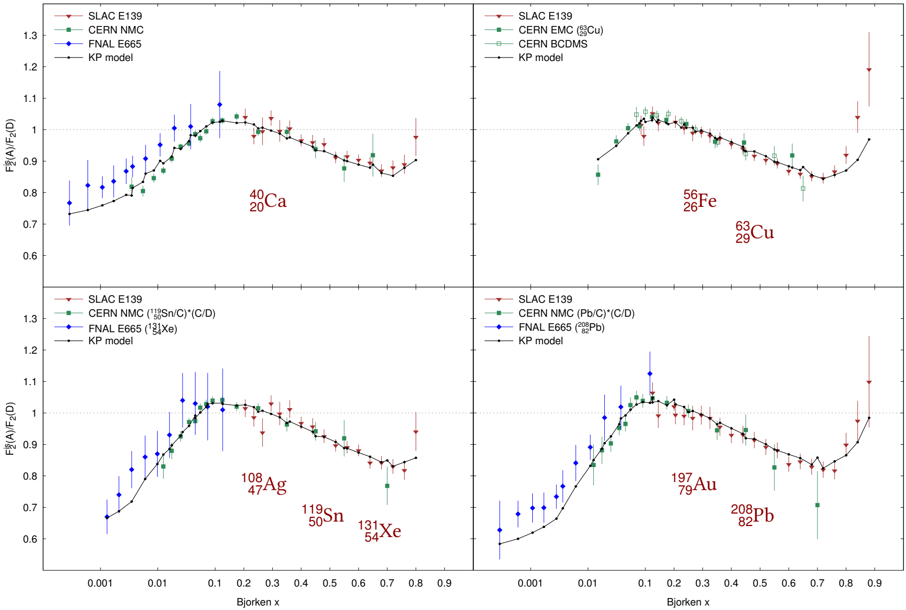
- Nuclear shadowing correction for the C-odd valence distribution $q - \bar{q}$ is also driven by same cross section σ. Note, however, important interference effect between the phases of C-even and C-odd effective amplitude.
- The cross section at high $Q^2 > 15\ \text{GeV}^2$ is not constrained by data. It is possible to evaluate σ in this region using the the normalization condition. Requiring exact cancellation between the off-shell and the shadowing correction in the normalization we have:

$$\int_0^1 \mathrm{d}x \left(\langle v \rangle\, q_{\mathrm{val}}(x, Q^2) \delta f(x) + \delta q_{\mathrm{val}}^{\mathrm{coh}}(x, Q^2) \right) = 0$$

with $\langle v \rangle = \left\langle p^2 - M^2 \right\rangle / M^2$ the average nucleon virtuality. Numeric solution to this equation is shown by dotted curve.

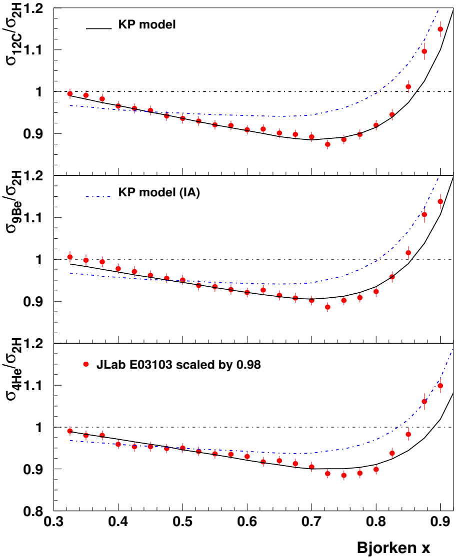
Summary of results on the nuclear ratios F_2^A/F_2^D





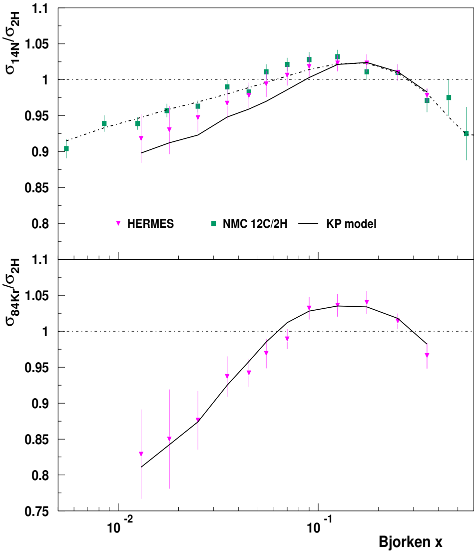
SLAC E139
CERN NMC
FNAL E665
KP model
$^{40}_{20}$Ca
SLAC E139
CERN EMC ($^{63}_{29}$Cu)
CERN BCDMS
KP model
$^{56}_{26}$Fe
$^{63}_{29}$Cu
SLAC E139
CERN NMC ($^{119}_{50}$Sn/C)*(C/D)
FNAL E665 ($^{131}_{54}$Xe)
KP model
$^{108}_{47}$Ag
$^{119}_{50}$Sn
$^{131}_{54}$Xe
SLAC E139
CERN NMC (Pb/C)*(C/D)
FNAL E665 ($^{208}_{82}$Pb)
KP model
$^{197}_{79}$Au
$^{208}_{82}$Pb
$F_2^{is}(A)/F_2(D)$
Bjorken x

Verification with recent JLab data (not a fit)



- Very good agreement of our predictions *S.K. & R.Petti, PRC82(2010)054614* 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 the modification of the slope and the position of the minimum of the ratios.

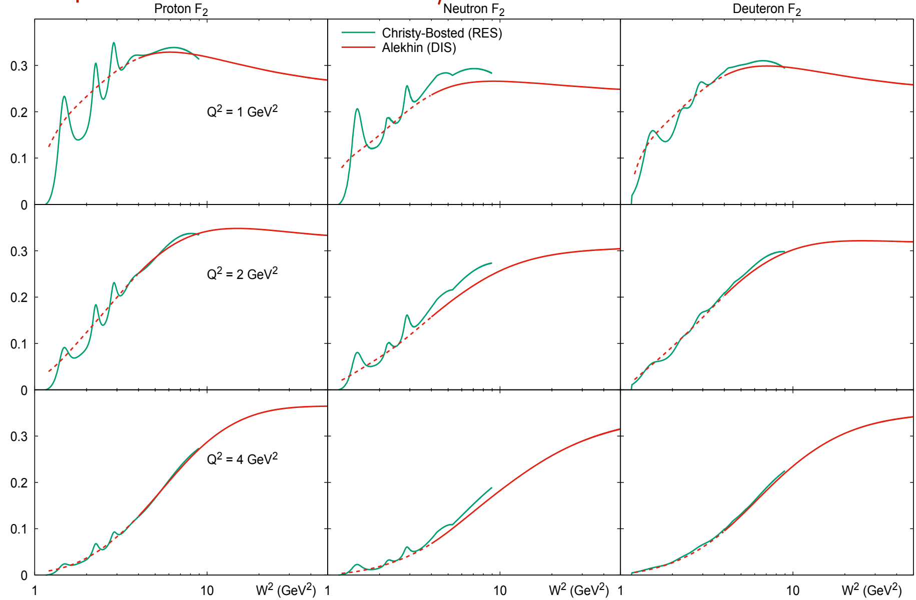
Verification with HERMES data (not a fit)



- A good agreement of our predictions *S.K. & R.Petti, PRC82(2010)054614* with HERMES data for $^{14}\mathrm{N}/\mathrm{D}$ and $^{84}\mathrm{Kr}/\mathrm{D}$ with $\chi^2/d.o.f. = 14.7/24$
- A comparison with CERN NMC data for $^{12}\mathrm{C}/\mathrm{D}$ shows a notable Q^2 dependence at small x in the shadowing region related to the Q^2 dependence of effective cross-section.

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

Comparison of DIS and RES/SIS fits



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 Christy-Bosted (RES) and Alekhin (DIS) analyses:

- 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.

Hybrid 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:

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

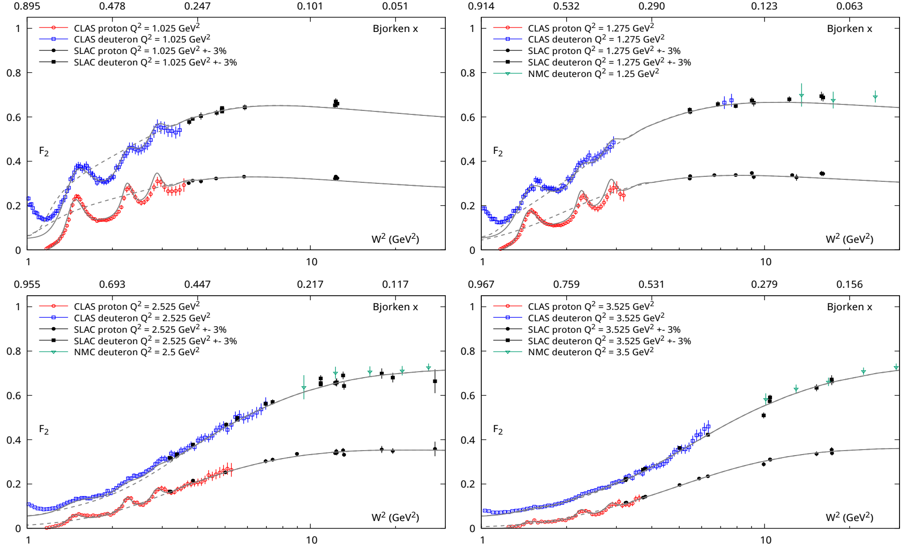
Here $W_1 = 1.8$ GeV and $W_2 = 2$ GeV.

Hybrid 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. The isospin conservation suggests equal contribution to the proton and the neutron from the $\Delta(1232)$ resonace $= F_2^\Delta$ (supported by analysis *Bosted & Christy, 2010*).

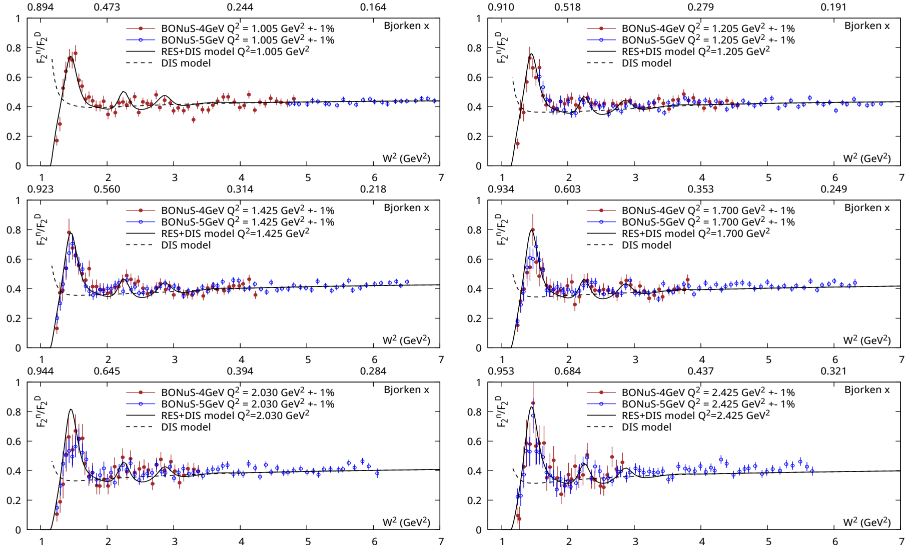
$$F_2^{n(\mathsf{RES})} = R_{np}\left(F_2^{p(\mathsf{RES})} - F_2^\Delta\right) + F_2^\Delta$$

Performance of the model vs. proton and deuteron data

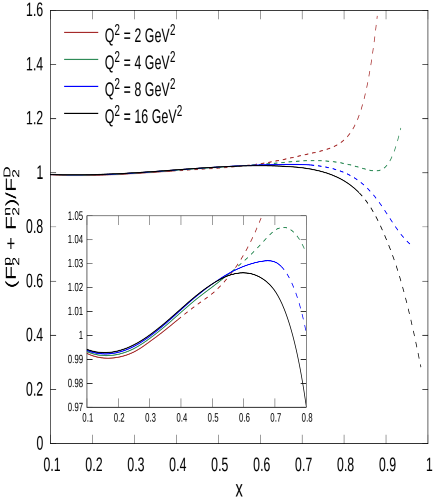


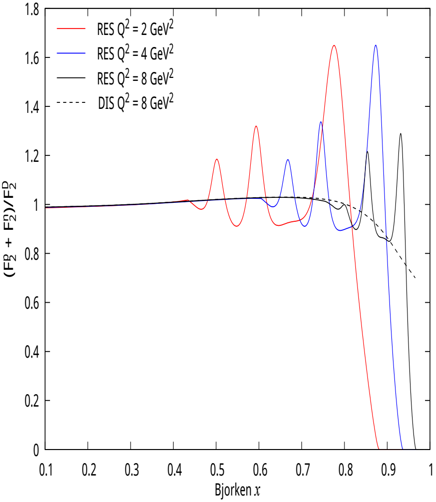
Proton and deuteron F_2 computed at $Q^2 = 1.025,\ 1.275,\ 2.525,\ 3.525$ GeV^2 in a combined RES-DIS model. Data from SLAC Whitlow,1991 and JLab-CLAS Osipenko,2003,2005 and NMC,1997.

Comparison with BONuS data F_2^n/F_2^D

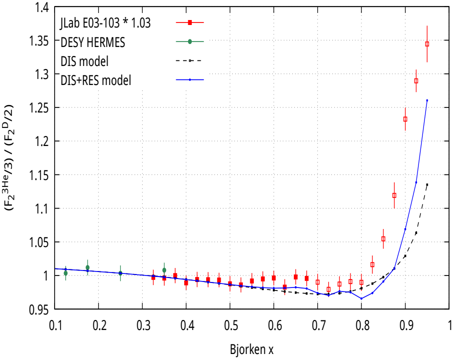


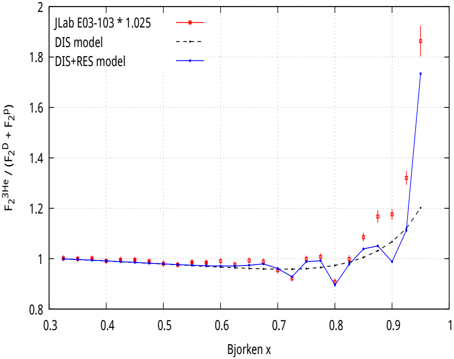
$(F_2^p + F_2^n)/F_2^D$ in the DIS and RES models





Comparison with ^{3}He from JLab E03103 experiment





$F_2^{3\mathrm{He}}/F_2^D$ from JLab *Seely et al, 2009* and HERMES measurement (both corrected for the proton excess) compared with model predictions. The dashed line is DIS model, the solid line is a combined DIS+RES model.

The isoscalar ratio $F_2^{3\mathrm{He}}/(F_2^D + F_2^p)$ from *Seely et al, 2009* (*D.Gaskell, private communication*) compared with our predictions. The notations are similar to those of the left panel.

Summary

- The data on the ratio of nuclear structure functions F_2^A/F_2^B (nuclear EMC effect) show nontrivial oscillating shape spanning different kinematical regions of Bjorken x.
- The data in the DIS region can be understood if we address a number of corrections including nuclear momentum distribution and binding effects, off-shell correction, meson-exchange currents as well as the matter propagation effects of hadronic component of virtual photon. Those nuclear effects result in the corrections relevant in different regions of x.
- In the resonance region (low Q^2 and/or large x) the nuclear ratios for light nuclei (2H, 3He and 3H) show a strong Q^2- and $x-$dependence. Current data on those ratios (JLab) can be understood in terms of smearing of the resonance structures with nuclear spectral function (the wave function in the deuteron case) except for a region of a very large x close to $\Delta(1232)$.

Extras

Table of χ^2 values for all nuclei

Targets	χ^2/DOF						
	NMC	EMC	E139	E140	BCDMS	E665	HERMES
^{4}He/^{2}H	10.8/17		6.2/21				
^{7}Li/^{2}H	28.6/17						
^{9}Be/^{2}H			12.3/21				
^{12}C/^{2}H	14.6/17		13.0/17				
^{9}Be/^{12}C	5.3/15						
^{12}C/^{7}Li	41.0/24						
^{14}N/^{2}H							9.8/12
^{27}Al/^{2}H			14.8/21				
^{27}Al/^{12}C	5.7/15						
^{40}Ca/^{2}H	27.2/16		14.3/17				
^{40}Ca/^{7}Li	35.6/24						
^{40}Ca/^{12}C	31.8/24					1.0/5	
^{56}Fe/^{2}H			18.4/23	4.5/8	14.8/10		
^{56}Fe/^{12}C	10.3/15						
^{63}Cu/^{2}H		7.8/10					
^{84}Kr/^{2}H							4.9/12
^{108}Ag/^{2}H			14.9/17				
^{119}Sn/^{12}C	94.9/161						
^{197}Au/^{2}H			18.2/21	2.4/1			
^{207}Pb/^{2}H						5.0/5	
^{207}Pb/^{12}C	6.1/15					0.2/5	

Values of χ^2/DOF between different data sets with $Q^2 \geq 1$ GeV^2 and the predictions of KP model *NPA765(2006)126; PRC82(2010)054614*. The sum over all data results in $\chi^2/\mathrm{DOF} = 466.6/586$.

Sketch of the mean-field picture

In the the mean-field model the bound states of $A-1$ nucleus are described by the one-particle wave functions ϕ_λ of the energy levels λ. The spectral function is given by the sum over the occupied levels with the occupied number n_λ:

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

- Due to interaction effects the δ-peaks corresponding to the single-particle levels acquire a finite width (fragmentation of deep-hole states).
- High-energy and high-momentum components of nuclear spectrum can not be described in the mean-field model and driven by short-range nucleon-nucleon correlation effects in the nuclear ground state as witnessed by numerous studies.

High-momentum part

- As nuclear excitation energy becomes higher the mean-field model becomes less accurate. High-energy and high-momentum components of nuclear spectrum can not be described in the mean-field model and driven by correlation effects in nuclear ground state as witnessed by numerous studies.
- The corresponding contribution to the spectral function is driven by $(A-1)^*$ excited states with one or more nucleons in the continuum. Assuming the dominance of configurations with a correlated nucleon-nucleon pair and remaining $A{-}2$ nucleons moving with low center-of-mass momentum we have

$$|A{-}1, -\boldsymbol{p}\rangle \approx \psi^\dagger(\boldsymbol{p}_1)|(A{-}2)^*, \boldsymbol{p}_2\rangle\delta(\boldsymbol{p}_1 + \boldsymbol{p}_2 + \boldsymbol{p}).$$

The matrix element can thus be given in terms of the wave function of the nucleon-nucleon pair embeded into nuclear environment. We assume factorization into relative and center-of-mass motion of the pair

$$\langle (A-2)^*, \boldsymbol{p}_2 \left| \psi(\boldsymbol{p}_1)\psi(\boldsymbol{p}) \right| A \rangle \approx C_2 \psi_{\mathrm{rel}}(\boldsymbol{k}) \psi_{\mathrm{CM}}^{A-2}(\boldsymbol{p}_{\mathrm{CM}}) \delta(\boldsymbol{p}_1 + \boldsymbol{p}_2 + \boldsymbol{p}),$$

where ψ_{rel} is the wave function of the relative motion in the nucleon-nucleon pair with relative momentum $\boldsymbol{k} = (\boldsymbol{p} - \boldsymbol{p}_1)/2$ and ψ_{CM} is the wave function of center-of-mass (CM) motion of the pair in the field of $A-2$ nucleons, $\boldsymbol{p}_{\mathrm{CM}} = \boldsymbol{p}_1 + \boldsymbol{p}$. The factor C_2 describes the weight of the two-nucleon correlated part in the full spectral function.

$$\mathcal{P}_{\mathrm{cor}}(\varepsilon, \boldsymbol{p}) \approx n_{\mathrm{cor}}(\boldsymbol{p}) \left\langle \delta \left(\varepsilon + \frac{(\boldsymbol{p} + \boldsymbol{p}_{A-2})^2}{2M} + E_{A-2} - E_A \right) \right\rangle_{A-2}$$

Average separation and kinetic energies

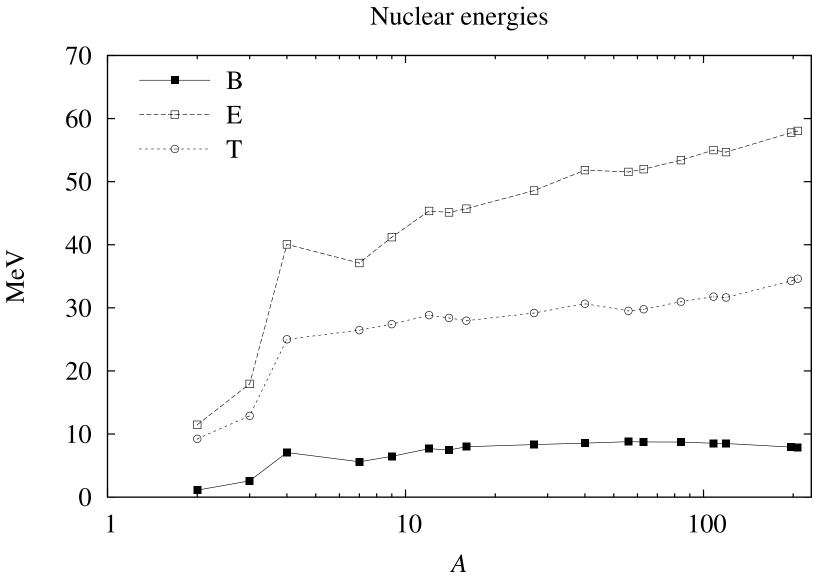
Average separation $\langle \varepsilon \rangle$ and kinetic $\langle T \rangle$ energies are related by the Koltun sum rule (exact relation for nonrelativistic system with two-body forces)

$$\langle \varepsilon \rangle + \langle T \rangle = 2\varepsilon_B,$$

where $\varepsilon_B = E_0^A/A$ is nuclear binding energy per bound nucleon

$$\langle \varepsilon \rangle = A^{-1} \int [\mathrm{d}p] \mathcal{P}(\varepsilon, \boldsymbol{p}) \varepsilon,$$
$$\langle T \rangle = A^{-1} \int [\mathrm{d}p] \mathcal{P}(\varepsilon, \boldsymbol{p}) \frac{\boldsymbol{p}^2}{2M}.$$

Nuclear binding, separation and kinetic energies



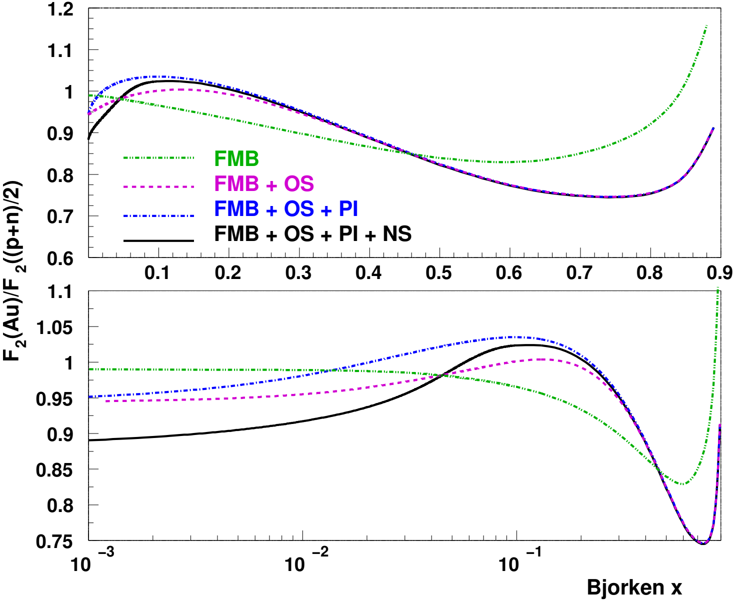
The two-component model of the spectral function

In what follows we combine the mean-field together with SRC contributions and consider a two-component model *Ciofi degli Atti & Simula, 1995 S.K. & Sidorov, 2000 S.K. & Petti, 2004*

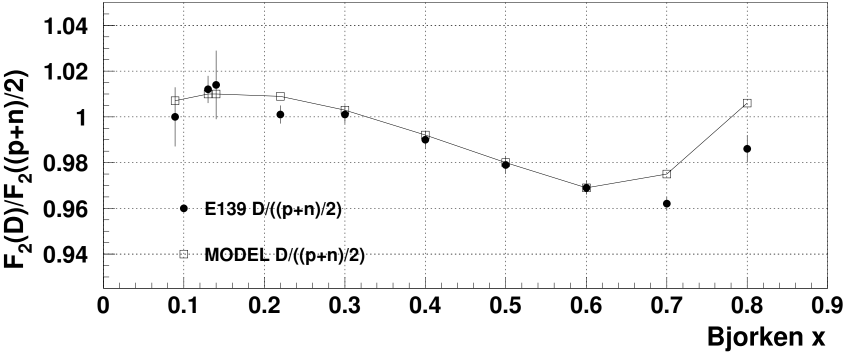
$$\mathcal{P} = \mathcal{P}_{\mathrm{MF}} + \mathcal{P}_{\mathrm{cor}}$$

We assume that the normalization is shared between the MF and the correlated parts as 0.8 to 0.2 for the nuclei $A \geq 4$ [for $^{208}\mathrm{Pb}$ 0.75 to 0.25] following the observations on occupation of deeply-bound proton levels *NIKHEF 1990s, 2001*.

Different nuclear corrections for $^{197}\mathrm{Au}$ at $Q^2 = 10\,\mathrm{GeV}^2$

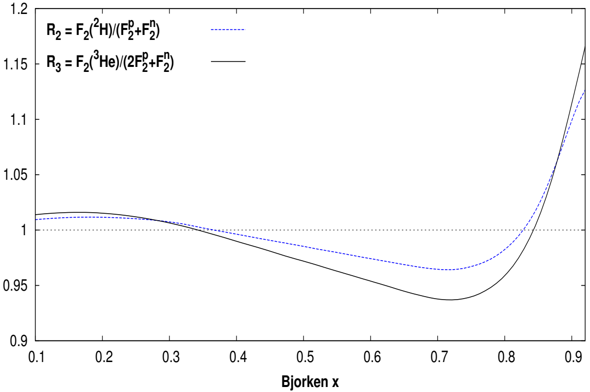


SLAC E139 Deuteron



Model predictions (curve with open squares) in comparison with the E139 data *Gomez et.al., 1994*. Note that the E139 data points are obtained by extrapolation to $A = 2$ using the nuclear density model *Frankfurt & Strikman, 1990*.

Comparison predictions for $D/(p+n)$ and $^3\mathrm{He}/(2p+n)$

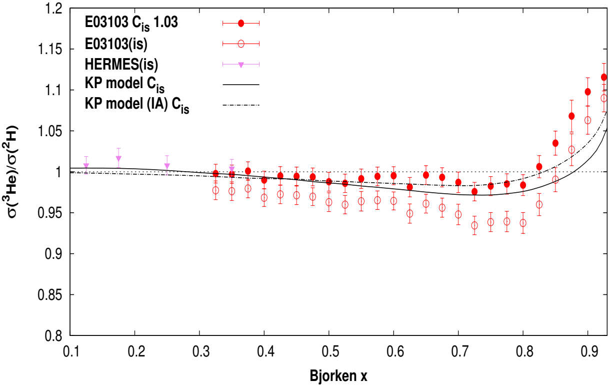


R_2 and R_3 were calculated in the DIS model at the values of x and Q^2 of JLab E03-103 experiment for $x > 0.3$ and at fixed $Q^2 = 3$ GeV^2 for $x < 0.3$.

The Paris wave function was used for the deuteron, and the Hannover spectral function was used for $^3\mathrm{He}$.

- R_2 and R_3 are similar in shape. A dip at $x \sim 0.7$ is somewhat bigger for R_3 because of stronger nuclear binding in ^{3}He.
- Nuclear effects cancel at $x \approx 0.35$, which is consistent with the measurement of EMC effect in other nuclei.

Comparison $^3\mathrm{He}/\mathrm{D}$ with HERMES and JLab E03-103 data



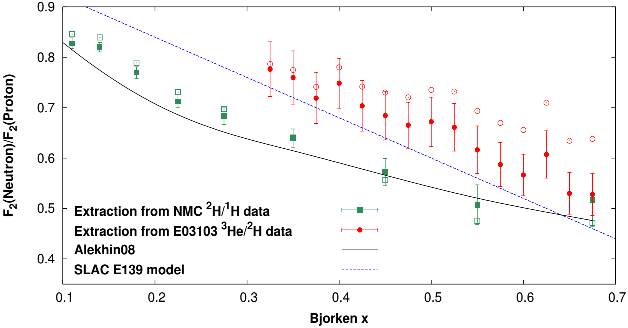
To correct for proton excess, HERMES applies the factor

$$C_{is} = \frac{AF_2^N}{ZF_2^p + NF_2^n}$$

with F_2^n/F_2^p from NMC. The E03-103 experiment does it differently, however correction factors are known.

- An unbiased way would be to compare uncorrected data, or corrected in a similar way. However, HERMES exact correction factors are not available. We uncorrect E03-103 data and then apply C_{is} together with the factor 1.03.
- After renormalization, E03-103 and HERMES data agree at the overlap ($x = 0.35$). Also our predictions are in a good agreement with both data (except the region $x > 0.8$).

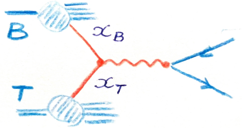
Extraction of F_2^n/F_2^p from $^3\mathrm{He/D}$ vs. $\mathrm{D/p}$



Extraction of F_2^n/F_2^p with the full treatment of nuclear effect (full symbols) and also with no nuclear effects ($R_2 = R_3 = 1$, 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 F_2^n/F_2^p from E03-103 is 15% higher than that from NMC.
- Normalization of F_2^n/F_2^p is directly related to normalization of $^3\mathrm{He/D}$. Requiring F_2^n/F_2^p from E03-103 match NMC, we obtain a renormalization factor of $1.03^{+0.006}_{-0.008}$ for $^3\mathrm{He/D}$ data.

Drell–Yan reaction



Production of a lepton pair in hadron collision $B + T \to \mu^+\mu^- + \ldots$ through the Drell-Yan mechanism:

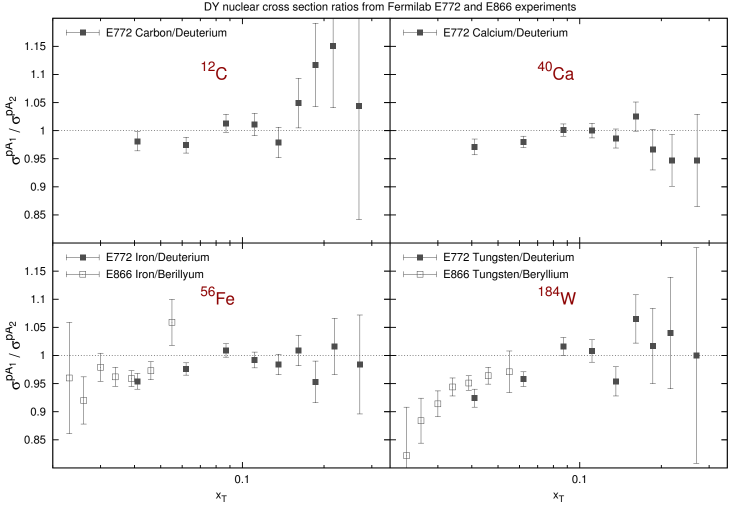
$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}x_B \mathrm{d}x_T} = \frac{4\pi\alpha^2}{9Q^2} K \sum_a e_a^2 \left[q_a^B(x_B, Q^2)\bar{q}_a^T(x_T, Q^2) + \bar{q}_a^B(x_B, Q^2) q_a^T(x_T, Q^2) \right]$$

- $Q^2 = s\, x_T x_B$ and $s = (p_B + p_T)^2$ the c.m. energy^2.
- At small $Q^2/s \ll 1$ and large x_B the DY process probes the target's antiquarks. For the ratios on different targets A_1 and A_2:

$$\frac{\sigma_{A_1}^{\mathrm{DY}}}{\sigma_{A_2}^{\mathrm{DY}}} \approx \frac{\bar{q}_{A_1}(x_T)}{\bar{q}_{A_2}(x_T)}$$

DY nuclear data from E772 and E866 experiments

Fermilab E772 and E866 experiments measure the ratio of DY yields for the DY process of 800-GeV proton with a number of targets with $s \approx 1600\,\mathrm{GeV}^2$ and $4 < Q < 9\,\mathrm{GeV}$ and $Q > 11\,\mathrm{GeV}$ (excluding J/ψ region).



Drell-Yan process with nuclear targets

DY process $p + A \to \gamma^* \to \mu^+\mu^- + X$

Cross section is driven by

$\sum e_q^2 \left[q^B(x_B)\bar{q}^T(x_T) + \bar{q}^B(x_B)q^T(x_T) \right]$

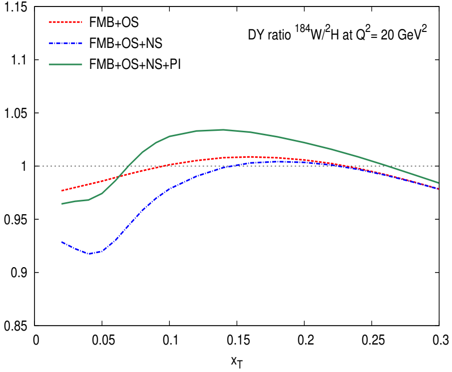
In the context of Fermilab E772 & E866 experiments:

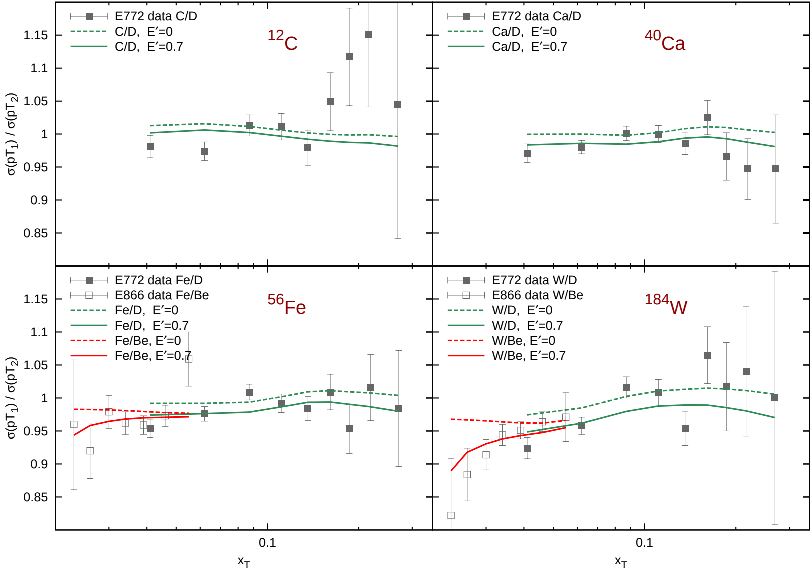
Energy $E_p = 800$ GeV, $s \sim 1600$ GeV^2

Muon pair masses: $4 < Q < 9$ GeV and $Q > 11$ GeV (exclude quarkonium)

Probed region of target's Bjorken variable $0.04 < x_T < 0.27$

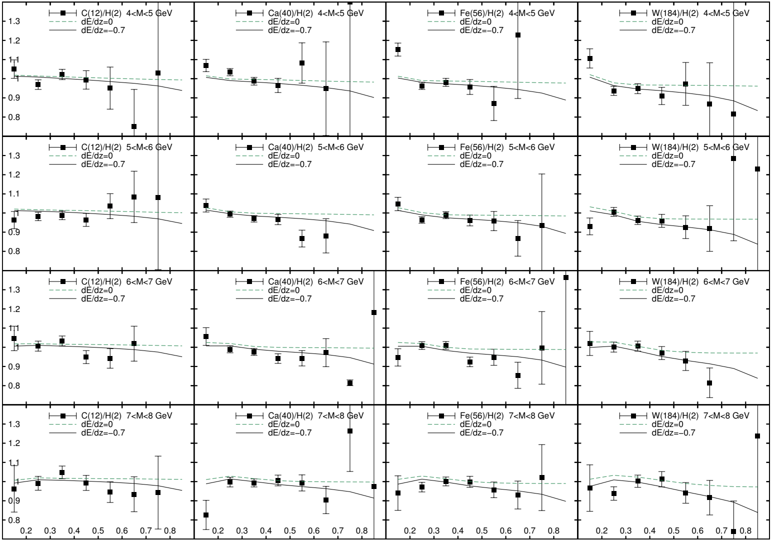
$\sigma(p^{184}\mathrm{W})/\sigma(pD)$ at $Q^2 = 20$ GeV^2





Comparison with the results of E772 & E866 Fermilab experiments *S.K. & R.Petti, PRC90(2014)045204*.

Detailed comparison with E772 by dimuon mass bin



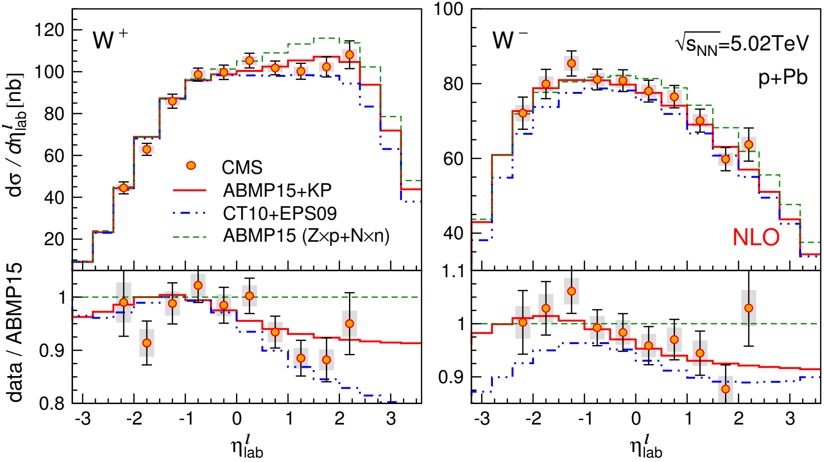
Production of W/Z in $p + Pb$ collisions at LHC

The DY mechanism of W/Z boson production in hadron/nuclear $A + B$ collisions:

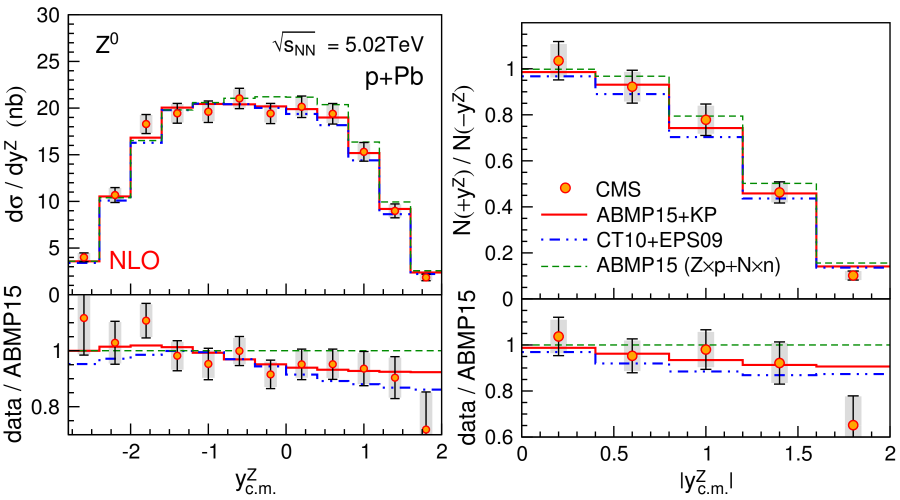
$$\frac{\mathrm{d}^2\sigma_{AB}}{\mathrm{d}Q^2\mathrm{d}y} = \sum_{a,b}\int \mathrm{d}x_a \mathrm{d}x_b q_{a/A}(x_a, Q^2) q_{b/B}(x_b, Q^2) \frac{\mathrm{d}^2\widehat{\sigma}_{ab}}{\mathrm{d}Q^2\mathrm{d}y}$$

We study rapidity (y) distributions of production of W/Z bosons in $p + Pb$ collisions at LHC with $Q^2 \sim M_Z^2$ and $\sqrt{s} = 5.02\,\mathrm{TeV}$ using KP NPDF *P.Ru, S.K., R.Petti, B-W.Zhang, arXiv:1608.06835*.

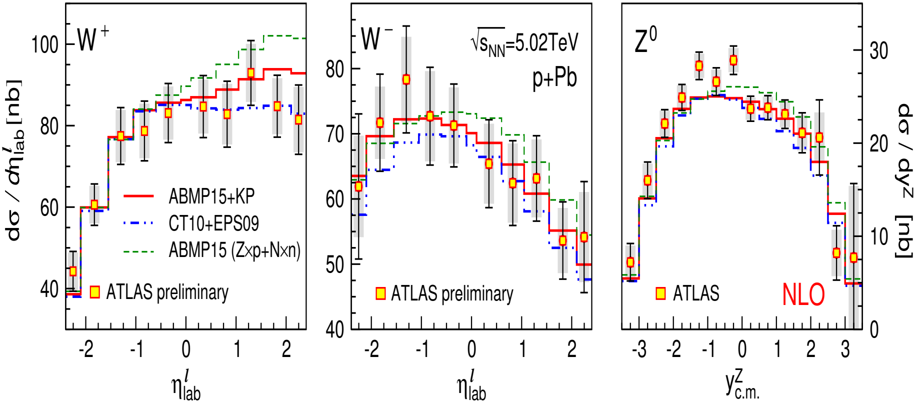
Predictions for W^+ and W^- and comparison with CMS data



Predictions for Z^0 and comparison with CMS data



Comparison with ATLAS data on W/Z production

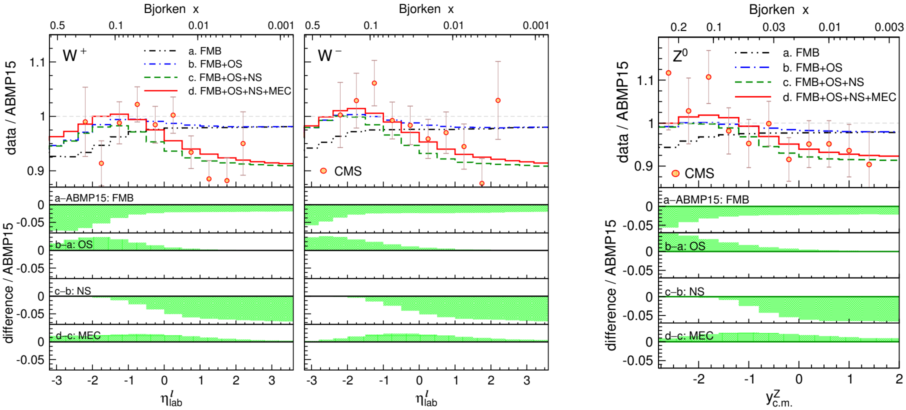


Performance of the model in terms of χ^2

Observable	N_{Data}	ABMP15 + KP	CT10 + EPS09	ABMP15 (Zp + Nn)
		CMS experiment:		
$d\sigma^+/d\eta^l$	10	1.052	1.532	3.057
$d\sigma^-/d\eta^l$	10	0.617	1.928	1.393
$N^+(+\eta^l)/N^+(-\eta^l)$	5	0.528	1.243	2.231
$N^-(+\eta^l)/N^-(-\eta^l)$	5	0.813	0.953	2.595
$(N^+ - N^-)/(N^+ + N^-)$	10	0.956	1.370	1.064
$d\sigma/dy^Z$	12	0.596	0.930	1.357
$N(+y^Z)/N(-y^Z)$	5	0.936	1.096	1.785
CMS combined	57	0.786	1.332	1.833
		ATLAS experiment:		
$d\sigma^+/d\eta^l$	10	0.586	0.348	1.631
$d\sigma^-/d\eta^l$	10	0.151	0.394	0.459
$d\sigma/dy^Z$	14	1.449	1.933	1.674
CMS+ATLAS combined	91	0.796	1.213	1.635

Splitting the nuclear effects in W/Z boson production

Different nuclear effects on the production cross section of W (left) and Z boson (right) in $p + \mathrm{Pb}$ collisions at $\sqrt{s} = 5.02\,\mathrm{TeV}$ *P.Ru, S.K., R.Petti, B-W.Zhang arXiv:1608.06835*.



Upper axis is Bjorken x of Pb while the lower axis is (pseudo)rapidity $(\eta)y$.

Nuclear effects on valence quarks vs. antiquarks

The ratios $R_a = q_{a/A}/(Zq_{a/p} + Nq_{n/A})$ computed for the valence u and d (left) and the corresponding antiquarks (right) *S.K. & R.Petti, PRC90(2014)045204*.