Nuclear Binding and Off-shell Corrections in the EMC Effect

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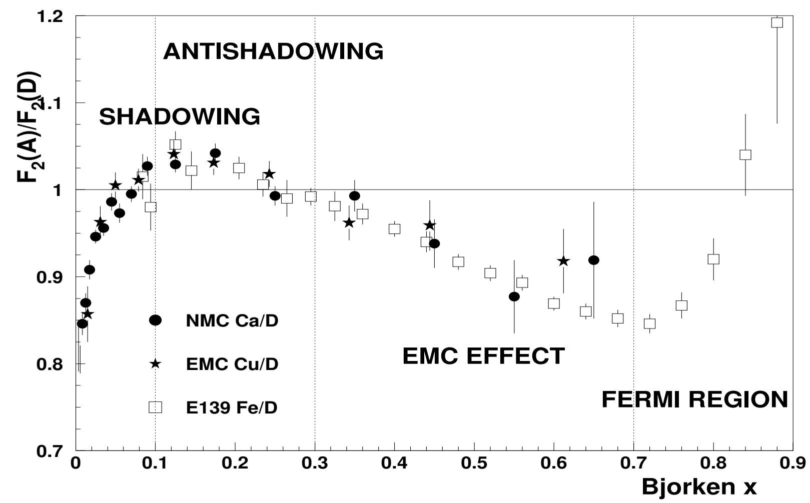
NUCLEAR MODEL

✦ GLOBAL APPROACH *aiming to obtain a quantitative model covering the complete range of x and Q^2 (S. Kulagin and R.P., NPA 765 (2006) 126; PRC 90 (2014) 045204):*

- *Scale of nuclear processes (target frame)* $L_I = (Mx)^{-1}$
  Distance between nucleons $d = (3/4\pi\rho)^{1/3} \sim 1.2Fm$
- $L_I < d$
  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 parton distributions and structure functions included:*

$$q_{a/A} = q_a^{p/A} + q_a^{n/A} + \delta q_a^{\mathrm{MEC}} + \delta q_a^{\mathrm{coh}} \qquad a = u, d, s.....$$

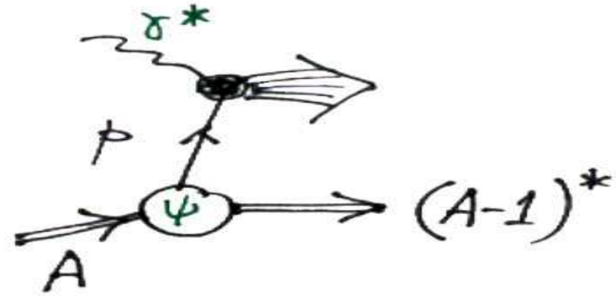
- $q_a^{p(n)/A}$ *PDF in bound p(n) with Fermi Motion, Binding (FMB) and Off-Shell effect (OS)*
- $\delta q_a^{\mathrm{MEC}}$ *nuclear Meson Exchange Current (MEC) correction*
- $\delta q_a^{\mathrm{coh}}$ *contribution from coherent nuclear interactions: Nuclear Shadowing (NS)*

INCOHERENT NUCLEAR SCATTERING

✦ FERMI MOTION AND BINDING in nuclear parton distributions can be calculated from the convolution of nuclear spectral function and (bound) nucleon PDFs:

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

$$xq_a^{p/A} = \int \mathrm{d}\varepsilon\, \mathrm{d}^3\mathbf{p}\, \mathcal{P}(\varepsilon,\mathbf{p}) \left(1+\frac{p_z}{M}\right) x' q^N(x',Q^2,p^2)$$



where $x' = Q^2/(2p\cdot q)$ and $p = (M+\varepsilon,\mathbf{p})$ and we dropped $1/Q^2$ terms for illustration purpose .

✦ Since bound nucleons are OFF-MASS-SHELL there appears dependence on the nucleon virtuality $p^2 = (M+\varepsilon)^2 - \mathbf{p}^2$ and expanding PDFs in the small $(p^2-M^2)/M^2$:

$$q_a(x,Q^2,p^2) \approx q_a^N(x,Q^2)\left(1+\delta f(x)(p^2-M^2)/M^2\right).$$

where we introduced a structure function of the NUCLEON: $\delta f(x)$

✦ Hadronic/nuclear input:

- Proton/neutron SFs computed in NNLO pQCD + TMC + HT from fits to DIS data
- Realistic nuclear spectral function: mean-field $\mathcal{P}_{\mathrm{MF}}(\varepsilon,\mathbf{p})$ + correlated part $\mathcal{P}_{\mathrm{cor}}(\varepsilon,\mathbf{p})$

OFF-MASS-SHELL $F_2(x, Q^2, p^2) \approx F_2(x, Q^2)\left(1 + \delta f(x)(p^2 - M^2)/M^2\right)$

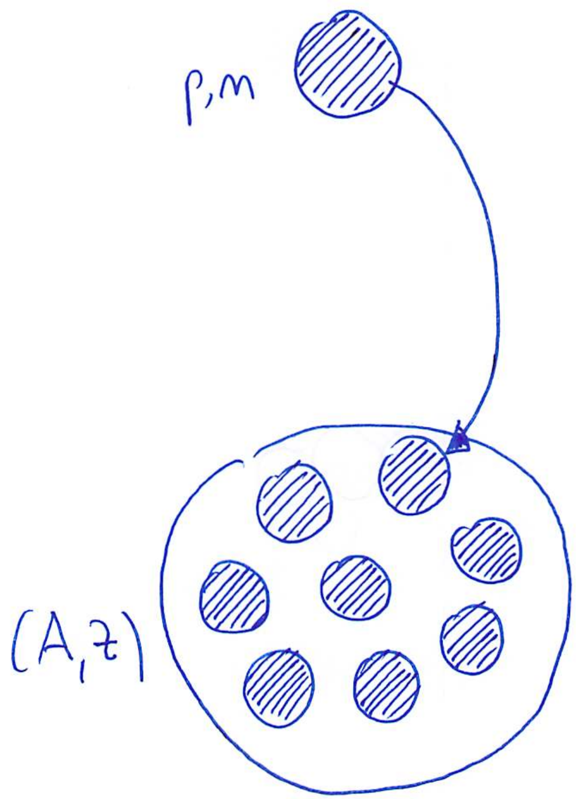
DESCRIPTION OF NUCLEON

Distribution of partons in a nucleon

STRUCTURE FUNCTIONS

$F_1(x, Q^2), F_2(x, Q^2), xF_3(x, Q^2), \ldots\ldots$

$\delta f(x)$



DESCRIPTION OF NUCLEUS

Distribution of bound nucleons

SPECTRAL/WAVE FUNCTION

$\mathcal{P}(\varepsilon, \mathbf{p}), \mathbf{\Psi}(\mathbf{p})$

Off-shell function measures the in-medium modification of bound nucleon

Any isospin (i.e. $\delta f_p \neq \delta f_n$) or flavor dependence ($\delta f_a$) in the off-shell function?

NUCLEAR SPECTRAL FUNCTION

- *The description of the nuclear properties is embedded into the nuclear spectral function*

- *Nucleons occupy energy levels according to Fermi statistics and are distributed over momentum (Fermi motion) and energy states. In the* MEAN FIELD *model:*

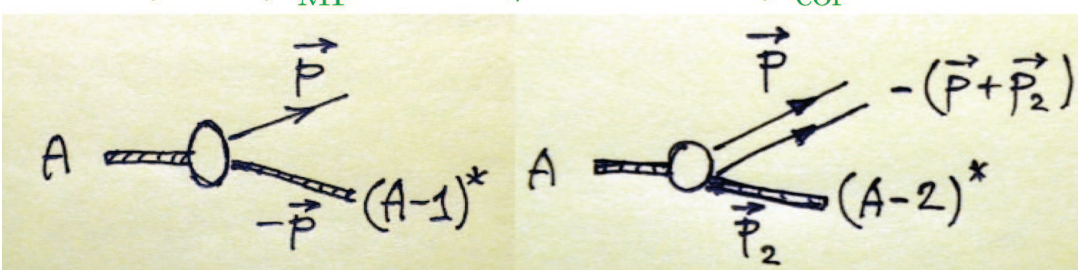
$$\mathcal{P}_{\rm MF}(\varepsilon, \mathbf{p}) = \sum_{\lambda<\lambda_{\rm F}} \mathbf{n}_\lambda \mid \phi_\lambda(\mathbf{p}) \mid^{\mathbf{2}} \delta(\varepsilon - \varepsilon_\lambda)$$

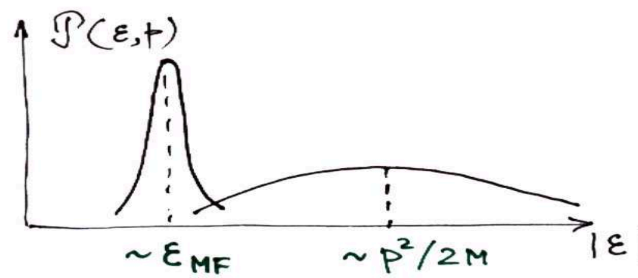
where sum over occupied levels with n_λ *occupation number. Applicable for* *small nucleon separation energy and momenta*, $\mid \varepsilon \mid < 50$ *MeV*, $p < 300$ *MeV/c*

- CORRELATION EFFECTS *in nuclear ground state drive the high-energy and high-momentum component of the nuclear spectrum, when* $\mid \varepsilon \mid$ *increases*

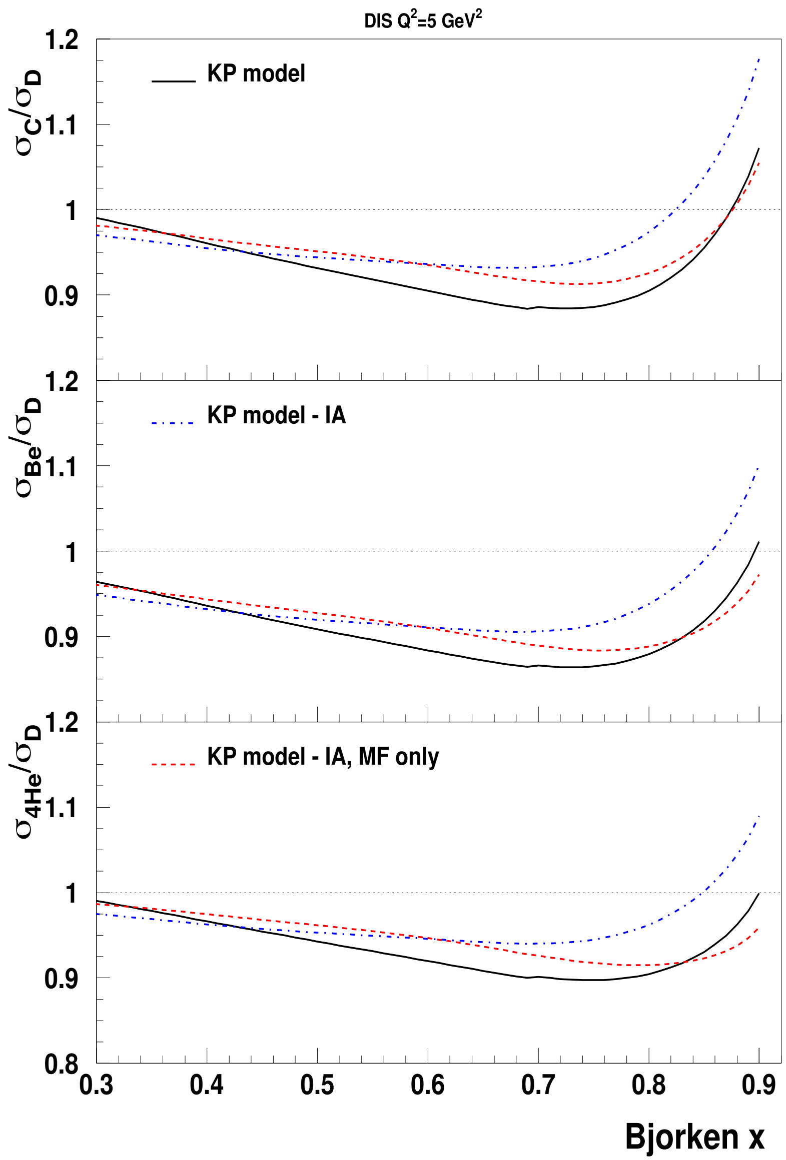
$$\mathcal{P}_{\rm cor}(\varepsilon, \mathbf{p}) \approx n_{\rm rel}(\mathbf{p}) \left\langle \delta \left(\varepsilon + \frac{(\mathbf{p}+\mathbf{p}_2)^2}{2M} + E_{A-2} - E_A \right) \right\rangle_{\rm CM}$$

$$\mathcal{P} = \mathcal{P}_{\rm MF} \qquad + \qquad \mathcal{P}_{\rm cor}$$





IMPACT OF NN CORRELATIONS



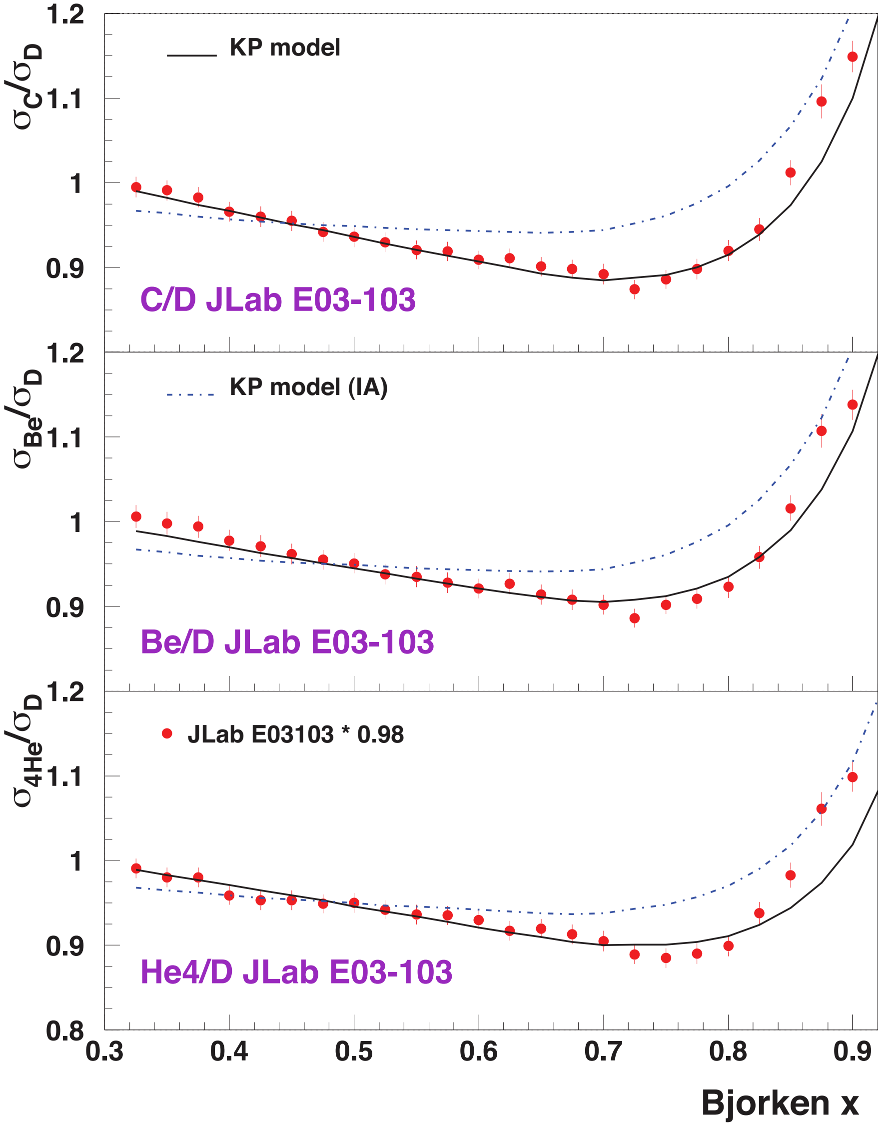
- *Impulse Approximation (IA) fails to quantitatively describe observed modifications*

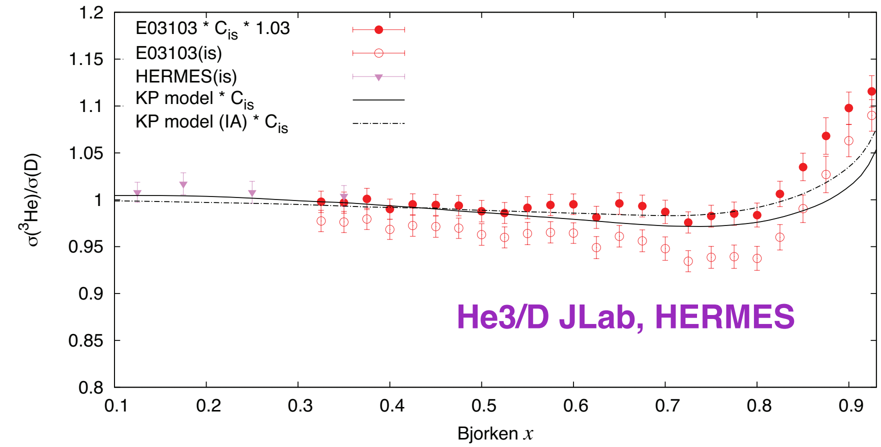
- *Instructive to drop $\mathcal{P}_{\rm cor}(\varepsilon, \mathbf{p})$ from spectral function to estimate effect of NN correlations*

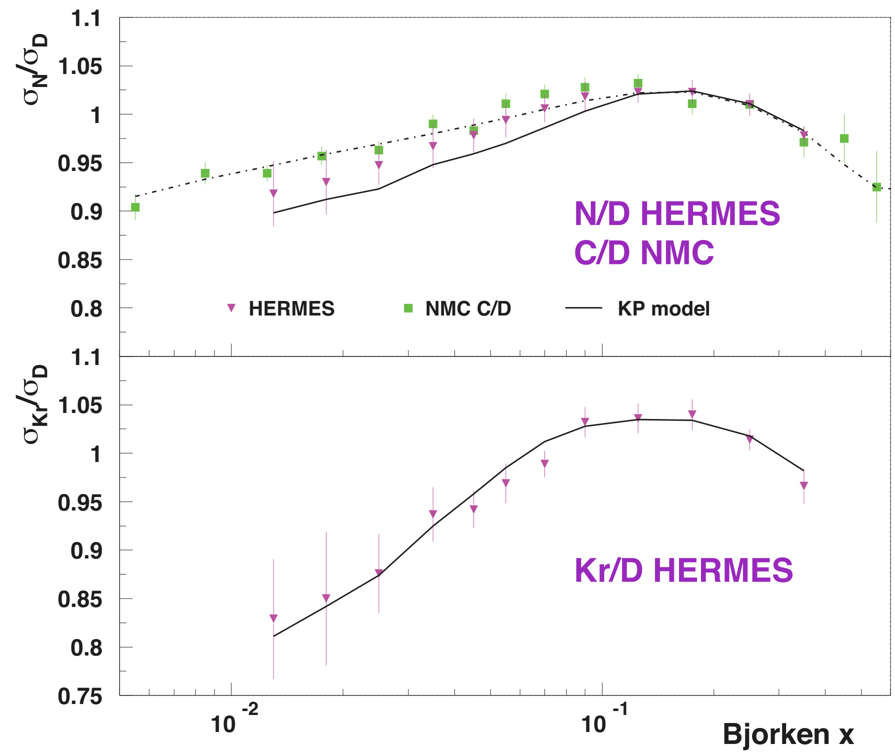
- *Significant change on structure functions in clear disagreement with data indicates mean-field $\mathcal{P}_{\rm MF}(\varepsilon, \mathbf{p})$ alone not sufficient*

$\Longrightarrow$ *Study NN correlations and refine description of spectral function*

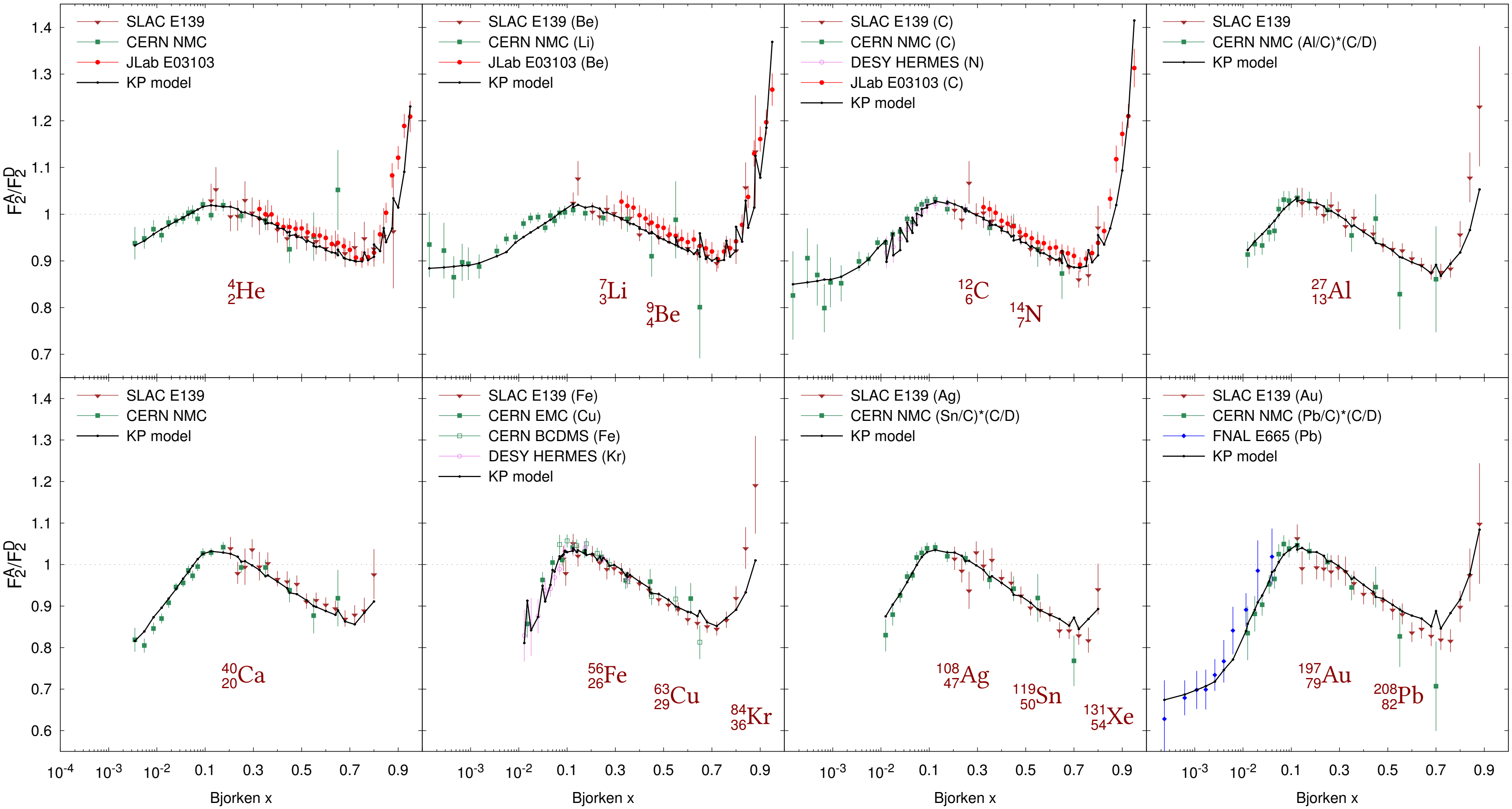
PREDICTIONS FOR CHARGED LEPTON DIS





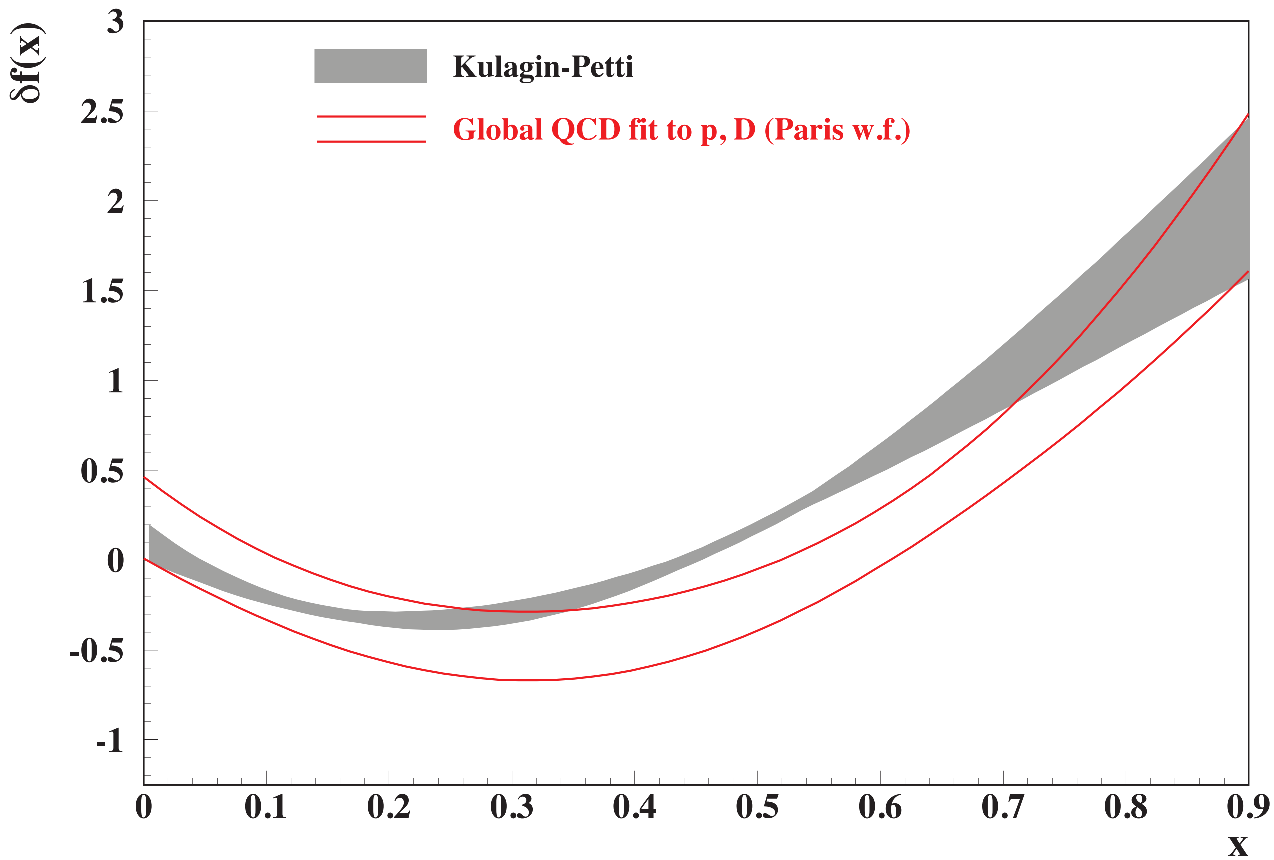


S. Kulagin and R.P., PRC 82 (2010) 054614



SLAC E139
CERN NMC
JLab E03103
KP model
$^{4}_{2}$He
SLAC E139 (Be)
CERN NMC (Li)
JLab E03103 (Be)
KP model
$^{7}_{3}$Li
$^{9}_{4}$Be
SLAC E139 (C)
CERN NMC (C)
DESY HERMES (N)
JLab E03103 (C)
KP model
$^{12}_{6}$C
$^{14}_{7}$N
SLAC E139
CERN NMC (Al/C)*(C/D)
KP model
$^{27}_{13}$Al
SLAC E139
CERN NMC
KP model
$^{40}_{20}$Ca
SLAC E139 (Fe)
CERN EMC (Cu)
CERN BCDMS (Fe)
DESY HERMES (Kr)
KP model
$^{56}_{26}$Fe
$^{63}_{29}$Cu
$^{84}_{36}$Kr
SLAC E139 (Ag)
CERN NMC (Sn/C)*(C/D)
KP model
$^{108}_{47}$Ag
$^{119}_{50}$Sn
$^{131}_{54}$Xe
SLAC E139 (Au)
CERN NMC (Pb/C)*(C/D)
FNAL E665 (Pb)
KP model
$^{197}_{79}$Au
$^{208}_{82}$Pb
F_2^A/F_2^D
Bjorken x

$\delta f(x)$ FROM $A \geq 4$ NUCLEI AND DEUTERON

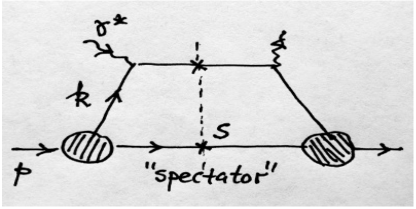


- *Precise determination of $\delta f(x)$ from RATIOS F_2^A/F_2^B from DIS off different nuclei, including SLAC, NMC, EMC, BCDMS, E665 data (NPA 765 (2006) 126)*
- *Independent determination from global QCD fit to p and D data with DIS,DY,$W^{\pm}/Z$ provides consistent results (S. Alekhin, S. Kulagin and R.P., arXiv:1609.08463 [nucl-th])*

INTERPRETATION OF $\delta f(x)$

Valence quark distribution in a covariant diquark spectator model (see *S.Kulagin et.al., PRC50(1994)1154*)

$$q_{\text{val}}(x,p^2) = \int^{x\left(p^2-\frac{s}{1-x}\right)} \mathrm{d}k^2 \; C\phi\left(k^2/\Lambda^2\right)/\Lambda^2$$

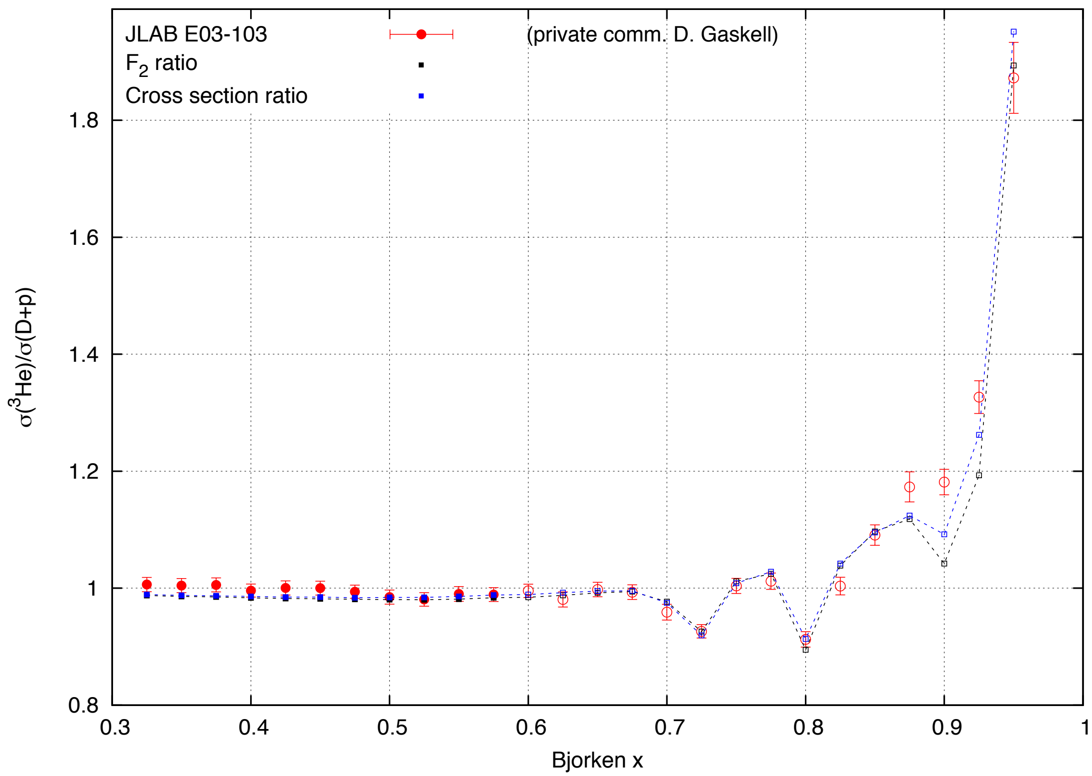


- Assume a single-scale quark distribution over the virtuality k^2. The model gives a resonable description of the nucleon valence distribution for $x > 0.2$
- Off-shell nucleon: $C \to C(p^2),\ \Lambda \to \Lambda(p^2)$. The function $\delta f = \partial \ln q_{\text{val}}/\partial \ln p^2$ depends on $c = \partial \ln C/\partial \ln p^2$ and $\lambda = \partial \ln \Lambda^2/\partial \ln p^2$.
- Tune c and λ to reproduce the node $\delta f(x_0) = 0$ and the slope $\delta f'(x_0)$ of phenomenological off-shell function. We obtain $\lambda \approx 1$ and $c \approx -2.3$.
- The positive parameter λ suggests smaller in-medium scale Λ or larger nucleon core size $R_c = \Lambda^{-1}$ ("swelling" of a bound nucleon).

$$\left.\frac{\delta R_c}{R_c}\right|_{\text{in-medium}} = -\frac{1}{2}\frac{\delta\Lambda^2}{\Lambda^2} = -\frac{1}{2}\lambda\frac{\langle p^2-M^2\rangle}{M^2}$$

$$^{208}\text{Pb}: \ \delta R_c/R_c \sim 10\% \qquad \text{Deuteron}: \ \delta R_c/R_c \sim 2\%$$

NUCLEAR EFFECTS IN RESONANCE REGION



- *Use Christy-Bosted SF parameterization for p and n in resonance region*
- *^{3}He spectral function from exact Faddeev three-body calculation by Hannover group (R.-W. Schulze and P. U. Sauer, Phys. Rev. C 48, (1993) 38)*
- *Apply nuclear corrections for ^{3}He/(D+p) as predicted from the DIS region to the cross-section in the resonance kinematics*

  $\Longrightarrow$ *Consistent treatment of nuclear effects in DIS and resonance regions?*

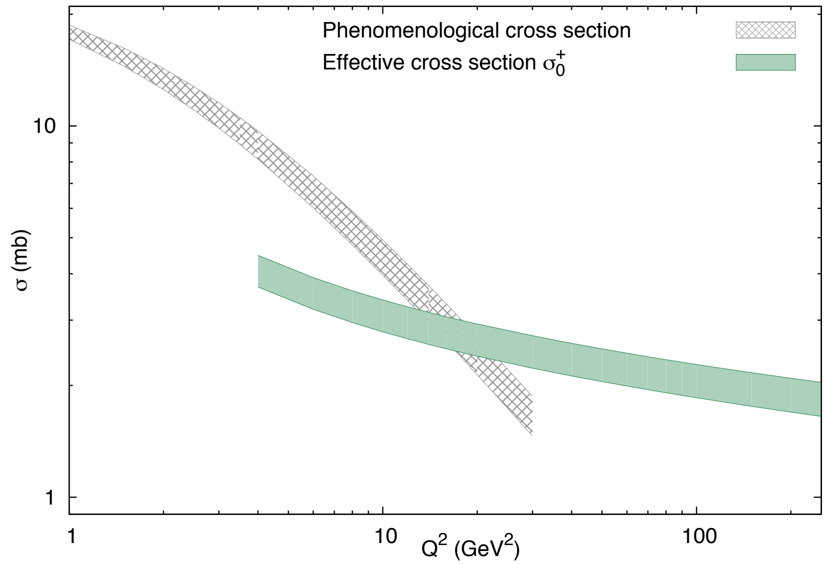
CONSTRAINTS FROM SUM RULES

- *Nuclear meson correction constrained by light-cone momentum balance and equations of motion.* (S. Kulagin, NPA 500 (1989) 653; S. Kulagin and R.P., NPA 765 (2006) 126; PRC 90 (2014) 045204)

- *At high Q^2 (PDF regime) coherent nuclear corrections controlled by the effective scattering amplitudes, which can be constrained by normalization sum rules:*

$$\delta N_{\rm val}^{\rm OS} + \delta N_{\rm val}^{\rm coh} = 0 \quad \longrightarrow \quad a_0$$
$$\delta N_1^{\rm OS} + \delta N_1^{\rm coh} = 0 \quad \longrightarrow \quad a_1$$

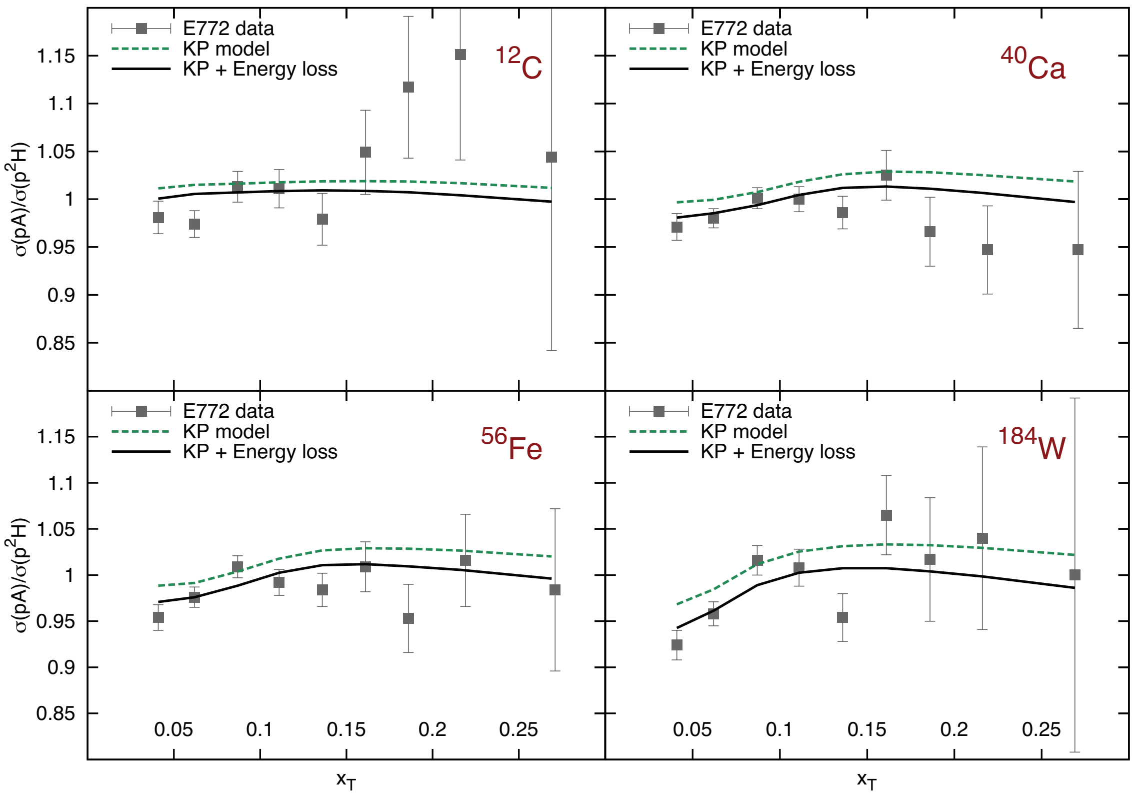
where $N_{\rm val}^A = A^{-1}\int_0^A dx q_{0/A}^- = 3$ *and* $N_1^A = A^{-1}\int_0^A dx q_{1/A}^- = (Z-N)/A$



Solve numerically in terms of δf and virtuality $v = (p^2 - M^2)/M^2$ (input) and obtain the effective cross-section in the $(I=0, C=1)$ state, as well as Re/Im of amplitudes

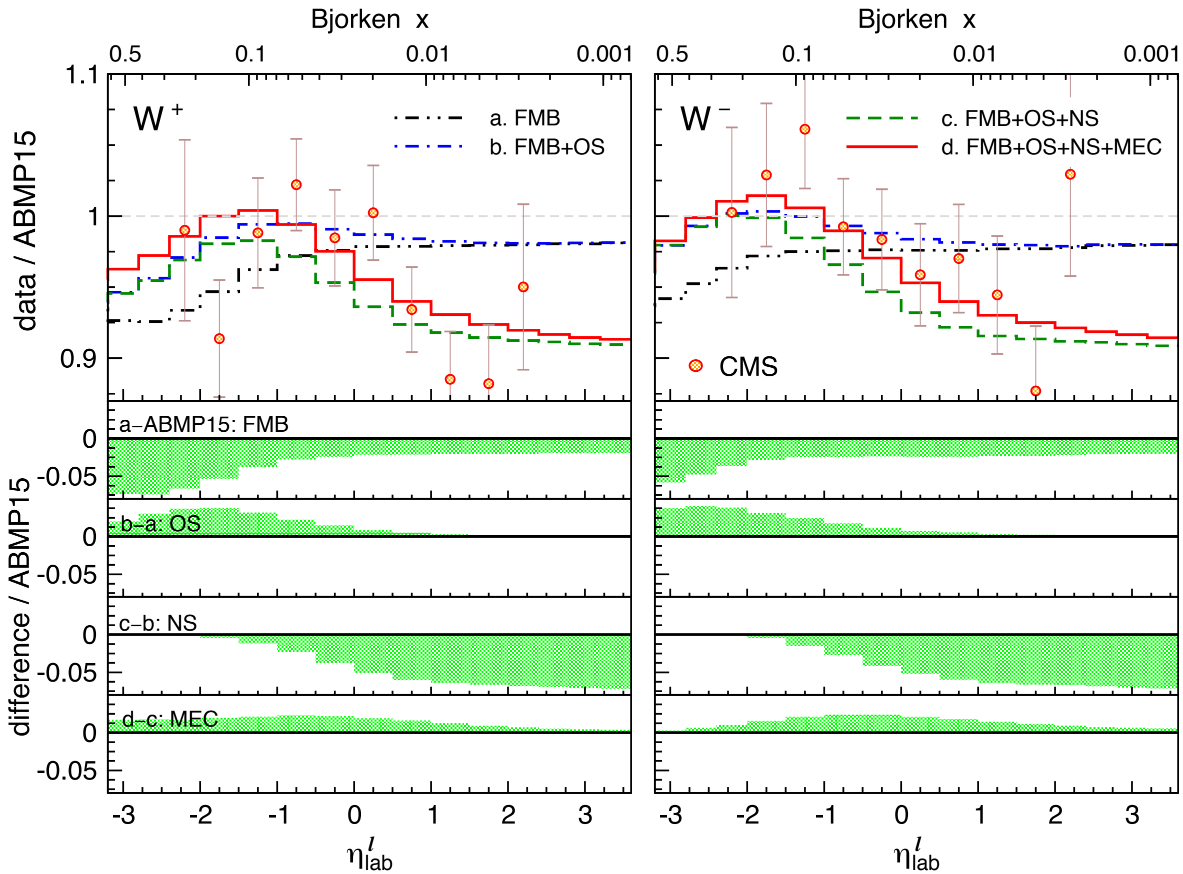
$\Longrightarrow$ *Nuclear corrections to PDFs largely controlled by $\mathcal{P}(\varepsilon, \mathbf{p})$ AND $\delta f(x)$*

PREDICTIONS FOR DRELL-YAN PRODUCTION IN pA



- *Predictions based on the assumption of a common off-shell function δf for both valence and sea quark distributions consistent with existing Drell-Yan data from E772 (S. Kulagin and R.P., Phys. Rev. C90 (2014), 045204)*
- *More precise data with kinematic coverage extended at larger x values from E906 could provide better insights on the flavor dependence of δf*

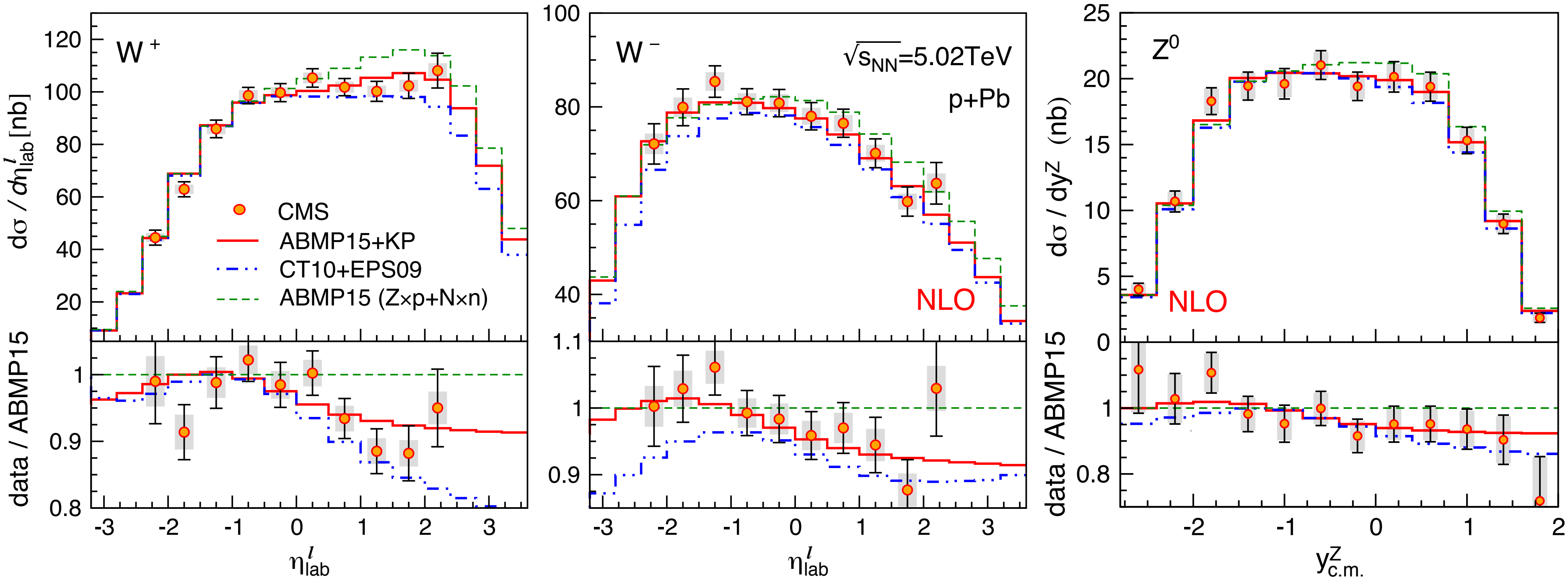
PREDICTIONS FOR $W^{\pm}, Z$ PRODUCTION IN pPb AT THE LHC



$Q^2 = m_W^2$

✦ *Sensitivity of $W^{\pm}, Z$ rapidity distributions in p+Pb collisions at the LHC to FMB and OS corrections $\Longrightarrow$ current data consistent with assumption no flavor dependence* (*P. Ru, S. Kulagin, R.P. and B-W. Zhang, arXiv:1608.06835 [nucl-th]*)

✦ *Future more precise measurements could provide additional insights on the flavor (isospin) dependence of δf*



P. Ru, S. Kulagin, R.P. and B-W. Zhang, arXiv:1608.06835 [nucl-th]

SUMMARY

- *The impulse approximation (FMB) alone cannot provide a quantitative description of data without the in-medium modification of bound nucleons from the OS effect.*

- *The off-shell modification of bound nucleons in a nucleus can be described by a universal function $\delta f(x)$, which can be regarded as a nucleon structure function describing the relative modification of nucleon SFs in the vicinity of the mass shell.*

  $\Longrightarrow$ *Any isospin (i.e. $\delta f_p \neq \delta f_n$) or flavor dependence ($\delta f_a$) in the off-shell function?*

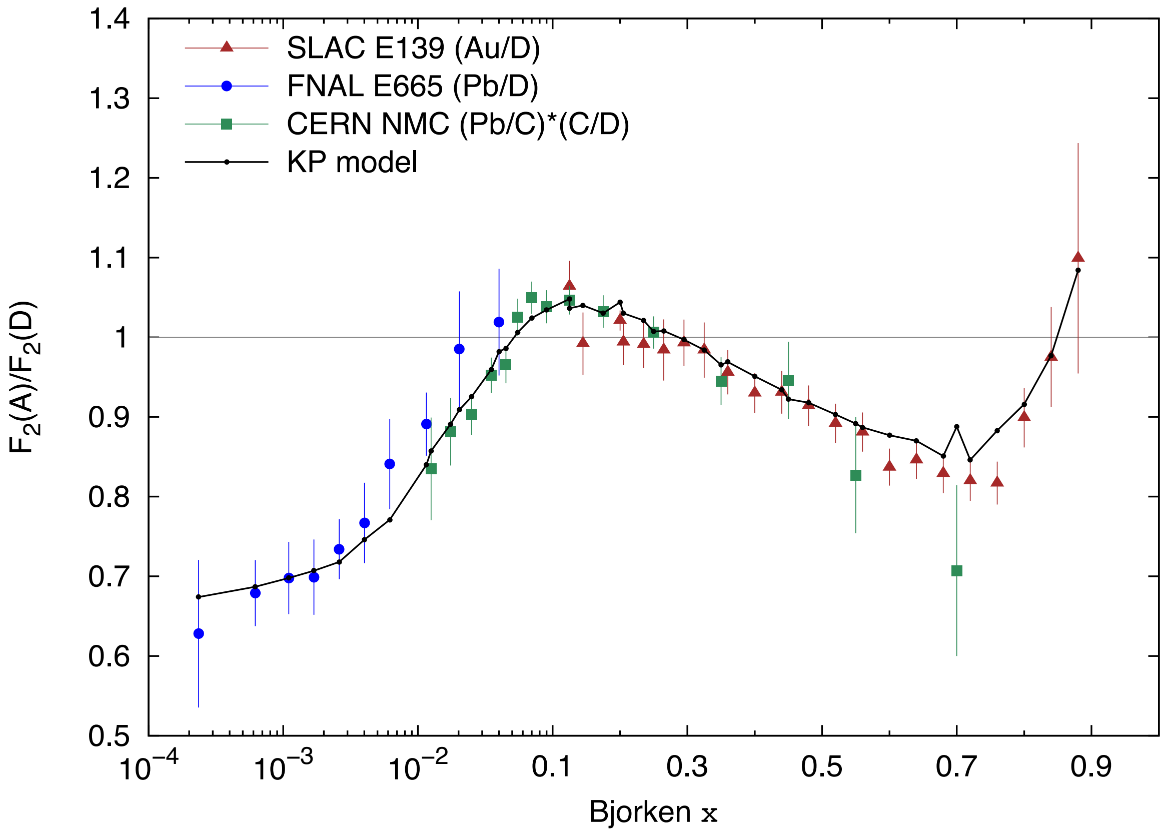
- *NN correlation effects in nuclear ground state drive the high energy/momentum component of spectral function and are required for a quantitative description of data.*

- *Interplay between nuclear effects in the DIS and resonance regions?*

- *Sum rules and normalization constraints relate different nuclear effects in different kinematic regions of x. Nuclear corrections to PDFs largely controlled by the spectral function $\mathcal{P}(\varepsilon, \mathbf{p})$ and the off-shell function $\delta f(x)$.*

- *Quantitative description of data in a wide range of nuclear processes including lepton-nucleus DIS, Drell-Yan production in pA, $W^{\pm}, Z$ production in p+Pb at LHC.*

Backup slides

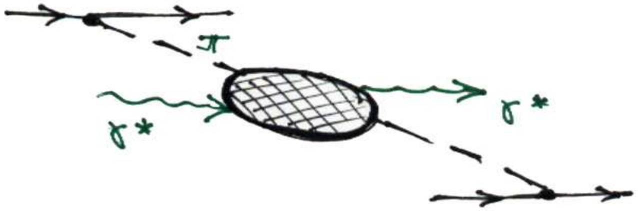


SLAC E139 (Au/D)
FNAL E665 (Pb/D)
CERN NMC (Pb/C)*(C/D)
KP model
F2(A)/F2(D)
Bjorken x
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
10^-4
10^-3
10^-2
0.1
0.3
0.5
0.7
0.9

NUCLEAR MESON EXCHANGE CURRENTS

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

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



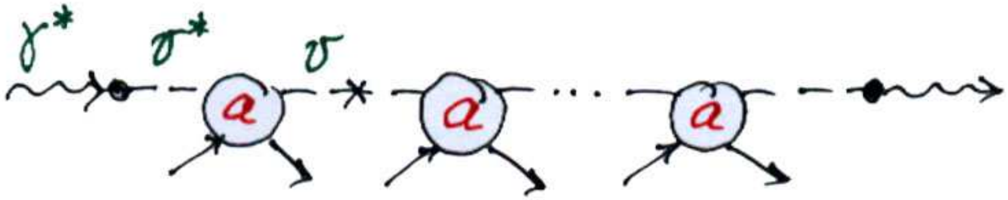
✦ *Contribution from nuclear pions (mesons) to balance nuclear light cone momentum* $\langle y \rangle_\pi + \langle y \rangle_N = 1$. *The pion distribution function is localized in a region of* $y \leq p_F/M \sim 0.3$ *so that the pion contribution is at* $x < 0.3$. *The correction is driven by the average number of "pions"* $n_\pi = \int \mathrm{d}y \, f_\pi(y)$ *and* $n_\pi/A \sim 0.1$ *for heavy nuclei.*

✦ *Hadronic/nuclear input:*

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

COHERENT NUCLEAR EFFECTS

✦ (ANTI)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:*



$$\delta \mathcal{R} = \frac{\delta q^{\mathrm{coh}}}{A q^N} \approx \frac{\delta \sigma^{\mathrm{coh}}}{A \sigma} = \mathrm{Im}\, \mathcal{A}(a) / A\, \mathrm{Im}\, a$$

$$\mathcal{A}(a) = i a^2 \int_{z_1 < z_2} \mathrm{d}^2\mathbf{b}\, \mathrm{d}z_1 \mathrm{d}z_2\, \rho_A(\mathbf{b}, z_1) \rho_A(\mathbf{b}, z_2) e^{i \int_{z_1}^{z_2} \mathrm{d}z' a\, \rho_A(\mathbf{b}, z')} e^{i k_L (z_1 - z_2)}$$

$a = \sigma(i+\alpha)/2$ *is the (effective) scattering amplitude ($\alpha = \mathrm{Re}\, a / \mathrm{Im}\, a$) 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*
- *Low Q^2 limit of scattering amplitude a given by Vector Meson Dominance (VMD) model*

TABLE II. Values of χ^2/DOF between different data sets with $Q^2 \geqslant 1$ GeV^2 and the predictions of Ref. [17]. The normalization of each experiment is fixed. The sum over all data results in $\chi^2/\text{DOF} = 466.6/586$.

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

S. Kulagin and R.P., PRC 82 (2010) 054614

TABLE I. Normalized χ^2 (per degree of freedom) for the various observables (rows) shown in the plots listed in the first column, calculated between each data set and three different model predictions: ABMP15+KP, CT10+EPS09, and ABMP15 without nuclear modifications (last column).

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

P. Ru, S. Kulagin, R.P. and B-W. Zhang, arXiv:1608.06835 [nucl-th]