Nuclear Modifications of Parton Distributions

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(based on work done in collaboration with S. Kulagin)

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OUTLINE

I *Introduction:*

- ✦ *Experimental evidence for nuclear effects on PDFs;*
- ✦ *Definition of nuclear parton distribution functions (NPDFs).*

II *The KP Nuclear Parton Distributions:*

- ✦ *Different mechanisms of nuclear effects in different kinematical regions;*
- ✦ *Off-shell correction $\Leftrightarrow$ in-medium modification of bound nucleons;*
- ✦ *Constraints/connections from PDF Sum Rules.*

III *Applications to Nuclear Processes:*

- ✦ *Predictions for $l^{\pm}$-nucleus DIS;*
- ✦ *Predictions for Drell-Yan production in proton-nucleus collisions;*
- ✦ *Predictions for $W^{\pm}, Z^{0}$ production in heavy ion collisions at the LHC with $\sqrt{s_{\rm NN}} = 5.02$ TeV.*

NAIVE PICTURE OF THE NUCLEUS

- *The structure of free protons and neutrons is relatively well understood in terms of Parton Distribution Functions (PDFs), which are universal characteristics of the target at high momentum transfer Q^2 driven by nonperturbative strong interactions.*

- *Nuclei are loosely bound systems with binding energy* $\boxed{E_B \ll M_N}$ *the nucleon mass.*

- *For a nucleus A with Z protons and N neutrons ($A = Z + N$ total number of bound nucleons) a naive expectation for the nuclear PDFs of flavor a is:*

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

where $q_{a/p}$ and $q_{a/n}$ are the corresponding PDFs for the free protons and neutrons.

$\Longrightarrow$ *System of quasi-free nucleons not much affected by the nuclear environment*

- *Experimental tests of this simplistic hypothesis revealed violations of this relation up to 30-50%, depending upon the specific kinematic region considered.*

EXPERIMENTAL EVIDENCE OF NUCLEAR EFFECTS

- *Discovery nuclear effects at $Q^2 \gg M$ in CERN (EMC, 1983) and SLAC experiments*

- *Experimental data with nuclear targets from ^{2}D to ^{207}Pb*

- *Kinematics and statistics:*
  Data cover the region $10^{-4} < x \leq 1.5$ and $0 < Q^2 < 150$ GeV^2.
  About 600 data points with $Q^2 > 1$ GeV^2.

- *Deep Inelastic Scattering (DIS) fixed target experiments with e/μ:*
  - *Muon beams at CERN (EMC, BCDMS, NMC) and FNAL (E665)*
  - *Electron beams at SLAC (E139, E140), HERA (HERMES) and recently JLab (E03-103)*

- *Neutrino DIS data on nuclear targets ^{20}Ne, ^{12}C, ^{56} Fe, ^{207}Pb:*
  BEBC, CDHS, CHORUS, NOMAD at CERN and CCFR, NuTeV, MINERνA at FNAL

- *Drell-Yan production from p-A fixed target experiments at FNAL (E772, E866, E906)*

- *Collider experiments with heavy ion beams at the LHC (CMS, ATLAS, ALICE, LHCb) and RICH (BRAHMS,PHENIX,STAR)*

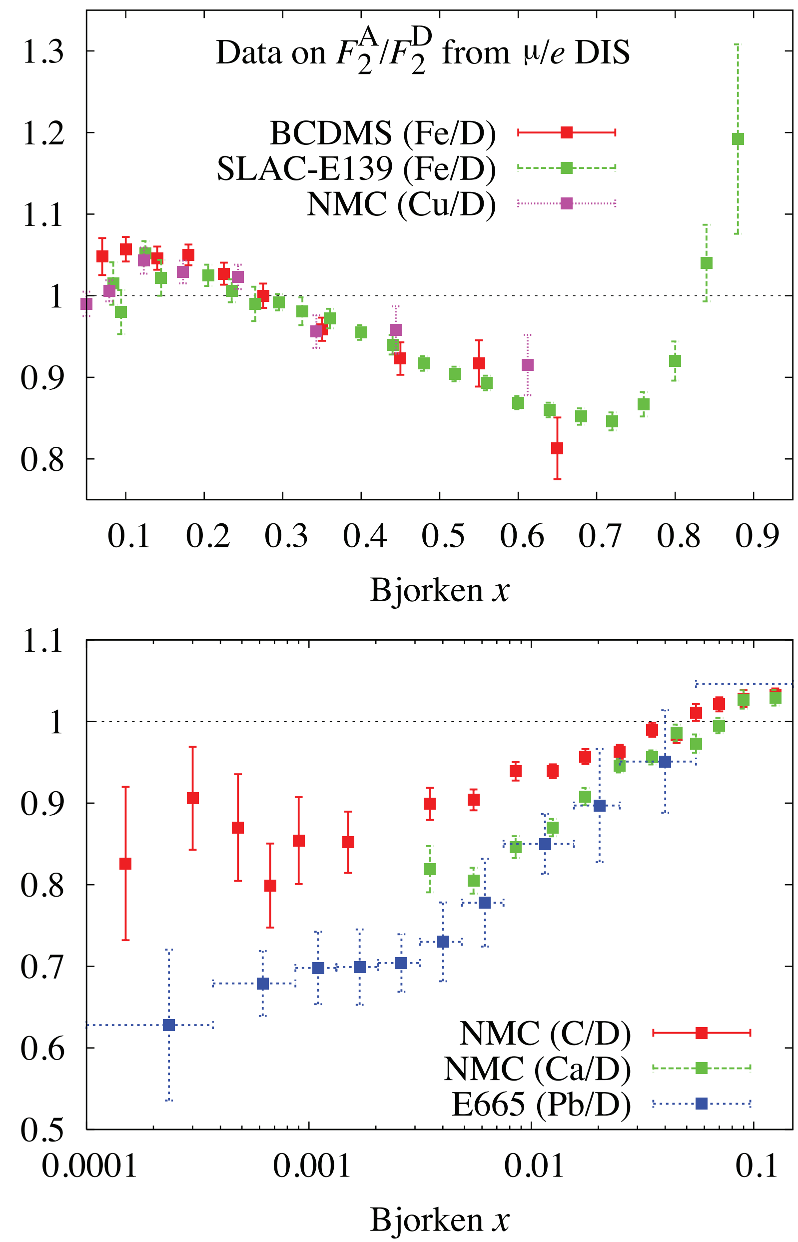
✦ SHADOWING:
suppression at small values of $x < 0.05$

✦ ANTISHADOWING:
enhancement at $0.1 < x < 0.3$

✦ EMC EFFECT:
a well with a minimum at $x \sim 0.6 \div 0.75$

✦ FERMI REGION:
enhancement at large values of $x > 0.75$

$\Longrightarrow$ *Different physics mechanisms in different regions of the Bjorken* x



NUCLEAR EFFECTS AT HIGH ENERGY?

✦ *The reason why nuclear effects survive at large Q^2 can be understood from the typical DIS space-time regions in the target rest frame, as derived from uncertainty principle:*

- *DIS occurs near the light cone: $t^2 - z^2 \sim Q^{-2}$ and $r_\perp \sim Q^{-1}$.*
- *The characteristic DIS time and longitudinal distance $t \sim z \sim L_I = (Mx)^{-1}$ (coherence length) is NOT SMALL in the hadronic scale.*

$\Longrightarrow$ *The nuclear environment can modify the bound nucleons.*

✦ *Since the QCD factorization theorem is expected to hold for nuclei, we can still describe high energy nuclear processes in terms of perturbative QCD, defining the nuclear parton distribution functions (NPDFs) for the given nucleus.*

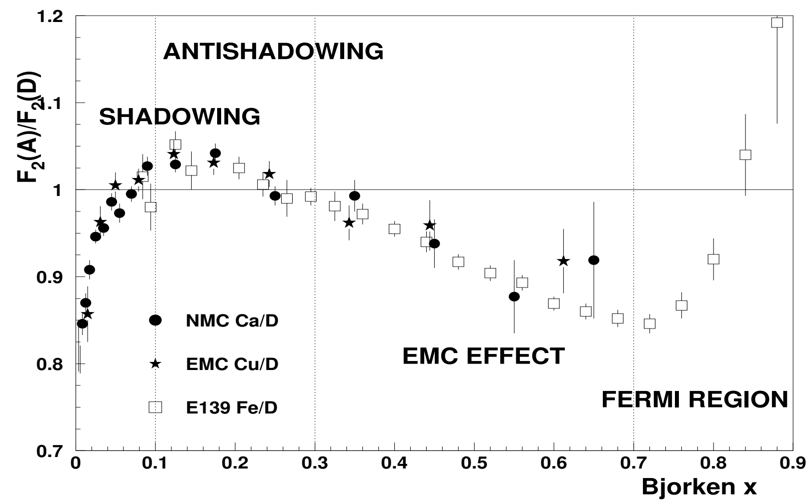
$\Longrightarrow$ *NPDFs substantially different from nucleon PDFs due to nuclear modifications.*

✦ *NPDFs can help to understand the impact of High Twist contributions on DIS structure functions at low and moderate Q^2.*

KP NUCLEAR PARTON DISTRIBUTIONS

✦ 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 $d = (3/4\pi\rho)^{1/3} \sim 1.2 Fm$
- $L_I < d$
  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 parton distributions (PDF) are taken into account:*

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

- $q_a^{p(n)/A}$ *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)*

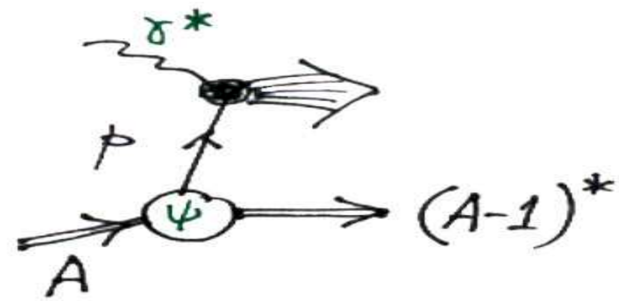
INCOHERENT NUCLEAR SCATTERING

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

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

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

$$q_a^{n/A} = \int \mathrm{d}\varepsilon\, \mathrm{d}^3\mathbf{p}\, \mathcal{P}_n(\varepsilon,\mathbf{p}) \left(1+\frac{p_z}{M}\right) \frac{x'}{x}\, q_{a/n}(x',Q^2,p^2)$$



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

✦ *Nuclear convolution driven by the nuclear* SPECTRAL FUNCTION $\mathcal{P}$ *giving the probability to find a bound nucleon with four-momentum* p.

✦ *Hadronic/nuclear input:*

- *Proton/neutron PDFs determined at NNLO from global QCD fits to DIS+DY data*
- *Realistic nuclear spectral function: mean-field* $\mathcal{P}_{\mathrm{MF}}(\varepsilon,\mathbf{p})$ + *correlated part* $\mathcal{P}_{\mathrm{cor}}(\varepsilon,\mathbf{p})$

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:*

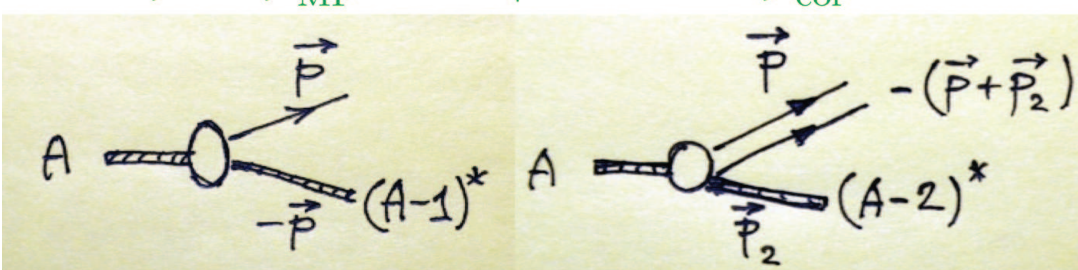
$$\mathcal{P}_{\mathrm{MF}}(\varepsilon, \mathbf{p}) = \sum_{\lambda<\lambda_{\mathbf{F}}} \mathbf{n}_{\lambda} \mid \phi_{\lambda}(\mathbf{p}) \mid^{\mathbf{2}} \delta(\varepsilon - \varepsilon_{\lambda})$$

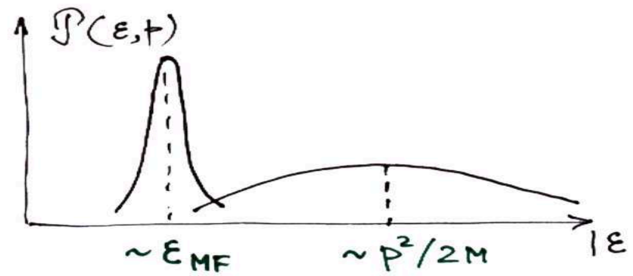
where sum over occupied levels with n_λ occupation number. Applicable for small nucleon separation energy and momenta, $\mid \varepsilon \mid < 50$ *MeV*, $p < 300$ *MeV/c*

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

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

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





IMPULSE APPROXIMATION

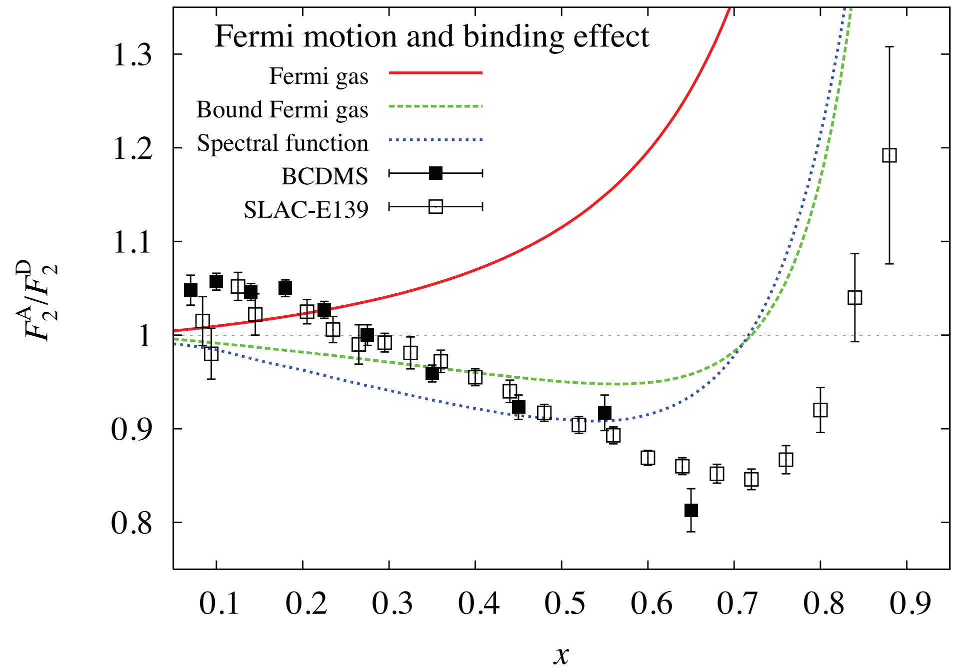
- *Impulse approximation:*

  $q_{a/p,n}(x', Q^2, p^2) = q_{a/p,n}(x', Q^2, p^2 = M^2)$

- *Fermi motion* $\Longrightarrow$ *rise at large Bjorken* x

- *Nuclear binding correction is important and results in a "dip" at* $x \sim 0.6 - 0.7$ *[PLB 158 (1985) 485]*

- *Fermi motion and nuclear binding effects are NOT enough for a quantitative understanding of data*



$\Longrightarrow$ *Impulse Approximation should be corrected for a number of effects*

NUCLEON OFF-SHELLNESS

- *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* $(p^2 - M^2)/M^2$*:*

$$q_{a/p,n}(x, Q^2, p^2) \approx q_{a/p,n}(x, Q^2)\left(1 + \delta f(x)(p^2 - M^2)/M^2\right).$$

$$\delta f(x) = \partial \ln q_{a/p,n} / \partial \ln p^2 \;|_{p^2=M^2}$$

where we introduce a structure function of the NUCLEON: $\boxed{\delta f(x)}$

- $\delta f(x)$ *is a special structure function describing the modification of the off-shell nucleon PDFs in the nuclear medium and accessible only in nuclear processes.*

  $\Longrightarrow$ *Response to interaction effects with the nuclear environment*

- *Using a model with a single-scale quark distribution over the virtuality, we can relate the large* x *shape and the node of the off-shell function* δf *to an increase of the size of the bound nucleon in the nuclear environment.*

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

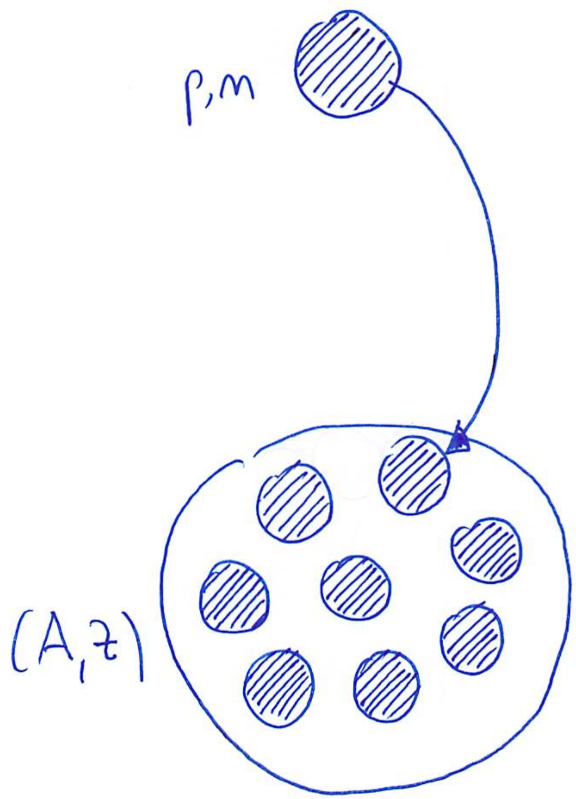
DESCRIPTION OF NUCLEON

Distribution of partons in a nucleon

STRUCTURE FUNCTIONS

$F_1(x,Q^2), F_2(x,Q^2), xF_3(x,Q^2)$, ...

$\delta f(x)$



DESCRIPTION OF NUCLEUS

Distribution of bound nucleons

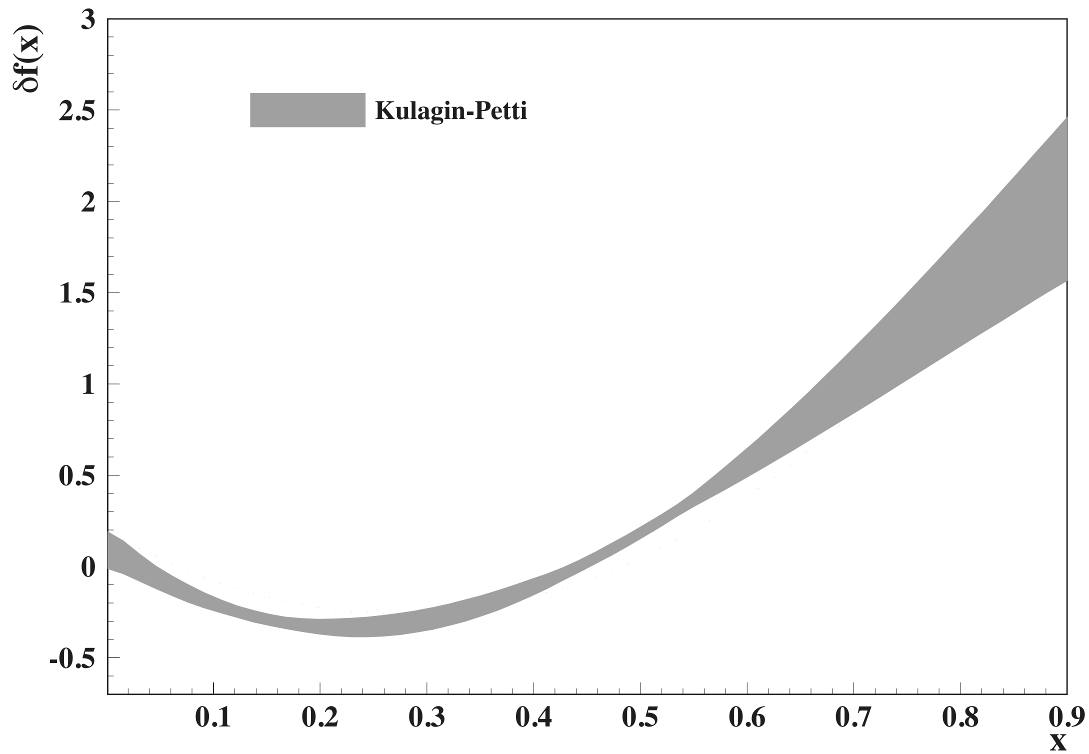
SPECTRAL/WAVE FUNCTION

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

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?

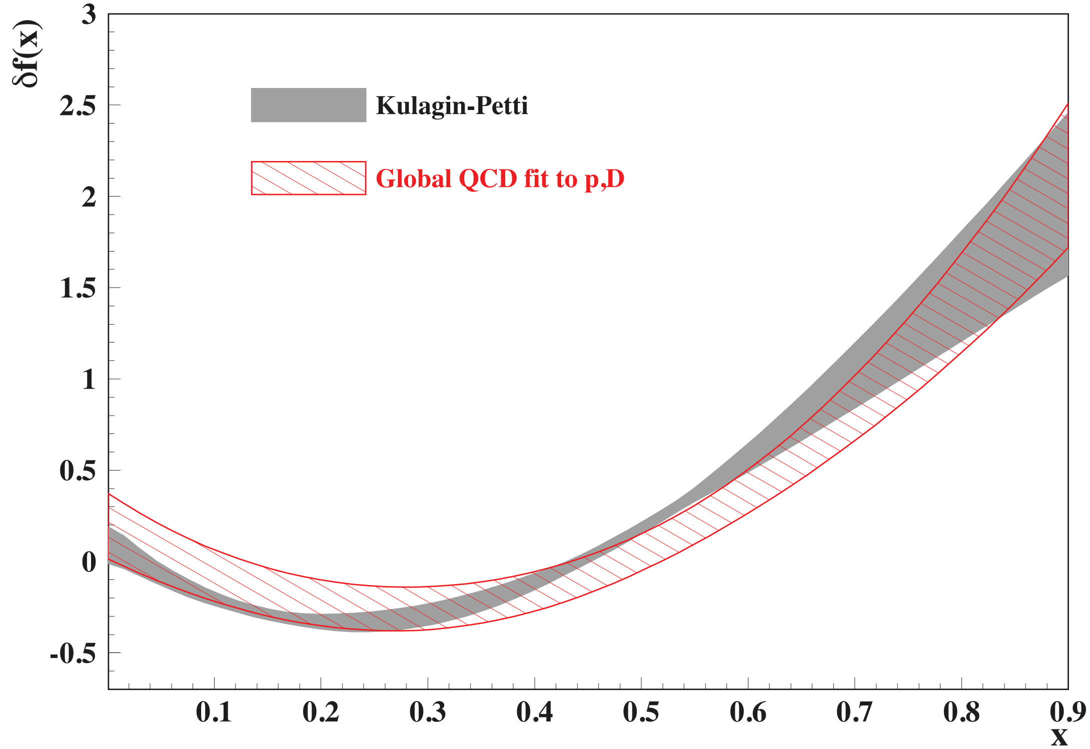
OFF-SHELL FUNCTION $\delta f(x)$



- *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)*
  $\Longrightarrow$ *Procedure similar to the one used for other structure functions.*

- *Resulting $\delta f(x)$ corresponds to an increase of the nucleon core radius $\delta R_c/R_c \sim 10\%$ in ^{208}Pb and $\sim 2\%$ in the Deuteron.*

OFF-SHELL FUNCTION $\delta f(x)$

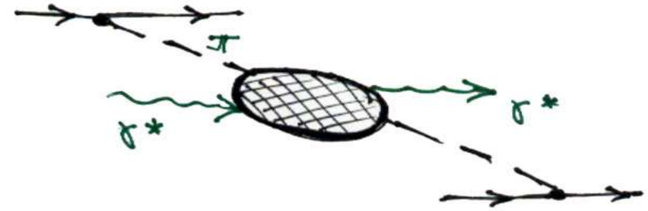


- *Independent determination from global QCD fit to p and D data with DIS,DY,$W^{\pm}/Z$*
  (S. Alekhin, S. Kulagin and R.P., PRD 96 (2017) 054005, arXiv:1609.08463 [nucl-th])
- *Results consistent with the $\delta f(x)$ function extracted from heavier targets with $A \geq 4$*
  $\Longrightarrow$ *Confirmation of δf universality and applicability to the deuteron.*

NUCLEAR MESON EXCHANGE CURRENTS

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

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

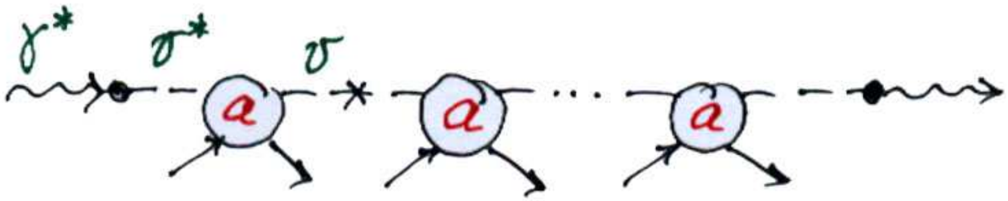


- *Contribution from nuclear pions (mesons) to balance nuclear light cone momentum* $\langle y\rangle_\pi + \langle y\rangle_N = 1$. *The pion distribution function is localized in a region of* $y \le p_F/M \sim 0.3$ *so that the pion contribution is at* $x < 0.3$. *The correction is driven by the average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



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

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

$a = \sigma(i+\alpha)/2$ *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*

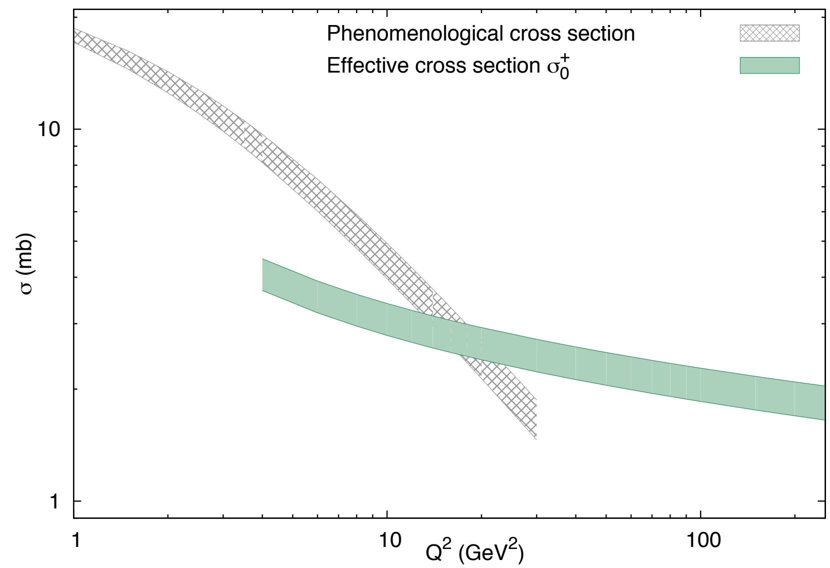
CONSTRAINTS FROM SUM RULES

- *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:*

$$\delta N_{\rm val}^{\rm OS} + \delta N_{\rm val}^{\rm coh} = 0 \quad \longrightarrow \quad a_0$$
$$\delta N_{1}^{\rm OS} + \delta N_{1}^{\rm coh} = 0 \quad \longrightarrow \quad a_1$$

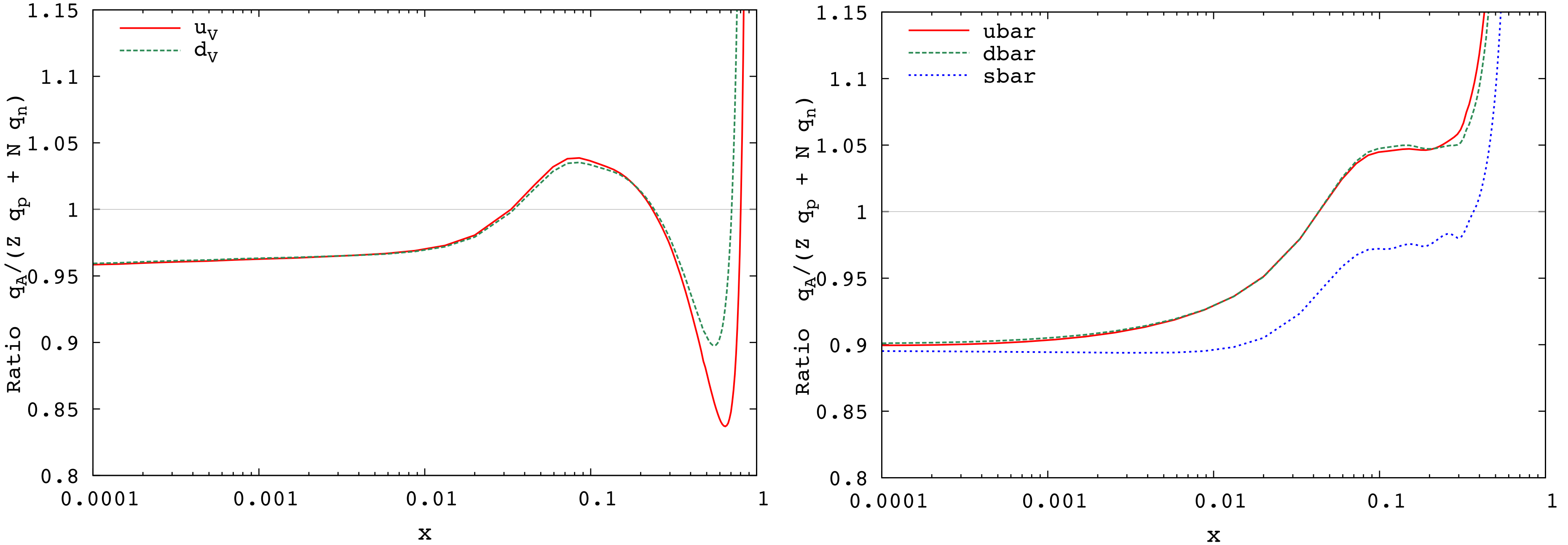
where $N_{\rm val}^A = A^{-1}\int_0^A dx q_{0/A}^- = 3$ *and* $N_1^A = A^{-1}\int_0^A dx q_{1/A}^- = (Z-N)/A$



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 controlled by $\mathcal{P}(\varepsilon, \mathbf{p})$ AND $\delta f(x)$*

NUCLEAR MODIFICATION OF PDFs



Ratio between our nPDFs and the corresponding ones calculated from free proton and neutron PDFs as $(Zq_p + Nq_n)$ at $Q^2 = 25$ GeV^2 in ^{207}Pb.

Flavor dependence driven by the proton PDF shape

NUCLEAR STRUCTURE FUNCTIONS

- *Operator product (twist) expansion in QCD:*

$$F_i(x, Q^2, p^2) = F_i^{\mathrm{LT,TMC}}(x, Q^2, p^2) + \frac{H_i(x)}{Q^2} + \mathcal{O}(Q^{-4}) \qquad i = 1, 2, 3$$

- *The leading twist (LT) term F_i^{LT} corresponds to free quark scattering and can be calculated in pQCD in terms of NPDFs convoluted with coefficient functions.*

- HIGH TWIST *terms $H_i(x)$ reflect the strength of multi-parton correlations (qq and qg), lack simple probabilistic interpretation, and are important for $Q^2 < 10$ GeV^2.*

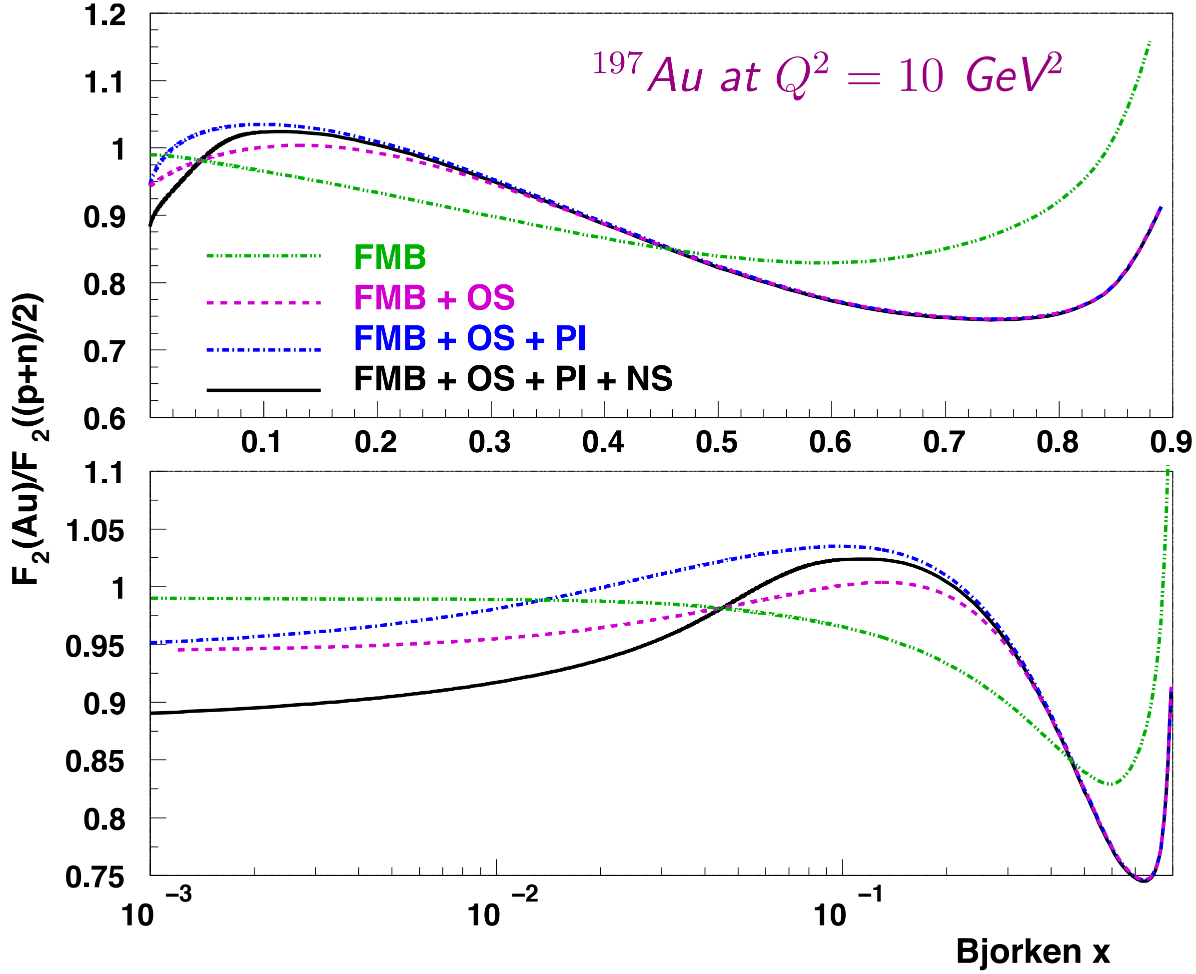
- TARGET MASS CORRECTIONS *describe the effect of finite M_N ($M_N^2 \to p^2$):*

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

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

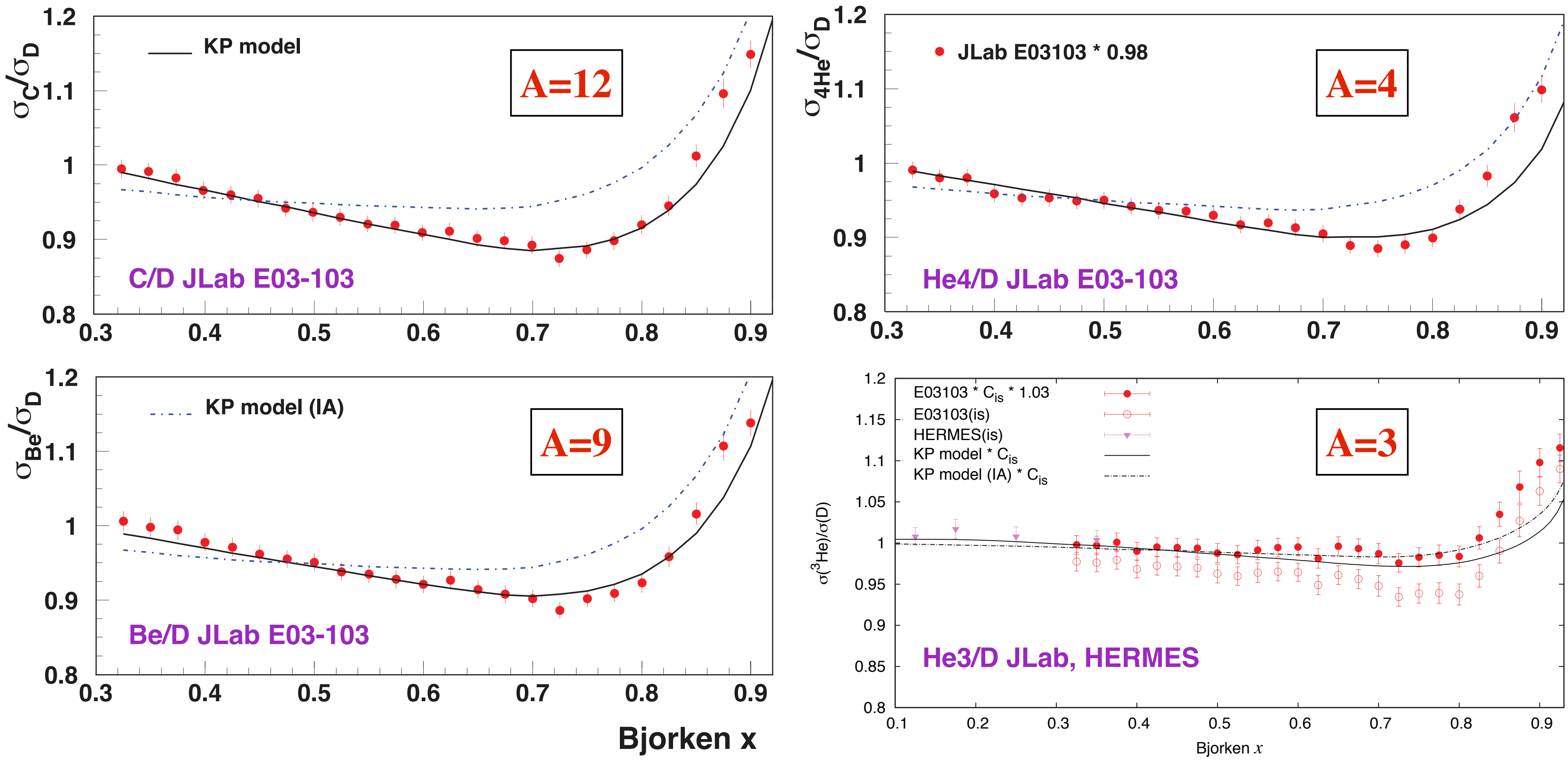
$\Longrightarrow$ *Nuclear structure functions are not just simple combinations of NPDFs!*

PREDICTIONS FOR CHARGED LEPTON DIS

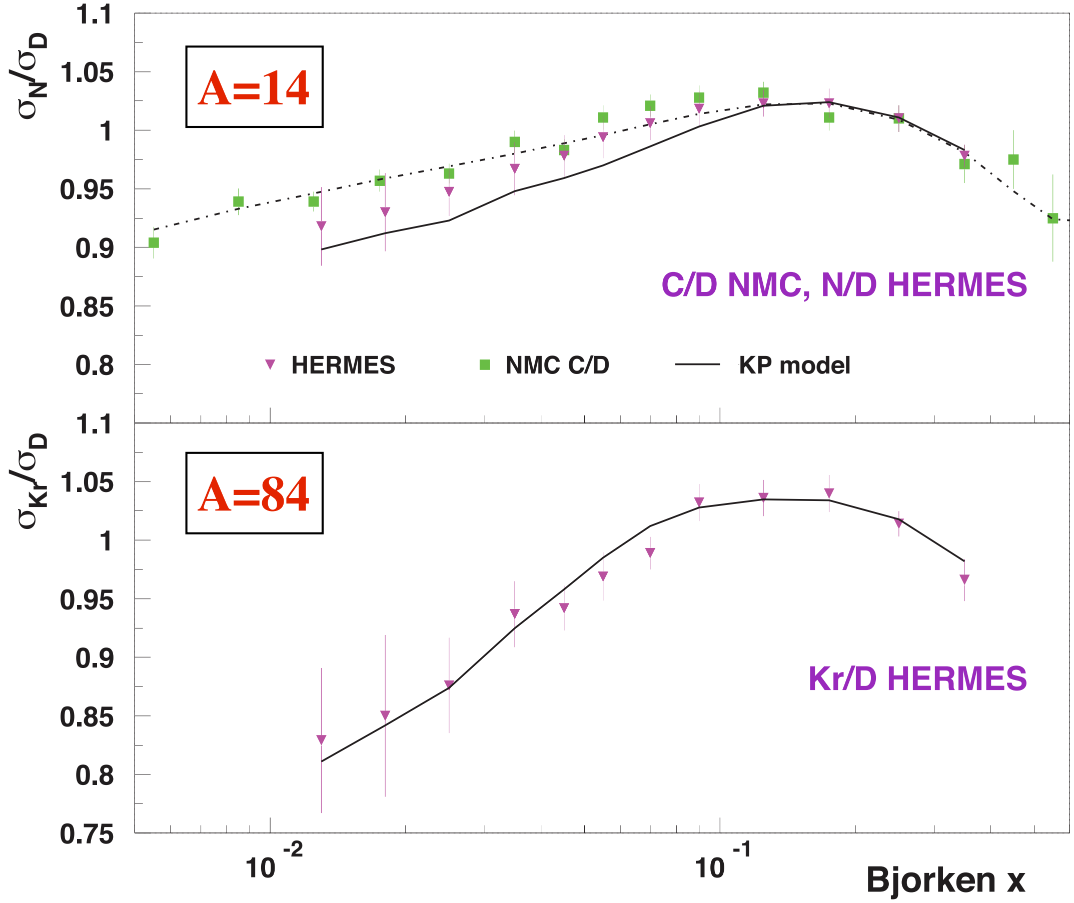


Interplay of different mechanisms $\Longrightarrow$ *Unfold individual nuclear effects*

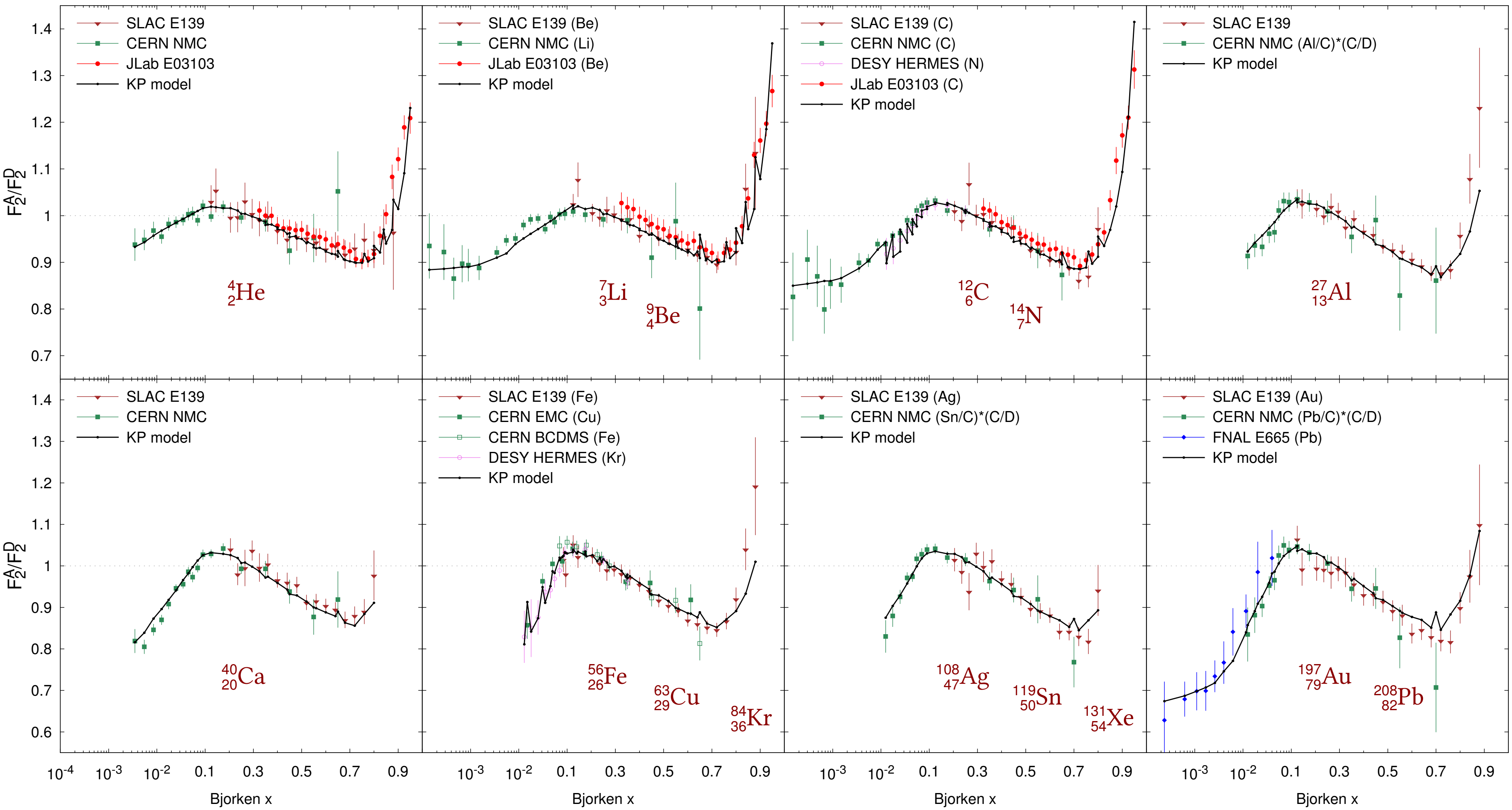
S. Kulagin and R.P., PRC 82 (2010) 054614



Independent predictions, NOT A FIT!



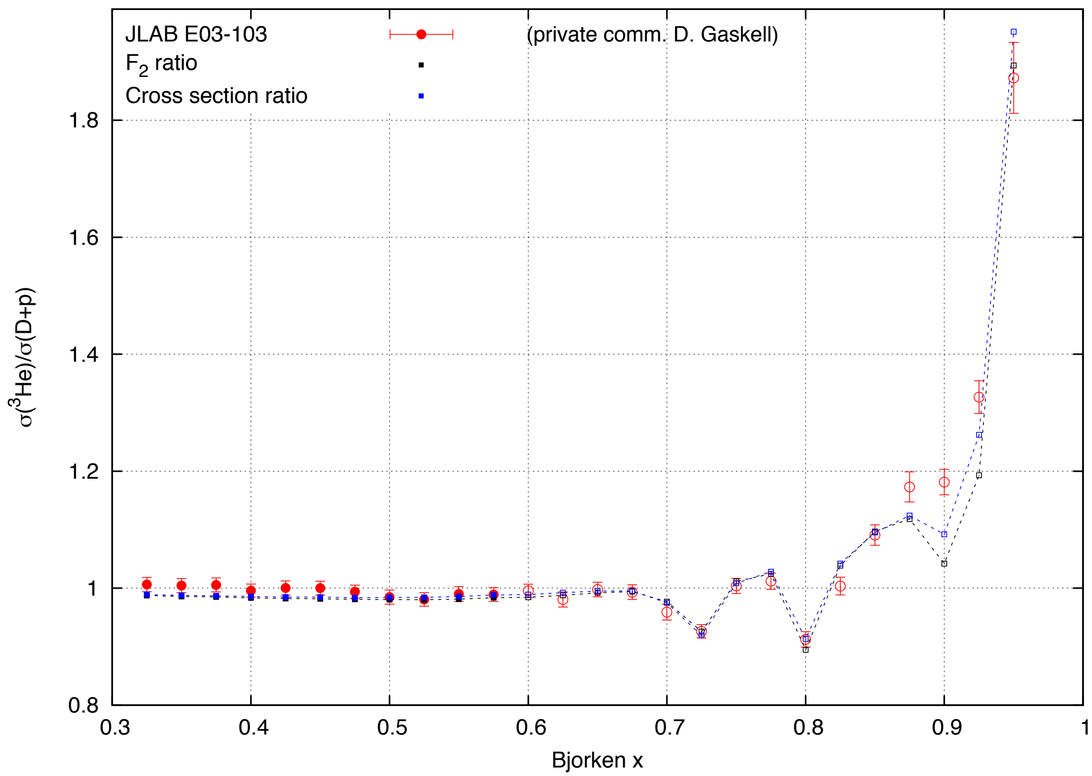
S. Kulagin and R.P., PRC 82 (2010) 054614



Overall we obtain $\chi^2/N_{\rm Data} = 466.6/586$ *for all DIS data with* $Q^2 \geq 1$ *GeV*^{2}

$\Longrightarrow$ *Microscopic model provides quantitative description of available data*

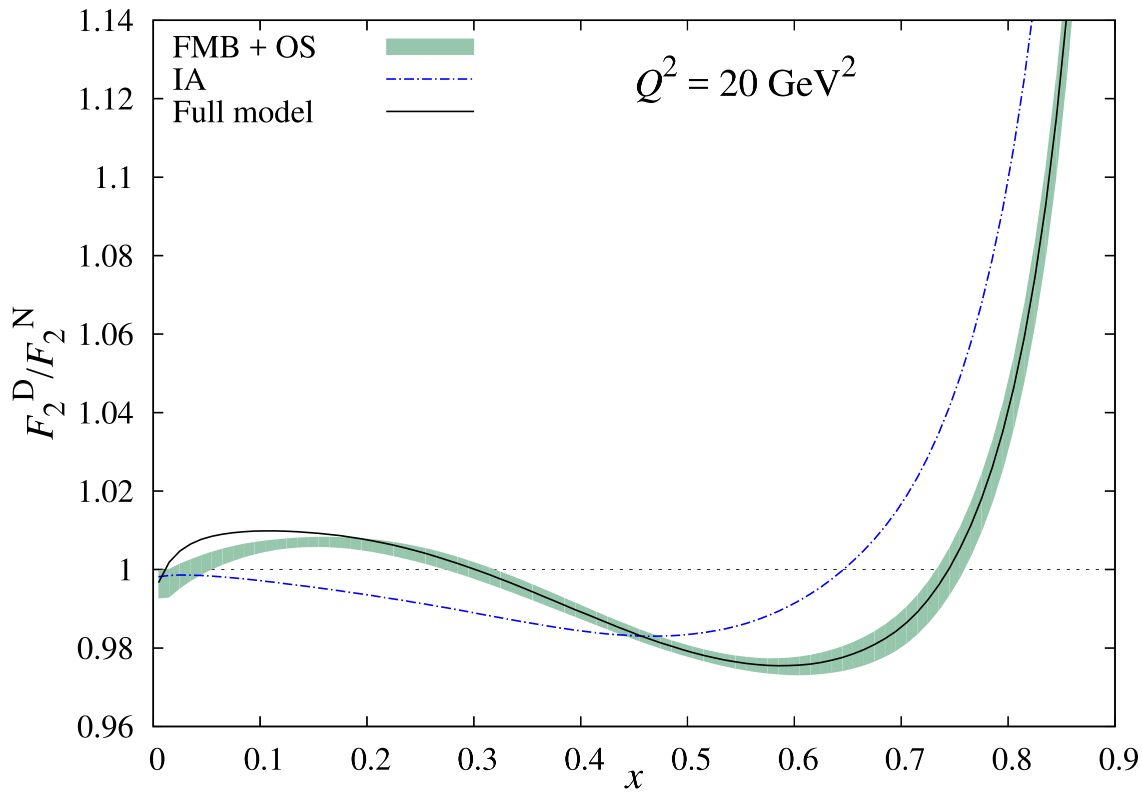
NUCLEAR EFFECTS IN RESONANCE REGION



- *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*

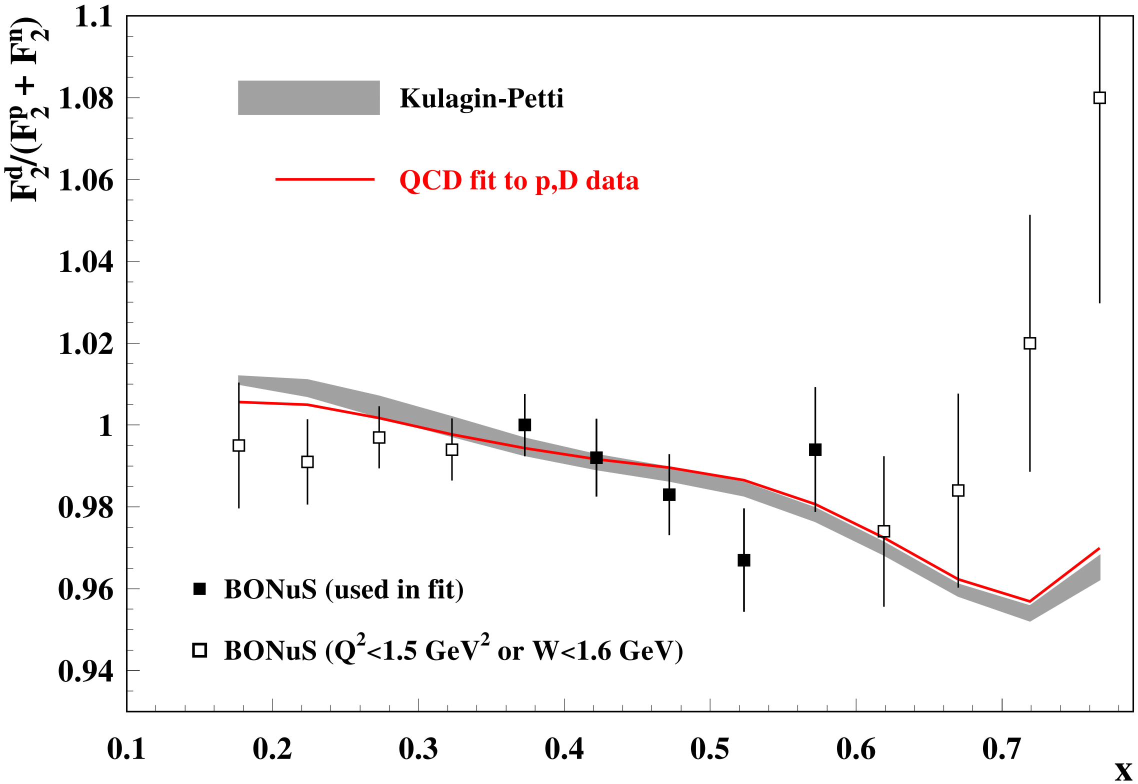
  $\Longrightarrow$ *Consistent treatment of nuclear effects in DIS and resonance regions?*

PREDICTIONS FOR THE DEUTERON



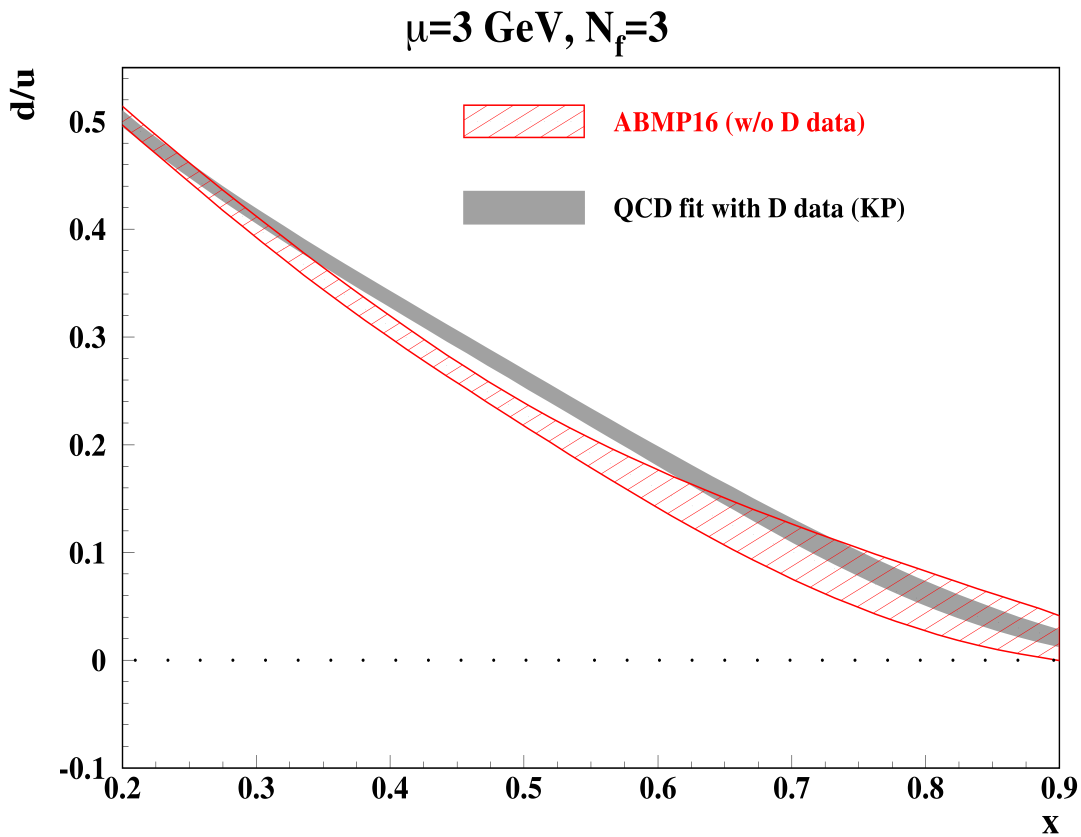
For $0.3 < x < 0.6$ *EMC slope* $dR_{\mathrm{EMC}}/dx = -0.099 \pm 0.006$ *predicted for* ^2D

Comparison with the direct BONuS measurement [PRC 92 (2015) 015211] of $F_2^D/(F_2^p + F_2^n)$:



S. Alekhin, S. Kulagin and R.P., PRD 96 (2017) 054005, arXiv:1609.08463 [nucl-th]

DETERMINATION OF d/u RATIO FROM GLOBAL FITS

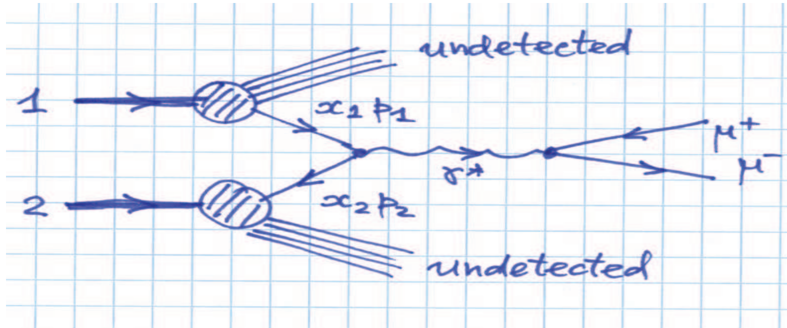


S. Alekhin, S. Kulagin, R.P., PRD 96 (2017) 054005

- *Uncertainty on d/u ratio without external constraints affected by the systematics on the deuteron off-shell correction at $x > 0.4$*
- *$\delta f(x)$ universality allows to use the more precise result obtained from heavy targets*

APPLICATION TO DRELL-YAN PRODUCTION IN pA

- *Selecting small Q^2/s and large x_F we probe sea quarks in the target nucleus*



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

$$x_T x_B = Q^2/s; \quad x_B - x_T = 2q_L/\sqrt{s} = x_F$$

- *Need to consider the energy loss by the projectile parton in the target nucleus:*

$$x_B \rightarrow x_B + E'L/E_B \qquad E' = -dE/dz$$

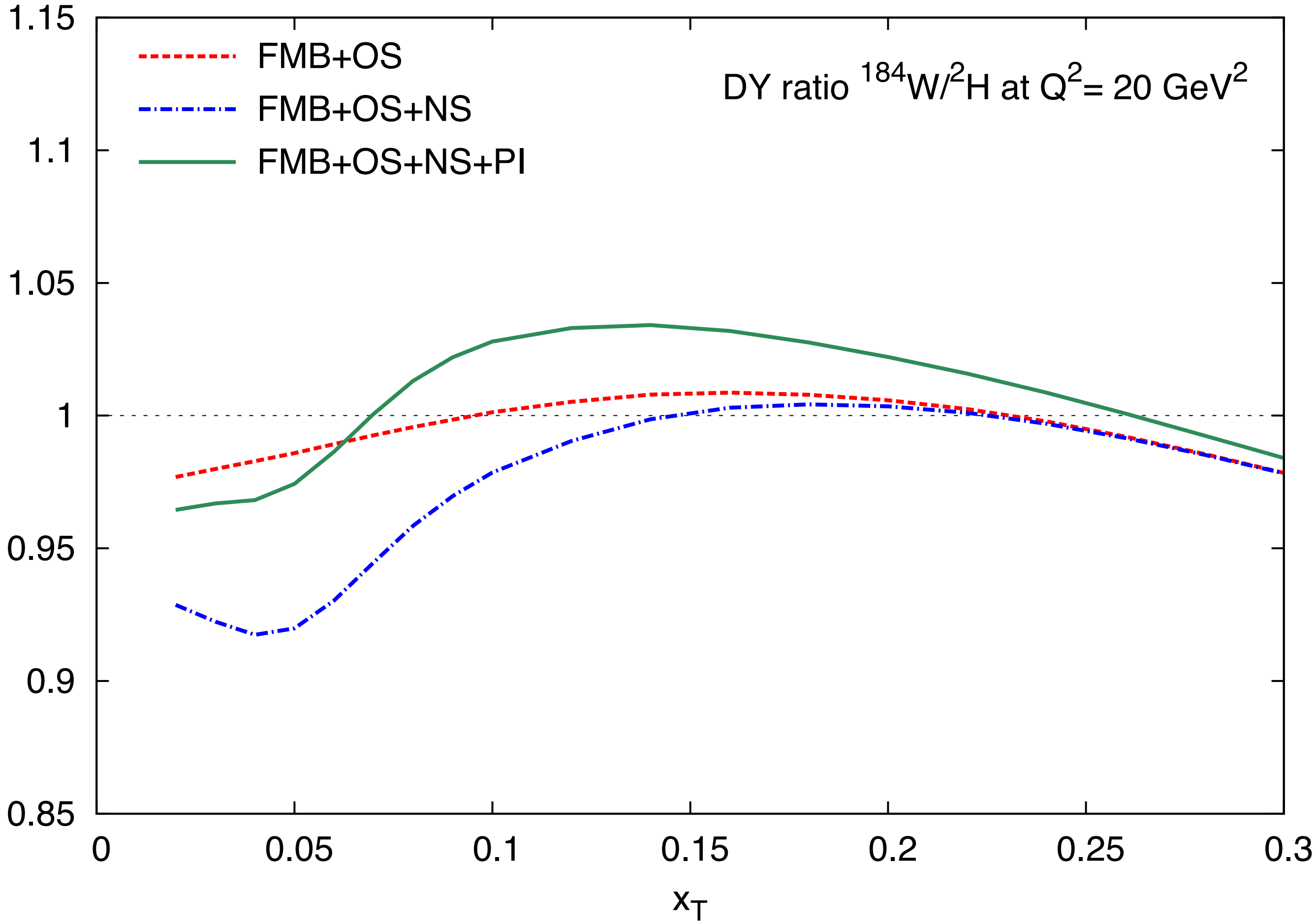
where E_B energy of proton, L distance traveled in nuclear environment

- *In E772/E866 s=1504 GeV^2 and at $x_F > 0.2$ dominated by $q^B\bar{q}^T$ annihilation:*

$$\frac{\sigma_A^{\rm DY}}{\sigma_B^{\rm DY}} \approx \frac{\bar{q}_A(x_T)}{\bar{q}_B(x_T)}$$

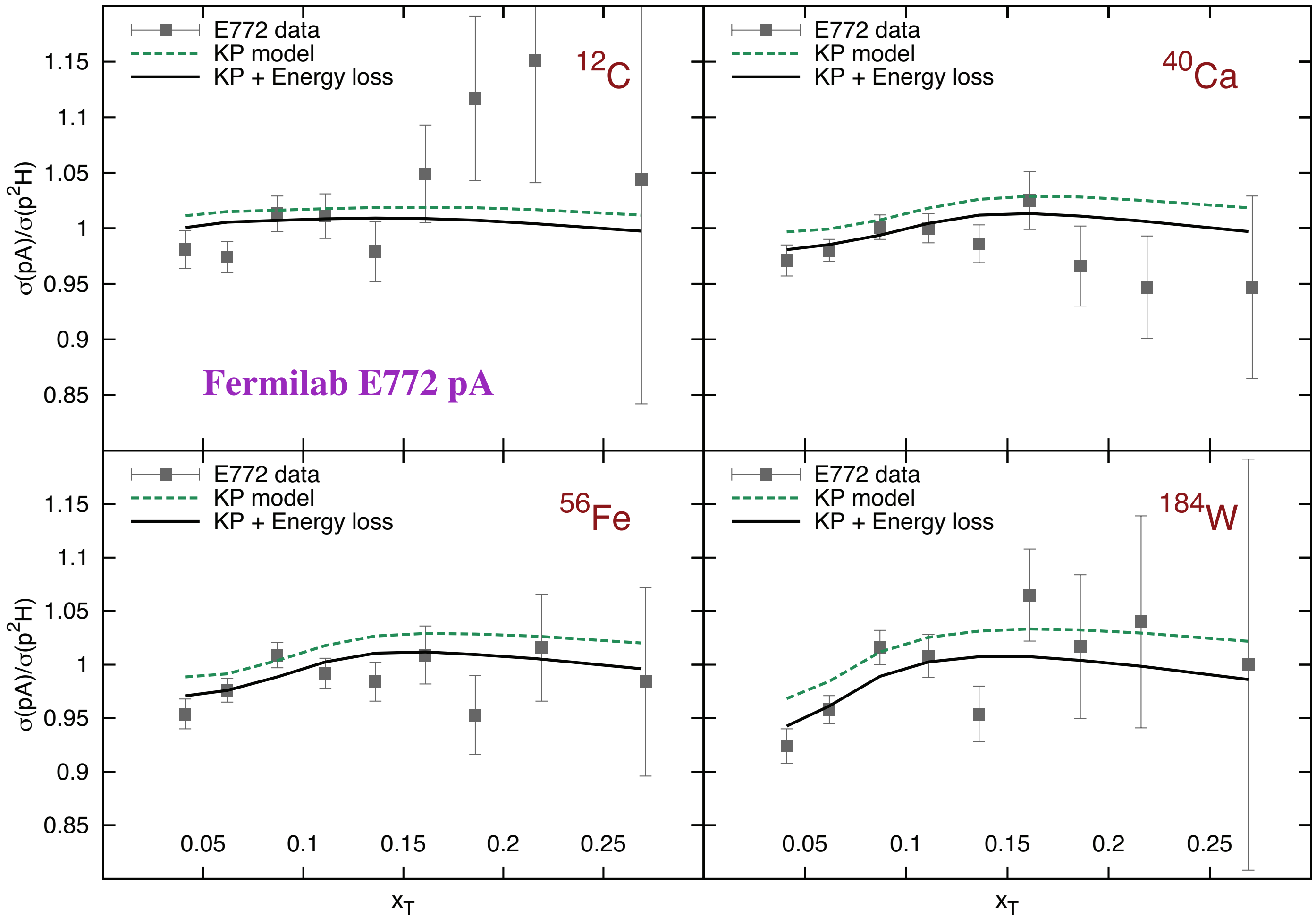
$\Longrightarrow$ *Nuclear data from Drell-Yan production in hadron collisions indicate no major enhancement to sea quarks for $x_T > 0.1$ as given by nuclear π excess*

PREDICTIONS FOR DRELL-YAN DATA



Partial cancellation between pion and shadowing effects for large $x \sim 0.05 - 0.1$

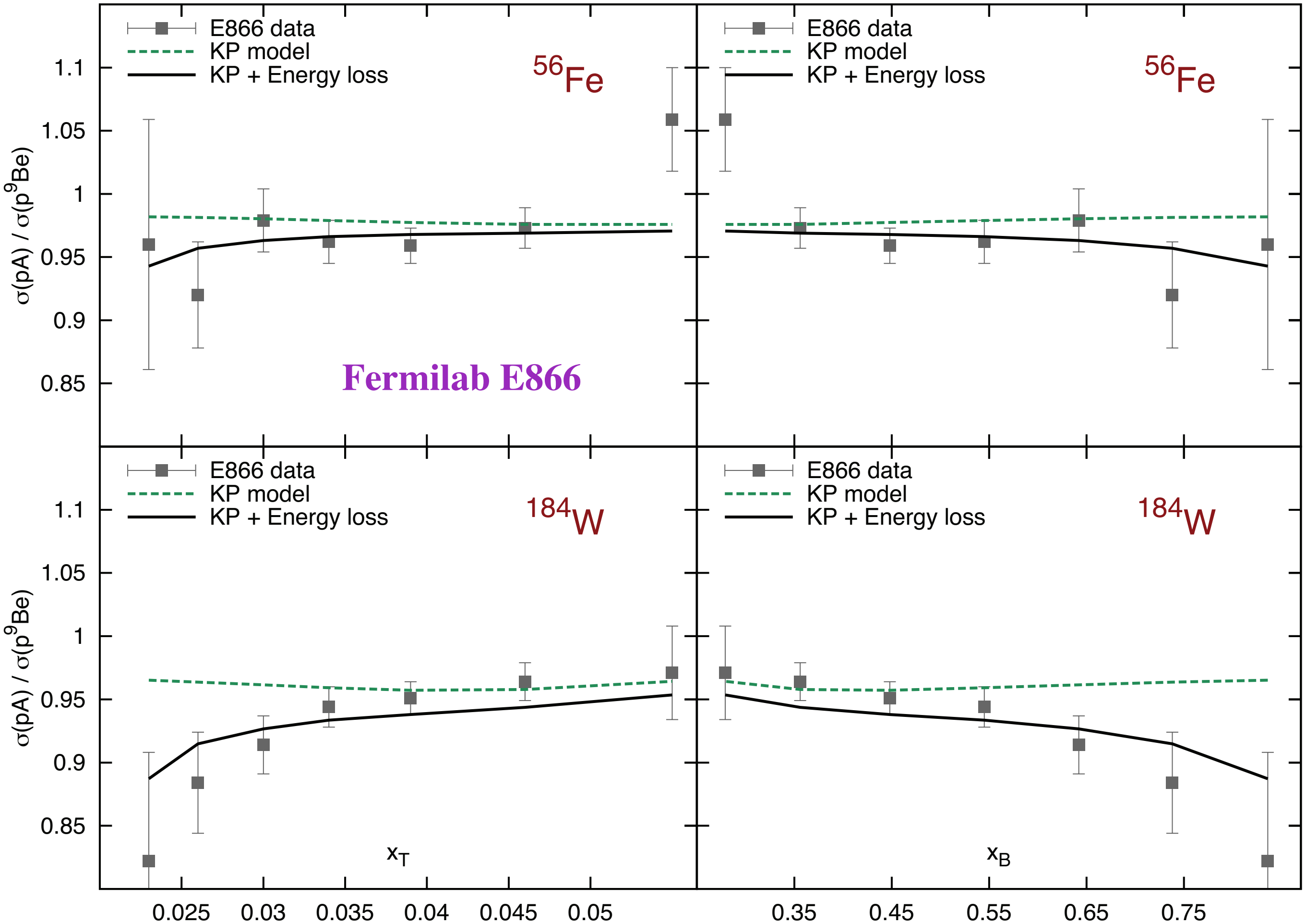
S. Kulagin and R.P., PRC 90 (2014) 045204



$\Longrightarrow$ *Validation of nPDF calculation with independent physics process and kinematic range*

$\Longrightarrow$ *No evidence of sea-valence differences in $\delta f(x)$ from Drell-Yan data*

S. Kulagin and R.P., PRC 90 (2014) 045204



APPLICATION TO $W^{\pm}, Z$ PRODUCTION IN p+Pb AT THE LHC

- $W^{\pm}, Z$ production in p+Pb collisions at the LHC *good tool to study nuclear PDFs:*
  - *Leptonic decays of electroweak bosons can directly probe cold nuclear matter (CNM) effects since leptons do not interact strongly with the medium produced in these collisions;*
  - *Access to a kinematic region not reachable by fixed target experiments;*
  - *Selecting different rapidity values can probe the Pb fragmentation region and nuclear modifications of PDFs in Pb at $x_{Pb} \simeq M_{W,Z}/\sqrt{s_{\rm NN}} \times \exp(-y)$.*

- *Using QCD factorization DY in $W^{\pm}/Z^0$ production in p-A collisions is given by:*

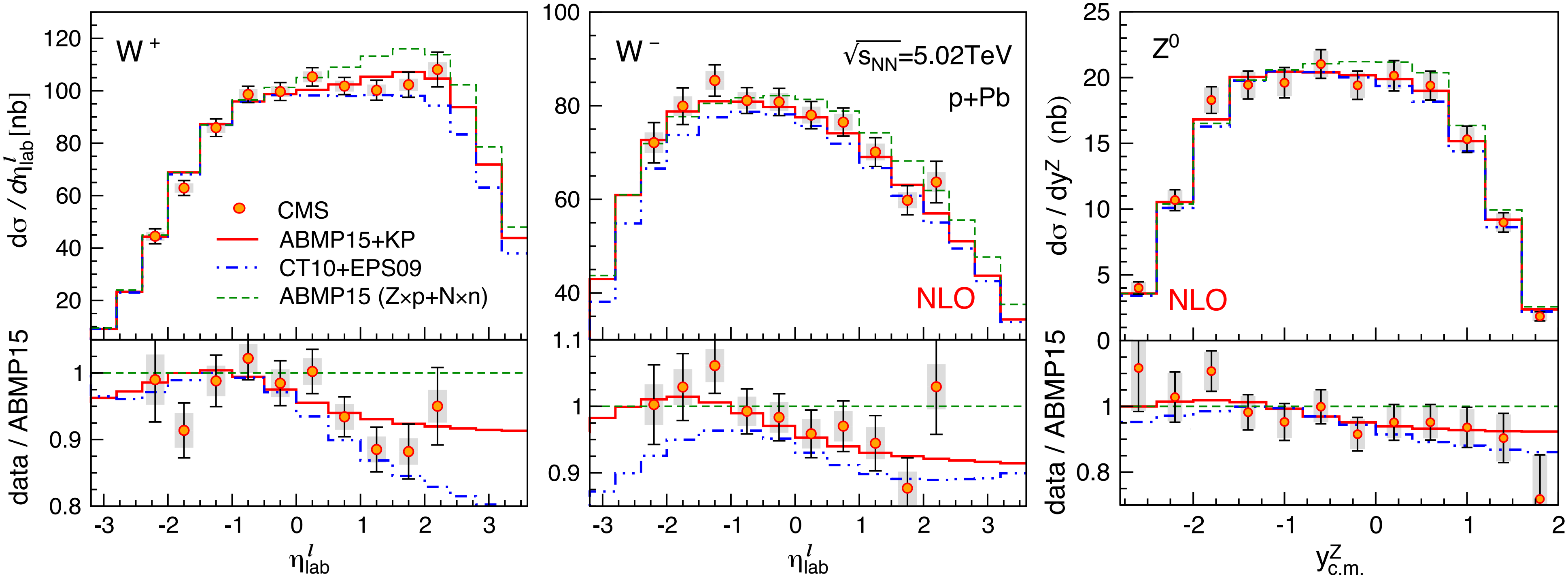
$$\frac{d^2\sigma_{pA}}{dQ^2dy} = \sum_{a,b} \int dx_a dx_b \, q_{a/p}(x_a, Q^2) \, q_{b/A}(x_b, Q^2) \frac{d^2\hat{\sigma}_{ab}}{dQ^2dy}$$

where σ_{pA} and $\hat{\sigma}_{ab}$ are the hadronic and partonic cross sections.

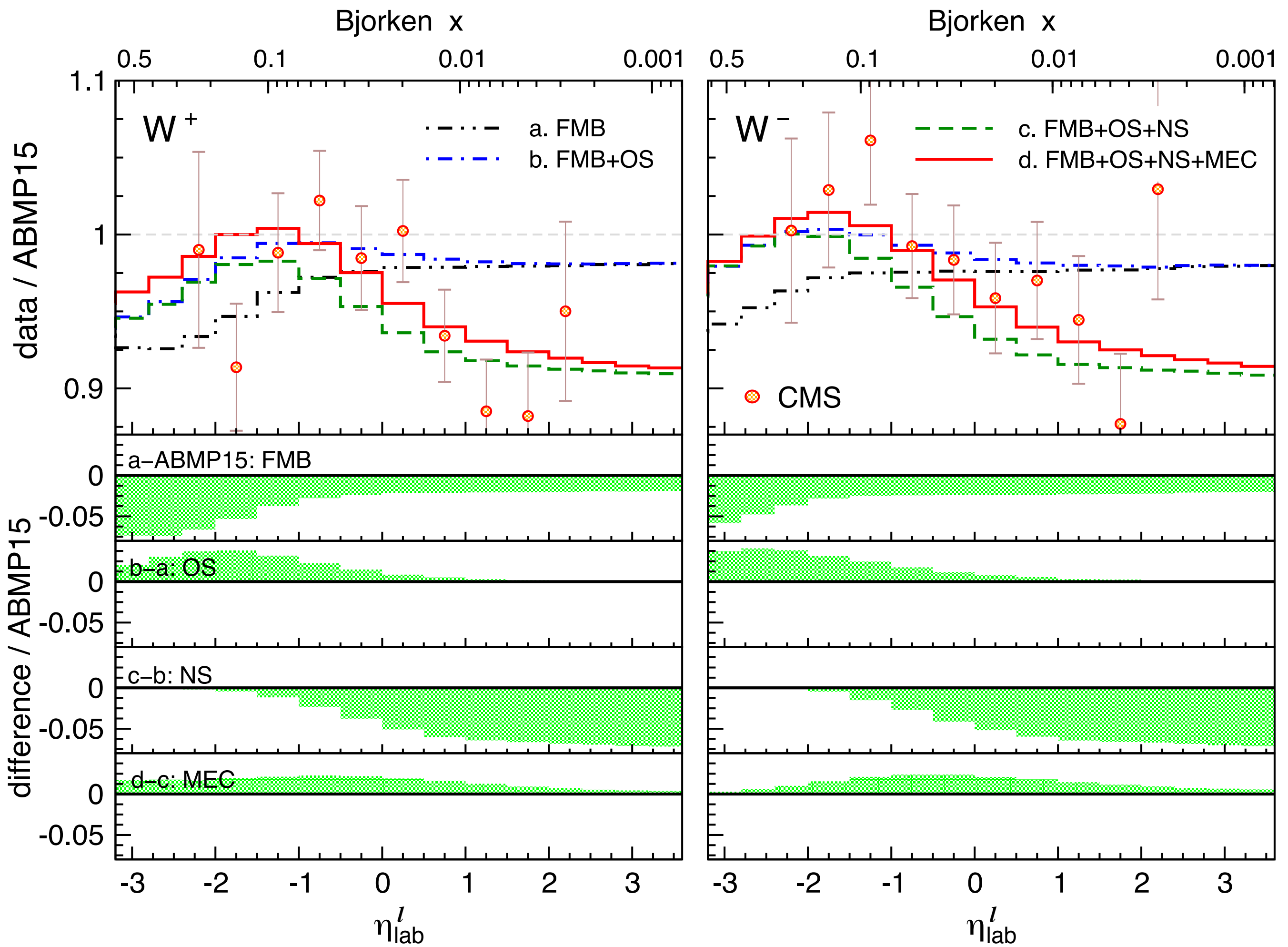
- *We study the (pseudo)rapidity distributions of $W^{\pm}/Z^0$ bosons in $p + \mathrm{Pb}$ collisions at the LHC at $\sqrt{s} = 5.02$ TeV using the DYNNLO program within the NLO QCD approximation with $\mu_r = \mu_f = m_{W,Z}$ [PRL 103 (2009) 082001]*

PREDICTIONS FOR $W^{\pm}$ AND Z^0 PRODUCTION IN p+Pb

$$Q^2 = m^2_{W,Z}$$



P. Ru, S. Kulagin, R.P. and B-W. Zhang, PRD 94 (2016) 113013, arXiv:1608.06835 [nucl-th]



$Q^2 = m_W^2$

$\Longrightarrow$ *Rapidity distributions sensitive to all nuclear effects: FMB, OS, NS, MEC*

$\Longrightarrow$ *Current data consistent with single universal δf (tests of flavor dependence)*

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

Independent predictions
NOT A FIT!

P. Ru, S. Kulagin, R.P. and B-W. Zhang, PRD 94 (2016) 113013, arXiv:1608.06835 [nucl-th]

SUMMARY

- *The KP nuclear PDFs are predicted on the basis of a microscopic nuclear model, including nuclear effects like shadowing, energy-momentum distribution of bound nucleons (spectral function), nuclear meson-exchange currents and off-shell corrections*

  $\Longrightarrow$ *Additional degree of freedom of the nucleon related to its off-shellness and described by a special structure function δf*

- *A quantitative study of existing data from charged lepton-nucleus DIS has been performed in a wide kinematic region of x and Q^2*

  $\Longrightarrow$ *Good agreement of predictions with data from nuclear DIS measurements*

- *Predictions in good agreement with Drell-Yan data indicating a partial cancellation between different nuclear effects*

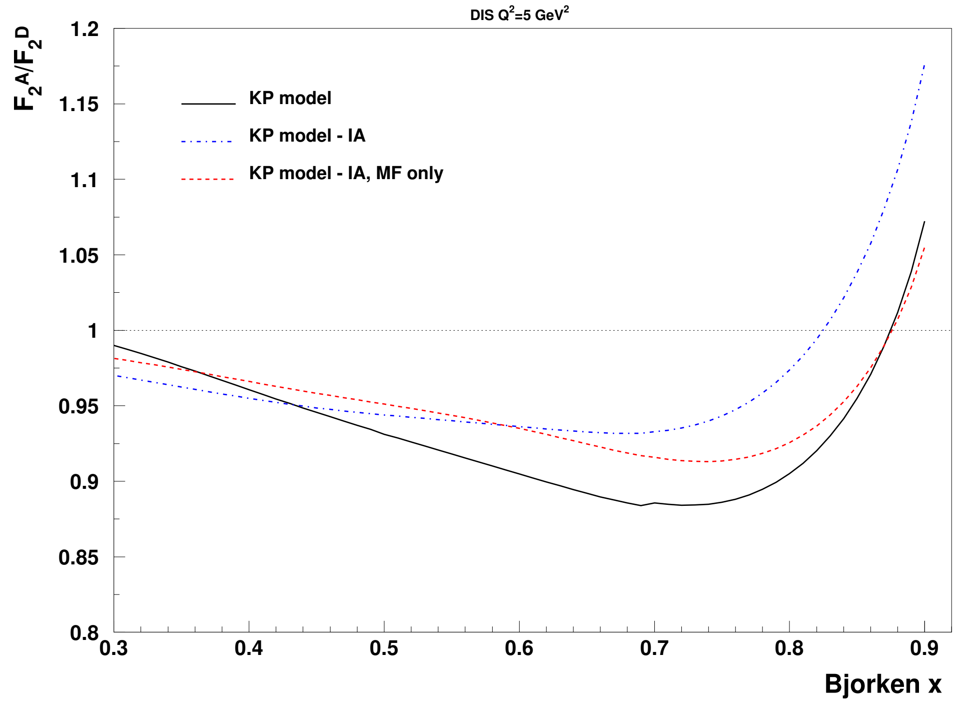
- *Predictions in good agreement with $W^\pm$ and Z boson production in pPb collisions at the LHC with much higher energies ($\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV) than fixed target experiments*

  $\Longrightarrow$ *Evidence of nuclear modification of cross-sections and support of factorization*

Backup slides

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*



$\Longrightarrow$ *Short range NN correlations relevant for the EMC slope and at large Bjorken* x

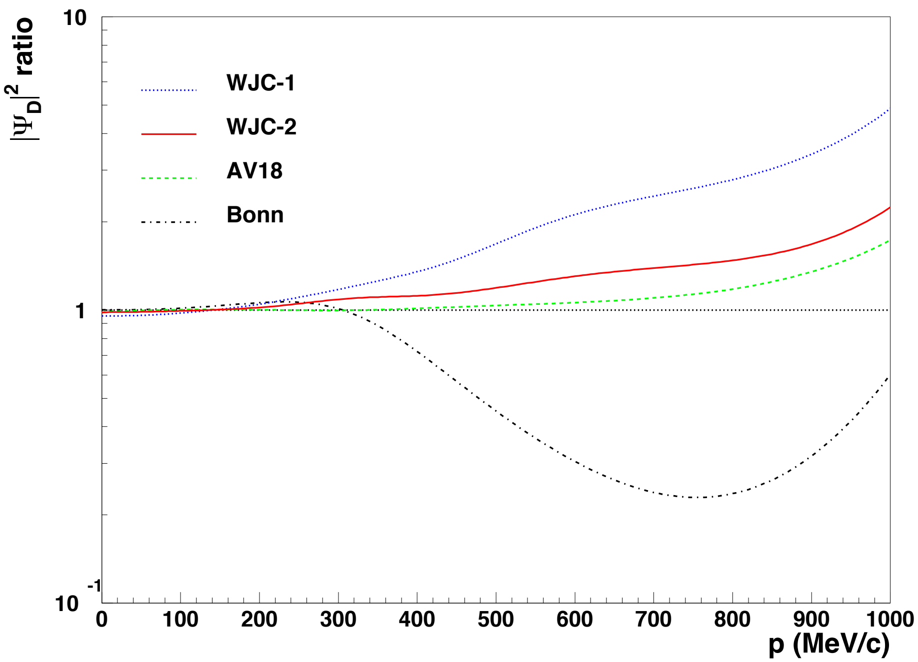
DEUTERON WAVE FUNCTION

- *For D the residual nuclear system is p or n and the spectral function becomes:*

$$\mathcal{P}(\varepsilon, \mathbf{p}) = 2\pi\delta\left(\varepsilon - \varepsilon_D + \frac{\mathbf{p}^2}{2M}\right)|\Psi_D(\mathbf{p})|^2$$

where $\varepsilon_D = M_D - 2M$ *is the binding energy and* $\Psi_D(\mathbf{p})$ *is the deuteron wave function.*

- *The description of the nuclear properties is provided by the deuteron wave function, which is a superposition of* s*- and* d*-wave states in momentum space, with a a small admixture of* p*-wave in relativistic models.*



$|\Psi_D(\mathbf{p})|^2$ *gives deuteron momentum distribution*

Different N-N potentials used

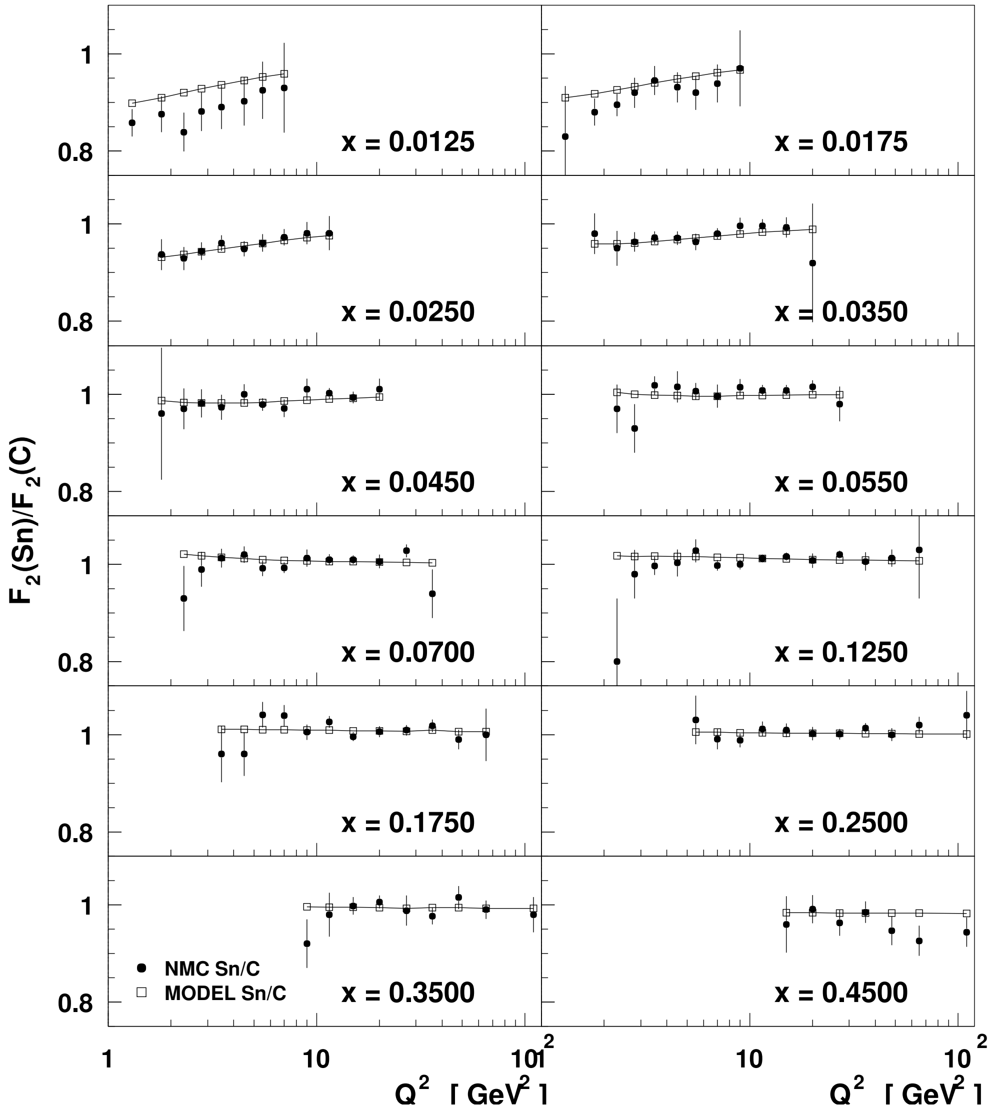
Paris: *PRC 21 (1980) 861*

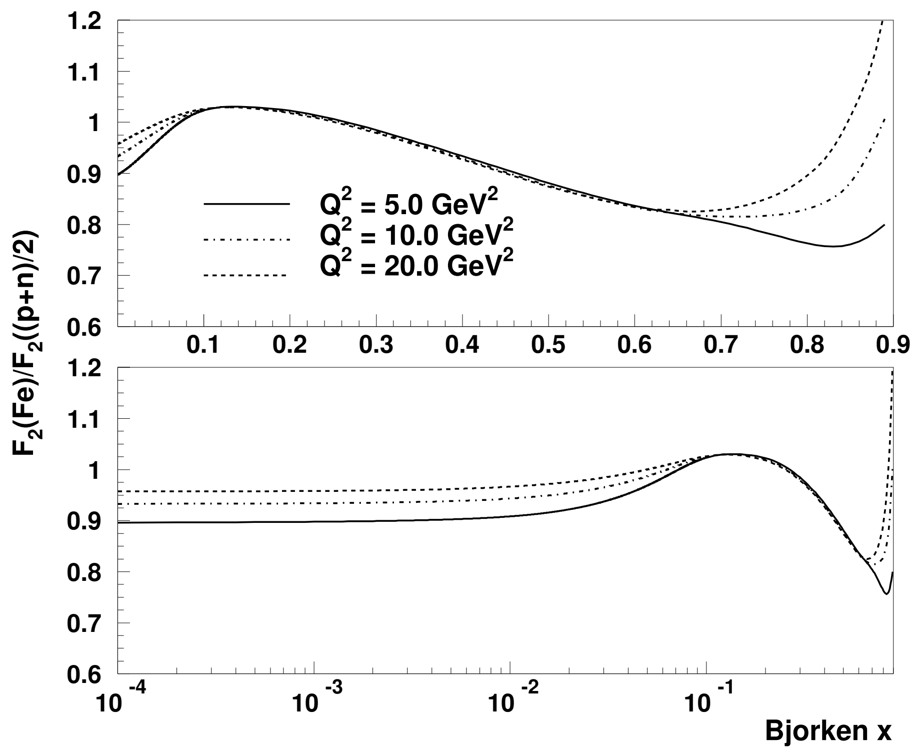
Bonn: *PR 149 (1987) 149*

AV18: *PRC 84 (2011) 034003*

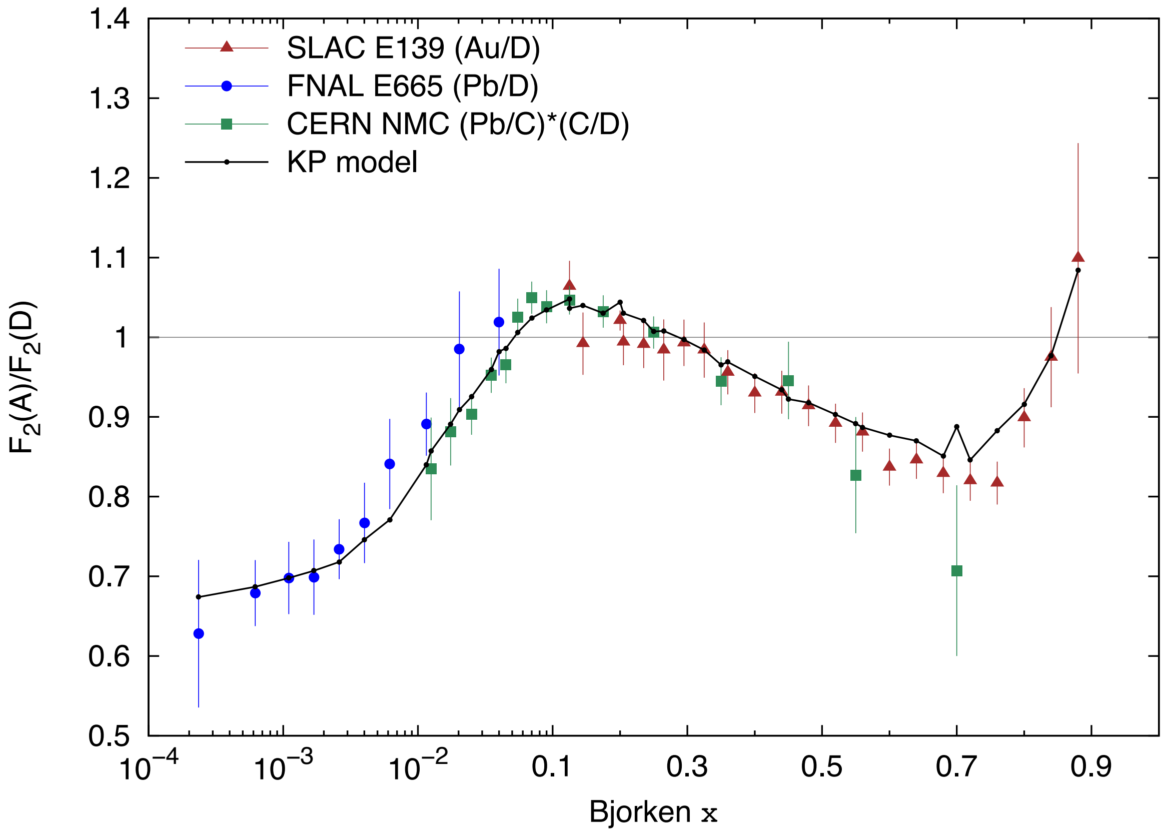
WJC-1,2: *PRC 82 (2010) 034004*

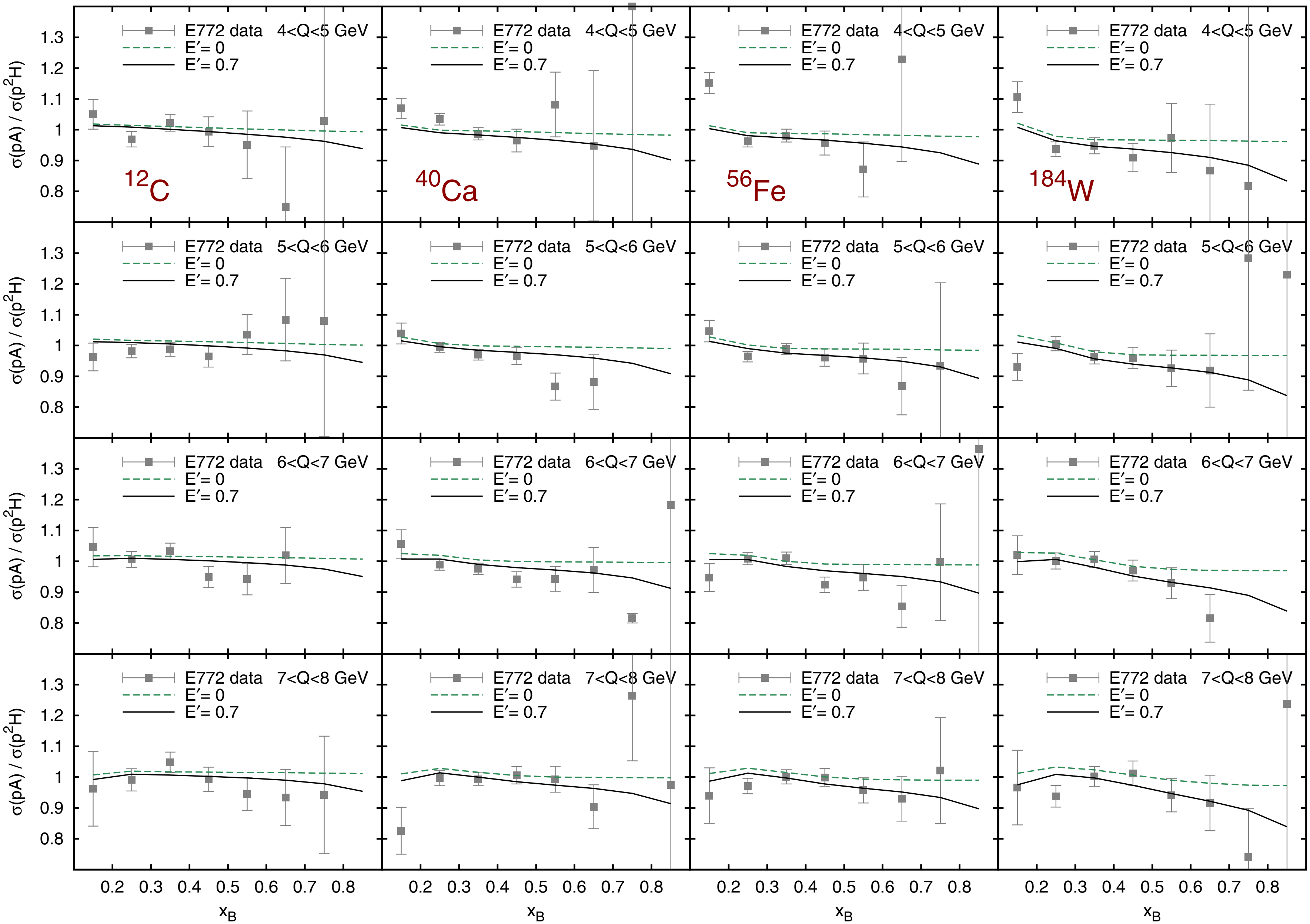
ANALYSIS OF Q^2 DEPENDENCE OF $\mathcal{R}_2$



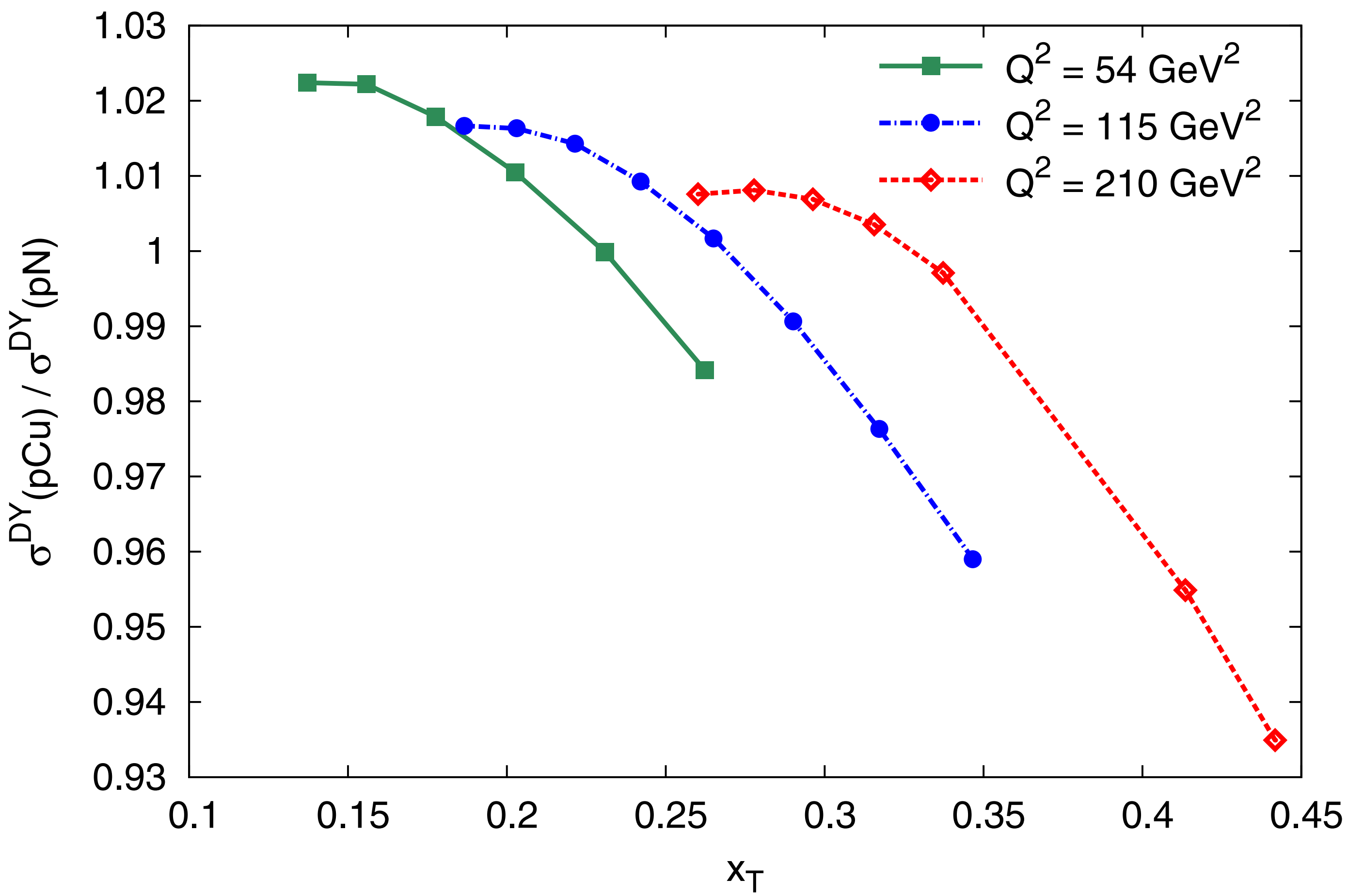


Significant Q^2 dependence only for $x < 0.1$ (shadowing) and $x > 0.65$ (TMC expansion)


SLAC E139 (Au/D)
FNAL E665 (Pb/D)
CERN NMC (Pb/C)*(C/D)
KP model
$F_2(A)/F_2(D)$
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

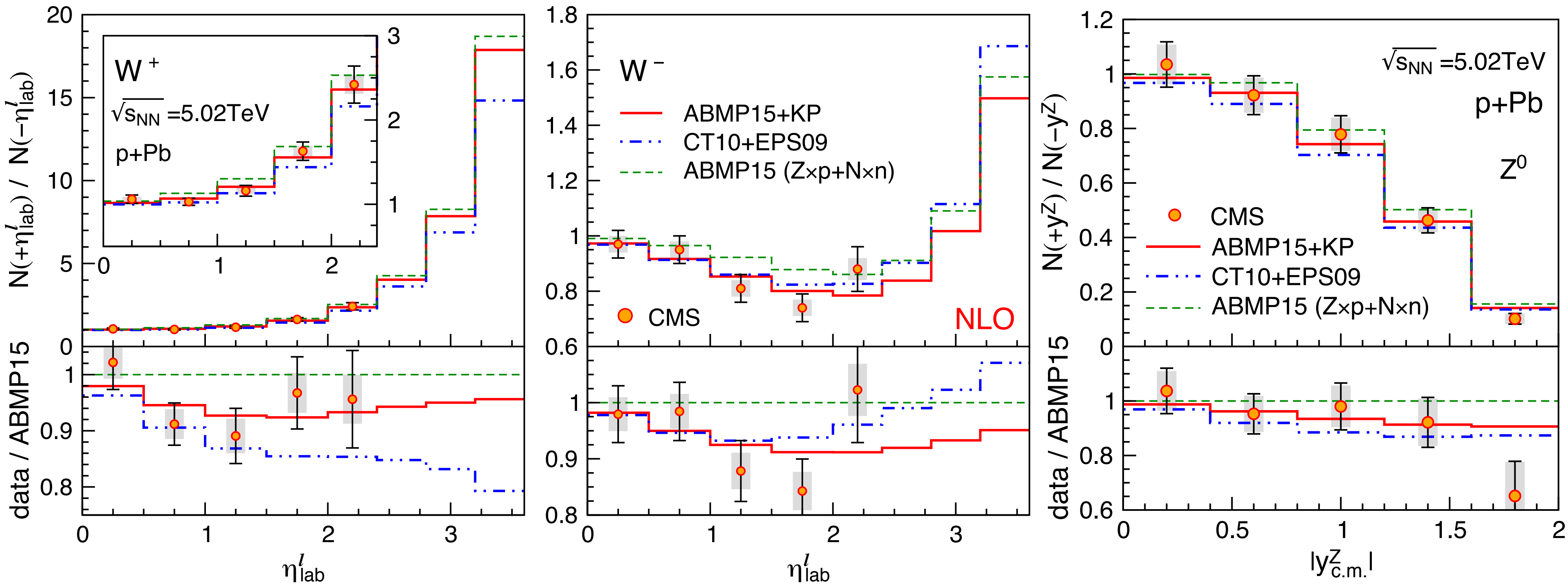


E772 Drell-Yan p-A data



Nuclear correction for E605 Drell-Yan p-Cu data

$Q^2 = m^2_{W,Z}$



P. Ru, S. Kulagin, R.P. and B-W. Zhang, PRD 94 (2016) 113013, arXiv:1608.06835 [nucl-th]

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 $\chi^2/\mathrm{DOF} = 466.6/586$.

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/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	

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

$\Longrightarrow$ *Microscopic model provides quantitative description of available data*

FLAVOR AND C-PARITY DEPENDENCE OF nPDFs

- *Impulse Approximation (IA) from the convolution of isoscalar $q_0 = u + d$ and isovector $q_1 = u\text{-}d$ nucleon PDF with the corresponding spectral functions:*

$$q_{0/A}^{\rm IA} = \left(f_{p/A} + f_{n/A}\right) \oplus q_{0/p} \qquad \mathcal{P}_0 = \mathcal{P}_{\rm MF} + \mathcal{P}_{\rm cor}$$
$$q_{1/A}^{\rm IA} = \left(f_{p/A} - f_{n/A}\right) \oplus q_{1/p} \qquad \mathcal{P}_1 = |\,\phi_F(\mathbf{p})\,|^2\,\delta(\varepsilon - \varepsilon_F)$$

- *Off-shell effect controlled by the nucleon $\delta f(x)$ function*

  $\Longrightarrow$ *We assume universal δf for all partons for simplicity*

  $\Longrightarrow$ *Verify isospin and/or flavor dependance with data from flavor-sensitive processes.*

- *Nuclear shadowing depends on C-parity $q^{\pm} = q \pm \bar{q}$:*

$$\delta\mathcal{R}^{+} = \operatorname{Im}\mathcal{A}(a^{+})/A \operatorname{Im} a^{+} \qquad \delta\mathcal{R}^{-} = \operatorname{Im} a^{-}\mathcal{A}_1(a^{+})/A \operatorname{Im} a^{-}$$

where $\mathcal{A}_1(a) = \partial\mathcal{A}(a)\partial a$ and $a^{\pm} = a \pm \bar{a}$ are the amplitudes of definite C parity.

  - $|\delta\mathcal{R}^{-}| > |\delta\mathcal{R}^{+}|$ *because of the nonlinear dependence $\mathcal{A}(a)$.*
  - $\delta\mathcal{R}^{-}$ *is independent of the cross section $\sigma^{-} = 2\operatorname{Im} a^{-}$. However it nonlinearly depends on a^{+}.*

- *For isoscalar targets nuclear pion (meson) correction to valence distributions cancels out (isospin symmetry) $\delta_\pi q_{0/A}^{-} = 0$*

EMPIRICAL NUCLEAR PDFs

✦ *NPDFs usually obtained from global QCD fits to nuclear DIS, DY, heavy ion collisions:*

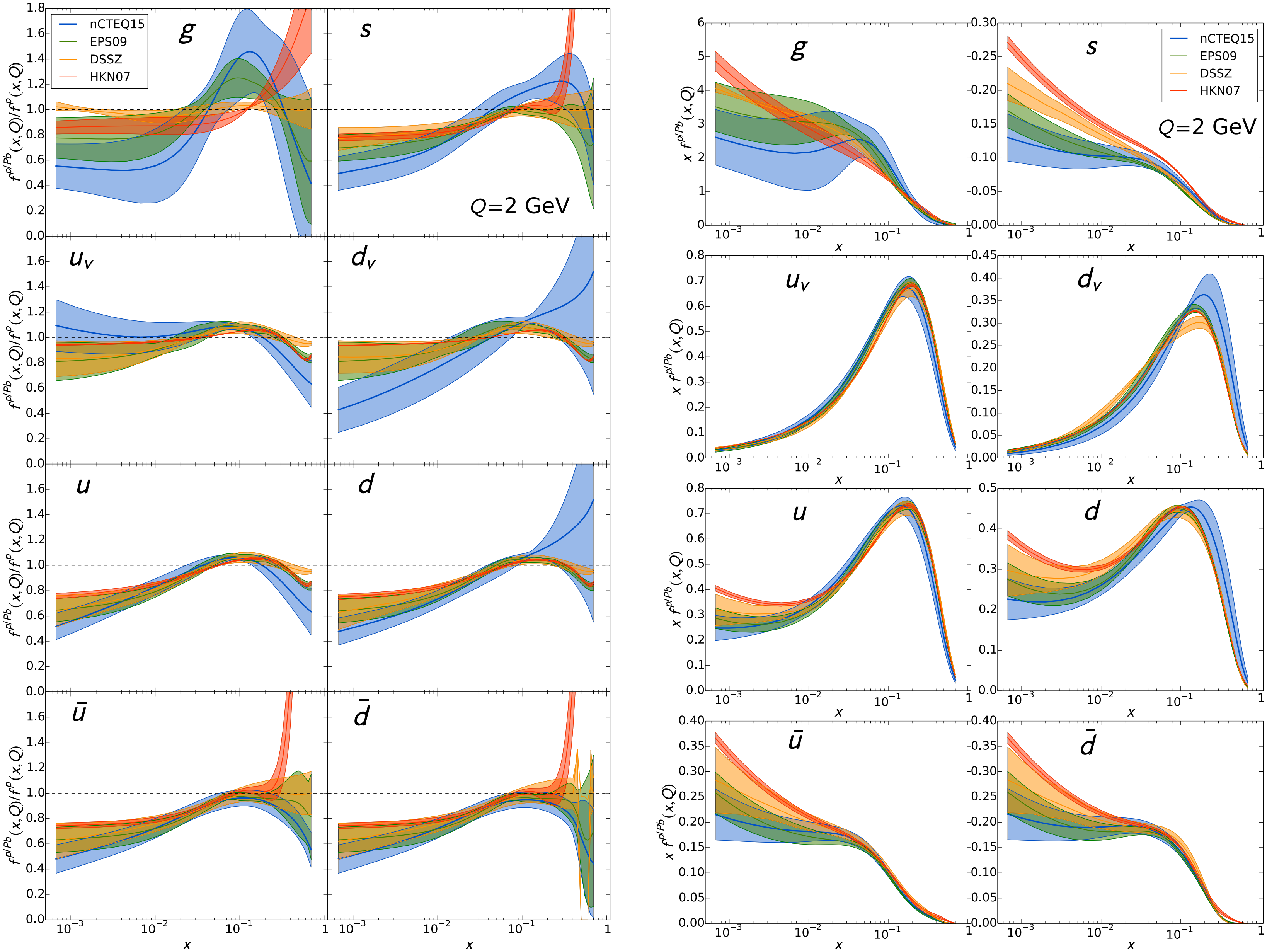
- *Assume* $f_{i/A}(x,Q^2) = Zf_{i/p}(x,Q^2) + Nf_{i/n}(x,Q^2)$ *where* $f_{i/p}$ *and* $f_{i/n}$ *are bound proton and neutron PDFs;*
- *Assume isospin symmetry relations* $u_p = d_n$, $d_p = u_n$, $s_p = s_n$, $g_p = g_n$*;*
- *Assume functional form for* $f_{i/A}$ *or for the ratio* $R_i^A = f_{i/p}/f_{i/p}^0$ *with free proton PDFs* $f_{i/p}^0$.

✦ *Several analyses available in literature using different parametrizations of the* x *and* A *dependencies of* $f_{i/A}$ *or* R_i^A*: EPS, DSSZ, HKN, nCTEQ.*

✦ *While useful to study and constrain nuclear corrections to PDFs, phenomenological NPDF fits are characterized by a few limitations:*

- *Little insight into the underlying nuclear mechanisms responsible for nucler modifications of PDFs;*
- *Many free parameters to describe both the* x *and* A *dependencies, which are difficult to determine from the limited nuclear data available;*
- *Not clear separation between leading twist and higher twists in the relatively low* Q^2 *DIS data.*

$\Longrightarrow$ *Will describe a different approach, in which NPDFs are predicted on the basis of an underlying microscopic nuclear model.*


nCTEQ15
EPS09
DSSZ
HKN07
g
s
u_v
d_v
u
d
$\bar{u}$
$\bar{d}$
Q=2 GeV
$f^{p/Pb}(x,Q)/f^p(x,Q)$
$x\ f^{p/Pb}(x,Q)$
x