Applications of KP Nuclear Parton Distributions

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OUTLINE

I *The KP Nuclear Parton Distributions*

- *Different mechanisms of nuclear effects in different kinematical regions;*
- *Off-shell correction $\Leftrightarrow$ in-medium modification of bound nucleons;*

II *Application to lA DIS*

- *Comparisons with JLab E03-103 and other DIS data;*
- *Nuclear effects in the Deuteron and constraints on d/u ratio.*

III *Application to $W^{\pm}, Z$ Production in $p + \mathrm{Pb}$ at the LHC*

- *$W^{\pm}, Z$ production in heavy ion collisions;*
- *Comparison with CMS data on $W^{\pm}, Z$ at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV.*

A MICROSCOPIC APPROACH TO NPDFs

- *QCD factorization suggests that Leading Twist cross-sections are driven by PDFs regardless of the hadronic target, leading naturally to the definition of nuclear PDFs. Nuclear PDFs are high Q characteristic of the target and process-independent.*

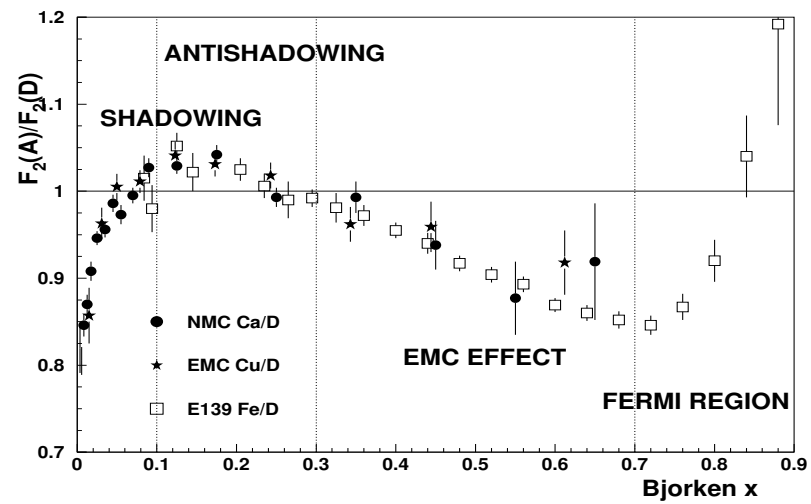
- *The KP nuclear PDFs are predicted from our microscopic model (NOT a fit unlike conventional approaches):*
  - *Offer insights on the underlying nuclear physics mechanisms;*
  - *Compact description in terms of few simple parameters describing properties of the NUCLEON (i.e. independent from the specific nucleus considered);*
  - *Nuclear properties described independently through the nuclear spectral function;*
  - *Clear definition of the Leading Twist contributions;*
  - *Available for a wide range of nuclei from deuteron ($A = 2$) to lead ($A = 207$).*

- *The KP nuclear PDFs have been validated with data from a wide range of processes including lepton-nucleus DIS, Drell-Yan production in pA collisions, $Z, W^{\pm}$ production in heavy ion collisions at colliders.*

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

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

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

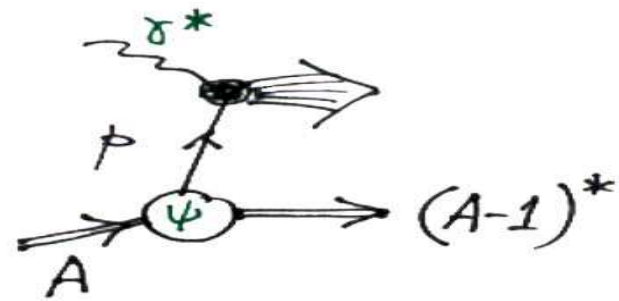
INCOHERENT SCATTERING OFF BOUND NUCLEONS

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

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

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

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: $\boxed{\delta f(x)}$

- *Hadronic/nuclear input:*
  - *Proton/neutron PDFs computed in NNLO pQCD + TMC + HT from fits to DIS data*
  - *Two-component nuclear spectral function: mean-field + correlated part*

OFF-MASS-SHELL

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

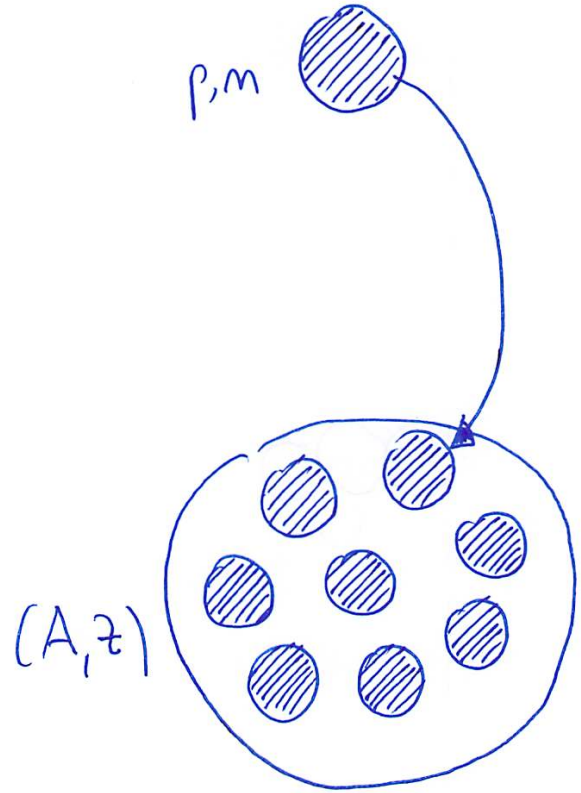
DESCRIPTION OF NUCLEON

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

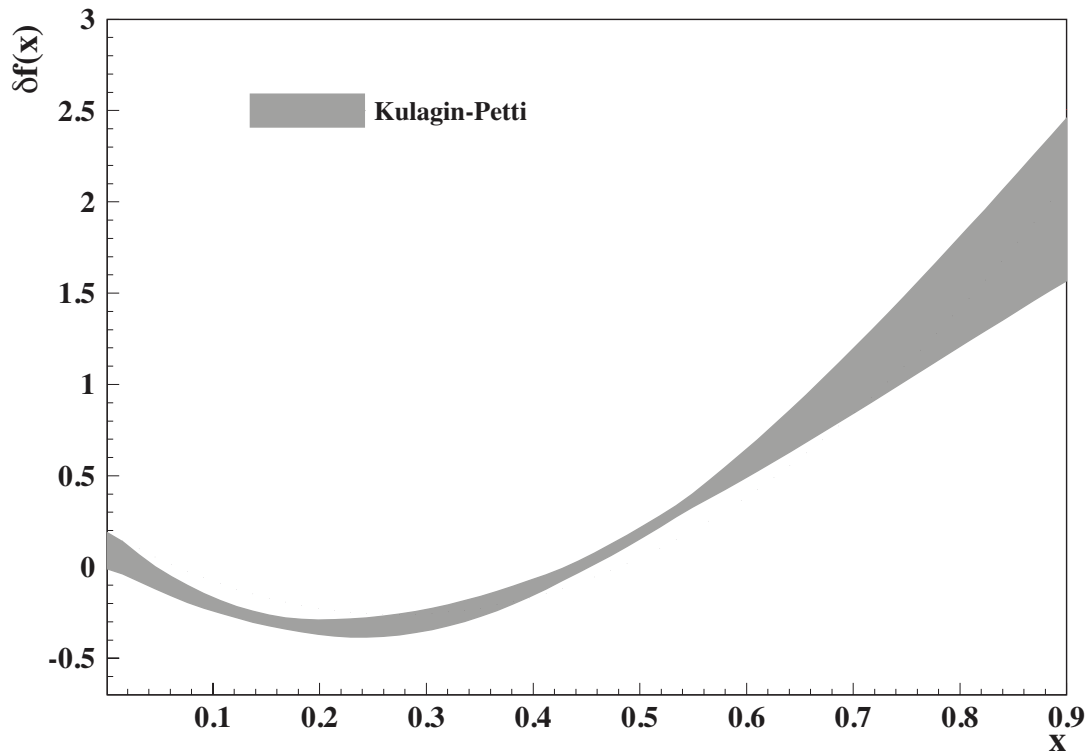
SPECTRAL/WAVE FUNCTION

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

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

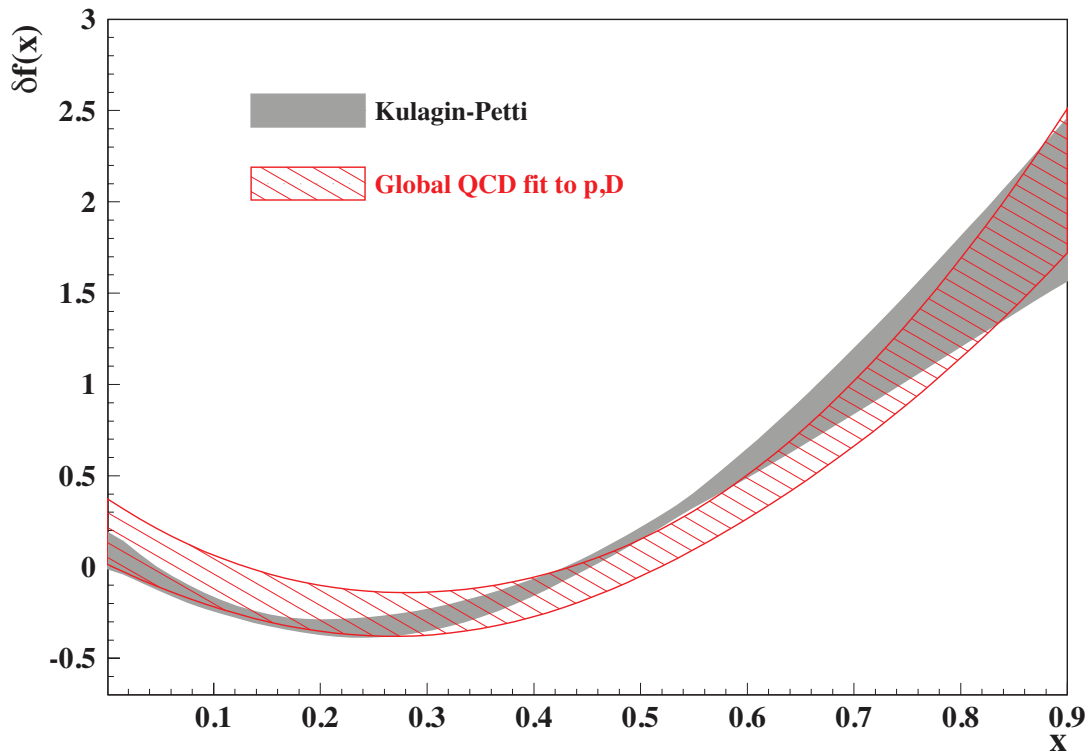
Any isospin (i.e. $\delta f_p \neq \delta f_n$) or flavor dependence ($\delta f_a$) in the off-shell function?

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., arXiv:1704.00204 [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 STRUCTURE FUNCTIONS

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

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

- *The leading twist (LT) term $F_i^{\rm LT}$ 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 ($M_N^2 \to p^2$):*

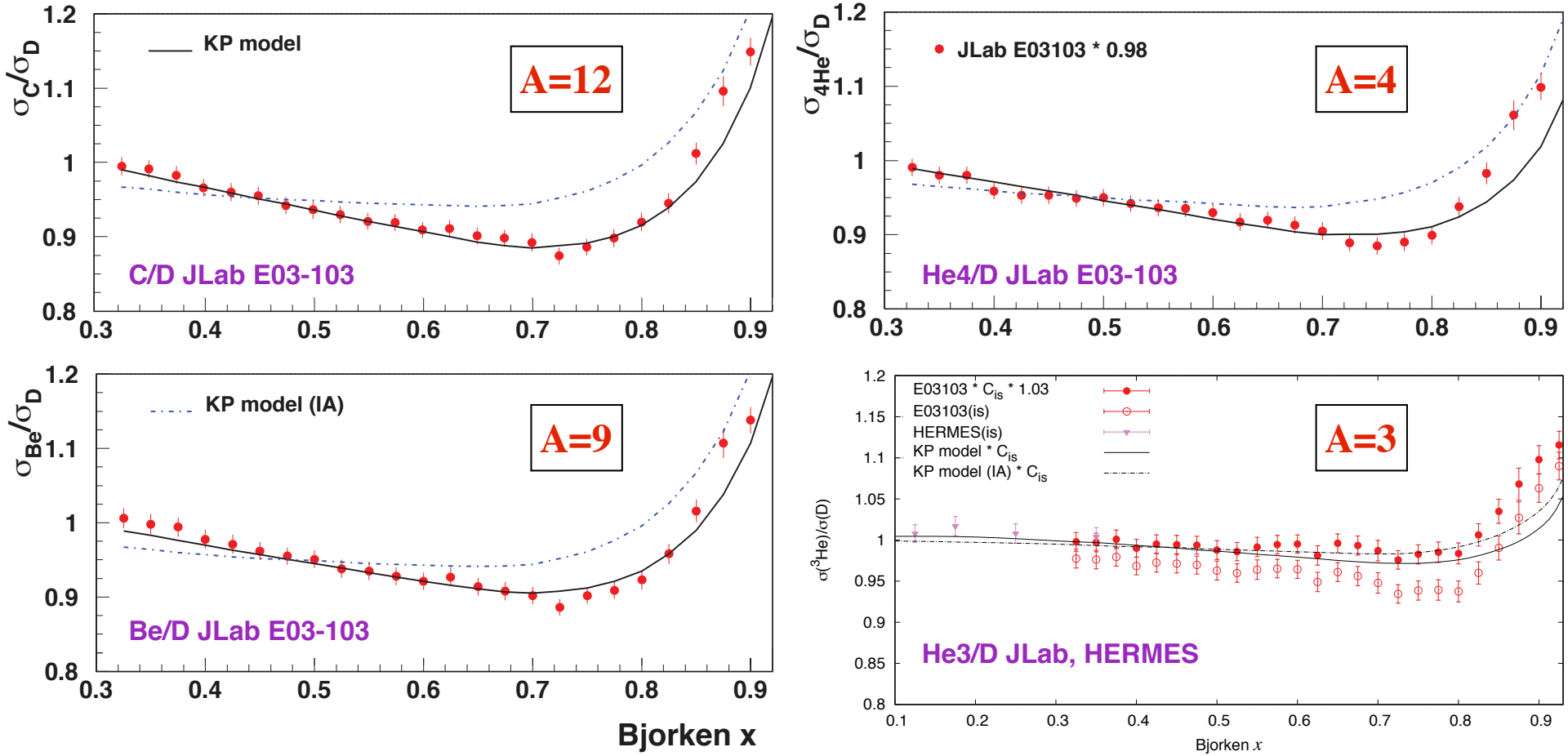
$$F_2^{\rm LT,TMC} = \frac{x^2}{\xi^2\gamma^2} F_2^{\rm LT}(\xi, Q^2, p^2) + \frac{6x^3p^2}{Q^2\gamma^4} \int_\xi^1 \frac{dz}{z^2} F_2^{\rm LT}(z, Q^2, p^2) + \mathcal{O}(Q^{-4})$$

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

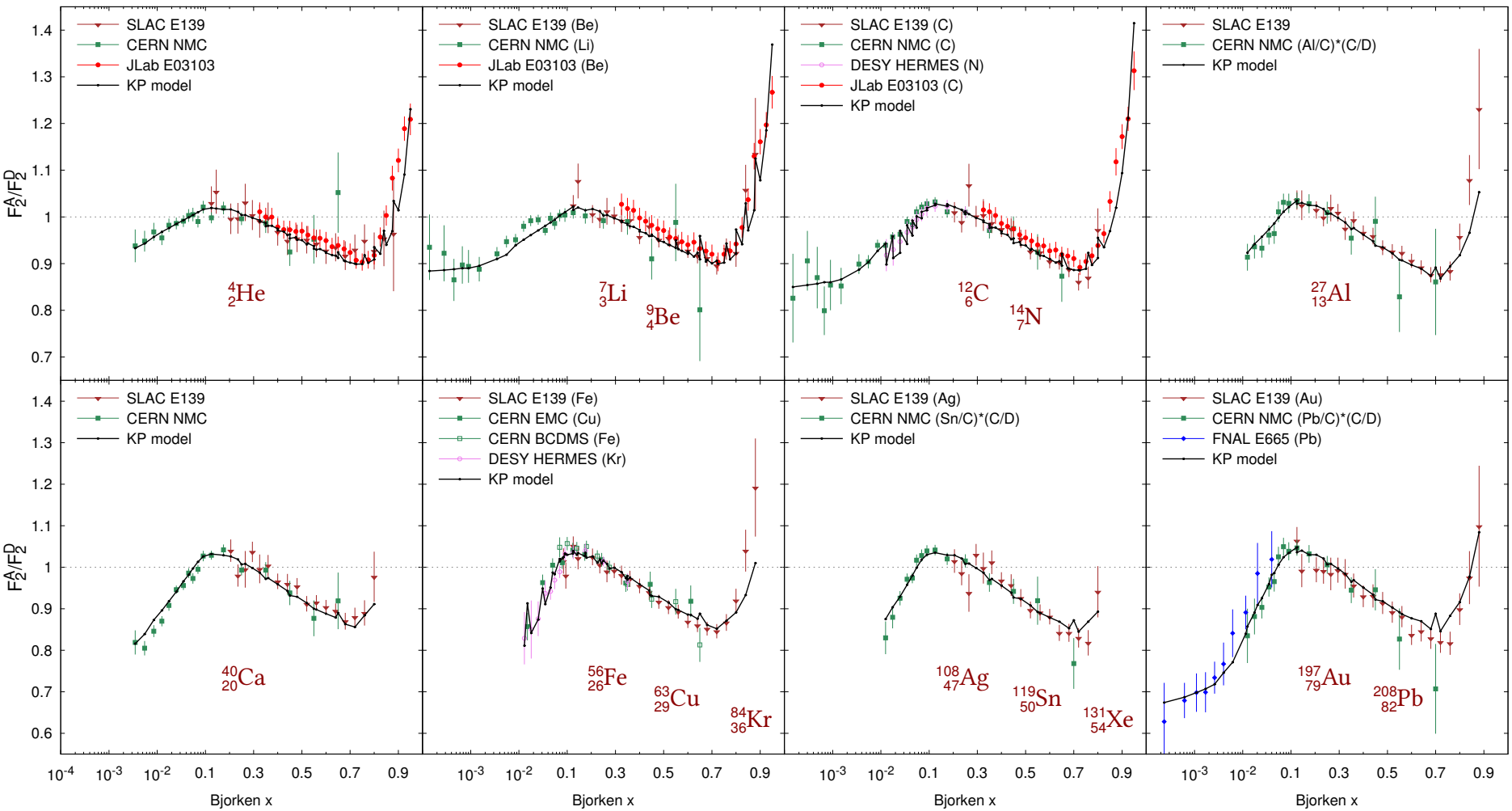
$\Longrightarrow$ *Nuclear structure functions are not just simple combinations of NPDFs!*

PREDICTIONS FOR CHARGED LEPTON DIS

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



Independent predictions, NOT A FIT!

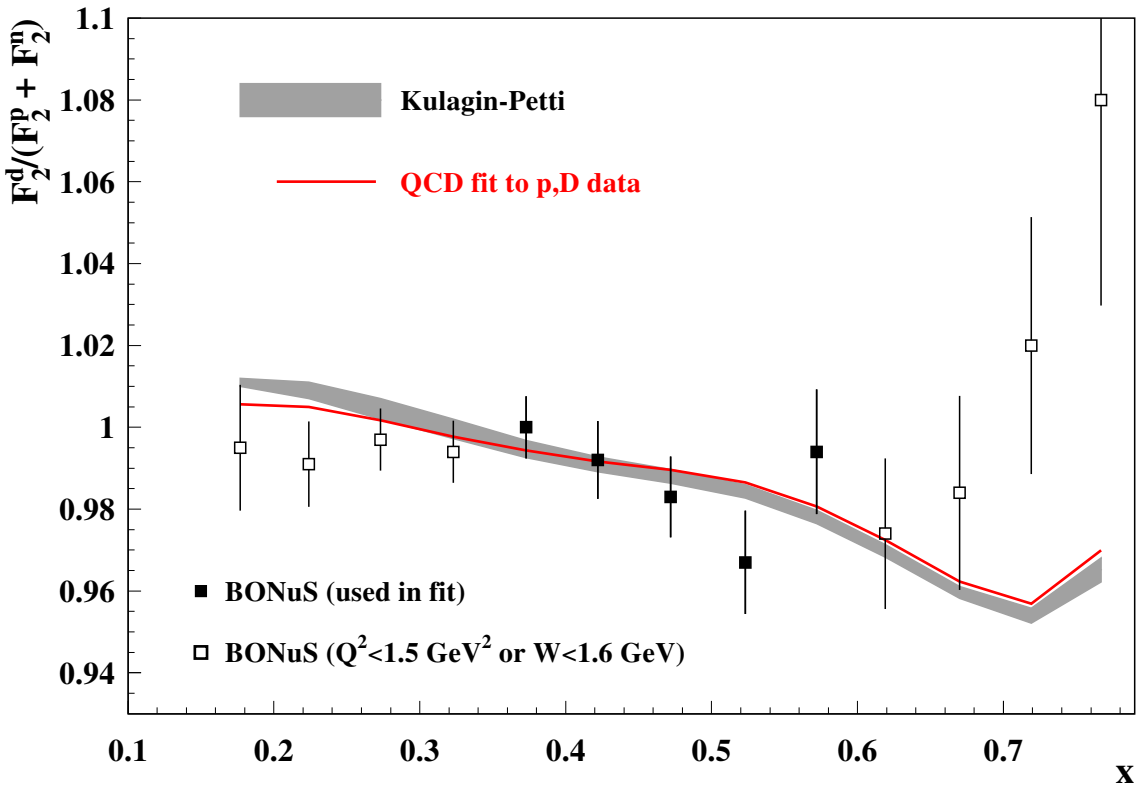


Overall we obtain $\chi^2/N_{\rm Data} = 466.6/586$ *for all DIS data with* $Q^2 \geq 1$ *GeV*^{2}

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

PREDICTIONS FOR THE DEUTERON

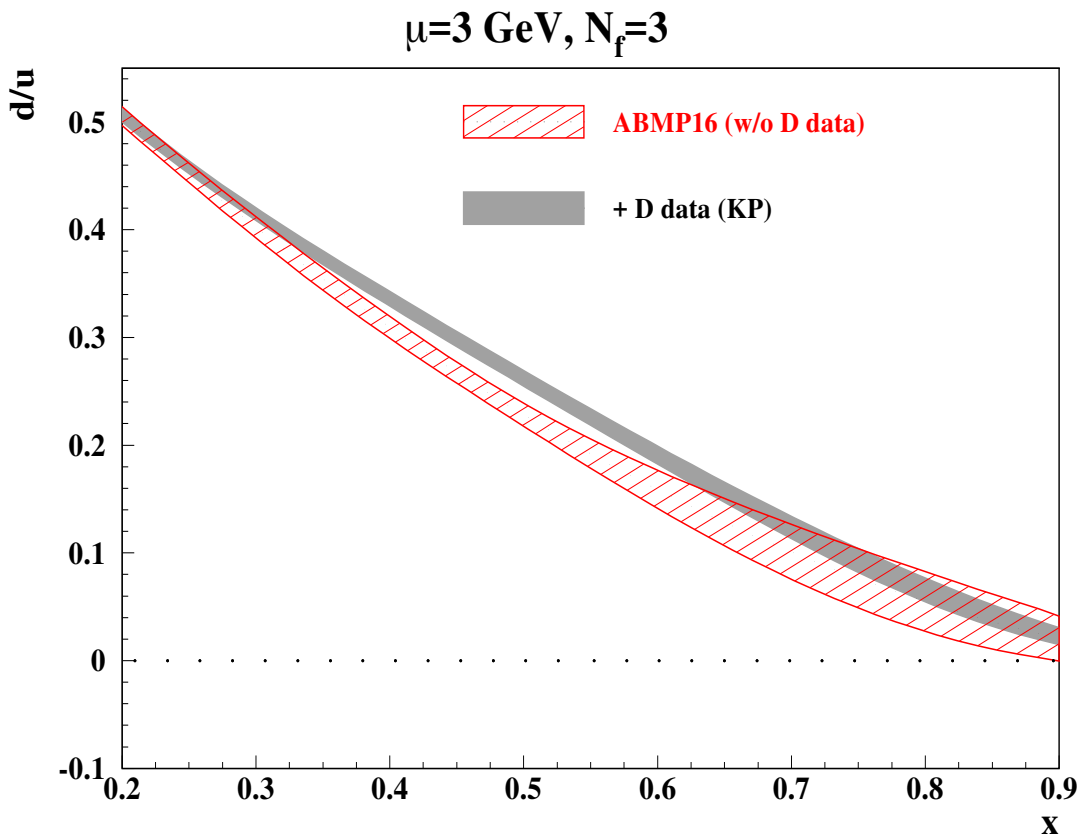
Comparison with the direct BONuS measurement [PRC 92 (2015) 015211] of $F_2^D/(F_2^p+F_2^n)$*:*



S. Alekhin, S. Kulagin and R.P., arXiv:1704.00204 [nucl-th]

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

DETERMINATION OF d/u RATIO FROM GLOBAL FITS



S. Alekhin, S. Kulagin and R.P., arXiv:1704.00204 [nucl-th]

- *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 $W^{\pm}, Z$ 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:*

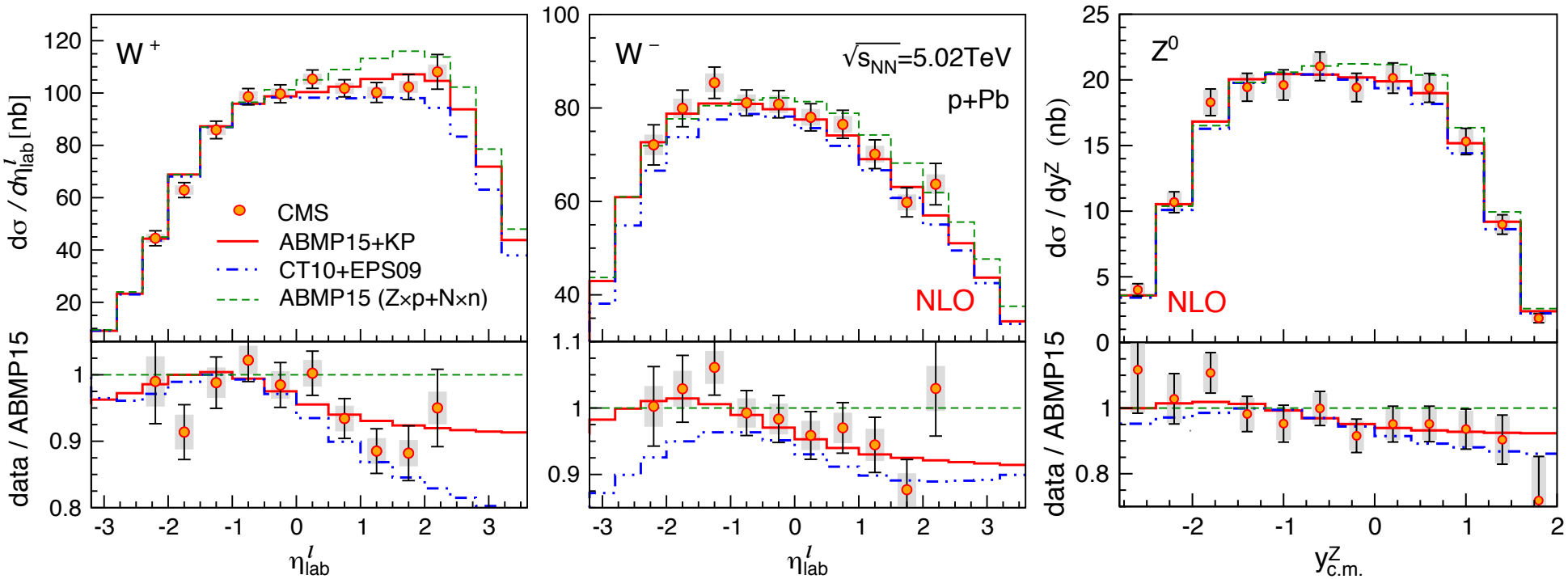
$$\frac{d^2\sigma_{pA}}{dQ^2dy} = \sum_{a,b} \int dx_a dx_b \, q_{a/p}(x_a, Q^2) \, q_{b/A}(x_b, Q^2) \frac{d^2\hat{\sigma}_{ab}}{dQ^2dy}$$

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

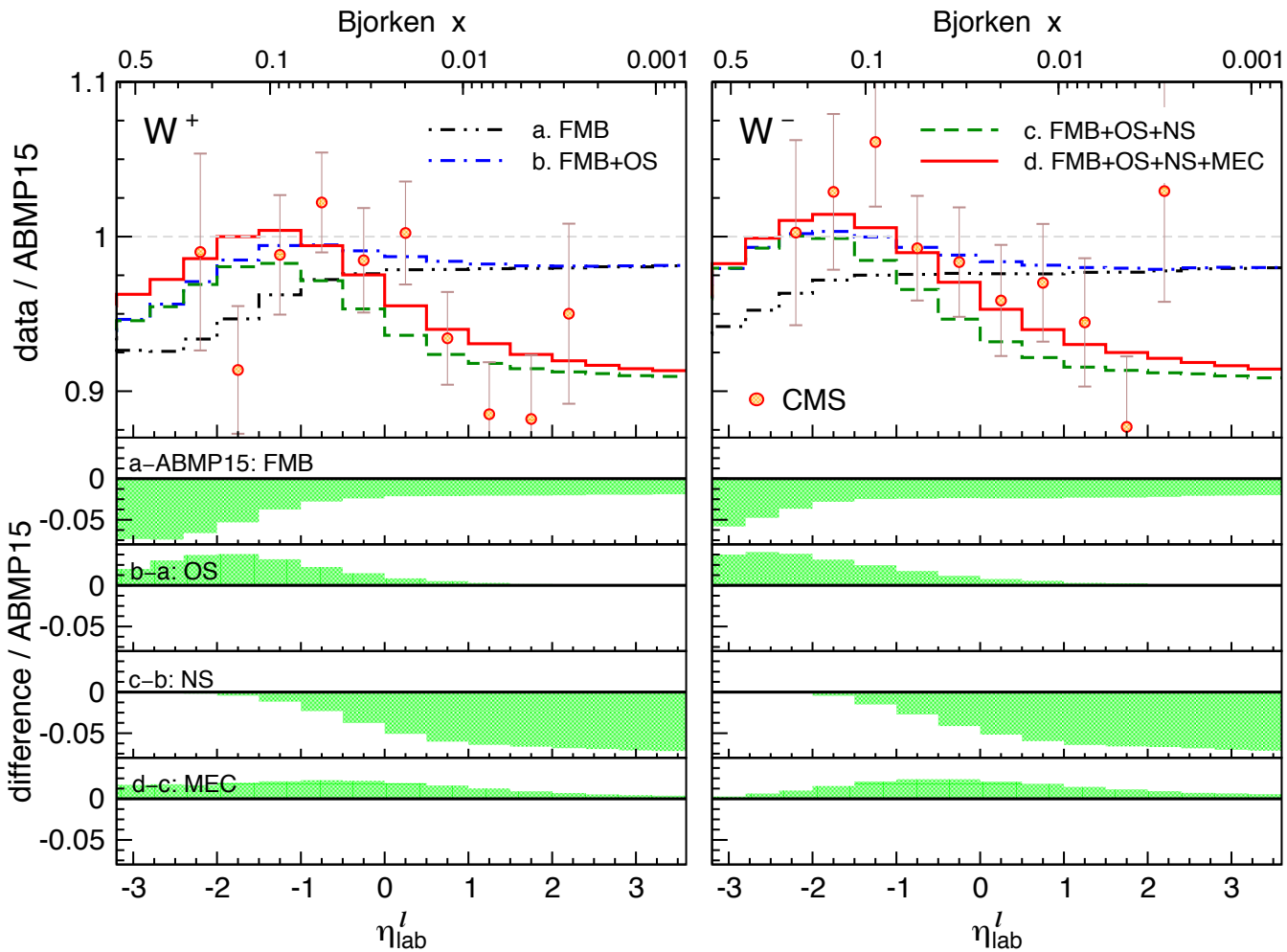
- *We study the (pseudo)rapidity distributions of $W^{\pm}/Z^0$ bosons in $p + \mathrm{Pb}$ collisions at the LHC at $\sqrt{s} = 5.02$ TeV using the DYNNLO program within the NLO QCD approximation with $\mu_r = \mu_f = m_{W,Z}$ [PRL 103 (2009) 082001]*

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	$N_{\rm Data}$	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*

- *The off-shell function extracted from D data in global PDF fits is consistent with the one obtained from heavy targets* ($A \geq 4$)

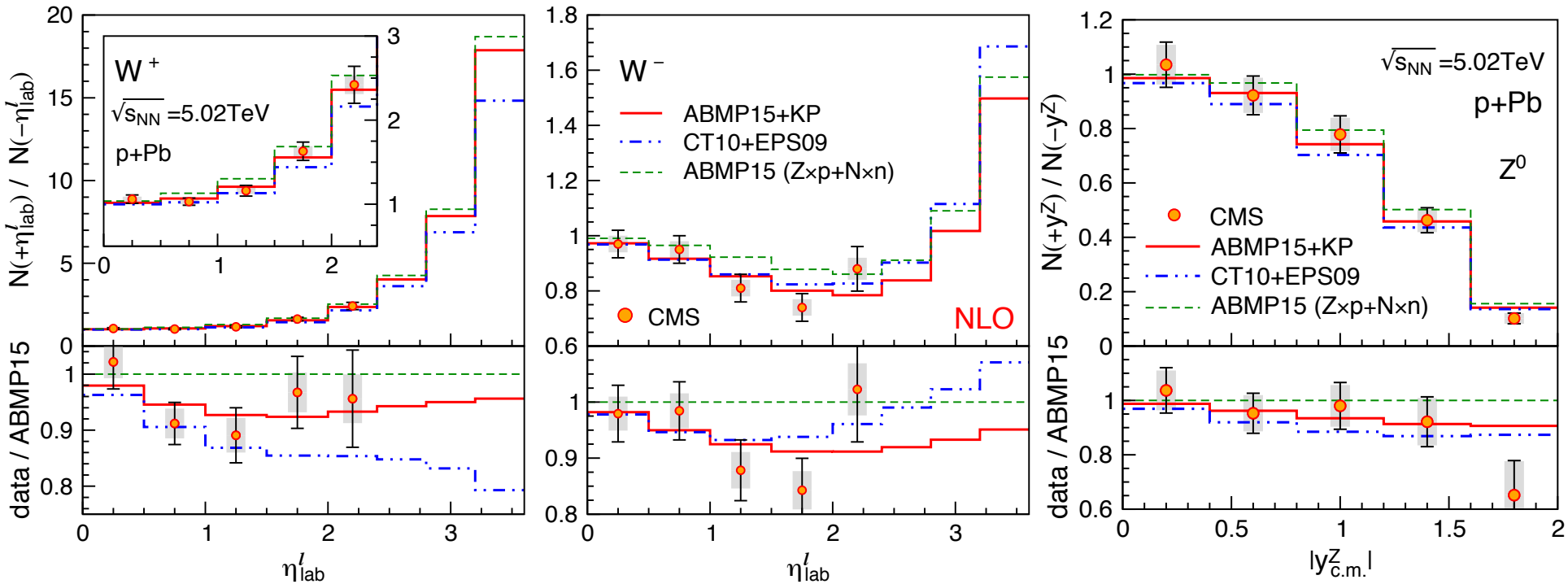
  $\Longrightarrow$ δf *universality allows substantial reduction of uncertainties on* d/u *ratio*

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

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

Backup slides

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



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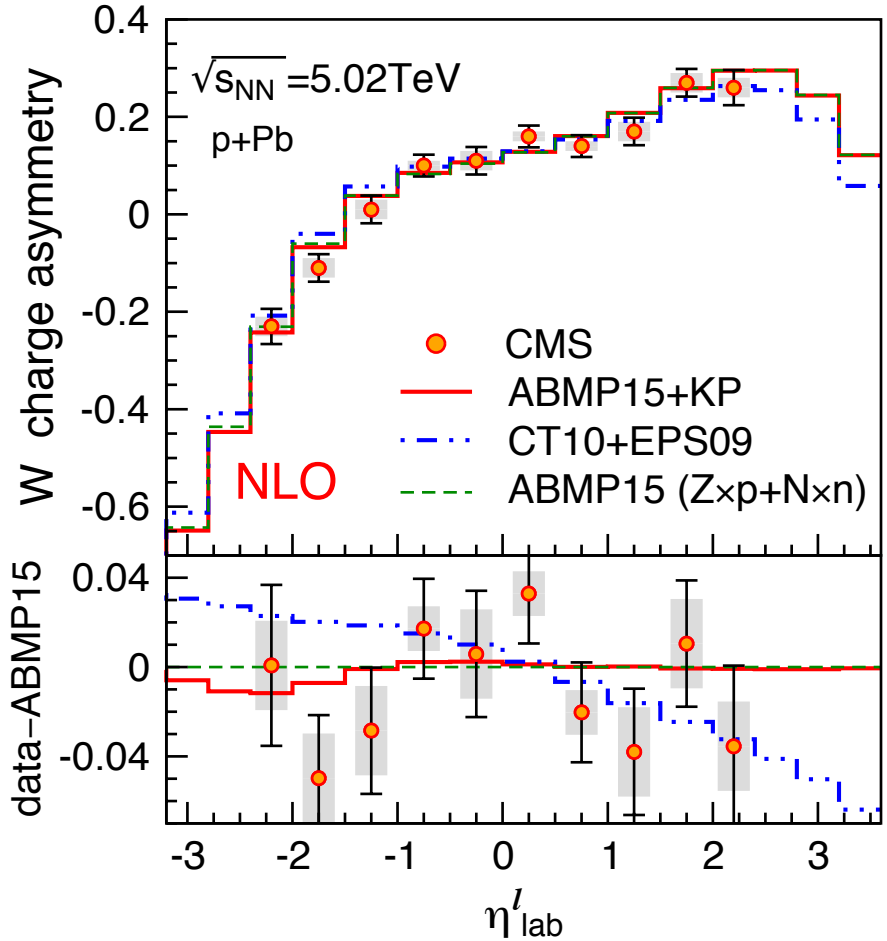

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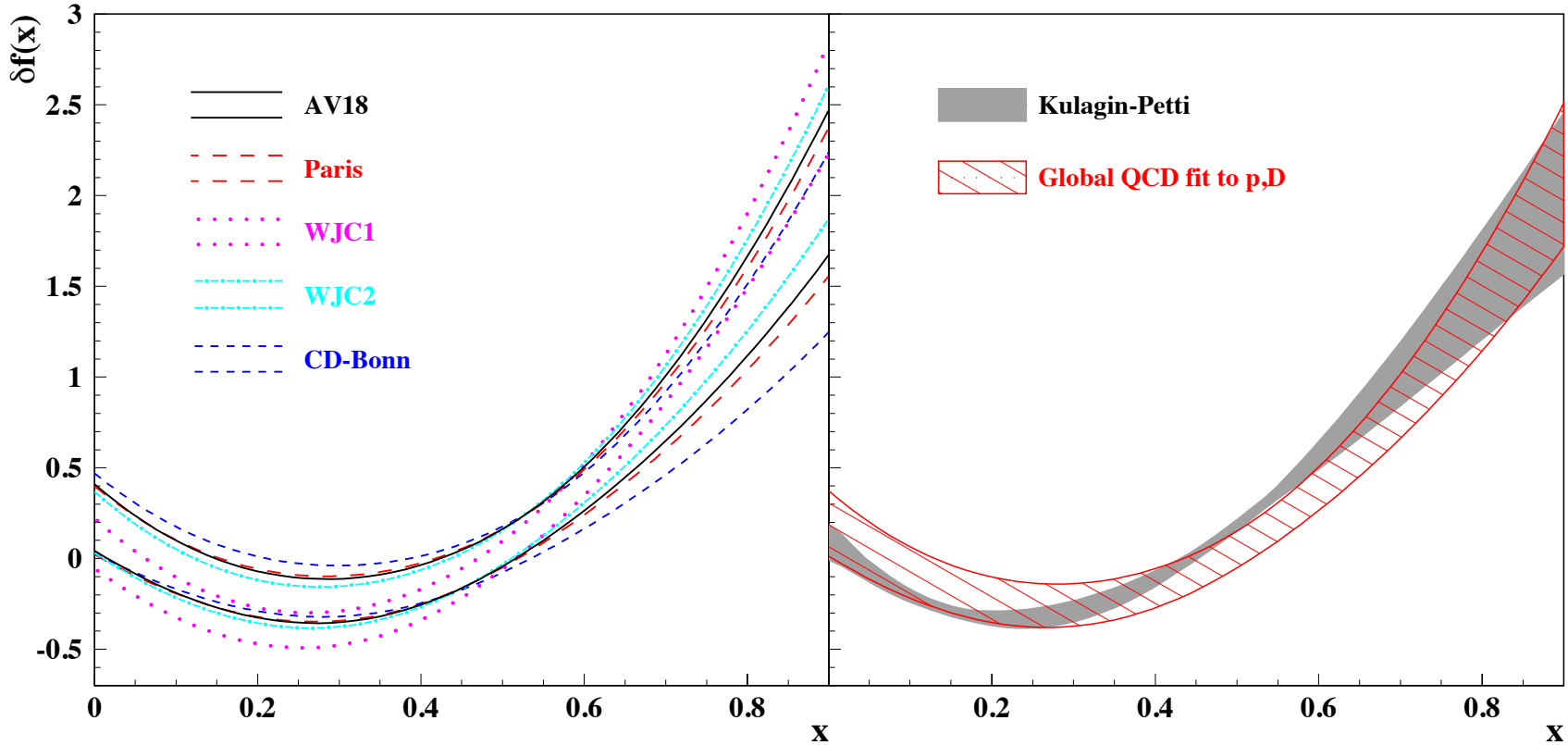
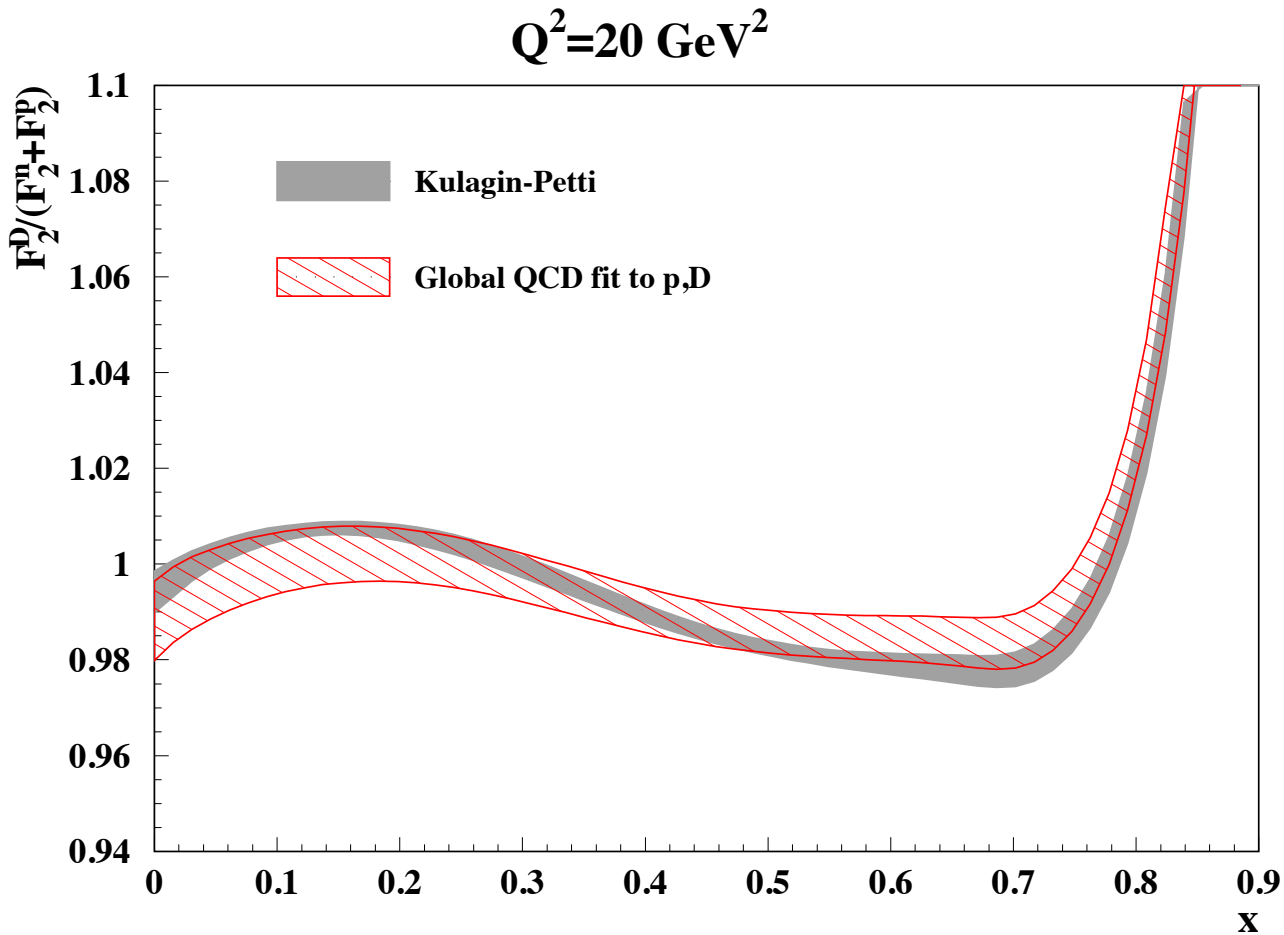
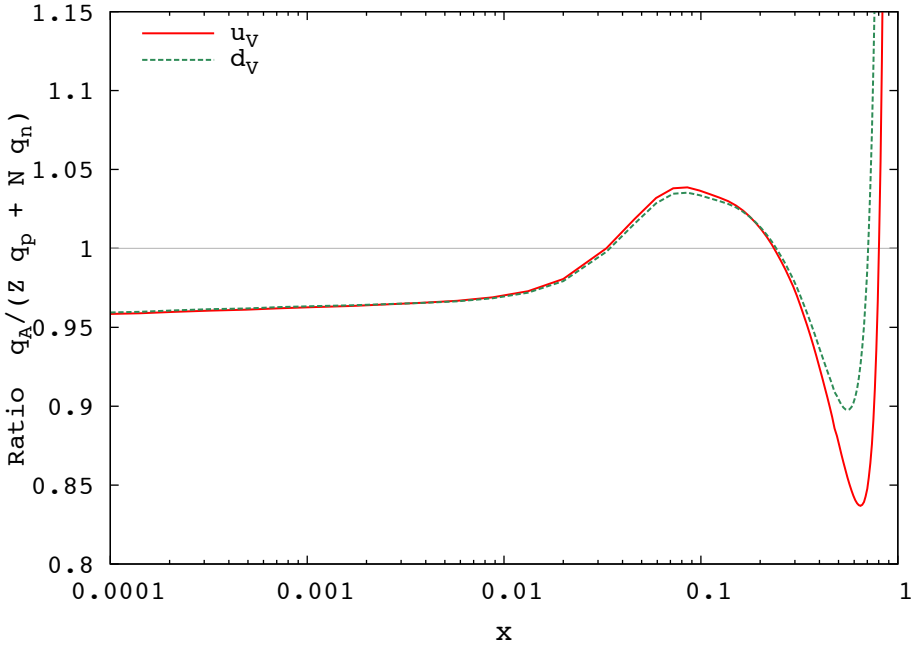
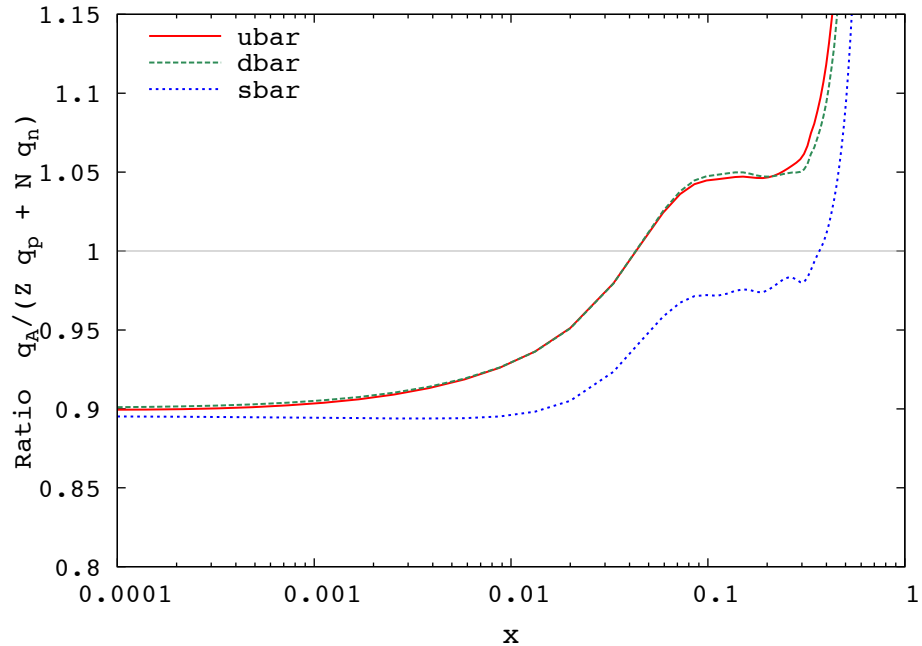

δf(x)
3
2.5
2
1.5
1
0.5
0
-0.5
AV18
Paris
WJC1
WJC2
CD-Bonn
Kulagin-Petti
Global QCD fit to p,D
0
0.2
0.4
0.6
0.8
x
0.2
0.4
0.6
0.8
x


Q^2=20 GeV^2
$F_2^D/(F_2^n+F_2^p)$
1.1
1.08
1.06
1.04
1.02
1
0.98
0.96
0.94
Kulagin-Petti
Global QCD fit to p,D
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
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.*

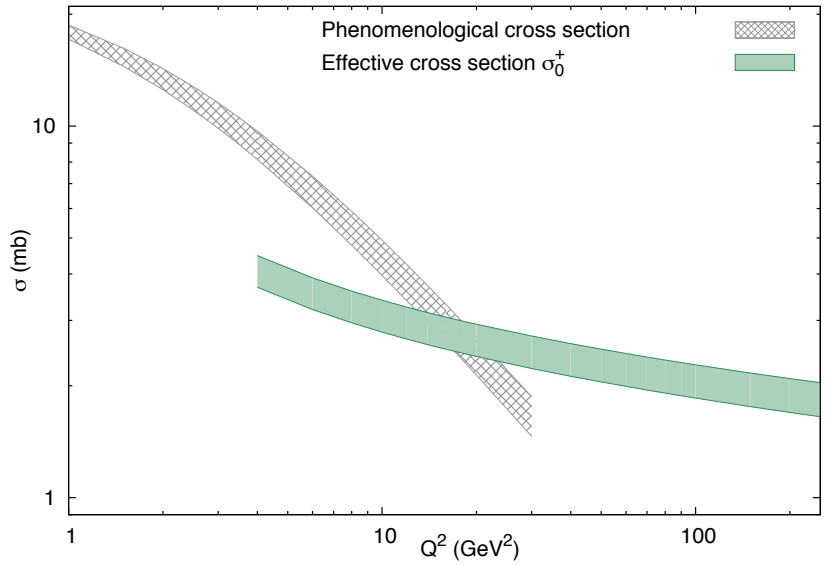
CONSTRAINTS FROM PDF SUM RULES

- *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 Leading Twist (LT) 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 equations above in terms of the δf function (input) and obtain the effective LT cross-section in the ($I=0, C=1$) state, as well as Re/Im *of amplitudes*

$\Longrightarrow$ *In our approach nuclear corrections to PDFs essentially defined by $\mathcal{P}(\varepsilon, \mathbf{p})$ AND $\delta f(x)$*

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:*

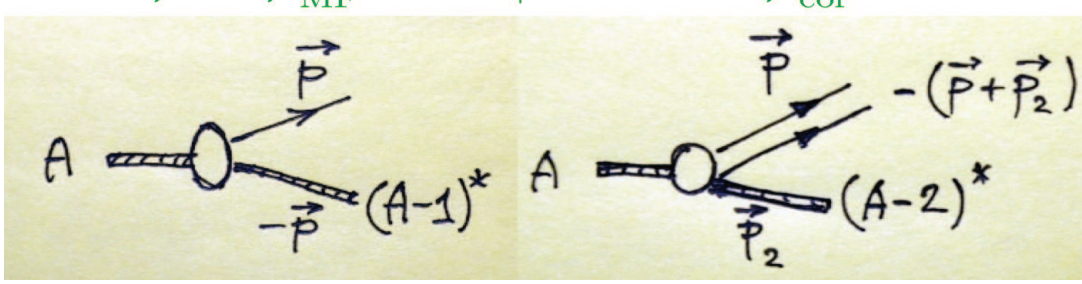
$$\mathcal{P}_{\rm MF}(\varepsilon, \mathbf{p}) = \sum_{\lambda<\lambda_{\mathbf{F}}} \mathbf{n}_\lambda \mid \phi_\lambda(\mathbf{p}) \mid^{\mathbf{2}} \delta(\varepsilon - \varepsilon_\lambda)$$

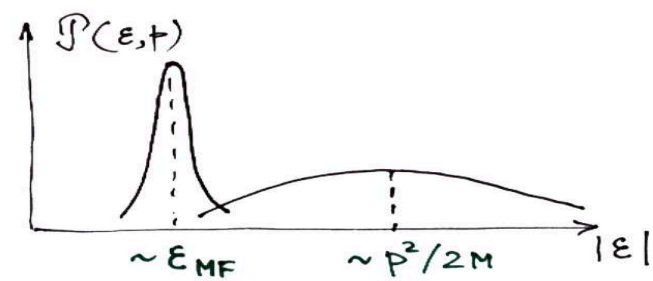
where sum over occupied levels with n_λ *occupation number. Applicable for small nucleon separation energy and momenta,* $\mid \varepsilon \mid < 50$ *MeV,* $p < 300$ *MeV/c*

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

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

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





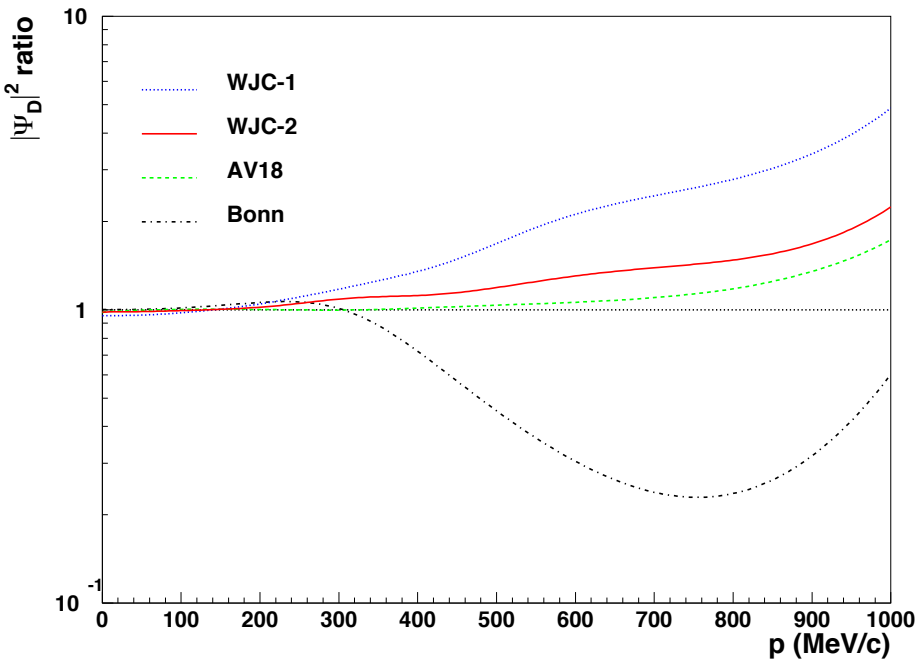
DEUTERON WAVE FUNCTION

- *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*

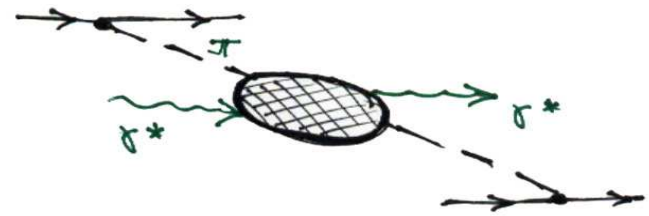
Different N-N potentials used

Paris: *PRC 21 (1980) 861*
Bonn: *PR 149 (1987) 149*
AV18: *PRC 84 (2011) 034003*
WJC-1,2: *PRC 82 (2010) 034004*

NUCLEAR MESON EXCHANGE CURRENTS

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

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

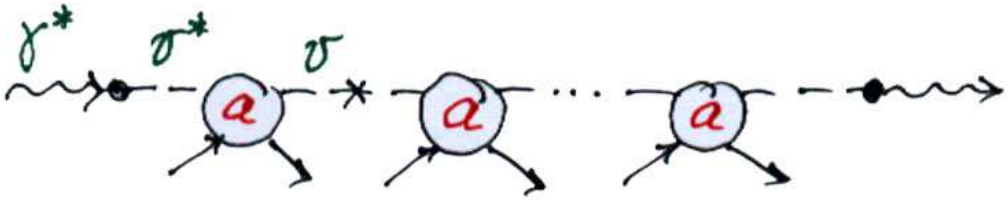


- *Contribution from nuclear pions (mesons) to balance nuclear light cone momentum* $\langle y\rangle_\pi + \langle y\rangle_N = 1$. *The pion distribution function is localized in a region of* $y \leq p_F/M \sim 0.3$ *so that the pion contribution is at* $x < 0.3$. *The correction is driven by the average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



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

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

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

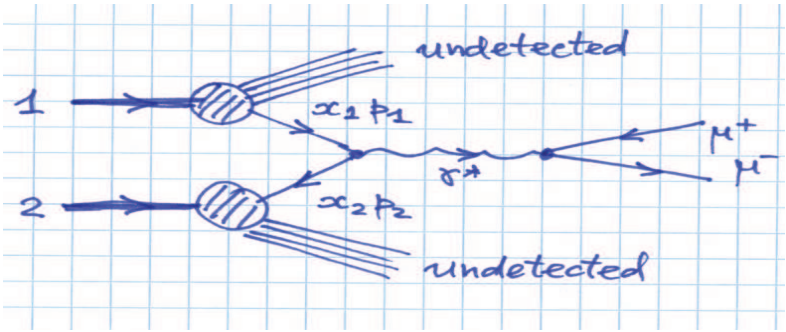
- *Hadronic/nuclear input:*
  - *Nuclear number densities* $\rho_A(r)$ *from parameterizations based on elastic electron scattering data*
  - *Low* Q^2 *limit of scattering amplitude* a *given by Vector Meson Dominance (VMD) model*

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:*

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

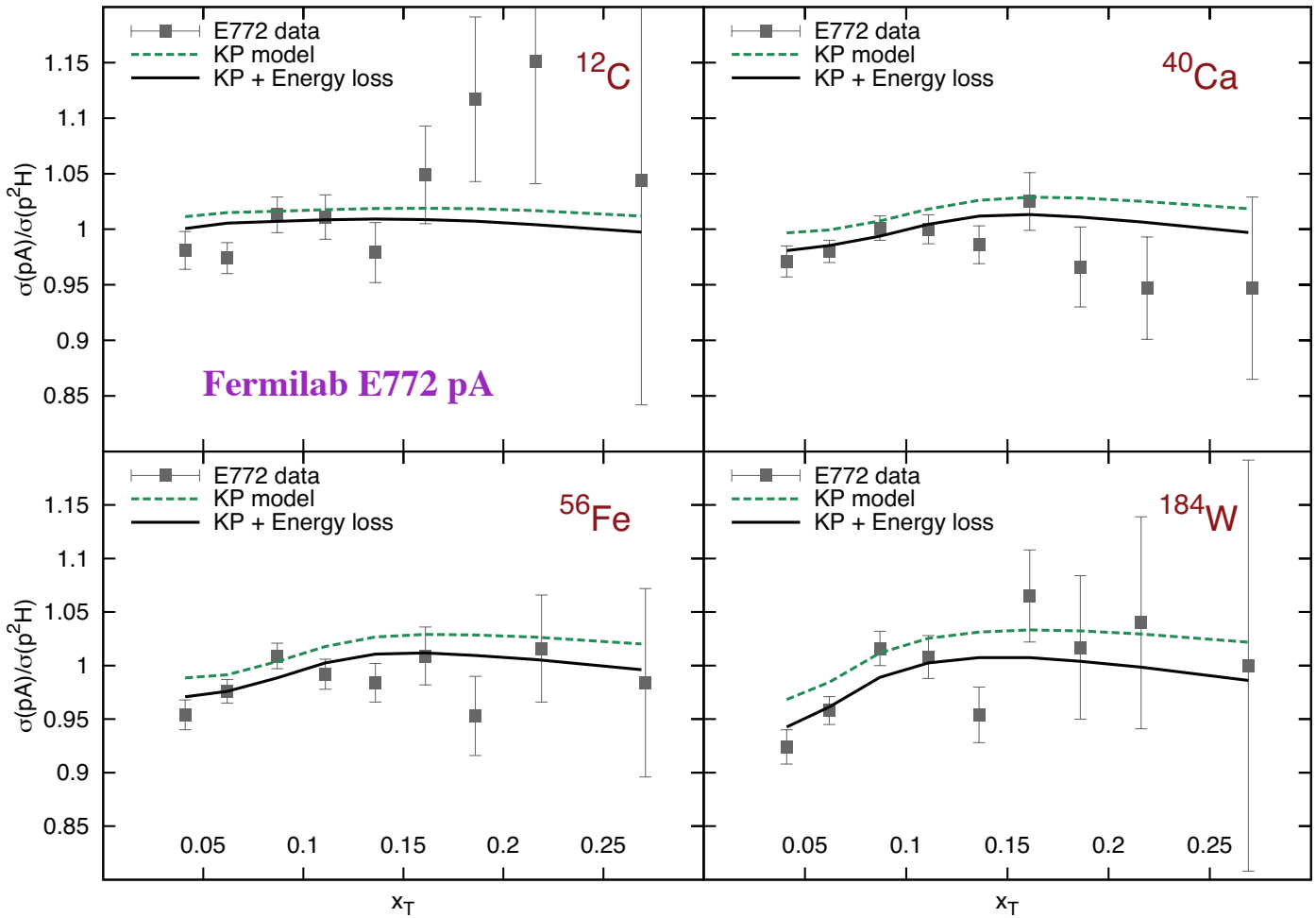
where E_B energy of proton, L distance traveled in nuclear environment

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

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

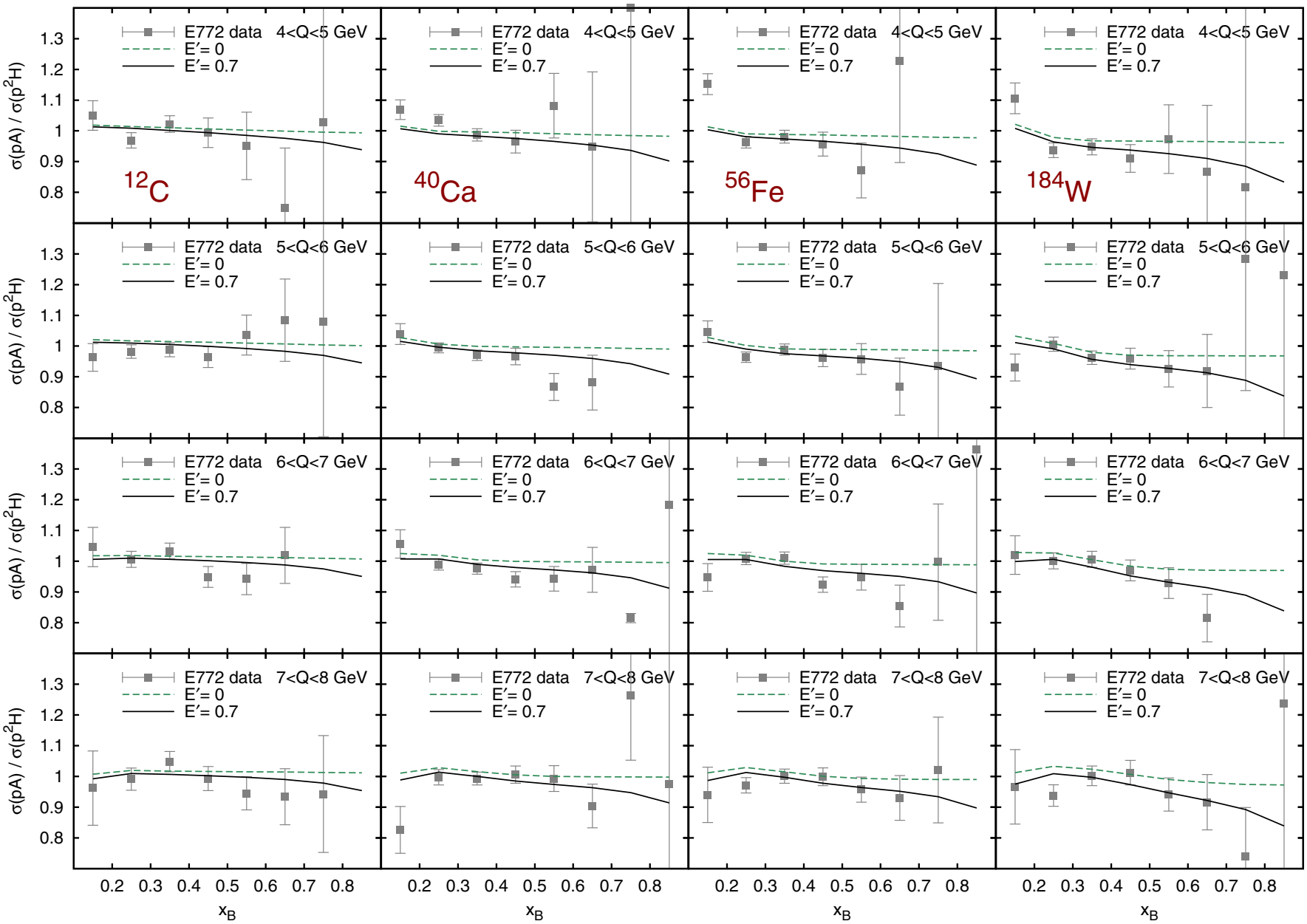
$\Longrightarrow$ *Nuclear data from Drell-Yan production in hadron collisions indicate no major enhancement to sea quarks for $x_T > 0.1$ as given by nuclear π excess*

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*



E772 Drell-Yan p-A data

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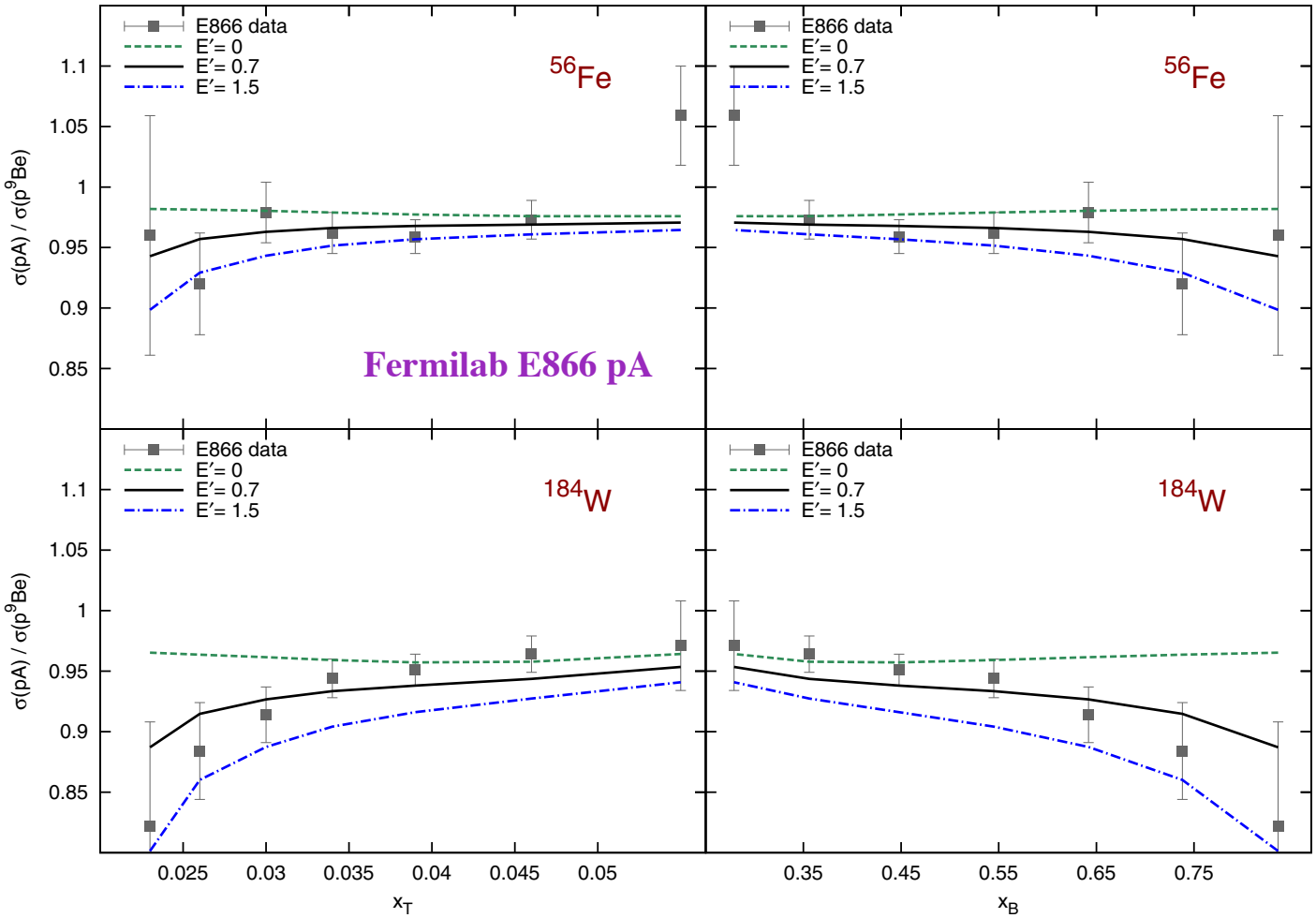


FLAVOR AND C-PARITY DEPENDENCE OF nPDFs

- *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:*

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

- *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 $q^{\pm} = q \pm \bar{q}$:*

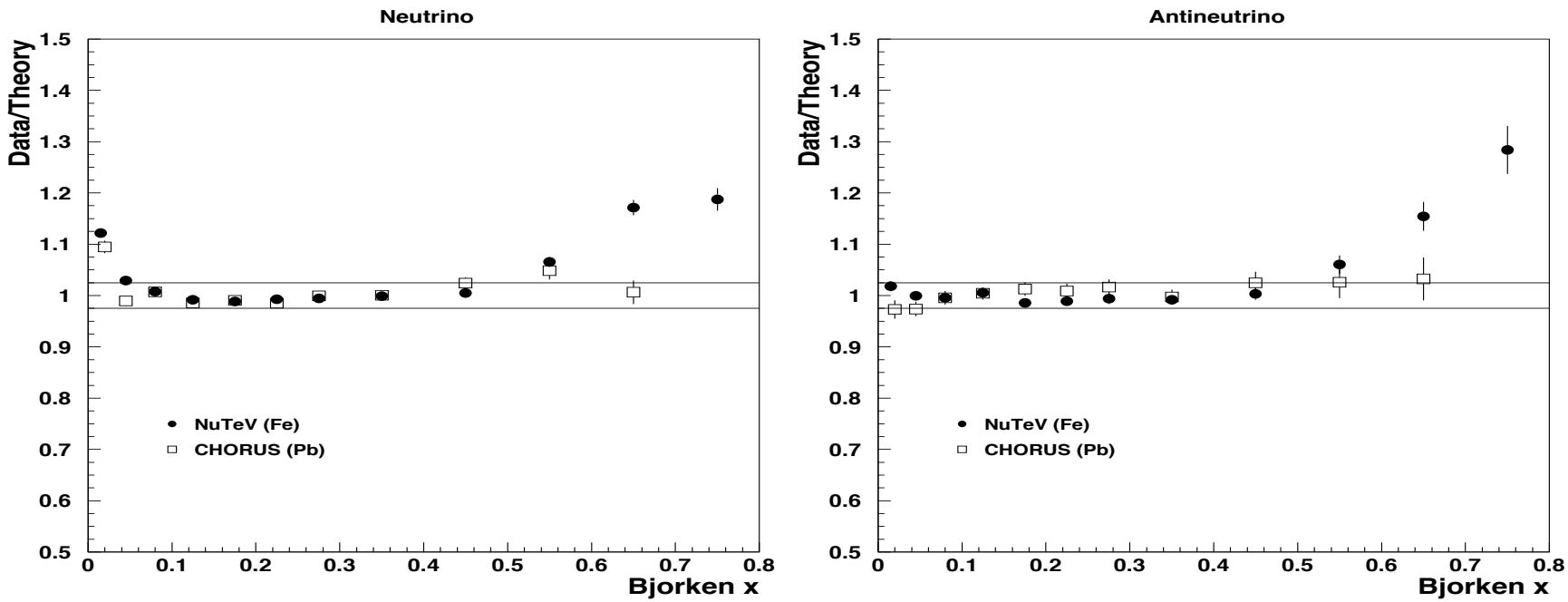
$$\delta\mathcal{R}^+ = \mathrm{Im}\,\mathcal{A}(a^+)/A\,\mathrm{Im}\,a^+ \qquad \delta\mathcal{R}^- = \mathrm{Im}\,a^-\mathcal{A}_1(a^+)/A\,\mathrm{Im}\,a^-$$

  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 $\sigma^- = 2\mathrm{Im}\,a^-$. However it nonlinearly depends on a^+.*

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

PREDICTIONS FOR (ANTI)NEUTRINO DIS DATA



- *Model of nuclear corrections for (anti)neutrino cross-sections based on results from e/μ DIS off nuclear targets and fully independent from (anti)neutrino data (S. Kulagin and R.P., NPA 765 (2006) 126; PRD 76 (2007) 094023, PRC 82 (2010) 054614).*
- *Comparison with NuTeV (Fe) and CHORUS (Pb) cross-section data (band $\pm 2.5\%$):*
  - *Systematic excess observed for $x > 0.5$ in both ν and $\bar{\nu}$ NuTeV data on Fe*
  - *CHORUS data on Pb target consistent with predictions at large x;*
  - *Consistent excess observed at $x < 0.05$ in both CHORUS and NuTeV neutrino data*