Update on KP
Nuclear Parton Distributions

S. Kulagin

INR Moscow, Russia

R. Petti

University of South Carolina, Columbia SC, USA

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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;*
- ✦ *Constraints/connections from PDF Sum Rules.*

II *Application to lA DIS and Drell-Yan Production in pA*

- ✦ *Comparisons with JLab E03-103 and HERMES data;*
- ✦ *Comparisons with E772 Drell-Yan data.*

III *Application to $W^{\pm}, Z$ Production in pPb at the LHC*

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

THE KP NUCLEAR PDFs

✦ *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 semi-microscopic model (NOT a fit unlike conventional approaches):*

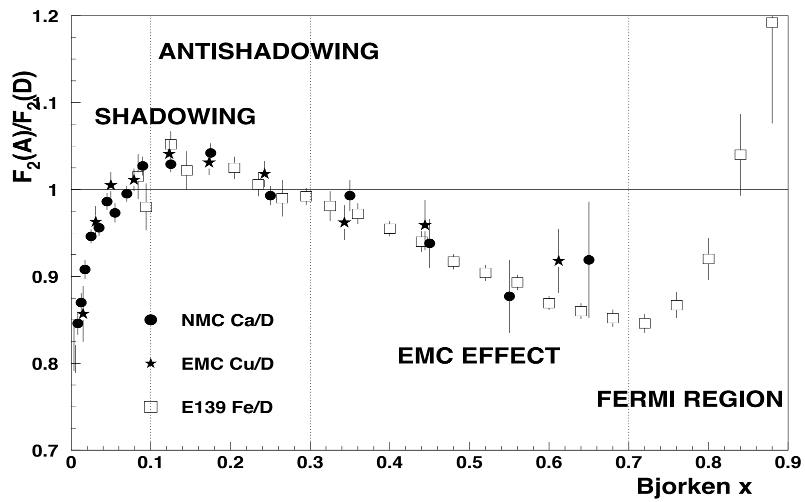
- *Offer insights on the underlying nuclear physics mechanisms;*
- *Compact description in terms of few simple parameters describing properties of the NUCLEON (i.e. independent from the specific nucleus considered);*
- *Nuclear properties described independently through the nuclear spectral function;*
- *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.*

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 $d = (3/4\pi\rho)^{1/3} \sim 1.2 Fm$
- $\boxed{L_I < d}$
  For $x > 0.2$ nuclear DIS $\sim$ incoherent sum of contributions from bound nucleons
- $\boxed{L_I \gg d}$
  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)*

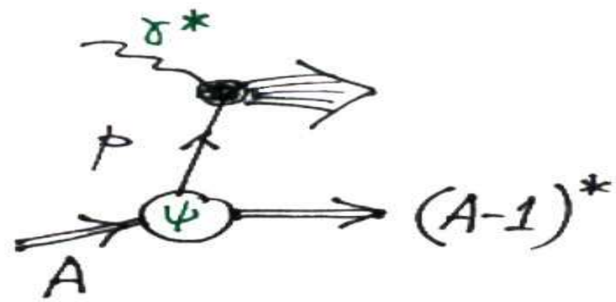
INCOHERENT NUCLEAR SCATTERING

✦ 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: $\boxed{\delta f(x)}$

✦ *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

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

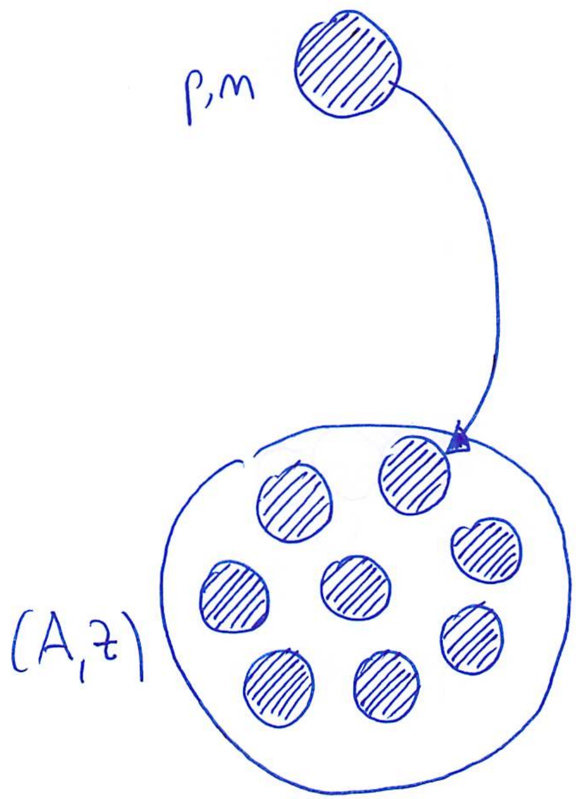
DESCRIPTION OF NUCLEON

Distribution of partons in a nucleon

STRUCTURE FUNCTIONS

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

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



DESCRIPTION OF NUCLEUS

Distribution of bound nucleons

SPECTRAL FUNCTION

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

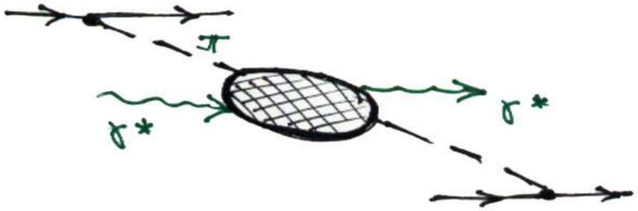
Off-shell function measures the in-medium modification of bound nucleon

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

NUCLEAR MESON EXCHANGE CURRENTS

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

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



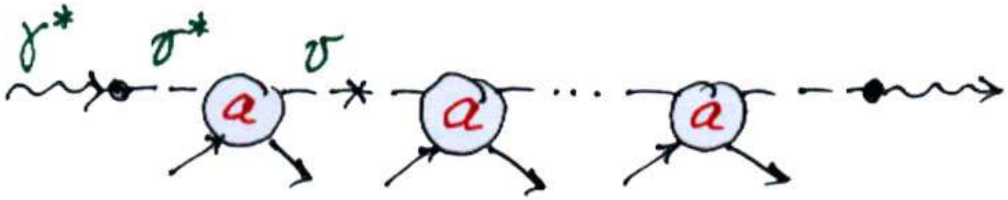
✦ *Contribution from nuclear pions (mesons) to balance nuclear light cone momentum $\langle y\rangle_\pi + \langle y\rangle_N = 1$. The pion distribution function is localized in a region of $y \leq p_F/M \sim 0.3$ so that the pion contribution is at $x < 0.3$. The correction is driven by the average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



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

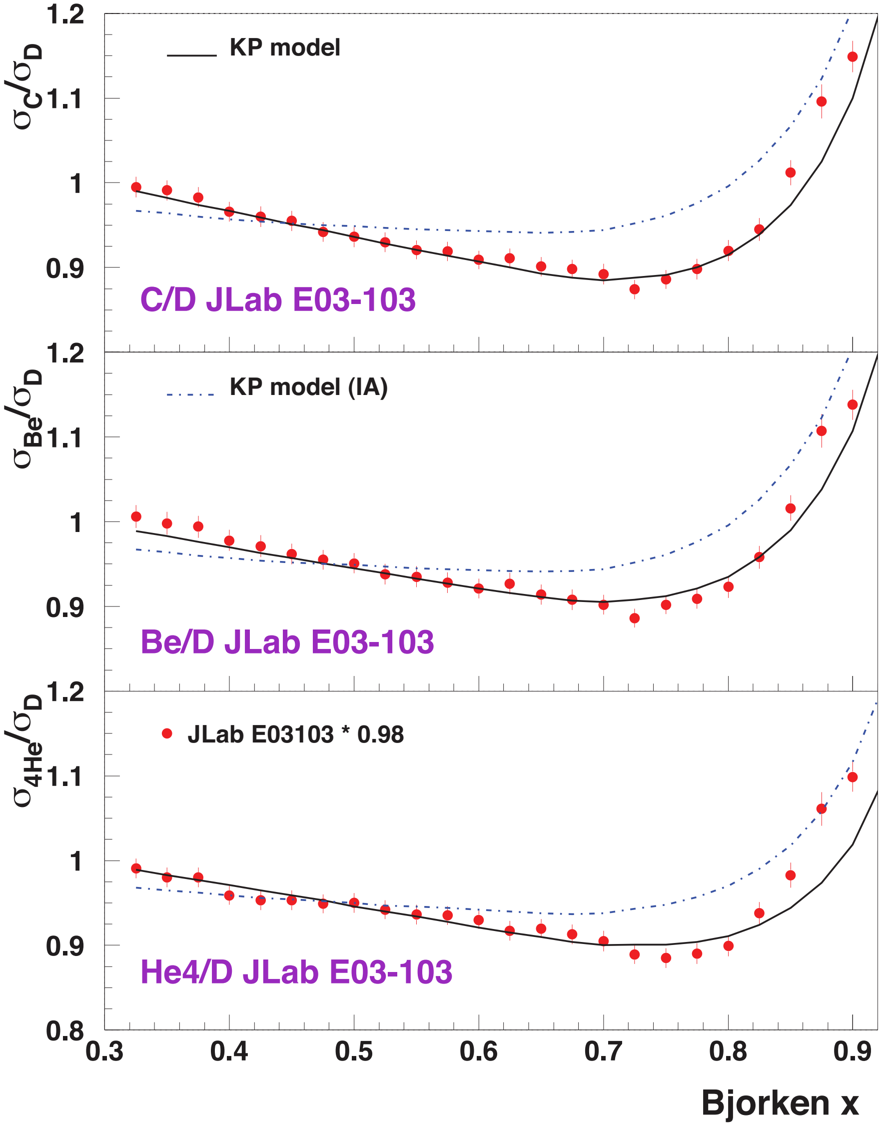
$$\mathcal{A}(a) = i a^2 \int_{z_1<z_2} \mathrm{d}^2\mathbf{b}\,\mathrm{d}z_1\mathrm{d}z_2\,\rho_A(\mathbf{b},z_1)\rho_A(\mathbf{b},z_2) e^{i\int_{z_1}^{z_2}\mathrm{d}z'\,a\,\rho_A(\mathbf{b},z')} e^{ik_L(z_1-z_2)}$$

$\boxed{a = \sigma(i+\alpha)/2}$ *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).*

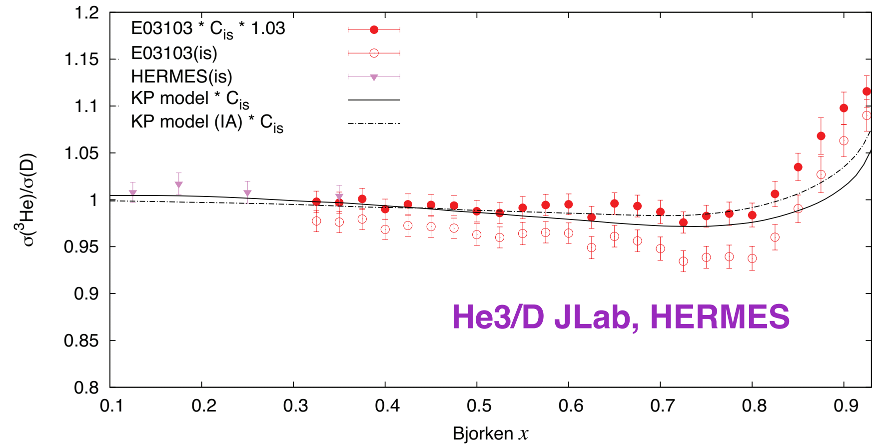
✦ *Hadronic/nuclear input:*

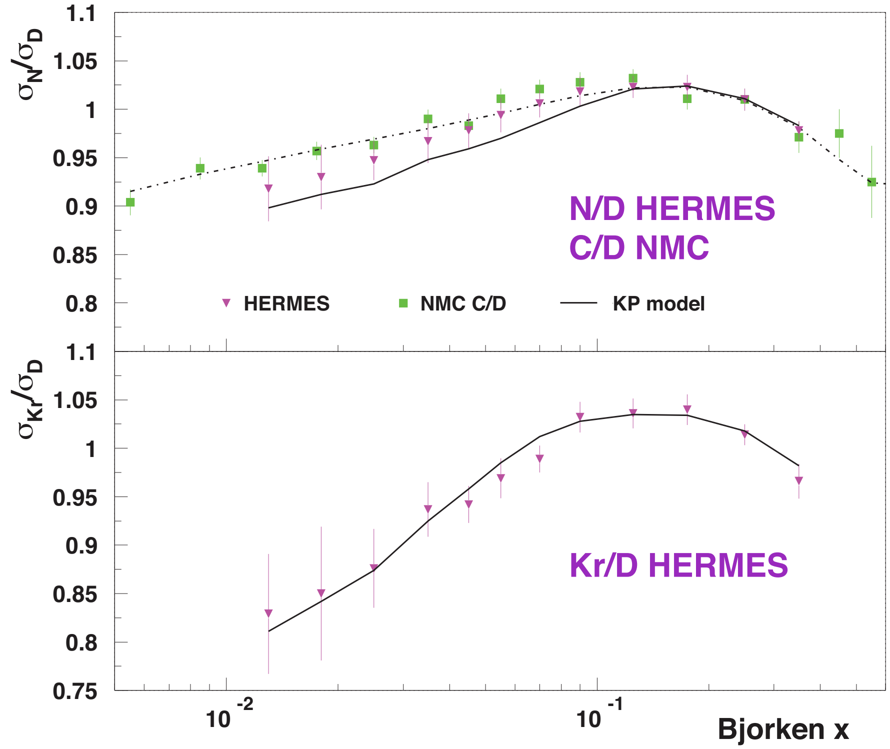
- *Nuclear number densities* $\rho_A(r)$ *from parameterizations based on elastic electron scattering data*
- *Low* Q^2 *limit of scattering amplitude* a *given by Vector Meson Dominance (VMD) model*

PREDICTIONS FOR CHARGED LEPTON DIS DATA



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





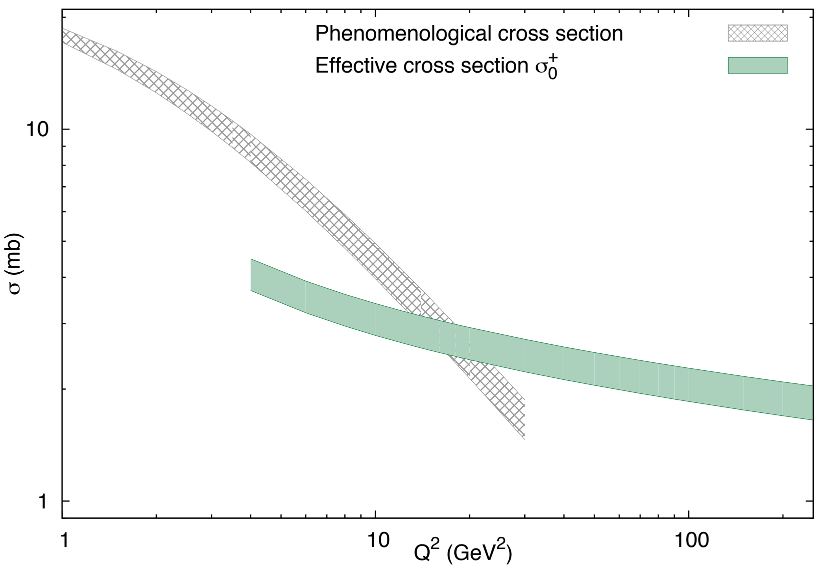
CONSTRAINTS FROM PDF SUM RULES

- *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:*

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

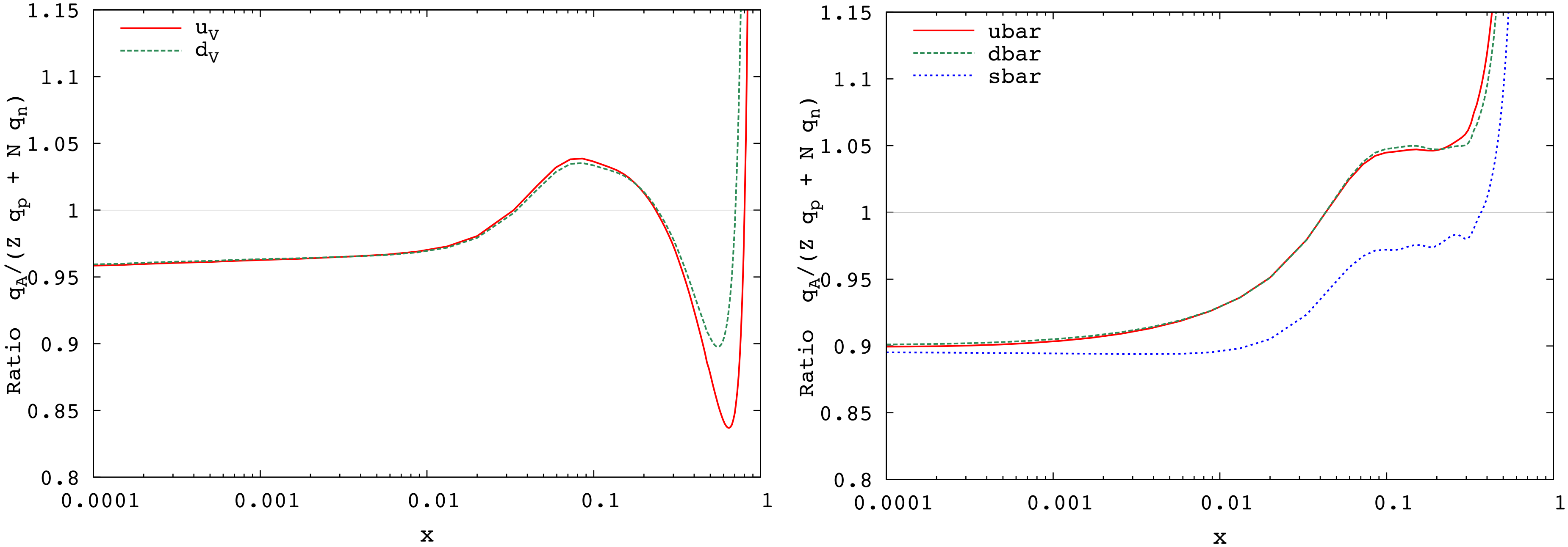
where $N^A_{\rm val} = A^{-1}\int_0^A dx q^-_{0/A} = 3$ *and* $N^A_1 = A^{-1}\int_0^A dx q^-_{1/A} = (Z-N)/A$



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 MODIFICATION OF PDFs



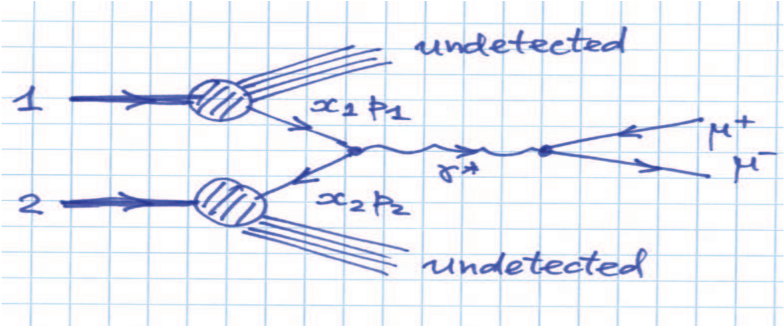
Ratio between our nPDFs and the corresponding ones calculated from free proton and neutron PDFs as $(Zq_p + Nq_n)$ at $Q^2 = 25$ GeV^2 in ^{207}Pb.

PREDICTIONS FOR 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:*

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

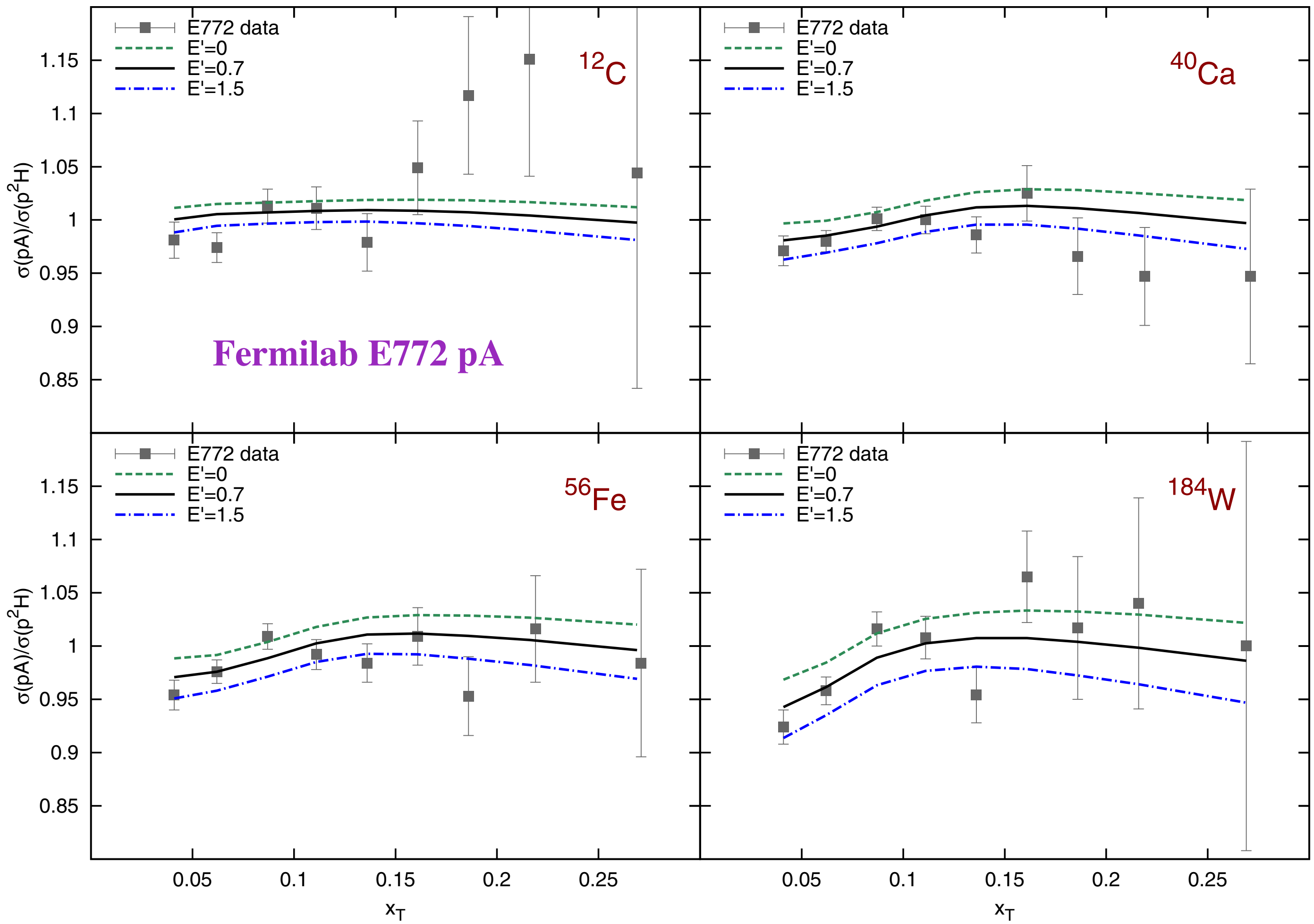
where E_B energy of proton, L distance traveled in nuclear environment

- *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



$\Longrightarrow$ *Partial cancellation between pion and shadowing effects*

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

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

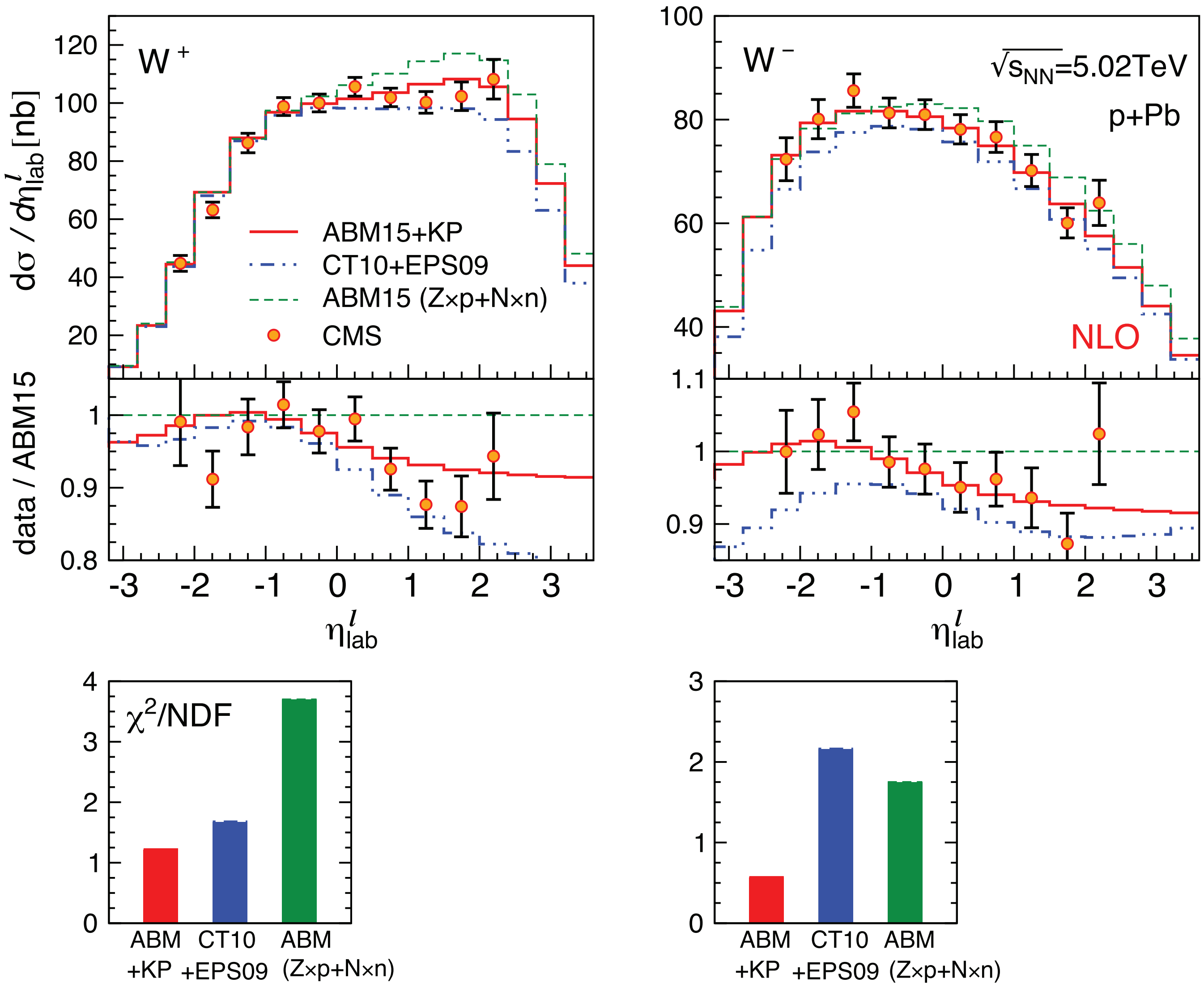
- *Collaboration with Ben-Wei Zhang (Central China Normal University, Wuhan, China) and Peng Ru (Dalian University of Technology, China) [see e.g. JPG 42 (2015) 085104]*

- *$W^{\pm}, Z$ production in pPb 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 $x \simeq M_{W,Z}/\sqrt{s_{\mathrm{NN}}} \times \exp(-\eta_{\mathrm{lab}} + 0.465)$.*

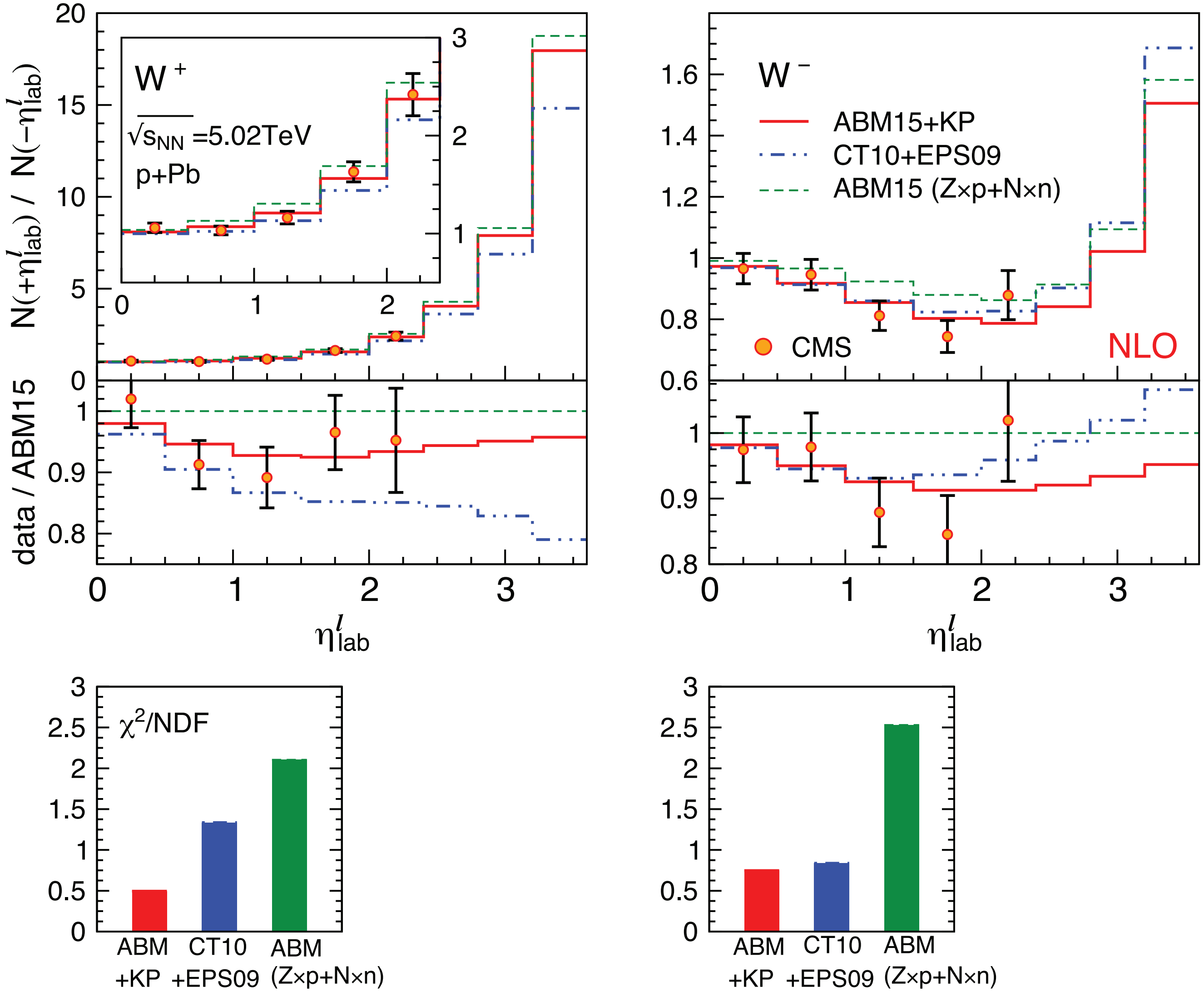
- *Analyze recent CMS measurement of $W^{\pm}, Z$ production in pPb at nucleon-nucleon center-of-mass energy $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV:*
  - *$W^{\pm}, Z$ Differential cross-sections as a function of rapidity;*
  - *Forward-Backward asymmetries vs. rapidity: $N_l(+\eta_{\mathrm{lab}})/N_l(-\eta_{\mathrm{lab}})$ for W, $N(+y^Z)/N(-y^Z)$ for Z;*
  - *W lepton charge asymmetry $(N_l^+ - N_l^-)/(N_l^+ + N_l^-)$.*

- *The cross-sections have been calculated at the NLO QCD approximation using the DYNNLO program [PRL 103 (2009) 082001] at $\mu_r = \mu_f = m_{W,Z}$*

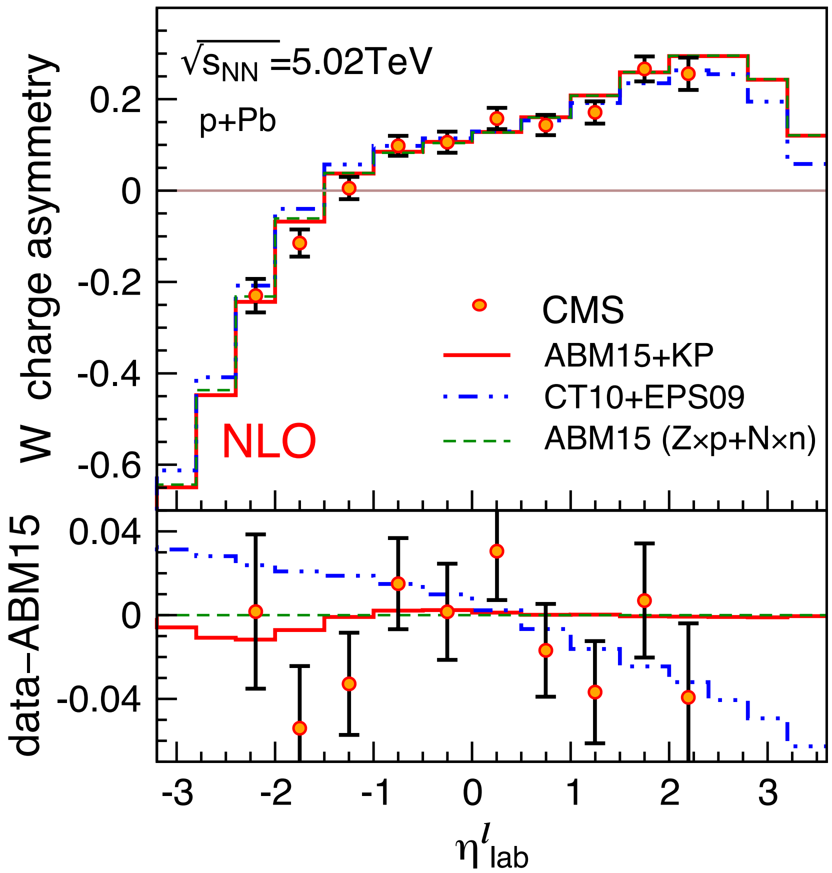
PREDICTIONS FOR $W^{\pm}$ DIFFERENTIAL CROSS-SECTIONS

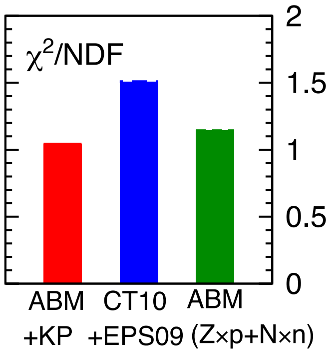


PREDICTIONS FOR $W^{\pm}$ FORWARD-BACKWARD ASYMMETRIES



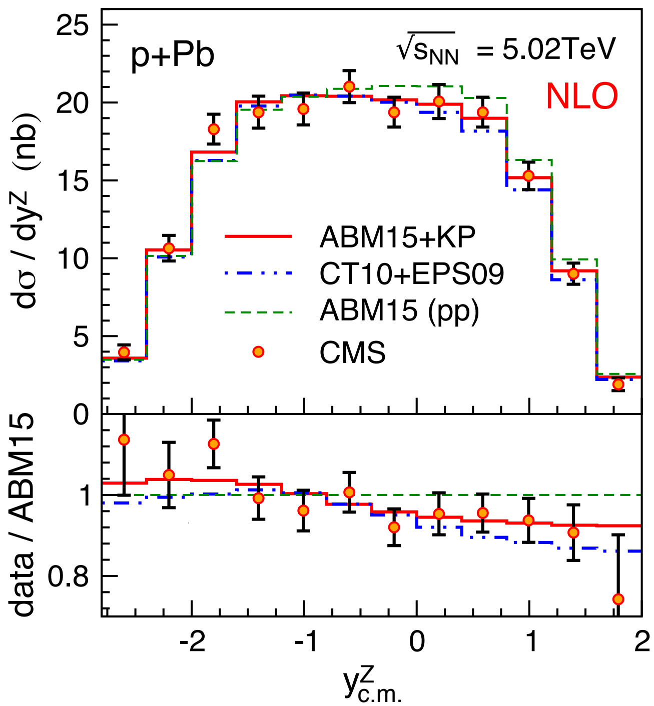
PREDICTIONS FOR W CHARGE ASYMMETRY



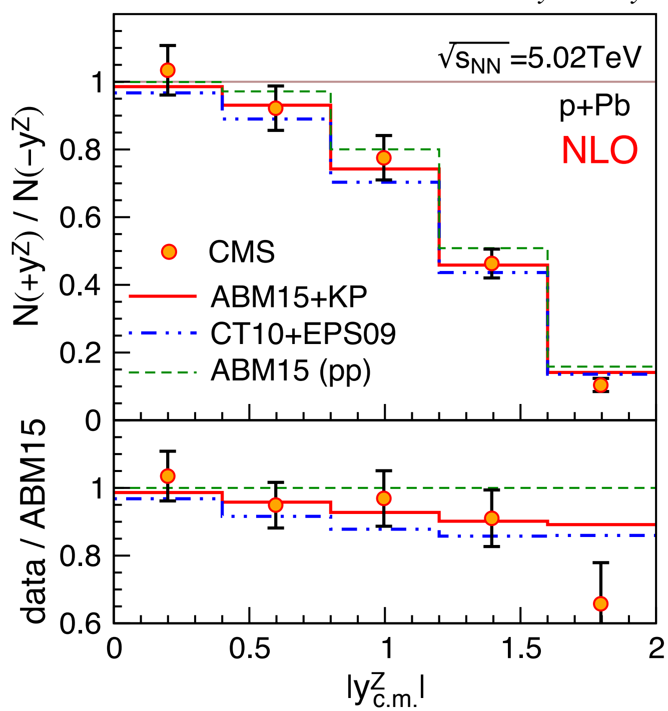


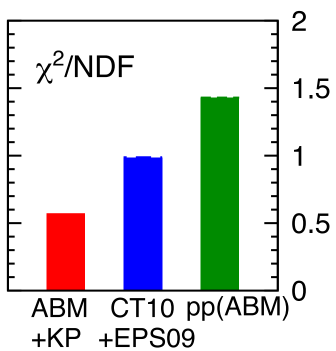
PREDICTIONS FOR Z PRODUCTION

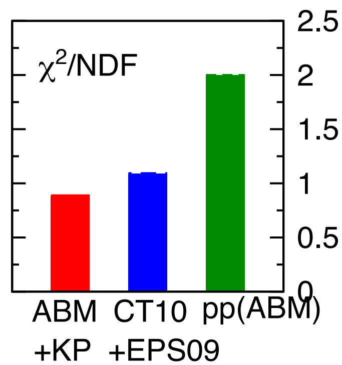
Differential cross-section



Forward-backward asymmetry







SUMMARY

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

- ✦ *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 JLab E03-103 and HERMES*

- ✦ *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*

Backup slides

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* $\boxed{\text{MEAN FIELD}}$ *model:*

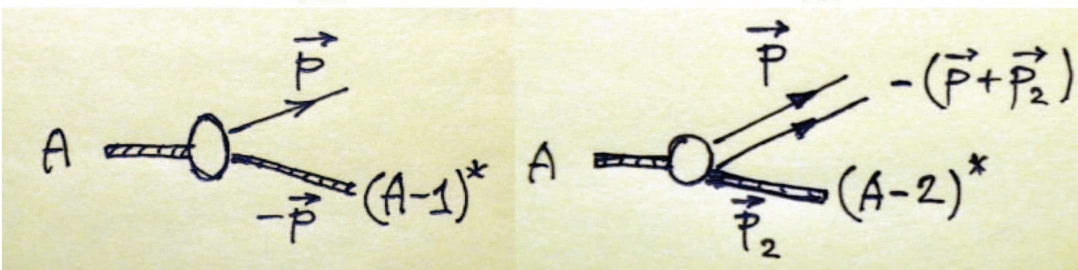
$$\mathcal{P}_{\rm MF}(\varepsilon, \mathbf{p}) = \sum_{\lambda<\lambda_{\rm F}} \mathbf{n}_\lambda \mid \phi_\lambda(\mathbf{p}) \mid^2 \delta(\varepsilon - \varepsilon_\lambda)$$

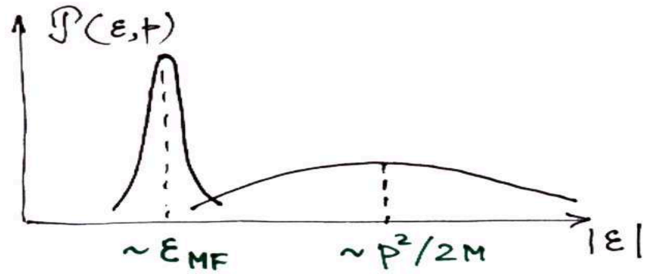
where sum over occupied levels with n_λ *occupation number. Applicable for small nucleon separation energy and momenta,* $\mid \varepsilon \mid < 50$ *MeV,* $p < 300$ *MeV/c*

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

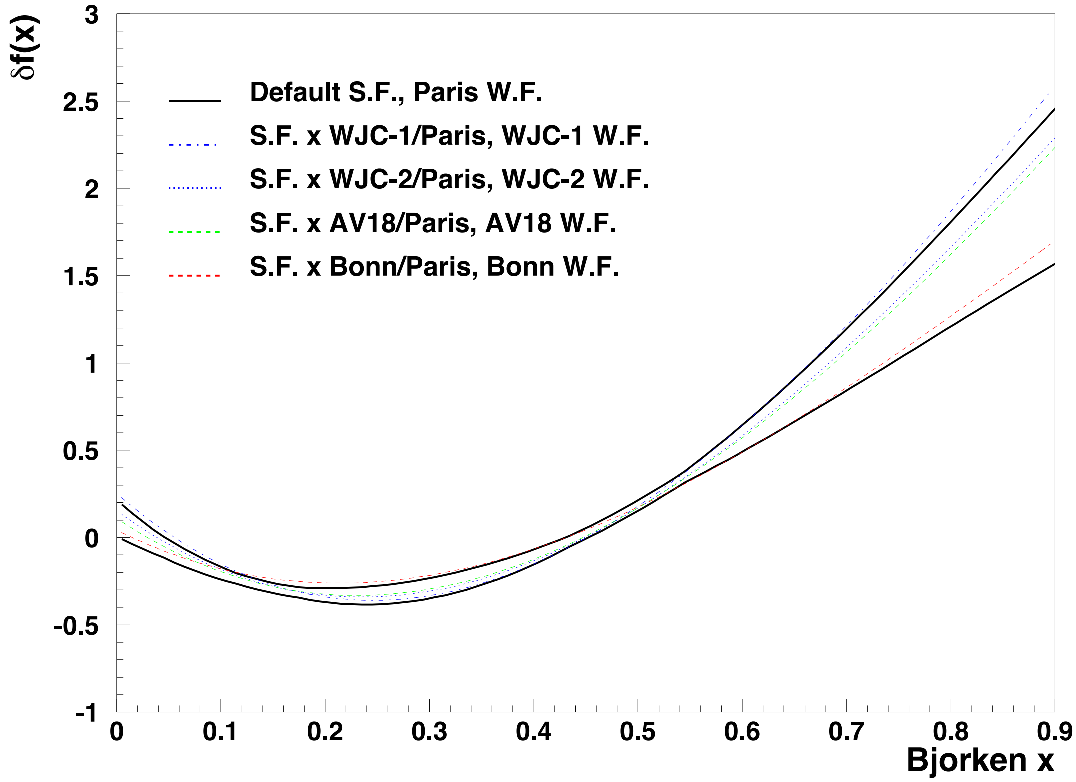
$$\mathcal{P}_{\rm cor}(\varepsilon, \mathbf{p}) \approx n_{\rm rel}(\mathbf{p}) \left\langle \delta \left(\varepsilon + \frac{(\mathbf{p}+\mathbf{p}_2)^2}{2M} + E_{A-2} - E_A \right) \right\rangle_{\rm CM}$$

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





OFF-SHELL FUNCTION FROM HEAVY TARGETS ($A \geq 4$)



- ✦ $\delta f(x)$ *extracted phenomenologically from nuclear DIS ratios* $\mathcal{R}_2(A,B) = F_2^A/F_2^B$*:*
  - *Electron and muon scattering from BCDMS, EMC,E139,E140,E665 and NMC*
  - *Wide range of targets* ^{4}*He,*^{7}*Li,*^{9}*Be,*^{12}*C,*^{27}*Al,*^{40}*Ca,*^{56}*Fe,*^{64}*Cu,*^{108}*Ag,*^{119}*Sn,*^{197}*Au,*^{207}*Pb*
  - *Systematic uncertainties including modeling, functional form and spectral/wave function variations*

$\Longrightarrow$ *Partial cancellation of systematics from spectral function in RATIOS* $\mathcal{R}_2(A,B)$

FLAVOR AND C-PARITY DEPENDENCE OF nPDFs

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

$$q^{\mathrm{IA}}_{0/A} = \left(f_{p/A} + f_{n/A}\right) \oplus q_{0/p} \qquad \mathcal{P}_0 = \mathcal{P}_{\mathrm{MF}} + \mathcal{P}_{\mathrm{cor}}$$

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

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

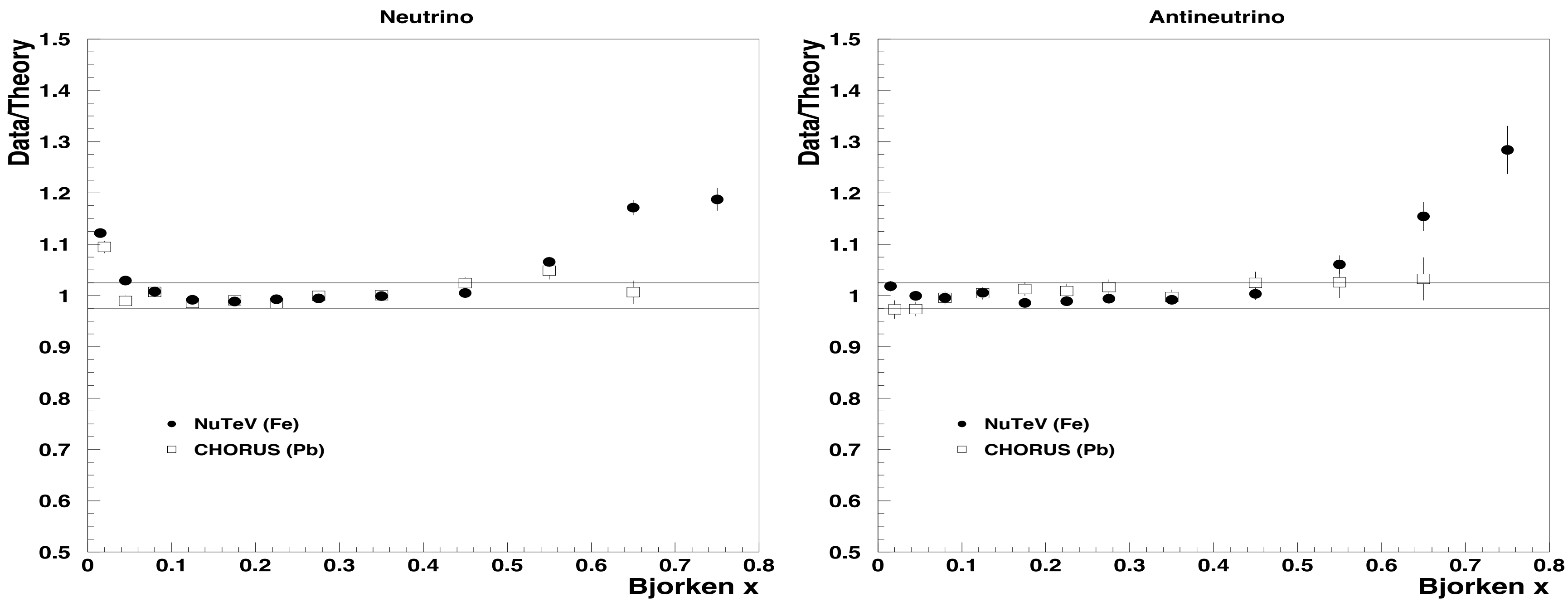
$$\delta\mathcal{R}^+ = \mathrm{Im}\,\mathcal{A}(a^+)/A\,\mathrm{Im}\,a^+ \qquad \delta\mathcal{R}^- = \mathrm{Im}\,a^-\mathcal{A}_1(a^+)/A\,\mathrm{Im}\,a^-$$

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) $\delta_\pi q^-_{0/A} = 0$*

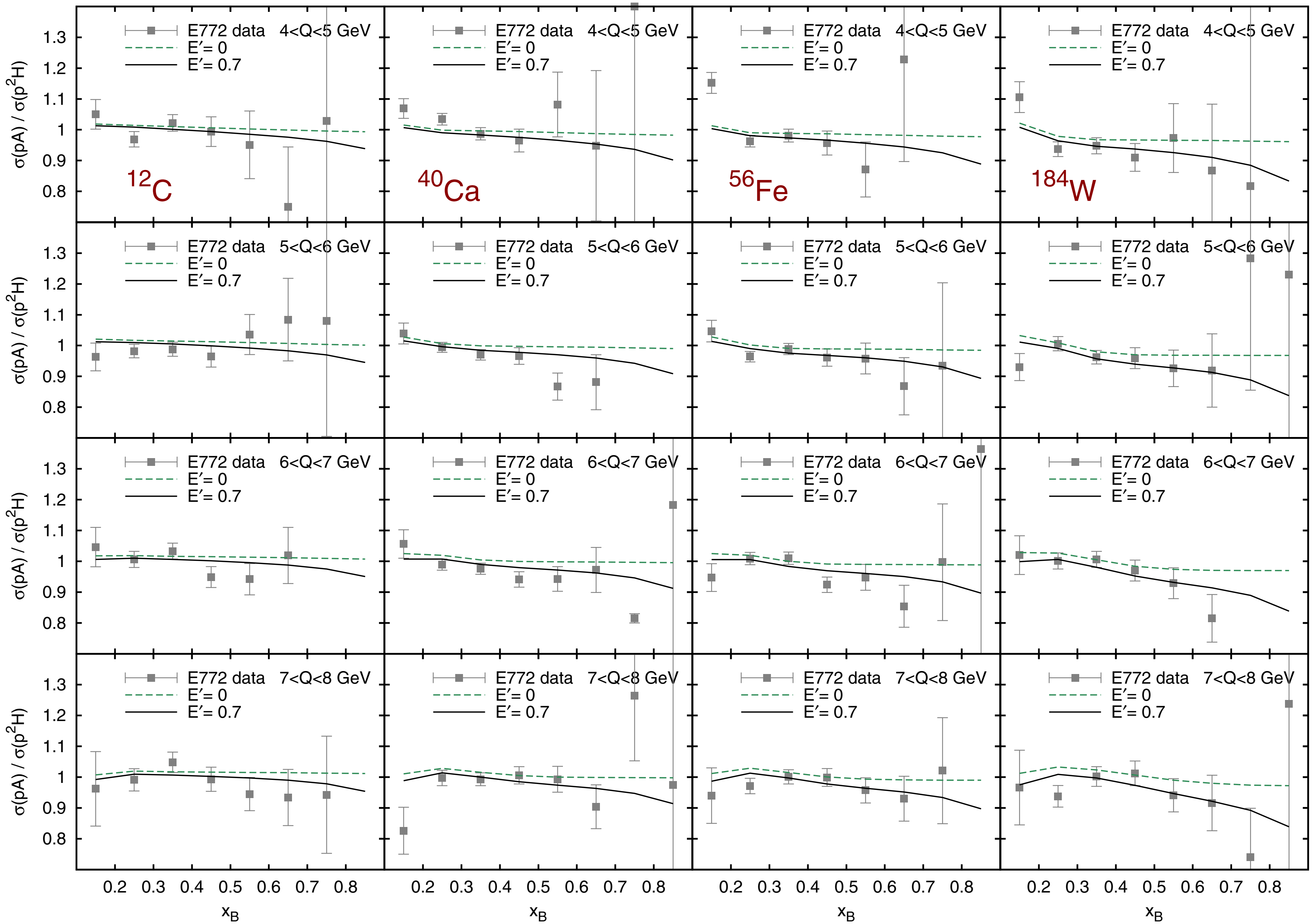
PREDICTIONS FOR (ANTI)NEUTRINO DIS DATA



✦ *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*



E772 Drell-Yan p-A data

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