Nuclear Parton Distributions and Applications to Drell-Yan and (Anti)neutrino Scattering

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OUTLINE

I *A Global Approach to 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 Drell-Yan production in pA*

- *Corrections from nuclear target and from projectile energy loss;*
- *Comparisons with E772 and E866 Drell-Yan data.*

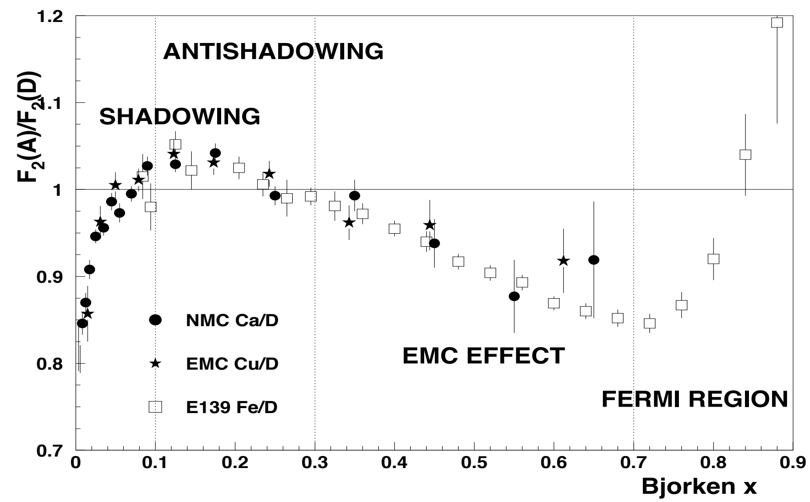
III *Application to (Anti)neutrino Scattering*

- *Comparisons with CHORUS and NuTeV differential cross-section data;*
- *Nuclear corrections for charm production.*

NUCLEAR PARTON DISTRIBUTIONS

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

- *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 ∼ 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)*

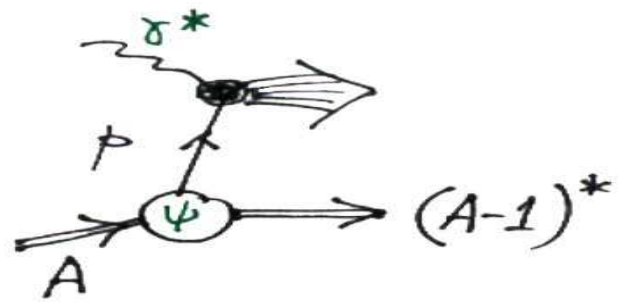
INCOHERENT NUCLEAR SCATTERING

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

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

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

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

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

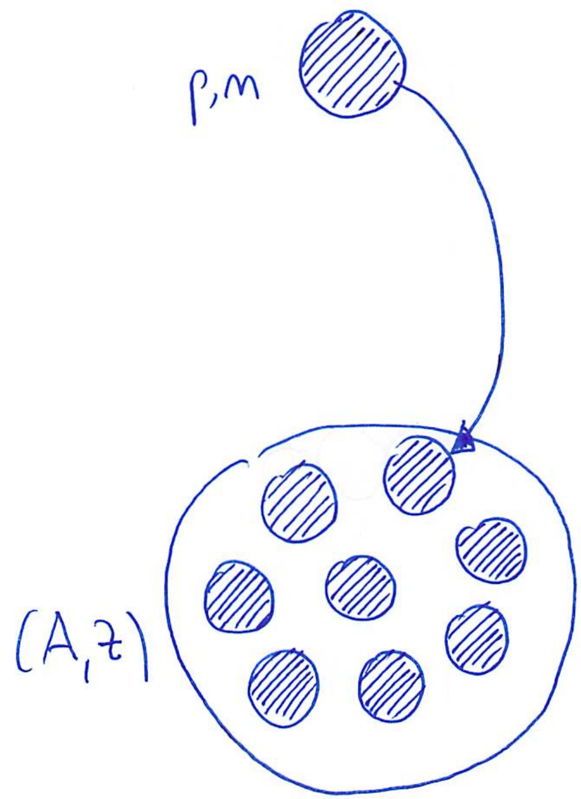
DESCRIPTION OF NUCLEON

Distribution of partons in a nucleon

STRUCTURE FUNCTIONS

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

$\delta f(x)$



DESCRIPTION OF NUCLEUS

Distribution of bound nucleons

SPECTRAL FUNCTION

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

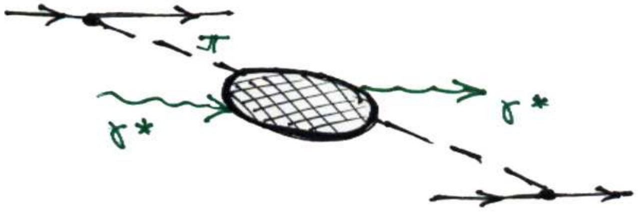
Off-shell function measures the in-medium modification of bound nucleon

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:*

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



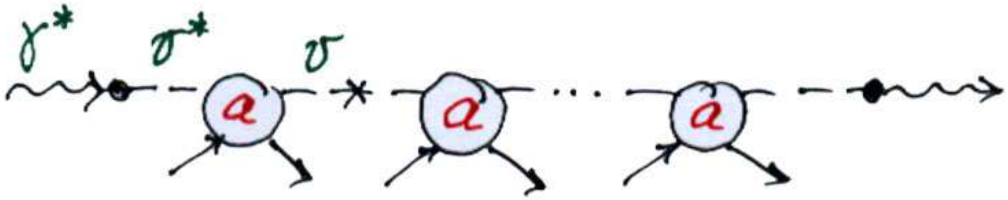
✦ *Contribution from nuclear pions (mesons) to balance nuclear light cone momentum* $\langle y \rangle_\pi + \langle y \rangle_N = 1$. *The pion distribution function is localized in a region of* $y \leq p_F/M \sim 0.3$ *so that the pion contribution is at* $x < 0.3$. *The correction is driven by the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



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

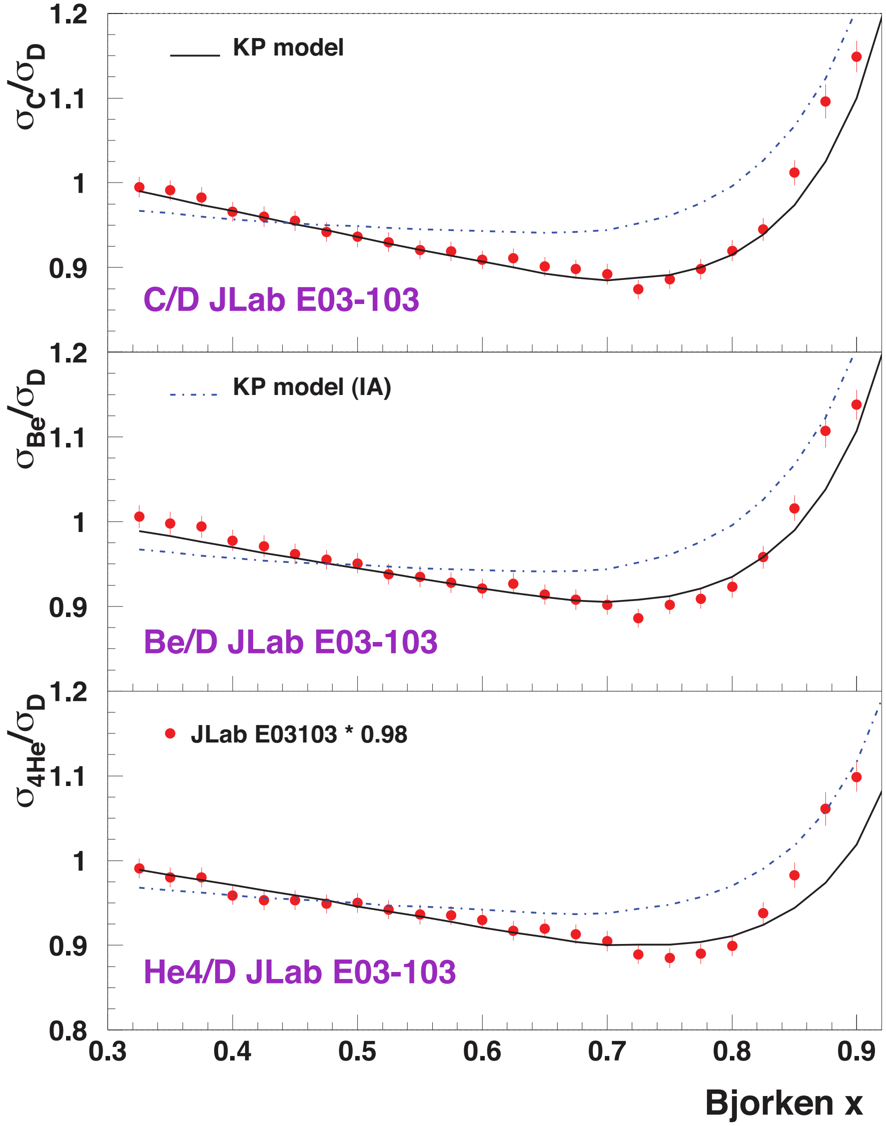
$$\mathcal{A}(a) = ia^2 \int_{z_1<z_2} {\rm d}^2\mathbf{b}\,{\rm d}z_1{\rm d}z_2\,\rho_A(\mathbf{b},z_1)\rho_A(\mathbf{b},z_2)e^{i\int_{z_1}^{z_2}{\rm d}z'\,a\,\rho_A(\mathbf{b},z')}e^{ik_L(z_1-z_2)}$$

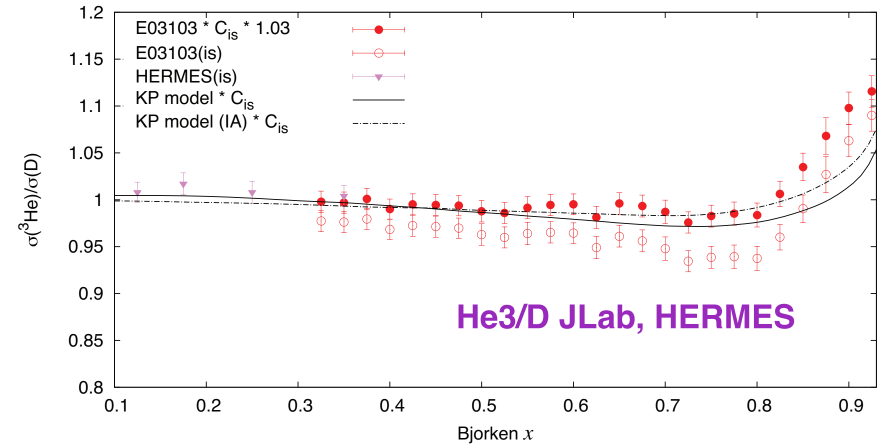
$a = \sigma(i+\alpha)/2$ *is the (effective) scattering amplitude* ($\alpha = {\rm Re}\,a/{\rm Im}\,a$) *in forward direction,* $k_L = Mx(1+m_v^2/Q^2)$ *is longitudinal momentum transfer in the process* $v^* \to v$ *(accounts for finite life time of virtual hadronic configuration).*

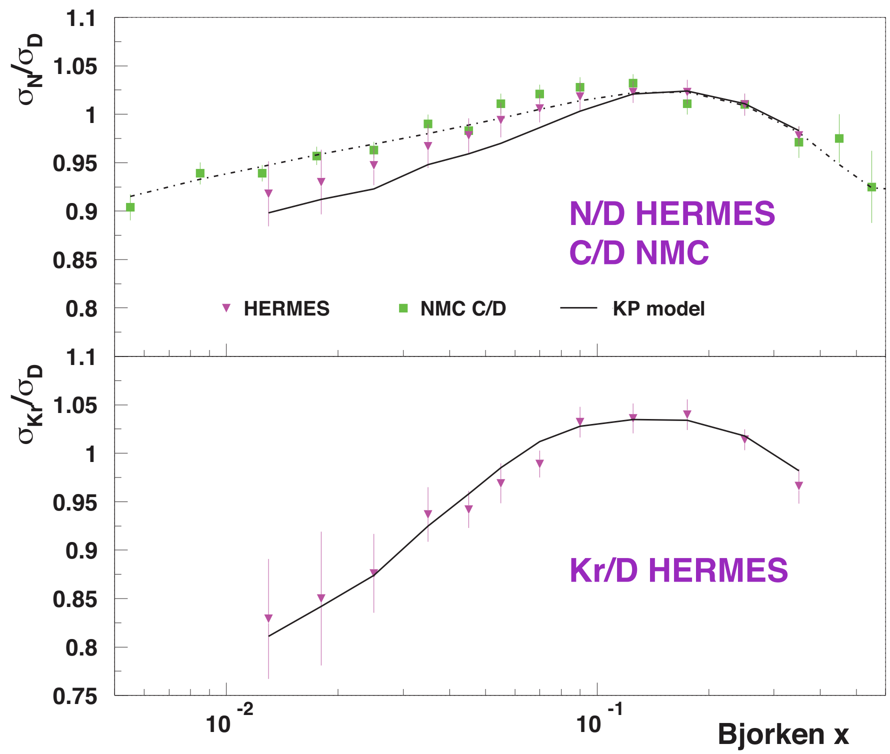
✦ *Hadronic/nuclear input:*

- *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*

PREDICTIONS FOR CHARGED LEPTON DIS DATA







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

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:*

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

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

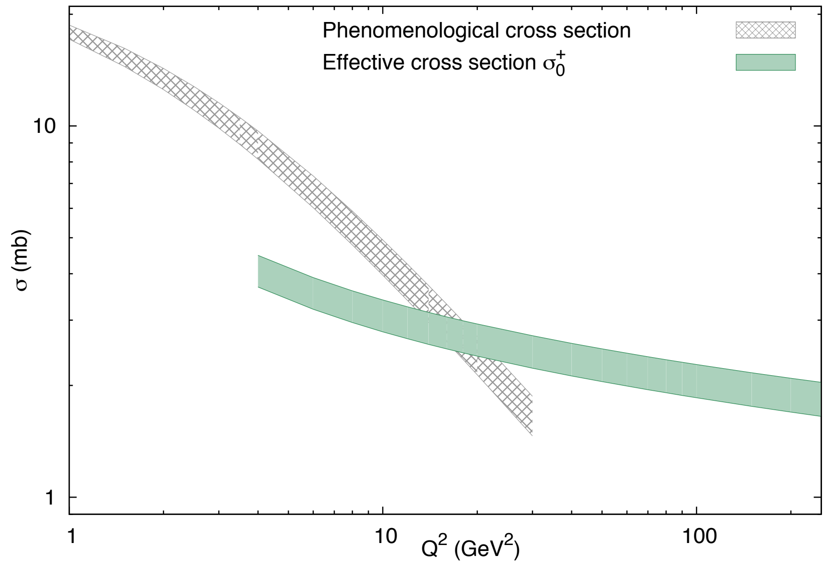
CONSTRAINTS FROM PDF SUM RULES

- *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:*

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

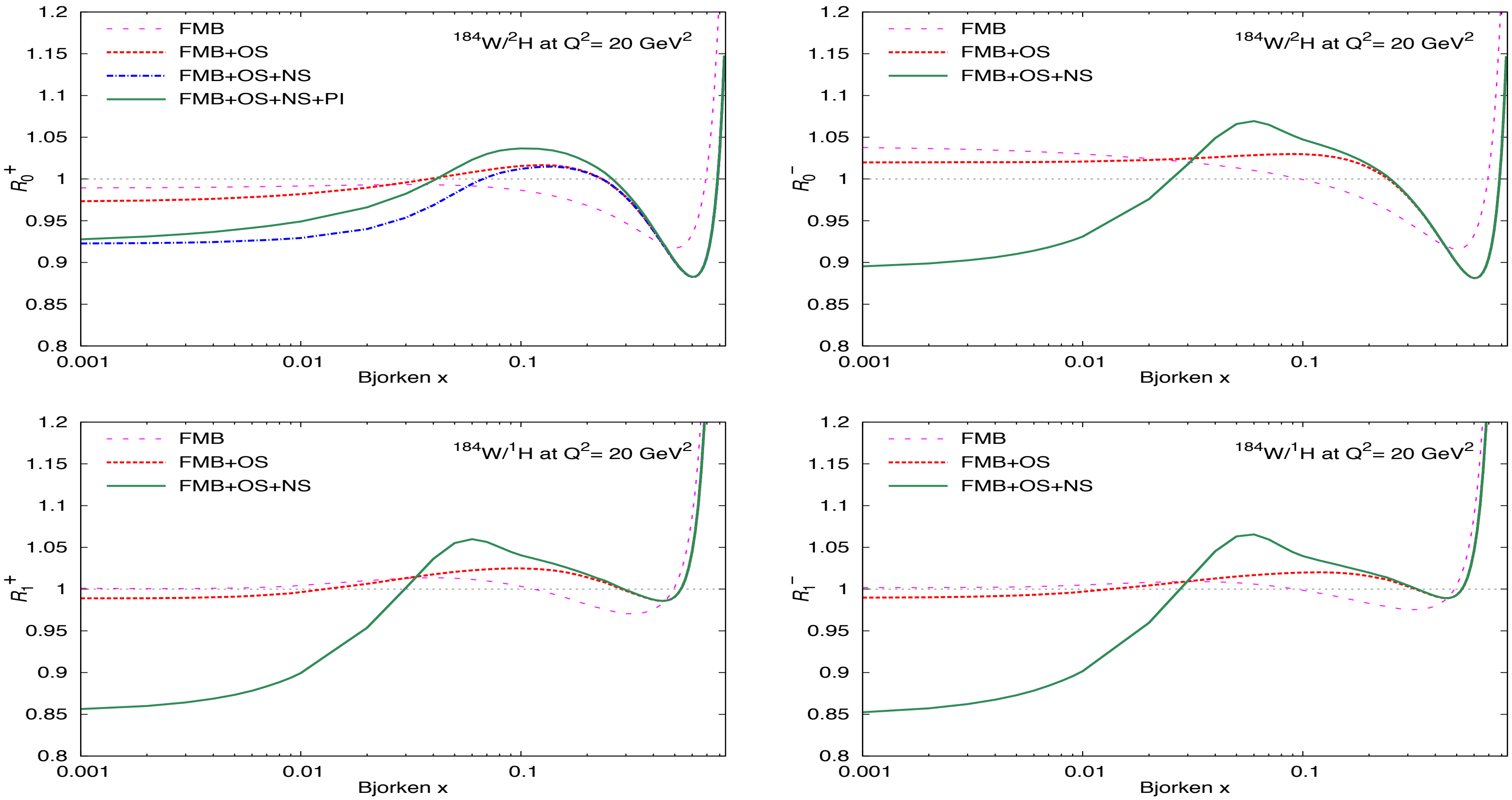
where $N^A_{\rm val} = A^{-1}\int_0^A dx q^-_{0/A} = 3$ *and* $N^A_1 = A^{-1}\int_0^A dx q^-_{1/A} = (Z-N)/A$



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 $\rm Re/Im$ of amplitudes

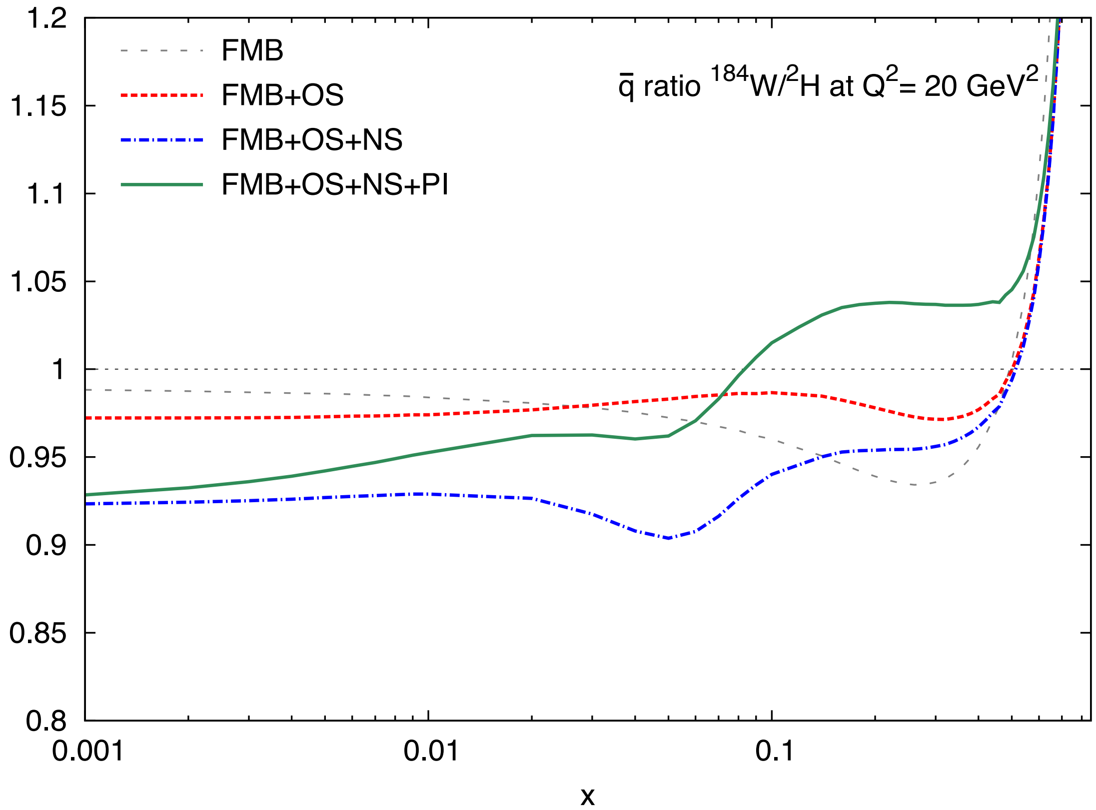
$\Longrightarrow$ *In our approach nuclear corrections to PDFs essentially defined by $\mathcal{P}(\varepsilon, \mathbf{p})$ AND $\delta f(x)$*

FLAVOR AND C-PARITY DEPENDENCE OF NUCLEAR EFFECTS



Nuclear effects on C-even and C-odd combinations of isoscalar $q_0 = u + d$ (upper panel) and isovector $q_1 = u - d$ (lower panel) PDFs at $Q^2 = 20$ GeV^2.
Ratios of ^{184}W to deuteron ^{2}H (upper panel) and proton ^{1}H (lower panel).

NUCLEAR ANTI-QUARKS



✦ $\delta\mathcal{R}_{\rm sea}$ *from corrections to C-even* $q_0^+ = q + \bar{q}$ *and C-odd* $q_0^- = q - \bar{q} = q_{\rm val}$

$$\delta\mathcal{R}_{\rm sea} = \frac{\delta\bar{q}^A}{\bar{q}^N} = \delta\mathcal{R}^+ + \frac{q_{\rm val}^N(x)}{2\bar{q}^N(x)}\left(\delta\mathcal{R}^+ - \delta\mathcal{R}^-\right)$$

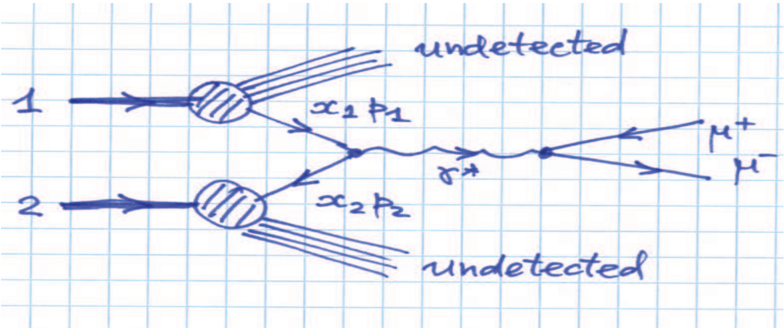
✦ *Same C-parity dependence for strange sea:* $s + \bar{s}$ *like* $\delta\mathcal{R}_{\rm sea}$, $s - \bar{s}$ *like* $\delta\mathcal{R}_{\rm val} = \mathcal{R}^-$

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:*

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

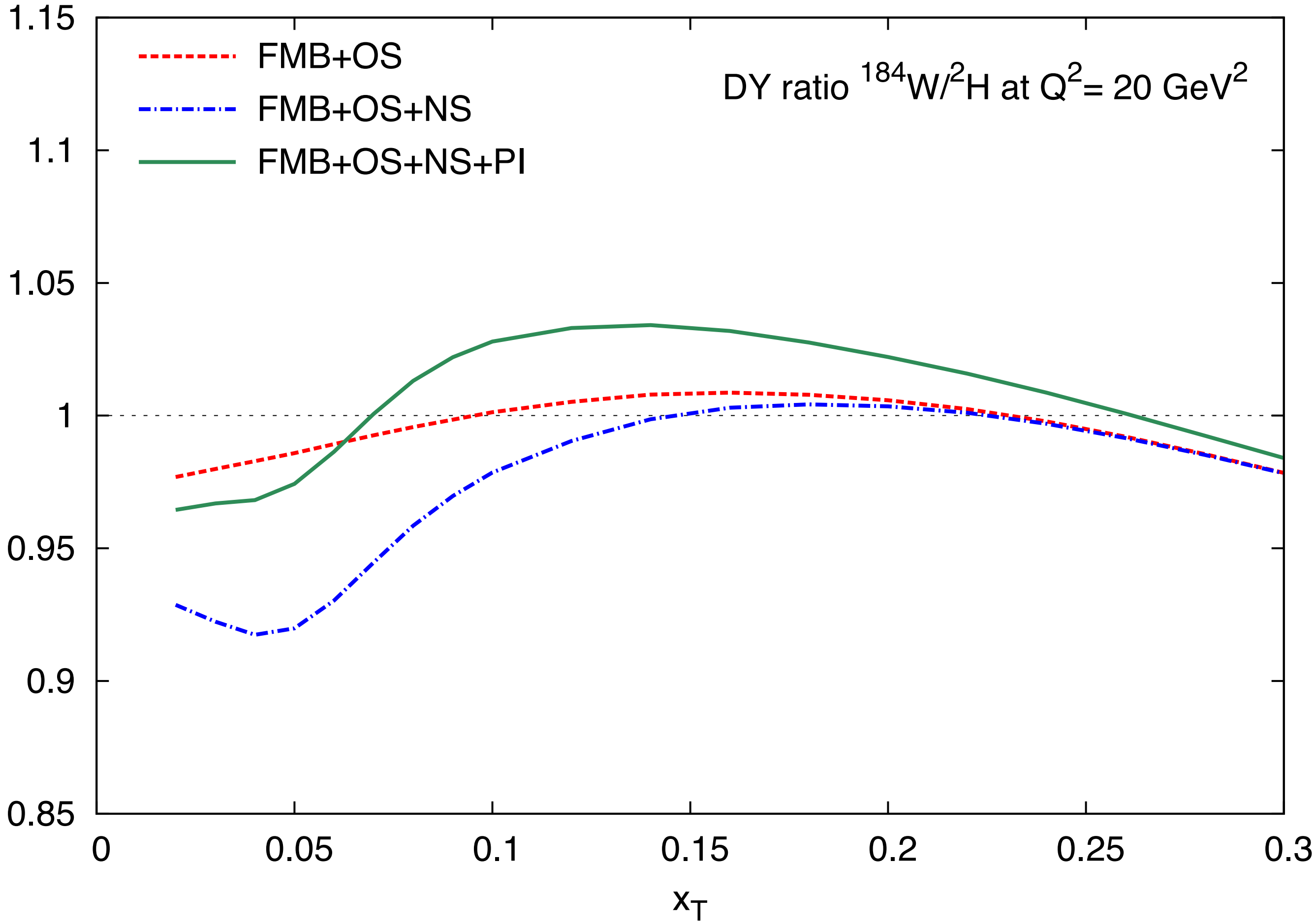
where E_B energy of proton, L distance traveled in nuclear environment

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

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

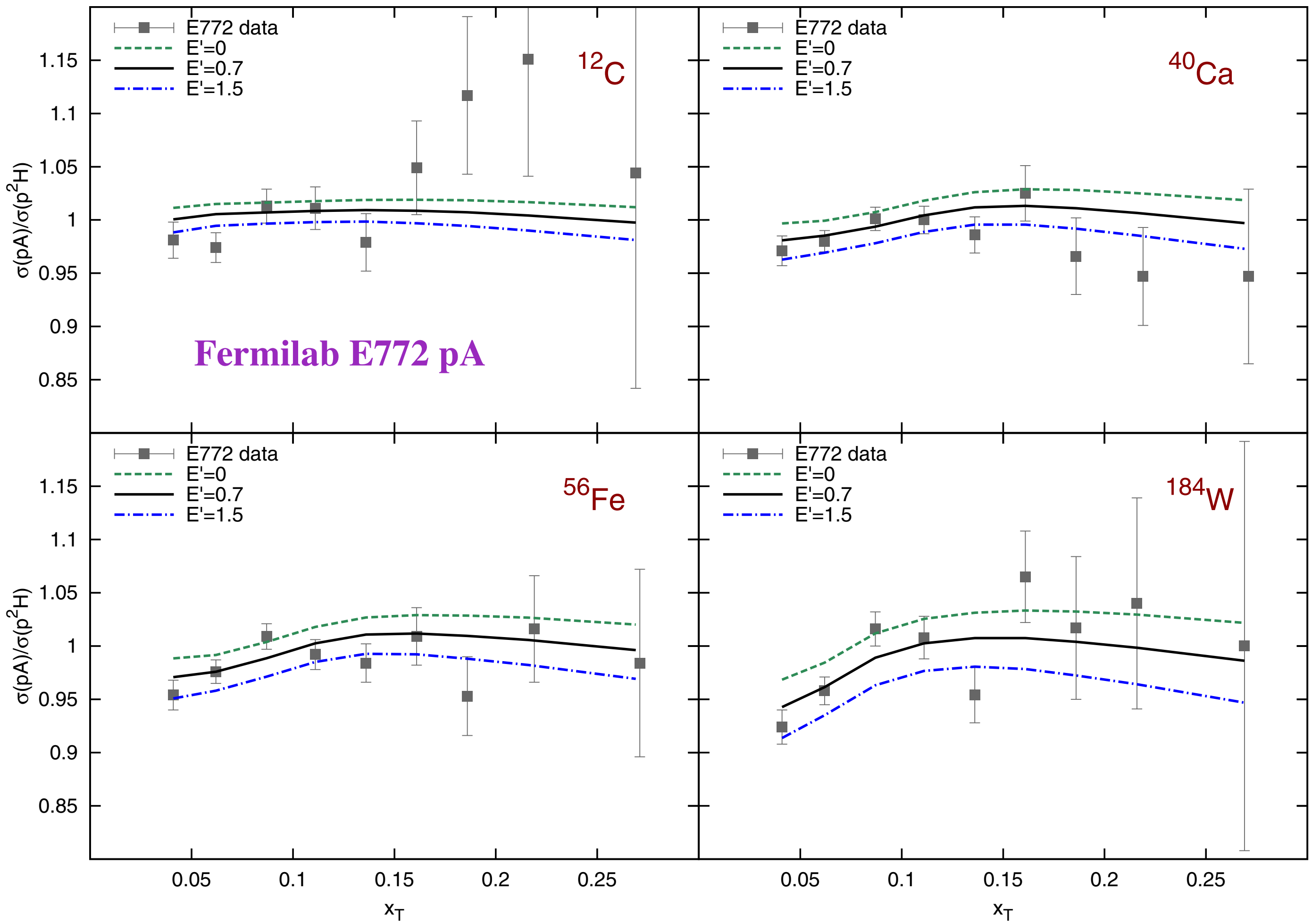
$\Longrightarrow$ *Nuclear data from Drell-Yan production in hadron collisions indicate no major enhancement to sea quarks for $x_T > 0.1$ as given by nuclear π excess*

PREDICTIONS FOR DRELL-YAN DATA



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

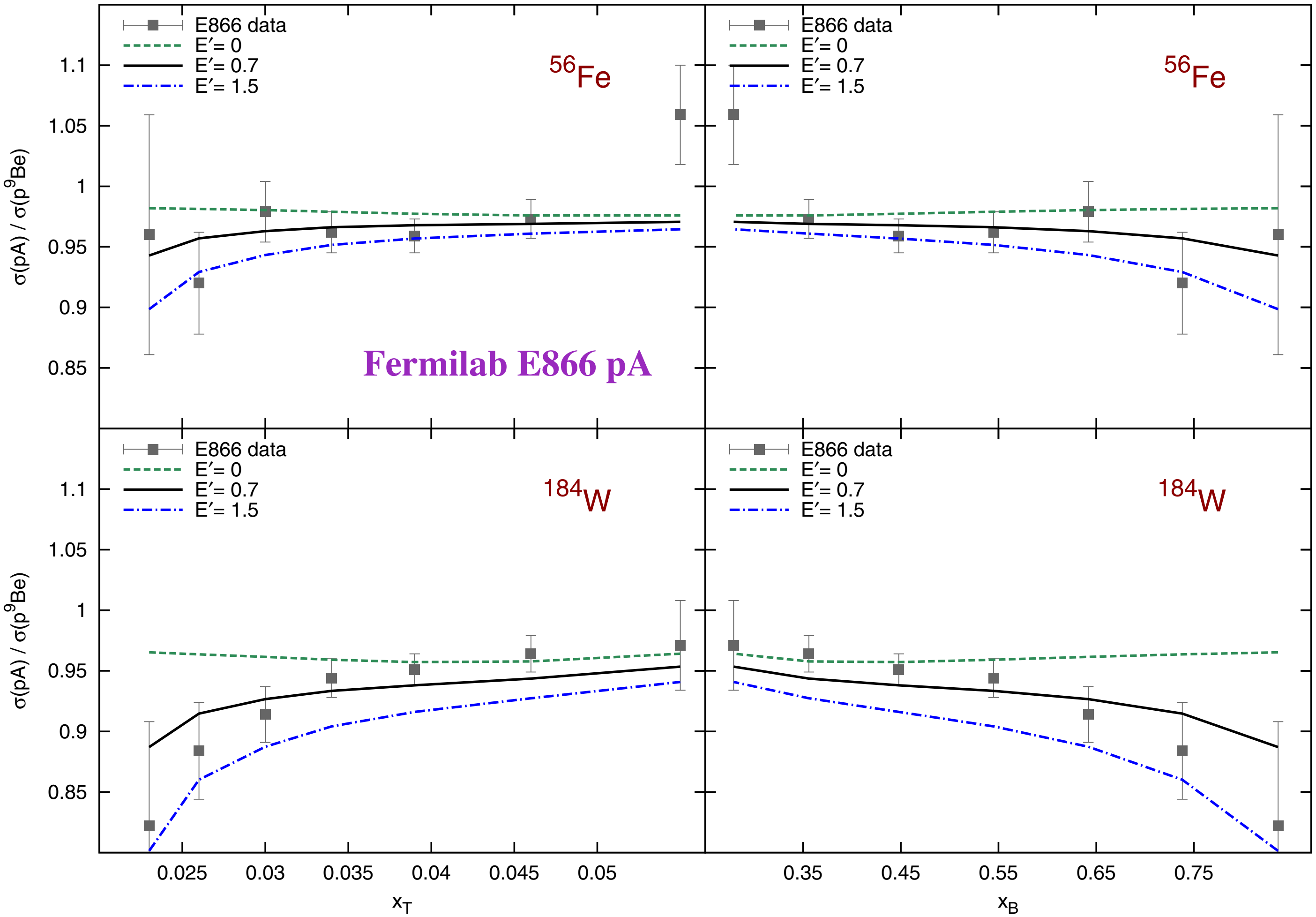
S. Kulagin and R.P., PRC 90 (2014) 045204



$\Longrightarrow$ *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 NEUTRINO SCATTERING

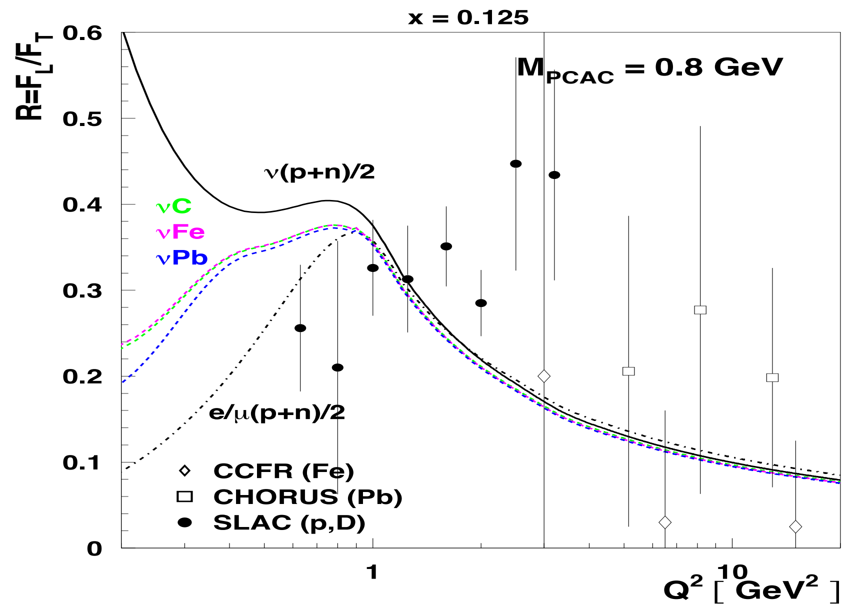
- *Nuclear structure functions (SFs) for lepton-nucleus scattering not simple combination of PDFs*

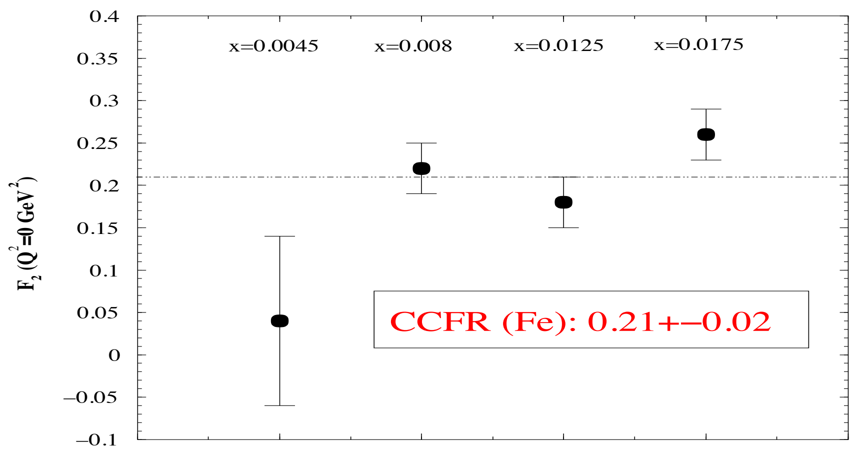
- *Modeling (anti)neutrino cross-sections in energy range relevant to modern experiments requires effects beyond nPDFs:*
  - *Target Mass corrections (TM);*
  - *High Twist contributions $\mathcal{O}(1/Q^2)$;*
  - *Radiative electroweak corrections;*
  - *Partial Conservation of the Axial Current (PCAC) dominating SFs at low Q^2.*

$\Longrightarrow$ *Finite value of F_2 in the limit $Q^2 \to 0$*

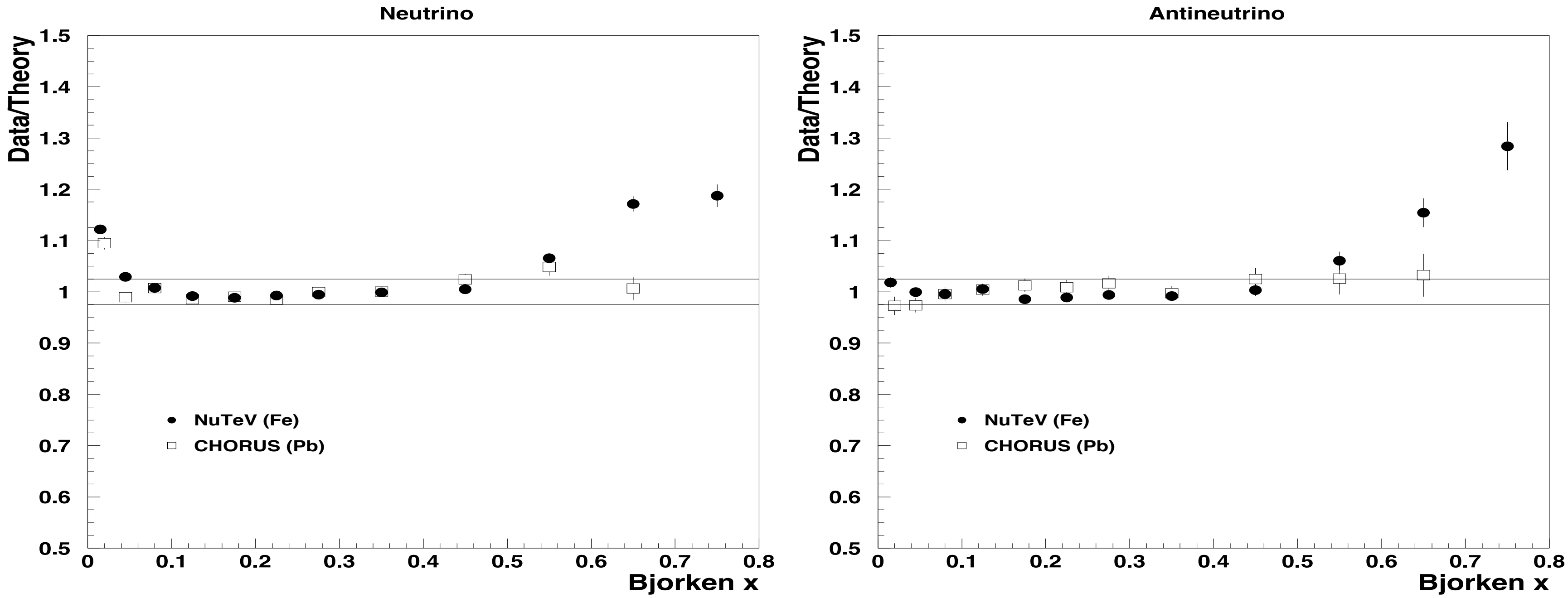
$\Longrightarrow$ *Finite value of F_L for $Q^2 \to 0$ implies different $R = \sigma_L/\sigma_T$ in (anti)neutrino and charged lepton scattering*

S. Kulagin and R.P., PRD 76 (2007) 094023





PREDICTIONS FOR CHORUS AND NuTeV



✦ *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 $\pm 2.5\%$):*

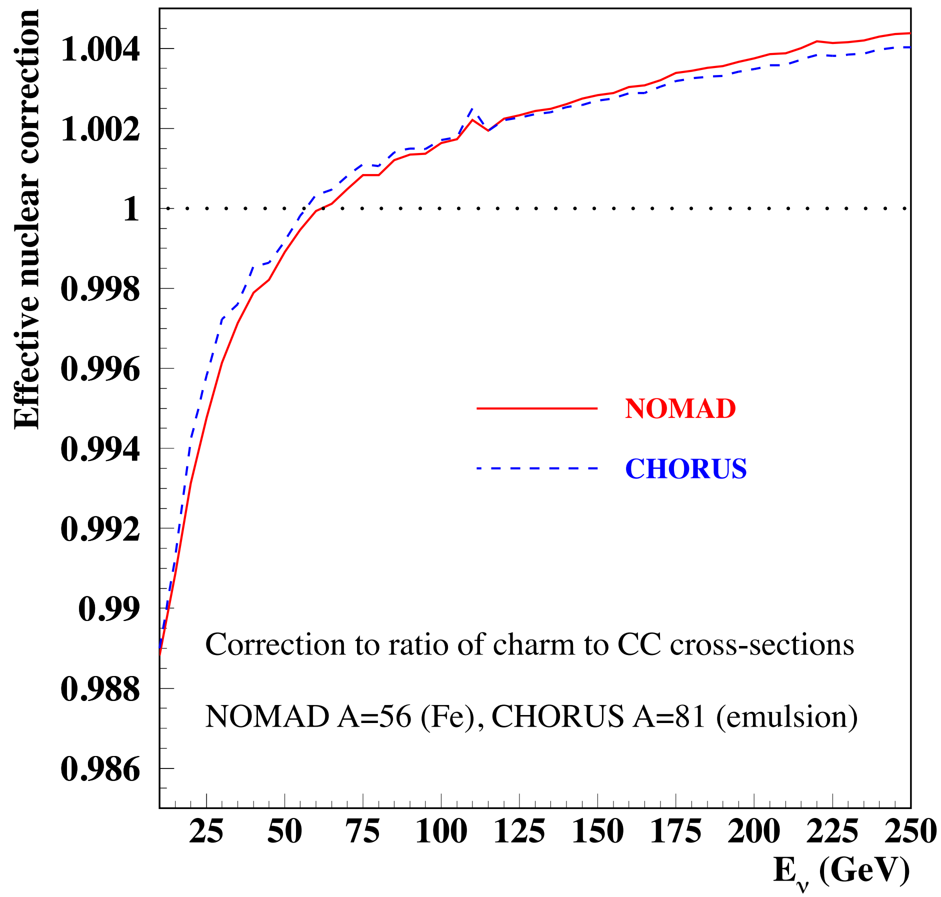
- *Systematic excess observed for $x > 0.5$ in both ν and $\bar{\nu}$ NuTeV data on Fe*
- *CHORUS data on Pb target consistent with predictions at large x;*
- *Consistent excess observed at $x < 0.05$ in both CHORUS and NuTeV neutrino data*

PREDICTIONS FOR CHARM PRODUCTION

- *Reduced nuclear corrections on total cross-sections from phase space integration*
- *Charm production in (anti)neutrino interactions direct probe of strange sea quark distributions*
- *Consider ratio of charm to inclusive CC total cross-sections*

$$\mathcal{R}_c = \sigma_{\mathrm{Charm}}/\sigma_{\mathrm{CC}}$$

$\Longrightarrow$ *Reduction of nuclear uncertainties on strange sea determinations (cancellation to $<1\%$ on $\mathcal{R}_c$)*



NPB 876 (2013) 339; NJP 13 (2011) 093002; arXiv:1404.6469 [hep-ph]

SUMMARY

- *Using a global approach we developed a detailed semi-microscopic model for the calculation of nuclear PDFs and structure functions, 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*

  $\Longrightarrow$ *Study off-shell function δf describing in-medium modifications of bound nucleons*

- *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 for neutrino scattering off nuclei in agreement with cross-section data from CHORUS at $x > 0.05$ and from NuTeV in the region $0.15 < x < 0.55$*

  $\Longrightarrow$ *Discrepancies at small x and for NuTeV at $x > 0.55$ require new precision data*

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* MEAN FIELD *model:*

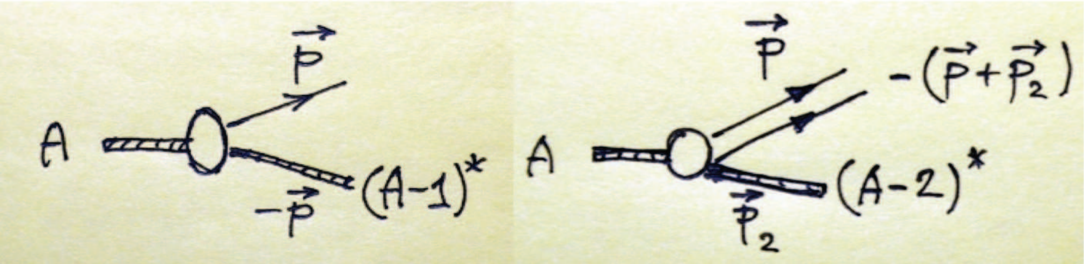
$$\mathcal{P}_{\rm MF}(\varepsilon, \mathbf{p}) = \sum_{\lambda<\lambda_{\rm F}} \mathbf{n}_\lambda \mid \phi_\lambda(\mathbf{p}) \mid^2 \delta(\varepsilon - \varepsilon_\lambda)$$

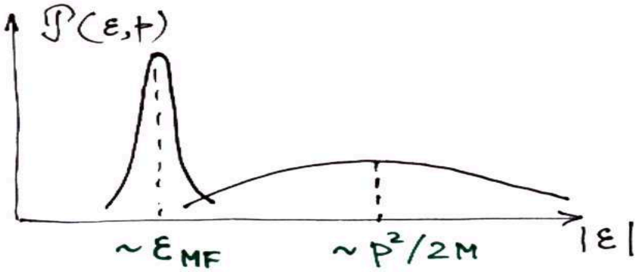
where sum over occupied levels with n_λ occupation number. Applicable for small nucleon separation energy and momenta, $\mid \varepsilon \mid < 50$ *MeV*, $p < 300$ *MeV/c*

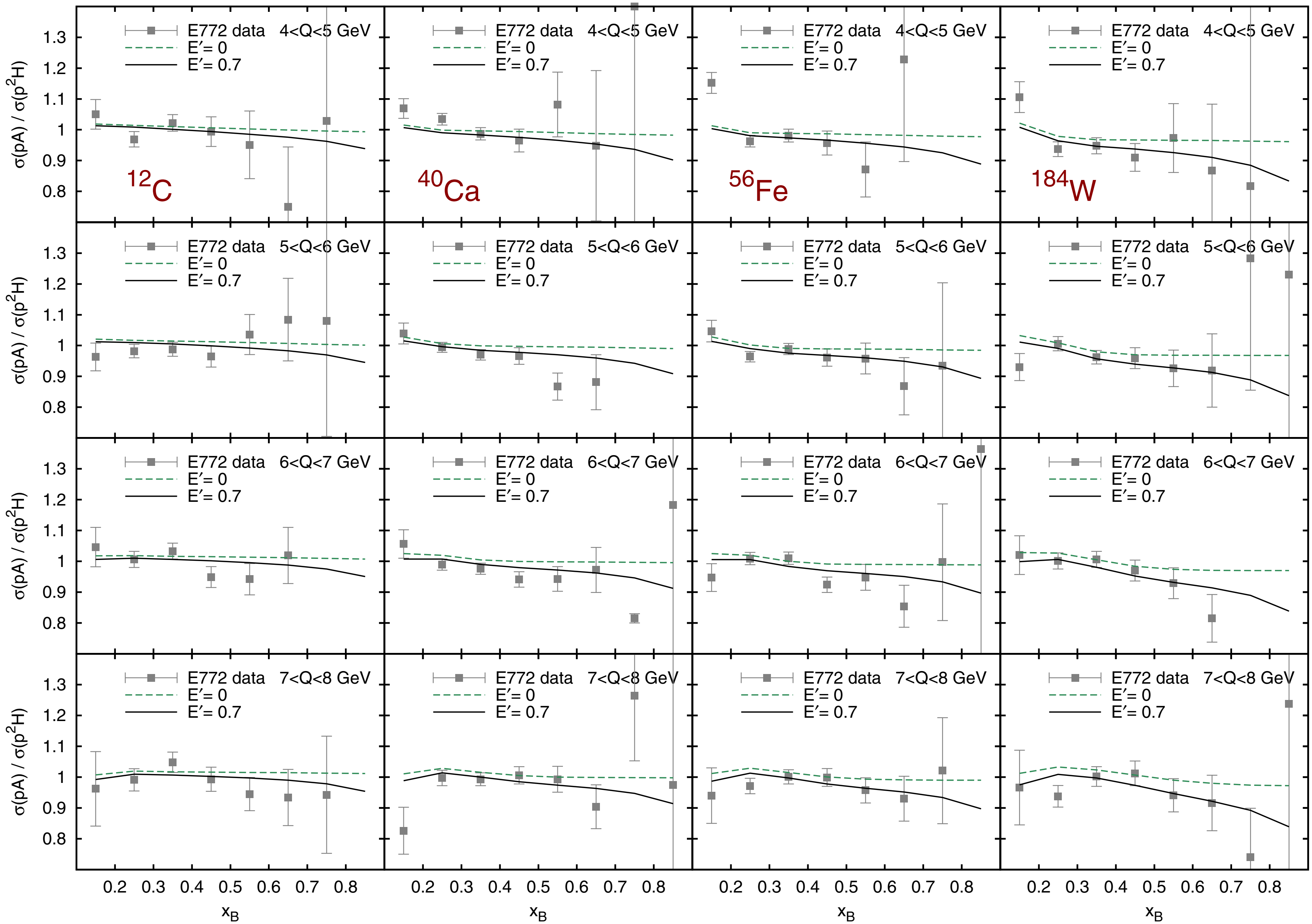
- CORRELATION EFFECTS *in nuclear ground state drive the high-energy and high-momentum component of the nuclear spectrum, when* $\mid \varepsilon \mid$ *increases*

$$\mathcal{P}_{\rm cor}(\varepsilon, \mathbf{p}) \approx \mathbf{n}_{\rm rel}(\mathbf{p}) \left\langle \delta \left(\varepsilon + \frac{(\mathbf{p}+\mathbf{p_2})^2}{\mathbf{2M}} + \mathbf{E_{A-2}} - \mathbf{E_A} \right) \right\rangle_{\rm CM}$$

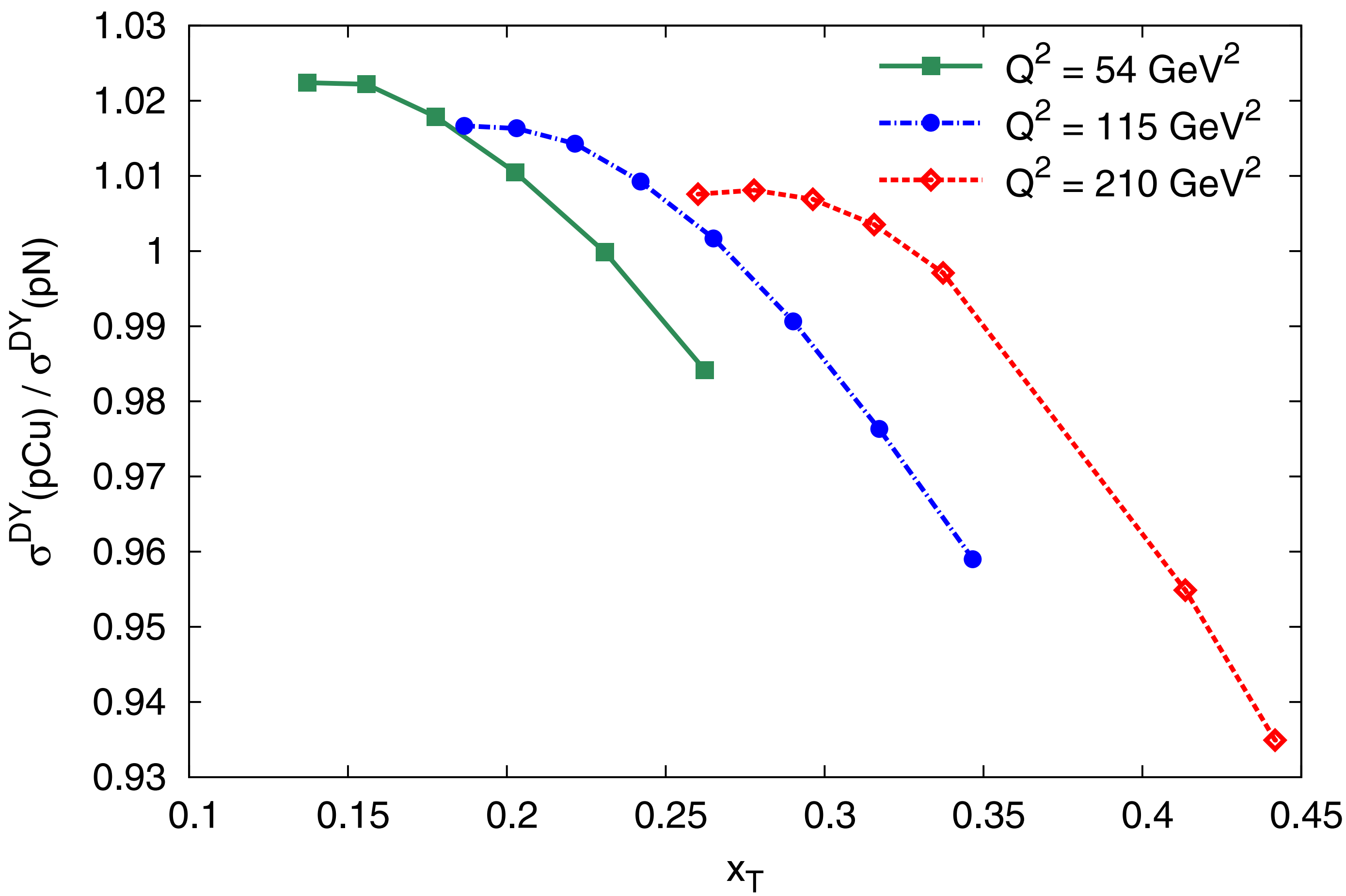
$$\mathcal{P} = \mathcal{P}_{\rm MF} \quad + \quad \mathcal{P}_{\rm cor}$$





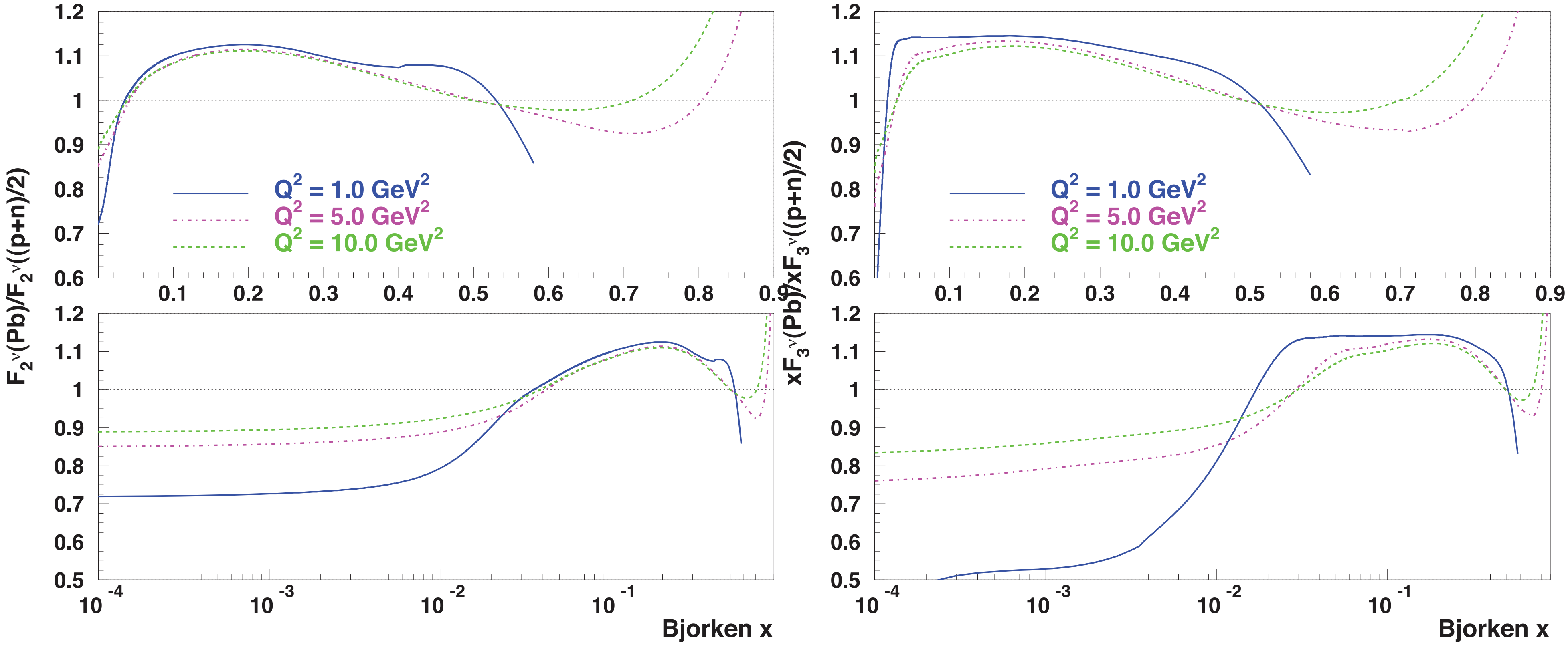


E772 Drell-Yan p-A data



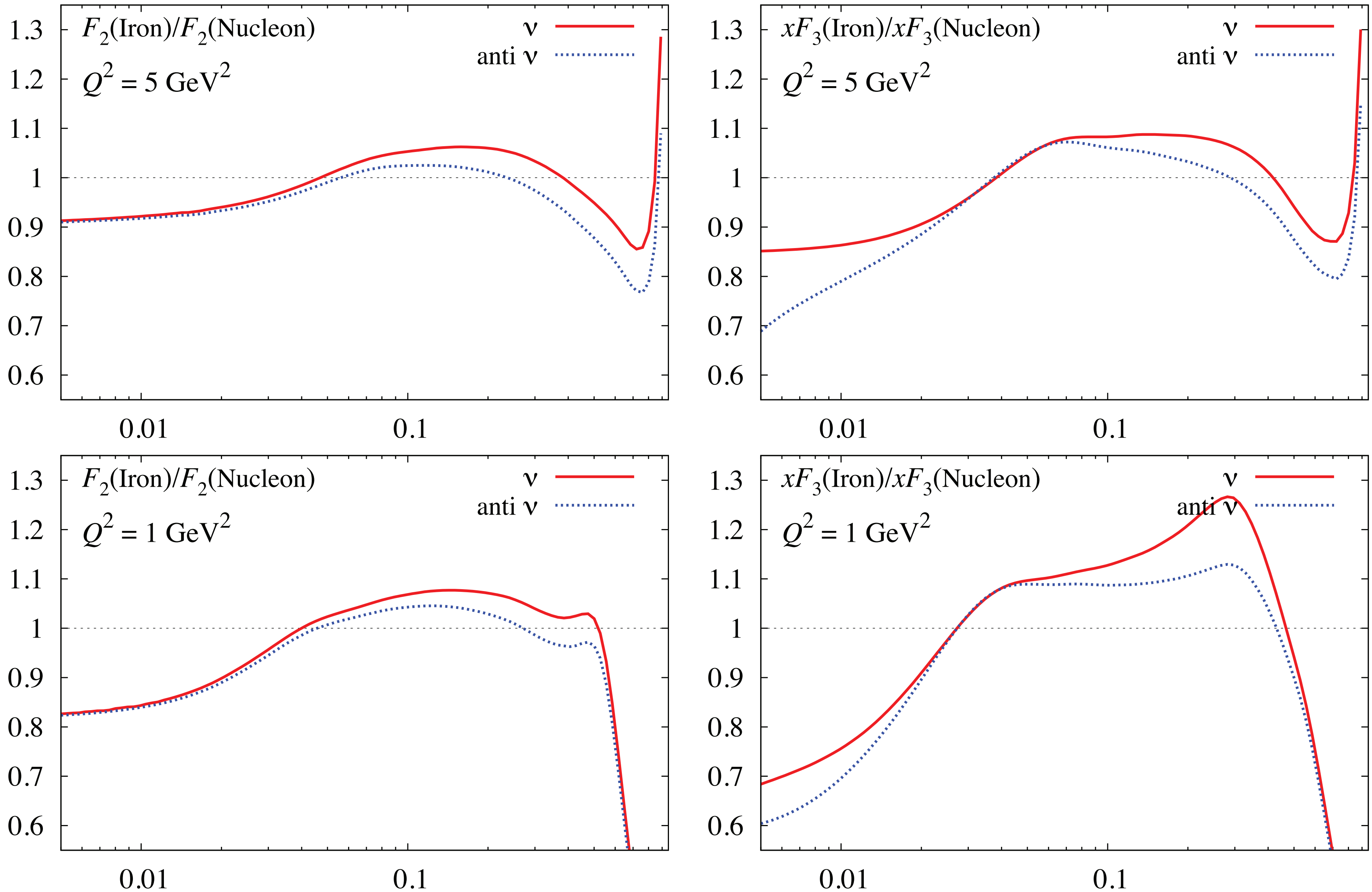
Nuclear correction for E605 Drell-Yan p-Cu data

NUCLEAR EFFECTS IN F_2 AND xF_3

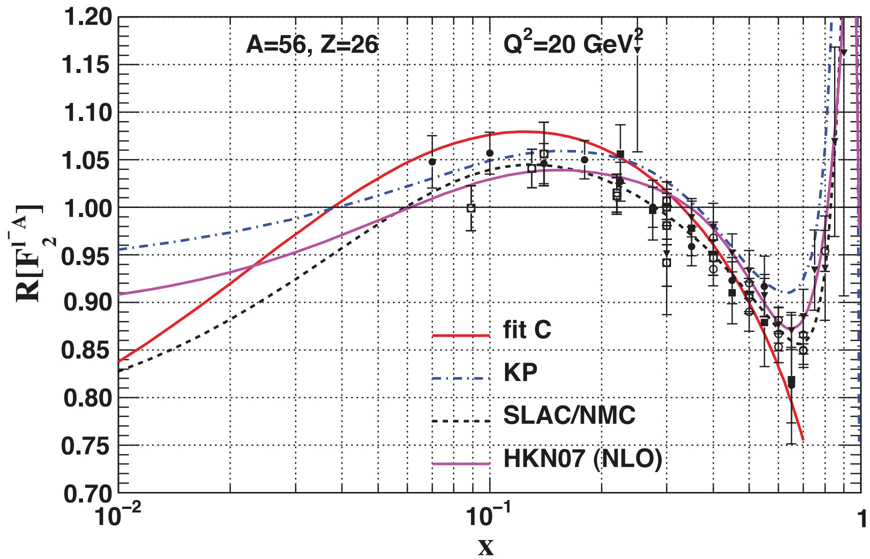


Ratio of Charged Current structure functions on ^{207}*Pb and isoscalar nucleon* $(p+n)/2$

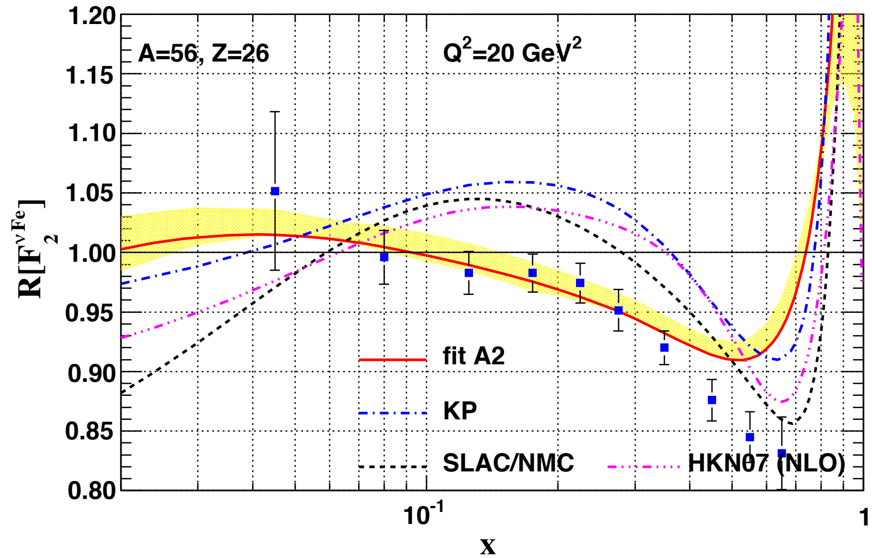
DIFFERENCES BETWEEN ν AND $\bar{\nu}$



CTEQ FITS TO $\nu(\bar{\nu})$ DATA



Fit to e, μ DIS + DY



Fit to $\nu + \bar{\nu}$ DIS

- *Within the CTEQ analysis introduce nuclear PDFs as modifications of nucleon PDFs:*

$$xf(x, Q_0) = f(x, c_0, c_1, ...c_n); \quad c_k \to c_k(A)$$

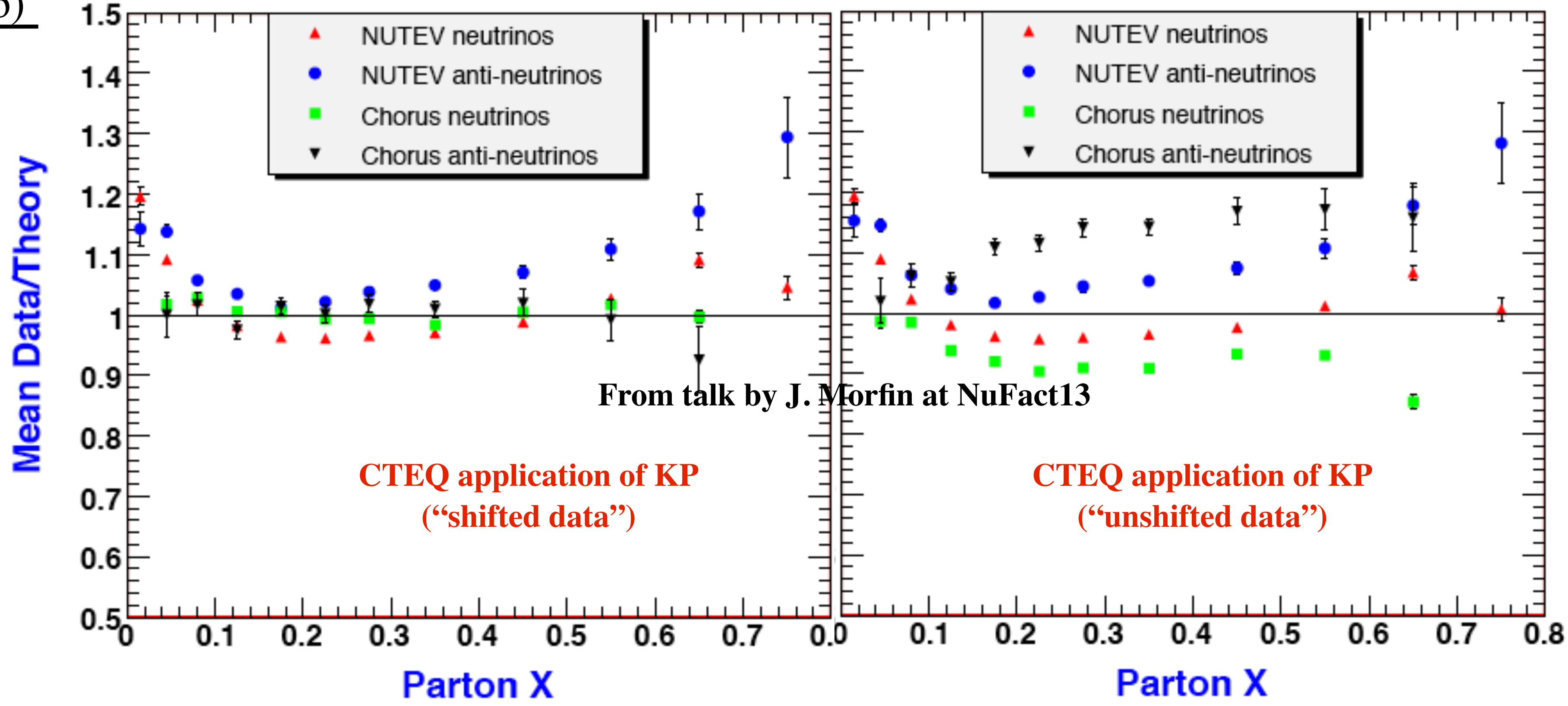
(I. Schienbein at al., PRD 80 (2009) 094004; PRL 106 (2011) 122301).

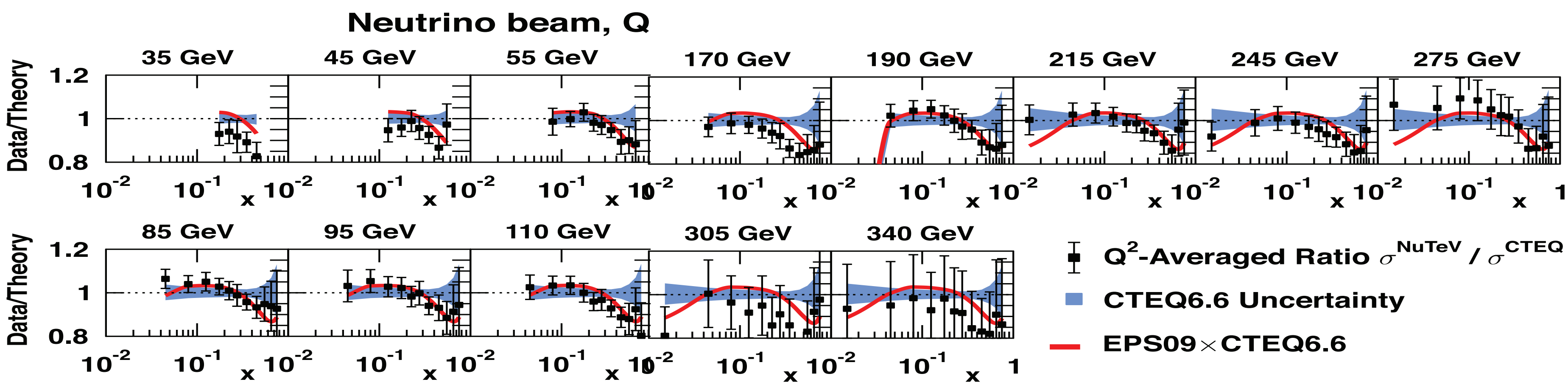
- *Perform separate global fits to $\nu(\bar{\nu})$ DIS data and e, μ DIS + Drell-Yan nuclear data*
- *Results show CHORUS+NuTeV $\nu(\bar{\nu})$ data not consistent with e, μ DIS:*
  - *No shadowing observed at small $x_{\rm Bj}$;*
  - *Different EMC slope.*
  - *Process-dependent corrections?*

CTEQ COMPARISONS

- *The ratio shown must include not only nuclear corrections, but also LT structure functions, HT contributions, electroweak corrections, heavy quark production etc.*
  $\Longrightarrow$ *EW or other corrections can be comparable to nuclear ones in some regions*
- *Nuclear corrections vanish at $x \sim 0.3$ as measured on a wide range of nuclei. Deviations shown above around $x \sim 0.3$ cannot be explained by nuclear corrections.*
- *Perhaps problem with isovector correction or underlying nucleon SF?*

$$\frac{\sigma(\text{Fe or Pb})}{\sigma(\text{n+p})}$$





✦ *Use nuclear corrections to PDFs from EPS09 fit to nuclear e, μ DIS and Drell-Yan (K. Eskola, H. Paukkunen and C. Salgado, JHEP 0904 (2009) 065; JHEP 1007 (2010) 032).*

✦ *Analysis of CHORUS, NuTeV and CDHSW $\nu(\bar{\nu})$ differential cross-sections and comparison with calculations based upon CTEQ6.6 + EPS09*

✦ *Results indicate CHORUS and CDHSW data are in agreement with calculations, but in disagreement with NuTeV data*

$\Longrightarrow$ *Anomalous E_ν-dependent fluctuations in NuTeV data*