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

S. Kulagin
INR Moscow, Russia

R. Petti
University of South Carolina, Columbia SC, USA

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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 ⇔ 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:

$$q_a/A = q_p^{p/A} + q_n^{n/A} + \delta q_a^\text{MEC} + \delta q_a^\text{coh} \quad a = u, d, s.....$$

- $q_p^{p(n)/A}$ PDF in bound $p(n)$ with Fermi Motion, Binding (FMB) and Off-Shell effect (OS)
- $\delta q_a^\text{MEC}$ nuclear Meson Exchange Current (MEC) correction
- $\delta q_a^\text{coh}$ 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:

\[ q_{a/A}(x, Q^2) = q_{a}^{p/A} + q_{a}^{n/A} \]

\[ xq_{a}^{p/A} = \int d\varepsilon d^3p \mathcal{P}_p(\varepsilon, p) \left( 1 + \frac{p_z}{M} \right) x' q^N(x', Q^2, p^2) \]

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

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

\[ q_a(x, Q^2, p^2) \approx q^N_a(x, Q^2) \left( 1 + \delta f(x)(p^2 - M^2)/M^2 \right) \]

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

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

\[
\delta q_a^{\text{MEC}}(x, Q^2) = \int_x^1 dy f_{\pi/A}(y) q_\pi^a(x/y, Q^2)
\]

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” \( n_\pi = \int dy f_\pi(y) \) 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:

\[
\delta R = \frac{\delta q_{coh}}{A q^N} \approx \frac{\delta \sigma_{coh}}{A \sigma} = \text{Im} \frac{A(a)}{A \text{Im} a}
\]

\[
A(a) = i a^2 \int_{z_1 < z_2} d^2 b \, dz_1 \, dz_2 \, \rho_A(b, z_1) \rho_A(b, z_2) e^{i \int_{z_1}^{z_2} d z' a \rho_A(b, z')} e^{i k_L (z_1 - z_2)}
\]

\[
a = \sigma (i + \alpha)/2
\]

is the (effective) scattering amplitude \((\alpha = \text{Re} a / \text{Im} a)\) in forward direction, \(k_L = M x (1 + m_v^2/Q^2)\) is longitudinal momentum transfer in the process \(v^* \rightarrow v\) (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
Roberto Petti
University of South Carolina

LBNE Near Detector Workshop
Columbia SC, December 12, 2009

PREDICTIONS FOR CHARGED LEPTON DIS DATA

**FLAVOR AND C-PARITY DEPENDENCE OF nPDFs**

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

  $$q_{0/A}^{IA} = (f_{p/A} + f_{n/A}) \oplus q_0/p$$
  $$q_{1/A}^{IA} = (f_{p/A} - f_{n/A}) \oplus q_1/p$$

  $$\mathcal{P}_0 = \mathcal{P}_{MF} + \mathcal{P}_{cor}$$
  $$\mathcal{P}_1 = |\phi_F(p)|^2 \delta(\varepsilon - \varepsilon_F)$$

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

  $\Rightarrow$ We assume universal $\delta f$ for all partons for simplicity

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

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

  $$\delta \mathcal{R}^+ = \text{Im} \mathcal{A}(a^+)/A \text{Im} a^+$$
  $$\delta \mathcal{R}^- = \text{Im} a^- A_1(a^+)/A \text{Im} a^-$$

  where $A_1(a) = \partial A(a) / \partial a$ 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 $A(a)$.
  - $\delta \mathcal{R}^-$ is independent of the cross section $\sigma^- = 2\text{Im} a^-$. However it nonlinearly depends on $a^+$.

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

At high $Q^2$ (PDF regime) coherent nuclear corrections controlled by the Leading Twist (LT) amplitudes, which can be constrained by normalization sum rules:

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

where $N_{\text{val}}^A = A^{-1} \int_0^A dq_0/A = 3$ and $N_1^A = A^{-1} \int_0^A dq_1/A = (Z - N)/A$

Solve numerically equations above in terms of the $\delta f$ function (input) and obtain the effective LT cross-section in the $(I = 0, C = 1)$ state, as well as $\text{Re/Im}$ of amplitudes

In our approach nuclear corrections to PDFs essentially defined by $P(\varepsilon, p)$ AND $\delta f(x)$
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 $^2H$ (upper panel) and proton $^1H$ (lower panel).
\[ \delta R_{\text{sea}} \text{ from corrections to C-even } q_0^+ = q + \bar{q} \text{ and C-odd } q_0^- = q - \bar{q} = q_{\text{val}} \]

\[
\delta R_{\text{sea}} = \frac{\delta q_A^A}{q^N} = \delta R^+ + \frac{q_{\text{val}}^N(x)}{2q^N(x)} \left( \delta R^+ - \delta R^- \right)
\]

\[ \text{\textbullet} \quad \text{Same C-parity dependence for strange sea: } s + \bar{s} \text{ like } \delta R_{\text{sea}}, \ s - \bar{s} \text{ like } \delta R_{\text{val}} = R^- \]
Selecting small $Q^2/s$ and large $x_F$ we probe sea quarks in the target nucleus:

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

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

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

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

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:

$$\frac{\sigma_{DY}^A}{\sigma_{DY}^B} \approx \frac{\bar{q}_A(x_T)}{\bar{q}_B(x_T)}$$

⇒ 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
Partial cancellation between pion and shadowing effects for large $x \sim 0.05 - 0.1$
Validation of nPDF calculation with independent physics process and kinematic range

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

We estimate the average propagation length in the nuclear medium, which is expected to increase with the average distance traveled by a projectile in a uniform nuclear medium of the projectile partons as

\[ n \text{cm} \]

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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 $O(1/Q^2)$;
- Radiative electroweak corrections;
- Partial Conservation of the Axial Current (PCAC) dominating SFs at low $Q^2$.

$\Rightarrow$ Finite value of $F_2$ in the limit $Q^2 \rightarrow 0$

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


CCFR (Fe): $0.21 \pm 0.02$

Comparison with NuTeV (Fe) and CHORUS (Pb) cross-section data (band $\pm 2.5\%$):

- Systematic excess observed for $x > 0.5$ in both $\nu$ 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

\[ R_c = \frac{\sigma_{\text{Charm}}}{\sigma_{\text{CC}}} \]

⇒ Reduction of nuclear uncertainties on strange sea determinations (cancellation to <1% on \( R_c \))

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. Study off-shell function \( \delta f \) 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 \( Q^2 \). 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 \( 0.15 < x < 0.55 \) require new precision data.

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:

\[
P_{MF}(\varepsilon, p) = \sum_{\lambda < \lambda_F} n_\lambda |\phi_\lambda(p)|^2 \delta(\varepsilon - \varepsilon_\lambda)
\]

where sum over occupied levels with \( n_\lambda \) occupation number. Applicable for small nucleon separation energy and momenta, \( |\varepsilon| < 50 \text{ MeV}, p < 300 \text{ MeV/c} \)

- CORRELATION EFFECTS in nuclear ground state drive the high-energy and high-momentum component of the nuclear spectrum, when \( |\varepsilon| \) increases:

\[
P_{\text{cor}}(\varepsilon, p) \approx n_{\text{rel}}(p) \langle \delta \left( \varepsilon + \frac{(p + p_2)^2}{2M} + E_{A-2} - E_A \right) \rangle_{\text{CM}}
\]

\[
\mathcal{P} = \mathcal{P}_{MF} + \mathcal{P}_{\text{cor}}
\]
Corrections for antiquarks at increasing $x_B$. It should be noted that the shadowing correction for antiquarks extends up to a value $x_B = 0.4$. Data points are from the E772 experiment [51]. Let $\sigma(pA)/\sigma(pH)$ be the ratio of the cross-sections for the Drell-Yan production in nuclear and proton collisions. The $x_B$ dependence of the $12C, 40Ca, 56Fe, 184W$ targets is shown for different energy bins. The E772 Drell-Yan p-A data is presented, with error bars indicating the statistical uncertainties.
Nuclear correction for E605 Drell-Yan p-Cu data
Ratio of Charged Current structure functions on $^{207}$Pb and isoscalar nucleon $(p+n)/2$
DIFFERENCES BETWEEN $\nu$ AND $\bar{\nu}$

$F_2(\text{Iron})/F_2(\text{Nucleon})$

$Q^2 = 5 \text{ GeV}^2$

$F_2(\text{Nucleon})$

$Q^2 = 1 \text{ GeV}^2$

$xF_3(\text{Iron})/xF_3(\text{Nucleon})$

$Q^2 = 5 \text{ GeV}^2$

$xF_3(\text{Nucleon})$

$Q^2 = 1 \text{ GeV}^2$
Within the CTEQ analysis introduce nuclear PDFs as modifications of nucleon PDFs:

\[ x f(x, Q_0) = f(x, c_0, c_1, \ldots, c_n) ; \quad c_k \to c_k(A) \]


Perform separate global fits to \( \nu(\bar{\nu}) \) DIS data and \( e, \mu \) DIS + Drell-Yan nuclear data

Results show CHORUS+NuTeV \( \nu(\bar{\nu}) \) data not consistent with \( e, \mu \) DIS:

- No shadowing observed at small \( x_{\text{Bj}} \);
- 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.  
⇒ 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?

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

From talk by J. Morfin at NuFact13
Use nuclear corrections to PDFs from EPS09 fit to nuclear $e, \mu$ 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

$\Rightarrow$ Anomalous $E_\nu$-dependent fluctuations in NuTeV data