

Modeling Nuclear Parton Distribution Functions

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Abstract

The presence of nuclear medium and collective phenomena which involve several nucleons modify the parton distribution functions of nuclei (nPDFs) compared to those of a free nucleon. These modifications have been investigated by different groups using global analyses of high energy nuclear reaction world data resulting in modern nPDF parametrizations with error estimates, such as EPS09(s), HKN07 and nDS. These phenomenological nPDF sets roughly agree within their uncertainty bands, but have antiquarks for large- x and gluons for the whole x -range poorly constrained by the available data. In the kinematics accessible at the LHC this has negative impact on the interpretation of the heavy-ion collision data, especially for the $p + A$ benchmarking runs. The EMC region is also sensitive to the proper definition of x , where the nuclear binding effects have to be taken into account, and for heavy nuclei one also needs to take into account that a fraction of the nucleus momentum is carried by the equivalent photons which modifies the momentum sum rule. We study how these effects affect the predictions for the nuclear modification ratios at the LHC kinematics using a model where we combine theoretical input for the leading twist nuclear shadowing (the FGS model) and the EKS98s/EPS09s nPDF set where the spatial dependence is formulated as a power series of the nuclear thickness functions T_A .

Keywords: Nuclear parton distribution function; LHC; impact parameter; EMC region

1 Proper definition of x

Nuclear parton distribution functions (nPDFs) are usually defined for each parton flavor in terms of nuclear modifications $R_i^A(x, Q^2)$ and the corresponding free proton PDF $f_i^p(x, Q^2)$ such that

$$f_i^A(x, Q^2) \equiv R_i^A(x, Q^2) f_i^p(x, Q^2), \quad (1)$$

where the Bjorken $x = A Q^2 / (2q \cdot p_A)$, with $0 \leq x \leq A$. In the collider frame, x is simply the fraction of the nucleus momentum scaled by the factor A . However, since these nPDF sets are built “on top” of proton PDF sets, the tail $1 \leq x \leq A$ is usually ignored.

Phenomenological parametrizations for nuclear modifications, such as EKS98 [1], EPS09 [2], HKN07 [3], DSZS [4], nCTEQ [5], etc., are largely based on deep inelastic scattering (DIS) data, which are given as a function of $x_p = Q^2 / (2q_0 m_p)$, which is independent of the target mass. The difference between x_p and x thus originates from

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the nuclear binding (see Refs. [6, 7]¹),

$$x_p = x(1 + r_x^A), \quad (2)$$

where

$$r_x^A = \frac{1}{m_p}((m_n - m_p)N/A - \epsilon_A) < 0. \quad (3)$$

As an example, the nuclear binding energy $\epsilon_A \approx 7.88$ (7.68) MeV for Pb (C).

In addition to the nuclear binding energy, the fraction of nucleus momentum carried by equivalent photons has to be taken into account in high energy heavy nuclear collisions. The fraction of the nucleus momentum carried by the photons is found to be [7]

$$\eta_\gamma(^{12}\text{C}) = 0.11\%, \quad \eta_\gamma(^{208}\text{Pb}) = 0.7\%. \quad (4)$$

Since the gluon nPDFs are least constrained by the DIS and DY data, presence of the photons in the momentum sum rule mostly affects the overall momentum carried by gluons. The effect of the equivalent photon field can be taken into account by rescaling the gluons after Eq. (2) has been applied to satisfy

$$\sum_i \int_0^1 dx x f_i^A(x, Q^2) = 1 - \eta_\gamma(A). \quad (5)$$

To apply the ‘‘conventional’’ nPDFs given as a function of x_p for the calculation of the nuclear effects in the ultra-relativistic heavy ion collisions where x is used, one has to translate to the ‘‘conventional’’ nPDFs, given as a function of x_p , by taking into account the difference between x_p and x which from now on we explicitly call x_{shift} , as follows:

$$x_{\text{shift}} f_i^A(x_{\text{shift}}, Q^2) = \begin{cases} \frac{x_p}{1+r_x^A} f_i^A\left(\frac{x_p}{1+r_x^A}, Q^2\right), & i = q, \bar{q} \\ g_{\text{scale}} \frac{x_p}{1+r_x^A} f_i^A\left(\frac{x_p}{1+r_x^A}, Q^2\right), & i = g \end{cases}, \quad (6)$$

where the scaling factor for gluons, g_{scale} , is determined via Eq. (5). Note that for a free proton, $x = x_p = x_{\text{shift}}$. It follows from Eq. (6) that while the fraction of the nucleus momentum carried by quarks is invariant with respect to the $x_p \rightarrow x_{\text{shift}}$ conversion, the amount of the nucleus momentum carried by gluons, $\eta_g \equiv \int_0^1 dx_{\text{shift}} x_{\text{shift}} g_A(x_{\text{shift}}, Q^2)$, decreases by the factor of $g_{\text{scale}} = \frac{\eta_g - \eta_\gamma(A)}{\eta_g}$ with the rescaling.

2 Theoretically motivated nPDF model

In this work we combine a small- x theoretical model for the leading twist nuclear shadowing, the FGS model [6], with the phenomenological EKS98/EPS09 nPDF set. The FGS model is based on the generalization of the Gribov–Glauber multiple scattering formalism and QCD factorization theorems. Using the picture of high energy scattering in the laboratory frame² and the notion of cross section fluctuations of energetic projectiles, multiple interactions are modeled using the effective x -dependent and flavor-dependent rescattering cross section $\sigma_{\text{soft}}^i(x, Q^2)$, which controls the strength of the resulting nuclear shadowing. In Ref. [6], based on the phenomenological analysis of cross section fluctuations in virtual photons, two models were suggested: model 1 (here referred to as FGS1) and model 2 (FGS2) corresponding to the upper and lower bounds on the predicted nuclear shadowing, respectively. Both models were built on top of CTEQ5 PDFs [8] (given as a function of x_p), and we will use this set for the combined model as well. In this paper, we will work in LO.

¹In Ref [7] there is a sign error in the corresponding formula, Eq. (20). For detailed discussion, see the revised version of [7].

²The equivalent picture can be formulated in the nucleus fast frame [6].

Table 1: The percentage of nucleus momentum carried by the gluons.

	EKS98		FGS1+EKS98		FGS2+EKS98	
	Pb	C	Pb	C	Pb	C
x_p :	43.98	42.61	44.20	42.58	44.30	42.62
x_{shift} :	43.58	42.54	43.81	42.52	43.91	42.56

In the following the initial scale sea quark and gluon ($Q_0^2 = 2.5 \text{ GeV}^2$) nuclear modifications for the region $10^{-4} \leq x \leq 0.01$, where data practically do not constrain nPDFs, are taken from the FGS1 and FGS2 parametrizations; for $0.03 \leq x \leq 1.0$, the nuclear modifications are taken from the EKS98 parametrization [1] (which in this region is very similar to the newer set EPS09 [2]). For the valence quarks, the nuclear modifications are taken from EKS98 for the whole x -range. The two parametrizations are combined by performing polynomial interpolation between them, and [after being corrected for the difference in the argument according to Eq. (2)] the gluons are rescaled as in Eq. (6). The resulting scaling factor at $Q_0^2 = 2.5 \text{ GeV}^2$ for the gluons is $g_{\text{scale}} \sim 0.984$ ($g_{\text{scale}} \sim 0.997$) for Pb (C) nucleus. (The change in the scaling factor is $\sim 0.4\%$ at $Q^2 = 10000^2 \text{ GeV}^2$, so in practice a uniform scaling factor can be used for any scale.) Consequently the amount of the momentum carried by the gluons decreases by 0.88% (0.14%) for Pb (C). The fraction of the momentum carried by the gluons for each model is listed in Table 1 (41.80% for the proton in CTEQ5L).

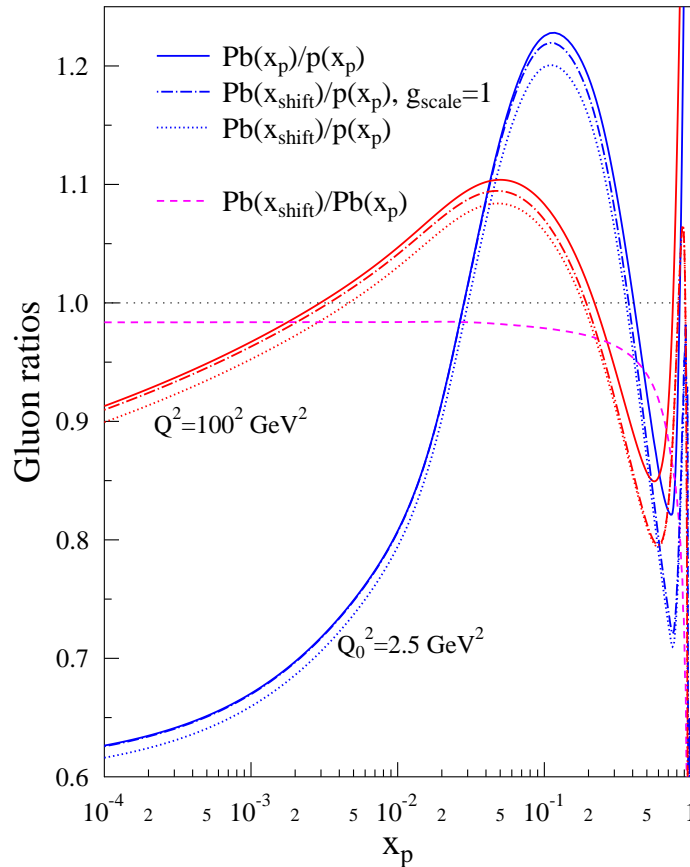


Figure 1: Gluon ratio for $\text{Pb}(x_{\text{shift}})/\text{Pb}(x_p)$ at $Q_0^2 = 2.5 \text{ GeV}^2$ and for Pb/p at $Q_0^2 = 2.5 \text{ GeV}^2$ and $Q^2 = 100^2 \text{ GeV}^2$ for EKS98.

In Fig. 1 we show how changing the definition of x affects the EKS98 gluon modification ratio Pb/p at the initial scale $Q_0^2 = 2.5 \text{ GeV}^2$ and how this effect evolves up to the higher scale $Q^2 = 100^2 \text{ GeV}^2$. In this work we use the QCDNUM DGLAP evolution code [9]. At the initial scale the original EKS98 gluon modification ratio $x_p G^{\text{Pb}}(x_p)/x_p G^p(x_p)$ (solid line) is first modified setting $g_{\text{scale}} = 1$ in Eq. (6) (dotted-dashed line). As a result, the gluon modification ratio is only essentially modified at the EMC-region, $x_p > 0.5$, where the (n)PDFs are decreasing rapidly. For the full conversion with $g_{\text{scale}} \sim 0.98$ (dotted line), the gluon nPDF is naturally scaled down over the whole x_p -range. When evolved up to $Q^2 = 100^2 \text{ GeV}^2$, the differences persist and spread towards smaller values of x_p . Using x_{shift} instead of x_p obviously affects gluons for the whole x_p -range due to the rescaling (and at higher scales also the sea quarks via the DGLAP evolution), but for all the parton flavors the most prominent effect sets in at the EMC-region, where the parton distribution functions change quickly. As seen from above, the gluon ratio $Pb(x_{\text{shift}})/Pb(x_p)$ (dashed line) is < 1 for the whole x_p -range.

Note in passing that even for the valence quark distributions, the experimental information on the EMC effect in the region where the leading twist contribution dominates is very limited as the higher twist effects give a large (dominant?) contribution to the eA scattering cross section for $x \geq 0.5$ in the SLAC and JLab kinematics. Hence, to date, practically no data on the quark modification for $x \geq 0.5$ in the scaling region is available for heavy nuclei such as, e. g., lead.

In Fig. 2 we show the gluon ratio (Pb/d) for the combined models FGS1+EKS98 (dotted-dashed) and FGS2+EKS98 (dotted), together with the EKS98 (solid) gluon

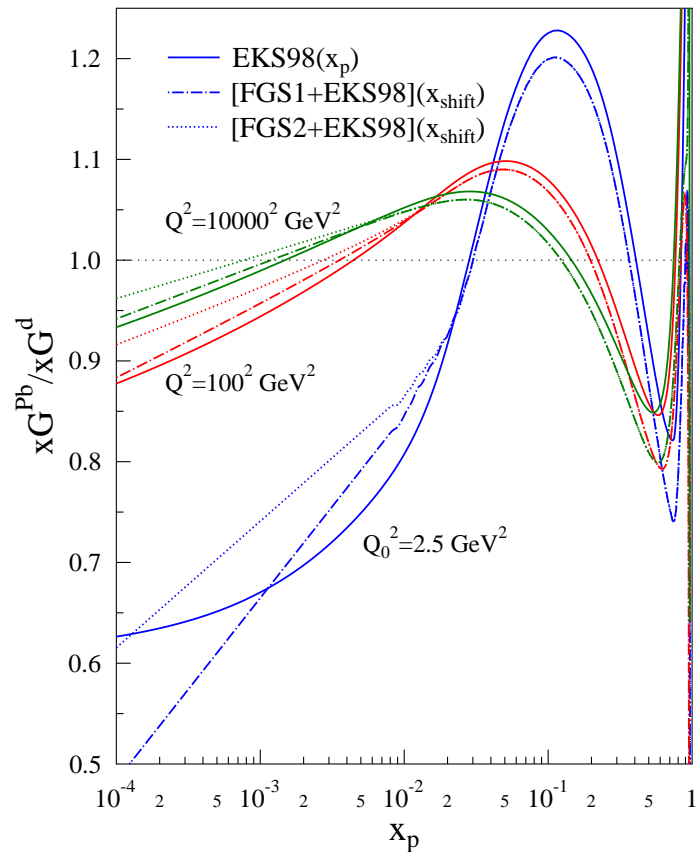


Figure 2: Gluon ratios for Pb/d at $Q_0^2 = 2.5, 100^2$ and 10000^2 GeV^2 for EKS98, and the combination model FGS1(2)+EKS98.

modification. At the initial scale above $x_p > 0.01$, the difference between the models originates only from the different definition of x ; below $x_p \leq 0.01$, the two FGS nuclear shadowing models span a region considerably smaller than the error band of EPS09 gluons (see Ref. [2] for details). When evolved up to $Q^2 = 10000^2 \text{ GeV}^2$, a relevant scale in the LHC kinematics, it is evident that processes which are sensitive to the EMC-region are also sensitive to the proper definition of x .

3 Consequences for the LHC

In order to understand the sensitivity of the LHC kinematics to the EMC effect, we study inclusive π^0 production in $p + \text{Pb}$ collisions, which schematically can be expressed as

$$\begin{aligned} & \sigma^{p+\text{Pb} \rightarrow \pi^0 + X} \\ &= \sum_{i,j,k=q,\bar{q},g} f_i^p(x_1, Q^2) \otimes f_j^{\text{Pb}}(x_2, Q^2) \otimes \hat{\sigma}^{ij \rightarrow k+X}(x_1, x_2, Q^2) \otimes D_{k \rightarrow \pi^0}(z, \mu_F^2), \quad (7) \end{aligned}$$

where the factorization and renormalization scales have been set equal (see, e.g., Ref. [10] for the formulae and details). In this work, we choose $\mu_F = p_T$ (the outgoing pion transverse momentum) and $Q = q_T$ (partonic transverse momentum).

In Fig. 3 we show the LO invariant cross section $E d^3\sigma/dp^3$ for $p + \text{Pb} \rightarrow \pi^0 + X$ at $p_T = 3.0, 10.0$ and 100.0 GeV as a function of x_2 [the momentum fraction carried

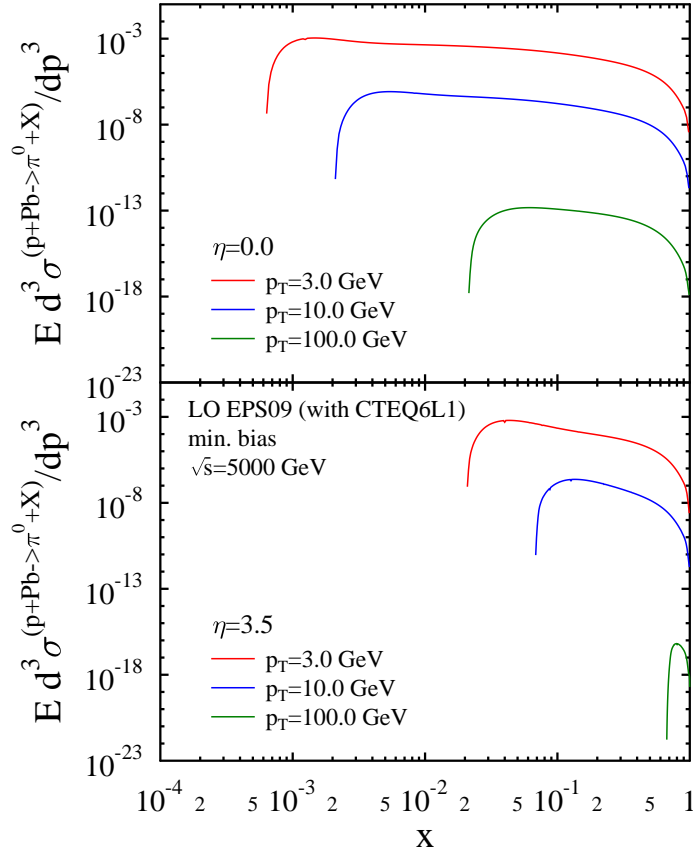


Figure 3: The x -distribution for the minimum bias π^0 production at the LHC at $\eta = 0$ and $\eta = 3.5$ for different p_T .

by the parton in Pb, without conversion given in Eq. (6)]. The results have been computed with the EPS09 nuclear modifications [2], CTEQ6L PDFs [11] and DSS fragmentation functions [12]. Working in LO the overall normalization of the spectra is not fixed, but the x_2 -distribution and the relative normalization are not affected by this. The upper panel shows the mid-rapidity and the lower panel — the forward rapidity (at the LHC, the Pb rapidity is positive) π^0 production. For each p_T value studied, the mid-rapidity production peaks at an order of magnitude smaller values of x_2 than the forward rapidity results, and remains significant over a wider range of x_2 . In the forward direction the pion production is concentrated on a rather narrow x_2 -range, making it a more sensitive probe of nuclear effects. In particular, at high- p_T , the pions are produced exclusively from the EMC-region, making them also sensitive to the definition of x_2 .

Figures 4 and 5 show the FGS1(2)+EKS98 results for the minimum bias nuclear modification ratio,

$$R_{pPb}^{\pi^0}(p_T, \eta) = \frac{d^3\sigma^{pPb}/dp^3}{d^3\sigma^{pp}/dp^3}, \quad (8)$$

at the LHC at $\sqrt{s} = 5500$ GeV. For comparison, the EKS98 results with the CTEQ5L

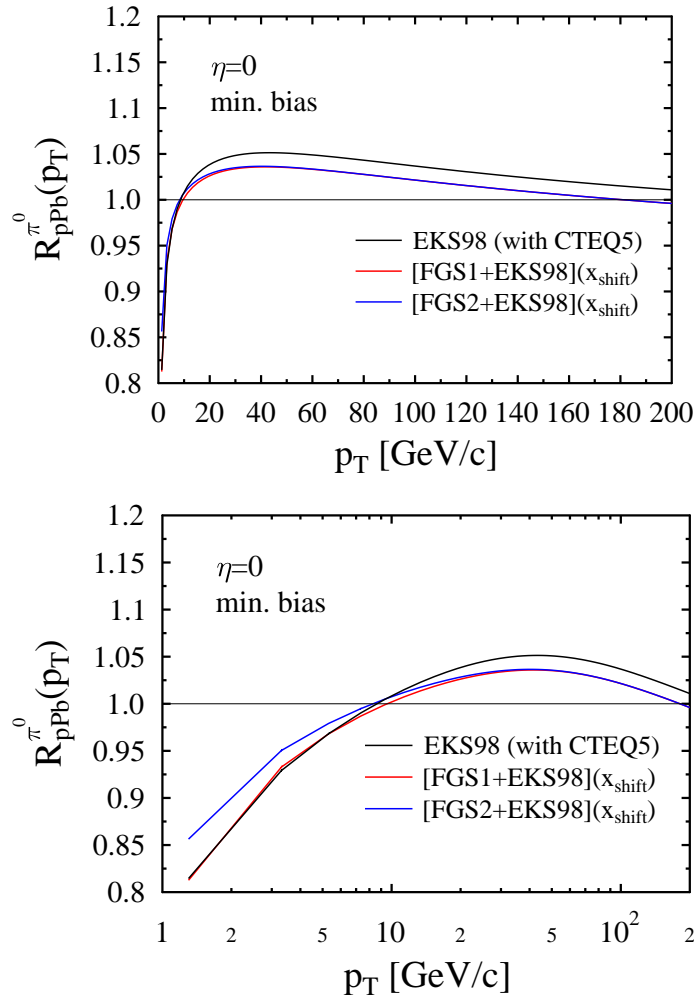


Figure 4: Minimum bias FGS1(2)+EKS98 results for $R_{pPb}^{\pi^0}(p_T)$ for the LHC at $\sqrt{s} = 5500$ GeV and $\eta = 0.0$. For comparison, the EKS98 result with CTEQ5L PDFs is also shown. Upper panel on linear scale, lower panel on logarithmic scale.

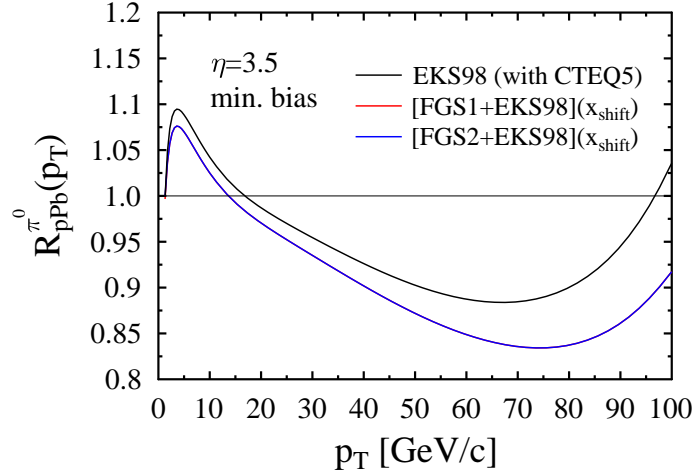


Figure 5: Minimum bias FGS1(2)+EKS98 results for $R_{pPb}^{\pi^0}$ for the LHC at $\sqrt{s} = 5500$ GeV and $\eta = 3.5$. For comparison, the EKS98 grid result with CTEQ5L PDFs is also shown. The FGS1+EKS98 and FGS2+EKS98 curves are indistinguishable.

PDFs are also shown. In the mid-rapidity (Fig. 4) the difference between the EKS98 and FGS+EKS98 results remain within a few %. As can be seen from Fig. 3 (upper panel), up to $p_T \sim 100$ GeV, the pion spectra mostly originate from the gluon distribution dominated x -range below the EMC-region. Therefore the differences between the models are caused both by the different assumptions about shadowing (see the lower panel where the small- p_T part is shown on a logarithmic scale) and the scaling of the gluon distribution with $g_{\text{scale}} < 1$. The difference between the models remain moderate even above $p_T > 100$ GeV.

As seen from Fig. 5, the situation is drastically different in the forward rapidity pion production. Above $p_T \sim 10$ GeV, the two FGS-models are indistinguishable, but start to deviate from the EKS98 result as p_T increases. This sizable effect is caused by the correction to the x -definition alone.

Until now we have discussed the minimum bias results, where the impact parameter dependence of the nuclear effects has been spatially averaged. In the FGS model the transverse position \mathbf{s} dependence is naturally built in as functions of $T_A(\mathbf{s})$ since the nuclear shadowing is first calculated for fixed \mathbf{s} and next the integral over \mathbf{s} is taken. In the EKS98s/EPs09s model [13], the EKS98 and EPs09 nPDF parametrizations were also assumed to have spatial dependence as a power series of $T_A(\mathbf{s})$. With the centrality classes modeled using the optical Glauber model, the EPs09s results were found to be consistent with the mid-rapidity PHENIX $R_{dAu}^{\pi^0}$ centrality systematics [14]. However, as already seen in Fig. 5, the proper definition of x has a major effect on the LHC predictions at forward rapidity. In Fig. 6 we applied the procedure described in Ref. [13] to $R_{pPb}^{\pi^0}$ at $\eta = 3.5$ for a selection of different centrality classes, and compared the EKS98s results (with CTEQ6L PDFs) with and without the x -corrections. Irrespective of the centrality, the correction causes a clear, measurable effect.

For an impact parameter dependent theoretically motivated nPDF model it is also important to pay special attention to the EMC region for another reason. In Ref. [15] the magnitude of the EMC effect was shown to be linearly related to the short range correlations (SRC) scale factor measured from electron inclusive scattering at $x \geq 1$. Consequently the impact parameter dependence of the EMC effect should be proportional to the local density [16] and the EMC effect thus should be strongest in the center of the nucleus. We will address this issue in Ref. [17], where a full NLO

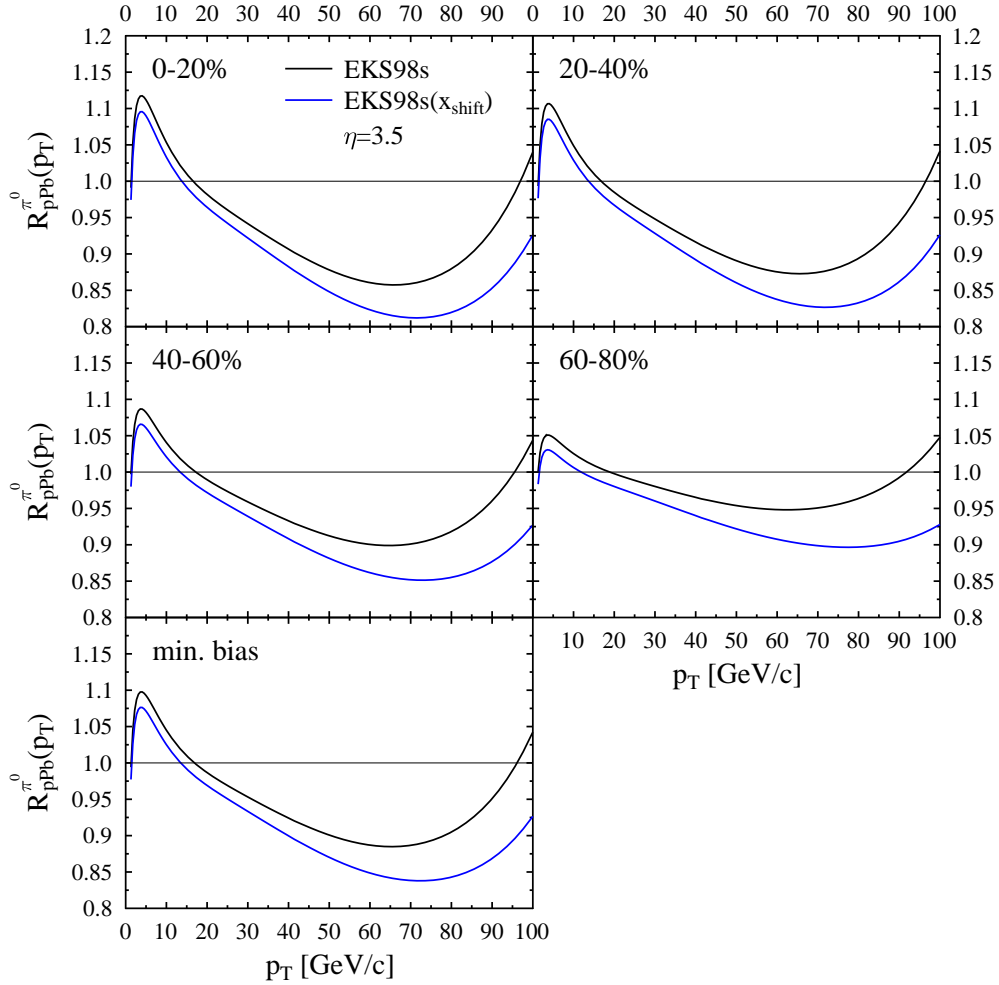


Figure 6: $R_{pPb}^{\pi^0}$ for the LHC at $\sqrt{s} = 5500$ GeV and $\eta = 3.5$ for the EKS98 (with CTEQ6L1) results computed with x_p and x_{shift} . The different centrality classes are computed as in [13]. The FGS1+EKS98 and FGS2+EKS98 curves are indistinguishable.

impact parameter dependent nPDF set will be released.

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