BNL-99754-2013-CP

Nuclear PDFs

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Presented at the 3rd Workshop on QCD Structure of the Nucleon (QCD-N'12)
Bilbao, Spain
October 22 to 26, 2012

February 2013

Physics Department/Nuclear Theory Group/Office of Science

Brookhaven National Laboratory

U.S. Department of Energy
[DOE Program Office of Science, Nuclear Physics]

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Summary. — We present the latest global QCD analysis of nuclear parton distribution functions. The emerging picture is one of consistency, with universal nuclear modification factors reproducing the main features of the data. Differences with previous analyses are addressed.

PACS 12.38.-t, 24.85.+p, 13.15.+g, 13.60.-r –
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1. – Motivation

The last years have been witness to a significant progress in the extraction on nuclear PDFs (nPDFs) from data. To the implementation of QCD corrections beyond the LO [1] and uncertainty estimates [2, 3], new types of data are added, advancing towards fully global analyses [3, 4, 5]. These hard probes have allowed for tighter constraints on each partonic species and put to test the assumed universality of nuclear effects.

The founding stone of the nPDFs studies is the deep inelastic scattering (DIS) of charged leptons off nuclear targets, which constrains the valence quark densities. A better discrimination between valence and sea (anti-)quarks can be achieved by considering data from Drell Yan (DY) and neutrino induced DIS off nuclear targets [6]. Examined in [4], the result that the correction factors for neutrino DIS have a different behaviour from the one seen with charged lepton probes [4], has caused some controversy. A check was done in [5] using the nPDFs of [3] and no disagreement was found.

However, DIS and DY data are not enough to determine the gluon density. Thus, we need to include data from gluon sensitive processes, such as the BNL-RHIC inclusive pion production in deuteron-gold (dAu) collisions. This was done in [3], where the gluon modification (w.r.t. the free proton) was found to be more pronounced than in [1, 2].

The extraction of nPDFs presented here [6] is a fully global QCD analysis. This results in a set of nPDFs at next-to-leading order accuracy that supersedes the previous work in [1]. We adopt as reference a contemporary set of free proton PDFs [7]. In accordance with it, we treat the heavy quark flavours (charm and bottom) using a general mass variable flavour number scheme. We also estimate the uncertainties of the nPDFs using the Hessian method [8] and examine their range of applicability.

2. – Framework

We assume that the theoretical expressions for observables involving a nucleus factorize into calculable partonic hard scattering cross sections, and appropriate combinations of non-perturbative collinear parton densities and fragmentation functions. The relation between the nPDFs and the proton PDFs is given by

$$f_i^A(x, Q_0) = R_i^A(x, Q_0) f_i^p(x, Q_0)\,, \tag{1}$$

with Q_0 the initial scale (1 GeV in the present case) and x the usual DIS scaling variable. We assigned the same nuclear modification factor to both valence distributions, parameterized as

$$R_v^A(x, Q_0) = \epsilon_1 x^{\alpha_v}(1-x)^{\beta_1}(1+\epsilon_2(1-x)^{\beta_2})(1+a_v(1-x)^{\beta_3})\,. \tag{2}$$

To achieve an excellent description of the data it is enough for the sea and gluon densities to relate the factors R_s and R_g to R_v, but giving a more flexible low x behaviour:

$$\begin{aligned} R_s^A(x, Q_0) &= R_v^A(x, Q_0)\frac{\epsilon_s}{\epsilon_1}\frac{1+a_s x^{\alpha_s}}{a_s+1}\,, \\ R_g^A(x, Q_0) &= R_v^A(x, Q_0)\frac{\epsilon_g}{\epsilon_1}\frac{1+a_g x^{\alpha_g}}{a_g+1}\,. \end{aligned} \tag{3}$$

Charge and momentum conservation fix three parameters and due to the limited kinematical coverage of the data, we can further impose $\epsilon_s = \epsilon_g$. The remaining parameters are given an A dependence through $\xi = \gamma_\xi + \lambda_\xi A^{\delta_\xi}$. Furthermore, the mild A dependence observed for some of the ξ's accommodates setting $\delta_{a_g} = \delta_{a_s}$ and $\delta_{\alpha_g} = \delta_{\alpha_s}$. This leaves us with 25 free parameters to be determined through a standard χ^2 minimization, in which no artificial weights for certain data sets were used, i.e. $\omega_i = 1$, and with statistical and systematic errors added in quadrature in Δ_i^2:

$$\chi^2 \equiv \sum_i \omega_i \frac{(d\sigma_i^{exp} - d\sigma_i^{th})^2}{\Delta_i^2}\,. \tag{4}$$

3. – Results

For 1579 data points we found a total $\chi^2/d.o.f. = 0.994$, with all sets reproduced within the nominal statistical range $\chi^2 = n \pm \sqrt{2n}$, with n the number of data points.

Fig. 1 exemplifies the goodness of the agreement between the fit and charged lepton DIS (left) and hadroproduction (right) data; see [6] for details. For the DIS data the agreement is remarkable, but the dAu collisions data are harder to understand in terms of nPDFs. The cross sections might be in principle sensitive to medium induced effects in the hadronization process. Assuming factorizability, such final-state effects can be absorbed into effective nuclear fragmentation functions (nFFs). The solid line in the right panel of Fig. 1 represents the result of our best fit using the nFFs of [9]. While a perfect description of the data is not achieved in the medium p_T region, the χ^2 for these data is nevertheless good, $\chi^2/n = 1.12$. In particular it is an improvement if compared to the equivalent fit using vacuum FFs (dashed) [10] where $\chi^2/n = 1.37$.

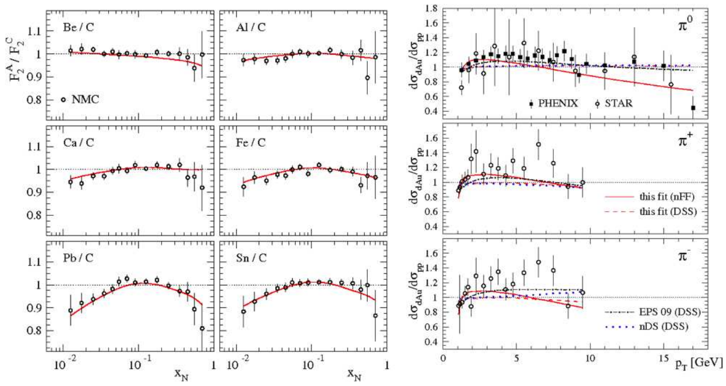

Fig. 1. – Left: charged lepton DIS data. Right: pion production in dAu collisions.

In contrast with recent results [4], the neutrino DIS data for the averaged structure function $(F_2^{\nu A} + F_2^{\bar{\nu} A})/2$ are well reproduced within the experimental uncertainties (left panel of Fig. 2). When comparing F_2^A/F_2^p for neutrino and electron DIS (right panel of

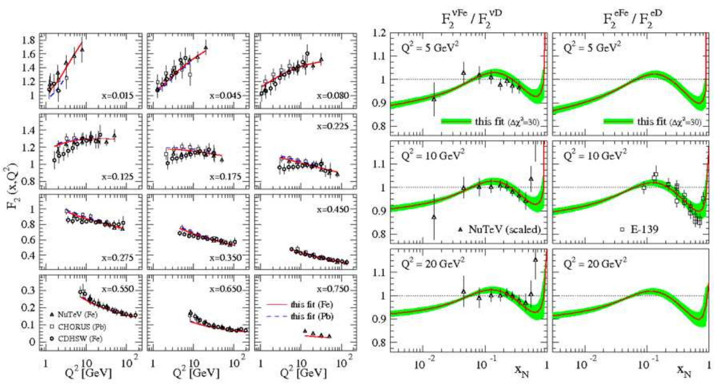

Fig. 2. – Left: neutrino DIS data. Right: nuclear effect for neutrino and electron DIS.

Fig. 2), the pattern of both ratios is similar, and the quality of our fit seems to point towards a universal initial state effect, rather than to an interaction dependent one.

In Fig. 3 we compare our results for lead (solid curve) with those obtained in [1] (dot-dashed) and [3] (dashed). The valence distributions are in good agreement, and a somewhat similar scenario is found for the sea distributions. The largest difference is found in the comparison with EPS09 [3] for the gluon nuclear factor. Even when using similar strategies the ratios turned out to be surprisingly different. This might be due to the fact that, at variance with our approach, the authors in [3] disregard any medium modications in the hadronization and assign a large ω_{dAu} in Eq.(4), which drives their

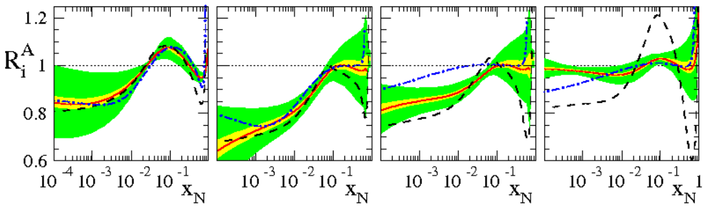

Fig. 3. – nuclear rates for lead at 10 GeV. Solid: this fit. Dot-dashed: nDS. Dashed: EPS09.

large nuclear modications of the gluon. On the contrary, our R_g^{Au} exhibits only moderate nuclear corrections, even less pronounced than found in [1]. Given the small amount of data available and its sensitivity to both initial and final state gluon densities, the matter is not at all solved and our result only calls for a more thorough study.

We used the Hessian method [8] to estimate the uncertainties with a tolerance criterion of $\Delta_{\chi^2} = 30$. The error are rather large [6], in particular when compared to the present knowledge of free proton PDFs. These estimates are, however, trustworthy only in the region constrained by data ($x > 0.01$). In particular, prompt photon and DY di-lepton production in dAu and pPb collisions at RHIC and the LHC, respectively, will help to further constrain nPDFs; see, e.g., [6] for some quantitative expectations.

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M.S. acknowledges support by the U.S. DOE under contract no. DE-AC02-98CH10886. P.Z. acknowledges support by European Research Council grant HotLHC ERC-2011-StG-279579 and by Xunta de Galicia. This work was also supported in part by CONICET, ANPCyT, UBACyT, and the E.U. under grant no. PITN-GA-2010-264564 (LHCPhenoNet).

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