Global Analysis of Nuclear PDFs

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DOI: will be assigned

We present a new global QCD analysis of nuclear parton distribution functions. In addition to the most commonly analyzed data sets for deep inelastic scattering of charged leptons off nuclei and Drell Yan di-lepton production, we include also measurements for neutrino-nuclei scattering as well as inclusive pion production in deuteron-gold collisions. The emerging picture is one of consistency, where universal nuclear modification factors for each parton flavor reproduce the main features of all data without any significant tension among the different sets.

1 Motivation

In the last few years, significant progress has been made in obtaining nuclear PDFs (nPDFs) from data. In addition to the theoretical improvements routinely used in modern extractions of free proton PDFs, such as the consistent implementation of QCD corrections beyond the LO [1] and uncertainty estimates [2, 3], the most recent determinations of nPDFs have also extended the types of data sets taken into account, moving towards truly global QCD analyses of nuclear effects [3, 4, 5, 6]. The addition of novel hard probes to the fit does not only lead to better constrained sets of nPDFs and allows one to study the nuclear modification to the different parton species individually, but also tests the assumed process independence of nuclear effects.

The deep inelastic scattering (DIS) of charged leptons off nuclear targets not only initiated all studies of nPDFs but still provides the best constraints on nuclear modifications for quark distributions. Upon combination with available data on Drell Yan (DY) di-lepton production off nuclear targets, a better discrimination between valence and sea quarks can be achieved. However, DIS and DY data only loosely constrain the nuclear modifications to the gluon density because they cover a too small range in the hard energy scale Q. To remedy this situation, data from BNL-RHIC for inclusive pion production in deuteron-gold (dAu) collisions have been included in the analysis of nPDFs performed in Ref. [3]. Not surprisingly, these data have a significant impact in the determination of the gluon distribution. The corresponding nuclear modification for gluons turned out to be much more pronounced than in previous estimates and also much larger than those found for all the other partonic species.

Another promising avenue for significant improvements is neutrino induced DIS off iron and lead targets, with results available from NuTeV, CDHSW, and CHORUS [7]. These data receive their importance from their discriminating power between nuclear modifications for quarks and antiquarks and have been included in a series of analyses in Refs. [4, 6]. Unexpectedly, the correction factors obtained from neutrino scattering data are found to differ significantly from those extracted with charged lepton probes [4, 6]. At variance with these results, Ref. [5] confronts the neutrino DIS cross sections with nPDFs obtained in [3] without any refitting and finds no apparent disagreement.

The novel global QCD analysis of nPDFs presented here [7] incorporates in a comprehensive way all of the above mentioned improvements and data sets. The resulting nPDFs at next-to-leading order accuracy supersede previous work presented in [1]. We adopt a contemporary set of free nucleon PDFs [8] as our reference distribution to quantify modifications of PDFs in nuclei. As in [8], we use a general mass variable flavor number scheme to treat charm and bottom quark contributions in our analysis. We use the Hessian method [9] to estimate the uncertainties of the nuclear modification factors and examine critically their range of validity.

2 Framework

Throughout the analysis, we make the usual assumption that theoretical expressions for measured cross sections involving a nucleus factorize into calculable partonic hard scattering cross sections, identical to those used for processes involving free nucleons, and appropriate combinations of non-perturbative collinear parton densities and fragmentation functions. The nPDFs $f_i^A(x, Q_0)$ at an initial scale $Q_0 = 1\,\mathrm{GeV}$ are related to proton distributions $f_i^p(x, Q_0)$ through a multiplicative nuclear modification factor $R_i^A(x, Q_0)$ as

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

where x is the usual DIS scaling variable for free nucleons. Both valence quark distributions are assigned the same nuclear modification factor $R_v^A(x, Q_0^2)$ which we parametrize as

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

We also assume that the light sea quarks and antiquarks share the same correction factor $R_s^A(x, Q_0^2)$. No significant improvement in the quality of the fit to data is found by relaxing this assumption. We choose another factor $R_g^A(x, Q_0^2)$ to parametrize medium effects for gluons. An excellent description of the data is achieved by relating both R_s^A and R_g^A to R_v^A specified in Eq. (2), allowing only for a different normalization and modifications in the low-x behavior. Hence we choose, without any loss in the quality of the fit,

$$R_s^A(x, Q_0^2) = R_v^A(x, Q_0^2)\, \frac{\epsilon_s}{\epsilon_1} \frac{1 + a_s x^{\alpha_s}}{a_s + 1}\,, \qquad R_g^A(x, Q_0^2) = R_v^A(x, Q_0^2)\, \frac{\epsilon_g}{\epsilon_1} \frac{1 + a_g x^{\alpha_g}}{a_g + 1}\,. \tag{3}$$

We note that the coefficients ϵ_1 and ϵ_2 in Eq. (2) are fixed by charge conservation, and if we further constrain ϵ_s and ϵ_g to be equal, which, again, has no impact on the quality of the fit, ϵ_s is fixed by momentum conservation. The A dependence of the remaining free parameters $\xi \in \{\alpha_v, \alpha_s, \alpha_g, \beta_1, \beta_2, \beta_3, a_v, a_s, a_g\}$ is parametrized in the usual way [1] as $\xi = \gamma_\xi + \lambda_\xi A^{\delta_\xi}$. The very mild A dependence found for some of the ξ's allows us to further reduce the number of additional parameters by setting $\delta_{a_g} = \delta_{a_s}$ and $\delta_{\alpha_g} = \delta_{\alpha_s}$, leaving a total of 25 free parameters, which are obtained by a standard χ^2 minimization, without artificial weights for certain data sets, i.e. $\omega_i = 1$, and with statistical and systematic errors added in quadrature in Δ_i^2:

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

3 Results

The total χ^2 for the optimum fit was found to be 1544.7 for 1579 data points ($\chi^2/d.o.f. = 0.994$). All data sets are adequately reproduced, well within the nominal statistical range $\chi^2 = n \pm \sqrt{2n}$ with n the number of data. More specifically, the partial contribution to χ^2 of all the charged lepton DIS data amounts to 897.52 units for 894 data points, for neutrino DIS we find 488.20 units compared to 532 data points, DY observables amount to 90.72 units for 92 points, and pion production in dAu collisions adds another 68.26 units to χ^2 for 61 data points.

In Figs. 1-3 we show some examples of the good agreement between the fit and charged lepton DIS, neutrino DIS, and hadroproduction data, respectively; see Ref. [7] for details. The remarkable agreement with charged lepton DIS data, shown in Fig. 1, is a common feature of all nPDFs analyses.

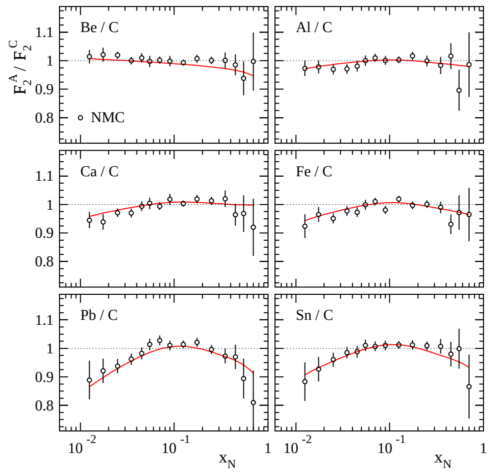

Figure 1: Comparison to charged lepton DIS

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 both in shape and in magnitude, see Fig. 2. The only noticeable exception are the CDHSW data at Q^2 values below $10\,\mathrm{GeV}^2$ where they exhibit a rather different slope than the other data. In fact, in this Q^2 region it appears to be impossible to simultaneously fit all data sets equally well, suggesting some systematic discrepancy among the different neutrino data which needs to be investigated further. Data for the averaged structure function F_3 are also well described by our fit [7].

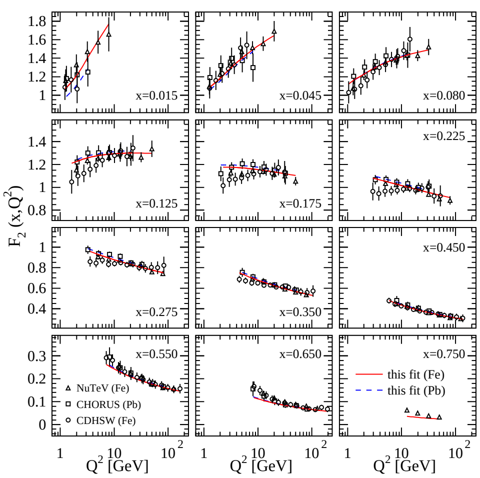

Figure 2: Comparison to neutrino DIS data

In general, results from dAu collisions are significantly less straightforward to interpret in terms of nuclear modification factors. Each value of p_T samples different fractions of the contributing partonic hard scattering processes, integrated over a range of x. Furthermore, since p_T sets the magnitude for the factorization scale, the ratios reflect also the energy scale dependence of the effects. Apart from the nuclear modifications of parton densities, accounted for by the nPDFs, the cross sections are in principle also sensitive to medium induced effects in the hadronization process.

Assuming factorizability for a given nucleus, such final-state effects can be absorbed into effective nuclear parton-to-hadron fragmentation functions (nFFs). The solid lines in Fig. 3 represent the result of our best fit of nPDFs using the nFFs of Ref. [10]. The fit follows well the rise and fall of the ratio at small and high p_T, respectively, but falls somewhat short in reproducing the enhancement found at medium p_T. Owing to the large experimental uncertainties, the χ^2 for this subset of data is nevertheless good, $\chi^2_{dAu}/n = 1.12$, in particular, if compared to the outcome of an otherwise similar fit using vacuum FFs [11] where $\chi^2_{dAu}/n = 1.37$. Data for π^0 yields in dAu collisions were first incorporated by EPS [3] and found to provide a vital constraint on R_g^{Au}. At variance with our approach, the authors in [3] disregard any medium modifications in the hadronization and assign a large weight ω_{dAu} in Eq. (4), which drives their observed large nuclear modifications of the gluon density. Our R_g^{Au} exhibits only moderate nuclear corrections.

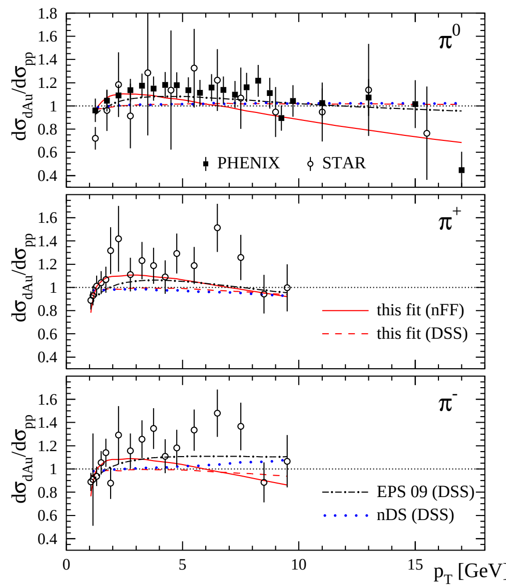

Figure 3: Pion production in dAu collisions

Uncertainties in the extraction of our nPDFs have been estimated with the Hessian method [9] for a tolerance criterion of $\Delta\chi^2 = 30$ and found to be rather large [7], in particular, when compared to the present knowledge of free proton PDFs. As always, these estimates are only trustworthy in the region constrained by data, i.e., $x > 0.01$. 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 in the future; see, e.g., Ref. [7] for some quantitative expectations.

Acknowledgements

M.S. acknowledges support by the U.S. DOE under contract no. DE-AC02-98CH10886. This work was supported in part by CONICET, ANPCyT, UBACyT, and the E.U. under grant no. PITN-GA-2010-264564 (LHCPhenoNet).

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