Status and prospects of nuclear PDFs at the LHC

Georgios K Krintiras,[1,*] Émilien Chapon,[2,†] and Hannu Paukkunen[3,‡]

[1]*Department of Physics and Astronomy 1082 Malott, 1251 Wescoe Hall Dr. Lawrence, KS 66045*

[2]*Institute of High Energy Physics Chinese Academy of Sciences 19B Yuquan Road, Shijingshan District Beijing, China*

[3]*University of Jyväskylä, Department of Physics, Finland*

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Abstract

The deep-inelastic-scattering (DIS) experiments have yielded accurate information on the partonic structure of the free proton. Notwithstanding the phenomenological success of quantum chromodynamics (QCD) analyses, a detailed understanding of the partonic structure modifications in bound nuclei is still lacking. Compared to the parton distribution functions (PDFs) in the proton, nuclear PDFs (nPDFs) are less constrained mainly because of the lack of data across the momentum fraction x–squared momentum transfer Q^2 plane and nuclear mass number (A) range. The scheduled LHC Runs 3–4 provide the opportunity to precisely constrain the nPDFs for the lead nucleus, while additional future runs with even higher partonic luminosity could offer further the chance for studying one or more lighter nuclei. Global QCD analyses should be as accurate as possible, e.g., theoretical calculations should be performed at the highest available order in perturbative QCD. This is currently next-to-leading order (NLO) for nPDFs, with recent advancements at next-to-NLO. There is complementarity between the physics programs at LHC and the planned Electron-Ion Collider, allowing for stringent tests of the nPDF universality too.

*Electronic address: gkrintir@ku.edu

†Electronic address: emilien.chapon@cern.ch

‡Electronic address: hannu.paukkunen@jyu.fi

I. STATUS

Experimental nuclear data, quantified in term of the nuclear modification factor R, indicate a "shadowing" behavior ($R < 1$) at low momentum fraction $x \leq 0.1$, followed by "antishadowing" ($R > 1$) in the $x \sim 0.1$ region, and lastly the EMC effect ($R < 1$) in the $x \sim 0.4$ region. While understanding of the theoretical mechanisms that are responsible for nuclear modifications with respect to the free-nucleon parton distribution functions (PDFs) remains an open challenge, these effects appear as general features in phenomenological determinations of nuclear PDFs (nPDFs), hence providing crucial information about parton behavior in the "cold" nuclear medium. On the one hand, precise extractions of nPDFs are important to study the strong interaction in the high-density regime and to model the initial state of heavy ion collisions. On the other hand, nPDFs contribute to global quantum chromodynamics (QCD) analyses of the proton structure.

Several groups have recently determined nPDFs based on different input data sets, theoretical assumptions, and methodological settings (Table I). While data sets are limited compared to the free-nucleon case, measurements of hard scattering cross sections from proton-lead (pPb) and lead-lead (PbPb) collisions at the LHC for processes such as prompt photon, dijet, W and Z, and heavy quark production, become increasingly available. These collider measurements can shed light on several not yet understood aspects of nPDFs, e.g., the quark flavor dependence of nuclear effects and the nuclear modifications of the gluon distribution [1]. The complementarity between the physics programs at LHC and the planned Electron-Ion Collider, allowing for stringent tests of the nPDF universality too, is discussed in Ref. [2].

Nuclear PDFs	nCTEQ15 [3]	EPPS16 [4]	nNNPDF**2**.0 [5] (**1**.0) [6]	TUJU19 [7]
Perturbative order	NLO	NLO	NLO, NNLO	NLO, NNLO
Heavy quark scheme	ACOT	S-ACOT	FONLL	FONLL
Value of $\alpha_S(m_Z)$	0.118	0.118	0.118	0.118
Input scale Q_0 [GeV]	1.30	1.30	1.00	1.69
Data points	708	1811	1467 (451)	2336
Fixed target DIS	✓	✓	✓(w/o ν-DIS)	✓
Fixed target Drell–Yan	✓	✓		
LHC W and Z		✓	✓(✗)	
Jet and had. prod.	(π^0 only)	(π^0, LHC dijet)		
Independent PDFs	6	6	6 (3)	3
Parametrization	simple pol.	simple pol.	neural network	simple pol.
Free parameters	16	20	256 (178)	16
Statistical treatment	Hessian	Hessian	Monte Carlo	Hessian
Tolerance	$\Delta\chi^2 = 35$	$\Delta\chi^2 = 52$	—	$\Delta\chi^2 = 50$

TABLE I: Theoretical, experimental, and methodological features of the most recent nPDF sets.

II. EXPERIMENTAL ADVANCEMENTS

Several studies have already demonstrated the valuable constraints that can be provided for the nPDFs from heavy ion collisions at the LHC. For example, the nCTEQ15 original analysis has since been updated with measurements of vector boson production in pPb and PbPb collisions [8], the EPPS Collaboration studied the impact of dijet [8] and D-meson [9] production in pPb collisions, while the nNNPDF Collaboration recently added available measurements of W and Z production in pPb collisions [5]. Top quark production in pPb and PbPb has been suggested as a valuable probe of the high-x gluon distribution in the Pb ions[10]. Global nPDF fits could be improved at the LHC in the future as [11] (and references therein):

- at high squared momentum transfer Q^2 and $x{\sim}10^{-3}$–10^{-2} with high-precision W, Z, and dijet measurements (e.g., inclusively, diferentially, forward-backward asymmetries) in pPb and PbPb collisions;
- for (anti-)quarks at low Q^2 and $x{\sim}10^{-5}$–10^{-3}, with prompt photon and low-mass Drell–Yan measurements in pPb collisions;
- including further heavy-flavor data (e.g., D-meson production) impacting the uncertainty down to $x{\sim}10^{-6}$;
- taking advantage from the heavy quark associated production with vector bosons in pPb collisions, similar to, e.g., the studied $\mathrm{W+c}$ and $\mathrm{W+b}$ processes in pp collisions, with sensitivity to the s and c quark nPDFs, respectively;
- using measurements from quarkonia (e.g., J/ψ) and dijet production in ultraperipheral collisions;
- using top quarks inclusively or differentially, for the first time, providing information about the gluon nPDF at very high Q^2 and $x{\sim}10^{-2}$–10^{-1} in pPb and PbPb collisions;
- colliding lighter ions, hence offering large luminosities and a "bridge" between small and PbPb systems, meaning constraining experimentally the A dependence.

Major upgrades of the four main LHC experiments, in the years 2019–2021 for ALICE and LHCb, and 2025–2027 for ATLAS and CMS, will be very beneficial in increasing the precision and opening new possibilities, beyond the increase in luminosity with respect to the already available data sets: we list some of the most significant instrumental improvements below. The upgraded time projection chamber [12] of the ALICE detector will dramatically increase the experiment's event recording rate, while the planned forward calorimeter (FoCAL) upgrade [13] will enable the measurement of prompt photons at forward rapidities, providing constraints on nPDFs at small x. The LHCb detector's data taking capabilities will also be enhanced [14], including access to more central PbPb events, and complemented with a new SMOG system [15] allowing a larger gas pressure to be injected into the interaction region for fixed target collisions (and the corresponding scan in collision system and energy). The ATLAS and CMS detectors both will benefit from upgraded inner trackers [16–19] covering up to $\eta \approx 4$ (up to only ≈ 2.5 today) and improved forward calorimetry especially for CMS [20], resulting in an increased acceptance and wider x coverage for nPDF.

III. THEORETICAL ADVANCEMENTS AND CONSIDERATIONS

Determinations of nPDFs should be as accurate and global as possible, i.e., performed at the highest available order in perturbative QCD and the range of the input data set should cover unexplored kinematic regions and new processes. In this respect,

- a next-to-next-to-leading order determination of continuously more nPDF sets is important;
- nPDF determinations should also resum large logarithms: large-x resummation is particularly important for searches of beyond-the-standard-model physics and matching of fixed-order calculations to parton showering, while small-x resummation is relevant to reveal the onset of BFKL dynamics and gluon saturation;
- heavy-quark nPDFs should be treated at the same footing as the light quark distributions;
- a complete characterization of the theoretical uncertainty, including the input from physical parameters and the omission of missing higher orders in QCD or other, e.g., electroweak, corrections should be implemented, specifically in view of precision physics;
- nPDF analyses could aim at becoming simultaneous, i.e., parameters from different QCD aspects (e.g., $\alpha_S(m_Z)$) to be determined at the same time;
- experimental uncertainties should be carefully scrutinized, in particular, the correlated systematic uncertainty for it dominates collider measurements;
- any observed tensions between data sets, and the different parton sensitivity to different observables across nPDF extractions, must be carefully understood with appropriate statistical tools;
- benchmarking for several high-energy cross sections can become standard, leading to an overall improvement in the description of the data, better compatibility among different nPDF sets, and, if beneficial, their combination;
- on the longer timescale:
  - in the spirit of the analyses of proton PDFs and fragmentation functions, an integrated fit of proton and nuclear PDFs would ensure the ultimate theoretical and methodological consistency of the determination of the nuclear modifications;
  - nPDF extractions could benefit from lattice QCD calculations and advancements in the understanding of nonperturbative functions that generalize collinear PDFs.

IV. SUMMARY

Global nuclear parton distribution function fits reflect the current state-of-the-art knowledge about parton modifications in bound nuclei (Section I), and could be significantly improved at the LHC in the near or less immediate future driven by both experimental (Section II) and theoretical (Section III) advancements.

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