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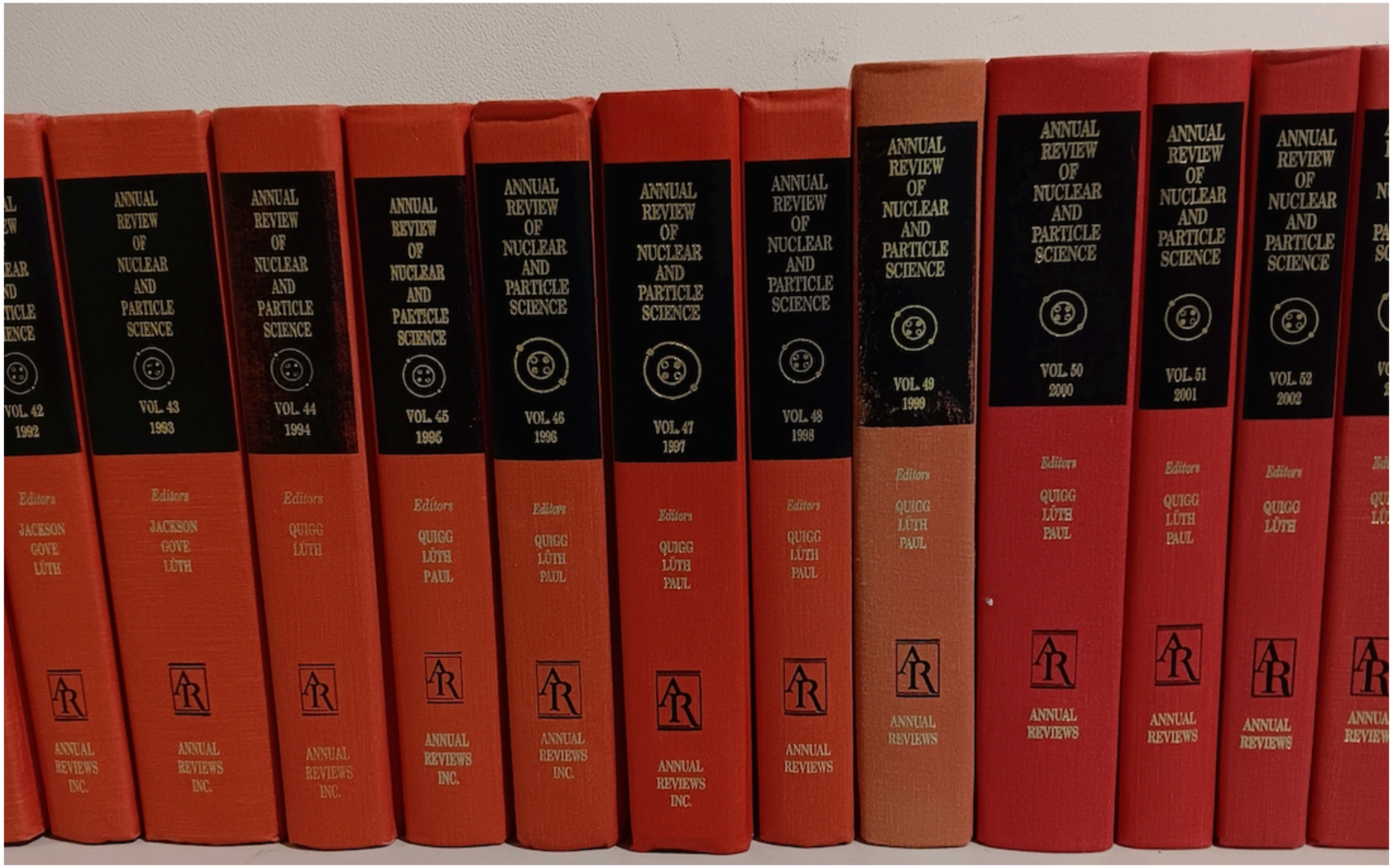

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Nuclear Parton Distribution Functions After the First Decade of LHC Data

Michael Klasen[1], and Hannu Paukkunen[2,3]

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ANNUAL REVIEWS

Annual Review of Nuclear and Particle Science

Nuclear Parton Distribution Functions After the First Decade of LHC Data

Michael Klasen[1] and Hannu Paukkunen[2,3]

[1]Institute for Theoretical Physics, University of Münster, Münster, Germany; email: michael.klasen@uni-muenster.de

[2]Department of Physics, University of Jyväskylä, Jyväskylä, Finland; email: hannu.paukkunen@jyu.fi

[3]Helsinki Institute of Physics, Helsinki, Finland

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Keywords

quantum chromodynamics, nuclear structure, parton distribution functions, collider physics, future developments

Abstract

We present a review of the conceptual basis, current knowledge, and recent progress regarding global analysis of nuclear parton distribution functions (PDFs). After introducing the theoretical foundations and methodological approaches for the extraction of nuclear PDFs from experimental data, we discuss how different measurements in fixed-target and collider experiments provide increasingly precise constraints on various aspects of nuclear PDFs, including shadowing, antishadowing, the EMC effect, Fermi motion, flavor separation, deuteron binding, and target-mass and other higher-twist effects. Particular emphasis is given to measurements carried out in proton–lead collisions at the Large Hadron Collider, which have revolutionized the global analysis during the past decade. These measurements include electroweak boson, jet, light hadron, and heavy flavor observables. Finally, we outline the expected impact of the future Electron Ion Collider and discuss the role and interplay of nuclear PDFs with other branches of nuclear, particle, and astroparticle physics.

(SIH) production at the LHC, three free parameters were added for $s+\bar{s}$. The 38 error PDFs are obtained with the Hessian method and a tolerance of $\Delta\chi^2 = 35$.

In the latest nCTEQ fit, nCTEQ15HQ (50), the weakly fragmentation-function (FF)-dependent SIH data were complemented by open heavy quark and quarkonium (HQ) production data from the LHC that had shown great potential to constrain the gluon in preceding reweighting studies (89, 90). These data were fitted with a data-driven method (91), in which the cross sections of hadrons A_1 and A_2 are taken to be dominated by the gluon–gluon subprocesses,

$$\sigma(A_1A_2 \to \mathcal{Q}+X) = \int \mathrm{d}x_1\mathrm{d}x_2 f_g^{A_1}(x_1,\mu^2)\, f_g^{A_2}(x_2,\mu^2)\, \frac{1}{2\hat{s}}\overline{|\mathcal{A}_{gg\to\mathcal{Q}+X}|^2}\mathrm{dPS}, \qquad 23.$$

where $\mathcal{Q} = D^0, J/\psi, B\to J/\psi, \Upsilon, \psi'$, and $B\to\psi'$; the squared factorization scale μ^2 is related to the geometric mean of $M_\mathcal{Q}^2$ and p_T^2; and dPS denotes the two-particle phase space. The effective matrix elements $\overline{|\mathcal{A}_{gg\to\mathcal{Q}+X}|^2}$ are parameterized by a generalized Crystal Ball function:

$$\overline{|\mathcal{A}_{gg\to\mathcal{Q}+X}|^2} = \frac{\lambda^2\kappa\hat{s}}{M_\mathcal{Q}^2}e^{a|y|} \times \begin{cases} e^{-\kappa\frac{p_\mathrm{T}^2}{M_\mathcal{Q}^2}} & \text{if } p_\mathrm{T} \le \langle p_\mathrm{T}\rangle \\ e^{-\kappa\frac{\langle p_\mathrm{T}\rangle^2}{M_\mathcal{Q}^2}}\left(1+\frac{\kappa}{n}\frac{p_\mathrm{T}^2-\langle p_\mathrm{T}\rangle^2}{M_\mathcal{Q}^2}\right)^{-n} & \text{if } p_\mathrm{T} > \langle p_\mathrm{T}\rangle \end{cases}, \qquad 24.$$

where $M_\mathcal{Q}$ denotes the mass of particle $\mathcal{Q}$, $\hat{s} = x_1x_2s$, and p_T and y correspond to the transverse momentum and rapidity of $\mathcal{Q}$. The free parameters $\lambda, \kappa, \langle p_\mathrm{T}\rangle, n$, and a are fitted for each final state to pp data. The fits agree with NLO GM-VFNS (92) and NRQCD (93) calculations within their scale uncertainties. In nCTEQ15HQ, the LHC p+Pb data are consistently included in the fit as absolute cross sections in the case of all observables.

3.2. The EPPS Framework

The latest EPPS analysis, EPPS21 (51), is rooted in a series of global fits (42, 94–97) that parameterize the bound-proton PDFs at the starting scale $Q_0 = 1.3$ GeV as follows:

$$f_i^{p/A}(x,Q_0^2) = R_i^{p/A}(x,Q_0^2)\, f_i^p(x,Q_0^2). \qquad 25.$$

Here, $i = u_v, d_v, g, \bar{u}, \bar{d}, s$ (with $s=\bar{s}$), and the free-proton PDFs $f_i^p(x,Q^2)$ are taken from the fit CT18A (98), which includes more LHC pp data sensitive to strange quarks than the default CT18 fit. This reduces the dependence of the proton baseline on the ν+Fe DIS data, which is also part of the CT18A analysis. The nuclear modifications $R_i^{p/A}(x,Q_0^2)$ are parameterized through 24 free parameters. The parameterization is piecewise smooth in x, so that parameters controlling different x regions mix as little as possible; that is,

$$R_i^{p/A}(x,Q_0^2) = \begin{cases} a_{0i} + a_{1i}(x-x_{ai})\left[e^{-xa_{2i}/x_{ai}} - e^{-a_{2i}}\right], & x \le x_{ai} \\ b_{0i}x^{b_{1i}}(1-x)^{b_{2i}}e^{xb_{3i}}, & x_{ai} \le x \le x_{ei} \\ c_{0i} + c_{1i}(c_{2i}-x)(1-x)^{-\beta_i}, & x_{ei} \le x \le 1, \end{cases} \qquad 26.$$

where x_{ai} and x_{ei} are the locations of the anticipated antishadowing maximum and minimum of the EMC effect, respectively. The A dependence is encoded in such a way that larger nuclei tend to have larger nuclear effects at $x=0, x_{ai}, x_{ei}$ through

$$R_i^{p/A}(x,Q_0^2) = 1 + \left[R_i^{p/A_\mathrm{ref}}(x,Q_0^2) - 1\right]\left(\frac{A}{A_\mathrm{ref}}\right)^{\gamma_i}, \quad \gamma_i > 0,\ A_\mathrm{ref} = 12. \qquad 27.$$

However, for very small nuclei, a monotonic A scaling is not necessarily a justified assumption (e.g., certain small nuclei are more tightly bound), and such deviations are also allowed in the

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Questions ? email mpeskin@slac.stanford.edu
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