Snowmass2021 LOI: **xFitter: An Open Source QCD Analysis Framework**

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I. xFitter OVERVIEW

xFitter [1] is an open-source software package that provides a framework for the determination of the **parton distribution functions** (PDFs) of the proton and related subjects. xFitter version 2.0.1 has recently been released, and offers an expanded set of tools and options. It incorporates experimental data from a wide range of experiments including fixed-target, Tevatron, HERA, and LHC data sets. xFitter can analyze this data using predictions up to next-to-next-to-leading-order (NNLO) in perturbation theory with a variety of theoretical calculations including numerous methodological options for carrying out PDF fits and plotting tools which help visualize the results. While primarily based on the collinear factorization foundation, xFitter also provides facilities for fits of dipole models and **transverse-momentum dependent** (TMD) distributions. The package can be used to study the impact of new precise measurements from hadron colliders, and also assess the impact of future colliders. This paper provides a brief overview of xFitter with emphasis of the features relevant for the Snowmass2021 study.

The need for precision PDFs: The PDFs are the essential components that allow us to make theoretical predictions for experimental measurements of collider experiments with initial state protons and hadrons. Despite the recent progress of PDF analyses (including NLO and NNLO calculations), the uncertainty for many precision measurements at the LHC stems nowadays primarily from the PDFs [2, 3]. Hence, our ability to fully characterize the Higgs boson and constrain SUSY signatures ultimately comes down to how accurately we determine the underlying PDFs; this is the focus of the xFitter project.

Open Source Code: The xFitter package is provided at `www.xFitter.org`, and a write-up of the program can be found in Ref. [1], and an overview of available tutorials in Ref. [4] including some presented at MCnet-CTEQ schools. The xFitter framework has already been used for more than 100+ analyses including many LHC studies. The code structure of the xFitter package is modular, and it allows for various theoretical and methodological options. Currently it contains interfaces to QCDNUM [5], APFEL [6], LHAPDF [7], APPLGRID [8], APFELGRID [9], FastNLO [10], HATHOR [11], among other packages.

xFitter also has a large number of data sets available, including a variety of fixed target experiments, HERA, Tevatron, and LHC. It is also possible to add new custom data sets such as LHeC [12] and EIC [13]) pseudo-data.

II. xFitter CAPABILITIES

PDF Fits & Analysis: First and foremost, xFitter provides a flexible open-source framework for performing PDF fits to data. The PDFs are the fundamental object that xFitter works with, and it has a variety of utilities to read, write, and manipulate the standardized PDF file format and associated uncertainties. For example, xFitter is able to read and write PDFs in the LHAPDF6 format [7].

xFitter-draw: xFitter can also automatically generate comparison plots of data vs. theory. There are a variety of options for the definition of the χ^2 function and the treatment of experimental uncertainties. Examples are presented in Ref. [1].

Nuclear PDFs: xFitter has also been extended to produce nuclear PDFs; this was used to produce the TUJU19 nPDF set of Ref. [14].

Pion PDFs: xFitter can also produce meson PDFs, and Ref. [15] illustrates this for the case of pion PDFs.

Pseudo-Data: An important application of xFitter is to understand how a particular data set or experiment will impact the PDFs. A typical study might be to use pseudo-data from a proposed experiment (e.g. LHeC or EIC) to constrain the relative uncertainty on the underlying PDFs. For example, Ref. [16] used LHeC pseudo-data to constrain the strange PDF with charged-current DIS charm production data. Additionally, forward-backward Drell-Yan asymmetry pseudo-data were prepared to simulate the end of Run-II LHC (i.e. 300 fb^{-1}), and also the HL-LHC; these pseudo-data have been used for PDF profiling in Refs. [3] and [17].

Profiling & Reweighting: xFitter is able to perform PDF profiling and reweighting studies. The reweighting method allows xFitter to update the probability distribution of a PDF uncertainty set (such as a set of NNPDF replicas) to reflect the influence of new data. For the PDF profiling, xFitter compares data and MC predictions based on the χ^2-minimization, and then constrains the individual PDF eigenvector sets taking into account the data uncertainties. For example, Ref. [2] used the Tevatron W-boson charge asymmetry and of the Z-boson production cross sections data to study the impact on the PDFs using Hessian profiling and Bayesian reweighting techniques.

In a separate study, the forward-backward asymmetry in neutral current Drell-Yan production provides powerful constraints the valence quark PDFs, and this in turn can impact both SM and BSM physics [3, 17].

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NNLO & QED PDFs: As many PDF analyses are now extended out to NNLO, the NLO QED effects can also become important. For example, including QED processes in the parton evolution will break the isospin symmetry as the up and down quarks have different couplings to the photon. xFitter is able to include NLO QED effects, and this is illustrated in Ref. [18] which computes the photon PDF as determined using a NNLO QCD and NLO QED analysis.

Transverse-momentum-dependent distributions: Transverse-momentum-dependent (TMD) parton distribution functions [19] encode nonperturbative information on hadron structure, extending to the transverse plane the one-dimensional picture given by collinear PDFs, and providing a 3D imaging of hadron structure. Similarly to collinear PDFs, TMDs can be parameterised and fitted to experimental data. Within the xFitter framework, the extraction of TMDs from fits to experimental data has been carried out in the cases of CCFM evolution [20, 21] and Parton Branching evolution [22, 23]. xFitter is able to write and manipulate TMDs in the TMDlib format [24].

Small-x resummation: xFitter can also study the impact of the $\ln(1/x)$-resummation corrections to the DGLAP splitting functions using DIS coefficient functions from the public code HELL [25, 26]; these effects are illustrated in Ref. [27]. In a related study [28], a more flexible PDF parametrisation is used with xFitter which provides a better description of the combined inclusive HERA I+II data, expecially at low-x.

Pole & $\overline{MS}$ running masses: Another feature of xFitter is the ability to handle both pole masses and $\overline{MS}$ running masses. While the pole mass is more closely connected to what is measured in experiments, the $\overline{MS}$ mass has advantages on the theoretical side of improved perturbative convergence. xFitter was used to perform a high precision determination of the $\overline{MS}$ charm mass in this new framework [29].

Dipole models: xFitter also has dipole models [30–32] implemented; fits to HERA data are shown in [33, 34].

III. xFitter and SNOWMASS2021

We briefly discuss how xFitter might contribute to some of the future projects being studied in the Snowmass2021 planning process.

LHC & HL-LHC: The xFitter package has been used for more than 100 analyses including many LHC studies; a more complete list is available at `www.xFitter.org`. Applying this work to data taken at HL-LHC is a natural extension.

To highlight just one LHC example, the strange quark PDF has generated considerable attention in the recent literature. There is a comprehensive study [35] that examines the compatibility of both the ATLAS [36, 37] and CMS [38] data in a uniform framework using the xFitter program.

EIC & LHeC: The EIC and LHeC facilities will provide lepton–nucleon scattering in a collider configuration with a variety of beams.

In addition to exploring the proton PDFs, these colliders can also study nuclear PDFs with nuclear beams, and also meson (pion & kaon) structure via leading neutron production. xFitter is capable of studying both nuclear PDFs [14] and meson PDFs [15]. Additionally, xFitter can also compute the transverse momentum dependent (TMD) distributions [1].

DUNE: The Deep Underground Neutrino Experiment (DUNE) will use an intense neutrino beam generated at Fermilab to study open questions about neutrino oscillations. The massive DUNE detectors will also contribute to the study of proton decay and Grand Unified Theories, as well as observe neutrino signals from supernova core-collapse [39].

In particular, the NuSTEC white paper [40] outlines the status and challenges of neutrino-nucleus interactions, with special attention to DUNE. Improvements in PDF nuclear correction factors and the generation of nuclear PDFs fit, specifically to neutrino–nucleus interactions in the relevant energy range, can help minimize systematic errors for the +30% fraction of DUNE events coming from the DIS region. This would enhance analyses in both the near and far detectors. Thus, improvements by xFitter on both proton and nuclear PDFs [14] can contribute to the DUNE project.

UHE Cosmic Rays Recent advances in neutrino astronomy have enabled us to study ultra-high energy cosmic rays (UHECR) by studying atmospheric neutrinos. For example, IceCube [41, 42] has isolated more than 100 high-energy cosmic neutrinos, with energies between 100 TeV and 10 PeV.

Interpretation of these measurements would benefit from accurate PDFs in the low-x region. An example application is the evaluation of the prompt flux of atmospheric neutrinos originating from the semileptonic decays of heavy-flavored hadrons produced in the interactions of UHECR with nuclei in the atmosphere [43, 44]. The prompt atmospheric-neutrino flux represents a relevant background for searches of highly energetic cosmic neutrinos. Thus, increased precision of both PDFs and nuclear corrections in the very low-x region would improve theoretical predictions in this extreme kinematic region.

IV. CONCLUSION

The xFitter program is a versatile, flexible, modular, and comprehensive tool that can facilitate analyses of the experimental data and theoretical calculations.

It is a valuable framework for bench-marking and understanding differences between PDF fits, and it can provide impact studies for possible future facilities including HL-LHC, EIC, LHeC, DUNE, and UHE Cosmic Ray experiments. We encourage use of xFitter, and welcome new contributions from the community to ensure xFitter continues to incorporate the latest theoretical advances and precision experimental data.

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