PROCEEDINGS OF SCIENCE

xFitter project

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An accurate knowledge of the Parton Distribution Functions (PDF) plays a critical role for the precision tests of the Standard Model (SM) and impact substantially the theory predictions of Beyond SM high mass production. We present the xFitter project (former HERAFitter) which provides a unique open-source software framework for the determination of the proton's PDFs and the interpretation of the physics analyses in the context of Quantum Chromodynamics. We highlight the new xFitter software release which includes many new features and additions, e.g. the possibility of the inclusion of photon PDF, updated variable and fixed-flavour-number schemes for heavy quarks, interface to the APFEL library and N-space evolution program MELA, updates to the latest theory calculations, fast grid tools and many more. We will also report the highlighted results based on the xFitter functionalities, as well as novel studies performed by xFitter.

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1. Introduction

The interpretation of the measurements in hadron collisions relies on the concept of the factorisation in QCD, when inclusive cross sections may be written as

$$\sigma(\alpha_s(\mu_r^2),\mu_r^2,\mu_f^2) = \sum_{a,b}\int_0^1 dx_1\, dx_2 f_a(x_1,\mu_f^2) f_b(x_2,\mu_f^2) \times \hat{\sigma}^{ab}(x_1,x_2;\alpha_s(\mu_r^2),\mu_r^2,\mu_f^2) \quad (1.1)$$

where the cross section σ is expressed as a convolution of Parton Distribution Functions (PDFs) f_a and f_b with the partonic cross section $\hat{\sigma}^{ab}$. At Leading Order (LO) in the perturbative expansion of the strong coupling constant, the PDFs represent the probability of finding a specific parton a (b) in the first (second) hadron carrying a fraction x_1 (x_2) of its momentum. The indices a and b in Eq. 1.1 indicate the various kinds of partons, i.e. gluons, quarks and antiquarks of different flavours that are considered as the constituents of the proton. The PDFs depend on the factorisation scale, μ_f, while the partonic cross sections depend on the strong coupling constant, α_s, and the factorisation and renormalisation scales, μ_f and μ_r. The parton cross sections $\hat{\sigma}^{ab}$ are calculable in perturbative QCD (pQCD) whereas PDFs are usually constrained by global fits to a variety of experimental data.

Many groups are doing the extraction of PDFs, using different input data, theoretical assumptions and fit strategies: ABM12 [1], CJ16 [2], CT14 [3], JR14 [4], HERAPDF2.0 [5], MMHT2014 [6], NNPDF3.0 [7]. Their recent reviews can be found e.g. in Refs. [8, 9]. The rapid flow of data from the LHC experiments and the corresponding theoretical developments, which are providing predictions for more complex processes at increasingly higher orders, has motivated the development of tools to combine them together in a fast, efficient, open-source framework.

The open-source QCD fit framework `xFitter` (former `HERAfitter`) [10, 11], which includes a set of tools to facilitate global QCD analyses of pp, $p\bar{p}$, ep and μp scattering data. It has been developed for the determination of PDFs and the extraction of fundamental parameters of QCD such as the heavy-quark masses and the strong coupling constant. It also provides a common framework for the comparison of different theoretical approaches. Furthermore, it can be used to test the impact of new experimental data on the PDFs and on the SM parameters.

2. Overview of the `xFitter` workflow

The diagram in Fig. 1 gives a schematic overview of the `xFitter` structure and functionality, which can be divided into four main blocks, described below.

Data: Measurements from various processes are provided in the `xFitter` package including the information on their uncorrelated and correlated uncertainties. The core of all PDF fits are HERA inclusive scattering data, which are directly sensitive to quark PDFs and indirectly sensitive to the gluon PDF through scaling violations and the longitudinal structure function F_L. For example, the legacy combination of H1 and ZEUS inclusive data [5] is available in `xFitter`. Measurements of charm and beauty quark production at HERA are sensitive to heavy-quark PDFs and heavy-quark masses. The H1 and ZEUS combined charm data [12] allow for stringent tests of various approaches to describe heavy-flavour production.

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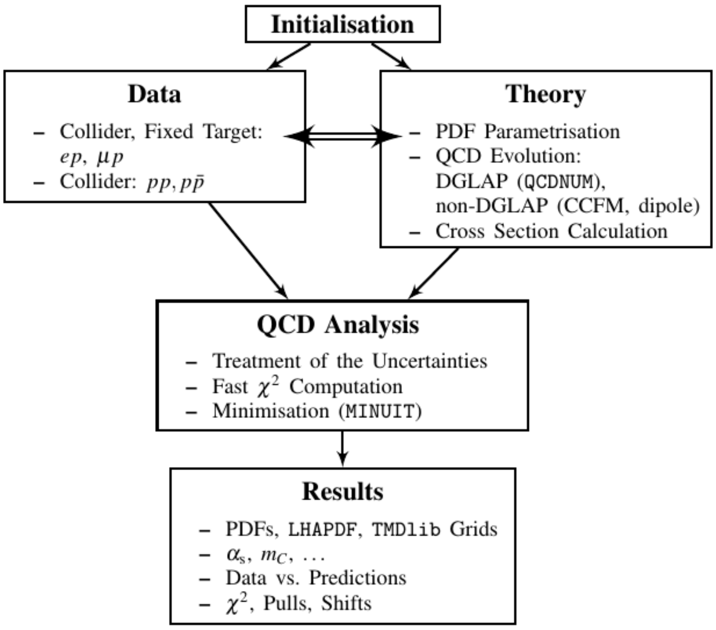

Figure 1: Schematic overview of the `xFitter` program.

Jet production in ep, pp and $p\bar{p}$ collisions can be used as an additional process to constrain the gluon PDF at moderate and large x, as well as for the determination of the strong coupling constant. The hadroproduction of top-quark pairs from pp and $p\bar{p}$ collisions is used to constraint the high-x gluons. On the other side, the low-x region can be constrained using data on charm and beauty production in the forward region.

Measurements from the fixed-target experiments provide additional constraints on the gluon and quark distributions at high-x, better understanding of heavy-quark distributions and decomposition of the light-quark sea. The Drell-Yan data are also an improtant ingredient for a PDF analysis since DIS data alone do not allow for a comprehensive disentangling of the quark and anti-quark distributions. The high precision Drell-Yan data obtained in pp and $p\bar{p}$ collisions from the LHC and the Tevatron constrain the PDFs at small and large x.

The processes that are currently available within the `xFitter` framework are listed in Tab. 1.

Theory: The PDFs are parametrised at a starting scale, Q_0^2, using a functional form and a set of free parameters. Several commonly used parametrisation forms are available. These PDFs are evolved to the scale of the measurements Q^2, $Q^2 > Q_0^2$. The evolution uses the DGLAP formalism [13–17] in x-space as implemented in `QCDNUM` [18] or `APFEL` [19], or in N-space as implemented in `MELA` [20]. Alternatively, the CCFM evolution [21–24] as implemented in `uPDFevolv` [25] can be chosen. The prediction of the cross section for a particular process is obtained, assuming factorisation, by the convolution of the evolved PDFs with the corresponding parton scattering cross section. A fast evaluation of cross sections for vaious processes is possible via an interface to fast grid computations (`APPLGRID` [26] and `fastNLO` [27–29]). Predictions using dipole

Experimental Data	**Process**	**Reaction**	**Theory schemes calculations**
HERA, Fixed Target	DIS NC	$ep \to eX$, $\mu p \to \mu X$	TR′, ACOT, ZM (`QCDNUM`), FONLL(`APFEL`), FFN (`OPENQCDRAD`, `QCDNUM`), TMD (uPDFevolv)
HERA	DIS CC	$ep \to \nu_e X$	ACOT, ZM (`QCDNUM`), FFN (`OPENQCDRAD`
	DIS jets	$ep \to e$ jets$X$	`NLOJet++` (`fastNLO`)
	DIS heavy quarks	$ep \to ec\bar{c}(b\bar{b})X$	TR′, ACOT, FONLL(`APFEL`), ZM (`QCDNUM`), FFN (`OPENQCDRAD`, `QCDNUM`)
Tevatron, LHC	Drell-Yan	$pp(\bar{p}) \to l\bar{l}(l\nu)X$	`MCFM` (`APPLGRID`)
	top pair	$pp(\bar{p}) \to t\bar{t}X$	`MCFM` (`APPLGRID`), `HATHOR`, `DiffTop`
	single top	$pp(\bar{p}) \to tl\nu X$, $pp(\bar{p}) \to tX$, $pp(\bar{p}) \to tWX$	`MCFM` (`APPLGRID`)
	jets	$pp(\bar{p}) \to$ jets$X$	`NLOJet++` (`APPLGRID`), `NLOJet++` (`fastNLO`)
LHC	DY heavy quarks	$pp \to VhX$	`MCFM` (`APPLGRID`)
	heavy quarks	$pp \to c\bar{c}(b\bar{b})X$	`MNR`

Table 1: The list of experimental data and theory calculations implemented in the `xFitter` package.

models [30–32] are available also. Available theory calculations for each process are listed in Tab. 1.

QCD Analysis: The free parameters of a QCD analysis are determined in a least squares fit: a χ^2 function, which compares the input data and theory predictions, is minimised with the `MINUIT` [33] program. In `xFitter` various choices are available for the treatment of experimental uncertainties in the χ^2 definition. Correlated experimental uncertainties can be accounted for using a nuisance parameter method or a covariance matrix method. Different statistical assumptions for the distributions of the systematic uncertainties, e.g. Gaussian or LogNormal [34], can also be studied. Besides the χ^2 minimisation, alternative approaches to PDF studies are available, such as reweighting (probability distribution based PDFs are updated with new data inputs) and profiling (the individual PDF eigenvector sets of the input PDFs are constrained taking into account the new data). Finally, the option just to calcualte the χ^2 accounitng for data and PDF uncertainties, provided in the LHAPDF format, is available as well.

Results: The resulting PDFs are provided in a format ready to be used by the `LHAPDF` library [35, 36] or by `TMDlib` [37]. `xFitter` drawing tools can be used to display the PDFs with their uncertainties at a chosen scale, as well as the comparison of data to theoretical predictions, pulls, shifts of nuisance parameters etc.

3. Recent developments and applications

The latest version of the `xFitter` program, 1.2.1, includes a number of new developments compared to `HERAFitter` version 1.1.1. On the theory side, these are QED PDF evolution via `QCDNUM` [18] or `APFEL` [19], an interface to the N-space evolution using `MELA` [20], an interface to `APFEL` [19] which provides access to the FONLL scheme as used for NNPDF, MNR caclulations [38] for heavy-flavour production in pp collisions as used for [39]. On the technical side, the most important improvements include a full installation script, stand-alone scripts for downloading data and theory files, unified theory interface for expression between `fastNLO` and `APPLGRID`, direct access to LHAPDF avoiding QCDNUM via 'LHAPDFNATIVE' option. In addition, a number of new data sets are included (see [11] for more details).

The xFitter program has been used in a number of experimental and theoretical analyses (for the full list see [11]), performed by xFitter developers, theory groups and experimentalists. The recent studies include a determination of the running charm-quark mass $m_c(m_c)$ from HERA data using the FONLL general-mass variable-flavour-number scheme [40], QCD analysis of the CMS $W^{\pm}$ charge asymmetry data [41], combined QCD and electroweak analysis of HERA data [42], QCD analysis of CMS inclusive differential Z production data [43], study of the impact of heavy-flavour production masurements by LHCb on PDFs at low x [39].

4. Summary

xFitter is the open-source code designed for studies of the structure of the proton and, more generally, for theoretical interpretation of the experimental measurements at hadron colliders. It provides a unique and flexible framework with a wide variety of QCD tools to facilitate analyses of the experimental data and theoretical calculations. The source code of the package is freely available under GPL v3 license. xFitter, in version 1.2.1, has sufficient options to reproduce the majority of the different theoretical choices made in the PDF analyses by various groups. This makes it a valuable tool for benchmarking and understanding differences between PDF fits and other QCD related benchmarks. The further progress of xFitter will be driven by the latest QCD advances in theoretical calculations and in the precision of experimental data.

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