PROCEEDINGS OF SCIENCE

HERAFitter project and its related studies

Vladimir KOLESNIKOV*
on behalf of the HERAFitter team

Joint Institute for Nuclear Research
E-mail: kolesnikov.volodya@gmail.com

HERAFitter is an open-source package that provides a framework for the determination of the parton distribution functions (PDFs) of the proton and for many different kinds of analyses in Quantum Chromodynamics (QCD). It encodes results from a wide range of experimental measurements at hadron colliders along with corresponding theoretical predictions. The framework covers a large number of the existing methods and schemes used for PDF determination. It can be used to study the impact of new precise measurements from hadron colliders. A short overview of the package is presented in this paper together with the recent analyses published by the HERAFitter developers team.

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*Speaker.

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1. Introduction

According to the factorisation theorem, the cross-section of hadron collisions is a convolution of hadron PDFs with perturbatively calculable partonic reactions. PDFs and their uncertainties are crucial for precision tests of Standard Model and for searching of physics beyond Standard Model. HERAFitter is an open source QCD fit framework designed for the extraction of PDFs of the proton and different analyses in QCD. HERAFitter implements various methodologies of PDF fits and tools to asses the impact of new data on PDFs. Further information about the package, downloads and documentation can be found at *http://herafitter.org*.

2. Functionality

In general PDFs are determined by a fit to experimental data for various processes. A common PDF fit workflow in HERAFitter is shown below:

- First, the PDFs are parametrised at the starting scale Q_0^2 below the charm mass threshold.
- Parametrised PDFs are evolved to the scale of experimental data using DGLAP formalism [1] in $\overline{MS}$ scheme. For PDF evolution several external libraries are used: QCDNUM [2] and APFEL [3].
- Evolved PDFs are convoluted with partonic crossections to get theoretical prediction of observables.
- The experimental and predicted crossections together with their corresponding errors are used to build a χ^2 and determine the PDFs parameters.
- The χ^2 is minimised with the MINUIT [4] program.
- The resulting PDFs are saved in formats corresponding to LHAPDF [5] or TMDlib [6].

In HERAFitter different data from ep, pp and $p\overline{p}$ colliders can be used in the QCD fits to constrain PDFs in various kinematic domains: inclusive cross sections from HERA DIS and fixed target experiments, Drell-Yan, jet production data, top quark pair production. Various schemes for the treatment of heavy quark production in DIS are covered by the package: Thorne-Roberts (TR) at LO, NLO, NNLO as provided by the MSTW group, the ACOT scheme at LO and NLO as provided by CTEQ group, zero-mass (ZM) and fixed flavour number (FFN) schemes implemented in QCDNUM, FONLL scheme via APFEL. FFN scheme is also available via OPENQCDRAD [7]. Several methods for calculation of processes crossection are available in HERAFitter. The NLO and NNLO predictions could be obtained using *k-factor* or *fast-grid* (via APPLGRID [8] or FastNLO [9]) techniques.

The PDFs can be parametrised using several predefined functional forms:

- the standard polynomial form is the most commonly used,
- bi-log-normal distributions can be regarded as a generalization of standard polynomial form,
- Chebyshev polynomials can be effectively used for the gluon and sea distributions.

HERAFitter can work with various forms of χ^2, e.g. using a covariance matrix or providing nuisance parameters to encode the dependence of each correlated systematic uncertainty for each measured data point:

- covariance matrix representation

$$\chi^2(m) = \sum_{i,k}(m_i - \mu_i)C_{ik}^{-1}(m_k - \mu_k), \tag{2.1}$$

  for a data point μ_i with a corresponding theory prediction m_i, where the covariance matrix C_{ik} is given by a sum of statistical, uncorrelated and correlated systematic contributions;
- nuisance parameter representation

$$\chi^2(m,b) = \sum_i \frac{\left[\mu_i - m_i\left(1 - \sum_j \gamma_j^i b_j\right)\right]^2}{\delta_{i,\mathrm{unc}}^2 m_i^2 + \delta_{i,\mathrm{stat}}^2 \mu_i m_i\left(1 - \sum_j \gamma_j^i b_j\right)} + \sum_j b_j^2, \tag{2.2}$$

  where, $\delta_{i,\mathrm{stat}}$ and $\delta_{i,\mathrm{unc}}$ are relative statistical and uncorrelated systematic uncertainties of the measurement i, γ_j^i quantifies the sensitivity of the measurement to the correlated systematic source j, the function χ^2 depends on the set of systematic nuisance parameters b_j;
- mixed form, where first two approaches are combined.

As an alternative to a complete QCD fit, several additional methods for estimation of the impact of new data on PDFs are available in `HERAFitter`:

Bayesian Reweighting was first proposed for PDF sets in the form of MC replicas [10] and further developed by the NNPDF Collaboration [11, 12]. More recently, a method to perform Bayesian Reweighting studies using PDFs with uncertainties provided in the eigenvector representation has been also developed [13]. Both reweighting methods are implemented in `HERAFitter`.

Another method is profiling procedure. The profiling is performed using a χ^2 function which includes both the experimental uncertainties and theoretical uncertainties arising from PDF variations:

$$\chi^2(\beta_{exp},\beta_{th}) = \sum_{i=1}^{N_{data}} \frac{\left(\sigma_i^{exp} + \sum_j \Gamma_{ij}^{exp}\beta_{j,exp} - \sigma_i^{th} - \sum_k \Gamma_{ik}^{th}\beta_{k,th}\right)^2}{\Delta_i^2} + \sum_j \beta_{j,exp}^2 + \sum_k \beta_{k,th}^2 \,. \tag{2.3}$$

The correlated experimental and theoretical uncertainties are included using nuisance parameter vectors β_{exp} and β_{th}. Their influence on the data and theory predictions is described by the Γ_{ij}^{exp} and Γ_{ij}^{exp} matrices. The measurements and the uncorrelated experimental uncertainties are given by σ_i^{exp} and Δ_i, respectively, and the theory predictions are σ_i^{th}.

3. Recent studies using HERAFitter

`HERAFitter` is actively used by experimental and theoretical high energy physics communities. There are several QCD analyses done by ATLAS and CMS collaborations using `HERAFitter` (for the most recent analyses see [14, 15, 16]).

A recent study done by `HERAFitter` developers team is dedicated to PDF sets at LO, NLO, NNLO accounting for correlated uncertainties between orders [17]. The sets are used to study

cross-section ratios and their uncertainties when calculated at different orders in QCD. A reduction of the overall theoretical uncertainty is observed if correlations between the PDF sets are taken into account for the ratio of WW di-boson to Z boson production cross sections at the LHC.

Another new work is related to assessing of the impact of the Tevatron W and Z boson data on PDFs using new developments in `HERAFitter` [18]. Recent measurements of the W boson charge asymmetry and of the Z boson production cross sections, performed at the Tevatron collider in Run II by the $D0$ and CDF collaborations, are studied using the `HERAFitter` framework to assess their impact on the proton PDFs. The Tevatron measurements, together with deep-inelastic scattering data from HERA, are included in a QCD analysis performed at next-to-leading order, and compared to the predictions obtained using other PDF sets from different groups. Good agreement between measurements and theoretical predictions is observed. The Tevatron data provide significant constraints on the d-valence quark distribution.

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