The HERAFitter project provides a framework for the determination of parton distribution functions (PDFs), and tools for assessing the impact of new data on PDFs. In this contribution, HERAFitter is used for a QCD analysis of the legacy 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. The Tevatron measurements are included in a PDF fit performed at next-to-leading order, and compared to the predictions obtained using other PDF sets from different groups. The measurements are in good agreement with NLO QCD theoretical predictions. The Tevatron data provide significant constraints on the $d$-valence quark distribution.

1 Introduction

According to the factorisation theorem, cross sections in hadron collisions are calculated by convoluting short distance partonic reactions with parton distribution functions (PDFs). Discovery of physics beyond the Standard Model at hadron colliders relies on the precise knowledge of the proton structure. Moreover, PDFs are among the dominant uncertainties for the measurement of the $W$ mass, and for $gg \to H$ production. HERAFitter provides a framework for the investigation of various methodologies in PDF fits, and tools for assessing the impact of new data on PDFs. It is widely used by the LHC experiments to improve the sensitivity of new measurements to PDFs. Full information about the project, downloads and documentation can be found at herafitter.org. A schematic view of a PDF fit, as implemented in HERAFitter, is shown in Fig. 1.

In this contribution, HERAFitter is used to perform a QCD analysis of the Tevatron Run II legacy measurements of the $W$-boson charge asymmetry and of the $Z$-boson production cross sections. At the Tevatron proton-antiproton collider, the production of $W$ and $Z$ bosons is dominated by valence-quark interactions. Whereas the primary source of information on the proton PDFs comes from deep-inelastic scattering (DIS), Drell-Yan production of $W$ and $Z$ bosons in proton-antiproton collisions can provide additional information, particularly on the $d$-valence quark PDFs.
Figure 1: Schematic representation of a PDF fit in HERA-Fitter.

2 Tevatron $W$ and $Z$ measurements and QCD settings

The most recent measurements of $W$-boson charge asymmetry and $Z$-boson inclusive production performed in Run II of the Tevatron collider are considered. They include the $Z$-boson differential cross section as a function of rapidity, measured by D0\cite{D0}, the $Z$-boson differential cross section as a function of rapidity, measured by CDF\cite{CDF}, the charge asymmetry of muons as a function of rapidity in $W \to \mu \nu$ decays, measured by D0\cite{D0}, the $W$-boson charge asymmetry as a function of rapidity, measured by CDF\cite{CDF}, the $W$-boson charge asymmetry as a function of rapidity, measured by D0\cite{D0}. Besides the Tevatron $W$- and $Z$-boson measurements, the HERA I combined measurements of the inclusive DIS neutral- and charged-current cross sections measured by the H1 and ZEUS experiments\cite{HERA} are used.

In general, the correlation model of the experimental uncertainties recommended by the Tevatron experiments is adapted and followed in the QCD analysis, with the exception of the experimental systematic uncertainties related to trigger and lepton identification efficiencies, which are treated as uncorrelated bin-to-bin.

The QCD analysis and PDF extraction is performed with the open-source framework HERA-Fitter. The charm mass is set to $m_c = 1.38$ GeV, as estimated from HERA charm production cross section\cite{HERA} and the bottom mass to $m_b = 4.75$ GeV. The strong-interaction coupling constant at the $Z$ boson mass, $\alpha_s(M_Z)$, is set to 0.118, and two-loop order is used for the running of $\alpha_s$.

The PDFs for the gluon, $u$-valence, $d$-valence, $\bar{u}$, $\bar{d}$ quark densities are parametrised at the input scale of $Q^2_0 = 1.7$ GeV$^2$. The contribution of the $s$-quark density is taken to be proportional to the $\bar{d}$-quark density by setting $x\bar{s}(x) = r_s x \bar{d}(x)$, with $r_s = 1.0$. The strange and anti-strange quark densities are taken to be equal: $x\bar{s}(x) = xs(x)$.

The impact of a new data set on a given PDF set can be quantitatively estimated with a profiling procedure\cite{Profiling}. The profiling is performed using a $\chi^2$ function which includes both the experimental uncertainties and the theoretical uncertainties arising from PDF variations:

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

The correlated experimental and theoretical uncertainties are included using the nuisance parameter vectors $\beta_{exp}$ and $\beta_{th}$, respectively. Their influence on the data and theory predictions is described by the $\Gamma_{ij}^{exp}$ and $\Gamma_{ik}^{th}$ matrices. The index $i$ runs over all $N_{data}$ data points, whereas the index $j$ ($k$) corresponds to the experimental (theoretical) uncertainty nuisance parameters.
Table 1: Results of a 15-parameters fit to the to the HERA I and Tevatron W- and Z-boson data. The contribution to the total $\chi^2_{\text{min}}$ of each data set and the corresponding number of points are shown.

| Data set                                      | $\chi^2$ / number of points |
|-----------------------------------------------|-----------------------------|
| HERA I                                        | 515 / 550                   |
| D0 $d\sigma(Z)/dy$                           | 23 / 28                     |
| CDF $d\sigma(Z)/dy$                          | 33 / 28                     |
| D0 muon charge asymmetry in $W \to \mu \nu$  | 12 / 10                     |
| CDF $W$ charge asymmetry in $W \to e \nu$    | 15 / 13                     |
| D0 $W$ charge asymmetry in $W \to e \nu$     | 16 / 14                     |
| Total $\chi^2_{\text{min}}$ / dof            | 615 / 628                   |

The measurements and the uncorrelated experimental uncertainties are given by $\sigma^\exp_i$ and $\Delta_i$, respectively, and the theory predictions are $\sigma^\th_i$.

3 Results

A QCD fit analysis performed on the Tevatron W- and Z-boson data, together with the HERA I data, is used to assess the impact of the Tevatron data on PDFs. The profiling is used to assess the impact of the Tevatron data on various PDF sets.

The optimal functional form for the PDF fit, which corresponds to 15 free parameters, is found through a parametrisation scan, and is used for a fit to the HERA I data only, and for a fit to the HERA I and Tevatron W- and Z-boson data. Table 1 shows the $\chi^2_{\text{min}}$ per degrees of freedom (dof) of the fit to the HERA I and Tevatron W- and Z-boson data. The contribution to the total $\chi^2_{\text{min}}$ of each data set, referred to as partial $\chi^2$, is also shown. The partial $\chi^2$ per number of points of each of the Tevatron and HERA I data set is close to unity.

The central value and the uncertainties of the PDFs are evaluated with MC replicas. Figure 2 shows the comparison of the PDFs extracted with the MC replica method by fitting the HERA I data, and by fitting the HERA I and Tevatron W- and Z-boson data. A significant reduction of the PDF uncertainties is observed in the fit which includes the Tevatron W- and Z-boson measurements, in particular for the $d$-valence quark.

The impact of the Tevatron W- and Z-boson measurements on the CT10nlo and MMHT2014 sets is assessed by profiling. The uncertainties of the CT10nlo PDFs are scaled to 68% confidence limit. The compatibility of the Tevatron data with the CT10nlo, MMHT2014 and NNPDF3.0 sets is tested by evaluating the $\chi^2$ function of Eq. (1). The partial $\chi^2$ per number of points of each of the Tevatron data set, and the total $\chi^2$ / dof, are close to unity for all the PDFs.

The CT10nlo and MMHT2014 PDFs are profiled to the Tevatron W- and Z-boson data. The results of the profiling on the relative uncertainty of the $d$-valence PDF are shown in Fig. 3. Significant reduction of the uncertainty is observed for both sets.

Tables of the Tevatron measurements, with updated correlation model, and corresponding APPLGRID theoretical predictions are publicly available at herafitter.org.

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Figure 2: (a) PDFs at the starting scale $Q^2 = 1.7$ GeV$^2$ as a function of Bjorken-$x$ for $d_v$ determined with a fit to the HERA I data (blue), and with a fit to the HERA I and Tevatron $W$- and $Z$-boson data (yellow). (b) Relative PDF uncertainties.

Figure 3: Relative uncertainties of the $d$-valence PDF at the scale $Q^2 = 1.7$ GeV$^2$ as a function of Bjorken-$x$ before and after profiling for the (a) CT10nlo and (b) MMHT2014 PDFs.
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