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Strange sea determination from collider data

S. Alekhin [a,b,*], J. Blümlein [c], S. Moch [a]

[a] II. Institut für Theoretische Physik, Universität Hamburg, Luruper Chaussee 149, D-22761 Hamburg, Germany
[b] Institute for High Energy Physics, 142281 Protvino, Moscow region, Russia
[c] Deutsches Elektronensynchrotron DESY, Platanenallee 6, D-15738 Zeuthen, Germany

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ABSTRACT

We consider determinations of the strange sea in the nucleon based on QCD analyses of data collected at the LHC with focus on the recent high-statistics ATLAS measurement of the $W^\pm$- and Z-boson production. We study the effect of different functional forms for parameterization of the parton distribution functions and the combination of various data sets in the analysis. We compare to earlier strange sea determinations and discuss ways to improve them in the future.

1. Introduction

The precise knowledge of the light-quark content of proton is very important for phenomenological studies at the Large Hadron Collider (LHC). QCD analyses of data from colliders and fixed-target experiments make this information available through the parton distribution functions (PDFs), which nowadays are accurate to next-to-next-to-leading order (NNLO) in perturbation theory [1]. It has been shown [2], that the recent LHC data on $W^\pm$- and Z-boson production provide valuable constraints on the light-quark distributions for up, down and strange and help to improve the flavor separation. Currently, however, the extraction of the strange sea carries the largest uncertainty, which, for instance, plays a crucial role in the precision of the recent M_W-mass measurement by the ATLAS experiment [3]. It is therefore of particular importance to pin down the strange sea determination to better accuracy.

Such an improvement can be achieved with the $W^\pm \to l^\pm \nu$ and $Z \to l^+l^-$ cross section measurements of the ATLAS experiment [4]. However, the ATLAS analysis, which has been published as the so-called epWZ16 set of PDFs [4], has obtained a strange-quark sea of a size comparable to the non-strange-quark ones in the kinematic range of Bjorken $x \sim 0.01$. In this way, ATLAS has confirmed with better accuracy its earlier results [5] based on a smaller data sample [6]. An enhancement of the strange-sea was reported by ATLAS also in an analysis of its data on the associated production of $W^\pm$-bosons and a charm-quark [7], which were well described by its epWZ12 PDF set published in Ref. [5]. On the other hand, an analysis including the $W^\pm +$ charm data collected by the CMS experiment [8] does not show any such strange sea enhancement [9].

In a wider context, this situation is problematic, because the ATLAS results also disagree with the strange sea PDFs extracted from other processes. First of all, there is data on charm-quark production in the neutrino-induced deep-inelastic scattering (DIS) off nucleons. This process, initially measured with a good accuracy by the CCFR and NuTeV experiments at Tevatron [10], was later studied with an even better accuracy by the NOMAD experiment at CERN's SPS collider [11]. All three experiments prefer a stronger suppression of the strange sea as compared to the ATLAS one [15]. Moreover, the ATLAS findings of an almost perfect flavor SU(3) symmetry among the three light sea quark distributions have not been confirmed in global fits of PDFs, as reviewed for instance in [1].

The present paper aims at clarifying these discrepancies and at consolidating the different strange sea determinations. For this purpose we use the global ABMP16 PDF fit [2] as a framework. We consider variants of the ABMP16 fit with different shapes for the functional form of the PDF parameterization at the initial scale of the fit as used by ATLAS and in the ABMP16 analyses. We also consider combinations of different sets of data from colliders and fixed-target experiments. In this way we can separate the impact of different effects on the strange sea determination and localize the origin of discrepancies.

2. Shape of PDF parameterizations

The ABMP16 analysis [2] is performed at NNLO accuracy in QCD and the PDF extraction is based on inclusive DIS and Drell–Yan

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[*] Corresponding author.
E-mail address: sergey.alekhin@desy.de (S. Alekhin).

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(DY) data supplemented by data on the DIS- and hadro-production of heavy quarks. In the ABMP16 fit, the PDFs are parameterized at a starting scale $\mu_0^2 = 9$ GeV^2 for the QCD evolution in a scheme with $N_F = 3$ light flavors as follows

$$\begin{aligned} xq_v(x, \mu_0^2) &= \frac{2\delta_{qu} + \delta_{qd}}{N_q^v} (1-x)^{b_{qv}} x^{a_{qv} P_{qv}(x)} , \\ xq_s(x, \mu_0^2) &= A_{qs} (1-x)^{b_{qs}} x^{a_{qs} P_{qs}(x)} , \\ xg(x, \mu_0^2) &= A_g (1-x)^{b_g} x^{a_g P_g(x)} , \end{aligned} \tag{1}$$

with the valence quark distributions (q_v for $q = u, d$), the sea quark distributions (q_s for $q = u, d, s$), assuming $q_s(x, \mu_0^2) = \bar{q}_s(x, \mu_0^2)$, and the gluon. The functional form of the PDFs is controlled by the exponents a_p and b_p and the functions $P_p(x)$ of the form

$$P_p(x) = (1 + \gamma_{-1,p} \ln x) \left(1 + \gamma_{1,p} x + \gamma_{2,p} x^2 + \gamma_{3,p} x^3\right) , \tag{2}$$

where $p = qv, qs, g$. The normalizations N_q^v and A_g in Eq. (1) have been determined from the fermion number and momentum conservation sum rules and $\delta_{qq'}$ denotes the Kronecker symbol. All other 25 parameters A_{qs}, a_p, b_p and γ_p are fitted to the data. A charge-symmetric ansatz is taken for the strange sea quark distributions at the starting evolution scale, i.e. $q_{\bar{s}}(x, \mu_0^2) = q_s(x, \mu_0^2)$ since no clear signal of such an asymmetry was found in the global PDF fits [12,13]. At larger scales a non-zero charge asymmetry appears due to NNLO corrections to the QCD evolution, however, the magnitude of this effect is well below the accuracy of the data analyzed [14]. The heavy-quark distributions with $N_F = 5$ flavors, which are employed in the computations of the DY cross sections, are generated from the ones with $N_F = 3$ using the QCD matching relations in the $\overline{\text{MS}}$-scheme. As a standard ansatz for the matching scales for the 4- and 5-flavor PDFs, we take masses of the c-quark m_c and the b-quarks m_b, respectively, with the values of $m_{c,b}$ determined in our fit, cf. Ref. [2] for details.

It has been checked in the ABMP16 fit, that Eq. (2) allows for sufficient flexibility of the PDFs in the entire range of Bjorken-x covered by the data which are included into the fit.

In contrast, the analysis of the ATLAS $W^\pm \to l^\pm \nu$ and $Z \to l^+ l^-$ cross section measurements for the extraction of the epWZ16 PDFs [4] at NNLO in QCD has used a much restricted set of data. ATLAS only includes its own data on $W^\pm$- and Z-production in combination with DIS data from the HERA collider. The epWZ16 PDFs are derived from the following parameterizations at the starting scale $\mu_0^2 = 1.9$ GeV^2,

$$\begin{aligned} xu_v(x, \mu_0^2) &= A_{u_v} x^{B_{uv}} (1-x)^{C_{uv}} (1 + E_{u_v} x^2) , \\ xd_v(x, \mu_0^2) &= A_{d_v} x^{B_{dv}} (1-x)^{C_{dv}} , \\ x\bar{u}(x, \mu_0^2) &= A_{\bar{u}} x^{B_{\bar{u}}} (1-x)^{C_{\bar{u}}} , \\ x\bar{d}(x, \mu_0^2) &= A_{\bar{d}} x^{B_{\bar{d}}} (1-x)^{C_{\bar{d}}} , \\ xg(x, \mu_0^2) &= A_g x^{B_g} (1-x)^{C_g} - A'_g x^{B'_g} (1-x)^{C'_g} , \\ x\bar{s}(x, \mu_0^2) &= A_{\bar{s}} x^{B_{\bar{s}}} (1-x)^{C_{\bar{s}}} , \end{aligned} \tag{3}$$

for $N_F = 3$ light flavors, and assuming $s = \bar{s}$ for the strange sea. Again, the sum rules for fermion number and momentum conservation determine the normalizations A_g, A_{u_v} and A_{d_v}. In addition, the parameter $C'_g = 25$ is fixed by hand to a large value and the assumption of iso-spin symmetry at small x, i.e., $\bar{u} = \bar{d}$ as $x \to 0$ is invoked to set $A_{\bar{u}} = A_{\bar{d}}$ and $B_{\bar{u}} = B_{\bar{d}}$. Finally, the strange sea at small x is assumed to be related to the light quark sea, $\bar{u}$ and $\bar{d}$, so that $B_{\bar{s}} = B_{\bar{d}} = B_{\bar{u}}$ is put by hand. For these assumptions there is neither theoretical evidence nor are they indicated by fits using more general parameterizations, as will be shown below. This leaves a total of 15 variables in Eq. (3) to be determined from data. The PDF shape Eq. (3) is motivated by the predecessors of the epWZ16 analysis, the PDF fits of HERAPDF family, which are based exclusively on HERA data and therefore have to impose several constraints on the PDF shapes in kinematic regions of Bjorken-x, which are not sufficiently covered by the HERA data.

In order to check the consistency of the assumptions underlying the epWZ16 PDFs with the data at large Bjorken-x, which commonly constrain the PDFs in global analyses we perform a test variant of the ABMP16 fit using the PDF shapes of Eq. (3). In addition, the collider data from the LHC and Tevatron on rapidity distributions for $W^\pm$- and Z-boson production in the electron- and muon-decay channels as well as for lepton-charge asymmetries (see Tab. 2 in [2]) are replaced by data for DIS off deuterons (see Tab. 3.2 in [16]). The latter had been omitted in the ABMP16 fit since they require taking into corrections for the nuclear effects in the deuteron target, which bring in an additional source of uncertainty. In the meantime, though, the PDFs extracted with deuteron DIS data included and using the shape of deuteron corrections suggested by the off-shellness model of Kulagin–Petti [17] have been shown to be in agreement with the ones preferred by the $W^\pm$- and Z-boson collider data [18]. Therefore, the deuteron DIS data allow to obtain a reliable constraint on the light-quark PDFs (u, d) in the range $x \gtrsim 0.01$. This approach avoids the tedious computation of predictions for the lepton rapidity distributions in $W^\pm$- and Z-boson production with account of kinematic cuts by means of fully differential codes, like `FEWZ` (version 3.1) [19,20]. Thus, the use of deuteron DIS data leads to a fast and efficient fit, since the relevant DIS cross sections are evaluated at NNLO in QCD with the code `OPENQCDRAD` (version 2.1) [21].

For the purpose of comparison we also consider the variant of fit with the same data selection and the ABMP16 shape for the PDFs in Eq. (1). The notations used throughout the paper to present results of these two variants are the following:

ABMP16 shape – a fit referring to the $W^\pm$- and Z-boson collider data replaced by deuteron DIS data and the PDF shape of Eq. (1),
epWZ16 shape – the same but with the PDF shape of Eq. (3).

In Fig. 1 we show the results of these test fits for the strangeness suppression factor

$$r_s(x, \mu^2) = \frac{s(x, \mu^2) + \bar{s}(x, \mu^2)}{\bar{d}(x, \mu^2) + \bar{u}(x, \mu^2)} \tag{4}$$

and the sea-quark iso-spin asymmetry

$$I(x, \mu^2) = \frac{\bar{d}(x, \mu^2) - \bar{u}(x, \mu^2)}{\bar{d}(x, \mu^2) + \bar{u}(x, \mu^2)} . \tag{5}$$

The comparison of the nominal ABMP16 fit in Fig. 1 with the variant ***ABMP16 shape*** shows good compatibility of both quantities in the range $x \gtrsim 0.01$. This confirms the capability of deuteron data to replace the DY ones in the present study. However, at smaller values $x \lesssim 0.01$, the uncertainty both in the iso-spin asymmetry $I(x)$ and in the strangeness suppression $r_s(x)$ increases significantly in the variant ***ABMP16 shape***. This happens due to flexibility of the PDF parameterization Eq. (1) at small x, which is determined in the nominal ABMP16 fit by the collider DY data relevant for this kinematics and lacks such constraints in the ***ABMP16 shape*** fit.

In contrast, for the ***epWZ16 shape*** variant of fit with the PDF parameterization of Eq. (3) the strange sea is enhanced, rising to about $r_s \sim 0.8$ in the region $x \simeq 0.1$. It is worth stressing that no ATLAS data is used in this case. It is also interesting that the statistical quality of the neutrino-induced DIS charm-production data