Update of the global fit of PDFs including the low-$Q$ DIS data

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We perform the next-to-next-leading-order (NNLO) QCD global fit of PDFs using inclusive charged-lepton and neutrino DIS data down to $Q = 1$ GeV. We also consider the data on neutrino-nucleon dimuon production, that allows us to disentangle the strange sea distribution. The fit results in $\chi^2/NDP = 5150/4338 = 1.2$ that demonstrates a good consistency of the data sets used in analysis. The resulting value of $\alpha_s(M_Z) = 0.1136 \pm 0.0007$ (exp.) is in a good agreement with the previous version of the fit with a more stringent cut on $Q$. This analysis allows us to improve the accuracy of PDFs. The HT terms of the neutrino-nucleon structure functions $F_2$ and $xF_3$ are determined, the former is found to be consistent with one for the charged-leptons if the charge factor is taken into account.

A check of the existing deep-inelastic scattering (DIS) data at low values of the transferred momentum $Q$ is necessary ingredient of a parton distribution functions (PDFs) fit. In principle, the concept of PDFs is applicable only at asymptotically big values of $Q$, where the QCD factorization is proved, while in the limit of small $Q$ it breaks due to the power corrections, which include the target mass effects and the dynamical high-twist (HT) contribution. Poor theoretical understanding of the latter does not allow to estimate the region of $Q$, where the power corrections can be neglected, from the first principles; only phenomenological studies can separate effect of the HT terms. Earlier we have used the low-$Q$ DIS charged-leptons data in the global fit of parton distribution functions (PDFs) and found that these data can be well described in the NNLO of pQCD with account of the target mass corrections and additional twist-4 terms down to $Q = 1$ GeV

Figure 1: Upper panel: The $1\sigma$ band of the twist-4 term in the neutrino-nucleon SF $F_2$ (solid lines) compared to one for the charged lepton DIS (dashes). Lower panel: The same for the neutrino-nucleon SF $xF_3$.

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fit independently, by the smooth functions of general form, agree within the experimental errors.

For further study of the HT terms in the DIS SFs we add to the fit of Ref.[2] the inclusive (anti)neutrino-nucleon DIS data by the CHOURUS collaboration [3], down to $Q = 1 \text{ GeV}$ as well. For the case of neutrino-nucleon DIS we have to take into account 3 additional independent HT terms, $H_{\nu 2}^T$, $H_{\nu 3}^T$, and $x F_3$, respectively. These three terms cannot be disentangled using only the CHORUS data therefore we impose constraint $H_{\nu 2}^T = H_{\nu 3}^T$ motivated by the results obtained for the twist-4 terms in the charged-leptons SFs. We also assume that the HT terms are equal for the neutrino and anti-neutrino SFs. The $x$-dependence of $H_{\nu 2}^T$ and $H_{\nu 3}^T$ obtained under these assumptions is given in Fig.1. The former is in a good agreement with $H_{l 2}^T$ obtained for the charged-leptons SFs scaled with the charge factor of $5/18$. This remarkable regularity is in favor of the dynamical nature of these terms. In practice, this can also be used to evaluate the HT terms for SFs for the neutral current neutrino-nucleon DIS, which are experimentally poorly known. The value of $H_3$ is basically negative, its integral over $x$ is $-0.084\pm0.033/(Q^2(\text{GeV}^2))$ that is in agreement with the early theoretical estimate of Ref.[4]. Earlier $H_3^\nu$ was also determined phenomenologically, in the NNLO QCD fit of Ref.[5]. Since that fit is based only on the data on $xF_3$ the errors in $H_{\nu 3}^T$ obtained in Ref.[5] are quite big therefore comparison with those results is inconclusive.

We also check impact of the data on dimuon production in the neutrino-nucleon scattering by the CCFR and NuTeV collaborations [6] adding these data to the fit of Ref.[7]. This input allows to constrain the strange quark distribution in the interval of $x = 0.01 \div 0.3$ that improves separation of the sea quarks distribution by flavors and eventually reduces the errors in PDFs extracted from the global fit. The $O(\alpha_s)$ (NLO QCD) corrections of Ref.[8] to the neutrino-nucleon charm production were taken into account. The HT contribution to the dimuon cross section was not included. Once we try to add the HT terms, which are observed in the inclusive SFs with account of the corresponding charge factors, results of the fit do not change. For this reason we include into the fit dimuon data with $Q$ down to 1 GeV, as in the case of inclusive cross sections. Traditionally, magnitude of the strange sea is described by the strange sea suppression factor $\kappa$ equal to the ratio of momentum carried by the strange quarks to the non-strange one. The value of $\kappa$ obtained in our fit with the dimuon CCFR/NuTeV data included is given in Fig.2. This value is bigger than ones obtained in the NLO QCD fit of Ref.[9] based on the CCFR data and in the LO fit of Ref.[10] based on the CCFR/NuTeV data (0.48 and some 0.42 at $Q^2 = 20 \text{ GeV}^2$, respectively).
Tracing this difference we found that it stems due to the non-strange sea in the PDFs set BGPAR used in Refs. [9,10] is enhanced as compared to our results and other modern PDFs parameterizations. For the LO fit of Ref. [10] the difference with our result is more significant since account of the NLO corrections leads to increase of the fitted magnitude of the strange sea. The values of $\kappa$ calculated using the CTEQ6 [11] and MSTW06 [12] PDFs sets are in agreement to our determination, the former is some smaller and the latter is some bigger than ours, but in both cases the difference is within the uncertainty in $\kappa$.

The dominant source of this uncertainty is due to the error in the charm quark semileptonic branching ratio $B_c$. The value of $B_c$ depends on the charmed hadrons production fractions in the neutrino-nucleon scattering, which are not known very well and, through these fractions, depends on the beam energy. For the beam energy typical for the CCFR and NuTeV experiments the value of $B_c$ was estimated in Ref. [13] using the charm fractions by the Fermilab experiment E531 [14] and the charmed hadrons branching ratios measured in the $e^+e^-$ experiments. With updated values of the charmed hadrons branching ratios [15] we obtain the value $B_c = 0.0886(57)$. We fit $B_c$ to the dimuon data simultaneously with the strange sea and we get a value of 0.089(7), which is in a good agreement to both estimates. The beam energy dependence of $B_c$ in the kinematic region covered by the CCFR/NuTeV data is found to be inessential for our fit. The fitted slope of $B_c$ on the beam energy is well consistent with zero within the errors.

The value of strange/anti-strange ($s/s\bar{s}$) sea symmetry we obtain is given in Fig. 2. If we include the NuTeV dimuon data only it is in agreement to one determined by the NuTeV collaboration from the NLO QCD analysis of their data [16]. The value of this asymmetry we obtain using the CCFR data only is also qualitatively consistent with one observed in the LO QCD fit of Ref. [10] (impact of the QCD correction on the asymmetry is marginal and does not affect the comparison). Averaging of these two results gives the asymmetry consistent with zero since the NuTeV and CCFR determinations are comparable in magnitude, but have different sign. Despite we do not set the constraint on the net strangeness in the nucleon, the resulting integral of $s/s\bar{s}$ asymmetry is 0.0011(13), i.e. comparable to zero; in the variant of fit with the net strangeness set to 0, the value of $\chi^2$ gets bigger nothing but by 1. This disagrees with the results of two other groups [17, 18], who observe positive $s/s\bar{s}$ asymmetry at $x \sim 0.2$ with statistical significance of about 2$\sigma$. In this context one can note that the resulting $s/s\bar{s}$ asymmetry is rather small, and, therefore, sensitive to subtle details of the fit: the specific value of $B_c$, the treatment of nuclear corrections, the choice of the cut on $Q$. Each of these factors can change the resulting value of $s/s\bar{s}$ by
about 0.01, and the combinations of them, in principle, can explain the difference with the results of Refs.\[17\]\[18\].

Combining the inclusive CHORUS data and the CCFR/NuTeV dimuon data with the data set used in the analysis of Ref.\[2\], we perform the global fit of PDF with the extraction of the HT terms in the charged-leptons and neutrino-nucleon inclusive DIS. In this fit, the total value of $\chi^2/\text{NDP} = 5150/4338 = 1.2$, which is somewhat bigger than the ideal value of 1. However, if we rescale the errors in data of the separate experiments, which have $\chi^2/\text{NDP} > 1$, in order to bring them to 1, and then recalculate the errors in PDFs, the change in these errors is moderate, factor of 1.2 at most. Thus the data are in satisfactory consistency with no need of the big overall rescaling of the errors for all data sets. The PDF accuracy improved as compared to PDFs of Ref.\[2\], because of additional experimental input. The typical errors in PDFs are $O(1\%)$ at $x \lesssim 0.1$. At larger values of $x$ the errors are bigger with the gluon distribution especially uncertain. The extracted value of $\alpha_s(M_Z) = 0.1136 \pm 0.0007\,(\text{exp.})$ is in a good agreement with the result of the fit of Ref.\[2\], in which a more stringent cut on $Q$ was applied. This justifies the use of the NNLO QCD analysis combined with the twist expansion down to $Q = 1$ GeV. Therefore, the PDFs, extracted in our fit, are relevant for the low-energy studies. A small experimental error in $\alpha_s$ in our fit is because of the impact of the low-$Q$ data, which are very sensitive to the details of the QCD evolution. On the other hand, the theoretical error rises at small values of $Q$, due to the variation of QCD scales. This becomes the dominant source of the uncertainty in $\alpha_s$, and, in order to reduce it, a consistent account of higher-order QCD corrections is necessary.

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