Strange and Anti-strange Sea Distributions from $\nu N$
Deep Inelastic Scattering

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We perform QCD fit of the nucleon strange and anti-strange sea distributions to the neutrino and anti-neutrino dimuon data by the CCFR and NuTeV collaborations, supplemented by the inclusive charged lepton-nucleon Deep Inelastic Scattering (DIS) and Drell-Yan data. The effective semi-leptonic charmed-hadron branching ratio is constrained from the inclusive charmed hadron measurements performed by the FNAL-E531 and CHORUS neutrino emulsion experiments as $B_\mu = (8.8 \pm 0.5)\%$. We obtain a strange sea suppression factor $\kappa(20 \text{ GeV}^2) = 0.62 \pm 0.04(\text{exp.}) \pm 0.03(\text{QCD})$. An $x$-distribution of total strange sea obtained in the fit is slightly softer than the non-strange sea, and an asymmetry between strange and anti-strange quark distributions is consistent with zero (integrated over $x$ it is equal to $0.0013 \pm 0.0009(\text{exp.}) \pm 0.0002(\text{QCD})$ at the scale of $20 \text{ GeV}^2$).

At Bjorken variable $x \lesssim 0.2$ the strange quarks give important contribution to the total quark sea in the nucleon. Therefore accurate determination of the strange sea is necessary for interpretation of the precise hadron-collider and fixed-target experimental data. In particular, the presence of a small positive $s - \bar{s}$ asymmetry in the nucleon may explain recent anomalous result on the weak mixing angle in the NuTeV experiment [3]. The best constraint on the strange sea comes from the DIS neutrino-nucleon dimuon production. This process stems from the charged-current production of the charm quark decaying semileptonically with a secondary muon in the final state. This mechanism is particularly sensitive to the strange quark distributions, as the contribution from non-strange quarks are greatly suppressed due to smallness of the corresponding Cabibbo-Kobayashi-Maskawa (CKM) matrix elements. This allows to disentangle the strange distribution from other quarks in the global PDF fit, which includes the dimuon data.

We extract the strange distribution from the dimuon data by the CCFR and NuTeV experiments [4, 5]. Those data were collected in the runs with the neutrino and anti-neutrino beams and allow separate determination of the strange and anti-strange distributions at $0.01 \lesssim x \lesssim 0.3$ and the values of the momentum transfer $1 \text{ GeV}^2 \lesssim Q^2 \lesssim 200 \text{ GeV}^2$. In order to consistently account for the contribution from other quarks and gluons, the dimuon data are supplemented by the inclusive DIS data and the fixed-target Drell-Yan data (cf. Ref. [7] for details of the data selection). The analysis is performed with account of the NNLO correction to the parton evolution [8] and the massless coefficient functions [9].

The heavy-quark DIS production is calculated in the 3-flavour factorization scheme with the perturbative corrections up to the NLO [10]. The latter are illustrated in Figure 1 for the representative kinematics of the data used in the fit and the factorization scale $\mu = \sqrt{Q^2 + m_c^2}$.
where $m_c$ is the charm quark mass. At small $x$ the NLO corrections of Ref. [10] reduce the value of calculated cross sections therefore they increase the strange distributions extracted from the data. Corrections for nuclear effects in the neutrino-nucleon DIS, which include the Fermi motion and binding, neutron excess and shadowing, nuclear pion excess and the off-shell effects [11] are also taken into account in our analysis. The value of nuclear corrections depends on the beam type (cf. Figure 1), therefore they affect the charge asymmetry in the strange distribution $x [s(x) - \bar{s}(x)]$. Other details of the analysis including treatment of the data and their uncertainties can be found elsewhere [12].

Assuming universality of the charmed hadron fragmentation function, the dimuon production cross section is related to the charm production cross section as follows

$$\frac{d\sigma_{\mu\mu}(E_{\mu} > E_{\mu}^0)}{dx dy} = \eta_{\mu} B_{\mu} \frac{d\sigma_{\text{charm}}}{dx dy},$$

(1)

where $y$ is inelasticity, $\eta_{\mu}$ is the acceptance correction accounting for the cut $E_{\mu} > E_{\mu}^0$ imposed on the muon energy to reject background, and $B_{\mu}$ is the effective semileptonic charm quark branching ratio. The value of $B_{\mu} = \sum f_h Br(h \rightarrow \mu X)$, where $f_h$ and $Br(h \rightarrow \mu X)$ are the rate and the semileptonic branching ratio of the charmed hadron $h$ produced in the (anti)neutrino-nucleon scattering, respectively; $h = D^0, D^+, D_s^+, \Lambda^c$. The value of $B_{\mu}$ depends on the beam type and energy, due to $f_h$. For kinematics of the NuTeV and CCFR experiments a value of $B_{\mu} = (9.19 \pm 0.94)\%$ averaged over neutrino and antineutrino beams was obtained in Ref. [13] using the charmed hadron fractions measured by the Fermilab-E-531 experiment. In our analysis we fit the value of $B_{\mu}$ simultaneously with the PDF parameters. In this case the strange quark distributions are constrained by the $Q^2$-slope of the dimuon cross sections, which depend on the strange sea magnitude due to the PDF evolution, and the value of $B_{\mu}$ is constrained by the magnitude of the cross.
sections. This approach provides a consistent determination of $B_{\mu}$ and allows to check the beam- and energy-dependence of $B_{\mu}$ for the kinematics of experiments used in the fit.

We do not observe statistically significant beam- and energy-dependence of $B_{\mu}$. The averaged over beam type and energy value of $B_{\mu} = (9.1 \pm 1.0)\%$ obtained in our fit is in good agreement with the result of Ref. [13]. The value of $B_{\mu}$ is anti-correlated with the magnitude of the strange sea, therefore an additional constraint on $B_{\mu}$ can improve the strange sea determination. The value of $B_{\mu}$ obtained in Ref. [13] does not provide efficient constraint since its uncertainty is consistent with the corresponding uncertainty in our fit. The uncertainty in $B_{\mu}$ can be reduced by utilizing the results of the recent measurement of the charmed hadron fractions by the CHORUS experiment [14,15] as well as the updated determination of the semileptonic branching ratios Ref. [16]. The value of $B_{\mu}$ obtained with these inputs is given in Table 1. The uncertainty of this determination is about factor of 2 smaller than that of Ref. [13] and the central value of $B_{\mu}$ is somewhat lower (cf. Table 1.). In the variant of our fit with the constraint of Table 1 for the beam energy cut $E_{\nu} > 30$ GeV, the central values of the strange and antistrange distributions are smaller, correspondingly. In this fit the uncertainty in the $C$-even combination $x(s(x) + \bar{s}(x))/2$ is about factor of 2 smaller than for the fit with no constraint on $B_{\mu}$ (cf. Figure [2]). For the $C$-odd combination $x(s(x) - \bar{s}(x))$, the effect of the

![Figure 2: The ±1σ uncertainties in the $C$-even (left panel) and $C$-odd (right panel) combination of the strange sea distributions determined in our fit with (solid lines) and without (dashed lines) the constraint on $B_{\mu}$ at the value of factorization scale $\mu = 3$ GeV. The difference between distributions obtained in these two variants of the fit is shown by the dashed-dotted lines.](image-url)
constrained $B_\mu$ is weaker because of a partial cancellation in the difference.

In the fit with the constrained $B_\mu$, we obtain the values of $\chi^2/NDP$ of 63/89 and 38/89 for the CCFR and NuTeV data sets, respectively. This is statistically consistent with the effective number of degrees of freedom for these experiments introduced in Ref. [5], in order to take into account statistical correlation between the different data points that is roughly twice smaller than $NDP$. The value of the strange sea suppression factor $\kappa$, which is the ratio of sum of momentum carried by the strange and anti-strange quarks to the one carried by the sea up- and down-quarks, is given in Figure 3. Due to the QCD evolution the value of $\kappa$ rises with the factorization scale $\mu$. The value of $\kappa(20 \text{ GeV}^2) = 0.48^{+0.06}_{-0.05}$ was obtained in the NLO fit of Ref. [4] based on the CCFR dimuon data. In our fit we get a bigger value, $\kappa(20 \text{ GeV}^2) = 0.62 \pm 0.04$. This is because the non-strange sea distribution used in Ref. [4] is not consistent with the distribution of the present fit as well as with other modern PDF sets [17, 18]. Our value of $\kappa$ is somewhat smaller than the value for the MSTW08 PDFs set of Ref. [17] and is somewhat bigger than one for the CTEQ6 PDFs set of Ref. [18]. In both cases, however, the discrepancy is within uncertainty in our determination of $\kappa$, which is obtained from propagation of the statistical and systematical errors in the data with the account of correlations. As can be seen from Figure 3, the C-even strange sea is somewhat steeper than the non-strange sea and at small $x$ overshoots the latter. At $x \lesssim 0.2$ the strange sea is enhanced due to the NLO corrections to the charm production coefficient functions. Were these corrections dropped, we obtain the value of $\kappa(20 \text{ GeV}^2) = 0.55 \pm 0.13$. The uncertainty in $\kappa(20 \text{ GeV}^2)$ due to the higher-order QCD corrections, estimated as the change due to variation of the dimuon cross section factorization scale from $\sqrt{Q^2 + m_c^2}$ to $Q$, is 0.03. This is comparable to the experimental uncertainty in $\kappa$. In this sense the theoretical and experimental uncertainties in our determination of $\kappa$ are balanced, and, in order to further improve it, more experimental data are needed and the NNLO QCD corrections have to be taken into account.

In a variant of our fit with only the NuTeV dimuon data, the strangeness charge asymmetry is somewhat positive. This is consistent with the results of the NLO analysis of Ref. [6]. The CCFR data prefer somewhat negative asymmetry and the result averaged over these two experiments is consistent with 0 in a wide range of $\mu$, even despite it rises with $\mu$ due to the NNLO corrections to the PDF evolution [19]. Furthermore, if we fix the strange sea asymmetry at 0, the value of $\chi^2$ rises by about 1 unit only. For the fit based on the combined NuTeV and CCFR dimuon data we obtain $S^- = \int_0^1 x[s(x) - \overline{s}(x)]dx = 0.0013 \pm 0.0009$ at $\mu^2 = 20 \text{ GeV}^2$, that is also consistent with 0 within the uncertainties. The theoretical uncertainty in $S^-$ due to the factorization scale variation is 0.0002, much smaller than both the experimental uncertainty and the theoretical uncertainty in $\kappa$.

In summary, we obtain the strange sea suppression factor $\kappa(20 \text{ GeV}^2) = 0.62 \pm 0.04(\text{exp.}) \pm 0.03(\text{QCD})$, the most precise value available. The $x$-distribution of the total strange sea is slightly softer than the non-strange one, and the integral strange sea charge asymmetry $S^-(20 \text{ GeV}^2) = 0.0013 \pm 0.0009(\text{exp.}) \pm 0.0002(\text{QCD})$ is consistent with 0 within uncertainties.

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Figure 3: Left panel: The ±1σ band for the strange sea suppression factor κ with respect to the factorization scale µ as obtained in our analysis (solid lines) in comparison with ones for the MSTW08 (dashes) and CTEQ6 (dots) PDF sets. Right panel: The ±1σ band for the C-even combination of the strange sea distributions determined in our fit (solid lines) compared to the non-strange one scaled by κ (dashes) at µ = 3 GeV.

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