Quark Asymmetries in Nucleons

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Abstract. We have developed a physical model for the non-perturbative x-shape of parton density functions in the proton, based on Gaussian fluctuations in momenta, and quantum fluctuations of the proton into meson-baryon pairs. The model describes the proton structure function and gives a natural explanation of observed quark asymmetries, such as the difference between the anti-up and anti-down sea quark distributions and between the up and down valence distributions. We also find an asymmetry in the momentum distribution of strange and anti-strange quarks in the nucleon, large enough to reduce the NuTeV anomaly to a level which does not give a significant indication of physics beyond the standard model.

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The low-scale parton density functions give a description of the hadron at a non-perturbative level. The conventional approach to these functions is to make parameterizations using some more or less arbitrary functional forms, based on data from deep inelastic scattering and hadron collision experiments. Another approach, however, is to start from some ideas of the behavior of partons in the non-perturbative hadron, and build a model based on that behavior. The advantage with this approach is that the successes and failures of such a model allows us to get insight into the non-perturbative QCD dynamics. The model presented here, and described in detail in [1, 2], describes the F_2 structure function of the proton, as well as sea quark asymmetries of the nucleon. Most noteworthy, our model predicts an asymmetry between the momentum distributions of strange and anti-strange quarks in the nucleon of the same order as the newly reported results from NuTeV [3].

This work extends the model previously presented in [4]. The model gives the four-momentum k of a single probed valence parton (see Fig. 1a for definitions of momenta) by assuming that, in the nucleon rest frame, the shape of the momentum distribution for a parton of type i and mass m_i can be taken as a Gaussian $f_i(k) = N(\sigma_i, m_i)\exp\left\{-\left[(k_0-m_i)^2+k_x^2+k_y^2+k_z^2\right]/2\sigma_i^2\right\}$ which may be motivated as a result of the many interactions binding the parton in the nucleon. The width of the distribution should be of order hundred MeV from the Heisenberg uncertainty relation applied to the nucleon size, *i.e.* $\sigma_i = 1/d_N$. The momentum fraction x of the parton is then defined as the light-cone fraction $x = k_+/p_+$. We impose constraints on the final-state momenta in order to obtain a kinematically allowed final state, which also ensures that $0 < x < 1$. Using a Monte Carlo method these parton distributions are integrated numerically without approximations.

To describe the dynamics of the sea partons, we note that the appropriate basis for the non-perturbative dynamics of the bound state nucleon should be hadronic. Therefore we

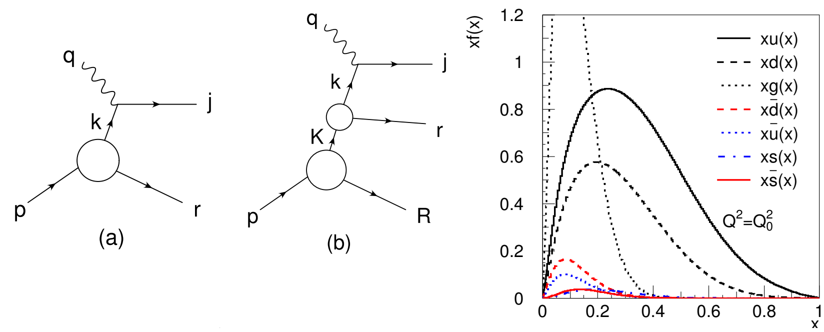

FIGURE 1. Illustration of the processes (a) probing a valence parton in the proton and (b) a sea parton in a hadronic fluctuation (letters are four-momenta). (c) shows the resulting parton distributions at the starting scale Q_0^2.

consider hadronic fluctuations, for the proton

$$|p\rangle = \alpha_0|p_0\rangle + \alpha_{p\pi^0}|p\pi^0\rangle + \alpha_{n\pi^+}|n\pi^+\rangle + \ldots + \alpha_{\Lambda K}|\Lambda K^+\rangle + \ldots \tag{1}$$

Probing a parton i in a hadron H of a baryon-meson fluctuation $|BM\rangle$ (see Fig. 1b) gives a sea parton with light-cone fraction $x = x_H x_i$ of the target proton. The momentum of the probed hadron is given by a similar Gaussian, but with a separate width parameter σ_H. Also here, kinematic constraints ensure that we get a physically allowed final state. The procedure gives $x_H \sim M_H/(M_B + M_M)$, *i.e.* the heavier baryon gets a harder spectrum than the lighter meson. The normalization of the sea distributions is given by the amplitude coefficients α_{BM}^2 of Eq. (1). These cannot be calculated from first principles in QCD and are therefore taken as free parameters to be fitted using experimental data.

The resulting valence and sea parton x-distributions apply at a low scale Q_0^2, and the distributions at higher Q^2 are obtained using perturbative QCD evolution at next-to-leading order.

The model has in total four shape parameters and three normalization parameters, plus the starting scale, to determine the parton densities u, d, g, $\bar{u}$, $\bar{d}$, s, $\bar{s}$. These are (with values resulting from fits to experimental data as described below):

$$\begin{array}{cccc} \sigma_u = 230\text{ MeV} & \sigma_d = 170\text{ MeV} & \sigma_g = 77\text{ MeV} & \sigma_H = 100\text{ MeV} \\ \alpha_{p\pi^0}^2 = 0.45 & \alpha_{n\pi^+}^2 = 0.14 & \alpha_{\Lambda K}^2 = 0.05 & Q_0 = 0.75\text{ GeV} \end{array} \tag{2}$$

The resulting parton densities are shown in Fig. 1(c).

In order to fix the values of the model parameters, we make a global fit using several experimental data sets: Fixed-target F_2 data to fix large-x (valence) distributions (Fig. 2a); HERA F_2 data for the gluon distribution width and the starting scale Q_0^2; $\bar{d}/\bar{u}$-asymmetry data for the normalizations of the $|p\pi^0\rangle$ and $|n\pi^+\rangle$ fluctuations (Fig. 3); and strange sea data to fix the normalization of fluctuations including strange quarks (Fig. 4a). We have also compared with $W^\pm$ charge asymmetry data as a cross-check on the ratio of Gaussian widths for the u and d valence quark distributions (Fig. 2b). It is interesting to note that this simple model can describe such a wealth of different data with just one or two parameters per data set.

In our model, the shape difference between the valence u and d distributions in the proton, apparent from the $W^\pm$ charge asymmetry data, is described as different Gaussian

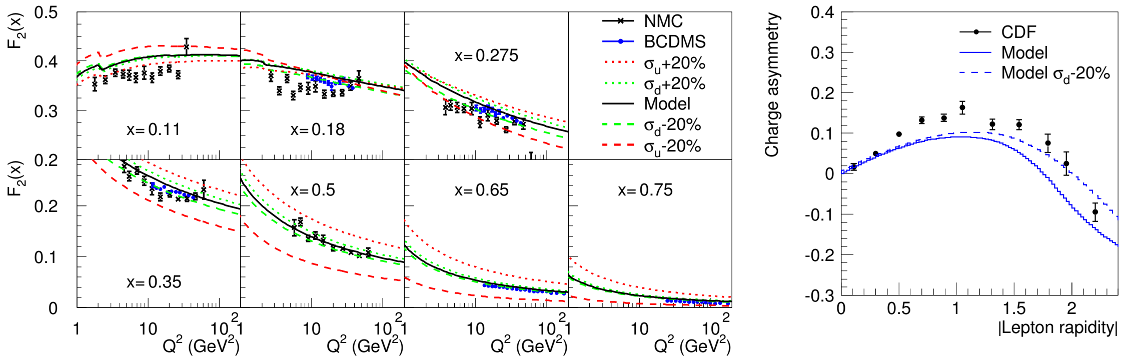

FIGURE 2. Left: The proton structure function $F_2(x,Q^2)$ for large x values; NMC and BCDMS data [5, 6] compared to our model, also showing the results of $\pm 20\%$ variations of the width parameters σ_u and σ_d for the u and d valence distributions. Right: The charge asymmetry for leptons from $W^{\pm}$-decays in $p\bar{p}$ collisions at the Tevatron [7] compared to our model, with best-fit parameters and a 20% reduced width of the valence d quark distribution.

widths. This would correspond to a larger effective volume in the proton for d quarks than for u quarks, an effect which could conceivably be explained by Pauli blocking of the u quarks.

Since the proton can fluctuate to π^0 and π^+ by $|p\pi^0\rangle$ and $|n\pi^+\rangle$, but to π^- only by the heavier $|\Delta^{++}\pi^-\rangle$, we get an excess of $\bar{d}$ over $\bar{u}$ in the proton sea. Interestingly, the fit to data improves when we use a larger effective pion mass of 400 MeV (see Fig. 3). This might indicate that we have a surprisingly large coupling to heavier ρ mesons, or that one should use a more generic meson mass rather than the very light pion.

The lightest strange fluctuation is $|\Lambda K^+\rangle$. If we let this implicitly include also heavier strange meson-baryon fluctuations, we can fit the normalization $\alpha^2_{\Lambda K}$ to strange sea data (see Fig. 4a). The result corresponds to $\int_0^1 (xs+x\bar{s})dx / \int_0^1 (x\bar{u}+x\bar{d})dx \approx 0.5$, in agreement with standard parton density parameterizations. We note that this indicates a normalization $\propto 1/\Delta M_{BM} = 1/(M_B+M_M-M_p)$ rather than the expected $\propto 1/\Delta M^2_{BM}$.

Since the s quark is in the heavier baryon Λ and the $\bar{s}$ quark is in the lighter meson K^+, we get a non-zero asymmetry $S^- = \int_0^1 dx[xs(x) - x\bar{s}(x)]$ in the momentum distribution of the strange sea, as seen in Fig. 4b and 5. Depending on details of the model, we get the range $0.0010 \leq S^- \leq 0.0023$ for this asymmetry.

This is especially interesting in connection to the NuTeV anomaly [9]. NuTeV found, based on the observable $R^- = \frac{\sigma(\nu_\mu N \to \nu_\mu X) - \sigma(\bar{\nu}_\mu N \to \bar{\nu}_\mu X)}{\sigma(\nu_\mu N \to \mu^- X) - \sigma(\bar{\nu}_\mu N \to \mu^+ X)} = g_L^2 - g_R^2 = \frac{1}{2} - \sin^2\theta_W$ a 3σ deviation of $\sin^2\theta_W$ compared to the Standard Model fit: $\sin^2\theta_W^{\mathrm{NuTeV}} = 0.2277 \pm 0.0016$ compared to $\sin^2\theta_W^{\mathrm{SM}} = 0.2227 \pm 0.0004$. However, an asymmetric strange sea would

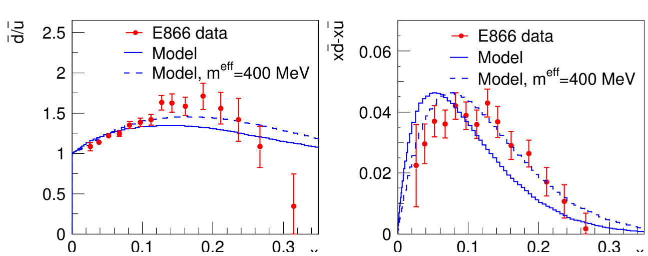

FIGURE 3. Comparison between our model and data from the E866/NuSea collaboration [8]: (a) $\bar{u}(x)/\bar{d}(x)$ (b) $x\bar{d}(x) - x\bar{u}(x)$. The full line uses the physical pion mass, while the dashed line uses an effective pions mass $m^{\mathrm{eff}} = 400$ MeV as discussed in the text.

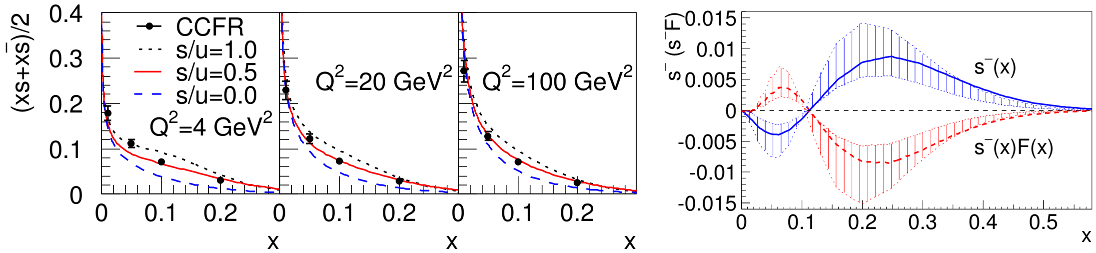

FIGURE 4. Left: CCFR data [10] on the strange sea distribution $(xs(x)+x\bar{s}(x))/2$ compared to our model based on $|\Lambda K\rangle$ fluctuations with different normalizations. Right: The strange sea asymmetry $s^-(x) = xs(x) - x\bar{s}(x)$ (at $Q^2 = 20\,\text{GeV}^2$) from the model and combined with the function $F(x)$ accounting for NuTeV's analysis giving $\Delta\sin^2\theta_W = \int_0^1 dx\, s^-(x)F(x) = -0.0017$. The uncertainty bands correspond to the uncertainties for S^- and $\Delta\sin^2\theta_W$ quoted in the text.

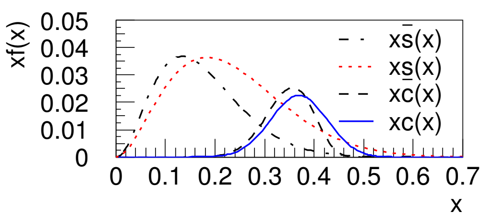

FIGURE 5. Comparison between the strange and charm sea obtained from our model with the inclusion of the $\Lambda_C\bar{D}$ fluctuation. The normalization is here taken to be $\propto 1/(M_B + M_M - M_p)$ as suggested by strange sea data.

change their result, since ν only have charged current interactions with s and $\bar{\nu}$ with $\bar{s}$. Using the folding function provided by NuTeV to account for their analysis, the s-$\bar{s}$ asymmetry from our model gives a shift $-0.0024 \leq \Delta\sin^2\theta_W = \int_0^1 dx\, s^-(x)F(x) \leq -0.00097$, *i.e.* the discrepancy with the Standard Model result is reduced to between 1.6σ and 2.4σ, leaving no strong hint of physics beyond the Standard Model.

We have also considered charmed fluctuations. The lightest charmed baryon-meson fluctuation $|\Lambda_C\bar{D}\rangle$ gives c and $\bar{c}$ distributions as in Fig. 5, where the normalization $\alpha^2_{\Lambda_C D}$ is taken to be $\propto 1/\Delta M_{BM}$, as suggested by the strange sea normalization. However, in order to conform to the EMC F_2^c data at large x, a normalization close to $1/\Delta M^2_{\Lambda_C\bar{D}}$ seems to be enough [11].

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