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Strangeness asymmetry of the nucleon in the statistical parton model

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Abstract

We extend to the strange quarks and antiquarks, the statistical approach of parton distributions and we calculate the strange quark asymmetry $s-\bar{s}$. We find that the asymmetry is small, positive in the low x region and negative in the high x region. In this framework, the polarized strange quarks and antiquarks distributions, which are obtained simultaneously, are found to be both negative for all x values.

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1 Introduction

Although strange quarks and antiquarks s and $\bar{s}$ play a fundamental role in the nucleon structure, they are much less known than the parton distribution functions (PDF) for the light quarks u and d. The measurements of the structure functions in deep inelastic scattering (DIS) of charged leptons on hadrons provide the best informations on u, d, whereas neutrino DIS and lepton-pair production in hadron collisions put some constraints on the sea quark distributions $\bar{u}$ and $\bar{d}$. Concerning the strange quarks, due to the fact that the structure functions are largely dominated by u and d, the extraction of the small components s and $\bar{s}$ is rather difficult. Therefore most of the phenomelogical models for the PDF studies use the simplifying assumption $s(x) = \bar{s}(x) = \kappa(\bar{u} + \bar{d})/2$ (with $\kappa \sim 0.5$). However, nothing prevents $s(x) \neq \bar{s}(x)$ and we will see how to achieve this inequality in the statistical parton model [1, 2, 3, 4].

An experiment on neutrino (antineutrino) -nucleon charged-current DIS by the CCFR collaboration [5] at the Fermilab Tevatron has measured the production of dimuon final states coming from a charm quark fragmentation. This process involves the interaction of a neutrino (antineutrino) with an s ($\bar{s}$) or d ($\bar{d}$) quarks, via a $W^{\pm}$ exchange, which can be used to isolate their distributions. Since the contribution of the down to charm production is Cabibbo suppressed, scattering off a strange quark is responsible for most of the total dimuon rate. Unfortunately, only an average value of $s + \bar{s}$ was extracted from this experiment, but the size of strange quark distribution was known for the first time. Later, the NuTeV collaboration [6] has reached a greater accuracy by a high-statistics dimuon measurement, allowing to study independent information on s and $\bar{s}$ and the difference $s - \bar{s}$.

On the theoretical side one of first attempt to separate the s and $\bar{s}$ distributions was investigated in a light-cone model [7] and more recently, other models based on nonperturbative mechanisms were proposed [8, 9]. A global QCD fit to the CCFR and NuTeV dimuon data has shown a clear evidence that $s \neq \bar{s}$ [10]. In another approach based on perturbative evolution in QCD at three loops [11], one is able to generate a strange-antistrange asymmetry although at the input scale $s = \bar{s}$.

In this Letter, we will show how to construct the strange and antistrange quark distributions in the statistical parton model. Since according to our method, the basic distributions are the helicity dependent ones, $s^{\pm}$ and $\bar{s}^{\pm}$, we will obtain simultaneously the unpolarized, $s = s^{+} + s^{-}$, $\bar{s} = \bar{s}^{+} + \bar{s}^{-}$,

and the polarized PDF, $\Delta s = s^+ - s^-$, $\Delta\bar{s} = \bar{s}^+ - \bar{s}^-$. We will also explain how to determine the few parameters involved. Our results will be compared with other theoretical predictions.

2 Strange quark and antiquark distributions

In the statistical approach the nucleon is viewed as a gas of massless partons (quarks, antiquarks, gluons) in equilibrium at a given temperature in a finite size volume. Like in our earlier work on the subject [1], we propose to use a simple description of the parton distributions $p(x)$ proportional to $[\exp[(x - X_{0p})/\bar{x}] \pm 1]^{-1}$, the *plus* sign for quarks and antiquarks, corresponds to a Fermi-Dirac distribution and the *minus* sign for gluons, corresponds to a Bose-Einstein distribution. Here X_{0p} is a constant which plays the role of the *thermodynamical potential* of the parton p and $\bar{x}$ is the *universal temperature*, which is the same for all partons. Since quarks carry a spin-1/2, it is natural to consider that the basic distributions are $q_i^{\pm}(x)$, corresponding to a quark of flavor i and helicity parallel or antiparallel to the nucleon helicity. From the chiral structure of QCD, we have two important properties which allow to relate quark and antiquark distributions and to restrict the gluon distribution:
- The potential of a quark q_i^h of helicity h is opposite to the potential of the corresponding antiquark $\bar{q}_i^{-h}$ of helicity -h, therefore $X_{0q}^h = -X_{0\bar{q}}^{-h}$.
- The potential of the gluon G is zero $X_{0G} = 0$.
The sum rules, coming from the quantum numbers of the proton, $u - \bar{u} = 2$ and $d - \bar{d} = 1$, give rise to higher values for the potentials of the u's than for the d's. In fact we have found $X_{0u}^+ > X_{0d}^- \sim X_{0u}^- > X_{0d}^+$, which is also consistent with the known facts that $\Delta u(x) > 0$ and $\Delta d(x) < 0$. This ordering leads immediately to some important consequences for the light antiquarks, namely

i) $\bar{d}(x) > \bar{u}(x)$, the flavor symmetry breaking, which also follows from the Pauli exclusion principle, whose effects are incorporated in the statistical model.

ii) $\Delta\bar{u}(x) > 0$ and $\Delta\bar{d}(x) < 0$.

We now turn to the procedure to construct the strange quark distributions. In the original version of the statistical parton model [1] we have assumed that the unpolarized strange quark and antiquark distributions are equal and they can be described by a linear combination of light antiquark

distributions at the input scale Q_0^2, namely

$$xs(x,Q_0^2) = x\bar{s}(x,Q_0^2) = \frac{1}{4}[x\bar{u}(x,Q_0^2) + x\bar{d}(x,Q_0^2)] \ , \tag{1}$$

where the coefficient 1/4 is an average value of some current estimates. For the corresponding polarized distributions a similar assumption was made, more precisely

$$x\Delta s(x,Q_0^2) = x\Delta\bar{s}(x,Q_0^2) = \frac{1}{3}[x\Delta\bar{d}(x,Q_0^2) - x\Delta\bar{u}(x,Q_0^2)] \ , \tag{2}$$

which leads to a large negative distribution, since $\Delta\bar{d} < 0$ and $\Delta\bar{u} > 0$ (See Fig. 18 of Ref. [1]). In order to introduce a difference between s and $\bar{s}$, here we follow the procedure used earlier to built the light quarks PDF, with the recent improvement obtained from the extension to the transverse momentum of the PDF [4]. So the strange quark distributions $s^h(x,Q_0^2)$ of helicity $h = \pm$, at the input energy scale $Q_0^2 = 4\text{GeV}^2$, have the following expressions

$$xs^h(x,Q_0^2) = \frac{AX_{0u}^+ x^{b_s}}{\exp[(x - X_{0s}^h)/\bar{x}] + 1} \frac{\ln\left(1 + \exp\left[kX_{0s}^h/\bar{x}\right]\right)}{\ln\left(1 + \exp\left[kX_{0u}^+/\bar{x}\right]\right)} + \frac{\tilde{A}_s x^{\tilde{b}}}{\exp(x/\bar{x}) + 1} \ , \tag{3}$$

and similarly [2] for the antiquarks $\bar{s}^h(x,Q_0^2)$

$$x\bar{s}^h(x,Q_0^2) = \frac{\bar{A}(X_{0d}^+)^{-1} x^{2b_s}}{\exp[(x + X_{0s}^{-h})/\bar{x}] + 1} \frac{\ln\left(1 + \exp\left[-kX_{0s}^{-h}/\bar{x}\right]\right)}{\ln\left(1 + \exp\left[-kX_{0d}^+/\bar{x}\right]\right)} + \frac{\tilde{A}_s x^{\tilde{b}}}{\exp(x/\bar{x}) + 1} \ . \tag{4}$$

The value of the input energy scale is arbitrary and should not affect the results which satisfy the Q^2 QCD evolution. Our choice was dictated in Ref. [1] by the existence of many accurate data at $Q^2 = 4\text{GeV}^2$. The first term in the right hand side corresponds to the non diffractive part, while the second is associated with a diffractive component common to all distributions. The ratio of the logarithms originates simply from our extension of the statistical distributions to the transverse degree of freedom and justifies the presence of a multiplicative factor in the Fermi-Dirac functions, first introduced in Ref.[1], as was explained in Ref.[4]. The above expressions involve some

[2] As mentioned above, quarks and antiquarks are not independent due to the relation between the potentials $X_{0s}^h = -X_{0\bar{s}}^{-h}$.

parameters already determined in our previous works [1, 4], which we recall now

$$A = 1.74938,\ \bar{A} = 1.90801,\ X_{0u}^{+} = 0.46128,\ X_{0d}^{+} = 0.22775,$$
$$\bar{x} = 0.09907,\ \tilde{b} = -0.25347,\ k = 1.42\,. \tag{5}$$

Therefore it remains only four free parameters to determine, namely the two potentials $X_{0s}^{\pm}$, b_s and the normalization of the diffractive part $\tilde{A}_s$.

In order to obtain these free parameters, we will use some constraints: first, the nucleon does not have any strangeness quantum number, as a consequence the asymmetry $[a^-]$ has to vanish for all x values

$$[a^-] = \int_0^1 [s(x) - \bar{s}(x)]dx = 0\ , \tag{6}$$

second, from the second Bjorken sum rule, the first moments of the polarized quark distributions must satisfy the relation

$$\Delta q_8 = \Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} - 2(\Delta s + \Delta\bar{s}) = 3F - D\ , \tag{7}$$

where F and D are the hyperon beta decay constants, so that $3F - D = 0.579 \pm 0.008$. From the values of the first moments of the light quarks calculated in Ref. [1], where quarks and antiquarks are related through their potentials, we can deduce another constraint, namely

$$[a^+] = \int_0^1 [\Delta s(x) + \Delta\bar{s}(x)]dx = -0.04675\ . \tag{8}$$

From the above discussion on the light quarks, it is now clear that the sum rule Eq. (6) will lead to strange potentials $X_{0s}^{\pm}$ smaller than $X_{0u}^{\pm}$ and $X_{0d}^{\pm}$. This obvious expectation has been observed in several earlier works on the same subject, see for example Ref. [12]. Similarly in order to satisfy Eq.(8), we anticipate that we will find $X_{0s}^{-} > X_{0s}^{+}$. To determine the free parameters, in addition to the above constraints, we will use some experimental results obtained by the CCFR and NuTeV collaborations [5, 6] on the production of dimuons from neutrino and antineutrino scattering on iron. We have performed a next-to-leading order (NLO) QCD analysis of the data, keeping the light quark distributions as in Ref. [1]. We have obtained the following values for the parameters, $X_{0s}^{+} = 0.08101$, $X_{0s}^{-} = 0.20290$, $b_s = 2.05305$ and $\tilde{A}_s = 0.05762$, all with an error of the order of few percents. We observe that

the chemical potentials for the strange quarks are smaller than the potentials for light quarks u and d and that $X_{0s}^- > X_{0s}^+$, like in the case of the d quark. Due to the large value of b_s, the contribution of the non diffractive component is strongly suppressed, in the small x region.
Our results are displayed in Figs. 1-5 and the fit is rather satisfactory since, as an indication, we have a χ^2/dof of the order of 1.5, compared to 2.75 if one uses instead, the simplifying assumption Eq. (1). We have also checked that in this ealier version, it is not possible to reproduce the rapid rise of $s + \bar{s}$ at low x and $Q^2 = 4\text{GeV}^2$ of the data, as shown in Fig. 1.

At the input scale $Q_0^2 = 4\text{GeV}^2$, $[a^-] = 0$ is satisfied to a great accuracy and we have checked that this constraint is not affected by the Q^2 evolution. We also find $[a^+] = -0.0221$, which is compatible with a recent HERMES determination [13], for this first moment in the measured region, $x > 0.02$ and $< Q^2 >= 2.5\text{GeV}^2$, namely $0.006 \pm 0.029(\text{stat.}) \pm 0.007(\text{sys.})$.

For the first moment of the asymmetry

$$[S^-] = \int_0^1 [s(x) - \bar{s}(x)]xdx \ , \tag{9}$$

we have $[S^-] = -0.00194$, to be compared with the value -0.0011 ± 0.0014 found by the NuTeV collaboration [14], and with the allowed range extracted from a global QCD fit by CTEQ [10] $-0.001 < [S^-] < 0.004$. The calculations in the light-cone meson-baryon model, lead to two positive results, namely $0.0042 < [S^-] < 0.0106$ for the choice of a Gaussian wave function or $0.0035 < [S^-] < 0.0087$ for a power-law wave function [9].

We now turn to discuss the main features of the distributions obtained from this fit and compare them with other theoretical models. We show the unpolarized and polarized strange quark distributions at the input scale $Q_0^2 = 4\text{GeV}^2$ in Fig. 6. We observe that the distributions $s(x)$ and $\bar{s}(x)$ are almost identical for $x < 0.05$, because the diffractive component dominates largely, whereas $s(x)$ is a little larger than $\bar{s}(x)$ for $0.05 < x < 0.25$ and $s(x) < \bar{s}(x)$ for $0.25 < x < 1$. These features remain unchanged for higher Q^2 values, as shown in Fig. 7 for the difference $s - \bar{s}$ plotted as a function of x, for $Q^2 = 4, 20, 100\text{GeV}^2$. This pattern is similar to that one gets in the meson cloud model [8] and also in another approach based on perturbative evolution in QCD at three loops [11], although, in this later case the sign change occurs at a much smaller value of x. On the contrary, in Ref.[9] they found that $s(x) < \bar{s}(x)$ in the small x region and $s(x) > \bar{s}(x)$ in the large x region.

Finally, both $\Delta s(x)$ and $\Delta\bar{s}(x)$ are negative for all x, as shown in Fig. 6, in reasonable agreement with the results of Ref. [12]. This contradicts the expectation of the meson cloud model [8], so it is clear that we need for a better measurement of the strange quark contribution to the nucleon spin, has was also stressed in Ref. [15].

3 Conclusion

We have investigated the possibility to introduce an asymmetry for the strange quark distributions in the framework of a statistical parton model. In the absence of direct precise experimental data, we have imposed different unpolarized and polarized constraints on the distributions and an extensive use of the recent results from CCFR and NuTeV. The main results are that $s(x) - \bar{s}(x)$ is indeed small, as expected, positive in the low x region and negative for $x > 0.25$. Our approach has the unique feature to provide simultaneously the polarized distributions for strange quarks and antiquarks which are found to be both negative for all x. New results on the strange quarks distributions are welcome, because they will produce further tests on the present determination and hopefully some improvement on them.

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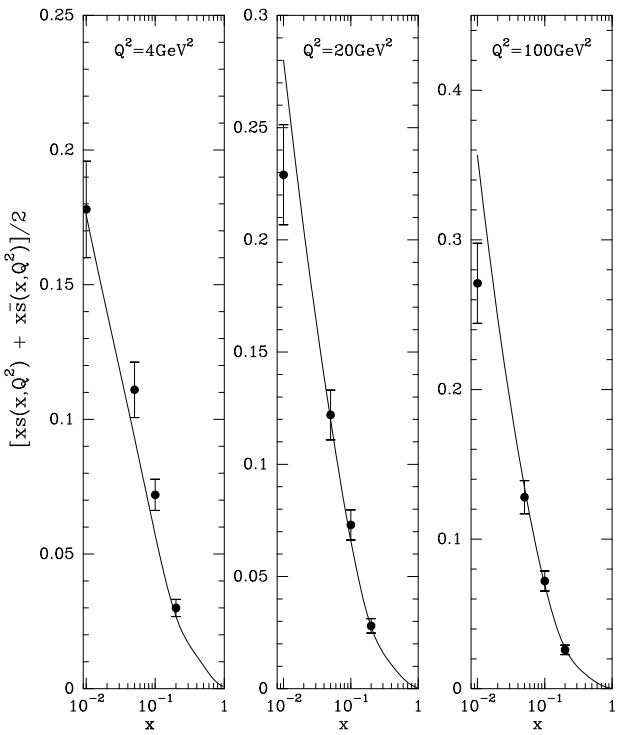

Figure 1: The average strange quark antiquark distributions determined at NLO as a function of x for $Q^2 = 4, 20, 100\text{GeV}^2$. Data from CCFR Collaboration [5].

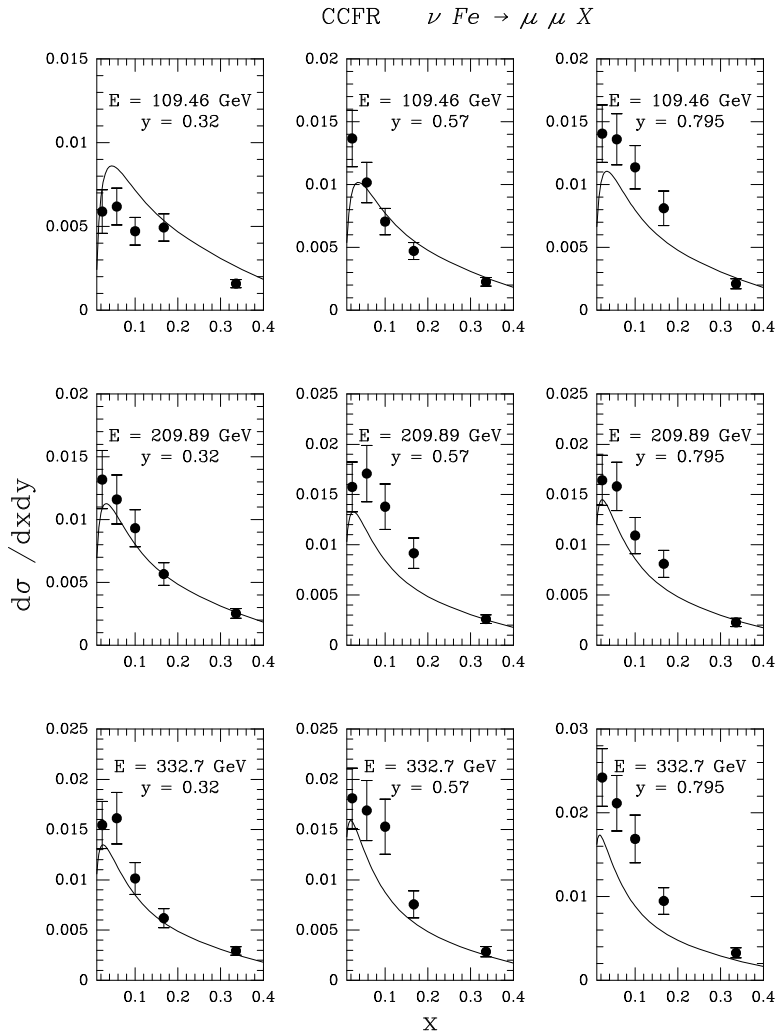

Figure 2: Comparison of the CCFR ν data [6] to the result of the fit for $d\sigma/dxdy$, in units of charged-current σ, for various kinematic ranges in energy, x and y.

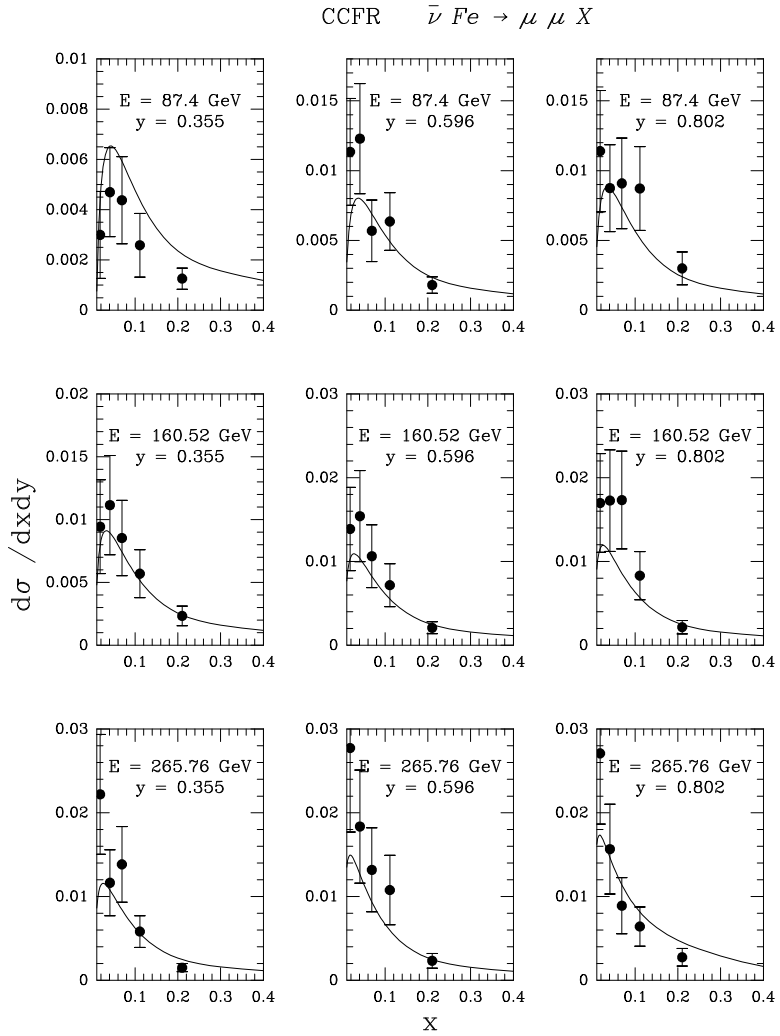

Figure 3: Comparison of the CCFR $\bar{\nu}$ data [6] to the result of the fit for $d\sigma/dxdy$ in units of charged-current σ, for various kinematic ranges in energy, x and y.

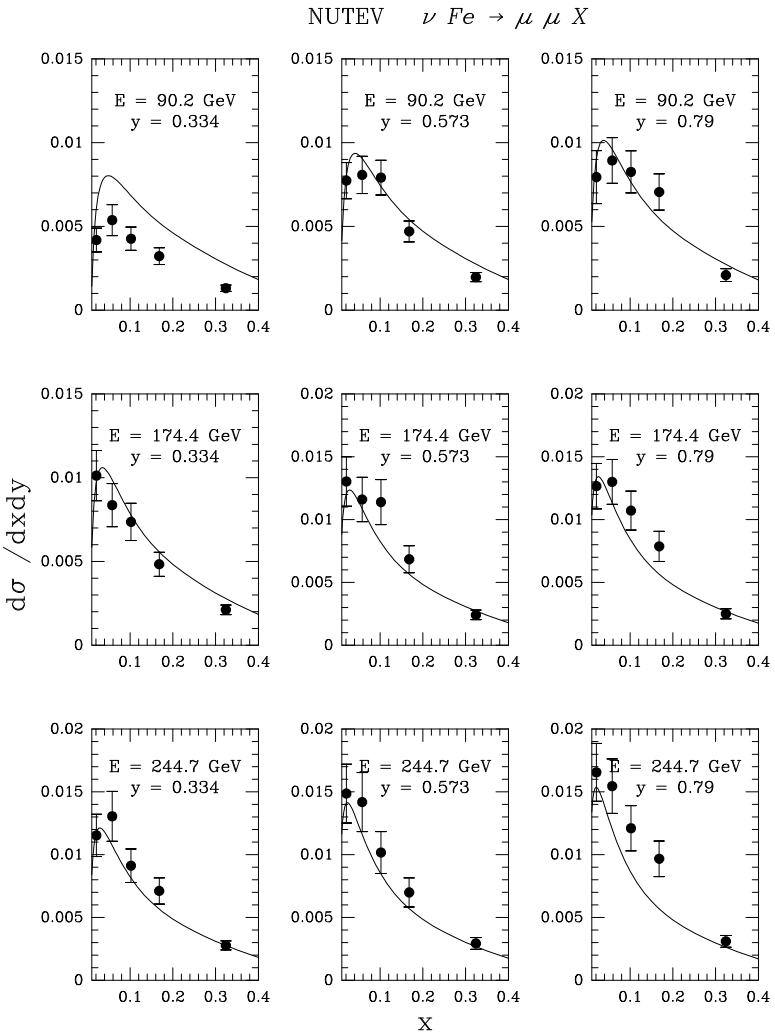

Figure 4: Comparison of the NuTeV ν data [6] to the result of the fit for $d\sigma/dxdy$, in units of charged-current σ, for various kinematic ranges in energy, x and y.

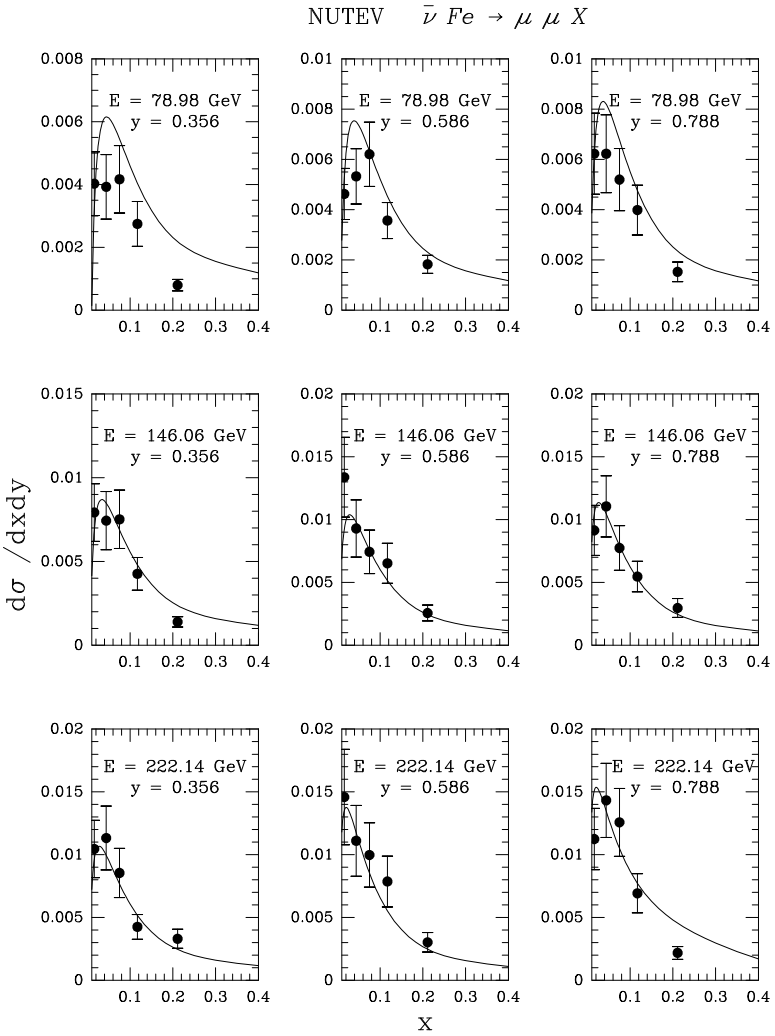

Figure 5: Comparison of the NuTeV $\bar{\nu}$ data [6] to the result of the fit for $d\sigma/dxdy$, in units of charged-current σ, for various kinematic ranges in energy, x and y.

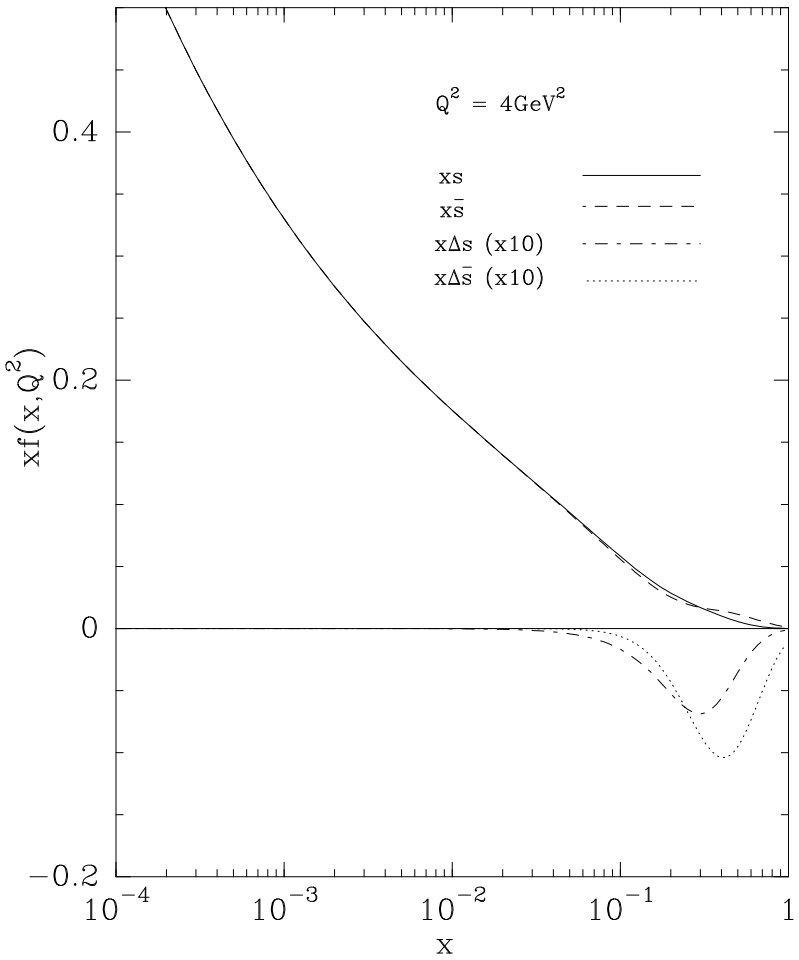

Figure 6: The unpolarized and polarized strange quark and antiquark distributions determined at NLO as a function of x for $Q^2 = 4\mathrm{GeV}^2$.

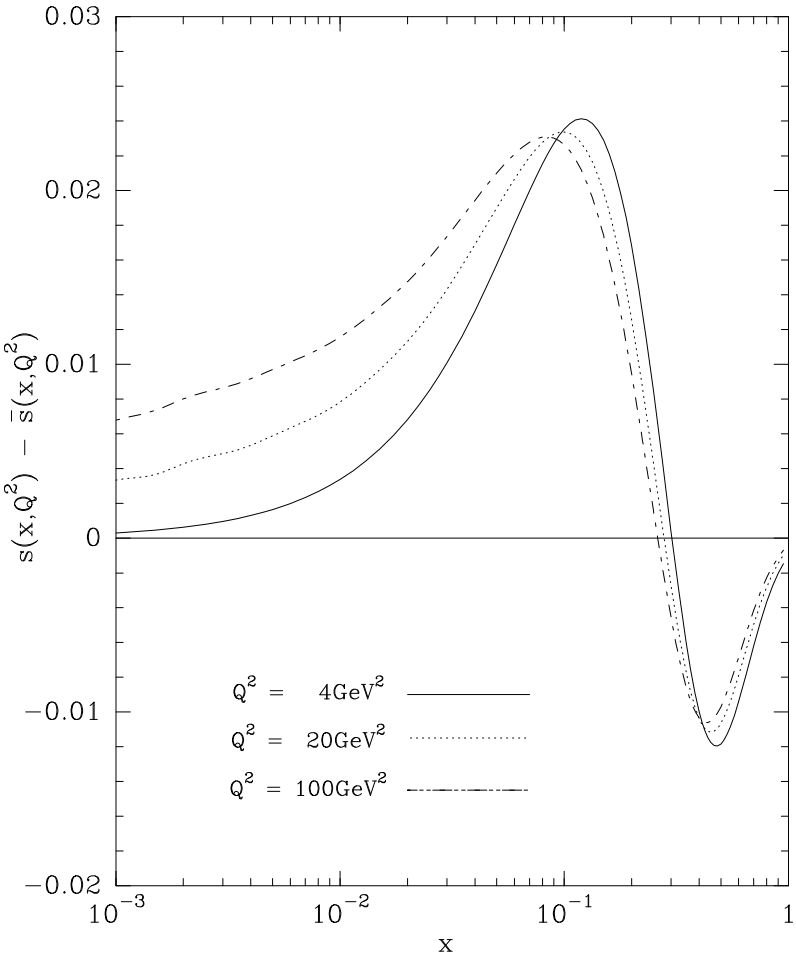

Figure 7: The difference $s - \bar{s}$ quark distributions determined at NLO as a function of x for $Q^2 = 4, 20, 100\text{GeV}^2$.