

A Model to Study the Strange Quark $s - \bar{s}$ Asymmetry in Nucleon Sea

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Abstract. We study the strange quark $s - \bar{s}$ asymmetry in the nucleon sea using a model in which the proton wave function includes a Kaon meson-Hyperon Fock state. Parameters of the model are fixed by fitting the $s - \bar{s}$ asymmetry obtained from global fits to Deep Inelastic Scattering data. We discuss possible effects of the $s - \bar{s}$ asymmetry on the measurement of the Weinberg angle by the NuTeV Collaboration.

Keywords: Strange sea · Asymmetry

1 Introduction

Nucleons are one of the most important particles in the nature, they compose majority of all matter in the universe. A nucleon is either a proton or a neutron, the component of an atomic nucleus. In the standard model of elementary particles proton and neutron are classified into family of particles known as hadrons, which are composed of more elementary particles named *quarks*. Proton is composed by three quarks: 2 quarks $up(u)$ and one quark $down(d)$. Particles with two quarks also exist and they are named mesons. Quarks into hadrons interact each other by gluons(g), particles mediator of the strong interaction. At the present there are six quarks with different mass values, associate to them their corresponding antiparticles, or in general antimatter. Currently the precise study of the quark physics into hadrons is a main challenge in the high energy of physics made by experiments as CERN in order to understand the nature and origin of the universe.

Quarks model was confirmed with the study of nucleons structure in process of deep inelastic scattering (DIS) in the 1960s by colliding leptons as electrons, muons and neutrinos with nucleon targets in a similar way as Rutherford's scattering, whose study determined the existence of the nucleons into atomos. In DIS leptons have a high energies to break up the nucleons and collide with the quarks, producing after of collision new particles, mainly hadrons. Additionally,

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in the scale of DIS energy values, gluon splitting process related with matter anti matter production of quarks q anti quarks $\bar{q}$ inside nuclons -known as *sea quarks*- was a astonishing result that scientifcts in that epoc could not expected. Parton model making by Feynman could explain in a better way the structure of nucleons: valence quarks, gluons process and sea quarks are inside nucleons with a momentum fraction given by a probability density function $q(x)$, known as *parton density functions*. In general quarks sea densities for quarks up u and down d inside nucleons are not symetrical, but in the case of heavier quarks as the strange s, charm c, bottom b and top t is expected that quarks sea densities would be symmetric.

The first studies about a possible asymmetry in the strange sea of the nucleon dates from 1987, when Signal and Thomas [1] discussed the possibility of a $K^+\Lambda$ pair component in the proton wavefunction. Since then on, several models have been propossed for the nucleon structure, allowing for an asymmetric $s-\bar{s}$ [2,3]. However, no experimental evidence was presented on this subject until the global fit of DIS data by Barone *et al.* [5] in 2000. Most recently, the $s - \bar{s}$ asymmetry in the nucleon sea was called for as a possible explanation.

From a theoretical point of view, it is interesting to note that although sea quarks in the nucleon originating in gluon splitting necessarily have symmetric momentum distributions, after interacting with the valence quarks and the remaining partons in the sea, their momentum distributions do not have to be equal. This can be interpreted as the formation of a virtual $K^+\Lambda$ pair in the nucleon structure. Being this the case, it is easy to see that, since the s and the $\bar{s}$ quarks are part of the Λ and K^+ respectively, then their momentum distributions would be different. This difference, which is merely a consequence of the interaction of sea quarks with the remaining partons in the nucleon, has to be understood as part of the non-perturbative dynamics responsible for the formation of the nucleon as a bound state of quarks and gluons. Recall also the $\bar{u} - \bar{d}$ asymmetry and the Gottfried Sum Rule violation, known since the New Muon Collaboration results [6,7], which can also been explained in terms of a $n\pi^+$ and $\Delta^{++}\pi^-$ components in the proton wave function [10].

In this work, we shall consider a model for the strange sea of the proton which can describe the form of the $s - \bar{s}$ asymmetry extracted from global fits to DIS data. After fixing the parameters of the model, in Sect. 2.3, we shall study the effect of this asymmetry, together with possible effects coming from the non isoscalarity of the target, in the determination of $\sin^2\theta_W$ by the NuTeV Collaboration [8]. Section 4 will be devoted to discussion and conclusions.

2 A Model for the $s - \bar{s}$ Asymmetry

Different models [1–4] have attempted to predict the $s - \bar{s}$ asymmetry. Among them, the most promising approach seems to be the Meson Cloud Model (MCM). In the MCM fluctuations of the proton to kaon-hyperon virtual states are responsible for the $s - \bar{s}$ asymmetry. Since the s quark belong to the hyperon particle state and the $\bar{s}$ quark to the Kaon particle state, the asymmetry arises naturally due to the different momentum carried by the kaon and the hyperon in the

fluctuation. A squeme view of these process are shown as a Feynman diagram in the Fig. 1. Here hyperon state is given Λ particle state which is compose uds quarks and Kaon particle state compose by $u\bar{s}$ quarks. Two different approaches exist within the MCM. The first is based in a description of the form factor of the extended proton-kaon-hyperon vertex [1,3] and, the second one, in terms of parton degrees of freedom [4]. In the first approach, the knowledge of the form factors is crucial to get a reasonable description of the $s-\bar{s}$ asymmetry (see e.g. Ref. [3]). In the second one, fluctuations are generated through gluon emission from the constituent valence and its subsequent splitting to a $s-\bar{s}$ pair [4]. This $s-\bar{s}$ pair then recombines with constituent quarks to form a kaon-hyperon bound state. In what follows, we will adopt the second approach.

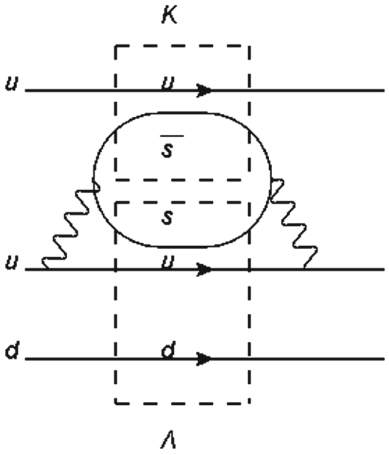


Fig. 1. Scheme view of Feynman diagram process: gluon emission from the constituent valence and its subsequent splitting process produces a $s\bar{s}$ pair which interact with valence quarks u and d generating K^+ and Λ^0 virtual states (shown with dashed boxes). After that virtual states, the $s\bar{s}$ pair recombines into a gluon which is reabsorbed by a valence quark

2.1 The Model

We start by considering a simple picture of the nucleon in the infinite momentum frame as being formed by three dressed valence quarks - valons, $v(x)$ - which carry all of its momentum [11]. In the framework of the MCM, the nucleon can fluctuate to a meson-baryon bound state carrying zero net strangeness, that is

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

where x is the momentum fraction. As a first step in such a process, we may consider that each valon can emit a gluon which, before interacting, decays

perturbatively into a $s\bar{s}$ pair The probability of having such a perturbative $q\bar{q}$ pair can then be computed in terms of Altarelli-Parisi splitting functions [12]

$$P_{qq}(z) = \frac{4}{3}\frac{1+(1+z^2)}{z},$$
$$P_{qg}(z) = \frac{1}{2}(z^2+(1+z)^2). \tag{2}$$

These functions have a physical interpretation as the probability of gluon emission and $q\bar{q}$ creation with momentum fraction z from a parent quark or gluon respectively. Hence,

$$q(x,Q^2) = \bar{q}(x,Q^2)\frac{\alpha_{st}^2(Q^2)}{(2\pi)^2}\int_1^x \frac{dy}{y}P_{qg}\left(\frac{x}{y}\right)\int_1^y \frac{dz}{z}P_{gq}\left(\frac{y}{z}\right)v(z) \tag{3}$$

is the joint probability density of obtaining a quark or anti-quark coming from subsequent decays $v \rightarrow v + g$ and $g \rightarrow q + \bar{q}$ at some fixed low Q^2. As the valon distribution does not depend on Q^2 [11], the scale dependence in Eq. 3 only exhibits through the strong coupling constant $\alpha_{st}(Q^2)$. The range of values of Q^2 at which the process of virtual pair creation occurs in this approach is typically below 1 GeV^2, as dictated by the valon model of the nucleon. For definiteness, we will use $Q = 0.7$ GeV as in Ref. [11], for which $\alpha_{st}(Q^2) \approx 0.3$, is still sufficiently small to allow for a perturbative evaluation of the $q\bar{q}$ pair production. Since the scale must be consistent with the valon picture, the value of Q^2 is not really free and cannot be used to control the flavor produced at the $gq\bar{q}$ vertex. Instead, this role can be ascribed to the normalization constant N, which must be such that to a heavier quark corresponds a lower value of N.

Once a $s\bar{s}$ pair is produced, it can rearrange itself with the remaining valons so as to form a most energetically favored meson-baryon bound state. When the nucleon fluctuates into a meson-baryon bound state, the meson and baryon probability densities $P_M(x)$, and $P_B(x)$ inside the nucleon are not independent. Actually, to ensure the zero net strangeness of the nucleon and momentum conservation, the in-nucleon meson and baryon distributions must fulfill two basic constraints,

$$\int_0^1 [P_B(x) - P_M(x)]dx = 0 \tag{4}$$

$$\int_0^1 [xP_B(x) + xP_M(x)]dx = 1 \tag{5}$$

for all momentum fractions x. The meson, $P_M(x)$, and baryon, $P_B(x)$, probability density functions have to be calculated by means of effective techniques in order to deal with the non-perturbative quatum cromodynamics (QCD) processes inherent to the dressing of quarks into hadrons. In Ref. [4], these probability densities have been related to the cross section for meson production by recombination, and the model by Das and Hwa [13] was used to obtain them. In this work, since the aim is to compare the model to experimental data by means

of a fit, we will follow a different approach. Let us note that, for reasonable valon distributions in the nucleon and sea quark distributions of the form given by Eq. (3), the result of using the recombination model gives for the meson probability density a function of the form $x^a(1-x)^b$. Then we will assume

$$P_M(x) = \frac{1}{\beta(a_{KN}+1, b_{KN}+1)} x^{a_{KN}}(1-x)^{b_{KN}} \tag{6}$$

which is properly normalized to one. If for the in-nucleon baryon probability we use the same functional form as for the meson,

$$P_B(x) = \frac{1}{\beta(a_{HN}+1, b_{HN}+1)} x^{a_{HN}}(1-x)^{b_{HN}} \tag{7}$$

it is automatically satisfied the requirement of zero net strangenes. In addition, interpreting a_{KN}, b_{KN}, a_{HN} and b_{HN} as parameters of the model, and recognizing that Eq. (4) fix one of them as a function of the remaining three by means of

$$\frac{\Gamma(a_{KN}+b_{KN}+2)\Gamma(a_{KN}+2)}{\Gamma(a_{KN}+1)\Gamma(a_{KN}+b_{KN}+3)} + \frac{\Gamma(a_{HN}+b_{HN}+2)\Gamma(a_{HN}+2)}{\Gamma(a_{HN}+1)\Gamma(a_{HN}+b_{HN}+3)} = 1 \tag{8}$$

then the momentum conservation sum rule is also fulfilled. The non-perturbative strange and anti-strange sea distributions in the nucleon can be now computed by means of the two-level convolution formulas

$$s_B(x) = \int_1^x \frac{dy}{y} P_B(y) s\left(\frac{y}{z}\right), \tag{9}$$

$$\bar{s}_M(x) = \int_1^x \frac{dy}{y} P_H(y) \bar{s}\left(\frac{y}{z}\right), \tag{10}$$

where the sources $s_B(x)$ and $\bar{s}_M(x)$ are primarily the probability densities of the strange valence quark and anti-quark in the baryon and meson respectively, evaluated at the hadronic scale Q^2 [1]. In principle, to obtain the non-perturbative distributions given by Eqs. (9) and (11), one should sum over all the strange meson-baryon fluctuations of the nucleon but, since such hadronic Fock states are necessarilly off-shell, the most likely configurations are those closest to the nucleon energy-shell, namely $\Lambda^0 K^+$, $\Sigma^0 K^+$ and $\Sigma^+ K^0$, for a proton state.

2.2 Fit to $x(s(x) - \bar{s}(x))$ Data

In order to fit to experimental data on the $s - \bar{s}$ asymmetry and to extract the parameters of the model, we will use

$$\bar{s}_K(x) = \frac{1}{\beta(a_K+1, b_K+1)} x^{a_K}(1-x)^{b_K} \tag{11}$$

$$s_H(x) = \frac{1}{\beta(a_H+1, b_H+1)} x^{a_H}(1-x)^{b_H} \tag{12}$$

which are consistent with the hypothesis that the in meson and baryon are formed by valons. Then the $s - \bar{s}$ asymmetry of the nucleon is given by

$$xs(x) - \bar{s}(x) = N^2(xs^{NP}(x) - \bar{s}^{NP}(x)) \tag{13}$$

at the valon scale $Q^2 = 0.49$ GeV^2, and where N^2 is the probability of the $|HK\rangle$ Fock state in the proton wave function, which is related to the probability of having a $s(x) - \bar{s}$ pair out of Eq. (3). The model has then a total of 8 parameters to be fixed by fits to experimental data. Results of the fit to experimental data from Ref. [14] are shown in Fig. 2 and Table 1. For the experimental data, we extracted 27 segments from the allowed band in Fig. 2 of Ref. [14] and assumed that the midpoint of each segment is the most probable value which we interpreted as the value for the asymmetry, while the half lenght of the segment was interpreted as the error bar. Notice however that this procedure has to be taken only as a way to fit our model inside the allowed region for the $s(x) - \bar{s}$ asymmetry. The fit was performed by minimizing the χ^2 using MINUIT. In the fitting procedure, since the allowed bars for the $s - \bar{s}$ asymmetry are given at $Q^2 = 20$ GeV^2, the parameters where chosen, then the asymmetry was evolved from $Q^2 = 0.49$ GeV^2 to $Q^2 = 20$ GeV^2, the $\chi^2$was evaluated and the procedure was repeated until a minimum was reached.

Table 1. Fit results. Parameters a_{KN}, b_{KN} are for the Kaon probability density in the nucleon, a_{HN}, b_{HN} for the Hyperon probability density, a_K, b_K for the anti-strange valon proba bility density in the Kaon and a_H, b_H for the strange valon density in the Hyperon. The χ^2/d.o.f. $= 0.15$ and $b_{HN} = 1.11$ is the result of the constraint due to the momentum sum rule of Eq. (7)

Parameter	Value
a_{KN}	$2.06 \pm 2.62 \times 10^{-7}$
b_{KN}	2.14 ± 0.11
a_K	5.14 ± 1.93
b_K	0.90 ± 0.34
a_{HN}	1.17 ± 0.35
a_H	9.47 ± 0.61
b_H	2.51 ± 0.61
N^2	0.04 ± 0.02

2.3 Discusion of Effects of $s(x) - \bar{s}(x)$

The effect of the asymmetry in the strange sea in the nucleon has a surprised result in the DIS. In general the size of this asymmetry depends of the scale value energy of Q^2. As it mentioned before analysis of results of $x[s(x) - \bar{s}(x)]$

asymmetry by Barone *et al.* [5] is given to a scale $Q^2 = 20$ GeV^2. Most recently, the $x[s(x) - \bar{s}(x)]$ asymmetry in the nucleon sea was called for as a possible explanation [6] for the almost 3σ difference between the NuTeV $\sin^2\theta_W$ result [8] and global fits [9]. The evolution has been done at next-to-leading order (NLO) with the Eq. (3) and a value of

$$S^- = \int_0^1 x[s(x) - \bar{s}(x)]dx = 0.87 \times 10^{-4} \tag{14}$$

at $Q^2 = 20$ GeV^2 has been obtained, which is also the average Q^2 reported by NuTeV. Although this value of S^- is small to account for the anomalous result for reported by NuTeV, it is positive. It is also conceivable that, by performing a next-to-next-leading-orden (NNLO) evolution, the negative contribution of the perturbative asymmetry in $s(x) - \bar{s}(x)$ be compensated by a bigger positive non-perturbative asymmetry. In Fig. 3, the xs and $x\bar{s}$ distributions are displayed at the Q^2 scale where the evolution starts, namely, $Q^2 = 0.49$ GeV^2.

3 The Effect of $s(x) - \bar{s}(x)$ on the Determination of $\sin^2\theta_W$

The weak mixing angle is one of the basic parameters of the standard model of electroweak interactions. An experimental value for $\sin^2\theta_W$ has been obtained, using the *on-shell* renormalization scheme, from a global fit to the precise electroweak measurements performed by the LEP experiments at CERN and the SLD experiment at SLC, together with data from several other experiments at Fermilab [9]. This global analysis lends a value of

$$\sin^2\theta_W = 0.2227 \pm 0.004 \tag{15}$$

excluding the data from CCFR and NuTeV experiments. The NuTeV collaboration reported a value of $\sin^2\theta_W$ extracted from the analysis of neutrino ν and anti-neutrino $\bar{\nu}$ charged current (CC) and neutral current (NC) scattering data [8]. The *on shell* value obtained by this experiment is

$$\sin^2\theta_W = 0.22773 \pm 0.00135_{\text{stat}} \pm 0.00093_{\text{sys}} \tag{16}$$

which is $\sim 3\sigma$ away from the electroweak global fit value. Due to an inevitable contamination of the muon and anti-muon neutrinos $\nu_\mu(\bar{\nu}_\mu)$ beams with electron muons $\nu_e(\nu_e)$, and the impossibility of separating CC $\nu_e(\nu_e)$ induced interactions from the NC $\nu_\mu(\nu_\mu)$ induced ones on an event by event bases, the NuTeV result was obtained by performing a full simulation of the whole experiment, in which the value of the weak mixing angle was adjusted so that the Monte Carlo yield the best de scription of the experimental data. The NuTeV Monte Carlo included, among may other things, a detailed simulation of the neutrino(antineutrino) beam, a detailed model of the N cross section, QED radiative corrections, charm-production-threshold effects, strange and charm sea scattering, quasi-elastic scattering, neutrino-electron scattering, non-isoscalar-target

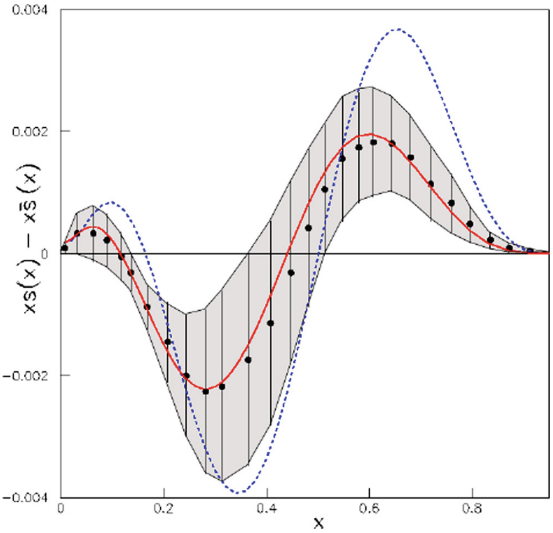


Fig. 2. The model compared to experimental data at $Q^2 = 20$ GeV^2 (full line). The curve is the result of the fit, data points were extracted to fit in the shadowed region as given in Ref. [14] (see the text). The dashed line is the model at $Q^2 = 20$ GeV^2

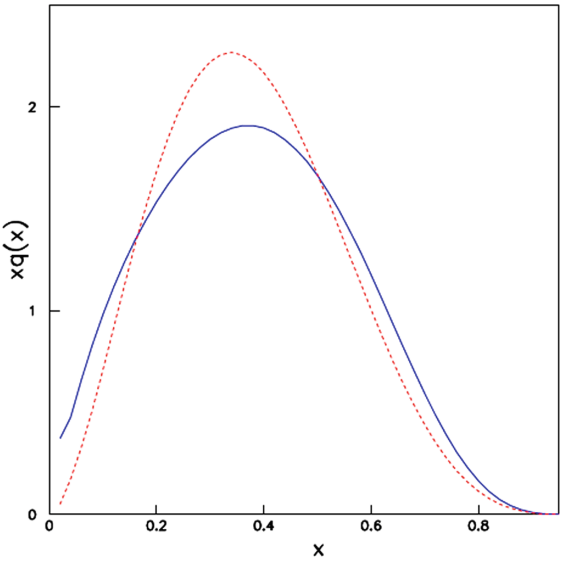


Fig. 3. The $xs(x)$ (full line) and $x\bar{s}$ (dashed line) at $Q^2 = 0.49$ GeV^2 as given by the model.

effects, higher twist effects, etc. [15]. The experimental data and the Monte Carlo results compare very well.

The NuTeV Monte Carlo simulation did not assume any asymmetry in the strange-antistrange sea of the nucleons. The effect of this asymmetry and possible effects due to nuclear medium modifications to the parton distributions have been explored as possible explanations for the discrepancy between the results for the $\sin^2\theta_W$ obtained by NuTeV and those obtained by the global fit to the DIS data [9]. The effect of the $s(x) - \bar{s}(x)$ asymmetry on the determination of $\sin^2\theta_W$ can be accounted for through the use of the Paschos-Wolfenstein (PW) relation [16]

$$R^- = \frac{\sigma_{NC}^{\nu N} - \sigma_{NC}^{\bar{\nu} N}}{\sigma_{CC}^{\nu N} - \sigma_{CC}^{\bar{\nu} N}} = \frac{1}{2} - \sin^2\theta_W. \tag{17}$$

Equation (17) does not assume any asymmetry in the strange sea of the nucleon, and has to be corrected when the target is a nucleus, due to effects of the nuclear medium. In most experimental cases, as for example the NuTeV experiment, the target is not isoscalar either and this effect has to be taken into account. A generalized PW relation that includes all these modifications can easily be obtained. The extraction of the $\sin^2\theta_W$ by NuTeV did not resort to any PW relation because of the impossibility to separate effectively the charged current form the neutral current signals.

Through the use of a generalized PW relation one can estimate the effect of the presence of a nucleon-strange- sea asymmetry over the extraction of the $\sin^2\theta_W$ done by NuTeV. The same procedure can also allow to estimate the effect of different nuclear medium modifications. The generalized PW relation can be written as:

$$\begin{aligned} R^- &= \frac{Z(\sigma_{NC}^{\nu p} - \sigma_{NC}^{\bar{\nu} p}) + N(\sigma_{NC}^{\nu n} - \sigma_{NC}^{\bar{\nu} n})}{Z(\sigma_{CC}^{\nu p} - \sigma_{CC}^{\bar{\nu} p}) + Z(\sigma_{CC}^{\nu n} - \sigma_{NC}^{\bar{\nu} n})} \\ &= \frac{2}{[(3N - Z)U^- + (3Z - N)D^- + 3(N + Z)S^-]} \times \\ &\quad \left[\left(\frac{1}{4} - \frac{2}{3}\sin^2\theta_W\right)(ZU^- + ND^-) + \left(\frac{1}{4} - \frac{1}{3}\sin^2\theta_W\right)(ZD^- + NU^-)\right. \\ &\quad \left. + \left(\frac{1}{4} - \frac{1}{3}\sin^2\theta_W\right)(N + Z)S^-\right], \end{aligned} \tag{18}$$

where

$$U^- = \int_0^1 x[u(x) - \bar{u}(x)]dx, \tag{19}$$

$$D^- = \int_0^1 x[d(x) - \bar{d}(x)]dx, \tag{20}$$

$$S^- = \int_0^1 x[u(x) - \bar{u}(x)]dx, \tag{21}$$

and Z and N are the proton and neutron numbers of the target nucleus. The NuTeV Collaboration extracted $\sin^2\theta_W$ from a full simulation of the experiment

in which a symmetric strange sea was assumed ($S^- = 0$). From this, and the use of the generalized PW relation, one could determine the value of R^- consistent with the results of NuTeV, by evaluating

$$R^-_{\rm NuTeV} = R^-[S^- = 0, Z, N, \sin^2\theta_W^{\rm NuTeV}], \tag{22}$$

where N and Z correspond to the iron target used, and $\sin^2\theta_W^{\rm NuTeV}$ to the value reported by the experiment. Assuming $R^-_{\rm NuTeV}$, the value of $\sin^2\theta_W$ from the global analysis of the DIS data ($\sin^2\theta^{\rm Global}$), and the parametrizations of Gluck, Reya and Vogt for the parton distributions of $u(x)$ and $d(x)$ [17], one can evaluate the level of asymmetry in the strange sea of the nucleon that could explain the NuTeV result,

$$\begin{aligned} S^- = & \frac{1}{[(\frac{3}{2}R^-_{\rm NuTeV} - (\frac{1}{4} - \frac{1}{3}\sin^2\theta_W)]}\left[(ZU^- + ND^-)\left(\frac{1}{4} - \frac{2}{3}\sin^2\theta_W^{\rm Global}\right) + \right. \\ & \left. (ZD^- + NU^-)\left(\frac{1}{4} - \frac{1}{3}\sin^2\theta_W^{\rm Global}\right) - \frac{R^-_{\rm NuTeV}}{2}[(3N - Z)U^- + (3Z - N)D^-]\right] \\ = & \ 0.004013. \end{aligned} \tag{23}$$

The strange asymmetries predicted by our model is, again, given by

$$S^- = \int_0^1 x[s(x) - \bar{s}(x)]dx = 0.87 \times 10^{-4}, \tag{24}$$

which are two orders of magnitude smaller. Since our parametrizations for $x[s(x) - \bar{s}(x)]$ are in agreement with the experimental data from [14], one can conclude that the anomalous value for $\sin^2\theta_W$ reported by NuTeV cannot be explained in terms of a possible asymmetry in the strange sea of the nucleon.

4 Conclusions

We have presented a model, based in fluctuations of the proton wavefunction to a generic Hyperon-Kaon Fock state, that closely reproduces experimental data on the extrange sea asymmetry of the nucleon. The model has a total of 8 parameters which have been fixed by fits to experimental data. No NNLO effects in the evolution of the xs and $x\bar{s}$ have been considered, however the negative asymmetry introduced by NNLO evolution effects should be compensated by a large and positive asymmetry coming from the non-perturbative dynamics associated to the confining phase of QCD.

We investigated also the effect of such an asymmetry on the result presented by the NuTeV experiment on the measurement of $\sin^2\theta_W$. In the study we considered, in addition, effects coming from the non isoscalarity of the NuTeV target. Considering all together, we found that the effect of the $x[s(x) - \bar{s}(x)]$ asymmetry in the nucleon sea is too small to account for the almost 3σ difference among the $\sin^2\theta_W$ result by NuTeV and the world average.

References

1. Signal, A.I., Thomas, A.W.: Phys. Lett. B **191**, 205 (1987)
2. Brodsky, S.J., Ma, B.Q.: Phys. Lett. B **381**, 317 (1996)
3. Burkard, M., Warr, B.J.: Phys. Rev. D **45**, 958 (1992)
4. Christiansen, H.R., Magnin, J.: Phys. Lett. B **445**, 8 (1998)
5. Barone, V., Pascaud, C., Zomer, F.: Eur. Phys. J. C-Part. Fields **12**, 243 (2000)
6. Amaudruz, P., et al. (New Muon Collaboration): Phys. Rev. Lett. **66**, 2712 (1991)
7. Arneodo, M., et al. (New Muon Collaboration): Phys. Rev. D **50**, 1 (1994)
8. Zeller, G.P., et al. (NuTeV Collaboration): Phys. Rev. Lett. **88**, 091802 (2002). [Erratum Phys. Rev. Lett. **90**, 239902 (2003)]
9. Report No. CERN-EP/2001-98; hep-ex/0112021. and reference [21] quoted in reference [7]
10. Magnin, J., Christiansen, H.R.: Phys. Rev. D **61**, 054006 (2000)
11. Hwa, R.C.: Phys. Rev. D **22**, 759 (1980); Phys. Rev. D **22**, 1593 (1980)
12. Altarelli, G., Parisi, G.: Nucl. Phys. B **126**, 298 (1977)
13. Das, K.P., Hwa, R.C.: Phys. Lett. B **68**, 459 (1977)
14. Portheault, B.: 11th International Workshop On Deep In- elastic Scattering (DIS 2003) (2003). hep-ph/0406226
15. Zeller, G.P.: Ph.D. thesis, Northwestern University (2002)
16. Paschos, E.A., Wolfenstein, L.: Phys. Rev. D **7**, 91 (1973)
17. Gluck, M., Reya, E., Vogt, A.: Eur. Phys. J. C **5**, 461 (1998)