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Parton distribution functions in a fit of DIS and related data

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Abstract: We present a NLO analysis of DIS and related data, including high-statistics $\nu, \bar{\nu}$ cross section measurements. The parton distributions functions of the proton are extracted. A detailed study of the strange and antistrange densities is performed, and the charge symmetry of the strange sea is tested. We discuss the impact of the results on the NuTeV $\sin^2\theta_W$ puzzle.

Keywords: QCD, Deep Inelastic Scattering.

Contents

1. Introduction

A few years ago we presented [1] a global analysis of deep inelastic scattering (DIS) and Drell-Yan (DY) data which included all ν, $\bar{\nu}$ DIS cross sections available at that time. Neutrino and anti-neutrino DIS plays an important rôle in the extraction of the parton distribution functions (pdf's), in particular of the strange-sea density. In fact, charged-lepton DIS is insufficient to constrain all flavor distributions, being essentially limited to one observable, F_2. Charged-current DIS provides four more independent combinations of parton densities: F_2^{ν}, $F_2^{\bar{\nu}}$, xF_3^{ν} and $xF_3^{\bar{\nu}}$. The abundance of $\nu, \bar{\nu}$ data in the analysis of [1] allowed the first unconstrained and fully consistent determination of $s(x)$ and $\bar{s}(x)$ within a global fit of parton densities, and the investigation of a hypothetical charge asymmetry of the strange sea, $s(x) \neq \bar{s}(x)$. Our choice of fitting $\nu(\bar{\nu})$ DIS differential *cross sections* instead of $\nu(\bar{\nu})$ DIS *structure functions* was motivated by the fact that $F_2^{\nu,\bar{\nu}}$ are extracted by a preanalysis which is often based on theoretical assumptions conflicting with those of the global fit that one is performing. For instance, the old CCFR structure functions [2] were obtained by applying slow rescaling corrections and adopting an oversimplified leading-order model for xF_3, and that is why they were not included in the NLO fits of [1].

The CCFR-NuTeV Collaboration [3] has released new data on $\nu(\bar{\nu})$ DIS cross sections and structure functions, which are not affected by the theoretical biases occurring in the analysis of [2]. The aim of the present paper is to use these data to update the fits of [1].[1] We will be especially interested in the strange sea distributions, and in particular in the strange-antistrange asymmetry (section 2). This is not only interesting from a theoretical point of view, but also relevant for the precise determination of one of the fundamental parameters of the standard model (SM), the Weinberg angle θ_W. The NuTeV extraction of $\sin^2\theta_W$ from DIS data [5] gives a value which is 3σ above the standard model prediction. A possible explanation of this discrepancy [6] is a non-zero second moment

[1] A preliminary account of this work was presented by one of us at the DIS03 Workshop [4].

of $s^-(x) = s(x) - \bar{s}(x)$, that is a strange-antistrange momentum asymmetry. A further correction to the NuTeV evaluation comes from non-isoscalarity effects. In section 4 we shall explore the implications of our results on the NuTeV $\sin^2\theta_W$ puzzle.

2. Extracting the strange-sea distributions

The strange and antistrange densities are still the least known pdf's. The reason for this persistent lack of knowledge is that the determination of $s(x)$ and $\bar{s}(x)$ relies on neutrino and antineutrino DIS structure functions, which are usually affected by many systematic, statistical and theoretical uncertainties. In [1] we started a program of full exploitation of ν and $\bar{\nu}$ data with the aim of extracting $s(x)$ and $\bar{s}(x)$ with no spurious constraints. One of our findings was some evidence of a *non zero*, and *positive*, *strange-antistrange momentum asymmetry* (for the definition of the errors, see section 3):

$$S^- \equiv \int_0^1 \mathrm{d}x\, x\, s^-(x) \approx 0.0020 \pm 0.0005 \qquad \text{at} \quad Q^2 = 20\,\mathrm{GeV}^2\,. \tag{2.1}$$

The charge symmetry of the strange sea is not dictated by any fundamental principle. Of course, the proton has no net strangeness, but this only requires

$$\int_0^1 \mathrm{d}x\, s^-(x) = 0\,, \tag{2.2}$$

that is a vanishing first moment of $s^-(x)$. As for s^- itself and its higher moments, they are not forced to be zero. Some non perturbative models [7] assume the existence, inside the proton, of a sea of intrinsic $q\bar{q}$ pairs, characterized by a relatively long timescale. Before recombining, these pairs interact with other partons and manifest themselves in meson-baryon fluctuations. For the strange sector, the relevant process is $p \to \Lambda\, K^+$, and since pseudoscalar mesons have small masses, the average momentum fraction of the $\bar{s}$ antiquark in the K^+ is expected to be smaller than the average momentum fraction of the s quark coming from the Λ. The prediction of the intrinsic-sea models is therefore consistent in sign (and in magnitude) with (2.1). Recently, Catani et al. [8] have pointed out that a strange asymmetry can also be generated perturbatively by NNLO evolution of valence distributions, due to the difference of flavor non diagonal splitting functions $P_{qq}^{\mathrm{ND}} - P_{q\bar{q}}^{\mathrm{ND}}$, which is non zero at order α_s^2. With $s - \bar{s} = 0$ at the initial scale, one gets

$$S^- \equiv \int_0^1 \mathrm{d}x\, x\, s^-(x) \approx -0.0005 \qquad \text{at} \quad Q^2 = 20\,\mathrm{GeV}^2\,. \tag{2.3}$$

which is a *negative*, but tiny, asymmetry. Therefore, a sizable and positive strange asymmetry (which would help to reduce the discrepancy between the NuTeV result on $\sin^2\theta_W$ and the SM expectations, see below) can only have a non perturbative origin.

The s^- distribution can be extracted from the difference of ν and $\bar{\nu}$ inclusive DIS cross sections. Sticking for illustration to leading order, one has

$$\frac{\mathrm{d}^2\sigma^{\nu N}}{\mathrm{d}x\,\mathrm{d}y} - \frac{\mathrm{d}^2\sigma^{\bar{\nu} N}}{\mathrm{d}x\,\mathrm{d}y} \propto xs^- + \left[1 - (1-y)^2\right](xu_v + xd_v)\,. \tag{2.4}$$

Since valence distributions are well constrained by other data, the quantity (2.4) is highly sensitive to s^-. What determines the strange asymmetry found in [1] is indeed the large-x (and large-y) CDHSW data, which are quite precise. Admittedly, a cross section difference is a delicate quantity to fit.

Another important source of information on strangeness is dimuon production in charged current $\nu(\bar{\nu})$ DIS. This process probes directly the strange sea, as it involves transitions of the type $W^+s \to c$ and W-gluon fusion processes $W^+g \to \bar{s}c$. However, the dimuon cross section $d\sigma_{2\mu}$ is related to the charm production cross section $d\sigma_{\rm charm}$, which contains the strange distributions, via some factor incorporating the details of fragmentation and acceptance corrections, which is experimentally computed by a Monte Carlo. The NuTeV Collaboration has published rather precise data on $d\sigma_{2\mu}$ [9], but the quantity which is theoretically relevant, that is $d\sigma_{\rm charm}$, is not yet accessible. Moreover, the Monte Carlo they use to relate $d\sigma_{2\mu}$ to $d\sigma_{\rm charm}$, and to extract the strange sea distributions, is based on a LO analysis.[2] From past experience (compare the results in [9] and [11, 12], and see the discussion in [13]) we know that the NLO correction to the strange distributions obtained from dimuon data can be as large as 50 %. Therefore, including the NuTeV dimuon data in a NLO fit raises serious consistency problems and may yield unreliable quantitative results. For this reason we do not use here the leading-order NuTeV dimuon data, but we look forward to a more comprehensive fit as soon as NuTeV will release data on $d\sigma_{\rm charm}$ reconstructed by a NLO analysis.

3. The fit

The global fit reported in the present paper incorporates: structure functions from charged-lepton DIS experiments: H1 [14], ZEUS [15], BCDMS [16] and NMC [17]; neutrino and anti-neutrino DIS cross section data from BEBC [18], CDHS [19], CDHSW [20] and CCFR [3]; Drell-Yan measurements: E605 [21], E772 [22] and E866 [23]. In particular, our database includes most of the available charged-current HERA data and the latest Drell-Yan results from Fermilab.

In order to avoid higher-twist effects we applied the cuts $Q^2 \geq 3.5\,\mathrm{GeV}^2$ and $W^2 \geq 10\,\mathrm{GeV}^2$. In this region, target mass corrections are also very small (but they have been taken into account). The strong coupling is set at the value $\alpha_s(M_Z^2) = 0.117$.

Imposing the isospin symmetry leads to the following relations among the pdf's: $u^p = d^n \equiv u$, $d^p = u^n \equiv d$, $\bar{u}^p = \bar{d}^n \equiv \bar{u}$, $\bar{d}^p = \bar{u}^n \equiv \bar{u}$, $s^p = s^n \equiv s$, $\bar{s}^p = \bar{s}^n \equiv \bar{s}$. The pdf's are parametrized at $Q_0^2 = 4\,\mathrm{GeV}^2$ as follows:

$$xu_v(x,Q_0^2) = A_{u_v}\, x^{B_{u_v}}\, (1-x)^{C_{u_v}}\, (1 + D_{u_v}\, x^{E_{u_v}})\,, \tag{3.1}$$
$$xd_v(x,Q_0^2) = A_{d_v}\, x^{B_{d_v}}\, (1-x)^{C_{d_v}}\, (1 + D_{d_v}\, x^{E_{d_v}})\,, \tag{3.2}$$
$$x(\bar{u}+\bar{d})(x,Q_0^2) = A_+\, x^{B_+}\, (1-x)^{C_+}\, (1 + D_+\, x^{E_+})\,, \tag{3.3}$$
$$x(\bar{d}-\bar{u})(x,Q_0^2) = A_-\, x^{B_-}\, (1-x)^{C_-}\, (1 + D_-\, x)\,, \tag{3.4}$$
$$xs(x,Q_0^2) = A_s\, x^{B_s}\, (1-x)^{C_s}\, (1 + D_s\, x^{E_s})\,, \tag{3.5}$$

[2] A preliminary NLO analysis of dimuon data has been presented in [10].

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exp.	# pts	χ^2
Charged–lepton DIS data		
H1 (low Q^2)	125	126.4
H1 (e^+p, NC)	277	267.3
H1 (e^+p, CC)	53	71.9
H1 (e^-p, NC)	139	135.9
H1 (e^-p, CC)	28	19.4
ZEUS (e^+p, NC)	237	291.6
ZEUS (e^+p, CC)	29	31.6
ZEUS (e^-p, NC)	92	58.9
ZEUS (e^-p, CC)	26	23.4
BCDMS (μd)	170	133.8
BCDMS (μp)	228	242.7
NMC (μd)	209	245.0
NMC (μp)	209	335.8
Neutrino DIS data		
BEBC (νd)	70	74.4
BEBC ($\bar{\nu} d$)	49	50.8
BEBC (νp)	68	68.2
BEBC ($\bar{\nu} p$)	49	75.7
CDHSW (νFe)	494	382.5
CDHSW ($\bar{\nu}$Fe)	492	293.8
CDHS (νp)	45	58.2
CDHS ($\bar{\nu} p$)	42	54.7
CCFR (νFe)	1892	1840.8
CCFR ($\bar{\nu}$Fe)	775	719.1
Drell-Yan data		
E605 (DY, pCu)	136	112.5
E772 (DY, pd)	212	223.9
E866 (DY, pp/pd)	15	13.55

Table 1: DIS and Drell-Yan data included in our fit, with the corresponding χ^2 values.

$$x\bar{s}(x, Q_0^2) = A_{\bar{s}}\, x^{B_{\bar{s}}} (1-x)^{C_{\bar{s}}} (1 + D_{\bar{s}}\, x^{E_{\bar{s}}}) \,, \tag{3.6}$$

$$xg(x, Q_0^2) = A_g\, x^{B_g} (1-x)^{C_g} (1 + D_g\, x^{E_g}) \,. \tag{3.7}$$

Some of the parameters in eqs. (3.1)–(3.7) are determined by physical constraints: A_g is fixed by the momentum sum rule, $\int_0^1 [xg + x \sum_i (q_i + \bar{q}_i)]\, \mathrm{d}x = 1$; A_{u_v} and A_{d_v} are fixed by the number sum rules $\int_0^1 u_v\, \mathrm{d}x = 2$ and $\int_0^1 d_v\, \mathrm{d}x = 1$. While the intermediate-x and large-x shape of the strange distribution is well constrained by the data entering the fit, the small-x behavior is not. Thus we set $A_s = A_{\bar{s}}$ and $B_s = B_{\bar{s}} = B_+$. We also set $B_{u_v} = B_{d_v} = B_-$, as suggested by Regge theory. One more parameter of s and $\bar{s}$ is fixed by imposing $\int_0^1 (s - \bar{s})\, \mathrm{d}x = 0$ (no net strangeness).

The details of the fit are illustrated in [1]. Here we just recall that the correlations between data points induced by systematic uncertainties for which information is available are taken into account. All the neutrino and antineutrino DIS data with nuclear targets

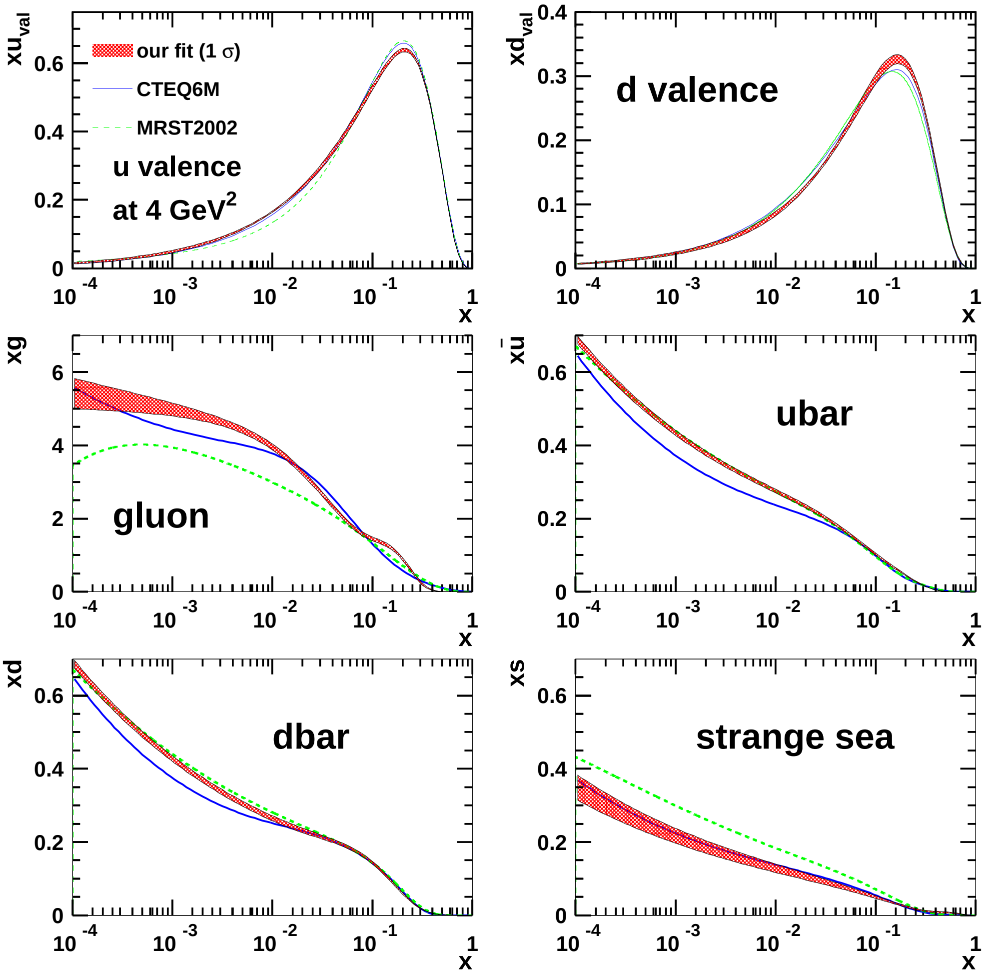

Figure 1: The parton distribution functions as obtained in our fit. The meaning of the error bands is explained in the text.

(deuteron or heavy nuclei) have been corrected for nuclear effects as explained in [1]. The χ^2 values for each data set are collected in table 1. The total χ^2 per degree of freedom is $\chi^2/\mathrm{dof} = 5945.15/(6161 - 21)$.

The resulting pdf's are shown in figure 1 (where they are compared to MRST2002 [24] and CTEQ6M [25]); the parameters of eqs. (3.1)–(3.7) are listed in table 2. The curves are accompanied by error bands obtained as follows. Calling $\boldsymbol{p} \equiv \{p_1, \ldots, p_n\}$ the vector of the free parameters of the fit, the width of the error band of some function $f(x, Q^2, \boldsymbol{p})$ is given at each (x, Q^2) point by [1, 26]:

$$\Delta f(x, Q^2; \boldsymbol{p}_0) = |f(x, Q^2; \boldsymbol{p}_0 + \boldsymbol{\Delta}_p(x, Q^2)) - f(x, Q^2; \boldsymbol{p}_0 - \boldsymbol{\Delta}_p(x, Q^2))|, \tag{3.8}$$

where $\boldsymbol{p}_0$ denotes the parameter set minimising the χ^2 and the vector $\boldsymbol{\Delta}_p(x, Q^2) \equiv \{\Delta_{p_1} \times (x, Q^2), \ldots, \Delta_{p_n}(x, Q^2)\}$ is given by

$$\boldsymbol{\Delta}_p(x, Q^2) = \frac{M^{-1}\boldsymbol{\partial}_p f(x, Q^2; \boldsymbol{p})}{\sqrt{\boldsymbol{\partial}_p f(x, Q^2; \boldsymbol{p}) M^{-1} \boldsymbol{\partial}_p f(x, Q^2; \boldsymbol{p})}} \tag{3.9}$$

	A	B	C	D	E
u_v	1.967	0.534	4.141	1.139497	5.841
d_v	0.932	0.534	4.865	0.80158	5.109
$\bar{u}+\bar{d}$	0.102	-0.208	9.060	0.922	7.914
$\bar{d}-\bar{u}$	0.139	0.534	18.872	1.0	-46.594
s	0.052	-0.208	4.950	6.352	251.137
$\bar{s}$	0.052	-0.208	5.084	3.911	48.973
g	4.117	-0.030	17.739	3.136	1538.793

Table 2: Parameters of the pdf's (see eqs. (3.1)–(3.7)).

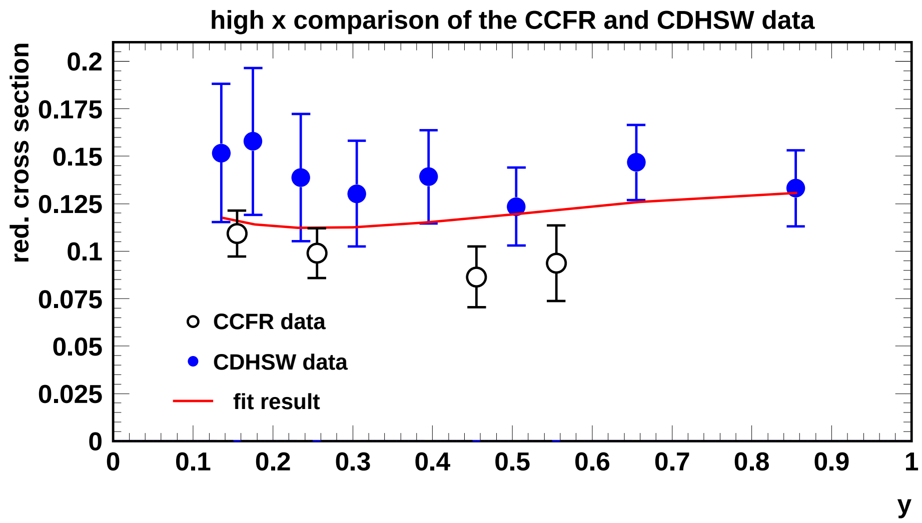

Figure 2: The reduced νDIS cross section.

with $M_{ij} = (1/2)\,\partial^2\chi^2/\partial p_i \partial p_j$ and $\boldsymbol{\partial}_p \equiv \{\partial/\partial p_1, \ldots, \partial/\partial p_n\}$. Note that the errors do not account for the uncertainties related to the functional form of the pdf's, but are determined by the abundance and the precision of the data, and by the constraints imposed on the pdf's. They represent an estimate of the goodness of the fit and correspond to an increase of the χ^2 by one unit (there other criteria for estimating the goodness of the fit, which give larger uncertainties, see [27]).

We already recalled that the strange-sea distributions are essentially determined by $\nu(\bar{\nu})$ DIS data. In our fit we have two major series of neutrino and antineutrino measurements, CDHSW [20] and CCFR [3]. Both experiments provide high-x data: while they agree for antineutrino DIS, in the case of neutrino DIS the CDHSW cross sections tend to be systematically higher, as one can see from figure 3, where the reduced cross section

$$\frac{\mathrm{d}^2\sigma_{\mathrm{red}}}{\mathrm{d}x\,\mathrm{d}y} = \frac{2\pi(M_W^2+Q^2)^2}{G_F^2 M_N M_W^4 E}\frac{1}{Y}\frac{\mathrm{d}^2\sigma}{\mathrm{d}x\,\mathrm{d}y}\,, \qquad Y = 1+(1-y)^2 - \frac{M_N x y}{E} \tag{3.10}$$

is shown for $x = 0.65$ and $E_\nu = 110\,\mathrm{GeV}$. Our curve lies between the two sets of data, being closer to CCFR at low y (where CDHSW data are more uncertain), and to CDHSW at high y (where there are no CCFR data).

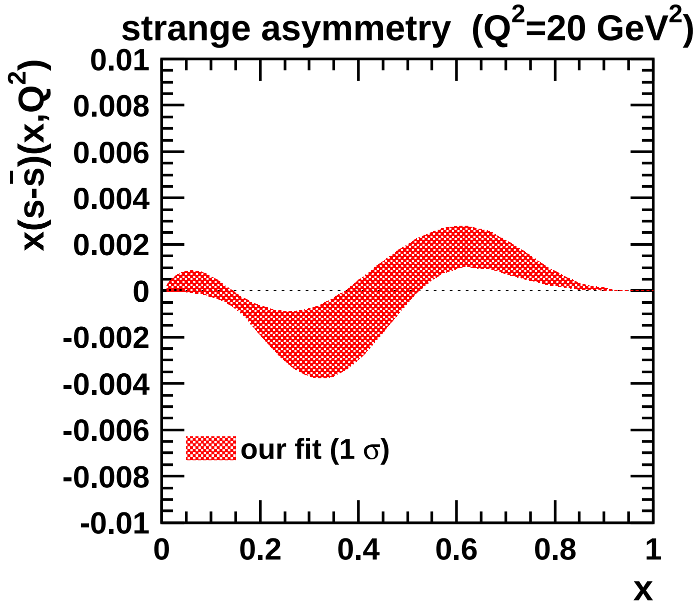

Figure 3: The distribution $s^-(x) = s(x) - \bar{s}(x)$ at $Q^2 = 20\,\text{GeV}^2$, as obtained in our fit.

The strange-antistrange asymmetry we obtained from our fit is plotted in figure 3. It is much smaller than the asymmetry found in our previous fits [1] which contained only the CDHSW cross section data. We find in fact

$$S^- \equiv \int_0^1 \mathrm{d}x\, x\, s^-(x) = (1.8 \pm 3.8) \times 10^{-4} \qquad \text{at} \quad Q^2 = 20\,\text{GeV}^2\,, \tag{3.11}$$

to be compared with the old value (2.1).

As already said, opposite-sign dimuon production in $\nu(\bar{\nu})$ DIS provides further information on the strange sea. The NuTeV dimuon data are not statistically significant for $x > 0.5$ but constrain the strange-sea densities at small x. Therefore, they affect the large-x region in an indirect way, because of the sum rule (2.2). A recent study by Olness et al. [27] shows that the NuTeV dimuon data drive a bump of $s^-(x)$ in the medium-large x region, in qualitative agreement with the finding of [1] (except for the position of the bump, which in our previous fit was driven to larger x by the CDHSW data). These authors conclude that the dimuon data tend to favor a positive strange-antistrange asymmetry, differently from the results of [9] (where, however, the sum rule (2.2) was violated).

4. Implications on the Weinberg angle extraction

The NuTeV experiment [5] uses a fit to the measured ratios of neutral current to charged current cross sections $R^{\nu(\bar{\nu})} = \sigma_{NC}^{\nu(\bar{\nu})}/\sigma_{CC}^{\nu(\bar{\nu})}$ to determine $\sin^2\theta_W$. They obtain the value

$$\sin^2\theta_W = 0.2277 \pm 0.0013\,(\text{stat.}) \pm 0.0003\,(\text{syst.}) \pm 0.0006(\text{theor.}) \tag{4.1}$$

The theoretical error incorporates uncertainties on charm production, strange and charmed sea, non-isoscalarity of the target, etc. Adding the errors in quadrature, one gets

$$\sin^2\theta_W = 0.2277 \pm 0.0016\,, \tag{4.2}$$

which is about 3σ larger than the value obtained by a standard model fit to other electroweak measurements, $\sin^2\theta_W = 0.22272 \pm 0.00036$ [28].

The Weinberg angle is directly related to another quantity, the Paschos-Wolfenstein ratio R, which is the combination

$$R = \frac{\sigma^{\nu}_{NC} - \sigma^{\bar\nu}_{NC}}{\sigma^{\nu}_{CC} - \sigma^{\bar\nu}_{CC}}\,. \tag{4.3}$$

In the parton model, and for an isoscalar target, R is simply given by

$$R = \frac{1}{2} - \sin^2\theta_W\,. \tag{4.4}$$

For a non isoscalar target like iron (the target used in the NuTeV experiment), including QCD corrections at order $\mathcal{O}(\alpha_s)$ and making no symmetry assumptions about the pdf's, one finds three extra terms [6, 29]:

$$R = \frac{1}{2} - \sin^2\theta_W + \delta R_s + \delta R_N + \delta R_{\rm iso}\,, \tag{4.5}$$

with ($q^- \equiv q - \bar q$ and $Q \equiv \int {\rm d}x\, xq(x)$, $\delta N \equiv (N-Z)/A$, $n \equiv N/A$)

$$\delta R_s = -\frac{S^-}{U^- + D^-}\, C(\theta_W)\,, \tag{4.6}$$

$$\delta R_N = -\delta N\,\frac{U^- - D^-}{U^- + D^-}\, C(\theta_W)\,, \tag{4.7}$$

$$\delta R_{\rm iso} = n\,\frac{\delta U^- - \delta D^-}{U^- + D^-}\, C(\theta_W)\,, \tag{4.8}$$

and

$$C(\theta_W) \equiv 1 - \frac{7}{3}\sin^2\theta_W + \frac{8\,\alpha_s}{9\pi}\left(\frac{1}{2} - \sin^2\theta_W\right). \tag{4.9}$$

In (4.6)–(4.8) we neglected terms of order $(U^- + D^-)^{-2}$, and all distributions refer to protons, except δU and δD which are isospin violating proton-neutron differences: $\delta U = U_p - D_n$, $\delta D = D_p - U_n$. The three corrections (4.6)–(4.8) have the following meaning: δR_s is proportional to the strange asymmetry S^- (with a minus sign in front); δR_N is the neutron excess correction (proportional to δN, which is 0.0574 for the NuTeV target); $\delta R_{\rm iso}$ is the isospin violation correction, arising from a possible non equality of u_p and d_n, and of d_p and u_n (in our analysis we impose isospin invariance, hence $\delta R_{\rm iso}$ is identically zero[3]).

[3] Various studies [30 – 32] show that the isospin violation correction may be quantitatively relevant and in the direction of reducing the NuTeV anomaly.

NuTeV consider only the neutron excess correction and report [33, 5]

$$\delta R_N = -0.0080 \pm 0.00005 \qquad \text{(NuTeV)} \tag{4.10}$$

(note the extremely small uncertainty). In our fit we find

$$\delta R_N = -0.0107 \pm 0.0005 \qquad \text{(this analysis)} \tag{4.11}$$

Taking the difference between (4.11) and (4.10) one can roughly evaluate the corresponding shift of $\sin^2\theta_W$: the result is $\sin^2\theta_W = 0.2249 \pm 0.0017$, which is now only $1.4\,\sigma$ above the standard model prediction. According to McFarland and Moch [34], the discrepancy between (4.11) and (4.10) can be understood in terms of experimental cuts and of the differences between the NuTeV fit to $R^{\nu,\bar{\nu}}$ and the Paschos-Wolfenstein ratio R that we are considering here. Using the tools provided in [34], we checked that only half of the difference between (4.11) and (4.10) is attributable to experimental cuts. The main point, however, is that the uncertainty we find on δR_N, due to the imperfect knowledge of the parton distributions, is one order of magnitude larger than the corresponding uncertainty evaluated by NuTeV (as first pointed out by Kulagin [29]).[4] As for the strange asymmetry contribution, due to the smallness of S^-, it is a tiny correction to the Paschos-Wolfenstein ratio, namely $\delta R_s = 2.5 \times 10^{-5}$.

Concluding this section, we notice that there are two possible ways to solve the NuTeV $\sin^2\theta_W$ anomaly: (i) the first way consists in finding large negative corrections to R; (2) the second, in discovering that the uncertainties of the experimental result are larger, so that the discrepancy with the world average value becomes less significant. From various studies [6, 29, 27], including the present one, it seems that a combination of the two possibilities occurs: there are non negligible, and probably quite relevant, nuclear and strangeness corrections with the right (negative) sign; on top of that, the error related to the imperfect knowledge of the pdf's is much larger than the one estimated by NuTeV. Another relevant source of uncertainty concerns the electroweak radiative correction: also in this case the NuTeV estimates seem to be too optimistic [35].

5. Final remarks

We presented a comprehensive and up-to-date NLO fit of DIS and Drell-Yan data, devoting a particular attention to the strange sector and to the valence. Using both the CDHSW and the CCFR measurements, we found that the strange sea asymmetry is very small. The main limitation of our fit is the lack of data on dimuon production in $\nu(\bar{\nu})$ DIS. Hence, a natural development of the present work will be the inclusion of the dimuon cross sections, as soon as the data on them will be suitable to a NLO analysis. This would lead to a more precise determination of $s^-(x)$ and to a further check of the strange-antistrange asymmetry.

[4] We should mention that the authors of [34] state that the uncertainty on the neutron excess correction estimated by NuTeV is 0.0003, in contrast with the much smaller value quoted in the original paper [5].

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