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NEW RELATIONS IN LEPTON-NUCLEON SCATTERING, INDEPENDENT OF THE NUCLEON STRUCTURE

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Precise measurement of the Standard Model (SM) parameters and the search for new-physics requires effort for elimination of theoretically weekly controllable factors. In lepton-nucleon scattering this is first of all the nucleon structure functions (SF) and form factors of the nucleon (FFN). Neither of them was found from the first principles of the theory as yet. So the values of SM parameters extracted from the experimental data, in principle, may have large systematic errors due to the uncertainty in the theoretical description of the nucleon structure. On the other hand, in νN-scattering there are relations for special combinations of cross sections (CS) which allow this uncertainty to be eliminated. A well known example is the Paschos-Wolfenstein relation [1]:

$$R_1(\nu) = \frac{\sigma_{NC}(\nu N^{I=0}) - \sigma_{NC}(\bar{\nu} N^{I=0})}{\sigma_{CC}(\nu N^{I=0}) - \sigma_{CC}(\bar{\nu} N^{I=0})} = \rho^2\left(\frac{1}{2} - \sin^2\theta_W\right). \qquad (1)$$

Despite the fact that the formula involves the CS of deep inelastic νN-scattering ($N^{I=0}$ is the isoscalar target), the right hand side of the relation containes only the SM parameters ρ, $\sin^2\theta_W$ and is independent of SF.

In this paper we shall obtain similar relations for deep inelastic and (quasi-)elastic scattering of longitudinally polarized electrons and positrons or $\mu^{\pm}$-mesons on non-polarized nucleons. Let us start from a more detailed consideration of such relations for $\overset{(-)}{\nu}$N-scattering and introduce the notation:

$$R_2(\nu) = \frac{(\sigma^{\nu p} - \sigma^{\nu n})_{NC} + (\sigma^{\bar{\nu} p} - \sigma^{\bar{\nu} n})_{NC}}{(\sigma^{\nu p} - \sigma^{\nu n})_{CC} - (\sigma^{\bar{\nu} p} - \sigma^{\bar{\nu} n})_{CC}}, \qquad (2)$$

$$R_3(\nu) = \frac{(\sigma^{\nu p} - \sigma^{\nu n})_{NC} - (\sigma^{\bar{\nu} p} - \sigma^{\bar{\nu} n})_{NC}}{(\sigma^{\nu p} - \sigma^{\nu n})_{CC} + (\sigma^{\bar{\nu} p} - \sigma^{\bar{\nu} n})_{CC}}, \qquad (3)$$

$$R_4(\nu) = \frac{(\sigma^{\nu p} + \sigma^{\nu n})_{NC} + (\sigma^{\bar{\nu} p} + \sigma^{\bar{\nu} n})_{NC}}{(\sigma^{\nu p} + \sigma^{\nu n})_{CC} + (\sigma^{\bar{\nu} p} + \sigma^{\bar{\nu} n})_{CC}}, \qquad (4)$$

$$R_5(\nu) = \frac{(\sigma^{\nu p} - \sigma^{\bar{\nu} p})^{el}_{NC}}{(\sigma^{\nu n} - \sigma^{\bar{\nu} p})^{el}_{CC}}, \qquad R_6(\nu) = \frac{(\sigma^{\nu n} - \sigma^{\bar{\nu} n})^{el}_{NC}}{(\sigma^{\nu n} - \sigma^{\bar{\nu} p})^{el}_{CC}} \qquad (5)$$

$$R_7(\nu) = \frac{(\sigma^{\nu p} + \sigma^{\nu n})^{el}_{NC} - (\sigma^{\bar{\nu} p} + \sigma^{\bar{\nu} n})^{el}_{NC}}{(\sigma^{\nu n} - \sigma^{\bar{\nu} p})^{el}_{CC}} = R_5(\nu) + R_6(\nu). \qquad (6)$$

In formulae (1)-(4) $\sigma_{NC,CC}(\overset{(-)}{\nu} p)$, $\sigma_{NC,CC}(\overset{(-)}{\nu} n)$, $\sigma_{NC,CC}(\overset{(-)}{\nu} N^{I=0})$ are the total CS of deep inelastic $\overset{(-)}{\nu}$p-, $\overset{(-)}{\nu}$n- and $\overset{(-)}{\nu} N^{I=0}$-scattering. Formulae (5),(6) involve the total CS of (quasi-)elastic scattering. We shall also use the quantities $\tilde{R}_i(\nu)$, obtained from $R_i(\nu)$ by substituting the differential CS $\frac{d^2\sigma}{dxdQ^2}$ and $\frac{d\sigma}{dQ^2}$ for the total one in formulae (1)-(4) and (5)-(6), respectively. All the results given below remain valid if the p and n in formulae (1)-(4) are replaced by arbitrary nuclei A_1 and A_2 with different isospins.

The nucleon-structure independent relations have the following form for deep inelastic $\overset{(-)}{\nu}$N- scattering [1,2]:

$$R_1(\nu) = \tilde{R}_1(\nu) = \frac{\alpha\beta + \gamma\delta}{2}, \qquad (7)$$

$$R_2(\nu) = \tilde{R}_2(\nu) = -\frac{\alpha\gamma + \beta\delta}{2}, \quad R_3(\nu) = \tilde{R}_3(\nu) = -\frac{\alpha\delta + \gamma\beta}{2}, \qquad (8)$$

$$R_4(\nu) = \tilde{R}_4(\nu) = \frac{\alpha^2 + \beta^2 + \gamma^2 + \delta^2}{4} \qquad (9)$$

and for (quasi-)elastic $\overset{(-)}{\nu}$N- scattering [3]:

$$R_{5,\sigma}(\nu) = \tilde{R}_{5,\sigma}(\nu) = \frac{2\lambda\delta \pm \beta}{4\cos^2\theta_c}\{3\gamma f \pm \alpha\}, \qquad (10)$$

$$R_7(\nu) = \tilde{R}_7(\nu) = \frac{1}{2\cos^2\theta_c}\{\alpha\beta + 6\lambda\gamma\delta f\}, \qquad (11)$$

where $f = \frac{\mu_p+\mu_n}{\mu_p-\mu_n}$ and $\mu_p = 2.79$, $\mu_n = -1.91$ are the total magnetic moment of the proton and neutron. Formula (7) is a general form of Pashcos-Wolfenstein relation (1). The parameters $\alpha,\beta,\gamma,\delta$ determine the structure of the weak hadronic neutral current (NC):

$$J^{NC}_{h\,\mu} = \frac{\alpha}{2} V^3_\mu + \frac{\beta}{2} A^3_\mu + \frac{\gamma}{2} V^0_\mu + \frac{\delta}{2} A^0_\mu. \qquad (12)$$

Here $V^{3,0}_\mu$, $A^{3,0}_\mu$ are the vector and axial-vector currents. At the tree level in the SM $\alpha = \rho(1-2x_W)$, $\beta = \rho$, $\gamma = -\frac{2}{3}\rho x_W$, $\delta = 0$, where $x_W = \sin^2\theta_W$ and $\rho = \frac{M_W^2}{\cos^2\theta_W M_Z^2}$. The parameter λ in formulae (10)-(11) fixes the normalization of the weak axial isoscalar FFN $F_A^{(0)}(0) = \lambda C_A$, $C_A = 1.25\pm0.06$ [4]. It can be taken from the experiment or calculated, for example, within the non-relativistic SU(6)-quark model. In the last case $\lambda=0.3$. Since δ is small, a slight difference in values of λ in different approaches has negligible influence on R_{5-7}.

Now we turn to $e(\mu)N$- scattering. Nucleon-stucture independent relations can be directly obtained from relations (7)-(11). To make this, we note the following.

Despite the fact that according to the standard Lagrangian

$$-\mathcal{L} = e\,J^{em}_\mu A^\mu + \frac{g}{\cos\theta_W} J^{NC}_\mu Z^\mu + \frac{g}{\sqrt{2}}(J^+_\mu W^\mu + J^-_\mu W^\mu) \qquad (13)$$

both weak and electromagnetic interactions contribute to $e^\pm(\mu^\pm)N$- scattering this process can be described in the Born approximation by the similar effective 4-fermion Lagrangian as $\overset{(-)}{\nu}N$- scattering. After simple transformation we obtain from (13):

$$-\mathcal{L}_{eff} = \frac{4G}{\sqrt{2}}\bar{\nu}_L\gamma_\mu e_L J_h^{-\mu} + \frac{4G}{\sqrt{2}}\bar{e}_L\gamma_\mu\nu_L J_h^{+\mu} + \frac{4G}{\sqrt{2}}\bar{\nu}_L\gamma_\mu\nu_L J_h^{NC\mu} +$$
$$\frac{4G}{\sqrt{2}}\bar{e}_L\gamma_\mu e_L \tilde{J}^{\mu}_{(L)} + \frac{4G}{\sqrt{2}}\bar{e}_R\gamma_\mu e_R \tilde{J}^{\mu}_{(R)}. \qquad (14)$$

The effective hadronic current is introduced:

$$\tilde{J}_{(i)\mu} = 2\varepsilon^e_i J^{NC}_{h\,\mu} - \frac{1}{2}\chi\frac{m_p^2}{Q^2} J^{em}_{h\,\mu}, \quad i = L,R; \qquad (15)$$

$$\chi = 2\pi\alpha\sqrt{2}/\,Gm_p^2 \approx 0.6\ 10^4. \qquad (16)$$

Here $\varepsilon^e_L = -\frac{1}{2} + x_W$, $\varepsilon^e_R = x_W$ are the chiral constants of the electron. Using the standard parametrization, we write down

$$\tilde{J}_{(i)\mu} = \frac{\alpha_i(Q^2)}{2}V^3_\mu + \frac{\beta_i(Q^2)}{2}A^3_\mu + \frac{\gamma_i(Q^2)}{2}V^0_\mu + \frac{\delta_i(Q^2)}{2}A^0_\mu. \qquad (17)$$

Taking into account that $J^{em}_{h\mu} = V^3_\mu + \frac{1}{3}V^0_\mu$ and using (15) we find the effective current parameters:

$$\alpha_i(Q^2) = 2\varepsilon^e_i\alpha - \chi\frac{m_p^2}{Q^2}, \quad \gamma_i(Q^2) = 2\varepsilon^e_i\gamma - \frac{1}{3}\chi\frac{m_p^2}{Q^2}, \qquad (18)$$
$$\beta_i(Q^2) = 2\varepsilon^e_i\beta, \qquad \delta_i(Q^2) = 2\varepsilon^e_i\,\delta.$$

Lagrangian (14) has an obvious symmetry. The charged current (CC) part does not change at the $\nu \leftrightarrow e$, $J^+ \leftrightarrow J^-$ substitutions and the NC part does not change at the $\nu_L \leftrightarrow e_L$, $\tilde{J}_{(L)} \leftrightarrow J^{NC}$, or $\nu_L \leftrightarrow e^c_L$, $\tilde{J}_{(R)} \leftrightarrow J^{NC}$ substitutions.

So, at high energies, when the electron (muon) mass can be ignored, the substitutions $\nu_L(\bar{\nu}_R) \leftrightarrow e^-_L(e^+_R)$, $p \leftrightarrow n$ in the CC differential CS and $\nu_L(\bar{\nu}_R) \leftrightarrow e^\mp_L$ $(e^\pm_R)$, $\alpha,\beta,\gamma,\delta \leftrightarrow \alpha_{L,R}, \beta_{L,R}, \gamma_{L,R}, \delta_{L,R}$ in the NC differential CS leave these CS unchanged.

Using this property it is easy to connect eN- scattering with $\overset{(-)}{\nu}N$- scattering, and, in particular, to generalize relations (7)-(11). We write them down as:

$$\tilde{R}_i(\nu) = \frac{N_i(\nu\bar{\nu}pn|x,y)}{C_i(\nu\bar{\nu}pn|x,y)} = \varphi_i(\alpha,\beta,\gamma,\delta). \qquad (19)$$

$N_i(x,y)$, $C_i(x,y)$ are the combinations of NC and CC cross sections mentioned in (1)-(6), φ_i is the function of parameters α, β, γ, δ independent of the nucleon structure and kinematic variables. For example, $N_1=\frac{d^2\sigma^{NC}}{dxdQ^2}(\nu N^{I=0})-\frac{d^2\sigma^{NC}}{dxdQ^2}(\bar{\nu}N^{I=0})$, $C_1=\frac{d^2\sigma^{CC}}{dxdQ^2}(\nu N^{I=0})-\frac{d^2\sigma^{CC}}{dxdQ^2}(\bar{\nu}N^{I=0})$ and $\varphi_1=\frac{\alpha\beta+\gamma\delta}{2}$. Relation (19) will be satisfied if

$$N_i(\nu\bar{\nu}pn|x,y) = f_i(x,Q^2)\,\varphi_i(\alpha,\beta,\gamma,\delta), \qquad (20)$$

$$C_i(\nu\bar{\nu}pn|x,y) = f_i(x,Q^2), \qquad (21)$$

where $f_i(x,Q^2)$ is the quantity absorbing the whole dependence on the nucleon structure (SF and FFN).

Now we may write down:

$$N_i(e_L^{\mp}\ e_R^{\pm}\ pn|x,y)=f_i(x,Q^2)\varphi_i(\alpha_{L,R}(Q^2),\beta_{L,R}(Q^2),\gamma_{L,R}(Q^2),\delta_{L,R}(Q^2)),$$

$$C_i(e_L^-\ e_R^+\ np|x,y) = f_i(x,Q^2). \qquad (22)$$

Combining these equations in such a way that the factor f_i is cancelled, we obtain three types of relations for differential CS of $e(\mu)N$- scattering:

$$\tilde{R}_{iL,R}=\frac{N_i(e_L^{\mp}e_R^{\pm}pn|x,y)}{C_i(e_L^-e_R^+np|x,y)}=\varphi_i(\alpha_{L,R}(Q^2),\beta_{L,R}(Q^2),\gamma_{L,R}(Q^2),\delta_{L,R}(Q^2)), \qquad (23)$$

$$\tilde{R}_{iN} = \frac{N_i(e_L^-e_R^+pn|x,y)}{N_i(e_L^+e_R^-pn|x,y)} = \frac{\varphi_i(\alpha_L(Q^2),\beta_L(Q^2),\gamma_L(Q^2),\delta_L(Q^2))}{\varphi_i(\alpha_R(Q^2),\beta_R(Q^2),\gamma_R(Q^2),\delta_R(Q^2))}. \qquad (24)$$

After substituting $\alpha_l,\beta_l,\gamma_l,\delta_l$ in formulae (18) we retain only the leading term in the large parameter $\chi \approx 10^4$ on the right hand side, which maintains the accuracy of about 1-2% for this relation at $Q^2 < 10^3 GeV^2$ and 0.1-0.2% at $Q^2 < 10^2 GeV^2$. As a result, the following relations with the dependence on x_w and ρ remain:

$$\tilde{R}_{1L,R} = \frac{N_1^{\pm}}{C_1} = -\chi\frac{m_p^2}{Q^2}\,\varepsilon_{L,R}^e(\beta + \frac{\delta}{3}) = -\chi\frac{m_p^2}{Q^2}(\rho\varepsilon_{L,R}^e), \qquad (25)$$

$$\tilde{R}_{3L,R} = \frac{N_3^{\pm}}{C_3} = -\chi\frac{m_p^2}{Q^2}\,\varepsilon_{L,R}^e(\delta + \frac{\beta}{3}) = -\chi\frac{m_p^2}{Q^2}(\frac{\rho}{3}\,\varepsilon_{L,R}^e), \qquad (26)$$

$$R_{5L,R}=\frac{N_5^{\pm}}{C_5}= -\frac{\chi m_p^2}{Q^2}\,\frac{\varepsilon_{L,R}^e}{2\cos^2\theta_c}(f+1)(2\lambda\delta+\beta)= -\frac{\chi m_p^2}{Q^2}\frac{\varepsilon_{L,R}^e}{2\cos^2\theta_c}(f+1)(\rho\varepsilon_{L,R}^e), \qquad (27)$$

$$\tilde{R}_{6L,R}=\frac{N_6^{\pm}}{C_6}= -\frac{\chi m_p^2}{Q^2}\,\frac{\varepsilon_{L,R}^e}{2\cos^2\theta_c}(f-1)(2\lambda\delta-\beta)= \frac{\chi m_p^2}{Q^2}\frac{\varepsilon_{L,R}^e}{2\cos^2\theta_c}(f-1)(\rho\varepsilon_{L,R}^e), \qquad (28)$$

$$\tilde{R}_{7L,R}=\frac{N_7^{\pm}}{C_7}= -\frac{\chi m_p^2}{Q^2}\,\frac{\varepsilon_{L,R}^e}{\cos^2\theta}(2\lambda\delta f+\beta)= -\frac{\chi m_p^2}{Q^2}\frac{\varepsilon_{L,R}^e}{\cos^2\theta_c}\,(\rho\varepsilon_{L,R}^e), \qquad (29)$$

$$\tilde{R}_N = \frac{N_1^+}{N_1^-} = \frac{N_3^+}{N_3^-} = \frac{N_5^+}{N_5^-} = \frac{N_6^+}{N_6^-} = \frac{N_7^+}{N_7^-} = \frac{\varepsilon_L^e}{\varepsilon_R^e} = \frac{2x_w - 1}{2x_w}. \qquad (30)$$

The right hand sides of these relations are determined by interference of electromagnetic and weak axial current interaction.

To make it shorter, we introduce the following notation:

$$N_1^{\pm} = \frac{d^2\sigma}{dxdQ^2}(e_L^{\mp}\ N^{I=0}\to e_L^{\mp}\ X) - \frac{d^2\sigma}{dxdQ^2}(e_R^{\pm}\ N^{I=0}\to e_R^{\pm}\ X), \qquad (31)$$

$$N_3^{\pm} = \frac{d^2\sigma}{dxdQ^2}(e_L^{\mp}\ p\to e_L^{\mp}\ X) - \frac{d^2\sigma}{dxdQ^2}(e_R^{\pm}\ p\to e_R^{\pm}\ X) -$$

$$- \frac{d^2\sigma}{dxdQ^2}(e_L^{\mp}\ n\to e_L^{\mp}\ X) + \frac{d^2\sigma}{dxdQ^2}(e_R^{\pm}\ n\to e_R^{\pm}\ X), \qquad (32)$$

$$N_5^{\pm} = \frac{d\sigma}{dQ^2}(e_L^{\mp}\ p\to e_L^{\mp}\ p) - \frac{d\sigma}{dQ^2}(e_{R,L}^{\pm}p\to e_{R,L}^{\pm}p), \qquad (33)$$

$$N_6^{\pm} = \frac{d\sigma}{dQ^2}(e_L^{\mp}\ n\to e_L^{\mp}\ n) - \frac{d\sigma}{dQ^2}(e_R^{\pm}\ n\to e_R^{\pm}\ n), \qquad (34)$$

$$C_1 = \frac{d^2\sigma}{dxdQ^2}(e_L^-N^{I=0}\to \nu X) - \frac{d^2\sigma}{dxdQ^2}(e_R^+N^{I=0}\to \bar{\nu}X), \qquad (35)$$

$$C_3 =\frac{d^2\sigma}{dxdQ^2}(e_L^-p\to\nu X)+\frac{d^2\sigma}{dxdQ^2}(e_R^+p\to\bar{\nu}X)-\frac{d^2\sigma}{dxdQ^2}(e_L^-n\to\nu X)-\frac{d^2\sigma}{dxdQ^2}(e_R^+n\to\bar{\nu}X), \qquad (36)$$

$$N_7^{\pm} = N_5^{\pm} + N_6^{\pm} \cong \frac{d\sigma}{dQ^2}(e_L^{\mp}\ d\to e_L^{\mp}\ pn) - \frac{d\sigma}{dQ^2}(e_R^{\pm}\ d\to e_R^{\pm}\ pn), \qquad (37)$$

$$C_{7,6,5}= \frac{d\sigma}{dQ^2}(e_L^-p\to\nu n)-\frac{d\sigma}{dQ^2}(e_R^+n\to\bar{\nu}p) \cong \frac{d\sigma}{dQ^2}(e_L^-d\to\nu nn)-\frac{d\sigma}{dQ^2}(e_R^+d\to\bar{\nu}pp). \qquad (38)$$

As in the case of $\overset{(-)}{\nu}$N- scattering, relations (25)-(30) are valid if p and n in formulae (32),(36) are replaced by nuclei A_1 and A_2 with different isospins. Besides, the replacement $\frac{d^2\sigma}{dxdQ^2} \to \frac{d\sigma}{dQ^2}$ is possible in formulae (31),(32),(35),(36), without violating relations (25),(26).

Relations (25)-(30) can be used for extraction of the SM parameters ρ and $x_W = \sin^2\theta_W$ from experimental data. From this point of view relations (30), like $\tilde{R}_N = N^+/N^-$, are of particular interest. They do not contain CS of the CC eN-scattering which is quite a rare process occuring only due to weak interactions. Being independent of parameter ρ is also an advantage of relation (30). When extracting the value of x_W from the data, it allows systematic uncertainties due to correlation between ρ and x_W to be avoided. This correlation takes place in all other relations (7)-(11), (25)-(29) both for eN- and νN- scattering which contain ρ and x_W in the form of a product. Using together relations (30) and (25)-(29) allows this correlation to be eliminated and ρ and x_W to be extracted with essentially lowered uncertainties. It is also important that $\tilde{R}_N$ of (30) is highly sensitive to x_W. This means that during the extraction of x_W from the data the error Δx_W, results from the relative error of $\tilde{R}_N$ measurement, is suppressed by sensitivity factor k:

$$\Delta x_W = \frac{1}{k}\frac{\Delta\tilde{R}_N}{\tilde{R}_N} \cong \frac{1}{8}\frac{\Delta\tilde{R}_N}{\tilde{R}_N}, \text{ where } k = \frac{1}{\tilde{R}_N}\frac{d\tilde{R}_N}{dx_W} = \frac{1}{x_W(2x_W-1)} \cong 8 \text{ at } x_W = 0.23.$$

The sensitivity of relation (8)-(11),(25)-(29) and, in particular, of Paschos-Wolfenstein relation to x_W is much lower: $k \cong 1$.

It can be significant for practical applications that

relations (36) are valid not only for the differential CS $\frac{d^2\sigma}{dxdQ^2}$ and $\frac{d\sigma}{dQ^2}$, but also for the total $\Delta\sigma$, taken in an arbitrary region of the variables Q^2 and x. The following substitutions in (30) are possible:

$$\frac{d^2\sigma^i}{dxdQ^2} \to \Delta\sigma^i = \int_{x_{min}}^{x_{max}} dx \cdot \int_{Q^2_{min}}^{Q^2_{max}} dQ^2 \frac{d^2\sigma^i}{dxdQ^2} \quad \text{and} \quad \frac{d\sigma^i}{dQ^2} \to \Delta\sigma^i = \int_{Q^2_{min}}^{Q^2_{max}} dQ^2 \frac{d\sigma^i}{dQ^2}.$$

An important question of electroweak corrections [5] to relations (25)-(30) has been left unconsidered, it requires a special consideration.

Finally, we'd like to mention the following. Since new physics can manifest itself as a weak deviation from the SM predictions, the relations obtained can be used to searching for these deviations in scattering of polarized electrons and positrons ($\mu^\pm$ - mesons) on non-polarized nucleons and nuclei. In this case the nucleon structure, which is difficult to be checked, will not disguise the effect to be found. For example, the contribution of the additional Z′-boson, which has been widely discussed recently, is reduced to a redetermination [6] of the parameters β and δ in formulae (25)-(29) and introduction of an additional factor in formula (30). Using the values of ρ and x_W obtained in the experiments free of the Z′-boson influence, one can try to separate this contribution on the basis of the above relations.

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