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дубна

E2-91-475

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# TOWARDS THE RESULTS OF GLOBAL ANALYSES OF DATA ON NUCLEON ELECTROMAGNETIC STRUCTURE

1991

# 2 Global analyses of nucleon EM structure data by the standard VMD model

There is a decomposition of nucleon electric $G_E(t)$ and magnetic $G_M(t)$ FF's into isoscalar and isovector parts of the Dirac and Pauli FF's as follows

$$
\begin{aligned}
G_E^p(t) &= [F_{1N}^s(t) + F_{1N}^v(t)] + \frac{t}{4m_p^2}[F_{2N}^s(t) + F_{2N}^v(t)] \\
G_M^p(t) &= [F_{1N}^s(t) + F_{1N}^v(t)] + [F_{2N}^s(t) + F_{2N}^v(t)] \\
G_E^n(t) &= [F_{1N}^s(t) - F_{1N}^v(t)] + \frac{t}{4m_n^2}[F_{2N}^s(t) - F_{2N}^v(t)] \\
G_M^n(t) &= [F_{1N}^s(t) - F_{1N}^v(t)] + [F_{2N}^s(t) - F_{2N}^v(t)].
\end{aligned}
\tag{1}
$$

Cesselli, Nigro and Voci [1] have saturated the latter by means of the following five $\omega(782)$,$\phi(1019)$,$\phi'(1660)$,$\rho(773)$,$\rho'(1600)$ resonances considering the standard VMD model parametrization

$$
\begin{aligned}
F_1^s(t) &= \sum_{s=\omega,\phi,\phi'} \frac{m_s^2}{m_s^2 - t}(f_{sNN}^{(1)}/f_s); \quad F_2^s(t) = \sum_{s=\omega,\phi,\phi'} \frac{m_s^2}{m_s^2 - t}(f_{sNN}^{(2)}/f_s); \\
F_1^v(t) &= \sum_{v=\rho,\rho'} \frac{m_v^2}{m_v^2 - t}(f_{vNN}^{(1)}/f_v); \quad F_2^v(t) = \sum_{v=\rho,\rho'} \frac{m_v^2}{m_v^2 - t}(f_{vNN}^{(2)}/f_v),
\end{aligned}
\tag{2}
$$

and carrying out a simultaneous analysis of 199 experimental points consisting of the proton and neutron space-like and the proton time-like data. In a fit of the proton FF data in the time-like region the $1/(m^2 - t)$ factor has been modified to $1/(m^2 - t + im\Gamma)$, where $\Gamma$ is the width of unstable vector-mesons under consideration.

The main result of this analysis is an estimate of the $e^+e^- \to n\bar{n}$ cross-section to be about 100 times larger than the $e^+e^- \to p\bar{p}$ cross-section. At the same time, a strong constraint on the fit from the time-like data has been observed. Really, if in a fit only space-like data are used, the calculated value of $|G_E^p(4m_p^2)| = |G_M^p(4m_p^2)|$ at the proton-antiproton threshold is 2.27 against the measured value 0.51. This means that it is impossible to reproduce the correct time-like behaviour of the proton EM FF's in the framework of the standard VMD model on the basis of the space-like data only. The latter property is observed in all our further analyses as well.

We have used the same model analysing the nucleon FF data, however, extended for proton FF's up to $t = -33GeV^2$ and for electric and magnetic neutron FF's up to $t = -4GeV^2$ and $t = -10GeV^2$, respectively. We confirm roughly the Cesselli, Nigro, Voci [1] result for a rate of $\sigma_{tot}(e^+e^- \to n\bar{n})$ to $\sigma_{tot}(e^+e^- \to p\bar{p})$ but it is no more acceptable from the statistical point of view of an elaboration of experimental data as we have $\chi^2/NDF = 7025/382$ to be compared with $\chi^2/NDF = 359/189$ in ref.[1]. The obtained values of the corresponding coupling ratios are presented in Table 1, where they are compared also with the results of Cesselli, Nigro, Voci [1].

We have tried to analyse all nucleon FF data also by a more sophisticated standard VMD model of the nucleon EM structure taking into account the newest experimental knowledge [4] about the radial excitations of vector mesons under consideration and simultaneously treating the Okubo-Zweig-Iizuka [5]-[7] (OZI) rule. Then the sums in (2) are saturated by $\omega(782)$,$\omega'(1390)$,$\omega''(1600)$ and $\rho(770)$,$\rho'(1450)$, $\rho''(1700)$, respectively, and we have two more free parameters of the model at our disposal in comparison with the previous analysis. Dispite this enlargement of a number of fitted parameters a description of the same 388 experimental points, characterized by $\chi^2/NDF = 8364/380$, is even worse, and moreover, the predicted ratio of $\sigma_{tot}(e^+e^- \to n\bar{n})$ to $\sigma_{tot}(e^+e^- \to p\bar{p})$ is just reversed, i.e. $\sigma_{tot}(e^+e^- \to n\bar{n})$ is half of the $\sigma_{tot}(e^+e^- \to p\bar{p})$. Almost the same result is observed also in a repeated analysis of the same data by means of the VMD model with an inclusion of the third excited state of the $\rho(770)$ meson which, however, leads to a remarkably improved value of $\chi^2$ (see Table 2).

Here, we would like to note that an assumption that false minima of $\chi^2$ have been found by the values of both sets of parameters presented in Table 2 is above any suspicion.

So, we come to the conclusion that the standard VMD model, even saturated with all the known [4] suitable resonances, is unable to describe the existing experimental information on the nucleon EM structure . There are two indications of the latter. In minimization procedures unacceptable values of $\chi^2$'s have been achieved and contradicting rates of $\sigma_{tot}(e^+e^- \to n\bar{n})$ to $\sigma_{tot}(e^+e^- \to p\bar{p})$ are predicted depending on the saturation of the standard VMD model with different sets of vector mesons.

It is shown in the next section that this is no more true if the unitary and analytic (UA) VMD model [2],[3] is applied to analyse the existing experimental information on the nucleon EM structure . The inequality $\sigma_{tot}(e^+e^- \to n\bar{n}) > \sigma_{tot}(e^+e^- \to p\bar{p})$ is in this case always conserved.

# 3 More refined unitary and analytic VMD model in a global analysis of data on the nucleon electromagnetic structure

The failure of the standard VMD model to describe the nucleon EM structure in the whole measured region of $t$ is not surprising because it does not possess correct analytic properties and the asymptotic behaviour as predicted by QCD for baryons. These shortcomings of the standard VMD model are removed in [2],[3] where a modified VMD model with the correct analytic properties and asymptotic behaviour as predicted by QCD for baryon FF's has been constructed. In this paper, by using the newest experimental information [4] on the excited states of vector mesons under consideration and applying the OZI rule [5]-[7] at the same time, another improvement of the previously modified [2],[3] VMD model is achieved. We include again the $\rho'''(2150)$ meson contribution to the model, because for its existence some evidence in $e^+e^-$ annihilation processes has recently been manifested [8],[9] and it appears just in the region of alredy measured values of $\sigma_{tot}(e^+e^- \to p\bar{p})$. Then, the isoscalar and isovector parts (2) of the



Dirac and Pauli nucleon EM FF's take the form

$$F_1^s(t) = \sum_{s=\omega,\omega',\omega''} \frac{m_s^2}{m_s^2 - t}(f^{(1)}_{sNN}/f_s); \quad F_2^s(t) = \sum_{s=\omega,\omega',\omega''} \frac{m_s^2}{m_s^2 - t}(f^{(2)}_{sNN}/f_s);$$
$$F_1^v(t) = \sum_{v=\rho,\rho',\rho'',\rho'''} \frac{m_v^2}{m_v^2 - t}(f^{(1)}_{vNN}/f_v); \quad F_2^v(t) = \sum_{v=\rho,\rho',\rho'',\rho'''} \frac{m_v^2}{m_v^2 - t}(f^{(2)}_{vNN}/f_v); \tag{3}$$

where in the isoscalar FF's we require the couplings of $\phi$ and $\phi'$ mesons to nucleons to be zero, taking the OZI rule [5]-[7] into account strictly. The ratios of the coupling constants in (3) are constrained by the equations

$$\sum_{s=\omega,\omega',\omega''} (f^{(1)}_{sNN}/f_s) = \frac{1}{2}; \quad \sum_{s=\omega,\omega',\omega''} (f^{(2)}_{sNN}/f_s) = \frac{1}{2}(\mu_p + \mu_n);$$
$$\sum_{v=\rho,\rho',\rho'',\rho'''} (f^{(1)}_{vNN}/f_v) = \frac{1}{2}; \quad \sum_{v=\rho,\rho',\rho'',\rho'''} (f^{(2)}_{vNN}/f_v) = \frac{1}{2}(\mu_p - \mu_n) \tag{4}$$

following from the normalization conditions of nucleon EM FF's at $t = 0$ where $\mu_p$ and $\mu_n$ are anomalous magnetic moments of the proton and neutron, respectively. This day, the most sophisticated improvement of the VMD model is obtained from (3) by applying the nonlinear transformations

$$t = t_0^s - \frac{4(t_{in}^{1s} - t_0^s)}{[\frac{1}{V} - V]^2} \quad t = t_0^s - \frac{4(t_{in}^{2s} - t_0^s)}{[\frac{1}{U} - U]^2}$$
$$t = t_0^v - \frac{4(t_{in}^{1v} - t_0^v)}{[\frac{1}{W} - W]^2} \quad t = t_0^v - \frac{4(t_{in}^{2v} - t_0^v)}{[\frac{1}{X} - X]^2} \tag{5}$$

where $t_0^s = 9m_\pi^2$; $t_0^v = 4m_\pi^2$ and $t_{in}^{1s}, t_{in}^{2s}$, $t_{in}^{1v}, t_{in}^{2v}$ are square-root branch points corresponding to the lowest normal and the effective inelastic threshold of $F_1^s$,$F_2^s$, $F_1^v$,$F_2^v$ FF's, respectively. Practically, besides (5) we use in (3) also the relations

$$m_s^2 = t_0^s - \frac{4(t_{in}^{1s} - t_0^s)}{[\frac{1}{V_{s0}} - V_{s0}]^2}; \quad m_s^2 = t_0^s - \frac{4(t_{in}^{2s} - t_0^s)}{[\frac{1}{U_{s0}} - U_{s0}]^2};$$
$$m_v^2 = t_0^v - \frac{4(t_{in}^{1v} - t_0^v)}{[\frac{1}{W_{v0}} - W_{v0}]^2}; \quad m_v^2 = t_0^v - \frac{4(t_{in}^{2v} - t_0^v)}{[\frac{1}{X_{v0}} - X_{v0}]^2}; \tag{6}$$

and

$$0 = t_0^s - \frac{4(t_{in}^{1s} - t_0^s)}{[\frac{1}{V_N} - V_N]^2}; \quad 0 = t_0^s - \frac{4(t_{in}^{2s} - t_0^s)}{[\frac{1}{U_N} - U_N]^2};$$
$$0 = t_0^v - \frac{4(t_{in}^{1v} - t_0^v)}{[\frac{1}{W_N} - W_N]^2}; \quad 0 = t_0^v - \frac{4(t_{in}^{2v} - t_0^v)}{[\frac{1}{X_N} - X_N]^2}; \tag{7}$$

where $V_{s_0}, U_{s_0}, W_{v_0}, X_{v_0}$ are the zero-width (therefore a subindex 0) VMD poles and $V_N, U_N, W_N, X_N$ are the normalization points (corresponding to $t=0$) in the $V-, U-, W-, X-$ planes, respectively. The relations (5),(6) and (7) transform the standard VMD model (3) in the zero-width approximation into the following factorized forms:

$$
\begin{aligned}
F_1^s(t) &= \left(\frac{1-V^2}{1-V_N^2}\right)^2 \cdot \\
&\cdot \left[\sum_{s=\omega,\omega',\omega''} \frac{(V_N-V_{s_0})(V_N+V_{s_0})(V_N-1/V_{s_0})(V_N+1/V_{s_0})}{(V-V_{s_0})(V+V_{s_0})(V-1/V_{s_0})(V+1/V_{s_0})}(f_{sNN}^{(1)}/f_s)\right] \\
F_2^s(t) &= \left(\frac{1-U^2}{1-U_N^2}\right)^2 \cdot \\
&\cdot \left[\sum_{s=\omega,\omega',\omega''} \frac{(U_N-U_{s_0})(U_N+U_{s_0})(U_N-1/U_{s_0})(U_N+1/U_{s_0})}{(U-U_{s_0})(U+U_{s_0})(U-1/U_{s_0})(U+1/U_{s_0})}(f_{sNN}^{(2)}/f_s)\right] \\
F_1^v(t) &= \left(\frac{1-W^2}{1-W_N^2}\right)^2 \cdot \\
&\cdot \left[\sum_{v=\rho,\rho',\rho'',\rho'''} \frac{(W_N-W_{v_0})(W_N+W_{v_0})(W_N-1/W_{v_0})(W_N+1/W_{v_0})}{(W-W_{v_0})(W+W_{v_0})(W-1/W_{v_0})(W+1/W_{v_0})}(f_{vNN}^{(1)}/f_v)\right] \\
F_2^v(t) &= \left(\frac{1-X^2}{1-X_N^2}\right)^2 \cdot \\
&\cdot \left[\sum_{v=\rho,\rho',\rho'',\rho'''} \frac{(X_N-X_{v_0})(X_N+X_{v_0})(X_N-1/X_{v_0})(X_N+1/X_{v_0})}{(X-X_{v_0})(X+X_{v_0})(X-1/X_{v_0})(X+1/X_{v_0})}(f_{vNN}^{(1)}/f_v)\right]
\end{aligned}
\tag{8}
$$

where the asymptotic behaviour of (3) is now completely determined by the terms in front of the square brackets because sums inside the brackets for $t \to \pm\infty$ turn out to be real constants. Now, using the relations between complex and complex conjugate values of corresponding pole positions

$$
\begin{array}{llll}
V_{\omega_0} = -V_{\omega_0}^*, & V_{\omega_0'} = -V_{\omega_0'}^*, & V_{\omega_0''} = 1/V_{\omega_0''}^*, & \\
U_{\omega_0} = -U_{\omega_0}^*, & U_{\omega_0'} = 1/U_{\omega_0'}^*, & U_{\omega_0''} = 1/U_{\omega_0''}^*, & \\
W_{\rho_0} = 1/W_{\rho_0}^*, & W_{\rho_0'} = 1/W_{\rho_0'}^*, & W_{\rho_0''} = 1/W_{\rho_0''}^*, & W_{\rho_0'''} = 1/W_{\rho_0'''}^*, \\
X_{\rho_0} = -X_{\rho_0}^*, & X_{\rho_0'} = 1/X_{\rho_0'}^*, & X_{\rho_0''} = 1/X_{\rho_0''}^*, & X_{\rho_0'''} = 1/X_{\rho_0'''}^*,
\end{array}
\tag{9}
$$

following from the fact that in a fitting procedure we find

$$
\begin{array}{l}
(m_\omega^2 - \frac{\Gamma_\omega^2}{4}) < t_{in}^{1s}, \quad (m_{\omega'}^2 - \frac{\Gamma_{\omega'}^2}{4}) < t_{in}^{1s}, \quad (m_{\omega''}^2 - \frac{\Gamma_{\omega''}^2}{4}) > t_{in}^{1s}, \\[2mm]
(m_\omega^2 - \frac{\Gamma_\omega^2}{4}) < t_{in}^{2s}, \quad (m_{\omega'}^2 - \frac{\Gamma_{\omega'}^2}{4}) > t_{in}^{2s}, \quad (m_{\omega''}^2 - \frac{\Gamma_{\omega''}^2}{4}) > t_{in}^{2s}, \\[2mm]
(m_\rho^2 - \frac{\Gamma_\rho^2}{4}) > t_{in}^{1v}, \quad (m_{\rho'}^2 - \frac{\Gamma_{\rho'}^2}{4}) > t_{in}^{1v}, \quad (m_{\rho''}^2 - \frac{\Gamma_{\rho''}^2}{4}) > t_{in}^{1v}, \quad (m_{\rho'''}^2 - \frac{\Gamma_{\rho'''}^2}{4}) > t_{in}^{1v}, \\[2mm]
(m_\rho^2 - \frac{\Gamma_\rho^2}{4}) < t_{in}^{2v}, \quad (m_{\rho'}^2 - \frac{\Gamma_{\rho'}^2}{4}) > t_{in}^{2v}, \quad (m_{\rho''}^2 - \frac{\Gamma_{\rho''}^2}{4}) > t_{in}^{2v}, \quad (m_{\rho'''}^2 - \frac{\Gamma_{\rho'''}^2}{4}) > t_{in}^{2v},
\end{array}
\tag{10}
$$



incorporating subsequently the nonzero values of vector meson widths $\Gamma \neq 0$ in a correct way and finally changing the power of the terms in front of the square brackets in (8) in conformity with the QCD predictions for nucleons [10],[11], one gets for every isoscalar and isovector Dirac and Pauli FF, one analytic function in the whole complex t-plane besides two right-hand cuts of the following forms:

$$
\begin{aligned}
F_1^s[V(t)] &= \left(\frac{1-V^2}{1-V_N^2}\right)^4 \cdot \\
&\cdot \left[\sum_{s=\omega,\omega'} \frac{(V_N-V_s)(V_N-V_s^*)(V_N-1/V_s)(V_N-1/V_s^*)}{(V-V_s)(V-V_s^*)(V-1/V_s)(V-1/V_s^*)}(f_{sNN}^{(1)}/f_s) + \right. \\
&+ \left. \frac{(V_N-V_{\omega''})(V_N-V_{\omega''}^*)(V_N+V_{\omega''})(V_N+V_{\omega''}^*)}{(V-V_{\omega''})(V-V_{\omega''}^*)(V+V_{\omega''})(V+V_{\omega''}^*)}(f_{\omega''NN}^{(1)}/f_{\omega''})\right] \\
F_2^s[U(t)] &= \left(\frac{1-U^2}{1-U_N^2}\right)^6 \cdot \\
&\cdot \left[\frac{(U_N-U_\omega)(U_N-U_\omega^*)(U_N-1/U_\omega)(U_N-1/U_\omega^*)}{(U-U_\omega)(U-U_\omega^*)(U-1/U_\omega)(U-1/U_\omega^*)}(f_{\omega NN}^{(2)}/f_\omega) + \right. \\
&+ \left. \sum_{s=\omega',\omega''} \frac{(U_N-U_s)(U_N-U_s^*)(U_N+U_s)(U_N+U_s^*)}{(U-U_s)(U-U_s^*)(U+U_s)(U+U_s^*)}(f_{sNN}^{(2)}/f_s)\right] \\
F_1^v[W(t)] &= \left(\frac{1-W^2}{1-W_N^2}\right)^4 \cdot \\
&\cdot \left[\sum_{v=\rho,\rho',\rho'',\rho'''} \frac{(W_N-W_v)(W_N-W_v^*)(W_N+W_v)(W_N+W_v^*)}{(W-W_v)(W-W_v^*)(W+W_v)(W+W_v^*)}(f_{vNN}^{(1)}/f_v)\right] \\
F_2^v[X(t)] &= \left(\frac{1-X^2}{1-X_N^2}\right)^6 \cdot \\
&\cdot \left[\frac{(X_N-X_\rho)(X_N-X_\rho^*)(X_N-1/X_\rho)(X_N-1/X_\rho^*)}{(X-X_\rho)(X-X_\rho^*)(X-1/X_\rho)(X-1/X_\rho^*)}(f_{\rho NN}^{(2)}/f_\rho) + \right. \\
&+ \left. \sum_{v=\rho',\rho'',\rho'''} \frac{(X_N-X_v)(X_N-X_v^*)(X_N+X_v)(X_N+X_v^*)}{(X-X_v)(X-X_v^*)(X+X_v)(X+X_v^*)}(f_{vNN}^{(2)}/f_v)\right]
\end{aligned}
\tag{11}
$$

defined on four-sheeted Riemann surfaces with poles corresponding to vector meson resonances placed on unphysical sheets. The relations (11) and (1) represent now the most accomplished (in comparison with the models in refs. [2],[3]), so-called, unitary and analytic (UA) VMD model of the EM structure of nucleons which depends on the following parameters

$$
\begin{array}{llll}
t_{in}^{1s}, t_{in}^{2s}, & t_{in}^{1v}, t_{in}^{2v}, & (f_{\omega NN}^{(1)}/f_\omega), & (f_{\omega NN}^{(2)}/f_\omega), \\
(f_{\omega' NN}^{(1)}/f_{\omega'}), & (f_{\omega' NN}^{(2)}/f_{\omega'}), & (f_{\omega'' NN}^{(1)}/f_{\omega''}), & (f_{\omega'' NN}^{(2)}/f_{\omega''}), \\
(f_{\rho NN}^{(1)}/f_\rho), & (f_{\rho NN}^{(2)}/f_\rho), & (f_{\rho' NN}^{(1)}/f_{\rho'}), & (f_{\rho' NN}^{(2)}/f_{\rho'}), \\
(f_{\rho'' NN}^{(1)}/f_{\rho''}), & (f_{\rho'' NN}^{(2)}/f_{\rho''}), & (f_{\rho''' NN}^{(1)}/f_{\rho'''}), & (f_{\rho''' NN}^{(2)}/f_{\rho'''})
\end{array}
\tag{12}
$$

and also on the masses and widths of the resonances under consideration, which, however, are fixed at the world averaged values. The number of coupling constant ratios in (12) is reduced by the relations (4) only to 10 linearly independent ones, and thus, the model finally depends on 14 free parameters. They are determined in a simultaneous analysis of 375 reliable experimental points (for references of data see [2]) on the proton and neutron electric and magnetic FF's in the space-like ($t < 0$) region and 13 experimental points on the $\sigma_{tot}(e^+e^- \to p\bar{p})$ in the time-like ($t > 0$) region. The results are presented in Table 3 where they are compared (see the second column of Table 3) also with the values of parameters obtained when in the analysis of data instead of proton FF's in the space-like region the measured data on the differential cross-section

$$\frac{d\sigma^{lab}(e^-p \to e^-p)}{d\Omega} = \frac{\alpha^2}{4E^2}\frac{\cos^2(\vartheta/2)}{\sin^4(\vartheta/2)}\frac{1}{1+(2E/M)\sin^2(\vartheta/2)}\cdot \left[\frac{G_E^2(t)-(t/4m_p^2)G_M^2(t)}{1-t/4m_p^2} - 2\frac{t}{4m_p^2}G_M^2(t)\tan^2(\vartheta/2)\right] \tag{13}$$

are used and the data on neutron EM FF's are disregarded at the same time. Graphically the results are presented in Figs. 1 and 2, where the predictions of our UA-VMD model are compared with the nucleon EM FF data. One can see immediately that an almost perfect description (see full lines in Figs. 1,2) is achieved if parameters obtained in the analysis of nucleon FF data are used.

On the other hand, only the magnetic proton FF is reproduced (see dashed lines in Fig. 1) if the parameters are substituted into the UA-VMD model of nucleon EM FF's which were obtained by analysing the data on the proton differential cross-section in the space-like region and on the total cross-section in the time-like region. As a result, the dashed lines in Fig. 2, corresponding to neutron EM FF's, are pure predictions.

Nevertheless, the predicted rates of $\sigma_{tot}(e^+e^- \to n\bar{n})$ to $\sigma_{tot}(e^+e^- \to p\bar{p})$ in both cases (up to the shape of $\sigma_{tot}(e^+e^- \to n\bar{n})$) are roughly (see Fig. 3) the same.

The inequality $\sigma_{tot}(e^+e^- \to n\bar{n}) > \sigma_{tot}(e^+e^- \to p\bar{p})$ is predicted also by a unitarized and analytic Cesselli, Nigro, Voci model [1] (see the third column of Table 1), however, with a coefficient equal to 10 (compare the latter with a coefficient 100 predicted by the standard VMD model).

The same inequality is predicted (see parameters in the third column of Table 3) even in the analysis of the nucleon FF data taken only in the space-like region with a coefficient equal to 4. Of course, since in this case the data on $\sigma_{tot}(e^+e^- \to p\bar{p})$ are disregarded, a theoretically predicted $\sigma_{tot}(e^+e^- \to p\bar{p})$ is three orders larger than it is given by experiment.

So, reviewing all analyses carried out in this paper, one can say the following. All modifications of the UA-VMD model (refs. [2],[3] and the present paper) applied to the description of the nucleon EM structure data, taken in the form of either differential cross-sections or EM FF's obtained from the latter by a straight-line Rosenbluth plot, are more or less successful and predict the following inequality $\sigma_{tot}(e^+e^- \to n\bar{n}) > \sigma_{tot}(e^+e^- \to p\bar{p})$. However, this is not enough to believe the inequality to be valid in general. Really, if we make artificial data on $\sigma_{tot}(e^+e^- \to n\bar{n})$ to be identical with the data on $\sigma_{tot}(e^+e^- \to p\bar{p})$ and carry out an optimal fit of them together with all existing



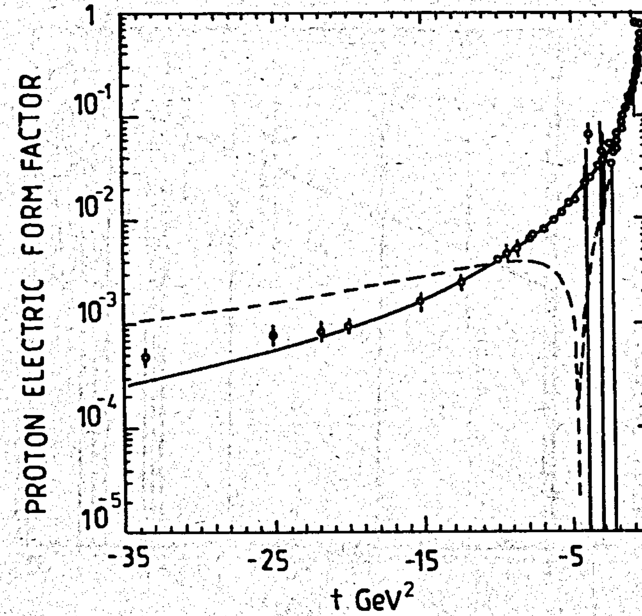
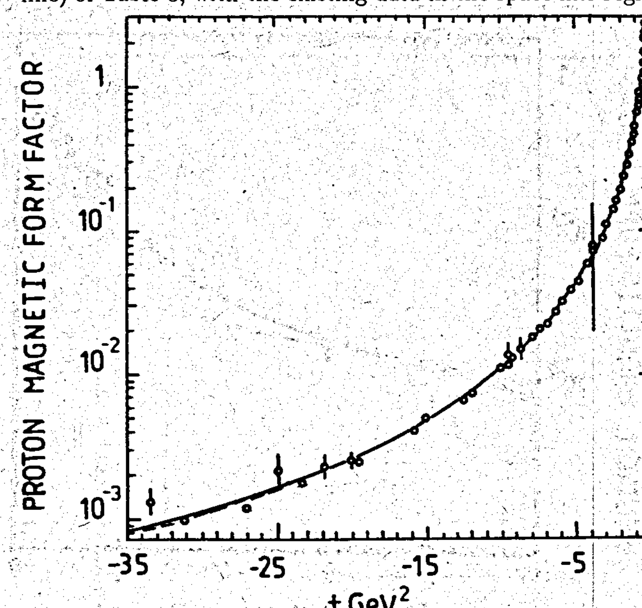



**Fig.1.** a) Comparison of the electric proton form factor calculated by the parameters, presented in the first column (full line) and in the second column (dashed line) of Table 3, with the existing data in the space-like region.




b) The same for magnetic proton form factor.

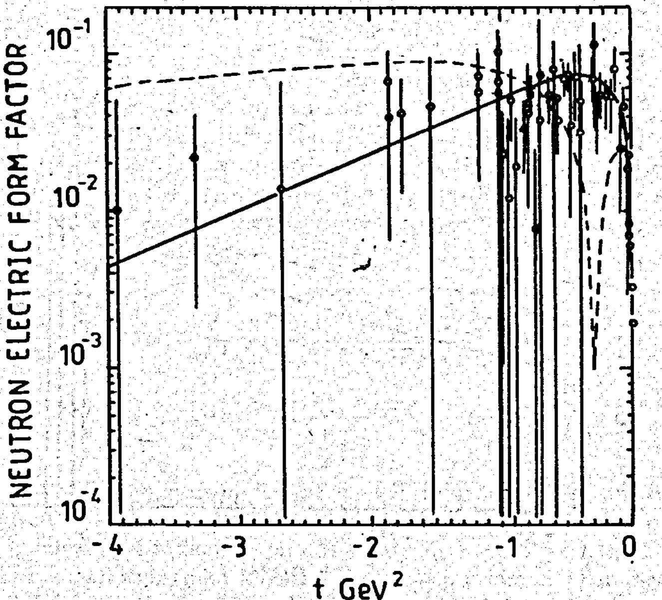
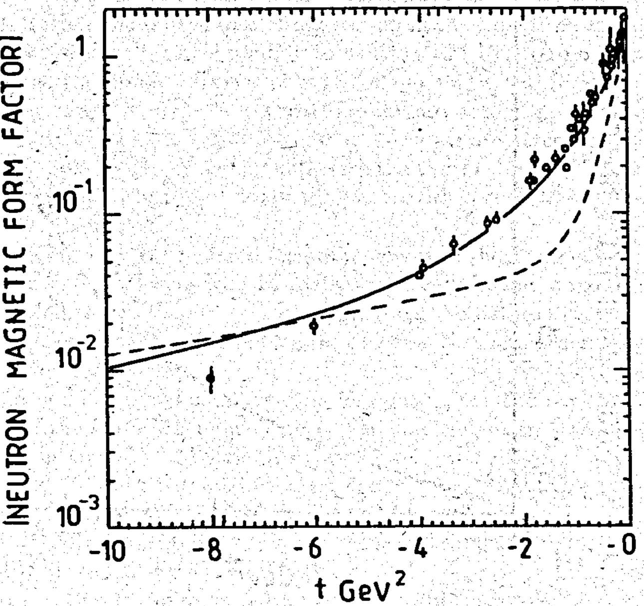



Fig.2. a) Comparison of the electric neutron form factor calculated by the parameters, presented in the first column (full line) and in the second column (dashed line) of Table 3, with the existing data in the space-like region.




b) The same for magnetic neutron form factor.



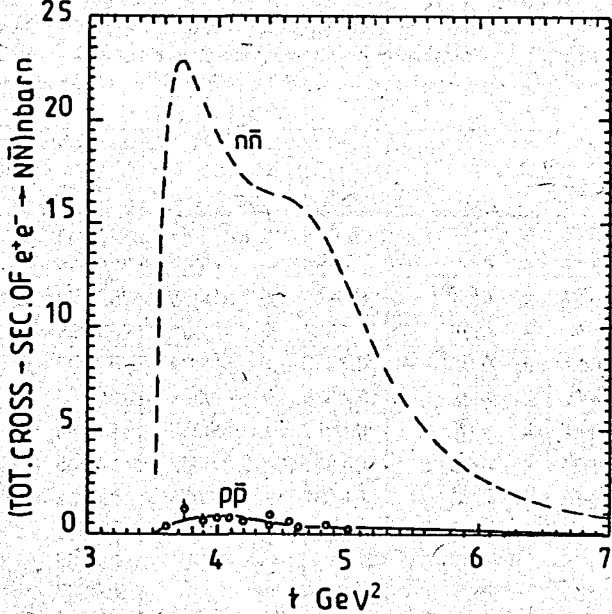
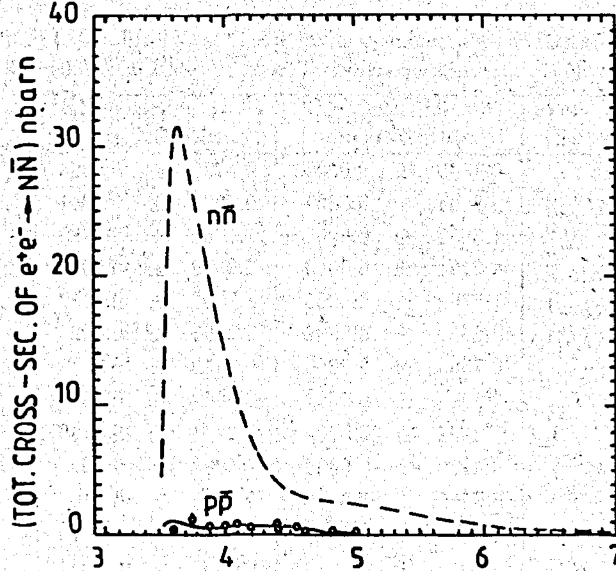



Fig.3. a) The predicted behaviour of the $e^+e^- \to n\bar{n}$ cross-section by the parameters, presented in the second column of Table 3 and its comparison with the $e^+e^- \to p\bar{p}$ cross-section .




b) Prediction of the $e^+e^- \to n\bar{n}$ cross-section behaviour by the parameters, presented in the first column of Table 3 and its comparison with the $e^+e^- \to p\bar{p}$ cross-section .

**Table 1:** The results of the fit of the data on nucleon EM structure by the five resonance standard VMD model and their comparison with the UA-VMD model results. Here the first excited state of the $\rho(770)$ meson is considered to be $\rho'(1600)$.

| Parameters of the model | CNV[1] | 5 resonance VMD applied to all existing data | 5 resonance UA-VMD applied to all existing data |
|---|---|---|---|
| $(f^{(1)}_{\rho NN}/f_\rho)$ | 0.66 ± 0.01 | 0.550 ± 0.0005 | -0.9355 ± 0.0667 |
| $(f^{(2)}_{\rho NN}/f_\rho)$ | 3.09 ± 0.02 | 2.7486 ± 0.0009 | 2.0935 ± 0.0201 |
| $(f^{(1)}_{\omega NN}/f_\omega)$ | 1.31 ± 0.04 | 0.9895 ± 0.0020 | 0.7152 ± 0.0026 |
| $(f^{(2)}_{\omega NN}/f_\omega)$ | 1.79 ± 0.06 | 2.5527 ± 0.0002 | -0.0065 ± 0.0095 |
| $(f^{(1)}_{\phi NN}/f_\phi)$ | -0.89 ± 0.06 | -0.3058 ± 0.0019 | -0.1210 ± 0.0022 |
| $(f^{(2)}_{\phi NN}/f_\phi)$ | -3.02 ± 0.08 | -3.6630 ± 0.0008 | -0.0455 ± 0.0136 |
| $(f^{(1)}_{\rho' NN}/f'_\rho)$ | -0.16 ± 0.01 | 0.0507 ± 0.0005 | 1.4355 ± 0.0667 |
| $(f^{(2)}_{\rho' NN}/f'_\rho)$ | -1.24 ± 0.02 | 0.8957 ± 0.0002 | -0.2406 ± 0.0201 |
| $(f^{(1)}_{\phi' NN}/f'_\phi)$ | 0.08 ± 0.10 | -0.1837 ± 0.0005 | -0.0942 ± 0.0034 |
| $(f^{(2)}_{\phi' NN}/f'_\phi)$ | 1.17 ± 0.10 | 1.0502 ± 0.0002 | -0.0081 ± 0.0166 |
| $t^{1s}_{in}$ | — | — | 2.5408 ± 0.0873 |
| $t^{2s}_{in}$ | — | — | 1.7930 ± 0.0914 |
| $t^{1v}_{in}$ | — | — | 0.2565 ± 0.0142 |
| $t^{2v}_{in}$ | — | — | 1.1649 ± 0.0600 |
| | $\chi^2/NDF = 359/189$ | $\chi^2/NDF = 7025/382$ | $\chi^2/NDF = 790/378$ |

**Table 2:** The results of the fit of data on nucleon EM structure by the standard VMD model with six and seven resonances charged by the OZI rule strictly. The excited states of the $\rho(770)$ meson are considered to be $\rho'(1450)$, $\rho''(1700)$ and $\rho'''(2150)$.

| Parameters of the model | 6 resonance VMD with OZI rule | 7 resonance VMD with OZI rule |
|---|---|---|
| $(f^{(1)}_{\omega NN}/f_\omega)$ | 0.4849 ± 0.0009 | 0.4732 ± 0.0223 |
| $(f^{(2)}_{\omega NN}/f_\omega)$ | 0.7234 ± 0.0004 | 0.7272 ± 0.0041 |
| $(f^{(1)}_{\omega' NN}/f'_\omega)$ | 1.6853 ± 0.0008 | 1.7365 ± 0.0158 |
| $(f^{(2)}_{\omega' NN}/f'_\omega)$ | -4.0494 ± 0.0003 | -4.0570 ± 0.0029 |
| $(f^{(1)}_{\omega'' NN}/f''_\omega)$ | -1.6702 ± 0.0005 | -1.7097 ± 0.0157 |
| $(f^{(2)}_{\omega'' NN}/f''_\omega)$ | 3.2659 ± 0.0002 | 3.2697 ± 0.0029 |
| $(f^{(1)}_{\rho NN}/f_\rho)$ | 0.7569 ± 0.0009 | 0.7799 ± 0.0174 |
| $(f^{(2)}_{\rho NN}/f_\rho)$ | 2.8594 ± 0.0004 | 2.8669 ± 0.0021 |
| $(f^{(1)}_{\rho' NN}/f'_\rho)$ | -1.2134 ± 0.0007 | -1.2264 ± 0.0130 |
| $(f^{(2)}_{\rho' NN}/f'_\rho)$ | -0.4129 ± 0.0003 | -0.4282 ± 0.0033 |
| $(f^{(1)}_{\rho'' NN}/f''_\rho)$ | 0.9565 ± 0.0005 | 0.9072 ± 0.0107 |
| $(f^{(2)}_{\rho'' NN}/f''_\rho)$ | -0.5935 ± 0.0002 | -0.5932 ± 0.0006 |
| $(f^{(1)}_{\rho''' NN}/f'''_\rho)$ | 0 | 0.0393 ± 0.0044 |
| $(f^{(2)}_{\rho''' NN}/f'''_\rho)$ | 0 | 0.0074 ± 0.0021 |
| | $\chi^2/NDF = 8364/380$ | $\chi^2/NDF = 6613/378$ |



nucleon EM FF data by the UA-VMD model, an acceptable description ($\chi^2/NDF = 747/387$) is achieved too. On the basis of the latter we come to a conclusion that one cannot predict a reliable rate between $\sigma_{tot}(e^+e^- \to n\bar{n})$ and $\sigma_{tot}(e^+e^- \to p\bar{p})$ in the framework of phenomenological analyses and it has to be determined in some experiment, like FENICE experiment in Frascati.

**Table 3:** The results of the analysis of data on nucleon EM structure by means of the seven resonance unitary and analytic VMD model.

| Parameters of the model | From nucleon FF data and $\sigma_{tot}(e^+e^- \to p\bar{p})$ | Only from $\frac{d\sigma(e^-p\to e^-p)}{d\Omega}$ data and $\sigma_{tot}(e^+e^- \to p\bar{p})$ | Only from nucleon FF data in $t<0$ region |
|---|---|---|---|
| $t^{1s}_{in}$ | 3.6002 ± 0.0129 | 2.985 ± 0.0042 | 3.1737 ± 0.0493 |
| $t^{2s}_{in}$ | 1.8397 ± 0.1080 | 1.8482 ± 0.0003 | 1.9933 ± 0.1856 |
| $t^{1v}_{in}$ | 1.4470 ± 0.0081 | 1.1323 ± 0.0001 | 3.1544 ± 0.3139 |
| $t^{2v}_{in}$ | 3.4501 ± 0.0130 | 2.5573 ± 0.0137 | 3.4896 ± 0.0518 |
| $(f^{(1)}_{\omega NN}/f_\omega)$ | 0.6424 ± 0.0014 | 0.7776 ± 0.0003 | 0.5915 ± 0.0156 |
| $(f^{(2)}_{\omega NN}/f_\omega)$ | 0.0218 ± 0.0026 | -1.0894 ± 0.0002 | 0.4746 ± 0.1449 |
| $(f^{(1)}_{\omega' NN}/f'_\omega)$ | -0.0214 ± 0.0084 | -0.0464 ± 0.0006 | 0.1398 ± 0.0314 |
| $(f^{(2)}_{\omega' NN}/f'_\omega)$ | -0.0232 ± 0.0397 | 2.1745 ± 0.0227 | -3.2693 ± 0.9196 |
| $(f^{(1)}_{\omega'' NN}/f''_\omega)$ | -0.1642 ± 0.0085 | -0.2312 ± 0.0007 | -0.2313 ± 0.0351 |
| $(f^{(2)}_{\omega'' NN}/f''_\omega)$ | -0.0154 ± 0.0398 | -1.1452 ± 0.0227 | 2.7346 ± 0.9309 |
| $(f^{(1)}_{\rho NN}/f_\rho)$ | 0.1207 ± 0.0087 | 0.0121 ± 0.0002 | 0.5059 ± 0.0437 |
| $(f^{(2)}_{\rho NN}/f_\rho)$ | 1.8957 ± 0.0058 | 1.4506 ± 0.0069 | 1.7281 ± 0.0254 |
| $(f^{(1)}_{\rho' NN}/f'_\rho)$ | -1.3947 ± 0.0293 | -2.3700 ± 0.0220 | -1.9575 ± 0.0534 |
| $(f^{(2)}_{\rho' NN}/f'_\rho)$ | 0.7338 ± 0.0211 | 0.9744 ± 0.0098 | 2.4078 ± 0.2142 |
| $(f^{(1)}_{\rho'' NN}/f''_\rho)$ | 1.9486 ± 0.0263 | 2.4088 ± 0.0209 | 2.6607 ± 0.0266 |
| $(f^{(2)}_{\rho'' NN}/f''_\rho)$ | -0.7257 ± 0.0190 | -0.4601 ± 0.0069 | -2.1946 ± 0.1935 |
| $(f^{(1)}_{\rho''' NN}/f'''_\rho)$ | -0.1746 ± 0.0095 | 0.4491 ± 0.0069 | -0.7091 ± 0.0154 |
| $(f^{(2)}_{\rho''' NN}/f'''_\rho)$ | -0.0508 ± 0.0070 | -0.1120 ± 0.0002 | 0.0884 ± 0.0691 |
| | $\chi^2/NDF = 678/374$ | $\chi^2/NDF = 1254/459$ | $\chi^2/NDF = 548/361$ |

## 4 Conclusions and summary

We have discussed peculiar features of phenomenological analyses of nucleon EM FF data in which the inequality $\sigma_{tot}(e^+e^- \to n\bar{n}) >> \sigma_{tot}(e^+e^- \to p\bar{p})$ has been predicted.

If only the standard VMD model (in various modifications) is used to analyse the present experimental information on the nucleon EM structure, an unacceptable description (too high value of $\chi^2$ is always obtained) is achieved from the statistical point of view of an elaboration of experimental data and as a consequence any its predictions cannot be taken into account seriously.

The application of various modification of the UA-VMD model to the description of the same sets of data leads cca to a ten-times improved value of $\chi^2$ and also mutually consistent predictions for the inequality $\sigma_{tot}(e^+e^- \to n\bar{n}) > \sigma_{tot}(e^+e^- \to p\bar{p})$.

However, the most sophisticated UA-VMD model, constructed in this paper, appears to be enough flexible to describe successfully all existing experimental points on the nucleon EM structure together with artificial data on $\sigma_{tot}(e^+e^- \to n\bar{n})$ taken to be identical with $\sigma_{tot}(e^+e^- \to p\bar{p})$. The latter shows that the rate of $\sigma_{tot}(e^+e^- \to n\bar{n})$ to $\sigma_{tot}(e^+e^- \to p\bar{p})$ is not reliably predicted in any phenomenological analyses and it can be specified only experimentally.

After tedious discussions [1]-[3], [12]-[14] there is an exceptional chance for the FENICE experiment realized in Frascati to stop any further conjectures about the behaviour of the $e^+e^- \to n\bar{n}$ cross-section just above the nucleon-antinucleon threshold.

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Received by Publishing Department
on October 31, 1991.