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JLAB PROTON POLARIZATION DATA IN RESPECT TO GLOBAL UNITARY AND ANALYTIC MODEL OF NUCLEON ELECTROMAGNETIC STRUCTURE

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It is demonstrated that the new JLab proton polarization data, which are in a rather strong disagreement with the proton electric form factor data in the space-like region obtained by the Rosenbluth technique, are consistent with all known form factor properties, including also the QCD asymptotics. However, they require the existence of a zero value (i.e. a diffraction minimum) of the proton electric form factor around $t = 15$ GeV^2. That leads to a change of our understanding of the charge distribution inside the proton.

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1. *Introduction*

The proton is charged particle compound of the (u, u, d) quarks and, therefore, it is not point-like. As a consequence, one doesn't know an explicit form of the matrix element of the electromagnetic (EM) current

$$J_\mu^{\mathrm{EM}} = (2/3)\bar{u}\gamma_\mu u - (1/3)\bar{d}\gamma_\mu d - (1/3)\bar{s}\gamma_\mu s \tag{1}$$

and, therefore, the current is parametrized

$$\langle p|J_\mu^{\mathrm{EM}}|p\rangle = \bar{u}(p')\left\{\gamma_\mu F_{1\mathrm{p}}(t) + \mathrm{i}\,\frac{\sigma_{\mu\nu}q_\nu}{2m_\mathrm{p}^2}F_{2\mathrm{p}}(t)\right\}u(p) \tag{2}$$

trough Dirac $F_{1\mathrm{p}}(t)$ and Pauli $F_{2\mathrm{p}}(t)$ form factors (FFs), where $t = q^2 = (p'-p)^2 = -Q^2$ is a four-momentum transferred by the virtual photon. From a practical point of view, it is advantageous to introduce Sach's FFs

$$\begin{aligned} G_{\mathrm{Ep}}(t) &= F_{1\mathrm{p}}(t) + \frac{t}{4m_{\mathrm{p}}^2} F_{2\mathrm{p}}(t) \\ G_{\mathrm{Mp}}(t) &= F_{1\mathrm{p}}(t) + F_{2\mathrm{p}}(t) \end{aligned} \tag{3}$$

to be normalized to the proton charge $G_{\mathrm{Ep}}(0) = 1$ and the proton magnetic moment $G_{\mathrm{Mp}}(0) = 1 + \mu_p$ ($\mu_p = 1.793\ \mu$ is the proton anomalous magnetic moment) and commonly they are called proton electric and proton magnetic FFs, respectively.

Prior to the year 2000, all data on $G_{\mathrm{Ep}}(t)$ and $G_{\mathrm{Mp}}(t)$ in the space-like ($t < 0$) region were obtained by measuring (mainly at SLAC) the differential cross-section of elastic electron scattering on proton

$$\begin{aligned} \frac{\mathrm{d}\sigma^{\mathrm{lab}}(\mathrm{e^-p} \to \mathrm{e^-p})}{\mathrm{d}\Omega} &= \frac{\alpha^2}{4E^2} \frac{\cos^2(\theta/2)}{\sin^4(\theta/2)} \frac{1}{1 + (2E/m_{\mathrm{p}})\sin^2(\theta/2)} \\ \times \quad & \left[\frac{G_{\mathrm{Ep}}^2(t) - (t/4m_{\mathrm{p}}^2) G_{\mathrm{Mp}}^2(t)}{1 - (t/4m_{\mathrm{p}}^2)} - 2\,\frac{t}{4m_{\mathrm{p}}^2}\, G_{\mathrm{Mp}}^2(t)\, \tan^2(\theta/2) \right], \end{aligned} \tag{4}$$

and utilizing the Rosenbluth technique in order to separate $G_{\mathrm{Ep}}(t)$ and $G_{\mathrm{Mp}}(t)$.

Up to almost $t = -35\ \mathrm{GeV}^2$, the obtained data show a smooth fall with increasing $Q^2 = -t$, and the ratio $(1 + \mu_{\mathrm{p}}) G_{\mathrm{Ep}}(Q^2)/G_{\mathrm{Mp}}(Q^2)$ has constant value at least up to $Q^2 = 6\ \mathrm{GeV}^2$, while the electric and magnetic proton FFs follow the dipole formula [1,2]

$$G_{\mathrm{Ep}}(Q^2) = G_{\mathrm{Mp}}(Q^2)/(1 + \mu_{\mathrm{p}}) = D(Q^2) = 1 \Big/ \left(1 + \frac{Q^2}{071}\right)^2. \tag{5}$$

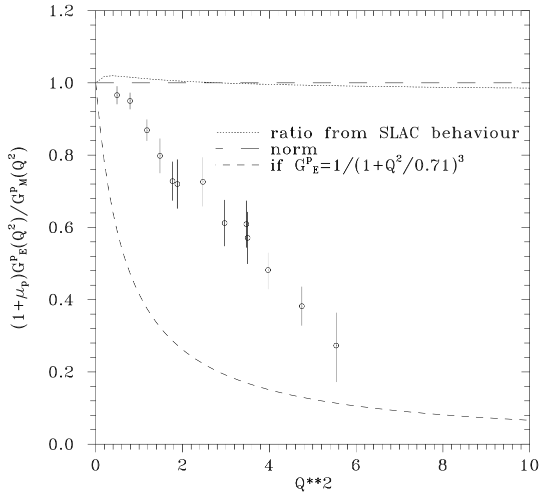

Fig. 1. Remarkable fall of $G_{\mathrm{Ep}}(Q^2)$ with increasing Q^2 in comparison with $G_{\mathrm{Mp}}(Q^2)$.

More recently [3,4], JLab data on $(1+\mu_\mathrm{p})G_\mathrm{Ep}(Q^2)/G_\mathrm{Mp}(Q^2)$, measuring simultaneously transverse P_t and longitudinal P_l components of the recoil proton's polarization in the electron scattering plane of the polarization transfer process $\vec{e}p \to e\vec{p}$, have been determined in the region 0.3 GeV$^2 \le Q^2 \le 5.6$ GeV^2 using the relation

$$\frac{G_\mathrm{Ep}}{G_\mathrm{Mp}} = -\frac{P_\mathrm{t}}{P_\mathrm{l}}\frac{E+E'}{2m_\mathrm{p}}\tan^2(\theta/2), \tag{6}$$

which reveal a remarkable fall of $G_\mathrm{Ep}(Q^2)$ (see Fig. 1) with increased Q^2 in comparison with $G_\mathrm{Mp}(Q^2)$, and so, these data are in a rather strong disagreement with the data obtained by the Rosenbluth technique.

In this contribution, we solve this puzzle by an investigation of the compatibility of the new data with all known FF properties within the framework of our global unitary and analytic model of the nucleon EM structure [5].

2. *Global unitary and analytic model of nucleon EM structure*

At present, it is the most sophisticated model [5] for the four independent analytic functions

$$\begin{aligned}
G_\mathrm{Ep}(t) &= [F_1^\mathrm{s}(t)+F_1^\mathrm{v}(t)] + \frac{t}{4m_\mathrm{p}^2}[F_2^\mathrm{s}(t)+F_2^\mathrm{v}(t)] \\
G_\mathrm{Mp}(t) &= [F_1^\mathrm{s}+F_1^\mathrm{v}(t)] + [F_2^\mathrm{s}(t)+F_2^\mathrm{v}(t)] \\
G_\mathrm{En}(t) &= [F_1^\mathrm{s}(t)-F_1^\mathrm{v}(t)] + \frac{t}{4m_\mathrm{n}^2}[F_2^\mathrm{s}(t)-F_2^\mathrm{v}(t)] \\
G_\mathrm{Mn}(t) &= [F_1^\mathrm{s}-F_1^\mathrm{v}(t)] + [F_2^\mathrm{s}(t)-F_2^\mathrm{v}(t)],
\end{aligned} \tag{7}$$

the so-called electric and magnetic proton and neutron FFs, to be defined on four-sheeted Riemann surface in t-variable with complex poles corresponding to unstable vector meson resonances placed only on unphysical sheets. The model contains all known FF properties, like experimental fact of a creation of vector-meson resonances in electron-positron annihilation processes into hadrons, the assumed nucleon FF analytic properties, unitary condition, normalization

$$F_1^\mathrm{s}(0) = F_1^\mathrm{v}(0) = \frac{1}{2};\;\; F_2^\mathrm{s}(0) = \frac{1}{2}(\mu_\mathrm{p}+\mu_\mathrm{n});\;\; F_2^\mathrm{v}(0) = \frac{1}{2}(\mu_\mathrm{p}-\mu_\mathrm{n}), \tag{8}$$

and the asymptotic behaviour as predicted by quark model of hadrons

$$F_1^\mathrm{s,v}(t)_{|_{|t|\to\infty}} \sim t^{-2};\quad F_2^\mathrm{s,v}(t)_{|_{|t|\to\infty}} \sim t^{-3}. \tag{9}$$

In such a way, it provides a very effective framework for a consistent superposition of complex conjugate vector-meson pole pair and continuum contributions with all other nucleon FF properties. It describes well (see Figs. 2 and 3) for the first time all existing space-like (obtained by Rosenbluth technique) and time-like nucleon FF data simultaneously. That is the case despite of the fact that the values obtained by the Rosenbluth-technique on electric proton FF $G_{\mathrm{Ep}}(t)$ in the $t < 0$ region are significantly less precise than the data on $G_{\mathrm{Mp}}(t)$, since $G_{\mathrm{Mp}}(t)$ is dominant in the differential cross-section (4).

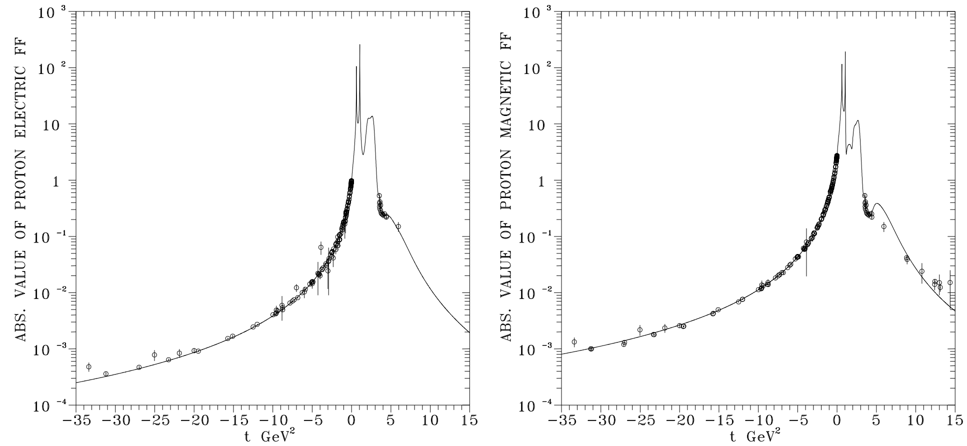

Fig. 2. Description of $G_{\mathrm{Ep}}(t)$ and $G_{\mathrm{Mp}}(t)$ data by the unitary and analytic model.

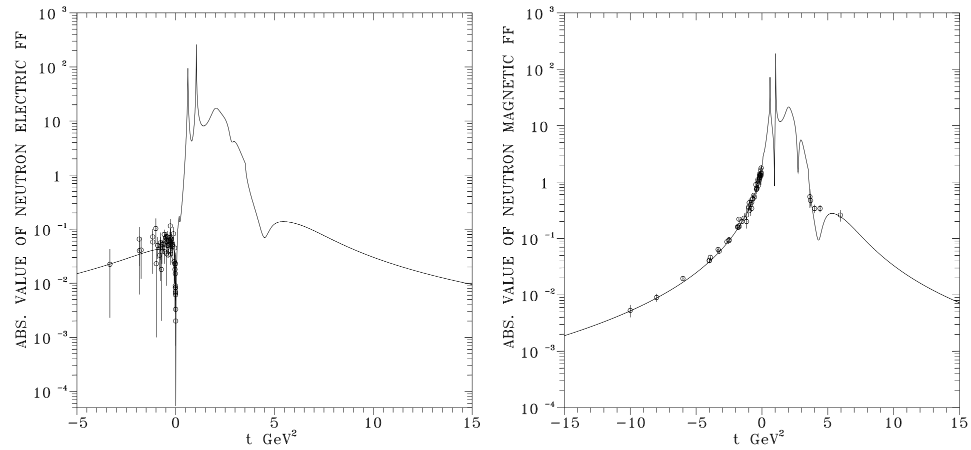

Fig. 3. Description of $G_{\mathrm{En}}(t)$ and $G_{\mathrm{Mn}}(t)$ data by the unitary and analytic model.

3. Consequences of the JLab proton polarization data

From Fig. 1, it is evident that the G_{Ep} decrease is steeper than the decrease of the dipole formula, but less steep than of the tripole one.

Knowing the ratio $G_{\rm Ep}/G_{\rm Mp}$, one can extract also data on the ratio $F_{\rm 2p}/F_{\rm 1p}$ using the expression

$$\frac{F_{\rm 2p}(Q^2)}{F_{\rm 1p}(Q^2)} = \left(1 - \frac{G_{\rm Ep}(Q^2)}{G_{\rm Mp}(Q^2)}\right) \Bigg/ \left(\frac{G_{\rm Ep}(Q^2)}{G_{\rm Mp}(Q^2)} + \frac{Q^2}{4m_{\rm p}^2}\right). \qquad (10)$$

Then $Q^2 F_{\rm 2p}/F_{\rm 1p}$ indicates a continuing increase (see Fig. 4) with Q^2. However, if we multiply the data on the ratio $F_{\rm 2p}/F_{\rm 1p}$ only by Q, then they acquire a constant behaviour with Q^2. So, the new JLab proton polarization data indicate that the proton Pauli FF has (at least in the interval 1.8 GeV$^2 \leq Q^2 \leq$ 5.6 GeV^2) the behaviour

$$F_{\rm 2p}(Q^2) \sim Q^{-5}, \qquad (11)$$

which is in contradiction with the PQCD predictions [6, 7]

$$F_{\rm 2p}(Q^2)_{||Q^2|\to\infty} \sim Q^{-6}. \qquad (12)$$

If the latter is true, then from the definition of the proton electric FF (3) it follows that $|G_{\rm Ep}(Q^2)|$ must have a zero, i.e. diffraction minimum, at some higher value of Q^2.

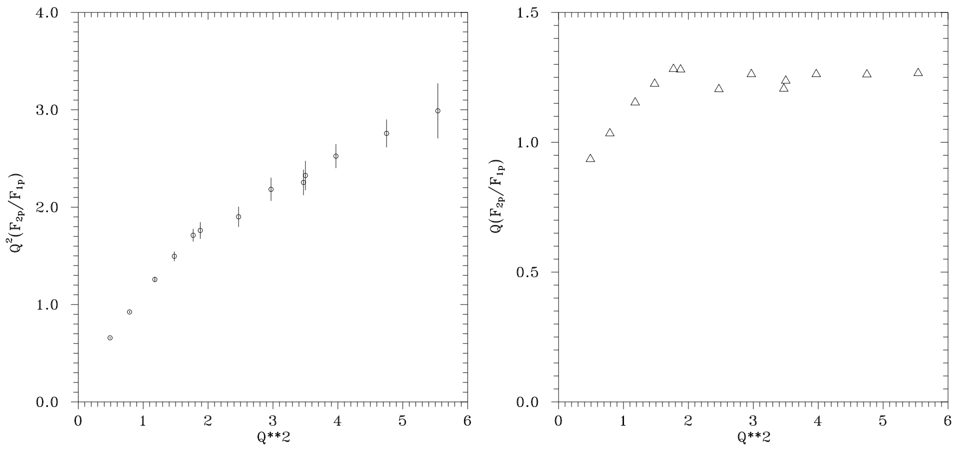

Fig. 4. Data on $F_{\rm 2p}/F_{\rm 1p}$ multiplied by Q^2 and Q respectively.

4. Solution of the puzzle

On the basis of our analysis above, we conclude:

i) The data on $G_{\rm Ep}(t)$ and $G_{\rm Mp}(t)$ in the $t < 0$ region, obtained by the Rosenbluth technique from $d\sigma/d\Omega$, are compatible with all other existing nucleon FF data and all known FF properties, including also the QCD asymptotics.

ii) The very precise JLab proton polarization data on $(1+\mu_{\rm p})G_{\rm Ep}(Q^2)/G_{\rm Mp}(Q^2)$ contradict (at least in the region $1.8 \leq Q^2 \leq 5.6$ GeV^2) predictions of PQCD.

Now, what data on $G_{\rm Ep}(t)$ in the $t < 0$ region are true and what data are wrong?

To solve the problem, we have proceeded as follows. Since the magnetic proton FF $G_{\rm Mp}(Q^2)$ is (owing to the factor $t/(4m_{\rm p}^2)$) dominant in the differential cross-section (4) of $\rm e^-p \to e^-p$ (at $Q^2 = -t \approx 3$ GeV^2, the electric proton FF contributes only 5% to the cross-section, and even less for higher momenta), the obtained data on electric proton FF could be unreliable, even wrong. On the other hand, a simultaneous measurement of the transverse and longitudinal components of the polarization of recoil proton in the electron scattering plane of the polarization transfer process $\vec{\rm e}^-{\rm p} \to {\rm e}^-\vec{\rm p}$ is a very effective and reliable method of the determination of the ratio $G_{\rm Ep}/G_{\rm Mp}$. As a result we believe that the obtained data presented in Fig. 1 and their violation of QCD asymptotics given by (11) should be considered to be a local effect.

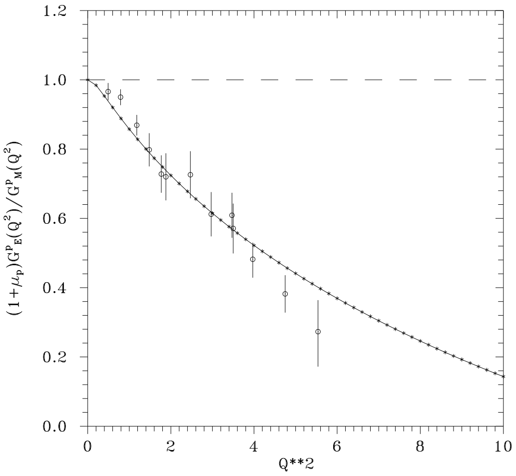

Fig. 5. Description of the JLab proton polarization data by the unitary and analytic model.

We verify this conjecture of ours within the framework of the global unitary and analytic model of the nucleon EM structure which contains the QCD asymptotic automatically. First, we exclude from the set of all existing proton and neutron EM FF data the space-like data on $G_{\rm Ep}(t)$ obtained from $\mathrm{d}\sigma/\mathrm{d}\Omega$ by the Rosenbluth technique. We substitute them for JLab proton polarization data on $(1 + \mu_{\rm p})G_{\rm Ep}(t)/G_{\rm Mp}(t)$. Then by means of the 10-resonance unitary and analytic model of the nucleon EM structure [5], we carry out a fitting procedure of all data simultaneously, which provides a test of:

i) consistency of the JLab proton polarization data with all other proton and neutron EM FF data;

ii) consistency of these data with the powerful tool of physics - the analyticity;

iii) their consistency with the asymptotic behaviour as predicted (up to logarithmic corrections) by QCD.

We have obtained very surprising results. A perfect description of the JLab proton polarization data (see Fig. 5) was achieved. The fitted parameters of the unitary and analytic model of the nucleon EM structure are almost unchanged in comparison with those given in Ref. [5]. A description of the $G_{\mathrm{Ep}}(t)$ time-like data, of all $G_{\mathrm{Mp}}(t)$ data and space-like and the time-like neutron EM FF data (see dashed lines in Figs. 6 and 7) changed very little.

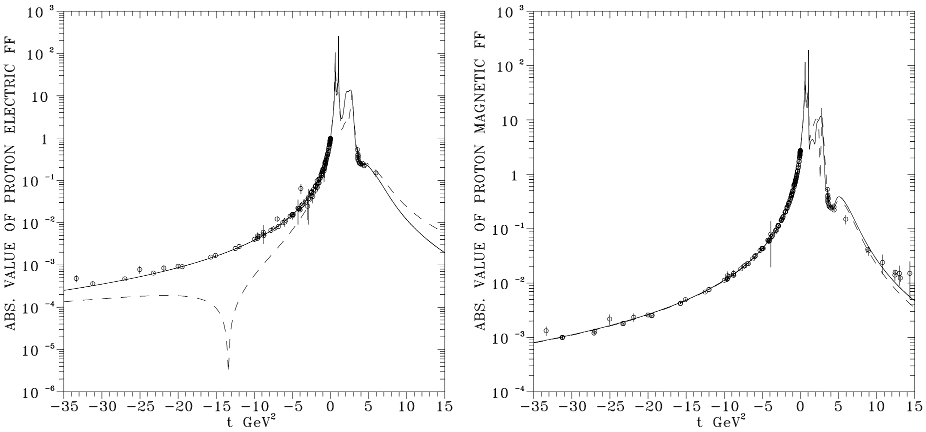

Fig. 6. Results of the JLab proton $t < 0$ data analysis (dashed lines) for $G_{\mathrm{Ep}}(t)$ and $G_{\mathrm{Mp}}(t)$.

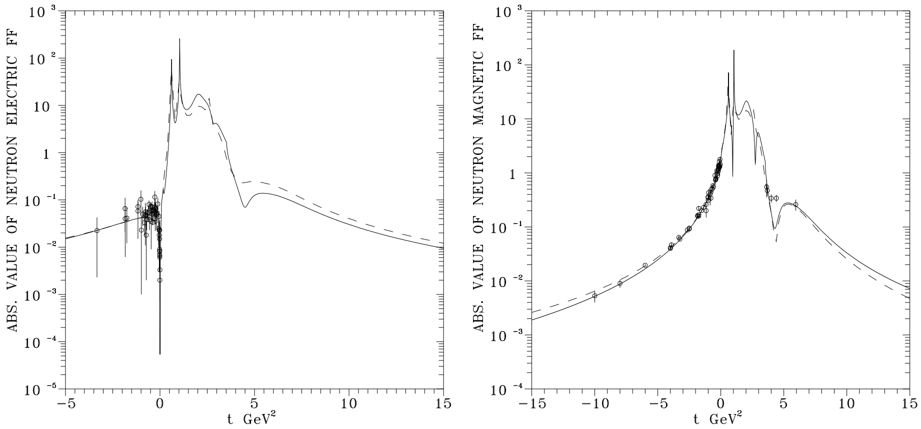

Fig. 7. Results of the JLab proton $t < 0$ data analysis (dashed lines) for $G_{\mathrm{En}}(t)$ and $G_{\mathrm{Mn}}(t)$.

So, we come to the conclusion, that the JLab proton polarization data are consistent with all other existing nucleon EM FF data except the space-like $G_{\mathrm{Ep}}(t)$ data obtained from $\mathrm{d}\sigma(e^-p \to e^-p)/\mathrm{d}\Omega$ by the Rosenbluth technique. They are consistent with analyticity and they don't contradict the QCD asymptotics, however, they strongly require the existence of a zero in $|G_{\mathrm{Ep}}(t)|$ (i.e. a diffraction minimum well known in nuclear EM FFs) around $t = -15$ GeV^2.

5. *Discussion and conclusions*

Recent JLab proton polarization data on $(1+\mu_{\rm p})G_{\rm Ep}(Q^2)/G_{\rm Mp}(Q^2)$, obtained by a simultaneous measurement of the transverse and longitudinal components of the recoil proton's polarization in the electron scattering plane of the polarization transfer process $\vec{e}p \to e\vec{p}$ in the region $0.3{\rm GeV}^2 \leq Q^2 \leq 5.6$ GeV^2, revealed a remarkable fall of $G_{\rm Ep}(Q^2)$ with increasing Q^2, which contradicts previous $G_{\rm Ep}(t)$ data determined from ${\rm d}\sigma({\rm e^-p} \to {\rm e^-p})/{\rm d}\Omega$ by the Rosenbluth technique and so, also the QCD asymptotics.

Omitting all $G_{\rm Ep}(t)$ data obtained by the Rosenbluth technique in the space-like region, we have analyzed new JLab proton polarized space-like data together with all other nucleon EM FF data within the framework of the unitary and analytic model of the nucleon EM structure of Ref. [5].

On the basis of the obtained results, we came to the conclusions that the JLab proton polarization data are consistent with all nucleon EM FF data, except the space-like $G_{\rm Ep}(t)$ data obtained by the Rosenbluth technique, and also with QCD asymptotics, however, they require the existence of a zero (i.e. diffraction minimum) of $|G_{\rm Ep}(t)|$ around $t = -15$ GeV^2. So there is a challenge to experimental groups to confirm our conclusion by measuring $(1+\mu_{\rm p})G_{\rm Ep}(Q^2)/G_{\rm Mp}(Q^2)$ at higher momenta.

Acknowledgements

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POLARIZACIJSKI PODACI ZA PROTONE IZ JLABA I GLOBALNI UNITARNI I ANALITIČKI MODEL EM STRUKTURE NUKLEONA

Pokazujemo da novi polarizacijski podaci iz JLaba za protone, koji su u velikom neskladu s podacima za protonski električni faktor oblika u prostornom području izvedenim Rosenbluthovom metodom, su u skladu sa svim poznatim svojstvima faktora oblika, uključivši i QCD asimptotičke vrijednosti. Međutim, oni zahtijevaju nultu vrijednost (tj., difrakcijski minimum) protonskog električnog faktora oblika oko t=15 GeV^2. To mijenja naše poznavanje raspodjele naboja u protonu.