

Electromagnetic Form Factors and the Hypercentral CQM

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Abstract

We present new results concerning the electromagnetic form factors of the nucleon using a semirelativistic version of the hypercentral Constituent Quark Model and a relativistic current. The calculations, performed without free parameters, provide an overall description of the form factors, with some difficulty for the neutron charge distribution. The complex structure of the constituent quarks is taken into account implicitly introducing phenomenological constituent quark form factors. In this way, a detailed reproduction of the experimental data up to 5 GeV^2 is obtained.

The new data on the ratio of the electric and magnetic form factors of the proton [1, 2, 3], showing an unexpected decrease with Q^2 , have again triggered interest in the description of the internal nucleon structure in terms of various effective models: bag models, chiral soliton models, constituent quark models, etc. .

In 1973 Iachello *et al.* [4] were able to obtain a good reproduction of all the existing nucleon form factor data using a Vector Meson Dominance (VMD) model introducing an intrinsic form factor to describe the internal structure of the nucleon. If the ratio G_E/G_M is plotted, the results of the original fit decrease with Q^2 and cross zero at about 8 GeV^2 . In 1996 Holzwarth [5] showed that the simple Skyrme soliton model, with vector meson corrections and with the initial and final nucleon states boosted to the Breit Frame, leads to a G_E^p that decreases with Q^2 and crosses zero at 10 GeV^2 . In this case the crossing is due to a zero in the Skyrme model form factor as it is also explained in Ref. [6]. In 2000 Cardarelli and Simula [7] using light cone constituent quark models extracted G_M^p from the matrix elements of the y-component of the current, and showed that the decreasing of the ratio is due to the Melosh rotations. In 1996, Frank *et al.* [8] have constructed a relativistic light cone constituent quark model and calculated the electric and magnetic form factors of the proton. If their

calculations are plotted as a ratio of the electric and magnetic form factors, one can see a strong decrease with Q^2 due to the presence of a zero in the electric form factor at $Q^2 = 6 \text{ GeV}^2$ [9]. In 1999 with the hypercentral Constituent Quark Model (hCQM) [10, 11], boosting the initial and final state to the Breit Frame and considering relativistic corrections to the non relativistic current [12], we showed explicitly that the decrease is a relativistic effect and it disappears without these corrections [13, 14, 15]. This calculation made use of the nucleon form factors previously determined in [12]. Using a chiral CQM and a point form dynamics, the Pavia-Graz group [16, 17] obtained a good reproduction of the form factors up to 4 GeV^2 and a decrease of the ratio. A similar reproduction [18] has also been obtained within a Bethe Salpeter approach to a constituent quark model with an instanton based interaction [19]. Using the MIT Bag model, a sharp decrease with Q^2 of the ratio is expected and a change of sign at $Q^2 = 1.5 \text{ GeV}^2$. The inclusion of the pion cloud not only improves the static properties of the model and restores the chiral symmetry, but also the behaviour of the ratio G_E^p/G_M^p [20, 21, 22]. Lattice QCD calculations extrapolated to the chiral limit [23] give rise to interesting results. Finally we can say that the new VMD fit by Iachello and Wan [24] and Iachello and Bijker [25], the extended VMD model by Lomon [26], the soliton model calculation by Holzwarth [5, 6], the calculation by Miller [9] and the relativistic two quark spectator model calculation by Ma *et al.*[27] describe the new Jlab data quite well. For reviews on the subject the readers are referred to [28, 29].

Here, we present new results obtained with the hCQM, using a semirelativistic Hamiltonian and a relativistic quark current. Preliminary results have been presented at various Conferences [30, 31, 32].

First, we briefly review the non relativistic hCQM [10]. The experimental 4- and 3- star non strange resonances can be arranged in $SU_{sf}(6)$ multiplets. This means that the quark dynamics has a dominant spin-flavour invariant part, which accounts for the average multiplet energies. In the hCQM it is assumed to be [10]

$$V(x) = -\frac{\tau}{x} + \alpha x, \quad (1)$$

where x is the hyperradius

$$x = \sqrt{\boldsymbol{\rho}^2 + \boldsymbol{\lambda}^2} \quad , \quad (2)$$

with $\boldsymbol{\rho}$ and $\boldsymbol{\lambda}$ being the Jacobi coordinates describing the internal quark motion. Interactions of the linear plus Coulomb-like type have been used for long time for the meson sector, e.g. the Cornell potential. Moreover this form has been supported by recent Lattice QCD calculations [34].

In the case of baryons, a so called hypercentral approximation has been introduced [35, 36]; this approximation amounts to average any two-body potential for the three quark system over the hyperangle $t = \text{arctg}(\frac{\rho}{\lambda})$ and the angles Ω_ρ and Ω_λ , and it works quite well, especially for the lower part of the spectrum [37]. In this respect, the hypercentral potential of Eq.(1) can be considered as the hypercentral approximation of a two-body linear plus Coulomb-like potential. The splittings within the multiplets are produced by a perturbative

term breaking the $SU_{sf}(6)$ symmetry, which, as a first approximation, can be assumed to be the standard hyperfine interaction H_{hyp} [38].

In the baryon rest frame, the three quark hamiltonian, in the non relativistic case, can be written as [10]:

$$H_{NR} = 3m + \frac{\mathbf{p}_\rho^2 + \mathbf{p}_\lambda^2}{2m} - \frac{\tau}{x} + \alpha x + H_{hyp}, \quad (3)$$

where m is the quark mass (taken equal to 1/3 of the nucleon mass) and \mathbf{p}_ρ , \mathbf{p}_λ are the conjugate momenta of the Jacobi coordinates. We construct the non strange baryons as bound states of three constituent quarks, taking properly into account the antisymmetrization with respect to all quark coordinates. Because of the hyperfine mixing, each baryon state is a superposition of various $SU(6)$ configurations. The hamiltonian (3) is diagonalized in the space of the baryon rest frame states. The strength of the hyperfine interaction is determined in order to reproduce the $\Delta - N$ mass difference and the remaining two free parameters are fitted to the spectrum leading to the values $\alpha = 1.61 \text{ fm}^{-2}$ and $\tau = 4.59$ [10]. Keeping these parameters fixed, this non relativistic constituent quark model has been used to calculate various physical quantities of interest: photocouplings [39], electromagnetic transition amplitudes [40] and, introducing relativistic corrections to the one-body non relativistic current, also the elastic nucleon form factors [12] and the ratio between the electric and magnetic form factors of the proton [14]. We have shown that kinematical relativistic corrections (such as boosts and a relativistic one-body current with an expansion in the quark momenta up to the first order, keeping the exact dependence on the momentum transfer Q^2) are very important for the elastic form factors [14, 12] but yield only minor corrections in the transition ones [41].

We propose a semirelativistic hypercentral constituent quark model based on the following hamiltonian [42]

$$H = \sum_{i=1}^3 \sqrt{\vec{k}_i^2 + m^2} - \frac{\tau}{x} + \alpha x + H_{hyp}. \quad (4)$$

which employs the relativistic kinetic energy, where \vec{k}_i are the quark three momenta in the rest frame ($\sum_{i=1}^3 \vec{k}_i = 0$). The hamiltonian of Eq. (4) is solved by means of a variational method (a complete description of the variational solution of this equation, using the hyperspherical formalism, will be published elsewhere [42]). The resulting spectrum is not much different from the non relativistic one and the parameters α and τ of the potential are only slightly modified, while the constituent quark masses are $m = 100 \text{ MeV}$.

The Hamiltonian 4 can be used within a covariant approach if a Bakamjian-Thomas (BT) construction [43] is performed. In the BT method the interaction is introduced by adding to the free mass operator $M_0 = \sum_{i=1}^3 \sqrt{\vec{k}_i^2 + m^2}$ an interaction term M_I , in such a way that the total mass $M = M_0 + M_I$ commutes with the Poincaré generators [44] A complete set of Poincaré generators can be built according to the prescriptions provided by the point form approach; in this

way the 4-momentum operators P_μ contain interactions while the rotations and the Lorentz boosts are interaction free [46]. The general 3-quark state is defined on the product space of the one-particle spin-1/2, positive energy representation of the Poincaré group [16]. The rest frame free states can be written as

$$|\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3, \rangle = u(\mathbf{k}_1)u(\mathbf{k}_2)u(\mathbf{k}_3) \quad (5)$$

where $u(\mathbf{k}_i)$ is the positive energy Dirac spinor of the i -th quark and the three-momenta satisfy the condition $\sum_{i=1}^3 \vec{k}_i = 0$. In the rest frame of the three quark system, the stationary part of the equation $P_\mu |\Psi \rangle = p_\mu |\Psi \rangle$ is identified with the eigenvalue problem corresponding to the hamiltonian 4. The nucleon state in the space provided by the states of Equation (5) is then given by

$$\Psi(\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3) = u(\mathbf{k}_1)u(\mathbf{k}_2)u(\mathbf{k}_3)\varphi(\mathbf{p}_\rho, \mathbf{p}_\lambda) \quad (6)$$

where $\mathbf{p}_\rho = (\mathbf{k}_1 - \mathbf{k}_2)/\sqrt{2}$ and $\mathbf{p}_\lambda = (\mathbf{k}_1 + \mathbf{k}_2 - 2\mathbf{k}_3)/\sqrt{6}$ are the Jacobi momenta calculated from the rest frame quark momenta \vec{k}_i and $\varphi(\mathbf{p}_\rho, \mathbf{p}_\lambda)$ is the eigenfunction of the Hamiltonian of equation (4). In order to perform the transformation to a different reference frame, we introduce the velocity states [46]

$$|v, \mathbf{p}_1, \mathbf{p}_2, \mathbf{p}_3 \rangle = U_{B(v)}|\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3 \rangle \quad (7)$$

where $U_{B(v)}$ is a Lorentz boost corresponding to the velocity v and p_i^μ are the quark momenta in the trasformed frame. We apply to each quark spinor a canonical boost, obtaining that the transformed quark momenta p_i^μ satisfy the relation

$$\sum_{i=1}^3 p_i^\mu = \frac{P^\mu}{M} \sum_{i=1}^3 \epsilon(\vec{k}_i), \quad (8)$$

where $\epsilon(\vec{k}_i)$ is the rest frame quark energy, P^μ is the observed nucleon 4-momentum and M its mass. Moreover, $p_i^\mu = B(v)k_i$. Having applied canonical boosts, the conditions for a Point form approach [46, 45] are satisfied. In particular, the three quark perform the same rotation and the quark spins can be coupled as in the nonrelativistic case [46, 47].

We now proceed to calculate the elastic nucleon form factors. We choose to work in the Breit frame, where the initial and final states acquire a momentum along the z -axis p_z and p_z , respectively, with $p_z = -p_z = -q/2$, q being the z -component of the virtual photon momentum.

The nucleon electromagnetic form factors can be extracted from the matrix elements of the nucleon electromagnetic current between the initial and final nucleon states of eq. 6, according to the formalism described in Ref. [46].

The current operator is written in impulse approximation, *i.e.* it is chosen to be the sum of the single quark currents [12, 14, 16, 17]; the matrix elements of the quark current in the space of the single quark free spinor states are given by

$$\langle p_1, p_2, p_3 | J_\mu | p'_1, p'_2, p'_3 \rangle = \sum_i \bar{u}_i(p_i) J_{i\mu} u_i(p'_i) \quad (9)$$

$$\bar{u}_j(p_j) u_j(p'_j) \delta(p_j - p'_j) \bar{u}_k(p_k) u_k(p'_k) \delta(p_k - p'_k)$$

where i, j, k is an even permutation of the indexes 1, 2, 3 and

$$\bar{u}_i(p_i) J_{i\mu} u_i(p'_i) = \bar{u}_i(p_i) e_i \gamma_\mu(i) u_i(p'_i) \quad (10)$$

where e_i is the quark charge and Q^2 is the virtual photon squared tetramomentum.

The single quark current is covariant but in principle not conserved, however a conserved current can be obtained by the simple transformation $j'_\mu = j_\mu - q_\mu(qj)/q^2$, where q_μ is the virtual photon tetramomentum; choosing the z-axis along the space component of q_μ , such procedure does not affect the 0, 1, 2 components of the current, from which the elastic form factors are extracted.

The nucleon matrix elements are then calculated making use of the wave functions of eq. (??) and are given by

$$\begin{aligned} J_\mu^N &= \frac{3}{J} \int \frac{d^3 p_1}{\epsilon(\vec{p}_1)} \frac{d^3 p_2}{\epsilon(\vec{p}_2)} \bar{\Psi}(\vec{p}_1, \vec{p}_2, \vec{P}_F) \\ & f(\vec{p}_1, \vec{p}_2, \vec{P}_F) e_3 (F_1^q(Q^2) + F_2^q(Q^2)) \gamma_\mu(3) \\ & - \frac{1}{2m} (p_3 + p'_3)_\mu F_2^q(Q^2) f(\vec{p}_1, \vec{p}_2, \vec{P}_I) \Psi(\vec{p}_1, \vec{p}_2, \vec{P}_I) \end{aligned} \quad (11)$$

where the factor 3 accounts for the symmetry of the wave function, J is the Jacobian for the transformation from the single quark to the Jacobi coordinates, $f(\vec{p}_1, \vec{p}_2, \vec{P})$ is a normalization factor which ensures the correct charge normalization of the current.

The resulting theoretical form factors of the nucleon can be seen in Figs. 1 and 2. The results reported in Figure 1 show a quite good reproduction of the data even if some problems are still present especially at low Q^2 . Nonetheless there is a great improvement in comparison with the non relativistic calculations of Refs [12, 14], where an expansion in the quark momentum was performed. Moreover another important improvement is given by the use of semirelativistic wave functions obtained from the hamiltonian (4).

Constituent quarks can be in principle considered as composite objects [75] and accordingly we parametrize phenomenologically their structure by means of constituent quark form factors, as already done by other authors [?, 75]. The matrix elements of the quark current 10 are substituted with the following ones

$$\begin{aligned} \bar{u}_i(p_i) J_{i\mu} u_i(p'_i) &= \\ \bar{u}_i(p_i) e_i (F_1^q(Q^2) + F_2^q(Q^2)) \gamma_\mu(i) & \\ - \frac{1}{2m} (p_i + p'_i)_\mu F_2^q(Q^2) u_i(p'_i) & \end{aligned} \quad (12)$$

where $F_1^q(Q^2)$ and $F_2^q(Q^2)$ are, respectively, the Dirac and Pauli quark form factors. We choose the Q^2 behavior of the constituent quark form factors as a linear combination of monopole and dipole.

By fitting the free parameters to the reproduction of G_M^p , G_M^n , G_E^n and $\mu_p G_E^p/G_M^p$ we obtain the curves shown in Fig. 3 and 4. The very recent data on the ratio from Jlab [78] are also reported in Fig. 4 for completeness, even if they have not yet been included in the fitting procedure.

As it can be seen in Fig. 3 and 4 the experimental data are very well reproduced. The goodness of the reproduction is emphasized by plotting the form factors divided by the dipole form. With respect to the non relativistic case, the semirelativistic wave functions have more high momentum components. This fact, together with the application of exact boosts to the Breit Frame, leads to an improvement in the reproduction of the existing data on the electromagnetic form factors. However, a good description of the data is obtained only if phenomenological constituent quark form factors are introduced in the electromagnetic current. In this way we have a very nice agreement with the available experimental data up to 5 GeV^2 .

Finally, it results that for a good reproduction of the elastic form factor data both the relativistic effects and the composite nature of the constituent quarks have to be taken into account. We observe that such constituent quark form factors actually parametrize not only the constituent quark structure but also the relativistic effects which have not yet been explicitly included in our calculations.

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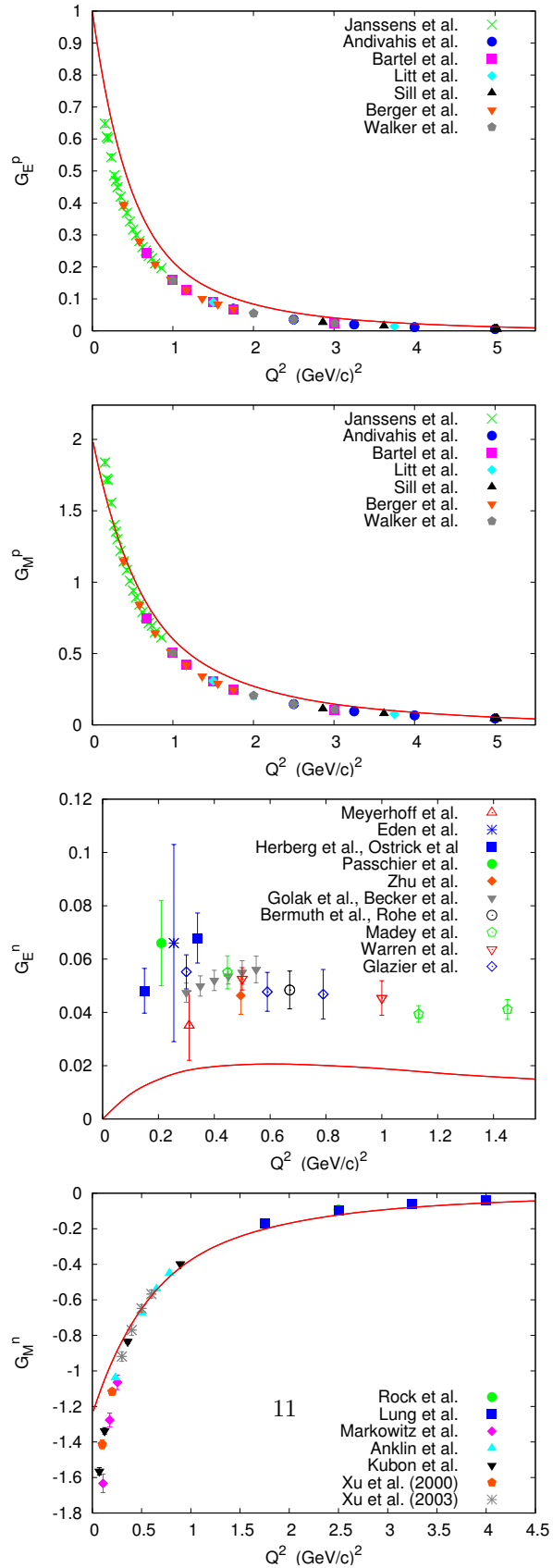


Figure 1: (Color online) Elastic form factors of the nucleon. The solid line

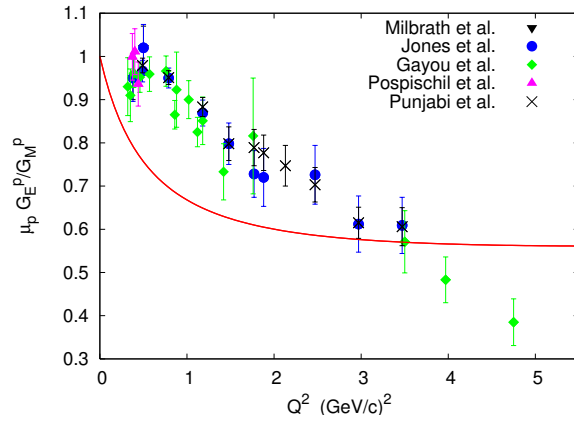


Figure 2: (Color online) The ratio $\mu_p G_E^p / G_M^p$ from polarization transfer compared with the semirelativistic hCQM calculation with the quark current of Eq. (10) (solid line). The experimental data are taken from [73, 1, 2, 3, 74, 78].

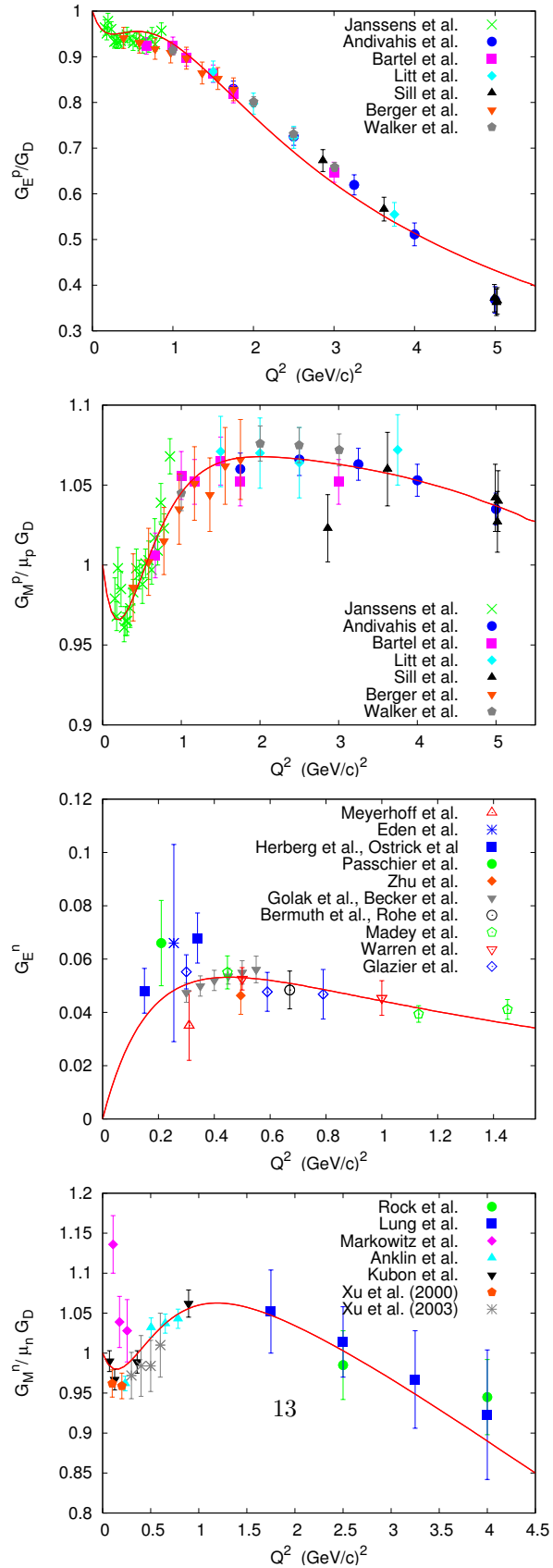


Figure 3: (Color online) Elastic form factors of the nucleon. The solid line

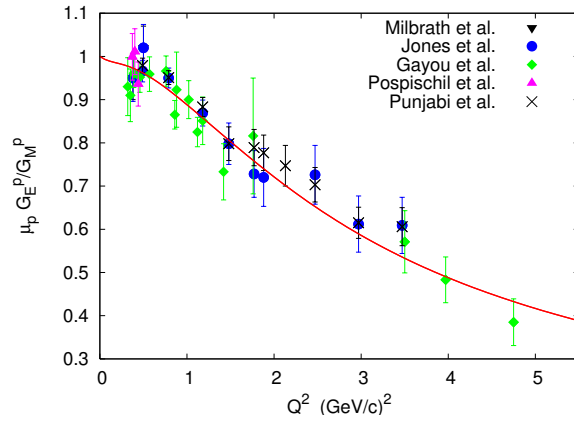


Figure 4: (Color online) The ratio $\mu_p G_E^p / G_M^p$ from polarization transfer compared with the semirelativistic hCQM calculation with constituent quark form factors (solid line). The experimental data are taken from [73, 1, 2, 3, 74, 78].