



Instanton contribution to the proton and neutron electric form factors

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Abstract

We study the instanton contribution to the proton and neutron electric form factors. Using the single instanton approximation, we perform the calculations in a mixed time-momentum representation in order to obtain the form factors directly in momentum space. We find good agreement with the experimentally measured electric form factor of the proton. For the neutron, our result falls short of the experimental data. We argue that this discrepancy is due to the fact that we neglect the contribution of the sea quarks. We compare to lattice calculations and a relativistic version of the quark-diquark model.

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1. Introduction

Electro-magnetic form factors provide valuable information about the structure of hadrons and the strong interaction dynamics. At low momenta, they directly probe the electric and magnetic charge distribution inside the hadron. In general, the form factors are related to the elastic amplitude for a given hadron to absorb a virtual photon. Thus, one can access the interaction responsible for the recombination of the partons into the hadron.

The electro-magnetic form factors of the nucleon are currently subject to a renewed experimental interest. At low momenta, the proton electric and magnetic

form factors can be very well described by the same dipole fit,

$$G_{E(M) \text{ dip}}^p = \frac{e(\mu)}{(1 + Q^2/M_{\text{dip}}^2)^2},$$

where $M_{\text{dip}} = 0.84 \text{ GeV}$. For larger momenta ($Q^2 \gtrsim 2 \text{ GeV}^2$), however, recent measurements at JLab show that the electric form factor falls off faster than the magnetic one [1,2]. On the other hand, the electric form factor of the neutron has been measured up to $Q^2 \approx 2 \text{ GeV}^2$ [3–9]. It was found to be positive, which indicates an inhomogeneous distribution of the positive and the negative charge in the neutron, with the positive charge concentrated near the center.

From the theoretical point of view, the nucleon form factor is one of the few hadronic quantities of fundamental importance. Perturbative QCD (pQCD)

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predicts power asymptotics $G \sim 1/Q^4$ [10] related to the minimal number (two) of exchanged gluons, which agrees with data. However, the coefficient which is related to the so-called light cone nucleon wave function (see, e.g., [11]) does not agree with the pQCD asymptotics. This gives rise to the question whether it is actually described by pQCD at all in the experimentally reached region.

The situation for the charged pion form factor is similar. The power of Q matches pQCD, but the coefficient does not, although it is well known asymptotically. Therefore, it must be produced by some non-perturbative effect. In our recent paper [12], we have calculated the instanton contribution to the pion form factor using the simplest single instanton approximation (SIA). This led to a very good description of the data, without any new parameters involved. In fact, the only relevant parameter is the average instanton size in the QCD vacuum. We further found that the contribution from a single instanton exceeds the one of asymptotic pQCD in a rather wide region $Q^2 \lesssim 10 \text{ GeV}^2$ accessible to current experiments. Moreover, the form factor of the pion was found to follow closely the well-known vector dominance monopole expression.

It is the guiding motivation of the current investigation to see whether the dipole form of the proton electric form factor can also be explained using instantons. One possible motivation comes from the similarity between the pion and the scalar diquark channel, i.e., the ud content of the nucleon. This similarity becomes exact in two color QCD and approximate (up to a factor 1/2) for three colors in the instanton context (see, e.g., the discussion in [13]). More formally, we find that the nucleon form factor also receives contributions from maximally enhanced instanton diagrams with two zero modes. In contrary, e.g., the form factor of the delta does not receive similar maximal instanton contributions. In fact, in the SIA it vanishes. As the main result of this investigation, we indeed find that the proton electric form factor at intermediate momentum transfer $Q^2 \sim 1\text{--}4 \text{ GeV}^2$ is well reproduced by the single instanton contribution with the same standard parameters of the instanton ensemble.

There are a number of other interesting questions which emerge from the experimental information on the proton form factors. For example, one would

like to understand why the low Q^2 data for both $G_E^p(Q^2)$ and $G_M^p(Q^2)$ follow the same dipole fit. In the case of the pion form factor, the success of the monopole fit can be understood in terms of vector meson dominance. However, there is not such a simple picture which can explain the dipole behavior of the proton form factors, although the mass in the dipole fit, M_{dip} , is close to the vector meson mass.

There are also interesting theoretical questions arising from the data for the neutron form factor. The fact that the electric form factor is non-zero is a clean signature that a naive non-relativistic quark model description based on $SU(6)$ symmetry is inadequate for the dynamic properties of the nucleon. It is then remarkable that such a picture works so well in describing the neutron to proton magnetic moment ratio. Clearly, in order to solve this puzzle, we need to understand what is the main source of $SU(6)$ breaking in the neutron wave function.

Such questions have been addressed in a number of phenomenological models as well as in lattice simulations [14,15]. In particular, we discuss two recent works which are related to our analysis. Dong et al. calculated the proton and neutron form factors in lattice QCD and studied the sea quark contribution [16] which is due to disconnected diagrams. It was found that the proton electric form factor can be very well reproduced by the connected components of the relevant Green functions, with the contribution of the sea being negligible. On the other hand, the connected contribution accounts for roughly only half of the neutron electric form factor. Therefore, their analysis shows that the sea cannot account for the entire $SU(6)$ breaking observed in the neutron wave function.

Ma et al. considered a different source of $SU(6)$ breaking [17]. They calculated the form factors of the nucleon in a simple quark–diquark model, in which relativistic covariance is enforced by using the light front dynamics formalism. In this model, they considered trial wave functions depending on phenomenological parameters, which were fixed in order to reproduce the static properties of the nucleon. By varying such parameters, they could tune the amount of $SU(6)$ breaking in their valence picture. They found that such a simple model can reproduce very well the existing data for the form factors of the nucleon up to $Q^2 \sim 2 \text{ GeV}^2$. Moreover, in this model, the ratio G_E^p/G_M^p at high momenta is a consequence

of the relativistic correlation between the spin and the momentum of the constituents.

We now come back and discuss the significance of the instanton contribution to the neutron and proton electric form factors. Instantons are topologically non-trivial solutions of the Euclidean Yang–Mills equation of motion. Physically, they describe tunneling events in the QCD vacuum and are associated with strong non-perturbative color fields. Form factors are amplitudes of a hadron retaining its identity after large momentum transfers and the strong fields of the instantons may transfer momentum between several quarks at once. Furthermore, instanton zero modes lead to a special importance of instantons for any problems involving light fermions, especially in spin-zero channels such as pions or diquarks.

In the Instanton Liquid Model (ILM) (for a review see [18]), the QCD partition function is assumed to be saturated by an ensemble of instantons and anti-instantons of a typical size, $\rho \approx 1/3$ fm, and a typical density, $n \approx 1$ fm⁻⁴. Previous works have shown that the ILM describes quantitatively the spectrum of the light mesons [19] and baryons [20]. The instanton induced interaction is effective only between quarks of different flavor and chirality. This implies that, in the nucleon, only two quarks can be bound by the 't Hooft interaction, while the third one is more loosely bound. Indeed, it was shown [20] that the u and d quark in the nucleon form a bound state, a scalar diquark with a mass comparable to that of a constituent quark. This analysis provided a microscopic motivation for the quark–diquark model of the nucleon.

There are, however, some differences between the quark–diquark picture which emerges from the ILM and the simplest phenomenological model described above. For example, Ma et al. considered a nucleon wave function with an equal mixture of a scalar and a vector diquark [17], while the 't Hooft interaction generates a scalar diquark only. Moreover, in [17], the diquark is treated as a point-like particle, while in the ILM its size has been estimated to be approximately 0.4 fm [21]. Finally, in the ILM it is possible to account for the contribution of the meson cloud and the sea quarks simultaneously, both contributing to the $SU(6)$ symmetry breaking of the nucleon wave function.

In a previous work, two of the authors calculated the proton electro-magnetic three-point function in co-

ordinate space [21] both from numerical simulations in the ILM, i.e., including multi-instanton effects, and analytically in the SIA. The Green function evaluated theoretically was then compared to a phenomenological one derived from the Fourier transform of several parametrizations of the experimental data. This approach had the advantage to consider large-sized correlation functions, for which the contribution of the continuum of excitations was certainly negligible. However, such a procedure has the shortcoming that it does not allow a direct comparison to the experimental data. From a theoretical point of view, the main result was that the proton electro-magnetic three-point function is completely dominated by the contribution of a single instanton, up to surprisingly large distances of ≈ 1.8 fm. From a phenomenological point of view, it was shown that the ILM predictions are consistent with a deviation of G_E^p from the dipole fit. This is in nice agreement with the result obtained by Ma et al. in their simple model.

In the present work we develop a much simpler single instanton calculation, based on the time-momentum correlators used in [12] and [22]. Such a scheme accounts for the leading single instanton effects. The calculation is physically very transparent and presents several analogies with perturbation theory. Moreover, we compare directly to the experimental data. In the pion and nucleon channel, the single instanton contribution is certainly dominant for hadronic processes at intermediate momenta, $Q^2 \geq 1$ GeV². Moreover, it constitutes the relevant gluonic configurations, which take over with the breakdown of perturbation theory.

We have not calculated the contribution of the quark sea (the disconnected diagrams) to the form factor, but argue it to be small, roughly $\sim 1/10$ of the proton form factor and half of the neutron form factor. We will proceed by describing the details of our calculation. In Section 3 we show our results and close by discussing the physical implications.

2. Computational setup

For the determination of the electric form factors of the nucleon, we follow the method used in the calculation of the charged pion electro-magnetic form factor [12]. In the wall-to-wall (W2W) formalism, the

electric form factors can be extracted from a combination of three- to two-point functions. In particular, we choose to work in the Breit frame and consider the following spatial Fourier transform of the Euclidean three-point correlator

$$G_4(t, \mathbf{q}/2; -t, -\mathbf{q}/2) = \int d^3\mathbf{x} d^3\mathbf{y} e^{i\mathbf{q}\cdot(\mathbf{x}+\mathbf{y})/2} \times \langle 0 | \text{Tr} \eta_{sc}(t, \mathbf{y}) J_4(0, \mathbf{0}) \bar{\eta}_{sc}(-t, \mathbf{x}) \gamma_4 | 0 \rangle. \quad (1)$$

J_4 is the fourth component of the electro-magnetic current operator and $\eta_s(x)$ is the so-called nucleon scalar current which, in the case of the proton, reads¹

$$\eta_s(x) = \epsilon_{abc} [u^a(x) C \gamma_5 d^b(x)] u^c(x). \quad (2)$$

Accordingly, we evaluate the Fourier transform of the nucleon two-point function given by

$$G(t, \mathbf{q}) = \int d^3\mathbf{x} e^{i\mathbf{q}\cdot\mathbf{x}} \langle 0 | \text{Tr} \eta_{sc}(t, \mathbf{x}) \bar{\eta}_{sc}(0) \gamma_4 | 0 \rangle. \quad (3)$$

In both Eqs. (1) and (3), the additional γ_4 has been inserted in order for the correlators to receive maximal single-instanton contribution (see the discussion in [21] and below).

For large Euclidean times, one can isolate the contribution of the lowest lying state to the Green function

$$G_4^{p(n)}(t, \mathbf{q}/2; -t, -\mathbf{q}/2) \rightarrow 2\Lambda_{sc}^2 \left(\frac{M}{\omega_{\mathbf{q}/2}} \right)^2 G_E^{p(n)}(Q^2) e^{-2\omega_{\mathbf{q}/2} t}, \quad (4)$$

where $G_E^{p(n)}(Q^2)$ denotes the proton (neutron) electric form factor and Λ_{sc} the coupling of the scalar current, Eq. (2), to the nucleon. The nucleon pole in the two-point function is similarly reached

$$G(t, \mathbf{q}) \rightarrow 2\Lambda_{sc}^2 e^{-\omega_{\mathbf{q}} t}. \quad (5)$$

In order to calculate the instanton contribution to such correlation functions, we use the SIA, which was introduced in [23] and studied in detail in [24]. In

¹ We note that the nucleon scalar current contains explicitly the operator which excites a scalar ud diquark. It is this combination that couples strongly to the instanton zero modes. The corresponding operator for the neutron is obtained through the substitution $u \leftrightarrow d$.

such an approach, only the contribution from the closest instanton is taken explicitly into account, while the effects of the other instantons are incorporated in two induced parameters, the quark effective mass, $m^* \approx 85$ MeV, and the average instanton density, $\bar{n} \approx 1 \text{ fm}^{-4}$.

The quark propagator in the instanton background is known exactly [25] and consists of a zero-mode part and a non-zero mode part, $S^I(x, y) = S_{zm}^I(x, y) + S_{nzm}^I(x, y)$. We showed that the SIA is reliable only if the relevant Green functions receive contribution from more than one zero-mode propagator [24]. In fact, the additional γ_4 matrix in Eqs. (1) and (3) has been inserted in order to guarantee such an enhancement.

In this Letter, we choose to further simplify the calculation by adapting the so-called “zero-mode approximation”, in which the non-zero mode part of the propagator is replaced by the free one, $S^I(x, y) \simeq S_{zm}^I(x, y) + S_0(x, y)$. This approximation is accurate in the case of the nucleon three- and two-point functions which we are considering [21]. Finally, it is convenient to work directly in a time-momentum representation for the Green functions. This is achieved by using the W2W quark propagators evaluated in [12]. Two typical diagrams contributing to the connected three-point function, Eq. (1), in the SIA are shown in Fig. 1(A) and (B). Due to the chiral and flavor structure of the instanton induced interaction, the zero modes are restricted to the u and d quark inside the nucleon. This reduces the possible diagrams to the structure depicted in Fig. 1(A) and (B) and a similar diagram with the instanton to the right. The total contribution is nevertheless still quite involved due to the charge conjugation matrix in the nucleon currents. The interpretation is that in diagram (A) of Fig. 1 the virtual photon probes the diquark content of the nucleon, whereas in diagram (B) the photon interacts with the residually bound quark.

After Wick contraction, the calculation of the three- and two-point functions, Eqs. (1) and (3), reduces to evaluating the averages of traces of W2W propagators in the single instanton (and anti-instanton) background. The average involves an integration over the position, size and color orientation of the instanton. We approximate the instanton size distribution to be simply $d(\rho) = \bar{n} \delta(\rho - \bar{\rho})$, with a typical instanton density, $\bar{n} = 1 \text{ fm}^{-4}$, and a typical instanton size, $\bar{\rho} =$

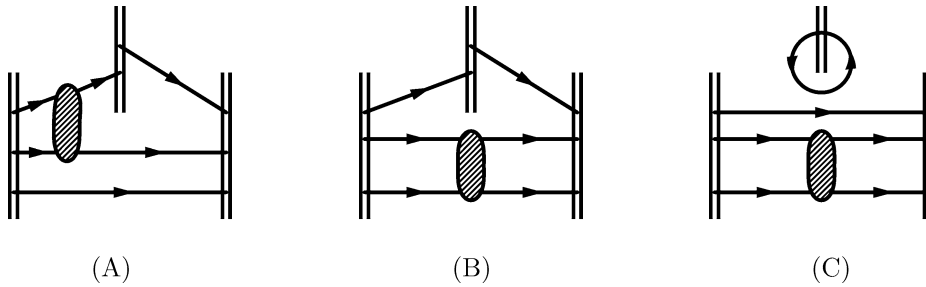


Fig. 1. Graphical representation of the typical contributions to the W2W nucleon electro-magnetic three point function. The double lined “walls” correspond to the spatial Fourier integration, see [12]. The dashed ellipse denotes the four quark (zero-mode) instanton interaction. The nucleon is excited at the left, struck by the virtual photon in the middle and absorbed at the right. Two contributions to the connected three-point function are shown. Diagram (A) probes the diquark content of the nucleon, whereas in diagram (B), the photon interacts with the remaining quark. Diagram (C) is disconnected, where the photon probes the sea quark content of the nucleon.

1/3 fm taken from the ILM.² In general, Wick contracting generates connected as well as disconnected averages.

The disconnected contribution, Fig. 1(C), requires some discussion. Physically, it corresponds to the effects of the sea quarks on the form factor. In perturbation theory, this contribution is subleading at large Q due to the additional gluon exchange required to transfer momentum from the struck sea quark to the valence one. In the instanton background field, this momentum transfer can occur via the instanton field itself³ and also leads to an extra suppression at large Q . The total momentum flowing into the sea quark loop \mathbf{q} has to be transferred to the valence quarks, which leads to an extra “instanton form factor” $\exp(-\rho|\mathbf{q}|)$ from the non-zero mode propagator in the sea quark loop. This small factor appears in addition to the form factors from the zero mode and non-zero mode propagators in the valence pieces.⁴

Unfortunately, the evaluation of the W2W non-zero mode propagator is extremely involved and we refrain from calculating the contribution of the disconnected

diagram, Fig. 1(C). We will argue below that it is indeed a small contribution to the proton form factor.

In this work, we focus on the *electric* form factors of the proton and the neutron only, as they come from maximally enhanced diagrams. The instanton contribution to the *magnetic* form factors of the nucleon can be extracted from a different combination of the three- and two-point functions [15,16], which, however, receives only subleading contributions from a single instanton.

Once the Green functions are evaluated, the electric form factor can in principle be determined from the ratio of the three- to two-point correlators in the large Euclidean time limit, $t \rightarrow \infty$. However, in the approach of this work focused on a single instanton, one cannot choose the time interval to be arbitrarily large. In fact, as t becomes comparable with the typical distance between instantons, $\bar{n}^{-1/4} = 1$ fm, many-instanton effects should begin to play a non-negligible role and the SIA will eventually break down. The SIA calculation of the three- and two-point functions are compared to numerical simulations in the ILM in [21]. We verified that the SIA calculation of the two-point correlator, Eq. (3), is reliable up to distances of ≈ 0.9 fm. On the other hand, we found that the single instanton contribution to the three-point function, Eq. (1), saturates the ILM results up to much larger distances of ≈ 1.8 fm.

In order to access the proton and neutron form factors, we need to ensure that, at the largest value of the Euclidean time allowed by the SIA, the nucleon pole is reasonably isolated in both the two- and

² In [12], we evaluated the pion form factor using different parametrizations of the instanton size distribution. We found that the predictions obtained from such a simple delta-function ansatz agree within 10% with those obtained using a parametrization of the lattice results for $d(\rho)$.

³ The chiral structure of the instanton interaction requires a non-zero mode propagator for the sea quark loop. The free propagator used in the zero-mode approximation would lead to a vanishing contribution.

⁴ These go as $\exp(-\rho|\mathbf{q}|/6)$ since every valence quark has a total momentum $|\mathbf{q}|/6$ on average in the Breit frame.

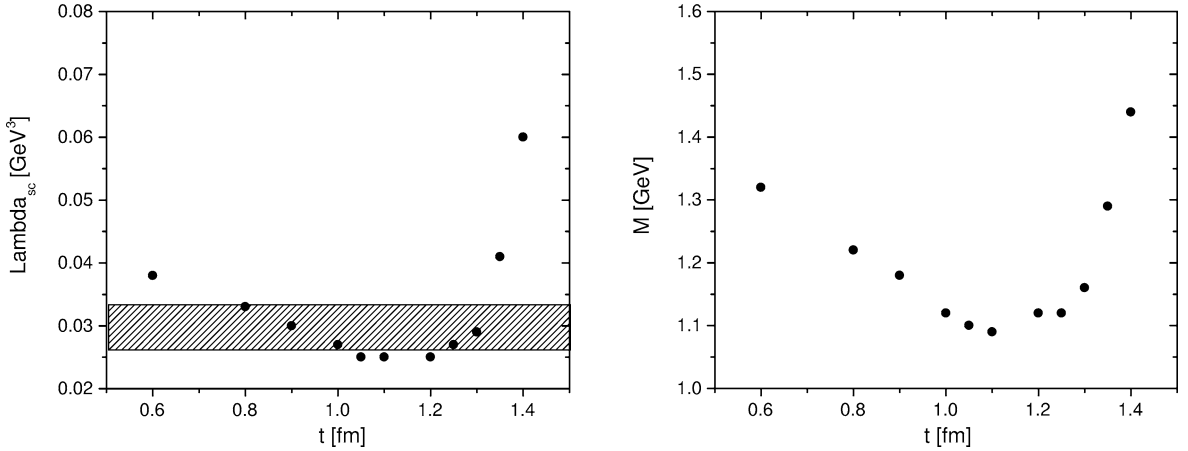


Fig. 2. The scalar coupling to the nucleon, Λ_{sc} , (left) and the nucleon mass (right) evaluated from the SIA two-point function for different Euclidean times. The shaded area in the left figure represents the range of values of Λ_{sc} obtained from quenched and unquenched lattice simulations, e.g., [26].

three-point correlation functions. This was assured for the pion, essentially due to the large separation from its resonances. For the nucleon, this is a more delicate task, because the first resonance with the same quantum numbers, $N(1440)$, is only a few hundred MeV heavier than the ground state. This implies that larger time intervals are needed to separate their contributions. Therefore, it is a priori not guaranteed that there is a window, in which the SIA is reliable and the nucleon is isolated from its resonances.

In Fig. 2, we show the SIA results for the nucleon coupling and mass, obtained from a fit of the two-point function, Eq. (3), retaining only the ground state in the spectral decomposition, as in Eq. (5). We find that a plateau, which indicates the complete isolation of the proton signal, is obtained for $t \gtrsim 1$ fm. Moreover, as t becomes larger than 1.3 fm, the single instanton contribution rapidly dies out and the approximation breaks down. Unfortunately, on the basis of the analysis developed in [21], we estimate the maximal time interval for which we can trust our two-point function SIA calculation to be $t \approx 0.9$ fm.⁵ This implies that, in our calculation, the nucleon is not completely isolated and we expect a small contamination of the correlation functions from excited states. From the two plots in Fig. 2, we

estimate that such effects result in corrections of the order of 10%.

We extract the electric form factors from the ratio

$$2\Lambda_{sc}^2(t) \left(\frac{\omega_{\mathbf{q}/2}(t)}{M(t)} \right)^2 \times \frac{G_4^{p(n)}(t, \mathbf{q}/2, -t, -\mathbf{q}/2, t)}{(G(t, \mathbf{q}/2))^2} \rightarrow G_E^{p(n)}(Q^2), \quad (6)$$

where $\Lambda_{sc}(t)$, $M(t)$ and $\omega_{\mathbf{q}/2}(t) = \sqrt{\mathbf{q}^2/4 + M(t)^2}$ denote the values extracted from a fit of the two point function $G(t, \mathbf{q}/2)$ keeping only the nucleon contribution in the spectral decomposition. The ratio of $G_4(2t)/G(t)^2$ ensures that both correlators can be calculated reliably in the SIA. The two factors of the two-point function are needed to sustain the nucleon pole over the total Euclidean distance $2t$ with a necessary $t = 0.9$ fm. It corresponds to the leading order in a virial expansion in the instanton density. This procedure is at the expense of a dependence on the multi-instanton induced parameters, namely the quark effective mass m^* and the average instanton density \bar{n} , or equivalently a dependence on the nucleon coupling Λ_{sc} and mass. For the pion form factor, it could be achieved that such a dependence cancels in the calculation, with only the average instanton size $\bar{\rho}$ remaining.

In Fig. 3, we give the resulting proton electric form factor in the SIA, obtained for different values of the Euclidean time. We observe that our outcome is nearly

⁵ We note that the total time interval in the three-point function is given by $2t$.

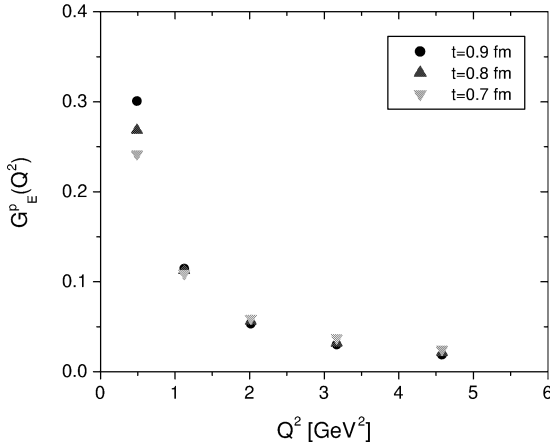


Fig. 3. The proton electric form factor G_E^p as a function of Euclidean time t . Although the relevant Green functions receive a contribution from the excited states of the order of 10%, for $t = 0.9$ fm, the form factor is independent of t .

independent on the chosen time interval restricted to the SIA window. This indicates a cancellation between the small contribution from the excited states to the numerator and the denominator in Eq. (6).

3. Results and discussion

The aim of the present calculation is to show that the dipole behavior of the proton electric form factor can be explained from the interaction of the quarks with the field of a single instanton. Our final result for G_E^p is presented in Fig. 4 in comparison with the dipole fit.⁶ The results show that the instanton-induced contribution can account for the correct magnitude of G_E^p . Thus, it should be included in any dynamical model. Whether there is indeed a direct relation between the nucleon form factor and instantons in the QCD vacuum can be further tested on the lattice, in many ways and on a configuration-per-configuration basis. We do not wish to claim that the SIA results have the accuracy to explain the high Q^2 precision

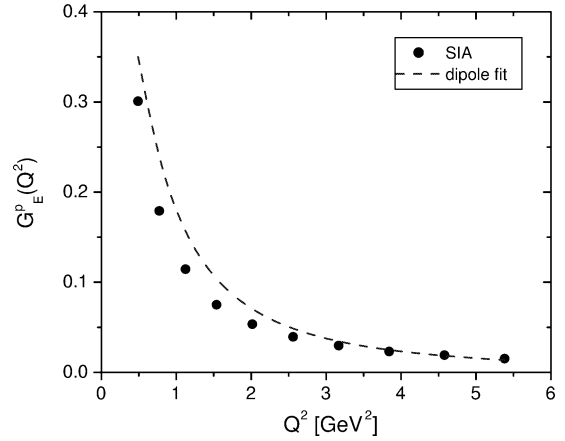


Fig. 4. The proton electric form factor evaluated in the SIA (points) compared to the dipole fit (dashed line). The shown results are obtained using $t = 0.9$ fm. The SIA results are reliable for $1 \text{ GeV}^2 \lesssim Q^2 \lesssim 4 \text{ GeV}^2$ (see the discussion in the text and in [12,22]).

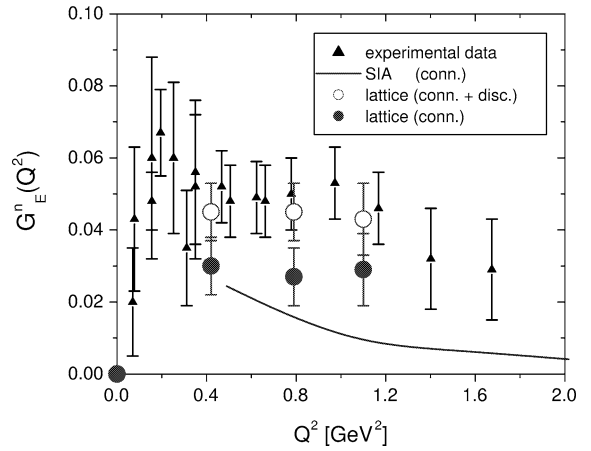


Fig. 5. The neutron electric form factor in the SIA (solid line again for $t = 0.9$ fm) in comparison to the experimental data [3–9] (triangles), lattice results retaining only the connected components (filled circles) as well as both connected and disconnected parts (empty circles) [16]. The SIA results are reliable for $Q^2 \gtrsim 1 \text{ GeV}^2$ (see the discussion in the text and in [12,22]).

data for the ratio of G_E^p/G_M^p . However, much more involved numerical simulations have shown that the ILM is consistent with the high momentum deviation of the proton electric form factor from the dipole fit [21].

The result for the neutron form factor is presented in Fig. 5 in comparison to the available experimental data and the lattice results of Dong et al. [16].

⁶ At large momenta, the electric form factor of the proton is experimentally less well resolved than both its ratio to the magnetic one and the magnetic form factor itself. From the measurements at JLab [1,2], one finds that at $Q^2 \sim 1\text{--}4 \text{ GeV}^2$ the electric form factor is reduced by about 20–50% relative to the magnetic one, whereas the magnetic form factor is still reproduced by the dipole fit very well.

As expected, the presence of a massive diquark generates an inhomogeneous charge distribution and leads to a positive form factor. However, in the instanton model, the masses of the scalar diquark and the constituent quark are not that different, which leads to a small neutron form factor. Furthermore, we observe that the connected component of the Green function accounts for roughly half of the form factor only. This is in qualitative agreement with lattice results, which also found that half of the neutron form factor comes from the disconnected diagrams we have neglected in the present calculation. This provides an estimate for its value and supports our assumptions that it is small compared to the proton form factor. In the instanton model it is subleading as explained above.

Summarizing, we have computed the single instanton contribution to nucleon electric form factors. We have carried out the calculations analytically in a window of momentum transfer in which the single instanton approximation can be used. The range of validity of the SIA for the nucleon was found to correspond to momentum transfers $Q^2 \sim 1\text{--}4 \text{ GeV}^2$. At smaller Q^2 , multi-instanton effects appear, and at larger Q^2 , there are admixtures of excited states (see the discussion in [22]). Already the existence of such a window for the nucleon in the SIA is highly non-trivial due to the presence of a rich and close spectrum of excited states. The only other hadron for which this was shown to be the case is the pion [12]. The physical reason is that the (single) instanton induces a compact quark-diquark structure of the nucleon. Other baryons, such as the decouplet members, do not have such a structure and thus are expected to have smaller form factors. For numerical results we used the standard parameters of the instanton ensemble [23], fixed 20 years

ago. A similar analysis of the proton to delta transition form factors is in preparation [27].

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