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Pure sea-quark contributions to the magnetic form factors of Σ baryons

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We propose the pure sea-quark contributions to the magnetic form factors of Σ baryons, $G^u_{\Sigma^-}$ and $G^d_{\Sigma^+}$, as priority observables for the examination of sea-quark contributions to baryon structure, both in present lattice QCD simulations and possible future experimental measurement. $G^u_{\Sigma^-}$, the u-quark contribution to the magnetic form factor of Σ^-, and $G^d_{\Sigma^+}$, the d-quark contribution to the magnetic form factor of Σ^+, are similar to the strange-quark contribution to the magnetic form factor of the nucleon, but promise to be larger by an order of magnitude. We explore the size of this quantity within chiral effective field theory, including both octet and decuplet intermediate states. The finite range regularization approach is applied to deal with ultraviolet divergences. Drawing on an established connection between quenched and full QCD, this approach makes it possible to predict the sea-quark contribution to the magnetic form factor purely from the meson loop. In the familiar convention where the quark charge is set to unity $G^u_{\Sigma^-} = G^d_{\Sigma^+}$. We find a value of $-0.38^{+0.16}_{-0.17}\,\mu_N$, which is about seven times larger than the strange magnetic moment of the nucleon found in the same approach. Including quark charge factors, the u-quark contribution to the Σ^- magnetic moment exceeds the strange-quark contribution to the nucleon magnetic moment by a factor of 14.

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It is well known that a complete characterization of baryon substructure must go beyond three valence quarks. For example, there is significant interest in the role of five-quark admixtures. This began with suggestions that there might be an intrinsic charm [1,2] or an intrinsic strange component [3,4] of the nucleon sea originating in nonperturbative QCD, rather than the familiar perturbative QCD evolution. Such configurations are widely believed to play a role in the famous $\bar{d} - \bar{u}$ asymmetry of the nucleon [5–8], first discovered by the New Muon Collaboration (NMC) [9]. Nonperturbative strange-quark contributions to the properties of the nucleon, which necessarily involve five-quark configurations, also attracted considerable interest because of the puzzling European Muon Collaboration (EMC) results concerning the proton spin [10–13].

One of the most powerful tools currently available for the investigation of the nonperturbative structure of hadrons is lattice QCD. There terms such as the strange or charm quark sea or the strange form factors of the nucleon necessarily involve so-called "disconnected graphs," that is, quark loops which are connected only by gluons to the valence quarks. With very few exceptions, the form factor studies in lattice QCD, which complement the recent experimental efforts at facilities such as Jefferson Lab, deal with so-called connected contributions, in which the external current acts on a quark line running directly from the hadronic source to sink. Only a few studies have directly addressed the disconnected contributions, the best-known example of which is the strange-quark contribution to the nucleon elastic form factors [14–22], which is analogous to the vacuum polarization contribution to the Lamb shift. Despite enormous effort [23], only two direct lattice QCD calculation have produced a nonzero result [24,25].

On the experimental side, under the assumption of charge symmetry, one can deduce these strange electric and magnetic form factors ($G^s_{E,M}(Q^2)$) from measurements of the proton and neutron electromagnetic form factors *and* the neutral-weak vector form factor of the proton, through its contribution to parity violating electron scattering (PVES). While PVES measurements are very challenging, a number of groups have succeeded, starting with SAMPLE at Bates [26] and then A4 at Mainz [27,28] and G0 [29] and HAPPEX [30–32] at Jefferson Lab. Up to now, the experiments have not provided an unambiguous confirmed answer to the sign of the strange form factors, although global analyses do tend to suggest that $G^s_M(0) < 0$ is favored [33,34], in agreement with indirect lattice calculations [16–22].

In this paper, we propose that the quantity $G^u_{\Sigma^-}$, the u-quark contribution to the magnetic form factor of Σ^- (or equivalently $G^d_{\Sigma^+}$, the d quark contribution to the magnetic form factor of Σ^+), presents an ideal opportunity for lattice QCD to unabiguously provide vital information on the existence of these intrinsic five quark components in baryon wave functions. Because the light quark mass of the u or d quark may be expected to govern the magnitude of the contribution, it is expected to be larger and therefore less difficult to measure in lattice QCD. It can only arise from the "disconnected" sea-quark contributions explained earlier. By investigating $G^u_{\Sigma^-}$ in the framework of effective field theory (EFT), where it is generated by a π meson loop, we show that it is indeed much larger than the strange form factor, which within EFT is generated by a K meson loop. If the lattice QCD study which we propose were to produce a result for $G^d_{\Sigma^+}$ significantly different from the result we obtain, it would provide profound new information on so far poorly understood aspects of QCD dynamics, such as colored diquark configurations [35].

Chiral effective field theory (EFT) is a useful tool with which to study hadron properties at low energy. There has been some work on strange form factors with heavy baryon chiral EFT [36,37]. However, there is an unknown low energy constant appearing in the chiral Lagrangian, which has limited the capacity to calculate the strange magnetic form factor. In other words, the quantity one wishes to predict—the strangeness vector current matrix element—is the same quantity one needs to know in order to make a prediction [38,39]. While this is the case in conventional chiral EFT, experience with finite-range regularization (FRR), has shown that by varying the regulator parameter, one can model the shift in strength from the loop contributions into the core. This suggests that within FRR χ-EFT one might identify the core contribution with the tree level contribution and make the approximation that, for Λ in the region of 0.8 GeV, the sea-quark content of the core is negligible. In this way, full QCD results have been obtained rather successfully from quenched lattice data [16–19,40,41]. We should emphasize that unquenching only works for the particular choice of regulator mass, Λ around 0.8 GeV, because only then does one define a core contribution that is approximately invariant between quenched and full QCD.

We will apply heavy baryon chiral effective field theory with finite range regularization to study the pure sea-quark contribution to the magnetic form factors of Σ baryons. In presenting the formalism, we choose to focus on the d-quark contribution to Σ^+ form factors. This channel is very similar to the s-quark contribution to the proton. In the standard convention where the quark charge is set to unity $G^u_{\Sigma^-} = G^d_{\Sigma^+}$.

In heavy baryon chiral EFT, the lowest-order chiral Lagrangian for the baryon-meson interaction which will be used in the calculation of the magnetic form factor, including the octet and decuplet baryons, is expressed as

$$\mathcal{L}_v = 2D\mathrm{Tr}\bar{B}_v S^\mu_v \{A_\mu, B_v\} + 2F\mathrm{Tr}\bar{B}_v S^\mu_v [A_\mu, B_v] + \mathcal{C}(\bar{T}^\mu_v A_\mu B_v + \bar{B}_v A_\mu T^\mu_v), \tag{1}$$

where S_μ is the covariant spin-operator defined as

$$S^\mu_v = \frac{i}{2}\gamma^5 \sigma^{\mu\nu} v_\nu. \tag{2}$$

Here, v^ν is the baryon four velocity [in the rest frame, we have $v^\nu = (1, 0)$] and D, F and $\mathcal{C}$ are the usual SU(3) coupling constants. The chiral covariant derivative, D_μ, is written as $D_\mu B_v = \partial_\mu B_v + [V_\mu, B_v]$. The pseudoscalar meson octet couples to the baryon field through the vector and axial vector combinations

$$V_\mu = \frac{1}{2}(\zeta\partial_\mu\zeta^\dagger + \zeta^\dagger\partial_\mu\zeta), \qquad A_\mu = \frac{1}{2}(\zeta\partial_\mu\zeta^\dagger - \zeta^\dagger\partial_\mu\zeta), \tag{3}$$

where

$$\zeta = e^{i\phi/f}, \qquad f = 93\ \mathrm{MeV}. \tag{4}$$

As explained above, following earlier successful studies of the connection between quenched and full QCD, our working hypothesis is that the d quark contribution to the magnetic form factor of the Σ^+ comes purely from the meson loop diagrams, which are shown in Fig. 1. There are two types of diagrams. Figure 1(a) is the leading-order contribution, where the external field couples to the meson. Figure 1(b) is the next-to-leading-order contribution, where the external field couples to the baryon. That the K meson loop provides a very small contribution to the magnetic form factor was shown in the previous study of the strange magnetic form factor [21]. Here we consider the π loop contribution. Both octet and decuplet intermediate states are included. The contribution from the process shown in Fig. 1(a) is expressed as

$$G^{d(1a)}_{\Sigma^+} = P_{\pi^+\Sigma^0} + P_{\pi^+\Lambda} + P_{\pi^+\Sigma^{*0}}, \tag{5}$$

where the respective terms correspond to the intermediate Σ^0, Λ and Σ^{*0} states. $P_{\pi^+\Sigma^0}$ can be obtained as

$$P_{\pi^+\Sigma^0} = -\frac{m_\Sigma F^2}{12\pi^3 f^2_\pi}\int d^3k \frac{k^2 u_1 u_2}{\omega^2_1 \omega^2_2}. \tag{6}$$

In the now standard notation, u_1 (u_2) is the regulator introduced in the finite range regularization with

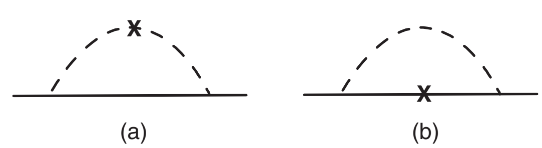

FIG. 1. Feynman diagrams for the calculation of the magnetic form factor of the Σ^+. Diagrams (a) and (b) correspond to the leading- and next-to-leading-order diagrams, respectively.

momentum $\vec{k}_1 = \vec{k} + \vec{q}/2$ ($\vec{k}_2 = \vec{k} - \vec{q}/2$). ω_1 (ω_2) is the energy of a pion with momentum $\vec{k}_1$ ($\vec{k}_2$). The charge of the d quark has been set to unity, consistent with the universal convention when discussing the strange-quark form factors of the proton.

The intermediate Λ contribution in Fig. 1(a) has the following relationship with the Σ^0:

$$P_{\pi^+\Lambda} = \frac{D^2}{3F^2} P_{\pi^+\Sigma^0}. \tag{7}$$

For the decuplet part, the contribution is written as

$$P_{\pi^+\Sigma^{*0}} = \frac{m_\Sigma \mathcal{C}^2}{432\pi^3 f_\pi^2} \int d^3k \frac{k^2 u_1 u_2 (1 + \Delta/(\omega_1 + \omega_2))}{\omega_1 \omega_2 (\omega_1 + \Delta)(\omega_2 + \Delta)}, \tag{8}$$

where Δ is the mass difference between the Σ^{*0} and Σ^0.

For the strange magnetic form factor of the nucleon, similar leading-order contributions are encountered. Compared with the formulas in Ref. [21], the coupling constants in front of the momentum integrals are different. For example, for the Λ and Σ intermediate states herein, the coupling constants are $D^2/3$ and F^2, respectively. For the strange magnetic form factor of the nucleon, the corresponding coupling constants are $(D + 3F)^2/12$ and $3(D - F)^2/4$, respectively. Using the standard values of $D = 0.76$ and $F = 0.50$ ($g_A = D + F = 1.26$), one finds the Σ intermediate state to be enhanced by a factor of five for $G^d_{\Sigma^+}(Q^2)$. However suppression in the coupling of the Λ intermediate state leaves the combined coupling to Λ and Σ intermediate states for the Σ and nucleon similar in magnitude, differing by 7%. Thus, the quantity ω in the denominator is the crucial element in comparing the magnitude of pure sea-quark contributions in the nucleon and in Σ. For pure sea-quark contributions in Σ baryons, ω is the energy of the pion instead of the energy of a kaon. As a result, the value of the leading-order contribution to $G^d_{\Sigma^+}(Q^2)$ is much larger than that for the strange magnetic form factor of the nucleon.

The next-to-leading-order contribution of Fig. 1(b) is

$$G^{d(1b)}_{\Sigma^+} = P_{\Sigma^0}\mu^d_{\Sigma^0} + P_{\Sigma^{*0}}\mu^d_{\Sigma^{*0}} + P_{\Sigma^{*0}\Sigma^0(\Lambda)}\mu^d. \tag{9}$$

This includes octet, decuplet and octet-decuplet transition contributions in Fig. 1(b). The octet contribution arising from the Σ^0 is written as

$$P_{\Sigma^0} = \frac{F^2}{16\pi^3 f_\pi^2} \int d^3k \frac{k^2 u_k^2}{\omega_k^3}, \tag{10}$$

corresponding to the Σ^0 state appearing in the configuration $\pi^+\Sigma^0$. The decuplet contribution from the Σ^{*0} is obtained as

$$P_{\Sigma^{*0}} = -\frac{5\mathcal{C}^2}{864\pi^3 f_\pi^2} \int d^3k \frac{k^2 u_k^2}{\omega_k(\omega_k + \Delta)^2}. \tag{11}$$

The $\Sigma^{*0}\Sigma^0(\Lambda)$ transition contribution to the magnetic form factor is written as

$$P_{\Sigma^{*0}\Sigma^0(\Lambda)} = -\frac{(D - F)\mathcal{C}}{36\pi^3 f_\pi^2} \int d^3k \frac{k^2 u_k^2}{\omega_k^2(\omega_k + \Delta)}. \tag{12}$$

Here μ^d_B is the d quark contribution to the magnetic moment of the baryon B at tree level, i.e.

$$\mu^d_{\Sigma^0} = \frac{2}{3}\mu^d_{\Sigma^{*0}} = \frac{2}{3}\mu_d. \tag{13}$$

For the last term in Eq. (9), the following transition moments is applied

$$\mu^d_{\Sigma^0\Sigma^{*0}} = \frac{\sqrt{3}}{3}\mu^d_{\Lambda\Sigma^{*0}} = \frac{\sqrt{2}}{3}\mu_d \tag{14}$$

Again, the next-to-leading-order contribution to the nucleon magnetic form factor also has terms similar to those above with different coupling constants. As in the case of the nucleon strange magnetic form factor, we will see that this next-to-leading-order contribution is much smaller than the leading-order contribution for $G^d_{\Sigma^+}(Q^2)$.

In the numerical calculations, the parameters are chosen as $D = 0.76$ and $F = 0.50$ ($g_A = D + F = 1.26$). The coupling constant $\mathcal{C}$ is chosen to be $-2D$. The form of the regulator function, $u(k)$, could be chosen to be a monopole, dipole or Gaussian function, any of which would give similar results [42]. In our calculations, a dipole form is chosen because that is the empirical shape of the nucleon axial form factor [43]

$$u_k = \frac{1}{(1 + k^2/\Lambda^2)^2}, \tag{15}$$

with $\Lambda = 0.8 \pm 0.2$ GeV.

As we explained earlier, this choice has been widely applied in the extrapolation of lattice data for hadron mass, moments, form factors, radii, first moments of GPDs, etc. [21,42,44–50]. With this choice it has been shown that reasonable physical results can be obtained from the quenched lattice data at both leading and next-to-leading order [16–19,21,40–42,44]. Λ around 0.8 GeV is the value required to identify a core contribution that is invariant between quenched and full QCD. This invariance of the core is based upon the assumption that the 3-quark core of the Σ^+ contains no d quark component.

While our calculation is motivated by chiral effective field theory with the same chiral Lagrangian, our calculation with FRR is at a physically motivated scale, where earlier work has suggested that the residual series of

TABLE I. Pure sea-quark contributions to the magnetic moments of Σ baryons, $G^u_{\Sigma^-}$ or $G^d_{\Sigma^+}$. Values are for unit charge sea quarks in μ_N. The dependence of the results on the finite-range regulator parameter, Λ is presented.

Λ (GeV)	0.6	0.7	0.8	0.9	1.0
LO	−0.21	−0.27	−0.34	−0.42	−0.49
NLO	−0.017	−0.025	−0.035	−0.045	−0.057
$G^u_{\Sigma^-}$ or $G^d_{\Sigma^+}$	−0.22	−0.30	−0.38	−0.46	−0.55

analytic terms best describes the three-quark core contributions. From the previous extrapolation of quenched lattice data, it is found that this preferred value of Λ in the dipole regulator is around 0.8 GeV. The variation of Λ from 0.6 to 1 GeV provides an estimate of the degree of model dependence of our result.

The contribution of the pure sea-quark contribution to the Σ magnetic moment at leading and next-to-leading order is shown in Table I. The leading-order diagram shown in Fig. 1(a) gives a negative contribution to the magnetic form factor. The contributions from the next-to-leading order diagrams are much smaller than the leading contribution. They depend on the parameter μ_d. Assuming SU(3) symmetry, one has $\mu_d = \mu_s = -\frac{1}{2}\mu_u = -\frac{1}{3}\mu_D$. In fact, this relation was applied in our previous investigation of nucleon magnetic form factors [41,45]. In the previous extrapolation of nucleon magnetic form factors, we found μ_D equal $2.55\,\mu_N$ and $2.34\,\mu_N$ for full QCD and quenched QCD extrapolations, respectively [41,45]. Therefore, $\mu_d = -0.8\,\mu_N$ should be a good estimate.

In Fig. 2, we show the magnetic form factor $G^d_{\Sigma^+}(Q^2)$ versus Q^2 at $\Lambda = 0.6$, 0.8 and 1.0 GeV. One can see that

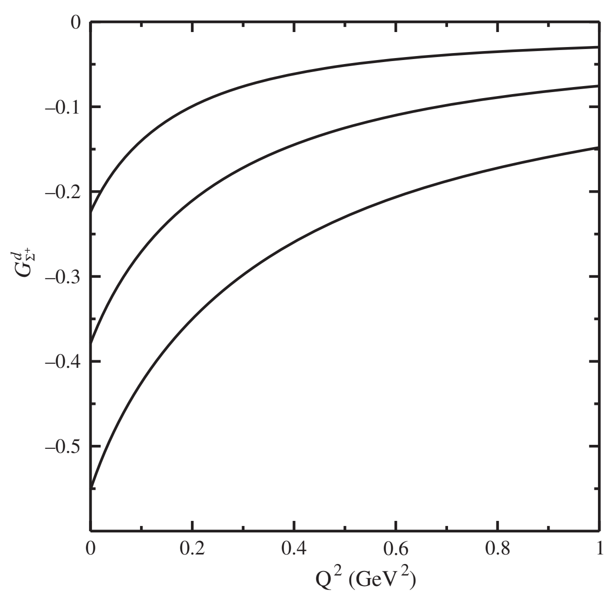

FIG. 2. The Q^2 dependence of the d-quark contribution to the magnetic form factor of Σ^+. The upper, middle and lower lines are for $\Lambda = 0.6$, 0.8 and 1.0 GeV, respectively. In the standard convention $G^d_{\Sigma^+} = G^u_{\Sigma^-}$.

$G^s_{\Sigma^+}(Q^2)$ decreases in magnitude with the increasing Q^2. It is obvious that the magnetic form factor does not change sign for any of the choices of Λ when Q^2 increases. This is just like the strange magnetic form factor of the nucleon. However, the absolute value of $G^d_{\Sigma^+}(Q^2)$ is about one order of magnitude larger than $G^s_N(Q^2)$. Since its absolute value decreases with the increasing Q^2, it would be preferable to attempt to measure the magnetic form factor at low Q^2. For example, when Q^2 is less than 0.2 GeV^2, the absolute central value of $G^d_{\Sigma^+}$ is larger than $0.2\,\mu_N$.

At $Q^2 = 0$, the d quark contribution to the magnetic moment of the Σ^+ is $\mu^d_{\Sigma^+} = G^d_{\Sigma^+}(0) = -0.38\,\mu_N$. If we vary Λ from 0.6 to 1 GeV, $\mu^d_{\Sigma^+}$ will change from $-0.22\,\mu_N$ to $-0.55\,\mu_N$. Numerical results show that $\mu^d_{\Sigma^+}$ remains negative over a large parameter range. Compared with the strange magnetic moment of the proton, the value of $\mu^d_{\Sigma^+}$ is about 7 times larger [16,21].

For unit charge sea quarks, $G^d_{\Sigma^+} = G^u_{\Sigma^-}$. Thus the magnitude of the sea-quark contribution further doubles in an experimental measurement of the contribution of the u quark to the form factor of Σ^-.

Motivated by the importance of establishing the properties of disconnected contributions to physical quantities in lattice QCD, we have shown that $G^u_{\Sigma^-}(Q^2)$ and $G^d_{\Sigma^+}(Q^2)$ have the practical advantage that their values are much larger than the strange magnetic form factor of the nucleon. Since the absolute value of $G^d_{\Sigma^+}(Q^2)$ is nearly one order of magnitude larger than the strange magnetic form factor of the nucleon, it would clearly be better to simulate this quantity in place of the strange form factor of the nucleon.

Since the lattice simulations will almost certainly be made over a range of light quark masses, we have investigated the pion mass dependence of $G^d_{\Sigma^+}(0)$. The results are shown in Fig. 3, where the upper, middle and lower lines are for $\Lambda = 0.6$, 0.8 and 1 GeV, respectively. From the figure, one can see that with increasing quark mass the absolute value of $\mu^d_{\Sigma^+}$ decreases. However, even at $m^2_\pi = 0.2$ GeV^2, $\mu^d_{\Sigma^+}$ is still much larger than the strange magnetic moment of the nucleon at the physical pion mass.

An additional feature of the Σ baryon is the presence of a strange quark in the two-point correlation function. In calculating the disconnected sea-quark contribution, one multiplies the disconnected loop by the standard two-point function in creating the full three-point function. The presence of a strange quark in the two-point function will assist in reducing statistical noise in the three-point correlation function for the pure sea-quark contribution.

Given that $G^d_{\Sigma^+}(Q^2)$ is dominated by the contribution of a π meson loop and having strange quarks in the two-point correlation function is advantageous, one might also consider the d quark contribution to the magnetic form factor of the Ξ^0 or the u quark contribution to the magnetic form factor of the Ξ^-. These quantities are also determined by a π

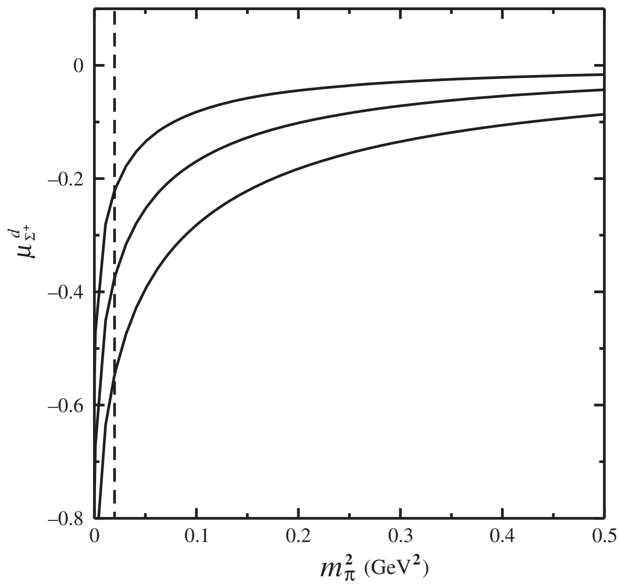

FIG. 3. The pion mass dependence of the d-quark contribution to the magnetic moment of the Σ^+. The upper, middle and lower lines are for $\Lambda = 0.6$, 0.8 and 1.0 GeV, respectively. In the standard convention $G^d_{\Sigma^+} = G^u_{\Sigma^-}$.

meson loop. However, the coupling of π and Ξ^0 is much smaller resulting in a very small value of $G^d_{\Xi^0}(Q^2)$. Thus $G^d_{\Sigma^+}$ has unique advantages with respect to studies of the contributions to the structure of baryons through disconnected sea-quark terms.

In summary, we have argued the importance of studying the pure sea-quark contributions to Σ-baryon form factors, $G^u_{\Sigma^-}(Q^2)$ and $G^d_{\Sigma^+}(Q^2)$. Because of the significant enhancement associated with the light u or d quarks, these observables have distinct quantitative advantages over the strange form factors of the nucleon. This enhancement arises because the pure light sea-quark contribution to the magnetic form factors of Σ baryons is dominated by the π-meson cloud contribution. This is much larger than the nucleon strange magnetic form factor which originates in the K-meson cloud.

We calculated $G^u_{\Sigma^-}(Q^2)$ and $G^d_{\Sigma^+}(Q^2)$ within heavy baryon chiral effective field theory including both octet and decuplet intermediate states. The pure sea-quark contribution to the magnetic moment is $G^u_{\Sigma^-}(Q^2) = G^d_{\Sigma^+}(Q^2) = -0.38^{+0.16}_{-0.17}\,\mu_N$, which is about seven times larger than the nucleon strange magnetic moment and 14 times larger for $G^u_{\Sigma^-}(Q^2)$ in experiment.

We also calculated the pion mass dependence of the pure sea-quark contributions. When the pion mass is about 300–400 MeV, the absolute value of $\mu^d_{\Sigma^+}$ is still around $0.2\,\mu_N$. It seems likely that future lattice simulations may be able to determine $G^d_{\Sigma^+}$ directly with more accuracy than the strange form factor of the nucleon, G^s_N. The value or even the sign of $G^d_{\Sigma^+}(Q^2)$ would be very helpful in pinning down the size and origin of five-quark configurations in baryons.

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