Parity-violating asymmetries in elastic $\vec{e}p$ scattering in the chiral quark-soliton model: Comparison with the A4, G0, HAPPEX and SAMPLE experiments

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We investigate parity-violating electroweak asymmetries in the elastic scattering of polarized electrons off protons within the framework of the chiral quark-soliton model (χQSM). We use as input the former results of the electromagnetic and strange form factors and newly calculated SU(3) axial-vector form factors, all evaluated with the same set of four parameters adjusted several years ago to general mesonic and baryonic properties. Based on this scheme, which yields positive electric and magnetic strange form factors with $\mu_s = (0.08\text{–}0.13)\mu_N$, we determine the parity-violating asymmetries of elastic polarized electron-proton scattering. The results are in a good agreement with the data of the A4, HAPPEX, and SAMPLE experiments and reproduce the full Q^2 range of the G0 data. We also predict the parity-violating asymmetries for the backward G0 experiment.

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I. INTRODUCTION

The complex structure of the nucleon goes well beyond its simplest description as a collection of three valence quarks moving in some potential. The sea of gluons and $q\bar{q}$ pairs that arises in quantum chromodynamics is expected to play an important role even at long distance scales. As the lightest explicitly nonvalence quark the strange quark provides an attractive tool to probe the $q\bar{q}$ sea, since any strange quark contribution to an observable must be the effect of the sea. Thus, the strange quark contribution to the distributions of charge and magnetization in the nucleon has been a very important issue well over decades, since it provides a vital clue in understanding the structure of the nucleon. For recent reviews, see, for example, Refs. [1–5]. Recently, the strangeness content of the nucleon has been studied particularly intensively since parity-violating electron scattering (PVES) has demonstrated to provide an essential tool for probing the sea of $s\bar{s}$ pairs in the vector channel [6,7]. In fact, various PVES experiments have been already conducted in order to measure the parity-violating asymmetries (PVAs) from which the strange vector form factors can be extracted [8–16]. While PVES experiments have direct access to the PVA with relatively good precision, a certain amount of uncertainties arise in the flavor decomposition for the nucleon vector form factors. As a result, the strange vector form factors extracted so far from the data have rather large errors [8–15].

The chiral quark-soliton model (χQSM) is an effective quark theory of the instanton-degrees of freedom of the QCD vacuum. It results in an effective chiral action for valence and sea quarks both moving in a static self-consistent Goldstone background field [17,18] originating from the spontaneous chiral symmetry breaking of QCD. It has very successfully been applied to mass splittings of hyperons, to electromagnetic and axial-vector form factors [17] of the baryon octet and decuplet, and to forward and generalized parton distributions [19–21] of the nucleon.[1] The present authors have recently investigated in the χQSM model the strange vector form factors [23,24] and they presented some aspects of the SAMPLE, HAPPEX, and A4 experiments. The results have shown a good agreement with the available data, though the experimental uncertainties are rather large, as mentioned above. Thus, it is theoretically more challenging to calculate directly the PVAs and to confront them with the more accurate experimental data. Moreover, since the G0 experiment has measured the PVA over a range of momentum transfers

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[1] The χQSM is sometimes attacked because it has predicted the pentaquark baryon Θ^+ [22] whose existence is presently heavily debated. There is a fundamental difference for the χQSM in calculating properties of the baryonic octet and decuplet on one side, and of the antidecuplet on the other. For the baryon octet and decuplet, the use of the χQSM is justified in the limit $N_c \to \infty$, and indeed basically all χQSM calculations yield agreement with experimental data with an accuracy of (10%–30%). For the antidecuplet the χQSM cannot be justified by large-N_c arguments and additional assumptions have to be invoked. The present application concerns the strange content of the nucleon which is a part of the octet and thus one cannot have a principal objection against applying the model to nucleon strange form factors and asymmetries.

$0.12 \leq Q^2 \leq 1.0\ \mathrm{GeV}^2$ in the forward direction [16], the check of the theory is on much firmer ground.

Actually, the PVA contains a set of six electromagnetic form factors ($G_{E,M}^{u,d,s}$) and three axial-vector ones ($G_A^{u,d,s}$). In fact, all these form factors have already been calculated within the SU(3)-χQSM [23–26] by using the well established parameter set consisting of $m_s = 180$ MeV and the other three parameters having been adjusted some years ago to the physical values of f_π, m_π and baryonic properties as e.g. the charge radius of the proton and the delta-nucleon ($\Delta - N$) mass splitting. Apart from reproducing the existing experimental data on the PVAs, we will predict the PVAs of the future G0 experiment at backward angles.

II. PARITY-VIOLATING ASYMMETRIES

The PVA in polarized $\vec{e}p$ scattering is defined as the difference of the total cross sections for circularly polarized electrons with positive and negative helicities divided by their sum:

$$\mathcal{A}_{PV} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}. \tag{1}$$

Denoting, at the tree level, the amplitudes for γ and Z exchange by $\mathcal{M}_\gamma$ and $\mathcal{M}_Z$, respectively, we find that the total cross section for a given polarization is proportional to the square of the sum of the amplitudes, which indicates the interference between the electromagnetic and neutral weak amplitudes:

$$\sigma_\pm \sim |\mathcal{M}^\gamma + \mathcal{M}^Z|^2_\pm. \tag{2}$$

The PVA comprises three different terms:[2]

$$\mathcal{A}_{PV} = \mathcal{A}_V + \mathcal{A}_s + \mathcal{A}_A, \tag{3}$$

where

$$\begin{aligned}
\mathcal{A}_V &= -a\rho'\left[(1 - 4\kappa'\sin^2\theta_W) - \frac{\varepsilon G_E^p G_E^n + \tau G_M^p G_M^n}{\varepsilon (G_E^p)^2 + \tau (G_M^p)^2}\right] \\
\mathcal{A}_s &= a\rho'\left[\frac{\varepsilon G_E^p G_E^s + \tau G_M^p G_M^s}{\varepsilon (G_E^p)^2 + \tau (G_M^p)^2}\right] \\
\mathcal{A}_A &= a\left[\frac{(1 - 4\sin^2\theta_W)\varepsilon' G_M^p G_A^e}{\varepsilon (G_E^p)^2 + \tau (G_M^p)^2}\right] \\
a &= G_F Q^2/(4\sqrt{2}\pi\alpha_{\mathrm{EM}}) \qquad \tau = Q^2/(4M_N^2) \\
\varepsilon &= [1 + 2(1+\tau)\tan^2\theta/2]^{-1} \\
\varepsilon' &= \sqrt{\tau(1+\tau)(1-\varepsilon^2)}.
\end{aligned} \tag{4}$$

The $G_{E,M}^p$, $G_{E,M}^s$, and G_A^e denote, respectively, the electromagnetic form factors of the proton, strange vector form factors, and the electroweak axial-vector form factors which will be defined later with electroweak radiative corrections. The G_F is the Fermi constant as measured from muon decay, α_{EM} the fine structure constant, and θ_W the electroweak mixing angle given as $\sin^2\theta_W = 0.2312$ [27]. The Q^2 stands for the negative square of the four momentum transfer. The parameters ρ' and κ' are related to electroweak radiative corrections and are given in Refs. [1,28].

[2]These formulas (4) are identical to those given by Maas *et al.* [12]. The $\tilde{G}_A^p$ of Maas *et al.* is identical to the G_A^e of the above formulas.

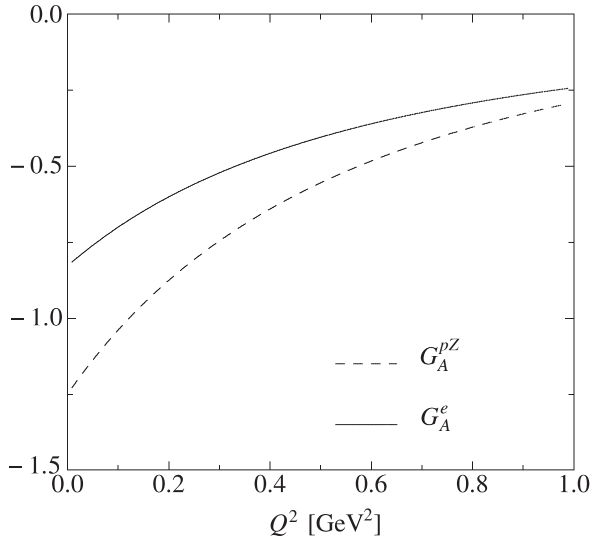

FIG. 1. The proton electroweak neutral axial-vector form factors G_A^e and G_A^{pZ} as functions of Q^2 calculated in the χQSM.

Factoring out the quark charges, we can express the electromagnetic and electroweak neutral axial-vector form factors of the proton in terms of the flavor-decomposed electromagnetic form factors:

$$\begin{aligned}
G_{E,M}^p &= \tfrac{2}{3} G_{E,M}^u - \tfrac{1}{3}(G_{E,M}^d + G_{E,M}^s) \\
G_A^{pZ} &= G_A^d - (G_A^u + G_A^s).
\end{aligned} \tag{5}$$

Including the electroweak radiative corrections [1,28], we find that the electroweak axial-vector form factors of the proton can be written[3] as [29]

$$G_A^e(Q^2) = -(1 + R_A^1) G_A^{(3)}(Q^2) + R_A^0 + G_A^s, \tag{6}$$

with the values for the electroweak radiative corrections [1]:

$$R_A^1 = -0.41 \pm 0.24, \qquad R_A^0 = 0.06 \pm 0.14. \tag{7}$$

Figure 1 depicts the electroweak and neutral axial-vector form factors expressed in Eqs. (4) and (6), which is ob-

[3]The $G_A^e(Q^2)$ is identical to G_A^{ep} and agrees with the quantity $-\frac{1}{2} G_A^{NC}$ of Alberico, Bilenky, and Maieron [29].

tained in the χQSM [26]. We will use G_A^e in Fig. 1 to yield the PVA.

The other six electromagnetic form factors, $G_{E,M}^{p,n,s}$ can be read out from Refs. [23–25].

III. RESULTS AND DISCUSSION: PARITY-VIOLATING ASYMMETRIES

We discuss now the results of the PVA obtained from the χQSM. In detail, the model has the following parameters: The constituent quark mass M, the current quark mass m_u, the cutoff Λ of the proper-time regularization, and the strange quark mass m_s. However, these parameters are not free but have been fixed to independent observables in a very clear way [17]: For a given M the Λ and the m_u are adjusted in the mesonic sector to the physical pion mass $m_\pi = 139$ MeV and the pion decay constant $f_\pi = 93$ MeV. The strange quark mass[4] is selected to be $m_s = 180$ MeV throughout the present work, with which the mass splittings of hyperons are produced very well [17]. The remaining parameter M is varied from 400 to 450 MeV. However, the value of 420 MeV, which for many years is known to produce the best fit to many baryonic observables [17], is chosen for our final result in the baryonic sector. We always assume isospin symmetry. With these parameters at hand, we can proceed to derive the form factors of the proton required for the PVA. On obtaining these form factors, we use the symmetry conserving quantization scheme [30] and take into account the rotational $1/N_c$ corrections, the explicit SU(3) symmetry breaking in linear order, and the wave-function corrections, as discussed in Refs. [17,23] in detail. With this scheme and using for the definition of the magnetic moments the soliton mass, we have obtained the magnetic moments of the baryon octet listed in Table I in units of the nuclear magneton (n.m.).

Actually the form factors of the baryon octet as they are the results [23,24] for the strange vector form factors, are in good agreement with the data of the A4, SAMPLE, and HAPPEX experiments as far as they were available .[5]

TABLE I. The magnetic moments of the octet baryons calculated within the χQSM in comparison to the experimental data, given in units of the nuclear magneton (n.m.).

Baryon	μ (n.m.)	Experiment [31]
p	2.40	2.79
n	-1.65	-1.91
Λ	-0.65	-0.61
Σ^-	-0.96	-1.16
Σ^0	0.68	...
Σ^+	2.31	2.46
Ξ^-	-0.61	-0.65
Ξ^0	-1.41	-1.25

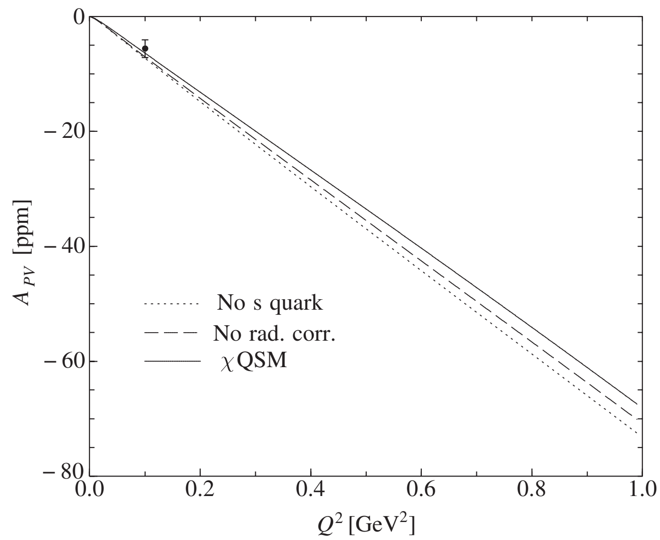

FIG. 2. The parity-violating asymmetries as a function of Q^2, compared with the SAMPLE measurement [9]. The dotted curve is calculated without the s-quark contribution. The dashed curve is obtained by using the form factors from the χQSM without the electroweak radiative corrections, while the solid one (χQSM) includes them and is our final result.

We present our numerical results in Figs. 2–6 at relevant kinematics to the A4, G0, HAPPEX, and SAMPLE experiments in comparison with the data. The dotted curves depict the PVA without the strange quark contribution. This means we put $\mathcal{A}_s = 0$ in Eq. (3). The dashed ones are obtained by using the form factors from the SU(3)-χQSM without the electroweak radiative correc-

[4]The strange current mass, as it is extracted from experiments, appears to be only 80–130 MeV and hence noticeably smaller than the m_s used in the χQSM. However, the "experimental" value is scheme and renormalization-point dependent. What one typically extracts from experiment is the product of the quark mass and quark condensate, and the separation of this product requires some theoretical assumptions. Even if its precise value had been known in a particular scheme and at a particular renormalization point, this value would not have too much to do with the value of the strange quark mass m_s used in the Lagrangian of the χQSM. In the χQSM the m_s is rather a model parameter and the comparison with the real physics should go (and has been done) via physical observables, as e.g. hadron mass splittings or hyperon magnetic moments, and not via bare parameters of QCD and of the model. Note that the situation is rather similar to the status of quark masses in the effective chiral Lagrangian of Gasser-Leutwyler used for the systematic construction of chiral perturbation theory.

[5]The value of the strange electric form factor at $Q^2 = 0.091$ GeV^2 is newly extracted by the HAPPEX experiment [14]: $G_E^s = (-0.038 \pm 0.042 \pm 0.010)$ n.m. which is consistent with zero. The G0 experiment indicates that G_E^s may be negative in the intermediate region up to $Q^2 \sim 0.3$ GeV^2. The present model predicts $G_E^s \simeq 0.025$ at $Q^2 = 0.091$ GeV^2 which is positive and slightly outside the error margins of HAPPEX.

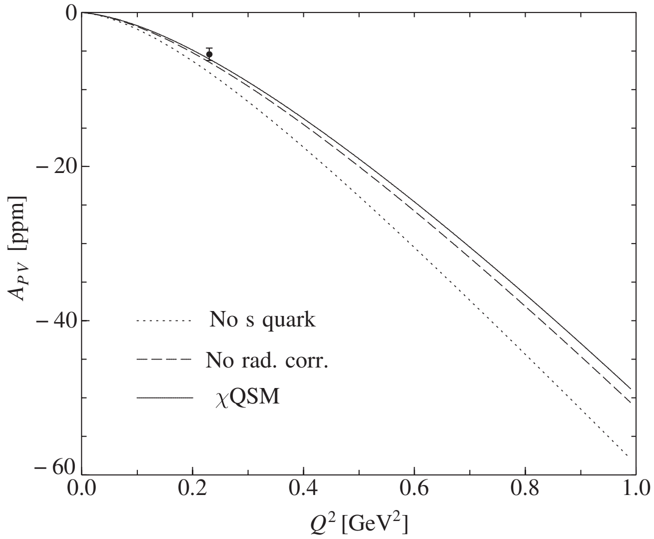

FIG. 3. The parity-violating asymmetries as a function of Q^2, compared with the A4 measurement [12]. The dotted curve is calculated without the s-quark contribution. The dashed curve is obtained by using the form factors from the χQSM without the electroweak radiative corrections, while the solid one (χQSM) includes them and is our final result.

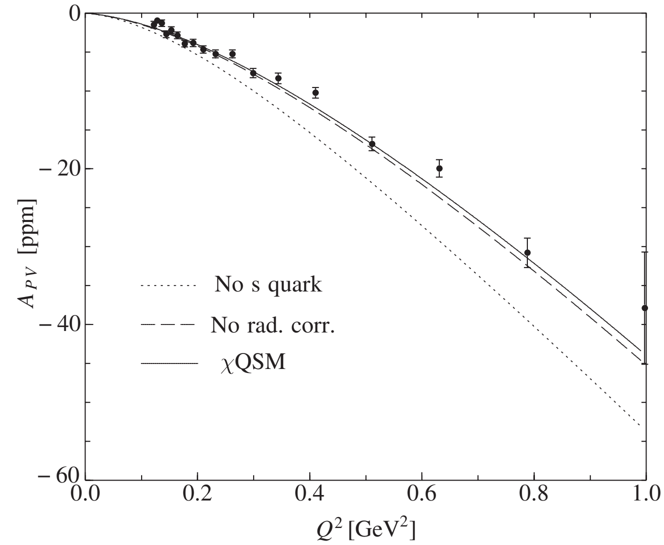

FIG. 5. The parity-violating asymmetries as a function of Q^2, compared with the forward G0 measurement [16]. The dotted curve is calculated without the s-quark contribution. The dashed curve is obtained by using the form factors from the χQSM without the electroweak radiative corrections, while the solid one (χQSM) includes them and is our final result.

tions, i.e. with ρ' and κ' set equal to zero, while the solid ones (χQSM) are our final theoretical asymmetries including those corrections. One notices that the effect of the electroweak radiative corrections is rather tiny. One also sees that with increasing Q^2 the PVA without strange contribution deviates more and more from the experiments, which means that with increasing Q^2 the contribution of the strange quarks gets larger and larger reaching in the end an amount up to 40% in the present model.

As shown in Figs. 2–5, the present results are in good agreement with the experimental data from the A4, HAPPEX, and SAMPLE at small and intermediate Q^2. However, since the G0 experiments have measured the

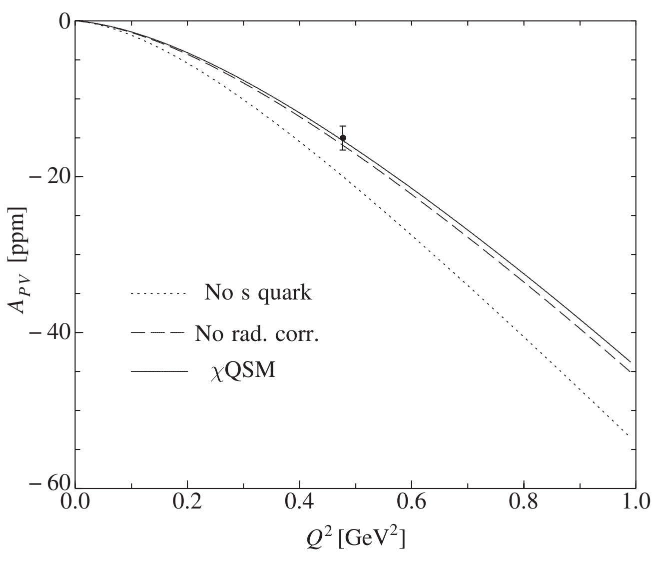

FIG. 4. The parity-violating asymmetries as a function of Q^2, compared with the HAPPEX measurement [11]. The dotted curve is calculated without the s-quark contribution. The dashed curve is obtained by using the form factors from the χQSM without the electroweak radiative corrections, while the solid one (χQSM) includes them and is our final result.

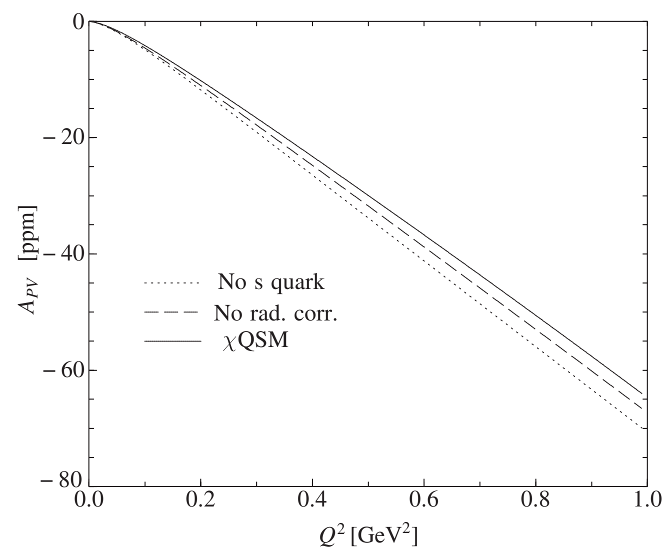

FIG. 6. The parity-violating asymmetries as a function of Q^2. They are the predictions for the backward G0 experiment ($\theta = 108°$). The dotted curve is calculated without the s-quark contribution. The dashed curve is obtained by using the form factors from the χQSM without the electroweak radiative corrections, while the solid one (χQSM) includes them and is our final result.

PVA over the range of momentum transfers $0.12 \leq Q^2 \leq 1.0\ \mathrm{GeV}^2$, it is more interesting to compare our results with them. In fact, the predicted PVA in the present work describes remarkably well the G0 data over the full range of Q^2-values. It indicates that the present model produces the correct Q^2 dependence of all the form factors relevant for the PVA.

Figure 6 depicts the prediction for the backward G0 experiment at $\theta = 108°$ whose data are announced to be available in the near future.

IV. RESULTS AND DISCUSSION: STRANGE FORM FACTORS

Figures 7–9 yield further data which allow a detailed comparison between experiment and theory. Figure 7 shows the typical combination $G_E^s(Q^2) + \beta(Q^2, \theta)G_M^s(Q^2)$ playing a key role in the experiments. In a forward direction the A4 has measured two points of this observable at small Q^2 values, which are both well reproduced by the χQSM calculations. The dotted error band indicates a systematic error of the χQSM, since the soliton is bound to have the same profile function in the up, down, and strange directions (see Ref. [23] for details). Figure 8 shows a similar combination for the G0, where the β is assumed to be equal to $\eta = 0.94Q^2$. In this plot the experimental data are again reasonably well reproduced by the χQSM.

Actually one can see from Fig. 10 how the χQSM values for G_E^s and G_M^s fit into the present world data at $Q^2 = 0.1\ \mathrm{GeV}^2$. The plot is taken from the HAPPEX [15] and the ellipse reflects the 95% confidence level. Apparently there

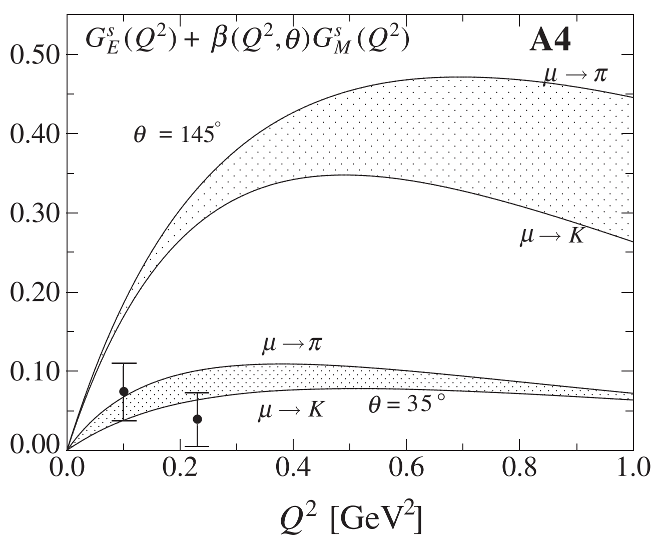

FIG. 7. The values of $G_E^s(Q^2) + \beta(Q^2, \theta)G_M^s(Q^2)$ as a function of Q^2. The dotted fields are the χQSM predictions for the A4 experiment at $\theta = 35°$ and $\theta = 145°$. The theoretical error fields are given by assuming the Yukawa mass of the solitonic profile in the χQSM to coincide with the pion mass or the kaon mass, respectively.

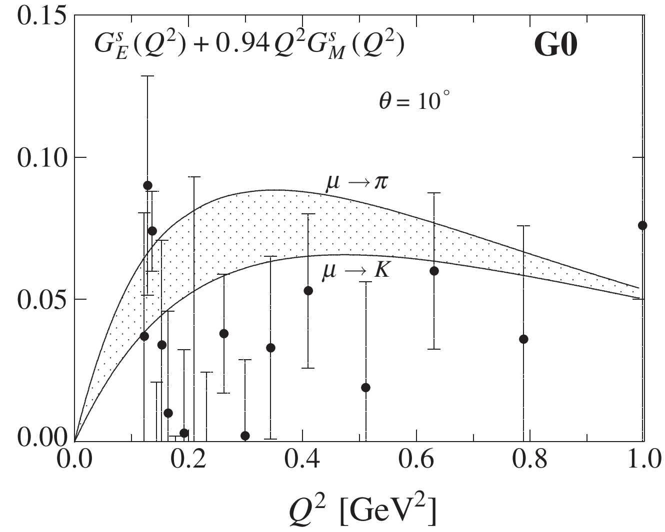

FIG. 8. The values of $G_E^s(Q^2) + \eta G_M^s(Q^2)$ with $\eta = 0.94Q^2$ as a function of Q^2. They are the predictions for the G0 experiment at $\theta = 10°$. The theoretical error field is given by assuming the Yukawa mass of the solitonic profile in the χQSM to coincide with the pion mass or the kaon mass, respectively.

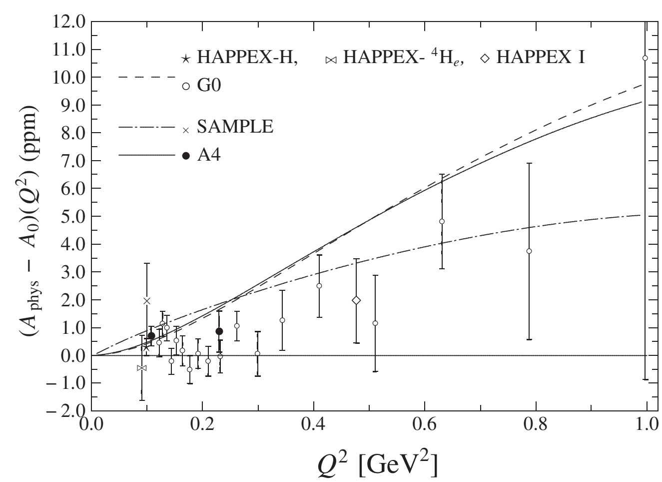

FIG. 9. Difference between the parity-violating asymmetries including strange quark effects (A_{phys}) and the asymmetry including just u and d quark contributions (A_0). The lines represent the χQSM results for the kinematics (laboratory angles) of the experiments enumerated. The curves for the small angle forward case (G0, HAPPEX: $\theta \sim 8°$) almost overlap each other and differ slightly from A4, $\theta = 35°$ (solid line). SAMPLE is a backward angle experiment, $\theta = 146°$.

is good agreement between the χQSM and the data. A similar conclusion can be drawn from Fig. 11, in which for G_M^s and $G_E^e(T = 1)$ the χQSM is confronted with the data.[6] Here the ellipse represents the 1σ overlap of the deuterium

[6]The $G_A^e(T = 1)$ is identical to $(G_A^{ep} - G_A^{en})/2$ and identical to $(1 + R_A^1)G_A^{(3)}$.

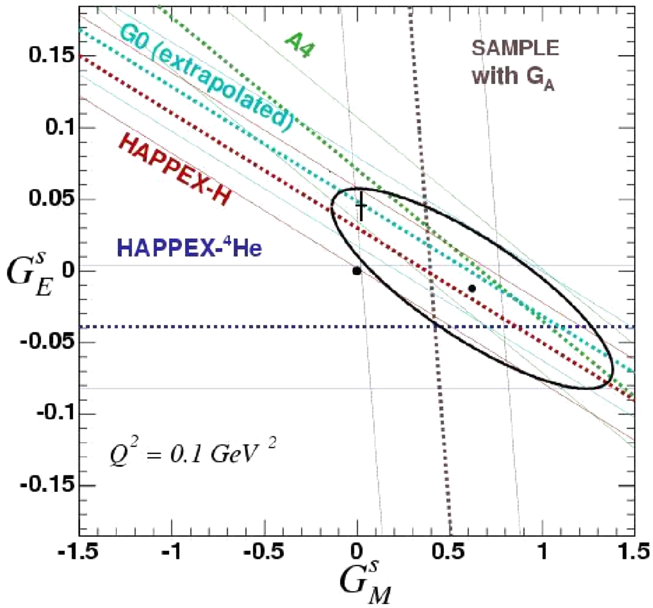

FIG. 10 (color online). The world data for G_E^s and G_M^s from A4, HAPPEX, SAMPLE, and G0 experiments at $Q^2 = 0.1\ \mathrm{GeV}^2$. The plot is taken from HAPPEX [15] and the ellipse reflects the 95% confidence level. The theoretical number obtained by the χQSM is indicated by a cross which reflects the theoretical errors. The dots indicate the center of the ellipse and the point with vanishing strange form factors.

and hydrogen measurements. This figure is taken from Beise *et al.* [32] of the HAPPEX collaboration.

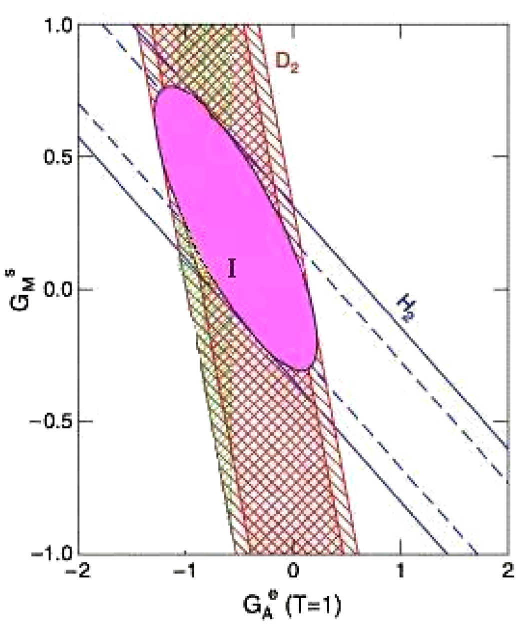

FIG. 11 (color online). The hydrogen and deuterium data for G_M^s and $G_A^e(T = 1)$ from HAPPEX at $Q^2 = 0.1\ \mathrm{GeV}^2$. The ellipse represents the 1σ overlap of the two measurements. The theoretical number obtained by the χQSM is indicated with the bar which reflects the theoretical error. The data- plot is taken from Ref. [32].

In Fig. 9 the PVAs of the various experiments are presented focusing on the strange contribution. Following Eq. (1), plotted are $\mathcal{A}_{\mathrm{phys}} - \mathcal{A}_0 = \mathcal{A}_s$. The curves are from the χQSM. Actually the calculations yield for the HAPPEX experiments and the G0 experiment nearly identical curves which cannot be distinguished in Fig. 9. One notes for this sensitive quantity, originating solely from the strange quarks of the Dirac sea, a good agreement between theory and experiment.

V. COMPARISON WITH LATTICE QCD

It is interesting to compare the above results of the χQSM, which yield a positive strange magnetic form factor, with the recent lattice QCD calculations (LQCD) of Leinweber *et al.* [33–35], which advocate a negative strange magnetic moment: $G_M^s(Q^2 = 0) = -(0.046 \pm 0.019)\mu_N$. The question arises whether this contradiction invalidates the χQSM. The analysis of the systematic errors of the LQCD has been performed in Ref. [34] and from this the above error bars are derived. Nevertheless from the very beginning the LQCD estimates are based on the assumption that in the lattice calculations of form factors (i) the quenched approximation is reasonable, (ii) current lattice spacings are close to the continuum limit, (iii) the chiral extrapolation is reliable, (iv) large volume and large time is reached, (v) the fermions are treated properly, (vi) the chosen scheme of the conversion of lattice data to physical units is reliable. The spectrum of opinions among the experts about these issues is rather wide as one can see e.g. in a recent paper on the extrapolation of lattice data to physical pion masses and chiral expansion [36]. Moreover, it has not been proven yet that the quenched approximation is compatible with the continuum limit. In this situation we believe that the results obtained in the χQSM should be taken seriously even if they contradict current lattice simulations. In particular, one should keep in mind that the χQSM takes into account those aspects which are problematic for lattice calculations, namely, (i) the chiral limit and chiral symmetry, and (ii) the large N_c limit of QCD. Actually, for a comparison of strange magnetic moments of the lattice QCD with those of the χQSM, it might be useful to perform the χQSM calculations at those large pion masses where the lattice simulations are done. In addition, one can then in the spirit of Ref. [37] investigate the trend toward smaller masses. We also mention that there is another LQCD calculation of the strange electromagnetic form factors together with quenched chiral perturbation theory [38] in which the positive strange magnetic form factor is allowed.

VI. SUMMARY AND CONCLUSION

In the present work, we have investigated the parity-violating asymmetries in the elastic scattering of polarized electrons off protons within the framework of the chiral quark-soliton model (χQSM). We used as input the electromagnetic and strange vector form factors calculated in the former works [23–25], yielding both positive magnetic and electric strange form factors, and the axial-vector form factors [26] from a recent publication. All these form factors, incorporated in the present work, were obtained with one fixed set of four model parameters, which has been adjusted several years ago to basic mesonic and baryonic observables. In fact, the parity-violating asymmetries obtained in the present work are in a good agreement with the experimental data, which implies that the present model (χQSM) produces reasonable form factors of many different quantum numbers. We also predicted in the present work the parity-violating asymmetries for the future G0 experiment at backward angles. Altogether, comparing the results of the χQSM with the overall observables of the SAMPLE, HAPPEX, A4, and G0, one observes a remarkable agreement. The question arises why the chiral quark-soliton model (χQSM) calculates strange form factors which have the sign and magnitude as they appear as results of the experiment. We only can state: The χQSM has been applied over several years to many observables of baryons in the octet and decuplet basically with one set of parameters adjusted to three [SU(2)) or four (SU(3)] physical data in the mesonic and baryonic sector. It has been reproducing electromagnetic and axial form factors, mass splittings, quark parton distributions, generalized quark parton distributions, antiquark distributions, etc. and with very few exceptions reproduced the experimental data within (10%–30)%. The model is the simplest quark model which describes spontaneous breaking of chiral symmetry; it is based on the $N \to \infty$ expansion of QCD and seems to describe the properties of the light baryons reasonably well. It seems to be that the degree of freedom of spontaneous breaking of chiral symmetry governs also the strange quark content of the nucleon.

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