

QCD Sum Rules and Soft-Hard Interplay for Hadronic Form Factors

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Abstract. We discuss two types of contributions to hadronic form factors in QCD: hard gluon exchange and soft wave function overlap. Within the QCD sum rule approach, the hard contribution has strong numeric suppression by factor $(\alpha_s/\pi) \sim 0.1$ for each exchange. For this reason, the soft contribution dominates at accessible momentum transfers. The “humpy” distribution amplitudes used to enhance hard terms cannot be derived from QCD sum rules in a self-consistent way. The estimates of soft terms obtained within the local quark-hadronic duality approach in all cases are close to existing data, providing an experimental evidence that hard terms are small.

1 Soft *vs.* Hard

It is still a matter of controversy whether hard scattering [1] or the soft wave function overlap mechanism [2]) is responsible for the experimentally observed power-law behaviour of elastic hadronic form factors. At sufficiently large momentum transfer, the soft mechanism is dominated by configurations in which one of the quarks carries almost all the momentum of the hadron. On the other hand, the hard scattering term is generated by the valence configurations with small transverse sizes and finite light-cone fractions of the total hadron momentum carried by each valence quark. For large Q^2 in QCD, this difference results in an extra $1/Q^2$ -suppression of the soft term compared to the hard scattering one.

The hard term can be written in a factorized form [3],[4],[5] as a product of a perturbatively calculable hard scattering amplitude and two distribution amplitudes (DAs) describing how the large longitudinal momentum of the initial and final hadrons is shared by their constituents. This mechanism involves exchange of virtual gluons, each exchange bringing in a noticeable suppression

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factor $(\alpha_s/\pi) \sim 0.1$. As a result, to describe existing data by the hard contribution alone, one should increase somehow the magnitude of the hard scattering term.

This is usually achieved by using the DAs with a ‘‘humped’’ shape [6]. However, the passive quarks in this situation carry a rather small fraction of the hadron momentum and, as pointed out in ref.[7], the ‘‘hard’’ scattering subprocess, even at rather large momentum transfers $Q^2 \sim 10 \text{ GeV}^2$, is dominated by rather small gluon virtualities. This means that the hard scattering scenario heavily relies on the assumption that the asymptotic pQCD approximations (*e.g.*, the $1/k^2$ -behaviour of the gluon propagator $D^c(k)$) are accurate even for momenta k smaller than 300 MeV , *i.e.*, in the region strongly affected by finite-size effects, nonperturbative QCD vacuum fluctuations, *etc.* Including these effects decreases the magnitude of the gluon propagator $D^c(k)$ at small spacelike k converting $D^c(k)$ into something like $1/(k^2 - \Lambda^2)$ and shifts the hard contributions significantly below the data level even if one uses the humpy DAs and other modifications increasing the hard term (see, *e.g.*, [8]).

An instructive illustration of possible modifications due to finite size or transverse momentum effects is given by the light-cone calculation of the $\gamma^* \gamma \pi^0$ amplitude [9, 10] in which hard propagator of a *massless* quark is convoluted with the two-body wave function $\Psi(x, k_\perp)$. Assuming the Gaussian dependence $\Psi(x, k_\perp) \sim \exp[-k_\perp^2/2xx\sigma]$ on transverse momentum, one can easily calculate the k_\perp integral to see that the pQCD propagator factor $1/xQ^2$ is substituted by the combination $(1 - \exp[-xQ^2/2\bar{x}\sigma])/xQ^2$ which monotonically tends to a finite limit $1/2\sigma$ as $x \rightarrow 0$. Hence, the effective virtuality is always larger than 2σ . The suppression of low virtualities has a simple explanation: propagation of quarks and gluons in the transverse direction is restricted by the finite size of the hadron. Numerically, $2\sigma \approx 1.35 \text{ GeV}^2$ in that case. However, even a milder modification of the ‘‘hard’’ propagators by effective quark and gluon masses $1/k^2 \rightarrow 1/(k^2 - M^2)$ with $M^2 \sim 0.1 \text{ GeV}^2$ or model inclusion of transverse momentum effects strongly reduces the magnitude of hard contributions [8], especially when the humpy DAs are used. For these reasons, a scenario with humpy DAs and bare $\sim 1/x_i y_j t$ propagators (which amounts to ignoring finite-size effects) considerably overestimates the size of hard contributions.

2 Lessons from Pion Studies

The relative smallness of hard contributions can be easily understood within the QCD sum rule context. The soft contribution is dual to the lowest-order diagram while the gluon exchange terms appear in diagrams having a higher order in α_s which results in the usual $\alpha_s/\pi \sim 1/10$ suppression factor per each extra loop. In particular, the α_s/π suppression factor is clearly visible in the expression for the hard contribution to the pion form factor [11, 12, 4, 13]

$$F_\pi^{\text{hard}}(Q^2)|_{\varphi_\pi = \varphi_\pi^{\text{qs}}} = \frac{8\pi\alpha_s f_\pi^2}{Q^2} = 2 \left(\frac{\alpha_s}{\pi} \right) \frac{s_0}{Q^2}. \quad (1)$$

Here, the combination $s_0 = 4\pi^2 f_\pi^2 \approx 0.67 \text{ GeV}^2 \sim m_\rho^2$ is what is usually called the “typical hadronic scale” in the case of the pion. At asymptotically high Q^2 , the $O(\alpha_s/\pi)$ suppression of the hard terms is more than compensated by their slower decrease with Q^2 . However, such a compensation does not occur in the subasymptotic region where the soft contributions, as we have seen, may have the same effective power behavior as that predicted by the asymptotic quark counting rules for the hard contributions. In ref. [14], both the soft contribution and the $O(\alpha_s)$ corrections for the pion form factor were calculated together within a QCD sum rule inspired approach. The ratio of the $O(\alpha_s)$ terms to the soft contribution was shown to be in full agreement with the expectation based on the α_s/π per loop suppression.

The use of the humpy DAs is usually motivated by the QCD sum rule analysis for the $\langle x^N \rangle$ moments of DAs [6]. However, applications of the QCD sum rules to DAs $\varphi(x)$ and form factors $F(Q^2)$ require a more detailed information about the nonperturbative QCD vacuum than those for the simpler classic cases [15] of hadronic masses and decay widths. The main problem is that the coefficients of the operator product expansion (OPE) for the relevant correlators now depends on an extra parameter, *e.g.*, on the order of the moment N for $\langle x^N \rangle$ or momentum transfer Q^2 for form factors. In particular, the higher condensates $\langle \bar{q}(D^2)^n q \rangle$ are accompanied in the $\langle x^N \rangle$ sum rule by large N^n -factors. Since for any reasonable shape of $\varphi(x)$ the moments $\langle x^N \rangle$ should decrease with growing N , the appearance of N^n -dependence is an artifact of the expansion procedure. Calculationally, the N^n -factors appear from the Taylor expansion of the nonlocal condensate $\langle \bar{q}(0)q(z) \rangle$. In this situation, one is forced to make, explicitly or implicitly an assumption about the structure of the OPE in higher terms. In the approach of ref.[6] only the lowest condensates were taken into account. A simple alternative is to model $\langle \bar{q}(0)q(z) \rangle$ by a smooth function with the width suggested by existing estimates $\langle \bar{q}D^2q \rangle / \langle \bar{q}q \rangle \approx 0.4 \text{ GeV}^2$. This model gives a QCD sum rule in which all terms decrease for large N . It produces the pion DA close to a smooth “asymptotic” form (see [16]).

It was also observed that the sum rules with nonlocal condensates have the property that the humps in the relevant correlator (corresponding to a sum over all possible states) get more pronounced when the relative pion contribution *decreases* (see ref.[17]). This means that the humps of the correlator are generated by oscillations in the DAs of the higher states rather than by the humps in the pion DA. The oscillatory behaviour of DAs of the radial excitations found in ref.[17] (see also [18]) is supported by the studies in two-dimensional QCD [19, 20].

An independent evidence in favour of the narrow form of the pion distribution amplitude $\varphi_\pi(x)$ is provided by the result of ref.[21], where it was found that $\varphi_\pi(1/2) \approx 1.2f_\pi$, to be compared with $\varphi_\pi^{as}(1/2) = 1.5f_\pi$ for the asymptotic distribution amplitude [4],[5] and $\varphi_\pi^{CZ}(1/2) = 0$ for the CZ form [3]. Furthermore, the lattice calculation of ref.[22] gives a rather small value $\langle \xi^2 \rangle \approx 0.11$ for the second moment of the pion DA incompatible with the humpy form (compare with $\langle \xi^2 \rangle^{CZ} = 0.43$ and $\langle \xi^2 \rangle^{as} = 0.2$). The statement that the pion DA is close to its asymptotic form even at a low normalization

point is also supported by calculation of the pion DA in the chiral soliton model [23] and by a direct QCD sum rule calculation of the large- Q^2 behavior of the $\gamma^*\gamma\pi^0$ form factor [24]. Within the light-cone QCD sum rule approach one can relate the pion DA to the pion parton densities [25] known experimentally. According to the analysis performed in [26], existing data favor the asymptotic shape. Finally, the humpy pion DA advocated in [27, 3] is now ruled out by recent experimental data [28] on the $\gamma^*\gamma\pi^0$ form factor. The data are fully consistent with the next-to-leading pQCD prediction calculated using the asymptotic DA [29, 10, 30].

If the pion DA is narrow, the hard contribution to the pion form factor is small. On the other hand, in many models, the soft term calculated as an overlap of model wave functions $\Psi(x, k_\perp)$ is comparable in size with the data [7, 31, 32, 33]. It should be noted that the relevant distribution amplitudes (obtained from $\Psi(x, k_\perp)$ by integration over k_\perp), are narrow and the hard term is small. Moreover, if one intends to increase the hard term by using wave functions enhanced in the end-point regions, one also increases the soft term (see, *e.g.*, [7, 33]), since the latter is dominated by the regions where one of the quarks has small momentum.

The pion form factor was also studied within the QCD sum rule approach, which is applicable in that case both in the region of moderately large [34],[35] and small momentum transfers [36]. In the whole region $0 \leq Q^2 \lesssim 3 GeV^2$, the QCD sum rule result for the contribution due to the Feynman mechanism is sufficiently large to explain the magnitude of existing data. In the region $Q^2 \gtrsim 4 GeV^2$, the OPE is ruined by $O(Q^2/M^2)^n$ enhancement of condensate contributions. This phenomenon has exactly the same nature as the $O(N)$ enhancement of the lowest condensate contributions in the CZ sum rule for $\langle x^N \rangle$ [37]. As a result, if we would assume that the higher condensate corrections can be neglected, we would get a very large soft contribution, marginally exceeding the data. Alternatively, using the nonlocal condensates [16] we would get the soft term comparable in size with the data [38]. As mentioned above, the same model produces a rather narrow pion DA [16] generating a small hard contribution which is subdominant up to $Q^2 \sim 10 GeV^2$. Since the QCD sum rules for $\langle x^N \rangle$ and $F^{soft}(Q^2)$ have similar structure, if one uses the same model for the condensates in both sum rules, the results for the hard term $F^{hard}(Q^2)$ (whose magnitude is determined by the shape of $\varphi(x)$) and soft term $F^{soft}(Q^2)$ are strongly correlated. Just like in quark model calculations, it is impossible to get a large hard term without getting a huge soft term. The existence of such a correlation is also supported by the light-cone QCD sum rules [39]. Just like in quark model calculations, it is impossible to get a large hard term without getting a huge soft term.

3 Nucleon Case

Since the structure of OPE in the pion and nucleon cases is very similar, there is no reason to expect a significant deviation of the nucleon DA from its asymp-

totic form. In particular, an evidence against humpy nucleon DAs is provided by a lattice calculation [40] which does not indicate any significant asymmetry. One may argue that the proton DA must be asymmetric to reflect the fact that the u -quarks carry on average a larger fraction of the proton momentum than the d -quarks. As shown in ref. [41], to accommodate this observation one needs only a moderate shift of the DA maximum from the center point $x_1 = x_2 = x_3 = 1/3$. Such a shift does not produce a drastic enhancement of the hard contribution provided by the humpy DAs. However, with the asymptotic DA, the leading twist hard contribution completely fails to describe the data: it gives zero for the proton magnetic form factor and a wrong-sign (positive) contribution for the neutron magnetic form factor, with the absolute magnitude of the latter being two orders of magnitude below the data [42].

In the case of the baryon form factors, the standard SVZ-Borel version of the QCD sum rule approach works only in the region of small momentum transfers $Q^2 \lesssim 1 \text{ GeV}^2$ [43]. Beyond this region, the OPE explodes because of $O(Q^2/M^2)$ -enhancements in condensate contributions, and a regular QCD sum rule analysis is impossible. In ref.[44], it was proposed to estimate the soft contributions by using the local quark-hadron duality prescription. It amounts to calculating the amplitude for transitions between the free-quark states produced (or annihilated) by a local current having the hadron's quantum numbers, and then averaging the invariant mass of the quark states over the appropriate duality interval s_0 . The latter has the meaning of the effective threshold for the higher hadronic states in the relevant channel and has a specific value for each hadron, *e.g.*, $s_0^\pi \approx 0.7 \text{ GeV}^2$ for the pion in the axial current channel.

For the pion form factor, the local quark-hadron duality is supported by the QCD sum rule analysis [34, 35] and agrees well with experimental data. Furthermore, as argued in ref. [44, 45] (see also [46]) the quark-hadron duality prescription has an intuitively appealing interpretation in terms of the light-cone wave functions: it can be treated as a cut-off model $\Psi(\{x_i\}, \{k_\perp\}) \sim \theta(\sum_i(k_\perp^2/x_i) \leq s_0)$ for the soft wave function. The sharp cut-off suggested by the local duality looks like a rough approximation for more smooth wave functions usually adopted in phenomenological quark models. However, the difference is that in the local duality model the width of the k_\perp -distribution is directly related to a parameter s_0 characterizing the hadronic spectrum. This parameter s_0 is calculated from the reliable two-point function QCD sum rule and considered as given in the form factor calculations.

The local duality estimate [44] of the soft term for the proton magnetic form factor, based on the standard value $s_0^N \approx 2.3 \text{ GeV}^2$ [42] of the nucleon duality interval is very close to available data [47], [48] over a wide region $3 \text{ GeV}^2 \lesssim Q^2 \lesssim 20 \text{ GeV}^2$. The same calculation [44] also correctly reproduces the observed magnitude of the helicity-nonconservation effects for the proton form factors: $F_2^p(Q^2)/F_1^p(Q^2) \sim \mu^2/Q^2$ with $\mu^2 \sim 1 \text{ GeV}^2$ [48]. Within the scenario based on hard scattering dominance, it is rather difficult to understand the origin of such a large scale, since possible sources of helicity nonconservation in pQCD include only small scales like quark masses, intrinsic transverse momenta, *etc.*, and one would rather expect that $\mu^2 \sim 0.1 \text{ GeV}^2$.

4 Proton to Delta Transition

Even more drastic difference between predictions of hard and soft scenarios is expected (see, *e.g.*, [49]) in the studies of spin effects in the $\gamma^*p \rightarrow \Delta^+$ transition. A renewed attention to this process was raised by the results [50] of the analysis of inclusive SLAC data which indicated that the effective transition form factor drops faster than one would expect from quark counting rules [1, 51, 52]. Within the hard scattering scenario, the DA-sensitivity of this process was originally analyzed in ref.[53]. It was observed there that the hard scattering amplitude in this case has an extra suppression due to cancellation between symmetric and antisymmetric parts of the nucleon distribution amplitude. Hence, from the hard scenario point of view, the faster fall-off found in [50] signalizes the dominance of a non-asymptotic contribution.

In ref.[54], the soft contribution to the $\gamma^*p \rightarrow \Delta^+$ transition form factors was estimated within the local quark-hadron duality approach. The duality interval for the Δ -resonance taken there is $s_0^\Delta = 3.5 \text{ GeV}^2$, which agrees with the results of the two-point function analysis [42]. The results for the effective form factor $G_T(Q^2)$ are close to those obtained from the analysis of inclusive data [55]. This means that the data can be described without a sizable contribution from the hard-scattering mechanism. Furthermore, the $\gamma^*p \rightarrow \Delta^+$ transition is described by three independent form factors, and a correct model should not only be able to adjust the absolute magnitude of one of them: it should also be able to explain the relations between different form factors. In particular, the pQCD calculation [53] predicts that the lowest-twist hard contribution always has the property $G_E^{*hard}(Q^2) \approx -G_M^{*hard}(Q^2)$. This prediction is a specific example of the helicity selection rules [5] inherent in the hard scattering mechanism. Experimentally, the ratio $G_E^*(Q^2)/G_M^*(Q^2)$ is very small [49, 56], which indicates that the leading-twist pQCD term is irrelevant in the region $Q^2 \lesssim 4 \text{ GeV}^2$. Small value for $G_E^*(Q^2)/G_M^*(Q^2)$ is also predicted in constituent quark model approaches [57, 58, 59, 60, 61]. However, these approaches usually do not claim applicability in the $Q^2 \gtrsim 2 \text{ GeV}^2$ region of momentum transfers. The local duality estimates were performed in ref. [54] for several Lorentz structures which appear in the decomposition of the basic γ -odd three-point amplitude. The results obtained from different invariant amplitudes are in satisfactory agreement with each other. All estimates indicate that the transition is dominated by the magnetic form factor $G_M^*(Q^2)$, with electric $G_E^*(Q^2)$ and Coulomb $G_C^*(Q^2)$ form factors being small compared to $G_M^*(Q^2)$ for all experimentally accessible momentum transfers (see Fig. 1).

To summarize, QCD sum rule based results for soft contributions to hadronic form factors are in good quantitative agreement with existing data providing a clear experimental evidence that at available Q^2 hard terms are relatively small.

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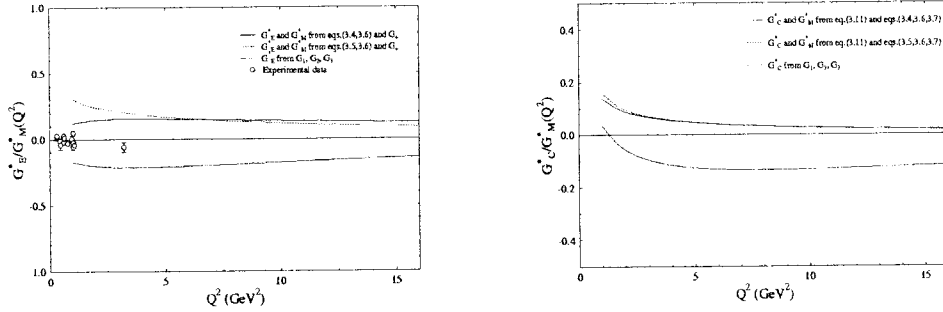


Figure 1. Local duality estimates for the ratio of form factors a) $G_E^*(Q^2)$ and $G_M^*(Q^2)$ and b) $G_C^*(Q^2)/G_M^*(Q^2)$.

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