Confinement, quark mass functions and spontaneous chiral-symmetry breaking in Minkowski space

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We present a study of the dressed quark mass function and the pion structure in Minkowski space using the Covariant Spectator Theory (CST) [1]. We propose a manifestly covariant model for the $q\bar{q}$ interaction based on previous work by Gross, Milana and Şavkli [2] that incorporates both spontaneous chiral symmetry breaking and confinement. Our model is particularly suited for the treatment of the light mesons such as the pion. In this case a four-channel CST equation is employed which is invariant under charge conjugation. On the other hand, in the limit of infinitely heavy quark masses, the CST equation reduces to the Schrödinger equation. This makes our approach suitable for a unified description of all $q\bar{q}$ mesons.

We use a momentum-space interaction kernel that is a relativistic generalization of the linear confining $q\bar{q}$ potential and a constant potential shift that defines the energy scale. Spontaneous chiral-symmetry breaking is included via a Nambu–Jona-Lasinio-type mechanism: A self-consistency condition ensures that the CST equation for a pseudoscalar bound state has a zero-mass solution (Goldstone pion) in the chiral limit of a vanishing current quark mass m_0. A finite dressed quark mass is then generated dynamically through the self-interactions of the quark with the $q\bar{q}$ interaction kernel. In previous models the quark mass function has been approximated by a phenomenological function. In the present approach we actually calculate the mass function directly from the $q\bar{q}$ interaction kernel, which makes our model completely self-consistent.

Another appealing feature of our model is the property that in the chiral limit the confining interaction does not contribute to the CST equation for a pseudoscalar bound state. This decoupling of confinement from chiral-symmetry breaking permits our confining potential to include, e.g. a Lorentz-scalar part as suggested from phenomenological approaches [3] and lattice-QCD calculations [4].

Our calculated mass function involves 3 free parameters which are fixed by the gap equation and by a fit to the lattice data [5] for a bare quark mass of $m_0 = 0.016$ GeV. The mass function for different values of m_0 is then found by solving the corresponding gap equation. Note that the lattice data calculated in Euclidean space must be compared with our Minkowski-space calculation at negative p^2, as shown in the left panel of Figure 1.

As a first application of the formalism we use our mass function in the computation of the pion electromagnetic form factor in the relativistic impulse approximation. For simplicity, we adopt an approximated pion vertex function that is an off-shell extension near the chiral limit, where the contribution from the confining interaction is expected to be small and is therefore neglected. It should be emphasized that this is a very simple model for the pion and we do not expect exact agreement with the experimental data [6]. The aim of this work is rather to show that our model is able to give sensible results for both, the quark and the pion structure at the same time, as illustrated in the left and the right panel of Figure 1, respectively. It is clear that for a more quantitative study of the light meson properties the solution of the complete four-channel CST equation is needed, which will be the subject of our future program.

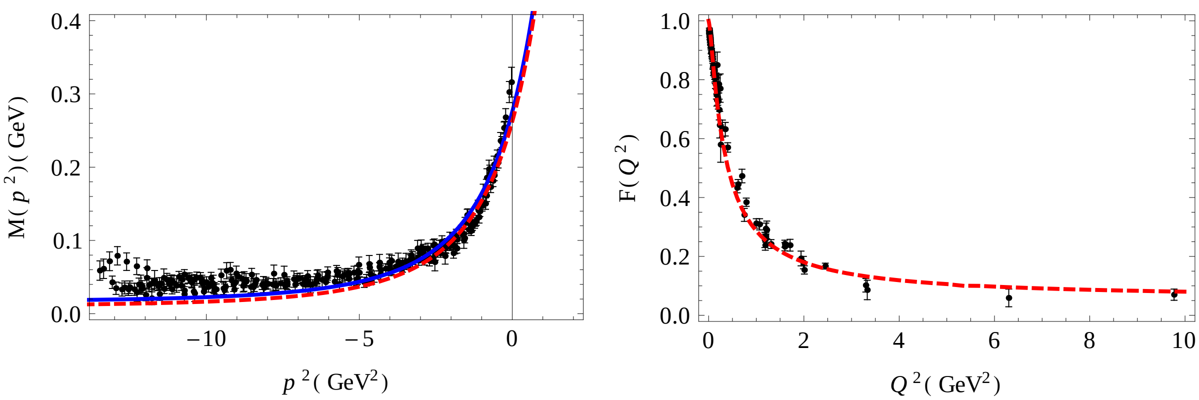

Figure 1: Left panel: The quark mass function fit (blue solid) to the LQCD data [5] for $m_0 = 0.016$ GeV and the mass function for $m_0 = 0.01$ GeV (red dashed line). Right panel: The pion form factor compared with experimental data [6]. With the mass function for $m_0 = 0.01$ GeV together with a pion mass of 0.19 GeV and an anomalous quark magnetic moment of 0.05 a good fit to the data is achieved.

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