Quark degrees of freedom in hadronic systems

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Abstract. The role of models in Quantum Chromodynamics is to produce simple physical pictures that connect the phenomenological regularities with the underlying structure. The static properties of hadrons have provided experimental input to define a variety of very successful Quark Models. We discuss applications of some of the most widely used of these models to the high energy regime, a scenario for which they were not proposed. The initial assumption underlying our presentation will be that gluon and sea bremsstrahlung connect the constituent quark momentum distributions with the partonic structure functions. The results obtained are encouraging but lead to the necessity of more complex structures at the hadronic scale. This initial hypothesis may be relaxed by introducing some non perturbative model for the constituent quarks. Within this scheme we will discuss some relevant problems in nucleon structure as seen in high energy experiments.

INTRODUCTION

The constituent quark, one of the most fruitful concepts in 20th century physics, was proposed to explain the structure of the large number of hadrons being discovered in the sixties [1]. Soon thereafter deep inelastic scattering of leptons off protons was explained in terms of pointlike constituents named partons [2]. Thus already at a very early stage of the study of hadron structure the need to connect the laboratory description, based on constituent quarks, and the light cone description, based on partons, arose as the way to understand phenomena at different scales. Sum rules and current algebra were very powerful tools to establish a conceptual link between the two descriptions.

The birth of Quantum Chromodynamics (QCD) and the proof that it is asymptotically free set the framework for an understanding of deep inelastic phenomena beyond the parton model [3]. However, the perturbative approach to QCD does not provide absolute values for the observables, it just gives their variation with momentum in terms of some unknown non perturbative matrix element. On order for the description based on the Operator Product Expansion (OPE) and QCD evolution to be predictive, these matrix elements have to be eliminated by comparing several processes or by the input of experimental data. Therefore the perturbative scheme is used, most of the time, to relate experiments at different momentum scales.

The phenomenological analysis proceeds by finding a parametrization which is appropriate at a sufficiently large momentum $Q^2_0$, where one expects perturbation theory to be fully applicable, and then QCD evolution techniques determine the parton distributions at a higher $Q^2$. As an example we show the parametrization due to Martin Sterling and Roberts ($Q^2_0 = 4 \text{ GeV}^2$) [4]:
\[ xu_v = 2.26x^{0.559}(1 - 0.54\sqrt{x} + 4.65x)(1 - x)^{3.96} \]
\[ xd_v = 0.279x^{0.335}(1 + 6.80\sqrt{x} + 1.93x)(1 - x)^{4.46} \]
\[ xS = 0.956x^{-0.17}(1 - 2.55\sqrt{x} + 11.2x)(1 - x)^{9.63} \]
\[ xg = 1.94x^{-0.17}(1 - 1.90\sqrt{x} + 4.07x)(1 - x)^{5.33} \]  

(1)

This parametrization incorporates the flavor and momentum sum rules. The distributions are defined in the \( \overline{\text{MS}} \) renormalization and factorization schemes and the QCD scale parameter \( \Lambda \) is found to be 0.231 GeV. With this fit a large body of data is reasonably described. However this parametrization is purely phenomenological with little theoretical input.

The work of Glück, Reya and Vogt [5] has shown that the high energy parton distributions when evolved to a low scale appear to indicate that a valence picture of hadron structure arises. This idea was suggested a long time ago by Parisi and Petronzio [6], who assumed that there exists a low energy scale \( \mu_0^2 \) such that the glue and sea are absent, i.e., the long range part of the interaction (confinement) is composed in the \( P_\infty \) frame of only three quarks. If one turns on the short range part of the interaction (perturbative QCD), using the renormalization group one introduces gluons and the sea.

The constituent quark concept embedded in a QCD framework, leads to models that are able to reproduce in an extraordinary way the low energy properties with very few parameters [7]. The goal was to use them as substitutes for QCD at low energies. The needed ingredient was provided by Jaffe and Ross [8]. According to these authors the quark model calculation of matrix elements give their values at a hadronic scale \( \mu_0^2 \) and for all larger \( Q^2 \) their coefficient functions evolve as in perturbative QCD.

We have developed a formalism, for potential quark models, based on these ideas which connects the parton distributions with the momentum distributions of the model [9]. A analogous procedure may be derived for bag models by using the bag model limit of light cone matrix elements [10]. The low energy scale \( \mu_0^2 \) is determined by evolving downward from the high energy data the second moment of the valence quark distribution until it reaches the value given by the quark model describing the hadronic behavior. The model provides the matrix elements of the needed twist operators characterizing observables at the high energy scale and their values are ascribed to this hadronic scale. Then, they are evolved to high momentum transfers, where comparison with experiments takes place, using perturbative QCD.

This approach describes successfully the gross features of the DIS results [9]. In order to produce more quantitative fits different mechanisms have been proposed: valence gluons, sea quarks and antiquarks, relativistic kinematics, etc... We will show that some of these mechanisms appear naturally if we endow the constituent quarks with structure following the work of Altarelli et al.[11]. In our scheme constituent quarks are complex objects, made up of point-like partons (current quarks (antiquarks) and gluons), interacting by a residual interaction described by a quark model [12]. The hadron structure functions are obtained as convolutions of the constituent quark wave function with the constituent quark structure functions.
Our aim here is neither technical nor bibliographical. We will simply guide the reader to the literature by discussing the physics behind the various formalisms. In the referred literature he will find a complete account of the needed references and technicalities, so that he may be able to reconstruct the calculations presented in detail. We will elaborate on the theoretical framework, discuss some of the main results and explore future directions.

**CONSTITUENT QUARKS AND PARTONS**

Constituent quark models have been designed to describe the static properties of hadrons and therefore aimed at modeling the non-perturbative aspects of QCD. They are in general very successful in their performance. We discuss a formalism which uses them to describe high energy data, whose basis lies on the following reasoning. QCD perturbation theory is non-predictive. The renormalization group relates different momentum scales. Experimental input is required to avoid the unknown non-perturbative properties of the theory. Our formalism substitutes the experimental input by model physics. In this way we define a predictive scheme, whose appeal lies in the relation it establishes between physics at very different scales and whose weakness is its model dependence.

**Parton distributions from quark models**

The basic idea in our approach arises from rephrasing the OPE which states that,

\[ F_i^n(Q^2) = M^n_{ij} F_j^n(Q_0^2), \]  \hspace{1cm} (2)

i.e., the nth moment of structure functions at one scale are related by means of perturbatively calculable transformation matrices to the same moments at another scale [3]. If \( Q_0^2 \) is taken to be a low scale, which we have named hadronic scale, the \( F \) functions become highly non-perturbative matrix elements in general. We substitute the matrix elements at the hadronic scale by the matrix elements calculated in the chosen model. In particular we are able to relate the valence quark distribution functions with the appropriate momentum distributions in the corresponding baryonic state \( n_a^q \), i.e. with the hadronic wave functions in the model,

\[ x q_V^a(x) = \frac{1}{(1-x)^2} \int d^3 p \ n^a_q(\vec{p}) \ \delta\left( \frac{x}{1-x} - \frac{p_+}{M} \right) \]  \hspace{1cm} (3)

where \( a \) represents the diverse degrees of freedom (unpolarized, \( \uparrow, \downarrow, \ldots \)), \( \vec{p} \) the momentum of the constituent, \( p_+ = p_0 - p_z \), \( x \) is the Bjorken variable and \( M \) the mass of the baryonic state.

In this way we have studied polarized and unpolarized structure function, transversity distributions and angular momentum distributions with various models [9, 13, 14]. The results of our calculations show that these models, with the parameters fixed by low energy properties are able to provide a qualitative description of the data and therefore
FIGURE 1. We show the unpolarized parton distribution $xu_v$: i) for a quark model [15] at the hadronic scale (dot dashed); ii) for the same model within the convolution approach at the hadronic scale (long dashed); iii) evolved (NLO) to the scale of the data at $10 GeV^2$ for the model in i) (dashed); iv) evolved for the convolution approach of ii) (full curve) to the scale of the data; v) as guide line through the data (dotted) [22].

the scheme becomes predictive. They are however too naive and new ingredients, not seen by low energy probes, have to be incorporated.

Applications

We comment on some of the calculations performed by stressing only the main results. We refer the reader to the figures and discussions in the given references for a complete account.

1) Parton distributions [9]

We have analyzed in this formalism the polarized and unpolarized experimental results and have shown that well-known Quark Models lead to a qualitative description of the data. The relevant features are: the original model distributions, which are vastly different from the data, evolve, via the Renormalization Group, towards them; sea quarks and gluons, initially absent, are generated by bremsstrahlung. In Fig. 1 one can see how the initial large quark model distribution at the hadronic scale approaches the data by evolution. The momentum lost by the valence quarks goes into the other components. In Fig. 2 we show the gluonic component obtained by evolution in a scheme to be specified later.

In the polarized case, the spin distribution function for the proton, which are too large
We show the gluon distribution $xg(x, Q^2)$ at $Q^2 = 10 GeV$ obtained with the ACMP approach for two different models of hadron structure [15, 23]. The data are those of ref. [22].}

for the model calculation, the famous proton spin problem, decreases and approaches the data via the same RG mechanism. In this way the spin is transferred to the new components and the problem greatly disappears. In Fig. 3 the remaining discrepancy between the model calculation and the data after evolution can be seen.

If one aims at a quantitative agreement with the data, the conventional low energy models have to be modified to include, higher momentum and higher angular momentum components for the quarks, and sea components at the hadronic scale. Moreover the experimental gluon distributions, at present extracted in a very indirect way, if taken at face value, imply the need for soft gluons at the hadronic scale. Moreover in the case of the spin parton distribution, the anomaly contribution helps in the explanation of the data.

2) Transversity distribution [14]

The feasibility of measuring chiral-odd parton distribution functions in polarized Drell-Yan and semi-inclusive experiments has renewed theoretical interest in their study. Models of hadron structure have proven successful in describing the gross features of the chiral-even structure functions. Similar expectations motivated our study of the, experimentally unknown, transversity parton distributions with these models. We confirmed, by performing a NLO calculation, the diverse low $x$ behaviors of the transversity and spin structure functions at the experimental scale and showed that it is fundamentally a consequence of the different behaviors under evolution of these functions. The inequalities of Soffer establish constraints between data and model calculations of the chiral-odd transversity function. The approximate compatibility of our model calculations with
FIGURE 3. We show the spin structure function $g_1$ for the proton. The dashed curve represents the results of a Quark Model calculation evolved at NLO to the scale of the data ($10\,\text{GeV}^2$). The full two curves represent the calculation in the ACMP scenario, within the same quark model, for two parametrizations of the quark structure functions. The data have been taken from [24].

these constraints confers credibility to our estimates.

3) Skewed parton distributions

A new type of observable, the so called skewed parton distributions (SPD), have been intensively studied in the last years [16]. The SPDs generalize and interpolate between the ordinary parton distributions and the elastic form factors and therefore contain rich structural information. They have been instrumental in understanding the Orbital Angular Momentum (OAM) and furthermore the Deeply Virtual Compton Scattering (DVCS) process has been proposed as a practical way to measure them. From the point of view of parton physics they appear, similarly to the conventional distributions, as light cone matrix elements of the quark-gluon operators, however here the initial and final states have different momenta, and in this way there is an additional $t$-dependence besides the conventional $x$ dependence. A model calculation within the MIT bag framework has provided estimates about their magnitude which serve as guidance for future experiments [17].

i) Orbital angular momentum [13]

We have studied OAM twist-two parton distributions, for the relativistic MIT bag model and for non-relativistic potential quark models. The contribution of quarks OAM to the nucleon spin evolves at high $Q^2$ to a vanishingly small value, while that of the gluons increases dramatically. As expected by general arguments, the large gluon OAM contribution is almost canceled by the gluon spin contribution. At large $Q^2$ the gluons contribute 50% to the angular momentum and the quarks carry only spin.
ii) Twist three contributions to DVCS [18]

The study of the gauge invariance of the DVCS amplitude leads to the inclusion of higher twist components [19]. We have performed an extensive study of the DVCS amplitude within a bag model framework of the single spin asymmetry in the case of spin 0 systems. Our results imply that the choice of kinematics is crucial in order to observe certain amplitudes and therefore unravel the structure of the system.

TOWARDS AN UNIFIED PICTURE OF CONSTITUENT AND CURRENT QUARKS

Our basic assumption has been that gluon and sea bremsstrahlung are the source of difference between the constituents and the current quarks. However the data seem to indicate that the hadronic structure is more complex, with primordial sea quarks (antiquarks) and gluons. Thus the analysis thus far implies that constituent models have to be of greater complexity in order to describe, simultaneously, low and high energy data. Next, we analyze one way to generate this complex structure from a quark model, by assuming that constituent quarks are non elementary and therefore have partonic structure. These ideas where investigated a long time ago by two groups, Altarelli et al. [11], starting from a quark model scenario, and Kuti and Weisskopf [20], who defined a more complex scenario which contained sea and gluons at the hadronic scale. We have studied the consequences of the former approach.

Current structure from the Constituent Quarks

We have gone beyond the bremsstrahlung formalism by incorporating structure to the constituent quarks following the procedure we have called ACMP [11]. Within this approach constituent quarks are effective particles made up of point-like partons (current quarks, antiquarks and gluons), interacting by a residual interaction described by a quark model [12]. The structure of the hadron is obtained by a convolution of the constituent quark model wave function with the constituent quark structure function. For a proton made up of $u$ and $d$ quarks,

$$f(x,\mu_0^2) = \int_x^1 \frac{dz}{z} [\mu_0(z,\mu_0^2)\Phi_{uf}(\frac{x}{z},\mu_0^2) + d_0(z,\mu_0^2)\Phi_{df}(\frac{x}{z},\mu_0^2)],$$

where $\mu_0^2$ is the hadronic scale, $f = q_v, q_s, g$ (valence quarks, sea quarks and gluons respectively) and $\Phi$ represents the constituents probability in each quark and has been parametrized following general arguments of QCD as

$$\Phi_{qf}(x,\mu_0^2) = C_f x^{\Delta_f}(1-x)^{\Delta_f-1}.$$  

The constants have been fixed by Regge phenomenology and the choice of the hadronic scale ($\mu_0 = 0.34$ GeV$^2$).
The discussion can be generalized to the polarized structure functions [21]. The procedure is able to reproduce the data extremely well and in this framework the so called spin problem does not arise.

**Applications**

1) **Unpolarized parton distributions** [12]

Using that the constituent quark is a composite system of point-like partons, we construct the parton distributions by a convolution between constituent quark momentum distributions and constituent quark structure functions, Eq.(4).

The different types and functional forms of the structure functions of the constituent quarks, \( \Phi \), are derived from three very natural assumptions:

i) The point-like partons are determined by \( QCD \), therefore, they are quarks, anti-quarks and gluons;

ii) Regge behavior for \( x \to 0 \) and duality ideas;

iii) invariance under charge conjugation and isospin.

These considerations define in the case of the valence quarks the following structure function,

\[
\phi_{qqv}(x, Q^2) = \frac{\Gamma(A + \frac{1}{2})}{\Gamma(\frac{1}{2})\Gamma(A)} \frac{(1 - x)^{A-1}}{\sqrt{x}}.
\]

(6)

For the sea quarks the corresponding structure function becomes,

\[
\phi_{qqs}(x, Q^2) = \frac{C}{x}(1 - x)^{D-1},
\]

(7)

and in the case of the gluons we take

\[
\phi_{qg}(x, Q^2) = \frac{G}{x}(1 - x)^{B-1}.
\]

(8)

The other ingredients of the formalism, i.e., the probability distributions for each constituent quark, are defined according to the procedure of Traini et al. [9], that is, a constituent quark has a probability distribution determined by Eq.(3).

Our last assumption relates to the scale at which the constituent quark structure is defined. We choose for it the hadronic scale \( \mu_0^2 \). This hypothesis fixes all the parameters of the approach except one, which is fixed by looking at the low \( x \) behavior of the \( F_2 \) structure function at the hadronic scale, where the sea is known to be dominant.

The resulting parton distributions and structure functions are evolved to the experimental scale and good agreement with the available DIS data is achieved (See Fig. 1). In Fig. 2 we show the gluonic components generated in the ACMP scheme for two models. The primordial sea and gluon components at the hadronic scale are instrumental in achieving a good agreement with the experimental observation.

When compared with a similar calculation using non-composite constituent quarks, the accord with experiment of the present calculation becomes impressive. We therefore
conclude that DIS data are consistent with a low energy scenario dominated by composite, mainly non-relativistic constituents of the nucleon.

2) Polarized parton distributions [21]

The previous discussion can be generalized to the polarized case. The functions $\Phi_{ab}$ now specify spin and flavor.

Let

$$\Delta q(x, \mu_0^2) = q_+(x, \mu_0^2) - q_-(x, \mu_0^2)$$  \hspace{1cm} (9)

where $\pm$ label the quark spin projections and $q$ represents any flavor. The generalized ACMP approach implies

$$q_i(x, \mu_0^2) = \int_x^1 \frac{dz}{z} \sum_j (u_0 j(z, \mu_0^2) \Phi_{u_j i j} \left( \frac{x}{z}, \mu_0^2 \right) + d_0 j(z, \mu_0^2) \Phi_{d_j i j} \left( \frac{x}{z}, \mu_0^2 \right))$$  \hspace{1cm} (10)

where $i = \pm$ labels the partonic spin projections and $j = \pm$ the constituent quark spins.

Using spin symmetry we arrive at

$$\Delta q(x) = \int_x^1 \frac{dz}{z} \left( \Delta u_0(x) \Delta \Phi_{qq v} \left( \frac{x}{z} \right) + \Delta d_0(x) \Delta \Phi_{qq s} \left( \frac{x}{z} \right) \right)$$  \hspace{1cm} (11)

where $\Delta q_0 = q_{0+} - q_{0-}$, and

$$\Delta \Phi_{qq v} = \Phi_{u+ q+} - \Phi_{u+ q-}$$  \hspace{1cm} (12)

$$\Delta \Phi_{qq s} = \Phi_{d+ q+} - \Phi_{d+ q-}$$  \hspace{1cm} (13)

We next reformulate the description in term of the conventional valence and sea quark separation, i.e.,

$$\Delta q(x) = \Delta q_v(x) + \Delta q_s(x)$$

After a series of simplifying assumptions we obtain for the various polarized parton distributions the following expressions:

$$\Delta q_v(x) = \int_x^1 \frac{dz}{z} \Delta q_0(x) \Delta \Phi_{qq v} \left( \frac{x}{z} \right),$$  \hspace{1cm} (14)

for the valence quarks,

$$\Delta q_s(x) = \int_x^1 \frac{dz}{z} (\Delta u_0(x) + \Delta d_0(x)) \Delta \Phi_{qq s} \left( \frac{x}{z} \right),$$  \hspace{1cm} (15)

for the sea quarks, and

$$\Delta g(x) = \int_x^1 \frac{dz}{z} (\Delta u_0(x) + \Delta d_0(x)) \Delta \Phi_{q g} \left( \frac{x}{z} \right)$$  \hspace{1cm} (16)

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1 We omit writing explicitly the hadronic scale dependence from now on.
for the gluons

Thus the ACMP procedure can be extended to the polarized case just by introducing three additional structure functions for the constituent quarks: $\Delta \Phi_{qq}$, $\Delta \Phi_{qs}$, and $\Delta \Phi_{qg}$.

In order to determine the polarized constituent structure functions we add some assumptions which will tie up the constituent structure functions for the polarized and unpolarized cases completely, reducing dramatically the number of parameters. They are:

iv) factorization assumption: $\Delta \Phi$ cannot depend upon the quark model used, i.e, cannot depend upon the particular $\Delta q_0$;

v) positivity assumption: the positivity constraint $\Delta \Phi \leq \Phi$ is saturated for $x = 1$.

These additional assumptions determine completely the parameters of the polarized constituent structure functions.

Using unpolarized data to fix the parameters we achieve good agreement with the polarization experiments for the proton (see Fig. 3), while not so for the neutron. By relaxing our assumptions for the sea distributions, we define new quark functions for the polarized case, which reproduce well the proton data and are in better agreement with the neutron data (see discussion in ref. [21]).

When our results are compared with similar calculations using non-composite constituent quarks the accord with the experiments of the present scheme is impressive. We conclude that, also in the polarized case, DIS data are consistent with a low energy scenario dominated by composite constituents of the nucleon.

**CONCLUDING REMARKS**

The high energy parton distributions when evolved to a low energy scale appear to indicate that a valence picture of hadron structure arises. This valence picture is well represented theoretically by Quark Models which are very successful in explaining the low energy properties of hadrons. We have developed a formalism based on a laboratory partonic description which connects the parton distributions with the momentum distributions of the constituents giving us a description of partons in terms of Quark Model wave functions. Our basic assumption is that gluon and sea bremsstrahlung are the source of difference between the various momentum scales. We have implemented the Renormalization Group program by defining a hadronic scale and using as initial, non perturbative, conditions those obtained from the parton distributions of the low energy model.

Our analysis, based on a NLO formalism of evolution, has shown that the perturbative scheme is applicable to the low energy scales of interest. The formalism used has the correct support for the parton distributions and allows the discussion of a large class of Quark Models.

The results of our calculations show that low energy models, with their parameters fixed by low energy properties, tend to give a qualitative description of the data. Fig. 1 is very clarifying in this respect. This feature allows one to use them in order to be predictive in new observations.
The next step, which our formalism allows, is to proceed to define models which describe quantitatively the data at all energy scales. Our analysis has shown that present models are too naive. The new models seem to require: primordial gluons and sea.

The limitations associated with naive Quark Models of DIS data can be overcome by a very appealing scheme where the constituent quarks are not elementary. Partons (the quarks, antiquarks and gluons of QCD) at the hadronic scale are generated by unveiling the structure of the constituent quarks. We have seen that incorporating this structure in a very physical way improves notably the agreement with the DIS data (see Fig. 1). From the point of view of the calculation, we must stress, that no parameters of the model have been changed with respect to the original fit to the low energy properties. The new parameters arising from the description of the constituent quark structure functions have been adjusted to describe the input scenario according to the hadronic scale philosophy. In this way the sea and gluon distributions are generated in a consistent way (see Fig. 2).

The same analysis can be easily performed for the polarized case. Using a physically motivated minimal prescription for the polarized case, with no additional parameters, we are able to obtain a good prediction of the the proton data (see Fig. 3). The minimal procedure fails, however, to reproduce the accurate neutron data. Relaxing the minimal procedure, with the addition of only one new parameter to define the polarized sea, we obtain a significantly improved description also for the neutron data [21]. The calculation has also clarified the role of the gluons and the valence quarks. It is clear that the gluons become important through the evolution process, i.e., it is the soft bremsstrahlung gluons which acquire a large portion of the partonic spin.

We would like to stress that within our procedure the spin problem, as initially presented, does not arise. The constituent quarks carry all of the polarization. When their structure is unveiled this polarization is split among their different partonic contributions in the manner we have described and which is consistent with the data. The quality of both unpolarized and polarized data thus far analyzed confirm the validity of the approach. We have showed also, that with very reasonable assumptions, the scheme becomes highly predictive, a feature which is necessary for the planning of future experiments.

We feel safe to conclude that, the current quarks seen at the parton level seem to be embedded in the composite constituent quarks seen at lower $Q^2$. An unified picture of current quarks, successfully describing DIS, and constituent quarks, successfully describing static properties is possible.

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