

QCD Aspects of Polarized Hard Scattering Processes ¹

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ABSTRACT

I give an overview of what our present knowledge of QCD predicts and does not predict for polarized hard scattering. For experimental programs, a big issue is how much further we can expect our theoretical understanding of QCD to improve.

1 Introduction

In the area of high-energy spin physics, there are many experiments that are in various stages of construction and proposal whose data will need to be analyzed. They will cover a much wider range of phenomena than previous experiments. Therefore, I will review what we know from QCD about hard processes, what we don't know (at least not yet), and the areas in which it is realistic to expect our knowledge to improve.

2 State of QCD

Our ability to make predictions from QCD is highly conditioned by its asymptotic freedom. Thus perturbation theory can be used to make useful predictions for processes governed by short-distance phenomena. For non-perturbative infra-red phenomena, the only currently available methods for making predictions from first principles are lattice Monte-Carlo calculations. However, these only provide results in Euclidean (imaginary) time, and so are only useful for static quantities like masses.

Scattering processes combine short- and long-distance phenomena, and calculations are based on use theorems about the asymptotics of amplitudes and cross sections. Thus we have “factorization theorems” for processes with a hard scattering (deep-inelastic scattering, jet production, etc), where a cross section is a product of a non-perturbative and a perturbative factor. The well-known Monte-Carlo event generators result from a particularly complicated (but approximate) case of these theorems.

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2.1 Factorization

Now I will review the features of a typical factorization theorem [1]. Illustrated in Fig. 1, is the one for a deep-inelastic structure function. The lines in the upper part of the graph are far off-shell, while those in the lower part of the graph form a single-particle density (called a parton distribution function). The final-state lines in the upper part of the graph can be treated as effectively off shell in the context of a sufficiently inclusive cross section that the details of the final-state are not resolved.

The corresponding formula is

$$F_1(x, Q) = \text{pdf}(x) \otimes \text{“Wilson coefficient”} \\ + \text{power-suppressed terms.} \quad (1)$$

This is a provable impulse approximation, with the parton distribution being a function only of a longitudinal momentum fraction, because of the relativistic kinematics. The hard scattering coefficients (“Wilson coefficients”) are perturbatively calculable in powers of $\alpha_s(Q)$. The parton densities can (in principle) be measured in a few experiments and then used to predict other processes that have a factorization theorem.

The non-trivial features of factorization are the need for higher-order corrections to the coefficient functions and the DGLAP evolution of the parton densities.

2.2 Spin

When we treat polarized processes, simple generalizations of the same factorization theorems continue to be provable [2]. The complication is that the parton lines entering the hard scattering need to be equipped with helicity density matrices. The combination of parton densities and the density matrices can be conveniently represented in terms of the unpolarized parton densities and some spin-asymmetry densities. For a spin-half hadron (like a proton), we have longitudinal spin asymmetries ($\Delta u, \Delta d, \dots, \Delta g$) and transverse spin asymmetries (or ‘transversity’ densities, δu , etc). Jaffe has used the notation h_1 for the transversity densities, but I prefer the notation δ or δ_T . Because the gluon has spin 1, it can be proved from rotation invariance that there is no transversity asymmetry for the gluon in a spin-half hadron.

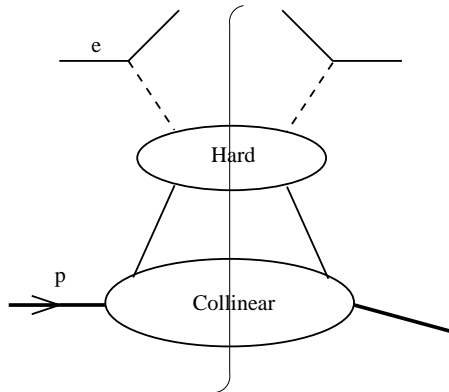


Figure 1: Factorization for deep-inelastic structure function.

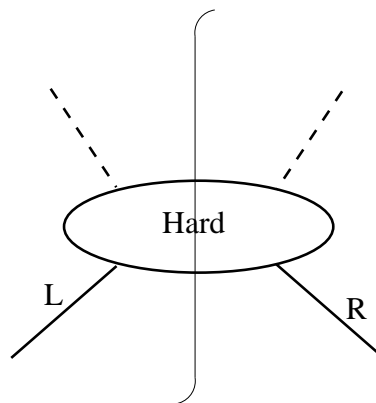


Figure 2: Interference between amplitudes with left and right handed quarks is zero for perturbative hard-scattering coefficients.

A particularly important set of predictions arises because QCD predicts that chirality is conserved in hard scattering coefficients. This implies that there is no interference between amplitudes for left and right-handed quarks (Fig. 2). Thus many transverse spin asymmetries are zero in the leading twist-2 approximation. A typical case [3] is g_2 in DIS. The phenomenology of higher twist processes is much more difficult.

In full QCD, including its non-perturbative part, chirality conservation is broken both by quark masses and by the spontaneous symmetry breaking that gives the pion its small mass. This breaking is relevant for parton densities (and fragmentation functions) but not for the coefficient functions.

2.3 Status

The factorization theorems are established [1] for many processes to all orders of perturbation theory (and not just to the leading logarithm approximation). A certain amount of intuition together with some non-perturbative parts of the proofs indicate that the theorems are valid more generally. The primary difficulties in establishing the theorems and generalizing them are the intricate cancellations of initial- and final-state interactions that is necessary to avoid correlations between the hadrons in hadron-hadron collisions.

Typical processes for which we have factorization theorems are:

- DIS (deep-inelastic scattering): inclusive.
- DIS: semi-inclusive, production of jets, heavy quarks, etc.
- Drell-Yan, i.e., hadron-hadron to high mass muon pairs, etc.
- Hadron-hadron to jets and high p_T hadrons.
- Hadron-hadron to direct photons at high p_T .
- Hadron-hadron to heavy quark inclusive.
- e^+e^- to jets, etc.

In addition, there are theorems on elastic scattering [4], but with complications that I will review in the next section.

3 What don't we know? (At present, from theory)

First, we do not know how to obtain the parton densities from first principles, except for certain moments that correspond to conserved Noether charges. Hence the

parton densities must be obtained from experiment, with the aid of the perturbatively predicted hard scattering coefficients. However, the evolution of the parton densities is predicted perturbatively.

Identical remarks apply to fragmentation functions.

Another area of uncertainty is higher twist physics, that is, power-law corrections to a normal (“twist-2”) factorization theorem that obeys dimensional counting rules for its Q -dependence. (By Q , I mean a measure of the scale of the hard scattering.) To some extent there are real theorems of the factorization type, at least for twist-3 and twist-4.

The difficulties arise in two areas. First, it is hard to separate a non-leading power from the leading power, in view of the logarithmic corrections to the leading power. This problem does not apply to observables that are zero at the twist-2 level; such observables are common in transverse polarization asymmetries. Cases are G_2 in DIS and the single-spin asymmetry in high p_T particle production ($p+p \rightarrow \pi+X$).

Even when one can extract the higher twist observable, it is hard to analyze phenomenologically. The difficulty is that the cross-section is expressed in terms of non-perturbative quantities that in the case of higher twist involve things like quark-gluon correlations in a hadron. Integrals over longitudinal momentum fractions are involved, which make it difficult to extract, for example, a correlation function $C(x_1, x_2)$ as a function of x_1 and x_2 . At the present state of the art, we must treat such non-perturbative functions as unknown theoretically and only obtainable by analysis of experiments.

Of course, there has been much work in these areas, but the important point is that it is hard to do really crisp phenomenology.

There are also results [4,5] for elastic scattering at large t . But these results, from the phenomenological point of view, suffer from the same disadvantage as higher-twist quantities, of involving integrals over light-cone wave functions. Again, it is very hard to extract the wave functions unambiguously from experiment for that precise reason. In addition, the correct form of the factorization theorem is not so simple, with a combination of different mechanisms: In addition to the pure short distance process [4], there is the Landshoff process [5], with its Sudakov suppression.

I do not want to minimize the amount of good work that has been done. But in view of the large effort needed to make twist-2 phenomenology precise, I tend to blanch at what is needed to do corresponding work for higher twist and for (high t) elastic scattering.

4 Fragmentation and quark polarimetry

Another area of unknown quantities is that of fragmentation. The fragmentation functions, i.e., the distribution of hadrons in the fragmentation of partons, are less widely discussed than that parton densities, but are of approximately equal status theoretically. There has been useful phenomenology of the unpolarized case [6], but

the polarized case is almost *terra incognita*.

The basic idea is given by considering semi-inclusive DIS, for which the parton model is summarized in Fig. 3. The full QCD factorization differs only by having higher order corrections to the hard scattering and needing evolution of the parton densities and fragmentation functions. The process is one like $e + p \rightarrow e + \Lambda + X$ or $e + p \rightarrow e + \pi\pi + X$, where one considers the production of a system of one or more hadrons away from the beam fragmentation region. We have a theorem of the form

$$\sigma = \text{pdf} \otimes \text{hard scatter} \otimes \text{fragmentation}, \quad (2)$$

for the leading power.

A number of people [7–9], including myself, have worked on this subject recently. We consider the concept of measuring the polarization state of a quark or a gluon to be both fundamental and interesting.

There are at least three measurements that have been proposed:

- Measure the polarization of a Λ : $q \rightarrow \Lambda + X$. Data has recently become [10] available from the ALEPH collaboration for the case of longitudinal polarization. They indicate a large polarization transfer (tens of percent) at large z — see Fig. 4.
- Handedness of jets [8], for measuring the helicity of a quark or gluon.
- The azimuthal distribution of hadrons around a jet axis, for measuring quark transverse polarization.[9]

The last two were reviewed by Efremov in his talk here [11], particularly as regards the experimental situation, where data in e^+e^- begins to show a possible non-zero effect, at present of marginal significance.

Any non-zero results in this area are of importance, since they can be used as an analyzer of parton polarization, for example in DIS.

5 Where next?

I see at least three areas where progress can reasonably be expected. When planning experiments, it is important to attempt to anticipate these areas, for otherwise the design of experiments to be performed up to a decade ahead will be tied to the current state of theory rather than to the state of theory when the experiments are performed.

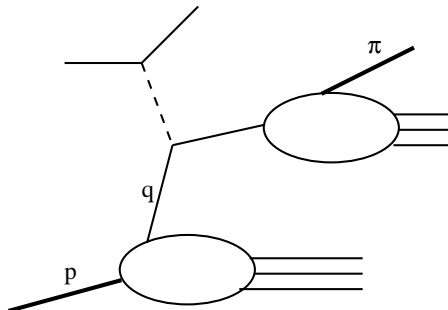


Figure 3: Parton model for semi-inclusive DIS.

- In the short term it is important to get the errors in both theoretical calculations and in QCD phenomenology under better control. Uncertainty in our knowledge both of perturbative quantities (predicted from theory) and of non-perturbative quantities (measured from experiment with the aid of theoretical formulae) are often the most significant source of systematic error in the analysis of data.
- In the long term, we need to find ways of treating non-perturbative QCD in real time (as opposed to the imaginary time that is used in lattice Monte-Carlo calculations). Even without calculations purely from first principles, it would be useful to have better discussing these phenomena.
- A characteristic phenomenon of non-perturbative QCD is, of course, the spontaneous breaking of chiral symmetry. The underlying degree of freedom here is spin, and so we should expect polarized scattering to provide important tests of any future understanding of non-perturbative QCD.

At this conference many of the talks have concerned the measurement of polarized parton densities. These are of direct relevance to the non-perturbative structure of hadrons. For example the spin distributions of anti-quarks, of gluons, and of strange quarks are directly related to the unusual properties of chiral symmetry and of the proton wave function. This particularly applies to the sum rules related to the integrals of the densities over all x .

Moreover a comparison of the transversity distribution of a quark ($\delta q(x)$ or h_1) and the helicity distribution $\Delta q(x)$ directly probes relativistic effects in the wave function. (Normal non-relativistic quark models have this distributions equal.) The azimuthal distribution of quarks in the fragmentation of transversely polarized quarks (the “sheared jet effect”) [4] can only exist if chiral symmetry is broken.

Measurements of all these quantities is very likely to be of great interest in testing any future understanding of non-perturbative QCD.

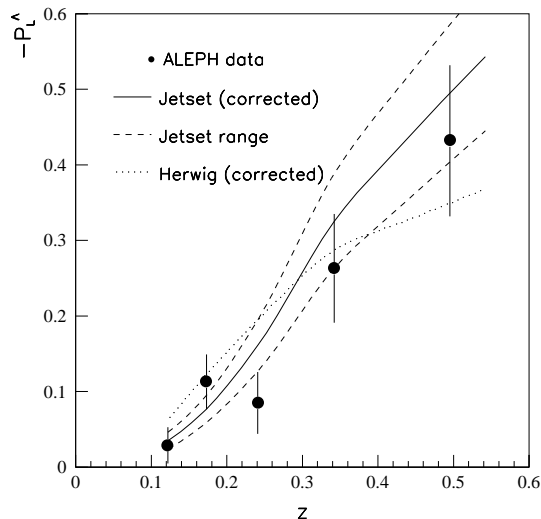


Figure 4: ALEPH result for longitudinal polarization of Λ 's in jets.

6 Conclusions

As is well-known, QCD provides many perturbatively based predictions, but only with the aid of measurable non-perturbative functions, the parton densities and fragmentation functions, etc. However, the present accuracy of the predictions leaves much to be desired; this situation is improving under the stimulus of experimental data.

The most important question in QCD is to find how to treat it non-perturbatively in Minkowski space (i.e., with real time). Since chiral symmetry breaking is an important part of this area, polarized probes should be important.

7 Acknowledgements

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