SPIN AND HARD PROCESSES

P. KROLL

Fachbereich Physik, Universität Wuppertal,
D-42097 Wuppertal, Germany
Email: kroll@physik.uni-wuppertal.de

It is argued that spin is a fundamental aspect of gauge theories at short distances. As a consequence there are characteristic helicity asymmetries in hard inclusive and exclusive reactions of which a few are discussed.

1. Introduction

The jibe, occasionally heard in the late sixties and early seventies, that spin is an inessential complication of elementary particle physics, does not match reality. On the contrary, spin is a fundamental aspect of gauge theories at short distances. In the electroweak theory, based on broken SU(2) × U(1) gauge symmetry, the left-handed quarks and leptons form SU(2) doublets, the right-handed ones singlets while right-handed neutrinos do not exist. These characteristics evidently lead to a wealth of polarization phenomena. Although it is not so obvious, QCD leads to characteristic spin dependences, too. The basis of any calculation within QCD is the factorization of a reaction into a hard parton-level subprocess to be calculated from perturbative QCD and/or QED, and process-independent soft hadronic matrix elements which are subject to non-perturbative QCD and are not calculable to a sufficient degree of accuracy at present. Factorization has been shown to hold for a number of inclusive and exclusive reactions provided a large momentum scale (corresponding to short distances) is present. For other reactions factorization is a reasonable hypothesis as yet. In the absence of a large scale we do not know how to apply QCD and, for the interpretation of scattering reactions, we have to rely upon effective theories or phenom enological models as for instance the Regge pole one.

If an almost massless quark interacts with a number of gluons and/or photons, helicity flips are suppressed since

$$\frac{m_{q}^{2}}{Q^{2}}$$

If
The current quark mass, $m_q$, is of order $M\text{eV}$ while the hard scale, $Q$, is of order $G\text{eV}$. Therefore, to a very good approximation, a quark line will always carry the same helicity, i.e., quark helicity is conserved. Now, to leading-twist order which dominates in hard processes, the helicity of the quark is transferred to its parent hadron to a large extent. From these considerations follows that helicity asymmetries of hadronic processes reflect the route of the quark lines through the process $^1$.

2. Inclusive reactions

As an example let us discuss prompt photoproduction, $AB \rightarrow X$, at large transverse momentum of the produced photon. Two parton-level subprocesses contribute, $g\gamma^* g$ and $gq!q$. In the first process quark and antiquark have opposite helicities according to (1) leading to the parton-level helicity correlation

$$A_{LL}^c (g\gamma^* g) = \frac{d^+(q = +; \bar{q} = +)}{d^+(q = +; \bar{q} = +) + d^+(q = +; \bar{q} = -)} = \frac{\gamma^2}{\gamma^2 + \delta^2};$$  \hspace{1cm} (2)

In the second process, the correlation of the incoming gluon and quark helicities reads (the relevant Feynman graphs are shown in Fig. 1)

$$A_{LL}^c (gq!q) = \frac{\delta^2 \gamma^2}{\gamma^2 + \delta^2};$$  \hspace{1cm} (3)

where $\delta$ and $\gamma$ are the subprocess Mandelstam variables. We note that (3) holds for $gq!gq$ and $q!q$ as well. The subprocess helicity correlations lead to characteristic differences in the proton-antiproton helicity correlations of, say, $p \bar{p} \rightarrow X$, where the $g\gamma^*$ subprocess dominates, and $pp \rightarrow X$ which is under control of $gq!q^2$.  

Figure 1. Lowest order Feynman graphs for Compton scattering on quarks. The wavy lines represent either gluons or photons.
3. Leading-twist factorization in hard exclusive processes

For asymptotically large $s$, $t$, $u$ the dominant (leading-twist) contribution to an exclusive reaction is produced by the valence quarks of the involved hadrons. The quarks move approximately collinear with their parent hadrons and participate in the hard scattering while the soft physics is encoded in distribution amplitudes, $(x_1; \cdots ; x_n)$, representing the momentum distribution of the quarks in a hadron. For Compton scattering, for instance, the hard process is $qqq \rightarrow qqq$, see Fig. 2, and the Compton amplitude is given by the convolution

$$M = H \ast ;$$

where $H$ is the parton-level subprocess amplitude.

To leading-twist accuracy the helicities of the valence quarks, conserved in the hard process, sum up to the parent’s hadron helicity, there is no quark orbital angular momentum, $L_q$, involved. Configurations where the hadron helicity differs from the sum of the valence quark helicities which obviously require $L_q \neq 0$, are of higher-twist nature and are suppressed by inverse powers of the hard scale, $t(u)$, as compared to the leading-twist contribution. Hence, to leading-twist order, the conservation of quark helicity converts into hadronic helicity conservation for all hadrons that are connected by light quark lines. Experimentally however hadronic helicity conservation is violated for hard scales of the order 10 GeV$^2$; the ratio $\sigma^p$ to non-$\sigma$ amplitudes is typically 20–30%. Examples for reactions where such violations have been observed are the Pauli form factor of the proton, the polarization in proton-proton elastic scattering or the charmonium decays $c(\rightarrow p\pi)$ and $J=$. It is to be stressed that, with very few exceptions, the absolute magnitudes of observables calculated to

$^a$The most prominent example is the transition form factor. The process is special in so far as the handbag and the leading-twist factorization fail together (see Sect. 4).
leading-twist accuracy, are way below experiment. The observation that a number of hard processes respect the dimensional counting rules is not sufficient to establish the dominance of the leading-twist mechanism and to rule out other explanations (see, for instance, Ref. 6). Scaling violations due to perturbative QCD, namely the running of \( \alpha_s \) and the evolution of the distribution amplitudes, have to be observed as well. In contrast to deep inelastic lepton-nucleon scattering there is no experimental evidence for scaling violations in exclusive reactions.

4. The handbag factorization

For hard exclusive processes there is an alternative scheme, the handbag factorization (see Fig. 2) where only one parton participates in the hard subprocess (e.g. \( q \rightarrow q \) in Compton scattering (CS)) and the soft physics is encoded in generalized parton distributions (GPDs). The handbag approach applies to deep virtual exclusive scattering (e.g. DVCS) where the incoming photon has a large virtuality, \( Q^2 \), while the squared invariant momentum transfer, \( t \), is small. It also applies to wide-angle scattering (e.g. WACS) where \( Q^2 \) is small while \( t \) (and \( u \)) are large.

Since neither the generalized parton distributions nor the distribution amplitudes can be calculated within QCD at present, it is difficult to decide which of the factorization schemes provides an appropriate description of say, WACS at \( t' \sim 10 \text{ GeV}^2 \). The leading-twist factorization probably requires larger \( t \) than the handbag one since more details of the hadrons have to be resolved. Recent phenomenological and theoretical developments support this conjecture 7. The ultimate decision which of the factorization schemes is appropriate at scales of the order of 10 GeV\(^2\) is to be made by experiment.

As an example of the handbag contribution let me discuss WACS 8,9. One can show that the subprocess Mandelstam variables \( s \) and \( t \) approximately equal the corresponding ones for the full process, Compton scattering on protons. The active partons, i.e. the ones to which the photons couple, are approximately on-shell, move collinear with their parent hadrons and carry a momentum fraction close to unity, \( x_{j';j} \sim 1 \). Thus, like in DVCS, the physical situation is that of a hard parton-level subprocess, \( q \rightarrow q \), and a soft emission and reabsorption of quarks from the proton. The helicity amplitudes for WACS then read

\[
M_{q^+;s,t} = 2 c_{\text{em}} T_{q^+;s,t} (R_V(t) + R_A(t)) + T_{q^+;s,t} (R_V(t) - R_A(t));
\]  

(5)
\[ M^0(s; t) = \sum_{n=1}^\infty t_n \left( T^0 + (s; t) + T^0(s; t) \right. \]

\[ R_T(t) \]

\[ \text{; denote the helicities of the incoming and outgoing photons, respectively. The helicities of the protons in } M \text{ and quarks in the hard scattering amplitudes } T \text{ are labeled by their signs. The subprocess amplitudes have been calculated to next-to-leading order of perturbative QCD. The form factors } R_1 \text{ represent } l=x-m \text{ moments of GPDs at zero skewness. } R_T \text{ controls the proton helicity } \lambda \text{ amplitude while the combination } R_V + R_A \text{ is the response of the proton to the emission and reabsorption of quarks with the same helicity as } T \text{ and } R_V + R_A \text{ that one for opposite helicities. The identification of the form factors with } l=x-m \text{ moments of GPDs is possible because the plus components of the proton matrix elements dominate as in DIS and DVCS.} \]

\[ \text{In order to make predictions for Compton scattering a model for the soft form factors or rather for the underlying GPDs is required. A first attempt to parameterize the GPDs } H \text{ and } \tilde{H} \text{ at zero skewness reads} \]

\[ H^a(x; 0; t) = \exp \left( a^2 \frac{1}{2x} x q_a(x) \right); \]

\[ \tilde{H}^a(x; 0; t) = \exp \left( a^2 \frac{1}{2x} x q_a(x) \right); \]

\[ (6) \]

where \( q(x) \) and \( q(x) \) are the usual unpolarized and polarized parton distributions in the proton. The only free parameter is \( a \), the transverse size of the proton and even it is restricted to the range of about 0.8 to 1.2 GeV\(^{-1}\) for a realistic proton. Note that a mainly refers to the lowest Fock states of the proton which, as phenomenological experience tells us, are rather compact. The model (6) is designed for large \( t \) which, forced by the Gaussian in (6), also implies large \( x \). The model can be motivated by overlaps of light-cone wave functions and it may be improved in various ways. For instance, one may treat the lowest Fock states explicitly or take into account the evolution of the GPDs.

\[ \text{From the GPDs } H \text{ one can calculate the proton's Dirac and Compton } (R_V) \text{ form factors by taking appropriate moments} \]

\[ F_1 = \frac{1}{e_q} \int dx \, H^q(x; 0; t); \quad R_V = \frac{1}{e_q} \int dx \, H^q(x; 0; t); \]

\[ (7) \]

The axial vector form factor and \( R_A \) are analogously related to the GPD \( \tilde{H} \). Evaluation of the form factors reveals that the scaled form factors \( t^2 F_1 \) and \( t^2 R_1 \) exhibit broad maxima which in \( k \) dimensional counting in a range of \( t \) from, say, 3 to about 20 GeV\(^2\). For very large values of \( t \), well
above 100 GeV, the form factors gradually turn into a \(1/t^4\) behaviour; this is the region where the leading-twist contribution takes the lead.

The Pauli form factor, \(F_2\), and its Compton analogue \(R_T\) contribute to proton helicity 4 \(q^2\) matrix elements and are related to the GPD \(E_F^2 = \int_{-1}^{1} \frac{dx}{x} E(x,t)\):

\[
F_2 = \sum_q Z_1 e_q^2 \int_{-1}^{1} \frac{dx}{x} E^q(x,0;0) ; \quad R_T = \sum_q Z_1 e_q^2 \int_{-1}^{1} \frac{dx}{x} E^q(x,0;0) \quad (8)
\]

The overlap representation of \(E^{11}\) involves components of the proton wave functions where the parton helicities do not sum up to the helicity of the proton. The associated form factors are therefore suppressed by at least \(\frac{1}{1-t}\) compared to \(F_1\) and \(R_{V\Lambda}\). An estimate of the size of \(R_T\) can be obtained by simply assuming that \(R_T = R_V\) roughly behaves as its experimentally known electromagnetic counterpart \(F_2 = F_1\).

The predictions for the Dirac form factor and the Compton cross section are in fair agreement with experiment. The approximate \(s^6\)-scaling behaviour of the Compton cross section observed experimentally \(12\) is related to the broad maxima in the scaled form factors exhibited in the handbag approach \(6,10\) also provide interesting predictions for polarization observables in Compton scattering \(6,10\) among them the helicity correlation \(A_{LL}\) which I already discussed in the context of inclusive reactions in Sec. 2. Within the handbag approach, the correlation between the initial state photon and proton helicities reads \(6,10\)

\[
A_{LL} = \frac{A_{LL}^R A}{R} ;
\]

where the \(q^1 q\) subprocess correlation \(A_{LL}^R\) is given in \(3\). The latter is diluted by the ratio of the form factors \(R_A\) and \(R_V\) (as well as by other corrections) but its shape essentially remains unchanged. The predictions for \(A_{LL}\) from the leading-twist approach drastically differ from the handbag ones. For \(7 < 110\) negative values for \(A_{LL}\) are found for all but one examples of distribution amplitudes \(13\). The JLab E99-114 collaboration \(14\) has reported a first, yet preliminary measurement of \(A_{LL}\) at a cm s. scattering angle of 120 which seems to be in agreement with the prediction from the handbag while the leading-twist calculations fail badly. A measurement of the angular dependence of \(A_{LL}\) would be highly welcome for establishing the handbag approach.

The handbag mechanism also applies to wide-angle photo- and electroproduction of mesons \(15\). It turns out that, for the production of pseudoscalar mesons, \(P\), the \(q^1 P q\) subprocess helicity correlation coincides with \(3\). Therefore, \(A_{LL}\) for the full process is very similar to that of
5. Fermion polarizations

The polarization of the proton in two-body reactions is notoriously difficult to calculate within QCD. It requires proton helicity $\uparrow$ and phase differences between $\uparrow$ and non-$\uparrow$ amplitudes. Both the ingredients are, in general, difficult to produce. Despite this, the proton polarization in hard processes is often substantial, e.g., in proton-proton elastic scattering. As an example, let me consider WACS again. In the leading-twist approach hadronic helicity conservation forbids proton helicity $\uparrow$ while phases are generated by on-shell going subprocess propagators. Thus, to leading-twist accuracy, the proton polarization is zero. In the handbag approach, on the other hand, proton helicity $\uparrow$ is connected with the form factor $R_T$ and phases appear in the subprocess to next-to-leading order of perturbative QCD. Although non-zero, the proton polarization amounts only to a few percent.

Another example of a fermion polarization is the beam asymmetry, $A_L$, in $ep!ep$, which measures the imaginary part of the interference between the amplitudes for longitudinal and transversal polarizations of the virtual photon. The combination of Compton and Bethe-Heitler contribution leads to a characteristic dependence of $A_L$ on the azimuthal angle which agrees with experiment.

6. Summary

In gauge theories at short distances the helicity state of an elementary particle (leptons, quarks) plays a fundamental role as its other quantum
numbers. The properties of gauge theories lead to characteristic helicity asymmetries which may allow for a discrimination between the leading-twist mechanism and power corrections (as for instance the handbag) in exclusive processes or between different subprocesses in inclusive ones. The helicity correlation \( A_{LL} \) is a particularly interesting observable because, first, its corresponding subprocess correlation is large and, secondly, it is often only mildly affected by the soft physics. Opposed to it is the polarization of the proton which is extremely sensitive to the soft physics and therefore difficult to predict.

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