I briefly review: (a) some recent developments in the theory of hard scattering in QCD with polarized beams, and (b) coherent hard diffraction (that is, hard scattering in diffractive events, with the Pomeron behaving in an apparently point-like fashion).

1. Polarized Hard Scattering

Interest in polarized hard scattering has increased recently. An important reason is that it appears feasible to use polarized protons in the Relativistic Heavy Ion Collider at Brookhaven\(^\text{1}\). The aim is an energy of 200+200 GeV at a luminosity of \(2 \times 10^{32}\) cm\(^{-2}\) s\(^{-1}\) and a polarization of 70% for each beam. So the theoretical study of polarization in perturbative QCD is no longer academic. Polarized hard scattering probes the spin-dependence, and hence the chiral properties, of both the proton wave function and quark fragmentation, as is particularly evident in recent work.

Rather intriguing are the measurements of spin asymmetries in pion production at large \(x_T\) in collisions of transversely polarized protons with unpolarized hadrons. Leading twist QCD predicts no asymmetry, so the large measured asymmetries\(^\text{2}\) indicate large higher twist effects.

2. Twist 3

Qiu and Sterman\(^\text{3}\) have recently shown that the first non-leading twist contributions in hadron-hadron scattering (to make jets or high \(p_T\) photons etc) can be fitted into the factorization framework. They and other investigators, like Jaffe and Ji\(^\text{4}\), have looked at the various contributions.

One particularly interesting contribution involves a quark-gluon correlation function for the polarized proton. Qiu and Sterman argue that a pole in the hard scattering picks out a derivative of the correlation function, and thereby enhances

\(^{1}\)Presented at annual meeting of Division of Particles and Fields of American Physical Society, Fermilab 10–14 November 1992.
the contribution at large parton $x$. The flavor systematics appear appropriate to the pion production results.

In general, it is rather difficult to extract the quark-gluon correlation function in a model-independent way, since there are two longitudinal momentum fractions involved on the polarized side, and the kinematics of the hard scattering final state can only determine the sum of these momentum fractions.

3. Spin-dependence of Fragmentation

We now return to leading twist. To treat deep-inelastic scattering, for example, with a polarized proton, one must equip the parton entering the hard scattering with a helicity density matrix.

Transverse spin is particularly interesting because it corresponds to off-diagonal terms in the helicity density matrix. Unfortunately, the usual hard scattering coefficient is diagonal in helicity, because of helicity conservation for massless quarks, which is true to all orders of perturbation theory. Hence single transverse spin asymmetries are zero in leading twist for inclusive deep inelastic scattering, etc.

We can evade this result by performing a spin-sensitive measurement on the outgoing quark jet. Nachtmann was the first to suggest measuring the spin of a jet, for the longitudinally polarized jets produced in neutrino scattering. His idea was recently rediscovered by Efremov, Mankiewicz and Tornqvist. They define a ‘handedness’ by $H \propto \epsilon_{ijk}k_1^ik_2^jk_3^k$. Here $k_1$, $k_2$ and $k_3$ are 3-momenta of, for example, two leading particles and the jet itself, as measured in the center-of-mass of the hard scattering. The average handedness is equal to the helicity $\lambda$ of the parton initiating the jet times a nonperturbative analyzing power. The analyzing power must be measured, of course, but it is universal between different processes.

One can apply the same idea to jets initiated by transversely polarized quarks, as shown by Efremov et al. and by myself and collaborators. There, we consider $\epsilon_{ijk}s^ik_1^lk_2^k$, which is a scalar. Here $s$ is the transverse spin of the quark. Notice that it is now only necessary to measure two outgoing momenta: two leading hadrons of opposite charges, or one leading hadron and the jet momentum. This is in distinct contrast to the decay of a real particle, where it would be necessary to do a three body measurement.

This quantity then allows a $\cos \phi$ dependence on the azimuthal angle between the transverse spin of the quark and normal to the plane of two leading particles. Again there is a nonperturbative analyzing power to be measured. Many possibilities now appear. There should be twist 2 asymmetries in deep inelastic scattering for an unpolarized electron on a transversely polarized proton, with measurement of the current quark jet, and in jet production in singly polarized proton-proton scattering. There can also a jet-jet correlation in $e^+e^-$ annihilation at LEP.

A simple model for nonperturbative QCD is the Georgi-Manohar sigma model of quarks and pions. Ladinsky and I have done a calculation of the
transverse spin asymmetry of quark fragmentation in this model. We find a large asymmetry that relies on chiral symmetry breaking and large imaginary parts in nonperturbative strong interactions.

4. Coherent Hard Diffraction

I now describe recent work with Frankfurt and Strikman[11, 12] on what we call ‘coherent hard diffraction’. Defining the term will explain what we are doing. Diffraction is a process like \( p + p \rightarrow p + X \) where one of the initial hadrons is almost undeflected and retains a fraction \( 1 - \xi \) of its initial momentum, with \( \xi \) close to zero. The mass-squared of the \( X \) system is \( s' = \xi s \). Diffraction is generally attributed to Pomeron exchange between the diffracted proton and \( X \); effectively, \( X \) is the result of a Pomeron-proton collision. UA8[13] has data at the CERN collider with \( \sqrt{s'} \) in the 130 to 200 GeV range, and \( \sqrt{s} = 630 \) GeV. They then look for jets in \( X \), which gives an example of ‘hard diffraction’.

The simplest model for hard diffraction is due to Ingelman and Schlein[14]. They assume that there are parton distributions in the Pomeron, and apply the usual hard scattering formalism. With a reasonable ansatz for the gluon distribution, one gets an appropriate size to fit the UA8 data, and so UA8 make at least a rough measurement[13] of the gluon distribution in a Pomeron.

However, there is no proof of the Ingelman-Schlein model. Indeed, Frankfurt and Strikman[11] made a calculation of hard diffraction with two gluon exchange as a model for the Pomeron. They found a leading twist contribution where all the momentum of the Pomeron goes into the jets. Experimentally, this looks as if there is a \( \delta(x-1) \) term in the gluon distribution in the Pomeron. This was predicted in advance of the UA8 data, and the data, after allowing for smearing by gluon radiation and by the detector, etc, shows strong evidence for such a delta function, in addition to the Ingelman-Schlein term.

This process we call ‘coherent hard diffraction’. As I have shown, in collaboration[12] with Frankfurt and Strikman, it results from a breakdown of the factorization theorem. The proof of the factorization theorem requires an inclusive sum over the spectators to the hard scattering, but the diffractive condition on the final state prohibits the inclusive sum.

One striking part of the breakdown of factorization is that the delta function term is not universal. As shown by a calculation by Donnachie and Landshoff[15], coherent hard diffraction in deep inelastic lepton-hadron scattering is higher twist.

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Note: Twist-3 parton densities were earlier considered by Shuryak and Vainshtein\[16\]. Another way of probing the polarization of a jet is from the decays of Λs in the jet\[17, 18\].

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