Exclusive Hadronic Reactions at High $Q^2$ (90°) and Polarization Phenomena, An Experimental Proposal

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Abstract.

Arguments are presented for the expected behaviour of $\pi N \rightarrow \pi N$ scattering and the $\bar{p} p \rightarrow \pi^- \pi^+$ reaction at high energy and large scattering angles. The annihilation reaction has close to maximal asymmetry ($\approx 1$) for $p_{lab} \lesssim 2.2$ GeV/c. As will be presented for fixed (90°) angle this large asymmetry will not become zero but will start to oscillate with energy at higher energies and large $Q^2$ when perturbative QCD becomes applicable. This is due to the energy dependence of a QCD phase difference between the independent quark-quark scattering (Landshoff) and short-distance processes at high but not asymptotic energies. A consequence of the existence the Landshoff process is that even if helicity is conserved at the quark level ($m_q = 0$ MeV), helicity does not have to be conserved on the hadronic level. We will discuss the implications for spin observables in $pp$ elastic scattering and argue that these QCD phenomena are easier to explore theoretically in the $\pi N \rightarrow \pi N$ scattering and/or in the crossed channel reaction $\bar{p} p \rightarrow \pi^- \pi^+$ where the analysis is simpler because these two processes have only two helicity amplitudes.

1 Introduction

For short-distance perturbative QCD exclusive hadronic scattering processes the quarks are all connected by high $Q^2$ gluons and all quark propagators are far off-shell [1].

Figure 1: Illustrations of contributions to $\pi N \rightarrow \pi N$ scattering amplitudes. On the left an example of a short-distance contribution to $f_{SD}$. On the right a contribution to the Landshoff amplitude $f_{L}$. The dashed lines signify that this quark-quark scattering does not have to occur in the same plane as the other scattering.
This means the short distance amplitudes \( f_{SD} \) are all real and no polarization effects are expected. However, the Landshoff amplitudes \( f_L \) will contribute to the same exclusive hadronic scattering processes \( [2] \). In the \( f_L \) amplitudes the hard gluons are also at high \( Q^2 \) but the two independent quark-quark scatterings can take place in two parallel scattering planes leading to the same final hadrons. The distance between these two independent quark-quark scatterings are determined by the sizes of the hadrons involved. The only requirement is that after the hard (high \( Q^2 \)) scattering the final quarks (antiquarks) move parallel with roughly the same speed to be able to form the final hadrons as illustrated for \( \pi N \rightarrow \pi N \) scattering in Fig.1. The distance between the two quark-quark scatterings implies one has a relative angular momentum which can couple to the spin and give for the hadronic reaction at least a \( L \cdot S \) amplitude. Such an amplitude violates helicity conservation on the hadronic level \( [4] \). Or said differently, since the Landshoff amplitudes contain soft QCD processes where a propagator is (almost) on-shell (Sudakov form factors), called "the Landshoff pinch" in the review by Mueller \( [3] \), the amplitudes \( f_L \) will in general be complex. As a consequence we will observe polarization phenomena in hadronic reactions.

2 Asymmetries

2.1 The Reaction \( \bar{p}p \rightarrow \pi\pi \)

Figure 2: (a) An example of short-distance QCD diagram to order \( \alpha_s^4 \) for the process \( \bar{p}p \rightarrow \pi\pi \). The diagram has an \( s^{-3} \) dependence. (b) An example of diagrams for large-angle Landshoff process for the same reaction of order \( \alpha_s^3 \). The timelike gluon and one quark are off-shell and the diagram gives an \( s^{-5/2} \) behavior when we neglect radiative corrections.

First let us concentrate on the \( \bar{p}p \rightarrow \pi^-\pi^+ \) reaction which has a large analysing power, \( A_{0n} \approx 1 \) for \( p_{lab} \lesssim 2.2 \) GeV/c \( [5, 6, 7] \) as discussed at this workshop \( [8, 9] \). If helicity is conserved on the hadronic level at very high energy, then \( A_{0n} \) should be zero at these energies. This is correct only if the short distance amplitude \( f_{SD} \) illustrated in Fig. 2a acts alone. However, as discussed in Ref. \( [10] \), the Landshoff amplitude, \( f_L \) illustrated in Fig. 2b, will contribute as well. Including the radiative corrections \( f_L \) will be at least of order \( \alpha_s^3 \) like \( f_{SD} \) illustrated in Fig. 2a, but \( f_L \) will fall off with increasing energy like \( s^{2.85} \), i.e., slower than \( f_{SD} \).

The elementary quark-quark scattering amplitude has an energy-dependent phase, as inferred by Ralston and Pire \( [11] \) and calculated in perturbative QCD by Sen \( [12] \). Its analytic form is

\[
\Phi \sim \frac{\pi}{6} \ln \ln (Q^2/\Lambda^2) \tag{1}
\]

where \( \Lambda \approx 100 \) MeV. Ralston and Pire used this phase in their phenomenological hadronic Landshoff amplitudes to describe the energy oscillations of the scaled \( pp \) elastic \( 90^\circ \) cross section. They needed a
constant $a \approx 50$ in front of the double log instead of $\pi/6$ of eq.(1) to reproduce the observed (see Fig. 3) period of the energy oscillations in the scaled $pp$ elastic $90^\circ$ scattering. Botts and Sterman analysed this phase factor in hadronic reactions and found the expression [13]

$$\Phi = a \ln \left( \frac{\ln s/\Lambda^2}{\ln 1/(b \Lambda)^2} \right) + \text{constant},$$

(2)

where the constant $a$ in perturbative QCD is $\pi/6$, and $\Lambda = 100$ MeV as before. The impact parameter $b$ can be thought of as the average distance between the independent quark-quark scatterings. It has the following energy dependence [13]

$$b \Lambda = (\sqrt{s}/\Lambda')^{-\tau}$$

(3)

where $\tau \approx 0.7$ for three flavors of quarks. As discussed by Botts and Sterman [13, 14] the phase eq.(2) should become independent of energy at asymptotic energies ($s \to \infty$).

Figure 3: The elastic $pp$ cross section at $90^\circ$ scaled by $s^{10}$ as a function of energy. Figure taken from Carlson et al. [10].

2.2 Elastic $pp$ Scattering

If we apply these ideas to $pp$ elastic scattering we can show that not only the oscillations in the scaled cross section at $90^\circ$, see Fig. 3, can be reproduced (see here Ref. [11]), but also the spin-correlation observable $A_{nn}$ at $90^\circ$ can be described [10]. The phenomenological arguments leading to these results are following Ref. [10]: For elastic $pp$ scattering the five helicity amplitudes $M_i$ ($i = 1, \ldots, 5$) are of the form (the energy scale is factored out in $\phi_i$):

$$\phi_i \propto s^{-4} M_i = s^{-4} \left( B_i + C_i s^{0.2} e^{i[\Psi_i + \delta_i]} \right),$$

(4)

where $B_i$, which originates from the short distance $pp$ amplitude $M_{SD}$, $C_i$ from the Landshoff amplitude $M_L$, and $\delta_i$ are real constants. The phase is deduced from eqs.(2) and (3) to be

$$\Psi_i = a \ln \left( \frac{\ln(s/\Lambda^2)}{\ln(s/\Lambda_i^2)} \right).$$

(5)

The energy dependence of $A_{nn}$ at $90^\circ$ is then understood to be a "beating" of the different energy-periods in the phases of the helicity amplitudes above [10]. With the interplay of the two amplitudes, $M_{SD}$ and $M_L$, it is not difficult to reproduce the spin observables in $pp$ elastic scattering. However, since $pp$ elastic scattering has in general five helicity amplitudes, there is too much freedom in fitting data. Only for $90^\circ$ c.m. scattering do the expressions simplify since $\phi_5 = 0$ and $\phi_4 = -\phi_3$ so we have only three independent helicity amplitudes.
3 Ideas for experimental proposals

To examine if this phenomenological analysis is reasonable, it would be preferable to test the predictions in the two reactions $\pi N \rightarrow \pi N$ and $\bar{p}p \rightarrow \pi\pi$. Each of these reactions are described by only two helicity amplitudes, the helicity non-flip $f_{++}$ and the helicity flip $f_{+-}$ amplitude. Furthermore, these measurements can be done at existing facilities like AGS at Brookhaven National Laboratory or at Fermilab, and certainly at the proposed facilities like SuperLEAR or KAON.

In terms of these two helicity amplitudes the cross section and the asymmetry are given as

$$\frac{d\sigma}{d\Omega} = |f_{++}|^2 + |f_{+-}|^2 \quad \text{and} \quad A_{0n} = 2\Im(m(f_{++}^* f_{+-}))/\left(\frac{d\sigma}{d\Omega}\right).$$

For the $\bar{p}p \rightarrow \pi\pi$ reaction the short-distance real amplitude $f_{SD}$ contributes only to $f_{+-}$, whereas the Landshoff amplitude $f_L$ contributes to both helicity amplitudes. The energy dependences of the two amplitudes are as follows:

$$f_{SD} \propto s^{-3} \quad \text{and} \quad f_L \propto s^{-2.85}$$

meaning the Landshoff amplitude will also dominate at high enough energies for these reactions.

For both reactions some data already exist for the scaled cross sections $s^8 \frac{d\sigma}{d\Omega}$ at $90^\circ$. For the reaction $\bar{p}p \rightarrow \pi^-\pi^+$ data exist for momenta up to $p_{lab} = 6.2$ GeV/c [13, 14] as shown in Fig. 4 taken from Ref. [10]. The elastic $\pi N \rightarrow \pi N$ scattering at $90^\circ$ have been measured for momenta as high as 30 GeV/c [17]. In Fig. 5 we show the scaled cross section data for the $\pi N \rightarrow \pi N$ scattering, a figure taken from G. Blazey’s thesis [18]. Unfortunately the highest energy measurement at $p_{lab} = 30$ GeV/c has uncertainties too large to be useful in this discussion and is not shown in this figure. As is clear from Figs. 4 and 5, a few measurements at different energies with reasonable statistics are needed to establish the possible oscillatory pattern of the scaled cross section.

Figure 4: The cross section for $\bar{p}p \rightarrow \pi^-\pi^+$ at $90^\circ$ scaled by $s^8$ as a function of $\ln s$. Figure taken from Ref. [10].
Figure 5: The cross section for elastic $\pi N \rightarrow \pi N$ scattering at $90^\circ$ scaled by a factor $s^8$. Figure taken from Ref. [18].

The question being asked is if both of these scaled cross sections oscillate with energy similar to what is observed for $pp$ elastic scattering, see Fig.3. If this is found to be the case then a further confirmation of the ideas presented here would be to see similar energy oscillations in $A_{0_n}$ for the same two reactions. Experimentally, the annihilation reaction might be better since the asymmetry at low energies $p_{lab} \approx 2$ GeV/c is very large [5, 6, 7]. However, we do expect the geometric hadronic impact parameter ideas used to explain this large asymmetry [6, 9] to break down when the perturbative QCD regime of exclusive hadronic reactions is reached at higher energies [10]. The onset of the perturbative QCD regime may be signaled by a significant change in the energy and angular variation of the asymmetry, for example, the large $A_{0_n}$ at $90^\circ$ will become smaller and start to oscillate with increasing energy if the QCD phenomenology outlined above is reasonable.

This work is supported in part by NSF grant no. PHYS-9006844.

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