Hard Exclusive Electroproduction of $\pi^+\pi^-$ Pairs

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Much of our current knowledge of the quark-gluon structure of the nucleon comes from inclusive and semi-inclusive deep inelastic scattering experiments. In this kind of experiments, the nucleon target is probed by a photon with a wavelength smaller than the size of the nucleon, in order to resolve its internal structure composed by quarks and gluons. These two types of particles are generically referred to as partons. From the analysis of such reactions, information about the nucleon's overall shape (via the Form Factors) and its internal constituents (via the Parton Distribution Functions) has been extracted. However, our understanding of quark-gluon dynamics can be extended considerably by measurements sensitive to the **Generalized Parton Distributions** (GPD) which also describe the dynamical correlations between partons with different momenta. In particular, by measuring the GPDs the still unknown orbital angular momentum of quark and gluons may be extracted. Unfortunately, even though the GPDs theoretical formalism is ready, these quantities cannot be evaluated by *first principles*. They should somehow be extracted from the experimental data. Experimentally, GPDs can be investigated through the analysis of hard exclusive processes, which are processes where the target is probed by photons with wavelength smaller of 10^{-13} cm, and is left intact after the interaction, and all the particles in the final state are measured.

In order to provide new constraints on the GPDs, the hard exclusive electroproduction of two oppositely charged pions ($\pi^+\pi^-$) has been studied with the HERMES spectrometer. The 27.6 GeV HERA positron beam at DESY was scattered off protons, while emitting a photon which interacts with the target. The process is diagrammatically shown in Fig. 1. Each diagram describes qualitatively how the incoming photon (waved line) interacts with the target, which is represented by the bottom blobs of the panels. The above interaction, going through the emission and the subsequent absorption of either a quark (straight line) or a gluon (twisted line) from the proton, in technical terms is referred to either as two-quark or two-gluon exchange, respectively. The partons produced in the interaction subsequently interact with each other (smallest blobs) forming the $\pi^+\pi^-$ pair. This last process of the interaction may also go through the formation of an unstable particle (a resonance) which subsequently decays into two pions, and we refer to it as a resonant production. Instead, when pions are produced without going through any resonance, the production channel is referred to as non-resonant. The two-quark exchange mechanism gives rise to pion pairs with either an odd value of the total angular momentum J ($J = 1, 3...$), or an even value ($J = 0, 2...$). The competing two-gluon channel gives rise to pion pairs with odd J only. The $\pi^+\pi^-$ pairs are dominantly produced in P-wave ($J = 1$) state.

In order to study the relative importance of the various graphs shown in Fig. 1, an observable was identified that is particularly sensitive to the interference between the various processes. It is important to be sensitive to interference effects as otherwise the observable is entirely driven by the single most important graph in the two-pion production process (diagram a). For this purpose, the Legendre moment $\langle P_1(\cos\theta)\rangle$ has been measured. The Legendre moment of order n is namely the Legendre Polynomial $P_n(\cos\theta)$ of the same order weighted by the differential cross section, and is given by

$$\langle P_n(\cos\theta)\rangle^{\pi^+\pi^-} = \frac{\int_{-1}^{1} d\cos\theta\, P_n(\cos\theta)\, \frac{d\sigma^{\pi^+\pi^-}}{d\cos\theta}}{\int_{-1}^{1} d\cos\theta\, \frac{d\sigma^{\pi^+\pi^-}}{d\cos\theta}} \,, \tag{1}$$

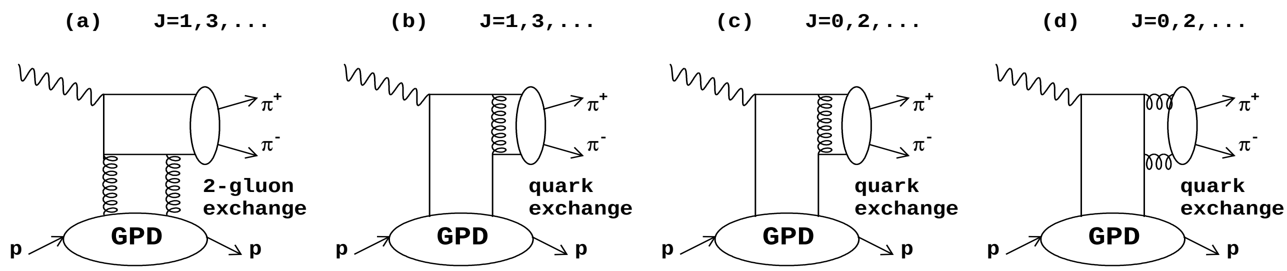

FIG. 1: Relevant diagrams for the hard exclusive reaction $e^+p \to e^+p\,\pi^+\pi^-$. Gluon exchange (*a*) gives rise to pions with odd total angular momentum J, while the quark exchange mechanism (*b,c,d*) gives rise to pions in states with either odd or even J.

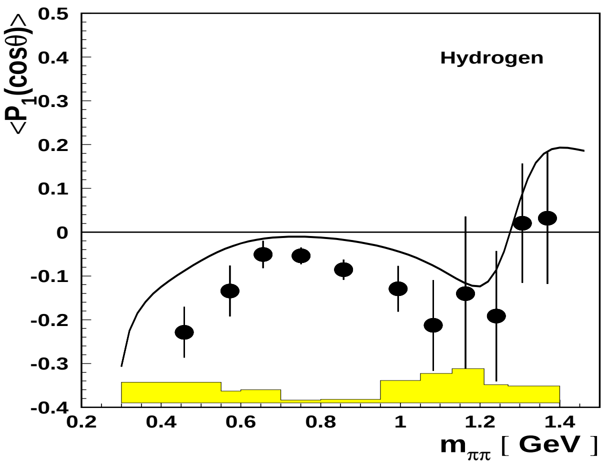

FIG. 2: The $m_{\pi\pi}$-dependence of the Legendre moment $\langle P_1 \rangle$ for hydrogen. Predictions including both the $q\bar{q}$ and two-gluon exchange mechanism contributions (solid curve) at the kinematical conditions similar to the experimental data ones are shown. The systematic uncertainty is represented by the error band.

where θ is a particular scattering angle of the π^+ meson. In particular, $\langle P_1 \rangle$ is sensitive only to P-wave interference with S and D-waves ($J = 0$ and $J = 2$ respectively).

In order to analyze the data which likely belong to the studied process, we selected the events where there are exactly three tracks. One track has to be related to the initial positron which is scattered off the target while emitting a photon. Instead, the remaining two tracks have to be related to the produced two oppositely charged pions. What is still missing in our sample is detecting the last particle in the final state of the analyzed process: the proton. Anyway, within this preliminary selection, events when the target breaks up into several other undetected particles may be also present. How can we filter out the events where the proton is the only undetected particle? At this stage, a basic physical law helps us: by using the energy-momentum conservation law we can finally select from the initial selection the events which have the proton as the only undetected particle. Therefore, with this procedure, we are able to analyze only the events we are interested in, that is the events which have in the final state one positron, one proton, and two oppositely charged pions only.

In this analysis, we have measured the moment $\langle P_1 \rangle$ for different values of the mass of the pion pair system, referred to as $m_{\pi\pi}$. The $m_{\pi\pi}$-dependence of $\langle P_1 \rangle$ for exclusive $\pi^+\pi^-$ production off protons is presented in Fig. 2. The values for $\langle P_1 \rangle$ differ significantly from zero, and depend strongly on $m_{\pi\pi}$. How to interpret our data?

We know that the ρ^0 meson with $J = 1$ may decay into two pions in the entire $m_{\pi\pi}$ range with a huge peak at $m_{\pi\pi} \approx 0.770$ GeV. Instead, the particle f_2 meson with $J = 2$ can decay only for $m_{\pi\pi}$ values larger than ≈ 1.100 GeV, with a peak at $m_{\pi\pi} = 1.270$ GeV. Also, pion pairs may be produced without passing through any resonance, and in this case the energy favors the formation of $\pi^+\pi^-$ in a state with $J = 0$, and with a production peak at small values of $m_{\pi\pi}$. Now we can try to interpret our data, while taking into account the known location of the dominant resonances mentioned above. At small $m_{\pi\pi}$ values, the non-zero $\langle P_1 \rangle$ moment is interpreted as originating from the interference between the lower tail of the ρ^0 meson ($J = 1$) with the non-resonant $\pi^+\pi^-$ in $J = 0$ state. At $m_{\pi\pi}$ values around 0.770 GeV, the absolute value of this quantity shows a minimum which is explained in terms of the overwhelming dominance of ρ^0 meson production in the denominator of the moment expression. At larger invariant mass, the size of $\langle P_1 \rangle$ increases again, being due to the interference of the ρ^0 with the non-resonant $\pi^+\pi^-$ production in a state with $J = 0$. Moreover, in the $m_{\pi\pi}$ region where f_2 can be formed, the data suggest a sign change caused by the interference between the ρ^0 upper tail and the pion pairs in $J = 2$ state (f_2 meson decay into $\pi^+\pi^-$).

In Fig. 2 the $m_{\pi\pi}$-dependence of $\langle P_1 \rangle$ is compared with theoretical calculations based on the GPD framework. The agreement of the calculations with the data is qualitatively good, even though the size of the measured Legendre moment is larger. While interpreting these data in the GPDs framework, theoreticians may further model the GPDs in order to reach a better quantitative agreement with the experimental results. This will allow to improve the knowledge of some important properties of the internal structure of the protons, e.g. the still unknown orbital angular momentum of partons.