Exclusive Leptoproduction of ρ^0 Mesons from Hydrogen at Intermediate Virtual Photon Energies

The structure of the microscopic world can be investigated by scattering light from the object under study and observing the pattern of the reflected or transmitted light. This is the principle of the microscope, which has been used for many centuries to investigate biological cells and other objects with sizes of about 0.1 - 1 μm.

When investigating the fundamental constituents of matter – the quarks and gluons – the same principle is used. A photon of very small wave length is scattered from a collection of quarks and gluons (as bound in a proton for instance), and special detection equipment is used to register what has happened. Photons of very small wave length are generated when a high energy electron or positron is scattered from a proton. In this way it is possible to investigate objects as small as a femtometer ($= 10^{-15}$m) or less.

In this paper results are presented of measurements of this type, which have been carried out by the HERMES experiment at HERA. In this experiment 27.5 GeV positrons are used to generate (virtual) photons that are scattered from stationary protons. Of the many types of particles produced, the probability to produce ρ^0 mesons is determined. It is the purpose of these measurements to provide more insight into the quantum mechanical processes that lead to the production of ρ^0 mesons.

The ρ^0 meson is a particle consisting of a quark and an antiquark with a mass of about 770 MeV. It is a remarkable particle as it has the properties (quantum numbers) of a photon: uncharged, an intrinsic angular momentum (spin) of 1 $\hbar$ and an odd parity. The ρ^0 meson only differs from the photon because of its internal (quark) structure and its non-zero mass.

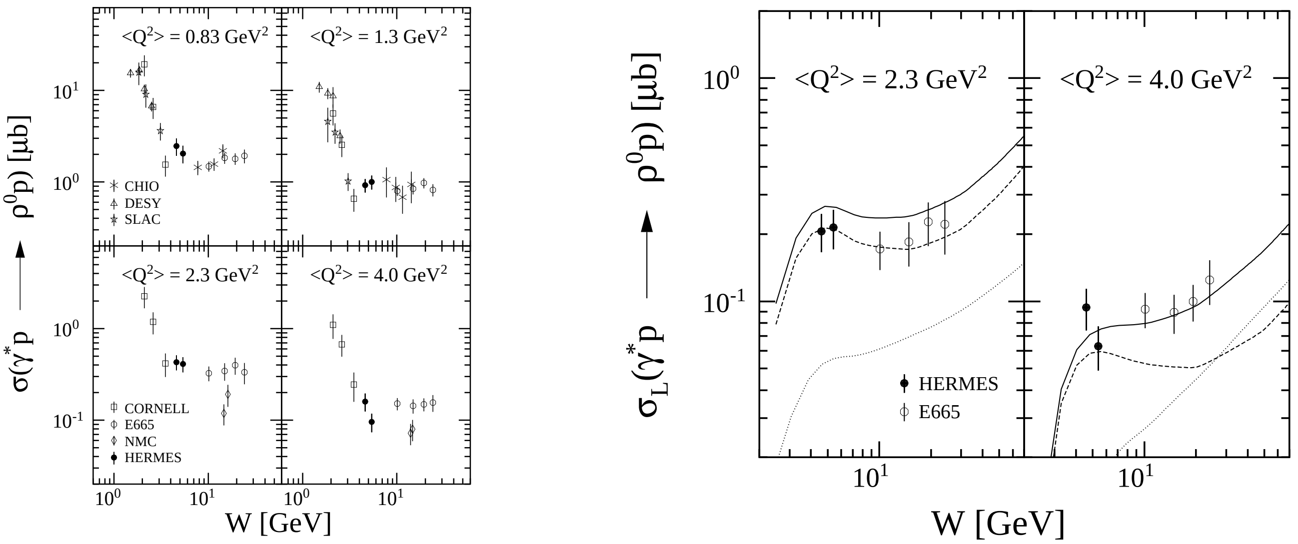

Figure 1: *Probability for producing a ρ^0 meson as a function of the total energy available. On the left-hand side the new HERMES data (filled circles near $W = 5$ GeV) are compared to results of earlier experiments (open symbols). On the right-hand side the high-energy data are compared to the results of a model calculation. The dotted line is based on a two-gluon exchange mechanism, while the dashed line represents the quark-exchange mechanism. The solid line represents the sum of both contributions.*

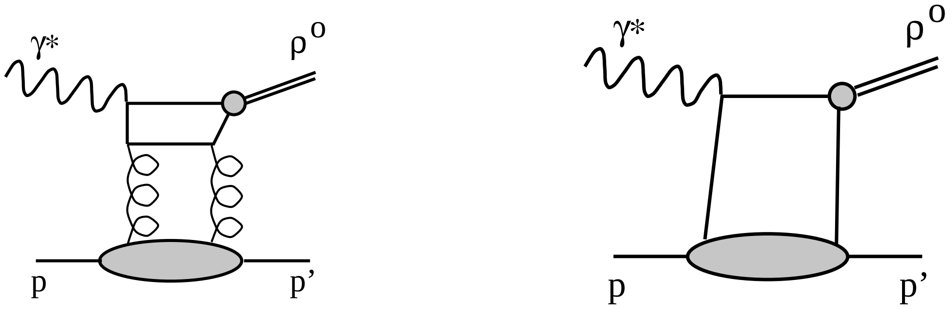

Figure 2: *Possible mechanisms for the production of a ρ^0 meson in electron scattering. In both cases a virtual photon (labeled as γ^*) is seen to fluctuate into a quark-antiquark pair, which interacts with the proton through the exchange of gluons (left) or quarks (right).*

At the very small length scales probed in the HERMES experiment, quantum mechanical phenomena are important. For example, according to the Heisenberg uncertainty principle, a short-wave length photon may fluctuate for a short amount of time into a quark-antiquark pair. During this short time interval energy and momentum can be exchanged with the proton via the so-called strong force. The virtual $q\bar{q}$-pair, which previously was not in a well-defined bound state, can then be converted into a real observable particle such a ρ^0 meson by even a relatively gentle interaction transfering little momentum. Such a gentle interaction occurs with relatively high probability.

In the experiment the probability to produce a ρ^0 meson has been measured. This probability is known as the total production cross section, and is indicated in the figure by $\sigma(\gamma^* p \rightarrow \rho^0 p)$. This cross section has been measured as a function of two kinematical variables: the square of the total virtual-photon momentum Q^2 and the total energy available in the photon-nucleon system W. The new HERMES data are compared to other data in the left-hand side of figure 1.

The new HERMES data are seen to mark the transitional energy domain where the probability to produce a ρ^0 meson obtains a fundamentally different character. While the data below 4 GeV are steeply declining with energy, only a weak dependence on energy is observed above 4 GeV. The decline at low W is attributed to decreasing contributions from nucleon excitations and meson-exchange processes, which are difficult to treat theoretically. At higher energies the reaction is simple enough to be understood quantitatively. In this region it is possible to compare the data to theoretical models that distinguish the various mechanisms by which energy and momentum can be transfered to the nucleon. An example of such a comparison is shown in the right-hand side of figure 1, where only data above 4 GeV are displayed.

The curves in the right-hand-side of figure 1 represent the result of calculations involving two different mechanisms for the production of a ρ^0 meson. The dotted curves correspond to a mechanism in which gluons are responsible for the exchange of energy and momentum between the $q\bar{q}$ pair and the proton (see left-hand side of figure 2). In the second mechanism (represented by dashed curves in figure 1) one of the quarks of the initial $q\bar{q}$ fluctuation is absorbed by the nucleon. Thereafter, the other quark forms a ρ^0 meson together with a (sea-)quark of the nucleon (see right-hand-side of figure 2). The data in the intermediate energy domain offer some support for the importance of the quark-exchange mechanism. The calculations shown in figure 1 are of particular interest as they have been evaluated in the so-called “Off-Forward Parton Distribution” (OFPD) framework, which makes it possible to calculate various observables (radial shape of the proton, quark momentum distributions inside the proton, meson production probabilities etc.) in one unified approach.