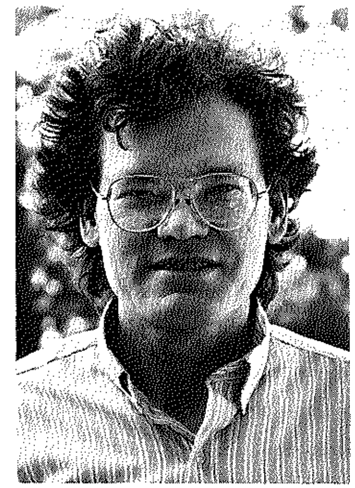
PION STRUCTURE AS OBSERVED IN FERMILAB EXPERIMENT E 615

Kirk T. McDonald

Princeton University, Princeton, New Jersey, USA



In an experiment performed at Fermilab we explore the structure of the pion via the Drell-Yan process, in the reactions $\pi^{\pm}N \rightarrow \mu^{+}\mu^{-}X$ at 80 and 255 GeV/c. The emphasis is on the kinematic region in which the momentum of the pion is largely carried by a single quark, which proves to be rather accessible to experimental study. The data indicate substantial departures from the expectations of asymptotic QCD, but agree well with a calculation which includes the effect of gluon exchange among the quarks inside the pion. With our large sample of muon pairs, we also set the current-best limits on the decay $D^{\circ} \rightarrow \mu^{+}\mu^{-}$ and on D°-$\bar{D}^{\circ}$ mixing.

Our knowledge of the structure of hadrons is largely empirical, and is derived in most part from deep-inelastic lepton-hadron scattering experiments conducted at SLAC, Fermilab, and CERN. An interpretation of these results has been provided by theoreticians, beginning with the parton model of Bjorken and Feynman, and later the theory of QCD. However, these theories make no predictions of the detailed structure of matter, as they can give (at present) little understanding into the confinement of quarks and gluons in observable hadrons, and provide instead only a sense of the behavior when the fundamental constituents are 'asymptotically free.' Fermilab experiment E 615 extends the exploration of hadron structure by pursuing the limit in which a single quark carries nearly all of the momentum of a π meson. Significant departures are observed from the more 'standard' QCD expectations for this experiment, but which appear to agree well with a QCD calculation of pion structure that includes non-asymptotic effects of the binding of the quarks inside the pion.

Experiment E 615 is the successor to Fermilab experiments E 331[1] and E 444[2], all of which studied the reaction $\pi N \rightarrow \mu^+\mu^- X$. The basic view of this reaction is that an antiquark from the pion annihilates with a quark from the nucleon to produce a virtual photon which materializes as the muon pair in the laboratory. The method for relating measurements of this process to the structure of the incident hadrons was developed by Drell and Yan[3] following the pioneering experiment on $pN \rightarrow \mu^+\mu^- X$ by a group headed by Lederman[4] in the late 1960's. The virtual photon 'x-rays' the beam- as well as the target-particle, so that any long-lived hadron may be studied.

Fermilab experiment E 444[2] was the first to use this technique to probe the pion, and to extract the pion structure function. The momentum distribution of valence quarks in the pion was found to be roughly $\sqrt{x}(1-x)$, where x is the fraction of the pion's momentum carried by the quark. This distribution indicates it is much more probable for a single quark to carry most of the momentum of a pion than of a proton. Hence the use of a pion beam permits the study of elementary processes in the interesting limit that a laboratory particle is nearly equivalent to a quark. Since the quantum numbers of quarks and pions are different the equivalence cannot be complete, and there may emerge unusual features not encountered in other investigations of the strong interaction.

Fermilab experiment E 615 was designed to emphasize the forward production of muon pairs by pions. The detector, shown in Figure 1, was built by a collaboration of physicists from the University of Chicago, Iowa State University, and Princeton University.[5] A large-aperture magnetic spectrometer was preceded by the 'selection' magnet which served to focus

high-mass muon pairs into the spectrometer, and to absorb the unscattered beam and secondary hadrons in low-Z material which filled its gap. The selection magnet was constructed out of steel and copper recycled from the main-ring magnets of the Argonne Zero Gradient Synchrotron. The experiment took data during the first running period of the Tevatron in 1983-84, and utilized an 80-GeV pion beam derived from 400-GeV protons, and a 255-GeV beam from 800-GeV protons. For a detailed discussion of the apparatus, see ref. 6.

Results from the 80-GeV run[7] (and from the 255-GeV test run[8]) confirm the expectation of interesting physics when a pion is almost a quark. An important piece of evidence is related to the angular distribution of the muon pairs, as shown in Figure 2. Muon pairs produced by the one-photon annihilation of free quarks should follow the familiar $1 + \cos^2\theta$ distribution in the pair rest frame. However the experimental result is that the angular distribution approaches $\sin^2\theta$ when the antiquark in the pion has a large momentum fraction. This is a model-independent indication that the virtual photon had longitudinal polarization, and suggests that the antiquark is off mass-shell due to its containment inside the pion. The new evidence confirms a preliminary indication of the same effect in experiment E 444[9], but which was not found in the CERN experiment NA 3[10].

Another striking result is the behavior of the average transverse momentum of muon pairs produced by large-x antiquarks in the pion. While the average squared transverse momentum is about 1 GeV^2/c^2 at low and moderate x, at large x the average dips sharply to 0.6 GeV^2/c^2. The relatively large average transverse momentum observed in muon-pair production by hadrons is often taken as a sign of the effects of gluon bremsstrahlung. Now there is evidence that the 'standard' gluon corrections become less relevant in the same kinematic region that the muon-pair angular distribution changes markedly.

A third noteworthy feature concerns a detail of the pion structure function. An intriguing question which requires considerable experimental sensitivity is whether the probability distribution of the valence quark extrapolates to a finite intercept at $x = 1$. The analysis of the 80-GeV run of E 615 indicates that this is so, although the statistical and systematic significance of this result is only three standard deviations.

All three of the above experimental results are consistent with the expectations of a QCD calculation by Berger and Brodsky[11]. This calculation is somewhat non-standard in that it takes explicit account of the fact that the annihilating quark and antiquark are contained in a nucleon and a pion. As a bonus they are led to an actual prediction of the form of the pion structure function applicable to the limit that the antiquark carries most of the momentum

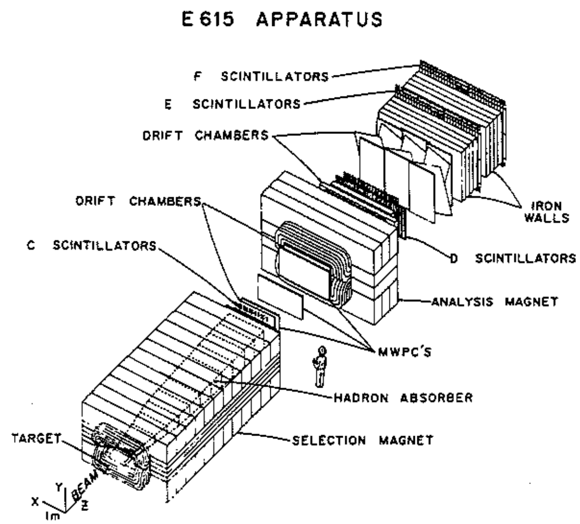


Figure 1. View of the apparatus of E 615.

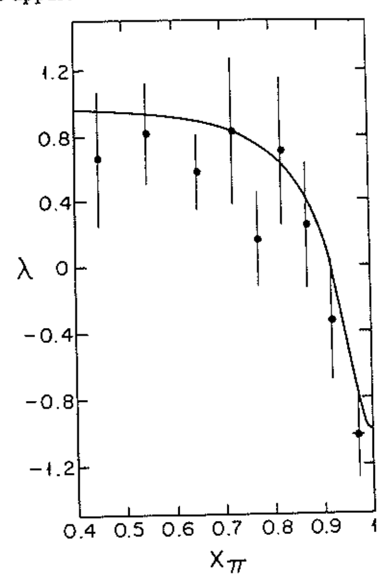


Figure 2. The parameter λ as a function of x_π obtained from fits to the angular distribution of muons in the muon-pair rest frame, using the form $d\sigma/d\cos\theta \propto 1 + \lambda\cos^2\theta$. The solid curve is based of the QCD model of Berger and Brodsky[11] using the value $\langle P_T^2 \rangle = 0.62\ \text{GeV}^2/c^2$ deduced from the observed pion structure function.

of the pion. In addition to a piece of the pion structure function associated with a $1 + \cos^2\theta$ angular distribution of the muon pair, they find a piece which has a finite intercept at $x = 1$ and is associated with a $\sin^2\theta$ angular distribution.

The intercept of the pion structure function at $x = 1$ measured in E 615, when interpreted according to the model of Berger and Brodsky, leads to a prediction that the average squared trasnverse momentum of the muon pair should be $0.6 \pm 0.16\ \text{GeV}^2/c^2$, in close agreement with the observed value. The model may then be used to predict the variation of the muon-pair angular distribution with x, yielding the solid curve shown in Figure 2.

Additional and much more accurate studies of the structure of the pion will become available when analysis of the 255-GeV run of E 615 is complete. Figure 3 shows the raw mass spectrum of the muon pairs collected in the 255-GeV run, and Figure 4 shows a preliminary version of the pion structure function obtained from that data.

A confirmation that quark-antiquark annihilation is responsible for muon-pair production even at large x_F is provided in Figure 5, which plots the ratio of the cross sections for muon-pair production by π^+ and π^- beams. This ratio would be 1/4 if only valence quarks contribute, while the solid curve in Figure 5 shows the expected ratio taking into account the sea-quark distribution of the nucleon. Note that for moderate x the data points lie above the curve, but for large x the data drop below the curve. This suggests that there are charge-symmetric QCD corrections to the cross section at moderate x which die out at large x.

Another result from the analysis of the 255-GeV data does not concern pion structure, but rather properties of the decays of charmed mesons[12]. We have used our large sample of muon pairs to search for the decay $D^o \to \mu^+\mu^-$, and set an upper limit on the branching fraction to this channel of $< 10^{-5}$. We also examined our sample of $\mu^+\mu^+$ pairs for evidence of D^o-$\bar{D}^o$ pair production followed by a 'charm oscillation' in which the $\bar{D}^o$ is converted into a D^o. Then both charmed mesons could decay semileptonicall: $D \to \mu^+ X$. We are able to set an upper limit on the D^o-$\bar{D}^o$ mixing parameter of 6×10^{-3}, which is the best limit on this quantity obtained in any experiment to date.

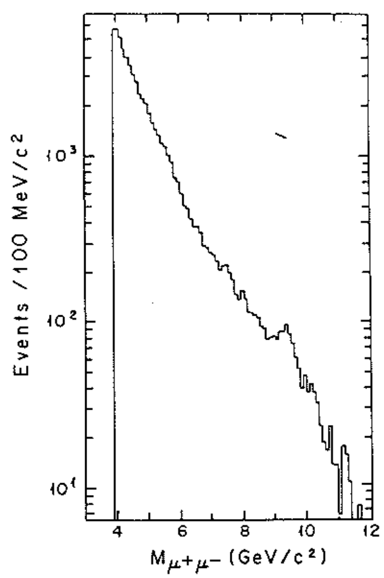


Figure 3. The invariant-mass spectrum of muon pairs collected in the 255-GeV run, uncorrected for acceptance.

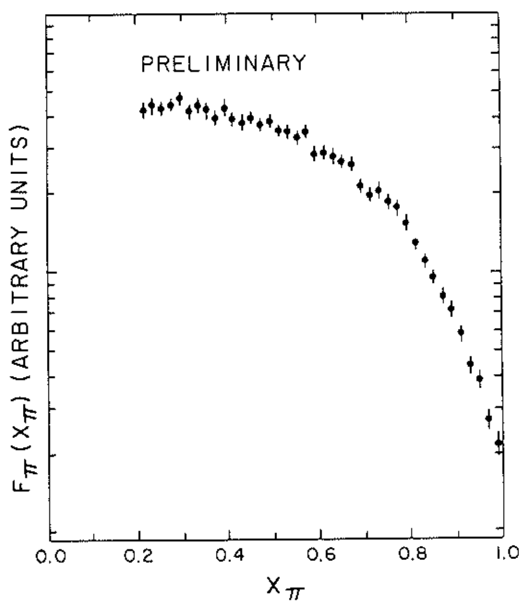


Figure 4. The pion structure function from a preliminary analysis of the 255-GeV data sample.

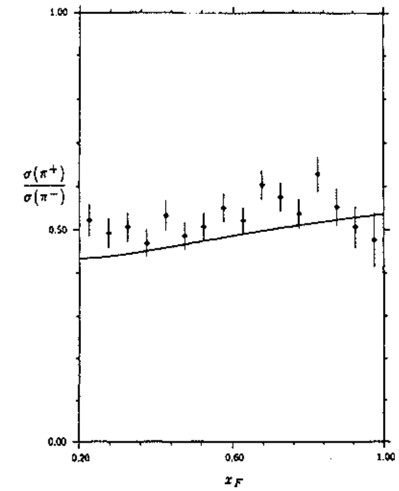


Figure 5. The ratio of the cross sections for muon-pair production by π^+ and π^- beams. The solid curve is a calculation which assumes that quark-antiquark annihilation is the production mechanism.

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