# Azimuthal asymmetry of negatively charged hadrons in the reaction $\bar{\nu}N \to \mu^+ h^- X$

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An azimuthal asymmetry of hadrons in the semi-inclusive reaction $\bar{\nu}N \to \mu^+ h^- X$ has been found through an analysis of data from the Fermilab 15-foot bubble chamber. The results are compared with various theoretical predictions.

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Several models predict an asymmetry of the distribution of hadrons around the momentum-transfer vector ($\mathbf{q}$) in lepton-nucleon interactions. In perturbative quantum chromodynamics (QCD) the cross section for the scattering of a lepton by a parton accompanied by the emission of a gluon has a $\cos\Phi$ and $\cos 2\Phi$ dependence,[1] where $\Phi$ is the azimuthal angle of the parton after the scattering, in first order in $\alpha_s$. Figure 1 shows the meaning of the angle $\Phi$ in the plane perpendicular to the vector $\mathbf{q}$ and the direction in which it is measured from the lepton plane. An analogous $\Phi$ dependence of the lepton-parton cross section arises in the quark-parton model when motion of the quark within a nucleon is taken into account.[2] Furthermore, for $T$-odd processes both QCD and the Abelian gluon model assume the appearance of a $\sin\Phi$ and $\sin 2\Phi$ dependence of the cross section.[3] According to all these predictions, the effects of the nonuniformity in the $\Phi$ distribution should be greatest in antineutrino interactions of a charged current.

An azimuthal asymmetry has been observed in muon production,[4] but attempts to detect it in neutrino reactions have yielded contradictory results.[5–7] The difficulties

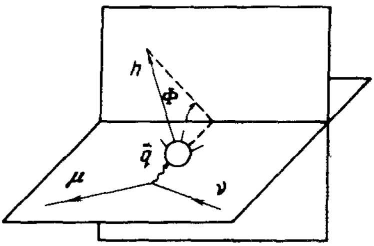

FIG. 1. Definition of the azimuthal angle $\Phi$.

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in working with neutrino data stem from the inaccuracy of the experimental reconstruction of the vector $\mathbf{q}$ because of the incomplete detection of the hadrons. In any real experiment one studies the asymmetry of the fragmentation products of the quark, not of the quark itself. This circumstance introduces some further difficulties, since the fragmentation causes a partial loss of information about the angular distribution of the quark.

Our purpose in the present study was to determine the $\Phi$ distribution of fast negative hadrons ($h^-$) from the semi-inclusive reaction $\bar{\nu}N \rightarrow \mu^+ h^- X$. In antineutrino interactions of a charge current, the forward hadron jet results from a fragmentation of a $d$ quark, so that the fast hadrons $h^-$ should most accurately reflect the angular characteristics of the ejected quark. A preliminary result of this study was reported at the Tenth International Symposium on Lepton and Photon Interactions at Bonn.[8]

The data were obtained through a processing and analysis of 155 000 photographs taken during the bombardment of the Fermilab 15-foot bubble chamber, filled with the heavy liquid $\mathrm{Ne} + \mathrm{H}_2$, by an antineutrino beam with a broad spectrum. Antineutrino interactions of a charged current with an energy $E_{\bar{\nu}} = 10\text{–}200$ GeV were identified by singling out the $\mu^+$ meson with an external muon identifier. The experimental details are discussed in more detail elsewhere (Ref. 9, for example). For the present study we selected $\sim 1100$ antineutrino interactions of a charged current which satisfied three conditions: (1) The invariant hadron mass was $W > 2$ GeV; (2) the square of the 4-momentum transfer was $Q^2 > 1$ GeV$^2$; (3) the total transverse momentum in the plane perpendicular to the beam was less than 500 MeV/$c$. The first two of these requirements reduce the overlap of the target and current fragmentation regions, while the last selects interactions with a low loss of hadron energy. The vector $\mathbf{q}$ is constructed as the orthogonal projection of the resultant measured hadron momentum onto the lepton plane. Condition (3) greatly reduces the number of antineutrino interactions of a charged current, but in return the vector $\mathbf{q}$ is determined more accurately in the selected events, so that the effects which tend to distort the $\Phi$ distribution are kept to an acceptable level. The surviving events of an antineutrino interaction of a charged current had the average values $\langle Q^2 \rangle = 5.5$ GeV$^2$ and $\langle E_{\bar{\nu}} \rangle = 37$ GeV.

For the $\sim 710\ h^-$ particles emitted into the forward hemisphere in the c.m. frame of the hadrons and carrying off a fraction ($z$) of the hadron energy greater than 0.2 we found $\langle \cos \Phi \rangle = -0.077 \pm 0.026$ and $\langle \cos 2\Phi \rangle = 0.021 \pm 0.026$. The minus sign on $\langle \cos \Phi \rangle$ indicates an excess of fast $h^-$ on the side of the vector $\mathbf{q}$ opposite $\mu^+$. [For fast positive hadrons ($h^+$), $\langle \cos \Phi \rangle$ is $0.044 \pm 0.028$; i.e., the fast $h^+$ tend to be closer to the $\mu^+$ meson.] We used a Monte Carlo method to study how the angular distribution of hadrons was affected by intranuclear cascades and the loss of hadron energy. The corresponding corrections lead to the final result $\langle \cos \Phi \rangle = -0.155 \pm 0.052$ and $\langle \cos \Phi \rangle = 0.036 \pm 0.031$. The errors given here do not reflect possible errors stemming from the Monte Carlo calculations.

Figure 2 shows the corrected values of $\langle \cos \Phi \rangle$ and $\langle \cos 2\Phi \rangle$ for various $Q^2$ intervals. The solid curves, from Ref. 10, are QCD calculations for fast ($z > 0.2$) charged $\pi$ mesons of both signs for two energies, $E_{\bar{\nu}} = 20$ GeV and 100 GeV. The dashed curve reflects our attempt to reconcile the observed behavior of $\langle \cos \Phi \rangle$ with the quark-parton model. The corresponding calculations were carried out in accor-

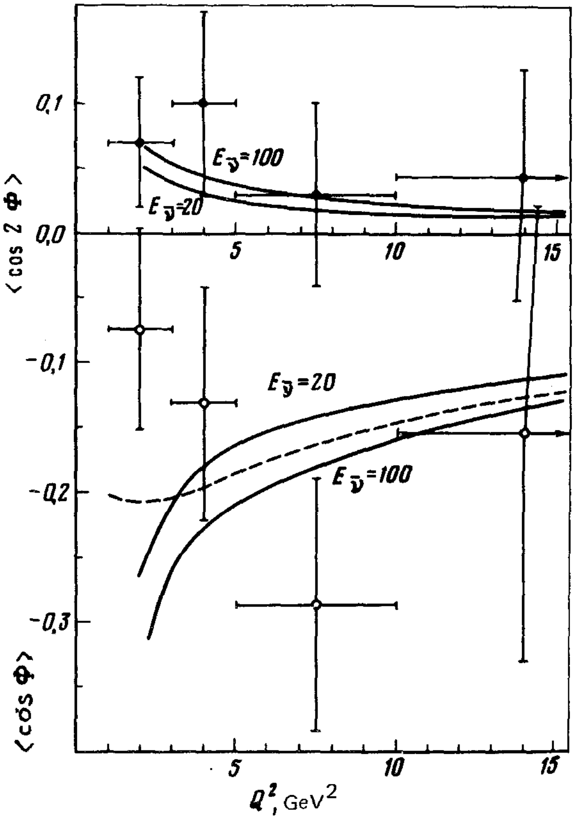

FIG. 2. Measured values of ⟨cos $\Phi$⟩ and ⟨cos $2\Phi$⟩ for various $Q^2$ intervals. Solid curves—QCD predictions, taken from Ref. 10; dashed curve—present calculation of ⟨cos $\Phi$⟩ in the quark-parton model for an average transverse momentum of 800 MeV/$c$ of the quark in the nucleon.

dance with Ref. 2 at an average transverse momentum of 800 MeV/$c$ of a quark in a nucleon and at an average transverse momentum of 360 MeV/$c$ of a hadron in a jet. Within the errors, the experimental data do not contradict either the QCD or quark-parton predictions.

An estimate of the contribution of $T$-odd processes was found by measuring the ratio $R = (N^+ - N^-)/(N^1 + N^-)$, where $N^+$ and $N^-$ are the numbers of fast $h^-$ "above" ($0° < \Phi < 180°$) and "below"($180° < \Phi < 360°$) the lepton plane. The ratio $R$, which tells us about the up-down asymmetry, is insensitive to the accuracy with which the vector $\mathbf{q}$ is the reconstructed, and it is related to sin $\Phi$ by $R = 4\langle \sin \Phi \rangle/\pi$. The value found for $\langle \sin \Phi \rangle$ from $R$ is $-0.056 \pm 0.035$, in agreement with the QCD prediction but at odds with the Abelian gluon model, which predicts a positive[3] $\langle \sin \Phi \rangle$. The quantity $\langle \sin 2\Phi \rangle$ is found to be $0.016 \pm 0.026$.

In summary, an anisotropy in the distribution of fast $h^-$ in the angle $\Phi$ has been observed in the semi-inclusive process $\bar{\nu}N \to \mu^+ h^- X$. This anisotropy is expressed most clearly as a left-right asymmetry with the value $\langle \cos \Phi \rangle = -0.155 \pm 0.052$. On the whole, all the results of our measurements are consistent with the QCD and quark-parton predictions, within the errors.

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