# Left-right asymmetry in neutrino-produced hadron jets

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In an experiment (E546) to study interactions of $\langle E\rangle=100$ GeV and $\langle Q^2\rangle=17$ GeV$^2$ neutrinos in the Fermilab 15-foot bubble chamber, we have looked for a left-right asymmetry in the azimuthal angle $\phi$ of individual hadrons about the direction of the lepton momentum transfer ($q$ vector). Significant asymmetry is found for forward positive hadrons; for $x_F>0.10$, we find $\langle\cos\phi\rangle=-0.029\pm0.008$, where $x_F$ is the Feynman $x$ variable. Negative hadrons with $x_F>0.10$ show no asymmetry, $\langle\cos\phi\rangle=0.004\pm0.011$. A model which includes parton intrinsic transverse momentum $k_t$ reproduces the asymmetry of combined positive and negative hadrons with $x_F>0.10$, $\langle\cos\phi\rangle=-0.018\pm0.0065$, if $\langle k_t^2\rangle=0.065\pm0.024$ GeV$^2/c^2$. But the model predicts almost equal asymmetries for positive and negative hadrons. The model also agrees poorly with the observed dependence on the kinematic variables $x$ and $Q^2$ if the $k_t$ distribution is assumed to be independent of kinematic variables.

## INTRODUCTION

This paper reports on further studies of the hadron system produced in charged-current neutrino-nucleon interactions.[1–5] Here, we report on a search for a left-right asymmetry in the azimuthal angle $\phi$ of individual hadrons about the direction of the lepton momentum transfer (i.e., the $q$ vector).

A small left-right asymmetry is predicted to arise from gluon bremsstrahlung,[6] from parton transverse momenta,[7–9] and perhaps from higher-twist effects.[10] The earliest search for such an asymmetry was apparently made in an analogous electroproduction experiment.[11] Significant asymmetries have been reported in muon-hydrogen experiments,[12,13] in an antineutrino bubble-chamber experiment,[14] in a neutrino counter experiment,[15] and in preliminary studies from a second antineutrino bubble-chamber experiment[16] and from the present experiment.[1,2] The present experiment has also reported on a possible up-down asymmetry.[4]

The present experiment used the Fermilab 15-foot bubble chamber filled with a neon-hydrogen mix. The neutrino beam energy ranged from approximately 10 to 320 GeV, and the mean event energy was 100 GeV.

The azimuthal angle $\phi$ is defined as follows. A right-handed coordinate system is defined in which the $z$ axis is in the $q$ vector direction and the $y$ axis is in the neutrino-cross-muon direction. Then, for a hadron with momentum coordinates $(p_x,p_y,p_z)$ and momentum $p_t$ in the $x$-$y$ plane, we take $\sin\phi=p_y/p_t$ and $\cos\phi=p_x/p_t$. Thus, a hadron will have a positive $\cos\phi$ value if its projection onto the lepton plane lies on the muon side of the $q$ vector, and a negative value if on the side away from the muon.

## THEORY

In first-order QCD, a gluon may be emitted from either the incoming parton or the outgoing parton. Interference between these two cases leads to the gluon being preferentially on one side of the outgoing parton, and hence to a left-right asymmetry. Calculation of this asymmetry is rather complex,[9,17,18] involves dealing with divergent terms, and at the hadron level involves a three-jet fragmentation model. Calculations have been reported on the asymmetry of fast forward hadrons (i.e., hadrons with $z>0.2$, where $z$ is the ratio of an individual hadron's energy to the total hadron energy), for incident muons[17] and incident neutrinos.[9] In both cases a negative asymmetry, that is, a negative value of $\langle\cos\phi\rangle$, was predicted. In the neutrino case the size of the predicted asymmetry decreased as $Q^2$ increased, as expected if the $Q^2$ dependence is primarily via the coupling constant $\alpha_s(Q^2)$. However, in detail the $Q^2$ dependence varied with neutrino energy and was different for antineutrinos. In the muon case, the size of the predicted asymmetry showed little or no $Q^2$ dependence. We do not know the reason for this different $Q^2$ dependence. In the muon case, a strong dependence on $p_t$, the hadron's transverse momentum, was noted. The neutrino calculation[9] did not report on $p_t$ dependence. A third calculation of the asymmetry due to gluon emission[18,15] also found that a negative asymmetry was predicted. However, only results for a particular event variable, namely, an energy-weighted average of the asymmetry over all the hadrons in an event, were reported from this calculation.

Qualitatively, we note that all three calculations on the asymmetry due to gluon emission predict a negative asymmetry for forward hadrons. Further, gluons are emitted predominantly in the forward hemisphere (in the center-of-mass frame), and are correlated with larger hadron transverse momenta.[3] Therefore, we may expect the predicted asymmetry to be small in the backward hemisphere, and in the forward hemisphere to increase with increasing hadron transverse momentum $p_t$ (as noted in Ref. 17).

A second possible source of a left-right asymmetry is parton intrinsic transverse momentum. The cross section depends on the neutrino-parton total center-of-mass energy $\hat{s}$ (in the case of left-handed neutrino on left-handed quark) and $\hat{s}$ in turn depends on which side of the current vector the parton lies. In a simple parton model (see, e.g., Ref. 19 for the case that $k_t$ is zero), we write the current four-vector in the laboratory frame as $q=(\nu,0,0,P_q)$, with $q^2=-Q^2$ in the usual notation. The target nucleon is $P=(M,0,0,0)$, and the target parton is $p_i=(\xi M,k_t\cos\phi,k_t\sin\phi,0)$, where $k_t$ is the parton's intrinsic transverse momentum. The parton "mass" squared is $p_i^2=(\xi M)^2-k_t^2$. If elastic scattering implies $(p_i+q)^2=p_i^2$, then $\xi=Q^2/(2M\nu)=x$, where $x$ is the usual scaling variable. If we boost in the longitudinal ($z$-axis) direction to any frame, we have the familiar result that $\xi$ is the fraction of parton to proton longitudinal momentum. In the same laboratory frame, the neutrino and muon four-vectors are $k=E_\nu(1,\sin\theta_h,0,\cos\theta_h)$ and $k'=(E_\mu,P_\mu\sin(\theta_h+\theta_\mu),0,P_\mu\cos(\theta_h+\theta_\mu))$, respectively. Here $\theta_h$ and $\theta_\mu$ are the laboratory frame angles that the neutrino direction makes with the $q$ vector and with the muon directions, respectively.

The neutrino-parton cross sections are proportional to $\hat{s}^2$ for left-handed partons and to $\hat{u}^2$ for right-handed partons (Ref. 8), with

$$\hat{s}=(k+p_i)^2$$
$$=2E_\nu(xM-k_t\sin\theta_h\cos\phi)+(xM)^2-k_t^2$$

and

$$\hat{u}=(k'-p_i)^2$$
$$=-2E_\mu[xM-k_t\sin(\theta_h+\theta_\mu)\cos\phi]+\mu^2+(xM)^2-k_t^2$$

using the four-vectors written above. With some appropriate approximations, including $E_\nu\theta_h^2\simeq 2xM(1-y)/y$ and $E_\nu\theta_\mu^2\simeq 2xMy/(1-y)$, these results become the same as those given in Ref. 8. Thus, for the dominant left-handed parton case, $\hat{s}$ is approximately proportional to $1-2k_t\cos\phi(1-y)^{1/2}/Q$, and hence $\langle\cos\phi\rangle\simeq-2k_t(1-y)^{1/2}/Q$. Note that Ref. 18 takes the cross sections as proportional to $\hat{s}$ and $\hat{u}^2/\hat{s}$ rather than the above $\hat{s}^2$ and $\hat{u}^2$; there is a subtle question of whether there is an extra $1/\hat{s}$ factor here.[20]

There is little guidance on the $k_t$ distribution, either on the shape or on whether there should be some dependence on kinematic variables such as $x$ or $Q^2$. In Ref. 17 an implicit kinematic dependence occurs in that the maximum allowed value of $k_t$ depends on $x$. This dependence is derived in a model in which the variable $\xi$ (ratio of parton to proton longitudinal momentum) is required to be greater than zero in the current-hadron center-of-mass frame. But this result is frame dependent in the model used, and it is not clear why this particular frame is chosen. In our simple parton model described above, a negative value of $\hat{s}$ is possible if the parton "mass" squared is negative, i.e., if $xM<k_t$. Our calculations described below do require $\hat{s}>0$, implying a maximum allowed $k_t$ value at a given $x$, $\theta_h$, and $\phi$, with the result that $\langle k_t^2\rangle$ decreases slightly at small $x$ or $Q^2$ in the absence of any explicit dependence.

A third possible source of a left-right asymmetry comes from some higher-twist effects. Berger[10] has predicted that higher-twist effects will lead to correlations among observables in deep-inelastic scattering. The correlations include a $z-\cos\phi$ correlation which would produce a positive left-right asymmetry at large $z$, i.e., $z>0.5$, say. Explicitly, Berger predicts, for $\nu N\to\mu^-\pi^+X$,

$$d\sigma/d\phi\sim(1-z)^2+0.66(1-z)(1-y)^{1/2}(4p_t^2/Q^2)^{1/2}\cos\phi$$
$$+0.44(1-y)p_t^2/Q^2$$

in the case that $z$ is large and $p_t^2\ll Q^2$. The expected correlations have been searched for in a muon-hydrogen experiment[21] and in neutrino experiments,[22,23] with mixed results. The predicted left-right asymmetry increases as a hadron's transverse momentum increases and as $Q^2$ decreases.

## PREVIOUS EXPERIMENTS

Two bubble-chamber experiments with hydrogen targets[24,25] have reported no significant left-right asymmetries in charged-hadron $\phi$ distributions. Both experiments had wideband beams and approximately 2000 charged-current (CC) events; one had a neutrino beam and one an antineutrino beam.

A wide-band antineutrino neon bubble-chamber experiment[16] has reported preliminary results which include an asymmetry. In 12 300 CC events, the observed $\langle\cos\phi\rangle$ at $z>0.2$ was $-0.029\pm0.008$ for negative hadrons and $0.005\pm0.009$ for positive hadrons. Another wideband antineutrino neon bubble-chamber experiment[14] has reported a somewhat similar asymmetry. Here a strong cut was made in missing transverse momentum, to ensure that the $q$-vector direction was well determined. In the remaining 1100 CC events, at $z>0.2$, $\langle\cos\phi\rangle$ values of

$-0.077\pm0.026$ for negative hadrons and $0.021\pm0.026$ for positive hadrons were found. The negative hadron asymmetry was consistent with that expected from parton transverse momentum with $\langle k_t \rangle$ of approximately 0.8 GeV/$c$.

A neutrino counter experiment with a mean event energy of approximately 100 GeV has recently reported a left-right asymmetry.[15,18] This experiment did not detect individual hadrons, but was able to measure an energy-weighted average value of $\cos\phi$ for each event. In 9200 CC events, the average value of this quantity was $-0.0224\pm0.0032\pm0.0022$ (statistical and systematic errors, respectively). Distributions in $y$ and $Q^2$ were compared to predictions from parton transverse momentum, without and with gluon emission, leading to $\langle k_t \rangle$ values of $0.44\pm0.03$ and $0.30\pm0.04$ GeV/$c$, respectively (as noted in the preceding section, an extra $1/\sqrt{\hat{s}}$ factor was included in the parton theory here). A better fit was found if $\langle k_t \rangle$ was taken to be proportional to the scaling variable $x$.

In a muon-hydrogen experiment,[12] a significant negative asymmetry was seen for charged hadrons with $z>0.15$ and $p_t>0.2$ GeV/$c$. The results were compared to the theory of Ref. 17, which includes first-order gluon emission and intrinsic parton transverse momentum, $k_t$, with an $x$-dependent maximum allowed $k_t$ value. It was found that most of the asymmetry was attributable to intrinsic parton $k_t$, and the data were consistent with $\langle k_t \rangle = 0.7$ GeV/$c$.

A later muon-hydrogen experiment[13] was able to detect charged hadrons in the full range of $x_F$, and was able to identify the mass of 50% of the hadrons. For charged hadrons with $p_t>0.2$ GeV/$c$ a small positive asymmetry at $x_F<0$ and a sizable negative asymmetry in the region $0<x_F<0.9$ was observed. Compared again to the theory of Ref. 17, the $x_F$ dependence indicated a $\langle k_t^2 \rangle$ value of $>0.19$ GeV$^2$/$c^2$, although even for $\langle k_t^2 \rangle = 0.77$ GeV$^2$/$c^2$ the predicted asymmetry at $x_F>0$ was less than that observed. Also, the rapid change in the asymmetry around $x_F=0$ did not agree with the theory. The $Q^2$ dependence observed was not explicitly compared to the theory; but for $x_F>0$, and particularly for $x_F>0.3$, the negative asymmetry was largest in the highest $Q^2$ bin ($Q^2>20$ GeV$^2$).

In summary, experiments have seen an asymmetry, with the sign as expected from parton transverse momentum and from gluon emission. But the different beams, the different cuts employed, and differences in the theories with which the data are compared, lead to a confused overall picture.

## EXPERIMENTAL DETAILS

The present data come from an experiment[26] (E546) in the Fermilab 15-foot bubble chamber with a two-plane external muon identifier (EMI). The chamber was filled with a neon-hydrogen mix (47% atomic neon) and was exposed to the quadrupole triplet neutrino beam produced by 400-GeV incident protons. We start with approximately 8500 fully measured CC events. Each event has a $\mu^-$ with energy $E_\mu>4$ GeV and a good two-plane match in the EMI, and has a primary vertex at least 70 cm from the downstream chamber wall. We then require each event to have at least two primary hadrons that are not identified protons and that have fractional momentum error $<100\%$. These hadrons can be charged or neutral; a neutral primary is either (1) a gamma, i.e., an $e^+e^-$ pair or a Compton electron that appears within two radiation lengths of the primary vertex and points to the primary vertex, or (2) a $V^0$ that fits to either a $K^0$ or a lambda and points to the primary vertex. A positive hadron is identified as a proton only if it stops in the bubble chamber (possibly after a scatter). We also require the reconstructed hadron-system effective mass to be greater than the proton mass. With these minimal cuts, 8061 events remain.

For each event, the neutrino direction is known to better than 1 mr, and the muon energy and direction are well measured. However, because some neutral particles are not seen, and detected hadrons occasionally have large momentum errors (due to secondary interactions), the total hadron system energy and direction must be estimated. Here we get the energy by energy balance after estimating the incident neutrino energy as $E_\nu = P_{\mu x} + fP_{hx}$, where the $x$ direction is the neutrino direction and $f$ is a correction factor which depends on the event's transverse-momentum imbalance.[27] Also, $P_h$ refers to the observed hadron system. For comparison we sometimes use an "average-correction" method,[26] where $fP_{hx}$ is replaced by a function of $P_{hx}$ determined from transverse-momentum studies. The hadron system direction we take as the projection, on the lepton plane, of the observed hadron system. Note that here, and in all that follows, "observed" hadrons are taken to be charged or neutral primary hadrons that are not identified protons and that have fractional momentum errors of $<100\%$.

The neutrino energy $E_\nu$, estimated as above, is typically accurate to $\pm15\%$. The ratio of detected energy to estimated neutrino energy has a mean value of 0.92 and a rms width of 0.09. For our events, $E_\nu$ ranges from 10 to 320 GeV, with a mean of 100 GeV. The usual event kinematic quantities $Q^2$ (negative squared four-momentum transfer), $W^2$ (hadron-system mass squared), $x$, and $y$ (the scaling variables) are calculated using the $E_\nu$ estimate and the measured muon momentum, assuming a nucleon target that is at rest and on the mass shell.

The error in the estimated total-hadron-system direction is expected to have a distribution similar to the distribution in $\theta_{hz}$, the angle between the lepton plane and the observed hadron-system direction. The rms width of the $\theta_{hz}$ distribution varies with $P_h$ and is approximately $(500/P_h)$ mr, where $P_h$ is in GeV/$c$. The median $P_h$ value for our events is 24 GeV/$c$.

For individual hadrons, the variables $z$ and $x_F$ are used, with $z=E_h/(E_\nu - E_\mu)$ and $x_F = 2P'_{hx}/W$. Here, $E_h$ is the hadron's energy in the laboratory, and $P'_{hx}$ is the hadron's longitudinal momentum in the hadron-system center-of-mass frame. Since charged hadrons are given the pion mass, a charged kaon or proton will be assigned a $z$ value that is smaller than the true value, and assigned an $x_F$ value that is larger than the true value.

Gammas that come from muon inner bremsstrahlung[3] are removed statistically. If a gamma makes an angle $\theta$ with the muon such that $\cos\theta > 0.9995$, it is deleted with an appropriate probability, so that the total number deleted at a given $\theta$ equals the net inner bremsstrahlung signal at that $\theta$. The result is that 0.9% of the observed gammas are assigned as inner bremsstrahlung.

## RESULTS

Here we search for an asymmetry by looking at $\langle \cos\phi \rangle$ for hadrons that pass various selections. The errors given on $\langle \cos\phi \rangle$ are statistical, and are always very close to $1/\sqrt{(2N)}$, where $N$ is the number of hadrons. To avoid subtle (and obvious) biases that cuts may introduce, we generally use the minimal cuts on event quantities described above.

Values of $\langle \cos\phi \rangle$, in $x_F$ bins, are shown in Fig. 1 for positive, negative, and neutral hadrons. Neutral hadrons are mostly (97%) gammas, presumably almost all from neutral-pion decays.

We see that negative and neutral hadrons have $\langle \cos\phi \rangle$ generally consistent with zero over the entire $x_F$ range, apart from a possible positive value for the neutrals at around $x_F = -0.15$. But positive hadrons indicate a positive value near $x_F = -0.20$ and a negative value near $x_F = 0.20$. For the eight $x_F$ bins, the $\chi^2$ values for the $\langle \cos\phi \rangle = 0$ hypothesis are 22.3, 3.2, and 16.2 for positive, negative, and neutral hadrons, respectively. We now cautiously combine bins in various ways.

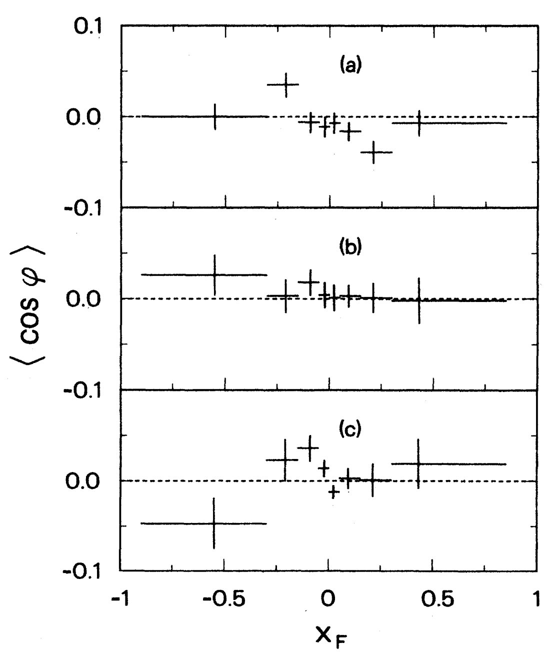


FIG. 1. Left-right asymmetry as a function of Feynman $x$ for (a) positive particles, (b) negative particles, and (c) neutral particles.

For all hadrons combined, $\langle \cos\phi \rangle = 0.000 \pm 0.003$. A zero value is expected if there is no asymmetry. But if there is some asymmetry, the value may or may not be zero, depending on the nature of the asymmetry and on details of the hadronization process.

In Table I, $\langle \cos\phi \rangle$ values are given for forward positive and negative hadrons with various minimum $x_F$ values. We see values for positives that are three standard deviations from zero, and values for negatives that are close to zero. For $x_F > 0.10$ there is a greater than two standard deviation difference between positive and negative hadrons. If we use the variable $z$, rather than $x_F$, the positives' three standard deviation effects persists, as does the difference between positives and negatives (see Table I).

Also in Table I are $\langle \cos\phi \rangle$ values for backwards charged hadrons with various maximum $x_F$ values. There may be a suggestion of a positive asymmetry here. If we combine both charges, we get $\langle \cos\phi \rangle = 0.017 \pm 0.007$ for $x_F < -0.010$.

We have looked for possible biases in the determination of $\langle \cos\phi \rangle$. Sources of bias are not readily apparent, for two reasons. First, since we use the observed hadrons to estimate the total hadron direction, we need an effect that biases the angle of one class of hadrons relative to other observed hadrons. Second, in a bubble-chamber coordinate system, our events have the lepton plane approximately uniformly distributed in azimuthal angle about the neutrino direction (the distribution is not perfectly uniform because the EMI was not completely symmetric). Therefore the hadron system is approximately equally up and down and left and right in that coordinate system.

In one particular bias study, focusing on charged hadrons with $x_F > 0.10$, we divided the events into two roughly equal parts in eight different ways. We divided the events in five different ways according to the event vertex coordinates in the bubble-chamber coordinate system, in two ways according to the lepton-plane orientation, and finally according to the ratio of observed to corrected neutrino energy. We found no case where either the positive or the negative hadrons (with $x_F > 0.10$) had $\langle \cos\phi \rangle$ values that differed between the two parts by two or more standard deviations (and three cases each where they differed by one or more standard deviations).

Since it may be easier to conceive of a bias in the observed neutral hadrons, we tried using just charged hadrons in estimating the total hadron system direction. The results for charged hadrons with $x_F > 0.10$ are given in Table I. The significant nonzero value for positives remains, and the positive-negative hadron difference increases by a very small amount. Therefore, these results cannot be attributed simply to a neutral-hadron bias.

Any problems in estimating the neutrino energy are unlikely to introduce appreciable bias in the asymmetry. A misestimate of the energy will shuffle some hadrons between $x_F$ bins (and between $Q^2$, etc., bins), but will not affect the $\cos\phi$ value of a given hadron. Nevertheless, we tried the average-correction method (see preceding section), and found very little change (see Table I). We also

TABLE I. Values of $\langle \cos\phi \rangle$ for positive and negative hadrons with various selections. The variables $x_F$, $z$, $z_{\rm vis}$, $P_t$(miss), and $p_t$ are defined in the text.

| Selection | Positive hadrons | Negative hadrons |
|---|---|---|
| $x_F > 0.0$ | $-0.018 \pm 0.006$ | $0.001 \pm 0.008$ |
| $x_F > 0.05$ | $-0.021 \pm 0.007$ | $0.002 \pm 0.009$ |
| $x_F > 0.10$ | $-0.029 \pm 0.008$ | $0.004 \pm 0.011$ |
| $x_F > 0.15$ | $-0.026 \pm 0.009$ | $0.000 \pm 0.014$ |
| $z > 0.10$ | $-0.023 \pm 0.007$ | $-0.002 \pm 0.010$ |
| $z > 0.15$ | $-0.028 \pm 0.008$ | $-0.003 \pm 0.012$ |
| $z > 0.20$ | $-0.024 \pm 0.009$ | $-0.005 \pm 0.014$ |
| $x_F < 0.0$ | $0.002 \pm 0.006$ | $0.011 \pm 0.008$ |
| $x_F < -0.05$ | $0.008 \pm 0.007$ | $0.015 \pm 0.010$ |
| $x_F < -0.10$ | $0.013 \pm 0.008$ | $0.024 \pm 0.012$ |
| $x_F < -0.15$ | $0.018 \pm 0.009$ | $0.012 \pm 0.014$ |
| $x_F > 0.10$[a] | $-0.026 \pm 0.008$ | $0.010 \pm 0.011$ |
| $x_F > 0.10$[b] | $-0.025 \pm 0.008$ | $-0.003 \pm 0.011$ |
| $z_{\rm vis} > 0.12$ | $-0.021 \pm 0.007$ | $-0.003 \pm 0.009$ |
| $x_F > 0.10$[c] | $-0.032 \pm 0.008$ | $0.003 \pm 0.011$ |
| $x_F > 0.10, P_t(\text{miss}) < 0.5$ GeV/$c$ | $-0.004 \pm 0.013$ | $0.035 \pm 0.018$ |
| $x_F > 0.10,\ p_t < 0.3$ GeV/$c$ | $-0.022 \pm 0.013$ | $0.011 \pm 0.018$ |
| $x_F > 0.10, 0.3 < p_t < 0.5$ GeV/$c$ | $-0.031 \pm 0.014$ | $0.006 \pm 0.020$ |
| $x_F > 0.10, p_t > 0.5$ GeV/$c$ | $-0.036 \pm 0.014$ | $-0.008 \pm 0.021$ |

[a]Using only charged hadrons to estimate the total-hadron-system direction.
[b]Using the average-energy correction method (see text).
[c]Determined without removing inner-bremsstrahlung gammas.

tried the variable $z_{\rm vis}$, the ratio of a hadron's energy to the total observed hadron energy. For $z_{\rm vis} > 0.12$, which gives approximately the same number of hadrons as $z > 0.10$, very little change was observed (see Table I).

We conclude that we cannot find an instrumental or analysis bias that is causing the observed asymmetry.

To check the inner bremsstrahlung removal procedure (see previous section), we recalculated $\langle \cos\phi \rangle$ values without removing these gammas. The resulting changes were small and in the expected direction—see Table I for charged hadrons with $x_F > 0.10$. We conclude that inner bremsstrahlung uncertainties contribute negligibly to errors in $\langle \cos\phi \rangle$.

The dependence of $\langle \cos\phi \rangle$ on the kinematic variables $x$, $y$, and $Q^2$ are shown in Figs. 2–4, for positive and negative hadrons, and for both charges combined, with $x_F > 0.10$. We see no strong $y$ or $Q^2$ dependence. But, at the two-standard deviation level, the magnitude of the positives' asymmetry decreases at low $x$.

Following Ref. 14, we tried requiring the missing transverse momentum $P_t$(miss) to be less than 0.5 GeV/$c$. Such a cut could well be biased, since events with missing neutrals in the neutrino direction will be preferentially selected. That is, we could expect a bias in the smearing of the $q$-vector direction. The results for $x_F > 0.10$ are given in Table I. The $\langle \cos\phi \rangle$ values are shifted in the expected direction, but the difference between them is maintained.

We looked for a dependence on $p_t$, the transverse momentum of a hadron with respect to the estimated to-

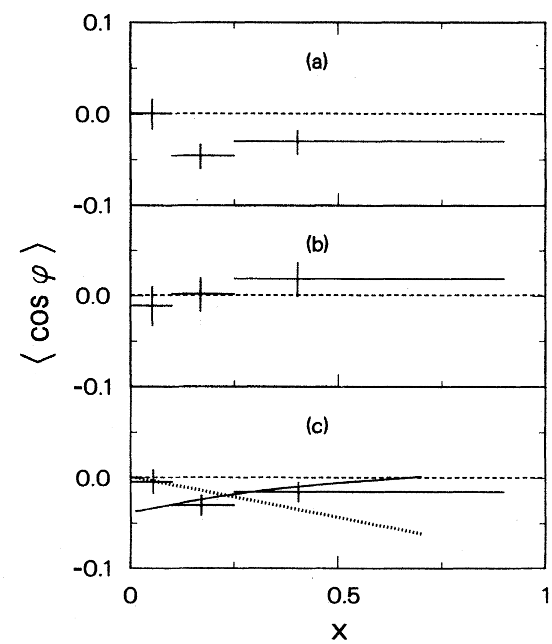


FIG. 2. Left-right asymmetry as a function of Bjorken $x$ for (a) positive particles, (b) negative particles, (c) both charges combined, all for Feynman $x$ greater than 0.1. The curves in (c) are the theoretical predictions, described in the text, with $\sigma_k^2 = 0.065$ GeV$^2/c^2$ (solid curve) and $\sigma_k^2 = 1.49x^2$ GeV$^2/c^2$ (dotted curve).

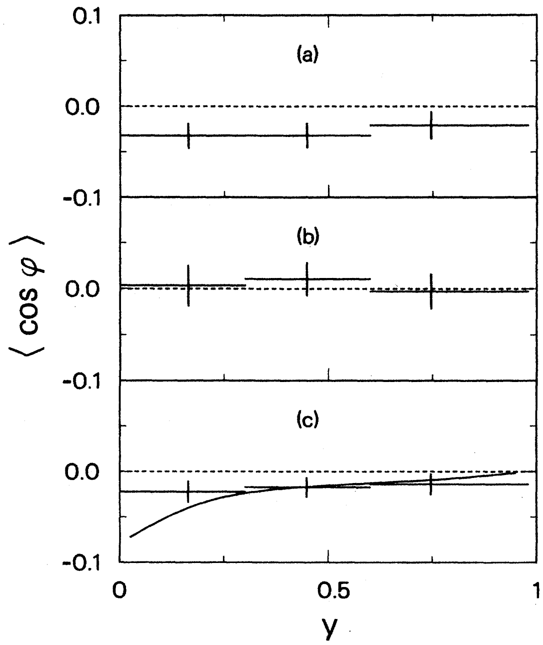


FIG. 3. Left-right asymmetry as a function of $y$ for (a) positive particles, (b) negative particles, (c) both charges combined, all for Feynman $x$ greater than 0.1. Solid curve in (c) as in Fig. 2(c).

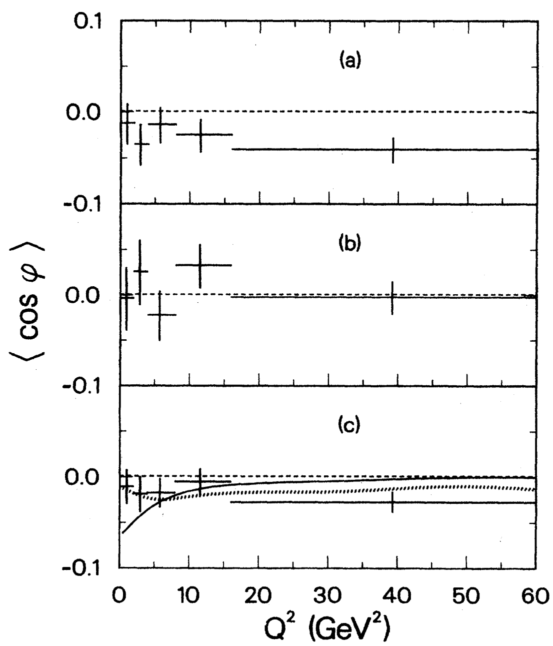


FIG. 4. Left-right asymmetry as a function of four-momentum transfer squared at the lepton vertex, for (a) positive particles, (b) negative particles, (c) both charges combined, all for Feynman $x$ greater than 0.1. Solid and dotted curves in (c) as in Fig. 2(c).

tal hadron direction. The results for $x_F > 0.10$ in three bins of $p_t$ are given in Table I. We do not see any strong $p_t$ dependence.

For comparison with the predicted higher-twist contribution[10] (see below), we looked at positive hadrons with $z > 0.5$. We found $\langle \cos\phi \rangle$ values of $0.022 \pm 0.022$ for all events, and $0.021 \pm 0.027$ for events with $Q^2 < 10$ GeV$^2$.

Finally, we calculated an energy-weighted $\cos\phi$ for each event, $\cos\phi' = \sum(E_i \cos\phi_i)/\sum(E_i)$, where $\sum$ is over the observed hadrons in the event (positive, negative, and neutral). Apart from unobserved hadrons, this is the quantity used in Ref. 15. We found $\langle \cos\phi' \rangle = -0.0066 \pm 0.0033$ for all events, and $-0.0056 \pm 0.0051$ for events with $y < 0.30$ (Ref. 15 found that the asymmetry was larger at low $y$). We repeated the calculation for all events with the summations being over just positive or just negative hadrons, and found $\langle \cos\phi' \rangle$ values of $-0.0066 \pm 0.0030$ and $-0.0002 \pm 0.0022$, respectively. Again we see negative asymmetry for positives and no asymmetry for negatives, but the statistical significance is somewhat reduced when we use this event quantity.

## COMPARISON WITH THEORY AND OTHER EXPERIMENTS

We have studied the asymmetry for forwards (i.e., $x_F > 0.05$) hadrons that is expected from intrinsic transverse momentum. We use the simple model described above, and do not include gluon emission. In a Monte Carlo simulation, we generate neutrino charged-current events with appropriate $E_\nu$, $x$, and $y$ distributions. We assume that the struck parton has a $k_t$ distribution of $\exp[-k_t^2/(2\sigma_k^2)]$ out to a maximum value. The latter follows from requiring $\hat{s}$ to be greater than zero.[28] We select $k_t$, and a random $\phi$, and give the event a weight which depends on $\hat{s}^2$ and $\hat{u}^2$ and is such that the average over all $\phi$ is unity (for the given $k_t$, $E_\nu$, $x$, and $y$). We include both neutrino-quark and neutrino-antiquark scattering terms, but the former dominates. From the outgoing parton, a single charged hadron is generated. The distribution in the ratio of hadron energy to parton energy is taken to be the observed $z$ distribution (different for positive and negative charges). The hadron's momentum transverse to the parton is assumed to follow a Gaussian distribution of width $\sigma$ given by $\sigma^2 = \sigma_1^2 - z^2 \langle k_t^2 \rangle$, where $\sigma_1$ is taken from the observed $p_t$ distribution of hadrons' parametrized[29] as a function of $W^2$ and $z$ (and charge). Finally, the hadron system direction is smeared, in the lepton plane. For this smearing, we assume that the distribution in smearing angle in the lepton plane is equal to that perpendicular to the plane, and take the latter from our events. The correlation between the observed hadron and the smearing angle is taken into account. Fermi motion of the struck nucleon is included, but has only a small effect.

As is well known,[8,17,18] there is considerable reduction in asymmetry when one goes from the parton level to the hadron level. For $\sigma_k^2 = 0.10$ GeV$^2/c^2$, we find $\langle \cos\phi \rangle = -0.145$ for the parton (unsmeared), and $-0.027$ for a hadron with $x_F > 0.10$ after smearing. At the smeared hadron level, the size of the asymmetry is proportional to $\sigma_k^2$ for $\sigma_k^2 < 0.15$ GeV$^2/c^2$, but increases less rapidly with increasing $\sigma_k^2$ at larger $\sigma_k^2$ values. Thus, predicted $\langle \cos\phi \rangle$ values for $x_F > 0.10$ hadrons are $-0.027$, $-0.047$, and $-0.078$ for $\sigma_k^2 = 0.10$, 0.20, and 0.40 GeV$^2/c^2$, respectively.

To reproduce the observed $\langle \cos\phi \rangle$ for $x_F > 0.10$ positive hadrons, the model requires $\sigma_k^2 = 0.10 \pm 0.03$ GeV$^2/c^2$. However, the model predicts an almost equal asymmetry for negative hadrons. This near equality follows essentially from the similar observed $p_t$ distributions of positives and negatives (other neutrino experiments[30,31] also see such similar $p_t$ distributions). If we simply combine the two charges, the resulting $\langle \cos\phi \rangle$ value of $-0.018 \pm 0.0065$ ($x_F > 0.10$) is reproduced if $\sigma_k^2 = 0.065 \pm 0.024$ GeV$^2/c^2$. The observed difference between positives and negatives, at the two-standard-deviation level, is suggestive but not compelling evidence against the model. Therefore, it is still sensible to compare the predicted and observed kinematic dependences for positive and negative hadrons combined.

The predictions of the model, with $\sigma_k^2 = 0.065$ GeV$^2/c^2$, are shown as solid curves in Figs. 2(c), 3(c), and 4(c). Here, positive and negative hadrons with $x_F > 0.10$ are combined. The agreement between data and model is poor for the $x$ and $Q^2$ dependences; after appropriately binning the model's predictions, the $\chi^2$ confidence levels are 2.5% for $x$ and 1% for $Q^2$. In Ref. 15, agreement with a similar model was found to improve appreciably if the parton transverse momentum was taken to be proportional to $x$. Therefore, we tried $\sigma_k = bx$, with $b$ set to 1.22 to reproduce the $\langle \cos\phi \rangle$ value of all bins combined of $-0.018$. The resulting predictions are shown as dotted curves in Figs. 2(c) and 4(c) (the predicted $y$ dependence is essentially unchanged). The agreement in $Q^2$ dependence is considerably improved, with a $\chi^2$ confidence level of 55%. However, the agreement in the $x$ dependence is worse, with a $\chi^2$ confidence level of 0.7%. In Ref. 15, improvement in the $Q^2$ distribution was also noted, but no comparison of the $x$ dependence was made. Better agreement, in our case, results if we take $\sigma_k = 0.64\sqrt{x}$, where the 0.64 is again chosen to reproduce the $-0.018$ value for all bins combined. Then we get $\chi^2$ confidence levels of 28% for the $Q^2$ bins and 16% for the $x$ bins (and again the predicted $y$ dependence is almost unchanged).

We conclude that agreement of our data with this parton intrinsic-transverse-momentum model is marginal. The difference between positive and negative hadrons is not predicted, and the kinematic distributions require that the mean parton transverse momentum increase with $x$ something like $\sqrt{x}$.

We have also studied the asymmetry predicted for high-$z$ positive pions by the higher-twist contribution[10] [explicitly, by Eq. (4b) of Ref. 10]. The hadron transverse-momentum distribution and the hadron-system-direction smearing were taken to be the same as described earlier in this section. For $Q^2 > 1$ GeV$^2$ and $z > 0.5$, the predicted $\langle \cos\phi \rangle$ value for positive pions is 0.13, or 0.18 if we require $Q^2 < 10$ GeV$^2$. Such large values are clearly inconsistent with the observed values. It is possible that this contribution is canceled by the intrinsic-transverse-momentum contribution. The prediction from the latter (at $z > 0.5$) is $\langle \cos\phi \rangle = -0.04$ if $\sigma_k^2 = 0.10$ GeV$^2/c^2$, or $-0.12$ if $\sigma_k^2 = 0.40$ GeV$^2/c^2$. However, we cannot pursue this line of argument, because we do not know whether the two contributions are additive, and we do not know the higher-twist predictions for negative hadrons or at lower $z$ values.

We have not calculated the expected asymmetry arising from gluon emission, because of the difficulties in such calculations. However, we can compare our results with the qualitative predictions made earlier. Our results do agree with the predicted sign of the forward hadrons' asymmetry. But we do not see any significant $p_t$ dependence, and we see a more than two-standard-deviation asymmetry in backwards ($x_F < -0.10$) hadrons. Therefore, our results may argue against a dominant contribution from gluon emission. However, detailed calculations are required before any stronger conclusion can be drawn.

It is interesting that the charge dependence we observe is similar to that seen in two antineutrino experiments.[14,16] In all cases, only hadrons with the "leading hadron" charge show an asymmetry (although in all cases, the significance of the positive-negative difference is less than three standard deviations). In muon experiments, most or all of the intrinsic difference between charges is lost, and experiments have reported only the combined data.

Our average energy-weighted $\cos\phi$ value, $-0.0066 \pm 0.0033$, has the same sign as that found in Ref. 15, but is smaller in size. Smearing of the hadron-system direction in our experiment due to unobserved hadrons should reduce the size of the asymmetry. But it is difficult to make this reduction large enough. Monte Carlo studies show that a true average energy-weighted $\cos\phi$ value with the magnitude and $y$ dependence of Ref. 15 would be reduced by hadron direction smearing to $-0.0135 \pm 0.0025$ (error from Ref. 15). This value is 1.7 standard deviation larger than our observed value. We conclude that we see a smaller asymmetry than Ref. 15, although the two experiments have similar mean $E_\nu$ and $Q^2$ values.

Comparison with the muon experiments is not straightforward, but we can look at the implied $\langle k_t^2 \rangle$ values. Reference 13 required $\langle k_t^2 \rangle$ greater than 0.77 GeV$^2/c^2$ in order for their model, which included gluon emission, to reproduce their $x_F > 0$ results. Our data are clearly inconsistent with such a large value, even after allowing for their maximum allowed $k_t$ value. If this maximum value is included in our model calculations, our observed positive hadron asymmetry is reproduced if $\sigma_k^2 = 0.19 \pm 0.08$ GeV$^2/c^2$ ($\langle k_t^2 \rangle = 0.15 \pm 0.06$ GeV$^2/c^2$).

## CONCLUSIONS

In a neutrino-neon experiment with $\langle E_\nu \rangle = 100$ GeV and $\langle Q^2 \rangle = 17$ GeV$^2$, we have looked for a left-right asymmetry in the azimuthal-angle distribution of individual hadrons. A significant asymmetry was found for forward positive hadrons; for $x_F > 0.10$ we found $\langle \cos\phi \rangle = -0.029 \pm 0.008$. In contrast, negative hadrons with $x_F > 0.10$ gave $\langle \cos\phi \rangle = 0.004 \pm 0.011$, a greater than two-standard-deviation difference. Positive and negative hadrons combined, with $x_F > 0.10$, gave $\langle \cos\phi \rangle = -0.018 \pm 0.0065$.

For hadrons with $x_F > 0.10$, the predictions of a model which included parton intrinsic transverse momentum $k_t$ were compared with the data. The model reproduced the combined $\langle \cos\phi \rangle$ value of $-0.018 \pm 0.0065$ if $\langle k_t^2 \rangle = 0.065 \pm 0.024$ GeV$^2/c^2$. But the model predicted almost equal asymmetries for positive and negative hadrons. Moreover, the model showed poor agreement with the observed $x$ and $Q^2$ dependences of $\langle \cos\phi \rangle$ if the $k_t$ distribution was taken to be independent of kinematic variables.

The large asymmetry for $z > 0.5$ positive pions, predicted by particular higher-twist terms,[10] was not observed.

The charge dependence of the asymmetry was similar to that seen in two antineutrino experiments; at the two-standard-deviation level, only "leading charge" hadrons have an asymmetry. The asymmetry we found was somewhat less than that seen in a neutrino counter experiment. Indirect comparisons suggested that the asymmetry we found was considerably less than that seen in muon-hydrogen experiments.

We conclude that more work on this topic, both experimental and theoretical, is needed.

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