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Current and Target Jets produced
in High Energy Neutrino-Deuterium Interactions

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ABSTRACT

In an analysis of $\sim 7,000$ charged current ν -deuterium interactions from an exposure of the Fermilab 15 foot bubble chamber to a wide band neutrino beam, we observe that the single quark jet (current fragments) has a wider spread in P_t than that from the recoiling diquark jet (target fragments) for $W > 9$ GeV which suggests an effect of gluon emission from the single quark.

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In the naive quark parton model (QPM), an outgoing single quark produced in lepton-nucleon collisions is expected to have the same jet behaviour as in e^+e^- interactions. Indeed, it has been reported [1, 2] that the jet behaviour in the two processes are quite similar in terms of the variables of sphericity, thrust, and energy flow, in the c.m. energy range $5 < W < 15$ GeV. However, it has been suggested [3, 4] that, due to gluon emission, the single quark jet (the current fragment) produced in lepton-nucleon collisions has a wider jet size compared to that from the recoiling diquark system (target fragment), implying different properties of jets produced in lepton-nucleon and in e^+e^- collisions.

In this paper, we present results obtained from a study of jets produced in high energy ν -deuterium interactions. In particular, we analyze the data in terms of the transverse momentum, P_t , and the hadronic energy, W , in the rest frame of the virtual boson-nucleon system. The use of the variable, W , has been suggested by Mazzanti et al [5], to avoid unwanted complication due to the finite experimental energies. We also examine that the current axis (direction of the virtual boson) is the appropriate axis for the jet analysis of ν -nucleon collisions and compare the size of the outgoing single jet with that of the recoiling diquark jet in the energy range $2 < W < 18$ GeV and show difference in $\langle P_t^2 \rangle$ between these two jets.

The data sample is obtained from an exposure of the Fermilab 15-foot deuterium filled bubble chamber to a wide-band single-horn focussed neutrino beam produced by 350 GeV/c protons. The present analysis is based on the event measurements obtained from 53% of the

total film, corresponding to a flux of 2.6×10^{18} protons on target. The film was scanned twice for events with two or more charged prongs with visible energy > 2 GeV produced by neutral particles. Measurements of these events were processed through TVGP. The overall processing efficiency is ~ 76 % including rescanning and remeasurement.

To reduce background induced from low energy neutral hadron events, we require that the sum of P_L for all visible secondaries be greater than 5 GeV/c, where P_L is the longitudinal momentum in the ν beam direction. The charged current events are, then, extracted by applying the kinematic method [6] to these selected sample, where we take a cut value of the μ^- transverse momentum relative to the other total visible particles, $P_{Tr} > 1$ GeV/c. The ν energy, E_ν , is calculated by

$$E_\nu = P_L^\mu + P_L^c + P_\ell^c \cdot [\vec{P}_t^\mu + \vec{P}_t^c] / P_t^c \quad (1)$$

where $P_L^\mu (P_t^\mu)$ and $P_L^c (P_t^c)$ are the longitudinal (transverse) momentum of the μ^- and the charged hadron system relative to the ν direction, respectively. From these selections, we obtained a raw data sample of 7021 ν -d events with $E_\nu > 10$ GeV in a fiducial volume of 18.8 m^3 . We further require that the charged hadron multiplicity be greater than 3 following the e^+e^- jet analysis. We also remove events with the Bjorken variable $y > 0.9$ where the ν -energy obtained from Eq. (1) gives large deviation from the true value. These

selections yields a final sample of 3162 events for $W > 2$ GeV.

Background events from γ -neutral and $\bar{\nu}$ -charged current events are estimated by using a Monte Carlo simulation and is found to be $\sim 4\%$ and $< 1\%$ of these selected events. Background induced from neutral hadron interactions is difficult to estimate. Using the two-prong events fitted to $K_S^0 \rightarrow \pi^+ \pi^-$ and $\Lambda \rightarrow p \pi^-$ hypotheses, we calculate the K^0 and Λ fluxes and estimate background from the neutral strange particles to be less than 3%. No reliable estimate of neutron induced background is obtained; our best estimate is $\sim 5\%$ in this sample.

Because of neutral particle missing in $\gamma + N$ collisions, the jet axis defined by thrust, sphericity and spherocity does not represent the direction of the single quark. Instead, we take the current axis (direction of the virtual boson) as a reference axis and consider the transverse momentum, P_t , measured from this axis for the forward and backward particles in the virtual boson-nucleon c.m. system. Of course, the current axis would deviate from the single quark axis because of the smearing effect due to the primordial transverse momentum of the confined quarks in the nucleon and the small internal motion of nucleons in the deuterium. However, the P_t vector sums for all particles from such effects would balance between the forward and backward hemispheres. Hence, if any difference is observed in P_t^2 between the two hemispheres, it exhibit the difference in the jet properties between the single quark and the recoiling diquark system.

Fig.1 shows the P_t^2 distributions in the forward and backward hemispheres, defined by a plane perpendicular to the current axis; (a) for the hadronic energy $5 < W < 8$ GeV and (b) for $9 < W < 18$ GeV. The data points are corrected for the prong-dependent scan-measuring efficiency. The data are also corrected for an effect arising from our kinematic selection of the charged current events by using a Monte Carlo simulation, where the largest correction comes from contamination of antineutrino charged current events which becomes important in the hadronic energy $W > 12$ GeV for the forward hemisphere. As seen in Figs. 1, the two distributions for $5 < W < 8$ GeV are indistinguishable, while for $9 < W < 18$ GeV, the shape in the forward hemisphere is wider than that in the backward hemisphere.

The curves in Figs. 1 are obtained from fits of the form, $\exp(-B\sqrt{P_t^2 + m_{ll}^2})$ indicating that such a function describes the data fairly well for both hemispheres. The slope parameters, B , obtained from the fits are given in Table 1.

In order to show the W -dependence of the P_t^2 distributions, we show in Fig. 2 (a) the $\langle P_t^2 \rangle$ as a function of W in the current and target hemispheres. The most striking feature in this figure is that the two $\langle P_t^2 \rangle$'s have approximately the same magnitudes and rise together with W upto 8 GeV and then start deviating from each other for $W > 9$ GeV: the current $\langle P_t^2 \rangle$ keeps increasing, whereas the target $\langle P_t^2 \rangle$ levels off at about 0.15 GeV^2 , indicating different jet properties of the single quark and the diquark system.

Fig. 2 (b) shows the W -dependences of $\langle P_t^2(T) \rangle$ for the forward

and backward hemispheres, where $P_t(T)$ is the transverse momentum measured from the thrust axis. Apparently, both the current and target $\langle P_t^2(T) \rangle$'s having almost the same magnitudes rise together with W and no deviation as seen in Fig. 2 (a) is observed in the energy range discussed here. This is due to the fact that the procedure used to determine the thrust axis tends to balance the transverse momenta between the forward and backward particles. Therefore, analyses using the thrust or sphericity axis is not so sensitive to see a small difference between the two hemispheres. The open square points in Fig. 2 (b) are the $\langle P_t^2(T) \rangle$ from the e^+e^- experiment [7] and plotted for comparison. Fairly good agreement is seen between the γ -d and the e^+e^- data for $W < 18$ GeV.

The inaccuracy of the γ energy calculation in Eq. (1) primarily comes from the missing neutral particles and causes deviation of the current axis. Consequently, this might give the incorrect $\langle P_t^2 \rangle$ value. We have examined this effect using the $\langle P_t^{2 \text{ out}} \rangle$ defined as the transverse momentum squared measured perpendicular to the plane containing the incident γ and the outgoing μ^- . This $\langle P_t^{2 \text{ out}} \rangle$ is not influenced by the deviation of the current axis and is related as $\langle P_t^{2 \text{ out}} \rangle = \langle P_t^2 \rangle / 2$ if the $\langle P_t^2 \rangle$ is correctly measured. From this examination, we find that the $\langle P_t^{2 \text{ out}} \rangle$ agrees with the $\langle P_t^2 \rangle / 2$ within error for both hemispheres in the whole energy range $2 < W < 18$ GeV. The results of these $\langle P_t^{2 \text{ out}} \rangle$'s are shown in Fig. 3.

The value of $\langle P_t^2 \rangle$ could also change if the P_t is measured from the direction of momentum vector sum of all charged and neutral particles in the forward hemisphere. This is examined by using

the Monte Carlo simulation. This axis defined in this way might not give the correct single quark axis, but this is used as an example of the quark axis. The results of the simulation show that the jet axis differs from the current axis by an average of 7° for $W > 9$ GeV in the virtual boson-nucleon c.m. system, but the value of $\langle P_t^2 \rangle$ with respect to the jet axis is reduced by only $\sim 10\%$ compared to that relative to the current axis.

In order to see whether the observed $\langle P_t^2 \rangle$ deviation in Fig. 2 (a) is correlated with the charged multiplicity, Fig. 4 show the averaged charged multiplicities $\langle n_{ch} \rangle$, for the forward and backward hemispheres. The $\langle n_{ch} \rangle$ for the target hemisphere in general gives smaller values than the current $\langle n_{ch} \rangle$. Both target and current $\langle n_{ch} \rangle$ rise together with W , but no significant $\langle n_{ch} \rangle$ behaviour which explains the $\langle P_t^2 \rangle$ deviation is observed for $W > 9$ GeV. Recall that we have used the events with the hadron multiplicity equal or greater than 4.

Figs. 5 (a) and (b) show the X_F distributions of $\langle P_t^2 \rangle$ for $5 < W < 8$ GeV and $9 < W < 18$ GeV, respectively, where X_F is the Feynman variable defined in the virtual boson-nucleon system. Fig. 5 (a) seems to indicate the seagull effect for $5 < W < 8$ GeV which reflects the larger target $\langle P_t^2 \rangle$ compared to the current $\langle P_t^2 \rangle$ in Fig. 2 (a). Fig. 6 show the $\langle P_t^2 \rangle$ for the positive and negative charged particles in the forward hemisphere. It is interesting to note that both $\langle P_t^2 \rangle$'s rise together with W , but start deviating from $W > 6$ GeV.

Since non-perturbative effects such as the primordial quark motion inside the nucleon are expected to give W -independent contribution to $\langle P_t^2 \rangle$, the flattening of the target $\langle P_t^2 \rangle$ observed in Fig. 2 (a) suggests that the recoiling diquark receives only the non-perturbative contribution for $W > 9$ GeV, while the rise of the current $\langle P_t^2 \rangle$ seems to indicate the presence of the additional contribution to the outgoing single quark due to the gluon emission. As has been suggested in the theoretical works on lepton-nucleon jets [3, 4, 8, 9], the first-order QCD calculations indicate that the perturbative effects are expected to be small and to be masked by the non-perturbative effects in the energy range discussed here. However, our observation seems to indicate that the first-order QCD effect begins to be observed in the $\langle P_t^2 \rangle$ for the current fragmentation region of $W > 9$ GeV. This could also suggest that our analysis of $\langle P_t^2 \rangle$ behaviour as a function of W is sufficiently sensitive to see the small QCD effect in this energy region.

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Table 1 Slope parameters for P_t^2 distributions
in the form $\exp(-B\sqrt{P_t^2 \text{ (mb}^2\text{)}}$)

energy range W (GeV)	current B (GeV ⁻¹)	target B (GeV ⁻¹)
5 < W < 8	6.6 $\pm$ 1.2	6.5 $\pm$ 1.2
9 < W < 18	6.1 $\pm$ 1.3	6.6 $\pm$ 1.3

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Figure Captions

- Fig. 1 P_t^2 distributions (a) for $5 < W < 8$ GeV and (b) for $9 < W < 18$ GeV. The dark dot points are for the current and the open circle points are for the target fragmentation region. The data points for the target fragmentation region are reduced by a factor of 1/10.
- Fig. 2(a) Plot for $\langle P_t^2 \rangle$ vs. W .
 (b) Plot for $\langle P_t^2(T) \rangle$ vs. W , where $P_t(T)$ is the transverse momentum measured from the thrust axis. The dark dot points are for the current and the open circle points are for the target fragmentation region. The open squared points are the e^+e^- data [7].
- Fig. 3 Plot for $\langle P_t^{2 \text{ out}} \rangle$ vs. W . The dark points are for the current and the open circle points are for the target fragmentation region.
- Fig. 4 Plot for $\langle n_{ch} \rangle$ vs. W for the current (dark points) and the target fragments (open circle points)
- Fig. 5 X_F distribution of $\langle P_t^2 \rangle$ for (a) $5 < W < 8$ GeV
 (b) $9 < W < 18$ GeV.
- Fig. 6 $\langle P_t^2 \rangle$ vs. W for (a) positive (dark points) and
 (b) negative tracks (open circle points) in the forward hemisphere.

Fig. 1

Fig. 2

IMSTT Collaboration

Fig. 3

IMSTT Collaboration

Fig. 4

Fig. 5

IMSTT Collaboration

Fig. 6