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Evidence for Hard-Gluon Bremsstrahlung in a Deep-Inelastic Neutrino Scattering Experiment

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Data from νN interactions in the Fermilab 15-ft bubble chamber show that the mean transverse momentum (p_T) of forward hadrons in the hadron c.m. system exceeds that of backward hadrons for $W^2 > 100$ GeV^2. Events with high π_F, a measure of forward p_T, tend to have planar hadron systems and show a three-jet structure in their angular energy flow; their number exceeds that expected in two-jet models. These observations are consistent with quantum chromodynamic predictions of hard-gluon bremsstrahlung.

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Gluon bremsstrahlung can account for the results of several recent experiments. Groups at PETRA[1] observe evidence for three-jet events whose origin may be $e^+e^- \to q\bar{q}g$ (q denotes quark; g denotes gluon). The analogous process in weak (electromagnetic) deep-inelastic scattering is $W^\pm q(\gamma^* q) \to qg$ ($W^\pm$ are the intermediate vector bosons, γ^* is the exchanged virtual photon), where the remaining diquark in the target nucleon is a spectator to the interaction. Evidence that this process contributes substantially to the total deep-inelastic cross section at high energy comes from both neutrino[2,3] and muon[4] experiments. We report here the observation, in a neutrino experiment, of three-jet events whose properties are consistent with those expected for hard-gluon bremsstrahlung ($W^\pm q \to qg$) events.

Neutrinos (ν_μ) from the Fermilab quadrupole-triplet beam interacted in the 15-ft bubble chamber filled with a 47-at.% Ne-H mixture. Muons from charged-current interactions were identified by the two-plane external muon identifier.[5] A sample of 5433 charged-current events was completely measured. Charged primary tracks, pointing γ's, and pointing V^0's are accepted if they have momentum errors $<30\%$ (90% of such tracks), while all other particles are treated as undetected. Tracks with $x_F < -0.7$ ($x_F \equiv 2p_L^{\text{c.m.}}/W$, with p_L the longitudinal momentum and W the mass of the hadron system) are discarded, as they are predominantly neon fragments, and very few tracks from the weak interaction have $|x_F| > 0.7$. For each event the neutrino energy, E_ν, is then computed by using a method that accounts for undetected hadrons by balancing perpendicular momentum in the lepton plane.[6] The muon momentum, $\vec{P}_\mu$, and E_ν are used to compute kinematic quantities such as Q^2 and W^2. Hadron transverse momenta (p_T) and Lorentz transformations to the hadron c.m. system are taken with respect to the direction of the sum of the accepted hadrons' momenta, $\hat{Q}_{\text{vis}}$.

Only deep-inelastic events in which reconstruction of the hadron system is likely to be reliable are analyzed. Starting with 4514 events with $E_\nu > 10$ GeV, $Q^2 > 2$ GeV^2, and $W^2 > 4$ GeV^2, we discard 84 in which $\vec{P}_\mu^{\perp}\cdot\vec{P}_H^{\perp} > 0$, and 830 with $P_H^{\parallel} > 2.4\,P_{H\,\text{vis}}^{\parallel}$, in which most of the hadron energy is not visible ($\perp$ and $\parallel$ denote the components of a vector perpendicular and parallel to $\vec{P}_\nu$). Requiring at least three charged-hadron tracks per event leaves a final sample of 3180 events. The average values of E_ν, Q^2, and W^2 in this sample are 107 GeV, 23 GeV^2, and 70 GeV^2. Monte Carlo studies show that for individual events the rms errors in the above quantities are 14%, 18%, and 32%, respectively, with -3%, $+3\%$, and -5% biases, and the typical error in the direction of $\hat{Q}_{\text{vis}}$ (in the laboratory) is $\approx 5°/W$, with W in GeV.

We analyze our data in the framework provided by perturbative quantum chromodynamics (QCD). The weak current in νN scattering defines a forward longitudinal direction, $\hat{Q}$, in the hadron c.m. system. QCD predicts that the hard gluons in $W^{\pm}q \to qg$ events will be emitted predominantly in the forward hemisphere[7] (in contrast to the symmetry in $e^+e^- \to q\bar{q}g$). Thus we look for a signal in the forward direction and use the backward direction as a source of information on nonperturbative effects. In Fig. 1 we plot $\langle p_T^2\rangle_F$, $\langle p_T^2\rangle_B$, and $\Delta p_T^2 \equiv \langle p_T^2\rangle_F - \langle p_T^2\rangle_B$ as functions of W^2 for charged hadrons that have $|x_F| > 0.05$ (the subscripts B and F stand for backward and forward). We see a forward-backward-symmetric rise in $\langle p_T^2\rangle$ with W^2 up to ≈ 50 GeV^2, as predicted by conventional (non-QCD) longitudinal phase-space and two-jet models. At high W^2, $\langle p_T^2\rangle_F$ is significantly larger than $\langle p_T^2\rangle_B$; combining all $W^2 > 100$ GeV^2 events yields $\Delta p_T^2 = 0.047 \pm 0.011$ GeV^2. Monte Carlo studies show that, for all W^2, $\hat{Q}_{\text{vis}}$ tends to lie closer to the direction of the forward hadrons than to that of the backward hadrons; thus the true Δp_T^2 values are actually slightly larger than those of Fig. 1. We have

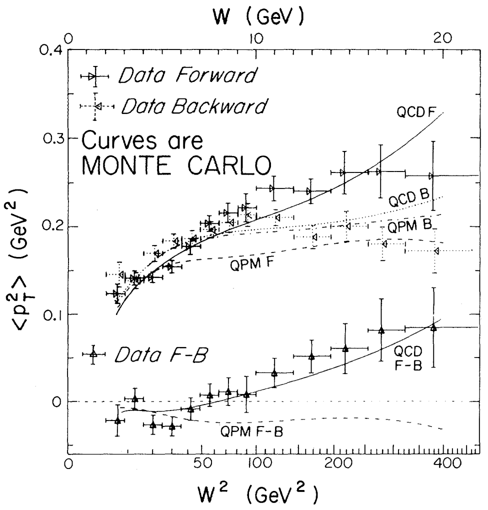

FIG. 1. $\langle p_T^2\rangle_F$, $\langle p_T^2\rangle_B$, and Δp_T^2 for tracks with $|x_F| > 0.05$. The two-jet QPM and the QCD model calculations are described in the text.

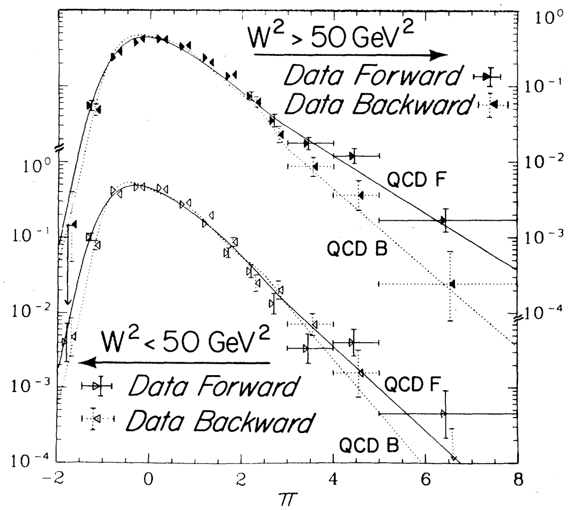

FIG. 2. The $\pi_{F(B)}$ distributions for $W^2 < 50$ GeV^2 and $W^2 > 50$ GeV^2, with the QCD model curves superimposed. $n_{F(B)} = 0$ events are not included.

checked that we obtain results consistent with those above when we analyze momenta perpendicular to the lepton plane, which are independent of $\hat{Q}_{\text{vis}}$.

To investigate the origin of the increasing Δp_T^2, we study variables that describe the transverse momentum structure of individual events, in contrast to variables such as $\langle p_T^2\rangle$ that describe averages over tracks in an ensemble of events. Extending a suggestion by Georgi and Sheiman,[8] we consider first $\pi_{F(B)} = [A/(n_{F(B)})^{1/2}]\sum_{F(B)}(p_T - p_{T0})$, where the sum is taken over the $n_{F(B)}$ forward (backward) charged hadrons with $|x_F| > 0.05$. In two-jet events, each track on average has p_T equal to the typical two-jet value p_{T0}; thus the sum is almost a random walk of $n_{F(B)}$ steps starting from zero, giving the $\pi_{F(B)}$ distribution a mean near zero and a width approximately independent of multiplicity. The constant A is chosen to give $\langle \pi_F^2\rangle \approx 1$. In $W^{\pm}q \to qg$ events, if the gluon p_T is much greater than p_{T0}, most of a hadron's p_T comes from its share of its parent parton's transverse momentum. Most such events should have both the quark and the gluon moving forward in the hadron c.m. system, and so should contribute significantly to a tail at high π_F but not to a tail at high π_B.

Taking p_{T0} to be 0.320 GeV and A to be 4.0 GeV^{-1} gives the π_F and π_B distributions shown in Fig. 2. For $W^2 < 50\ \text{GeV}^2$ the π_F and π_B distributions are very similar; however, for $W^2 > 50\ \text{GeV}^2$ the forward distribution has a larger tail at high π. As they do for Δp_T^2, instrumental effects tend to diminish the forward/backward difference we observe at high π.

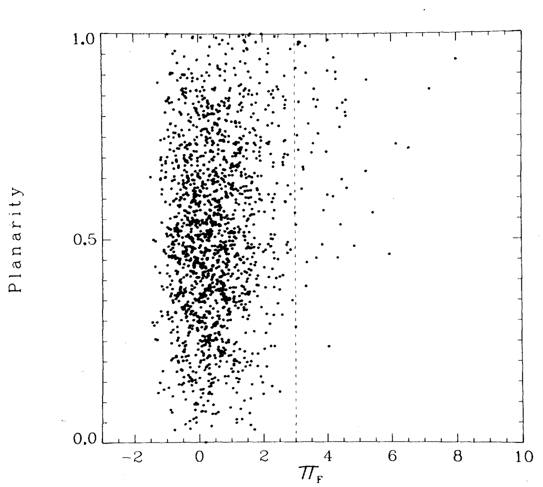

FIG. 3. π_F vs P for events with $W^2 > 50\ \text{GeV}^2$ and $n_{F(B)} > 0$.

The p_T due to hard-gluon bremsstrahlung should be found in the plane formed by the three partons. Therefore, in the plane normal to $\hat{Q}_{\text{vis}}$ we determine the two orthogonal directions $\hat{u}_1$ and $\hat{u}_2$ which maximize planarity, $P = \sum(p_{T1}^2 - p_{T2}^2)/\sum(p_{T1}^2 + p_{T2}^2)$, where p_{T1} and p_{T2} are the projections of a hadron's transverse momentum on $\hat{u}_1$ and $\hat{u}_2$. These sums are taken over all hadrons (including neutrals) so that P measures the transverse shape of the hadron system as a whole. In Fig. 3 we show a scatter plot of π_F vs P for the 1552 events with $W^2 > 50\ \text{GeV}^2$. High-π_F events are clearly more planar than those in the bulk of the sample (for $\pi_F < 2.0$, $\langle P\rangle = 0.51 \pm 0.01$; for $\pi_F > 3.0$, $\langle P\rangle = 0.73 \pm 0.02$). Monte Carlo studies show that this correlation is not required by phase space. Nor does it result from the small variation of the multiplicity distribution with π_F.

The *angular energy flow* in the hadron c.m. system, $\Sigma^{-1}d\Sigma/d\Omega$ [where $d\Sigma \equiv (2E^{\text{c.m.}}/W)d\sigma$ is the energy-weighted cross section], is projected onto the $(\hat{Q}_{\text{vis}}, \hat{u}_1)$ plane for the $W^2 > 50\ \text{GeV}^2$ sample as a whole in Fig. 4(a), and for the subsample with $\pi_F > 3.0$ and $P > 0.5$ in Fig. 4(b). The first plot has an apparent two-jet structure and the second an apparent three-jet structure. Events in the region of phase space defined by high π_F and high P for our range of W^2 are kinematically constrained to give a two-lobed shape in their forward angular energy flow. Some such events

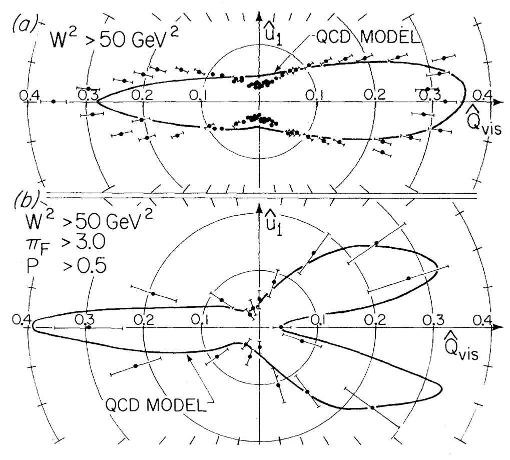

FIG. 4. (a) The angular energy flow, projected onto the $(\hat{Q}_{\text{vis}}, \hat{u})$ plane, for all events with $W^2 > 50\ \text{GeV}^2$. The curve is the QCD model calculation. (b) Same as (a), but for the 47 events with $\pi_F > 3.0$ and $P > 0.5$. Kinematic effects and forward-backward–symmetric backgrounds are discussed in the text.

will be generated in two-jet models as extreme fluctuations and constitute background for any real three-jet signal. For $W^2 > 50$ GeV^2 we observed 18 events with $\pi_B > 3.0$. From Monte Carlo studies we have determined that our experimental acceptance for $\pi_F > 3.0$ is only 75% of that for $\pi_B > 3.0$. Thus, the forward-backward-symmetric (two-jet) component of $\pi_F > 3.0$ is $\approx 14 \pm 4$ events. We observe 55, leaving a net signal of 41 ± 9 three-jet events in this particular region of phase space.

We have made Monte Carlo calculations[6] based on a quark-parton model (QPM) and on a QCD model. E_ν and the Bjorken scaling variables, x and y, are generated for each event from the beam spectrum and standard structure functions. These variables determine the quark and diquark momenta in QPM. The QCD calculation uses the $W^{\pm} q \rightarrow qg$ cross section from Peccei and Ruckl,[7] cut off at low p_T by the Sudakov form factor,[9] to generate the hard-gluon bremsstrahlung events. Fermi motion in neon and charm production (of order 5%–10%) are included in both models. Partons are turned into hadron jets by the TUBES[10] implementation of a Field and Feynman model.[11] The detector response is simulated event by event, and the Monte Carlo sample is analyzed with the cuts and reconstruction procedures described for the data.

We adjusted two parameters in the TUBES program to fit our $\langle p_T^2 \rangle_B$ and π_B data. We increased the $\langle k_T \rangle_{\rm rms}$ of vacuum-polarization quark-antiquark pairs from Field and Feynman's 350 to 380 MeV, and set the fraction of primary mesons produced as vector mesons to rise linearly from 0 to $\frac{1}{2}$ between $W = 2$ and 10 GeV. In the QCD model we also adjusted α_s so that our calculations of $\langle p_T^2 \rangle_F$ and π_F agree with the data. In the resulting Monte Carlo calculation 20% of the $W^2 > 50$ GeV^2 events are $W^{\pm} q \rightarrow qg$ with the quark-gluon invariant mass $M_{qg} > 2$ GeV and 80% of those with $\pi_F > 3.0$ are $W^{\pm} q \rightarrow qg$. For $W^{\pm} q \rightarrow qg$ events with $\pi_F > 3.0$, the Monte Carlo calculation gives $\langle Q^2 \rangle = 43$ GeV^2, $\langle W^2 \rangle = 154$ GeV^2, $\langle M_{qg}{}^2 \rangle = 25$ GeV^2, and $\langle \alpha_s \rangle = 0.29$.[12] This value of α_s is somewhat higher than those measured by groups at PETRA,[1] as expected in QCD since ours is a lower-energy experiment.

While the two-jet QPM calculation adequately accounts for most features of the data, including the backward p_T structure, it does not account for the forward-backward asymmetries in p_T. Since these are not instrumental effects (and not due to charm production), there must be an underlying process which distinguishes between the two directions. The QCD calculation shows that hard-gluon bremsstrahlung can account quantitatively for our Δp_T^2 results and for the three-jet signal we observe at high π_F.

We confirm earlier observations[2-4] that the transverse momentum of forward hadrons increases with W^2 in deep-inelastic scattering, and that this increase is greater than that for backward hadrons. Using π_F and P, which measure transverse momentum properties of individual events, we have identified 55 events ($\pi_F > 3.0$) that have three-jet structure, two jets forward and one backward, where 14 ± 4 are expected from two-jet events (assuming forward-backward symmetry). Our Monte Carlo calculations agree with the data only if we include the $W^{\pm} q \rightarrow qg$ term predicted by QCD. We interpret this as evidence for hard-gluon bremsstrahlung.

We are grateful to C. Day for providing us with his TUBES program and much useful advice. We are also pleased to acknowledge valuable discussions of QCD with J. Sheiman, F. Halzen, I. Hinchliffe, and D. M. Scott and thank S. Ellis for suggesting that we could study angular energy flow in this experiment. This work was supported in part by the U. S. Department of Energy and the National Science Foundation.

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Two-Body Scaling in *p*-Nucleus Inclusive Reactions at Large Momentum Transfer

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Inclusive reactions $p+A \to p'+X$ are studied at large angles. Binding and Pauli exchange effects are treated in a consistent way. These effects restore the two-body scaling in spite of the orthogonality of the ground and continuum states. Kinematic variables that enter our calculations are very much different from those in the phenomenological analyses. This leads to a very good agreement with the data for light nuclei ^{4}He, ^{6}Li, and ^{9}Be at $T_p = 500-800$ MeV, $\theta = 180° - 90°$ with use of one universal one-nucleon momentum density.

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In the recent series of papers[1,2] we proposed a new microscopic approach to hadron-nucleus (or nucleus-nucleus) reactions with an emphasis on the consistent treatment of the Pauli and binding effects, which play a very important role in the hadron-nucleus large-angle scattering. In this Letter our approach is extended to the inclusive large-angle proton production. In this framework we find the two-body scaling suggested earlier by Frankel from phenomenological analysis of data.[3,4] We obtain, however, that this scaling is due to a quite different explanation, and the Frankel formula should thus be essentially modified. Detailed derivation and extension to the nucleus-nucleus scattering and π production will be given in a separate publication.[5] This Letter describes our results for pA inclusive reactions and presents our analysis of existing data for light nuclei.

The most interesting idea in the analysis of inclusive reactions $p+A \to p'+X$ for large momentum transfer is the quasi-two-body scaling,[3,4] according to which the inclusive cross section can be written as[3]

$$\frac{1}{A}\frac{d\sigma_{pA}}{d^3p'} = C\,\frac{G(k_{\min})}{|\vec{p}-\vec{p}'|}. \tag{1}$$

Here $G(k_{\min})$ is the integral over the universal one-nucleon momentum density distribution $n(k)$,

$$\int_{k_{\min}}^{k_{\max}} n(k)k\,dk = G(k_{\min}) - G(k_{\max}) \cong G(k_{\min}). \tag{2}$$

$k_{\min}$ ($k_{\max}$) is the minimum (maximum) momentum of the recoil nucleus $(A-1)$ in the reaction $p+A \to p'+N+(A-1)$. The interpretation of Eqs. (1) and (2) is as follows. The projectile proton ($\vec{p}$) scatters forward off the off-shell target proton (of momentum $\vec{k}$) which is put on shell by the scattering and is then detected with momentum $\vec{p}'$. The residual target $(A-1)$ recoils with momentum $\vec{k}$. Since in the final state only one proton ($\vec{p}'$) is detected, $\vec{k}$ is integrated over in the cross section, Eq. (2). The quantity C therefore corresponds to the *off-shell pp* scattering. This quantity has usually been approximated by the elastic *on-shell* cross section,[6,7]

$$C = \frac{s(s-4m_p^2)}{32\pi^2 p m_p E_{p'}}\,\frac{d\sigma_{pp}(s,t)}{dt}. \tag{3}$$

(The contribution from pn charge exchange must also be added. However, it is small for high-energy scattering.) The Mandelstam variables s,t in Eq. (3) are usually put equal to those in the off-