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Study of parton transverse momentum using jets from hadron interactions

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We study the momentum unbalance in two-jet events which we have obtained with a two-arm calorimeter array at Fermilab. Although the unbalance is relatively sharply peaked near zero, the rms unbalance is considerably greater than that due to instrumental effects alone. We interpret the unbalance as being principally due to effects of parton transverse momentum K_T. We give results for the resolution-corrected rms unbalance (approximately equal to K_T) for a range of values of jet p_T. pp collisions are studied at three s values, and π^+p collisions are compared with them at two of these s values. The results are compared with information on K_T obtained from other experiments, principally experiments on dimuon production. Implications of the similarities and of the differences are discussed.

I. INTRODUCTION

The transverse momentum K_T of partons in a hadron has recently attracted considerable attention for two reasons. If K_T is sufficiently large, it may partially explain the apparent failure of the single-particle high-p_T spectrum to exhibit the expected p_T^{-4} dependence of simple hard scattering.[1,2] In addition quantum chromodynamics (QCD) should be able to calculate the details of that part of the K_T spectrum due to the radiation of gluons before and after the hard scatter.[3] Because of this, information on the K_T spectrum may serve as a test of QCD.

Previous experimental results have come primarily from two types of measurements: (1) Noncoplanarity of hadrons in single-hadron-triggered high-p_T studies and (2) transverse-momentum measurements of dimuons produced in hadron collisions. In the high-p_T single-hadron-trigger studies, carried out principally at CERN ISR, the noncoplanarity of the triggering hadrons with respect to other single hadrons in the opposite-azimuth hemisphere has been measured and described with a variable p_{out}, the momentum component of the away hadron which is orthogonal to the scattering plane defined by the beam and trigger particle. The first of these measurements, by Darriulat *et al.*[4] at the ISR, gave a mean magnitude of about 500 MeV/c for p_{out}. Similar results have been reported by Della Negra *et al.* at the ISR.[2] p_{out} values as measured for single away-side hadrons have also been reported by Bromberg *et al.*,[5] who found $\langle p_{out}\rangle \approx 350$ MeV/c. These values, all roughly similar, have been interpreted to imply $0.49 \lesssim \langle K_T^2\rangle \lesssim 0.58$ (GeV/c)^2 for a parton.[2,6]

More recently, the CERN-Columbia-Oxford-Rockefeller (CCOR) group at the ISR has made measurements for much higher values of p_T on both the trigger-side and the away-side hadrons. They have found that $\langle p_{out}\rangle$ shows a continuing increase with p_T of the away-side hadron, reaching values above 1.2 GeV/c for p_T (away-side hadron) of 5 GeV/c or more.[7] From their results it is evident that $\langle p_{out}\rangle$ increases both with p_T of the triggering particle and with p_T of the away-side hadron, at least for dihadron effective masses up to 10 GeV/c^2 or more. Their new larger values of $\langle p_{out}\rangle$ at higher p_T indicate that $\langle K_T^2\rangle$ is larger than previously indicated in high-p_T hadronic events.

Production of dimuon pairs in hadron collisions also relates to the K_T spectrum of the partons since the basic reaction is presumably a quark-gluon or quark-antiquark collision.[8] If the transverse momentum p_T of the dimuon[9] is thought of as coming simply from the two colliding constituents, then $\langle K_{T1}^2\rangle + \langle K_{T2}^2\rangle = \langle p_T^2\rangle$. For p-nucleus collisions at 400 GeV experimental values[10] of $\langle p_T^2\rangle$ increase with dimuon mass to a value of $\langle p_T^2\rangle \approx 1.9$ (GeV/c)^2 which is approximately constant for $M_{\mu\mu}$ above 5 GeV/c^2. If one naively assumes the colliding constituents contribute equally, then for the dimuon production one obtains $\langle K_T^2\rangle = \frac{1}{2}\langle p_T^2\rangle = 0.95$ GeV/c^2. It is to be noted that the mass dependence of $\langle p_T^2\rangle$ for the dimuon process shows a flattening above 5 GeV/c^2, while for the dihadron events the CCOR data show a continuing increase of $\langle p_{\text{out}}\rangle$ with mass for masses up to 10 GeV/c^2.

We discuss in this paper a detailed study of K_T using the data obtained in a two-arm "jet-pair" experiment. It was previously reported briefly[11-13] that in this experiment we have observed for the first time approximate p_T balance in the two arms. It appears that the p_T *un*balance gives information on the magnitude of parton $\langle K_T\rangle$. We start in the next section with a brief discussion of the nature of hadron jets as observed with a calorimeter trigger.

II. HADRON JETS

If parton-parton collisions give rise to pairs of hadron jets similar to those observed in e^+e^- collisions,[14] then one may hope to study K_T in parton collisions by studying jet pairs. Although it is not possible to define two jets in hadron collisions with the same simplicity as in e^+e^- collisions, two large calorimeters set to trigger when the scalar sum of the collected p_T exceeds a threshold appear to define a pair of high-p_T jets in a useful manner.[13,15,16] Jets thus defined tend to balance p_T, to yield expected πp and pp asymmetries,[11] and to give a pion structure function[15] that agrees both with data from the Drell-Yan process[17-19] and general theoretical expectations.[20,21] Results such as these coupled with our improved understanding of the reasons why a calorimeter is able to define a jet in a useful manner[22-24] lead us to believe that the information presented here may be directly related to parton scattering.

In the discussion which follows we rely heavily on one feature which we have found to be characteristic of calorimeter triggered jets. *Most of the jets which trigger the calorimeter have a spatial and momentum distribution such that a large fraction of the jet momentum and jet energy is contained in the calorimeter.* This fortunate result is the simple consequence of the steep p_T spectrum for jets at Fermilab energies $[dN/dp_T \approx \exp(-3p_T)$ to $\exp(-4p_T)]$. Those jets which incorrectly record appreciably lower jet momentum and jet energy because of missed fragments tend to be overwhelmed by lower-p_T jets which have less momentum and energy missing. We have verified this intuitive conclusion to our satisfaction both experimentally[25] and with extensive Monte Carlo calculations.[13]

III. APPARATUS

All data presented here were collected from an 18-in. liquid hydrogen target viewed by two calorimeter arms.[11] At each energy we have used only data collected when the calorimeters were positioned such that each arm subtended ~1.5 to ~2 sr centered around 90° in the center-of-mass system (c.m.s.). Six drift chambers located between the target and the calorimeters were used to identify sources of background and to study whether events originated in the target.

Target-empty rates were about 20% of target-full rates at every p_T value. The drift chamber information showed that the origin of these events was in the target wall and superinsulation, in target-empty gas, and in the scintillator immediately preceding the target. The apparent p_T for these last events is only a few percent greater than their true p_T so that no correction is made for their vertex location. We found no significant difference in the p_T depedence of target-full and target-empty data and have made no subtraction for this background in the distributions presented in this paper.

For runs at 130 and 200 GeV the left and right calorimeters subtended approximately the same c.m.s. solid angle. At 400 GeV the right calorimeter subtended a solid angle ~20% larger than the left calorimeter. At this energy some segments at the edge of the right calorimeter were omitted in the software trigger to symmetrize the two arms for subsequent K_T analysis. We have checked that this software reduction in the size of the right calorimeter does not affect the standard deviations of the p_T unbalance reported below.

IV. TRIGGER

Data were recorded for an event when the scalar sum of p_T in the two arms exceeded a preset threshold p_{th}: $|\vec{p}_T(\text{left})| + |\vec{p}_T(\text{right})| > p_{\text{th}}$. Three such thresholds were used in order to keep the copious lower-p_T events from dominating the trigger.

The highest threshold required the p_T hardware sum to be greater than about 6 GeV/c. A scatter plot of data taken with this threshold is seen in Fig. 1 for 400-GeV/c pp events. The plotted points are the magnitudes of the software sums of the $\vec{p}_T$(left) and $\vec{p}_T$(right) vectors, calculated by summing over all the individual calorimeter modules.

A software cut has been made along the line $|\vec{p}_T(\text{left})| + |\vec{p}_T(\text{right})| \approx 6$ GeV/c which corresponds roughly to the hardware threshold. In addition a very small number of events has been excluded because of unphysically large signals in

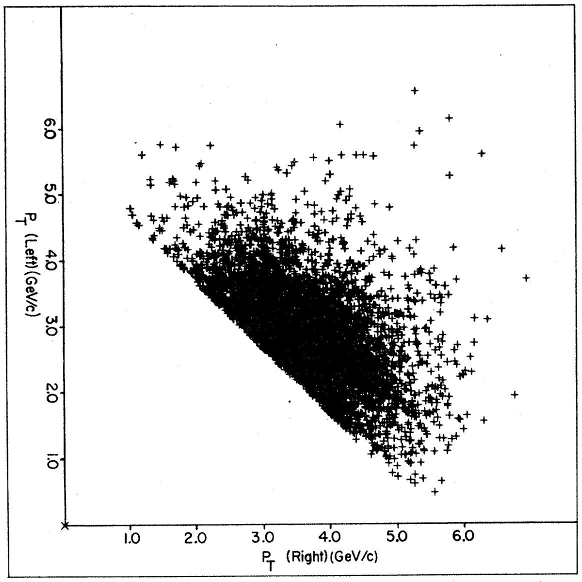

FIG. 1. Scatter plot of the uncorrected software scalar sum of p_T captured in the left calorimeter arm vs that captured in the right calorimeter arm for a trigger which requires $p_T(\text{left})+p_T(\text{right}) \gtrsim 6$ GeV/c. Beam particles are 400-GeV/c protons.

one module. Most of these appear to come from noise or large energy deposits from muon-produced δ rays.

A prominent feature of this scatter plot is the tendency for the p_T collected in the left arm to balance that collected in the right arm. There is no restriction in the trigger itself that would prefer such a balance. In fact this balance does not occur in a double-arm dihadron experiment which collects only one hadron in each arm.[26] As will be seen later, the balance we observe is much sharper than one can perceive in a simple scatter plot.

V. EVENT SELECTION

For the purpose of this study we have made a fiducial cut which restricts analysis to events which have the two jets directed in the laboratory at the central areas (±10° in c.m.s. azimuth and polar angles) of the respective calorimeter arms. About 15 to 20 percent of the events survive this central-region cut. We define a jet direction by the vector sum of observed momenta in the calorimeter modules of a particular arm. The original intent of this selection was to limit our sample of data to events in which almost all of the energetic jet fragments were captured by the calorimeters. We note that even without fiducial cuts the triggering events are heavily concentrated in these central regions of the calorimeter arms. This is because the steeply falling p_T spectrum for jet production strongly favors a trigger for those events in which almost all of the jet energy is collected, as discussed in Sec. II.

If we define a coordinate system having an x axis in a horizontal plane containing the beam and the calorimeter arms and having a vertical y axis, then this event selection constrains p_{TY} of the dijet system to small values while leaving p_{TX} unconstrained. In terms of the transverse momentum of parton constituents this event selection would remove from our data sample those scatters whose initial parton pair had a net component of transverse momentum (greater than ~600 MeV/c) perpendicular to the plane containing the beam and calorimeter arms.

We thus present only the unbalance p_{TX} in the x component of the transverse momentum for the two jets.[27] If the two colliding partons, 1 and 2, are assumed to have similar K_T distributions, then $\langle K_T^2\rangle^{1/2}$ of a single parton is the same as $\langle p_{TX}^2\rangle^{1/2}$.

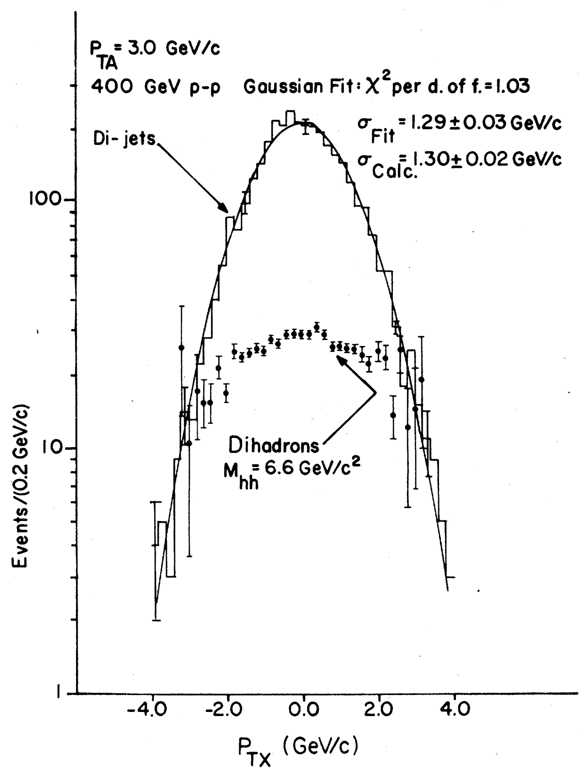

FIG. 2. x-components of the transverse-momentum unbalance for two jets having an average transverse momentum, p_{TA}, of 3.0 GeV/c per jet. Transverse-momentum *unbalance* is also the magnitude of the *vector sum* of the transverse momenta of the two jets. Dihadron data for a dihadron mass of 6.6 GeV/c^2 is proportional to invariant cross section taken from Ref. 26.

$$\langle p_{TX}{}^2\rangle = \langle K_{TX1}{}^2\rangle + \langle K_{TX2}{}^2\rangle$$
$$= \langle K_{TX1}{}^2\rangle + \langle K_{TY1}{}^2\rangle = \langle K_{T1}{}^2\rangle .$$

Therefore in what follows $\langle p_{TX}{}^2\rangle^{1/2}$ may also be interpreted as the rms transverse momentum of a single parton after applying some corrections to be discussed in Secs. VII and VIII.

Figure 2 shows a sample logarithmic plot of the distribution of this transverse-momentum unbalance centered in a band 0.8 GeV/c wide in a region of average transverse momentum $p_{TA} = [p_T(\text{left}) + p_T(\text{right})]/2.0 = 3.0$ GeV/c. It is strongly peaked at p_{TX} near zero and has a Gaussian behavior. Unlike the dimuon[28,29] experiments we are unable to see a significant deviation from Gaussian behavior, and our first and second moments are simply related by $\langle p_T\rangle^2 = \pi\langle p_T{}^2\rangle/4$, where $\langle p_T{}^2\rangle = 2\langle p_{TX}{}^2\rangle$. As a result we will hereafter mainly confine our discussion to $\langle p_{TX}{}^2\rangle$.

VI. DISTRIBUTION OF MOMENTUM UNBALANCE; COMPARISON OF π^+p AND pp COLLISIONS

The value of $\langle p_{TX}{}^2\rangle$ for the dijet is calculated directly from events meeting previously discussed selection criteria. It is in fact the square of the standard deviation of p_{TX} about the mean value of p_{TX}. The experimental mean value is not necessarily zero, but it is zero *within statistical limitations* for all data points presented here.

Figure 3 shows values of $\langle p_{TX}{}^2\rangle^{1/2}$ calculated using data from pp collisions with various values of the scalar sum $p_{TA} = [|\vec{p}(\text{left})| + |\vec{p}_T(\text{right})|]/2.0$. These values of p_{TA} correspond to bands of events orthogonal to the diagonal in Fig. 1. A value of p_{TA} is the average transverse momentum of the two jets in an event. For values of p_{TA} below ~1.5 GeV/c the range of p_{TX} in the selected bands becomes limited by their intersection with the coordinate axes of Fig. 1. No attempt is made to de-

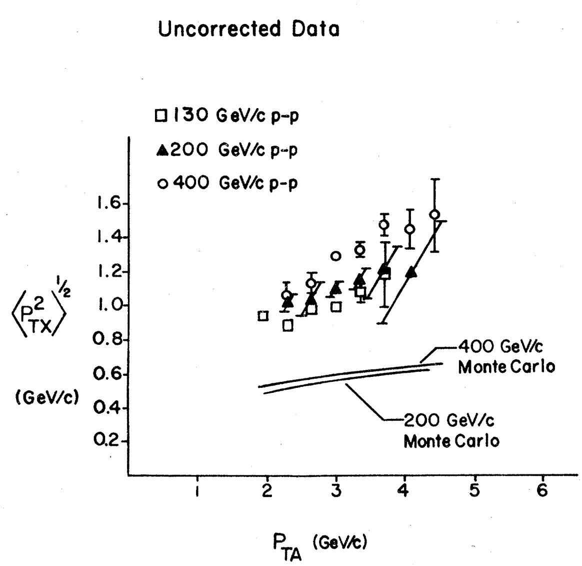

FIG. 3. Measured rms value of the x component of the transverse momentum of a jet pair as a function of the average transverse momentum, p_{TA}, of a jet in the pair. Points are data, and curves are Monte Carlo estimates of instrumental effects. Monte Carlo results at 130 and 200 GeV/c are identical.

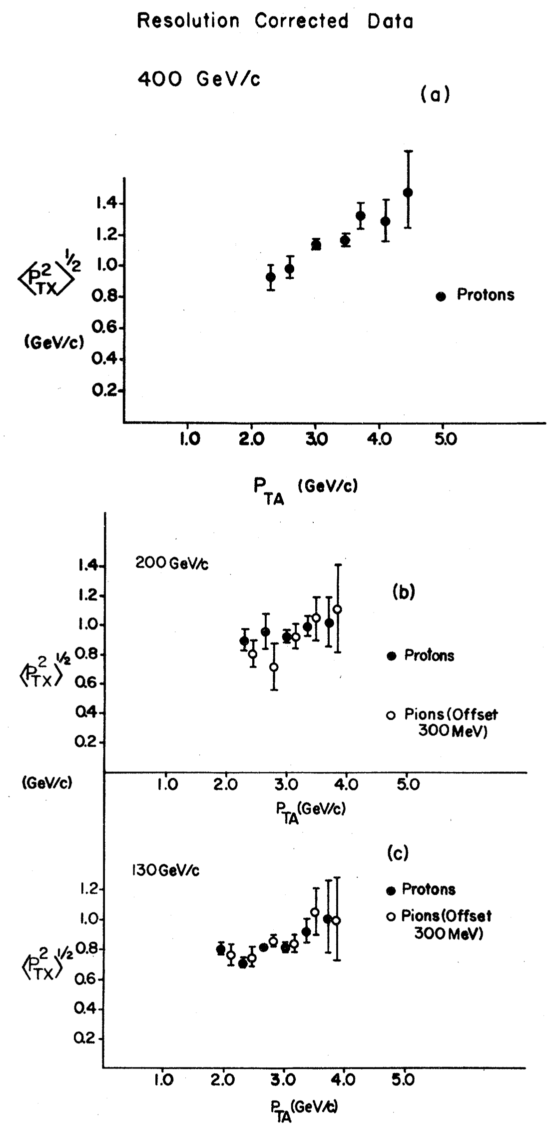

FIG. 4. rms value of the x component of the dijet transverse momentum after Monte Carlo correction for instrumental contributions as a function of the average transverse momentum p_{TA} of the two jets in an event. (a) 400-GeV/c pp data. (b) and (c) Comparison of proton and pion projectiles at 200 and 130 GeV/c. Pion data is plotted 300 MeV too high in p_{TA} in order to improve clarity.

TABLE I. The rms value of the x-component of the dijet transverse momentum corrected for instrumental resolution is tabulated at three different beam momenta as a function of the average transverse momentum transfer in an event $p_{TA} = [p_T(\text{left}) + p_T(\text{right})]/2.0$. Data for pion and proton beams are listed separately except at 400 GeV/c where a pion beam was not available.

Beam momentum (GeV/c)	p_{TA} (GeV/c)	p_{TX}(rms) protons (GeV/c)	p_{TX}(rms) pions (GeV/c)
130	1.9	0.81 ± 0.04	0.78 ± 0.07
	2.3	0.72 ± 0.03	0.75 ± 0.06
	2.7	0.82 ± 0.02	0.87 ± 0.04
	3.0	0.82 ± 0.04	0.85 ± 0.06
	3.4	0.93 ± 0.09	1.07 ± 0.16
	3.7	1.02 ± 0.23	1.01 ± 0.29
200	2.3	0.90 ± 0.08	0.81 ± 0.09
	2.7	0.89 ± 0.12	0.73 ± 0.16
	3.0	0.94 ± 0.04	0.93 ± 0.08
	3.4	1.00 ± 0.07	1.07 ± 0.14
	3.7	1.03 ± 0.17	1.12 ± 0.30
	4.1	1.06 ± 0.34	
400	2.3	0.93 ± 0.08	
	2.7	0.99 ± 0.08	
	3.0	1.15 ± 0.03	
	3.4	1.18 ± 0.04	
	3.7	1.33 ± 0.08	
	4.1	1.30 ± 0.13	
	4.4	1.39 ± 0.24	

termine $\langle p_{TX}^2 \rangle$ for p_{TA} below 1.5 GeV/c.

One can see that uncorrected values of $\langle p_{TX}^2 \rangle$ in Fig. 3 exhibit a definite dependence on the incident beam energy. A similar dependence is seen in hadron production of dimuons. Figure 3 also indicates that $\langle p_{TX}^2 \rangle$ may increase somewhat with increasing p_{TA}, especially in the 400 GeV data.

Figures 4(a), 4(b), and 4(c) show data which have been corrected for instrumental resolution as described in the next section. Figures 4(b) and 4(c) make comparisons of $\langle p_{TX}^2 \rangle$ values obtained from πp collisions with those obtained in pp collisions for beam momenta of 200 and 130 GeV/c. Data used in these plots are given in Table I. The πp data points have been displaced to a higher p_{TA} to make them distinguishable from the pp points. The similarity of $\langle p_{TX}^2 \rangle$ for our πp and pp data is distinctly different from what is observed in dimuon experiments where πN data give a transverse momentum that is systematically higher by about 20% than that obtained from pN data.[29,30]

VII. MONTE CARLO CORRECTIONS

In order to obtain a more precise value for $\langle p_{TX}^2 \rangle$ one must unfold various instrumental contributions to the measured values presented thus far. A major source of such instrumental contributions to the observed momentum unbalance comes from the energy resolution spread in the calorimeter, the angular uncertainty resulting from the finite size of calorimeter segments, and uncollected jet fragments.

To estimate these effects we have constructed a Monte Carlo program which generates jets of a given p_T in the hadron-hadron center of mass. The p_T spectra of the Monte Carlo jets generated are taken to be exponential with the slopes observed experimentally. Jets are then allowed to fragment randomly into pions ($\frac{1}{3}$ neutral and $\frac{2}{3}$ charged) with a flat distribution in rapidity y: $[1/\sigma(d\sigma/dy) = 2]$.[31] The transverse momentum of the pions with respect to the jet axis is Gaussian in each dimension with a width of 300 MeV/c. The shape of the rapidity spectrum for jets generated in this way compares favorably with that observed at SPEAR.[14]

Monte Carlo-generated jet-pair events are subjected to the same selection criteria applied to real events. Experimentally measured energy resolution is imposed. (See Ref. 31.) A crude spread of hadron-shower energy into adjacent calorimeter segments is assumed which is consistent with our measurements of this effect in a test beam.

The values of $\langle p_{TX}^2 \rangle$ obtained by the Monte Carlo program are approximated by the smooth curves in Fig. 3. In applying these results to obtain a corrected value of $\langle p_{TX}{}^2\rangle$ (see below) we have assumed a random combination of true p_T and instrumental p_T, giving

$$\langle p_{TX}{}^2\rangle_{\text{corrected}} = \langle p_{TX}{}^2\rangle_{\text{raw data}} - \langle p_{TX}{}^2\rangle_{\text{instrumental}}\,. \qquad (1)$$

VIII. OTHER CORRECTIONS

When the Monte Carlo corrections described in the previous section are subtracted from the p_{TX}(rms) values shown in Fig. 3, the resulting corrected values of p_{TX}(rms) continue to show an increase with p_{TA} and with s. Before drawing conclusions as to the preciseness with which these corrected p_{TX} values give the parton K_T, we discuss several other corrections which in principle should be made to the data. We can make rough estimates of the magnitudes of almost all of these effects. Our estimates, described below, indicate that the growth of p_{TX} with p_{TA} and particularly with s, probably represents a true increase of K_T with these variables.

In the following, we are interested in two questions for each type of possible correction effect: (1) Is p_{TX} *changed* by that effect? (2) if it *is* changed, can we estimate whether the change will have a systematic dependence on p_{TA} and/or on s?

A. t variation with p_{TX}

The dependence of the parton cross section $d\sigma/d\hat{t}$ on the square of the four-momentum transfer $\hat{t}$ will have an effect on the values of $\langle p_{TX}{}^2\rangle$ that we measure. This occurs because a band of fixed p_{TA} does not correspond exactly to a region of fixed $\hat{t}$. Larger unbalances in jet transverse momenta will be fed on the average by collisions with smaller $\hat{t}$. Since in general the parton-parton scattering cross section can be expected to increase as $\hat{t}$ becomes smaller, larger values of the transverse-momentum unbalance will be weighted more heavily.[32]

Using the QCD forms of $d\sigma/d\hat{t}$ given by Combridge *et al.*,[33] we have made Monte Carlo calculations to estimate the percentage increase in our measured $\langle p_{TX}{}^2\rangle^{1/2}$ from this effect for each species of parton-parton collision without regard to the relative weighting of the structure functions. A Gaussian K_T distribution for the partons was assumed with a fixed rms value of 0.7 GeV/c. For all permutations of colliding parton species the percentage increase in $\langle p_{TX}{}^2\rangle^{1/2}$ was about 4% at $p_{TA}=3.0$ GeV/c and 2% at $p_{TA}=4.0$ GeV/c. At $p_{TA}=2.0$ GeV/c, however, the percentage increase is about 12% for unlike quarks and 6% or less for other permutations of partons, so that a good estimate would depend on the relative structure functions for the various parton species and on our relative detection efficiency of them.

Thus in this model we conclude

(1) $\langle p_{TX}{}^2\rangle^{1/2}$ is less than 4% larger than K_T(rms) for values of p_{TA} greater than 3.0 GeV/c, and

(2) this effect tends to make the measured $\langle p_{TX}{}^2\rangle^{1/2}$ *decrease* with increasing p_{TA}.

B. Jet-capture efficiency and geometry effects

We discuss here three types of possible effects from detector geometry. Consider first an event in which a jet pair with given p_T values is produced, with each jet aiming at the fiducial solid angle region of its arm. There is some detection efficiency, ϵ_{frag}, which depends on the probability that each jet will fragment "compactly," so that essentially all of the jet's momentum and energy is directed toward the detector. (see Sec. II and Refs. 15 and 23.) The question then arises as to how ϵ_{frag} might vary with p_{TX}—i.e., with transverse motion of the parton-parton rest systems with respect to the beam direction. This is an important theoretical question but a very difficult one. We know of no theoretical guidance as to the answer. We can give some results bearing on this question, however, based both on simple models and on experimental information.

(1) ϵ_{frag} has no *first*-order dependence on p_{TX}.[34]

(2) There is experimental evidence which indicates that ϵ_{frag} is not varying significantly with p_{TX}.[35]

A second type of possible geometry effect which could introduce a "spurious" change of $\langle p_{TX}{}^2\rangle$ with s occurs because the calorimeter arms were repositioned at each beam energy to compensate roughly for the change in Lorentz contraction effects with changing beam energy. It was not possible to preserve exactly the same c.m.s. geometry for every beam energy. Consequently ϵ_{frag}, the effective "detection efficiency" averaged over the fragmentation modes of the jets, could be expected to change from one beam energy to another. To some extent our Monte Carlo subtractions should compensate for this geometry effect. The Monte Carlo corrections, and their change with beam energy, are quite small. We therefore believe that this geometry effect is not likely to be producing a substantial spurious rise in $\langle p_{TX}{}^2\rangle$ with s—but it must be realized that this conclusion rests on our belief that our Monte Carlo jet model is not grossly in error in giving an instrumental correction to $\langle p_{TX}{}^2\rangle$ which is relatively small.

A third type of detection-efficiency effect occurs because the left arm is not as thick as the right arm.[11] As one goes to higher s and higher p_{TA}, the laboratory energies of the jet fragments increase, and nonelectromagnetic hadron fragments may tend to give increasing leakage out the rear of the calorimeter array. From our understanding of the trigger-bias effect pointed out by Dris[23] we do not believe this increasing leakage affects p_{TX}(rms) for the events observed, but this thickness effect might cause a different relative intensity of gluon jets detected compared to quark jets detected at 400 GeV and at high p_{TA} as compared to the relative intensity detected at lower p_{TA} and lower s. Conceivably this change could affect the behavior of p_{TX}(rms) as a function of s and of p_{TA}. We are not able to calculate this effect quantitatively.

C. Multiplicity effects

As s and p_T increase, the multiplicity of fragments in the beam jet and in the high-p_T jets increases. Secondary interactions in the hydrogen target can thus give an increasing rms unbalance $\langle p_{TX}^2\rangle^{1/2}$. We have estimated the magnitude of this effect and we find it to be small compared to the observed increase in the resolution-corrected $\langle p_{TX}^2\rangle^{1/2}$. In addition we have measured $\langle p_{TX}^2\rangle$ for target lengths of 6 and 12 in. and find the value is independent of target length. This tends to support the same conclusion.

D. Effects from final-state radiative gluon jets

In a parton-parton scattering process "bremsstrahlung" gluons may be emitted by the scattered partons as well as by the initial partons. Such radiative gluons must be expected also to form jets, and we have no way to determine how much

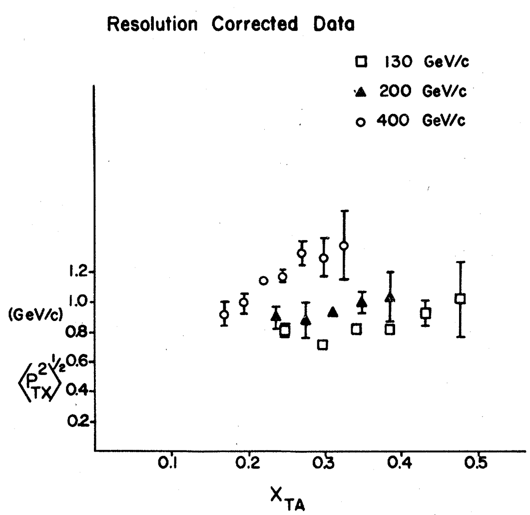

FIG. 5. rms value of the x component of the dijet transverse momentum as a function of the average jet transverse x, $x_{TA}=2p_{TA}/\sqrt{s}$, for pp collisions at three different beam energies. Data points are corrected by the Monte Carlo program for contribution from instrumental fluctuations.

our measured jets, and $\langle p_{TX}^2\rangle$, are affected by partial capture of these soft radiative fragments. It does seem probable, however, that in general some but not all of these radiative fragments will be captured along with fragments from the scattered parton. If we could correct to the case in which *no* radiative fragments were captured, we could expect that $\langle p_{TX}^2\rangle^{1/2}$ would be larger. Since bremsstrahlung effects in QCD are expected to increase with p_T and with s,[36] it seems likely that the increase in our $\langle p_{TX}^2\rangle$ values with p_T and with s would become an even larger increase if we could exclude radiative gluon fragments from the detector.

We summarize the discussion of this section. To the best of our ability to estimate the character of the effects discussed here, these effects do not seem likely to give any appreciable spurious growth of $\langle p_{TX}^2\rangle$ with p_T and with s. Some of the above effects, in fact, seem likely to produce a *decrease* in the apparent value of $\langle p_{TX}^2\rangle$ with increasing p_T and increasing s.

IX. DEPENDENCE OF $\langle p_{TX}\rangle$ ON x_{TA} AND ON ENERGY

Figure 5 is a plot of $\langle p_{TX}^2\rangle^{1/2}$ for pp collisions versus $x_{TA}=2p_{TA}/\sqrt{s}$ as corrected by the Monte Carlo program for instrumental effects. The dependence on incident beam energy is seen to persist after correction for these instrumental effects.

The energy dependence of p_{TX} suggests that a scaling law may apply.[37] The simplest form would be $\langle p_{TX}^2\rangle=F(x_{TA})s$, where s is the invariant energy squared of the colliding hadrons, F is some function of unitless variables, and $x_{TA}=2p_{TA}/\sqrt{s}$. However, most attempts to describe K_T recognize a primordial K_T in the hadrons which is not described by the gluon radiation in QCD. This suggests the addition of a constant term $\langle p_{T0}^2\rangle$ to the scaling law.

$$\langle p_{TX}^2\rangle=F(x_{TA})s+\langle p_{T0}^2\rangle .$$

Figure 6(a) is an attempt to plot $\langle p_{TX}^2\rangle$ from pp collisions as a function of center-of-mass energy squared for several values of x_{TA} having the best statistics. There is a definite increase in $\langle p_{TX}^2\rangle$ with energy and possibly some dependence on x_{TA}.

We have explored the usefulness of the above scaling relation by trying a χ^2 fit to our entire sample of data for two arbitrary forms for F, F = constant and F = constant $\times x_{TA}$. The first function gives $\langle p_{TX}^2\rangle=(0.001\,25\pm0.000\,10)\times s+(0.353 \pm 0.042)$ (GeV/c)^2 with a χ^2 confidence level of 1.5%. This confidence level might be considered adequate for data with the systematic errors of our experiment. The second function gives

$$\langle p_{TX}^2\rangle = (0.007\,23\pm 0.000\,55)x_{TA}s + (0.075\,0\pm 0.059\,8)\ (\mathrm{GeV}/c)^2$$

with a χ^2 per degree of freedom of 0.94 and is thus certainly sufficient to describe the present data. This latter fit along with the data used is shown in Fig. 6(b).

The first fit implies a primordial transverse momentum of 594 ± 35 MeV/c and the second implies a value of 270 ± 111 MeV/c where the errors are statistical only. It is apparent from these results that extrapolation to $s=0$ depends sensitively on knowing the correct scaling law to use.

X. COMPARISON OF $\langle p_{TX}^2\rangle^{1/2}$ WITH DIMUON RESULTS AND WITH OTHER RESULTS

A. Dependence of $\langle p_{TX}^2\rangle$ on p_{TA}

In dimuon production $\langle p_T\rangle_{\mu\mu}$ at fixed s and at rapidity y near zero typically rises with the mass

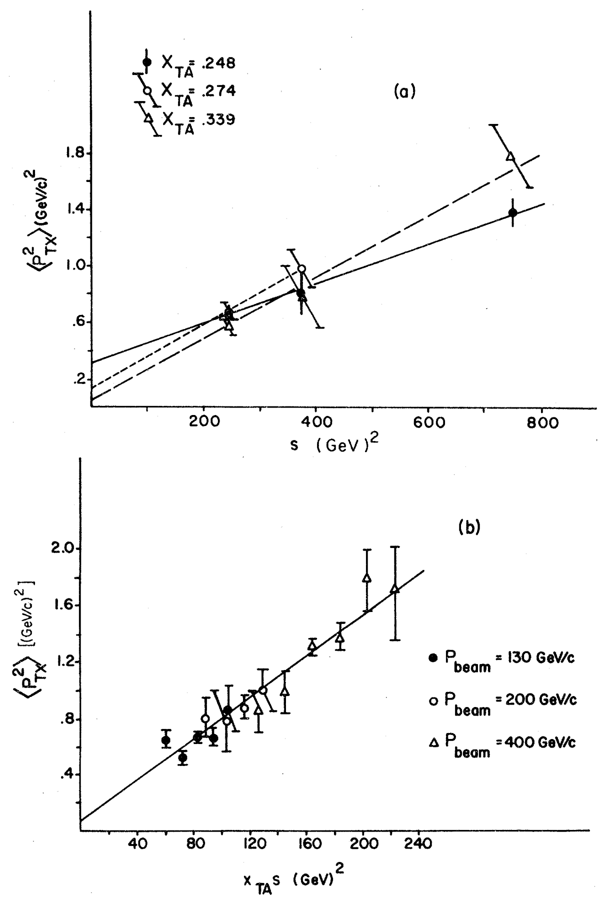

FIG. 6. The dependence of the x component squared of the dijet transverse momentum as a function of (a) center-of-mass energy squared for three different values of average jet x_{TA} and (b) the product of x_{TA} and center-of-mass energy squared. The line is a χ^2 fit to $p_{TX}^2 = ax_{TA}s+b$.

$M_{\mu\mu}$ at low $M_{\mu\mu}$ and then clearly flattens at higher $M_{\mu\mu}$. This occurs both for pN collisions[38] and for πN collisions.[30]

Since the transverse momenta in our dijet experiment nearly balance and both jets are roughly at 90° in the center of mass, p_{TA} is closely related to the dijet mass M_{JJ} by $M_{JJ}=2(p_{TA}^2+M_J^2)^{1/2}$. The average mass of a jet varies with p_{TA}, but $M_J\approx 2$ GeV/c^2 in the range of this experiment. Thus our dijet data with p_{TA} from about 2.5 to 4.5 GeV/c have M_{JJ} ranging from about 6 to 10 GeV/c^2. In this interval we observe (Fig. 5) that for beam energies of 130 and 200 GeV the corrected p_{TX} is approximately independent of M_{JJ}, but for 400 GeV it shows a definite increase with mass.

Thus the dijet data indicate that at 400 GeV $\langle p_T\rangle_{JJ}$ increases somewhat with M_{JJ} in contrast to the flatness of $\langle p_T\rangle_{\mu\mu}$ with $M_{\mu\mu}$ for the same range of mass—i.e., for the same range of parton x values or of $\sqrt{\tau}=M/\sqrt{s}$. Lederman[29] suggests that the flattening of $\langle p_T\rangle_{\mu\mu}$ may be due to the dominance of quark-*gluon* collisions in the pN case. We note that the dijet process differs from the dimuon process for pN collisions in three respects: (1) quark-quark collisions can readily contribute, (2) the QCD diagrams which contribute to $\langle p_T\rangle$ for the two types of collisions can be very different, and (3) the target is not a complex nucleus as it is in the dimuon experiment.

B. The magnitude and s dependence of $\langle p_T\rangle_{JJ}$ compared to $\langle p_T\rangle_{\mu\mu}$

The dashed line in Fig. 7 shows the fitted energy dependence of $\langle p_T^2\rangle_{\mu\mu}$ presented by Yoh *et al.*,[38] for $pN\to$ dimuons with $M_{\mu\mu}>5$ GeV/c^2. We compare this to a fit of our values of $\langle p_T^2\rangle=2\langle p_{TX}^2\rangle$ at $M_{JJ}\approx 7.0$ GeV/c^2 ($p_{TA}=3.0$ GeV/c) where we have the best statistical accuracy. Two points are of interest here. (a) The dijet system has a transverse momentum which appears to be systematically higher than that of the dimuon system at a particular mass. As was pointed out earlier in this section the QCD diagrams contributing to these two processes are quite different, so one might expect a quantitative difference. (2) The qualitative increase of $\langle p_T^2\rangle$ with incident energy which one observes is anticipated by QCD for both processes, and the intercept at $s=0$ might be interpreted as a primordial transverse momentum associated with colliding hadrons. Although the closeness of the two intercepts suggests that the QCD picture of parton collisions for these two processes may be correct, it does not necessarily imply the correct

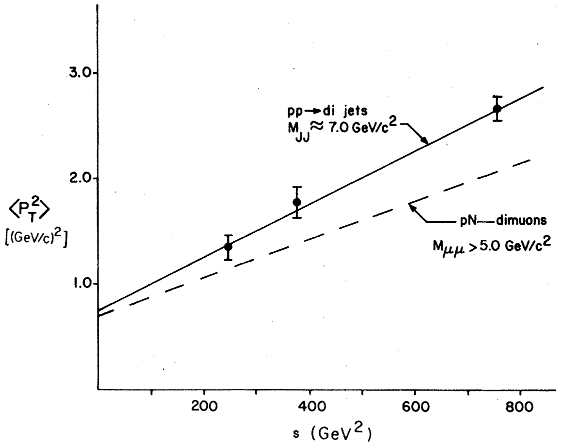

FIG. 7. Comparison of the energy dependence of $\langle p_T^2 \rangle$ for dimuons and dijets produced in pN and pp collisions, respectively. The dimuon fit was taken from Ref. 38.

extrapolation has been used to obtain the primordial K_T of the partons.

Figure 8 compares the magnitude of $\langle p_T \rangle$ for dimuon pairs produced in πN and pN collisions with $\langle p_T \rangle$ of dijet pairs produced in pp collisions. The pN data[29] were collected at 200 GeV and scaled to 225 GeV using the energy dependence[38] of Fig. 7 for comparison with the πN data.[30]

Since pp and πp collisions give the same $\langle p_T \rangle$ [see Fig. 4(b) and 4(c)] for dijets, we have displayed pp data only. For our Gaussian-distributed data we use $\langle p_T \rangle = (\pi/2)^{1/2} \langle p_{TX}^2 \rangle^{1/2}$. The 200-GeV

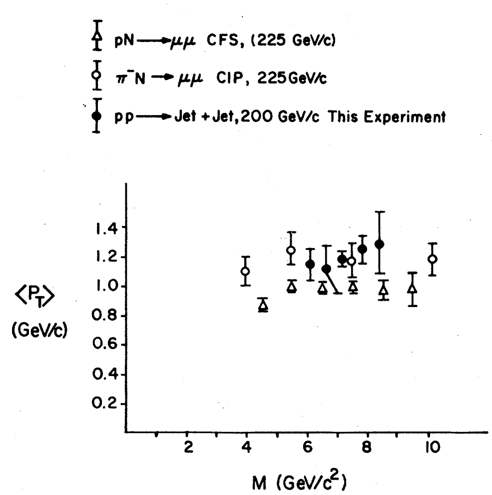

FIG. 8. A comparison of $\langle p_T \rangle$ for dimuons produced in πN and pN collisions with that for dijets produced in pp collisions. pN and pp data are "scaled" from 200 to 225 GeV/c beam energy. $\langle p_T \rangle$ is displayed as a function of dimuon and dijet mass, respectively. pN data are from Ref. 29 and πN data are from Ref. 30.

data points for dijets were not scaled up to 225 GeV because the $\hat{t}$ correction discussed in Sec. VIII might be expected to lower them by a comparable amount.

It would appear from Fig. 8 that $pp \to$ dijets has $\langle p_T \rangle$ that is more readily compared with $\pi N \to$ dimuons than with $pN \to$ dimuons.[39] The process $pN \to$ dimuons should rely heavily on quark-gluon collisions whereas all the other processes can proceed most easily by valence-quark collisions.

C. Comparison with dihadron results for p_{out}

The CCOR collaboration has reported $\langle p_{\text{out}} \rangle$ values for a range of values of p_T(trigger π^0) and p_T(away-side charged fragments).[7] They give data for $\sqrt{s} = 62.4$ GeV. We note that in the coordinate system defined above in Sec. I $\langle p_{\text{out}} \rangle$ is $\langle p_{TY} \rangle$, which is presumably approximately equal in magnitude to $\langle p_{TX} \rangle$. Examining the CCOR results for the case $p_T(\text{away}) \approx p_T(\text{trigger})$, one finds that (1) their $\langle p_{\text{out}} \rangle_{\text{dihadron}}$ values for a given p_T are quite similar to our $\langle p_{TX} \rangle_{\text{dijet}}$ values for jets of the same p_T, e.g., ~1 GeV/c for $p_{TA} \approx 5$ GeV/c, and (2) their $\langle p_{\text{out}} \rangle_{\text{dihadron}}$ values continue to increase with p_T up to the highest p_T values they give, ~8 GeV/c (or ~16 GeV dihadron mass). This increase of $\langle p_{\text{out}} \rangle_{\text{dihadron}}$ with p_T at $\sqrt{s} = 62$ GeV is similar to the increase in $\langle p_{TX} \rangle_{\text{dijet}}$ with p_{TA} at $\sqrt{s} = 27$ GeV and different from the flat behavior of $\langle p_T \rangle_{\mu\mu}$ above 5 or 6 GeV/c^2 mass at $\sqrt{s} = 27$ GeV.

There is some indication that a significant variable in the flattening behavior of $\langle p_T \rangle_{\mu\mu}$ is perhaps $\sqrt{\tau} = M_{\mu\mu}/\sqrt{s}$, rather than $M_{\mu\mu}$ alone. The dimuon data[29] indicate that flattening occurs above $\sqrt{\tau} = 0.2$. In this connection we note that both the dihadron data of CCOR[7] and the present dijet data show evidence of $\langle p_T \rangle$ continuing to increase as $\sqrt{\tau}$ goes beyond 0.2. The dihadron data go to $M_{\text{had-had}} \approx 15$ GeV at $\sqrt{s} = 62.4$ GeV, with evidence that $\langle p_{\text{out}} \rangle$ is still increasing. If these dihadron events come from *jet* pairs, then $\sqrt{\tau}$ for the jet pairs would be >0.25. The present dijet data at $\sqrt{s} = 27.4$ GeV indicate that $\langle p_{TX} \rangle$ is continuing to increase substantially as $\sqrt{\tau}$ passes 0.2 ($M_{JJ} \approx 5.5$ GeV/c^2, $p_{TA} \approx 2.5$ GeV) and is continuing to increase as $\sqrt{\tau}$ goes to its limit in the present data of ~0.35.

XI. CONCLUSIONS

We have argued that the observed transverse-momentum unbalance in the two-jet events we have studied is due mostly to the transverse momentum of the colliding constituents. Evidence is presented for the following conclusions:

(1) The transverse momentum obtained is equal for πp and pp collisions in contrast to the

difference observed in dimuon production in πN and pN collisions.

(2) $\langle p_T \rangle$ grows with s.

(3) $\langle p_T \rangle$ increases with dijet mass at 400 GeV, up to the highest masses seen (~10 GeV/c^2), in contrast with the flattening observed in dimuon production at masses above ~5 GeV/c^2.

(4) The close similarity in magnitude of transverse momentum in dimuon and dijet production and the general similarity in s dependence constitute strong evidence that both processes involve parton collisions, with similar types of partons entering in the two processes.

(5) The fact that the magnitude of $\langle p_T \rangle$ is closely the same for dimuon and dijet production seems to imply that there is no substantial additional fluctuation in p_T introduced in jet formation from a parton that is not experienced in dimuon formation.

ACKNOWLEDGMENT

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[31]The response of the calorimeter, pulse-height distribution for a given particle energy, is different for π^0's as compared to other hadrons. We correct for this difference by using suitably chosen relative weighting for the energy deposited in the front part of each calorimeter segment and for the energy deposited deeper in each segment. Detailed study using the experimentally measured E resolution function of the calorimeter shows that with this correction the results for the p_T distribution of the observed jets are quite insensitive to the exact fraction of pions which is taken to be neutral.

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[34]Although ϵ_{frag} can be expected to change with trans-

verse motion of the parton-parton rest system, from symmetry $\epsilon_{\rm frag}$ must be a relative minimum or maximum at $p_{TX}=0$. Thus $\epsilon_{\rm frag}$ has no first-order dependence on p_{TX}.

[35]We have studied the width of the p_{TX} distribution for different size $\Delta\phi$ fiducial intervals. If $\epsilon_{\rm frag}$ changed significantly with p_{TX}, one can show that $\langle p_{TX}^2\rangle$ would also be expected to change with $\Delta\phi$. We find no measurable change in going from $\Delta\phi=\pm 10°$ to $\Delta\phi=\pm 20°$ and $\pm 30°$ at 400 GeV for all values of p_{TA} covered by the data in Table I. This negative result indicates that $\epsilon_{\rm frag}$ is not varying significantly with p_{TX}.

[36]See e.g. R. D. Field, Phys. Scr. 19, 131 (1979).

[37]We have benefited greatly from discussions on this matter with F. Halzen, D. Scott, J. Leveille, J. Owens, and E. Berger.

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[39]The πN data were obtained with a π^- beam on Cu and W targets at 225 GeV/c (Ref. 30), the pN data with a Pt target at 200 GeV/c.