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[5]D. Antreasyan *et al.*, Phys. Rev. D 19, 764 (1978).
[6]R. D. Field, private communication. This model does not yet include baryon production and so has no prediction for the $\bar{p}/p$ ratio.

Evidence that High-p_T Jet Pairs Give Direct Information on Parton-Parton Scattering

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New results for parton transverse momentum obtained from two-jet high-p_T hadron events are presented. These results, and results for quark structure functions in the pion, are compared with results from dimuon production experiments. The results for the two types of experiments are very similar. This indicates that jet pairs give direct information on parton-parton scattering.

The search for high-p_T hadron jets and the study of their properties has been motivated by the hope that jet-pair events might provide the possibility of studying parton-parton scattering.[1] No other method of studying parton-parton scattering is known. In this Letter we report the first detailed results on parton transverse momentum, k_T, to be obtained in a hadron jet-pair experiment. These results and results on quark structure functions are compared with results from dimuon production. The close similarity of these results supports the conclusion that jet-pair events give direct information on parton-parton scattering.

Jets studied with calorimeters.—Recent calorimeter experiments have provided the first direct observation of jet events from hadron collisions.[2-4] Detailed study of these events shows that, with a calorimeter trigger of solid angle ≥ 1 sr, well-defined, well-contained jets are found.[5,6] Because of the rapidly falling p_T spectrum, a calorimeter trigger preferentially selects narrow jets through the operation of a trigger bias effect pointed out by Dris.[7] The result is that for those jets which are detected there is little missing momentum and energy in undetected fragments, typically only a few tenths of a gigaelectronvolt.[8] Thus one can expect that in spite of residual uncertainties the momentum of a jet with such a calorimeter trigger may correspond closely to the momentum of a scattered parton. In the present report we examine further results and evidence bearing on the closeness of this correspondence.

Dijet transverse momentum p_T and parton transverse momentum k_T.—The apparatus consisted of a double-arm calorimeter array, which has been described elsewhere.[4] Data for this analysis were taken with a "double arm" jet trigger, which required the sum of the p_T magnitudes in all the calorimeter segments of the two arms to exceed an adjustable threshold. Both pp and πp collisions at beam momenta of 130 and 200 GeV/c were studied. For all of the results reported here, the calorimeter arms were centered near 90° c.m. The jet vector was determined by adding vectorially the momentum deposited in each calorimeter module. A fiducial-angle cut of ± 10° about the center of each arm in both $\theta_{\text{c.m.}}$ and φ was applied to the two jet vectors.

In essentially all the events, we have observed an approximate p_T balance in the two arms. This balance is a very prominent feature of the data, and in fact occurs with no software cuts of any

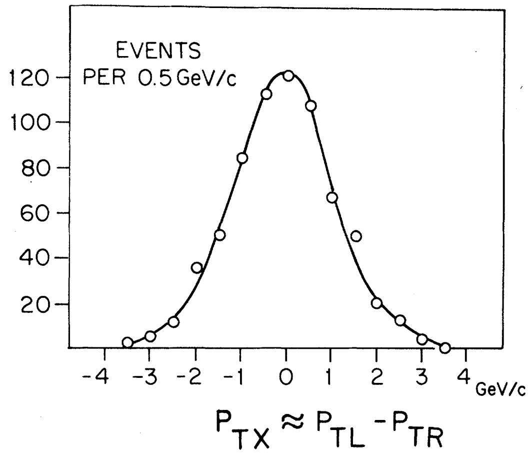

FIG. 1. p_T unbalance distribution for data in the band $|\vec{p}_{TL}| + |\vec{p}_{TR}| = 6.0$ to 6.5 GeV/c. (See text for cuts.)

kind. Such a balance, of course, is expected from a hard-scattering model in which the jets are the result of the hard elastic scattering of two partons. We have previously reported an important difference in jet-pair angular correlations for πp collisions compared to pp collisions which gives evidence that this p_T balance corresponds closely to a hard-scattering mechanism.[4]

In a parton-scattering model, the *unbalance* of $\vec{p}_T$ for the two jets gives information on parton transverse momentum $\vec{k}_T$. We use $\vec{p}_{TL}$ and $\vec{p}_{TR}$ to identify the momentum vectors of the "left" and "right" jets. The dijet transverse momentum is then

$$\vec{p}_T = \vec{p}_{TL} + \vec{p}_{TR}. \qquad (1)$$

If $\vec{p}_T$ were produced solely by the $\vec{k}_T$'s of the scattering partons, one finds that the rms value of one component of $\vec{p}_T$ (say p_{TX}) would correspond to the rms value of k_T for a single parton.[5,9] Abbreviating the unbalance with the symbol U, we write

$$(k_T)_{\rm rms} = U, \text{ with } U \equiv (p_{TX})_{\rm rms}. \qquad (2)$$

In actual application we must distinguish between U for the raw data and U corrected for contributions other than k_T effects.

In a parton scattering model, the distribution of p_{TX} due to k_T effects at fixed parton x and fixed parton-parton momentum transfer is given approximately by the distribution of events in a band of fixed average p_T, $p_{T,\rm av} = \frac{1}{2}(|\vec{p}_{TL}| + |\vec{p}_{TR}|)$. Such a distribution is shown in Fig. 1. The relatively sharp clustering of events near p_T balance is apparent. Because of the fiducial angle cuts, we have $p_{TX} \cong |\vec{p}_{TL}| - |\vec{p}_{TR}|$, since the vertical ($y$) component is restricted to small values.

U is calculated as the standard deviation of the x component of $\vec{p}_{TL} + \vec{p}_{TR}$. The results for pp collisions at 130 and 200 GeV are plotted in Fig. 2(a). Also shown in Fig. 2(a) is our estimate of the instrumental contribution to U due to missing jet fragments and finite calorimeter resolution. The instrumental contribution has been calculated using a Monte Carlo jet model which closely simulates many features of the data.[5,6] A resolution-corrected value, $U_{\rm rc}$, is obtained by subtracting the Monte Carlo contribution in quadrature from $U_{\rm data}$. $U_{\rm rc}$ is plotted in Fig. 2(b).

Comparison of U for πp and pp collisions.—As we discuss below, the magnitude of $U = (p_{TX})_{\rm rms}$ and the resulting value of $\langle p_T \rangle \equiv \langle |\vec{p}_T| \rangle$ are quite similar for dijet and dimuon production. However, there is one important difference—for di-

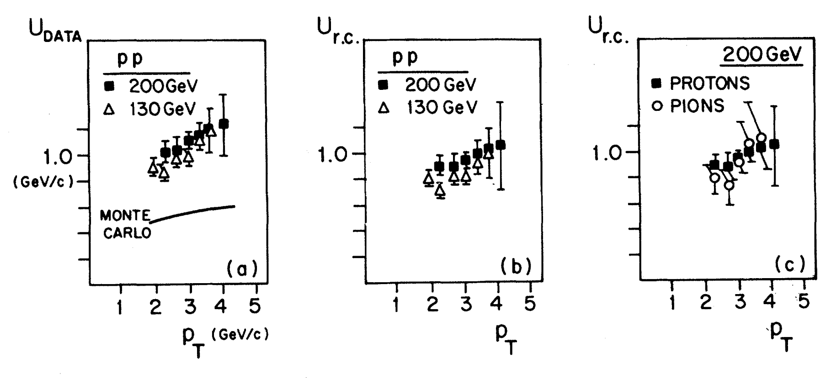

FIG. 2. The rms unbalance U (Eq. 2). p_T is defined as $(|\vec{p}_{TL}| + |\vec{p}_{TR}|)/2$. (a) The points show $U_{\rm data}$; the curve shows the instrumental contribution to U, from a Monte Carlo calculation. (b) U corrected for the instrumental effect. (c) Comparison of pp and πp results.

muons, the $\langle p_T \rangle$ values for proton-induced and pion-induced events are different,[10,11] but for dijets they are *not* different, as shown in Fig. 2(c).[12] This difference is understandable if in the dijet process similar constituents are colliding in πp and pp cases[13] while for dimuon production different species of partons dominate for pN and πN events.[10]

Comparison of $\langle p_T \rangle$ *for dijets and dimuons.* —The $\langle p_T \rangle$ magnitudes in Fig. 2(b) show a slight indication of increase with s and $p_{T,\mathrm{av}}$. The increase with s is qualitatively similar to the results obtained for dimuons by Lederman *et al.*[10] Before comparing the $\langle p_T \rangle$ values for the two types of experiments, however, several differences must be noted.[6,14] (1) The dijet data were obtained with a hydrogen target, the dimuon data with nonhydrogen targets. (2) Different Feynman diagrams enter in the two processes, and different types of parton species may play major roles. (3) Strong-interaction effects could be present for dijet production in the quark fragmentation process; no such effects are present in dimuon production. (4) For the dijet process there are several types of corrections which must be applied to $(p_{TX})_{\mathrm{rms}}$ before k_T values can be extracted. The instrumental resolution effect discussed above appears to be dominant, but there are several additional corrections which appear to be small but perhaps not negligible.[14]

We plot in Fig. 3 the corrected $\langle p_T \rangle$ values for the dijet experiment along with the dimuon $\langle p_T \rangle$ results reported by Anderson *et al.*[11] For the dijet case, the U_{rc} values shown in Fig. 2(c) have been multiplied by $(\pi/2)^{1/2}$.[12,15] The abscissa used is $M_{\mu\mu}$ for dimuons or $|\vec{p}_{TL}| + |\vec{p}_{TR}|$ for dijets. (The actual effective mass for the dijet events is experimentally about 20% larger than $|\vec{p}_{TL}| + |\vec{p}_{TR}|$.)

Figure 3 shows that the dijet and dimuon experiments give very similar results for $\langle p_T \rangle$, in spite of the differences in the two processes noted above.

Comparison of pion structure-function results. —Another similarity between dijet and dimuon results can be seen in a comparison of pion structure functions. Results for the effective quark-plus-antiquark structure function of the pion, $f_\pi^{\mathrm{eff}}(x)$, have been reported from the dijet experiment,[13] and similar information has been reported from a dimuon experiment.[16] Both experiments report a systematic uncertainty of about 20%. In Fig. 4 we plot the results from the two experiments with an adjustment of 25% in absolute scale. With this adjustment, the results are found to agree quite closely. The similarity of $f_\pi^{\mathrm{eff}}(x)$ in both shape and magnitude (within experimental uncertainties) offers substantial support for the conclusion that both experiments give information on the quark structure function of the pion. (Reference 16 also includes additional results for $x > 0.6$.)

Conclusions.—We have analyzed the transverse-momentum distribution of jet pairs from hadron

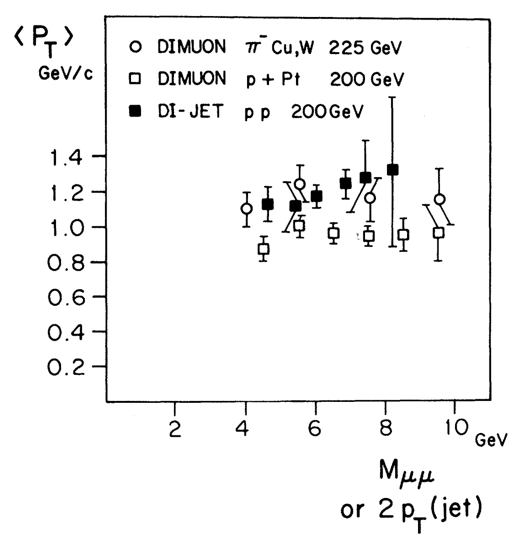

FIG. 3. $\langle p_T \rangle$ for dijet and dimuon events. See text for calculation of $\langle p_T \rangle$ for the dijets.

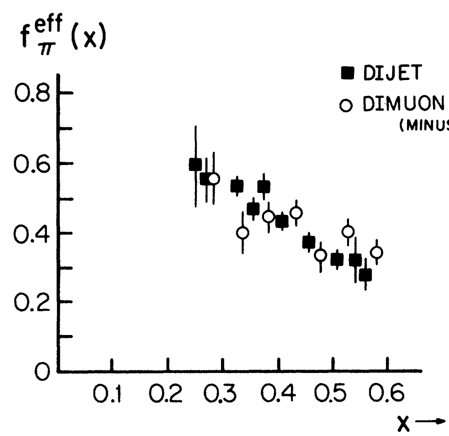

FIG. 4. Comparison of quark-plus-antiquark structure-function results. The dimuon results for the $\bar{u}$, from Ref. 16, were multiplied by 2 to include both valence quarks. The results were then decreased by 25% for this plot.

collisions to obtain information on the transverse momentum of the scattering partons. The rms transverse momentum value obtained is quite similar to that found in dimuon production experiments. We have also compared the pion quark-plus-antiquark structure-function information obtained from the jet-pair experiment with that obtained from a dimuon experiment and in this case also find close agreement. These agreements are especially striking when one considers the totally different experimental techniques used. In spite of some difficulties and ambiguities in the interpretation of the dimuon data, a strong case has developed for the interpretation of the data in terms of $q\bar{q}$ annihilation, the original Drell-Yan process, as modified by quantum chromodynamics effects.[12,17,18] If we take this Drell-Yan interpretation as being better established than the interpretation of jet events, the close similarity of the results implies that the measurements and analysis of dijet events with large-solid-angle calorimeters gives direct information on parton-parton scattering. The study of hadron jets in hadron collisions, and particularly jet pairs, thus appears to provide a practical and unique means for the study of the strong interaction in parton-parton scattering.

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[6]W. Selove, in Proceedings of the Fourteenth Rencontre de Moriond, March 1979 (to be published).
[7]M. Dris, Nucl. Instrum. Methods 158, 89 (1979).
[8]Jets detected with a calorimeter trigger near 90° c.m. appear to have only a small contribution from low-p_T background particles, no more than a few tenths of 1 GeV/c per steradian. (See Refs. 5 and 6). Other experimenters also conclude that the p_T detected with a 1–2-sr calorimeter appears to be within a few tenths of 1 GeV/c of the true jet momentum [C. Bromberg *et al.*, Phys. Rev. Lett. 43, 565 (1979)]. We also believe that background from nonjet-type events is small. This conclusion is supported by the nature of the high-p_T events, as described in Refs. 5 and 6, as well as peripheral phase space Monte Carlo calculation. Double-arm triggers from the phase-space Monte Carlo have a p_T dependence of about $\exp(-8p_T)$ while we observe a dependence of $\exp(-3p_T)$. Also, multiplicities from the phase-space calculation are almost twice the observed multiplicities [see Refs. 5 and Fermilab, Lehigh Pennsylvania, Wisconsin Collaboration, in *New Results in High Energy Physics—1978*, edited by R. S. Panvini and S. E. Csorna, AIP Conference Proceedings No. 45 (American Institute of Physics, New York, 1978), p. 64].
[9]Equation (2) follows if we assume that $\langle k_{TX}^2\rangle$ and $\langle k_{TY}^2\rangle$ are equal to each other and equal for the two scattering partons.
[10]L. M. Lederman, in *Proceedings of the Nineteenth International Conference on High Energy Physics, Tokyo, Japan, August 1978*, edited by S. Homma, M. Kawaguchi, and H. Miyazawa (Physical Society of Japan, Tokyo, 1979), p. 706.
[11]K. J. Anderson *et al.*, Phys. Rev. Lett. 42, 944 (1979).
[12]The p_{TX} distributions for dijets (see Fig. 1) are found to be closely gaussian. It is thus a very good approximation to take

$$\langle p_T\rangle = \tfrac{1}{2}\pi^{1/2}(p_T)_{\rm rms} = (\pi/2)^{1/2}(p_{TX})_{\rm rms} = (\pi/2)^{1/2}U.$$

[13]M. Dris *et al.*, Phys. Rev. D 19, 1361 (1979).
[14]M. D. Corcoran *et al.*, to be published.
[15]Two roughly compensating effects of a few percent each have been ignored in the results plotted in Fig. 2(c). (1) There is a slight increase in $\langle p_T\rangle$ for the dijet process produced by variation of parton-parton momentum transfer $\hat{t}$ in a band of fixed $p_{T,\rm av}$. (2) The $\langle p_T\rangle$ values shown in Fig. 3 are slightly different beam momenta for the different processes.
[16]C. B. Newman *et al.*, Phys. Rev. Lett. 42, 951 (1979).
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