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Evidence for Local Compensation of Transverse Momentum in *pp* Collisions at 200 and 300 GeV/*c*

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Evidence is presented for local compensation of transverse momentum in *pp* collisions at 200 and 300 GeV/*c*. We compare the data with a model which contains no dynamical transverse-momentum correlations. These data are used to determine a lower bound on the slope of the Pomeranchuk trajectory.

In general terms, local compensation of some conserved, additive quantum number in high-energy particle production[1-3] requires that each final-state particle carrying a value q be accompanied by a small group of particles carrying a total value of $-q$ located nearby in rapidity space. Recent data[4,5] support the hypothesis of local compensation of electric charge. In this Letter we describe data from 200- and 300-GeV/*c* *pp* collisions which strongly suggest that local compensation of transverse momentum (LCTM) is also a characteristic of strong-interaction dynamics. With a plausible assumption concerning the behavior of the undetected neutral particles, these data determine a lower bound[2,3] on the slope of the Pomeranchuk trajectory.

A formulation of LCTM which can be tested by experiments which detect only charged particles has been presented by Weingarten[2]: Let $\vec{Z}_>(y)$ $[\vec{Z}_<(y)]$ be the total transverse momentum carried by all final-state charged particles with rapidities greater (less) than y in an inelastic collision. We define the correlation function $C(y_1, y_2)$ for $y_1 \leq y_2$ by

$$C(y_1, y_2) = -\langle \vec{Z}_<(y_1)\cdot \vec{Z}_>(y_2)\rangle, \tag{1}$$

where the angular brackets represent an average over all inelastic events. LCTM requires that as the total center-of-mass energy, $\sqrt{s}$, increases without limit, (a) $C(y_1, y_2)$ approaches an energy-independent limit; and (b) $C(y_1, y_2)$ falls rapdily to zero as $y_2 - y_1$ becomes greater than some energy-independent correlation length, λ.

A model which contains no dynamical correlations among transverse momenta and which may be compared with the data can be constructed as follows: Consider events in which all neutral and charged particles are detected. In each event, assign to each particle the longitudinal rapidity at which it is actually observed, but reassign random transverse momenta subject to the requirements (i) that the probability distribution of transverse momentum for each individual particle be proportional to the observed inclusive single-particle transverse-momentum distribution (averaged over rapidity), and (ii) that the set of transverse momenta, $\vec{p}_{\perp 1}, \ldots, \vec{p}_{\perp N}$, for each N-particle event conserve momentum. Then, by momentum conservation, for any $i \neq k$, the averages $\langle |\vec{p}_{\perp i}|^2 \rangle_N$ and $\langle \vec{p}_{\perp i} \cdot \vec{p}_{\perp k} \rangle_N$ taken over all N-particle events obey the relation

$$\langle |\vec{p}_{\perp i}|^2 \rangle_N = -\sum_{j \neq i} \langle \vec{p}_{\perp i} \cdot \vec{p}_{\perp j} \rangle_N = -(N-1) \langle \vec{p}_{\perp i} \cdot \vec{p}_{\perp k} \rangle_N. \quad (2)$$

Our rule for assigning transverse momenta implies that $\langle |\vec{p}_{\perp i}|^2 \rangle_N = \langle |\vec{p}_\perp|^2 \rangle$, where $\langle |\vec{p}_\perp|^2 \rangle$ is the overall observed average of the square of the transverse momentum. If $N_c^<(y)$ $[N_c^<(y)]$ is the total number of charged particles with rapidities greater [less] than y in an event, then for this model,

$$C(y_1, y_2) = \left\langle \frac{N_c^<(y_1) N_c^>(y_2)}{N-1} \right\rangle \langle |\vec{p}_\perp|^2 \rangle. \quad (3)$$

Let $\langle N_0 \rangle_{N_c}$ be the average number of final-state neutral particles for a fixed number N_c of charged particles. Introducing the approximation,

$$C(y_1, y_2) = \left\langle \frac{N_c^<(y_1) N_c^<(y_2)}{N_c + \langle N_0 \rangle_{N_c} - 1} \right\rangle \langle |\vec{p}_\perp|^2 \rangle, \quad (4)$$

we obtain a prediction which can be evaluated[6] with use of charged-particle data combined with published results for $\langle N_0 \rangle_{N_c}$.[7] Models suggest that the value given by Eq. (4) is about 3% smaller than that given by Eq. (3). This model duplicates the actual data except for possible dynamical correlations among transverse momenta, which have been replaced by a random distribution.

The data used for this analysis come from a study of 6329 (4060) pp interactions with four or more charged particles at 200 (300) GeV/c in the 30-in. hydrogen bubble chamber and wide-gap spark chamber hybrid facility at Fermilab. Bubble-chamber tracks and tracks in the downstream spark chambers were fully reconstructed in space, and track matching was then attempted. For successfully matched tracks, a hybrid track with momentum resolution greatly improved over the one with the bubble-chamber measurement alone is produced.[8] Particles which do not enter the downstream spectrometer are relatively slow in the laboratory and may therefore be measured reliably in the bubble chamber. Fast forward particles without a successful match with the spark-chamber data generally scatter in the exit window of the bubble chamber.

To reduce biases caused by particles with poorly determined momenta, we have discarded all events with one or more charged particles with transverse momenta greater than 4 GeV/c. We have performed calculations without this cut, and have also placed this cut at 1.5 GeV/c, and find no significant change in any results. In addition, we have restricted the sample to (1) only those events with spark-chamber hookup tracks (37% at 200 GeV/c and 31% at 300 GeV/c) and to (2) only those events in the upstream half of the fiducial volume, and have again found no significant change in any results. Furthermore, a Peyrou plot of the data shows reasonable symmetry $(F-B/F+B = 0.013 \pm 0.014)$ about $y_{\text{c.m.}} = 0$, indicating the absence of any significant bias. Our analysis also has a built-in mechanism for detecting bias, as described below. We are thus left with a sample of 5998 (3847) events at 200 (300) GeV/c for the subsequent analysis. These events have been weighted to restore the measured inelastic multiplicity distributions.

Data for $C(y_1, y_2)$ as a function of $\delta y = (y_1 - y_2)$, with $y_0 = (y_1 + y_2)/2 = 0$, are shown in Fig. 1 for pp scattering at 200 and 300 GeV/c.[9] The errors shown in Fig. 1 include approximately equal contributions from statistical and systematic effects. The latter arise from errors in measuring $p_\perp$ and y for some forward-hemisphere tracks and were determined by examining forward-backward asymmetries in the correlation functions. The curves in Fig. 1 are the predictions of the random model described above. At 200 (300) GeV/c, the curve given by the model is more than 40% (60%) above the data. These differences are explicitly demonstrated through the values of $C(0,0) = 0.202 \pm 0.009$ (0.208 ± 0.008) at 200 (300) GeV/c for the data and $C(0,0) = 0.289 \pm 0.010$ (0.331 ± 0.015) for the model. This is a deviation from randomness in the direction required by LCTM. At high energy, the average multiplicity rises approximately as $\ln(s)$, and thus the quantity given by Eq. (4) will also rise asymptotically as $\ln(s)$. Condition (a), however, requires $C(y_1, y_2)$ to approach a constant as $s \to \infty$. Therefore, $C(y_1, y_2)$ for the random model will asymptotically exceed $C(y_1, y_2)$ for the data which obeys LCTM, and this difference will grow with energy. This is qualitatively just what is observed.[10] The data and random model have also been calculated for $y_0 = \pm 1$ and ± 2, and graphs similar to those in Fig. 1 have been produced. In all cases, the $C(y_1, y_2)$ for the model is significantly higher than the data and this difference grows with increasing energy.

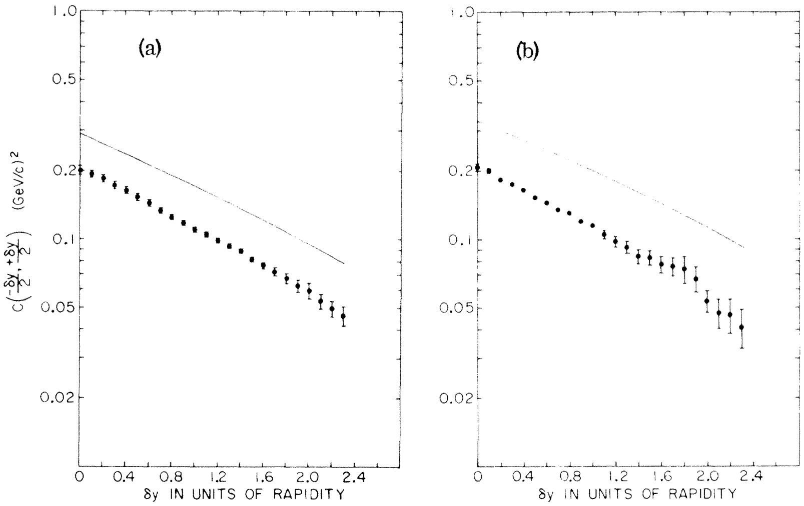

FIG. 1. Plot of $C(-\delta y/2, +\delta y/2)$ as a function of δy at (a) 200 and (b) 300 GeV/c. The smooth curves indicate the values of C for the random uncorrelated model.

If the data at $y_0 = 0$ are fitted to a function of the form $C(-y/2, +y/2) = A\exp(-y/\lambda)$, we obtain the value $\lambda = 1.60 \pm 0.05$ (1.63 ± 0.07) at 200 (300) GeV/c. Condition (b), in effect, requires λ to be bounded as a function of energy. Within errors, λ for the data is energy-independent. However, the prediction of the random model, $\lambda = 1.81 \pm 0.05$ (1.97 ± 0.06), is larger than the data and this difference increases with increasing energy. This deviation from randomness and its energy dependence are in the direction required by LCTM. It is worth noting that the correlation length which we obtain here is somewhat larger than the corresponding parameter, $\lambda_c \sim 1.2$, obtained from charge-transfer correlation functions.[5]

We believe that these data are significant evidence in favor of LCTM. This being the case, these data yield a lower bound[2,3] on the slope of the Pomeron:

$$\alpha_{P}' \geq [8_0\int^\infty C_\infty'(-y/2, +y/2)\,dy]^{-1}. \qquad (5)$$

The function $C_\infty'(y_1, y_2)$ is the limit as $s \to \infty$ of the correlation function which would have been given by Eq. (1) if $\vec{Z}_>(y)$ and $\vec{Z}_<(y)$ had been obtained from the transverse momenta of all the particles rather than only from the transverse momenta of the charged particles. Suppose, however, that $\vec{Z}_>^q(y)$ and $\vec{Z}_<^q(y)$ are the total transverse momenta carried by particles with charge q and rapidities, respectively, greater than y and less than y. Then it seems reasonable that at high energy the integrated average

$$\int_0^\infty \langle \vec{Z}_<^{q_1}(-y/2)\cdot\vec{Z}_>^{q_2}(+y/2)\rangle\,dy \qquad (6)$$

will be approximately independent of q_1 and q_2. This assumption combined with (5) yields

$$\alpha_{P}' \geq [8(\tfrac{3}{2})^2\int_0^\infty C_\infty(-y/2, +y/2)\,dy]^{-1}, \qquad (7)$$

where $C_\infty(y_1, y_2)$ is the limit as $s \to \infty$ of $C(y_1, y_2)$.[11] Since the $C(y_1, y_2)$ for the data does not change significantly from 200 to 300 GeV/c, we may assume that the data have reached approximate stability, and thus the 300-GeV/c data reasonably approximate $C_\infty(y_1, y_2)$. We therefore assume that the correct asymptotic form of Eq. (7) would yield a bound on $\alpha_P'(0)$ about as strong as the bound given by the data at 300 GeV/c. With these assumptions, we obtain the bound[12] $\alpha_P'(0) > 0.16$ GeV^{-2}, compared with a typical phenomenologically determined value[13] of $\alpha_P'(0) \sim 0.28$ GeV^{-2}.

Equation (5) is derived[2,3] by using unitarity to relate elastic scattering to multiparticle production, and then showing that if multiparticle production obeys LCTM, a minimum rate of shrinkage is necessarily generated in elastic diffraction peaks. We find that the minimum thus obtained accounts for about 60% of the observed rate of shrinkage. Thus, our data suggest that the underlying dynamical mechanism responsible for the shrinkage of the elastic diffraction peak is largely local compensation of transverse momentum.

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[6]The numbers that we use for $\langle|\vec{p}_\perp|^2\rangle$ [0.202 ± 0.007 $(\mathrm{GeV}/c)^2$ at 200 GeV/c and 0.226 ± 0.010 $(\mathrm{GeV}/c)^2$ at 300 GeV/c] are the experimental values for backward-hemisphere charged particles only and represent our best estimates of the true values of $\langle|\vec{p}_\perp|^2\rangle$.

[7]K. Jaeger *et al.*, Phys. Rev. D 11, 2405 (1975); A. Sheng *et al.*, Phys. Rev. D 11, 1733 (1975); F. T. Dao *et al.*, Phys. Rev. D 10, 3588 (1974). $\langle\nu_0\rangle_{\nu_c}$ was obtained by summing data for $\langle\pi^0\rangle$, $\langle K^0\rangle$, $\langle\Lambda^0\rangle$, and $\langle n\rangle$.

[8]G. A. Smith, *Particles and Fields—1973*, in AIP Conference Proceedings No. 14, edited by H. H. Bingham, M. Davier, and G. R. Lynch (American Institute of Physics, New York, 1974), p. 500.

[9]$C(-y/2,y/2)$ for π^-p scattering at 147 GeV/c is given in Fong *et al.*, Ref. 4.

[10]Alternatively, it follows from Ref. 2 that $C(y,y)$ is proportional to the mean-squared transverse-momentum transfer across the value y. Thus, our data show that transverse-momentum transfer actually occurs less easily than a random model would predict. This is a trend in the direction required by LCTM.

[11]Strictly speaking, $C_\infty'(y_1,y_2)$ in Eq. (5) and $C_\infty(y_1,y_2)$ in Eq. (7) should be obtained from averages restricted to nondiffractive final states. Following Ref. 2, however, we expect the integrals of correlation functions from all final states to differ from those from nondiffractive states by at most a few percent.

[12]We do not quote errors on the lower bound for $\alpha_P'(0)$, because such errors are primarily theoretical, and arise from the assumption concerning neutrals, which was used to replace Eq. (5) with Eq. (7). We expect this uncertainty to be at most 10%.

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Pion-Absorption Contribution to the π-d Scattering Length in a Simple Dispersion-Theoretic Approach

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The pion-absorption contribution to the π-d scattering length ($a_{\pi d}'$) is calculated in the Hulthén model in a simple dispersion-theoretic approach with Koltun-Reitan input modified through the introduction of the off-shell S-wave range parameter α_0 with $\alpha_0 = 500$ MeV/c. In this approach one finds the uncrossed result, $a_{\pi d}' = -2.69\times10^{-3}m_\pi^{-1}$, increased by $1.30\times10^{-3}m_\pi^{-1}$ with the inclusion of crossing.

The role of pion-absorption in low-energy pion-nucleus scattering as well as the possible importance of crossing in this context has generated renewed interest in the study of such effects in threshold π-d elastic scattering. The quantity of experimental and theoretical interest in this process is $a_{\pi d}$, the π-deuteron scattering length. For $a_{\pi d}^S$, the contribution to $a_{\pi d}$ with *no* intermediate pion absorption, double scattering and explicit Fadeev calculations[1] yield the value $a_{\pi d}^S \simeq -0.035m_\pi^{-1}$. The remaining contribution to $\mathrm{Re}\,a_{\pi d}$ coming from intermediate pion absorption, $a_{\pi d}'$ which is less well understood theoretically and for which, it has been noted, few calculations exist, is thought to be of the order of 10% (although this estimate is based on a recent measurement[2] of $\mathrm{Re}\,a_{\pi d}$ for which the uncertainty is about 50%).