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Study of High-Transverse-Momentum π^0 Pairs Produced at the CERN Intersecting Storage Rings

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Correlations of two π^0 mesons with transverse momenta p_T up to 13 GeV/c have been measured with large azimuthal acceptance. Results for cross sections, p_{out} , and z distributions are compared in detail with models based on two-constituent scattering and fragmentation. The width of the constituent transverse-momentum Gaussian distribution would have to be doubled to match that from experiments with p_T below 5 GeV/c. A more likely explanation is the presence of processes with more than two constituents in the final state.

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Experiments at PETRA¹ studying jet structure in hadronic reactions from e^+e^- collisions report that Feynman-Field-type models,² which describe hadronic final states in terms of two-constituent (quark-antiquark) fragmentation, while fitting the data well below $\sqrt{s} \approx 10$ GeV, fail at higher energies. This failure has been attributed to the lack of a third constituent (gluon) in these models.

The analysis of jet structure in hadronic collisions is substantially more difficult, primarily because of the presence of "spectator" particles not associated with the jets, and the (not well un-

derstood) degrees of freedom of the confined constituents in the initial state, such as their transverse momentum and longitudinal rapidity. These parameters, not encountered in e^+e^- collisions, cause ambiguity in identifying the jet-associated particles.

Despite these problems, much progress has been made by studying the characteristics of high-transverse-momentum particles produced in high-energy hadron collisions.³ Experimentally observed⁴ correlations of such particles have been compared to predictions of quantum chromody-

namic (QCD) models based on two-constituent scattering and fragmentation. Up to transverse momenta of the triggering particle $p_T = 5 \text{ GeV}/c$, such models describe the data⁵ reasonably well. In this Letter we extend the comparison to the region $7 < p_T \leq 13 \text{ GeV}/c$, where the center-of-mass energy of the scattering constituents are in the range of the PETRA experiments.

The apparatus used in this experiment has been described elsewhere.⁶ For this study, four liquid-argon calorimeter modules (octants) detect two π^0 's with rapidity $|y| < 0.8$, coplanarity angle $\alpha < 70^\circ$, and trigger momentum $p_{T1} > 7 \text{ GeV}/c$, as illustrated in Fig. 1, where both p_{T1} and p_{T2} are momentum components transverse to the beam direction. The CERN intersecting storage rings provided an integrated luminosity of 10^{38} cm^{-2} at $\sqrt{s} = 62.4 \text{ GeV}$, yielding 110 000 $2\pi^0$ events in the kinematic regions specified above. The empirical variables important to this discussion are the invariant cross section, $I = E d^3\sigma/dp^3$, the scaling variable $x_e = p_{T2} \cos\alpha / p_{T1}$, which defines the fragmentation along the jet direction, and the transverse variable $p_{\text{out}} = p_{T2} \sin\alpha$, where p_{T2} is the transverse momentum of the second π^0 . To remove "spectator" background from "jet"-associated particles, only events with $x_e > 0.2$ are considered.

Below we discuss the experimentally measured correlations, and compare the data with a representative two-constituent scattering model⁷ developed by Feynman, Field, and Fox. This version of their model incorporates scale-violating effects in the hadronic structure and fragmenta-

FIG. 1. Illustration of coplanarity angle α , p_{T1} , p_{T2} , p_{out} , and longitudinal scaling variable x_e . Plane of illustration is perpendicular to the direction of the proton beam.

tion functions. We utilize their Monte Carlo program, modified to include our experimental acceptance. This model is known to describe well the shape of the inclusive single- π^0 invariant cross section as measured up to $p_T = 16 \text{ GeV}/c$ by this⁸ and other experiments.⁹

The model prediction for the invariant cross section in the p_T range under consideration here is shown in Fig. 2 together with our previously reported result.⁸ The shape is well reproduced, with the predicted absolute scale about 35% smaller than the experimental points, consistent with an uncertainty in normalization of $\sim 40\%$ but also consistent with the presence of a single-photon component in the measured points as seen in other experiments.¹⁰ When a second π^0 in the specified kinematic region is required, the predicted cross section integrated over the variables of the second π^0 is given by the lower curve shown in Fig. 2. In earlier versions of the model¹¹ this $2\pi^0$ cross section was calculated to be substantially larger than the experimental values in the lower p_T range. With the addition of scale invariance violation as required by QCD, the inclusion of gluons as constituents and with an increase

FIG. 2. Measured value of the invariant cross section I at $y = 0$ for π^0 inclusive events (solid circles) and $2\pi^0$ events with $|y| < 0.8$, $\alpha < 70^\circ$, and $x_e > 0.2$ (open circles). Model predictions are indicated by solid and dashed lines, respectively.

from the width $\sigma_s = 0.35$ GeV/c to $\sigma_s = 0.66$ GeV/c of the Gaussian distribution of constituent transverse momentum, the model as now formulated agrees remarkably well with our cross-section data of Fig. 2 as well as with data at lower p_T .⁴ Note that hard-gluon bremsstrahlung is not included.

Having noted good agreement in the magnitude of the $2\pi^0$ cross section, we turn to model predictions for the distributions in the x_e and p_{out} variables. The predicted x_e distribution for two p_T ranges, shown in Fig. 3 and normalized to our experimental points at $x_e = 0.45$, changes very little in shape from $p_T = 7$ to 11 GeV/c and fits the data quite well. In this connection we remark that the fragmentation function used² has a finite intercept at $x_e = 1$ before convoluting with constituent transverse momentum. Previous attempts⁴ to parametrize this distribution failed to account for the number of events at large x_e .

The rms value $\langle p_{out}^2 \rangle^{1/2}$ is a measure of the noncoplanarity of the $2\pi^0$ events. In this model the noncoplanarity caused by the transverse momentum of the initial constituents is more important than the transverse momenta associated with

FIG. 3. Distribution in x_e for $2\pi^0$ events with $7 < p_T \leq 8$ GeV/c (triangles) and $10 < p_T \leq 11$ GeV/c (crosses). Model predictions (solid lines) are normalized at $x_e = 0.45$. Note that if an event has, e.g., a 7.5-GeV/c π^0 and a 10.5-GeV/c π^0 , it contributes to a point on the 7–8-GeV/c curve at $x_e = 1.4 \cos\alpha$ and to a point on the 10–11-GeV/c curve at $0.71 \cos\alpha$.

fragmentation.¹² In Fig. 4 we plot $\langle p_{out}^2 \rangle^{1/2}$ as a function of x_e . The dashed lines show the range of predictions for the model for p_T from 7 to 11 GeV/c, which are seen to be insensitive to p_T in this range, but grow with x_e . It is clear that there has been a drastic change in p_{out} compared with the low- p_T results used to fix the parameters of the model.

The only parameter in this two-constituent model sensitively affecting the transverse distribution is the width σ_s of the transverse momentum Gaussian distribution of the scattering constituents. We find that *doubling* this width brings the model predictions for our higher p_T range into much better agreement with the data (solid curves of Fig. 4) with little change ($\lesssim 10\%$) in the predicted inclusive cross sections. In order for this model to fit the data over the whole range of p_T , it would thus appear that σ_s must increase rather suddenly as p_T changes from < 5 to ~ 7 GeV/c. Note that the width $\sigma_s = 1.33$ GeV/c corresponds to an average constituent transverse momentum of 1.67 GeV/c.¹³

The invariant cross sections and x_e distributions are correctly predicted by the two-constituent scattering model, but the breadth of the observed p_{out} distributions in the p_T range, when

FIG. 4. The rms value $\langle p_{out}^2 \rangle^{1/2}$ as a function of x_e for various p_T values: $7 < p_T \leq 8$ GeV/c (triangles), $8 < p_T \leq 9$ GeV/c (diamonds), $9 < p_T \leq 10$ GeV/c (circles), and $10 < p_T \leq 11$ GeV/c (crosses). Dashed lines: Predictions in the p_T range 7–11 GeV/c of original model with $\sigma_s = 0.66$ GeV/c. Solid lines: Predictions of model with $\sigma_s = 1.33$ GeV/c.

compared to previous experiments, indicates that a two-constituent scattering model requires a sudden growth of σ_s to quite high values. Within a QCD framework, such an effect may be naturally caused by the presence of subprocesses with more than two constituents¹⁴ in the final state, as observed at PETRA.

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$$\langle K_{\perp} \rangle = \int_0^{\infty} dk_{\perp}^2 [(1/2\sigma_s) \exp(-k_{\perp}^2/2\sigma_s^2)] k_{\perp} = (\pi/2\sigma_s)^{1/2}.$$

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