Comparison of High-Transverse-Momentum π^0 Production from π^-, K^-, p, and $\bar{p}$ Beams

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We compare high-transverse-momentum ($P_\perp$) inclusive π^0 production from π^-, K^-, p, and $\bar{p}$ beams, at 100 and 200 GeV/c, for center-of-mass (c.m.) angles ranging from 2° to 115°, and $P_\perp < 4.5$ GeV/c. The ratio $\sigma(pp\to\pi^0X)/\sigma(\pi p\to\pi^0X)$ decreases with increasing $P_\perp$, and changes dramatically with c.m. angle. Also, the ratios $\sigma(K^-p\to\pi^0X)/\sigma(\pi^-p\to\pi^0X)$ and $\sigma(\bar{p}p\to\pi^0X)/\sigma(pp\to\pi^0X)$ are approximately constant. These measurements are consistent with a theoretical viewpoint in which constituents of the incident hadrons undergo a hard-scattering subprocess.

One of the motiviations in the study of high-transverse-momentum inclusive reactions has been that this research could shed light on the role of constituents within the hadrons. Our technique has been to vary the quark content of the initial state and observe the resultant production of a single meson (π^0) at high transverse momentum. Certain characteristics of the scattering in $\pi^\pm p$ and pp reactions have been published,[1,2] and in this Letter we present the first available data for the inclusive reactions $K^-p\to\pi^0X$ and $\bar{p}p\to\pi^0X$ at 100 and 200 GeV/c. The content of the beams allows us to measure how the cross sections depend on the presence of quarks versus antiquarks, and strange quarks versus nonstrange quarks, in the initial state. A comparison between reactions places constraints on theoretical models, both in the relative magnitude of their predicted cross section and in the dependence on center-of-mass (c.m.) angle.

The experiment was performed in the $M2$ beam at Fermilab. The π^0's were detected using a lead-scintillator photon calorimeter which provided position and energy information for each electromagnetic shower. The angular acceptance was varied by arranging the position of the photon detector relative to a hydrogen target. The data were taken in three broad angular regions: "90°" (48°–115° c.m.), "30°" (15°–52° c.m.), and "10°" (2°–20° c.m.).[3]

Incident particles in the unseparated beam were identified by two independent differential Cherenkov counters. Each of these counters had two photomultiplier tubes and, under typical running conditions, a pion would produce a signal in one of these, and kaons would produce a signal in the other. (Protons were below threshold.) For the present analysis, we accept only signatures in which both Cherenkov counters unambiguously identify the beam particle. The beam compositions are determined from special runs taken with the photon detector not required in the trigger. The overall flux was corrected for electrons in the negative beams (7.5% at 100 GeV/c and 1.3% at 200 GeV/c). A study of the ambiguous signatures in the Cherenkov counters determined the contamination within the accepted signatures. For $\pi^\pm$ and p beams this effect is negligible; the only large contaminations occur in the K^- beam at 200 GeV/c (which was composed of 22% π^-'s) and in the 200-GeV/c $\bar{p}$ beam (which was composed of 23% π^-). The cross sections have been corrected appropriately in these instances. Since the data were gathered concurrently, and only the two Cherenkov counters distinguished these reactions, ratios of variously induced cross sections are relatively free of systematic errors which may affect the individual cross sections.

In order to compare the effects of these beams on π^0 production, we form the "beam ratio"

$$R(A/B)=\frac{Ed\sigma(Ap\to\pi^0X)/dp^3}{Ed\sigma(Bp\to\pi^0X)/dp^3},$$

where A and B are $\pi^\pm$, K^-, p, and $\bar{p}$. We present our results for angular regions in bins of $P_\perp$, because the relatively small flux of K^- (~ 2%) and $\bar{p}$ (~ 1–2%) beams has forced us to use the widest available regions of $x_{\parallel} = (p_{\parallel}/p_{max})_{c.m.}$ at each detector setting. These beam ratios are shown in Figs. 1 and 2.

Beginning with the pion-proton comparison, the upper row of plots in Figs. 1 (110 GeV/c) and 2 (220 GeV/c) display the ratio $R(p/\pi^-)$ versus $p_\perp$. For the "90°" data at $p_\perp$ ~ 1 GeV/c, this ratio has a value ~1.5 which is expected, since it is the ratio of the total cross sections. As $p_\perp$ increases, this ratio decreases until the πp cross section exceeds that from pp at the highest measured $p_\perp$. The same ratio $R(p/\pi^-)$ taken at "30°" is dramatically lower than that at "90°" and falls much more quickly with $p_\perp$. Finally, at the most forward region, the π^- cross section exceeds the pp cross section by an order of magnitude. Therefore, a systematic trend is seen for $R(p/\pi)$ to decrease with increasing $p_\perp$ and decreasing angle.

In contrast, the ratios $R(\pi^-/K^-)$ shown in the second row of plots in Figs. 1 and 2 have no such trend as a function of $p_\perp$ or angle. The average $R(\pi/K) = 1.02 \pm 0.12$ at 100 GeV/c and 1.22 ± 0.07 at 200 GeV/c. The third row of plots compares kaons with protons, and at 90° c.m. the ratio $R(p/K)$ for $p_\perp < 1.5$ GeV has the expected value (the total-cross-section ratio is ~ 1.8). The $R(p/K)$ ratios then fall with increasing $p_\perp$ closely resembling the $R(p/\pi)$ plots, as they must if $R(\pi/K)$ is constant.

Finally, the bottom row of plots in Figs. 1 and 2 show the ratio $R(\bar{p}/p)$ as a function of $p_\perp$ and angle. The $\bar{p}$ cross sections, although not as well determined, show that the ratio $R(\bar{p}/p)$ lies between 1 and 2. For example, the "30°" data at 200 GeV/c shows the ratio $R(\bar{p}/p)$ to be ~ 1.2 and independent of $p_\perp$.

Recent hard-scattering models compute the cross section as an integral (over kinematic variables) of the product of probabilities for three processes to occur: (a) The incident hadrons break up and each emits a constituent; (b) these constituents then scatter according to some chosen scattering rule; (c) one or the other of the scattered constituents then reforms into the observed secondary particle. All these models must account for the fact that $p_\perp^{-4}$ falloff that would arise from quark-quark elastic scattering via one-gluon exchange is not seen.[4] This has been accomplished in one of two ways: Either the scattering probability for q-q elastic scattering is modified[5-8] or the scattering is assumed to be between objects other than single quarks,[9,10] such as quark-hadron, quark-diquark, or hadron-hadron scattering. In these models, most of the $p_\perp$ dependence of the cross section arises from the scattering rule chosen, while the angular (or $x_\parallel$) behavior originates in the breakup of the incident hadrons, which in turn depends on the distribution of momentum among quarks (or other constituents) making up the particles.

The measurements seem to be consistent with the general features of this approach: The pion-

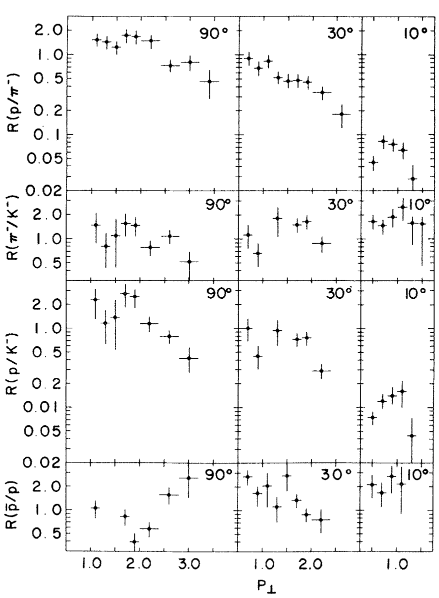

FIG. 1. Ratios of invariant cross sections vs $p_\perp$ at 100 GeV/c.

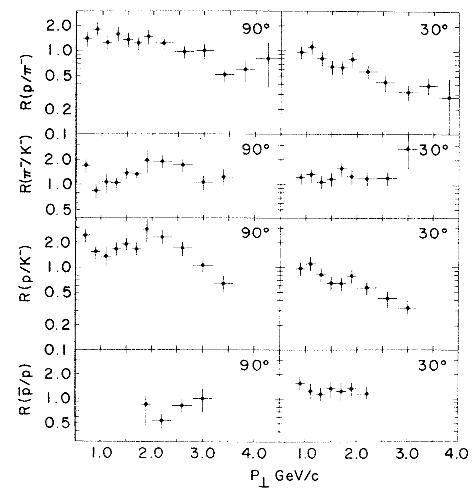

FIG. 2. Ratios of invariant cross sections vs $p_\perp$ at 200 GeV/c.

proton comparison effectively samples the ratio of pion and proton structure functions. The πp cross section falls more slowly with $x_{\parallel}$ than the pp cross section, thereby supporting the notion that each of the two valence quarks in the pion has, on the average, a higher momentum than those in the proton. When the quarks have a similar average momentum, as is the case in πp scattering at 200 GeV/c and pp scattering at 300 GeV/c, one finds the same $p_{\perp}$ dependence of the cross sections as has been noted by Fredriksson.[11]

Two aspects of kaons could alter the π^0 inclusive cross section in Kp interactions compared with that produced by other beams: (a) a difference in the momentum distribution of the valence quarks in the kaon, and (b) the fact that the strange quark does not couple directly to the π^0. The lack of variation of our ratio $R(\pi/K)$ with $p_{\perp}$ seen in Figs. 1 and 2 suggests that the pion and kaon structure functions are similar. The proton structure function must be quite different to account for the variation in the ratios $R(p/\pi)$ and $R(p/K)$.

If the strange quark never reformed into a π^0, but still scattered off a constituent of the target, one might assume that the magnitude of the π^0 cross section would be reduced relative to πp interactions, but that the shape would be the same. The difference between kaons and pions will be particularly apparent at forward angles, where constituents from the beam dominate the high-$p_{\perp}$ production. It may be that the slight rise of $R(\pi/K)$ at "10°" is due to this reduction of the kaon cross section even though the data are at rather low $p_{\perp}$.

If the production of a high-$p_{\perp}$ π^0 required a $\overline{q}$ to initiate the scattering (such as quark fusion and $q\overline{q}$ annihilation models),[12,13] the cross section in $\overline{p}p$ interactions (three valence $\overline{q}$ in the initial state) would be greatly enhanced relative to pp interactions. For example, the predicted ratio is 10 with $p_{\perp}=2.7$ GeV/c at 100 GeV/c. On the other hand, in the absence of quark fusion and annihilation, one expects from the symmetry of q and $\overline{q}$ in the π^0 wave function that subprocesses which emit a single high-$p_{\perp}$ quark should produce as many π^0 as those emitting an antiquark, thus $\overline{p}p$ scattering and pp scattering should be very similar. As shown in the bottom row of Figs. 1 and 2, the ratio $R(\overline{p}/p)$ is close to 1, so that quark fusion and quark annihilation do not dominate,[14] and it appears that a $\overline{q}$ behaves similarly to a q for producing π^0's. This interpretation is consistent with the behavior of the ratio $R(p/\pi)$. The results presented here imply that large-transverse-momentum phenomena in $\overline{p}p$ reactions are not much different those in pp reactions. This is quite relevant when considering the expected rates for $\overline{p}p$ colliding-beam facilities.

To conclude, the behavior of these ratios supports the idea that quarks scatter without regard to flavor (u, d, or s) and type (q or $\overline{q}$), so that variation in the ratios originate in the larger probability for the quarks in the pion and kaon to have a greater portion of the incident momentum.

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[3]Because of the variation of the cross sections within these angular ranges [which subtend large intervals of $x_{\parallel} = (p_{\parallel}/p_{\max})_{\text{c.m.}}$], one should regard the values given as an average over the angular region rather than at the particular $\theta_{\text{c.m.}}$ used. We have corrected the data for variations in the acceptance over these angular ranges.

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quires a detailed knowledge of both the pion and proton structure function, and a prescription for how the scattering occurs. In the constituent-interchange model, for example, entirely different subprocesses may dominate.

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[13]P. V. Landshoff and J. C. Polkinghorne, Phys. Rev. D 10, 891 (1974).

[14]See, for example, the calculation of $R(\bar{p}/p)$ appearing in M. K. Chase and W. J. Stirling, University of Cambridge Report No. DAMTP-77/15, (to be published).

Unification of the Basic Particle Forces at a Mass Scale of Order $1000m_W$

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By considering a semisimple group [e.g., $SU(4)^4$] subject to discrete symmetries which ensure one coupling constant in the unification limit, we show that the unification mass scale need be no higher than $1000m_W$. The possible emergence of a light octet of *axial* color gluons is noted.

The hypothesis[1,2] that the fundamental particles and their interactions are unified at a basic level through a Lagrangian characterized by a single gauge coupling constant raises two important questions: (1) At what energy scale would this "complete" unification[3] (lost at low energies through spontaneous breaking of the symmetry) exhibit itself? (2) What is the value of the renormalized weak angle $\sin^2\theta_W$?

In attempting to answer these questions several authors[4-6] have claimed that the so-called super-unifying mass scale M needs to be ultraheavy ($\gtrsim 10^{15}$ GeV) for the "strong" interactions to be strong at low energies. The purpose of this Letter is to show that there exist simple patterns of a hierarchical breakdown of a unifying group G {for example, the previously proposed semisimple group[7] $[SU(4)\otimes]^4$}, which permit unification at a mass scale ten to twenty orders of magnitude below previous estimates. This relatively low, unifying mass scale raises the exciting possibility that the unification hypothesis may be tested through ongoing cosmic-ray experiments and perhaps also with the next generation of accelerators. We obtain a value for renormalized $\sin^2\theta_W \approx \frac{2}{7}$ consistent with the value allowed presently by experiments.[8] Implications of possible lower values[9] of $\sin^2\theta_W$ ($\simeq\frac{1}{4}$) are also stated.

The reason why the unification mass M encountered by previous authors is so large may be traced to the following underlying special assumption: The embedding of the low-energy weak (G_W) and strong $[SU(3)_{col}]$ groups within the unifying symmetry G is such that the gauge coupling constants associated with G_W and $SU(3)_{col}$ are *equal* to each other in the (bare) symmetric limit.

The embeddings presented in this Letter permit a departure from this assumption—here the coupling constants of G_W are smaller (e.g., by a factor of $1/\sqrt{2}$) than SU(3)-color coupling. Correspondingly, the unification mass scale is found to be dramatically lower than those obtained in previous estimates.[10]

We now proceed to demonstrate the role which embedding plays in the determination of the unifying mass scale M by considering the unifying symmetry $[SU(4)\otimes]^4 \equiv SU(4)_A\otimes SU(4)_B\otimes SU(4)_C{}' \otimes SU(4)_D{}'$. The discrete symmetries $A\leftrightarrow B\leftrightarrow C \leftrightarrow D$ ensure that the theory starts with one basic coupling constant. For notational purposes, we recall the following salient features of this symmetry.[7] The symmetry operates on a set of 4×4 four-component "*basis*" *fermions* $F_{L,R}$ possessing four flavors (u,d,s,c) and four colors, plus an analogous set of *mirror fermions* $F_{L,R}{}^m$ needed for the cancellation of anomalies. There are two possible ways to gauge the fermions: (I) *(Chiral flavor ⊗ chiral color) gauging:* As-