# COMPARISON OF PROTON MOMENTUM SPECTRA IN PROTON-PROTON COLLISIONS INVOLVING PION AND KAON PRODUCTION*

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Striking similarities are found in the proton momentum spectra involving pion and kaon production processes. Except for the falloff near the kinematical limits, the longitudinal-momentum distributions are isotropic. In the transverse-momentum spectra, a sharp break near $P_\perp^2 = 0.2$ (GeV/$c$)$^2$ is observed in both processes. The breaks are attributed to the production and decay of peripherally produced nucleon resonances.

We have measured the differential cross sections for the inelastically scattered protons in proton-proton collisions near 6 GeV/$c$. The purpose of this study is to compare the proton spectra in processes involving the production of pions and kaons. Previous experiments to study this subject[1] utilized a single-armed proton spectrometer technique. Inelastic events below kaon production threshold were used in the pion sample and those above kaon threshold were accepted in the kaon sample. It will be shown in this Letter that the cross section for pion production is 50 times greater than that for kaon production; therefore, the abovementioned technique cannot be sensitive to the presence of the kaon events.

The data were obtained using the Lawrence Radiation Laboratory 72-in. hydrogen bubble chamber exposed to proton beams of 5.4- and 6.6-GeV/$c$ momenta. The following categories of events have been included in the pion sample:

$$pp \to pp + m\pi^0 \quad (m \geq 1), \tag{1}$$

$$\to pn\pi^+ + m\pi^0 \quad (m \geq 0), \tag{2}$$

$$\to pp\pi^+\pi^- + m\pi^0 \quad (m \geq 0), \tag{3}$$

and

$$\to pn\pi^+\pi^+\pi^- + m\pi^0 \quad (m \geq 0). \tag{4}$$

It has been verified that the omission of the six-prong and higher topologies, which account for less than 5% of the inelastic cross section, does not affect the results of this study.

In the kaon or strange-particle group we have included the following types of events:

$$pp \to p + K_s^0 + \text{anything} \tag{5}$$

and

$$p + \Lambda^0 + \text{anything}. \tag{6}$$

The cross sections for these processes have been corrected for unobserved decay modes. Events in which only charged strange particles were produced have not been included; however, they constitute only about 10% of the total strange-particle cross section with protons in the final state. In the following analyses for either the pion or kaon samples, if two protons were observed in the final state, both were plotted to permit comparisons with results from counter experiments of the one-armed-spectrometer type.

In Fig. 1, the differential cross sections $d^2\sigma/dP_\perp^2 dP_\parallel$ are plotted versus $P_\parallel$, the c.m. longitudinal momentum of the outgoing proton for the pion and the kaon samples. It is apparent that the production mechanism for both types of events is insensitive to the variable $P_\parallel$. This phenomenon has been observed previously by Anderson et al.[2] in pion production and it is interesting to note that the same characteristic exists in the kaon sample. The distributions of Fig. 1 integrated over $P_\perp^2$ are shown in Fig. 2. One notes that for pion production, the differential cross section $d\sigma/dP_\parallel$ is essentially constant up to 1.3 GeV/$c$, whereas the kaon sample displays a flat differential cross section up to 1 GeV/$c$. This difference reflects the fact that the available phase space for pion production is larger than that for kaon production. It is also worth noting that the cross section for pion production processes is 50 times greater than that for kaon production. Therefore, in order to study the proton spectrum involving kaon production, one must be able to separate the pion events from the kaon sample.

In Fig. 3, we show the distribution of the square of the proton transverse momentum. A clear break in the slope is visible in both the pion and

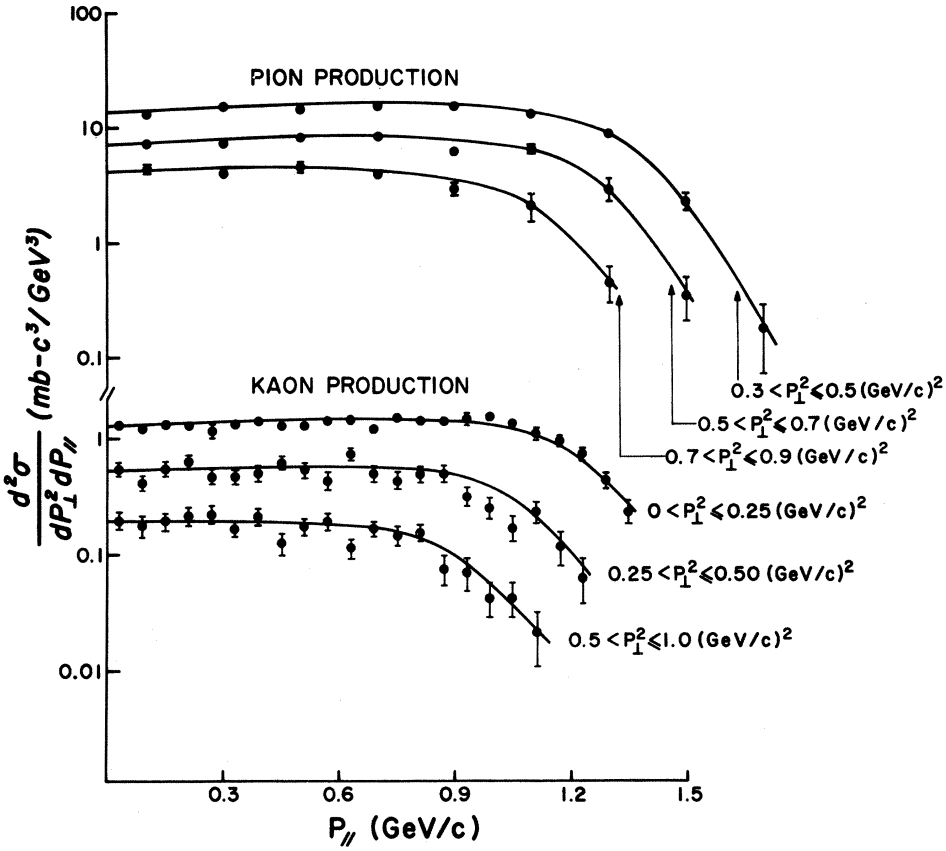


FIG. 1. Proton c.m. longitudinal-momentum distributions for various values of $P_\perp^2$. The solid lines are freehand fits to the data.

the kaon samples near $P_\perp^2 = 0.2$ $(\text{GeV}/c)^2$. We have divided each sample into two groups, one with $P_\perp^2 \leq 0.2$ $(\text{GeV}/c)^2$ and the other with $P_\perp^2 > 0.2$ $(\text{GeV}/c)^2$. The distribution of each group is fitted to an expression of the form

$$d\sigma/dP_\perp^2 = \exp(a + bP_\perp^2 + cP_\perp^4). \qquad (7)$$

The coefficient $c$ is introduced to allow a slight deviation of the differential cross section from linear behavior at high $P_\perp^2$ in Fig. 3. The resultant slope $b$ is given in the inset. The parameter $c$ is small for both samples. The slopes for the pion data are consistent with those for the kaon data, and both appear to have breaks near $P_\perp^2 = 0.2$ $(\text{GeV}/c)^2$.

It is well known that breaks exist in the transverse-momentum distribution of the elastically scattered proton.[3] Phenomenologically, the distribution of $P_\perp^2$ may be represented by three Gaussian regions with the slope parameter "$b$" equal to 7.3, 2.6, and 1.1 $(\text{GeV}/c)^{-2}$, respectively. It has been suggested[4] that these observations can be accounted for if the proton possesses different interaction radii for processes producing

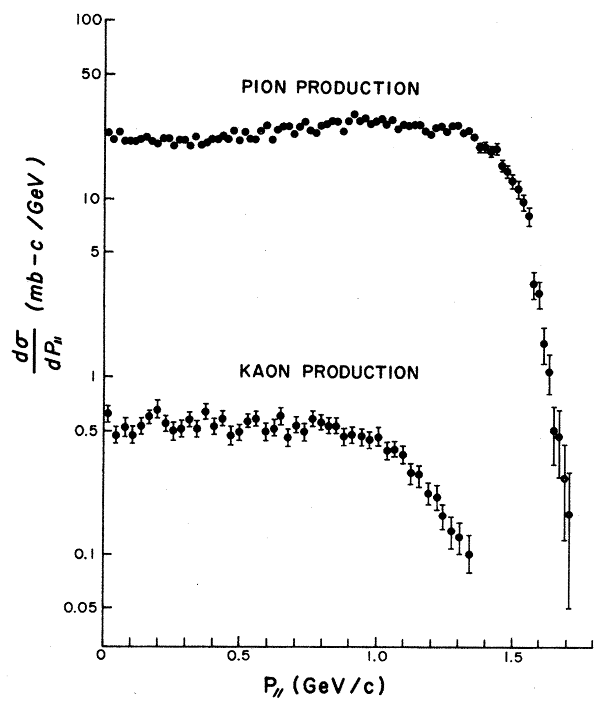


FIG. 2. The integrated proton c.m. longitudinal-momentum distributions for both the pion- and kaon-production processes.

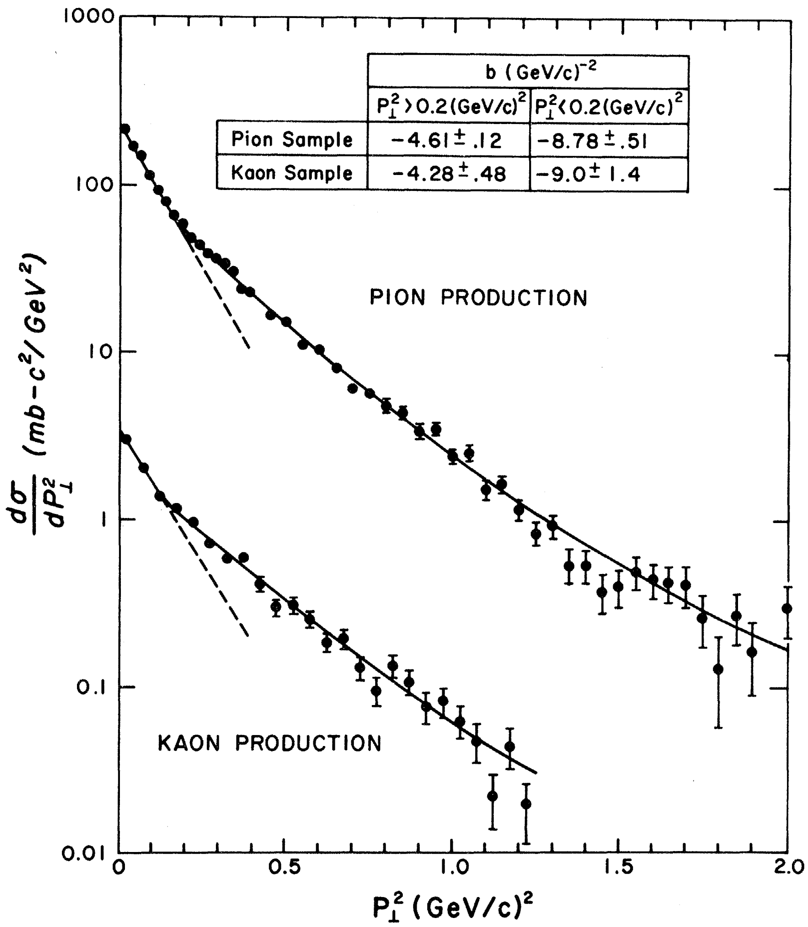


FIG. 3. Proton transverse-momentum distributions. The solid curves represent fits to the data as described in the text.

only pions or kaons or antinucleons. These characteristic sizes would display themselves through shadow scattering in the distribution of the elastic process. The results of this experiment are clearly inconsistent with such a notion, for the pion-producing processes not only have the same slope as the kaon-producing ones, but also exhibit breaks at nearly the same value of $P_\perp^2$. Therefore, in terms of the variables $p_\parallel$ and $P_\perp^2$, it appears the only difference between the two samples lies in their magnitude.

A similar sharp break has been reported in the pion transverse-momentum distribution.[1,5] The break is attributed by Yen and Berger[6] to the low-$Q$-value decay of the peripherally produced nucleon resonances. It is argued that if the production of a low-$Q$-value nucleon resonance can be described by $e^{-BP_\perp^2}$, the differential cross section $d\sigma/dP_\perp^2$ of the decay product, a pion in this case, will have a greater slope. The sharpening, according to the model, is proportional to the square of the ratio of the resonance mass to the mass of the observed decay particle. One may thus deduce that a forward peak of lesser slope should exist in the distribution of the squared proton transverse momentum than in that of the squared pion transverse momentum. The slope of the forward peak is typically 9 for protons as compared with 15 for pions as reported in Ref. 5. Thus, we conclude that our results for the pion sample are consistent with the model. Finally, we note that in order to apply this model to kaon events, one must invoke the presence and decay of a low-$Q$-value $Z^*$ resonance. The presently available data[7] on strange particles in $p$-$p$ collisions do not support such a notion. A reasonable explanation may be that the steep forward peak is due to the proton recoiling against a peripherally produced nucleon resonance, e.g., in the process $pp \rightarrow pN^*(1688)$, where $N^*(1688)$ decays into a nonstrange nucleon and pions, and less often, but not negligibly, into kaon-hyperon pairs. In the $\Lambda K^+p$ final state, a strong $N^*(1688)$ signal is seen,[7] and the cross section corresponding to this signal is roughly consistent with the size of the forward peak observed in this experiment.

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# MEASUREMENT OF ELECTROPRODUCTION OF MUON PAIRS*

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An experiment on electroproduction of muon pairs with invariant masses between 400 and 900 MeV is reported. The experiment, interpreted as a text of the timelike photon propagator, shows agreement with QED. Photon propagator modifications representing (+) metric and (−) metric heavy photons are limited to masses $\Lambda > 1260$ and $\Lambda > 750$ MeV, respectively (15 times the mass limits of positronium experiments). A model used to calculate $\rho$-QED interference yields a best $\rho$-QED phase angle of $16° \pm 22°$.

Muon or electron production of lepton pairs and colliding-beam experiments at present provide the only techniques that selectively probe QED for the behavior of the timelike photon propagator far off its mass shell.[1] The lowest order QED amplitudes for lepton-pair electroproduction consist of one set (the "timelike" amplitudes) which involves a timelike virtual photon coupled to the produced lepton pair, and of another set (the "spacelike" amplitudes) which are Bethe-Heitler amplitudes with an electron line attached to the incident photon. The contribution of the timelike amplitudes is itself gauge invariant. It is therefore meaningful in any gauge to examine separately the behavior of the timelike and the spacelike amplitudes.

The eight-dimensional kinematic phase space for electroproduction of muon pairs was studied[2] to find regions in which the timelike amplitudes either dominate the spacelike amplitudes or are at least significant (a) when the electron is not observed and (b) when the electron is observed. The regions (a) and (b) were found to exist. Region (a) is most favorable when the muons carry off nearly all of the available energy and are produced nearly symmetrically about the direction of the incident electron. This region has been discussed by Yamamoto.[3] It was decided to first perform an experiment in region (a) since this avoided the need to construct, at the outset, a large solid-angle electron detector. In this experiment lepton charge is not observed, hence interference of the $V^0 \to l^+ + l^-$ electroproduction amplitude (where $V^0$ is any neutral vector meson) with the spacelike QED amplitudes vanishes.[2] But interference with the timelike amplitudes does not vanish. Therefore, the timelike photon propagator may be studied either directly, in regions of muon-pair invariant mass $m$ away from vector-meson masses $M_V$ or indirectly by