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NEW RESULTS ON MULTIPARTICLE PRODUCTION USING NUCLEAR TARGETS AND A COMMENT ON JETS*

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Preliminary results are presented for the dependence of inclusive-particle production on atomic number in neutron-nucleus interactions at ~300 GeV/c. In addition, a comment is made on the transverse momentum properties of multipion systems produced in high-energy collisions.

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In the first section of this paper I will present some preliminary measurements of inclusive particle production in neutron-nucleus collisions at high energies. The data were obtained as a byproduct of a search for charm particles in hadronic reactions, an experiment which was conducted in the M-3 neutral beam at Fermilab[1]. In the second part of this note I will discuss the correlation observed between the mass (M) and the transverse momentum (p_T) of multipion systems produced at high energies[2], and indicate how clusters of particles, with individual particles within such clusters having small p_T, may account for the large cross section ascribed to "jet" production[3].

Particle Production Using Nuclear Targets

The recent resurgence of interest in studies of hadronic production using nuclear targets has been greatly enhanced, in my view, by the availability of new reliable inclusive measurements from Fermilab such as those of Busza and his collaborators[4], and by the hope that through examining inelastic production in nuclear material we can learn about the early space-time development of elementary hadronic processes. Halliwell[4] has reviewed the current experimental situation, and presented at this meeting several of the interesting ideas which permeate this subject matter. I will restrict my remarks here to our preliminary measurements of charged-particle production in neutron collisions with Be, Al, Cu, Sn and Pb nuclei[5]. The neutron beam was a broad-band neutral beam, containing mainly neutrons, with negligible K_L^0 , $\bar{n}$ and γ contamination. The momentum spectrum peaked at ~300 GeV/c, had a full width at half maximum of ~200 GeV/c, and a cut off at 400 GeV/c[6]. Although the experiment had a capability for electron/hadron discrimination, there was no provision made for Cerenkov particle-identification. Consequently, rapidities were calculated assuming pion-mass interpretations for all the charged tracks.

Figure 1 displays the differential charged-particle multiplicity, as a function of laboratory rapidity for negatively and positively charged particles

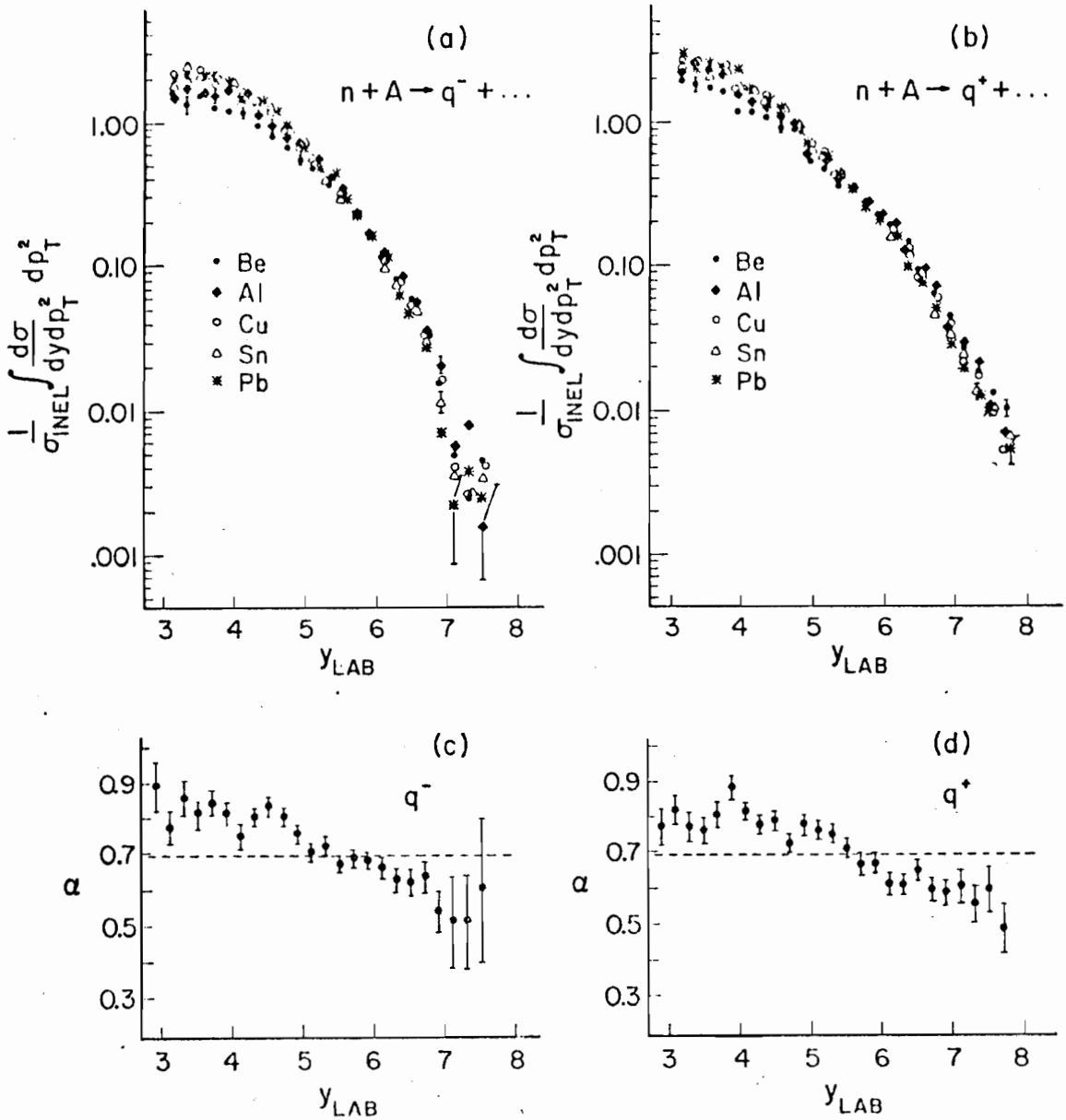

Figure 1 - Negative and positive charged-particle multiplicities as a function of rapidity in (a) and (b), respectively. The parameter α as a function of rapidity for negative and for positive-particle production in (c) and (d),

in (a) and (b), respectively. (The rapidity is defined in the usual way as $y = \frac{1}{2}\,\ell n[(E+p_\ell)/(E-p_\ell)]$, with E and p_ℓ being the energy and longitudinal momentum of a produced particle.) To obtain the multiplicity for any target nucleus the measured inclusive cross section was divided by the total inelastic nuclear cross section (σ_{INEL}); the specific form used for σ_{INEL} as a function of atomic number was $46\,A^{0.69}$ mb[4]. The rapidity distributions display characteristic fall offs at large values of y_{LAB}, with the positive spectra showing an excess over the negative distributions for $y_{LAB} \gtrsim 6$; presumably this excess can be ascribed to the contribution from proton production in the positive-multiplicity data. To determine the precise dependence of inclusive production on the atomic number (A) of the target material, we performed fits to the measured invariant cross sections assuming a dependence of the type A^{α}, where α is a parameter which can, in principle, depend both on y and on p_T. Although this simple $A^{\alpha(p_T,y)}$ form yields an adequate description of the invariant cross sections, there is nevertheless an apparent trend in the data in that the value of α becomes smaller when targets of lowest-A are excluded from consideration. In Figs. 1(c) and (d) the value of α is displayed for data integrated over p_T, as a function of y_{LAB}, for negatively and positively charged particles. It is apparent that α changes monotomically over the entire region of y_{LAB}, indicating that the produced multiplicity is a smoothly falling function of A as y_{LAB} increases. (The dashed lines in Fig. 1 correspond to A-independent multiplicities, i.e., a value of $\alpha = 0.69$.) This result supports the recent measurements from the Soviet Union described at this Symposium by Halliwell[4,7]. It is interesting that a very similar dependence of α on y_{LAB} was predicted by Capella and Krzywicki at this meeting[8].

Figure 2 displays the variation of α with p_T for three regions of y_{LAB}. For more central rapidities (the average value of y for pions produced at 90° in the center of mass is $y_{LAB} \sim 3.2$) the value of α drops from $\alpha \sim 1.0$ at

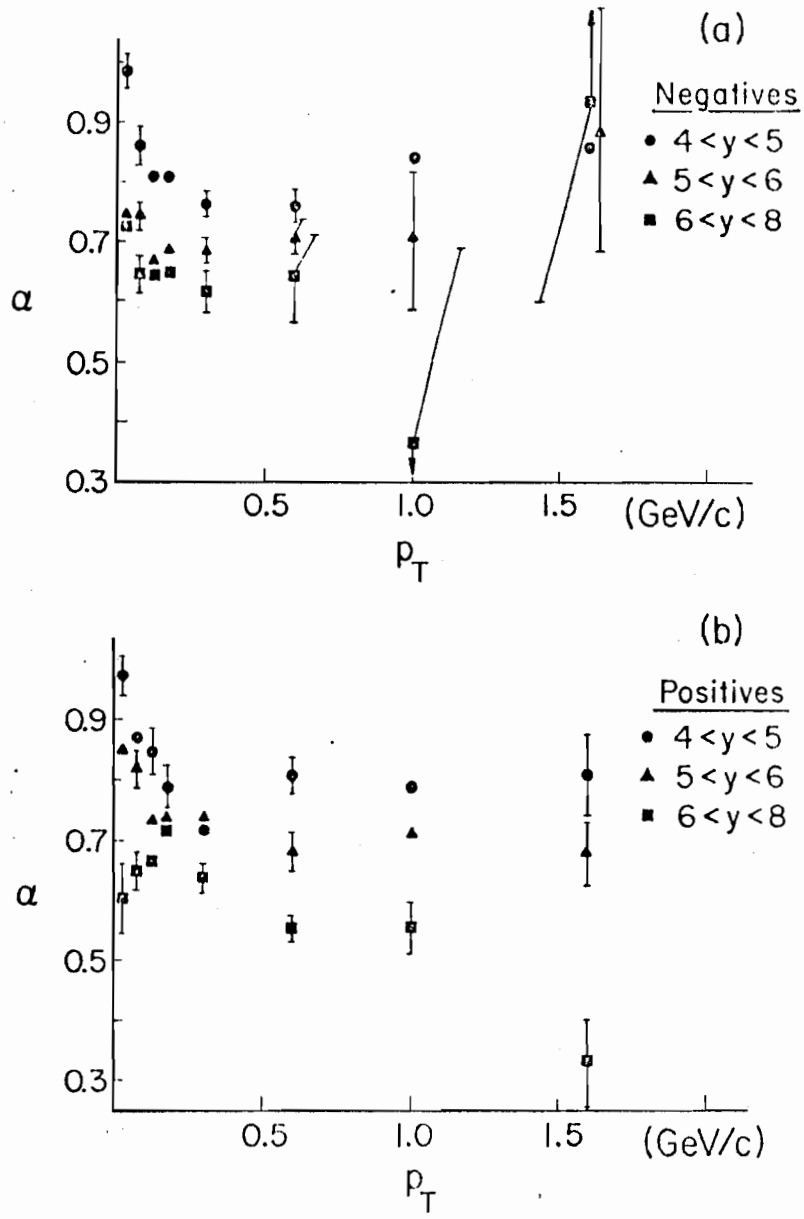

Figure 2 - The α parameter from fits of invariant cross sections for positive and negative particle production on nuclei.

small p_T to $\alpha \sim 0.7$ at $p_T \sim 0.3$ GeV/c; thereafter, as p_T increases, α appears to rise again[9]. At larger values of y_{LAB} the dependence of α on p_T is less pronounced, except for positive particles at the largest y values, where α appears to fall steadily with increasing p_T (it is natural to attribute this effect to the presence of a proton contribution to the positive-particle data at largest y_{LAB}).

A qualitative understanding of the rise of α at small as well as large p_T may be found in considerations of secondary scattering of particle clusters[10] within the nucleus; such cascading produces two effects: 1) Rescattering usually degrades an individual particle's original p_T, and also tends to shift particle rapidities to smaller values. 2) Occasionally, however, rescattering can increase the effective production angle and thereby also increase the original p_T value. The probability for the latter is small and is strongly dependent on the precise form of the p_T distribution of the cluster of particles produced in the first scattering. Although it is feasible that playing these two effects off against each other can provide a framework for understanding the gross features of the kind of data I have shown in Fig. 2, a detailed investigation is required to make certain that there is not more to Fig. 2 than casually meets the eye.

I wish to end this section with several comments on the small value of α measured for large rapidities[11]. Although a value of α as small as $\sim \frac{1}{3}$ could be expected on the basis of classical arguments, I believe such arguments may be far too naive. One such argument concerning exclusive channels proceeds as follows: In interactions involving large absorbing nuclei only the external rims of these nuclei can contribute to the production, consequently, the cross section must be proportional to the nuclear circumference multiplied by some constant skin thickness, viz., a cross section varying as the radius, or $A^{1/3}$. Another related argument is based on prejudices derived from studies

of nuclear coherent production in exclusive channels at lower energies. Such studies have shown that cross sections for coherent dissociation on large nuclei have almost no A-dependence, suggesting that $\alpha \sim 1/3$ might be quite reasonable for inclusive data at large rapidities. To counter the first kind of argument I point to the great differences observed between total cross sections of kaons on nuclei and baryons on nuclei[12], which imply that even large nuclei are rather transparent, and consequently expectations of small values for α cannot hold. As for an answer to the second argument, I note that, at high energies, Coulomb contributions to coherent production become sizeable, and, in fact, often dominant in large nuclei. The consequent A-dependence becomes very strong, and although coherent processes account for only several percent of the inelastic channels, their influence should be most apparent at the largest rapidities. Figure 3 illustrates a typical situation for coherent production on nuclei. The data are from our investigation of neutron dissociation into $(p\pi^-)$ systems at Fermilab[13]. The cross section for coherent neutron dissociation into $(p\pi^-)$ masses between 1.35 GeV and 1.45 GeV (a regime where the Coulomb-production contribution is relatively small) is shown as a function of A. (The curves on the data are fits to an optical model which provides a method for extracting total cross sections for the interaction of the unstable $(p\pi^-)$ systems, "N^*'s", with nucleons contained within the nucleus.) It is clear from this figure that a value of $\alpha \sim 1$ would be more natural than $\alpha \sim 1/3$ for large rapidities. Consequently, I believe that the small values of α observed in Figs. (1) and (2) for $y_{LAB} > 6$ may be more puzzling than not!

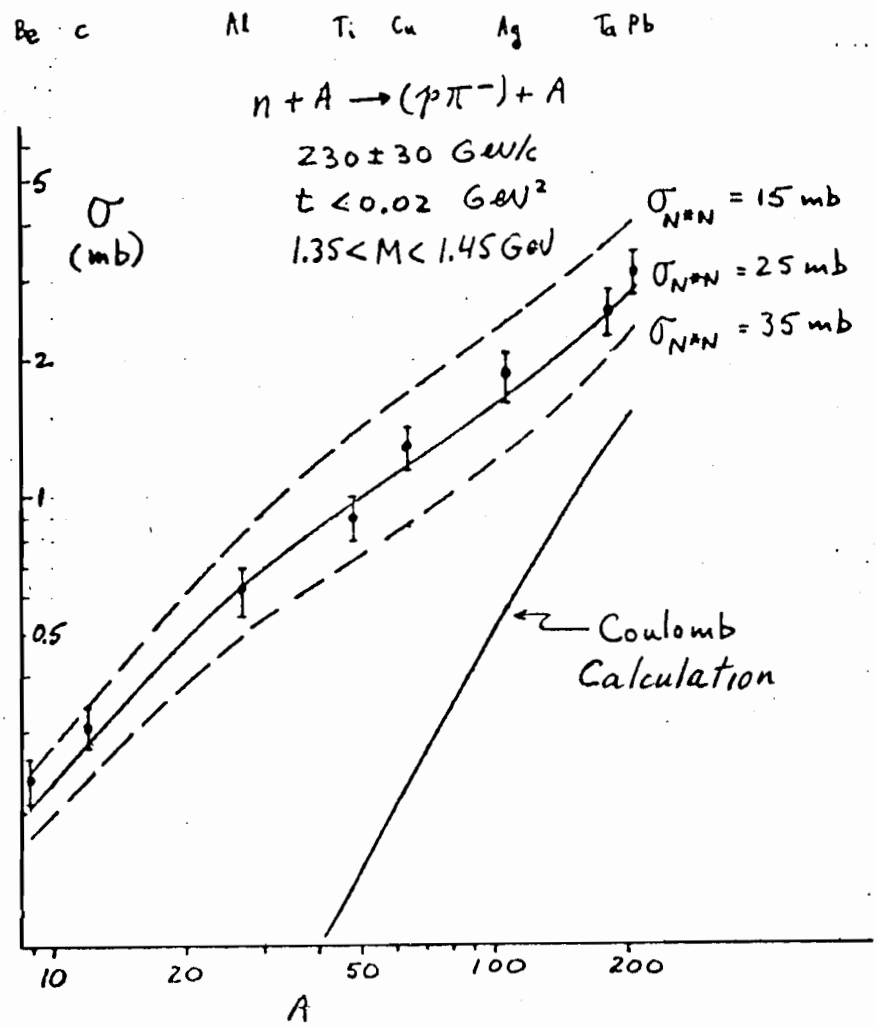

Figure 3 - Coherent cross section for neutron dissociation into $p\pi^-$ systems as a function of atomic number of target nucleus.

Transverse-Momentum Properties of Multipion Systems

We have recently investigated the correlation between the mass and the transverse momentum of multipion systems produced in pp collisions at high energies, and Ludlam has extended these studies to $\pi^- p$ interactions[2]. Because Kittel[14] has already described the original work of Stix et al., I will only briefly summarize those data, and present a fascinating result obtain by Ludlam.

The following are the essential findings of the above studies: 1) For fixed mass, the p_T distributions of multipion systems are independent of the net charge of the systems; in addition, for fixed M, the p_T spectra are essentially independent of the incident energy as well as of the multiplicity of the produced systems. 2) The dependence of the p_T properties on mass is quite strong and similar to that measured for discrete hadronic states. Figure 4 displays typical dependences of p_T distributions on multipion masses. (The data have been normalized relative to each other at the peak values of the spectra.) Aside from the clear shift of the p_T distributions with increasing mass, the data indicate that the fall-offs for $p_T \gtrsim 1$ GeV/c are similar for all masses ($d\sigma/dp_T^2 \sim e^{-3.8p_T}$). Kittel[14] displayed the variation of $\langle p_T \rangle$ with mass, and mentioned that there appear to be two regimes of multipion production: one, for $M \lesssim 2$ GeV, in which particles are produced strongly correlated and $\langle p_T \rangle$ rises rapidly with increasing mass (with $\langle p_T \rangle$ being independent of multiplicity); and, the second regime for $M > 2$ GeV, where $\langle p_T \rangle$ is almost independent of M but increases with multiplicity in the manner of a random walk ($\sim \sqrt{N}$). (The dependence of the root-mean-square value of p_T on mass is almost identical to the dependence of $\langle p_T \rangle$ on M.)

Ludlam has attempted to relate the above studies of multipion systems to production of jets of particles at high energies[3]. Instead of examining all charged multipion combinations in any given event, he devised an algorithm for grouping particles into unique clusters and then studied the p_T- behavior of

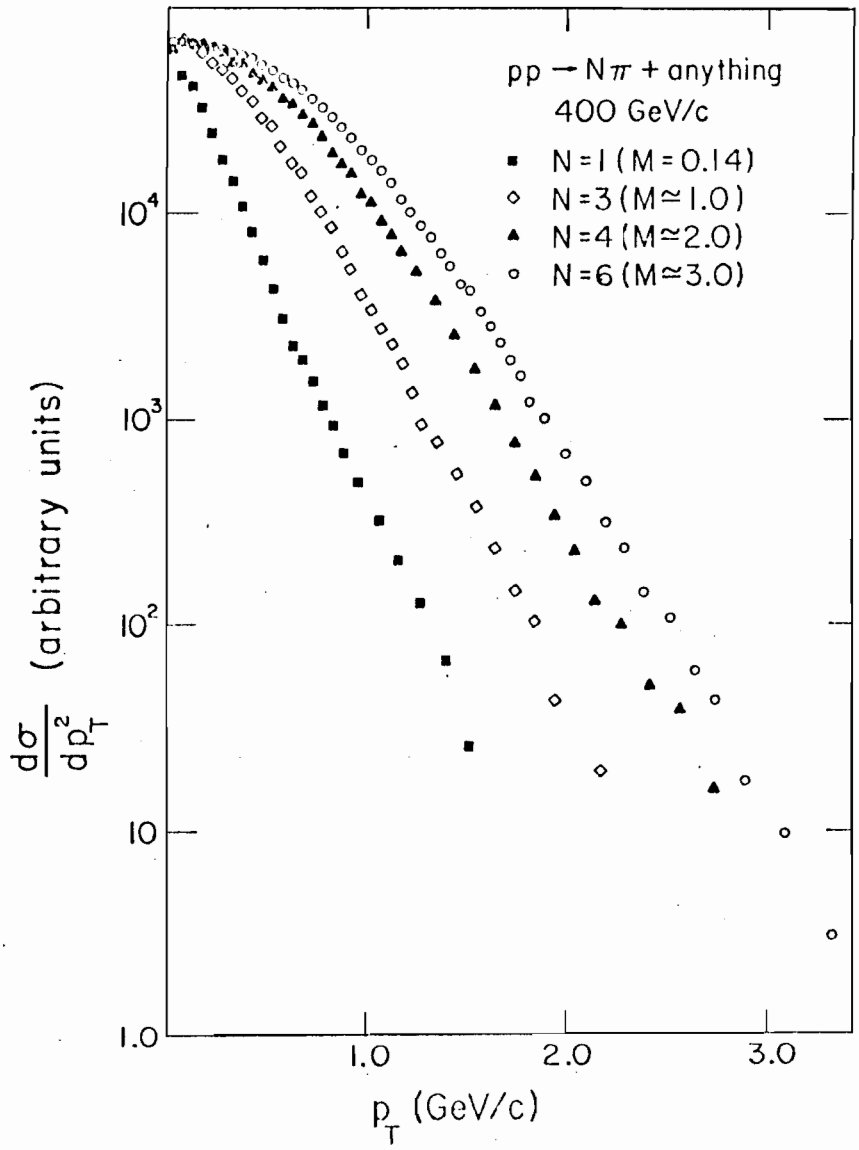

Figure 4 - Transverse momentum distributions for the production of charged-particle systems of fixed mass. N specifies the number of charged pions and M the mass of the multipion system.

these clusters. Ludlam chose to group particles not according to their clustering in rapidity space but rather according to two-particle mass values, as follows. First, all possible two-particle masses in an event were calculated. The smallest of all these masses determined an unique two-particle cluster or a possible kernel for a multipion system of larger charged-particle multiplicity. This two-particle kernel was enlarged to three or more particles only when the coupling of a pion outside the kernel with one of the particles inside it yielded the outside pion's smallest two-particle mass combination. For 150 GeV/c $\pi^- p$ collisions Ludlam found that, on the average, about two charged-multipion groups are produced per event (of course, with any single pion contributing to just one of these groups).

Figure 5 displays the absolute cross section, as a function of p_T, for single-pion inclusive production compared with the cross section for the production of multipion groups, selected according to Ludlam's algorithm. The two distributions appear to cross near a p_T of 0.8 GeV/c, beyond which the cross section for multipion groups exceeds that for single pions. Extrapolating the data to larger p_T (dashed curves), I estimate a cross section of 0.4 to 1.0 mb for production of multipion groups at $p_T > 2$ GeV/c. This is in remarkable agreement with predictions for jet production at these energies[15]. If this agreement is not merely coincidental, it may then be taken to imply that all hadronic production involves some form of scattering between constituents.

I will conclude with the following remarks. Bøggild indicated at this meeting[16] how he can understand many of the essential results from jet studies at Fermilab and at the ISR just on the basis of what is known about the inclusive single-particle spectrum. Vanryckeghem[17] has made similar claims on the basis of his phenomenological investigations. In addition, Feynman reported that rapidity-gap distributions for data from low-p_T events

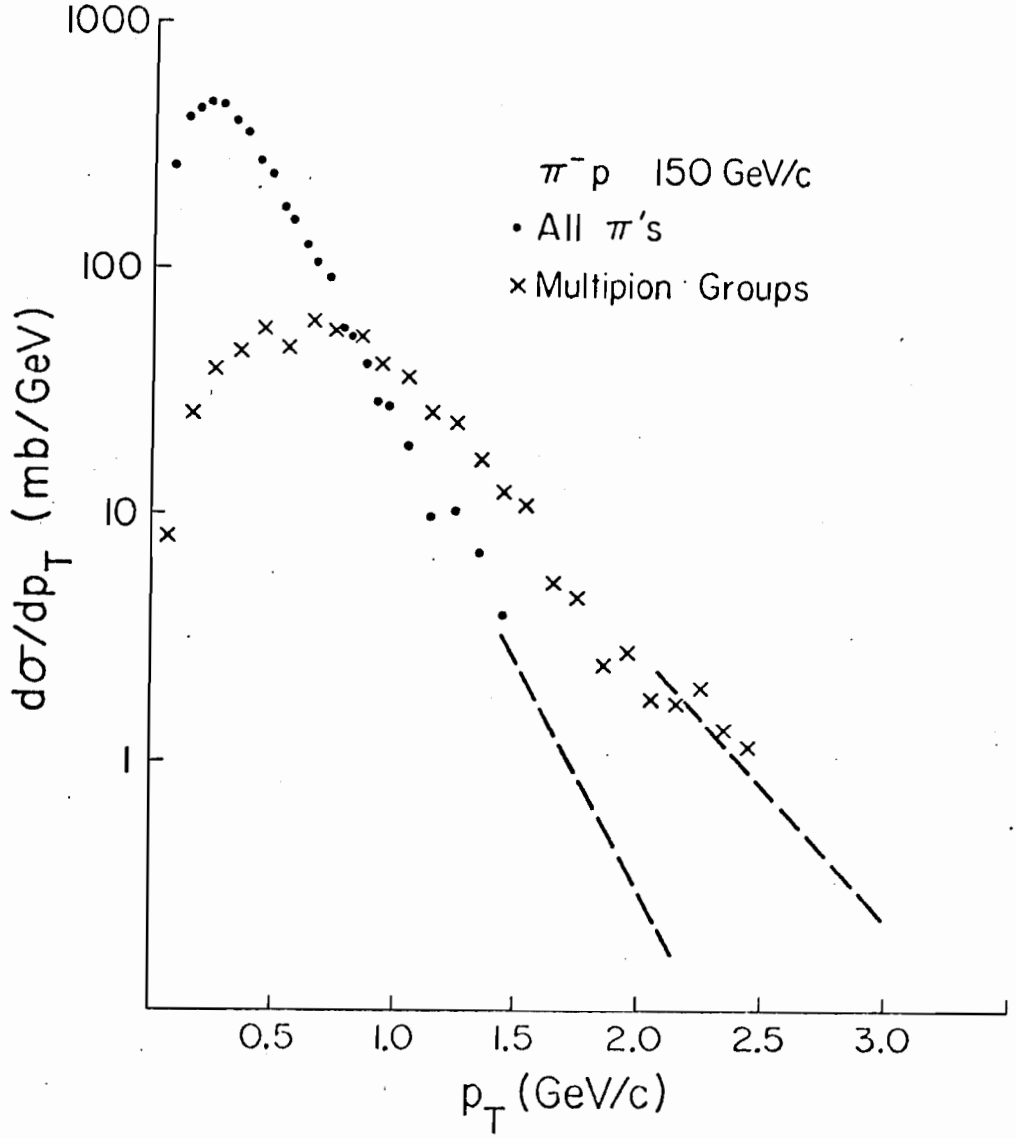

Figure 5 - Cross section for the production of multipion groups compared to the inclusive single-particle cross section in $\pi^- p$ collisions at 150 GeV/c.

observations, coupled with the result from Ludlam's work, leads me to conclude that we have not yet learned anything new from experimental studies of jets. It appears, thus far at least, that the discoveries made in 1972, namely, that the single-particle distribution does not fall off exponentially in p_T, and that particles are produced as correlated clusters in rapidity, can account for essentially all of the jet phenomenallia. Therefore,we may probably regard jets as old-fashioned clusters at larger p_T. Unfortunately, no one still knows what clusters really are[18], but the fact that Feynman is interested in them, I guess, must mean that they are important and should be studied further. I therefore urge all my colleagues who have abandoned investigations of strong interactions using bubble chambers to return home. Study particle clustering. The work is fashionable again!

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18. Except possibly for Feynman, who regards clusters simply as resonances (private communication).