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PARTICLE MULTIPLICITIES AND CORRELATIONS AT NAL ENERGIES*

T. Ferbel†
University of Rochester, Rochester, N.Y. 14627

ABSTRACT

A summary is presented of the latest data concerning particle multiplicities and correlations between particles produced in pp collisions at high energies.

INTRODUCTION

The emphasis of this paper will be on the most recent data pertaining to measurements of charged-particle multiplicities and two-particle correlations in pp collisions at high energies. I will also make several remarks pertaining to single-particle inclusive data not covered by the other plenary speakers at this Meeting. Much of what I present on correlations comes directly from Carl Bromberg's summary given in the parallel sessions.

INCLUSIVE CROSS SECTIONS

In Fig. 1 I present the latest compilation of inclusive cross sections for the reactions[1]:

$$pp \to \Lambda^o/\Sigma^o + \text{anything} \quad (1)$$

$$pp \to K_s^o + \text{anything} \quad (2)$$

$$pp \to \pi^o + \text{anything} \quad (3)$$

$$pp \to \pi^- + \text{anything} \quad (4)$$

Cross sections for reactions (3) and (4) are shown reduced by a factor of 100. It is observed that by 400 GeV/c the K_s^o cross section, after a rather dramatic rise for energies above 10 GeV/c, appears to be approaching the sort of slow rate of increase which is more characteristic of π and Λ production.

Figure 2 displays the variation of the inclusive x-spectra for reactions (1)-(3) as a function of incident energy ($x \equiv p_\ell^*/p_o^*$, with p_ℓ^* and p_o^* being the longitudinal momentum and the incident momentum in the CM frame). The data have been integrated over transverse momenta (p_T) and consequently reflect mainly the small-p_T behavior of these cross sections[2]. (Reaction (3) is not really measured in the NAL bubble chamber, what is observed is the process $pp \to \gamma$+anything. It is assumed throughout that the cross sections for these two reactions

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†A. P. Sloan Fellow.

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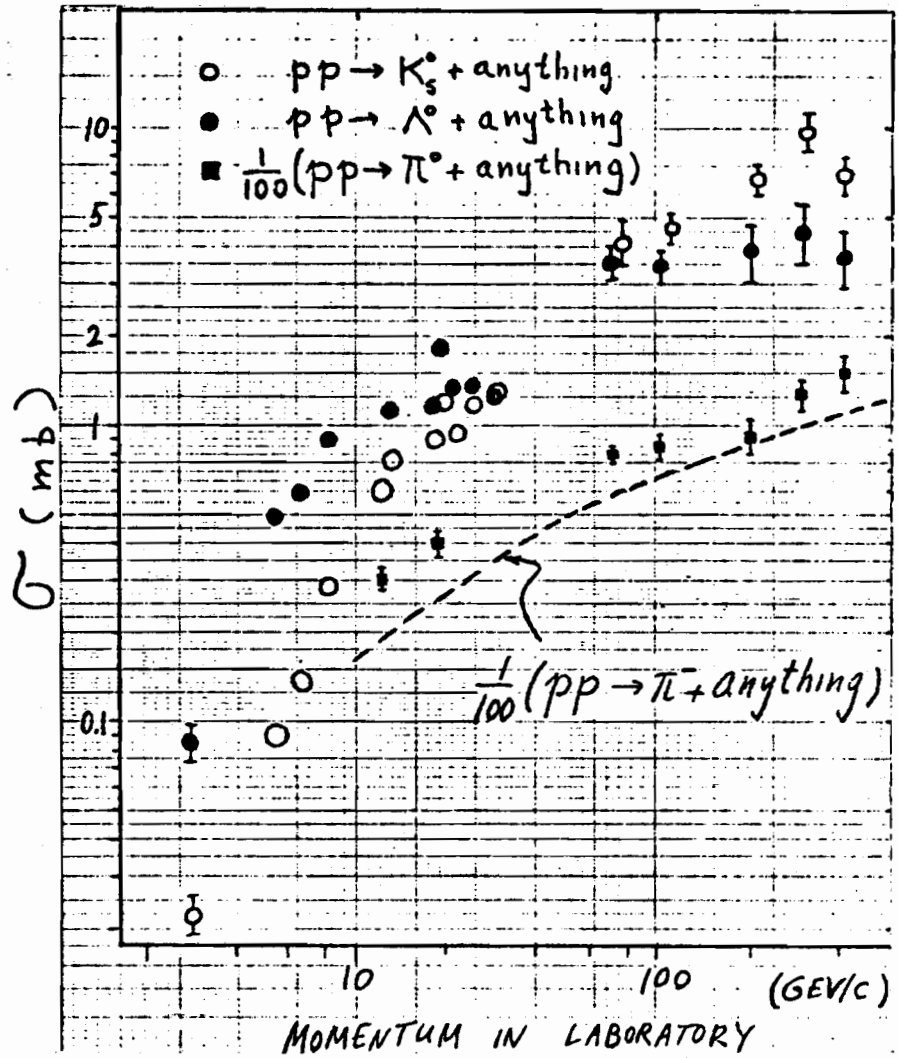

Fig. 1. Energy dependence of the total inclusive cross sections for π^-, π^0, K_s^0 and Λ^0/Σ^0 production in pp collisions.

are related just by a factor of two.) All the data show rather clear violation of scaling (i.e., the cross sections change) in the $\lesssim$ 400 GeV/c momentum range at x=0. For larger x-values the statistics are poor; however, above 100 GeV/c, the data in the proton fragmentation regime are consistent with a faster approach to limiting behavior than the data in the central region of particle production.

Figure 3 displays inclusive pion-production y-spectra for reaction (4) and for the π^+ channel:[3]

$$pp \rightarrow \pi^+ + \text{anything} \qquad (5)$$

Both π^+ and π^- production data are shown integrated over p_T (the y_{CM} scale is for the 102 GeV spectra, with the rapidity defined in the standard manner: $y=\frac{1}{2}\ln(E+p_\ell/E-p_\ell)$. The spectra for reaction (4) appear to have reached their limiting form at $\lesssim$12 GeV/c for $y_{LAB}\lesssim 0.5$. At larger values of y_{LAB} we note substantial changes in the cross sections. Similar remarks apply to reaction (5). The π^+/π^- production ratio changes from ~4 at y_{LAB} = -0.5 to ~1.2 at y_{CM} = 0 for both

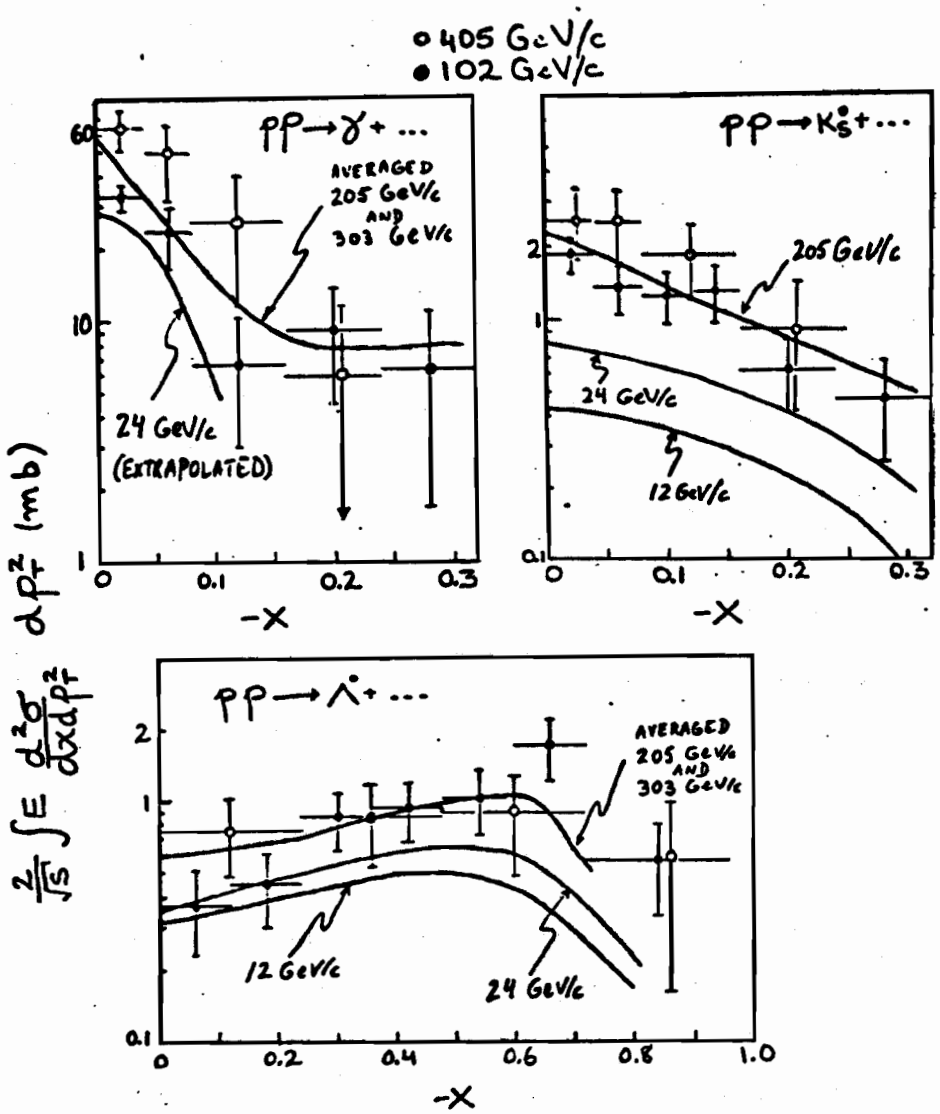

Fig. 2. Variation with incident energy of the invariant cross sections for γ, K^o_s and Λ^o/Σ^o production in pp collisions.

the 102 GeV/c and 205 GeV/c data; clearly, these spectra (particularly at $y_{CM}=0$) must be far from their limiting form. The energy dependence of reactions (1)-(5) at $y_{CM}=0$, when integrated over p_T, follows the $s^{-\frac{1}{4}}$ trend noted for similar data at lower energies.[4]

MULTIPLICITIES AND KNO SCALING

At the time of the last "Rochester" Conference at Chicago/NAL, Olesen and Slattery presented[5] astonishing evidence for the rapid onset of Koba-Olesen-Nielsen[6] scaling in the charged-particle multiplicities. This KNO semi-inclusive scaling, which was hoped for as an asymptotic dream, turned out to represent the data remarkably well between 50 GeV/c and 300 GeV/c. However, since Slattery's fit, the

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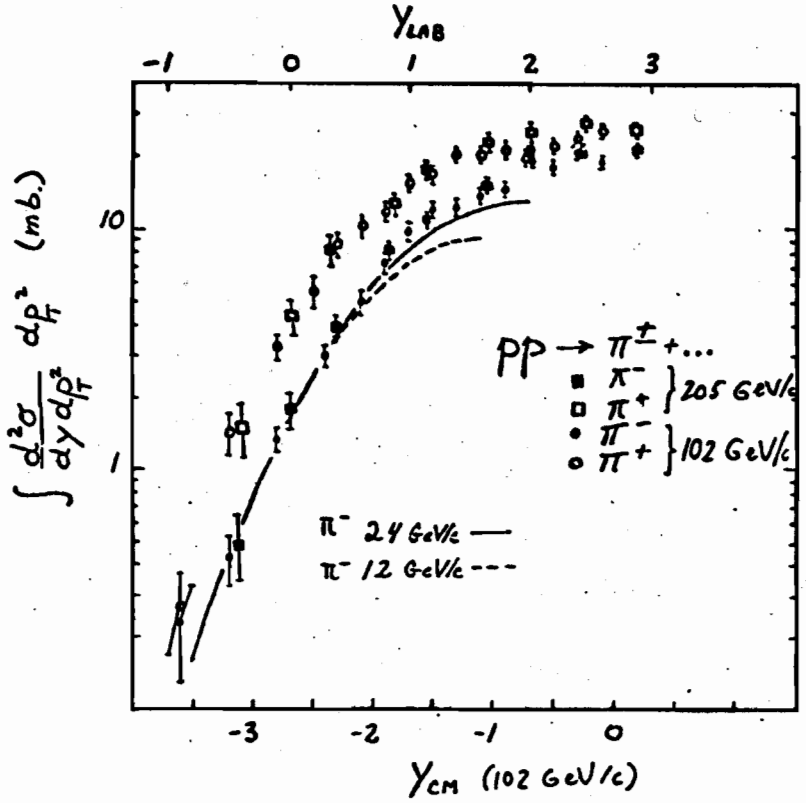

Fig. 3. Variation with incident momentum of the invariant cross section for π^+ and π^- production in pp collisions.

50 GeV/c and 303 GeV/c data have changed somewhat;[7] the 102 GeV/c data have improved considerably;[8] and the 405 GeV/c data have become available.[8] The present conclusions concerning the onset of KNO scaling are that, at best, the limit is being approached slowly ($\sim\frac{1}{\langle n\rangle}$).

The most recent results pertaining to the lower moments of charged-particle multiplicities observed in pp collisions at high energies are shown in Fig. 4. Simple fits to these data are also given. The average charged-particle multiplicity, $\langle n\rangle$, is consistent with a logarithmic dependence on the square of the energy in the CM system(s) in the 50 GeV/c to 405 GeV/c momentum range[9]. It should be remarked, however, that the fit to a $\ln s$ form does not yield an acceptable χ^2, indicating the presence of additional systematic errors in the individual experiments (higher order $\ln s$ terms do not substantially affect the quality of the fit). The Mueller f_2^- moment[10], which prior to the availability of the 405 GeV/c data also appeared to have a $\ln s$ dependence, now definitely exhibits curvature, which can be parameterized in terms of a sizeable $(\ln s)^2$ term. The f_3^- moment is at present consistent with a $\ln s$ form.

Now, to investigate in more detail the question of the early onset of KNO scaling, I present in Fig. 5 some relevant parameters of the charged-particle multiplicity spectrum. If KNO semi-inclusive scaling were valid at present energies then the multiplicity spectrum would scale as follows:

$$\langle n\rangle \frac{\sigma_n}{\sigma_{INEL}} = \psi\left(\frac{n}{\langle n\rangle}\right) \qquad (6)$$

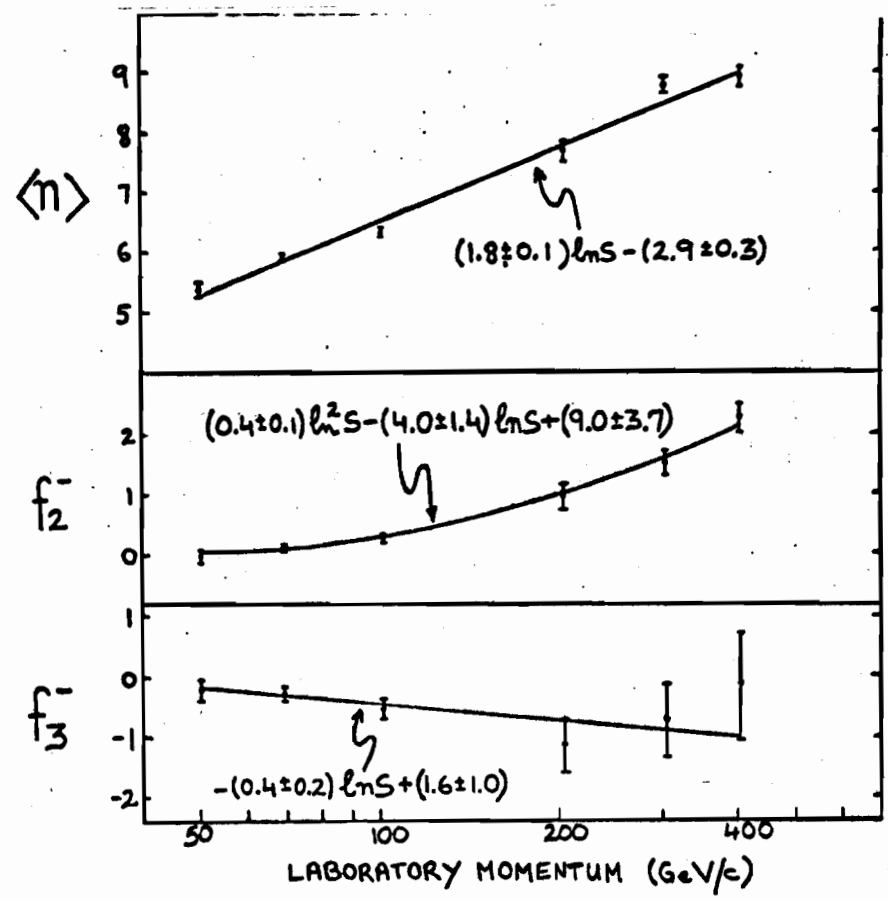

Fig. 4. Energy dependence of the charged-particle multiplicity, and of the f_2 and f_3 moments for negative particle production.

where σ_{INEL} and σ_n are the total inelastic and n-prong cross sections, and $\psi(\frac{n}{\langle n\rangle})$ is the asymptotic scaling function. Equation (6), which embodies the KNO scaling prediction, can be expressed equivalently through the following sets of relationships relating the moments of the multiplicity spectrum:

$$\langle n^q\rangle = C_q \langle n\rangle^q \tag{7}$$

where the C_q are constants at high enough energies. Consequently, if KNO asymtopia had been reached in the 50-400 GeV/c momentum range, than the value of $\frac{\langle n\rangle}{D}$ as well as $\langle n^2\rangle/\langle n\rangle^2$, $\langle n^3\rangle/\langle n\rangle^3$, etc. would all be constant. It is clear that the present data do not substantiate such a conclusion. Wroblewski has emphasized that all pp data (even down to energies of ~10 GeV) are consistent with a slow onset of KNO scaling (as ~ $\frac{1}{\langle n\rangle}$)[11]. Wroblewski's phenomenological predictions for $\frac{\langle n\rangle}{D}$ and for $\frac{\langle n^2\rangle}{\langle n\rangle^2}$ and $\frac{\langle n^3\rangle}{\langle n\rangle^3}$ are shown for comparison with the data. (Predictions are based on the observation that at lower energies $D=0.58[\langle n\rangle-1]$ and $\frac{\mu_3}{D^3} \equiv \frac{(n-\langle n\rangle)^3}{D^3}$ and $\frac{\mu_4}{D^4} \equiv \frac{(n-\langle n\rangle)^4}{D^4}$ appear

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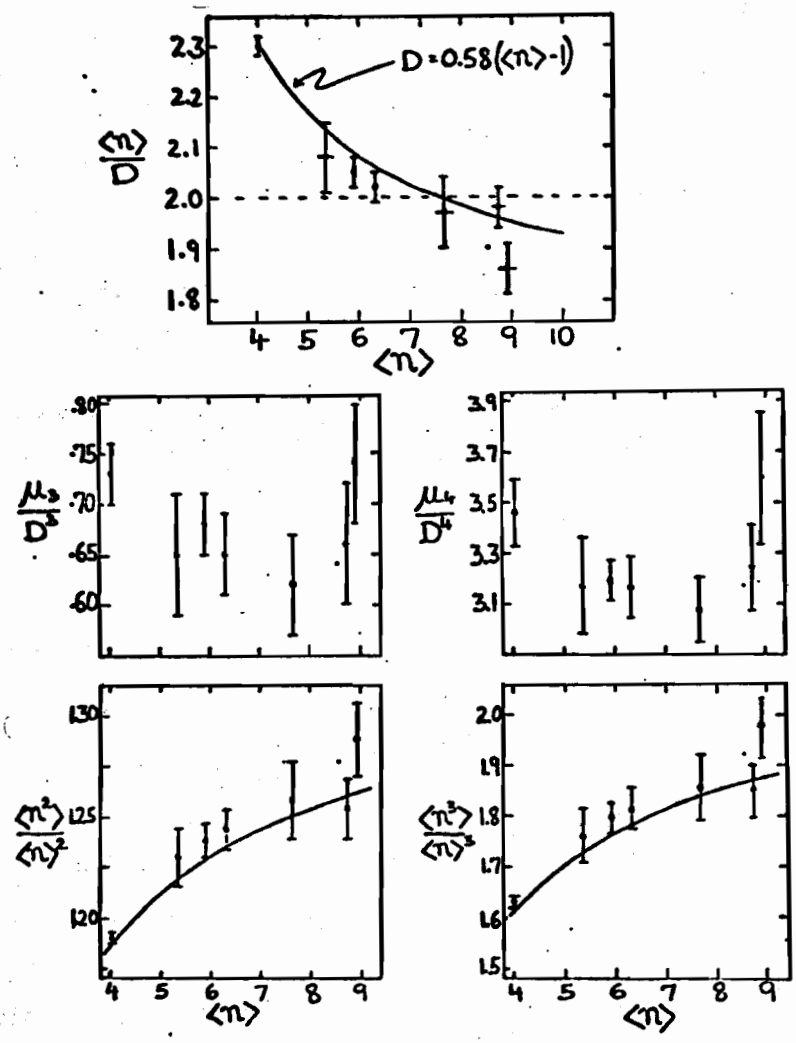

Fig. 5. Parameters of the charged-particle multiplicity spectrum relevant to the question of the early onset of KNO scaling. The curves are based on Wroblewski's conjectures.

to be energy independent constants.) The trends suggested by Wroblewski are certainly supported by the new data. The implications of these results is that KNO scaling has not as yet been reached but is perhaps being approached as $1/\langle n\rangle$. (It is interesting to note that deviations from KNO scaling in the 405 GeV/c multiplicity data occur mainly for the higher charged-prong cross sections.)

Although KNO scaling has not as yet set in, it is clear that this form of approach to limiting behavior gives a surprisingly good overall description of the particle multiplicity spectrum. This is true not only for charged-particle data but also for π^o,K^o_s and even Λ^o production[12].

CORRELATIONS[13]

Extensive studies of two-particle correlations have recently been conducted at the ISR[14]. These have demonstrated the presence of substantial positive correlation among particles having small rapidity differences. Here I would like to present some recent

results pertaining to correlations observed in the production of pions at NAL energies. The data are from bubble chamber experiments and can consequently distinguish the dependence of these correlations on the charges of the produced particles.

TWO-PARTICLE CORRELATIONS

In Figs. (6)-(9) I display data pertaining to two-particle correlations for the reactions (8)-(11):

$$pp \rightarrow \pi^c\pi^c + \ldots \tag{8}$$

$$pp \rightarrow \pi^+\pi^- + \ldots \tag{9}$$

$$pp \rightarrow \pi^+\pi^+ + \ldots \tag{10}$$

$$pp \rightarrow \pi^-\pi^- + \ldots \tag{11}$$

where the "c" indicates no selection on the charge of the pion. To minimize K and p background in the 102 GeV/c data all protons identifiable by ionization, and all tracks which had a measured value for the longitudinal momentum in the center of mass in excess of 4 GeV/c were removed. This last selection removed forward produced protons while removing only a small fraction ($\leq 5\%$) of the forward produced pions[13]. The remaining $K^{\pm}$, $\bar{p}$ backgrounds and the asymmetry in the positive spectra (caused by the remaining proton background) do not seriously affect the shapes or magnitudes of the correlations. The correlations are displayed in terms of the now standard correlated rapidity density. This density is defined as:

$$R_{12} = \frac{\sigma_{INEL} \dfrac{d^2\sigma}{dy_1 dy_2}}{\dfrac{d\sigma}{dy_1}\dfrac{d\sigma}{dy_2}} - 1$$

where σ_{INEL}=31.9 ± 0.8 mb is the total inelastic cross section for the 102 GeV/c data[8].

The smooth curves shown in Figs. (6)-(9) represent the results of a pion-production model calculated at 102 GeV/c, with the following properties:

(a) The <u>a priori</u> probabilities of each pion being a π^+, a π^-, or a π^0 are equal, as are those for each nucleon being a neutron or a proton. Charge and baryon conservation alone are used to determine which final states are possible. The probability for the production of any particular number of pions is obtained by constraining the resultant charged particle multiplicity for the model to agree with that observed for the data[8].

(b) The pions are produced with a cutoff transverse momentum distribution of the form $e^{-\alpha p_T^2}$, which is in approximate agreement with the data. The rapidity distribution of the generated pions is also chosen to be Gaussian in shape, with a variance which

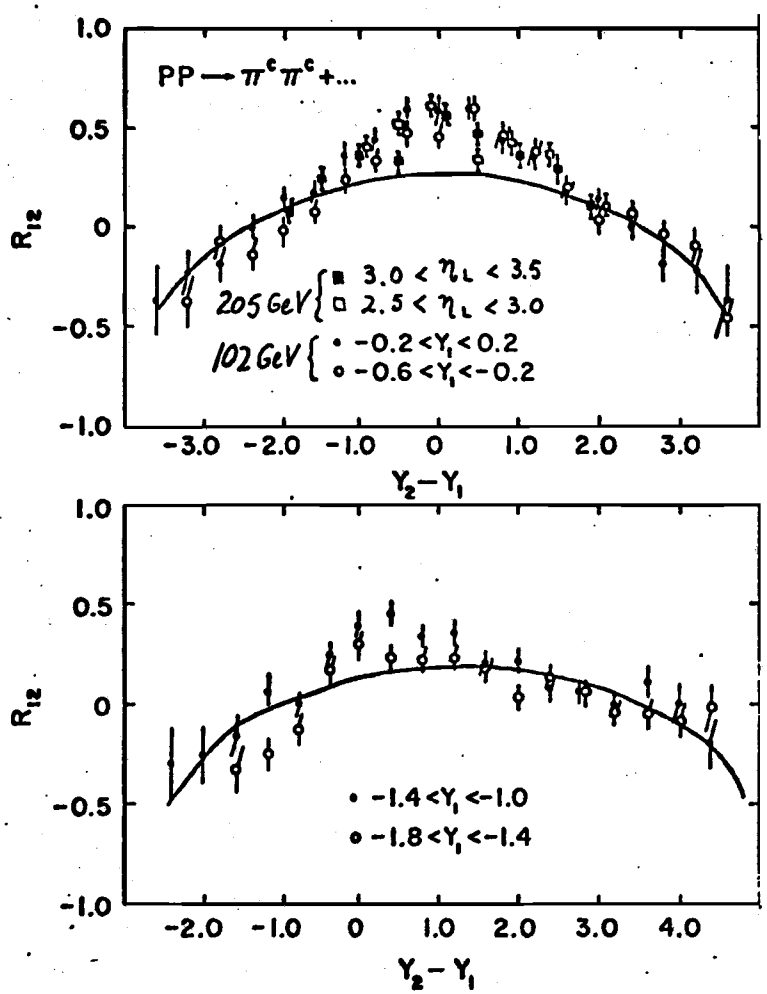

Fig. 6. Correlations in rapidity among all charged particles produced in pp collisions. For explanation of curves see text.

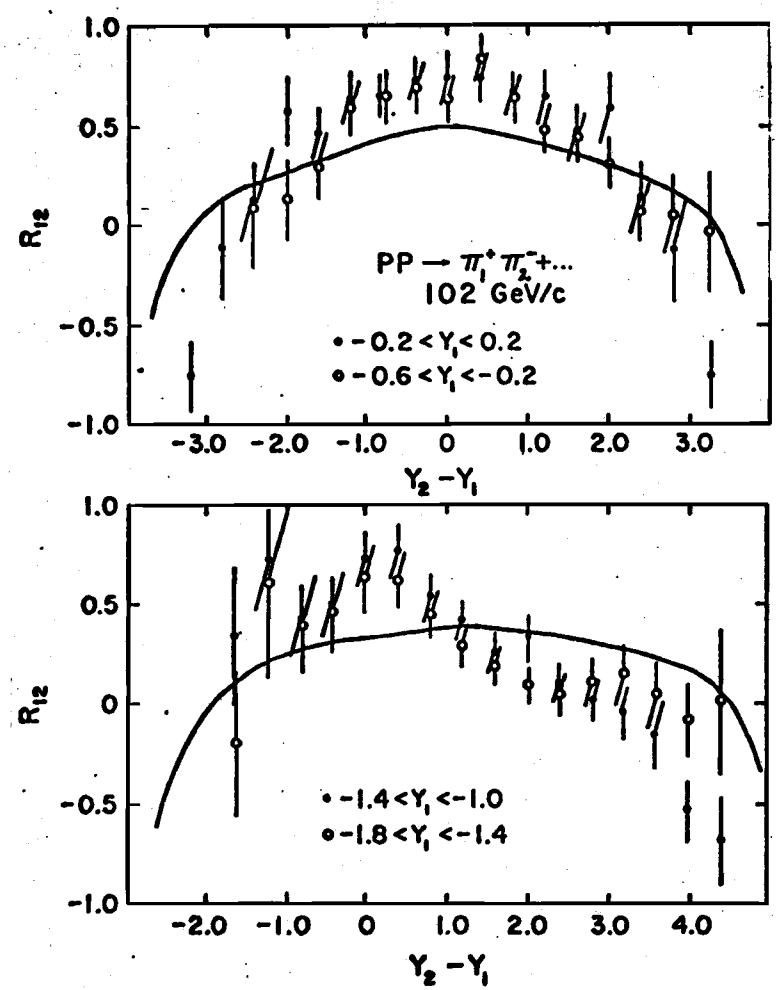

Fig. 7. Correlations between π^+ and π^- mesons produced in pp collisions. For explanation of curves see text.

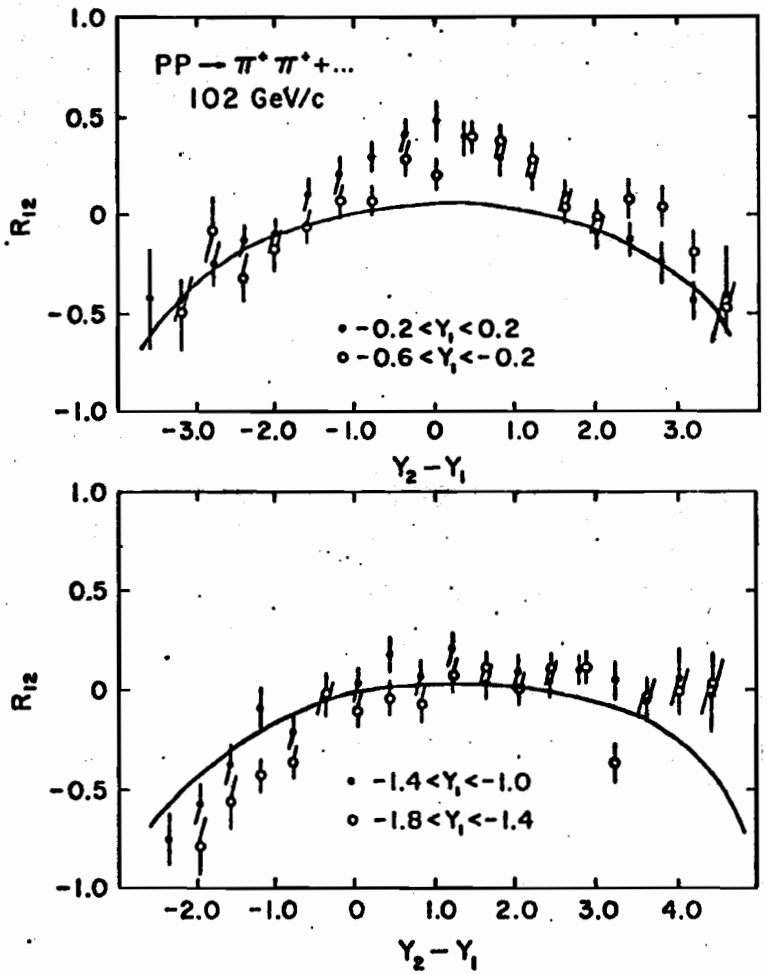

Fig. 8. Correlations between two π^+ mesons produced in pp collisions. For explanation of curves see text.

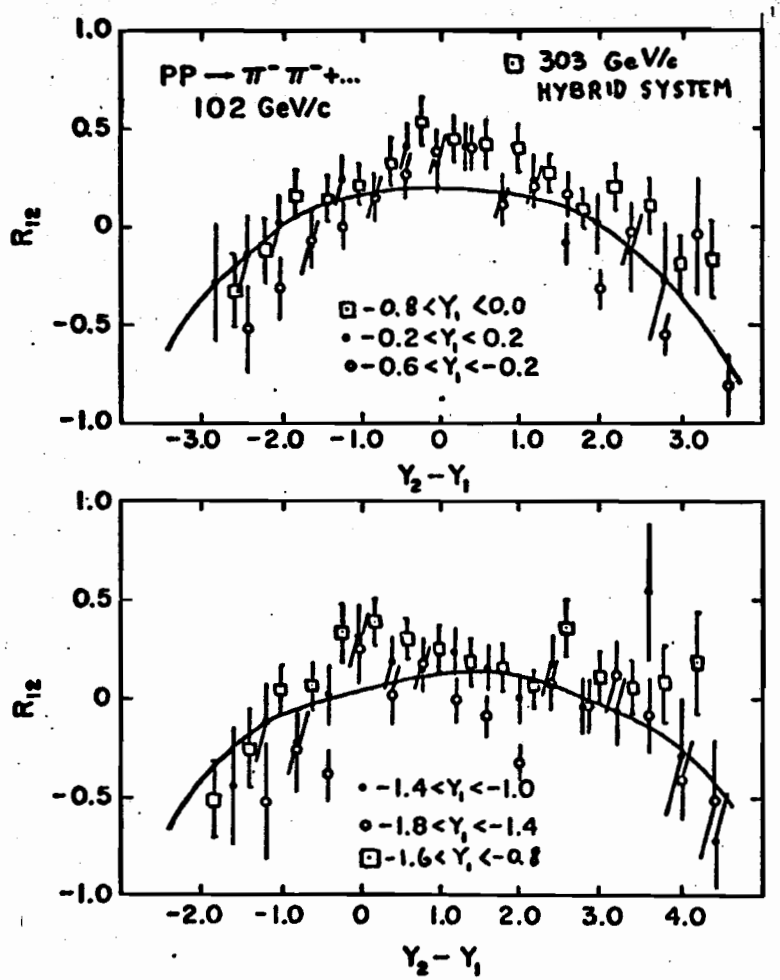

Fig. 9. Correlations between two π^- mesons produced in pp collisions. For explanation of curves see text.

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decreases with total pion multiplicity as $1/\sqrt{n}$ (also in approximate agreement with the data), and with an overall scale factor which was chosen so that on the average the total energy carried away by all of the pions in an event amounts to one half the total center-of-mass energy.

The intent of the model was to compare the experimental data with a "control sample" of the same general kinematic character. Although the nature of this comparison can at best only be semi-quantitative, the following general observations can be made:

(a) The R_{12} parameters for $\Delta y=0$ are consistently larger than expected on the basis of the model. This is true for all charge configurations. In particular, the $\pi^+\pi^+$ and $\pi^-\pi^-$ correlations near $y_1 \approx y_2 \approx 0$ have $R_{12} \approx 0.4$; this is surprisingly large when compared to expectations from simple Mueller-Regge ideas[15].

(b) The magnitude of R_{12} for pions of all charge (Fig. 6a) agrees well with that observed for the central region of pion production at 205 GeV/c [16] and at ISR energies[14]. A similar statement can be made concerning the comparison of the results for $\pi^-\pi^-$ correlations (Fig. 9a) at 102 GeV/c with data for the same process at 303 GeV/c [17]. Consequently, the maxima in R_{12} appear to be essentially energy independent.

(c) The model does not reproduce the magnitude or shape of R_{12}, particularly for the $\pi^+\pi^-$ data, when the two particles are produced away from the most central region. (Data at 303 GeV/c for the $\pi^-\pi^-$ charge state also exhibit the peaking behavior in R_{12} at $\Delta y=0$ when both π^- are produced away from $y=0$.) The observed correlations for $\Delta y=0$ can be taken as evidence for additional particle clustering in the production process, a possibility not admitted in the model.

Transverse momentum correlations (the azimuth angles between transverse momenta of two particles) are given in Fig. 10. The results are at 102 GeV/c for events with six or more charged prongs. Again, I wish to note that the data for unlike-charged pions appear to show more structure than for pions of same charge. Here, however, momentum conservation requires some anti-correlation and, consequently, the lack of correlation in reactions (10) and (11) and the reduced correlation in reaction (9) for large rapidity gaps between the two pions, would appear to have a dynamic origin[18]. The diminution in the azimuthal correlation for large rapidity difference may be related to the nature of the Pomeranchuck trajectory[19].

FORWARD/BACKWARD CORRELATIONS IN THE CENTER OF MASS

The charge transfer distribution, i.e., half the difference between the charge moving in the forward direction (Q_F) and in the backward direction in the center of mass (Q_B) is shown in Fig. 11a. (There is a very slight asymmetry in the data due to misidentification of protons.) The variance of the distribution, $\langle U^2 \rangle = \frac{1}{4}\langle (Q_F - Q_B)^2 \rangle$ has important bearing on the nature of the production mechanism. This variable has a weak dependence on laboratory momentum (Fig.11b), and is more in line with predictions based on a multiperipheral mechanism than with those afforded by a fragmentation or fireball model[20].

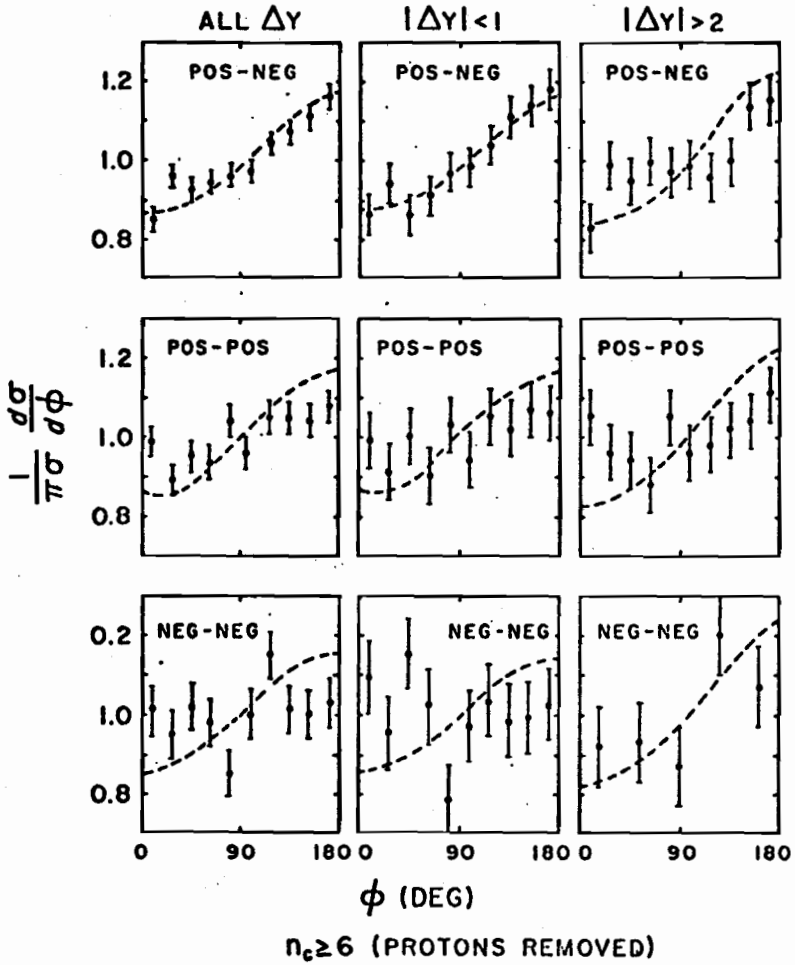

Fig. 10. Transverse correlations between charged particles produced in pp collisions at 102 GeV/c. For explanation of curves see text.

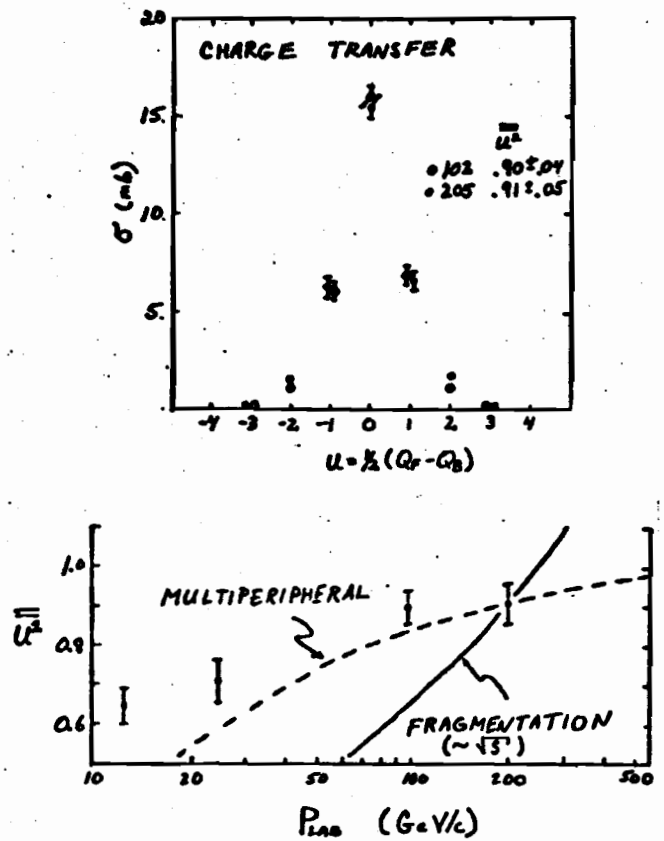

Fig. 11. Charge transfer between the forward and backward hemispheres in the center of mass. Curves for the prediction of the energy variation of the variance ($\overline{\overline{U}}^2$), normalized to the data at 205 GeV/c, have been privately communicated (C.Quigg and G.Thomas).

FERMILAB-CONF-73-149-E

Figure 12 displays the average multiplicity in the forward hemisphere $\langle N_F \rangle$ as a function of the number of particles emitted backward in the center of mass frame (N_B). Note that there is a weak positive correlation for all multiplicities between N_B and $\langle N_F \rangle$; furthermore, the effect of the low-multiplicity diffractive contribution is discernible in the dips observed for $N_B = 1,3$ and perhaps $N_B = 5$. The data clearly do not exhibit a strong dependence on incident energy.

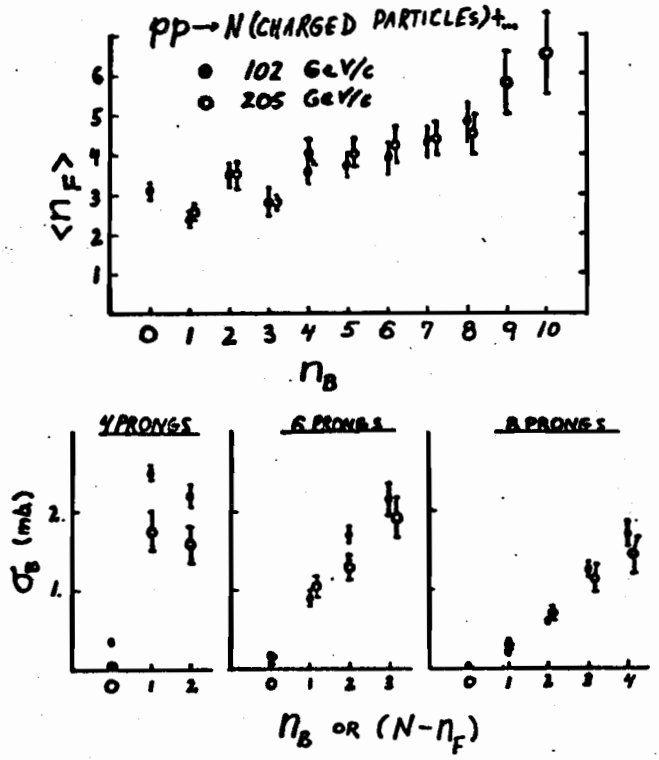

Fig. 12. Forward/Backward charge correlations in the center of mass frame.

POT POURRI

In this section I would like to make a remark pertaining to the growth of the large-p_T component in inclusive cross sections at yesteryear's high energies, that is, at incident momenta below 100 GeV/c. I would also like to make several observations pertaining to diffraction production at high energies. (The latter subject is discussed more fully by David Leith elsewhere in these Proceedings.)

Thus far I have presented bubble chamber data which were integrated over the p_T variable and consequently displayed characteristics of production processes at small p_T values. To remind you of the fact that inclusive p_T spectra at low incident momenta are not simply exponentials in p_T or p_T^2, I have plotted in Fig. 13 the average values of p_T, p_T^2 and the dispersion ($D=[\langle p_T^2\rangle-\langle p_T\rangle^2]^{1/2}$) for inclusive π^- production in various incident channels as a function of the incident momentum[21]. The substantial growth of $\langle p_T\rangle$,$\langle p_T^2\rangle$ and D with increasing energy gives another clear indication of the fact that Feynman scaling is being violated in inclusive pion production reactions at large p_T values. I expect that as the incident momenta increase the average values of the low-order moments of the p_T spectrum will start saturating, while ever higher order moments of p_T will continue to grow with energy (and again saturate at even greater incident momenta). The growth of the p_T moments is far stronger than

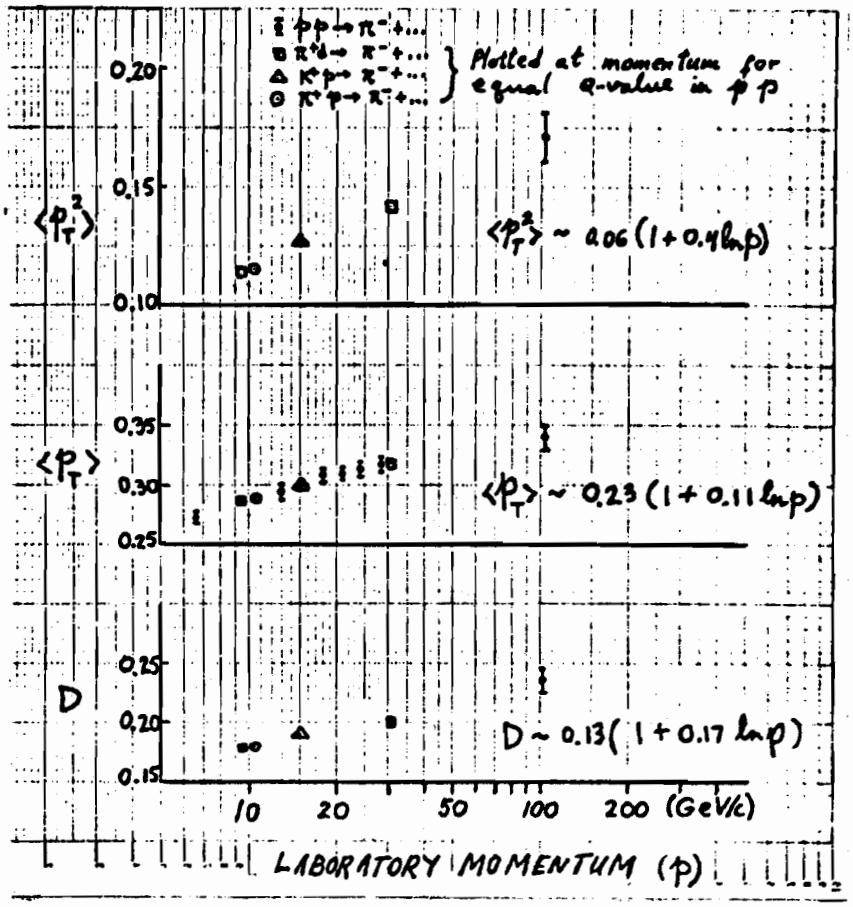

Fig. 13. Dependence on incident momentum of the low moments of the transverse-momentum spectrum for inclusive π^- production.

expected on the basis of just increasing phase space, and consequently may be related to conjectured substructure of hadronic matter[22].

Finally, I wish to present three ways of examining the reaction

$$pp \rightarrow p + \text{anything} \qquad (12)$$

In Fig. 14 I display the cross section for reaction (12) integrated over p_T in terms of the mass (M) recoiling from the final-state proton[23]. The trend of the data with energy is quite clear. As the value of s increases the cross section for $s/2 \gtrsim M^2 \gtrsim 16$ GeV^2 falls approximately as 1/s while the cross section for $M^2 \lesssim 16$ GeV^2 falls far less rapidly with energy and may, in fact, be approaching a limiting form. (The cross section for $M^2 < 16$ GeV^2 at 405 GeV/c is ~3.8 mb counting both target and projectile fragmentation.)

The same data can be displayed in terms of the x-variable for the proton ($x \sim 1 - M^2/s$). In Fig. 15 the cross section in x is compared between the 102 GeV/c data and the data at 405 GeV/c[23]. Here it is clear that for $x \gtrsim -0.9$ the cross section is s-independent to ~10% accuracy[24]. Also, the total cross section for $x < -0.9$ appears to be energy independent ($\sigma = 6.2 \pm 0.4$ mb counting both target and projectile excitation). However, the shape of the cross section near $x = -1$ changes drastically with energy indicating that reaction (12) does not scale near the kinematic boundary.

The last graph (Fig. 16) is another comparison between the

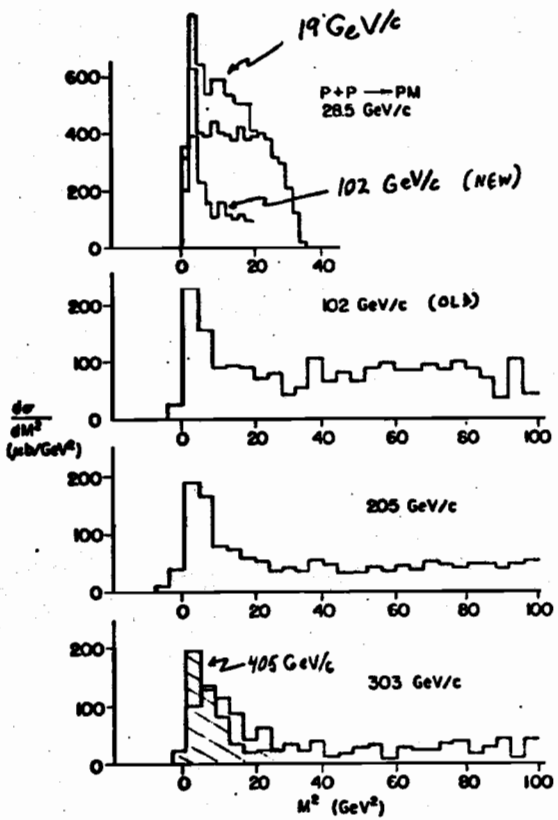

Fig. 14. Cross section for producing a hadronic system of mass M in association with an inelastically scattered proton in pp collisions between 19 GeV/c and 405 GeV/c.

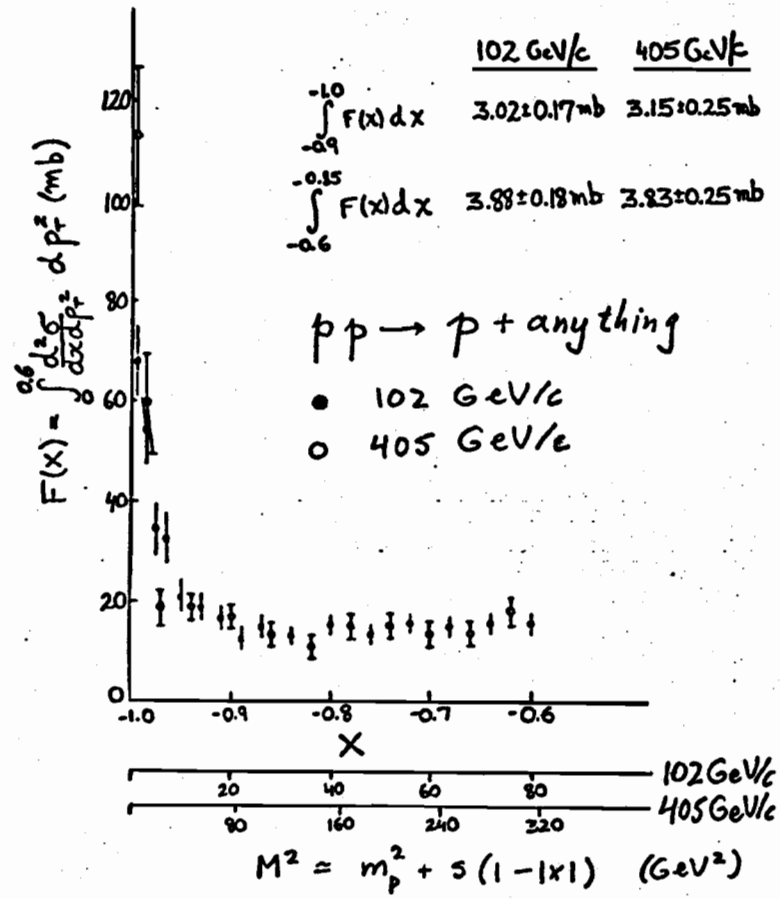

Fig. 15. The x-spectra for inelastic proton production at 102 GeV/c and 405 GeV/c.

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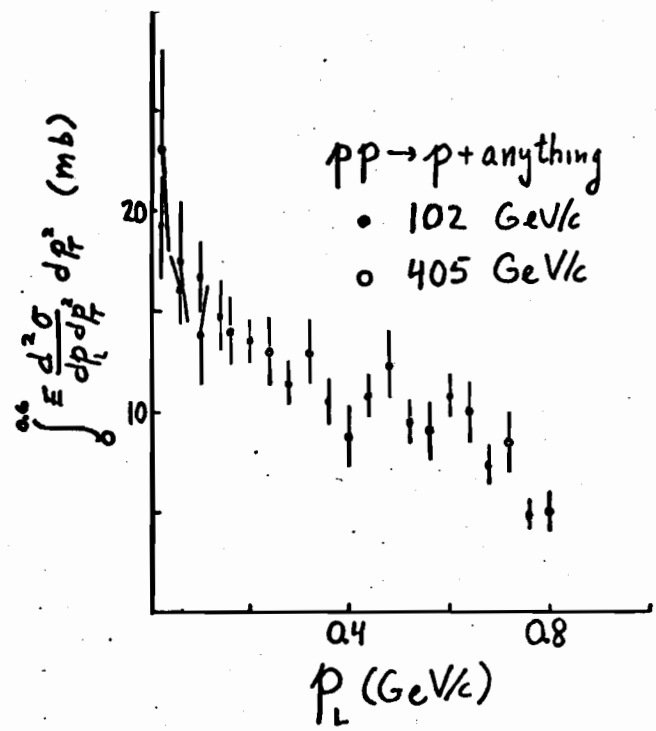

Fig. 16. Inclusive proton-production data displayed in terms of the invariant cross section as observed in the rest frame of the incident proton.

102 GeV/c and the 405 GeV/c data, but this time the invariant cross section is examined in the target rest frame as a function of longitudinal momentum (p_ℓ). We note that in this rest frame the cross section appears to be energy independent! At asymptotic energies the x and the p_ℓ variable will become identical (as far as their limiting behavior is concerned) at present energies, however, it appears that p_ℓ is a better scaling variable than x[25]. It remains to be seen whether at ISR energies these cross sections will also start scaling in x or whether they will stop scaling in p_ℓ[26].

I wish to thank my colleagues at Michigan and Rochester for invaluable assistance in providing much of the data presented in this report. In particular I acknowledge the enthusiastic cooperation of C. Bromberg, D. Chaney, D. Cohen and P. Slattery. Finally, I thank G. Lynch and the organizing committee of the Berkeley DPF Meeting for inviting me to present this paper.

REFERENCES

1. The new data at 69 GeV/c are from the French-Soviet Collaboration report appearing in the Proceedings of the Vanderbilt Conference (1973) AIP Series No. 12, R. S. Panvini ed.; The 102 GeV/c data are from the Michigan-Rochester Groups Reports UMBC-73-20, UR-457; The 205 GeV/c data are from G. Charlton et al, Phys. Rev. Letters 30, 574 (1973); the data at 303 GeV/c are from F. Dao et al, Phys. Rev. Letters 30, 1151 (1973); The preliminary 405 GeV/c data are from the Michigan-Rochester Collaboration (to be published).
2. The K_s^o and Λ data from 12 and 24 GeV/c are from the Bonn-Hamburg-Munich Group, H. J. Mück et al, DESY Report F1-72/1; the 6 GeV/c data are from a Michigan State preprint, B. Y. Oh et al. The 24 GeV/c extrapolated γ spectrum of Fidecaro et al, Nuovo Cimento 24, 73 (1962), is taken from the NAL-UCLA Report NAL 73/31, UCLA-1075.

3. Data at 12 and 24 GeV/c are from H. J. Mück et al, loc cit. The data at 102 GeV/c are from the Michigan-Rochester Report UMBC 73-19, UR-460. The 205 GeV/c data are from a recent ANL-NAL-Stony Brook Report submitted to the Berkeley DPF Meeting (1973).
4. T. Ferbel, Phys. Rev. Letters 29, 448 (1972) and an update in Phys. Rev. D (in press).
5. P. Olesen, Physics Letters 41B, 602 (1972); P. Slattery, Phys. Rev. Letters 29, 1624 (1972).
6. Z. Koba, P. Olesen, H. B. Nielsen, Nuclear Physics B40, 317 (1972).
7. French-Soviet Collaboration, Physics Letters 42B, 519 (1972); NAL-UCLA Collaboration Report NAL 73/38, UCLA-1077.
8. Michigan-Rochester Report UMBC 73-18, UR-459.
9. This is only true for this "narrow" range of incident momenta; See, for example, T. Ferbel, Phys. Rev. D7, 925 (1973) for a discussion of a departure from a simple logarithmic form.
10. The f_2 moment is defined in terms of the square of the dispersion ($D^2=\langle n^2\rangle-\langle n\rangle^2$) as $f_2=D^2-\langle n\rangle$. For a discussion of the f moments see A. H. Mueller, Phys. Rev. D4, 159 (1971).
11. A. Wroblewski in the Proceedings of the XIII Cracow School of Theoretical Physics (1973). For related phenomenological observations see P. K. Malhotra, Nucl. Phys. 46, 559 (1963), and O. Czyzewski and K. Rybicki, Nuclear Physics B47, 633 (1972).
12. See the papers of F-T. Dao and J. Whitmore, NAL preprint NAL-Pub-73/47-Exp, and D. Cohen, University of Rochester Report UR-449 (1973), and the review of T. Ferbel in Proceedings of the International Symposium on High Energy Physics at Tokyo (1973).
13. The material presented in this section is based largely on the Michigan-Rochester report of C. Bromberg et al, UMBC 73-19, UR-460.
14. See, for example, the early work presented by G. Bellettini in the Proceedings of the XVI International Conference on High Energy Physics, Vol.I, J. D. Jackson and A. Roberts eds.
15. See, for example, the discussion of C. Quigg in Proceedings of the Vanderbilt Conference, AIP Series No. 12, R. S. Panvini, ed.
16. See the report of J. Whitmore in the Vanderbilt Conference Proceedings, loc cit.
17. See the report of the 30-inch bubble chamber Hybrid Spectrometer Group submitted to the Berkeley DPF Meeting (1973).
18. For comparison with results at lower energies, see S. Stone et al, Phys. Rev. D5, 1622 (1972).
19. See, for example, D. F. Freedman et al, Phys. Rev. Letters 26, 1197 (1971), and references given therein.
20. Private communication from C. Quigg and G. Thomas. The data at 12 and 24 GeV/c in Fig.11 are from the Bonn-Hamburg-Munich Group, the 205 GeV/c results are from J. Whitmore's summary at the Vanderbilt Conference.
21. This was discussed previously by T. Ferbel at the Tokyo Symposium loc. cit.
22. See, for example, the review by J. Gunion in the Proceedings of the Vanderbilt Conference (1973), loc. cit.
23. The old data at 28.5 GeV/c, 102 GeV/c, 205 GeV/c and 303 GeV/c are from the review of P. Slattery in the Proceedings of the

Vanderbilt Conference, loc. cit. The new 19 GeV/c results have been privately communicated to the author by H. Bøggild. The new 102 GeV/c and preliminary 405 GeV/c data are from the Michigan-Rochester report UMBC-73-21, UR-458.

24. The detailed energy dependence for a smaller range of x and t has been measured at NAL by the Rutgers-London (IC) Group. See K. Abe et al, paper submitted to the Berkeley DPF Meeting (1973).

25. A similar observation was made for the reaction $\pi^+ p \to \pi^- +$ anything at lower energies by T. Ferbel in the Proceedings of the III International Colloquium on Multiparticle Production (Zakopane, 1972), A. Bialas et al, eds.

26. The CHLM Collaboration at the ISR has thus far only examined a small region of reaction (12); their data are most reliable for $|t| \gtrsim 0.15$ GeV^2 and $M^2 \gtrsim 6$ GeV^2, consequently they sample only a small fraction of the data between $x = 0.9$ and $x = 1.0$. See the report of D. Leith in these proceedings for more information.