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SUMMARY OF PARTICLE CORRELATION STUDY RESULTS

Winston T. Ko

University of California, Davis

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SUMMARY OF PARTICLE CORRELATION STUDY RESULTS

Winston T. Ko

University of California, Dav

As a step beyond the study of inclusive part le spectra in high energy collisions, correlation studies try to inv igate whether there is any clustering in the phase space of the partic produced. The distribution of the charges in the phase space plays an imp it role in the understanding of the dynamics. Although enormous th tical development[1] had been made on this subject and lower energy data[2,3] h een around for some time now, never had there been so much information on thi bject available at high energies as the contribution to this conference.

Inclusive Correlations

Concentration of particles of small transverse momentum in the phase space is a well known fact. The study of clustering effect is therefore concentrated in the longitudinal variable y, the rapidity. The density of particles in the rapidity space is

$$\rho(y) \equiv \frac{1}{\sigma_{inel}} \frac{d\sigma}{dy} \tag{1}$$

The density of coincidence of two particles at y_1 and y_2 is

$$\rho(y_1,y_2) \equiv \frac{1}{\sigma_{inel}} \frac{d^2\sigma}{dy_1 dy_2} \tag{2}$$

The difference of coincidence density and the product of single particle densities is the standard inclusive correlation function of two particle at y_1 and y_2,

$$C(y_1,y_2) \equiv \rho(y_1,y_2) - \rho(y_1)\,\rho(y_2) \tag{3}$$

An alternative measure is the deviation from unity of the ratio of coincidence density to the product of single particle densities,

$$R(y_1,y_2) \equiv \frac{\rho(y_1,y_2)}{\rho(y_1)\,\rho(y_2)} - 1 = \frac{C(y_1,y_2)}{\rho(y_1)\,\rho(y_2)} \tag{4}$$

These are familiar quantities and are measured in every experiment on correlations. There is experimental advantage to the use of R, in that the efficiency of measuring tracks cancels in the ratio. It should also be pointed out that in the bubble chamber experiments both C and R do not have normalization problems since the densities are normalized to the <u>number</u> of inelastic events.

The qualitative dependence of R on y_1 and y_2 can be illustrated by a contour plot such as Fig. 1. A large excess appears when the two particles are

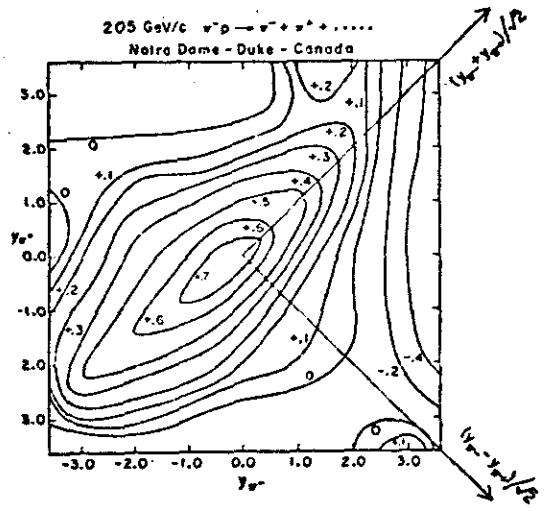


Fig. 1. A typical contour plot of $R(y_1,y_2)$. This is taken from the reaction $\pi^- p \to \pi^+ \pi^- x$ and therefore there are not a priori symmetries along the diagonals.

both in the central region and when their rapidity difference is small. We can also see that R is a rapidly changing function of $y_1 - y_2$ but a slowly changing function of $y_1 + y_2$. The rate of drop of $R(y_1,y_2)$ as the two particles separate in rapidity is shown in Fig. 2, with one of the particles fixed in rapidity.[5, 6, 7, 8] We can see several distinct features: (1) The peak value $R^{+-}(0,0)$ is almost twice that of the peak value of $R^{--}(0,0)$. (2) The shapes of $R^{--}(0,y)$ and $R^{+-}(0,y)$ are the same. If we define some coincidence distance $y_d = y_1 - y_2$ where the relative excess of coincidence is 0.5 less than $R(0,0)$, $R(0,y_d) = R(0,0) - 0.5$, then y_d is very similar for R^{--} and R^{+-}. As a matter of fact, y_d is between 2 and 2.5 for all R^{--}, R^{+-}, R^{cc}, $R^{c\gamma}$ and for

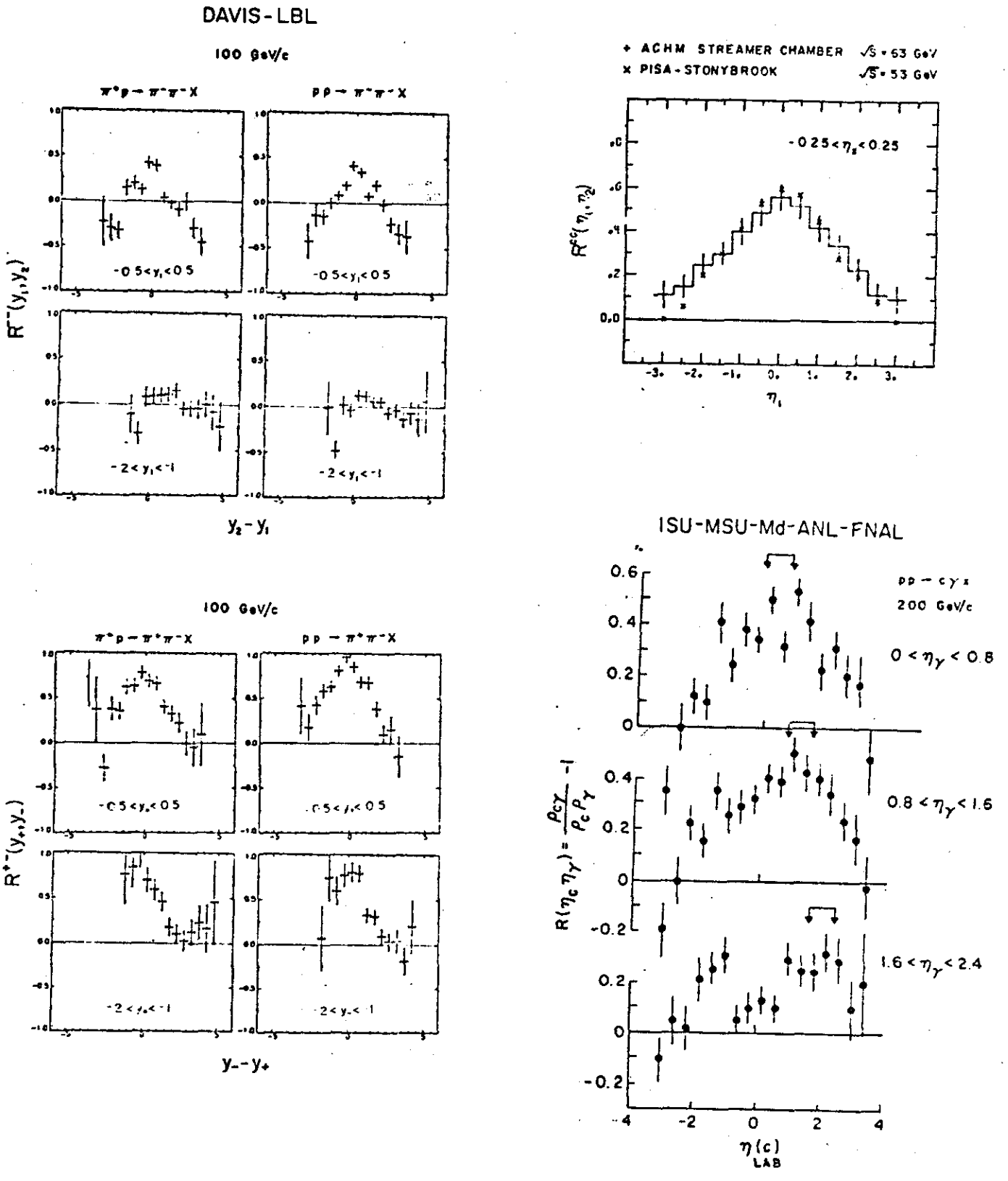


FIG. 2. Inclusive $R(y_1,y_2)$ at fixed values of y_1.

energies ranging from Superkov to FNAL to ISR. (3) R^{--} becomes weaker as one of the particles is near the end region while R^{+-} remains strong.

A compilation of R(0,0) is made in Fig. 3 for several reactions. The $\pi^-\pi^-$, $\pi^+\pi^-$ data[4, 5, 6, 9, 10, 11, 12, 13] are available for energies below 300 GeV/c and charge-charge, charge-γ data[7, 8, 14, 15] up to ISR energies. We see a

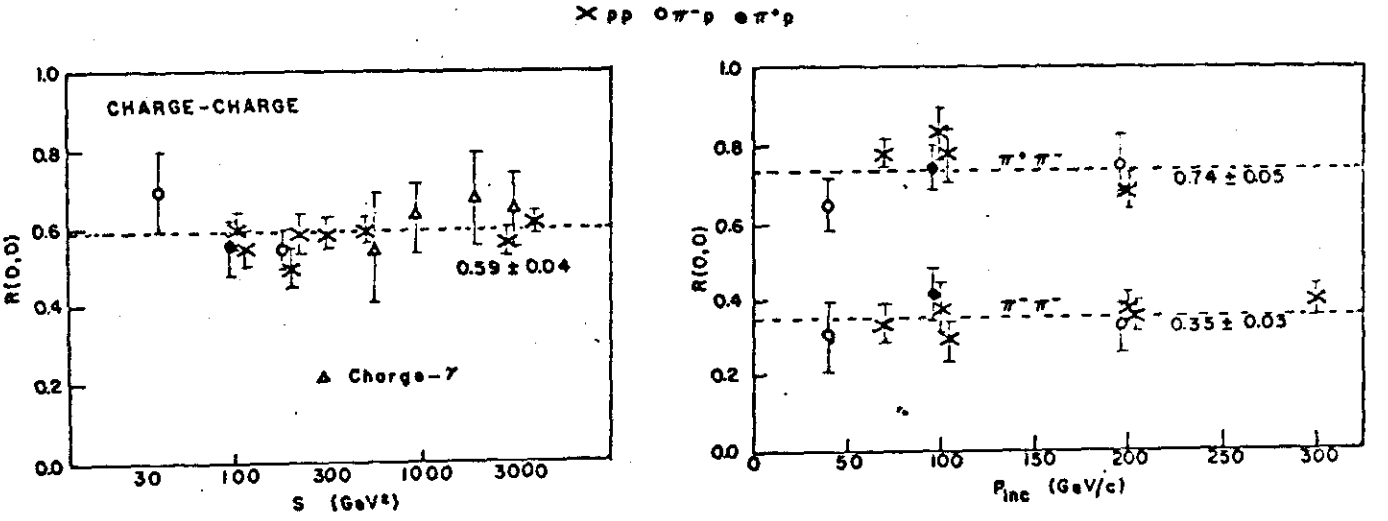


FIG. 3. A compilation of R (0,0) as function of reaction energies.

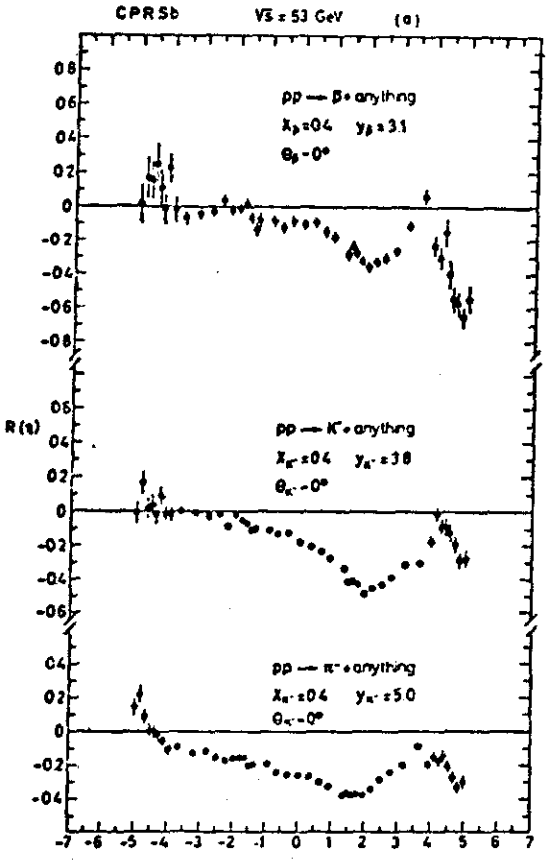
striking constancy of R(0,0) with $R^{+-}(0,0)$ about twice that of $R^{--}(0,0)$ and with $R^{cc}(0,0)$ and $R^{c\gamma}(0,0)$ roughly the average of $R^{+-}(0,0)$ and $R^{--}(0,0)$. If $\rho(0)$ is to be 0.95 ± 0.05 asymptotically for all pions independent of incident particles[16], we can also find C(0,0) at infinite energy,

	R(0,0)	C(0,0)
− −	0.35 ± 0.03	0.32 ± 0.03
+ −	0.74 ± 0.05	0.67 ± 0.05
cc, cγ	0.59 ± 0.04	2.2 ± 0.2

TABLE 1. R(0,0) and the asymtotic values of C(0,0).

The constancy of R(0,y) both in its shape and its peak value at (0,0) is a remarkable regularity for high energy collisions.

As we have noted, correlation at the small rapidity separation in $\pi^+\pi^-$ remains strong in the end region. Recent data[17, 18] are also available from ISR with one particle identified to be K^-, $\bar{p}$ or proton. Just like those with pions, there is a peak in the correlation for small rapidity differences as we can see in Fig. 4.



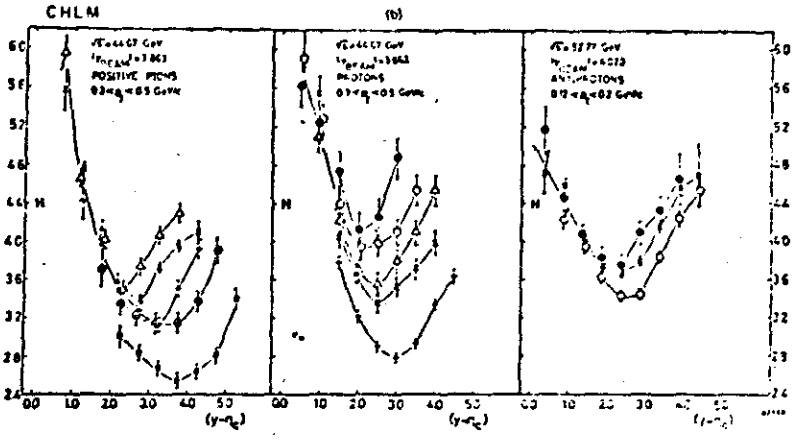


FIG. 4. Correlation of one identified particle with all other charged particles. In 4(b) different symbols are for different rapidity cuts of the identified particle. The correlation at small rapidity difference is shown to be independent of the rapidity cuts.

Semi-Inclusive Correlations of Like and Unlike Charges pions

Two sources of correlations are to be distinguished. The first is the effect of the existance of a particle on the chances of some other particles

being produced. We shall save the discussion of this kind until the end. The second is the correlations in the distribution for a given number of particles. This is called the semi-inclusive correlation and is something that can be understood from simple-minded probability. Given n π^-'s, the probability of finding a π^- with rapidity y is $\rho_n^-(y)/n$, with $\rho_n(y)$ defined as

$$\rho_n(y) \equiv \frac{1}{\sigma_n} \frac{d\sigma_n}{dy} \tag{4a}$$

The probability of finding a pair of π^- at y_1 and y_2 respectively is $\rho_n^-(y_1)\,\rho_n^-(y_2)/n^2$. Since there are n(n-1) possible pairs, the coincidence density without correlation is then $\frac{(n-1)}{n}\rho_n^-(y_1)\,\rho_n^-(y_2)$. The excess coincidence is[2], therefore $\rho_n^{--}(y_1,y_2) - (1-\frac{1}{n})\,\rho_n^-(y_1)\,\rho_n^-(y_2)$, where

$$\rho_n(y_1,y_2) \equiv \frac{1}{\sigma_n} \frac{d^2\sigma_n}{dy_1 dy_2} \tag{5}$$

If one defines a semi-inclusive correlation function analoguous to (3),

$$C_n(y_1,y_2) \equiv \rho_n(y_1,y_2) - \rho_n(y_1)\,\rho_n(y_2) \tag{6}$$

then in the case of no correlation,

$$C_n^{--}(y_1,y_2) + \frac{1}{n_-}\rho_n^-(y_1)\,\rho_n^-(y_2) = 0 \tag{7}$$

Dividing by $\rho_n^-(y_1)\,\rho_n^-(y_2)$, one has

$$R_n^{--}(y_1,y_2) + \frac{1}{n_-} = 0 \tag{8}$$

with

$$R_n^{--}(y_1,y_2) \equiv \frac{\rho_n^{--}(y_1,y_2)}{\rho_n^-(y_1)\rho_n^-(y_2)} - 1 \quad .$$

For unlike pions, π^+ and π^-, there are n_+n_- pairs of them. We therefore will have $C_n^{+-}(y_1,y_2) = 0$ and $R_n^{+-}(y_1,y_2) = 0$ if there is no correlation.

With the above reasoning in mind, we see[5, 6, 9] in Fig. 5, with one π^- fixed

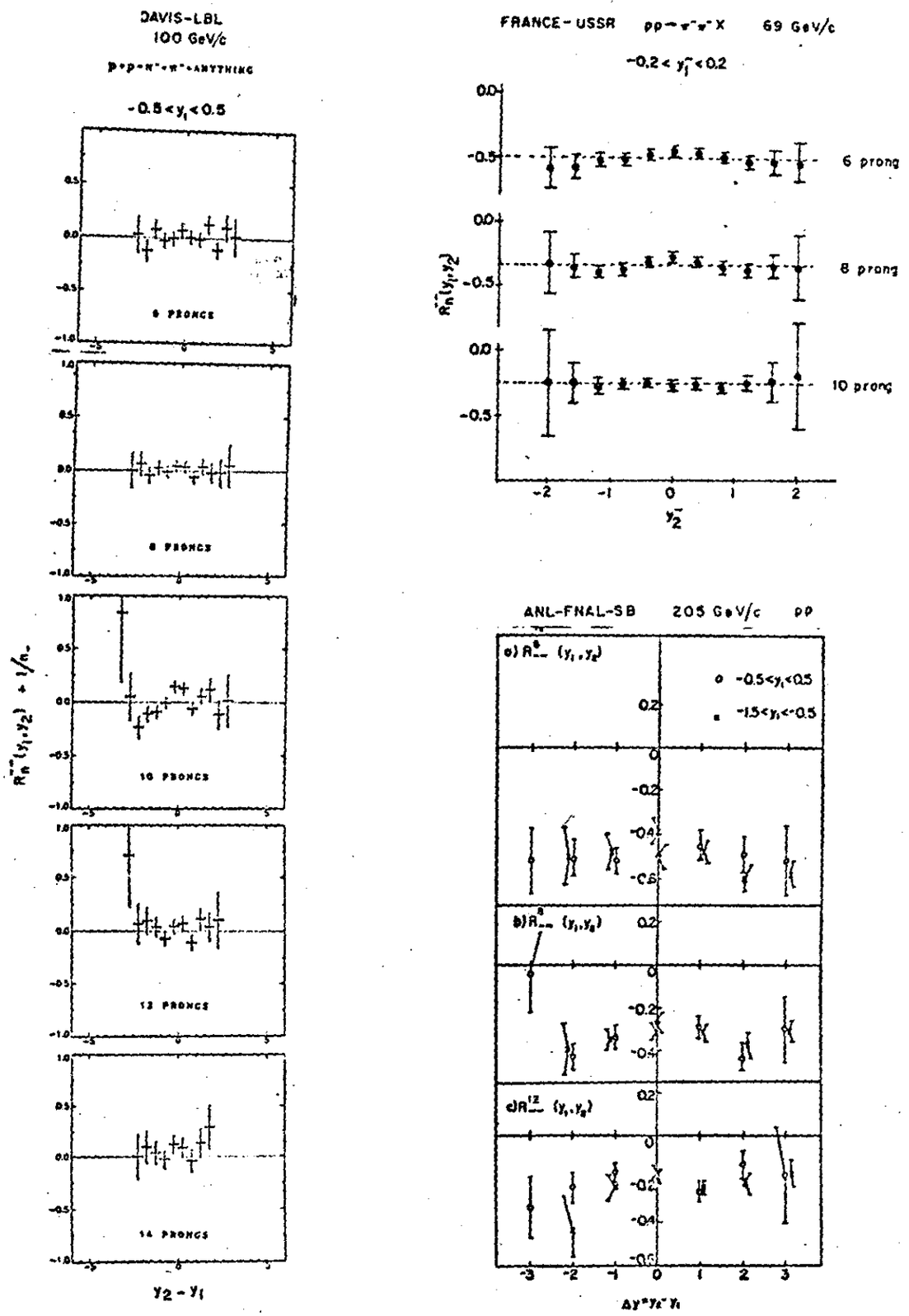


FIG. 5. With y_1 fixed nere 0, the semi-inclusive correlation $R_n^{--}(y_1,y_2)$ as a function of $y_2 - y_1$ is shown to be consistant with a constant equal to $-1/n_-$.

near the center, the correlation function $R_n^{--}(0,y)$ is constant for all y and equal to $-1/n_-$. The π^-'s are uncorrelated. This is a very important result that with a given number of π^-'s there is no $\pi^-\pi^-$ correlation in the distribution near the central region. Because of the different width of $\rho_n(y)$ at different n, the interference among different prongs gives the shape of the inclusive $R^{--}(y_1,y_2)$ we have seen.

At low energies, for K^+p interaction at 12 GeV/c, structure peaking at $y_2 - y_1 = 0$ is seen[2] in R_2^{--} and R_3^{--}. Those structures are probably to be attributed to resonances productions. Independent production of π^-'s start only at high energies.

The correlation between the unlike pions, R^{+-}, clearly show a deviation at low prong numbers, as we can see from Fig. 6. This correlation, however is enhanced either when y_+ is fixed near the end region (in the case of π^+p interaction of Fig. 6) or when a large rapidity gap is required (in the case of 205 GeV/c pp in Fig. 6). The positive correlation in the distribution of $\pi^+\pi^-$ arises perhaps from diffractive processes.

The conclusion we draw from the bubble chamber semi-inclusive data at around 100 GeV/c is that there is no like pion ($\pi^-\pi^-$) correlation in the distribution in the central region where $\pi^+\pi^-$ are correlated in the distribution in the low prong events.

Semi-Inclusive Charge-Charge Correlation at ISR

An interesting charge clustering effect is observed at very high energy at ISR. Before we examine the data let me point out two difficulties with the present experiments. The first is that the sign of the charge is not determined one studies instead the correlation functions

$$C_n^{cc}(y_1,y_2) \equiv \rho_n^{cc}(y_1,y_2) - \rho_n^c(y_1)\,\rho_n^c(y_2)$$
$$R_n^{cc}(y_1,y_2) \equiv \frac{\rho_n^{cc}(y_1,y_2)}{\rho_n^c(y_1)\,\rho_n^c(y_2)} - 1 \qquad (9)$$

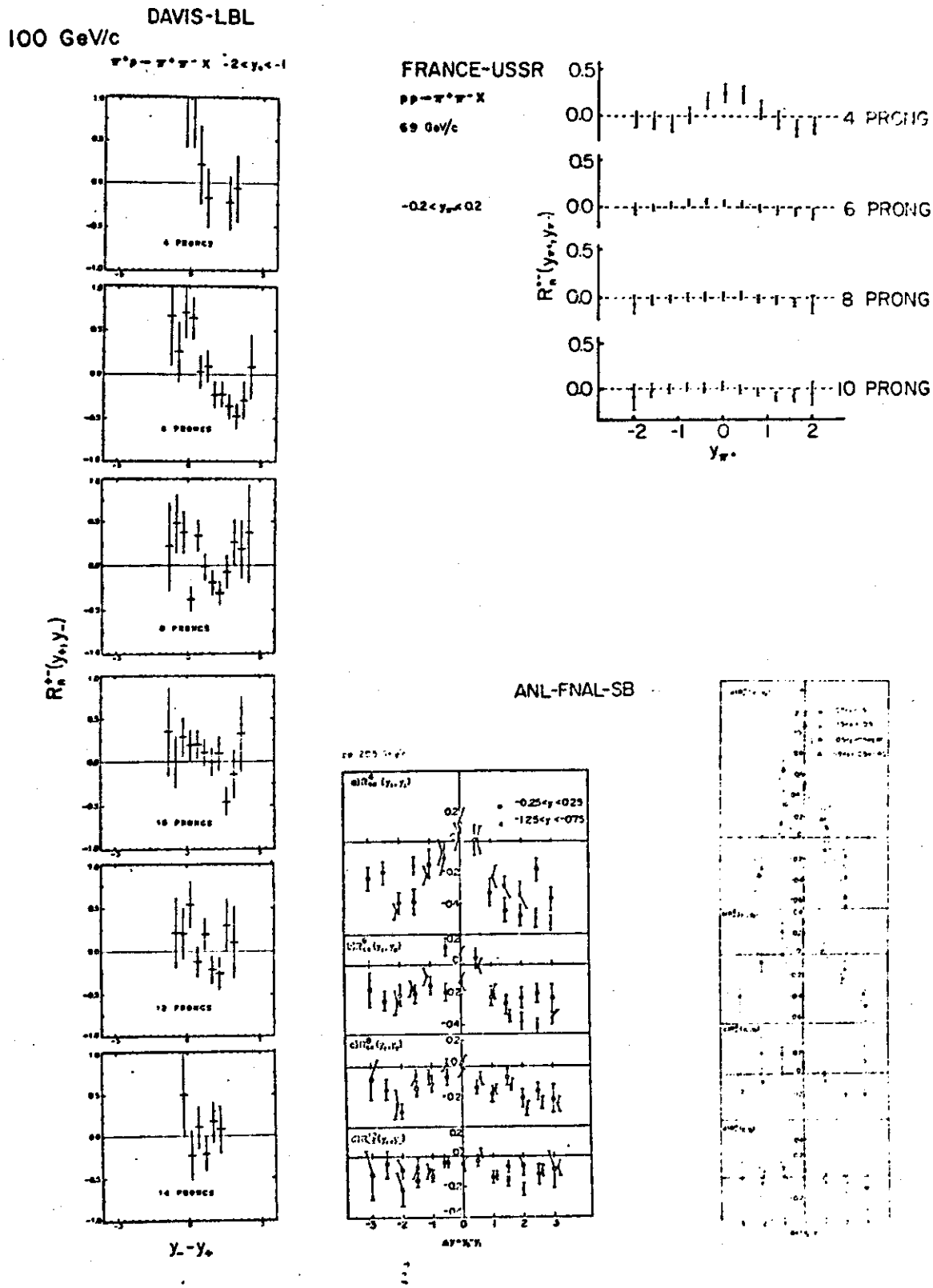


FIG. 6. The semi-inclusive correlations $R_n^{+-}(y_1,y_2)$ and $R_n^{cc}(y_1,y_2)$ at fixed values of y_1.

It is worthwhile to note that if there is no semi-inclusive correlations in --, ++, +-, and -+, R_n^{cc} still can have structures. From (7) we see that if there is no semi-inclusive correlation then

$$C_n^{cc}(y_1,y_2) + \left[\frac{1}{n_-}\rho_n^-(y_1)\,\rho_n^-(y_2) + \frac{1}{n_+}\rho_n^+(y_1)\,\rho_n^+(y_2)\right] = 0 \qquad (10)$$

If $\rho_n^-(y)$ and $\rho_n^+(y)$ are different functions of y, then it is easy to see R_n^{cc} can have structures in y.

The second difficulty is that the exact multiplicity for each event is not known in the ISR experiments. A simple check on the data that

$$\int_{\text{all } y} C_n(0,y)\,dy = \int_{\text{all } y} \rho_n(0,y)\,dy - \int_{\text{all } y} \rho_n(0)\,\rho_n(y)\,dy \qquad (11)$$

$$= (n-1)\,\rho_n(0) - n\rho_n(0) = -\rho_n(0)$$

is not satisfied. Actually only $C_{\langle n\rangle}(0,y)$ is obtained where $\langle n\rangle$ is the average over several close-by multiplicities. In this case one has

$$\int_{\text{all } y} C_{\langle n\rangle}(0,y)\,dy \approx \frac{\langle n(n-1)\rangle}{\langle n\rangle}\,\rho_{\langle n\rangle}(0) - \langle n\rangle\,\rho_{\langle n\rangle}(0)$$

$$= \left[\frac{\langle n^2\rangle - \langle n\rangle^2}{\langle n\rangle} - 1\right]\rho_{\langle n\rangle}(0) \qquad (12)$$

The effect of this lumping of multiplicity on the average enhanced $C_n(0,0)$ by about 0.15, and it can apparently account for the discrepency between the ISR data[14] at $\sqrt{S}$ = 23 GeV and the NAL 205 GeV/c pp data[6].

At $\sqrt{S}$ = 63 GeV, the Pisa-Stony Brook data[14] shows a clear structure in $C_n^{cc}(0,y)$ for all prongs in Fig. 7. One may view this behavior as a Gaussian function, which characterize the correlations, sitting on a background, proportional to $\rho_n(y)$.

$$C_n(0,y) = A_n e^{-\frac{y^2}{2\delta_n'^2}} - B_n\,\rho_n(y) \qquad (13)$$

A good fit of (13) to the data is obtained. There is little n dependence of

PISA-STONYBROOK $\sqrt{S}$ = 63 GeV

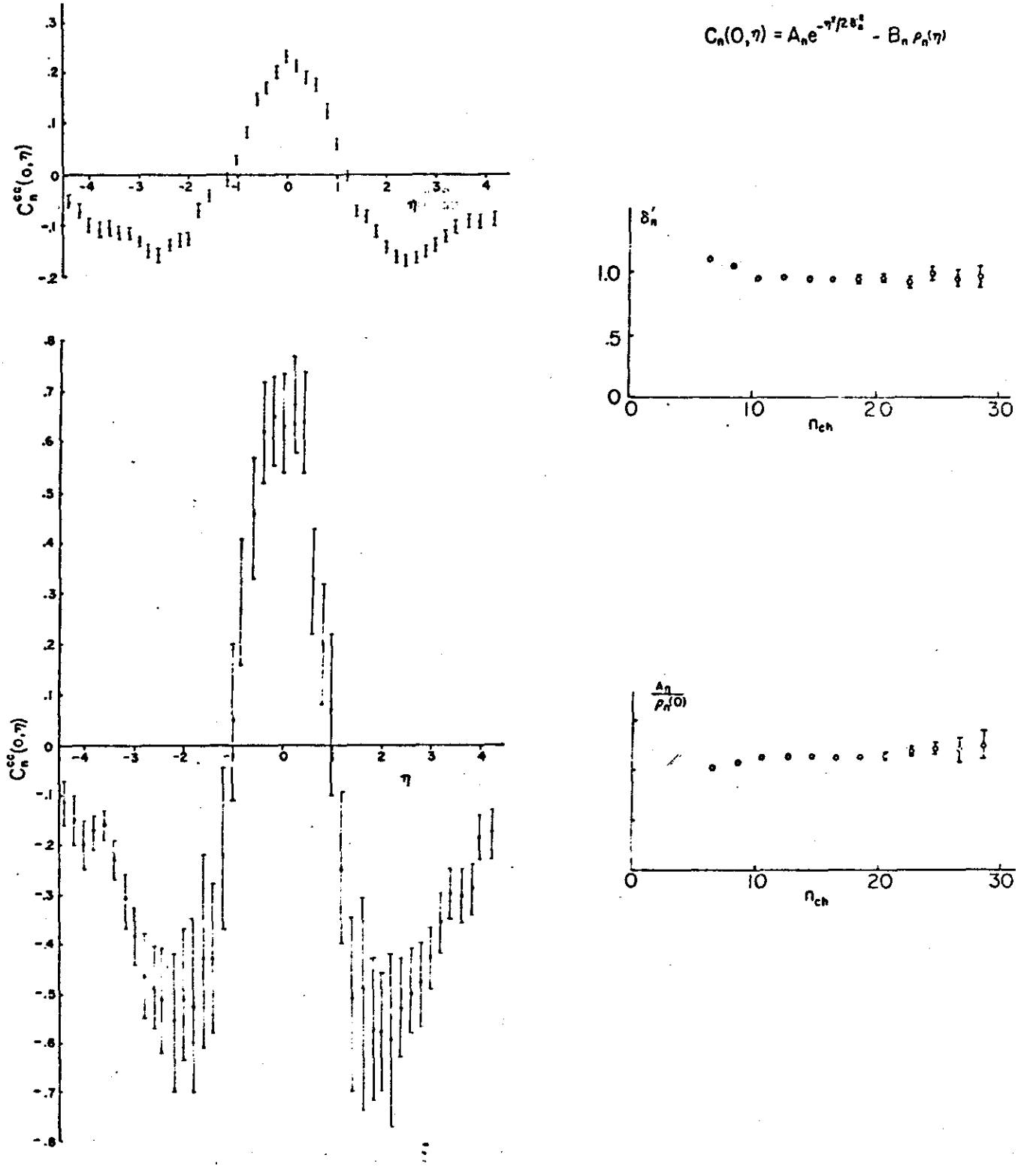


FIG. 7. The semi-inclusive correlations $C_n^{cc}(0,y)$ at the highest ISR energy. The parameters of the fit to (13) shown as function of n.

δ'_n and $A_n/\rho_n(0)$. Because of the normalization problem mentioned above the absolute value $A_n/\rho_n(0)$ is not shown. The correlation or the clustering of charge can be characterized by a Gaussian of width of $\delta' = 0.95 \pm 0.05$, independent of n.

In the ACHM Streamer Chamber experiment[8], at $\sqrt{S} = 53$ GeV, a ridge along the $(y_1-y_2)/\sqrt{2} = 0$ line (like that in Fig. 1 and schematically in Fig. 8) is seen in the semi-inclusive data. It is convenient to parameterize the data $C_n(y_1,y_2)/n$ as a normalized Gaussian in the variable $(y_1-y_2)/\sqrt{2}$ and width δ sitting on a background which is proportional to the product of probabilities of the particles having coordinates of y_1 and y_2.

$$\frac{C_n(y_1,y_2)}{n} = a_n \left[\frac{1}{\sqrt{2\pi}\,\delta\sqrt{2}}\, e^{-\frac{(y_1-y_2)^2}{4\delta^2}}\right] - (a_n+1)\left[\frac{1}{n}\rho_n(y_1)\right]\left[\frac{1}{n}\rho_n(y_2)\right] \tag{14}$$

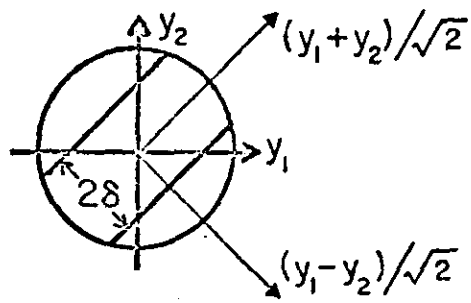


Fig. 8

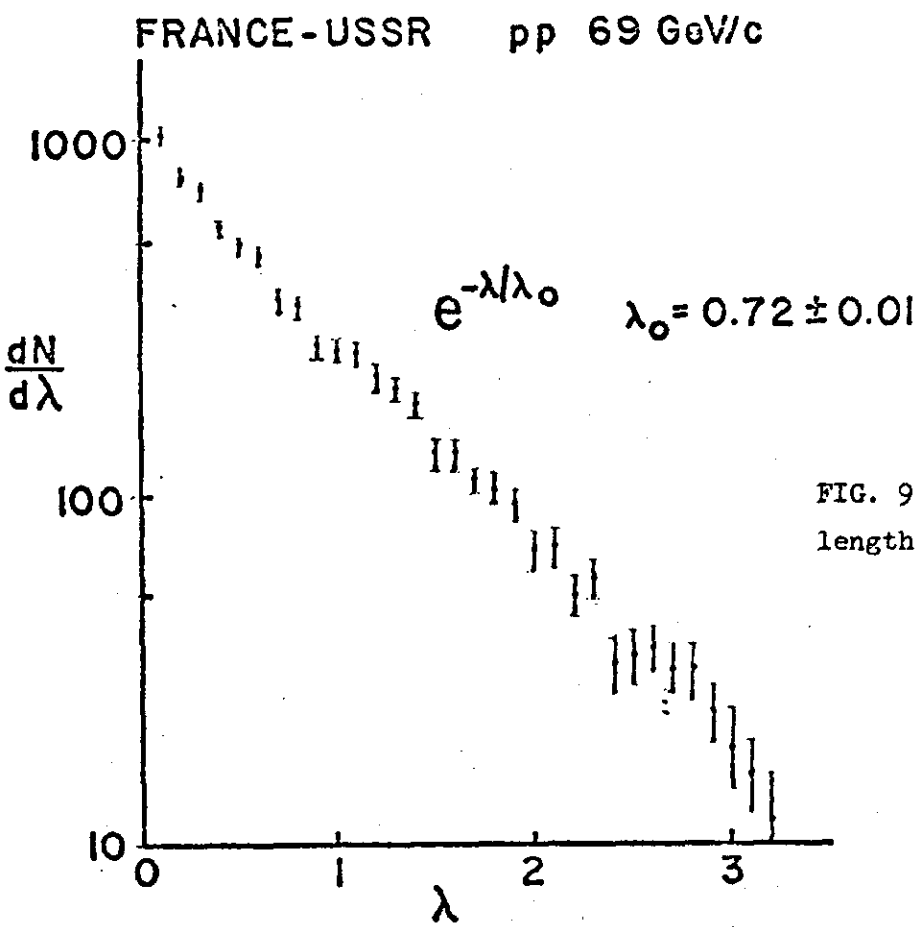
This parameterization is to be applied to a fixed domain of y_1 and y_2. The charge multiplicity n is <u>that in the domain</u>, to avoid the normalization problem. The coefficients in the two terms of (14) are self-consistent as one gets -1 on both sides of the equation after integrating over all y_1 and y_2. For the domain $-3 < y_1 < 3$, $-3 < y_2 < 3$ and the multiplicity in the domain $10 \leq n \leq 16$, values of $\delta = 0.62 \pm 0.04$ and $a_n = 1.2 \pm 0.1$ are found and are independent of n. To compare with the Pisa-Stony Brook data, one notes from Fig. 8 the Gaussian along the $y_1 = 0$ line have width $\sqrt{2}\,\delta$ in y_2.

$$\sqrt{2}\,\delta = \delta' \tag{15}$$

These two sets of ISR data consistently point to the conclusion that a charge clustering effect that can be characterized by a Gaussian in $(y_1-y_2)/\sqrt{2}$ with width between .6 to .7 is seen in the semi-inclusive data at higher energies of ISR.

Neutral Clusters of Charges

The relationship between the positive and negative charges in the rapidity space leads to the investigation of "local compensation of charges"[1]. The essence of the investigation is to find out whether there is any ordering of the positive and negative charges. One particular ordering is that within a length λ in the rapidity space the sum of all charges is zero; this length λ should be smaller than one expects from random charge distribution[19]. Fig. 9 shows that the distribution of λ is an exponential with a mean of λ_o= 0.72. This is from pp interactions at 69 GeV/c with total rapidity of 4.9.



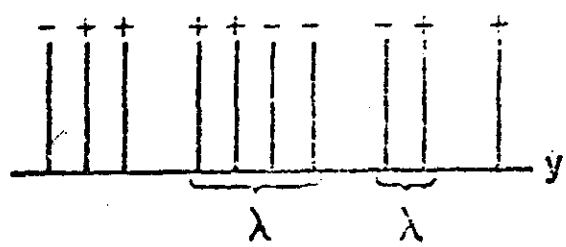


FIG. 9. The distribution of the rapidity length for a neutral zone as defined.

An alternative but almost equivalent method of investigatingthe charge distribution is the study of "charge transfer fluctuations" as functions of y. Charge transfer at certain y for each event is the net positive charge of all the charged particles with rapidity greater than y in this event (subtract the charge of the beam). For a set of events, one then measures the event to event fluctuation $D^2(y)$ of the charge transfer. If charges are locally compensated, i.e. there is a zone Δ, around the given y, outside which the net produced charges are neutral, the charge transfer will arise only from particles in Δ and the fluctuation is then proportional to Δ and the density of particles at y.

$$D^2(y) - \Delta \times \rho(y) \tag{16}$$

Fig. 10 shows[20] that in 205 GeV pp interaction, $D^2(y)$ is well represented by $0.72\,\rho(y)$.

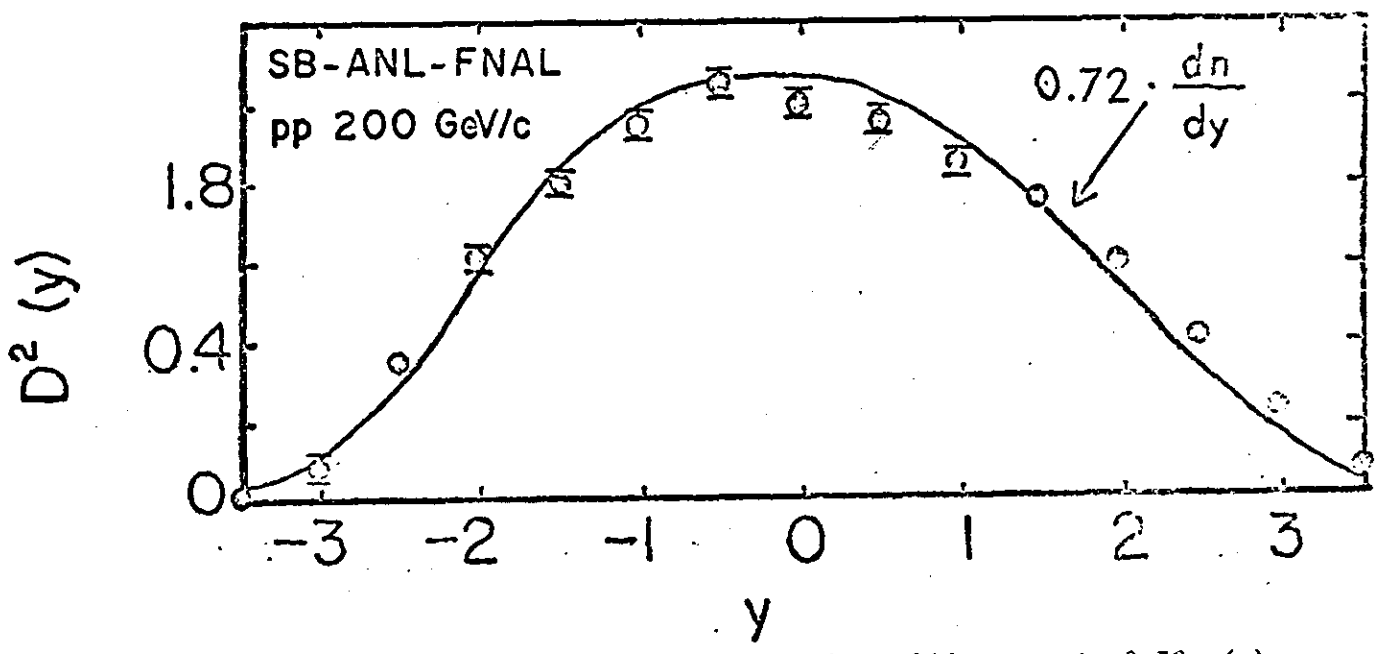


FIG. 10. Charge transfer fluctuation across y. The solid curve is $0.72\,\rho(y)$.

Although we have established that <u>charges tend to cancel out within a short distance in rapidity space</u> there is no distinction here whether there are real neutral clusters produced or particles are produced in a multiperipheral type of mechanism[1] with zero or one charge transferred between each link.

An unambiguous cluster is a neutral resonance. Unfortunately only the production of those resonance decaying solely into charged particles can be observed. A shoulder is observed[21] at ρ mass in the invariant mass combination of π^+ and π^- in the $\pi^- p$ interaction at 205 GeV, as shown in Fig. 11. It is estimated that the ρ^o production cross section for $-3 < y_\rho < -1$ is 2.4 ± 0.8 mb and for $-1 < y_\rho < 1$ is 8.9 ± 2.2 mb. There is no estimate for the forward region because of bad momentum resolution. The ρ^o production accounts for 8% of all π^-'s produced in the end region and 13% of all π^-'s in the central region. A ρ^o signal can also be seen[6] in the 205 GeV/c pp data, in Fig. 11, especially in in the six-prong events.

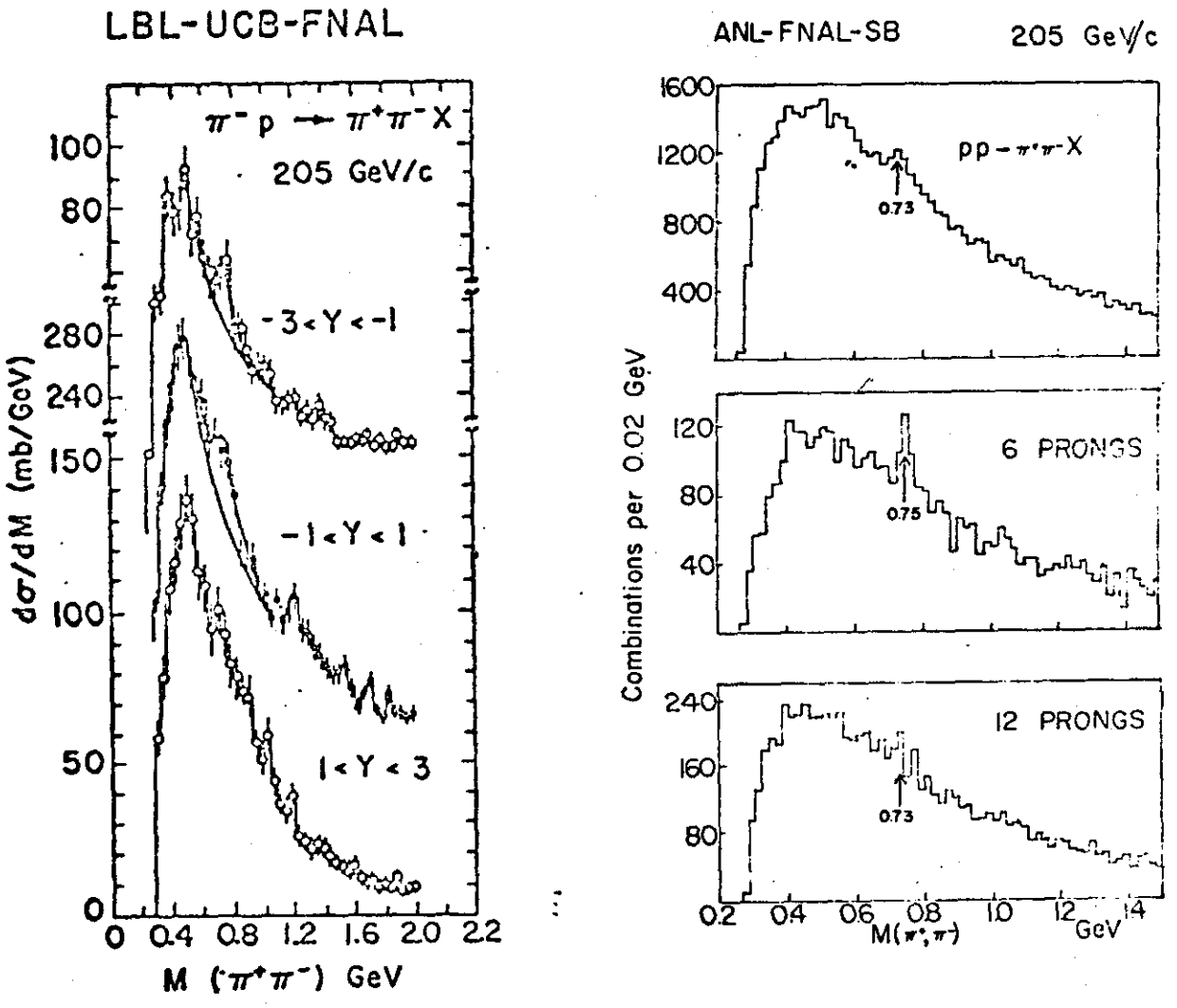


FIG. 11. Distribution of invariant mass $M(\pi^+\pi^-)$.

Production Correlations

Finally, let us turn to the question of production correlation, the influence of the production of one kind of particle on the other kind. In a previous compilation[23], it was shown that $\langle n_{\pi^o}\rangle$ rises linearly with the number of π^-'s averaged to about 0.7 π^o per π^-'s. This point is also illustrated by new data in Fig. 12 from interactions at high energies with different beams.[7, 23, 24, 25, 26] In the 100 GeV/c data, we see the average number of π^o produced per charge prong is the same for π^+p and pp interaction. In the π^-p interaction at 205 GeV/c the average number of π^o per charged prong is higher than that in the pp interaction. The difference is reduced, but not entirely, for the average number of π^o per the number of π^-'s.

The 200 GeV/c and 300 GeV/c pp data[7] shown are from the analysis of γ-conversion in the wide gap chambers behind the FNAL 30" bubble chamber. The γ-ray conversion efficiency is improved to 20% from 2% in the bare chamber. With the error bars largely reduced, one sees that the linear dependence of $\langle n_{\pi^o}\rangle$ on n_{ch} stops at $n_{ch} \approx 1.5\langle n_{ch}\rangle$. Actually this saturation of $\langle n_{\pi^o}\rangle$ after $n_{ch} \approx 1.5\langle n_{ch}\rangle$ are present in all data. Kinematics must have played an important role for π^o production in high prong events. This saturation affects the measurement of the correlation coefficient between $\pi^\pm$ and π^o.

$$f^{\pm o} \equiv \langle n_o n_\pm\rangle - \langle n_o\rangle \langle n_\pm\rangle \tag{17}$$

This coefficient in table 2, is now smaller than the previous measured since now $\langle n_{\pi^o}\rangle$ become independent of n_{π^-} at high prongs. More interesting is the correlation between π^o and π^o.

$$f^{oo} \equiv \langle n_o(n_o-1)\rangle - \langle n_o\rangle^2 \tag{18}$$

This value in table 2 is now closer to $f_2^{\pm o}$ as one expects from simple charge symmetry argument. In the 69 GeV/c pp interaction[24] f_2^{oo} was negative and much smaller

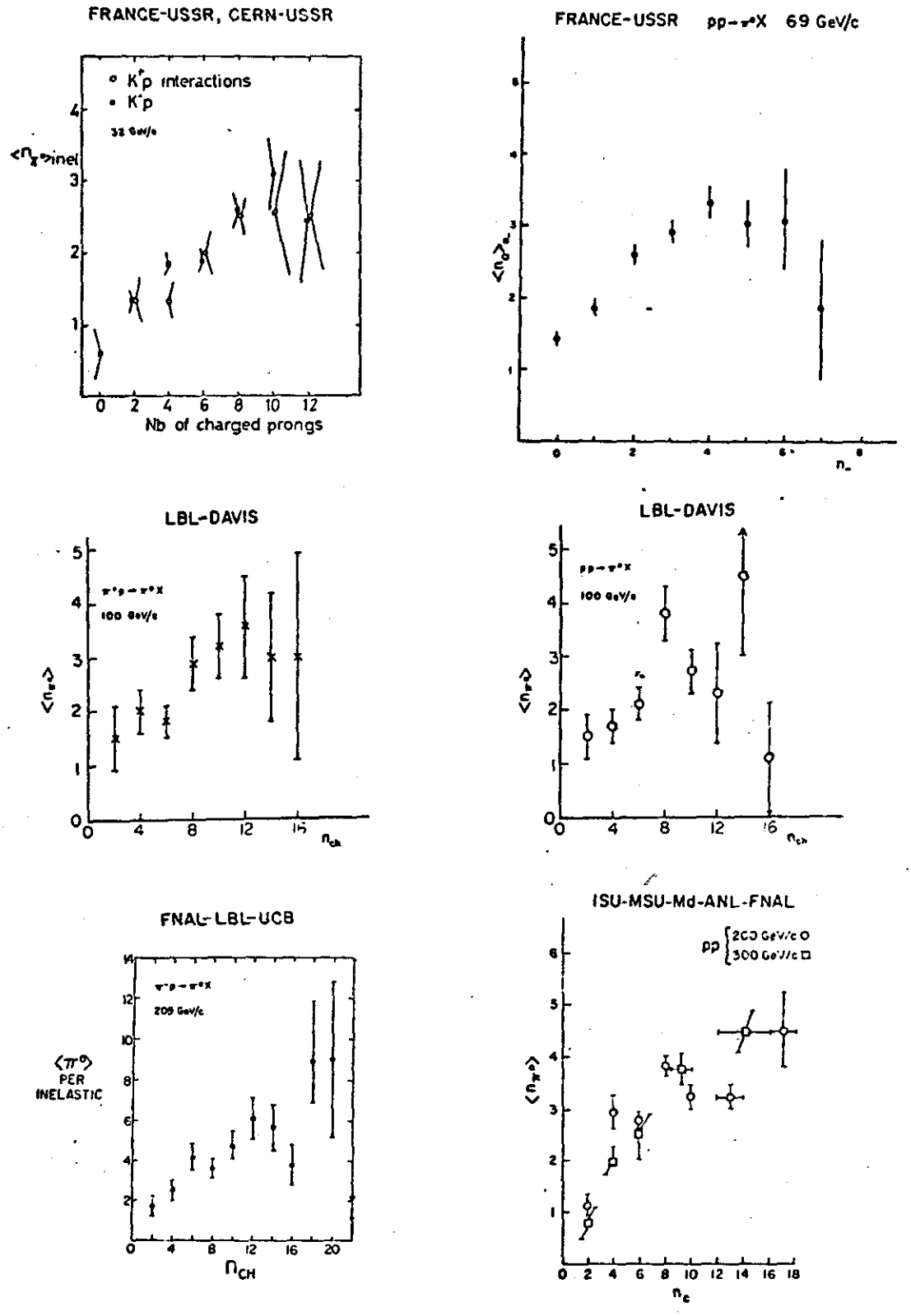


FIG. 12. Average number of π^0's produced at different charged prongs.

than $f_2^{\pm o}$.

pp interactions	69 GeV/c	200 GeV/c	300 GeV/c
$f_2^{\pm o}$	1.0±0.2	0.9±0.7	2.3±0.6
f_2^{oo}	-2.0±1.0	-0.5±0.6	1.8±0.6

Table 2.

The average number of K^o's produced[25, 26] at 100 GeV/c π^+p and pp and 205 GeV π^-p interactions seems to have very little dependence on the number of charges produced as we see in Fig. 13, with the exception perhaps of a weak dependence in the π^+p data. Again this may just be due to kinematics. On the average one K^o is produced in every six inelastic events.

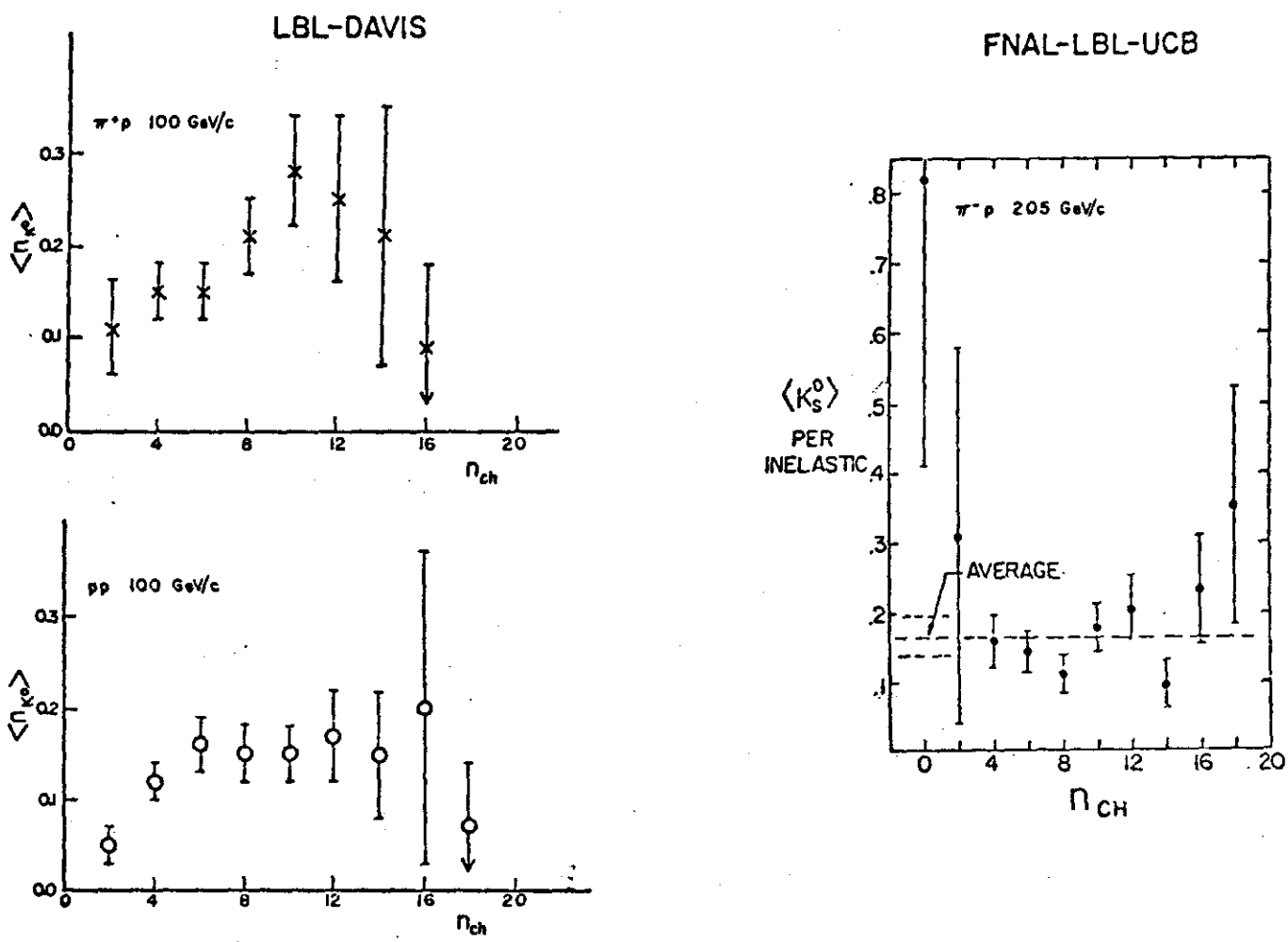


FIG. 13. Average number of K^o's produced at different charged prongs.

Concluding Remark and Acknowledgement

It is hoped that the picture emerged from this short summary of the contributions to this conference on the experimental studies of particle correlation may make the understanding of the dynamics of inclusive reactions clearer.

My thanks to R.G. Roberts and J.C. Sens for providing me with this opportunity and for their many suggestions in the preparation of this summary. I am indebt to Richard Lander for his encouragement. Discussions with E.L. Berger, W.J. Knox, A. Kryzwicki, G.H. Thomas and K. Zalewski have been fruitful. Help from K. Hayes, S. Sharrock, R. Smith and P.M. Yager is appreciated.

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1. The author wishes to apologize that due to space limitation references in this review are limited to experimental work.

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