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Correlations in multiparticle production

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The correlations among the charged particles, produced in interactions of 200, 300, and 400 GeV protons and 200 GeV pions with emulsion nuclei are investigated. An asymmetry between the projectile and the target hemispheres is observed. For two-particle distributions, short-range pseudorapidity correlation is found. The correlation between the azimuthal difference $\Delta\phi = |\phi_1 - \phi_2|$ and the pseudorapidity difference $\Delta\eta = |\eta_1 - \eta_2|$ indicates that the short-range rapidity correlation persists over the full $\Delta\phi$ range.

I. INTRODUCTION

Within the last several years, much information has been gathered about hadron production at high energies. The bulk of the particles are produced through clusters and correspond to slow particles which are mainly pions of low transverse momentum. In the central region hadronic clusters are produced but with loose correlations among themselves. Their fragmentation eventually gives the short-range correlation effects. The study of correlations between final-state particles in hadron collision is a very wide field of research. There have been a number of studies of the single- and two-particle distributions. One of the most popular approaches consists of analyzing correlations between pairs of secondaries. Over much of the kinematical range the correlation between pairs of secondaries decreases as the rapidity difference is increased (short-range effect). There are also long-range contributions; short- and long-range effects are clearly both present and happen together. At both Fermi National Accelerator Laboratory and the CERN Intersecting Storage Rings, the correlations in the central regions have been found to be approximately independent of the incident beam and its momentum and are apparently short ranged in nature. Most of the available information still refers to rapidity correlations; other correlations studies which we intend to discuss in this paper should also be very valuable. Moreover, it has been pointed out by several authors[1–5] that the study of multiparticle final states in high-energy hadronic interactions with nuclei offers a unique opportunity of studying the space-time development of the final state of a hadron-nucleon interaction.

In the first part of this paper, we shall study the particle production in the hadron-nucleus interactions in the forward and backward hemispheres. We discuss the multiplicity distributions in each hemisphere separately, and the effect of the multiplicity distribution in one hemisphere on that in the other hemisphere. In the second part, we shall study the two-particle correlations of particle production in p-nucleon, p-nucleus, and π-nucleus interactions at different primary energies. Finally, we shall study the two-particle correlation density as a function of both pseudorapidity difference $|\eta_1 - \eta_2|$ and azimuthal angular separation $|\phi_1 - \phi_2|$.

II. EXPERIMENTAL PROCEDURES

Small stacks of G-5 nuclear emulsions were exposed to 200, 300, and 400 GeV proton and 200 GeV pion beams with a flux density of 2×10^4 particles/cm^2 at Fermi National Accelerator Laboratory. The emulsions were scanned by the along-the-track scanning[6] method. In this way, we separated out the white stars (which have zero or one black or gray track, i.e., $N_h = 0$ or 1, present along with all the high-energy tracks) for π- or p-nucleon interactions from π- or p-nucleus interactions. For white stars, we accepted an inelastic event if there was no recoil blob or Auger electron at the vertex. Further details are given in Refs. 2, 3, and 6. Angular distributions of the secondary particles are given in terms of the pseudorapidity distribution variable $\eta \approx -\ln\tan(\theta_L/2)$, where θ_L is the laboratory angle of the emitted particles with respect to the projectile direction. This quantity is easily derived from the high-energy limit of the true rapidity, $y = \frac{1}{2}\ln(E+p_l)/(E-p_l)$; as $s\to\infty$, $y\to\eta = -\ln\tan(\theta_L/2)$, where p_l is the longitudinal momentum. In the center-of-mass system, pseudorapidity η_c is defined as $\eta_c \approx -\ln(\gamma_c \tan\theta_L)$, where γ_c is the Lorentz factor.

III. EXPERIMENTAL RESULTS

A. Forward-backward correlations

Two colliding hadrons, projectile and target, represent two hemispheres in their center-of-mass system. The particles which are produced in the forward and backward directions have pseudo rapidity $\eta_c > 0$ and $\eta_c < 0$, respectively. In Figs. 1(a), 1(b), 1(c), and 1(d) are shown the average multiplicity in the forward cone $\bar{n}_f$ (or backward cone $\bar{n}_b$) as a function of multiplicity in the backward cone n_b (or forward cone n_f) for hadron-nucleus interactions at 200, 300, and 400 GeV proton and 200 GeV pion beams, respectively. For proton-nucleon (white stars $N_h \leqslant 1$) interactions the average multiplicity in one hemisphere is almost independent of the multiplicity in the opposite hemisphere as one would expect due to the symmetry of the initial state. But this is not the case in the pion-nucleon interaction where we observed an asymmetry in the backward hemisphere ($\bar{n}_b > \bar{n}_f$) and $\bar{n}_b$ (or $\bar{n}_f$) is almost constant as a function of n_f (or n_b). This is shown in Figs. 1(e) and 1(f) for 200 GeV proton and pion, respectively.[7] For proton-nucleus interactions (with $N_h > 1$) we see that the two nucleons do not fragment independently and this dependency we see at all beam energies. But the correlation between the average multiplicity in the backward hemisphere as a function of multiplicity in the forward hemisphere is stronger than the average multiplicity in the forward hemisphere as a function of multiplicity in the backward one. These results show the presence of a backward asymmetry in proton-nucleus interactions at high energies, which increases very slowly with the increase in energy. With the increase in the projectile energy, the rate of increase in the correlation between the average multiplicities in the backward hemisphere is slightly more than the correlation in the forward hemisphere as a function of multiplicities in the opposite hemisphere. For 200-GeV pion-nucleus collision, the value of $\bar{n}_f$ as a function of n_b is lower than the corresponding values for 200-GeV proton-nucleus interactions. In order to

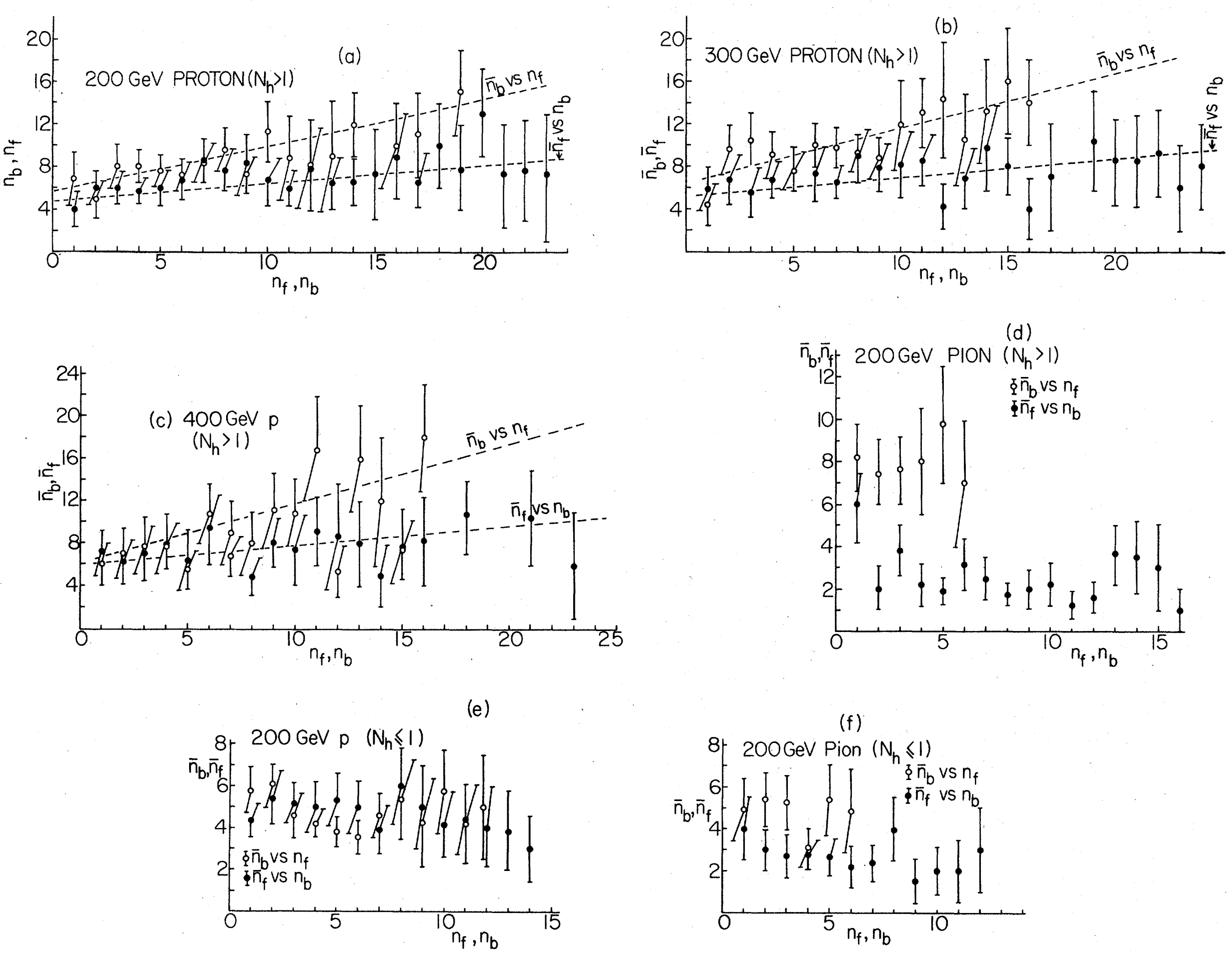

FIG. 1. Average multiplicity $\bar{n}_f$ in the forward cone vs multiplicity in the backward cone and vice versa (i) for hadron-nucleus interactions in (a) 200 GeV proton, (b) 300 GeV proton, (c) 400 GeV proton, and (d) for 200 GeV pion and (ii) for hadron-nucleon interactions in (e) 200 GeV proton and (f) for 200 GeV pion, respectively. The dashed lines are drawn by free hand to fit the experimental points for hadron-nucleus interactions.

separate out the contributions from the central and fragmentation region we discuss the multiplicity distribution for different values of pseudorapidity. In Figs. 2(a) and 2(b) are shown the average multiplicity in the forward cone $\bar{n}_f$ (or backward cone $\bar{n}_b$) as a function of multiplicity in the backward cone n_b (or forward cone n_f) for p-nucleus interactions at 200 and 400 GeV proton, respectively, for three different regions of pseudorapidity ($0<\eta_c\leq 1$, $1<\eta_c\leq 2$, and $2<\eta_c\leq 3$) covering the central and fragmentation regions. We observe that in the central region $0<\eta_c\leq 1$, the distributions of $\bar{n}_f$ and $\bar{n}_b$ are practically the same as a function of multiplicities at different energies. But their differences become apparent with the increase in η_c values (the fragmentation regions).

It is well known that the dispersion $D=(\langle n^2\rangle-\langle n\rangle^2)^{1/2}$ is a linear function of the average charged multiplicity $\langle n\rangle$. In Figs. 3(a), 3(b), 3(c), and 3(d) we plot the ratios $D_f/\bar{n}_f$ and $D_b/\bar{n}_b$ for forward and backward hemispheres for 200, 300, and 400 GeV proton and 200 GeV pion as a function of η_c, respectively. We see that for the central region ($0<\eta_c<1$), the values of these two ratios $D_f/\bar{n}_f$ and $D_b/\bar{n}_b$ are almost equal and for $\eta_c>1$ the distribution in the backward hemisphere $D_b/\bar{n}_b$ connected with the target nucleus has little larger ratio than $D_f/\bar{n}_f$, connected with the projectile, at all four beams. Thus, the detailed investigation of the properties of secondaries in p-p and p-nucleus interactions will help to understand the difference between the two types of collisions.

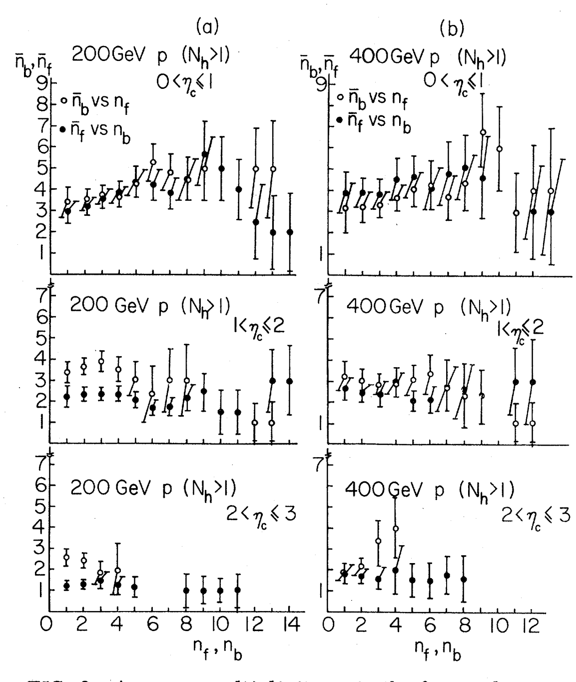

FIG. 2. Average multiplicity $\bar{n}_f$ in the forward cone vs multiplicity in the backward cone and vice versa for three different regions of pseudorapidity $0<\eta_c\leq 1$, $1<\eta_c\leq 2$, and $2<\eta_c\leq 3$ for (a) 200 GeV proton and (b) 400 GeV proton, respectively.

B. Two-particle correlations

Most of the studies on two-particle correlations have been done when the particles are produced in nucleon-nucleon[8] or pion-nucleon interactions. But for nucleon-nucleus interactions, very little data are available on two-particle correlations. We shall present here our experimental results on two-particle correlations when they are produced in p-nucleon as well as p-nucleus interactions at high energies. A two-particle correlation function is defined as

$$R(\eta_1,\eta_2)=\left[\frac{1}{\sigma_{\text{in}}}\frac{d^2\sigma}{d\eta_1 d\eta_2}-\frac{1}{\sigma_{\text{in}}^2}\frac{d\sigma}{d\eta_1}\frac{d\sigma}{d\eta_2}\right]\Big/\frac{1}{\sigma_{\text{in}}^2}\frac{d\sigma}{d\eta_1}\frac{d\sigma}{d\eta_2}$$

$$=\frac{N_T N_2(\eta_1,\eta_2)}{N_1(\eta_1)N_1(\eta_2)}-1,$$

where

σ_{in} = total inelastic cross section,

N_T = total number of inelastic interactions,

$N_1(\eta_1)$ = number of charged particles at η_1,

$N_2(\eta_1,\eta_2)$ = number of pairs of charged particles at both η_1 and η_2 within the same event.

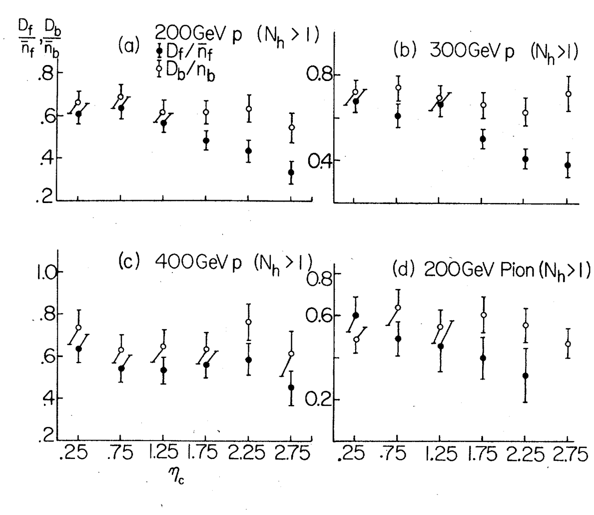

FIG. 3. Dependence of the $D_f/\bar{n}_f$ and $D_b/\bar{n}_b$ ratios for the forward and backward hemispheres on the value of pseudorapidity η_c in (a) 200 GeV proton, (b) 300 GeV proton, (c) 400 GeV proton, and (d) for 200 GeV pion, respectively.

R is dimensionless, so that normalization difficulties which might occur in certain experiments are canceled out. R should be constant and equal to zero for uncorrelated particles. In Figs. 4(a) and 4(b) are shown the plots of the function $R(\eta_1, \eta_2)$ for p-nucleon ($N_h \leq 1$) and p-nucleus ($N_h > 1$) interactions, respectively, for 200, 300, and 400 GeV proton beams. $R(\eta_1, \eta_2)$ is plotted as a function of rapidity separation ($\eta_2 - \eta_1$) for two values of $\eta_c \approx 0$ and 0.8. In general, there is a strong tendency of particles to emerge preferentially with small difference in $\eta_2 - \eta_1$ for $\eta_c \approx 0$ showing a strong short-range correlation. There is a definite difference in the behavior of the correlation between p-nucleon and p-nucleus interactions for $\eta_c \approx 0.8$. $R(\eta_1, \eta_2)$ is not symmetrical for $\eta_1 = \eta_2$ in Fig. 4(b), but is almost flat (and positive) for the backward hemisphere and this shows a clear preference towards higher correlations in the backward hemisphere (where $\eta_c < 0$) in the proton-nucleus interactions. There is a slight asymmetry present for events with $N_h \leq 1$ and although there is a dominant dependence of function R on $|\eta_2 - \eta_1|$, there is also a dependence on $\eta_1 + \eta_2$ as evidenced by the nonsymmetric shape for large η_1.

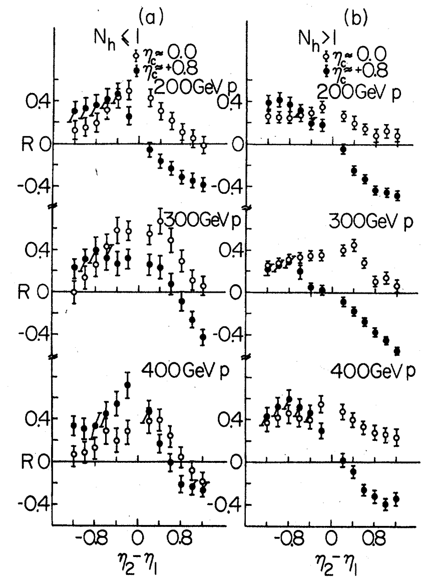

FIG. 4. Two-particle correlation function $R(\eta_1, \eta_2)$ as a function of pseudorapidity separation ($\eta_2 - \eta_1$) in 200, 300, and 400 GeV proton and 200 GeV pion, for two values of $\eta_c \approx 0$ and 0.8. (a) is for $N_h \leq 1$ and (b) is for $N_h > 1$.

C. Rapidity and azimuthal correlations

In the previous section (Sec. III B), about the measurement of rapidity correlation, no reference was made to a possible azimuthal dependence of the correlation which we shall discuss in this section. For each track from its dip (δ) and projection (α) angles, its azimuthal angle ϕ was calculated by the relation $\phi = \tan^{-1}(\sin\alpha / \tan\delta)$. In order to eliminate the coherent events, we used interactions with multiplicity $n_s > 5$. The correlation between the azimuthal-angle difference $\Delta\phi = |\phi_1 - \phi_2|$ and the rapidity difference $\Delta\eta = |\eta_1 - \eta_2|$ between the charged particles produced in proton-nucleon and proton-nucleus interactions at 200, 300, and 400 GeV and 200 GeV pion-nucleus interactions are shown in Fig. 5. All the parts of the figure show the existence of azimuthal correlations, most of which are interpreted as arising from momentum conservation within one cluster. Azimuthal distributions $\Delta N / \Delta\phi$ for small $\Delta\eta < 1.0$ indicate that there are strong asymmetrics due to short-range azimuthal correlation which prefer back-to-back configurations. We find that the short-range rapidity correlation is strongest when two particles are produced in the same or in the transverse plane and is persistent over the whole $\Delta\phi$ range in all the beams. This correlation has an interesting application in the study of jet physics.

IV. CONCLUSIONS

From this experiment of p-nucleus interactions at three different energies, we conclude that the correlation between the average number of particles in the backward cone increases with the multiplicity in the forward hemisphere as compared to the correlation between the average number of particles in the forward cone with the multiplicity in the backward hemisphere. These correlations change very slowly with the energy and the mass of the projectile.

The correlation function R has maximum (positive) values near $\eta_1 - \eta_2 \approx 0$. For fixed η_c, R is not symmetric around $\eta_1 = \eta_2$ for hadron-nucleus interactions. It is almost constant for $\eta_2 < \eta_1$ but de creasing for $\eta_2 > \eta_1$.

From the angular distributions of the secondary particles, we find a correlation between the rapidity and the azimuthal angles. The short-range rapidity correlation $\Delta\eta = 0$ appears to be a dominant feature over the whole $\Delta\phi$ range in all the beams. This observed dependency of this short-range rapidity correlation on $\Delta\phi$ has interesting consequences, i.e., the production of jets which is an interesting topic and should be studied very carefully.

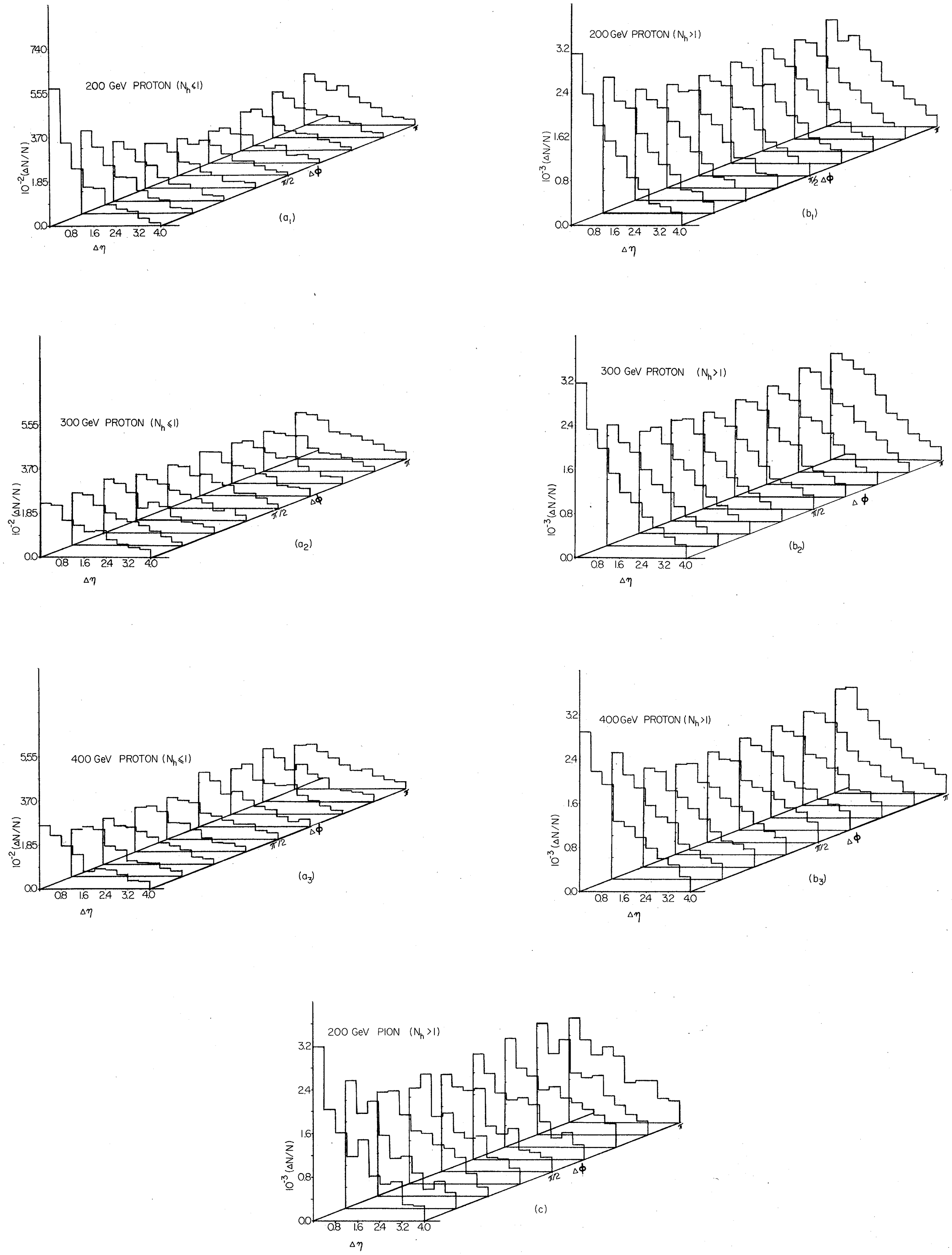

FIG. 5. $\Delta\eta = |\eta_1 - \eta_2|$ distribution for all particles which have the same azimuthal-angle difference $\Delta\phi = |\phi_1 - \phi_2|$ for 200, 300, and 400 GeV proton. (a_1), (a_2), and (a_3) are for $N_h \leq 1$. (b_1), (b_2), and (b_3) are for $N_h > 1$, and (c_1) is for 200 GeV pion $N_h > 1$.

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[7]We may point out that the selection of p-nucleon interactions by $N_h \leq 1$ criterion includes a small contamination of p-nucleus events. This is clear from the fact that p-p mean multiplicity at 200 GeV is 7.6. Half of this should be in one hemisphere, i.e., 3.8, and we see a small excess of this number in each hemisphere.

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