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CONDITIONAL CHARGE DISTRIBUTIONS AT VERY HIGH ENERGIES

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Recently there has been an increasing interest in studying charge distributions in high-energy hadronic collisions [1-8]. In this note, we shall be concerned with the asymptotic constraints imposed by the laws of energy and charge conservation on the conditional charge distributions introduced in ref. [5].

Let us consider the inclusive hadronic reaction

$$a + b \to c_1 + \ldots + c_m + \text{anything}, \qquad (1)$$

where $a, b, c_1, \ldots,$ and c_m are specific stable particles. We adopt the Feynman variables $\vec{\xi}_i = (x_i, \vec{p}_{i\perp})$, where $x_i = 2s^{-1/2}\, p_{i\parallel}$, $p_{i\parallel}$ and $\vec{p}_{i\perp}$ are the longitudinal and transverse momenta of particle c_i, and s is the square of total energy (all variables are given in the c.m. system). Let k be a system of independent kinematical variables as functions of $\vec{\xi}_1, \ldots, \vec{\xi}_m$. Throughout this note, we assume that $x_1, \ldots, x_m$ belong to k.

Let us define the following conditional charge distributions:

$$\langle Q_m^{ab}(s,k)\rangle = \sum_{c_1,\ldots,c_m} (Q_{c_1} + \ldots + Q_{c_m}) \frac{d\sigma^{ab}_{c_1\ldots c_m}}{dk} \times$$

$$\times \Big(\sum_{c'_1,\ldots,c'_m} \frac{d\sigma^{ab}_{c'_1\ldots c'_m}}{dk} \Big)^{-1}, \qquad (2)$$

where $d\sigma^{ab}_{c_1 \ldots c_m} / dk$ is the differential cross section for reaction (1), Q_{c_i} is the charge of c_i, and the summation over c_i is over all species of stable particles. Here the charge means any additively conserved quantum number. The c.c. distribution $\langle Q^{ab}_m(s,k) \rangle$ is regarded as the average charge of an m-particle system produced in the ab collision under the condition that it is found at the momenta given by k.

Using certain model-independent assumptions, we will show that the c.c. distributions at very high energies are small in the central region and follow the initial charges in the fragmentation regions.

1. Central Charges

We shall establish that if the average total (resp. charged) multiplicity for the ab collision goes to infinity for at least one sequence of values of s, then the c.c. distribution $\langle Q^{ab}_m(s,k) \rangle$ (resp. the ratio of the charge k-densities of positive and negative m-particle systems produced in the ab collision) approaches a zero (resp. unity) limiting value in the central region at asymptotic energies. Another limiting values are not excluded. For an illustration at present accelerator and ISR energies, fig. 1 shows that the electric and baryonic values of the c.c. distributions for πp and pp collisions are relatively small near $x=0$ [5] *. Moreover, the ISR data seem to indicate the approach to unity of the ratio of particles to antiparticles in the central region [10].

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* No error bars are shown in fig. 1, because here the statistical errors are less important than the systematical ones due to: 1) the reading of the single-particle distributions from plots; 2) the construction of the neutral spectra (for pp collisions: $sp(n)=0.6\, sp(p)$ [2]; $sp(K^0)=sp(K^+)$, $sp(\bar{K}^0)=sp(K^-)$, $2sp(\pi^0)=sp(\pi^+)+sp(\pi^-)$; for $\pi^{\pm}p$ collisions: $sp(\pi^0)=sp(\pi^{\mp})$, $sp(n)=r\,sp(p)$, $r=0.78$ (0.49) in $\pi^- p$ $(\pi^+ p)$ collisions [9]; for comments, see ref. [5]); 3) the normalization of data from different experiments [8,9].

Let us introduce the m-particle number functions

$$N^{ab}_{c_1\ldots c_m}(s,\vec{\xi}_1,\ldots,\vec{\xi}_m)=(\sigma^{ab}_{tot}(s))^{-1}\,\xi^{\circ}_{c_1}\ldots\xi^{\circ}_{c_m}\frac{d\sigma^{ab}_{c_1\ldots c_m}}{d^3\vec{\xi}_1\ldots d^3\vec{\xi}_m}, \tag{3}$$

where $\xi^{\circ}_{c_i}=[x_i^2+4s^{-1}(p^2_{i\perp}+M^2_{c_i})]^{1/2}$, M_{c_i} is the mass of c_i, and $\sigma^{ab}_{tot}(s)$ is the total cross section for the ab collision. Then the usual c.m. energy and charge sum rules [11] can be written in the form

$$(2-\sum_{i=1}^{m-1}\xi^{\circ}_{c_i})N^{ab}_{c_1\ldots c_{m-1}}(s,\vec{\xi}_1,\ldots,\vec{\xi}_{m-1})=$$

$$=\sum_{c_m}\int d^3\vec{\xi}_m N^{ab}_{c_1\ldots c_m}(s,\vec{\xi}_1,\ldots,\vec{\xi}_m), \tag{4}$$

$$(Q_a+Q_b-\sum_{i=1}^{m-1}Q_{c_i})N^{ab}_{c_1\ldots c_{m-1}}(s,\vec{\xi}_1,\ldots,\vec{\xi}_{m-1})=$$

$$=\sum_{c_m}Q_{c_m}\int\frac{d^3\vec{\xi}_m}{\xi^{\circ}_{c_m}}N^{ab}_{c_1\ldots c_m}(s,\vec{\xi}_1,\ldots,\vec{\xi}_m), \tag{5}$$

where the l.h.s. of eq. (4)(resp. (5)) with $m=1$ one replaces by 2 (resp. Q_a+Q_b).

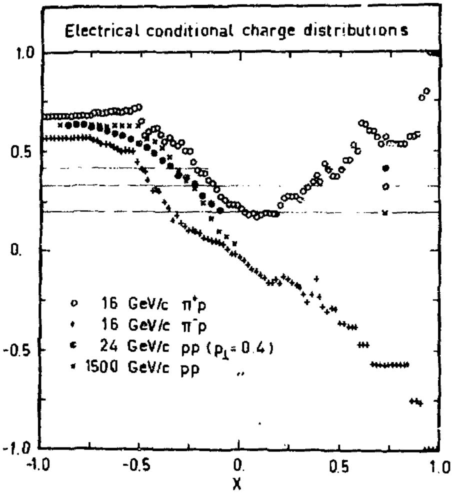
The average total number and charge of the m-particle systems produced in the ab collision and found in the $(\vec{\xi}_1,\ldots,\vec{\xi}_m)$-region R are defined by

$$\nu^{ab}_m(s,R)=\sum_{c_1,\ldots,c_m}\int_R\frac{d^3\vec{\xi}_1}{\xi^{\circ}_{c_1}}\ldots\frac{d^3\vec{\xi}_m}{\xi^{\circ}_{c_m}}N^{ab}_{c_1\ldots c_m}(s,\vec{\xi}_1,\ldots,\vec{\xi}_m), \tag{6}$$

$$\chi^{ab}_m(s,R)=\sum_{c_1,\ldots,c_m}(Q_{c_1}+\ldots+Q_{c_m})\int_R\frac{d^3\vec{\xi}_1}{\xi^{\circ}_{c_1}}\ldots\frac{d^3\vec{\xi}_m}{\xi^{\circ}_{c_m}}\times$$

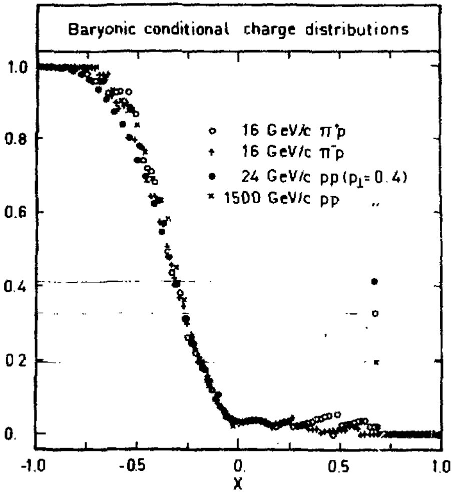
$$\times N^{ab}_{c_1\ldots c_m}(s,\vec{\xi}_1,\ldots,\vec{\xi}_m), \tag{7}$$

Fig. 1. Conditional charge distrbutions versus reduced c.m. longitudinal momentum. a). Electrical c.c. distributions. b). Baryonic c.c. distributions. The data are from ref. /2/: $\pi^+ p$ 16 GeV/c o ; $\pi^- p$ 16 GeV/c + ; pp 24 GeV/c • ; and pp 1500 GeV/c × . All c.c. distributions are given by eq. (2), where $m = 1, k = \{x\}$ for $\pi^{\pm} p$ collisions, and $k = \{x, p_{\perp}^2\}$ for pp collisions at $p_{\perp} = |\vec{p}_{1\perp}| = 0.4$ GeV/c. The straight lines represent the ratios of the initial total charges to the average total multiplicities for the above collisions.*



a)

* See the foot-note on page 4.



b)

where R is dropped when the integration is done on the whole $(\vec{\xi}_1, \dots, \vec{\xi}_m)$ – space. For example, $\nu_1^{ab}(s)$ is the average total multiplicity for the ab collision. We shall use the conventions $\nu_0^{ab}(s)=1$ and $\chi_0^{ab}(s)=0$.

Let $0<\epsilon\leq 1$ and consider the decomposition of the $(\vec{\xi}_1, \dots, \vec{\xi}_m)$ -space into two regions: the region R_0 of all points $(\vec{\xi}_1, \dots, \vec{\xi}_m)$ such that $|x_i|\leq\epsilon$ for any $i=1, \dots, m$, and the region R' of all points $(\vec{\xi}_1, \dots, \vec{\xi}_m)$ with $|x_i|\geq\epsilon$ for at least one index i.

We next list some useful bounds. Equations (6) and (7) give

$$\chi_m^{ab}(s,R)\leq m\,Q_{max}\;\nu_m^{ab}(s,R),\;Q_{max}=\max_c Q_c. \tag{8}$$

By eq. (4) and its permutations, we obtain

$$\nu_m^{ab}(s,R')<2m\,\epsilon^{-1}\,\nu_{m-1}^{ab}(s), \tag{9}$$

$$\nu_m^{ab}(s,R_0) > \nu_m^{ab}(s) - 2m\epsilon^{-1}\nu_{m-1}^{ab}(s). \tag{10}$$

Equation (5) implies

$$\chi_m^{ab}(s) = m(Q_a + Q_b)\,\nu_{m-1}^{ab}(s) - m\chi_{m-1}^{ab}(s). \tag{11}$$

Combining eqs. (8), (9), and (11), we get

$$|\chi_m^{ab}(s,R_0)| < m(m+1+2m\epsilon^{-1})\,Q_{max}\,\nu_{m-1}^{ab}(s). \tag{12}$$

Let us suppose that there exists no energy-independent upper bound on the average total multiplicity for the ab collision:

$$\overline{\lim_{s\to\infty}}\,\nu_1^{ab}(s) = \infty. \tag{13}$$

The above assumption is predicted by most models [12] and suggested by data [13].

We now recall that

$$\nu_m^{ab}(s) = (\sigma_{tot}^{ab}(s))^{-1} \sum_{n\geq m} n(n-1)\ldots(n-m+1)\,\sigma_n^{ab}(s), \tag{14}$$

where $\sigma_n^{ab}(s)$ is the n-particle production cross section for the ab collision. Then eqs. (13) and (14) imply

$$\underline{\lim_{s\to\infty}}\,\nu_{m-1}^{ab}(s)(\nu_m^{ab}(s))^{-1} < \underline{\lim_{s\to\infty}}(\nu_1^{ab}(s))^{-1} = 0. \tag{15}$$

The central region at asymptotic energies consists of all points $(\vec{\xi}_1,\ldots,\vec{\xi}_m)$ with $x_1 = \ldots = x_m = 0$. According to eqs. (10) and (15), the central region is dominantly populated relative to the other regions for at least some asymptotic energies. Moreover, by eqs. (10), (12), and (15) with ϵ falling slower than $(\nu_m^{ab}(s))^{-1}$ as $s\to\infty$, we obtain a <u>zero</u> limiting value for the average charge of an m-particle system found in the region R_0:

$$\underline{\lim_{s\to\infty}}\,|\chi_m^{ab}(s,R_0)|(\nu_m^{ab}(s,R_0))^{-1} = 0. \tag{16}$$

Using eqs. (2), (6), and (7), it is easy to see that there exist some k such that $|x_i| \leq \epsilon$ for any $i = 1, ..., m$, and

$$<Q_m^{ab}(s,k)> = \chi_m^{ab}(s,R_0)(\nu_m^{ab}(s,R_0))^{-1}. \qquad (17)$$

From eqs. (16) and (17) in the limit $\epsilon \to 0$, it follows that $<Q_m^{ab}(s,k)>$ has a zero limiting value in the central region at asymptotic energies (i.e. in the limits $s \to \infty$ and $x_1, ..., x_m \to 0$).

The charge k-densities of the positive and negative m-particle systems produced in the ab collision are defined by

$$Q^{ab\pm}(s,k) = (\sigma_{tot}^{ab}(s))^{-1} \sum_{c_1,...,c_m} (\sum_{i=1}^{m} Q_{c_i}) \times \\ \times Q(\pm \sum_{j=1}^{m} Q_{c_j}) \frac{d\sigma_{c_1...c_m}^{ab}}{dk}. \qquad (18)$$

Let us suppose that there exists a sequence of primary energies for which the average charged multiplicity goes to infinity:

$$\overline{\lim_{s\to\infty}} \sum_{c_1, Q_{c_1} \neq 0} \int \frac{d^3 \vec{\xi}_1}{\xi^0_{c_1}} N_{c_1}^{ab}(s,\vec{\xi}_1) = \infty. \qquad (19)$$

Then using eqs. (4) and (5) only for $Q_{c_1} + ... Q_{c_{m-1}} \neq 0$ and repeating step by step the preceding proof, we get that the ratio of $Q^{ab+}(s,k) + Q^{ab-}(s,k)$ to $Q^{ab+}(s,k) - Q^{ab-}(s,k)$ (resp. the ratio of $Q^{ab+}(s,k)$, to $-Q^{ab-}(s,k)$) admits a zero (resp. unity) limiting value as $s \to \infty$ and $x_1, ..., x_m \to 0$. Thus both the considered assertions hold.

We finally compare the experimental c.c. distribution $<Q_1^{ab}(s,k)>$ with the uniform distribution $(Q_a+Q_b)(\nu_1^{ab}(s))^{-1}$ (i.e. the average charge of a particle produced in the ab collision). Suppose that $Q_a + Q_b > 0$. Let ϵ_0 denote the maximum value of ϵ such that $|x_1| \leq \epsilon$ implies

$$<Q_1^{ab}(s,k)> \leq (Q_a + Q_b)(\nu_1^{ab}(s))^{-1} \qquad (20)$$

for all available charges (for example, the electric and baryonic ones in fig. 1). Figure 1 shows that $\epsilon_0 = 0.1$, 0.3, 0.15 for 16 GeV/c $\pi^+ p$, 24 GeV/c pp, and 1500 GeV/c pp reactions, respectively. According to eqs. (5) and (20), there is a positive average total charge in the region $|x_1| \geq \epsilon_0$ for each of these reactions, but we know no reasonable argument (without certain dual models [14]) for the observed positive deep of the corresponding c.c. distributions in the region $|x_1| \leq \epsilon_0$. However, we propose the region $|x_1| \leq \epsilon_0$ as a natural candidate for the experimental study of smallness of c.c. distributions in the central region.

2. Fragmentation Charges

We now present briefly some charge correlations of the initial particles with the particles produced in the fragmentation regions.

Let us suppose that the Pomeranchuk hypothesis of Cornille and Martin [15,16] holds:

$$\lim_{s\to\infty} N^{ab}_{c_1\ldots c_m}(s,\vec{\xi}_1,\ldots,\vec{\xi}_m) = \lim_{s\to\infty} N^{\bar{a}b}_{d_1\ldots d_m}(s,\vec{\xi}_1,\ldots,\vec{\xi}_m), \qquad (21)$$

where the limits exist and are finite, $\vec{\xi}_i$ is fixed with $x_i \neq 0$, $d_i = c_i$ if $x_i < 0$, and $d_i = \bar{c}_i$ if $x_i > 0$ for any $i = 1,\ldots,m$. Here and throughout the remainder of this note, the c.m. longitudinal momentum of a is taken to be positive and $\bar{c}$ denotes the antiparticle of c. Moreover, we attach to eq. (21) the following weak condition of smallness of transverse momentum in the fragmentation regions at asymptotic energies (i.e. $x_i \neq 0$ for $i = 1,\ldots,m$ as $s\to\infty$) [16]:

$$\lim_{s\to\infty} (\sigma^{ab}_{tot}(s))^{-1} \frac{d\sigma^{ab}_{c_1\ldots c_m}}{dx_1\ldots dx_m} = |x_1 \ldots x_m|^{-1} \times$$

$$\times \int d^2\vec{p}_{1\perp} \ldots d^2\vec{p}_{m\perp} \lim_{s\to\infty} N^{ab}_{c_1\ldots c_m}(s,\vec{\xi}_1,\ldots,\vec{\xi}_m). \qquad (22)$$

By eqs. (2), (3), (21), and (22), we get

$$\lim_{s\to\infty} < Q^{ab}_m (s,k) > = \lim_{s\to\infty} \sum_{c_1,\dots c_m} (-Q_{c_1} \mathrm{sgn}\, x_1 - \dots - Q_{c_m} \mathrm{sgn}\, x_m) \times$$

$$\times \frac{d\sigma^{\bar{a}b}_{c_1\dots c_m}}{dk} \left(\sum_{c'_1,\dots,c'_m} \frac{d\sigma^{\bar{a}b}_{c'_1\dots c'_m}}{dk} \right)^{-1}, \tag{23}$$

where k is fixed with $x_i \neq 0$, $i=1,\dots,m$. Equation (23) shows that the limiting c.c. distrbution given by eq. (2) is equal to the limiting charge transfer (from one hemisphere to the other) of an m-particle system produced in the $\bar{a}b$ collision at a fixed k in the fragmentation regions. If $m=1$, the difference (resp. the sum) of the limiting c.c. distributions for the ab and $\bar{a}b$ collisions vanishes in the left (resp. right) hemisphere. This result is expected to be true at asymptotic energies. However, fig. 1a) shows that the electric c.c. distributions for 16 GeV/c $\pi^{\pm}p$ reactions have opposite signs in the right hemisphere. Moreover, according to an approximate validity of factorization /14/, fig. 1b) shows a similar shape for all $\pi^{\pm}p$ and pp baryonic c.c. distributions in the left hemisphere /5/.

Let $R_{h,m-h}$ denote the region of all points $(\vec{\xi}_1,\dots,\vec{\xi}_m)$ with $x_i > \epsilon$ for $1 \le i \le h$ and $x_j < -\epsilon$ for $h < j \le m$. $R_{h,m-h-1,0}$ denotes the region of all points $(\vec{\xi}_1,\dots,\vec{\xi}_m)$ such that $(\vec{\xi}_1,\dots,\vec{\xi}_{m-1})$ belongs to $R_{h,m-h-1}$ and $|x_m| \le \epsilon$. Suppose that ϵ is fixed at a strictly positive value and define

$$\nu^{ab}_{h,m-h} = \lim_{s\to\infty} \nu^{ab}_m (s, R_{h,m-h}), \quad \nu^{ab}_{00} = 1, \tag{24}$$

$$\chi^{ab}_{h,m-h} = \lim_{s\to\infty} \chi^{ab}_m (s, R_{h,m-h}), \tag{25}$$

$$\gamma^{a\bar{a}b\pm}_{h,m-h-1} = \frac{1}{2} \lim_{s\to\infty} \sum_{c_1,\dots,c_m} Q_{c_m} \int_{R_{h,m-h-1,0}} \frac{d^3\vec{\xi}_1}{\xi^0_{c_1}} \dots \frac{d^3\vec{\xi}_m}{\xi^0_{c_m}} \times$$

$$\times (N^{ab}_{c_1\dots c_m}(s,\vec{\xi}_1,\dots,\vec{\xi}_m) \pm N^{\bar{a}b}_{c_1\dots c_m}(s,\vec{\xi}_1,\dots,\vec{\xi}_m)). \tag{26}$$

According to eqs. (4), (5), (21), and (22), these limits exist and are finite. $\chi^{ab}_{h,m-h}$ (resp. $\nu^{ab}_{h,m-h}$) is the average total charge (resp. number) of the m -particle systems produced in the ab collision in the fragmentation region $R_{h,m-h}$ (with h and $m-h$ particles in the right and left hemispheres, respectively).

Combining eqs. (4), (5), (21), (22), and (24)-(26), we get the following limiting charge sum rule:

$$\chi^{ab}_{h,m-h} = h! \sum_{i=1}^{h} \frac{(-1)^{i-1}}{(h-i)!} \left(Q_a \nu^{ab}_{h-i,m-h} - \gamma^{a\bar{a}b-}_{h-i,m-h} \right) + (m-h)! \sum_{j=1}^{m-h} \frac{(-1)^{j-1}}{(m-h-j)!} \left(Q_b \nu^{ab}_{h,m-h-j} - \gamma^{a\bar{a}b+}_{h,m-h-j} \right), \qquad (27)$$

where the sum over i (resp. j) is omitted if $h=0$ (resp. $h=m$).

Notice that eq. (21) can be replaced in the proof of eq. (27) by the condition that the difference of $N^{ab}_{c_1 \ldots c_m}(s, \vec{\xi}_1, \ldots, \vec{\xi}_m)$ and $N^{\bar{a}b}_{d_1 \ldots d_m}(s, \vec{\xi}_1, \ldots, \vec{\xi}_m)$ admits a finite limit as $s \to \infty$. The signs of the limiting c.c. distributions in every fragmentation region of the type $R_{h,m-h}$ are determinated by eq. (27) at least for some k. These signs coincide with $sgn(hQ_a \nu^{ab}_{h-1,m-h} + (m-h)Q_b \times \nu^{ab}_{h,m-h-1})$ if ν^{ab}_{10} and ν^{ab}_{01} go to infinity and the terms $\gamma^{a\bar{a}b-}_{h-i,m-h}$ and $\gamma^{a\bar{a}b+}_{h,m-h-j}$ are non-dominant in the l.h.s. of eq. (27) as $\epsilon \to 0$. The last condition is satisfied by a wide class of models /8/. For example, according to certain fragmentation, multiperipheral, and Mueller models /8,17,18/, one expects a limiting separate conservation of the charge in the right and left hemispheres (i.e. $\lim_{\epsilon\to 0} \chi^{ab}_{10} = Q_a$ and $\lim_{\epsilon \to 0} \chi^{ab}_{01} = Q_b$). Thus the c.c. distributions follow the initial charges in the fragmentation regions at energies large enough: if $Q_a \neq 0$ (resp. $Q_b \neq 0$), the signs of Q_a (resp. Q_b) and $\langle Q^{ab}_1(s,k) \rangle$ are the same at high s for some k with $x_1 > 0$ (resp. $x_1 < 0$). This behaviour has been remarked in ref. /5/ (cf. fig. 1).

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