Long-range azimuthal correlations in multiple-production processes at high energies

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The interaction between chromoelectric tubes formed in high-energy hadron reactions leads to an azimuthal asymmetry in the distribution of secondary particles.

1. In a currently popular picture of hadron reactions, the final multiparticle state is formed from ruptures in a system of chromoelectric tubes which "stretch out" as the color states that arise in the collision fly off. This picture is naturally blended in with the Regge and dual-topology models, in which a pomeron and branchings are described approximately by a gluon exchange followed by the formation of several quark tubes. The ruptures of these tubes occur in a quasi-independent way.[1] The quark tubes have a finite radius $r_0 \sim 1$ fm, and the transverse distances between them are also on the order of r_0. They accordingly overlap and may interact. The exact form of this interaction is not known, but an examination of the tubes on a lattice shows that in the $SU(3_C)$ gauge theory tubes in which the chromoelectric fields are in the same direction attract each other in the transverse direction, while tubes with oppositely directed chromoelectric fields repel each other [in $SU(N_C)$, the energy of this interaction is $\sim N_C^{-1}$; Ref. 2].

2. Because of this repulsion or attraction of tubes, they acquire a transverse momentum over the time between their formation and their decay into hadrons. This transverse momentum combines with the "random" transverse momenta of the hadrons which arise from the decay of the tube to cause an anisotropic distortion of the transverse angular distribution. Since the density of this transverse momentum is identical over the entire length of the tube (i.e., over all rapidities of the secondary hadrons), the distortion of the spectrum of a given tube reduces to a displacement of this spectrum by a transverse vector $\mathbf{q}$, which is the same for all hadrons. If the transverse spectrum from the rupture of an isolated quark tube is $f(\mathbf{k})$, the total spectrum from two repulsive tubes (pomerons) will evidently be

$$f(\mathbf{k}+\mathbf{q}) + f(\mathbf{k}-\mathbf{q}). \quad (1)$$

Adopting $f \sim \exp[-B\mathbf{k}^2]$, taking an average over $|\mathbf{k}|$, and using the approximation of small values of $\mathbf{q}^2/\langle \mathbf{k}^2 \rangle \ll 1$, we find the following azimuthal distribution of the secondary particles for a given $\mathbf{q}$:

$$F_1(\varphi, y) \sim 1 + a_1(y)\cos^2\phi, \qquad a \approx 2Bq^2, \quad (2)$$

where ϕ is the angle between $\mathbf{q}$ and $\mathbf{k}$. The higher (N-pomeron) branchings correspond to a system of $2N$-quark tubes, which may either attract or repel each other. By the time of the rupture, each of the tubes acquires a certain transverse-momentum density $\mathbf{q}_m$. In the same approximation as above, we find

$$F_N \sim \sum_{m=1}^{2N} f(\mathbf{k}+\mathbf{q}_m) \sim e^{-B\mathbf{k}^2}\left[1+\frac{2B^2}{N}\sum_m (\mathbf{k}\mathbf{q}_m)+\ldots\right] \tag{3}$$

After an integration over $|\mathbf{k}|$, this expression again reduces to the form of (2) with an asymmetry of a_N which depends on[1] q.

3. The order of magnitude which we would expect for this asymmetry can be estimated on the basis of the following considerations. We assume that when the tubes are far apart their energy density is ρ, and when they completely overlap this energy density is $2\rho + 2\rho_1$. A section of a tube of length l thus acquires a transverse momentum

$$p = l((\rho+\rho_1)^2 - \rho^2)^{1/2} \approx l(2\rho\rho_1)^{1/2} \tag{4}$$

as it flies out. Taking l to be on the order of the length of the primary fragment, which decays into ν hadrons on the average, we find the transverse momentum per hadron to be $q = p/\nu \approx (2\rho\rho_1)^{1/2} l/\nu$. We thus find the estimate

$$a \approx 2Bq^2 \lesssim \frac{4B}{\nu^2} l^2 \rho^2 (\rho_1/\rho) \approx \frac{1}{5} - \frac{1}{3}, \tag{5}$$

where we have used $B \approx 4\ \mathrm{GeV}^{-1}$, $\nu = 2$, $l \sim 1$ fm, $\rho \sim 1$ GeV/fm, and $\rho_1/\rho = 1/2[G(8)/G(2)] - 1 = 1/8$, where $G(8)$ and $G(3)$ are the values of the quadratic Casimir operators of $SU(3_C)$ in the corresponding representations.

4. It is unlikely that we would be able to determine $F(\phi)$ directly from experiments. We might instead, for example, calculate the square of the quadrupole-asymmetry tensor for each event (for a multiplicity of n particles):

$$\kappa_n = \frac{1}{n^2}\sum_{i,j=1}^{n}\left[(\vec{\mu}_i\vec{\mu}_j)^2 - \frac{1}{2}\right]; \qquad \vec{\mu}_i = \mathbf{k}_i/|\mathbf{k}_i|, \tag{6}$$

where the $\mathbf{k}_i$ are the transverse momenta of the particles. Taking an average over the events, we can then construct distributions $w_n(\kappa_n)$. From (2) we find the estimate $\langle\kappa_n\rangle \sim a$, while the statistical contribution is $\langle\kappa_n\rangle \sim n^{-1}$.

5. The ϕ asymmetry which results from the interaction of tubes is also manifested in the inclusive cross sections, beginning with the two-particle cross sections. For example, f_2 contains a long-range (in terms of $|y_1 - y_2|$) correlation between the azimuthal angles at which the particles are emitted. Since f_2 can be expressed in terms of $F(\phi)$, we find

$$f_2(y_1,\phi_1;y_2,\phi_2) \sim \int_0^{2\pi} d\phi F(\phi_1-\phi, y_1)F(\phi_2-\phi, y_2)$$

$$\sim 1 + \frac{1}{2}a(y_1)a(y_2)\cos^2(\phi_1-\phi_2). \tag{7}$$

The asymmetry in f_2, in contrast with F, is small: $1/2\langle a^2\rangle \sim 1/30$ at $a\sim 1/4$, possibly in agreement with experimental data.[3] Since the ends of quark tubes in a pomeron fluctuate wildly in rapidity, the quantity f_2 in (7) depends on the rapidities of observable particles. The reason is that the product $a(y_1)a(y_2)$ is proportional to the weight with which both quark tubes are present at the given y_i.

6. In an interaction of heavy nuclei with nuclei, many overlapping quark tubes form, and a large azimuthal asymmetry may be observed.[2)] Furthermore, since an $A\times A$ collision is noncentral on the average, the system of quark tubes fills a transversely anisotropic region. It is clear geometrically that its anisotropy is oriented along the impact parameter of the collision. We might thus expect correlations between the azimuthal distribution of secondary hadrons and the azimuthally anisotropic distribution of the decay products of the nucleus.

Again, we wish to emphasize that data on the azimuthal asymmetry in soft multiple-production processes may contain some very nontrivial information.

[1)] In events with quantum-chromodynamics jets there is also a ϕ asymmetry, but of a slightly different type: In jet events, the **k** values of the particles are not canceled out locally at the given y, in contrast with the case of repulsive tubes. Furthermore, it may prove to be a complicated matter to distinguish these effects.

[2)] In $A\times A$ interactions there are examples of events[4] which have a large azimuthal asymmetry of the type under discussion here.

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[3] M. Basile *et al.*, Nuovo Cimento **39A**, 441 (1977).

[4] T. H. Barnet *et al.*, Phys. Rev. **D35**, 824 (1987).

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