Signatures of Flux Tube Fragmentation and Strangeness Correlations in *pp* Collisions

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Abstract.

In the fragmentation of a color flux tube in high-energy *pp* collisions or e^+-e^- annihilations, the production of q-$\bar q$ pairs along a color flux tube precedes the fragmentation of the tube. The local conservation laws in the production of these q-$\bar q$ pairs will lead to the correlations of adjacently produced hadrons. As a consequence, the fragmentation of a flux tube will yield a many-hadron correlation in the form of a chain of hadrons ordered in rapidity, with adjacent hadrons correlated in charges, flavor contents, and azimuthal angles. It will also lead to a two-hadron angular correlation between two hadrons with opposite charges or strangeness that is suppressed at $\Delta\phi \sim 0$ but enhanced at $\Delta\phi \sim \pi$, within a rapidity window $\Delta y{\sim}1/(dN/dy)$.

1. Introduction

The reaction mechanisms in *pp* collisions provide insights in AA collision at high energies. The importance of each reaction mechanism depends on the collision energy and the p_T domain. The flux-tube fragmentation process [1, 2] is expected to dominate at low p_T and low $\sqrt{s_{pp}}$, whereas the hard-scattering process [3, 4] at high p_T and high $\sqrt{s_{pp}}$. The two mechanisms cross-over at a certain transverse momentum $p_{Tb}(\sqrt{s_{pp}})$ that is a function of the collision energy, $\sqrt{s_{pp}}$. There are in addition other mechanisms such as the recombination of partons [5] and the production of resonances.

It is desirable to establish, even if approximately, the boundary function $p_{Tb}(\sqrt{s_{pp}})$ that separates the region of flux-tube fragmentation dominance from the region of hard-scattering dominance. We need signatures for these two mechanisms to facilitate such a separation.

The signature for the hard scattering process is well known. It is given as a two-hadron $\Delta\phi{-}\Delta\eta$ angular correlation which shows a peak at $(\Delta\phi, \Delta\eta){\sim}0$ and a ridge along $\Delta\eta$ at $\Delta\phi \sim \pi$. The peak at $\Delta\phi{\sim}0$ arises from the fragmentation of the jet associated with the trigger and the ridge at $\Delta\phi{\sim}\pi$ arises from the fragmentation of the other jet associated with colliding partons with unbalanced longitudinal momenta.

However, the signature for flux tube fragmentation has not been well studied. We would like to present here two signatures for flux-tube fragmentation [6, 7].

2. Many-hadron signatures of Flux Tube Fragmentation

In the semi-classical description of the flux-tube fragmentation process [1, 2] for hadron production, the production of quark-antiquark pairs along a color flux tube precedes the fragmentation of the tube. The production of these quark-antiquark pairs must however obey conservation laws at the local production points. As a consequence, the produced q-$\bar q$ pairs will lead to correlations of adjacently produced hadrons, and the hadrons are ordered according to their rapidities along the tube. The rapidity-space-time ordering and the local conservation laws will yield a many-body correlation of the hadrons in charge, flavor, and momentum, which may provide vital information on space-time dynamics of quarks and hadrons in the flux-tube fragmentation process.

As an example, we examine the fragmentation of a flux tube with an invariant mass of 8.65 GeV, corresponding to the average invariant mass of one of the two flux tubes in a *pp* collision at 17.3 GeV, with the flux tube formed by a quark of one proton with the diquark of the other proton. We carry out a Monte Carlo generation of hadrons in flux-tube fragmentation using the PYTHIA 6.4 program [8]. An example of the produced hadrons involving the production of a pair of strange hadrons is shown in Fig. 1, with the production of 5 hadrons listed in Table I.

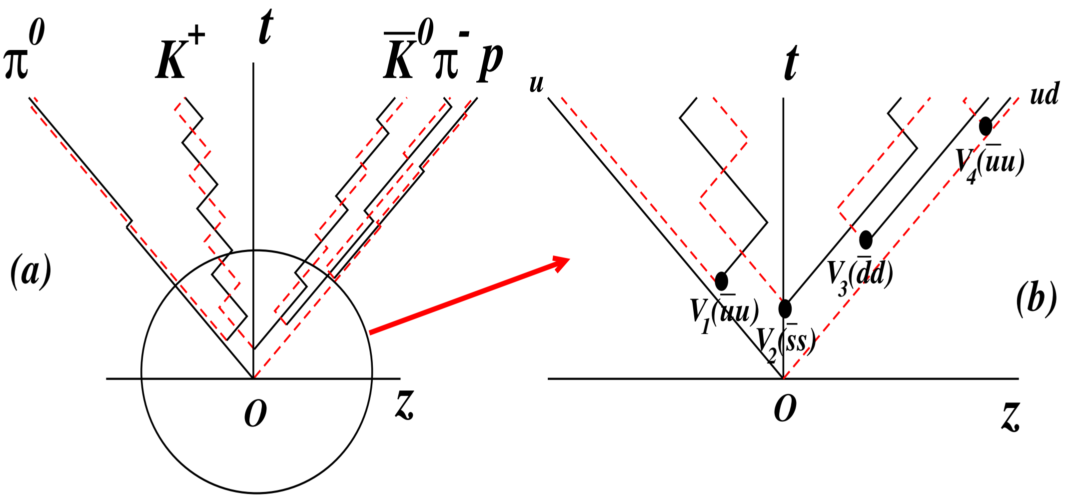

Figure 1. Fig. 1(a) shows an example of the space-time diagram in the fragmentation of a u-(ud) flux tube with an invariant mass of $\sqrt{s}$=8.65 GeV, obtained with PYTHIA 6.4 [8]. Quark lines are shown as solid lines, and antiquark (or diquark) lines as dashed lines. Fig. 1(b) is an expanded view of the pair-production vertices $V_i(\bar{q}_i q_i)$ of Fig. 1(a).

Table 1. An example of primary hadrons i, their rapidities y_i, their azimuthal angles ϕ_i and their constituents q_i-$\bar{q}_i$ produced in the fragmentation of the u-(ud) flux tube at an energy of $\sqrt{s}$=8.65 GeV obtained with PYTHIA 6.4 [8].

i	1	2	3	4	5
particle	π^0	K^+	$\bar{K}^0$	π^-	p
q_i-$\bar{q}_i$	u-$\bar{u}$	u-$\bar{s}$	s-$\bar{d}$	d -$\bar{u}$	u -(ud)
y_i	-1.55	- 1.15	- 0.75	0.27	1.78
ϕ_i	1.00	-2.01	1.44	-2.43	0.17
$\phi_i - \phi_{i+1}$	-3.01	3.46	-3.87	2.60	

In Table 1, the row of q_i-$\bar{q}_i$ shows that upon ordering the hadrons according to their repidities y_i as in a chain, the flavors of the constituent antiquark $\bar{q}_i$ and the flavors of the neighboring constituent quark q_{i+1} are correlated along the chain, on an event-by event basis. The row of ϕ_i-ϕ_{i+1} of neighboring hadrons in Table I indicates that neighboring pairs of hadrons are azimuthally correlated, approximately in a back-to-back manner. The many-hadron signature requires the identification of all hadrons detected in the events. Predicted signature of this kind is yet to be observed.

3. Two-hadron angular correlation signature of flux-tube fragmentation

Another signature of the flux tube fragmentation utilizes the two-hadron angular correlations arising from the productions of q-$\bar{q}$ pairs. Because of local conservation laws, the production of q-$\bar{q}$ pairs will lead to correlations of adjacently produced hadrons. Adjacently produced hadrons however can be signaled by their rapidity difference Δy falling within the window of $|\Delta y|{\sim}1/(dN/dy)$, on account of the space-time-rapidity ordering of produced mesons in a flux-tube fragmentation. Therefore, the local conservation laws of momentum, charge, and flavor will lead to a suppression of the angular correlation function $dN/(d\Delta\phi\, d\Delta y)$ for two hadrons with opposite charges or strangeness at $(\Delta\phi, \Delta y){\sim}0$, but an enhanced correlation on the back-to-back, away side at $\Delta\phi{\sim}\pi$, within the window of $|\Delta y|{\sim}1/(dN/dy)$. When we approximate the rapidity y as the pseudorapidity η, the two-hadron angular correlations can be used as signatures for the fragmentation of a color flux tube as shown in Fig 2.

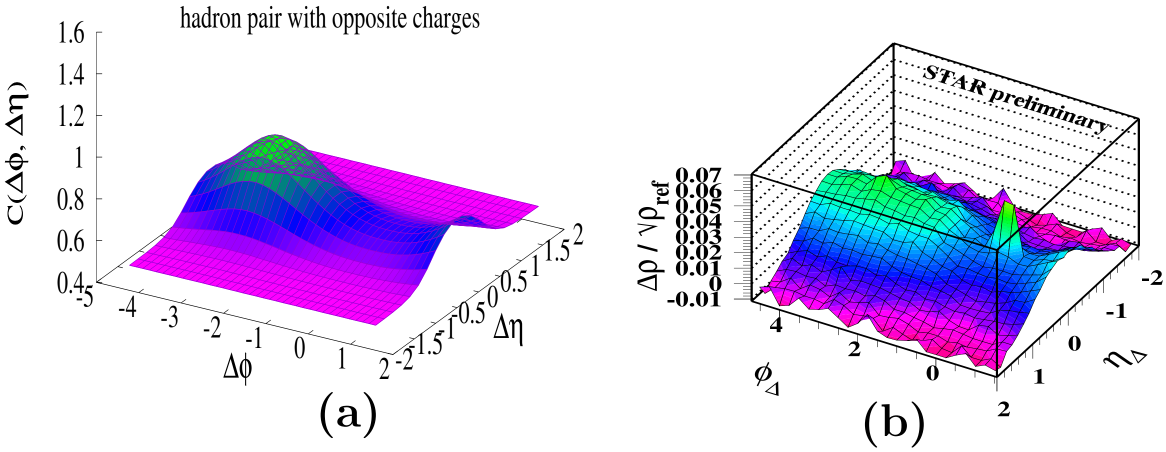

Figure 2. Fig. 2(a) gives the theoretical correlations for two two hadrons with unlike charges [6] and Fig 2(b) gives the experimental correlation data for two hadrons with unlike charges and p_T<0.5 GeV obtained by the STAR Collaboration for pp collisions at $\sqrt{s_{pp}}$=200 GeV [9]. The sharp peak at $(\Delta\phi, \Delta\eta) \sim 0$ in Fig. 2(b) is an experimental artifact.

Comparison of theoretical angular correlations for two hadrons with unlike charges in Fig. 2(a) [6] with experimental data from the STAR Collaboration in Fig. 2(b) [9] indicates that in high-energy pp collisions at $\sqrt{s_{pp}}$ =200 GeV, the production of unlike-charge hadron pairs in the region of p_T<0.5 GeV/c are qualitatively consistent with the flux-tube fragmentation mechanism. However, the correlations for two hadrons with unlike-charges in the region with p_T>0.5 GeV/c exhibit a completely different pattern. Namely, they shows a peak at $(\Delta\phi, \Delta\eta) \sim 0$, and a ridge along $\Delta\eta$ at $\Delta\phi \sim \pi$, which is a signature of the hard scattering process [9]. This indicates that for pp collisions energy at $\sqrt{s_{pp}}$ = 200 GeV, the boundary between the flux-tube fragmentation process and the hard-scattering process is p_{Tb} = 0.5 GeV/c. At the LHC energy of $\sqrt{s}_{pp}$ =5 TeV, the minimum bias data for the correlation of two hadrons with p_T>0.1 GeV/c show a pattern that appears to be a linear combination of the patterns for flux tube fragmentation and hard scattering [11]. Results in Fig. 2, together with the two hadron correlation data from lower energies [10] and higher energies [11] reveal that the p_{Tb} boundary of separation moves to lower p_T values as the collision energy increases.

Similarly, because of local conservation of strangeness in $q\bar{q}$ production, adjacently produced hadrons with opposite strangeness are correlated back-to-back in azimuthal angles.

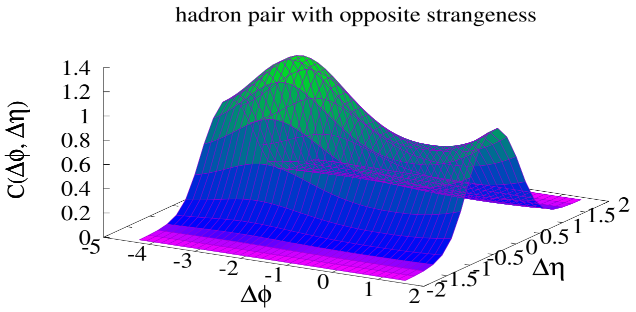

Fig.3 The correlation function for two hadrons with opposite strangeness in flux-tube fragmentation.

Adjacently produced mesons however can be signaled by their rapidity difference Δy falling within the window of $|\Delta y|{\sim}1/(dN/dy)$. The theoretical correlation function for two primary hadrons with opposite strangeness is shown in Fig. 3, with a suppression at $(\Delta\phi, \Delta\eta) \sim 0$ and an enhancement at $\Delta\phi{\sim}\pi$, within the window of $|\Delta y|{\sim}1/(dN/dy)$.

4. Conclusions and Discussions

In the fragmentation of a flux tube, the production of $q\bar{q}$ pairs obey local conservation laws and the hadrons follow space-time-rapidity ordering. As a consequence, a signature of the flux tube fragmentation consists of a chain of produced hadrons, correlated in rapidities, charges, flavors, and azimuthal angles. The observation of the chain of hadrons requires the identification of the produced hadrons which may be possible if the fraction of unobserved hadrons is small.

Another signature uses two-hadron angular correlations with opposite charges or strangeness, which exhibits a suppression at $(\Delta y, \Delta\phi){\sim}0$, but an enhancement at $\Delta\phi{\sim}\pi$, with the window of $|\Delta y|{\sim}1/(dN/dy)$. It should be kept in mind however that resonance production and resonance decay into hadrons will exhibit angular correlations similar to the pattern of the flux-tube fragmentation. The resonance fraction give rise to complications and the two-hadron signature will work well if the resonance fraction is not dominant. Various estimates give the resonance fractions to be of order 10 to 30% for pp collisions at $\sqrt{s_{pp}} = 17.3$ GeV [7].

In flux-tube fragmentation, the production of two adjacent hadrons with like charges or the same strangeness is prohibited [6]. Experimentally, two-hadron angular correlation of like charges with $\Delta\eta{\sim}0$ is not zero [9, 10] which indicates that there may be an additional mechanism for like charge production with $(\Delta\phi, \Delta\eta){\sim}\ 0$. Further theoretical search for the origin of the source of like charge and strangeness correlations at $(\Delta\phi, \Delta\eta){\sim}\ 0$ will be of interest.

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