RAPIDITY SIGNALS FOR TOP†

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Summary

Rapidity signals for top production in high energy jets are examined in the framework of the Lund and QCD-Cluster hadronization models. Selection of events with large particle multiplicities inside narrow rapidity windows is found to reduce the normal QCD background for top jets by a factor of four or five.

1. Introduction

Identification of top jets at SSC will be a non-trivial task. For jet energies much above 100 GeV, jet masses from perturbative QCD radiation are sufficiently large that the lepton isolation techniques presently used at S$\bar{\text{P}}$PS may well be ineffective. The rather large top mass indicated by various UA1 presentations at this meeting[1] suggests another strategy for detecting inclusive top production. That is, high energy top jets will be characterized by large particle densities within relatively small rapidity bins.

This note contains some simple, preliminary investigations of top identification through jet rapidity profiles. The basic idea, which can be traced back at least as far as Bjorken's work on heavy flavor fragmentation,[2] is illustrated in Fig. 1. Fig. 1a shows the rapidity profile of a top jet before top meson decay. The top meson carries most of the jet energy and is separated from the rest of the jet by a rapidity gap. Fig. 1b shows the rapidity profile of the jet after top decay. The higher particle density from top decay is largely a kinematic effect--hence, a reliable signal.

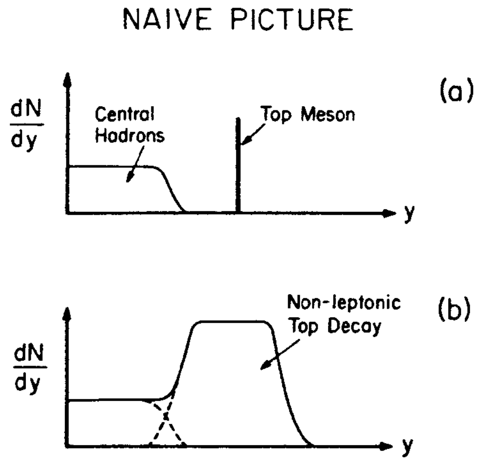

Fig. 1 Schematic illustration of rapidity distributions for top jets.

2. Model Calculations

The flat rapidity plateau for top decay in Ref. 2 and Fig. 1 is incorrect. Proper treatment of weak $t \rightarrow bq\bar{q}$ decays gives a strong peak. Fig. 2 shows more realistic estimates of the qualitative effect of Fig. 1. The curves give single jet rapidity distributions for the evolution of 500 GeV $u\bar{u}$ and $t\bar{t}$ systems without perturbative QCD bremsstrahlung, as calculated in the Lund[3] and QCD-Cluster[4] hadronization models. The top meson mass is taken to be $M_T = 45$ GeV. Top decay in Ref. 4 is described by weak decay into two colorless clusters (strings)

$$T^*(t\bar{d}) \rightarrow C_1(b\bar{d}) + C_2(q_i\bar{q}_j) \qquad (1)$$

followed by cluster evolution according to the string model of Ref. 4. Charged particle multiplicities for top decay are quite large

$$\langle N_{ch}\,(\text{Total})\rangle = 14.8 \qquad (2)$$

$$\langle N_{ch}\,(\text{Semileptonic})\rangle = 8.0 \qquad (3)$$

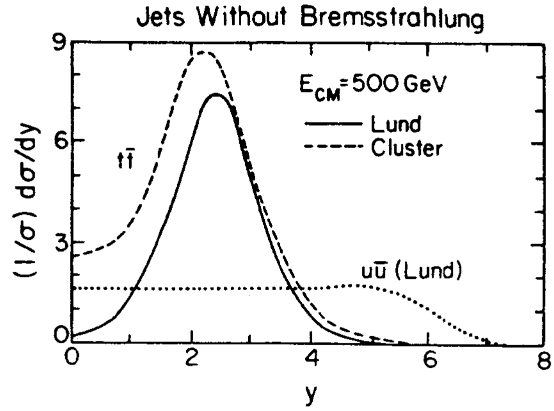

Fig. 2 Top jet hadronization in the Lund and QCD-Cluster models.

where Eq. (3) applies only for $t \rightarrow bl^+\nu$ decays. The Lund description of top decay is generally similar to that used in Ref. 4.

For $E_{jet} \gtrsim 200$ GeV, both the Lund and Cluster descriptions yield rapidity peaks for top which are well separated from the central region. The only significant difference between the Lund and Cluster predictions concerns the levels of soft hadron production at small rapidities. The Lund formalism gives a strong suppression of hadron production for $y \simeq 0$, due to the very hard fragmentation of top quarks according to Ref. 5. This point is discussed further in Section 3.

Perturbative QCD radiation will tend to diminish the clear signal seen in Fig. 2. Unfortunately, as is discussed in Ref. 6, present Monte Carlo models for hadron-hadron scattering are not yet sufficiently well developed to give completely reliable predictions. Instead, we simply estimate QCD shower effects by examining the final state evolution of $(u\bar{u})$ and $(t\bar{t})$ systems of mass $W = E_{CM}$, using the e^+e^- annihilation model of Ref. 4 with parameters

$$\Lambda = 250 \text{ MeV} \qquad (4)$$

$$t_{cut} = 9 \text{ GeV}^2 \qquad (5)$$

for perturbative shower evolution.

As noted in Ref. 6, there are some problems with the final state evolution formalism of Ref. 4. In particular, (1) the shower does not include soft gluon coherence effects, and (2) the "color flow" description of final state gluons is not quite adequate. To the extent that these shortcomings affect evolution of all $q\bar{q}$ systems, we expect the predicted differences In top quark and light quark jets to be at least qualitatively reliable.

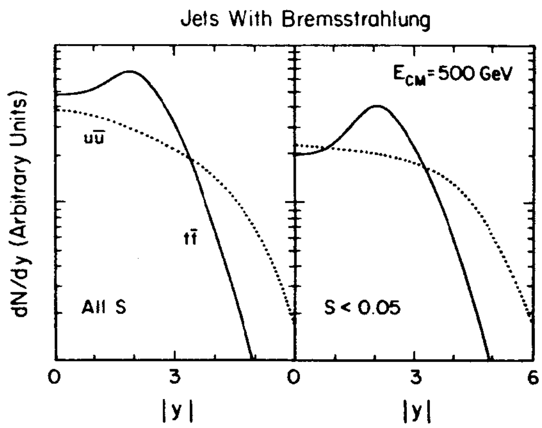

Fig. 3 Rapidity distributions including perturbative QCD radiation.

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Fig. 3 shows rapidity distributions for charged particles produced in the evolution of 500 GeV ($u\bar{u}$) and ($t\bar{t}$) systems. Rapidities are calculated with respect to the sphericity axis. For plotting convenience, the overall normalization in Fig. 3 is arbitrary, but relative normalizations of the four curves are as predicted by the model. It is seen that the rapidity signal for top survives QCD radiation, particularly if the cut $S < 0.05$ is used to exclude wide angle gluon bremsstrahlung. In subsequent discussions, we consider only events which satisfy this sphericity cut.

In order to determine useful experimental cuts for top identification, it is important to explore event-by-event signatures for the behavior seen in Fig. 3. We discuss here only a single, simple example.

Consider $q\bar{q}$ systems with $S < 0.05$. Each system is divided into two jets according to the sign of the particle rapidities. Let $\bar{y}$ be the mean rapidity within a jet and define

$$N(\bar{y},\Delta y) \equiv \sum_j \theta\,(\Delta y - 2|y_j - \bar{y}|) \qquad (6)$$

where the sum is over all charged particles within the jet. $N(\bar{y},\Delta y)$ is simply the number of charged particles inside a window of width Δy centered at the mean rapidity within the jet.

Fig. 4 compares the probability distributions $P[N_{ch}(\bar{y},\Delta y)]$ of 500 GeV ($u\bar{u}$) and ($t\bar{t}$) systems for rapidity windows $\Delta y = ½$ and $\Delta y = 1$. The error bars reflect Monte Carlo statistics for 4000 total events for each curve.

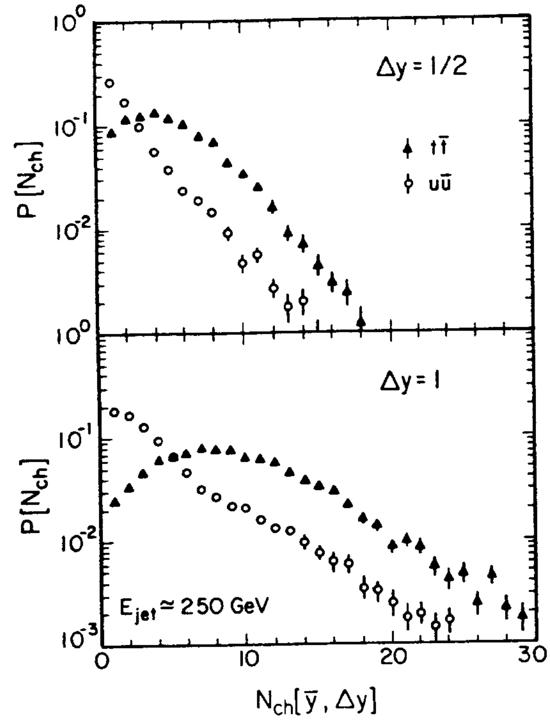

Fig. 4

Charged multiplicity probabilities in 250 GeV and top jets for rapidity windows $\Delta y = ½$ and $\Delta y = 1$.

The results in Fig. 4 demonstrate that cuts on $N_{ch}[\bar{y},\Delta y]$ can provide reasonable discrimination between top quark and light quark jets. For example, about 35% of top jets survive the cut

$$N_{ch}[\bar{y},\Delta y = ½] > 5 \qquad (7)$$

compared to only about 7% of the light quark jets. This separation between light quark and top quark jets is fairly insensitive to the value of the rapidity bin width Δy. The cuts $N_{ch}[\bar{y},1] > 10$ and $N_{ch}[\bar{y},2] > 16$ reduce the light quark background by at least a factor of four while retaining more than 30% of the top jet sample.

There are many possibilities for improving the separation in Fig. 4, such as minimum y_j cuts or better estimates of the central value $\bar{y}$ in Eq. 6 (e.g., selecting $\bar{y}$ so as to maximize $N_{ch}[\bar{y},\Delta y]$). The separation of top jets from gluon jets may be a bit less clean then the quark jet separations shown in Fig. 4. The Cluster model calculations in Ref. 7 suggest an increased mean multiplicity

$$\langle N_{ch}(G)\rangle / \langle N_{ch}(q)\rangle \simeq 1.7-1.8 \qquad (8)$$

for jet energies between 100 GeV and 1 TeV. This increase in mean multiplicity is at least partially offset by a narrowing of the KNO distributions for gluon jets in Ref. 7. The Cluster model in Ref. 7 uses very small cutoffs on perturbative evolution--which tends to accentuate differences between quark and gluon jets. The differences in the energy distributions of quark and gluon jets in Ref. 7 are larger than appears to be the case experimentally[8,9] for high-E_T hadron-hadron scattering.

In spite of the many uncertainties in our present understanding of quark and gluon hadronization, the results in Figs. 3 and 4 suggest that careful analyses of rapidity profiles could provide a useful tool in identifying top quark jets at SSC. The factor ~4 discrimination in Fig. 4 is not by itself sufficient to separate top jets from the dominant gluon jet background,

$$\frac{\sigma(GG \to GG)}{\sigma(GG \to t\bar{t})} \simeq \frac{243}{7} \simeq 35 \qquad (9)$$

at 90° in the parton-parton CM frame. However, if the rapidity selection in Fig. 4 is coupled with simultaneous cuts on various transverse momentum profiles, using the discriminant techniques discussed in Ref. 10, it should be possible to reduce the normal jet background to an acceptable level.

3. Top Fragmentation

The isolation of the rapidity peak from top decay in Fig. 3 is minimal in the sense that top fragmentation is somewhat softer in the scheme of Ref. 4 than in other standard hadronization descriptions. Fig. 5 compares energy distributions for top hadrons according to Ref. 4 with the widely used Peterson et al. parameterization[11].

$$zD(z) \sim \left[1 - \frac{1}{z} - \frac{\varepsilon}{1-z}\right]^{-2} \qquad (10)$$

with

$$\varepsilon \sim \left(\frac{m_0}{m_t}\right)^2 \simeq \left(\frac{1}{100}\right)^2 \qquad (11)$$

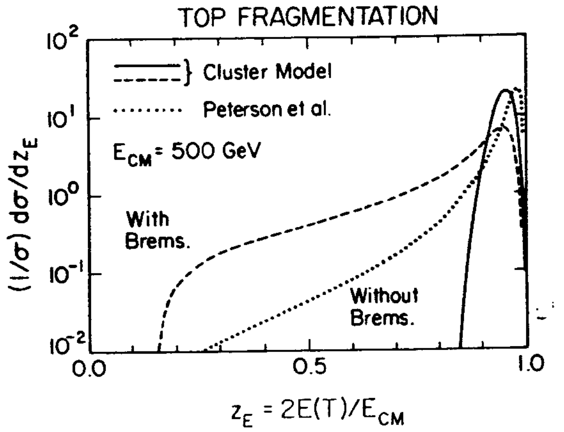

Fig. 5 Various models for top fragmentation.

Eq. (10), without bremsstrahlung, gives a long tail at low z. However, most of the top mesons fragmented according to Eq. (10) have larger z than expected according to the Cluster model. Top fragmentation is even harder in the Lund picture with

$$D(z) \simeq (1-z)e^{-bM_t^2/z} \qquad (12)$$

with $b \sim 1/(2.25\ \text{GeV}^2)$ in Ref. 5. $D(z)$ in Eq. (12) is completely negligible for $z \lesssim 0.99$. Clearly, Eq. (12) would be softened by including gluon emissions, with generation of a long tail extending to small z--perhaps not unlike the Peterson et al. curve in Fig. 5.

The relative hardness of top fragmentation affects not only the position of the rapidity peak from top decay but also the amount of soft hadrons produced during top jet hadronization. As already seen in Fig. 2, the Lund description can give a much lower "central plateau" than the Cluster approach. In principle, measured rapidity profiles for top jet can thus provide information on the mechanisms of top fragmentation. This rapidity information might well be the best supplement to indirect measurements of top fragmentation from the lepton energy spectra of $t \rightarrow b\bar{l}\nu$ decays (reconstruction of exclusive top decay channels is most likely a hopeless task). As is noted in Ref. 6, heavy quark fragmentation is of particular interest in that it is one of the (potentially) cleanest areas for comparing the Lund and Cluster models for hadronization.

4. Conclusion

Enhanced particle multiplicities within small rapidity bins provide a useful kinematic signature for top quarks in high energy jets. Simple minimum multiplicity cuts on individual events can improve signal to noise by a factor of 4 or 5 while accepting a sizable fraction of hadronic top decays. In order to fully exploit this signal at SSC, a detector with good angular resolution for charged tracks is clearly required.

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