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Rapidity-alignment and p_T compensation of particle pairs in hadronic Z^0 decays

DELPHI Collaboration

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Abstract

Observation is made of rapidity-alignment of K^+K^- and $p\bar{p}$ pairs which results from their asymmetric orientation in rapidity, with respect to the direction from primary quark to antiquark. The K^+K^- and $p\bar{p}$ data are consistent with predictions from the fragmentation string model. However, the $p\bar{p}$ data strongly disagree with the conventional implementation of the cluster model. The non-perturbative process of 'gluon splitting to diquarks' has to be incorporated into the cluster model for it to agree with the data. Local conservation of p_T between particles nearby in rapidity (i.e., p_T compensation) is analysed with respect to the thrust direction for $\pi^+\pi^-$, K^+K^-, and $p\bar{p}$ pairs. In this case, the string model provides fair agreement with the data. The cluster model is incompatible with the data for all three particle pairs. The model with its central premiss of isotropically-decaying clusters predicts a p_T correlation not seen in the data.

1. Introduction

The analysis of correlations between particles produced in hadronic Z^0 decay is an effective tool for studying the fragmentation process. In particular, tests can be made of two basic classes of fragmentation models, 'string' and 'cluster' types, represented in this study by Jetset 7.3 [1] and Herwig 5.9 [2], respectively. Distinct differences in predictions from these models occur for certain particle pair correlations. In particular, the orientation in rapidity and in p_T of particle pairs is expected to be a distinguishing feature between models. Charged particle pairs, adjacent or nearby in rapidity, are predicted to be produced in a different way for the string and cluster models. For K^+K^- and $p\bar{p}$ pairs the string model predicts a definite rank-ordering in rapidity, with respect to the direction from primary quark to antiquark. Rapidity-rank is defined as the position a particle has in the rapidity chain after ordering the particles in an event according to their rapidity values. Rapidity ordering is expected to correspond closely to string-rank ordering (position on the string) as pictured in Fig. 1. By contrast, the cluster model produces $p\bar{p}$ pairs, and K^+K^- pairs (partially), via the isotropic decays of clusters. The clusters are rank-ordered; however, their decay products are not necessarily in rank-order. Consequently, one expects differences in the predictions for correlations in rapidity and p_T from the two models.

Asymmetric orientations of particle pairs in rapidity are expected from string-fragmentation models. In these models, mesons are formed from string elements when breaks occur between virtual flavour-neutral $q\bar{q}$ pairs. Baryons are considered to be formed when breaks occur between diquark–antidiquark pairs. An asymmetry occurs because each $q\bar{q}$ loop breaks such that the $\bar{q}$ is always nearer on the string to the primary quark, and the q nearer to the primary antiquark. For the diquark–antidiquark case, the converse orientation arises. This process causes K^+K^- and $p\bar{p}$ pairs to assume an asymmetric rapidity orientation, termed here rapidity-alignment, as shown in Fig. 1. First indications of ordering along the quark–antiquark axis have been reported by the SLD Collaboration [3].

The cluster model can be pictured approximately by replacing the hadrons in Fig. 1 by clusters which decay isotropically, usually into two hadrons. In this model, the specific cluster mass spectrum and the assumption of isotropic decay will affect particle-pair correlations in rapidity and in transverse momentum. In the following, the string and cluster models, with their different hadronization mechanisms, are compared to the data.

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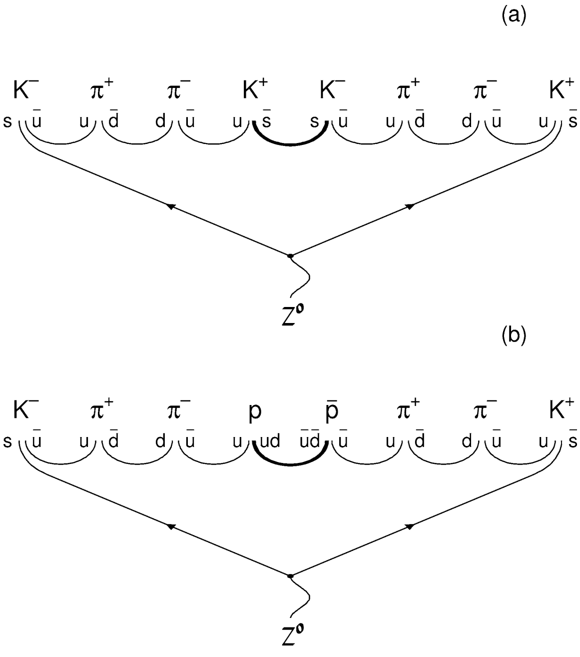

Fig. 1. Illustration of K^+K^- and $p\bar{p}$ production in the string model. Each loop represents a $q\bar{q}$ or diquark–antidiquark pair produced from potential energy in the string. (a) Production of K^+K^- from an $s\bar{s}$ virtual pair. (b) Production of $p\bar{p}$ from a diquark–antidiquark pair.

2. Data sample and event selection

This analysis is based on data collected with the DELPHI detector [4] at the CERN LEP collider in 1994 and 1995 at the Z^0 centre-of-mass energy. The charged particle tracking information relies on three cylindrical tracking detectors (Inner Detector, Time Projection Chamber (TPC), and Outer Detector) all operating in a 1.2 T magnetic field.

The selection criteria for charged particles are: momentum above 0.3 GeV/c, polar angle between 15° and 165° and track length above 30 cm. In addition the impact parameters with respect to the interaction point are required to be below 0.5 cm perpendicular to and 2.0 cm along the beam. These impact parameter cuts decrease the number of protons which result from secondary interactions in the detector. Also, protons from Λ and Σ decays are largely removed.

Hadronic Z^0 decays are selected by requiring at least three charged particle tracks in each event hemisphere, defined by the 'thrust' axis (see next section), and a total energy of all charged particles exceeding 15 GeV. The number of hadronic events is ∼2 million.

Charged particle identification is provided by a tagging procedure which combines Cherenkov angle measurement from the RICH detector with ionization energy loss measured in the TPC. Details on the particle identification can be found in Ref. [4]. In addition, the polar angle for identified particles is restricted to be in the barrel region, between 47° and 133°.

3. Rapidity-alignment of K^+K^- and $p\bar{p}$ pairs

In the following, the rapidity-alignment resulting from an asymmetric orientation of K^+K^- or $p\bar{p}$ pairs in rapidity with respect to the primary quark-to-antiquark direction is investigated. The rapidity, y, is defined as $\frac{1}{2}\ln((E + p_L)/(E - p_L))$, where p_L is the component of momentum parallel to the thrust axis, and E is the energy calculated using the RICH determined particle mass. The thrust approximates the directions of the primary q and $\bar{q}$, especially for two-jet events. Specifically, a study is made of the preference for either the positive, or negative, charged member of the pair to be nearer in rapidity to the particle containing the primary quark rather than primary antiquark, see Fig. 1.

To study the rapidity-alignment of particle pairs it is necessary to determine the directions of the primary quark and antiquark. Advantage is taken of the fact that a primary $s\bar{s}$ initiated event will frequently hadronize yielding a high momentum K^+ and K^-. An effective tagging of the directions of the primary quark (s) and the antiquark ($\bar{s}$) is achieved by selecting events where the highest momentum particle in each hemisphere, defined by 'thrust', is a charged kaon (a K^- in one hemisphere, and a K^+ in the other).

The data selected for this study are those tagged events (i.e., where the leading particle in each hemisphere is a kaon) that contain either an additional K^+K^- pair (*not* the tagged pair), or a $p\bar{p}$ pair. The restriction is made that events have only 'one K^+ and one K^-' (*not* including the tagged K's), or only 'one p and one $\bar{p}$' in a given hemisphere. Hemispheres are defined, one for positive y and one for negative y, with respect to the thrust direction. Each hemisphere is considered independently. Essentially no events had additional K^+K^- or $p\bar{p}$ pairs in both hemispheres. For the K^+K^- events the combined-probability tag for particle identification is required to be at the 'standard' level, see Ref. [4]. Because of reduced statistics, the combined-probability tag for $p\bar{p}$ events was taken at the 'loose' level. In each case, these respective levels also apply to the primary quark kaon tags. This selection yields 1250 events for K^+K^-, and 835 events for $p\bar{p}$.

The same procedure was used on Monte Carlo events from Jetset. Standard DELPHI detector simulation along with charged particle reconstruction and hadronic event selection are applied to the events from Jetset with parameters tuned as in Ref. [5]. The number of selected Monte Carlo events for K^+K^- ($p\bar{p}$) was found to be 1.02 (1.27) times that of the data, for equal luminosity. The difference in $p\bar{p}$ between data and Monte Carlo may result from some deficiency in the fragmentation properties of the model.

A study of events from Jetset including detector simulation determined the purity for the K^+K^- tagged events with an additional K^+K^- or $p\bar{p}$ pair to be ~45% and ~35%, respectively. The event detection efficiency for events with K^+K^- or $p\bar{p}$ pairs is ~7% and ~12%, respectively, resulting from the requirement to identify four particles (K's or p's) in each event. These values are nearly constant over the range of the analysis variable Δy defined later. The purity is computed from the ratio of Jetset events detected and congruous with a generated event, to the total number of events detected. The efficiency is obtained from the ratio of Jetset events detected to the total number of events generated.

The distributions of primary-quark flavour, for the events that are tagged, are shown in Fig. 2 for Jetset and Herwig by the solid and open circles, respectively. A background subtraction of like-sign pairs has been applied to account for uncorrelated kaon or baryon pairs. As seen, the $s\bar{s}$ contribution is enhanced for both the K^+K^- and $p\bar{p}$ events. It is also possible for $c\bar{c}$ primary quarks to generate rapidity alignment. This results from the production of $D^0[D^+]$ mesons from the c quark, which strongly favour decays to K^- rather than K^+; the opposite occurs for the $\bar{c}$. The $b\bar{b}$ primary quarks also produce an effect though through a longer chain from B meson to D meson to kaon.

The operational definition of rapidity-alignment is given as follows. For a K^+K^- pair to be *in* rapidity-rank order, the K^+ of the pair should be nearer in the rapidity chain to the tagged K^-. Equivalently, the K^- from the pair should be nearer to the tagged K^+. This is depicted in Fig. 1, assuming a correspondence between string-rank and rapidity-rank order. Similarly, for a $p\bar{p}$ pair the p of the pair should be nearer in rapidity to the tagged K^-; and the $\bar{p}$ from the pair nearer to the tagged K^+.

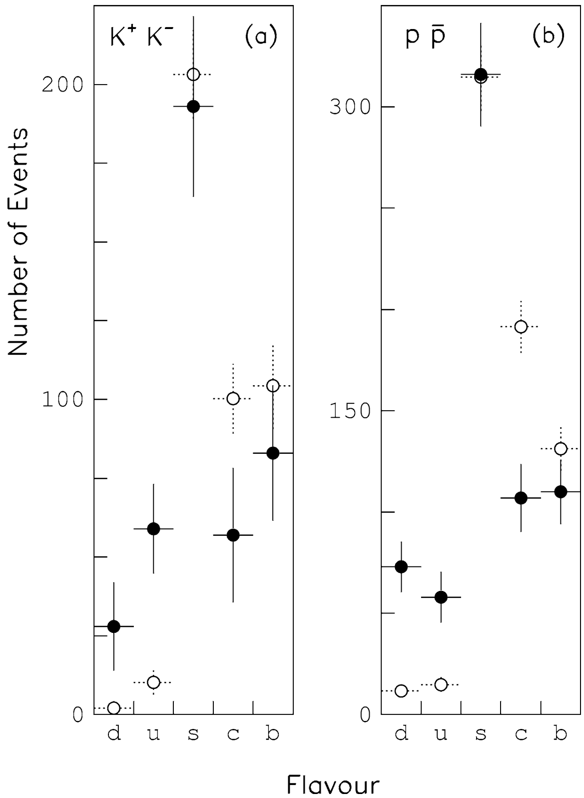

Fig. 2. Distribution of primary-quark flavour from Jetset and Herwig shown by the solid and open circles, respectively, for events that have been tagged by high momentum charged K's. (a) For K^+K^- production (in addition to the tagged K's). (b) For $p\bar{p}$ production.

Since particle pairs with small rapidity difference between them have a high probability to have 'crossed-over' (reversed rank), this study is performed as a function of the absolute rapidity difference between the two particles of the pair, $\Delta y = |y^+ - y^-|$, where y^+ (y^-) are the rapidities of the positive (negative) members of the pair. Rapidity-rank cross-overs can result from resonance/cluster decays, hard gluon production and p_T effects.

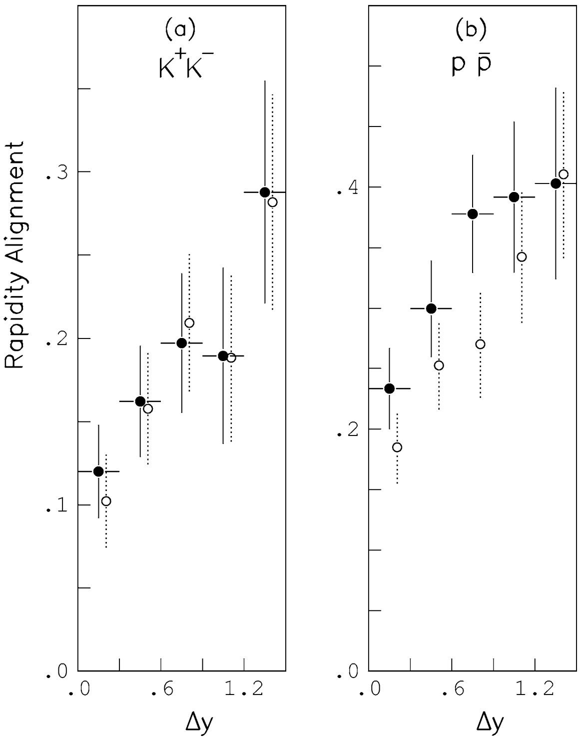

Fig. 3. Rapidity-alignment, uncorrected, as a function of the absolute rapidity difference, Δy, between the particle pair. The data points are indicated by the solid circles, and the predictions of Jetset are shown by the open circles. The plot is an integral; i.e., all pairs with Δy greater than a given (abscissa) value are plotted. (a) for K^+K^- pairs. (b) for $p\bar{p}$ pairs.

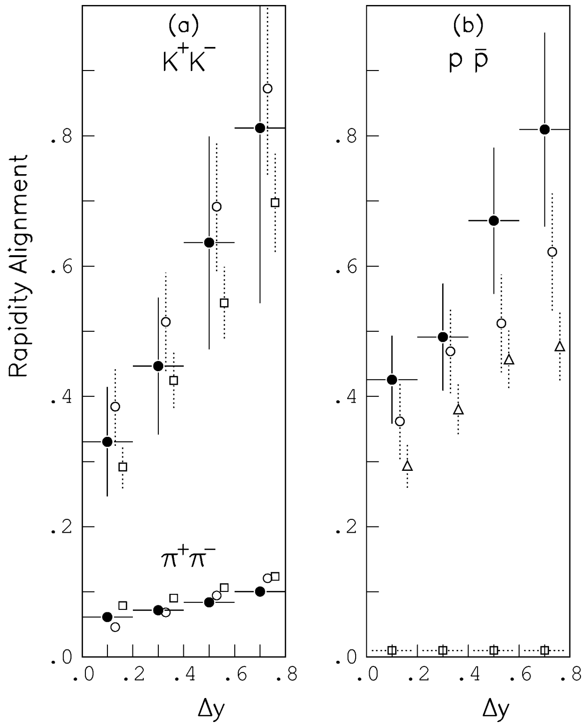

Fig. 4. Rapidity-alignment, corrected for background, as a function of the absolute rapidity difference, Δy, between the particle pair. The data points are indicated by the solid circles, and the predictions of Jetset and standard Herwig are shown by the open circles and squares, respectively. The plot is an integral; i.e., all pairs with Δy greater than a given (abscissa) value are plotted. (a) for K^+K^- pairs and $\pi^+\pi^-$ pairs; the $\pi^+\pi^-$ pairs do not have like-sign pair subtraction, see text. (b) for $p\bar{p}$ pairs. The Herwig result with the process gluon to diquarks included is shown by the open triangles.

The rapidity-alignment variable, $\mathcal{P}$, for K^+K^- and for $p\bar{p}$ pairs is defined as follows,

$$\mathcal{P}(\Delta y) = (N_{\text{in}} - N_{\text{out}})/(N_{\text{in}} + N_{\text{out}}), \tag{1}$$

where N_{in} and N_{out} are defined as the number of particle pairs with their charges *in* and *out* of rapidity-rank order, and are implicitly a function of Δy. In Figs. 3 and 4, the calculation is given as an integral over Δy; that is, all pairs with Δy greater than a given (abscissa) value are plotted. In the absence of rapidity-alignment N_{in} and N_{out} should be equal, within statistics, for all Δy.

The uncorrected values of $\mathcal{P}(\Delta y)$ for K^+K^- and $p\bar{p}$ pairs are displayed in Figs. 3(a) and (b), respectively. The data, shown by the solid circles, for both K^+K^- and $p\bar{p}$ exhibit a definite rapidity-alignment which increases with Δy. The predictions from Jetset, shown by the open circles, are in good agreement with the data. Herwig predictions incorporating detector simulation with misidentifications were not available for a comparison to the uncorrected values.

A correction has been applied to the values of $\mathcal{P}(\Delta y)$ for the data to account for particle misidentifications and uncorrelated kaon or baryon pairs. This is achieved by a background subtraction of like-sign kaon or baryon pairs. The like-sign pairs provide a direct measure of the background which would be contained in the K^+K^- and $p\bar{p}$ pairs. Since misidentifications or uncorrelated pairs would not favour a rank ordering, the background represented by one half of the like-sign pairs is subtracted from both *in* and *out* of order pairs equally. The corrected values of $\mathcal{P}(\Delta y)$ for K^+K^- and $p\bar{p}$ pairs are displayed in Figs. 4(a) and (b), respectively. The data, shown by the solid circles, now display a stronger rapidity-alignment with values approaching 1.0 for large Δy. However, larger errors result from the subtraction procedure.

For the study that incorporates corrections for misidentifications, the model predictions from Jetset and Herwig are taken from the generation level with momentum and angle cuts as were applied to the data. For Jetset the predictions are in agreement with those obtained from the detector simulation version which allows for misidentifications. The predictions from the string-model (Jetset) shown by the open circles are in agreement with both the K^+K^- and $p\bar{p}$ data. The cluster-model (Herwig) predictions, shown by open squares, also give agreement with the K^+K^- data. However, Herwig predicts no alignment for the $p\bar{p}$ case. This occurs because baryon–antibaryon pairs are produced jointly from individual isotropically-decaying clusters, see Ref. [2]. The 'detected' $p\bar{p}$ pairs cannot be rapidity aligned, whether they originate from the same cluster or from different clusters. It was found that 70% of detected $p\bar{p}$ pairs come from the same cluster.

The Herwig program is customarily employed in the 'standard' mode that does *not* include the non-perturbative process of splitting gluons into diquark–antidiquark pairs, see Ref. [2]. If the gluon-to-diquarks process were allowed, rapidity-aligned $p\bar{p}$ pairs could be produced. The diquark and antidiquark would separately adjoin into adjacent clusters which are rank ordered. In this case, a proton produced from the diquark, and an antiproton produced from the antidiquark would be rank ordered since they do not originate from the same cluster as in the case of standard Herwig. The rank ordering then allows the pairs to be rapidity-aligned. Herwig has a provision for this process, which is controlled by a scale and a rate parameter. The scale parameter sets the maximum four-quark mass sum, see below; and the rate parameter is a measure of the amplitude for the process. These parameters are normally set to the default values which suppress the non-perturbative process; the default rate parameter for this process is zero.

To attempt to reproduce the data with Herwig, the scale parameter for the gluon-to-diquarks process was set to 1.9, to include light diquarks (below the four (s) threshold). The rate parameter was set to the value 10.0, which produces a sufficient rapidity-alignment. The prediction, for these parameter values, is shown by the open triangles in Fig. 4(b). The agreement with the data in this case is satisfactory. This new parameter setting, however, causes the predicted baryon multiplicity to increase, and to be inconsistent with the data. This problem can be mitigated by reducing the value of the a priori weight-parameter, for the splitting of clusters to baryons, to ~ 0.25, from the tuned value of 0.74, Ref. [5]. The a priori hypothesized default value is 1.0.

For completeness, the potential rapidity-alignment of $\pi^+\pi^-$ pairs is also examined. In this case, the large pion multiplicity with a string-like alternating charge structure should preclude $\pi^+\pi^-$ pairs from having any substantial rapidity-alignment, see Ref. [6]. Each $\pi^+\pi^-$ combination in a given event is included in the calculation of $\mathcal{P}(\Delta y)$. Predominant pion production with normal occurrence of like-sign pion pairs makes background subtraction incongruous in this case. The subtraction technique used for K^+K^- and $p\bar{p}$ pairs to correct for particle misidentifications is not necessary for like-sign pion pairs since misidentifications are not their primary source. For charged pion identification the combined-probability tag is set at the 'standard' level. The values of $\mathcal{P}(\Delta y)$ for the $\pi^+\pi^-$ data, shown by the solid circles, are included in Fig. 4(a). The rapidity-alignment is quite small, as compared to that from K^+K^- and $p\bar{p}$. The small, but finite, rapidity-alignment indicates an incomplete cancellation of *in* and *out* of order $\pi^+\pi^-$ pairs expected from a string-like alternating charge structure. The predictions from Jetset and Herwig, shown by the open circles and open squares, respectively, are in qualitative agreement with the data.

4. p_T compensation of $\pi^+\pi^-$, K^+K^- and $p\bar{p}$ pairs

The mechanism of local p_T conservation (i.e., compensation) can be studied from correlations in p_T between particles which are adjacent or nearby in rapidity. The azimuthal-angle difference between particles, $\Delta\phi$, measured in the p_T-plane, where p_T is transverse to the thrust direction, is the variable used in this analysis. The tagging procedure used for the rapidity-alignment analysis is not employed here.

According to the string and cluster models, p_T correlations should be stronger for oppositely-charged like-particle pairs. In the case of the string model, this can be understood from examination of Fig. 1, where adjacent hadrons share quarks from a single 'breakup' vertex. For cluster models, p_T correlations can also be expected, for example, from the fact that clusters frequently decay into like-particle pairs.

The particle pairs $\pi^+\pi^-$, K^+K^-, and $p\bar{p}$, determined with the particle identification combined-probability tag at the 'standard' level, are used in this study [4]. The requirement is made that the absolute relative difference in p_T between the two particles, $|p_T^+ - p_T^-|/0.5(p_T^+ + p_T^-)$, be less than 0.1. In this formula p_T is treated as a scalar. In addition, the thrust value for the event is required to be greater than 0.95 for the events with $\pi^+\pi^-$ and K^+K^- pairs, and, because of reduced statistics, greater than 0.9 for the $p\bar{p}$ case. These stringent conditions provide better definition of p_T with respect to the initial $q\bar{q}$ direction, and thus more sensitivity to differences between the string and cluster models. Also, for the $\pi^+\pi^-$ pairs, the particles are required to be adjacent in rapidity (rapidity-ranks differ by one unit). For the K^+K^- pairs, the rapidity-ranks are allowed to differ by two units in order to increase statistics. For the $p\bar{p}$ pairs, this condition is not applied because of reduced statistics.

The uncorrected distributions of $\Delta\phi$ are shown in Figs. 5(a), (b), and (c) for $\pi^+\pi^-$, K^+K^-, and $p\bar{p}$ pairs, respectively. The data are represented by the solid circles. The string and cluster model predictions, from Jetset and standard Herwig, are shown by the 'dashed' and 'dot-dashed' lines, respectively. Error bars for Jetset (open circles) and Herwig (open squares) are shown for selected points. The Jetset errors are statistical. Since Herwig did not give good agreement with the data, systematic errors were evaluated by varying the parameters from Herwig according to the fit results of Ref. [5]. Only the cluster-mass cut-off parameter had a significant effect on the $\Delta\phi$ distribution.

In all three cases, the Jetset predictions give significantly better agreement with the data than does Herwig. However, Jetset does not predict quite enough peaking at $\Delta\phi = 0°$ for the K^+K^- and $p\bar{p}$ pairs. It should be mentioned that although Jetset contains p_T conservation in each string breakup, it does not take into account local p_T compensation between neighbouring vertices, see Ref. [7].

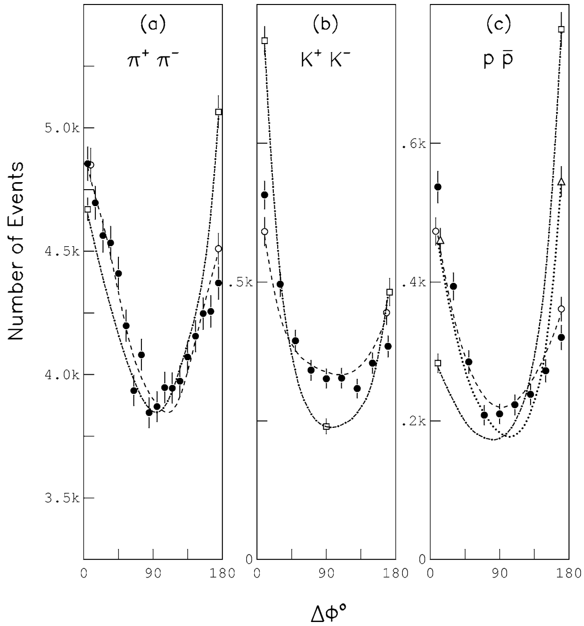

Fig. 5. Azimuthal-angle difference, $\Delta\phi$, between particles from the oppositely-charged particle pairs $\pi^+\pi^-$, K^+K^-, and $p\bar{p}$. $\Delta\phi$ is measured in the p_T-plane, where p_T is transverse to the thrust direction (defined in text). In addition, a requirement on thrust and p_T is made (see text). The data points are indicated by the solid circles. The predictions from Jetset and standard Herwig are shown by the dashed and dot-dashed lines, respectively. Error bars for Jetset (open circles) and Herwig (open squares) are shown for selected points (see text). (a) for $\pi^+\pi^-$ pairs, adjacent in rapidity. Plot has suppressed zero. (b) for K^+K^- pairs, rapidity-ranks differ up to two units. (c) for $p\bar{p}$ pairs, without a rapidity condition. The prediction from Herwig with the process gluon-to-diquarks implemented is shown by the dotted line, with error bars and open triangles for selected points.

A clear disagreement occurs for the model Herwig which predicts a stronger peaking of the distribution at $\Delta\phi = 180°$, for all three cases, as compared to the data. This comes about because the clusters decay predominantly into two particles which emerge back-to-back in p_T, for clusters with small initial p_T. This 'limitation' of the Herwig model design arises from the assumption of isotropically-decaying clusters which is basic to the model.

For comparison to the $p\bar{p}$ data one might expect better agreement from the Herwig model which incorporates the gluon-to-diquarks process. The prediction, for this case, is shown by the 'dotted' line in Fig. 5(c), with error bars and open triangles for selected points. As seen there is significant improvement in the Herwig prediction, however it still fails to give an adequate description.

5. Conclusions

The rapidity-alignment of K^+K^- and $p\bar{p}$ pairs resulting from their asymmetric orientation in rapidity, with respect to the direction from primary quark to antiquark, is observed. The Jetset string model agrees well with both the K^+K^- and $p\bar{p}$ data. The Herwig cluster model agrees with the K^+K^- data; however, agreement for the $p\bar{p}$ case can be achieved only if the non-perturbative process gluon-to-diquarks is implemented. In this case, the predicted baryon production is greatly increased. Inauspiciously, in order to obtain agreement with the data, it is essential to reduce a priori weight-parameter (hypothesized value 1.0) for splitting a cluster to form baryons to $\sim$0.25.

Particle pair correlations in p_T are in much better agreement with Jetset than with Herwig. Herwig fails to describe the p_T correlations for all cases, $\pi^+\pi^-$, K^+K^-, and $p\bar{p}$ because of the mechanism of isotropically-decaying clusters inherent in the model.

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