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Study of Baryon Production Mechanism in e^+e^- Annihilation into Hadrons

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Abstract

The mechanism of baryon-anti-baryon pair production in e^+e^- annihilation into hadrons has been studied using the TOPAZ detector at the TRISTAN e^+e^- collider at an average center-of-mass energy of 58 GeV. The distributions of various $\bar{p}p$ correlations were compared with two prominent models: the cluster-fragmentation model and the string-fragmentation model. We rejected the cluster-fragmentation model at the 90% C.L. Furthermore, in the context of the string-fragmentation model, we favor the "popcorn" model, rejecting the "diquark" model, where a diquark is considered to be a fundamental entity, at the 95% C.L.

Keywords: string-fragmentation, popcorn mechanism, $\bar{p}p$ correlation
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1 Introduction

Although QCD (Quantum ChromoDynamics) has become well established, its predictive power is lost in describing low-p_t processes, such as the fragmentation process, where colored quarks and gluons turn into colorless hadrons. Various models based on Monte-Carlo programs have been developed to describe such processes. By now, two prominent models remain: the cluster-fragmentation model [1] and the string-fragmentation model [2]. The philosophy behind these two models is quite different, but they successfully describe the general features of hadron production, such as inclusive baryon production in the e^+e^- annihilation process [3]. Further differentiation of the two models is very desirable.

In the cluster-fragmentation model, the mechanism of hadron formation proceeds in three steps: the production of a shower of quarks and gluons according to the leading log perturbative QCD, formation of finite mass colorless clusters from the parton final state of the showering process, and independent hadronization of each cluster, principally by a simple two-body decay model. This model has been realized into a Monte-Carlo code, HERWIG [4].

In the string-fragmentation model, a color field is formed between the primary $q\bar{q}$ pair, and new $q\bar{q}$ pairs are created to screen the initial color field, eventually forming mesons out of neighboring $q\bar{q}$ pairs. In this model, two schemes are proposed for baryon production: the diquark model [5] and the popcorn model [6]. In the former, a diquark (qq: color anti-triplet) is treated as a fundamental entity; some of the $q\bar{q}$ pairs are replaced by diquark pairs to form baryons, as depicted in Fig.1(a). In the latter, baryons appear from successive $q\bar{q}$ pair productions in the color field. The key difference from the diquark model is the existence of the BMB configuration as shown in Fig.1(b), where B (M) stands for baryon (meson). In the Monte-Carlo program JETSET [7], in which the string-fragmentation model is incorporated, the "popcorn" ratio (f) is defined as

$$f = \frac{BMB}{BB + BMB} \qquad (1)$$

and $f = 0$ corresponds to the diquark model.

The mechanism of baryon production has previously been studied in several experiments in this context. The PEP4-TPC collaboration at PEP (SLAC) observed angular correlations between $\bar{p}p$ pairs at a center-of-mass (cms) energy of 29 GeV and excluded the cluster-fragmentation model at 95% C.L. [8]. Further, they concluded that the string-fragmentation model reproduces the data, and that in about half of the cases mesons are formed in between the baryon and anti-baryon, thus giving evidence for the existence of the popcorn mechanism. The OPAL collaboration at LEP (CERN) observed rapidity correlations between $\Lambda\bar{\Lambda}$ pairs at a cms energy of 90 GeV, and concluded that the popcorn mechanism with a dominance of BMB configuration describes the data well [9]. It is important to study the mechanism of fragmentation at an intermediate energy in order to see if these results can be reproduced, and if this is indeed the case, to then study the energy dependence of the popcorn ratio.

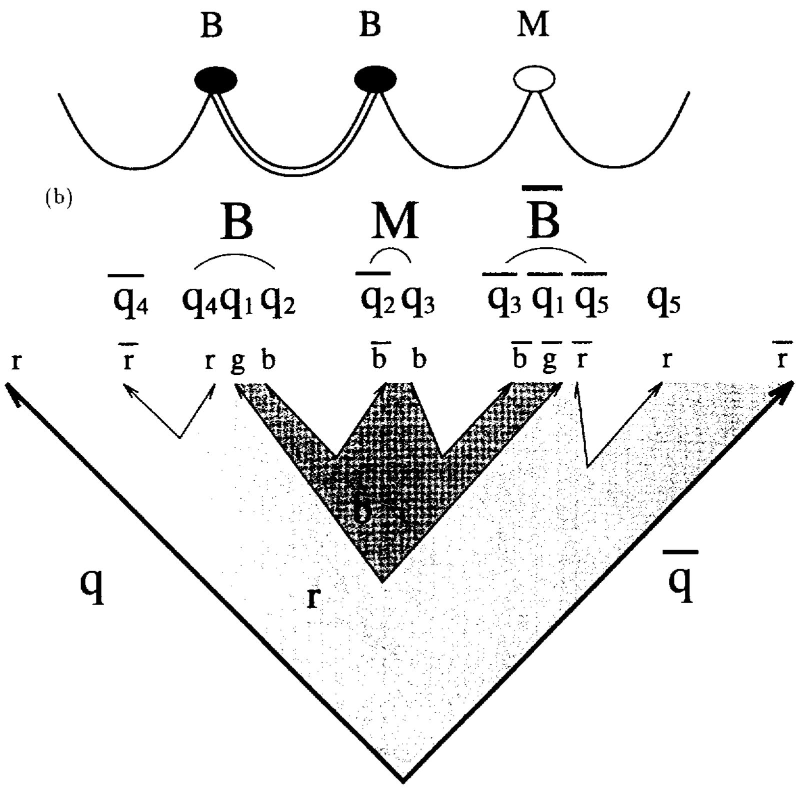

Fig. 1. Schematic representation of Baryon-production mechanisms in the (a)diquark-string-fragmentation model, (b)BMB configuration in the string-fragmentation model.

In this report, we consider the $\overline{p}p$ correlation in $e^+e^- \rightarrow$ hadrons using the data taken with the TOPAZ detector at the TRISTAN e^+e^- collider (KEK) at a cms energy of 58GeV. We first show that the cluster model is disfavored, and then that this popcorn mechanism indeed exists and thus that a diquark is not a fundamental entity. Also, the PEP4-TPC data were analyzed in a completely parallel way to study the consistency and energy dependence of the popcorn ratio, (f).

2 Experimental data

A detailed description of the TOPAZ detector can be found elsewhere [10-16]. The TPC was the main tracking device of the TOPAZ detector, and played an essential role in this analysis. It measured particle trajectories three dimensionally and gave information concerning particle identification through

an energy-loss (dE/dx) measurement. The momentum resolution it provided was $\sigma_{p_t}/p_t = (0.009 \pm 0.001) \cdot p_t(\text{GeV})$ through 10 pad rows/sector, and 175 wires/sector provided dE/dx information with a resolution of $\sigma(dE/dx) =$ 4.6%. An extensive calibration and correction effort was made to fully exploit the dE/dx information [17]. Time-of-flight counters (TOF) surrounded the TPC, giving further information about particle identification. A barrel lead-glass calorimeter (BCL), placed outside of the 1.0 Tesla superconducting solenoid coil, helped to discriminate positrons from protons.

We selected events which contained a proton-antiproton pair out of almost all of the TOPAZ data (305 pb^{-1}) at an average cms energy ($\sqrt{s}$) of 58 GeV. The standard cuts were used to select hadronic-event samples [18]. Protons and anti-protons were selected out of the hadronic events. In each stage of selection, the distributions of cut variables for the data were compared with those by a TOPAZ Monte-Carlo (MC) simulation having ten times as much statistics.

The following criteria were applied on charged tracks for optimum selection of protons and anti-protons:

(i) Those detected with good conditions without duplication well within the detector acceptance ($|\cos\theta| < 0.8$, where θ is the polar angle) and originated from the primary vertex; $|z| < 2.5$cm, where z is the distance from the origin along the beam direction, and momentum-dependent cuts were made on the closest approach, r between 0.8cm and 2.1cm, where r is the distance from the origin in the transverse plane to the beam direction.

(ii) Those with momentum less than 1.5 GeV and with at least 50 wire hits out of 175. The capability of identifying proton (antiproton) tracks mainly from dE/dx measurements in the TPC only goes up to 1.5 GeV, because the two dE/dx curves of protons and pions (kaons) overlap in the dE/dx-momentum plane at 1.7 GeV (2.5 GeV). It is also more useful to have low-momentum tracks when the $\overline{p}p$ correlation is studied, because the Lorentz boost together with the finite-angular resolution makes the correlation unclear for higher momentum tracks. The latter requirement is to ensure a good dE/dx resolution.

(iii) Those within the proton band ($\chi^2(p) < 10$) and away from K and π ($\chi^2(K \text{ or } \pi) > 5$) in the dE/dx-momentum plane.

(iv) Those that do not satisfy the criteria for an e^+e^- pair because of a gamma-conversion (the invariant mass less than 80MeV, etc.) at the detector material.

(v) Those not identified as pions or electrons through a TOF measurement, when the TOF information is cleanly available with no double-hit, etc. (typically requiring the mass from TOF be larger than 0.5 GeV).

(vi) For positive tracks only, those not identified as positrons through an E/p cut ($E/p > 0.5$), where E (p) is the energy deposit in BCL (momentum of the track). This cut was not applied to negative tracks because antiprotons would deposit a large amount of energy in BCL.

By the selection criteria, 2,345 proton and 1,724 antiproton candidates were chosen from 35,293 hadronic event samples, and 201 $\overline{p}p$ pairs remained, while a Monte-Carlo simulation predicted 2,376 proton and 1,673 antiproton candidates and 208 $\overline{p}p$ pairs. The MC prediction is consistent with the real data.

There were no events when more than one pair of $\bar{p}p$ was found. The purity and efficiency for selecting $\bar{p}p$ pairs were estimated to be 66% and 45%, respectively. The main component for the impurity was misidentified pions, according to the MC.

3 $\bar{p}p$ Correlation

We studied various correlations using 201 selected $\bar{p}p$ pairs and compared then with the models incorporated in the Monte-Carlo simulation. The correlations between $\bar{p}$ and p were investigated in the form of histograms. For the purpose of a comparison between the data and models, an acceptance correction was made bin-by-bin in a histogram so as to bring the data to the generation level. JETSET 7.3 was mainly used for a series of event generations and detector simulations, in which the popcorn mode was chosen with the popcorn ratio (f) in eq.(1) set at 1/2. The Monte-Carlo dependence of the acceptance was taken into account in the systematic error, as described later. For referential models, we used the JETSET 7.3 popcorn mode with $f = 2/3$ for the popcorn 2/3 model,[2] the JETSET 7.3 diquark mode with $f = 0$ for the diquark model, and HERWIG 5.5 for a cluster-fragmentation model. Acceptance-corrected data were compared with the referential models in relative normalization, in which the histograms were normalized so that each sum would be equal to 1; this gave more conservative results in a comparison.

We considered the opening angle ($\Delta\phi$) of $\bar{p}$ and p in the plane perpendicular to the jet axis. In this analysis, the tracks detected in the TPC were used for a thrust calculation. For two-jet-like events, the thrust axis is suitable for the jet axis; however, it may be unsuitable for three-jet events. We applied a jet-clustering algorithm to find the number of jets in an event, and then calculated the thrust for each jet using the tracks assigned to members of the jet cluster. For the jet-clustering algorithm, the "JADE clustering" algorithm [19] with $y_{cut} = 0.03$ was used; a choice of $y_{cut} = 0.05$ did not change the results. In calculating the azimuthal angle, rapidity, etc., we need to choose a jet axis which is common to both $\bar{p}$ and p from the point of view of investigating any $\bar{p}p$ correlation, even if they belong to different jets. We calculated the rapidity of p ($\bar{p}$) with respect to the jet which p ($\bar{p}$) belongs to. We then chose a jet which gave a larger absolute value, and regarded the thrust axis of the jet as being the common jet axis.

Figure 2 shows the $\Delta\phi$ distribution, the opening angle perpendicular to the jet axis. In this figure, the difference between the string and cluster fragmentation is clearly seen. The cluster-fragmentation model predicts that a proton and an antiproton tend to be emitted back-to-back after the parent cluster decays, and there is a large peak around $\Delta\phi = 180°$ in the distribution. On the other hand, the string model predicts almost a flat distribution. The string connects the quark and anti-quark, which constitute a baryon and an anti-baryon respectively, and pulls both the baryon and anti-baryon while being

[2] This choice is only technical; a larger value of f occasionally gave rise to some error in computation.

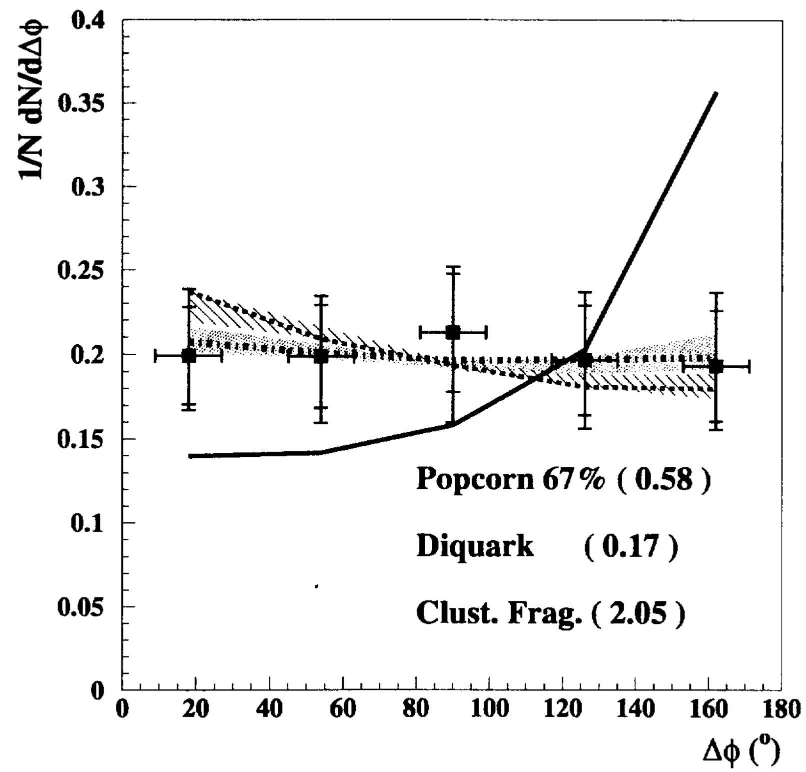

Fig. 2. Opening-angle ($\Delta\phi$) distribution in the plane perpendicular to the thrust axis. The points with error bars are data: the inner error bar is only a statistical error, and the outer error bar is a combination of statistical and systematic errors added in quadrature. The dashed curve is the popcorn 2/3 model, the dot-dashted curve is the diquark model, and the solid curve is the cluster-fragmentation model. The hatched region surrounding the curves shows the allowable region of prediction for the string-fragmentation model. The region is estimated by changing the fragmentation parameters in JETSET. The numbers in the parentheses are the reduced χ^2 ($= \chi^2/$ n.d.f.) for each model.

boosted in the jet. The cluster-fragmentation model can be rejected at more than the 90% C.L.

From now on, we concentrate on the string model and further try to differentiate the models of popcorn and diquark. The method used by the PEP4-TPC group [8] did not work well in this energy region; we need to find another way. The difference between the BB and BMB configurations is whether a meson exists between $\bar{p}$ and p in this rapidity range. We studied two-dimensional histograms of n vs. (Δy), where (Δy) is the rapidity difference of $\bar{p}$ and p and

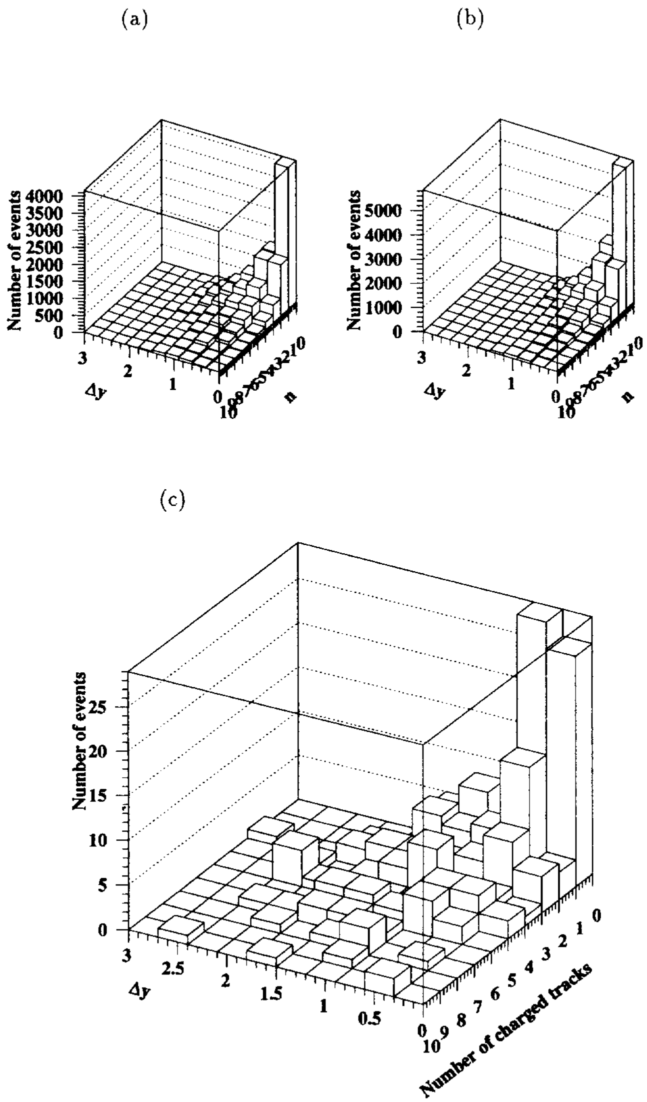

Fig. 3. Number of charged tracks vs. rapidity difference: (a) popcorn model, and (b) diquark model (both at the generation level). A big difference can be seen in the number of events in the peak. (c) data.

n is the number of charged particles found within (Δy). The diquark model predicts a larger concentration near $\Delta y = 0$ and $n = 0$ than does the popcorn model, as shown in Figs.3(a) and (b). Figure 3(c) gives the distribution of data. In comparing the data with models, we used a maximum-likelihood method, regarding the popcorn ratio (f) in eq.(1) as an unknown parameter. A probability density function (p.d.f.) at a certain f can be prepared by a

Monte-Carlo simulation. The p.d.f. (P_f) at f was calculated from the two p.d.f.'s (P_0 at $f = 0$ (diquark) and $P_{2/3}$ at $f = 2/3$ (popcorn 2/3)) as

$$P_f = \frac{(2/3 - f) \cdot P_0 + f \cdot P_{2/3}}{2/3} \quad . \tag{2}$$

The data and predictions were compared at the real-data level; in each bin, an acceptance correction was applied to generated data in the diquark and popcorn 2/3 mode. After this correction, the probability density functions P_0 and $P_{2/3}$ were obtained by normalizing them so that their sums over the plane became 1.

The Log likelihood function is defined as

$$\ln L = \sum_{i=1}^{N} \ln P_f(\Delta y_i, n_i), \tag{3}$$

where N is the number of selected $\bar{p}p$ pairs ($N = 201$). The resulting function was nearly equal to a parabola, with a maximum at $f = 0.47$, and $\ln L/L_{max} = -0.5$ at $f = 0.26$ and $f = 0.70$.

The systematic errors were evaluated by varying the cut parameters, etc. That of the acceptance was estimated by using HERWIG instead of JETSET. The largest errors came from the cut dependence on the momentum range and on the closest approach in the beam direction. The errors were combined by adding them in quadrature. The systematic errors given in Fig.2 were calculated in each bin. In an analysis using the maximum likelihood method, we regarded the change in the popcorn ratio (f) at which the log likelihood function ($\ln L$) became maximum as a systematic error. After combining the systematic errors in quadrature, we obtained an estimate of the popcorn ratio (f) in eq.(1) as

$$f = 0.47 \ ^{+0.23}_{-0.21} \ (\text{stat.}) \ ^{+0.09}_{-0.08} \ (\text{syst.}). \tag{4}$$

The systematic errors are relatively small compared with the statistical errors.

A completely parallel analysis was performed on the PEP4-TPC data to study the consistency and the energy dependence of the popcorn ratio. Hadronic events in the PEP4-TPC data consisted of 38,985 events (98 pb^{-1}) at a cms energy of 29GeV. A total of 111 $\bar{p}p$ pairs was selected with an expected purity of 94% and analyzed in the same way. The obtained result is [20]

$$f = 0.41 \ \pm \ 0.26 \ (\text{stat.}) \ \pm \ 0.10 \ (\text{syst.}). \tag{5}$$

This result is consistent with the result given above and the f parameter does not show a large energy dependence.

4 Summary and Conclusion

Baryon production in e^+e^- annihilation has been studied with the TOPAZ detector at the TRISTAN e^+e^- collider at KEK. A total of 201 $\bar{p}p$ pairs was selected with an efficiency of 45% and a purity of 66% out of 35,293 hadronic events, which are almost all of the available TOPAZ hadronic data corresponding to 305 pb^{-1}, at an average center-of-mass energy ($\sqrt{s}$) of 58 GeV. For identifying protons and anti-protons, the dE/dx information from the TPC was extensively used. Using selected $\bar{p}p$ pairs, the correlations between protons and anti-protons were investigated, and compared with predictions of two models, rejecting the cluster-fragmentation model (HERWIG 5.5) in favor of the string-fragmentation model (JETSET 7.3) through the distribution of the opening angle ($\Delta\phi$) perpendicular to the jet axis between $\bar{p}$ and p. Furthermore in the latter model, the popcorn ratio (f) was obtained by combining the statistical and systematic errors in quadrature;

$$f = 0.47\ ^{+0.25}_{-0.22}\ , \qquad (6)$$

and thus the popcorn ratio is proved to be non-zero at the 2σ level. This means that the diquark model in which only the BB configuration exists ($f = 0$) is rejected at the 95% C.L. A parallel analysis on PEP4-TPC data at $\sqrt{s} = 29$ GeV yielded $f = 0.41 \pm 0.28$, showing little energy dependence in these energy regions.

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