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BARYON PRODUCTION IN $e^+e^-$ ANNIHILATION AT $\sqrt{s} = 29$ GeV: CLUSTERS, DIQUARKS, POPCORN?

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Baryon Production in $\textit{e}^+\textit{e}^-$ Annihilation
at $\sqrt{s} = 29$ GeV: Clusters, Diquarks, Popcorn?


Lawrence Berkeley Laboratory, University of California, Berkeley, CA 94720,
University of California, Los Angeles, CA 90024,
University of California, Riverside, CA 92521,
Johns Hopkins University, Baltimore, MD 21218,
University of Massachusetts, Amherst, MA 01003,
University of Tokyo, Tokyo 113, JAPAN

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Abstract

We use the TPC detector to study mechanisms of baryon production in jets from $e^+e^-$ annihilation. Based on angular correlations between protons and antiprotons, we exclude the isotropic decay of heavy mesonic clusters as a dominant source of baryons at 95% C.L. The diquark mechanisms used in string fragmentation models reproduce the data, provided that diquarks are formed in a two-step process which allows mesons to be produced in between the baryon and antibaryon.
The study of baryon production in $e^+e^-$ annihilation provides a valuable tool for the investigation of confinement mechanisms. In this paper, we exploit angular correlations between protons and antiprotons to distinguish between different phenomenological descriptions of baryon production.

Baryons have been incorporated in string fragmentation models via diquark mechanisms. Produced through diquark-antidiquark creation, diquarks combine with ordinary quarks to form baryons. In one variant, diquark binding energies are large compared to momentum transfers in the confinement process and the diquarks appear as "fundamental" entities. Other variants provide a dynamical description (the "popcorn" mechanism) of how "effective" diquarks can be formed. Sometimes, non-screening quark pairs "pop up" in the color field, resulting in the formation of weakly-bound diquark-like systems. In such a scheme, baryon and antibaryon are not necessarily neighbors in rank, since mesons can be created in between. Technically, the mechanism is equivalent to models with diquarks which "break up" through the process diquark $\rightarrow$ diquark + meson.

An entirely different approach is provided by QCD models, where a parton shower creates low-mass color singlet clusters, some of which may be heavy enough to decay into.
baryon and an antibaryon (Fig. 1(c)). In the following, we compare these mechanisms for baryon production. For quantitative predictions, we use the LUND model as a typical color-string diquark scheme, and the Webber model as an example for the QCD cluster approach. In LUND the break-up probability \( f \) for diquarks is a free parameter. Stable "fundamental" diquarks correspond to \( f = 0 \); the "popcorn" mechanism yields \( f = 0.5 \).

Despite their fundamental differences, both string and cluster models reproduce the measured inclusive proton spectra quite well (Fig. 2); remaining minor differences can be removed by small changes in the model parameters and are of no consequence for the following analysis. However, the model predictions for the angular dependence of proton-antiproton correlations differ qualitatively. Consider the distribution of \( \theta^* \), the angle between the baryon momentum vector and the sphericity axis of the event, measured in the rest frame of the \( pp \) pair. If baryons are produced in the decay of unpolarized mesonic clusters, the distribution in \( \cos \theta^* \) will be flat. There may be a small non-isotropic contribution due to pairs where \( p \) and \( \bar{p} \) come from different clusters; the rate of this "background" equals the rate of \( pp \) and \( p\bar{p} \) combinations and can easily be subtracted. In string models with diquarks, diquark \( (qq) \) and anti-diquark \( (\bar{q}q) \) are pulled apart by the tension of the color string. Therefore the \( pp \) momentum difference has a
tendency to align with the jet axis, and the distribution in \( \cos \theta^* \) will peak near \( |\cos \theta^*| \approx 1 \) (Fig. 3(a)).

Angular correlations in the plane perpendicular to the jet axis discriminate between the variants of the diquark picture\(^9\). If diquarks are quasi-stable entities, then baryon and antibaryon will recoil against each other, reflecting the fact that in a one-dimensional color force field \( (qq) \) and \( (\bar{q}\bar{q}) \) will be produced with opposite transverse momenta\(^6\). If mesons are created in the color field between the \( (qq) \) and the \( (\bar{q}\bar{q}) \), this angular correlation is largely destroyed\(^4,9\).

The results presented in this paper\(^10\) are based on the analysis of 29000 multihadron events recorded with the Time-Projection-Chamber facility at the SLAC \( e^+e^- \) storage ring PEP. Detector and event sample have been described earlier\(^8\). Protons and antiprotons in the momentum range 0.5 GeV/c to 1.5 GeV/c are selected based on momentum and ionization energy loss (dE/dx) measured in the TPC. The lower cut-off in momentum is imposed by energy loss in the material in front of the TPC, the upper cut-off avoids pion-proton dE/dx ambiguities and emphasizes central baryon production, suppressing contributions from heavy quark decays. In the chosen momentum range protons are well separated from other particles, except for a dE/dx cross-over between electrons and protons at 1.2 GeV/c.
Particles located in this region are excluded. The electron background — mainly due to photon conversion — is further reduced by explicit reconstruction of conversion pairs. A more serious source of background in the proton sample are baryons produced in nuclear interactions of hadrons in the material preceeding the tracking chamber. Most of these protons are rejected by requiring the extrapolated orbit to miss the event vertex by less than 1 cm. Protons are also removed if a secondary vertex with another track can be reconstructed inside the material. After this selection, we find 110 \( p\bar{p} \), 8 \( pp \) and 13 \( p\bar{p}p \) pairs. The expected total background consists of about 7 \( pp \) pairs and 3 like-sign pairs.

Fig. 3(b) shows the distribution in \(|\cos \theta^*|\) of \( pp \) pairs, after subtraction of the distribution of \( pp \) and \( p\bar{p} \) pairs in order to account for \( pp \) combinations of independently produced baryons. Due to the momentum cuts, \( 0.5 < p < 1.5 \text{ GeV/c} \), the expected distributions in \( \theta^* \) differ from Fig. 3(a); the qualitative difference between the two models however is maintained. Whereas data are consistent with the behaviour expected for diquark models (full curve), the cluster model (dashed) is excluded at 95% C.L.. Based both on Monte-Carlo simulations and on studies of "fake" \( pp \) combinations including off-vertex p's, we are certain that this disagreement cannot be attributed to background \( p\bar{p} \) combinations accumulating at \(|\cos \theta^*| \approx 1\).
Next we consider correlations between the transverse momentum $\vec{p}_T$ (measured with respect to the sphericity axis) of $p$ and $\bar{p}$. We define a correlation coefficient $\alpha = \langle \vec{p}_T, p \cdot \vec{p}_T, p \rangle / \langle \vec{p}_T^2 \rangle$. For stable diquarks recoiling against antidiquarks we ideally expect $\alpha \approx -1/2$, compared to a much weaker correlation for configurations such as shown in Fig. 1(b). Because of resonance decays, errors in the determination of the event axis etc., the measured $\alpha$ will differ from the naive predictions. The most drastic change is due to events with radiative gluons: here $p$ and $\bar{p}$ are emitted from a moving string segment and experience a common boost, which induces a positive $p_T$ correlation and smears the intrinsic correlation. Hence the experimental sensitivity improves considerably if $\alpha$ is calculated using the momentum components $p_{out}$ out of the event plane (which are less influenced by the boost) instead of $\vec{p}_T$. For the determination of the sphericity axis and of the event plane defined by the eigenvectors of the sphericity tensor, only non-baryon tracks in an event are used, since baryons have larger mean transverse momenta and bias the determination of the event plane.

In Fig. 4, the correlation coefficient $\alpha_{out} = \langle p_{out}, p \cdot p_{out}, p \rangle / \langle p_{out}^2 \rangle$ and the analogously defined $\alpha_{in}$ are contrasted with predictions of the "popcorn" model (Fig. 1(b)), where mesons $(M)$ may form in between a baryon $(B)$ and the antibaryon $(\bar{B})$. The predictions are shown as a
function of the probability $f$ for such a BMFB configuration. For small $f$, the $p,\bar{p}$ momentum components out of the event plane tend to have opposite signs. This result is extremely insensitive to details of the modeling. Comparing e.g. the LUND model with standard parameters, a version tuned to best reproduce our measured meson and baryon spectra, a version where the perturbative part of the model is replaced by a QCD parton shower and finally an independent fragmentation model with diquarks, we find a variation of $\sigma_{\text{out}}$ of only $\pm 0.04$ with respect to the value given in Fig. 4(a). With increasing $f$, boost effects dominate, resulting in a positive value of $\alpha$. For the range of models mentioned, we derive the lower limit $f > 45\%$ at 90\% C.L. Momentum correlations in the plane are dominated by boosts and are less sensitive to $f$.

These tests of fragmentation models are based on qualitative differences in the physics input; the conclusions should be valid beyond details of the modeling. For the QCD model, better agreement with the data could be reached by introducing either baryonic or polarized clusters; however, at least in Webber's framework such extensions seem rather unnatural.

To summarize: based on the study of angular correlations between protons and antiprotons produced in the central rapidity region of hadronic events in $e^+e^-$.
annihilation, we exclude the isotropic decay of heavy mesonic clusters as a dominant source of baryons at 95% C.L. Diquark mechanisms such as the one used in the LUND model reproduce the data, provided that in at least half of the cases mesons are formed in between the baryon and antibaryon.

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References


10. Previous results on baryon correlations were reported e.g. by JADE Collab., W. Bartel et al., Phys. Lett. 104B, 325 (1981); TASSO Collab., M. Althoff et al.,
Figure captions

1. Schematic representation of baryon production mechanisms: (a) string models with stable diquarks\textsuperscript{1,2}, (b) the "popcorn" mechanism\textsuperscript{4}, (c) Cluster decay in QCD models.

2. Predictions by the LUND\textsuperscript{6} (full lines) and Webber\textsuperscript{7} (dashed lines) models for inclusive proton spectra as a function of (a) $x = 2E/\sqrt{s}$, (b) rapidity with respect to the sphericity axis and (c) transverse momentum with respect to the sphericity axis, compared to TPC data\textsuperscript{8}.

3. Distribution of $p\bar{p}$ pairs in the angle $\theta^*$ between the proton direction and the sphericity axis, measured in the $p\bar{p}$ rest frame, after subtraction of like-sign combinations. (a) Predictions of the LUND diquark model with stable diquarks (full lines) and of the Webber cluster model (dashed lines). For the mechanism of Fig. 1(h), the LUND predictions will increase slightly for $\cos\theta^* \geq 1$. (b) Experimental distribution of $p\bar{p}$ pairs where the $p$ and $\bar{p}$ momenta are in the 0.5 - 1.5 GeV/c range. Full and dashed lines: model predictions (as in (a)).

4. Correlation coefficient $\alpha$ of $p,\bar{p}$ momentum components out of the event plane (a) and in the event plane (b). Shaded bands: data ($\pm 1$ S.D.). Full lines: model
predictions as a function of the probability $f$ to find a BMW configuration instead of BB.
Fig. 2

(a) 

(b) 

(c) 

Rapidity $y$
Fig. 3

\[ \frac{1}{n} \frac{dn}{d|\cos \theta^*|} \]

Fig. 4

\[ f = \frac{BMB}{BMB + BB} \]
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