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TPC/Two-Gamma Collaboration

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Study of Baryon Correlations in e^+e^- Annihilation at 29 GeV

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Abstract. We report measurements of two-particle correlations in rapidity space between a $\bar{p}$ or $\bar{\Lambda}$ and an additional p, $\bar{p}$, Λ or $\bar{\Lambda}$. We find evidence for local conservation of baryon number, and for the first time observe a pronounced anticorrelation between baryons with the same value of baryon number. Such an anticorrelation is expected in fragmentation models where the rapidity order of particles closely reflects their "color order", as is the case, for example, in recent versions of the Lund string model.

Baryon production in e^+e^- annihilation events provides a tool to investigate the process of quark fragmentation into hadrons. Not only is the process of baryon production itself interesting and the subject of much speculation[1], but also because baryons are heavy and suffer relatively little momentum smearing due to resonance decays, they provide a convenient probe to study the dynamics governing the production of primary hadrons from the color field of the initial quarks[2]. In this paper, we present data on baryon-baryon and baryon-antibaryon correlations, based on the analysis of events containing two or more p, $\bar{p}$, Λ or $\bar{\Lambda}$.

The data were recorded with the TPC detector facility at the PEP e^+e^- storage ring operating at 29 GeV center-of-mass energy. The Time Projection Chamber[3] (TPC) was used to track charged particles over 87% of 4π and to identify particles via their ionization energy loss. Data were taken in two different detector configurations: a 77 pb^{-1} sample with the TPC operating in the 4 kG field of a normal solenoid, and a second sample of about 70 pb^{-1} with a 13.25 kG superconducting coil. At high momentum, typical momentum resolutions are 3.5% p [in GeV] and 0.65% p for the first and second sets, respectively. At low momentum, multiple scattering limits the momentum resolution to 6% and 1.5%, respectively. The average ionization energy loss ("dE/dx") is calculated as the 65% truncated mean of up to 183 individual measurements per track, resulting in a resolution of 3.7% for tracks with at least 80 usable samples. Hadronic annihilation events are selected by requiring at least 5 charged hadrons in the event, a sum ΣE of the energies of charged particles of at least 7.25 GeV, and a momentum imbalance $|\Sigma p_z| / \Sigma E$ along the beam (z) direction of at most 40%. After additional cuts to reject annihilation events into leptons, we are left with 27880 and 24164 events from the low-field and high-field data sets, respectively.

This study of baryon correlations uses p and $\overline{p}$ identified by dE/dx, and Λ and $\overline{\Lambda}$ reconstructed by secondary-vertex finding algorithms. In order to optimize sample purity, only p and $\overline{p}$ candidates in two distinct momentum regions are considered. At low momentum, $0.5\ \mathrm{GeV}/c < p < 1.5\ \mathrm{GeV}/c$, p and $\overline{p}$ can be identified on a track-by-track basis; details are given in ref. 4. For p candidates in this sample, we require that the extrapolated orbit passes within 1 cm of the event vertex, in order to eliminate p's produced in secondary interactions in the beam pipe. Contamination of the low-momentum sample due to misidentification or p's from secondary interactions is less than 5%. At high momentum, above 3.7 GeV/c, the typical dE/dx separation between $K^{\pm}$ and $p,\overline{p}$ is 1-2 s.d., and > 4 s.d. between $\pi^{\pm}$ and $p,\overline{p}$; here $p,\overline{p}$ are identified on a statistical basis by means of maximum-likelihood fits to the dE/dx distribution[3,5].

Λ ($\overline{\Lambda}$) are detected by reconstructing $\Lambda \rightarrow \pi^- p$ ($\overline{\Lambda} \rightarrow \pi^+ \overline{p}$) decays. Pion and proton candidates are selected as charged tracks whose dE/dx measurements are consistent with the pion and proton hypothesis, respectively, and are subjected to secondary vertex finding routines. If the tracks are consistent with a secondary vertex well separated from the main vertex and if the χ^2 of the secondary vertex fit for the Λ ($\overline{\Lambda}$) hypothesis is less than 6.6, a pair is accepted as a Λ ($\overline{\Lambda}$). Pairs are rejected if dE/dx values and kinematics are also consistent with a $K^0{}_S \rightarrow \pi^+\pi^-$ decay. Because of the superior signal to background ratio, only the high-field data is used for correlations involving Λ or $\overline{\Lambda}$. Depending on their momentum, the signal to background ratio for Λ ($\overline{\Lambda}$) candidates thus selected varies between 3:1 and 4:1.

As a measurement for the correlation between two baryons 'a' and 'b', we define the correlation function C_{ab}:

$$C_{ab}(y_a,y_b) = \rho_{ab}(y_a,y_b)/\rho_a(y_a)\rho_b(y_b) - 1 \qquad (1)$$

Here, $\rho(y) = (1/\sigma_{tot})(d\sigma/dy)$ denotes a single-particle density as a function of rapidity y, and $\rho_{ab}(y_a,y_b) = (1/\sigma_{tot})(d^2\sigma/dy_a dy_b)$ is a two-particle density (all rapidity values refer to the sphericity axis of the event). The indices 'a' and 'b' refer to particle type. $C = 0$ means that two particles are not correlated, $C > 0$ implies that the two particles are produced in association with each other. In particular, local compensation of quantum numbers such as baryon number implies that $C_{\overline{p}p}(y_{\overline{p}},y_p)$ is positive for small $|y_{\overline{p}} - y_p|$, and decreases towards 0 for larger $|y_{\overline{p}} - y_p|$. The correlation function C has the advantage that acceptance corrections cancel to first order; in our case remaining corrections are negligible compared to the statistical errors. If sample 'a' or 'b' contains contamination from other particle species, the raw measured C will deviate from its true value by an amount depending on the amount of contamination and on the correlations between the background particles among themselves (if both 'a' and 'b' are misidentified) and between background particles and correctly identified particles (if only one is misidentified). Using measured sample purities and correlations wherever possible, we correct C and include a conservative estimate of the uncertainty of the correction in the errors. With the exception of $\bar{\Lambda}\Lambda$ correlations, these corrections are typically less than the statistical errors. The influence on C of radiative corrections due to initial-state radiation is negligible.

To present the data, we display $C_{ab}(y_a,y_b)$ for a given combination of particle types 'a' and 'b' as a function of y_b, keeping y_a fixed within a certain interval. Ideally, the width of this interval should be small compared to the typical correlation length in rapidity. In our case, limited statistics does not allow such small intervals, and the two quantities are of the same order. Fig. 1 shows $C_{\bar{p}p}$ (a), $C_{\bar{p}\Lambda}$ (b), $C_{\overline{pp}}$ (c) and $C_{\overline{p\Lambda}}$ (d). In all cases, particle 'a' is a $\bar{p}$ with positive rapidity and a momentum between 0.5 and 1.5 GeV/c. The rapidity range of this $\bar{p}$ extends from 0 to 1.25, with a mean rapidity of 0.56 and an rms width of the distribution of 0.29 (indicated as a black bar in Figs. 1(a) to (d)). To derive C, we combined charge conjugated channels, except in the case of $C_{\overline{pp}}$ (because of possible nuclear-interaction backgrounds in the pp sample) and in cases where one combination of two tracks would be used twice (e.g for $C_{\bar{p}p}$ at low rapidity, where one $\bar{p}$ would serve as particle 'a' in one channel and as particle 'b' in the charge conjugated channel). In counting Λp $(\overline{\Lambda p})$ pairs, the decay p $(\bar{p})$ from the Λ $(\bar{\Lambda})$ is excluded.

We observe a strong positive correlation between baryons and antibaryons (Fig. 1(a),(b)), with evidence for local compensation of baryon number, in confirmation of earlier results[6]. Furthermore, we find a pronounced local anticorrelation between two particles with the same baryon number (Fig. 1(c),(d)). We will later return to this second point. Included in Fig. 1 are predictions for C based on the Lund hadronization model[7], which reproduces the data reasonably well. The corresponding set of correlations for a $\overline{\Lambda}$ as particle 'a' is displayed in Fig. 1(e) - (h). In this case, any detected $\overline{\Lambda}$ with positive rapidity is used as 'a'. The distribution of those $\overline{\Lambda}$ is roughly gaussian in y, with $<y_a> = 1.29$ and an rms width of 0.55 units, still (marginally) smaller than a typical correlation length. Again, we observe clear evidence for local conservation of baryon number and find evidence for an anticorrelation between particles with the same value of baryon number.

Whereas local conservation of baryon number appears natural, given that charge and strangeness are known to be conserved locally in the hadronization process[5,8], and given that most models of baryon production predict such a behavior, the dynamical origin of the anticorrelation between particles with the same baryon number is less obvious. The production of another heavy negative object besides the $\overline{p}$ 'a' (Fig. 1(a) - (d)) may be suppressed somewhat because of constraints due to energy-momentum conservation and charge conservation. However, the antiproton 'a' has energies between 1 and 1.8 GeV and drains only a small fraction of the beam energy of 14.5 GeV. We can estimate the maximum suppression of production rates for a second heavy object from the correlation between a $\overline{p}$ and a three-pion system of net charge -1 (like an additional $\overline{p}$) and a mass in the 2-3 GeV range (like the mass of a baryon-antibaryon pair produced in addition to the $\overline{p}$ 'a'). The $\overline{p}(3\pi)$ correlation data are shown in Fig. 2; we do not observe an anticorrelation comparable in strength to that seen for the $\overline{p}\overline{p}$ case. Another possible explanation is that we are seeing the effects of Fermi-Dirac statistics. However, using the usual effective source size of about 1 fm [9], the repulsive effects of Fermi-Dirac statistics should be limited to baryon pairs with momentum differences less than 200 MeV -- far too short a range to explain our observations. Also, the effect should then not be visible in the $\overline{p\Lambda}$ correlation.

The manner in which most fragmentation models describe particle production indicates another, more likely source of the anticorrelation: it is always assumed that new quark-antiquark pairs are created in the color field of the initial quarks. Quarks and antiquarks then recombine into mesons; occasional production of diquark-antidiquark pairs accounts for baryon production. In the $1/N_{color} \rightarrow 0$ approximation -- the limit used implicitly both in the Lund string model and in QCD shower models -- each colored quark has a well defined partner carrying the corresponding anticolor, with which it forms a color singlet hadron (or hadronic "cluster"). We can now assign each particle a rank[10,11], going along the "color connection" from the initial quark to the antiquark. Two primary hadrons with the same baryon number (or, for that matter, with the same charge or strangeness) are separated by at least two steps in rank. Provided that the order of particles in rapidity closely reflects their order in rank, we are not likely to find two baryons or two antibaryons at the same rapidity. In iterative fragmentation models such as the Lund scheme[10], this condition is fulfilled for appropriate choices of the momentum sharing function f(x) describing the distribution in the fraction x of parton momentum carried by the hadron in the basic process *parton → hadron(x) + parton'(1-x)*. The shape of f(x) determines the distribution g(Δy) in the rapidity difference Δy between two hadrons adjacent in rank. If the width of g(Δy) is smaller than, or comparable to the average spacing <Δy> of particles in rapidity, the rapidity order will closely reflect the order in rank. For example, the shape

$f(x) \sim x^{-1}(1-x)^{\alpha} \exp(-\beta m^2/x)$ of the "symmetric" Lund model[10] results (for 1 GeV hadrons and typical values of the parameters α,β) in a width of the Δy-distribution of about 0.9 units, and an average Δy of 0.8 units. By contrast, the shapes used in earlier versions of the Lund model ("standard Lund"[10,12]), $f(x) = (1-x)^{\alpha}$, and in the Feynman-Field model[11], $f(x) = (1-\alpha) + 3\alpha(1-x)^2$, peak at $x = 0$ and their Δy-distributions are rather wide (1.7 - 1.8 units rms) compared to the typical Δy. In the latter case, there is obviously no one-to-one correspondence between rank and rapidity. Indeed, the "symmetric" Lund model reproduces the anticorrelation effect, whereas models using the "standard" LUND or Feynman-Field fragmentation functions do not (Fig. 2). We note in passing that fragmentation models based on angular-ordered QCD parton showers[13] also predict a close relation between rank and rapidity order.

In summary, we find strong local rapidity correlations between baryons and antibaryons, and a significant anticorrelation between two baryons. The latter effect can be interpreted as evidence for a close correspondence between the order in which particles are created in rank, and their rapidity order; the effect is obscured in ordinary correlation studies using light hadrons such as pions, mainly because of the positive correlations and the rapidity smearing induced by resonance decays. By contrast, baryons provide a more direct probe of the primary production processes, revealing the observed color ordering effects.

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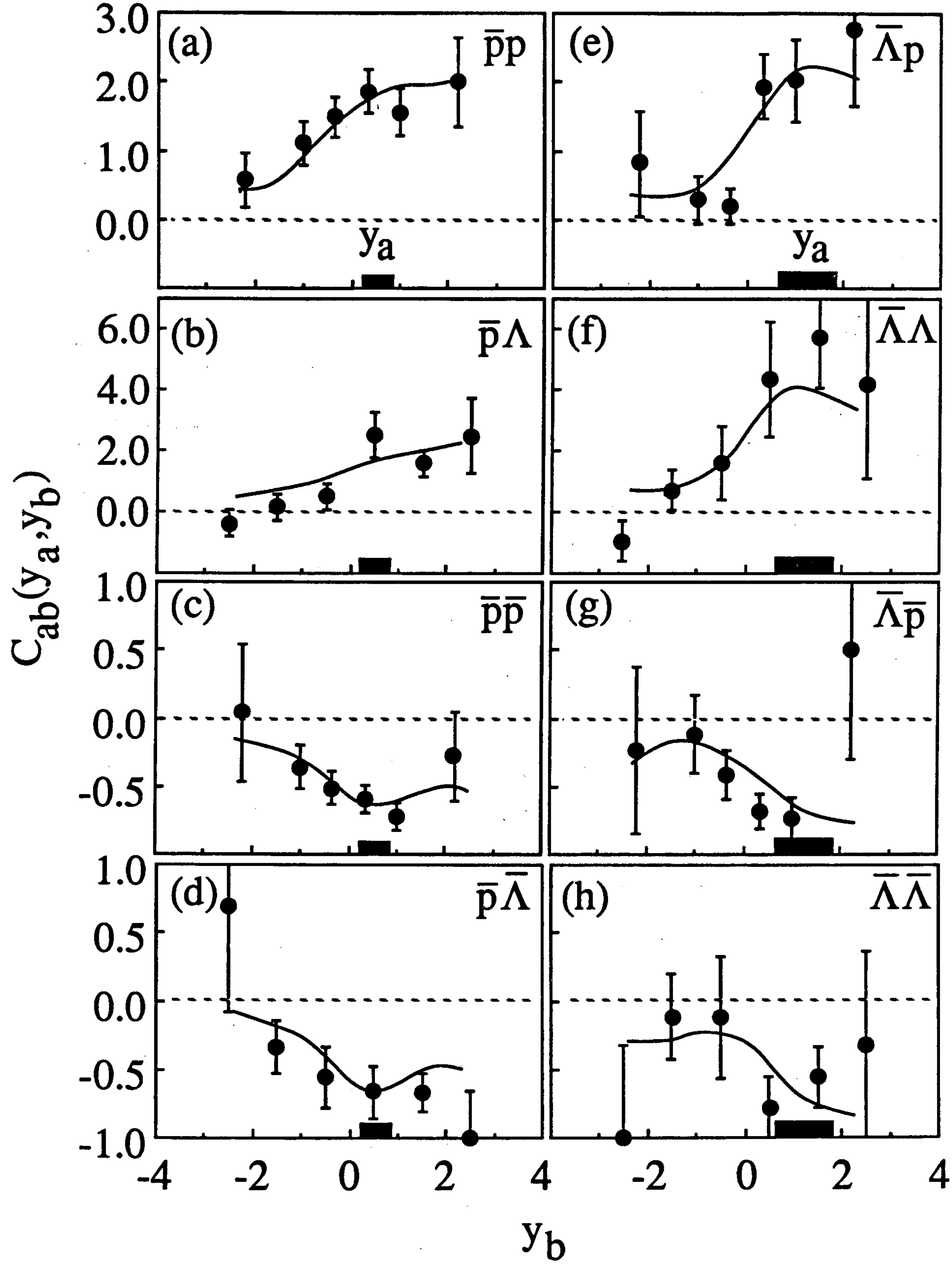
Figure Captions

Fig. 1 (a) - (d) Correlation function $C_{ab}(y_a,y_b)$ for a $\overline{p}$ in the rapidity interval $0 < y_a < 1.25$ and an additional baryon 'b' at rapidity y, for p (a), Λ (b), $\overline{p}$ (c), $\overline{\Lambda}$ (d). The rms width of the rapidity distribution of the $\overline{p}$ 'a' is indicated by the black bar. (e) - (h) show the corresponding correlation functions for a $\overline{\Lambda}$ in the rapidity range $y > 0$ as particle 'a'. Curves indicate predictions by the Lund hadronization model[7].

Fig. 2 Comparison of the measured $\overline{pp}$ correlation function (see Fig. 1(c)) with the correlation observed between a $\overline{p}$ and a $\pi^+\pi^-\pi^-$ system in the 2 - 3 GeV mass range. Also shown are predictions of $C_{\overline{p}\overline{p}}$ from the "symmetric" Lund fragmentation model[7] (——), the "standard" Lund model[12] (---) and the Lund model[7] with Feynman-Field fragmentation functions[11] (....).



(a)
$\bar{p}p$
(b)
$\bar{p}\Lambda$
(c)
$\bar{p}\bar{p}$
(d)
$\bar{p}\bar{\Lambda}$
(e)
$\bar{\Lambda}p$
(f)
$\bar{\Lambda}\Lambda$
(g)
$\bar{\Lambda}\bar{p}$
(h)
$\bar{\Lambda}\bar{\Lambda}$
y_a
y_a
$C_{ab}(y_a,y_b)$
y_b
3.0
2.0
1.0
0.0
6.0
4.0
2.0
0.0
1.0
0.5
0.0
-0.5
1.0
0.5
0.0
-0.5
-1.0
-4
-2
0
2
4
-2
0
2
4

Fig. 1

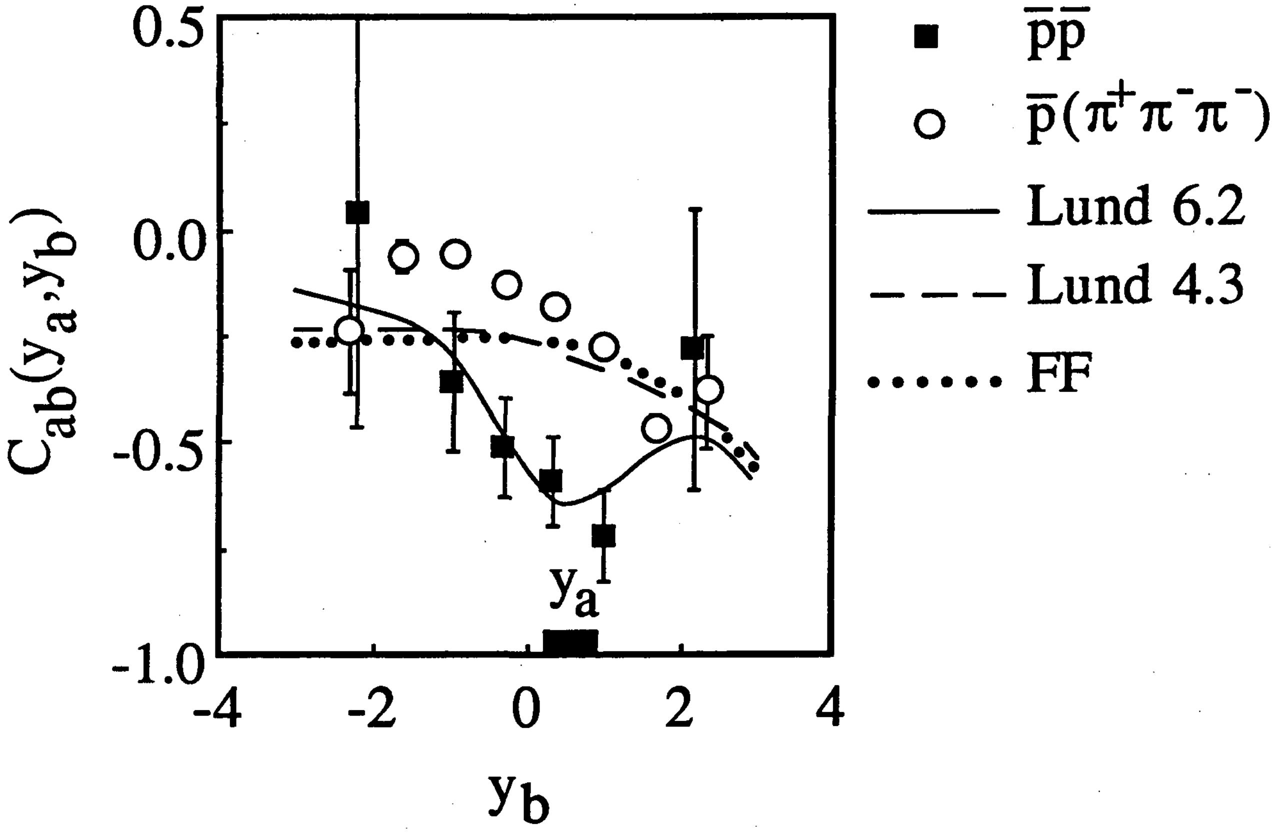

0.5
0.0
-0.5
-1.0
$C_{ab}(y_a,y_b)$
-4
-2
0
2
4
y_b
y_a
■ $\bar{p}\bar{p}$
○ $\bar{p}(\pi^+\pi^-\pi^-)$
Lund 6.2
Lund 4.3
FF

Fig. 2

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