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Baryon Production in Jet Fragmentation and T-Decay

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Abstract: The sizable baryon-antibaryon production, observed in quark and gluon jets, has been considered in different phenomenological contexts in particular in terms of diquark-antidiquark ("tunneling") production along the colour field or by means of colour fluctuations in the field. We show that when the colour fluctuations are treated by means of the uncertainty relation, the two frameworks become very similar and that the resulting "effective diquark" model presents a stable and useful phenomenological tool for treating the properties of baryon-antibaryon production. We also present an analysis of the gluonic decays of the T-resonances which strongly supports the notion of gluons as excitations on the stringlike colour triplet forcefield.

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1. Introduction

A sizeable baryon production is observed in jet fragmentation in e^+e^--annihilation [1-4] and in high energy μp-scattering [5]. Several different production models have been suggested. It is generally believed that the baryon production mechanism will give important information on the nature of the confining forces.

A few years ago we presented a simple model in which diquark-antidiquark pairs are produced in a stringlike colour force field [6]. It was assumed that the two quarks in a diquark, being a colour antitriplet although not as a fundamental unit, can be produced together in a tunneling process in a similar way as a heavy antiquark in a $q\bar{q}$-pair. The only essential difference is caused by the constraint that three quarks in a baryon must be in a totally symmetric state. In this model the final state baryon-antibaryon $B\bar{B}$-pairs are always nearest neighbours in rank. Other diquark-antidiquark models [7-9] have been presented (although in general neglecting the symmetrization constraint) in which the $B\bar{B}$-pairs are not necessarily nearest neighbours in rank. Further, a different production mechanism has been suggested [10] according to which the quarks and antiquarks in the $B\bar{B}$-pairs are produced stepwise, i.e. "popping out" one pair at a time from the colour force field.

We will in this note investigate a combination of the two models, i.e. try to give a precise structure to "the pop-corn mechanism" which at the same time will justify the treatment of $B\bar{B}$ production by means of more or less loosely bound diquark-antidiquark systems.

The basic assumption will be that the space time history of a confined force-field (we will use as a model the massless relativistic string [11,12]) should contain regions with quantum colour fluctuations. In a simple-minded language we expect that e.g. a red-antired $(r\bar{r})$ string-field (defined by a triplet (3) r quark at one end point and an antitriplet $(\bar{3})$ $\bar{r}$ antiquark at the other) should contain regions with green-antigreen $(g\bar{g})$ and blue-antiblue $(b\bar{b})$ fluctuations. Pictorially the development of such a string state should in one space and one time dimension look like fig. 1. The regions marked A and B correspond to the production and final annihilation of $q\bar{q}$-pairs with the "wrong" colours.

If we assume that the pair $q'\bar{q}'$ at the region A is $b\bar{b}$ and that the red and blue form a colour antitriplet (antigreen), then we note that also inside the region A we have a colour triplet field but with opposite direction (defined e.g. as going from 3 to $\bar{3}$). Thus the field strength is the same, i.e. the colour field is not screened and the energy per unit length or the string tension is the same outside and inside the region A. The particles q' and $\bar{q}'$ are thus pulled with the same strength in both directions and feel no net force; they will just "float around" in the force field.

The $r\bar{r}$ string field can break by the production of a $r\bar{r}$ $q\bar{q}$-pair. However the field can also break within one of the fluctuation regions. If e.g. a $g\bar{g}$-pair $q_2\bar{q}_2$ is produced between a $b\bar{b}$-pair $q_1\bar{q}_1$ (cf fig. 1), then the q_2 will be dragged towards (rb) and $\bar{q}_2$ towards $(\bar{r}\bar{b})$ resulting in a possible $B\bar{B}$ production. The difference between this picture and the one in ref [10] is that in our case the field strength between q_1 and $\bar{q}_1$ is the same although the field direction is different.

It is evidently the density and the size of the colour fluctuations which will determine the properties of the $B\bar{B}$ production process. The density will determine the rate of baryon production but in case the fluctuations are large on the scale of the meson masses it is possible that one or more mesons are produced between the $B\bar{B}$-pair. In section 2 we will consider the structure obtained in case we take into account the uncertainty principle for the colour fluctuations. It will turn out that there is a fast fall-off with the size of the space-time regions inside which colour fluctuations may occur. Therefore a $B\bar{B}$-pair produced in a model of this kind will basically either be nearest neighbours or next nearest neighbours in rank.

Inside the symmetric Lund fragmentation scheme [11] the notion of colour coherence regions is invoked. Inside such a region it is necessary to keep account of the colour properties of the force field in order that the final state hadrons should come out as colour singlets. The breakup probability is exponentially damped with the size of the colour coherence regions. In connection with colour fluctuation regions of the kind discussed above, it is necessary to keep colour coherence

both inside and outside the fluctuation. The question whether this requirement will further suppress the probability to produce mesonic systems in between the $B\bar{B}$-pair will not be considered here. It will anyhow give an exponential suppression for large masses of the mesonic system, just as the tunneling mechanism discussed above.

From the experimental point of view much more data is available now than at the time when we presented the simple model in ref [6]. Most of the general features of that model seem to be in agreement also with the new data but there are several indications that the $B\bar{B}$-pairs are not always nearest neighbours in rank. Thus the model predictions for a hard proton spectrum in a quark jet ($\sim (1-z)$), an increase with energy like $\ell n(s)$ in $B\bar{B}$ multiplicity and a strong suppression of strange diquark production implying a suppression of Ξ^- and Ω-particles are in agreement with recent data.

There is, however, a large difference between the p- and $\bar{p}$-spectra in a quark jet observed by the EMC group [5] and there are also (a lack of) transverse momentum correlations in $p\bar{p}$-pairs as observed by the TPC group [14]. Both these features are natural consequences of the possibility that the $B\bar{B}$-pairs are sometimes produced not as nearest neighbours in rank. The same mechanism will also give a somewhat faster increase with energy for the $B\bar{B}$ production rate.

The Cleo collaboration [15] has reported a very large baryon production in Υ-decay, a factor of two larger than in the nearby continuum (in agreement with earlier DASP-data from

ψ-decay [16].) This should be a severe constraint on the possible models. In jet calculus models based upon perturbative QCD the decay of preconfined clusters (with larger average mass on Υ than in the continuum) has been claimed as a possible source for $B\bar{B}$-production [17]. However, preliminary experimental results [14] indicate that such clusters then must have a highly anisotropic decay e.g. like ministrings.

In the Lund model Υ decay into three gluons is treated as a closed triangular string or colour triplet field, which is stretched and breaks into pieces in the same way as the colour field between a quark and an antiquark. This implies a larger total multiplicity on Υ than off Υ due to the "longer" string. Furthermore the fraction of baryons is higher on Υ, because in the continuum one colour $3\bar{3}$-pair is necessarily a quark-antiquark pair unless also diquark pairs are allowed to be produced at the photon vertex. These two effects combine to give about twice as many baryons on Υ than in the continuum. It is an interesting fact that beside baryon production also the predicted total multiplicity and kaon production agree very well with experiments. This supports the idea that gluons can be treated as transverse excitations on a stringlike colour triplet as we will advocate in section 5.

The paper is organized in such a way that the model is described in some detail in section 2, the general phenomenological features as compared to the earlier model is described in section 3. In section 4 and in the appendix we implement the model in a Monte Carlo simulation for the general Lund Model and discuss detailed comparisons to data and to other models. Finally in section 5 the results for the Υ-region are discussed.

2. Description of the model

We will subsequently only discuss the case of a single flavour in detail (and consequently only a single final state meson and baryon state). The generalization to several flavours is discussed in the appendix in connection with a description of the Monte Carlo simulation program.

The Lund string fragmentation model [12] is a stochastical process model for the breakup of a stringlike force-field. The process was originally defined in energy-momentum space in order to avoid quantum mechanical intricacies. In a one space and one time dimensional world with massless quarks there is actually a direct correspondence between energy-momentum space and space-time, and we will with due caution make use of space-time language subsequently.

The production of heavy flavours as well as transverse momentum generation along the string-field is in the Lund model governed by the same tunneling process which was involved already in the classical papers by Heisenberg and Euler and by Schwinger in connection with QED. While massless $q\bar{q}$-pairs can classically be produced at rest in a single space-time point, the force-field breakup is no longer classically allowed in connection with massive pairs. The classical trajectories of the produced $q\bar{q}$-pair will not overlap due to energy-momentum conservation. Nevertheless the quantum mechanical wave functions will have exponentially damped tails out into the unphysical region. In particular for the quark wave function ψ_q, corresponding to a zero energy particle with mass μ we obtain by WKB-methods

$$\Psi_q(0) \approx \Psi_q(x_c)\exp\left(-\int_0^{x_c} dx\sqrt{\mu^2-(\kappa x)^2}\right) = \Psi_q(x_c)\exp\left(-\frac{\pi}{4}\frac{\mu^2}{\kappa}\right) \qquad (1)$$

where $\psi_q(x_c)$ is the wave function at the classical boundary $x_c = \mu/\kappa$. Using wave packets localized along the classical orbits we obtain more generally for the overlap of the $q\bar{q}$-wave functions, M :

$$\mathcal{M} \propto \exp\left(-\frac{\pi}{2}\frac{\mu^2}{\kappa}\right) \qquad (2)$$

The main contribution to the overlap integral stems from a space-time "diamond" of size μ^2/κ, and in case we identify M as the production matrix element, the probability is governed by

$$|\mathcal{M}|^2 \approx \exp\left(-\frac{\pi\mu^2}{\kappa}\right) \qquad (3)$$

Thus the zero-point fluctuations in the ground state of a stringlike force-field is damped by essentially the amount of energy per unit length or the string tension κ.

It is instructive to compare the result to the uncertainty relation suppression obtained for a non-interacting pair at the spacelike distance x, i.e.

$$\Delta_F(x,\mu) \simeq \exp(-\mu|x|) \qquad (4)$$

At the distance $x = 2\mu/\kappa$ this is very similar to the overlap of the tunneling pair wavefunctions, i.e. M in eq. (2), except that the damping factor 2 is changed into $\pi/2$. This difference stems from the vanishing of the field in between the $q\bar{q}$-pair during the tunneling process which thereby provides some "help".

Generally we will assume that the uncertainty relation allows for colour fluctuations such that the probability to find a $q_1\bar{q}_1$-pair of the "wrong" colour (remember that there are no forces on the q_1 or $\bar{q}_1$ in the field, i.e. they are "free") at the space-like distance x_1 apart is

$$|\Delta_F(x_1,\mu)|^2 \simeq \exp(-2\mu_1|x_1|) \qquad (5)$$

Here μ_1 is the (transverse) mass of the q_1- or the $\bar{q}_1$-particle and we assume that together they conserve transverse momentum.

If in between the $q_1\bar{q}_1$-pair another pair $q_2\bar{q}_2$ (with transverse masses μ_2) is produced, the probability for them to tunnel a distance x_2 apart is suppressed by the factor

$$\exp\left(-\frac{\pi}{2}\mu_2|x_2|\right) \qquad (6)$$

In case there is no other pair produced between q_1 and $\bar{q}_1$ then the resulting baryon and antibaryon will be neighbours in rank. The minimum distances for the quarks to come on shell will be

$$x_1 = x_2 = 2(\mu_1+\mu_2) \equiv 2\mu \qquad (7)$$

where μ is the (transverse) mass of the q_1q_2 (effective) diquark system. The total probability will thus be given by the factor

$$\exp\left(-4\mu_1(\mu_1+\mu_2) - \pi\mu_2(\mu_1+\mu_2)\right)/\kappa \qquad (8)$$

Of course the amplitude has to be symmetrized because we could equally well produce the $q_2\bar{q}_2$-pair first. However, neglecting the difference between 4 and π we anyhow obtain directly the symmetric result

$$\exp(-4\mu^2/\kappa) \qquad (9)$$

We therefore find that large diquark masses will in this model be suppressed in a similar way as if they had tunneled out as one unit according to the earlier model [6].

In case there is more than one vertex inside the colour fluctuation region, i.e. along the string between "the wrong colour" $q_1\bar{q}_1$-pair, we need at least a colour fluctuation of size $x = M/\kappa$ in order to produce a mesonic state of mass M. Then we obtain an extra suppression factor

$$\sim \exp(-2\mu_1 M/\kappa) \qquad (10)$$

We note that the mass of a mesonic state increases quickly with multiplicity. For a mean distance $\Delta y \simeq 1$ between primary mesons we obtain for an n-meson state

$$M_n \approx M_1 \exp\left[\tfrac{1}{2}(n-1)\right] \frac{1-\exp(-n)}{1-\exp(-1)} \approx M_1 \exp(\tfrac{1}{2}n) \qquad (11)$$

Thus the suppression factor in eq. (10) decreases very quickly with the rank difference between the B and $\bar{B}$ in this model. This decrease is much more rapid than the one obtained e.g. in jet cascade models with fixed probabilities for the splittings $q \to Mq$, $q \to B(\overline{qq})$, $\overline{qq} \to M(\overline{qq})$, $(\overline{qq}) \to \bar{B}q$ [7,8].

3. Phenomenological consequences, qualitative results.

In this section we will qualitatively investigate the main consequences of the model, i.e. the spectrum changes in $B\bar{B}$-production due to the possibility that the $B\bar{B}$-pair is not necessarily nearest neighbours in rank.

We start by considering the mean (primary) meson multiplicity in between the $B\bar{B}$ pair. If the total (transverse) mass of a meson system produced in between the $B\bar{B}$-pair is M then the considerations in section 2 imply a production probability proportional to (eqs (9) and (10))

$$\exp(-2\mu(M+2\mu)/\kappa) \qquad (12)$$

If we neglect the rest-mass for u- and d-quarks we have $\mu = k_\perp$ and after summing over all values of $k_\perp$ we obtain

$$\int dk_\perp^2 \exp[-2k_\perp(M+2k_\perp)/\kappa] =$$

$$= \frac{\kappa}{2}\left[1-\sqrt{\pi}\frac{M}{2\sqrt{\kappa}}\exp\left(\frac{M^2}{4\kappa}\right)\operatorname{erfc}\left(\frac{M}{2\sqrt{\kappa}}\right)\right] \qquad (13)$$

As a numerical example we find that for a single meson transverse mass $\simeq 0.4$ GeV/c^2 the eqs (11) and (13) imply that the meson system multiplicity suppresses the production probability in accordance with

number of mesons:	0	1	2	3
Suppression factor:	1	$\frac{1}{2}$	$\frac{1}{4}$	$\frac{1}{10}$

For vector mesons the suppression factor will be larger, and we find that the mean number of primary final state mesons will on the average be close to 0.5 . This value is in good agreement with the experimental results as we will se below.

The most noticeable consequences of the possibility to produce mesons between a baryon and an antibaryon is a suppression of antibaryons (baryons) in a quark (antiquark) jet, and a suppression of baryon production at lower energies causing a steeper rise with energy for this production. We note that also in the earlier model there is a suppression of antibaryons in a quark jet; a $\bar{B}$ must always be preceeded by a B and cannot be first rank. If a meson is produced between the $\bar{B}$ and the B , then the $\bar{B}$ can at most be third rank and thus this suppression is further enhanced.

For the total baryon multiplicity, n_B , in e^+e^--annihilation we expect, if the primary hadrons are spaced about 1 unit in rapidity apart,

$$\langle n_B \rangle \approx P(qq) \left[\ln (W^2/M^2) - 1 - f \right] \qquad (14)$$

where $P(qq)$ is the probability to obtain an (effective) diquark at a breakup vertex along the string and f is the average number of primary mesons produced between a $B\bar{B}$-pair. In the parenthesis the term 1 follows because one of the $3\bar{3}$-pairs, which is produced at the photon vertex, is necessarily a $q\bar{q}$-pair. (We do not expect that diquark-antidiquark pairs can be produced directly by the photon.) This suppresses the baryon production at low energies and in our new model this suppression is further enhanced by the term f .

We note that in the diquark model, to reproduce the baryon production rate in high energy TASSO [2] and TPC data [4], one needs a value for the diquark production rate $P(qq)/P(q) \approx 0.09$, whereas for low energy SPEAR data [1] at 4 GeV a value $P(qq)/P(q) \approx 0.065$ was needed. Thus we conclude that both the high and low energy data can be reproduced with the same (high) diquark rate $P(qq)/P(q) \approx 0.1$ if $f \approx 1/2$, i.e. if on the average one half primary meson is produced between a baryon and an antibaryon.

It should be noted that theoretical estimates at low energies, e.g. by means of the Monte Carlo version of the Lund Model (cf section 4 below) are sensitive to the joining of jets. Further the SPEAR data exhibit some 20% systematic error and it is therefore difficult to distinguish between the present model with $f \sim 0.5$ and the earlier model with $f \equiv 0$.

A more sensitive measure of f is given by the spectrum difference of baryons and antibaryons in a quark jet. The EMC group has recently presented data on the ratio of p/h^+ and $\bar{p}/h^-$ [5] in μp-scattering with $x_B > 0.2$ corresponding to a sample of almost pure q-jets.

In order to estimate the difference between proton and antiproton spectra in a quark fragmentation region we consider the simple jet cascade model resulting from the fragmentation function $f(z) = 1$ [18]. We will for simplicity assume that the probability to produce one primary meson between the $B\bar{B}$ is f and we neglect the probability to produce two or more mesons in between. Then the baryon spectrum in the q-fragmentation region is unaffected but the antibaryons will be suppressed by the factor $g(z)$:

$$g(z) = 1 - f \frac{z}{1-z} \ln(1/z) \qquad (15)$$

Further investigations show that this suppression factor $g(z)$ is very insensitive to the shape of $f(z)$ and only changes very little by the production of several mesons in between as long as f denotes the mean number of such mesons. The form in eq. (15) also very accurately parametrizes the results of the Monte Carlo calculations discussed in the following section.

In fig. 2 we present estimates for p/h^+ and $\bar{p}/h^-$ and we see that the EMC data are well reproduced with $f \approx 1/2$ and $P(qq)/P(q) = 0.1$, i.e. the same values which fitted both high and low energy e^+e^- data.

4. Quantitative estimates from a Monte Carlo simulation

In order to study the consequences of the model in more detail we have implemented it within the framework of the Monte Carlo simulation program [19]. We have here assumed that a meson can be produced between a $\bar{B}$ and a B with probability f , but neglected the possibility to have two or more mesons. Adding av small probability for more mesons but with the same average number of mesons, f , would not modify the results significantly. Furthermore we expect a larger suppression for the heavier vector mesons to be produced in a $\bar{B}MB$ chain. This suppression is neglected and we thus let this extra amount of vector mesons simulate the neglected production of uncorrelated systems of two or three pions. In the Monte Carlo program f is an adjustable parameter, but the results presented below are obtained assuming $f = 0.5$ in accordance with the discussion in the previous section. For further details of the implementation we refer to the appendix.

From the discussion below we see that, apart from the effects discussed in section 3, very small differences are found between the new "popcorn model" and the old "diquark model".

A. Flavour composition

The particle production in the case of e^+e^--annihilation at 35 GeV (using second order QCD with parameters fitted to give good agreement with experimental data [19]) are presented in table 1. Here the full decay chains are taken into account so that e.g. the $p + \bar{p}$ figure also includes the decays from $\Lambda + \bar{\Lambda}$. The only significant difference between the two models is the enhancement of spin 3/2 baryons (Δ and Σ^*). This is due to a smaller suppression of spin 1 diquarks because they are no longer necessarily produced in pairs. It is possible to have a spin 1 diquark and a spin 0 antidiquark if they are separated by a meson. This can hardly be used to distinguish between the models, however, because we do not know accurately the magnitude of the spin 1 diquark suppression.

B. The momentum spectrum

The shape of the $p + \bar{p}$ momentum spectrum exhibits essentially no differences at 35 GeV between the models. We find that the $p + \bar{p}$ fraction of all charged hadrons increases with the momentum in accordance with

$0.2 < p \leq 0.4$ GeV/c	fraction 0.012
$0.8 < p \leq 1.2$ GeV/c	-"- 0.053
$2.0 < p \leq 3.0$ GeV/c	-"- 0.088
$5.0 < p \leq 7.0$ GeV/c	-"- 0.13
8.0 GeV/c $< p$	-"- 0.19

For a pure quark jet we obtain the result mentioned in section 3, i.e. the proton spectrum is unchanged while the antiproton suppression is well described by the function $g(z)$ in eq. (15)

C. Rapidity correlations

The baryons and antibaryons will of course come further apart in the popcorn model. Thus in a pure 2 jet system the average rapidity difference $\langle|\Delta y|\rangle$ for a $p\bar{p}$-pair with no meson in between is 1.1 whereas it is 1.6 for p and $\bar{p}$ which are part of a $BM\bar{B}$ system. However this is modified, firstly because at 35 GeV, in about 1/3 of the $p\bar{p}$ combinations the proton and the antiproton come from two different $B\bar{B}$-pairs, secondly because in 3- and 4-jet events the jet direction (or string direction) is not parallel to the experimentally

observable thrust axis. The result of this is that at 35 GeV $\langle|\Delta y|\rangle$ is only changed from 1.2 in the diquark model to 1.3 in the popcorn model.

D. Transverse momentum correlations

As a measure on the transverse momentum correlations we use here the average difference in the azimuth angle φ around the thrust axis for a proton and an antiproton. In the earlier diquark model the diquark and the antidiquark are assumed to have equally large but oppositely directed transverse momenta $\bar{k}_\perp$. In a pure 2-jet system a proton and an antiproton from one $B\bar{B}$-pair are therefore fairly well anticorrelated, with $\langle\Delta\varphi\rangle \approx 118^\circ$. This effect is diluted not only by protons and antiprotons from different $B\bar{B}$-pairs but also by the 3- and 4-jet events. As the jet axes in these cases are not parallel to the thrust axis, a proton and an antiproton in the same jet have a tendency to have parallel $\bar{p}_\perp$ with respect to the thrust axis. For these reasons $\langle\Delta\varphi\rangle$ is decreased to around 99° (or 96° if only protons with momenta below 4 GeV/c can be identified).

In the popcorn model the anticorrelation is reduced. In a $\bar{B}MB$-chain the baryon and antibaryon only share one quark and also this one has a strongly suppressed transverse momentum (cf eq. (10)). In the Monte Carlo we have neglected the $k_\perp$ of this quark, thus making these baryons totally uncorrelated ($\langle\Delta\varphi\rangle = 90^\circ$ for a pure 2-jet system), but the results are not changed much if it is allowed to have a small $k_\perp$. However, it is interesting to note that for this case there is a smaller tendency for gluon radiation to give a positive correlation of the transverse momenta. This follows from the fact that the B and $\bar{B}$ from a $BM\bar{B}$-chain are further apart in rapidity. If it is produced e.g. in the field between the quark and the gluon it may then frequently happen that the B is on the quark side of the thrust axis and the $\bar{B}$ on the gluon side, which tends to make them anticorrelated in $\vec{k}_\perp$. The result from the Monte Carlo is that for all $p\bar{p}$ combinations (including those from two different $B\bar{B}$-pairs) we get $\langle\Delta\varphi\rangle \approx 94^o$ as compared to $\langle\Delta\varphi\rangle \approx 99^o$ in the diquark model.

E. Flavour correlations

The $BM\bar{B}$ mechanism offers the possibility of producing baryon-antibaryon flavour combinations not possible in the $B\bar{B}$ one. There are two important smearing effects: subsequent decays of the primary baryons into the directly observed ones, and combinations between a B and a $\bar{B}$ coming from different pairs. For this, and for reasons of low rate, "testing signals" like $\bar{p}\Xi$ do not work. Only if it is possible to observe spin 3/2 baryons there is a testing signal from study of e.g. $p\bar{\Delta}$- or $\Delta\bar{\Delta}$-correlations. $(p\bar{\Delta}^+/p\bar{\Delta}^{--}$ is increased from 0.32 to 0.48 and $(\Delta^{++}\bar{\Delta}^o + \Delta^o\bar{\Delta}^{--})/(\Delta^{++}\bar{\Delta}^{--} + \Delta^o\bar{\Delta}^o)$ is increased from 0.06 to 0.26 when going from the diquark model to the popcorn model.)

5. Υ-decay

In the Lund model the $3g$ state obtained in Υ-decay is treated as a triangular closed string, with the gluons in the corners moving apart and stretching the stringlike force field. The field is thus a colour triplet field which breaks into pieces in just the same way as in a $q\bar{q}$ state, and the gluon fragmentation is completely determined from the quark fragmentation, with no extra freedom. However at Υ the invariant energy of two gluons is often so low that earlier Monte Carlo simulation programs have not been reliably applicable. In the latest version of the Lund Monte Carlo [19] it is however possible to treat gluon pairs with arbitrarily low invariant masses.

In table 2 we show results for the production of different particles in $3g$ decays and also in decays into $q\bar{q}$ systems in the continuum. For simplicity we have made all calculations at exactly 10 GeV with no contribution from $\Upsilon \to gg\gamma$. We have also studied the fragmentation of a gg system. With regard to multiplicity the results turn out to be almost exactly the same as for a ggg-system, and therefore e.g. the decay $\Upsilon(2S) \to \gamma + \Upsilon(1P) \hookrightarrow gg$ will give the same number of hadrons and the decay rates for $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ will all be equal.

The larger total multiplicity in ggg-fragmentation is due to the "longer" string for this case. For baryons there is an even larger difference because in the closed string there are no end regions with lower baryon production probability. This effect is very noticeable in the old diquark model and further enhanced in the popcorn model. The higher p/n ratio in continuum $q\bar{q}$ production is (at least partly) due to the $q\bar{q}$-pair being $u\bar{u}$ four times as often as $d\bar{d}$, and the higher Λ/p ratio in $q\bar{q}$ may be related to the production of Λ_c in $c\bar{c}$ events.

We note a very good agreement between the predictions and experimental data from the CLEO collaboration [15] both for the popcorn model and the old diquark model. Thus we can not regard this as a support for the popcorn model, but we do regard it as a support for the idea that a gluon can be treated as a transverse excitation on a stringlike colour triplet field. In case the three gluons stretched out colour octet fields, connected in a junction, then these fields would easily break by the production of gg pairs, and we would expect a significant production of glueballs or particles which mix with glueballs [20]. In that case it would be difficult to make firm predictions (they would e.g. depend on many mixing parameters), but we think that it would be a rather remarkable coincidence if both the total multiplicity and the rates for kaons and protons turned out to be the same as in our model based on a colour triplet field. (We notice that in our model the prediction for ggg fragmentation is completely fixed by the $q\bar{q}$ fragmentation with no extra freedom.)

Also in $q\bar{q}g$ events at PETRA or PEP energies the gluon jet contains a higher fraction of baryons than the other two. Considering three-jets only, with cut $T < 0.90$ on the parton level, the fraction of $p+\bar{p}$ of charged hadrons inside a 30° cone around the true jet axis is 5.4% for the q and $\bar{q}$ jets and 9.6% for the g jet, both for diquark and popcorn model. When we consider the ratio $(p+\bar{p})$/charged hadrons

for the whole event as a function of the experimental thrust values, the maybe expected enhancement at low thrust values is absent: the total multiplicity keeps pace with the $p+\bar{p}$ one. In addition, baryons are more frequent in low-multiplicity events, and these events also tend to have a thrust value closer to 1.

Appendix. Some remarks on the Monte Carlo simulation program

The baryon production model has been implemented within the framework of the Lund Monte Carlo (JETSET version 5.3) [19] which is available to the interested user. The "old diquark model" contains a number of parameters related to tunneling suppressions as follows:

$P_{qq} = P(qq)/P(q)$ determines the relative ratio of baryon production. For the diquark model we use the value 0.09 , whereas in the popcorn model this is increased to 0.10 so as to give the same overall baryon production rate.

$P_s = P(s)/P(u)$, the strange quark suppression is assumed to be 0.3.

$P_{qs} = (P(us)/P(ud))/(P(s)/P(d))$ is the extra suppression of a strange diquark in addition to the ordinary strange quark suppression, with assumed value 0.2 . In principle a further parameter would be necessary for the ss diquark suppression; since this is a very rare object anyhow, we use the expression $P(ss) = (P_s \cdot P_{qs})^2 P(uu)$, which is very close to the numerical result obtained with the tunneling formula.

$P_1 = (1/3)\ P(ud_1)/P(ud_o)$ the suppression of spin 1 diquarks, correcting for the factor of 3 coming from spin counting, is taken to be 0.05 .

Apart from these factors the probability to obtain a certain baryon is weighted by the probability that the diquark and the quark form a totally symmetric three quark system [6].

In the "popcorn" model it is possible to have a meson between the baryon and the antibaryon. In the Monte Carlo we neglect the (assumed small) possibility to have two or more mesons. On the other hand we have no extra suppression for the heavier vector mesons, and thus we let the somewhat overestimated production of ρ- and ω-mesons simulate the production of two or three uncorrelated pions. When the diquark and the anti-diquark only share one $q\bar{q}$-pair it is possible to have a strange diquark together with a nonstrange antidiquark or a spin 1 diquark together with a spin 0 antidiquark. Those cases are assumed to be suppressed by the square root of the factor for a strange or spin 1 diquark-antidiquark pair given above. The "popcorn model" also contains further extra parameters:

P_M is a parameter related to the possibility of producing a meson between the baryon and antibaryon, i.e. to have the $BM\bar{B}$ rather than the diquark model $B\bar{B}$ case. The actual rates obtained for the two depend somewhat on the other parameter values used; with the values above one approximately obtains $f = P(BM\bar{B})/(P(B\bar{B}) + P(BM\bar{B})) \approx P_M/(0.5 + P_M)$, such that the standard value $P_M = 0.5$ also corresponds to $f = 0.5$.

Because strange mesons are heavier than nonstrange, it is more difficult to have a strange meson between the $\bar{B}$ and B . The extra suppression in this case (P_{Su}) is estimated to be $P_{Su} \approx 0.5$.

According to eq. (10) it is more difficult for a heavier strange quark to "jump" over a meson. Thus the case when the $\bar{B}$ and B of a $\bar{B}MB$ configuration share an $\bar{s}s$-pair, is suppressed by a factor P_{Ms} which we estimate to be $P_{Ms} \approx 0.5$.

We note that although the Monte Carlo program contains many parameters, most of them control very rare events. Thus the result is generally very unsensitive to the values of these parameters. This is also seen from the usually small differences between the diquark and the popcorn models as discussed in section 4.

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Table 1 Particle production in e^+e^--annihilation at 35 GeV

particle species	number of particles per event: diquark model	popcorn model
all primary	10.3	10.2
all charged stable	13.3	13.3
$\pi^\pm$	10.8	10.8
$K^\pm$	1.47	1.46
p	0.71	0.71
n	0.62	0.63
Λ	0.22	0.22
$\Sigma^{+,0,-}$	0.096	0.091
$\Xi^{0,-}$	0.024	0.024
$\Delta^{++,+,0,-}$	0.26	0.42
$\Sigma^{*+,0,-}$	0.04	0.06

(p through $\Sigma^{*+,0,-}$: + antibaryons)

Table 2 Particle production at 10GeV

	ggg			$q\bar{q}$		
	diquark model	popcorn model	exp. Υ(1S)	diquark model	popcorn model	exp. cont.
N_{ch}	9.5	9.5	9.79±0.04±0.50	7.6	7.6	8.26±0.03±0.40
$\pi^\pm$	7.9	7.9		6.05	6.12	
$K^\pm$	0.92	0.88	0.991±0.027±15%	0.93	0.92	1.014±0.033±15%
$p,\bar{p}$	0.61	0.63		0.35	0.34	
(0.65<p<1.45 GeV/c)	0.35	0.34	0.245±0.005±20%	0.16	0.15	0.114±0.004±20%
$n,\bar{n}$	0.60	0.62		0.27	0.26	
$\Lambda,\bar{\Lambda}$	0.16	0.16	0.19±0.01±12%	0.12	0.12	0.080±0.008±12%
$\Sigma^{\pm,0}$ + antipart	0.08	0.08		0.05	0.05	
$\Xi^{0,-}$ + "	0.015	0.013		0.013	0.013	
Δ + "	0.24	0.45		0.10	0.13	
Σ^* + "	0.030	0.048		0.022	0.031	

Figure captions

Fig. 1 A colour field is stretched between a quark q and an antiquark $\bar{q}$. If virtual $q\bar{q}$-pairs are produced, the colour field can be changed from red-antired to green-antigreen or blue-antiblue. The direction of the field (going from triplet to antitriplet) is also changed. If a second pair is produced inside such a region the colour field can break and a $B\bar{B}$-pair can be produced. If two pairs are produced inside the region, the B and the $\bar{B}$ are separated in rank by a meson.

Fig. 2 Measurements of the ratios p/h^+ (O) and $\bar{p}/h^-$ (●) in μp-scattering from the EMC-collaboration [5] for $x_B > 0.2$. The lines --- and — are predictions from the old diquark model with $P(qq)/P(q) = 0.065$, modified accordning to the experimental acceptance. To estimate the results from the "popcorn model" with a larger value of $P(qq)/P(q) = 0.1$ we have for protons multiplied by $0.1/0.065$ and for antiprotons by $0.1/0.065 \cdot g(z)$, where $g(z)$ is the suppression factor in eq.(15). These predictions are shown by the lines -·- and ··· respectively.

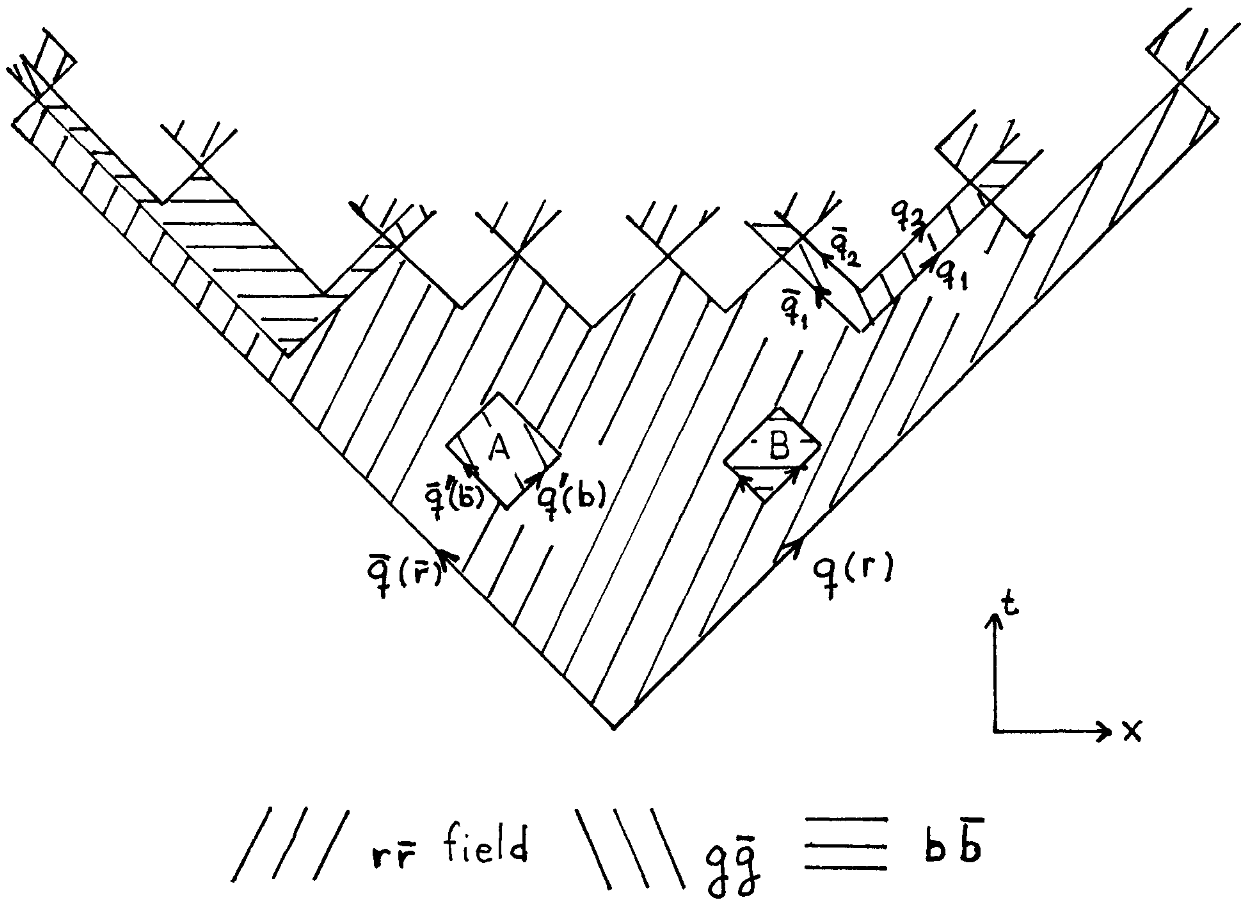
A
B
$\bar{q}''(\bar{b})$
$q'(b)$
$\bar{q}(\bar{r})$
$q(r)$
$\bar{q}_1$
$\bar{q}_2$
q_2
q_1
t
x
$r\bar{r}$ field
$g\bar{g}$
$b\bar{b}$

Fig. 1

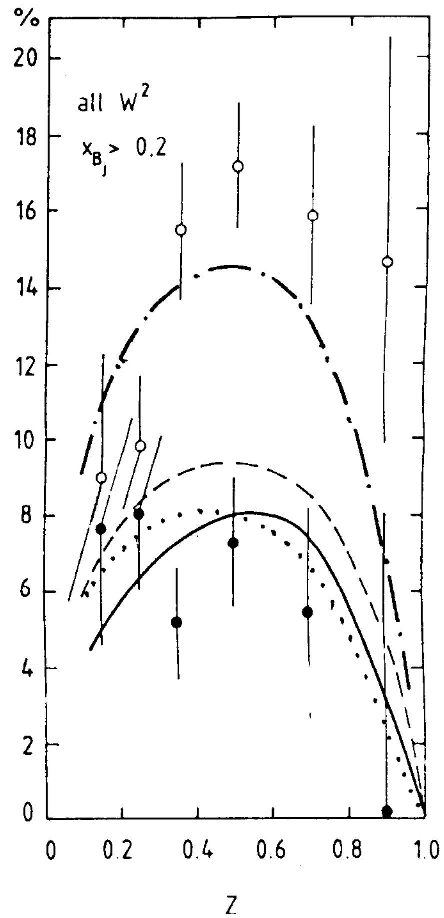
%
all W^2
$x_{B_j} > 0.2$
z
0
0.2
0.4
0.6
0.8
1.0
2
4
6
8
10
12
14
16
18
20

Fig. 2