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Colour Reconnections and Observable Features of Gluonic Colour Singlets in Z^0 Decays

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Abstract

When several identical colour charges appear in gluon cascades, problems arise in describing the confinement structure. In model descriptions of gluon emissions and how partons couple some approximations may be less accurate, and neglected contributions may become important when equal colour charges interfere. These charges give rise to new interesting connections between the partons which result in a different distribution of the hadrons which are finally produced.

Events which contain gluons with the same colour have some probability to form gluon singlets. Using the string picture several ways to draw the string are possible. A closed string of gluons can appear which would induce a gap in the rapidity distribution. This can be observed experimentally.

Colour reconnection may also be important in the perturbative cascade of gluons. A dipole description may not be a good approximation of the gluon emissions when identical colour charges arise. Reconnecting the colour charges during the cascade into new couples of colour and anticolour with less invariant mass may give a better approximation to the gluon emission. This reconnection may form a dipole chain with only gluons, which in a similar way as above would induce a rapidity gap which can be observed.

We will here present these two different models for forming gluonic colour singlets from $b\bar{b}$ and $c\bar{c}$ events produced by Z^0 decays at 91.2 GeV. In our simulation we have tried to select events which also are possible to identify experimentally. This presumes that the quark jet and the antiquark jet can be tagged. At present the tagging efficiency appears to be large enough to find an observable that demonstrates the existence of gluon singlets.

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1 Introduction

When a Z^0 is produced in a collision of an e^+e^- pair, at LEP1, this can decay into a $q\overline{q}$ pair (quark-antiquark pair) thus producing the $q\overline{q}$ pair at energies around 91.2 GeV. The energetic $q\overline{q}$ pair may emit gluons. When the quarks and gluons move apart the colour field can be described as concentrated in a linear so called 'colour flux tube' with constant energy density. This confined colour force field appears as a stringlike[3] structure which is stretched between the different colour charges, the partons. The string is stretched starting at the end with the quark and continues through all the gluons and ends up at the antiquark. Every string piece connects a colour with the corresponding anticolour. The gluons act like kinks in this chain, thus connecting two string pieces.

In string fragmentation, as described by the Lund model, the distribution of hadrons depends on how the strings are stretched. Given a $q\overline{q}g\ldots g$ system of two (or more) identical gluons, i.e. with the same colour, several ways of stretching the string are feasible. Then there are some more or less probable final states which one can obtain.

Study the process $e^+e^- \to q\overline{q}gggg$. To obtain the total cross section one squares the corresponding Feynman diagram which results in some orthogonal amplitudes and several interference terms. In descriptions of QCD cascades most interference terms are neglected. If planar[4] diagrams dominate, each Feynman diagram corresponds to a well defined connection between the gluons i.e. to a well defined string configuration.

Assume that in this way state (a) is obtained, see Fig 1. A knowledge[5] of quark and gluon colours specifies uniquely the stretching of the string if all the colours are different. When some of the gluons have identical colours other configurations might appear which are not negligible. The (b) configuration is only relevant if the gluons g_1 and g_2 have the same colour. This happens with a relative probability of order $1/N_c^2$, N_c is the number of colours.

One may also obtain two colour singlet systems as in (c) and (d). The anticolour of g_1 has to match the colour of g_2 to make these configurations possible. This happens with the same relative probability as before, of order $1/N_c^2$.

Thus when hadronizing the $q\overline{q}gggg$ state, using string fragmentation, it is not obvious which one of the configurations to choose. Using a Monte Carlo program we want to simulate different configurations, of special interest is if those like (c) and (d) above appear in Nature. Suppose that a configuration like (a) is given. We might reconnect this string into some of the other configurations provided that the relevant colour charges match. Configuration (c) and (d) in Fig 1 are both suppressed by approximately a probability factor of order $1/N_c^2$ compared to (a) due to the condition of matching anticolour and colour of the gluons g_1 and g_2. Besides this colour factor the reconnection probability may depend on dynamical effects. In perturbative QCD, states which correspond to 'short strings' are favoured. (With short strings we think of string states which produce few hadrons. Here we use the so

[3]The Lund model, see ref [1].

[4]As the name indicates these diagrams are possible to draw in one plane without any gluon (or quark) lines that cross each other.

[5]Obtained by perturbation theory.

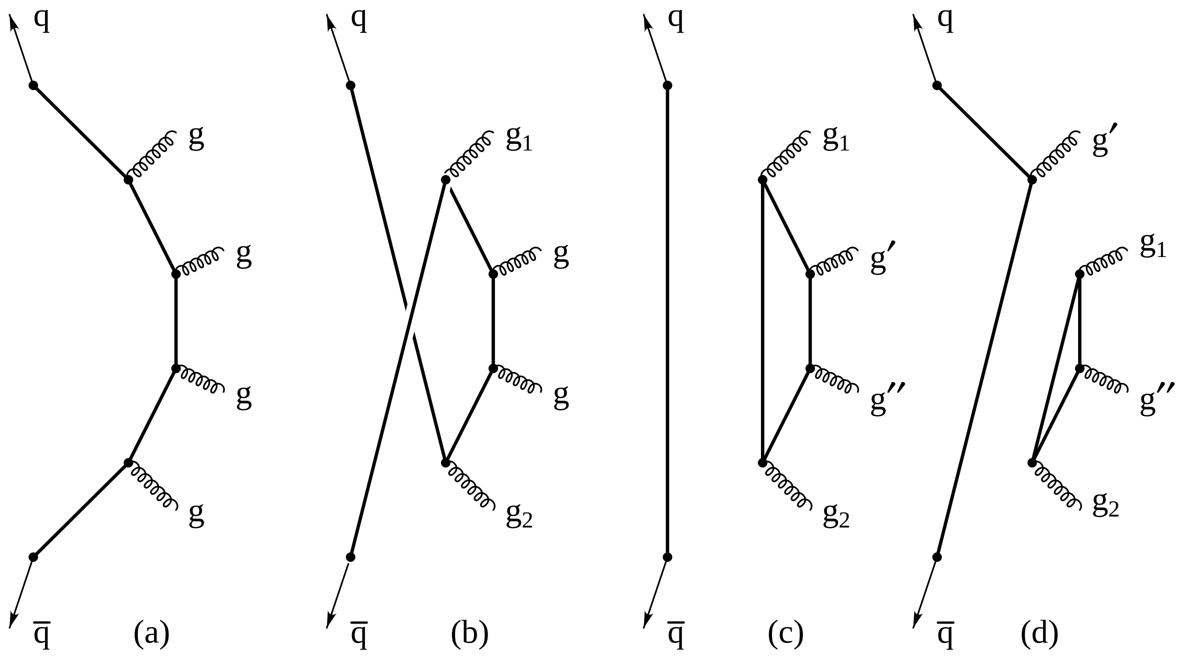

Figure 1: *Different string configurations for the process* $e^+e^- \to q\bar{q}gggg$*, only a few possibilities are shown.*

called lambda measure (see ref [2]) which corresponds to an effective rapidity length and is proportional to the expected hadron multiplicity.) If reconnection occurs it is conceivable that configurations with small lambda measures are favoured.

Is there any experimental signal for detecting these events? How do we find such a gluonic system? Our aim is to simulate gluonic singlets in Z^0 decays and to find a proper way to detect these events.

At LEP1 it was possible to study the reaction $e^+e^- \to q\overline{q}$ at energies around 91.2 GeV. We believe that events with two colour singlet systems may induce a rapidity gap between the two systems and thus give us an experimental signal that is detectable. Studying events with heavy flavours like $b\overline{b}$ and $c\overline{c}$ (beauty and charm) events makes it possible to experimentally distinguish the quark and the antiquark jets from a gluon jet in order to find a rapidity gap. The model in ref [3][6] could be extended to also include gluonic colour singlets.

2 Theory

In this section we will present some of the basic calculations that we have used in the implementation of our model.

[6]They study the reaction $e^+e^- \to W^+W^- \to (q_1\overline{q}_2)(Q_1\overline{Q}_2)$ and a possible recoupling of the $q\overline{q}$ pairs.

2.1 Colour singlets

Two gluons, each in a colour octet state, may together be in a colour singlet state with some probability. We will not calculate this probability explicitly, instead we will use some illustrative Feynman diagrams in order to calculate the relative probability. We symbolically write the different irreducible states of the two colour octets (the gluons) as

$$8 \otimes 8 \;=\; 1 \oplus 8_s \oplus 8_a \oplus 10 \oplus \overline{10} \oplus 27 \tag{1}$$

where 8_s, 8_a and $\overline{10}$ denote the symmetric octet, the antisymmetric octet and the antidecuplet states, respectively. All these states can be obtained if we apply the corresponding operator on the two colour octets. These operators (let us denote them $\Lambda_i,\ i = 1, 8_s, 8_a, 10, \overline{10}, 27$) are projector operators and satisfy the equalities

$$\sum_i \Lambda_i \;=\; 1 \qquad\qquad \Lambda_i^2 \;=\; \Lambda_i \tag{2}$$

The operation of Λ_1 (the singlet state projector operator) on the two gluon state is illustrated graphically in Fig 2. In the last step we have used that the square of the operator is the

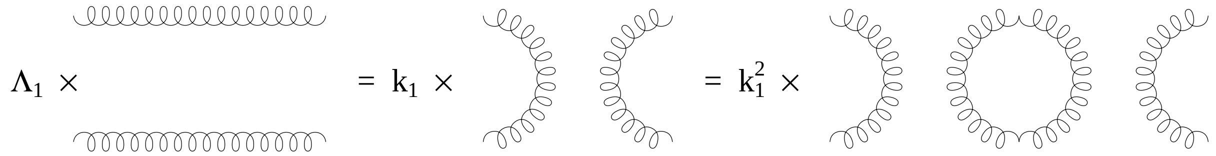

Figure 2: *Applying the singlet projector operator on two colour octet gluons, k_1 is a normalization factor.*

operator itself, Eq (2). The closed string that appears is in this representation[7] δ_{ii} is nothing more than the sum over the different colour states, $N_c^2 - 1$. Substituting this expression into Fig 2 it is easy to see that the normalization factor is $k_1 \;=\; 1/(N_c^2 - 1)$.

If we apply this singlet operator on the amplitude of two emitted gluons which belong to quark legs[8], as in Fig 3, we obtain the relative colour probability that the two gluons form a colour singlet state to be

$$\frac{singlet}{total} = \frac{1}{N_c^2 - 1} \tag{3}$$

In the last step of Fig 3 the two squared diagrams cancel because the diagram in the denominator can be rotated 90 degrees and gives exactly the same result as the other one. Thus it is a relative colour probability of $1/8$ ($N_c = 3$) for the gluons to form a singlet state.

[7]The size of our matrices are 8×8 with $N_c \;=\; 3$.
[8]The assigning of gluons is discussed in subsection 2.3.

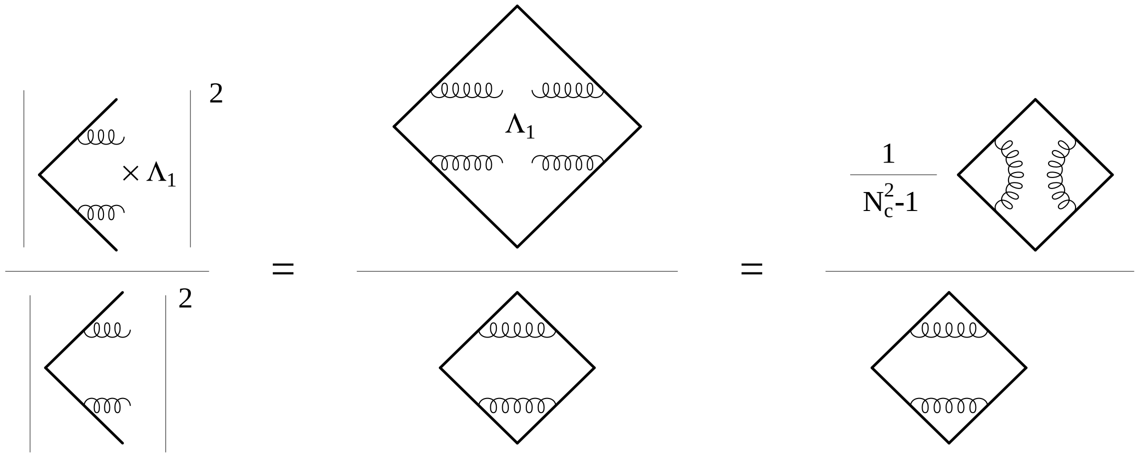

Figure 3: *The relative colour probability that two gluons emitted from fermions form a colour singlet state.*

2.2 Relative colour suppression of quark emitted gluons

Some QCD diagrams are exactly analogous to QED diagrams and a QCD cross section with quark-gluon vertices is obtained by the replacement $\alpha^n \to (C_F\alpha_s)^n$, where n is the number of quark-gluon vertices in the diagram. C_F is the relative quark-gluon coupling strength and has the value $\frac{1}{2}N_c(1-1/N_c^2)$. An e^+e^- pair radiates photons according to

$$dn = \frac{\alpha}{2\pi}\frac{x_1^2+x_3^2}{(1-x_1)(1-x_3)}dx_1dx_3 \tag{4}$$

where x_1 and x_3 are the scaled momenta of the electron and the positron respectively. By making the replacement $\alpha \to C_F\alpha_s$ we obtain the gluon radiation distribution of a high energy $\mathrm{q\overline{q}}$ pair. For the first gluon the transverse momentum $k_\perp$ and the rapidity y are defined by

$$k_\perp^2 = s(1-x_{\mathrm{q}})(1-x_{\overline{\mathrm{q}}}) \qquad\qquad y = \frac{1}{2}\ln\frac{(1-x_{\overline{\mathrm{q}}})}{(1-x_{\mathrm{q}})}, \tag{5}$$

which are Lorentz invariant quantities and the Mandelstam variable s is the square of the total *cms* energy. Energy conservation implies that $x_{\mathrm{q}}+x_{\mathrm{g}}+x_{\overline{\mathrm{q}}}=2$. For soft gluons, small x_{g}, we get $x_{\mathrm{q}}+x_{\overline{\mathrm{q}}}\approx 2$ and with the variable substitution $\kappa = \ln k_\perp^2/\Lambda$, together with Eq (5), the radiation from a $\mathrm{q\overline{q}}$ dipole modifies to

$$dn \approx C_F\frac{\alpha_s}{\pi}d\kappa dy \overset{\frac{1}{N_c^2}\to 0}{\longrightarrow} dn \approx N_c\frac{\alpha_s}{2\pi}d\kappa dy\,. \tag{6}$$

Also the emitted gluons carry charges which complicates the picture. This is solved by approximating with two colour dipoles, one between the quark and the gluon and another between the gluon and the antiquark, which emit gluons independently of each other. In the rest frame of each dipole the distribution looks like Eq (6). There is also a correction term corresponding to a $\mathrm{q\overline{q}}$ dipole which has the relative weight of -$1/N_c^2$.

Making use of $k_\perp \lesssim \sqrt{s} \cdot e^{-|y|}$ which is given by energy-momentum conservation we may write the phase space for the hardest gluon as

$$|y| < \frac{1}{2} \ln \frac{s}{k_\perp^2} \qquad\qquad \kappa = \ln \frac{k_\perp^2}{m_0^2}. \tag{7}$$

This is a triangular region in the (y, κ)-plane, Fig 4. m_0 is a hadronic mass scale. We restrict

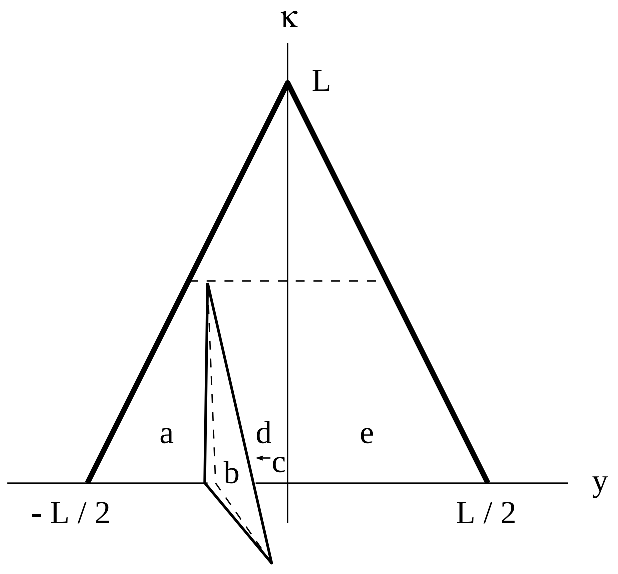

Figure 4: *Available phase space for a second softer gluon, the folded area corresponds to the first emitted gluon.* $L = \ln(s/m_0^2)$. *In surface d the gluon and the antiquark radiate coherently with a total colour charge that corresponds to the parent antiquark.*

every subsequent gluon to carry less transverse momentum[9] (softer) than the former one, i.e. $\kappa_i > \kappa_{i+1}$. Every gluon increases the phase space for further gluon emission. After one gluon has been emitted two dipoles arise, corresponding to the areas a+b and c+d+e.

The probability density of having a gluon at (y', κ') is proportional to α_s. The relative quark-gluon coupling strength is $C_F = \frac{1}{2} N_c(1 - 1/N_c^2)$ and the relative gluon-gluon coupling strength is N_c (C_A[10]). This gives rise to a relative suppression of the surfaces a,d and e compared to b and c which corresponds to the gluon. That is, the density in the gluon surfaces is $N_c\alpha_s/2\pi$ and in the quark surfaces it is reduced to $N_c(1-1/N_c^2)\alpha_s/2\pi$. Neglecting the term $-1/N_c^2$ we get the same density for quarks and gluons.

A gluon emitted from the surface d in Fig 4 is in a sense emitted from the combined antiquark-gluon jet. The smaller rapidity in this surface implies that it will get a larger opening angle[11] compared to the first gluon. Due to colour coherence[12] of the combined jet it will emit gluons

[9] In the rest frame of the emitting dipole.
[10] These relative strengths are by convention denoted by the Casimir factors C_F and C_A.
[11] Referred to the initial jetaxis ($q\bar{q}$).
[12] See ref [4].

as a colour charge that effectively corresponds to the colour of the initial antiquark. Hence it follows that it is possible to treat emissions from the surface d as emitted from an antiquark, a method to do this will be described in the next subsection.

In the string picture hadrons are produced when breaking the string which is stretched between the colour charges. A larger string results in more hadrons. In this way it is easy to imagine that the average hadron multiplicity is proportional to the length of the baseline (in Fig 4) at $k_\perp^2 = m_0^2$. In ref [2] the lambda measure is introduced which can be interpreted as an effective rapidity range.

$$< n >_{\text{hdr}} \sim \lambda \equiv \ln \frac{s}{m_0^2} + \sum_{i=1}^{n} \ln \frac{k_{\perp i}^2}{m_0^2} = \sum_{i=1}^{n-1} \ln \frac{(p_i + p_{i+1})^2}{m_0^2} \tag{8}$$

The term $\ln(s/m_0^2)$ is just the length of the baseline between the quark-antiquark and we count the baseline of the folded areas twice, that is, the baselines of surfaces b and c in Fig 4.

2.3 The association of gluons

Using a dipole description of the gluon emissions one looses information about the history of the gluon since the gluon is emitted by a colour dipole, two colour charged partons moving away from each other. In our model it is very important that we know if the latest emitted gluon belongs to a gluon or if it belongs to a quark (the following discussion is analogous for an antiquark). There are two reasons for this. First, we want to suppress the gluons that belong to a quark leg, as was discussed in subsection 2.2. The second reason is that a mother and daughter gluon is always in a colour octet state, since the mother gluon was a colour octet before the emission. Hence, a singlet state can never be formed with just these two gluons. On the other hand, each one of these gluons can match the colours with other gluons in such a way that a closed string can be stretched to form a colour singlet system.

Ariadne [5] generates QCD cascades with the colour dipole model, unfortunately an emitted gluon does not carry information about its parent parton. Now, consider the two systems in Fig 5, it shows two different cases for a new gluon to be emitted. The assigning of the gluon to a parton can be done as follows. In the left hand system of Fig 5 the new gluon g_{new} has been emitted between the quark and a gluon, let us call this gluon the mother gluon. The momentum of the quark, $\mathbf{q}$, is chosen to be along the z-axis. We rotate the frame in order to get the momentum of the mother gluon, $\mathbf{g}$, in the xz-plane. The emitted gluon has momentum $\mathbf{p}$, see Fig 6. Now, make a Lorentz transformation to a frame where the mother gluon becomes parallel to the x-axis. This new frame has a velocity g_3/g_0 (g_0 is the energy of the mother gluon) relatively the old frame. In this new frame (primed coordinates and momenta) we associate the emitted gluon to the mother gluon if its components satisfy

$$p_3' < p_1' , \tag{9}$$

otherwise the emitted gluon belongs to the quark. If we express Eq (9) in the unprimed coordinates the inequality looks like

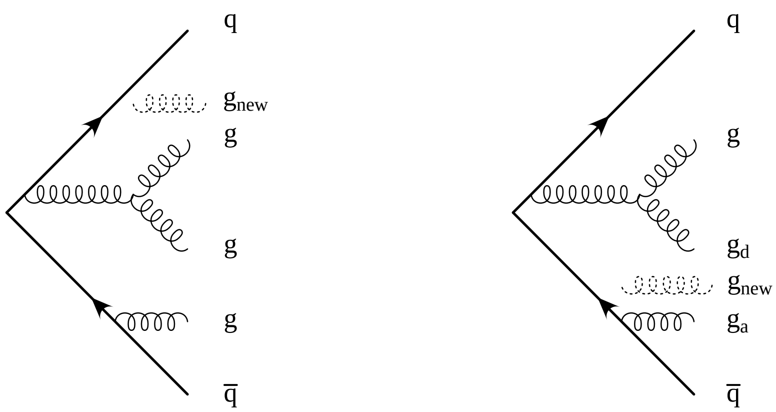

Figure 5: *The latest emitted gluon has to be associated to the correct parent parton.*

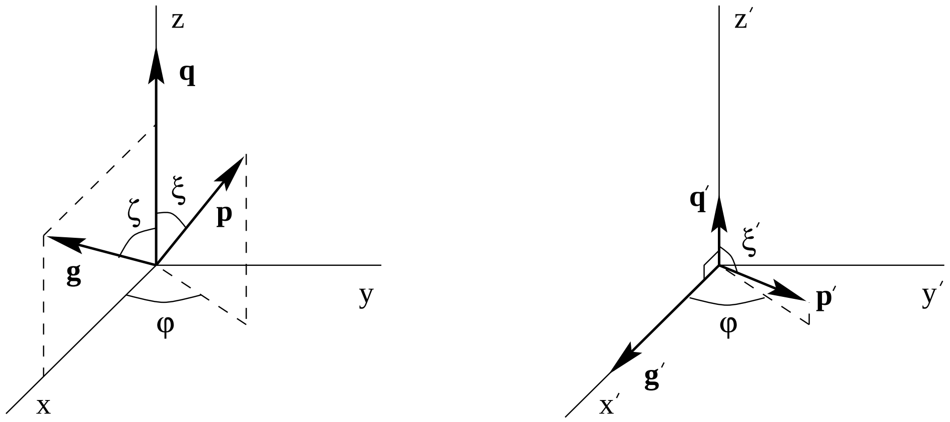

Figure 6: *Special Lorentz frames studied to associate a newly emitted gluon* **p** *to a quark* **q** *or a gluon* **g**.

$$p_3' \ = \ \gamma\,(p_3 - \frac{g_3}{g_0}\,p_0) \ < \ p_1 \qquad\qquad \gamma \ = \ \frac{1}{\sqrt{1-(\frac{g_3}{g_0})^2}} \tag{10}$$

since $p_1' = p_1$ under a Lorentztransformation along the z-axis. Expressing the original frame in polar coordinates

$$\left\{ \begin{array}{rcl} g_0 & = & |\mathbf{g}| \\ g_1 & = & |\mathbf{g}|\ sin\,\zeta \\ g_2 & = & 0 \\ g_3 & = & |\mathbf{g}|\ cos\,\zeta \end{array} \right. \qquad \left\{ \begin{array}{rcl} p_0 & = & |\mathbf{p}| \\ p_1 & = & |\mathbf{p}|\ sin\,\xi\ cos\,\varphi \\ p_2 & = & |\mathbf{p}|\ sin\,\xi\ sin\,\varphi \\ p_3 & = & |\mathbf{p}|\ cos\,\xi \end{array} \right.$$

and substituting this into the inequality above, one gets an expression like

$$cos\,\xi - cos\,\zeta - sin\,\xi\ sin\,\zeta\ cos\,\varphi \ < \ 0 \tag{11}$$

where the angles ζ and ξ are given by the scalar product between the quark momentum and each gluon's momentum respectively, see Fig 6. The x and y components of the emitted gluon's momentum can be used to calculate φ. If the left hand system in Fig 5 satisfies the inequality in Eq (11) then we associate g_{new} to the mother gluon otherwise the association is done to the quark.

Consider the system $q\overline{q}gg$, the phase space for a third softer gluon is shown in Fig 7. In the colour dipole model we will get contributions to the gluon emission from three different

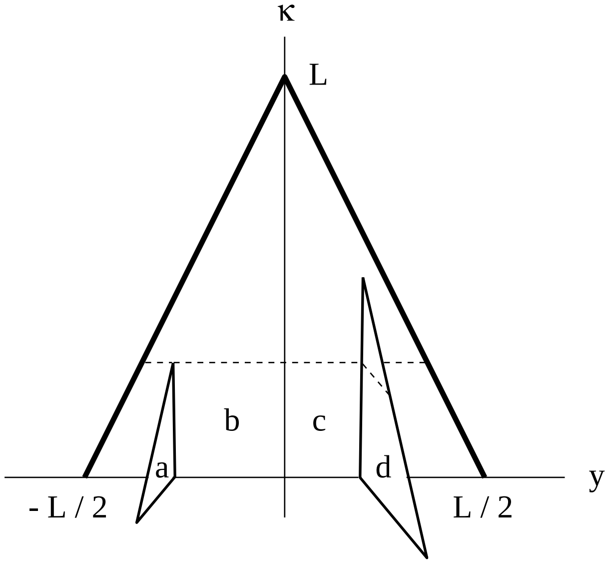

Figure 7: *The phase space for a third softer gluon. A gluon emitted from a gluon-gluon dipole, can be effectively emitted from a quark charge or an antiquark charge, surface c or d.*

dipoles, $\overline{q}g$, gg and gq. A correction term corresponding to a $q\overline{q}$ dipole has the relative weight of $-1/N_c^2$. Thus the surfaces in Fig 7 have different relative weights to emit a gluon. If the two folded triangles, corresponding to the gluons, have the weight 1 then the background surface of the large triangle has the weight 8/9. A gluon emitted from the gluon-gluon dipole can be effectively emitted from a quark charge, namely a gluon emitted from the surface c. Remember that a subsequent gluon has less transverse momentum $k_\perp^2$, lower κ, than the previous ones and thus only the surface below the dashed line is relevant.

Let us go back to the right hand system in Fig 5. In contrast to the left hand system we now have a gluon on each side of g_{new}. We want to make use of the inequality above and to include the correction term. We divide the problem in two parts. First, the momentum of the gluon above the emitted gluon g_d is denoted $\mathbf{g}$. Then we decide whether g_{new} is emitted from g_d or from the $(g_a, \overline{q})$ system. This separates surface d from a+b+c in Fig 7. The gluon g_a and the antiquark $\overline{q}$ is treated as one system with momentum $\mathbf{q}$. Using the inequality above we can assign the emission of the gluon g_{new} to either the gluon g_d, corresponding to a surface d in Fig 5, or to the $(g_a, \overline{q})$ system. If the gluon was associated to the $(g_a, \overline{q})$ system it may belong to either the gluon g_a or an antiquark charge which corresponds to a antiquark-gluon system which radiates coherently.

The second part is to check if the gluon g_a was the parent parton. (This will be a double check if g_{new} was assigned to g_d, if not we might determine g_a or a $\overline{q}$ charge as the parent.) The preceding method is used but now the momentum of g_a is denoted **g** and the remnant (g_d, g, q) have momentum **q**. Thus seperating surface a from surfaces b+c+d. With the above inequality we can decide if g_{new} was emitted from the gluon g_a or the (g_d, g, q) system. An association to the (g_d, g, q) system may imply that it belongs to the gluon g_d but in that case the first check would have confirmed that.

If no association has been done to neither g_d or g_a, corresponding to surfaces like a and d in Fig 5, then the gluon g_{new} was emitted from an effective colour charge corresponding to the total charge of system $(g_a, \overline{q})$ or (g_d, g, q). This would correspond to surfaces like b and c in Fig 7 which is the negative correction term corresponding to a $q\overline{q}$ dipole.

3 Implementation

Z^0 decays at 91.2 GeV were generated using Jetset (version 7.4, ref [6]) producing a $q\overline{q}$ pair with a natural mixture of flavours. Only events with flavours $b\overline{b}$ and $c\overline{c}$ were analyzed. The gluon emissions were generated within Ariadne (version 4.07, ref [5]) and finally the hadronization was done within Jetset.

Our model takes care of the assignment of the emitted gluons and checks the possibility of reconnecting the string and possibly it forms gluon singlets. After fragmenting the string the event is rotated into a specific direction. Along this direction the charged rapidity distribution and the charged multiplicity (in a special rapidity interval) are analyzed.

Two different models of forming gluon singlets were used, one after the gluon cascade and the other continuously during the cascade.

3.1 The post cascade model

After the gluon cascade from the $q\overline{q}$ pair we can use the string picture to describe the colour field. The quark emitted gluons have been suppressed relative to a parent gluon with a factor 8/9 (subsection 2.2 and 2.3). In the large N_c limit, an infinite number of colours, there is one unique way for the string to couple the partons. In Ariadne the colour dipole model is used with dipoles connecting the partons in a similar way as string pieces build up a string. Going from Ariadne to Jetset a particular string configuration is chosen.

When several identical colours appear we study the string configuration with the smallest λ. Since we believe that states with short strings may be favoured (from perturbative QCD). Colours and anticolours have to match of course. If this configuration differs from the initial one, reconnection of the string pieces is performed and we look for an observable indication of formed gluonic colour singlets.

A limitation of this model is the gluon association. We suppressed gluons that belonged to quark-antiquark leg but, for simplicity, we did not keep track of which gluons had a mother-daughter relation. However, in this model we have in average 10 emitted gluons in the cascade for those events that reconnect and survive the angular cut i.e. events which would be analyzed. A few recouplings contain a mother and a daughter gluon that can not form a colour singlet. Together they do form a colour octet, no doubt, but connected with other gluons they are able to form a singlet state. Therefore we believe that this contribution is negligible due to the many gluons in the cascade[13].

The hadronization of the formed colour singlet systems is performed independently[14] of each other.

3.2 The continuous model

The idea of this model is as follows. Consider a system $q\overline{q}gg$. If the colour of one gluon matches the anticolour of the other gluon, the emission can not be described as a set of independent dipoles. Study the colour content of the left hand system in Fig 8. If we want

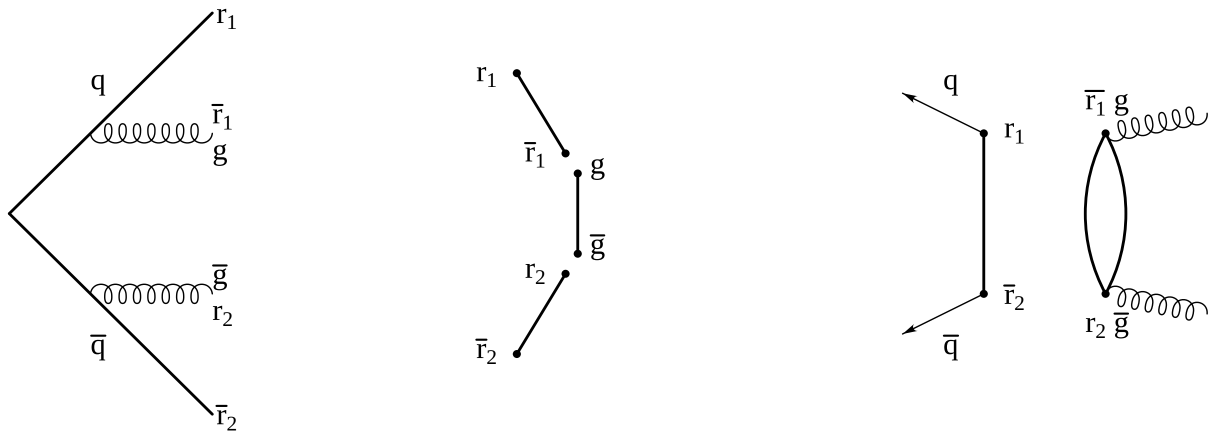

Figure 8: *The continuous model. Reconnecting the colour charges during the cascade of gluons may form a dipole chain with only gluons, as in the right hand system.*

to approximate the gluon emissions with a set of independent dipoles we expect to get the best approximation if we take those couples of charge and anticharge which are closest each other. This also implies that the invariant mass of the couple is small, which implies that this combination of charges corresponds to a small lambda measure.

The charges $r_1\overline{r}_1$, $g\overline{g}$ and $r_2\overline{r}_2$ would correspond to the qg, gg and $g\overline{q}$ dipoles, respectively. If r_1 and $\overline{r}_1$ are close to each other and well separated from the couple $r_2\overline{r}_2$ which also are close

[13]In the other model this would not be negligible since the larger part of the reconnected events happens with few gluons, already with just two.

[14]Actually, we fragment the different singlets in a common lujets in order to conserve energy, sometimes, in our model, energy has to tunnel between the singlet systems. In Nature the formed singlet would be quantized correctly instantly.

to each other we may approximate their gluon emission as two independent dipoles. These dipoles can normally be treated as independent since one dipole seems to be colour neutral for other dipoles. In situations where the couples $r_1\bar{r}_2$ are $r_2\bar{r}_1$ are closest to each other a better approximation might be to treat these two couples as independent dipoles.

Assume that the $r_1\bar{r}_2$, $g\bar{g}$ and $r_2\bar{r}_1$ dipoles are obtained in this way and can be treated as independent. This would correspond to a rearrangement of the dipole chain, which eventually can give a purely gluonic system as the gg singlet in the right hand system in Fig 8.

The probability for rearrangement of the dipoles might be enhanced if the lambda measure will decrease for the rearranged configuration. When two gluons are emitted a reconnection of the string pieces is allowed if both gluons belong to a quark leg and if the colour and the anticolours match. This happens with a probability 1:8, see subsection 2.1. A mother and a daughter gluon are always in a colour octet state and therefore they can never reconnect into a singlet.

We use Ariadne to emit gluons one by one, we check the parent parton and if it belongs to a quark leg (or a antiquark leg) we suppress it with a relative probability of 8/9 i.e. in one of nine emissions from a quark we reject the gluon and initiate the system as it was before the emission. Continuously we investigate the possibility to form gluon singlets (or other reconnected configurations) which gives a smaller λ for the system. Now, if the conditions for forming gluon singlets are satisfied we recouple the dipole chain (several combinations may appear) and calculate the lambda measure to compare it with the initial configuration. The configuration which gives the lowest lambda measure, i.e. has the shortest string length, will be chosen. This may of course be the initial configuration. The singlet systems continue emitting gluons separately.

If the lambda measure did not decrease or some of the other conditions failed then if there is enough energy a new gluon is emitted. We proceed as above, measure λ, reconnect, etc until we reach the cutoff in the cascade ($k_\perp \approx 1$ GeV) and no more gluons are emitted. Two gluons that earlier were in a colour octet state are not allowed to reconnect. The $q\bar{q}$ system may reconnect once more following the method above.

At this point we have several or just one colour singlet system. We fragment these singlets into hadrons within Jetset.

3.3 Event analysis

In both models mentioned above we want to study special events where we could find effects of our possibly formed singlet configurations. When studying the rapidity distribution of charged particles we rotate the z-axis of our initial system to be along a special axis. This special axis is chosen as the summed momentum direction of the quark and the antiquark, see Fig 9. A restriction of the angle between the quark-antiquark is used in order to obtain events where the gluonic singlet is well seperated from the remnant, the $q\bar{q}$ system. The rapidity of the charged particles (it would of course be possible to include π^0) along the modified z-axis is measured and stored in a corresponding rapidity bin. We count the number of charged

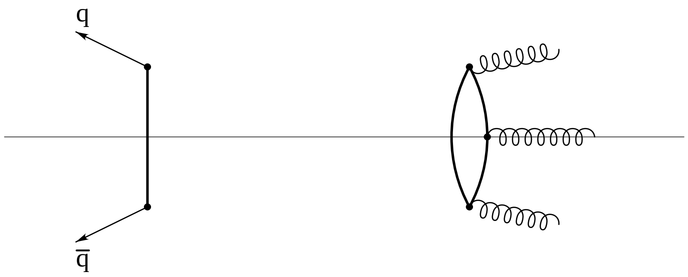

Figure 9: *Events like these might be identified with a rapidity gap.*

particles in a special rapidity interval for each event, this give us the charged multiplicity. Choosing a proper interval hopefully results in a large probability to have few particles in this region, i.e. an indication of a rapidity gap due to the formed gluonic singlets.

4 Results

When forming gluon singlets from our $q\overline{q}g\ldots g$ events we require the lambda measure to decrease. As discussed earlier this will give us fewer hadrons. Thus introducing gluonic colour singlets decreases the average multiplicity of charged particles. To reproduce a good description of the LEP data, which Jetset and Ariadne are known to do, we can adjust some of the parameters of the string fragmentation in Jetset. By tuning some of the parameters we obtain the correct average multiplicity of charged particles, mean number of jets, average transverse momenta etc and our distribution of the charged multiplicity is maintained, slightly different.

We have searched for specific events where the gluon singlets are well separated from the remnant system. Restricting the quark-antiquark to be within an angle of about $\pi/2$ radians enhances the possibility to detect the rapidity gap. It will select events with quark-antiquark-jets pointing more in a common direction than back-to-back and with an eventually formed gluon singlet a rapidity gap could appear. Choosing a proper rapidity interval will give a large probability to find no particles in this interval.

We have chosen the allowed angle region to be less than 110 degrees. Using this angular cut instead of, for example, 90 degrees we get almost twice as many accepted events. Allowing much larger angles gives us too many events with lots of particles in the central region of the rapidity distribution.

Looking at the rapidity distribution in Fig 10 one sees that the interesting interval for obtaining a rapidity gap is somewhere in the central region. We have analyzed the charged multiplicity in different rapidity intervals, large and small, and we found out that in the interval [-1,0] there is a large probability to find few particles, see Fig 11.

Experimentally it is sometimes hard to distinguish a quark jet from a gluon jet. Depending

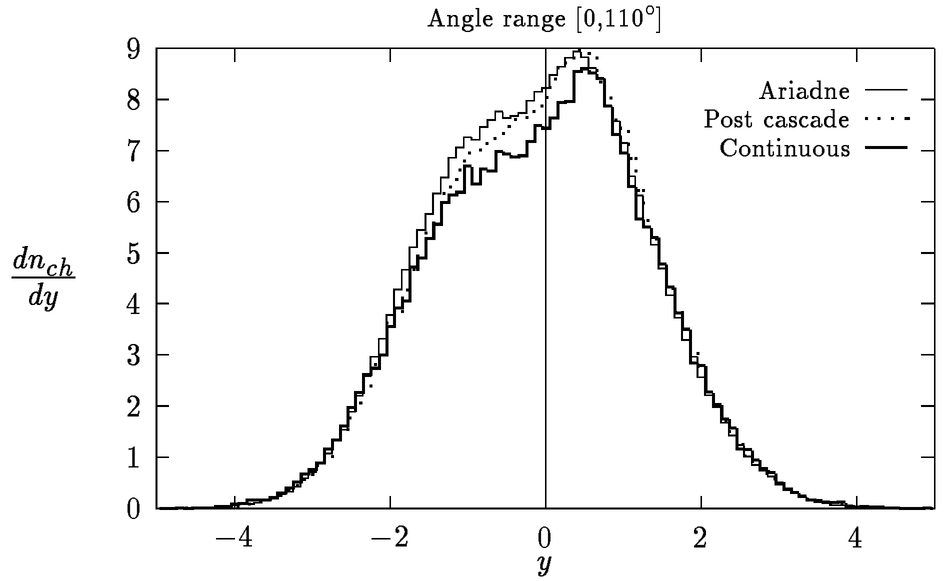

Figure 10: *Rapidity distribution of charged particles, default Ariadne, the post cascade model and the continuous model. Both our models are retuned i.e. with no angular restriction they reproduce the expected distribution. The distribution is normalised w.r.t. accepted events. Of one million Z^0 decays $b\bar{b}$ and $c\bar{c}$ events are analyzed. The rapidity is measured along the direction of the summed $q\bar{q}$ momenta.*

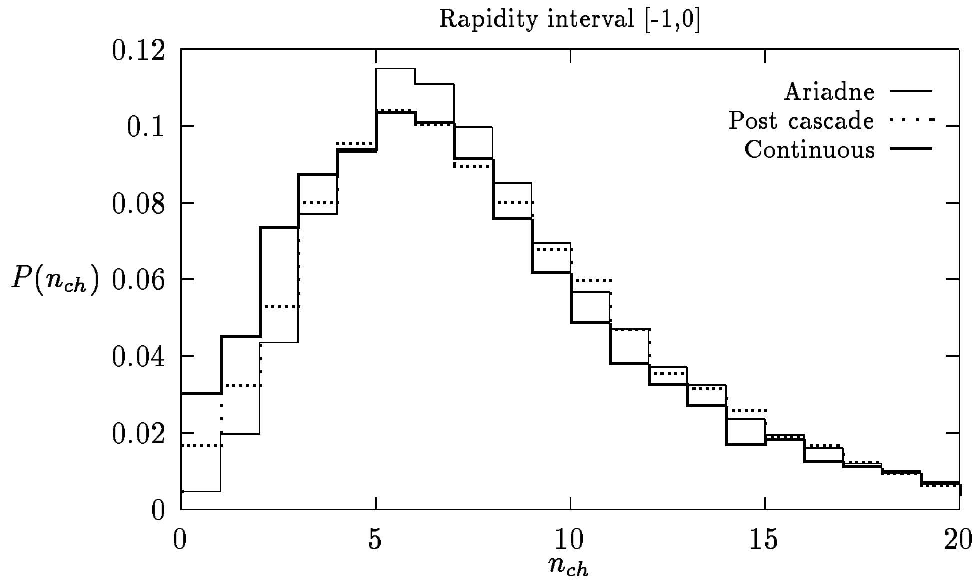

Figure 11: *Charged multiplicity in the rapidity interval [-1,0], default Ariadne, the post cascade model and the continuous model. Both our models are retuned. The distribution is normalised w.r.t. accepted events.*

on which method is used different problems arise. Using heavy quarks as b and c makes it possible to identify the quark-antiquark jets. We do not have to distinguish between b and c quarks, which gives more statistics and increases the tagging rate.

To compare our data we also generated Z^0 decays with default Ariadne i.e. with no rearrangement. In Fig 10 and 11 the obtained rapidity distributions and the charged multiplicities are shown. (The reconnection models have both been retuned. They reproduce the same data as default Ariadne when studying all $b\overline{b}$ and $c\overline{c}$ events i.e. we have no angular restriction between the quark-antiquark.)

Of one million Z^0 decays we restrict us to analyse $b\overline{b}$ and $c\overline{c}$ events. With the angular cut mentioned above about 12 000 events of the post cascade model survive these demands, approximately the same for default Ariadne and about 10 000 events of the continuous model. These data for the reconnection models contain a mixture of 'normal' and recoupled events. The post cascade model has 17 % of the total number of $b\overline{b}$ and $c\overline{c}$ events recoupled, while we obtain 11 % for the continuous model.

The probability to find no charged particles in the rapidity bin [-1,0] for each model are

$$\mathbf{P}^{\text{Post cascade}}_{[-1,0]}(\mathrm{n_{ch}} = 0) = 0.018 \quad \mathbf{P}^{\text{Continuous}}_{[-1,0]}(\mathrm{n_{ch}} = 0) = 0.030 \quad \mathbf{P}^{\text{dflt Ariadne}}_{[-1,0]}(\mathrm{n_{ch}} = 0) = 0.005\,.$$

This gives a factor 3.6 between our post cascade model and default Ariadne. The continuous model is a factor 6 larger than default Ariadne. We see from Fig 11 that it is a significant difference in probability also for fewer than five particles in this rapidity interval, enhancing the possibility to detect it experimentally.

About 38 % of the Z^0's decay into $b\overline{b}$ and $c\overline{c}$ events. The probability that these events survive the angular restriction $\theta_{q\overline{q}} < \theta_{cut} = 1.92$ (110°) is approximately

$$\mathbf{P}^{\text{Post cascade}}_{\theta_{\mathrm{q\overline{q}}} < \theta_{\mathrm{cut}}} = 0.032 \quad \mathbf{P}^{\text{Continuous}}_{\theta_{\mathrm{q\overline{q}}} < \theta_{\mathrm{cut}}} = 0.025 \quad \mathbf{P}^{\text{dflt Ariadne}}_{\theta_{\mathrm{q\overline{q}}} < \theta_{\mathrm{cut}}} = 0.032\,.$$

Assuming that the tagging efficiency for $b\overline{b}$ and $c\overline{c}$ jets are 10 % together, we expect, to find 58 and 75 events with the post cascade model and the continuous model, respectively. A background of 16 events is obtained from non recoupled events. These data are shown below together with their estimated errors, simply the square root of the obtained number of events.

$$10^6 \cdot \mathbf{P}_{\theta_{q\overline{q}}<\theta_{cut}} \cdot \mathbf{P}_{[-1,0]}(n_{ch} = 0) \cdot 0.10 \; = \; \begin{cases} 58 \;\pm\; 7.6 \; events & Post\ cascade \\ 75 \;\pm\; 8.6 \; events & Continuous \\ 16 \;\pm\; 4.0 \; events & default\ Ariadne \end{cases}$$

Lönnblad [7] has implemented a method for reconnecting colour dipoles in Ariadne, v4.07, see Fig 12. This is similar to our continuous reconnection. He studied average distributions and for these he obtained an undetectable effect after retuning. With our special method to select interesting events his implementation gives a result similar to our post cascade model. His model might also survive retuning for these special events. Notice that no recoupling model in Fig 12 has been retuned (except default Ariadne), in order to compare them.

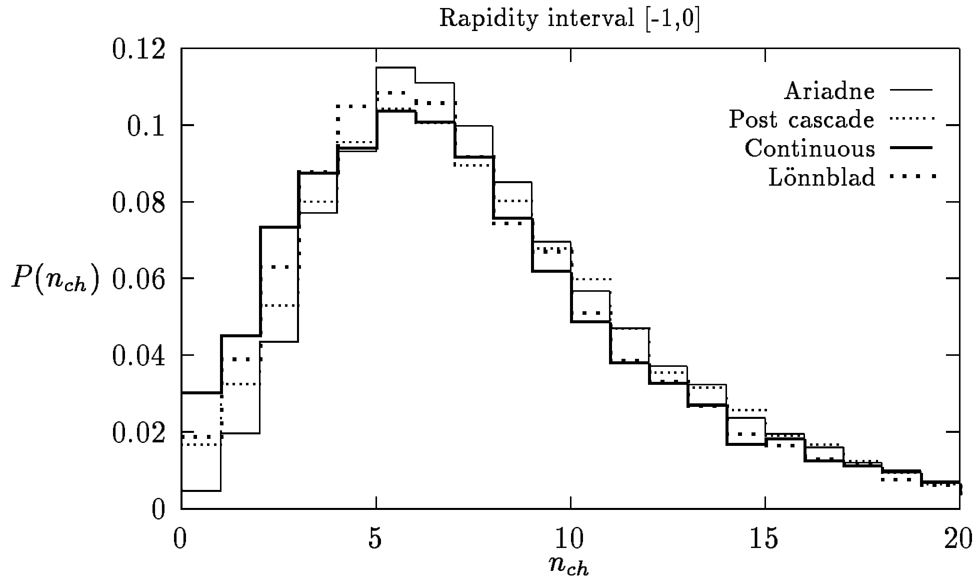

Figure 12: *Charged multiplicity in the rapidity interval [-1,0]. The distribution is normalised w.r.t. accepted events. The three reconnection models have not been retuned.*

In the model by Lönnblad the negative correction term from the $q\bar{q}$ dipole is neglected. A simplified treatment of the association between a mother and daughter gluon is used and no relative suppression for the gluons emitted from quark-gluon systems with effective quark charges. Thus the emission in surfaces b and c in Fig 7 is always associated with one of the gluons forming the emitting dipole. Using our assigning of the gluons results in more quark associated gluons which give rise to more possibilities to form gluon singlets.

5 Conclusions

There is a limited knowledge of the confinement structure in processes like $e^+e^- \rightarrow q\bar{q}g\ldots g$ when identical colour charges arise. The transition from a Feynman diagram to a string configuration is not straight forward, several possibilities are conceivable since equal colour charges imply several ways to connect the partons. Of the possible configurations we investigate the state which give the smallest string length, as states with short strings may be favoured. Some of these connections may form states with closed strings containing gluons. These gluon states may be well separated from the remnant system and can be observed as a rapidity gap.

A similar reconnection as above may be performed during the gluon emissions i.e. in the perturbative region. Approximating the emission with dipoles, Ariadne [5], is known to reproduce experimental data very well. If equal colour charges arise during a gluon cascade the emission of gluons can not be fully described by dipoles. If we want to use a dipole description it may give a better approximation if we reconnect the charges into dipoles with small invariant masses. This would connect the dipoles into a shorter dipole chain which also may form a colour singlet of gluons.

Restricting the quark and antiquark to have an angle less than 110° between their momentum directions selects events which may have a large rapidity gap. Studying the rapidity interval [-1,0] one notices that there is a large probability for having few particles in this region.

From one million Z^0 decays we expect from our post cascade model to find 58 $b\overline{b}$ or $c\overline{c}$ events with no particle in the rapidity bin [-1,0]. They also satisfy the angular restriction above. The continuous model gives, with the same demands, 75 events. Of these can we expect that 16 events are from the background i.e. obtained not using colour reconnection.

We conclude that with the proposed observable one could confirm whether gluonic singlets appear in Nature or not. A knowledge of how the multiplicity distribution looks like in the rapidity interval [-1,0] would tell something about parton interaction and gives important information about the confinement mechanism.

Reconnections in Z^0 decays indicate that a similar effect could be found at higher energies at LEP2. For example, in W^+W^- pair production two colour singlets $(q_1\overline{q}_2)$ and $(Q_1\overline{Q}_2)$ are produced which may reconnect into the combinations $(q_1\overline{Q}_2)$ and $(Q_1\overline{q}_2)$, see ref [3]. Such reconnections may also affect the determination of the W masses measured through the hadronic channel.

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