AC

LUTP 94-9
SW 9427LU TP 94-9
June 1994

CERN LIBRARIES, GENEVA

P00024180

Colour Interference and Confinement Effects in W-pair Production

Gösta Gustafson¹, Jari Häkkinen²
Department of Theoretical Physics,
Sölvegatan 14A,
SE-223 62 Lund, Sweden

Abstract:

In the reaction $e^+e^- \rightarrow W^+W^- \rightarrow (q_1\bar{q}_2)(Q_1\bar{Q}_2)$ we expect that normally the colour singlet systems $(q_1\bar{q}_2)$ and $(Q_1\bar{Q}_2)$ hadronize independently into two hadron chains or strings. However also the pairs $(q_1\bar{Q}_2)$ and $(Q_1\bar{q}_2)$ form colour singlets with probability $1/N_c^2 = 1/9$. This probability could be further enhanced by gluon exchange. We therefore expect that the hadronization can give "recoupled" colour strings between these quark-antiquark pairs with some small probability, and a study of this effect will give interesting information about the vacuum structure. In this paper we discuss a possible experimental signal for recoupled events and show that such events can be identified also when the effect of gluon emission before the recoupling is taken into account.

¹E-mail: gosta@thep.lu.se

²E-mail: jari@thep.lu.se

possible to study the reaction $e^+e^- \rightarrow W^+W^-$ where each of the two $q\bar{q}$ system. Normally it is assumed that these two $q\bar{q}$ systems hadronize producing two independent strings or chains of hadrons. As the lifetimes are very short the $q\bar{q}$ systems are essentially produced on top of each other, and it is conceivable that the hadronization processes interfere, and a study of the absence of an interference) would give valuable information about the mechanism and the vacuum structure. In this paper we discuss possible aspects of this effect.

When the two W s decay into quark-antiquark pairs called $q_1\bar{q}_2$ and $Q_1\bar{Q}_2$ the lifetime is approximately 0.1fm, which implies that the distance in space between the decay points, at LEP2 energies, is of the order $\Delta x \sim 0.05\text{fm}$ and these values are small compared to the confinement scale. Therefore, when the quarks move away from each other, how does the quark q_1 know that its partner $\bar{q}_2$ is moving that a string or a hadron chain should be formed between q_1 and $\bar{q}_2$?

The pair $q_1\bar{q}_2$ initially forms a colour singlet, but *also* $Q_1\bar{Q}_2$ forms a singlet with probability $1/9$. Thus we might possibly expect that, if the pairs are produced in the same point, the strings are "recoupled" and stretched between the pairs $q_1\bar{Q}_2$ and $Q_1\bar{q}_2$ with a probability of the order $1/N_c^2$. The recoupling probability can be further modified if the colour structure can be changed by gluon exchange. A gluon exchanged between Q_1 and q_1 would imply that the pairs $q_1\bar{q}_2$ and $Q_1\bar{Q}_2$ are colour octets, and they would normally form within the pairs $q_1\bar{Q}_2$ and $Q_1\bar{q}_2$. As discussed in refs [4, 1] hard gluons (with $E \geq \Gamma_W$) are emitted independently by the decay products of the W s. For this reason the exchange hard gluons, or interference effects from hard gluon exchange, are expected to be a small effect. The effect of *soft* gluon exchange can however not be easily calculated and depends on the vacuum structure and cannot be calculated perturbatively.

Questions of the vacuum structure on the recoupling probability were pointed out in the bag-type model the string between a quark and an antiquark is a colour flux tube with a thickness of the order 1fm and an essentially homogeneous colorelectric field. In this case the vacuum behaves like a type I superconductor. When the vacuum is then natural to imagine that the quarks and antiquarks are surrounded by a colorelectric field in vacuum, and that recoupling is likely if the distance (in space-time) between the production points for the pairs is less than 1fm.

Alternatively, one might imagine that the vacuum is more similar to a type II superconductor. Here the vacuum consists of a thin core surrounded by an extended colorelectric field. The thickness of the field ought to be of the order 1fm, but the core may be significantly more extended. In this case we can imagine that recoupling is more improbable and only likely if the distance between the production points is small compared to the thickness of the core.

Finally, a study of the probability for recoupling (and if possible how it depends on the distance between the W decay points) can give interesting information

about the structure of the vacuum and the confinement mechanism. Two questions are essential, i) what recoupling probability could be expected?, and ii) is it possible to observe recoupled events?

When trying to answer these questions it is important to take into account the emission of (real) gluons. As mentioned above hard gluons are emitted very early in the decay. The space-time distance between the W decay points is of the order $1/\Gamma_W$, and thus gluons with energies larger than Γ_W are produced incoherently by the two pairs ($q_1\bar{q}_2$ and $Q_1\bar{Q}_2$). Thus rather than a possible recoupling between two $q\bar{q}$ systems we have two independent systems each containing a $q\bar{q}$ pair and a set of gluons, which can be recoupled, or regrouped, into colour singlet systems, in many different ways.

2 What recoupling probabilities may be expected

When trying to estimate what recoupling probabilities could be expected it is useful to compare with a similar situation in the B meson decay $B \rightarrow \psi + X$. If q denotes a quark, this decay can proceed via the reaction $q\bar{b} \rightarrow q\bar{c}W^+ \rightarrow q\bar{c}c\bar{s}$. Here the $q\bar{b}$ pair normally forms colour singlets, and thus the $c\bar{c}$ pair normally forms a colour octet. Colour singlet formation of a ψ meson implies the same form of colour recoupling, and so the branching ratios have indicated a recoupling probability around 15 or 20%. In B decay the energy is comparatively low and the W^+ is very much off shell and the c and the $\bar{c}$ are essentially produced in the same space-time point. Thus we expect that at low distance and lower energies there is apparently a significant recoupling probability.

The situation in W pair production is different from B decay in two respects. Firstly, the W s decay in different space-time points, separated by 0.05–0.1fm. This is expected to affect the recoupling probability, more in case vacuum is like a type II superconductor than if it is like a type I superconductor. Secondly the emission of gluons implies that the $q\bar{q}$ systems can be recoupled in many different ways, and this fact can in principle affect the total recoupling probability.

Before we discuss these dynamical effects it is interesting to study what the recoupling probability would be, due to only $SU(3)$ Clebsch-Gordan coefficients, if there were no gluon emission or the vacuum structure. Assume that two colour singlets, $q_1\bar{q}_2$ and $Q_1\bar{Q}_2$, are produced in the same space-time point. The probability that the $q_1\bar{q}_2$ form colour singlets is then $1/9$, as mentioned earlier. If $q_1\bar{q}_2$ and $Q_1\bar{Q}_2$ form colour singlets we may expect that they also can form separate hadron chains or strings. If q_1 forms a colour singlet with both $\bar{q}_2$ and $\bar{Q}_2$, the structure of the objects is not clear. The state can *not* be determined without further dynamical assumptions. As discussed in detail in the appendix, the algebraic group properties only give a rather weak constraint on the recoupling probability, P , must lie in the range $\delta < P < 1 - \delta$, where $\delta = 1/2$. Thus the recoupling probability could in principle be anything above a lower bound.

As mentioned in the introduction hard gluons are emitted early, and therefore

only soft gluons are emitted with a relative probability $1 - \frac{1+\pi(1-\epsilon)}{1+2\pi(1+\epsilon)+\pi^2(1-\epsilon)^2}$, θ , v is the speed of the W , θ is the angle between the gluon and W momenta, but if it is chosen to be 0.9fm^{-4} the total recoupling probability is 35% just the boundaries). The magnitude of this recoupling probability density is a tubes overlap, there is a constant recoupling probability (with a Gaussian proportional to $\exp(-r_{\text{had}}^2/2r_{\text{had}}^2)$, where $r_{\text{had}} = 0.5\text{fm}$). In every space-time point, treated as a flux tube with radius around 0.5fm . (More precisely the field 5% at $\sqrt{s} = 170\text{GeV}$. Scenario I corresponds to a type I superconductor and only the one first in time is kept). As a result the recoupling probability is n , it is assumed that they can recouple with probability one (if they cross as an infinitely thin string. When two strings cross and have a space-time product, it is assumed that the confining field has a very narrow core, and we studied two different scenarios. In scenario II, which corresponds to a re that all these recoupling possibilities are equally probable. Sjöstrand and

probability could in principle be very large. of the order $1/N_c^2$ for each of these $(n+1)(m+1)$ possibilities, the total $1 > k_{\text{rec}} = 1\text{GeV}$ is $< n > \approx 4.3$, and thus if the probability for for every choice of i and j (see Fig 1). The average number of gluons with n and m are colour singlets with $Q_1, Q_2, \dots, Q_n$ and $Q_1, Q_2, \dots, Q_m$ are colour singlets with recoupling between the two original systems in many different ways. The respectively. Every set of particles $q_1, q_2, \dots, q_n$ is now a colour triplet. Thus hadronization and before a possible recoupling two sets of colour connected and $G_1, G_2, \dots, G_m$ (with $E > E_0$) are emitted independently by the q_1, q_2 and than E_0 are produced incoherently by the two pairs q_1, q_2 and Q_1, Q_2 [4, 1].

orm independent hadron chains or strings. $q_1, q_2, \dots, q_n$ are then colour singlets with probability $1/9$ for each value of i and j . are emitted from the Q_1, Q_2 pair. The two systems $q_1, q_2, \dots, q_n$ and Q_1, Q_2 and gluons $q_1, q_2, \dots, q_n$ (with $E > E_0$) are emitted from the original q_1, q_2 pair

The "length" of a string is correlated with its invariant mass and thus on be to select and study that recoupling possibility (i.e. those values of i and $s_1 \cdot s_2$ is minimum. (Here $\sqrt{s_1}$ and $\sqrt{s_2}$ are the invariant masses of the recoupling). A more efficient measure for the "length" of a string state is tied in ref [6]. It corresponds to an "effective rapidity length", and is close hadronic multiplicity. For hard gluons it is approximately given by $\lambda \approx \sum$ same direction. recoupling might be more probable if it connects gluons which move in a favour short "strings" may be further enhanced by dynamical effects. The discussed above, it is conceivable that the tendency in the scenarios studied a "longer" string, is disfavoured. When comparing different possibilities illustrated in Fig 2, we note that the colour connection in Fig 2b, which depends on the geometrical motion of the fields. If we study $qq\bar{q}\bar{q}$ depends on the geometrical overlap of the field configurations in coordinate In the analysis by Sjöstrand and Khoze it is assumed that the recoupling in order to facilitate a comparison between the scenarios, and has no dyn 0.9fm^{-4} for the probability density which is studied in refs [1, 5], is just the initial gluon emission, the total probability may in principle be very from our present knowledge of QCD, and with all the recoupling possibilities always overlap to a larger or lesser degree. The recoupling probability can occur when the space-time structure makes it possible. In a type I scenario strings cross, and the result from B decay may indicate that a recoupling an upper limit. This result was obtained assuming unit probability for re In a type II scenario we think that the recoupling probability of 35% might which give fewer hadrons); this is more pronounced for scenario I than for the origin in the cms, it is natural that most recouplings give "shorter" s energy. As the normal (not recoupled) systems correspond to "long" strings are cut and recoupled in the "middle", so that the two pieces have approx as in scenario II. In both scenarios those recouplings are favoured, in which

Figure 2: The production probability for a $qq\bar{q}\bar{q}$ state is, in perturbative Q colour connection which corresponds to a "shorter string" as in fig a).

unrecoupled) parton momenta and the hadronic mass scale m_0 is around 1 GeV. It is conceivable that those recouplings for which $\lambda_1 + \lambda_2$ is significantly reduced are favoured (where λ_1 and λ_2 are the λ -measures for the two recoupled systems). The case corresponds to the assumption that only the recoupling for which $\lambda_1 + \lambda_2$ is minimum is likely, perhaps with a probability around 10%. It is also possible that the recouplings for which $\lambda_1 + \lambda_2$ is significantly reduced, have a fair recoupling probability, which would increase the total recoupling probability.

For the recoupled states with minimum $\lambda_1 + \lambda_2$, the average change $\langle \Delta\lambda \rangle$ is small. For a sample with a cut on thrust, as studied in the next section, the change is even larger. This can be compared with the recoupled states studied in ref [2] selected only from purely geometrical considerations, for which $\langle \Delta\lambda \rangle$ is around 0.1 (scenario I (and somewhat smaller for scenario II)). In the same way as this sample, also the states with minimum $\lambda_1 + \lambda_2$ normally corresponds to the case where the initial states are cut in two approximately equal pieces. The average rapidity $y_{\text{rec}} = |E_1 - E_2|/(E_1 + E_2)$ (where E_1 and E_2 are the energies of the decay products in the W decay system) is given by $\langle y_{\text{rec}} \rangle \approx 0.2$ which is comparable to the

Recoupled events be identified?

Whether the recoupled events can be identified was addressed in ref [2]. In this analysis the emission of gluons before recoupling was neglected, and with this simplification a very clear difference was seen between recoupled and “normal” events. If the angle between the outgoing q_1 and $\bar{q}_2$ is fairly small, e.g. around 30° , the two recoupled systems are produced in the cms with large velocities, thus producing few particles in the central region. Looking at the number of central particles, e.g. particles with $|y| < 2$, the recoupled events could easily be identified on an event by event basis.

Gluons are emitted independently by the two systems in the early phase, as discussed in ref [2]. This gives extra particles in the central region, which will reduce the difference between recoupled and non-recoupled events. Sjöstrand and Khoze [1, 5] studied effects of gluon emission on the determination of the W mass and on *average* distributions, and in their analysis found small effects. Our aim here is different. We want to study if there are recoupled systems which are sufficiently different from the “normal” systems to be identified experimentally.

The recoupled systems with two “short strings” may be particularly favoured. These are the ones which differ most from the nonrecoupled systems, because the two systems are produced away in opposite directions in a way which is most similar to the situation for the initial gluon emission, studied in ref [2]. They will thus be more easily identified experimentally. We will therefore concentrate on those recoupling possibilities which give the smallest $\lambda_1 + \lambda_2$, i.e. those for which $\lambda_1 + \lambda_2$ is minimum.

Figure 3: Rapidity distributions for “normal” events (solid line) and recoupled events (dashed line) with thrust cuts $T > 0.92$ (fig a) and $T > 0.76$ (fig b).

In order to have a large difference between the recoupled and nonrecoupled events, the angle between e.g. q_1 and $\bar{q}_2$ should not be too large. In ref [2] (and also in ref [1]) events where this angle was 30° were selected. In our analysis we found that the recoupled events imply that a cut on this angle is less suitable, and instead we study the effect of a cut on the thrust variable T .

As mentioned above it would be interesting to study how the recoupling probability varies with the total energy, which implies a variation in the distance between the two systems. However, as discussed in ref [1], also at the threshold energy, $\sqrt{s} = 2m_W$, the distance between the two systems is large. This implies that they are not produced at rest. Therefore the distance varies with the LEP2 range from threshold to 180 GeV. For this reason we here present results for the LEP2 range, where the effect of the spread in the W mass is small and can be neglected. Our results are representative also for energies close to threshold, where the average distance between the two systems are of the same order of magnitude [1].

In our simulations gluons with $E > \Gamma_W$ are emitted using the Ariadne model [6]. For the recoupled events we have chosen to give minimum values for the sum $\lambda_1 + \lambda_2$, as discussed in ref [2]. For the hadronization process we have used the Lund string model [8] implemented in the Jetset MC [9]. In string fragmentation soft gluons with $E < \Gamma_W$ give very little contribution, and they have therefore been neglected. In Fig 3 we show the inclusive rapidity distributions for “normal” and “recoupled” events. We see that the central region is suppressed for the recoupled events, but due to the initial gluon emission it is not totally empty. This means that the average distribution can not be used as an experimental signal for the recoupled events. It would not be possible to ascertain an admixture of recoupled event of the order of 10%. We note that the results in Fig 3 are similar to the corresponding results obtained in ref [2] and Khoze [1].

However, even if the average recoupled event is not sufficiently different from the normal event, it turns out that events with no central particles are much more common in the recoupled sample. Fig 4 shows the multiplicity distribution (including π^0) in the central region for “normal” and recoupled events with the thrust cuts $T > 0.92$ and $T > 0.76$. For the higher thrust cut the difference between normal and recoupled events is large.

only around 4% of the events pass this cut. For $T > 0.76$ we keep 60% of the probability is a factor 55 larger for the recoupled events than for the normal 000 events with hadronic W -decays, and with 10% probability for recoupling, recoupled events with $n_{central} = 0$ with a background constant in the entire LEP2 energy threshold to 190GeV). The signal to background ratio can be further enhanced if data from different cuts in thrust and rapidity. The dependence on the thrust in Fig 4 it is seen that also the probabilities $P(1)$ are very different between coupled events, and thus information from events with exactly one particle in rapidity bin can also be used. The best choice of observables will depend on the acceptances properties of the detectors, and for those who are interested the for the recoupling is available upon request.

This example we have assumed that a recoupling occurs only to states with similar results could of course be obtained if recoupling occurs also to other

ected number of events with zero central particles, N_0 , as a function of the $e^+e^- \rightarrow \gamma\gamma$ cut. The dashed line shows the recoupled events and the solid line

licity distributions for $|y| < 0.5$ for "normal" events (solid line) and recoupled events (dashed line) with thrust cuts $T > 0.92$ (fig a) and $T > 0.76$ (fig b).

4 Conclusions and comments

states with small λ -values, but with a correspondingly larger total recoupling

In the reaction $e^+e^- \rightarrow W^+W^- \rightarrow (q_1\bar{q}_2)(\bar{q}_1q_2)$ hadron chains or strings are expected to be stretched within the colour singlet systems $q_1\bar{q}_2$ and $\bar{q}_1q_2$ systems $q_1\bar{q}_2$ and $\bar{q}_1q_2$ are singlets with probability $1/N_c^2 = 1/9$, and expect "recoupled" chains or strings with a probability of this order of magnitude. Due to the finite lifetime of the W s hard gluons (with $E > \Gamma_W$) are emitted by the two initial quark-antiquark pairs. This reduces the observable difference between the "normal" and the "recoupled" events. On the other hand it may also increase the probability, because the two initial colour singlet systems can be recoupled in principle with a probability of order $1/N_c^2$.

The presence or absence of such recoupled events gives valuable information about the colour fluxtube would be similar to an elongated bag, which is like a type I superconductor than if vacuum is more like a type II superconductor. Thus we would expect a larger recoupling probability in the former case the colour fluxtube would be similar to an elongated bag, which is like a type I superconductor than if vacuum is more like a type II superconductor.

Sjöstrand and Khoze [1, 5] have studied observable effects if the recoupling is determined purely by the geometrical structure of the confining force. They found generally small effects. In this paper we have argued that it is dynamical effects enhance the recoupling probability for states which produce strings" producing few hadrons. These states are also the ones which are normal events, and we have seen that they can be experimentally identified with a rate of about 10%.

Sjöstrand and Khoze have also studied the effects of recoupling on the W mass [5, 1]. Assuming 35% recoupling probability they find an extra 40MeV. The recoupling effects the softer hadrons, and the states studied give a similar uncertainty in the mass determination as those studied as a first approximation the uncertainty in the mass determination will be the total recoupling probability. This probability cannot be calculated with knowledge of QCD, and could in principle be large.

It would also be interesting to study effects of recoupling in other reactions. The recoupling is also possible in normal Z -decay events. We can e.g. consider $e^+e^- \rightarrow q\bar{q}g$. If both gluons are emitted from the quark or antiquark straightforward calculation shows that the probability for the two gluons to correspond to a string between the quark and the antiquark, together with the gluons, as shown in Fig 5b. (If the two gluons originate

Figure 6: $q\bar{q}$ state and ring of gluons.

course always in a colour octet state. Thus the momentum distribution (6 is the same as for two emitted photons). In a following paper we want to study the features of such recoupled systems in this and other reactions.

ts
dr T. Sjöstrand for valuable discussions. This research is supported in the Programme "Human Capital and Mobility", Network "Physics at High Energies" contract CHRX-CT93-0537 (DG 12 COMA).

Appendix

To study what the recoupling probability would be, due to only SU(3) colour coefficients, if there were no dynamical effects from soft gluons and the quarks are produced in the same space-time point. For this we study two pairs $q_1\bar{q}_2$ and $Q_1\bar{Q}_2$ produced in the same space-time point. We define the states $|1\rangle$ and $|2\rangle$ in the following way:

- state $|1\rangle$: $q_1\bar{q}_2$ and $Q_1\bar{Q}_2$ form separate colour singlets,
- state $|2\rangle$: $q_1\bar{Q}_2$ and $Q_1\bar{q}_2$ form separate colour singlets.

There is a probability $1/N_c^2 = 1/9$ that also $q_1\bar{Q}_2$ and $Q_1\bar{q}_2$ form singlets. Only however, that $q_1\bar{Q}_2$ and $Q_1\bar{q}_2$ form independent hadron strings with antiquarks hadronize we assume that the hadrons are formed in two strings or strings, and we then have two possible final states, which we denote

- state $|a\rangle$: $q_1\bar{q}_2$ and $Q_1\bar{Q}_2$ form ends of separate strings,
- state $|b\rangle$: $q_1\bar{Q}_2$ and $Q_1\bar{q}_2$ form ends of separate strings.

These are eigenstates to observables with different eigenvalues and are therefore orthogonal; $\langle a|b\rangle = 0$. States $|1\rangle$ and $|2\rangle$ can be written as linear combinations

of $|a\rangle$ and $|b\rangle$. Due to the symmetry of the situation they can be written as

$$\begin{aligned} |1\rangle &= \alpha|a\rangle + \beta|b\rangle \\ |2\rangle &= \beta|a\rangle + \alpha|b\rangle \end{aligned}$$

The recoupling probability is obviously given by $|\beta|^2$ and the scalar product $\langle 1|2\rangle$ gives the relation

$$\langle 1|2\rangle = 2\text{Re}(\alpha^*\beta) = 1/3.$$

We can choose α real and with the notation $\alpha = \sin\theta$, $\beta = \cos\theta \exp i\varphi$ we obtain

$$\sin(2\theta) \cdot \cos\varphi = 1/3 \Rightarrow |\sin(2\theta)| \geq 1/3$$

Thus the recoupling probability $|\beta|^2$ is restricted by the relation

$$\delta < |\beta|^2 < 1 - \delta, \quad \delta = 1/2 - \sqrt{2}/3 \approx 0.03$$

We conclude that we only obtain a rather loose restriction. The recoupling probability can be anything above a lower limit of 3% (and below 97%). (It is easy to see that the result is obtained if $|a\rangle$ and $|b\rangle$ are not single states but corresponds to mixed states).

References

- [1] T. Sjöstrand, V.A. Khoze, *CERN-TH 7011/93, to be published in Z. Phys.*
- [2] G. Gustafson, U. Pettersson, P.M. Zerwas, *Phys. Lett.* **B209** (1988) 90
- [3] M. Neubert *et al.* in Heavy Flavours, Ed. A.J. Buras, M. Lindman, World Scientific, S. Henderson, Proceedings of XXIX Rencontres de Moriond, 1994 and in [2]
- [4] Yu.L. Dokshitzer, V.A. Khoze, L.H. Orr, W.J. Stirling, *Nucl. Phys.* **B**
- [5] T. Sjöstrand, V.A. Khoze, *Phys. Rev. Lett.* **72** (1994) 28
- [6] B. Andersson, P. Dahlqvist, G. Gustafson, *Phys. Lett.* **B214** (1988) 604 (1989) 455
- [7] U. Pettersson, Lund preprint LUTP 88-5 (1988)
L. Lönnblad, DESY preprint DESY 92-046 (1992)
- [8] B. Andersson, G. Gustafson, G. Ingelman, T. Sjöstrand, *Phys. Rep.* **9**
- [9] T. Sjöstrand, *Comp. Phys. Comm.* **39** (1986) 347
T. Sjöstrand, M. Bengtsson, *Comp. Phys. Comm.* **43** (1987) 367