Probing Colour Separate States in $e^+e^- \rightarrow Z^0$ annihilation at $Z^0$ pole

Shi-yuan Li,1,† Feng-lan Shao,1 Qu-bing Xie,2,1,‡ and Qin Wang1

1 Department of Physics, Shandong University, Jinan, Shandong 250100, People’s Republic of China
2 China Center of Advanced Science and Technology (CCAST), Beijing 100080, People’s Republic of China

(Dated: March 25, 2022)

Hadronic processes in high energy collisions are generally described by two distinct phases: the perturbative phase and the non-perturbative hadronization one. The perturbative phase is well described by perturbative QCD (PQCD) while the hadronization phase is non-perturbative and cannot be described from first principle. Therefore a natural problem arises as to how to link these two phases, i.e. how to connect the partonic system produced by the PQCD evolution with the hadronization models, to give the final state hadrons. This problem is also beyond the capability of PQCD.

The parton cascade and hadronization models [1, 2] assume the string or cluster chain connections. They correspond to the partonic states where a color charge of one parton is specifically connected to its anti-color in an accompanying parton. This approximation implies $N_C \rightarrow \infty$, thus with infinitely many colors the probability that two (or more) partons have the same color is zero [3]. The present hadronization models work well, which shows that the large $N_C$ limit reflects some feature of the real world.

However the colour structure of a multi-parton state is copious and complex at finite $N_C$ [4, 5, 6, 7]. This implies that the colour connections of a multi-parton system can be of many kinds. The ordinary one, which is used in the string and the cluster model [1, 2], is just what we called the colour singlet chain (CC) state. The PQCD calculations show that, when projected onto the colour space of the final partonic state, such kind of colour states never appear with probability 1 at finite $N_C = 3$. Its probability is shown to even decrease as the parton number of the partonic system increases [4, 5, 6]. Another kind of the colour connection is the colour separate (CS) state with several groups of gluons forming the colour singlet clusters each of which can hadronize independently [4, 5, 6, 7]. Such a possibility can be demonstrated by a simple example in $e^+e^- \rightarrow q\bar{q} + ng$ when two gluons have ‘opposite’ colours (e.g. $\bar{t}b$, $br$), they can form a colour singlet cluster by a closed string. When the parton number is large [3], it is inevitable that more and more gluons have chances to form the CS states [3]. These two kinds of colour connections at the hard-soft interface correspond to different string/cluster configurations [4, 5] and may lead to differences in hadronic states through the subsequent hadronization process. In this sense the probability for any kind of colour connections depends on the non-perturbative QCD (NPQCD) mechanism. The cross sections of the CC and CS states calculated in the PQCD framework [4, 5, 6, 7] are not the final answer.

To study the effects of the CS states on the hadronic events, we need phenomenological models. The straightforward way is to modify the event generators, e.g. JETSET, by putting the CS states as one way of the colour connections. One can use the modified generators to give the hadronic states to see if there are any deviations from those produced by JETSET with the default colour connections (i.e. the CC connections). Recently we proposed a CS model [8] based on JETSET 7.4 by replacing the default colour connections with the CS-allowed connections. Hereafter we also use CS and CC to refer to the modified JETSET and the default JETSET respectively. The simulated results show that there are no significant differences between the observables for the CS and CC unbiased events [9, 10]. This result is not hard to understand considering that for unbiased events the observables describing global properties are mainly determined by PQCD and they are not much sensitive to the hadronization details. This property is nothing but the so-called local parton-hadron duality [10]. Therefore we have to look for possible sensitive observables defined for a specific set of events. We know that the baryon- antibaryon rapidity correlation is sensitive to the hadronization models [10]. It has been investigated if this correlation is also sensitive to the way of colour connections. But the answer is negative [10]. Considering that in a CS state only the phase space region around the glueball cluster and the two string pieces in its neighbourhood is much different from that of the corresponding CC state, the sensitive observables may exist in a specified window of the phase space.

Based on the above analysis, in this paper we propose...
to select two-jet-like events in $e^+e^- \rightarrow Z^0 \rightarrow$ hadrons as an effective probe of the CS states.

We use the CS model in Ref. [5]. In the model, we proposed a method to estimate the rate of the CS states for a group of partons produced in a hadronic event in high energy electron-positron collisions. We implement this model into a Monte-Carlo program based on JETSET 7.4. In the program we replace the default way of colour connections for the partonic system in JETSET 7.4, i.e. the CC connections, with the CS-allowed connections. The CS clusters formed by two or more gluons in a CS state also hadronize in the usual way as closed strings [1]. We use the T-measure to weight the CS states.

In this paper, a two-jet-like event at the partonic level is referred to that with an energetic back to back quark-antiquark pair and some associated soft gluons whose energies are smaller than a definite value $E_0$. In this case the thrust axis is approximately along the quark’s momentum. Therefore in this paper we define the longitudinal and transversal directions with respect to the thrust axis. In the following numerical analysis, we require that the energies of all gluons including those appearing in the intermediate stage of the parton shower process are less than 2.5 GeV. This is to eliminate the possibility that the energetic gluons would significantly change the shape of a two-jet-like event.

We know that the larger the number of gluons in an event, the more possible does the CS state occur. To enlarge the effect, we only consider those events where the initial quark pair produced by the electroweak process is of $u, d$ or $s$ type because the number of gluons in heavy quark events is suppressed.

For these events two different ways of colour connections really lead to differences in the hadronic states. Figs. [3] are the rapidity and thrust distributions of the hadronic states. One can see that the CS events have more particles with small rapidity and have smaller thrusts than the CC ones. The reason for this is that the formation of the closed strings in the CS events brings more momentum from the longitudinal to the transversal direction compared to the CC events. This point can be further strengthened by the polar angle and the transversal momentum distributions for the hadrons inside the rapidity window $|y| < 0.8$, see Figs. [3]. The average transversal momentum of the hadrons in the CS events are larger than those in the CC events. There is a similar trend for the charged particle that there are more charged particles in the CS events than in the CC ones inside the central rapidity region.

Furthermore we define the following observable:

$$SP_t = \sum_i |\vec{p}_{ti}|, ~ \forall |y_i| < y_0.$$  \hspace{1cm} (1)

where the $\vec{p}_{ti}$ and $y_i$ are the transversal momentum and rapidity of a final state hadron in an event respectively. In the numerical calculation we take $y_0 = 0.8$. This observable is introduced to accumulate the above differences of the CS and CC events. Fig. [3] (a) shows $SP_t$ is a sensitive observable to the way of the colour connections at the hard-soft interface.

To make sure the observable $SP_t$ is really sensitive only for the two-jet-like events we have to check if colour connections affect the $SP_t$ distribution for unbiased events. The answer is yes, see Fig. [3] (a). But $SP_t$ is the sum of

![Fig. 1: The two-jet-like events selected at the partonic level. (a) Rapidity distribution of hadrons. (b) Thrust distribution. The solid line is for the CC events and dashed line for the CS ones, the same convention is implied for other figures.](image1)

![Fig. 2: The two-jet-like events selected at the partonic level. (a) The polar angle (the angle between the momentum of a hadron and the thrust) distribution of hadrons. (b) The transversal momentum distribution of hadrons.](image2)

![Fig. 3: The distribution of $SP_t$ for the two-jet-like events selected at the partonic level; (a) $\sigma = $ default value; (b) $\sigma = 0.29$.](image3)
FIG. 4: $SP_t$ distribution for unbiased events; (a) $\sigma =$ default value; (b) $\sigma = 0.29$.

FIG. 5: The transversal momentum distribution of final state hadrons for the two-jet-like events which is selected at parton level (dashed line) and that for unbiased events.

The transversal momenta which depend on the parameter $\sigma$ in JETSET [3], which measures the average transversal momentum of the quark pair in the string breakings. Though $\sigma$ has been fitted by experimental groups [13], the dependence of $SP_t$ on $\sigma$ has never been measured. Here we change $\sigma$ to see the dependence of $SP_t$ on $\sigma$.

Fig. 4 (b) shows that when $\sigma$ is changed from the default value 0.36 to 0.29, the difference in the $SP_t$ distribution for the unbiased events between the CS and CC events are nearly smeared. In contrast, the global properties of the unbiased events are not sensitive to this parameter.

It is then critical to check for the two-jet-like events if the observable $SP_t$ is sensitive to the parameter $\sigma$. Comparing Fig. 3 (b) with (a), we see that the shape of the distribution is more or less affected by this parameter, but for whatever values of $\sigma$ the difference of $SP_t$ between the CS and CC events are always significant.

The proposal in the above is at the partonic level which is an ideal situation. The events selected by requiring that the energy of each gluon must be smaller than a certain value cannot be realized in experiments since partons cannot be seen directly. Now we extend it to the real case, i.e. selecting the two-jet-like events according

FIG. 6: The rapidity distribution for the two-jet-like events selected at the hadronic level.

FIG. 7: Global properties of the two-jet-like events selected at the hadronic level.

FIG. 8: $n_{ch}$ distribution with $|y| < 0.8$ for two-jet-like events selected at the hadronic level.
to the criteria defined at the hadronic level. We notice from Fig. 3 that the $p_t$ distribution of final state hadrons (in our case pions, protons and kaons) for these events is significantly different from that for the unbiased events in the small $p_t$ region. Hence in this work we require that the transversal momentum of the hadron is smaller than 0.5 GeV/c.

These results show that the CS two-jet-like events have more particles in the small-rapidity region compared to the CC ones. The average thrust for the CS two-jet-like events is smaller than the CC ones. The comparison with Ref. [5] shows that the differences in the global properties between the CS and CC two-jet-like events are more obvious than the unbiased events, as is exhibited in Fig. 3. The most essential fact is that $SP_1$ is still a sensitive observable for the way of colour connections. One can see this in Fig. 4 which shows there are significant differences between the CC and CS two-jet-like events.

Note that our definitions for the two-jet-like events and the observable $SP_1$ look similar to those in Ref. [4] at first sight. Actually they are different from many aspects. Ref. [4] needed the events with small number of gluons to address the issue of quark jet hadronization, while in this work we prefer those events with large number of gluons to make the probability of forming the CS states as large as possible. Ref. [4] took the sum of $\hat{p}_t$ to demonstrate correlation properties for different models, while we use the sum of the magnitude of $\hat{p}_t$ to enlarge the differences between the events of different colour connections.

In this paper we extend our previous work on the CS states by proposing a possible method to probe these types of states in the hadronic process of electron-positron annihilation via $Z^0$. We find that there would be substantial differences in the distribution of $SP_1$ in the two-jet-like events for the CS-allowed and for the normal colour connections. Other distributions, such as those of the central rapidity, the $p_t$ and the charged particle multiplicity inside a central rapidity window, etc., also show detectable differences for the CS and the CC two-jet-like events. In average there is one two-jet-like event in every one thousand hadronic events at the $Z^0$ pole. Since large number of events have been accumulated at LEP I, one can expect to get a good statistics in selecting the two-jet-like events to probe the presence of the CS states. We should mention that the two-jet-like events defined in this paper and the observable $SP_1$ have never been used before. The future comparison with data for this type of events and the $SP_1$ distribution would also provide an alternative way of testing different hadronization models.

We thank G. Gustafson, Z.-T. Liang and X.-N. Wang for insightful discussions. This work is supported in part by the National Natural Science Foundation of China (NSFC).

---

1. T. Sjöstrand, Comp. Phys. Commun. 82, 74 (1994); B. Andersson, G. Gustafson, G. Ingelman and T. Sjöstrand, Phys. Rep. 97, 31 (1983).
2. G. Corcella et al., JHEP 0101, 010 (2001); B. R. Webber, Nucl. Phys. B238, 492 (1984); G. Marchesini and B. R. Webber, ibid B238, 1 (1984).
3. C. Friberg, G. Gustafson, and J. Häkkinen, Nucl. Phys. B490, 289 (1997).
4. Q. Wang, G. Gustafson, Y. Jin, and Q.-B. Xie, Phys. Rev. D64, 012006 (2001).
5. Q. Wang, G. Gustafson, and Q.-B. Xie, Phys. Rev. D62, 054004 (2000).
6. Q. Wang, Q.-B. Xie, and Z.-G. Si, Phys. Lett. B388, 346 (1996); Q. Wang and Q.-B. Xie, Phys. Rev. D52, 1469 (1995).
7. Y. Jin et al., in preparation.
8. T. Sjöstrand and V. A. Khoze, Phys. Rev. Lett. 72, 28 (1994); Z. Phys. C62, 281 (1994).
9. L. Lönnblad, Z. Phys. C70, 107 (1996).
10. F.-L. Shao and Q.-B. Xie, High energy Physics and Nuclear Physics (in Chinese) 25, 710 (2001); F.-L. Shao and Q.-B. Xie, to be published in High energy Physics and Nuclear Physics (in Chinese).
11. B. Andersson, P. Dahlqvist, and G. Gustafson, Z. Phys. C44, 461 (1989); ibid C44, 455 (1989).
12. Z.-G. Si, Q.-B. Xie, and Q. Wang, Commun. Theor. Phys. 28, 85 (1997).
13. G. Altarelli, T. Sjöstrand, and Zvirner (Eds.), Physics at LEP2, vol.2, CERN yellow book 96-01.
14. P. Eden and G. Gustafson, Euro. Phys. Jour. C8, 435 (1999).
15. as calculated by JETSET, the average numbers of gluons are: $\sqrt{s} = 91$ GeV, $\langle n \rangle \sim 6$; $\sqrt{s} = 200$ GeV, $\langle n \rangle \sim 9$; $\sqrt{s} = 1$ TeV, $\langle n \rangle \sim 17$. 

---

**FIG. 9:** $SP_1$ distribution in the rapidity window $|y| < 0.8$ for the two-jet-like events selected at the hadronic level.