

INTERCONNECTION PHENOMENA IN W^+W^- and $t\bar{t}$ EVENTS

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Abstract

I will attempt to survey some selected physics issues on QCD interconnection phenomena in the processes $e^+e^- \rightarrow W^+W^- \rightarrow 4$ jets and $e^+e^- \rightarrow t\bar{t} \rightarrow bW^+\bar{b}W^-$. Possible consequences for LEP2 and future linear e^+e^- colliders are briefly discussed.

1 Introduction

It is widely believed that in particle physics “tomorrow belongs” to the detailed studies of heavy unstable objects. Firstly, we anticipate the exciting discoveries of new heavy particles (Higgs boson(s), SUSY particles, W' , Z' , ...) at increasingly higher energies. Secondly, for the precision tests of the Standard Model one needs the high accuracy determination of the parameters of the W boson and of the top quark, primarily their masses.

Let us briefly address the latter point. These years we have witnessed some important developments in precision electroweak tests. One can consider as an impressive success of the Standard Model the fact that the top mass m_t predicted from the electroweak data agrees within the stated errors with the direct Tevatron result [1]

$$m_t = 173,8 \pm 5,2 \text{ GeV} \quad (1)$$

There has also been further progress with the determination of the W boson mass m_W at the Tevatron [2]. Preliminary results on the Tevatron average is

$$m_W = 80.41 \pm 0.09 \text{ GeV} \quad (2)$$

Meanwhile, at LEP2 the combined statistical uncertainty on m_W has reached a level of about 70 MeV [3]-[6].

The precise measurements of m_W and m_t is a priority of present and future experimental studies. These will allow to fully exploit the remarkable accuracy of exploring the Z^0 physics and other precision electroweak measurements. One may hope to pin down the Higgs mass or/and to look for evidence for physics beyond the Standard Model.

What are the prospects of the experimental studies?

Run II at the Tevatron and LEP2 are aiming for an uncertainty on m_W of about 35-40 MeV, see Refs. [2],[5]. An upgrade of the Tevatron, beyond Run II, and the LHC may allow a precision on m_W of about 15 MeV, see, e.g., [7]. It seems reasonable to expect that future experiments at the Tevatron and the LHC will increase an accuracy of m_t measurements up to 1-2 GeV.

A unique precise determination of m_t (with an accuracy of a few hundred MeV) will be one of the most attractive physics topics at future linear e^+e^- and muon colliders [8]-[10].

An obvious requirement for success of these precise studies is that the accuracy of the theoretical predictions should match or better exceed the experimental errors. This requires a detailed understanding of production and decay mechanisms and, in particular, of the effects arising from the large width, $\Gamma \sim O(1 \text{ GeV})$. Recall that in production processes of heavy unstable particles it is natural to separate the production stage from the decay processes. In general these stages are not independent and may be interconnected by radiative interference effects. Particle(s) (e.g. gluon(s) and/or photon(s)) could be produced at one stage and absorbed at another; we speak of virtual interference. Real interference will occur as well since the same real particle can be emitted from the different stages of the process.

Many observations rely on a clear understanding of the role of these interference effects. Indeed there is a long list of examples where a detailed knowledge of interferences can be important for the interpretation of experimental data (see [11]-[13] and references therein).

In this talk I concentrate mainly on the QCD interconnection phenomena that may occur when two unstable particles (W bosons, top quarks) decay close to each other. The word ‘interconnection’ is here introduced to cover those aspects of final-state particle production that are not dictated by the separate decays of unstable objects, but can only be understood in terms of the joint action of the two. Such a cross-talk between heavy unstable particles could occur because they decay at short distances of order $1/\Gamma \sim 0.1$ fm, and their decay products hadronize close to each other in space and time at the typical hadronic scale of ~ 1 fm.

2 QCD Interconnection in Hadronic W^+W^- Events

The accurate determination of the W -boson mass is one of the main objectives of LEP2. However, the systematic uncertainties due to hadronic final-state interactions and QCD interferences between the W decay products may induce substantial ambiguities, for reviews see Refs. [14],[15].

The cross-talk between the W^\pm decay products undermines the traditional meaning of a W mass in the process

$$e^+e^- \rightarrow W^+W^- \rightarrow q_1\bar{q}_2q_3\bar{q}_4, \quad (3)$$

called the (4q) mode. It is not even in principle possible to subdivide the final-state hadrons into two groups, one of which corresponds to the $W^+ \rightarrow q_1\bar{q}_2$ decay and the other to the $W^- \rightarrow q_3\bar{q}_4$ decay: the identities of individual W^\pm decay products are not well-defined any more. If the W -boson lifetime could be considered as very short, $1/\Gamma_W \rightarrow 0$, both the $q_1\bar{q}_2$ and $q_3\bar{q}_4$ pairs appear almost instantaneously, and they radiate coherently, as though produced at the same vertex. In the other extreme, $\Gamma_W \rightarrow 0$, the $q_1\bar{q}_2$ and $q_3\bar{q}_4$ pairs appear at very different times t_1, t_2 after the W^+W^- production,

$$\tau_p \sim \frac{1}{m_W} \ll \Delta t = |t_1 - t_2| \sim \frac{1}{\Gamma_W}. \quad (4)$$

The two dipoles therefore radiate gluons and produce hadrons according to the no-reconnection scenario.

The crucial point is the proper choice of the scale the W width should be compared with. That scale is set by the energies of primary emissions, real or virtual, see Ref. [11] and references therein. Let us clarify this supposing, for simplicity, that we are in the W^+W^- threshold region. The relative phases of radiation accompanying two W decays are then given by the quantity

$$\omega_i \Delta t \sim \frac{\omega_i}{\Gamma_W}. \quad (5)$$

When $\omega_i/\Gamma_W \gg 1$ the phases fluctuate wildly and the interference terms vanish. The argumentation remains valid for energies above the W^+W^- threshold as well.

An instructive Gedanken experiment to highlight the filtering role of Γ can be obtained [13] by comparing the emission of photons in the eV to MeV range for the two processes

$$\gamma\gamma \rightarrow W^+W^- \rightarrow \mu^+\nu_\mu\mu^-\bar{\nu}_\mu, \quad (6)$$

$$\gamma\gamma \rightarrow K^+K^- \rightarrow \mu^+\nu_\mu\mu^-\bar{\nu}_\mu, \quad (7)$$

near threshold, in the extreme kinematical configuration where the μ^+ is collinear with the μ^- . For the first process, $\omega \ll \Gamma_W$, and one expects hardly any radiation at all, because of the complete screening of the two oppositely charged muons. For the second process, $\omega \gg \Gamma_K$, the parent particles have long lifetimes and the μ^+ and μ^- appear at very different times. The photon wavelength is very small compared with the size of the $\mu^+\mu^-$ dipole and, therefore, the μ^+ and μ^- radiate photons independently, with no interference.

Suppression of the interference in the case of radiation with $\omega_i \gg \Gamma_W$ can be demonstrated also in a more formal way, see e.g., [11].

Note that the limiting case when $\tau_{\text{dec}} \sim \frac{1}{\Gamma_W} \sim \tau_p \sim \frac{1}{m_W}$ represents an example of the so-called instantaneous reconnection scenario, where the alternative colour singlets are immediately formed and allowed to radiate perturbative gluons with an energy up to $O(m_W)$, see for details Refs. [12],[16].

The strong-interaction dynamics induces a variety of interconnection effects between the hadronic decays of different W's, such as:

1. Quantum short-distance effects due to exchanges of perturbative gluons between the two initial $q\bar{q}$ systems.
2. Final-state radiative gluon interferences on the stage of parton-shower development.
3. Long-distance effects in the parton-to-hadron transition phase caused by a large overlap between the products of the two decays (non-perturbative rearrangement/reconnection).
4. Bose–Einstein (BE) correlations between identical bosons (in practice, pions).

The possibility of colour rearrangement in the process (3) was first considered in Ref. [16]. The rôle of QCD interconnection in hadronic WW decays in the framework of the W mass measurement was first discussed in Ref. [12]. This challenging topic has been quite intensively studied theoretically since then. We do not attempt to cover the consequences of BE effects here, see Refs. [17].

It is necessary to emphasize that there is no question of whether interconnection between the W's exists or not; it is certainly there even in the QED context. Thus, the final-state QED interconnection induces a sizeable mass shift, $(\delta m_W)_{\text{QED}} \sim O(\alpha_{em}\pi\Gamma_W) \sim 50$ MeV, in $e^+e^- \rightarrow 4$ fermions in the threshold region [18],[19]. However, at energies above 170 GeV, $(\delta m_W)_{\text{QED}} \sim O(\alpha_{em}\Gamma_W/\pi)$, and cannot exceed a few MeV [19]-[21]. Another well-known

precedent is J/ψ production in B decay: the $c\bar{c} \rightarrow J/\psi$ transition requires a cross-talk between the two original colour singlets, $\bar{c} + s$ and $c + \text{spectator}$. The real challenge is to understand how large the ambiguities for various observables can be. Evidently, it is not only the W mass that can be affected by interconnection. Various event characteristics in hadronic WW decay could, in principle, show effects even an order of magnitude bigger than that in m_W . On the other hand, in the inclusive cross section for process (3), the effects of the QCD (and QED) cross-talk are negligible [22]:

$$\frac{\Delta\sigma_{WW}^{\text{intercon}}}{\sigma_{WW}} \sim \left(\frac{C_F\alpha_s(\Gamma_W)}{\pi} \right)^2 \frac{1}{N_C^2} \frac{\Gamma_W}{m_W}, \quad (8)$$

where $C_F = (N_C^2 - 1)/2N_C$, $N_C = 3$ being the number of colours.

A precise measurement of the $e^+e^- \rightarrow W^+W^-$ threshold cross section (see e.g., Ref. [14] for details) would provide an interconnection-free method for measuring m_W . Unfortunately, the combined total luminosity accumulated at LEP2 at $\sqrt{s} = 161$ GeV is not sufficient to reach an interesting level of precision. So the direct kinematic reconstruction of m_W from the W hadronic decays remains the only realistic method at current and future energies of LEP2, see Refs. [4]-[6].

The potential significance of the cross-talk phenomena for the W mass reconstruction at LEP2 obviously warrants a detailed understanding of the size of the corresponding ambiguities. Note also that QCD reconnection is of interest in its own right, since it may provide us with a prospective laboratory for probing hadronization dynamics in space and time.

The perturbative aspects of QCD interconnection are, in principle, well controllable. Since the corresponding W mass shift is expected to be well within the uncertainties of the hadronization models (and about on the same level as QED corrections) we only recall here an estimate of Ref. [12],

$$(\delta m_W)_{\text{PT}} \sim \left(\frac{C_F\alpha_s(\Gamma_W)}{\pi} \right)^2 \frac{1}{N_C^2} \Gamma_W, \quad (9)$$

which is of order of a few MeV. The perturbatively calculated mass-shift (as well as other observables) is colour suppressed, by two powers of N_C , which is typical for the gluon-mediated interaction between the two colour-singlet objects.

In the non-perturbative stage, which is our main concern, the colour-suppression situation varies between scenarios. Here factors like $1/N_C^2$ may present, as in the perturbative phase, but they are multiplied by model-dependent coefficients, which are functions of the space-time variables. These coefficients, in principle, could be anything, even much larger than unity.

Since the space-time separation between the W^+ and W^- decay vertices is typically of order $\tau_{\text{dec}} \sim 1/\Gamma_W$, only rather soft gluons (real or virtual) with an energy $\omega \lesssim \Gamma_W$ could feel the collective action of both the $q_1\bar{q}_2$ and $q_3\bar{q}_4$ antennae/dipole systems, and thus participate in the cross-talk. This explains the origin of the last factor in eq. (9).

Non-perturbative reconnection can occur wherever the hadronization regions of the two W bosons overlap. As was first emphasized in Ref. [12], the space-time picture of the evolution of

the final state plays an essential rôle in understanding the size of the interconnection effects at the hadronic level. At the moment, the possible consequences of the hadronic cross-talk between the W 's can only be studied within the existing model-dependent schemes of hadronization. These have done a very good job in describing a vast amount of information on hadronic Z^0 decays, so one may expect that (after appropriate modifications) they could provide a reasonable estimate for the magnitude of interconnection-induced effects, see Ref. [23] for a recent review.

The currently used algorithms for treating the non-perturbative cross-talk all assume a local interaction. Reconnection-unrelated parameters are tuned to optimize the agreement with Z^0 data. Some models allow reconnection also among the partons of a single Z^0 , and then consistency requires reconnection to be included in the above-mentioned tuning stage.

Some essential phenomenological aspects appear to be common for different interconnection models:

1. The cross-talk dampens comparatively slowly with center-of-mass energy, \sqrt{s} , over the range that can be tested by LEP2.
2. Interconnection effects tend to be strongly dependent on the event topology, and could induce azimuthal anisotropies in the particle flow distributions.
3. The low-momentum final particles ($p \lesssim 1$ GeV) are the main mediators in the hadronic cross-talk, and they are most affected by it.
4. Not far from the WW threshold the invariant mass of an original non-reconnected $q\bar{q}$ system is larger than that for a reconnected one. Therefore, most of the model predictions show that the mean particle multiplicity in the (4q) mode, $\langle N^{(4q)} \rangle$, is lower than twice the mean multiplicity of a hadronically decaying W in the mixed hadronic–leptonic channel ((2q) mode), $\langle N^{(2q)} \rangle$,

$$\frac{\langle N^{(4q)} \rangle}{2\langle N^{(2q)} \rangle} < 1. \quad (10)$$

With increasing \sqrt{s} , the multiplicity in the purely hadronic final state may start to rise [24]. However, at least within the models based on colour-confinement strings [25], the inequality (10) remains valid in the whole range of LEP2 energies.

5. All the models on the market (except of Ref. [26]) predict rather small cross-talk effects. Thus, a conservative upper limit on the m_W shift seems to be something like around 50 MeV. Changes in the standard global event characteristics are expected at the per cent level. In marked difference with all other approaches, the colour-full scenario of Ref. [26] allows much larger signals. Thus, the W mass and the relative multiplicity shifts are predicted to be around 400 MeV and 10%, respectively. The strong claims of Ref. [26] have made the whole subject of connectometry attractive for experimentalists.

The word connectometry was introduced in Ref. [24] to cover various ways to detect interconnection-induced effects by measuring characteristics of the WW final state. The first experimental results on connectometry in the W^+W^- events have already been reported, and new

experimental information continues to pour out from LEP2, see Refs. [4]-[6]. At the current level of statistics, there is no evidence for interconnection effects from the standard distributions in hadronic WW events. This agrees with the mainstream of model predictions, which suggests rather small effects. However, it should be remembered that a WW statistics larger by an order of magnitude is still to come.

An important point to bear in mind is that the values – even the signs – of shifts in various observables can depend strongly on the hadronization scenario and on the choice of model parameters. Moreover, results may be strongly sensitive to the adopted experimental strategy.

It would be extremely valuable to establish a model-independent correlation between the shift in m_W and measurable quantities in the final-state distributions. Unfortunately, so far studies do not suggest any convincing correlation of such a type. So one has to proceed within the framework of a certain QCD Monte Carlo model. Thus, Ref. [24] attempted to quantify the expectations based on the string hadronization model [25] in terms of the distributions of low-momentum hadrons. This idea was motivated by an observation [12] that it is the soft particles that are most sensitive to hadronic cross-talk. Essential advantages of such an approach to connectometry is that here the no-reconnection case can be well described, and that there is no (direct) dependence on the jet reconstruction method or event selection strategy. Within string models, there are some general qualitative predictions for the soft-particle spectra in the $WW \rightarrow 4q$ events, dn_{4q}^h/dp , in the LEP2 energy range.

1. Depopulation of the low-momentum hadrons, relative to the no-reconnection scenario, due to the Lorentz boosts of the alternative $q_1\bar{q}_4$ and $q_3\bar{q}_2$ dipoles/antennae.
2. As in the case of the well-known standard string effect [25],[27], such a depopulation should become more pronounced for heavier hadrons (K, p, ...).
3. A gradual reduction of the cross-talk with center-of-mass energy, since the two outgoing W hadronic systems are more and more boosted apart.

As it follows from Ref. [24], at $\sqrt{s} = 172$ GeV within the realistic hadronization scenarios, the depletion of low-momentum spectra, as compared to the no-reconnection case is $\sim 2\%$ for charged particles and $\sim 5\%$ for $K + p$ ¹. At $\sqrt{s} = 195$ GeV, the effects drop down to about a half of what they were at 172 GeV.

The studies in Ref. [24] do not encourage a too optimistic prognosis concerning the prospects of connectometry on the basis of low-momentum spectra, even having the whole aimed-for statistics of LEP2. The best one can hope is that the expected signal would be at the edge of observability. In such a case one would need a lot of hard work (and good luck) in order to detect the signal reliably. However, I would like to emphasize that it is only experiment that could lead the way and may cast light on the challenging issues of the hadronic cross-talk.

I would also like to make it clear that the nonobservation of the reconnection effects on

¹On experimental studies using tagged K and p , see Ref. [28].

the low-momentum spectra, by no means, indicates their nonexistence. Most likely it may just mean that the “queen of observables” is still to be nominated.

Some other ideas may be useful, see Refs. [12],[23],[24]. For example, one may attempt an event-by-event reconstruction of the colour string/dipole topology [30] (see also [29]).

Finally, let us recall that the Z^0 data provide an excellent experimental reference point, thanks to LEP1. When the Z^0 results are used for calibration, the actual model dependence of the low-momentum spectra proves to be rather weak. Due to colour coherence in QCD cascades, the difference in the evolution scales corresponding to the Z^0 and the W could cause only small changes (on the per cent level) at low momenta, see Refs. [31],[32]. Effects due to the difference in the primary quark flavour composition also remain on the per cent level for soft particles. Such small corrections could readily be accounted for, see Ref. [24] for details and applications.

3 Correlations of Particle Flow in Top Events

One of the main objectives of a future linear e^+e^- collider will be to determine the top mass m_t with high accuracy. Besides the traditional measurements of the $t\bar{t}$ excitation curve, several other approaches are discussed, see, e.g., [10]. One method is to reconstruct the top invariant mass event by event, another is to measure the top momentum distribution^[33]. In either case, the QCD interconnection effects could introduce the potentiality for a systematic bias in the top mass determination.

It is not my intention to go here through all the details of the problem. As a specific topical example, following Ref. [13], we consider the production and decay of a $t\bar{t}$ pair in the process

$$e^+e^- \rightarrow t\bar{t} \rightarrow bW^+\bar{b}W^- \quad (11)$$

and concentrate on the possible manifestations of the interconnection effects in the distribution of the particle flow in the final state. For simplicity we assume that the W 's decay leptonically, so the colour flow is generated only by the t and b quarks. Further, we restrict ourselves to the region a few GeV above the $t\bar{t}$ threshold to exemplify the size of effects.

Recall that the dominance of the $t \rightarrow bW^+$ decay mode leads to a large top width Γ_t , which is about 1.5 GeV for a canonical mass $m_t \simeq 175$ GeV. This width is larger than the typical hadronic scale $\mu \sim 1 \text{ fm}^{-1}$, and the top decays before it has time to hadronize [34],[35]. It is precisely the large width that makes top physics so unique. Firstly, the top decay width Γ_t provides an infrared cut-off for the strong forces between the t and the \bar{t} [36]. Secondly, Γ_t controls the QCD interferences between radiation occurring at different stages of the $t\bar{t}$ production processes [37]. These interferences affect the structure of the colour flows in the $t\bar{t}$ events and may provide a potentially serious source of uncertainties in the reconstruction of the final state.

The interplay of several particle production sources is reminiscent of the effects we have studied for process (3), but there are important differences. From the onset, W^+W^- events

consist of two separate colour singlets, $q_1\bar{q}_2$ and $q_3\bar{q}_4$, so that there is no logical imperative of an interconnection between the two. Something extra has to happen to induce a colour rearrangement to $q_1\bar{q}_4$ and $q_3\bar{q}_2$ singlets, such as a perturbative exchange of gluons or a non-perturbative string overlap. This introduces a sizeable dependence on the space-time picture, i.e. on how far separated the W^+ and W^- decay vertices are. The process (11) only involves one colour singlet. Therefore the cross-talk is here inevitable. Recall also that, contrary to the W^+W^- case, there are no purely leptonic channels which could provide an interconnection-free environment. Analogously to the W^+W^- case we expect that the perturbative restructuring is suppressed. However, a priori there is no obvious reason why interconnection effects have to be small in the fragmentation process. Moreover, the b and \bar{b} coming from the top decays carry compensating colour charges and therefore have to ‘cross-talk’ in order to produce a final state made up of colourless hadrons.

Let us start from the perturbative picture. In the process (11) the standard parton showering can be generated by the systems of quarks appearing within a short time scale, namely the $\widehat{t\bar{t}}$, $\widehat{t\bar{b}}$ and $\widehat{\bar{t}b}$ antennae/dipoles.

As was discussed in [37], the energy range of primary gluons, real or virtual, generated by the alternative quark systems of the type $\widehat{t\bar{b}}$, $\widehat{\bar{t}b}$ and $\widehat{b\bar{b}}$ is strongly restricted, and one expects $\omega \lesssim \omega_{max}^{int} \sim \Gamma_t$. Therefore the would-be parton showers initiated by such systems and can hardly lead to a sizeable restructuring of the final state. In other words, the width of an unstable particle acts as a kind of filter, which retains the bulk of the radiation (with $\omega > \Gamma_t$) practically unaffected by the relative orientation of the daughter colour charges.

The general analysis of soft radiation in process (11) in terms of QCD antennae was presented in [37]. Here we focus on the emission close to the $t\bar{t}$ threshold.

The primary-gluon radiation pattern can be presented as:

$$dN_g \equiv \frac{d\sigma_g}{\sigma_0} = \frac{d\omega d\Omega}{\omega} \frac{C_F \alpha_s}{4\pi} \mathcal{I}, \quad (12)$$

where Ω denotes the gluon solid angle; \mathcal{I} is obtained by integrating the absolute square of the overall effective colour current over the virtualities of the t and \bar{t} .

Near threshold the $\widehat{t\bar{b}}$ and $\widehat{\bar{t}b}$ antennae are completely dominated by the emission off the b quarks. The distribution \mathcal{I} may then be presented in the form

$$\mathcal{I} = \mathcal{I}_{indep} + \mathcal{I}_{dec-dec}. \quad (13)$$

Here \mathcal{I}_{indep} describes the case when the b quarks radiate independently and $\mathcal{I}_{dec-dec}$ corresponds to the interference between radiation accompanying the decay of the top and of the antitop

$$\mathcal{I}_{dec-dec} = 2\chi(\omega) \frac{\cos\theta_1 \cos\theta_2 - \cos\theta_{12}}{(1 - v_b \cos\theta_1)(1 - v_{\bar{b}} \cos\theta_2)}. \quad (14)$$

Here $\theta_1(\theta_2)$ is the angle between the $b(\bar{b})$ and the gluon, θ_{12} is the angle between the b and \bar{b} and $\chi(\omega)$ is the profile function [37], which controls the radiative interferences between the different stages of process (11).

Near threshold

$$\chi(\omega) = \frac{\Gamma_t^2}{\Gamma_t^2 + \omega^2} \quad (15)$$

The profile function $\chi(\omega)$ cuts down the phase space available for emissions by the alternative quark systems and, thus, suppresses the possibility for such systems to develop QCD cascades. As $\Gamma_t \rightarrow \infty$, the b and \bar{b} appear almost instantaneously, and they radiate coherently, as though produced directly. In particular, gluons from the b and \bar{b} interfere maximally, i.e., $\chi(\omega) = 1$. At the other extreme, for $\Gamma_t \rightarrow 0$, the top has a long lifetime and the b and \bar{b} appear in the course of the decays of top-flavoured hadrons at widely separated points in space and time. They therefore radiate independently. Thus a finite top width suppresses the interference compared to the naïve expectation of fully coherent emission. The same phenomena appear for the interference contributions corresponding to virtual diagrams.

The bulk of the radiation caused by primary gluons with $\omega > \Gamma_t$ is governed by the $\widehat{t\bar{b}}$ and $\widehat{\bar{t}b}$ antennae. It is thus practically unaffected by the relative orientation of the b and \bar{b} jets. In particular, the $\widehat{b\bar{b}}$ antenna is almost inactive. The properties of individual b jets are understood well enough, thanks to our experience with $Z^0 \rightarrow b\bar{b}$ at LEP1.

Because of the suppression of energetic emission associated with the interferences, the restructuring could affect only soft particles.

Interconnection phenomena could affect the final state of $t\bar{t}$ events in many respects, but multiplicity distributions are especially transparent to interpret. As a specific example, we examined in Ref. [13] the total multiplicity of double leptonic top decays as a function of the relative angle between the b and \bar{b} jets. Let us make some comments concerning the basic ideas of these studies:

1. As usual, one needs to model the fragmentation stage and study quantities accessible at the hadron level.
2. A complication of attempting a full description is that it is no longer enough to give the rate of primary-gluon emission: one must also allow for secondary branchings and specify the colour topology and fragmentation properties of radiated partons. It is then useful to benefit from the standard parton shower plus fragmentation picture for $e^+e^- \rightarrow \gamma^*/Z^0 \rightarrow q\bar{q}$, where these aspects are understood.
3. The relation between $\gamma^*/Z^0 \rightarrow q\bar{q}$ and $t\bar{t} \rightarrow bW^+\bar{b}W^-$ is most easily formulated in the antenna/dipole language, see e.g., [38]. The independent emission term corresponds to the sum of two dipoles, $\mathcal{I}_{indep} \propto \widehat{t\bar{b}} + \widehat{\bar{t}b}$, while the decay-decay interference one corresponds to $\mathcal{I}_{dec-dec} \propto \chi(\omega)(\widehat{b\bar{b}} - \widehat{t\bar{b}} - \widehat{\bar{t}b})$. In total, therefore,

$$\mathcal{I} \propto (1 - \chi(\omega))\widehat{t\bar{b}} + (1 - \chi(\omega))\widehat{\bar{t}b} + \chi(\omega)\widehat{b\bar{b}}. \quad (16)$$

Each term here is positive definite and can be translated into a recipe for parton shower evolution, see [13] for details.

4. The top quarks are assumed to decay isotropically in their respective rest frame, i.e., we do not attempt to include spin correlations between t and \bar{t} . Breit-Wigner distributions are included for the top and W masses.

On the phenomenological side, the main conclusions of the analysis in [13] are:

- The interconnection should be readily visible in the variation of the average multiplicity as a function of the relative angle between the b and \bar{b} .
- A more detailed test is obtained by splitting the particle content in momentum bins. The high-momentum particles are mainly associated with the $\hat{t}\hat{b}$ and $\hat{\bar{t}}\hat{\bar{b}}$ dipoles and therefore follow the b and \bar{b} directions, while the low-momentum ones are sensitive to the assumed influence of the $\hat{b}\hat{\bar{b}}$ dipole.
- A correct description of the event shapes in top decay, combined with sensible reconstruction algorithms, could give errors on the top mass that are on the level of 100 MeV (on top of possible BE effects). We recall here also a naïve perturbative estimate $(\delta m_t)_{PT} \sim \frac{\alpha_s(\Gamma_t)}{\pi} \Gamma_t \sim 70$ MeV.

The possibility of interference reconnection effects in $t\bar{t}$ production is surely not restricted to the phenomena discussed here. They could affect various other processes/characteristics.

One topical example concerns the top quark momentum reconstruction. As was first emphasised in Ref. [33], the momentum measurement combined with the threshold scan could significantly improve the overall precision in determination of m_t and Γ_t . As a supplementary bonus, the top momentum proves to be less sensitive to the beam effects.

In order to reconstruct the top momentum we need at least one of the secondary W 's decaying hadronically. So the final state configurations are either a lepton plus four quark jets or six quark jets. In the latter case there is the WW piece and the $b-W$ and $\bar{b}\bar{W}$ interferences. Recall that the cross-talk between the b and \bar{b} jets is not colour suppressed. QCD interconnection may efface the separate identities of the top and antitop systems and, thus, could produce a potential source of the systematic error in the top momentum determination². The interference pattern here is more complicated than in the case of double leptonic decays because of an additional cross-talking between the hadronically decaying W and the $b\bar{b}$ products.

²The reconstruction of the W -momentum could be affected as well. The QCD interferences can have some impact also on the top momentum distribution itself.

4 Summary and Outlook

The large width ($\Gamma \sim O(1 \text{ GeV})$) of the W boson and of the top quark controls the radiative interferences between emission occurring at different stages of the production processes. The QCD interferences may efface the separate identities of these particles and produce hadrons that cannot be uniquely assigned to either of them. Here we concentrated mainly on two topical problems, namely the QCD interconnection phenomena in events of the type $e^+e^- \rightarrow W^+W^- \rightarrow q_1\bar{q}_2q_3\bar{q}_4$ and $e^+e^- \rightarrow t\bar{t} \rightarrow bW^+\bar{b}W^-$. On the perturbative level these interference effects are small, and one has to apply hadronization models to estimate the non-perturbative effects.

The existing theoretical literature, based on quite different philosophies, shows a rather wide range of expectations for the shift in m_W , from a few MeV to several hundred MeV. The cross-talk between the W 's may have an impact on various other properties of hadronic W^+W^- events as well.

Different hypotheses about the confinement dynamics may lead to different expectations for the final-state event characteristics. So, in principle, the experimental tests of hadronic interconnection between the W 's – connectometry – could provide a new laboratory for probing the structure of the QCD vacuum.

In order to establish the evidence for a cross-talk in hadronic W^+W^- events, one has to find an observable which, on the one hand, proves to be quite sensitive to this effect and, on the other hand, could allow rather straightforward interpretation. The necessary requirements for such a connectometer are that the no-reconnection predictions should be well understood, and that the expected signal is strong enough to be detectable within the limited statistics of LEP2. The latter is, by no means, a simple task.

In Ref. [24], an attempt was made to quantify the expectation based on the string hadronization model [25] in terms of the distributions of low-momentum hadrons. Essential advantages of such an approach to connectometry is that here the no-reconnection case can be well described, and that there is no (direct) dependence on the jet reconstruction method or event selection strategy. The first experimental results on connectometry in the W^+W^- events have already been reported, see Refs. [3]-[6], and new experimental information continues to pour out from LEP2. The best we can hope is that the expected signal would be at the edge of observability. In such a case one would need a lot of hard work (and good luck) in order to detect the signal reliably. However, I would like to emphasize that, given the present lack of deep understanding of the non-perturbative QCD dynamics, it is only experiment that could lead the way.

It is anticipated that the systematic error on the top mass reconstruction in the process (11) would not exceed 100 MeV, see e.g. [13]. One may hope that with sophisticated analysis method such uncertainty can be reduced.

In some sense, the interconnection effects discussed here could be considered as only the tip of the iceberg. Colour reconnection can occur in any process which involves the simultaneous presence of more than one colour singlet. Many of the techniques developed in Refs. [12],[13],[22],[37] could be directly applied to these problems.

Among other examples of practical importance are $e^+e^- \rightarrow Z^0 H^0$, $e^+e^- \rightarrow Z^0 Z^0$, $pp/\bar{p}p \rightarrow W^+W^-$, $pp/\bar{p}p \rightarrow t\bar{t}$, $pp/\bar{p}p \rightarrow t\bar{b}$, $pp/p\bar{p} \rightarrow W^\pm H^0$, etc. One could discuss also interferences with beam jets. The problem with these processes is that there are too many other uncertainties which make systematic studies look very difficult.

Finally, let us recall that many aspects of the high accuracy determination of the parameters of the W boson and of the top quark require a careful analysis of the QED radiative phenomena. Recall, for instance, that the W -width effects seriously modify the QED Coulomb corrections to the cross-section of the process $e^+e^- \rightarrow W^+W^-$, which should be known with a high accuracy for the measurements scanning across the WW threshold region [39].

The non-factorizable QED final-state interaction could induce some systematic effects in other W -mass measurements, for instance in $\bar{p}p$ collider experiments. Of particular interest is the subprocess $qg \rightarrow Wq'$ with $W \rightarrow \ell\nu_\ell$. Collider experiments normally rely on the equivalent process for Z^0 production, $qg \rightarrow Zq$ with $Z \rightarrow \ell^+\ell^-$, to calibrate the W mass scale. Non-universal interference effects are not included in such a procedure, e.g., a charged (W^\pm) versus a chargeless (Z^0) intermediate state. Within current experimental errors this would be negligible, but it could become relevant for future high-precision measurements.

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