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QCD Interconnection Studies at Linear Colliders

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Abstract

Heavy objects like the W, Z and t are short-lived compared with typical hadronization times. When pairs of such particles are produced, the subsequent hadronic decay systems may therefore become interconnected. We study such potential effects at Linear Collider energies.

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The widths of the W, Z and t are all of the order of 2 GeV. A Standard Model Higgs with a mass above 200 GeV, as well as many supersymmetric and other Beyond the Standard Model particles would also have widths in the (multi-)GeV range. Not far from threshold, the typical decay times $\tau = 1/\Gamma \approx 0.1\,\mathrm{fm} \ll \tau_{\mathrm{had}} \approx 1\,\mathrm{fm}$. Thus hadronic decay systems overlap, between pairs of resonances (W^+W^-, Z^0Z^0, $t\bar{t}$, Z^0H^0, ...), so that the final state may not be just the sum of two independent decays. We would like to emphasize that there is no doubt whether a cross-talk between the two unstable objects exists or not — this being a property of quantum theory it is certainly there even in the QED context. The only question concerns its "intensity". Pragmatically, one may distinguish three main eras for such interconnection:

1. Perturbative: this is suppressed for gluon energies $\omega > \Gamma$ by propagator/timescale effects; thus only soft gluons may contribute appreciably.
2. Nonperturbative in the hadroformation process: normally modelled by a colour rearrangement between the partons produced in the two resonance decays and in the subsequent parton showers.
3. Nonperturbative in the purely hadronic phase: best exemplified by Bose–Einstein effects.

The above topics are deeply related to the unsolved problems of strong interactions: confinement dynamics, $1/N_{\mathrm{C}}^2$ effects, quantum mechanical interferences, etc. Thus they offer an opportunity to study the dynamics of unstable particles, and new ways to probe confinement dynamics in space and time [1, 2], *but* they also risk to limit or even spoil precision measurements [2].

So far, studies have mainly been performed in the context of W mass measurements at LEP2. Perturbative effects are not likely to give any significant contribution to the systematic error, $\langle \delta m_W \rangle \lesssim 5$ MeV [2]. Colour rearrangement is not understood from first principles, but many models have been proposed to model effects [2, 3, 4], and a conservative estimate gives $\langle \delta m_W \rangle \lesssim 40$ MeV. For Bose–Einstein again there is a wide spread in models, and an even wider one in results, with about the same potential systematic error as above [5, 6, 4]. The total QCD interconnection error is thus below m_π in absolute terms and 0.1% in relative ones, a small number that becomes of interest only because we aim for high accuracy.

More could be said if some experimental evidence existed, but a problem is that also other manifestations of the interconnection phenomena are likely to be small in magnitude. For instance, near threshold it is expected that colour rearrangement will deplete the rate of low-momentum particle production [7], Fig. 1. Even with full LEP2 statistics, we are only speaking of a few sigma effects, however. Bose-Einstein appear more promising to diagnose, but so far experimental results are contradictory [8].

One area where a linear collider could contribute would be by allowing a much increased statistics in the LEP2 energy region. A 100 fb^{-1} W^+W^- threshold scan with longitudinally polarized electrons and positrons would give a ~ 6 MeV accuracy on the W mass [9], with negligible interconnection uncertainty. This would shift the emphasis from m_W to the understanding of the physics of hadronic cross-talk. A high-statistics run, e.g. 50 fb^{-1} at 175 GeV, would give a comfortable signal for the low-momentum depletion mentioned above, and also allow a set of other tests [10, 7]. Above the Z^0Z^0 threshold, the single-Z^0 data will provide a unique Z^0Z^0 no-reconnection reference.

Thus, high-luminosity, LEP2-energy LC (Linear Collider) runs would be excellent to *establish* a signal. To explore the *character* of effects, however, a knowledge of the energy dependence could give further leverage.

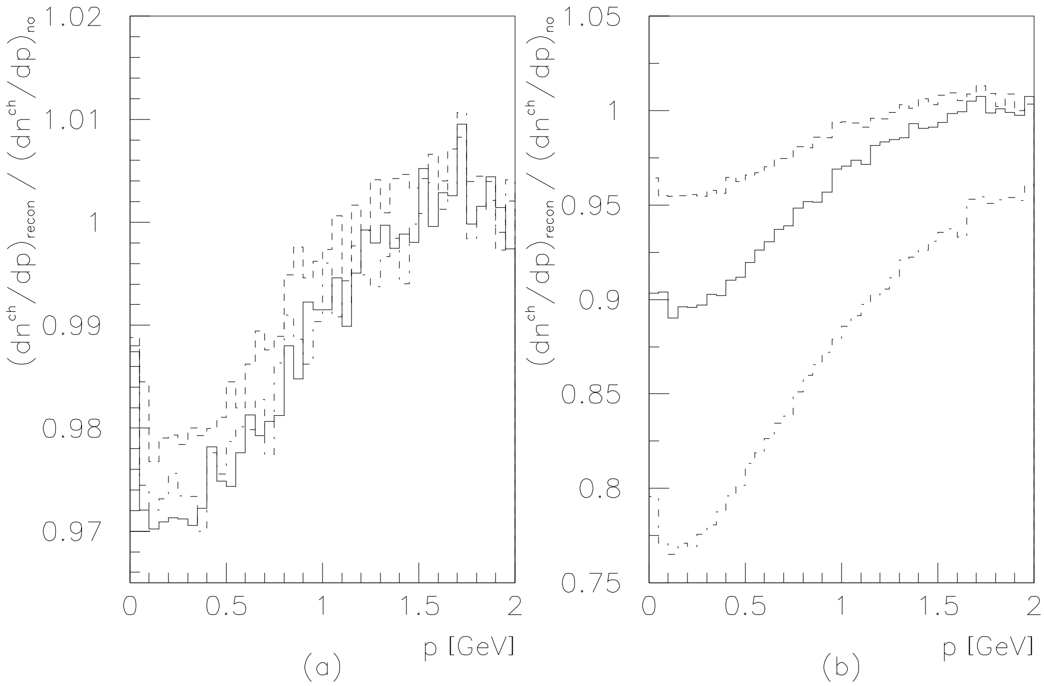

Figure 1: Depletion of low-momentum particles in some realistic (left) and toy (right) scenarios [7].

To get an insight into the various perturbatively-based aspects of interconnection physics, as a model one may consider the QED second-order contribution to the interference non-factorizable corrections (NFC) in Z^0Z^0 production with subsequent charged-lepton decays. Despite all the ideological similarity between the interconnection effects and the NFC, they are not the same, however, so one should be very careful with drawing any phenomenological conclusions solely based on this model.

Based on the analysis of [11], one would expect a very sharp decrease of the NFC with increasing energy, roughly like $(1-\beta)^8$, with β the velocity of each Z in the CM frame. By contrast, the nonperturbative QCD models we studied show an interconnection rate dropping more like $(1-\beta)$ over the LC energy region (with the possibility of a steeper behaviour in the truly asymptotic region), Fig. 2. If only the central region of W masses is studied, also the mass shift dampens significantly with energy, Fig. 2. However, if also the wings of the mass distribution are included (a difficult experimental proposition, but possible in our toy studies), the average and width of the mass shift distribution do not die out. Thus, with increasing energy, the hadronic cross-talk occurs in fewer events, but the effect in these few is more dramatic.

The depletion of particle production at low momenta, close to threshold, turns into an enhancement at higher energies [7]. However, in the inclusive W^+W^- event sample, this and other signals appear too small for reliable detection. One may instead turn to exclusive signals, such as events with many particles at low momenta, or at central rapidities, or at large angles with respect to the event axis, Fig. 3. Unfortunately, even after such a cut, fluctuations in no-reconnection events as well as ordinary QCD four-jet events (mainly $q\bar{q}gg$ split in $qg+\bar{q}g$ hemispheres, thus with a colour flow between the two) give event rates that overwhelm the expected signal. It could still be possible to observe an excess, but not to identify reconnections on an event-by-event basis. The possibility of some clever combination of several signals still remains open, however.

Since the Z^0 mass and properties are well-known, Z^0Z^0 events provide an excellent

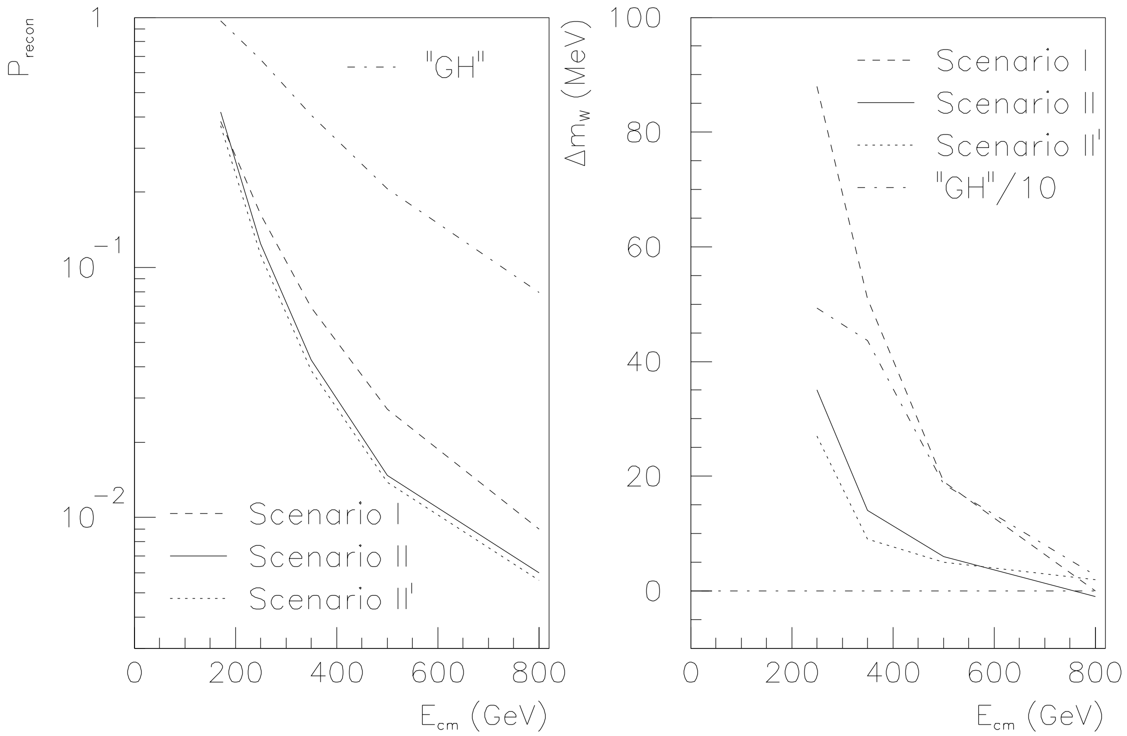

Figure 2: Energy dependence of the reconnection probability and the average reconstructed W mass shift in some scenarios; see [2, 7] for definitions. The masses are derived from a clustering procedure to four jets, with jets paired to give best agreement with the nominal W mass, and with mass shifts above 4 GeV cut out. Somewhat different (and energy-dependent) selection criteria are used here than in [2, 7], so the mass-shift curves are not expected to extrapolate directly to the earlier LEP2 numbers.

hunting ground for interconnection. Relative to W^+W^- events, the set of production Feynman graphs and the relative mixture of is different, however, and this leads to non-negligible differences in angular distributions, Fig. 4. Furthermore, the higher Z^0 mass means that a Z^0 is slower than a $W^\pm$ at fixed energy, and the larger Z^0 width also brings the decay vertices closer. Taken together, at 500 GeV, the reconnection rate in Z^0Z^0 hadronic events is likely to be about twice as large as in W^+W^- events, while the cross section is lower by a factor of six. Thus Z^0Z^0 events are interesting in their own right, but comparisons with W^+W^- events will be nontrivial.

It is worthwhile to mention that, in the QED model case, the second-order NFC in Z^0Z^0 production do not decrease drastically after averaging over the angles of the decay products (contrary to the known first-order case). But here, as well, there is a certain difference between the W^+W^- and Z^0Z^0 results, stemming in particular from the difference in the vector and axial couplings.

As noted above, the Bose–Einstein interplay between the hadronic decay systems of a pair of heavy objects is at least as poorly understood as is colour reconnection, and less well studied for higher energies. In some models [5], the theoretical mass shift increases with energy, when the separation of the W decay vertices is not included, Fig. 5. With this separation taken into account, the theoretical shift levels out at around 200 MeV. How this maps onto experimental observables remains to be studied, but experience from LEP2 energies indicates that the mass shift is significantly reduced, and may even switch

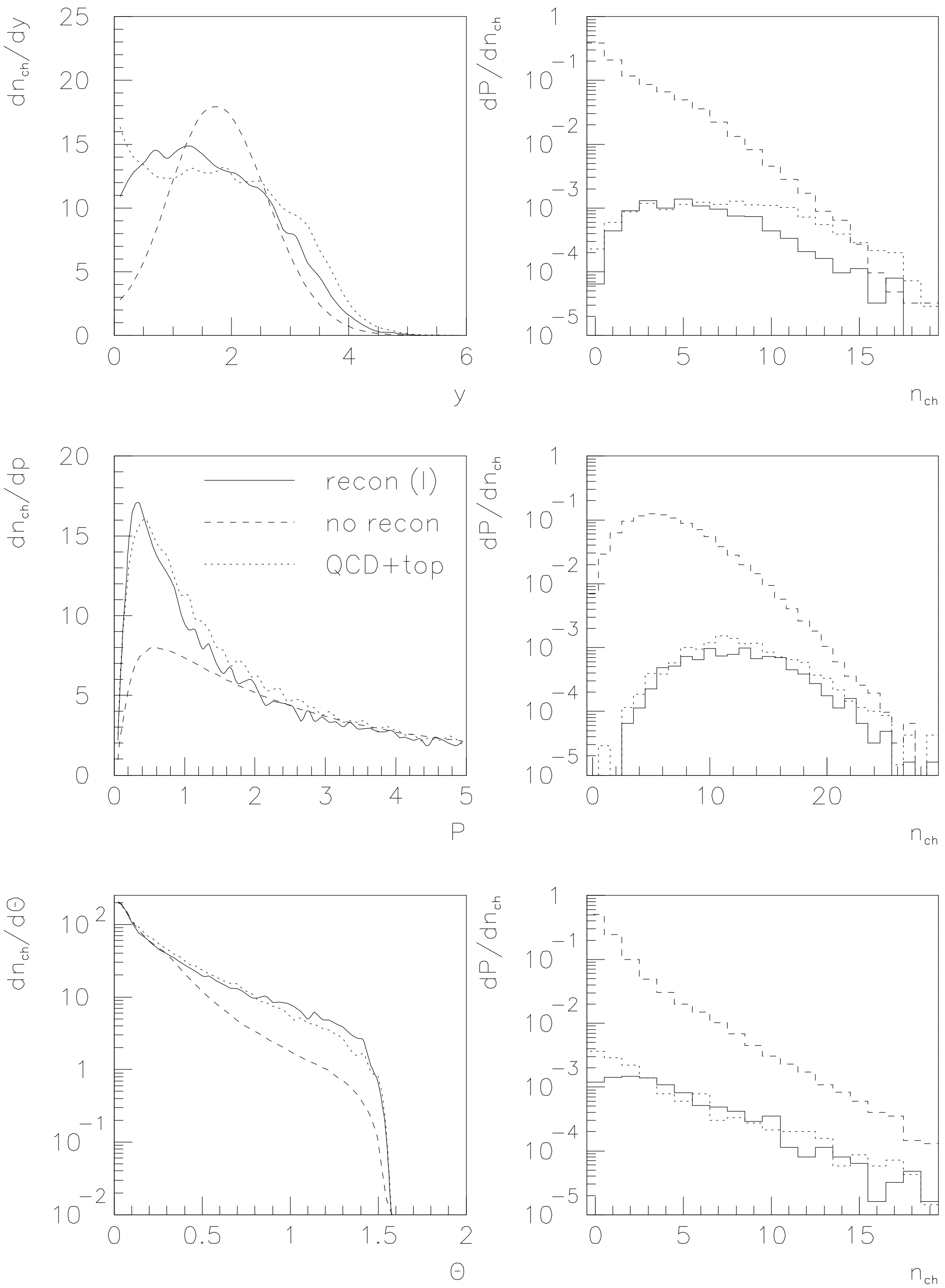

Figure 3: Some potential reconnection signals at 500 GeV, for one realistic reconnection scenario. Left frames: charged particle distribution, per event, in rapidity, momentum and angle relative to the linearized sphericity axis of the event. Right frames: charged multiplicity distribution for $|y| < 0.5$, $|p| < 1$ GeV and angles away from each of the four jet directions more than the respective same-side jet–jet opening angle. Only events that survive four-jet selection criteria are shown, and in the right frames the curves are normalized in proportion to the respective cross section.

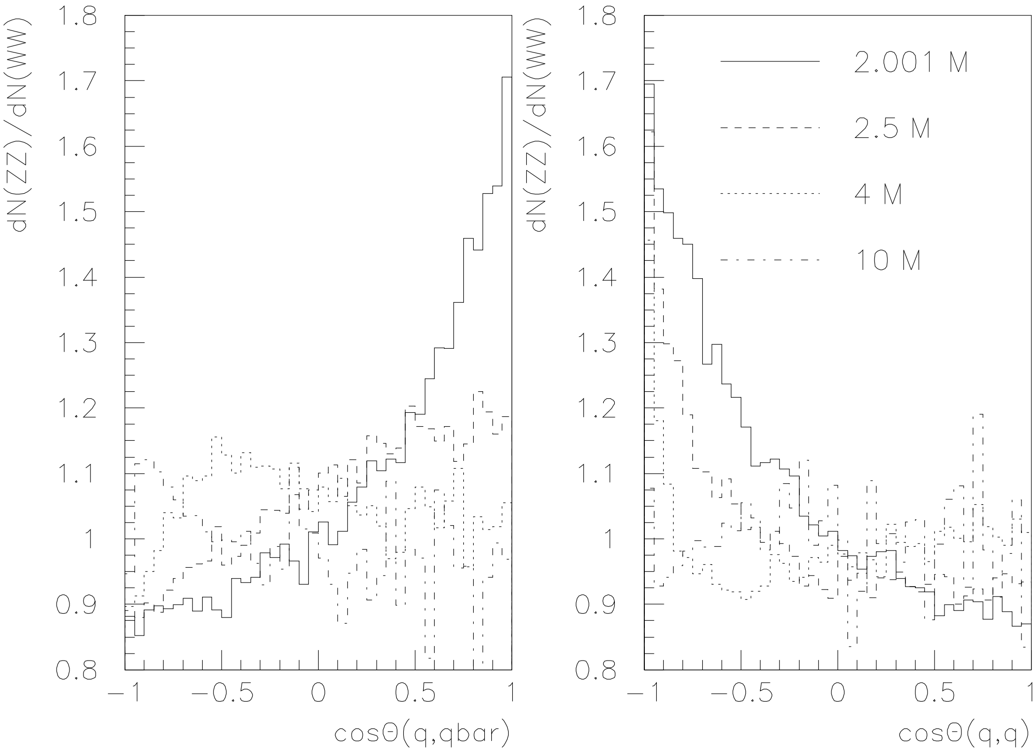

Figure 4: The ratio of angular distributions in the Z^0Z^0 and W^+W^- events, at different multiples of the respective gauge boson mass, and without any Breit-Wigner broadening (in order to let low masses correspond to bosons almost at relative rest). Left frame: between a quark from one boson and an antiquark from the other. Right frame: between the quarks or the antiquarks.

sign.

The $t\bar{t}$ system is different from the W^+W^- and Z^0Z^0 ones in that the t and $\bar{t}$ always are colour connected. Thus, even when both tops decay semileptonically, $t \to bW^+ \to b\ell^+\nu_\ell$, the system contains nontrivial interconnection effects. For instance, the total hadronic multiplicity, and especially the multiplicity at low momenta, depends on the opening angle between the b and $\bar{b}$ jets: the smaller the angle, the lower the multiplicity [12], Fig. 6. On the perturbative level, this can be understood as arising from a dominance of emission from the $b\bar{b}$ colour dipole at small gluon energies [13], on the nonperturbative one, as a consequence of the string effect [14].

Uncertainties in the modelling of these phenomena imply a systematic error on the top mass of the order of 30 MeV already in the semileptonic top decays. When hadronic W decays are included, the possibilities of interconnection multiply. This kind of configurations have not yet been studied, but realistically we may expect uncertainties in the range around 100 MeV. Note that at such a level of precision, it is currently not completely clear how to relate unambiguously the reconstructed top mass to a theoretically adequate quark mass definition.

In summary, LEP2 may clarify the Bose–Einstein situation and provide some hadronic cross-talk hints. A high-luminosity LEP2-energy LC run would be the best way to establish colour rearrangement, however. Both colour rearrangement and BE effects (may) remain significant over the full LC energy range: while the fraction of the (appreciably) affected events goes down with energy, the effect per such event comes up. If the objective

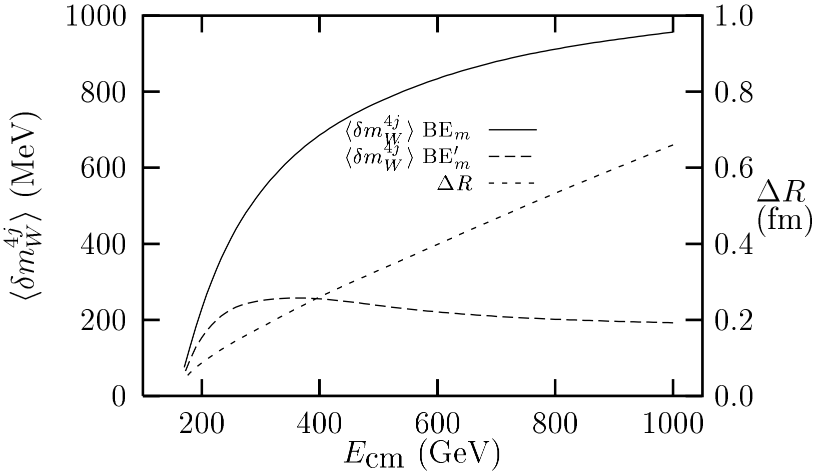

Figure 5: The average shift of the W mass as a function of energy in one model, without or with reduction of effects by the separation of the W^+ and W^- decay vertices [5]. Also shown is the average separation in fm between the two decay vertices.

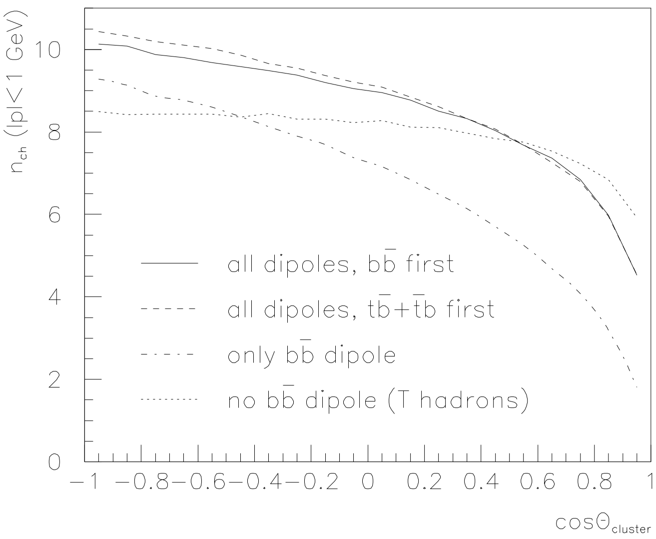

Figure 6: Charged multiplicity in the region $|p| < 1$ GeV as a function of the angle between the b and $\bar{b}$ jets, for $m_t = 174$ GeV and $E_{\mathrm{cm}} = 360$ GeV.

is to do electroweak precision tests, it appears feasible to reduce the WW/ZZ "interconnection noise" to harmless levels at high energies, by simple proper cuts. It should also be possible, but not easy, to dig out a colour rearrangement signal at high energies, with some suitably optimized cuts that yet remain to be defined. The Z^0Z^0 events should display about twice as large interconnection effects as W^+W^- ones, but cross sections are reduced even more. The availability of a single-Z^0 calibration still makes Z^0Z^0 events of unique interest. Further handles for probing the hadronic cross-talk physics may be provided by the W^+W^- studies with polarized electrons and positrons and in photon-photon collisions, where one could benefit from (an order of magnitude) higher production cross sections. While detailed studies remain to be carried out, it appears that the direct reconstruction of the top mass could be uncertain by maybe 100 MeV. Finally, in all of the studies so far, it has turned out to be very difficult to find a clean handle that would help to distinguish between the different models proposed, both in the reconnection and Bose–Einstein areas. So, many questions need to be addressed in further studies and much work thus remains for the future.

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