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TWO TOPICS IN MULTIPARTICLE DYNAMICS AT LEP: MULTIPLICITY IN $b\bar{b}$ EVENTS AND SCREWINESS AT THE END OF THE QCD CASCADE

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This talk deals with two topics in multiparticle dynamics investigated by means of the DELPHI detector at LEP. Related to the first topic, we have used the data collected at 183 GeV to measure the average charged particle multiplicity in $e^+e^- \to b\bar{b}$ events. The result is remarkably in agreement with QCD predictions, while it is more than two standard deviations larger than calculations assuming that the multiplicity accompanying the decay of a heavy quark is independent of the mass of the quark itself. The second topic deals with a recent theoretical model by Andersson et al., in which soft gluons order themselves in the form of a helix at the end of the QCD cascades. In our data at the Z peak, we have found no evidence for such an effect.

1   Charged Particle Multiplicity in $b\bar{b}$ Events

The study of the properties of the fragmentation of heavy quarks compared to light quarks offers insights in perturbative QCD. Particularly important is the difference in charged particle multiplicity between light quark and heavy quark initiated events in e^+e^- annihilations. QCD predicts (see [1,2,3,4] and [5] for a recent review), somehow counter-intuitively [6], that this difference is energy independent; this is motivated by mass effects on the hadronization.

The present experimental tests, although preferring the QCD-motivated scenario, were not conclusive (see [1] and references therein, [7,8,9,10]). At LEP 2 energies, however, the difference between the QCD prediction and the model ignoring mass effects is large, and the experimental measurement can firmly distinguish between the two hypotheses.

Data corresponding to a total luminosity of 54 pb^{-1} collected by DELPHI at centre-of-mass energies around 183 GeV during 1997 were analysed. A description of the DELPHI detector can be found in [11]; its performance is discussed in [12].

Hadronic events were selected as in [13]. The cross-section for $e^+e^- \to q\bar{q}(\gamma)$ above the Z peak is dominated by radiative $q\bar{q}\gamma$ events, such that the effective hadronic centre-of-mass energy, $\sqrt{s'}$, is generally smaller than $\sqrt{s}$. Only events with $\sqrt{s'}$ (determined using the procedure described in [15]) larger than 170 GeV were used.

The influence of the detector on the analysis was studied with the full

DELPHI simulation program, DELSIM [12]. Events were generated with PYTHIA 5.7 and JETSET 7.4 [14] Parton Shower (PS). The particles were followed through the detailed geometry of DELPHI giving simulated digitisations in each subdetector. These data were processed with the same reconstruction and analysis programs as the real data.

A 90% b enriched sample has then been obtained by requiring that the b-event tagging variable y defined as in Ref. [12] was lower than 5×10^{-5}. From this sample the average $b\bar{b}$ multiplicity has been measured by unfolding via simulation for detector effects, selection criteria and initial state radiation. The value obtained was $< n_{b\bar{b}} >= 29.54 \pm 0.79(stat)$.

The relative systematic uncertainty on $< n_{b\bar{b}} >$ was assumed as in [7], so that:

$$< n_{b\bar{b}} >= 29.54 \pm 0.79(stat) \pm 0.63(syst).$$

It was verified that the value above is stable within ± 0.13 units with respect to variations of the cut on the y variable.

The difference δ_{bl} between the $b\bar{b}$ multiplicity and the multiplicity in generic light quark $l = u, d, s$ events can then be extracted by using the equation:

$$< n_{ch} >= R_b < n_{b\bar{b}} > + R_c < n_{c\bar{c}} > + R_l < n_{l\bar{l}} >,$$

where the fractions $R_b = 0.16$, $R_c = 0.26$, $R_l = 0.58$ are the ones predicted by the Standard Model. For the $c\bar{c}$ multiplicity, the PYTHIA prediction of 27.6 was assumed, with a systematic error of ± 1.5 units. For $< n_{ch} >$, we used the result published by DELPHI in [13]:

$$< n_{ch} >= 26.58 \pm 0.24(stat) \pm 0.54(syst). \tag{1}$$

Finally we obtain:

$$\delta_{bl} = 4.23 \pm 1.09(stat) \pm 1.40(syst). \tag{2}$$

The value assumed for $< n_{c\bar{c}} >$ is consistent within better than 1.5 standard deviations with both $< n_{l\bar{l}} >$ and $< n_{b\bar{b}} >$, neglecting the errors on $< n_{l\bar{l}} >$, $< n_{b\bar{b}} >$: we thus verified a-posteriori that the systematic error assumed for $< n_{c\bar{c}} >$ was conservative. The dependence of δ_{bl} on $< n_{c\bar{c}} >$ is anyhow small, and the systematic error assumed gives a contribution of ± 0.67 units to the systematic error on δ_{bl}.

Flavour-Independent Fragmentation — In a model in which the hadronization is independent of the mass, one can assume that the non-leading multiplicity in an event, i.e., the light quark multiplicity which accompanies the decay products of the primary hadrons, is governed by the effective energy

available to the fragmentation system following the production of the primary hadrons [6]. One can thus write:

$$\delta_{bl}(E_{cm}) = 2 < n_B^{(decay)} > + \int_0^1 dx_B f(x_B) \int_0^1 dx_{\bar{B}} f(x_{\bar{B}}) \; n_{l\bar{l}}\left(\left(1 - \frac{x_B + x_{\bar{B}}}{2}\right) E_{cm}\right)$$
$$- n_{l\bar{l}}(E_{cm}),$$

where $< n_B^{(decay)} >$ is the average number of charged particles coming from the decay of a B hadron, x_B ($x_{\bar{B}}$) is the fraction of the beam energy taken by the B ($\bar{B}$) hadron, and $f(x_B)$ is the b fragmentation function.

We assumed $2 < n_B^{(decay)} >= 11.0 \pm 0.2$ [1], consistent with the average $< n_B^{(decay)} >= 5.7 \pm 0.3$ measured at LEP [18]. For $f(x_B)$, we assumed a Peterson function of average 0.70 ± 0.02 [19]. The value of $n_{l\bar{l}}(E)$ was computed from the fit to a QCD formula [20] including the resummation of leading (LLA) and next-to-leading (NLLA) corrections, which reproduces well the measured charged multiplicities [13], with appropriate corrections to remove the effect of heavy quarks [17].

The prediction of the model in which the hadronization is independent of the mass is plotted in Figure 1 as a function of the centre-of-mass energy. There are several variations of the model in the literature, leading to slightly different predictions (see [18] and references therein).

QCD Calculation — The large mass of the b quark, in comparison to the scale of the strong interaction, $\Lambda \approx 0.2$ GeV, results in a natural cut off for the emission of gluon bremsstrahlung, thereby avoiding the treatment of divergences in perturbation theory. Furthermore, where the centre-of-mass energy greatly exceeds the scale of the b quark mass, the inclusive spectrum of heavy quark production is expected to be well described by perturbative QCD in the Modified Leading Logarithmic Approximation (MLLA).

The value of δ_{bl} has been calculated in perturbative QCD[1,3]:

$$\delta_{bl} = 2 < n_B^{(decay)} > - < n_{l\bar{l}}(e^{1/2}m_b) > + O(\alpha_s(m_b)) < n_{l\bar{l}}(m_b)) > .$$

Although the last term in the equation limits the accuracy in the calculation of δ_{bl}, one can conclude that δ_{bl} is approximately independent of E_{cm}.

The calculation of the actual value of δ_{bl} in [1] gives a value of 5.5 ± 0.8; an approximation including the last term in the above equation gives a value of 3.68 [3]. This demonstrates the importance of the contribution $O(\alpha_s(m_b))$. A condition less restrictive is the calculation of upper limits. An upper limit $\delta_{bl} < 4.1$ is given in [3], while from phenomenological arguments, $\delta_{bl} < 4$ is predicted in Ref. [4].

In Figure 1 the high energy prediction from QCD is taken from the average of the experimental values of δ_{bl} up to m_Z included, $< \delta_{bl} >= 2.96 \pm 0.20$.

Our measurement of δ_{bl} is fully consistent with the hypothesis of energy independence, and more than two standard deviations larger than predicted by the naive model presented in the beginning of this section.
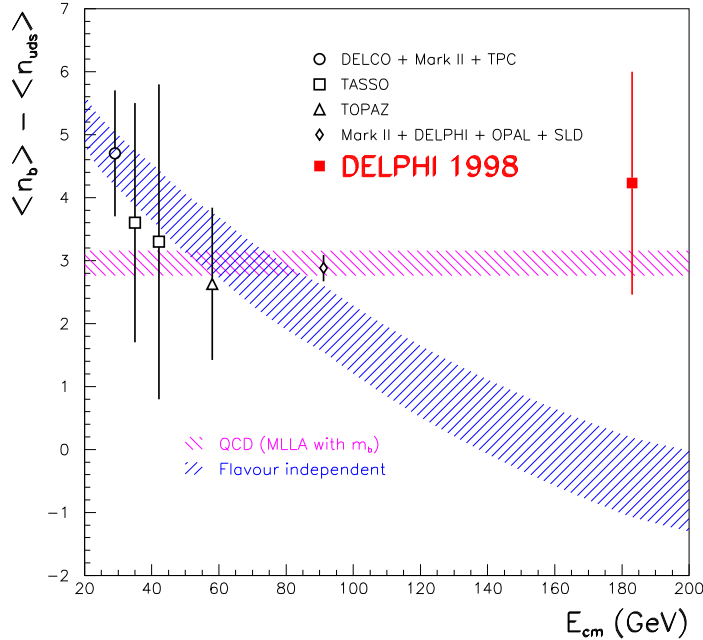
Figure 1. The present measurement of δ_{bl} compared to previous measurements as a function of the centre-of-mass energy, to the QCD prediction, and to the prediction from flavour-independent fragmentation.

2 Is There Screwiness at the End of the QCD Cascades?

Two colour charges moving apart from each other produce colour radiation in the form of gluons. At the end of the parton cascade one enters into a non-perturbative region, where perturbative QCD breaks up due to the small momentum transfer and hence large strong coupling constant α_s. There are non-perturbative models to describe the transition regime between the perturbative region and final state hadrons, in which the largest contributing Feynman diagrams are chosen based on the coherence of the gluons. The gluon emissions are ordered by the transverse momentum in the dipole model [21], and by emission angle in the Webber-Marchesini model [22]. The azimuthal angle of the gluons is taken to be uniformly distributed ignoring possible spin effects.

In a recent theoretical paper [23], it is studied what happens at the end of the QCD cascades: the soft gluons have a transverse momentum of the same order as the mass of the emitter, leading to a situation in which a large recoil may spoil the original coherence. With the assumptions that:

- the effective coupling is large enough so that the number of emitted gluons is as large as possible;

- the emissions conserve helicity;

the Authors show that the closest packing of soft gluons is obtained by using the extra degree of freedom provided by the azimuthal angle and arranging the gluons along a helix. The helix is described by the parameter $\tau = dy/d\phi$, where y is rapidity and ϕ is the azimuthal angle with respect to the original parton direction. The correlation between the azimuthal angle and rapidity can be tested by using a Fourier power spectrum, which is called screwiness S in Ref. [23] and defined as:

$$S(\omega) = \sum_e P_e |\sum_j \exp(i(\omega y_j - \phi_j))|^2, \tag{3}$$

where the second sum goes over the gluons, the first sum goes over all the events, and P_e is an event weight. Screwiness would then manifest itself as a peak in the power spectrum at $\omega = 1/ < \tau >$. If a large number of gluons were emitted isotropically, there should be no peak. Asymptotically screwiness should only depend of the number of emitted gluons at large values of ω.

Experimentally one observes stable final state particles instead of gluons. Moreover, in such an analysis it is convenient to use charged particles only, due to the better accuracy in the measurement of the momenta at low energy. Normalized screwiness can now be defined as

$$S(\omega) = \frac{1}{N_{event} < N_{particle} >} \sum_e |\sum_j \exp(i(\omega y_j - \phi_j))|^2, \tag{4}$$

where the second sum goes over the final state particles, and the first sum goes over all the events. Rapidity y and azimuthal angle ϕ are defined with respect to the thrust axis. Ordering of the final state particles would produce a peak in the $S(\omega)$ spectrum, with a maximum peak size of $S(\omega)_{max} = < N_{particle} >$ for maximal ordering. An isotropical particle emission would give asymptotically $S(\omega) \simeq 1$ at large values of ω, and no peak. When ω approaches zero, screwiness measures the transverse momentum balance of the final state particles and it should approach zero.

For a fixed $\sqrt{s}$, a certain finite rapidity interval is available. The central rapidity plateau is not flat, producing fluctuations in the power spectrum. Selecting the central rapidity region and using only charged particles with experimental acceptance cuts, the number of final state particles available to calculate the screwiness is reduced.
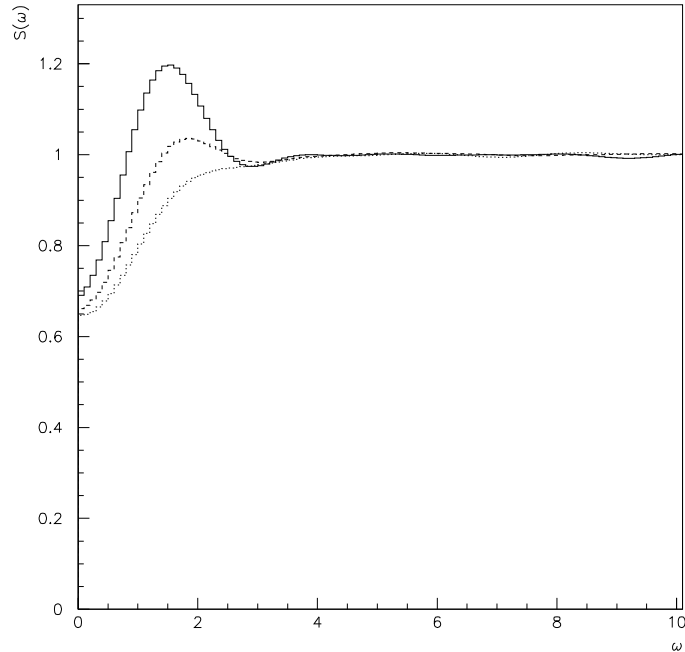
Figure 2. Power spectrum for simulated data samples with $\tau = 0.7$ (full line), $\tau = 0.5$ (dashed line) and $\tau = 0.3$ (dotted line). Only stable charged particles with $p > 0.15$ GeV/c in $|y| < 2$ were retained.

A typical screwiness spectrum is shown in Figure 2 where the parameter τ was set to 0.3, 0.5 and 0.7. Only charged particles with $p > 0.15$ GeV/c in $|y| < 2$ were retained. A clear peak can be observed at $\omega = 1/ < \tau >$ when $\tau = 0.7$. With a τ value of 0.5 there is still peak in the spectrum which could be observable, while with $\tau = 0.3$ the winding is too fast to be observed. The events were generated using a JETSET Monte Carlo simulation program, which did not contain parton showering, but in which a helix-ordering of the final state clusters was implemented. The average multiplicity of charged particles with the above selections was 5.2, which was roughly the same as with the default JETSET.

With soft gluons included in the event generator, the transverse momentum fluctuations event-by-event cause that the screwiness does not decrease when ω goes
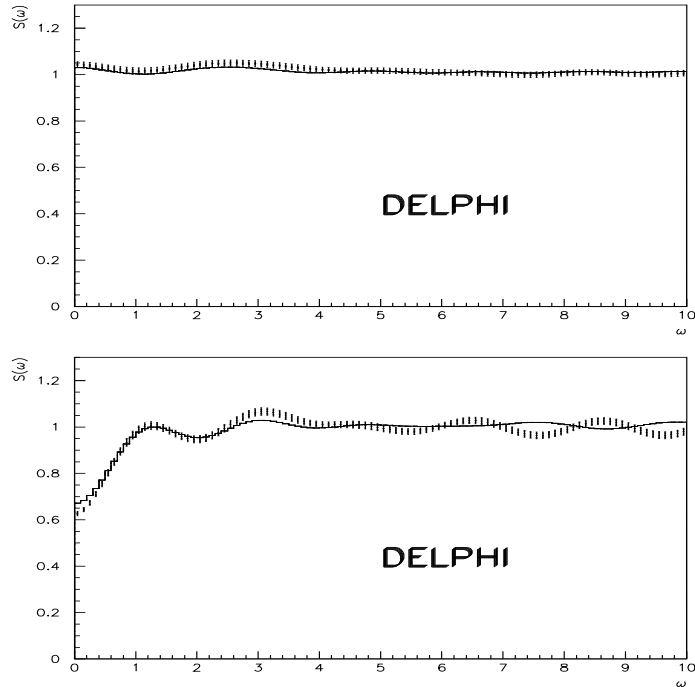
Figure 3. Upper: power spectrum for DELPHI data (points) compared to JETSET with full detector simulation (histogram). The inner error bars on the data points correspond to the statistical errors, the outer ones to the sum in quadrature of the statistical and systematic errors. Lower: as for the upper part, for events with at least five charged particles and a missing momentum component transverse to the thrust axis smaller than 1 GeV/c.

to zero if one considers a narrow window in rapidity space with a few particles. The multiplicity of particles in the event affect the behaviour of the screwiness at small values of ω. At large values of ω the normalized screwiness approaches one.

A sample of hadronic Z decays collected in 1994 were selected by requiring that the events contained at least five charged particles within the angular range of $|\cos\theta| < 0.96$, that the thrust axis was within the angular range of $|\cos\theta_T| < 0.7$, and that the thrust value was larger than 0.98. Charged particles were accepted if the measured momentum was greater than 0.15 GeV/c, track length greater than 30 cm and the transverse and longitudinal impact parameters less than 5 and 10

cm, respectively. Particles within $|y| < 2$ were retained for the calculation of the power spectrum. The final selected sample used for this analysis consisted of 50,000 events.

Screwiness of the selected events is shown in the upper part of Figure 3 together with the full simulation. The simulated data were generated with the JETSET 7.3 parton shower simulation program, using input parameters reproducing the main features of the DELPHI data [24]. The generated events were then simulated with the DELSIM full detector simulation program [12] and reconstructed as data. The data show no peak in the screwiness distribution, and the JETSET model, with random emission of soft gluons in the azimuthal angle, reproduces well the data distribution.

The statistical error of the data was about 0.5%, computed as the standard deviation of a set of Monte Carlo simulation samples with the same population as the data. The systematic uncertainty was estimated to be around 1%. The main source of systematic uncertainty was expected to originate from the small differences in the rapidity distribution in data and simulation. The following procedure was used to estimate the inability of the simulated events to reproduce the data. The data were first weighted in such a way that the rapidity distribution was flat. The data were then weighted with the weights which would make the simulated rapidity distribution flat. The difference of the results, divided by the data distribution, was then the estimate of the relative systematic error.

The same analysis was repeated by selecting only events with at least five charged particles with $|y| < 2$, but no effect was seen. Finally, 10,000 events were selected with at least five charged particles with $|y| < 2$ and such that the sum of the momenta of these particles had a momentum component transverse to the thrust axis smaller than 1 GeV/c (lower part of Figure 3). The disagreement between data and simulation after these cuts is at the 5% level. The data does not show, however, a typical screwiness pattern.

In conclusion, no evidence for screwiness was found, and results were consistent with random emission of gluons in the azimuthal angle. Given the DELPHI experimental sensitivity, it was found that the helix parameter $\tau = dy/d\phi$ cannot be larger than about 0.5.

Acknowledgements

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