STUDIES OF FRAGMENTATION AND COLOUR RECONNECTION AT LEP

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Hadronic events at the Z pole have been investigated in search for Colour Reconnection effects and QCD coherence. Colour Reconnection effects are searched for in three-jet events and the data results are compared to the predictions of different Monte Carlo models. QCD colour coherence effects are tested through the multiplicity distributions of hadrons with restricted momenta, and the LEP1 e^+e^- data is compared to HERA e^+p data under the equivalence assumption of the e^+e^- hemisphere with the current region of the Breit frame of reference.

1. Colour Reconnection effects at the Z pole

Colour Reconnection (CR) effects are higher-order and/or non perturbative QCD effects arising in the hadronisation of multi-parton systems. There is a specific interest in these effects due to related uncertainties when performing precision measurements of invariant masses in multi-jet events, and in particular for the measurement of the W mass, where possible CR effects in the $W^+W^- \to q\bar{q}q\bar{q}$ channel are the main limitation on the overall m_W precision.

To assess CR effects it has been proposed[1] to search for CR effects in $q\bar{q}gg$ systems in hadronic Z decays, benefiting greatly from larger statistics with respect to the W pair data. In hadronic Z decays CR effects would enhance the probability to find a colour singlet gluon system isolated from the $q\bar{q}$ state. Such events would show up as three-jet events with a zero charge gluon jet, associated with a gap of particles around the gluon jet.

1.1. *OPAL results*

The OPAL collaboration has selected gluon jets from Z decays in events with two opposite tagged quark jets. A total of 439 gluon jets are selected with an expected purity of 82% and an average energy of 40 GeV. Studying the distribution of charged particles at small rapidities ($y \leq 2$) around the gluon-jet axis, the expected multiplicity depletion due to CR effects is not observed, and the Ariadne[2] CR model was excluded at the level of five standard deviations[3].

In a subsequent publication by OPAL[6] lower energy gluon jets are selected in three-jet Z decays, where two jets are lifetime-tagged as heavy quark jets, and the third gluon jet has an average energy of 21 GeV. A gap in rapidity of both charged and neutral particles is ensured by requiring an upper bound on the minimum particle rapidity in the gluon jet ($y_{\min} < 1.4$) and a lower bond on the maximum difference between the rapidity of adjacent particles ($\Delta y_{\max} > 1.3$). The selection leads to a sample of 655 gluon jets with an expected purity of 86%. CR effects are expected to enhance the rates of those events for which the leading part of the gluon jet is neutral. The enhancements predicted by the Ariadne[2] and GAL[4] CR models are not observed in the data, and retuning the parameters of the two models to describe both the gluon jet data and the inclusive Z data, leads to a huge degradation of the χ^2 values of the global fit, therefore excluding these two CR models. For this analysis, the excess predicted by the Herwig CR model[5] is much less prominent, so that no definite conclusion could be obtained on this model.

1.2. *L3 results*

The L3 collaboration has also published studies of CR effects in three-jet hadronic Z decays[7]. Events are selected with two lifetime-tagged quark jets and an anti-tagged gluon jet. Observables based on angular separations of particles in the inter-jet regions are found to be very sensitive to colour singlet gluon productions and CR effects. The data χ^2 confidence level (CL) based on these observables are then $\sim 10^{-8}$ for the Ariadne CR model and $\sim 10^{-6}$ for the GAL CR models, so that both these CR models are excluded with their default settings. The same observables exclude also the Herwig[5] model with a $\sim 10^{-9}$ CL including CR effects, but also exclude, with a $\sim 10^{-8}$ CL, the same model with no CR effects, suggesting that Herwig can't simulate with sufficient precision the soft hadronisation effects important for CR studies.

1.3. *DELPHI results*

In recent preliminary studies from DELPHI[8], three-jet events are selected from Z decays, and the quark or gluon jets are singled out by energy ordering. The leading system of both kind of jets are selected by demanding a rapidity gap of charged particles for $\Delta y \leq 1.5$. In this way about 50,000 gluon jets and 50,000 quark jets are selected. Studying the total charge of the leading system, a higher rate of neutral systems is found in the gluon jets data with respect to the predictions of string models, while no such enhancement is found in the quark jets sample. The excess of leading neutral gluon jets is measured to be roughly 10% with a significance of three standard deviations, and could be due to CR effects or colour-octet neutralisation of the gluon field (glueballs).

1.4. *ALEPH results*

In a new paper by the ALEPH collaboration[9] Z decays to three jets are also used to test CR models. The main fragmentation parameters of the CR models considered[2,4,5] have been re-tuned with fits to the hadronic Z global event shape and charged particle momentum distributions, and without degrading the fits χ^2 values with respect to the models with no CR.

To select three-jet events the Durham clustering scheme is applied to hadronic Z decays with a resolution parameter $y_{\rm cut} = 0.02$, and only events which cluster into exactly three-jets are selected. The events are also required to be planar, with no isolated and energetic photon. The three jets are required to be well-contained in the detector acceptance and separated by inter-jet angles larger than 40°. Jets are energy-ordered and the softest jet (jet 3) is assigned to the gluon jet, with an expected purity of 70%.

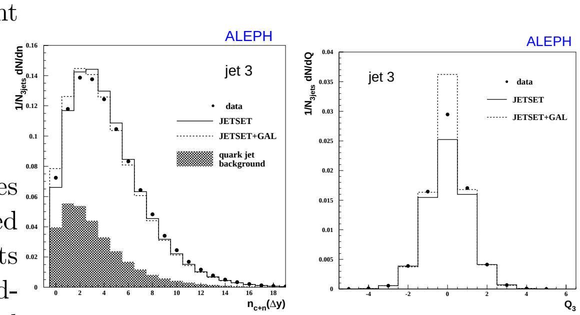

Fig. 1. Number of charged and neutral particles in the $0 < y < 1.5$ interval of jet 3, compared to the prediction of a fragmentation model with and without GAL CR effects [4] (left). Charge distribution of jet 3 with a rapidity gap in the $0 < y < 1.5$ interval (right).

The particle multiplicity within the central rapidity interval $0 < y < 1.5$ of jet 3 is shown in figure 1(left). Focusing on the first bin with no particles in the rapidity interval (rapidity gap) it can be seen that there is an excess of data events with respect to the predictions of the fragmentation model with no CR effects, but the data excess is smaller than the predictions of the same model with CR effects[4]. The differences of the data yields and the models are enhanced by requiring zero total charge for jet 3, as visible in figure 1(right).

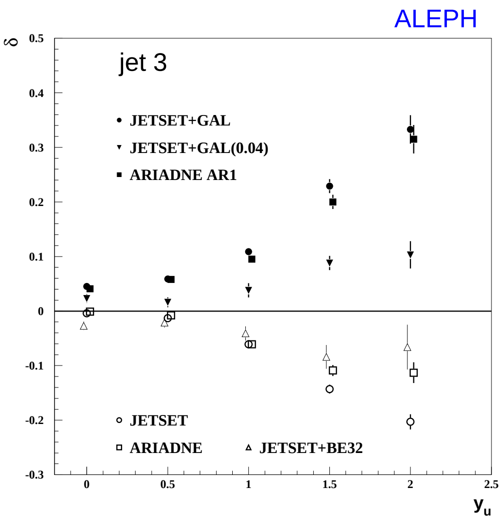

Fig. 2. Relative model-data differences in the rate of neutral gluon jets as a function of the required rapidity gap.

The differences δ=(model-data)/data of the rate of neutral gluon jets, as a function of the required rapidity gap is shown in figure 2 for different models. It can be seen that at large rapidity gaps the data is in disagreement both with models with or without CR effects included. To fit the data rates with the Ariadne and GAL CR models, it would be necessary to decrease their CR strength parameters roughly by a factor five, from 0.1 to 0.02, in disagreement with the $1/N_c^2 \simeq 1/9$ prescription for the reconnection probability.

Figure 3 shows the δ values for the leading quark jet. In this case the agreement of data with models with or without CR effects is good, except for the Herwig model that in both cases fails to reproduce the particle rapidity distributions, over a wide rapidity range, and is therefore not suited for these

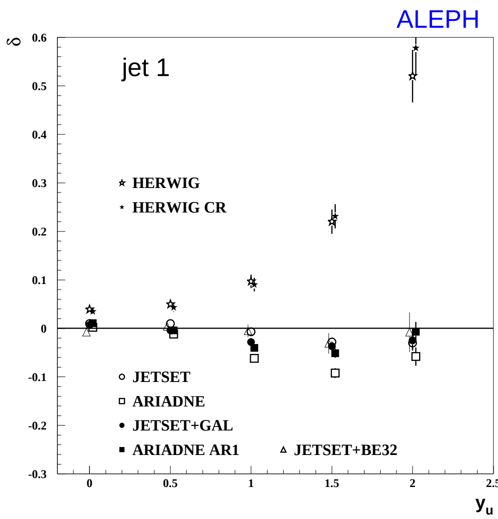

Fig. 3. Relative model-data differences in the rate of neutral quark jets as a function of the required rapidity gap.

studies.

2. QCD Coherence and Correlations at the Z pole

Recent analytical perturbative QCD calculations, in conjunction with Local Parton-Hadron Duality (LPHD), suggest that, while the general multiplicity distribution of partons in a jet is broader than a Poisson distribution, due to positive correlations in the gluon emissions, for gluons produced with limited momenta transverse to the primary parton, the emissions are independent due to colour coherence, and their multiplicity distribution becomes Poissonian[10].

To verify this perturbative prediction and to what extent it is affected by the hadronisation, it has been proposed to measure factorial moments F_q and cumulants K_q, defined as

$$F_q = \langle n(n-1)\dots(n-q-1)\rangle / \langle n\rangle^q$$
$$K_2 = F_2 - 1 \qquad K_3 = F_3 - 3F_2 + 2$$
$$K_4 = F_4 - 4F_3 - 3F_2^2 + 12F_2 - 6$$

where n is the number of particles in some phase-space region, and the angle brackets denote the average over the observed events. The K_q moments are by construction the measure of the q-particle correlations.

Restricting the phase-space of the multiplicity measurements cylindrically in transverse momentum ($p_T < p_T^{\rm cut}$) the Poisson limit is expected to be reached as $p_T^{\rm cut}$ decreases, with $F_q \simeq 1$ and $K_q \simeq 0$. The same Poisson limit is not expected to be reached when limiting the phase-space spherically in absolute momentum ($p < p^{\rm cut}$)[10].

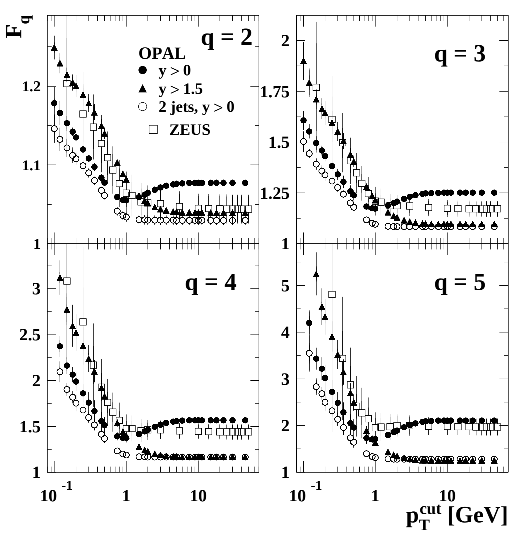

Fig. 4. Factorial moments F_q of charged particles with limited transverse momenta, as a function of $p_T^{\rm cut}$, compared to those measured in high thrust two jet events, in a restricted rapidity window, and in HERA e^+p data from ZEUS [12].

The OPAL collaboration has recently published results on the measurements of these proposed correlation variables[11]. Results for cylindrically cut F_q moments are shown in figure 4. Decreasing $p^{\rm cut}$ the moments decrease to a minimum at the common value $p^{\rm cut} \simeq 1$ GeV, suggesting that the strong hadronisation effects mask the validity of the perturbative calculations at the scale of 1 GeV.

Results on cumulants reveal similar structures and show evidence for the presence of two- and three-particle correlations, while four-particle correlations K_4 are compatible with zero, within errors.

Results on F_q moments measured by ZEUS[12] in e^+p data are also shown in figure 4 but do not reveal the same minimum that could signal the border between perturbative and non-perturbative dynamics.

To understand the differences, further cuts have been applied to the LEP e^+e^- data to mimic the HERA e^+p experimental conditions, including (i) a cut $y > 1.5$ to exclude the central rapidity region and (ii) a cut on the event thrust $T > 0.96$ to select a pure sample of two-jet events.

With the additional cuts, also shown in figure 4, the qualitative behaviour of the e^+e^- and e^+p measurements looks more similar, but the compatibility of the two measurements is still problematic. These results suggest that for soft particle production, the assumed equivalence of a single event hemisphere in e^+e^- events with the current region in the e^+p Breit frame may be misleading.

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