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RECENT RESULTS IN JET PHYSICS*

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I present some recent experimental results in jet physics. The general themes are color reconnection, rapidity gaps, particle multiplicities in jets, and differences between gluon and quark jets. Data from e^+e^-, $p\overline{p}$ and ep collisions are presented.

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1. Test of models of color reconnection in Z^0 decays

Color reconnection (CR) concerns soft color exchange between "final-state" partons which alters the color structure of an event from its original configuration, *i.e.* its configuration as created in an electroweak or strong interaction scattering process. A well known example is $B \to J/\Psi + X$ decays, in which the W boson produced in the decay of the b quark creates a color singlet $\overline{c}s$ pair, but then the $\overline{c}$ ends up within the color-singlet J/Ψ. Color reconnection (CR) has been postulated as the source of rapidity gap and diffractive events in ep and $p\overline{p}$ collisions, as in the Generalized Area Law (GAL) model [1].

In contrast to ep and $p\overline{p}$ events, inclusive e^+e^- events do not exhibit anomalous rates of events with a large rapidity gap [2]. Nonetheless, CR — if present — should yield events with a significant rate of rapidity gaps in the "non-inclusive" process $e^+e^- \to q\overline{q}g$, as illustrated in Fig. 1. Compared to events with normal color connection (Fig. 1(a)), events with CR (Fig. 1(b)) are characterized by a reduction in particle production in the central rapidity region and thus by an increase in the probability for a rapidity gap in the gluon jet.

To assess the sensitivity of data to CR, simulations of color reconnection have been incorporated into standard QCD Monte Carlo programs. Three

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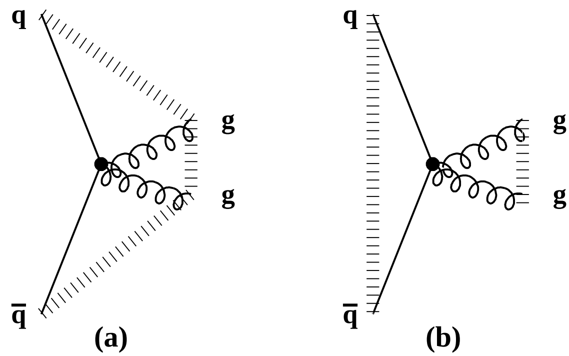

Fig. 1. Schematic illustrations of events with (a) standard "planar" color flow and (b) reconnection. The hatched regions represent color flux tubes or "strings" stretched between the quark q, antiquark $\overline{q}$ and gluons g.

of these models are the Ariadne–CR model [3], the Rathsman–CR model [1] and the Sjöstrand–Khoze SK-I model [4]. The Ariadne–CR model is implemented in the Ariadne Monte Carlo. The Rathsman–CR and SK-I models are implemented in the Pythia Monte Carlo. For e^+e^- annihilations, Jetset is essentially the same as Pythia. Thus, the Rathsman–CR model effectively represents a version of Jetset with CR. The Rathsman–CR model is based on the GAL model mentioned above.

CR has been much discussed in recent years because of its potential impact on the accuracy with which the W boson mass can be determined in $e^+e^- \rightarrow W^+W^- \rightarrow hadrons$ events [4, 5]. Indeed, CR forms the largest systematic uncertainty in the W mass measurement at LEP. It has proved difficult to find experimental variables which are sensitive to CR, to potentially reduce the size of this uncertainty. One of the most sensitive variables to CR found in studies of $e^+e^- \rightarrow W^+W^-$ events is based on particle flow in four-jet events [6]. A pair of jets is associated with each W based on the event kinematics (angles between jets, kinematic fits, *etc.*). Particles are projected into the plane defined by two jets, and the number of particles in the region from 20 to 80% between the jets peaks is counted. The process is iterated over the four jet pairs. A ratio R is then formed to compare the particle density in the inter-W regions to that in the intra-W regions:

$$R \equiv \frac{\int_{0.2}^{0.8} dn/d\phi\,(\text{inter}-W)}{\int_{0.2}^{0.8} dn/d\phi\,(\text{intra}-W)}\,.$$

For CR events, the particle density in the intra-W regions is enhanced: therefore R is smaller. To avoid biases, the data and Monte Carlo predictions are examined at the detector level. To eliminate differences between the selection criteria of the four LEP experiments so that their results can be combined, R is normalized to the non-CR version of each model being examined, resulting in a ratio of ratios denoted r:

$$r \equiv \frac{R_i}{R_{\rm MC}^{\rm no-CR}}\,.$$

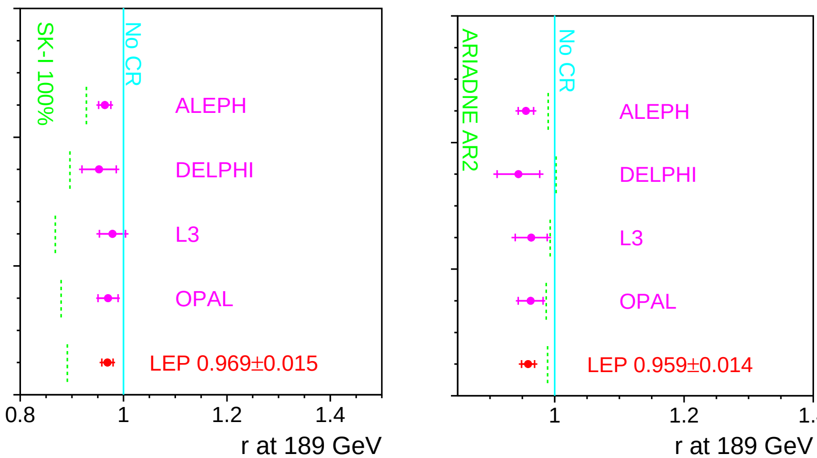

Fig. 2. Results for the ratio r of particle flow in $e^+e^- \to \mathrm{W}^+\mathrm{W}^-$ events (see text), (left) for the SK-I model of color reconnection *versus* Pythia, (right) for the Ariadne–CR model *versus* Ariadne. (Figures taken from [6].)

The results for r for the SK-I model *versus* Pythia are shown in Fig. 2(left) and for the Ariande-CR model *versus* Ariadne in Fig. 2(right). Note that the results for the SK-I model represent an extreme version in which essentially every event contains color reconnection. The results of Fig. 2(left) imply that the particle flow method is sensitive to CR, *i.e.* the CR and non-CR predictions are quite different. The data lie between the predictions of the SK-I and Pythia models implying that they are consistent with a finite level of reconnection. The conclusions from Fig. 2(right) are quite different, however: the predictions of the Ariadne–CR and Ariadne models are essentially the same, implying that the particle flow method is *not* sensitive to CR. This leaves the conclusiveness of the particle flow method unclear. For example, the data in Fig. 2(right) are equally in disagreement with the CR and non-CR models, implying that there are systematic uncertainties unrelated to CR which are not understood.

The difficulties in finding an experimental variable which yields a unambiguous signal for CR in W^+W^- events establish the interest in studies of CR based on three-jet $q\bar{q}g$ events from Z^0 decays (Fig. 1). There is a

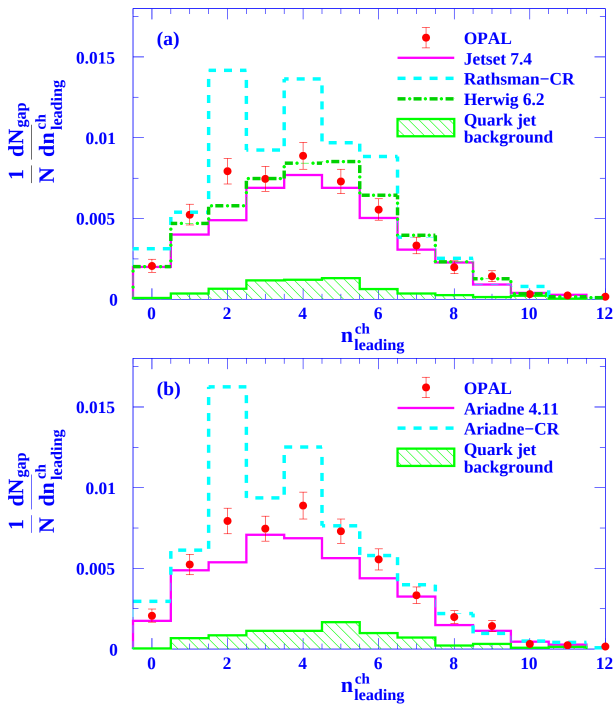

Fig. 3. Charged particle multiplicity distribution in the leading part of gluon jets with a rapidity gap. The data are compared to the predictions of models both with and without color reconnection. (Figures taken from [8].)

very clear signal for CR in these events: CR leads to an excess of events in which the gluon jet has a large rapidity gap, for which the leading part of the gluon jet (the part of the jet beyond the rapidity gap) is electrically neutral [7]. Fig. 3 shows the charged particle multiplicity distribution of the leading part of gluon jets with a rapidity gap [8], denoted $n_{\mathrm{ch.}}^{\mathrm{leading}}$. The most striking feature of these distributions is the large excess of entries predicted by the Rathsman–CR (Fig. 3(a)) and Ariadne–CR (Fig. 3(b)) models at $n_{\mathrm{ch.}}^{\mathrm{leading}} = 2$ and 4. These spikes are due to color-isolated electrically neutral gluonic systems created through CR. The isolated gluonic systems decay into an even number of charged particles, yielding the spikes. The description of the data by the non-CR models (Jetset and Ariadne) is not perfect: this is analogous to the situation discussed for the particle flow method in $\mathrm{W^+W^-}$ events (*cf.* Fig. 2(right)). The data are seen to lie between the predictions of the CR and non-CR models, in both Figs. 3(a) and (b) (this is analogous to Fig. 2(left)). The only unambiguous signal for CR is the spikes at even values of charged multiplicity, however, and these are not exhibited by the data. Therefore, the discrepancies of Jetset and Ariadne with the data in Figs. 3(a) and (b) are consistent with other inadequacies in the simulations, not related to CR. From these data, the Rathsman–CR (GAL) and Ariadne–CR models can be effectively excluded [8].

2. Rapidity gaps and glueballs

Gluon jets with a rapidity gap represent an environment which might favor the production of glueballs [9]. A hard isolated gluon with a rapidity gap in $e^+e^- \to q\overline{q}g$ events might build up an extended color octet field with the $q\overline{q}$ pair, see Fig. 4. An octet field connected to a gluon is analogous to a color triplet field connecting a quark and antiquark. The most natural mechanism to neutralize an octet field is through gg pair production from the vacuum, which leads to the formation of glueballs (Fig. 4).

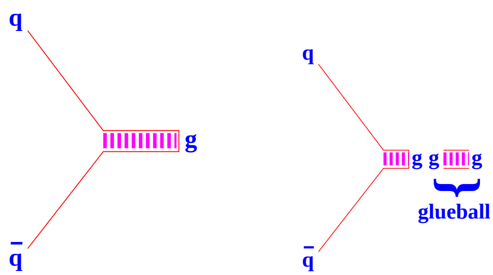

Fig. 4. (Left) A gluon jet with a rapidity gap in a $q\overline{q}g$ event might build up a color octet string with the residual $q\overline{q}$ system. (Right) The octet field can be neutralized by the production of gg pairs from the vacuum, leading to the formation of glueballs.

Resonant production of glueballs could result in an enhancement in the rate of $q\overline{q}g$ events in which the leading part of the gluon jet is electrically neutral. Such an enhancement is in fact seen, at least in comparison to the predictions of Jetset and Ariadne (but not Herwig [8]). This excess was first reported by the DELPHI Collaboration [10] and was subsequently confirmed by OPAL [7] and ALEPH [11]. The effect is visible in Fig. 3: the data lie above the predictions of Jetset and Ariadne for most values of multiplicity.

To investigate this possibility further, DELPHI and OPAL examined the invariant mass distributions of the leading parts of gluon jets, for gluon jets with a rapidity gap in which the leading part of the jets is electrically neutral. The results are shown in Fig. 5. For both DELPHI and OPAL, there is a deviation of the data above the MC predictions at mass values between about 1 and 3 GeV/c^2, with a significance of 2-3 standard deviations. Although somewhat intriguing, the signal is not clear enough to provide a definite conclusion.

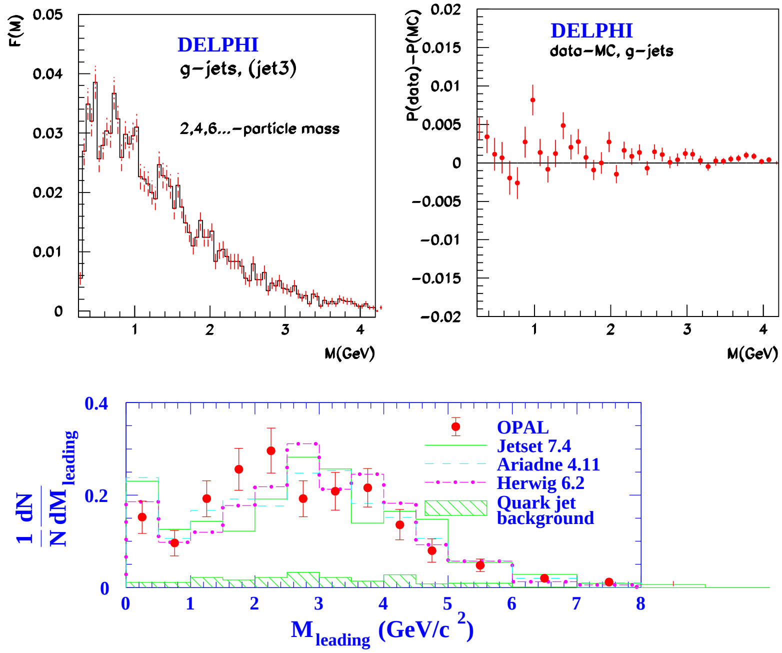

Fig. 5. (Top left and bottom) Invariant mass spectra of the leading part of gluon jets for which the leading part is electrically neutral, from DELPHI and OPAL. (Top right) Difference between the data and prediction of Jetset from DELPHI. (Figures taken from [8] and [10].)

3. Differences between gluon and quark jets

Quark and gluon jets have different coupling strengths for gluon emission, expressed by the color factors C_A and C_F: $C_A = 3$ specifies the relative probability for a gluon jet to emit a gluon while $C_F = 4/3$ specifies the relative probability for a quark jet to emit a gluon. In this sense, the color charge of a gluon jet is a factor of $(C_A/C_F) = 2.25$ larger that the color charge of a quark jet.

In QCD calculations, quark and gluon jets are usually defined through production of a $q\overline{q}$ or gg pair from a color singlet point source, respectively. The jet properties are defined by an inclusive sum over the event or event hemispheres. Quark and gluon jets defined in this manner are called "unbiased". In contrast, jets defined using a jet-finding algorithm usually exhibit a dependence on the algorithm chosen as well as the resolution criteria and are called "biased".

Measurement of the properties of unbiased quark jets is easy because $q\overline{q}$ production from a point source corresponds to inclusive e^+e^- annihilations, studied at many energy scales. So far, only two direct techniques have been found to measure properties of gluon jets in an unbiased manner. First, radiative $\Upsilon \rightarrow \gamma gg$ decays have been studied [12]. Second, rare events from $\mathrm{Z}^0 \rightarrow q\overline{q}$ decays have been selected [13] in which the q and $\overline{q}$ are approximately colinear: the event hemisphere "$g_{\text{incl.}}$" against which the q and $\overline{q}$ recoil corresponds almost exactly to an unbiased gluon jet as shown in [14]. The jet energies associated with these two techniques are $E_{\text{jet}} \sim 5$ and 40 GeV, respectively.

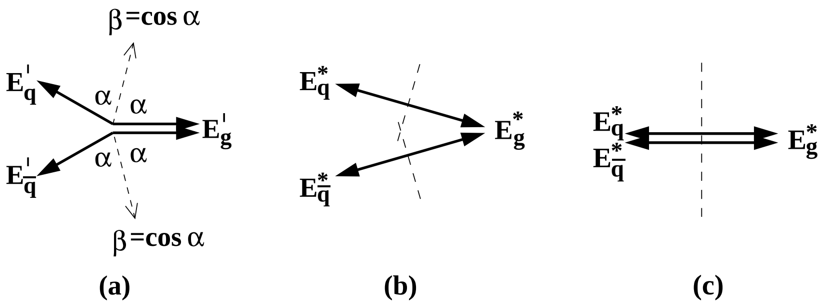

Fig. 6. (a) A symmetric three-jet $q\overline{q}g$ event in which the angle $\theta = 2\alpha$ between the quark and gluon jets is the same as the angle between the antiquark and gluon jets. In the QCD dipole model, the $q\overline{q}g$ event consists of two independent color dipoles. (b) Each of the dipoles can be independently boosted to a back-to-back frame. (c) The dipoles in the back-to-back frames can be combined to yield an event with the color structure of a gluon-gluon event in a color singlet. Note that the combined quark-antiquark jet system in $e^+e^- \rightarrow q\overline{q}g$ events has the color structure of a gluon jet.

A new study [15] from the OPAL Collaboration employs a technique proposed in [16] to measure properties of unbiased gluon jets at many energy scales, not just at a fixed scale as for the two studies mentioned above. The technique, called the jet boost algorithm, is illustrated in Fig. 6. Any three-jet $e^+e^- \rightarrow q\overline{q}g$ event can be boosted to the symmetric frame shown in Fig. 6(a), in which the angle between the q and g jet is the same as the angle between the $\overline{q}$ and g. In the QCD dipole model, a $q\overline{q}g$ event is described by two independent dipoles, one between the q and g and the other between the $\overline{q}$ and g. The two dipoles can be independently boosted to back-to-back frames along the bisectors of the dipoles (Fig. 6(b)) and combined to yield an event with the color structure of an unbiased gg event from a color singlet (Fig. 6(c)). This provides an indirect way to measure properties of unbiased gluon jets at a variety of energy scales.

The results for the mean charged particle multiplicity of unbiased gluon jets obtained using the boost algorithm are divided by the corresponding re-

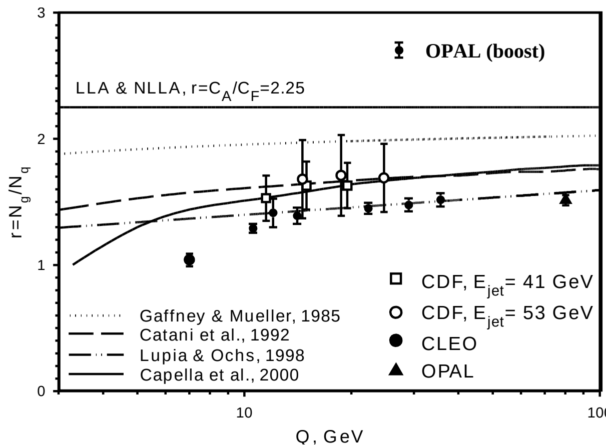

Fig. 7. The ratio between the mean charged particle multiplicities of gluon and light (*uds* flavored) quark jets *versus* the jet energy scale Q. The data are shown in comparison to various QCD predictions at the parton level.

sults for unbiased quark jets [15]. The results are shown by the solid points between about 10 and 40 GeV in Fig. 7. The results are in remarkable agreement with the theoretical predictions in [17], based on numerical evaluation of the QCD evolution equations for particle multiplicity in gluon and quark jets. Analytic results from [18] lie 15–20% above these data, presumably because of a more incomplete treatment of energy conservation effects and phase space limits compared to the numerical solutions.

4. Particle multiplicity of gluon jets in $p\overline{p}$ collisions

New results on particle multiplicity in gluon jets have also been reported by the CDF Collaboration at the Tevatron [19]. Jets are defined using the cone jet finder with a cone half opening angle of 0.7 radians. Since jets are defined with a jet-finder, they are not unbiased: as a systematic check the study is also performed using cone opening angles of 0.4 and 1.0 radians and the results are found to be essentially unchanged.

Samples of di-jet and γ+ jet events are selected, in which the jets have similar kinematics (with the photon treated as a "jet"). The jets are examined in two bins of "di-jet" invariant mass M_{ij}, with means of 82 and 105 GeV$/c^2$. The energies of the jets are given by $E_{\rm jet} = M_{ij}/2$. The events are boosted to the c.m. frames of the di-jet systems, and the number of charged tracks in cones of size $\theta_{\rm C} = 0.28$, 0.36 and 0.47 radians around the jet axis are counted. The energy scale of these multiplicity measurements is given by $Q = E_{\rm jet}\theta_{\rm C}$.

The fraction of gluon jets in the di-jet events is about 60%, compared to about 20% for the $\gamma+$ jet events. Assuming the gluon and quark jet properties to be the same in the two samples, this difference in the quark and gluon jet fractions allows the data to be combined algebraically to determine the mean charged particle multiplicities corresponding to pure gluon and quark jets. The results for the corresponding ratio of particle multiplicities between gluon and quark jets are shown by the open symbols in Fig. 7. The results from the $p\overline{p}$ collisions are seen to be remarkably consistent with the e^+e^- results presented in the previous section, albeit with larger uncertainties.

5. Differences between gluon and jets from *ep* collisions

Last, the Zeus Collaboration at HERA has presented preliminary results [20] demonstrating that differences between gluon and quark jets are also observed at *ep* colliders. The examine photoproduction of di-jets

$$\gamma p \to (q\overline{q} \textit{ or } gg \textit{ or } qg) + X$$

with jets defined using the longitudinally invariant $k_\perp$ jet finder. The final-state quark and gluon jets are then identified using differences in their properties: (1) gluon jets have a larger sub-jet multiplicity than quark jets, and (2) gluon jets are less collimated around the jet axis than quark jets. Both these features distinguishing gluon jets from quark jets have been well established at e^+e^- and $p\overline{p}$ colliders using model independent techniques.

Using cuts on the sub-jet multiplicity and collimation of the jets, samples of gluon and quark enriched jets are identified, denoted "thick" and "thin" jets, respectively. The gluon jet purity of the thick jet sample is 65%. The quark jet purity of the thin jet sample is 99%. The angular distributions of di-jet events with either two thick or two thin jets are then examined in terms of the angle θ^* of the jets with respect to the beam axis in the di-jet rest frame.

Thin-thin events are mostly direct events in which the initial-state γ couples directly to partons in the proton, corresponding to t-channel exchange of a quark and a fairly flat angular distribution $\mathrm{d}\sigma/\mathrm{d}|\cos\theta^*| \sim 1/(1-|\cos\theta^*|)$. The angular distribution of thin-thin events is shown by the open points in Fig. 8: indeed this distribution is quite flat, confirming that selecting a thin jet selects a quark jet. Thick-thick events are mostly resolved events in which the γ acts as a source of partons, corresponding to t-channel exchange of a gluon and a much steeper angular distribution $\mathrm{d}\sigma/\mathrm{d}|\cos\theta^*| \sim 1/(1-|\cos\theta^*|)^2$. The angular distribution of thick-thick events is shown by the solid points in Fig. 8: indeed this distribution is quite steep, confirming that selecting a thick jet selects a gluon jet.

These observations provide experimental verification of differences between gluon and quark jets in the ep environment, complementing the observations in e^+e^- and $p\overline{p}$ events and emphasizing the universality of jets.

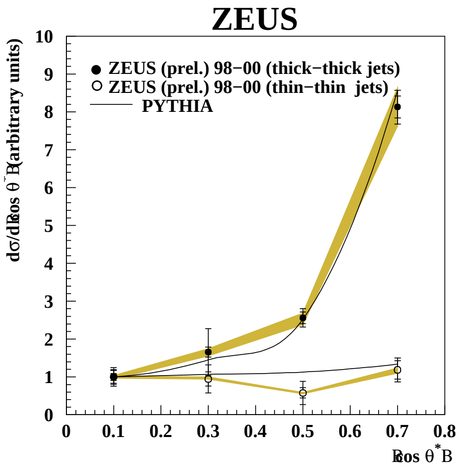

Fig. 8. Angular distribution of di-jet events in the di-jet rest frame for thick-thick and thin-thin jet final states, where a thick jet is gluon enhanced and a thin jet quark enhanced.

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