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QUARK AND GLUON JET DIFFERENCES FROM SYMMETRIC Z^0 EVENTS*

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ABSTRACT

Symmetric three-jet events are selected from hadronic Z^0 decays such that the two lower energy jets are each produced at an angle of about 150° with respect to the highest energy jet. In some cases, a displaced secondary vertex is reconstructed in one of the two lower energy jets, which permits the other lower energy jet to be identified as a gluon jet through anti-tagging with about 93% purity. Comparing these gluon jets to the inclusive sample of lower energy jets from the symmetric data set yields direct, model independent measurements of quark and gluon jet properties, for which the quark jets have a normal mixture of flavors for Z^0 decays. The energies of the jets being studied are about 24 GeV. Clear differences are observed between the properties of the quark and gluon jets. In other cases, the highest energy jet is tagged as a b jet or as a light quark (uds) jet using secondary vertex or track impact parameter and momentum information. Comparing the two lower energy jets of the events with a tag in the highest energy jet to the anti-tagged gluon jets yields a direct comparison of b, uds and gluon jets. The b and gluon jets are observed to have similar properties. The uds and gluon jets exhibit large differences. The measurements are well described by QCD Monte Carlo event generator programs.

1. Introduction

In QCD, the gluon is associated with the Casimir factor or "color charge" $C_A = 3$ and the quark with a charge $C_F = 4/3$. The larger color charge of the gluon means that it is more likely to radiate an additional gluon than a quark, leading to differences in the expected properties of quark- and gluon-induced jets. For quark and gluon jets produced with the same energy and under the same conditions, gluon jets are expected to have a larger mean particle multiplicity than quark jets[1]. The larger multiplicity of the gluon jet implies that its particle energy spectrum, known as the fragmentation function, is softer. A related prediction is that the mean opening angle of particles in a gluon jet is larger than in a quark jet[2]: thus that gluon jets are

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broader. Much experimental effort has been invested in an attempt to observe these predicted differences (for a recent compilation, see ref.[3] and references therein), but these studies often yielded inconclusive results either because the jets could not be selected without biasing them or because the analysis technique was not sensitive to quark-gluon jet differences. Before LEP, there were experimental indications that gluon jets were indeed broader than quark jets, based on measurements of the mean transverse momentum of particles in a jet with respect to the jet axis, or similar variables. Contradictory results were published concerning differences between the quark and gluon jet fragmentation functions, however, while no evidence was found for a multiplicity difference between the two jet types.

Beginning with a series of papers published in 1991[4], the OPAL experiment at LEP introduced a technique to study differences between quark and gluon jets which settled the basic experimental question concerning those differences. There are three principal aspects to the OPAL study which allowed this success. (1) Symmetric events were selected in which the quark and gluon jets being compared had the same energy and angles relative to the other jets, allowing a direct, model independent comparison of the jet properties. The events were selected with a one-fold symmetry such that the two lower energy jets, one of which was assumed to be a quark jet and the other a gluon jet, were both produced at an angle of about 150° with respect to the highest energy jet. The lower energy jets upon which the study was based each had an energy of about 24 GeV. (2) The quark jets were tagged, leading to identification of the gluon jets through anti-tagging (in the latest version of this work[5], 93% gluon jet purity is achieved). (3) The anti-tagged gluon jet data were combined algebraically with the quark and gluon jet data of the lower energy jets in the untagged, symmetric events, leading to separated quark and gluon jet information with essentially no bias except from the jet definition. The first OPAL studies[4,6] employed the $k_\perp$ jet definition[7] and the "normal mixture" of quark jets for Z^0 decays, determined by the Z^0 coupling strength to the individual flavors (roughly 20% d, u, s, c and b quarks). Similar analyses were subsequently performed by other e^+e^- experiments operating at the Z^0 peak[8]. The OPAL study has been recently updated[5] by extending it to include a cone definition of the jets. Use of the cone algorithm is expected to facilitate the comparison of the e^+e^- data with jet data from $p\bar{p}$ experiments. The results of this update are summarized below in section 2.

In addition, a second OPAL study has recently been completed[9] in which b quark jets and uds quark jets are selected to compare to the gluon jets. Theoretical calculations in QCD often assume zero quark masses. It is therefore relevant to select a light quark (uds) sample to compare to gluon jets, to facilitate comparison of data to analytic results. At the Tevatron collider at Fermilab, the t quark has been observed through its decay to b quarks[10]. A comparison of b quark jets to gluon jets is thus also of interest, to establish whether general jet properties can help to distinguish t quark events containing b jets from QCD background events containing gluon jets.

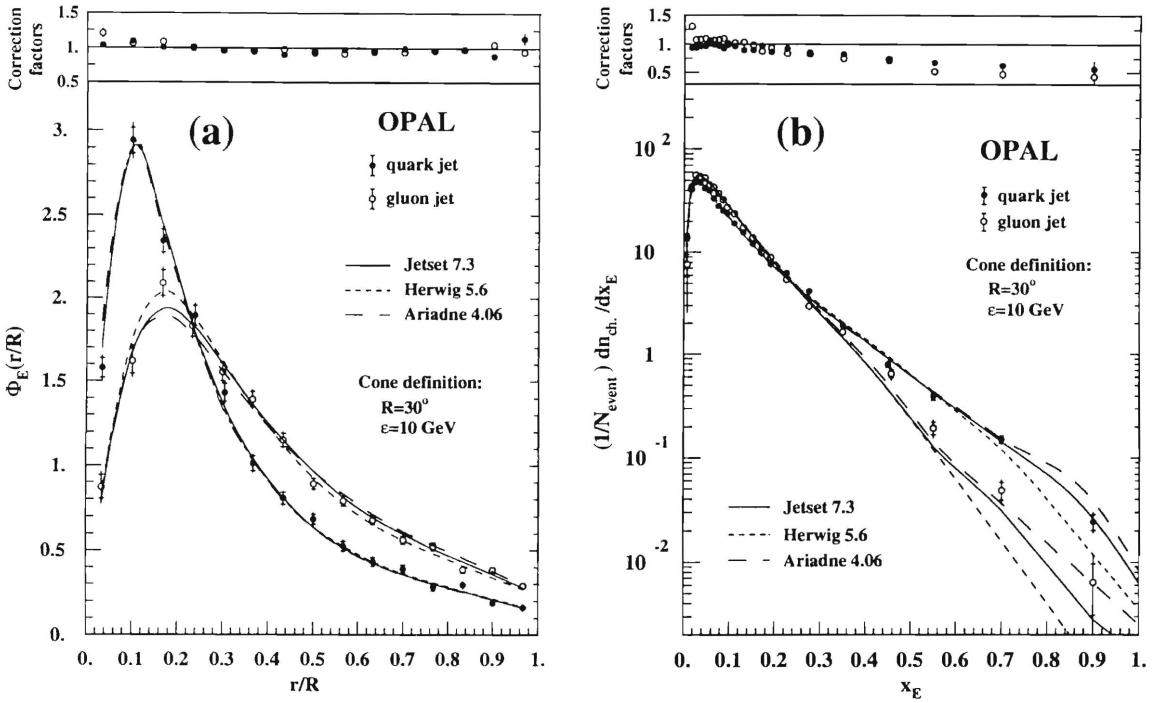

Figure 1: (a) The differential energy profiles of gluon and normal mixture quark jets defined using the cone algorithm. The detector correction factors are shown in the small figure above the data distributions. (b) Charged particle fragmentation functions of gluon and normal mixture quark jets defined using the cone jet finder.

The results of this second study are summarized below in section 3.

In section 4, a comparison of OPAL e^+e^- and Tevatron $p\bar{p}$ jet data is given.

2. Comparison of normal mixture quark jets with gluon jets

To characterize the width of a jet, the differential energy profile, $\phi_E(r/R)$, is used: $\phi_E(r/R)$ is defined as the distribution of the fractional jet energy contained in annular rings around the jet axis. For the results shown here, the jets are defined using the cone algorithm[11]. A cone size R of 30° is used since the angle between the two lower energy jets of the symmetric events is about 60°. In Fig. 1(a), the measurements of $\phi_E(r/R)$ versus r/R for the gluon and normal mixture quark jets are shown, where r is the angle of a particle with respect to the jet axis. Gluon jets are seen to be substantially broader than quark jets, in agreement with the expectation from QCD. The ratio of the full width at half maximum of the gluon to the quark jet distribution is about 1.6. Similar results are obtained for the multiplicity profiles of the jets[5]. The predictions of the QCD Monte Carlo event generator programs Jetset, Herwig and Ariadne, included in Fig. 1(a), are in good agreement with the data.

The charged particle fragmentation functions of the gluon and normal mixture quark jets are shown in Fig. 1(b). Gluon jets are observed to have a strikingly

softer particle energy spectrum than quark jets, also in agreement with the QCD expectation.

For a cone size of R= 30°, the ratio of the mean charged particle multiplicity values of the gluon to quark jets is found to be $\langle n^{\rm ch.}_{\rm cone}\rangle_{\rm gluon}/\langle n^{\rm ch.}_{\rm cone}\rangle_{\rm quark} = 1.096 \pm 0.023\,({\rm stat.}) \pm 0.023\,({\rm syst.})$. This value increases to about 1.26 if a cone size of R= 50° is used, which emphasizes the importance of soft particles at relatively large angles to the jet axes to the multiplicity measurements. With the $k_\perp$ jet algorithm, the result $\langle n^{\rm ch.}_{k_\perp}\rangle_{\rm gluon}/\langle n^{\rm ch.}_{k_\perp}\rangle_{\rm quark} = 1.251 \pm 0.024\,({\rm stat.}) \pm 0.029\,({\rm syst.})$ is obtained, in agreement with the earlier OPAL measurement[6]. That the mean particle multiplicity of a gluon jet exceeds that of a quark jet confirms the third general expectation of QCD concerning quark and gluon jet differences. (The result in ref.[6] is the first experimental measurement of a multiplicity difference between quark and gluon jets; that this difference is typically 20-25% for jets produced in Z^0 decays has now been confirmed by other experiments[8].)

3. Comparison of b and uds quark jets with gluon jets

A study of b and light quark jets in comparison to gluon jets can easily be performed using the established OPAL analysis method discussed above by tagging the flavor of the highest energy jets in the inclusive symmetric sample. By requiring the highest energy jet to be a b jet, for example, the lower energy quark jet is forced to be a b jet even though no tagging conditions are imposed on it, and similarly for uds quark jets. Thus the two lower energy jets of the symmetric samples can be forced to be about 50% b or uds quark jets and 50% gluon jets without introducing large biases. These data may be compared to the anti-tagged gluon jet data obtained as in our earlier studies to extract a b or uds quark jet comparison to gluon jets.

To obtain a b quark jet sample to compare to the gluon jets, displaced secondary vertices are reconstructed in the highest energy jets, resulting in an estimated b jet purity for the lower energy quark jets of about 92%. To obtain a light quark jet sample to compare to the gluon jets, selection criteria based on the signed impact parameter significance, b/σ_b, and the scaled energy value, $x = 2 \cdot E/E_{c.m.}$, are applied to charged tracks in the highest energy jets of the events: the number of tracks in the highest energy jets which have $b/\sigma_b > 2.5$ is required to be zero, and the maximum x value of tracks in the highest energy jets is required to exceed 0.45. The resulting uds purity of the lower energy quark jets is estimated to be about 90%.

In Fig. 2(a), the measurements of $\phi_{\rm E}(r/R)$ for the b and gluon jets are shown. Comparing the b jet data to the gluon jet data, it is seen that there is only a relatively small difference between the widths of the two jet types: thus the b jets are similar to the gluon jets. The ratio of the gluon to the b jet measurements is shown in Fig. 2(b). The descriptions of the data by the QCD models Jetset, Herwig and Ariadne are seen to be adequate. That of the Cojets QCD event generator is seen to be somewhat less

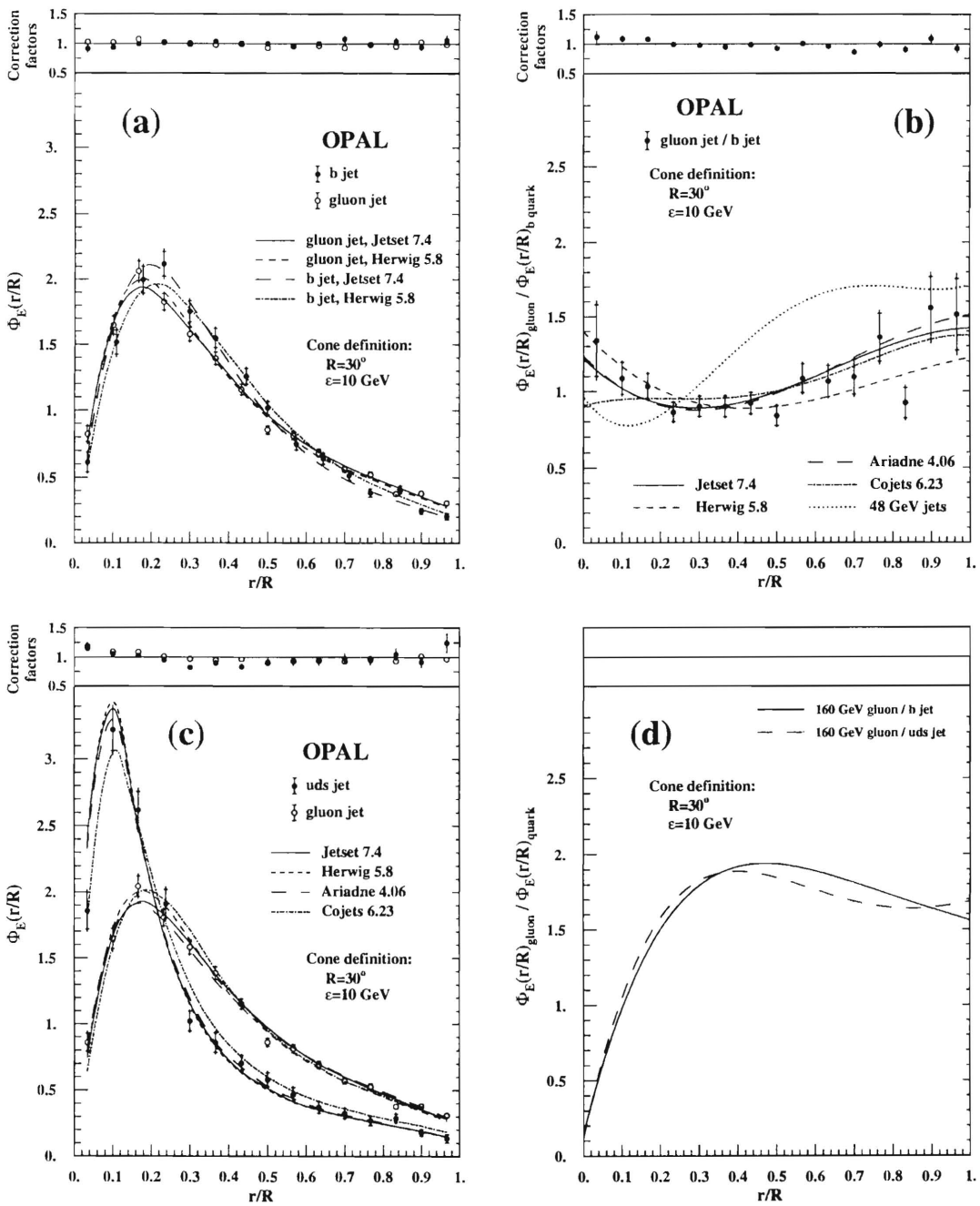

Figure 2: (a) The differential energy profiles of gluon and b jets defined using the cone algorithm. The data have been corrected for b jet misidentification and for the effects of the detector. The correction factors are shown in the small figure above the data distributions. (b) The ratio of the gluon to b jet measurements for the data shown in (a). (c) The differential energy profiles of gluon and uds jets. (d) Monte Carlo results for the ratio of the gluon to b and uds jet differential energy profiles for 160 GeV jets.

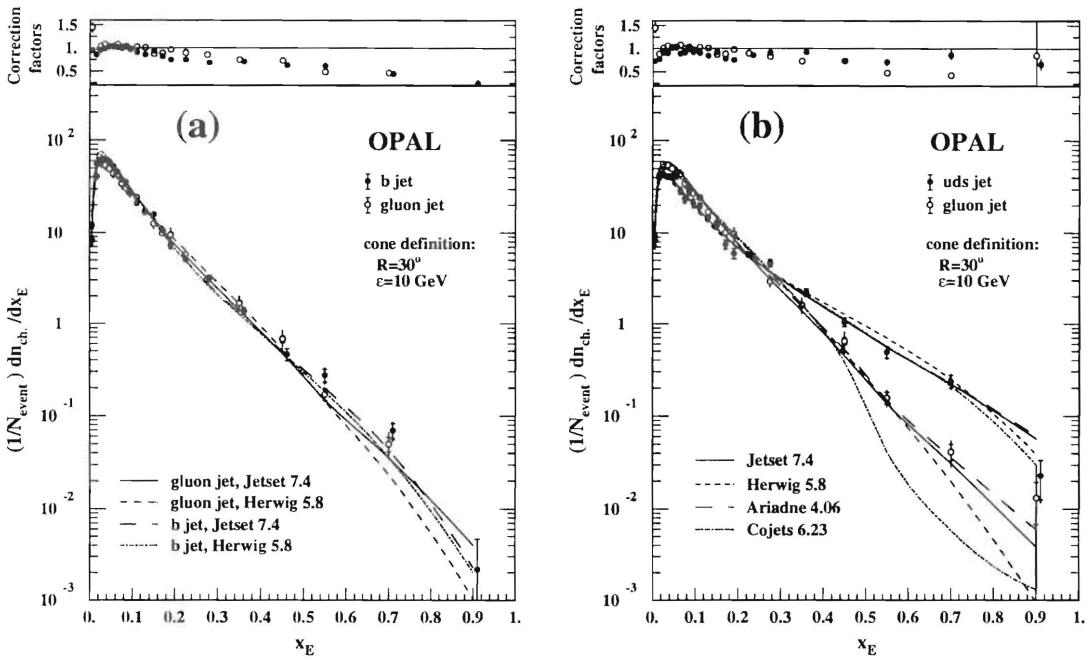

Figure 3: (a) Charged particle fragmentation functions of gluon and b jets defined using the cone jet finder. (b) Charged particle fragmentation functions of gluon and uds jets.

good.

In Fig. 2(c), a comparison of the uds and gluon jet widths is presented. Large differences are observed between the uds and gluon jets: the latter are seen to be much broader than the former. This result is not surprising, since large differences were also observed in our study of gluon and normal mixture quark jets (Fig. 1(a)). Since the b jet component (about 21% of the normal mixture quark jet sample) has been removed for the study presented in this section, and since b jets and gluon jets are observed to have similar widths, it can be anticipated that the differences between uds and gluon jets will be large.

The similarity of the b and gluon jet data shown in Figs. 2(a) and (b) suggests that it will be difficult to separate t quark events from QCD background events at the Tevatron collider using jet shape information. However, the jets studied at the Tevatron generally have a larger energy than those studied at LEP. To assess the effect of the jet energy, Fig. 2(b) includes the prediction of Jetset for 48 GeV jets, obtained by applying the event selection of the OPAL quark and gluon jet analysis to Monte Carlo events generated at e^+e^- center-of-mass energies of 180 GeV. Similarly, Fig. 2(d) shows the Jetset results for 160 GeV jets obtained in an analogous manner. It is seen that Jetset predicts a substantially larger difference between b and gluon jets for the larger jet energies. The Jetset prediction for 160 GeV b jets is almost the same as for 160 GeV uds jets (Fig. 2(d)).

Fig. 3(a) shows the charged particle fragmentation functions of the b and gluon

jets. The corresponding distributions for the uds and gluon jets are shown in Fig. 3(b). It is again seen that the properties of b and gluon jets do not differ much. The gluon jet fragmentation function is seen to be much softer than that of the uds quarks.

Using the cone jet finder, the multiplicity difference between gluon and b jets is found to be $\langle n^{\mathrm{ch.}}\rangle_{\mathrm{gluon}}/\langle n^{\mathrm{ch.}}\rangle_{\mathrm{b\,quark}}= 0.917 \pm 0.021\,(\mathrm{stat.}) \pm 0.033\,(\mathrm{syst.})$ while that between gluon and uds jets is $\langle n^{\mathrm{ch.}}\rangle_{\mathrm{gluon}}/\langle n^{\mathrm{ch.}}\rangle_{\mathrm{uds\,quark}}= 1.135 \pm 0.031\,(\mathrm{stat.}) \pm 0.029\,(\mathrm{syst.})$. The corresponding results found for the $k_\perp$ jet finder are $1.089 \pm 0.024\,(\mathrm{stat.}) \pm 0.024\,(\mathrm{syst.})$ and $1.390 \pm 0.038\,(\mathrm{stat.}) \pm 0.032\,(\mathrm{syst.})$.

In Fig. 4(a), the result for $\langle n^{\mathrm{ch.}} - 1\rangle_{\mathrm{gluon}}/\ \langle n^{\mathrm{ch.}} - 1\rangle_{\mathrm{uds\,quark}}$ found using the $k_\perp$ jet definition is plotted against the c.m. energy of 91.2 GeV. A value of unity has been subtracted from both the numerator and denominator to account for the contribution of the parton which initiates the jet. The corresponding results from the Herwig Monte Carlo at both the hadron and parton levels are shown as a function of $E_{c.m.}$. Herwig is chosen for this study because it is expected to best represent the analytic calculation for quark and gluon jet multiplicity differences compared to the other available models[3]. It is seen that the measurement is well reproduced by Herwig and that the hadronization correction is fairly small.

To leading order (l.o.) and in the asymptotic limit of very large jet energies compared to the energy of gluons radiated within the jets, the mean multiplicities of a gluon- or quark-induced jet, $\langle n\rangle_{\mathrm{gluon}}$ or $\langle n\rangle_{\mathrm{quark}}$, are predicted to differ by the ratio of the Casimir factors: $(\langle n\rangle_{\mathrm{gluon}}/\langle n\rangle_{\mathrm{quark}})_{\mathrm{l.o.}} = \mathrm{C_A}/\mathrm{C_F} = 9/4$[1]. The corrections to this result have been calculated analytically up to the next-to-next-to-leading order (n.n.l.)[12]. These corrections are found to be small and imply that the perturbative series is strongly convergent: $(\langle n\rangle_{\mathrm{gluon}}/\langle n\rangle_{\mathrm{quark}})_{n.n.l.} = 9/4 \cdot [1 - 0.273 \cdot \sqrt{\alpha_S(Q)} - 0.071 \cdot \alpha_S(Q)]$, assuming five active quark flavors and the QCD values for $\mathrm{C_A}$ and $\mathrm{C_F}$; $\alpha_S(Q)$ is the value of the strong coupling constant evaluated at energy scale Q. This expression yields $\langle n\rangle_{\mathrm{gluon}}/\langle n\rangle_{\mathrm{quark}} \approx 2$ for $Q \approx M_{\mathrm{Z^0}}$. It is clear from Fig. 4(a) that the Herwig result will not reach a value of 2 even for very large energies, however. As discussed in ref.[3], this result is not surprising, because the analytic result is based on an inclusive definition of jets which does not employ a jet finder: all particles radiated within a $q\bar{q}$ or gg event are used to define the multiplicity of a quark or gluon jet, respectively. In contrast, the experimental results employ a jet finder to select three jet events, leading to a different jet definition, especially since events with four or more jets are eliminated. Thus it is erroneous to compare the experimental values that have so far been presented for $\langle n^{\mathrm{ch.}}\rangle_{\mathrm{gluon}}/\ \langle n^{\mathrm{ch.}}\rangle_{\mathrm{quark}}$ to the analytic result of $\langle n\rangle_{\mathrm{gluon}}/\langle n\rangle_{\mathrm{quark}} \approx 2$, contrary to common practice. In ref.[3], it is shown that Herwig approximately reproduces the analytic result at the parton level if the total multiplicity of gg and $q\bar{q}$ events are compared as in the analytic calculation, but the

hadronization correction in this case turns out to be large.

4. Comparison of e^+e^- and $p\bar{p}$ jet data

One of the principal motivations for introducing a cone jet definition into the OPAL jet studies was to facilitate the comparison of jet properties between e^+e^- and $p\bar{p}$ experiments. In a previous publication[13], OPAL presented the $\phi_E(r/R)$ distribution using jets with energies of about 45 GeV: these jets are almost always quark jets since they are close to the kinematic limit in Z^0 decays. The e^+e^- distributions were compared to measurements of $\phi_E(r/R)$ for jets measured by the CDF Collaboration[14] in $p\bar{p}$ collisions at a c.m. energy of 1.8 TeV. The $p\bar{p}$ jets were produced in the central region of pseudorapidity, $0.1<|\eta|<0.7$, where $\eta=-\ln(\tan\frac{\theta}{2})$, and also had energies of about 45 GeV: $p\bar{p}$ jets selected under these conditions are expected to be predominantly gluon jets. The jets from $p\bar{p}$ collisions were observed to be substantially broader than the ones from LEP. The OPAL[13] and CDF[14] measurements of $\phi_E(r/R)$ for the 45 GeV jets are displayed in Fig. 4(b). A cone size of R=57° has been used. Shown in contrast to these measurements are the results from Fig. 1(a) for 24 GeV gluon and normal mixture quark jets, with R=30°. The CDF data have been corrected for the presence of underlying events using an energy density of 0.7 GeV/R^2 as explained in ref.[13]. The uncertainties shown for the CDF data include the difference between the 0.7 GeV/R^2 corrected data and the data with no correction for underlying events.

Interpreting the results for the 45 GeV jets to correspond to quark jets for OPAL and to gluon jets for CDF, it is seen that the 45 GeV jets are narrower than the 24 GeV ones for both jet types. This can be explained as a simple consequence of jet narrowing at larger jet energies. The difference between the 45 GeV jets from the e^+e^- and $p\bar{p}$ experiments bears a striking resemblance to the difference between quark and gluon jets observed in the OPAL study of 24 GeV jets, however. This is emphasized in Fig. 4(c), in which the ratios of the 45 GeV (solid points) and 24 GeV (open points) gluon to quark jet distributions are displayed. A larger fractional difference is observed between the jet data at 45 GeV than at 24 GeV, as seen from Fig. 4(c). Monte Carlo study suggests that much of the difference between the 45 and 24 GeV distributions in Fig. 4(c) is due to the different choice of cone size R, however, as is demonstrated by the dashed and dash-dotted curves in that figure which show the results from Jetset for the OPAL analysis of 24 GeV quark and gluon jets using cone sizes of 30° and 50°, respectively. The results yielded by Jetset for 45 GeV jets with R=50°, obtained by running the event generator at a e^+e^- c.m. energy of 175 GeV rather than 91.2 GeV, are also shown. Thus the results of Fig. 4 support the conclusion that was made in ref.[13]: that much of the difference between the e^+e^- and $p\bar{p}$ data can be attributed to differences between quark and gluon jet properties

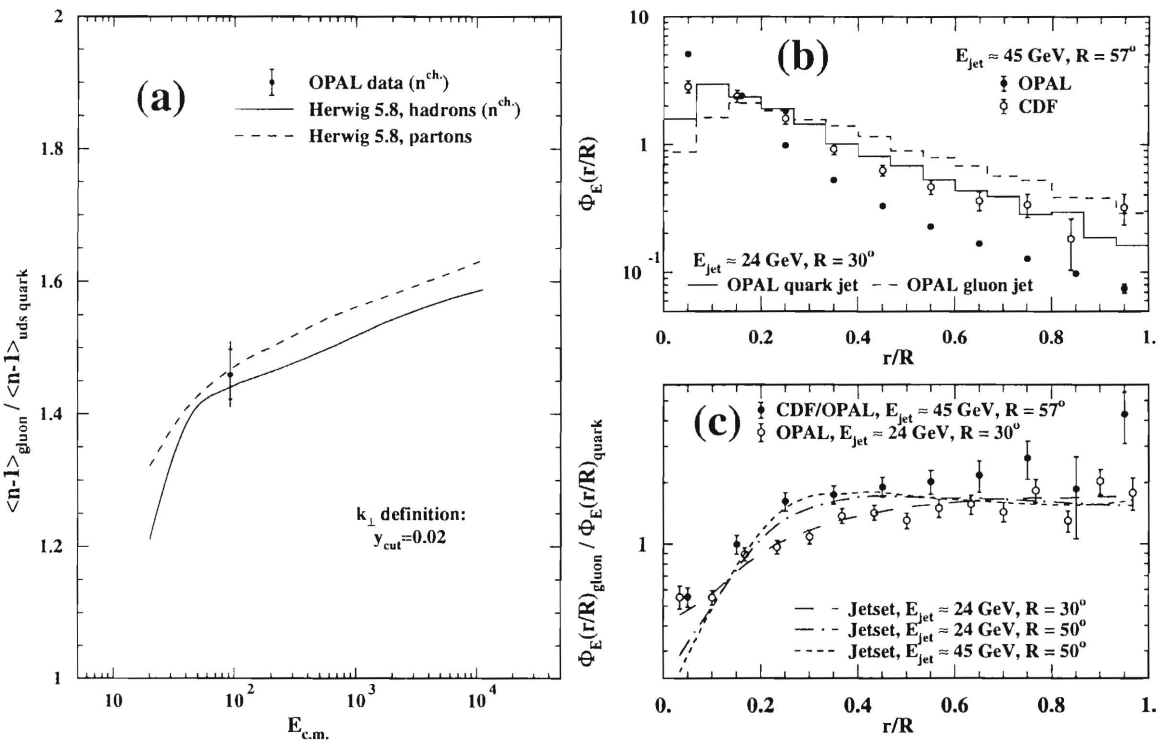

Figure 4: (a) Comparison of the measured mean multiplicity difference between gluon and uds jets to the predictions of the Herwig Monte Carlo at the hadron and parton levels. The Herwig results are shown as a function of the center-of-mass energy. (b) The differential energy profiles of 45 GeV jets measured by OPAL and CDF, using the cone jet finder, compared to the OPAL measurements of 24 GeV gluon and normal mixture quark jets. (c) Ratios of the data shown in (b); the predictions of the Jetset Monte Carlo for 24 GeV jets with two choices for the cone size R, and for 45 GeV jets with R=50°, are also shown.

such as are experimentally established by the OPAL studies discussed above.

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