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OJI continuation proposal

**A study of quark and gluon jets and of the long
distance QCD force field at the Z^0**

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(1) Introduction

Quantum Chromodynamics (QCD) is widely accepted as the correct theory of the strong nuclear force in elementary particle physics. The precision to which QCD has been tested is relatively limited, however, compared to the precision to which other interactions such as the electro-weak one have been tested. In part, this is because the large value of the QCD coupling constant, α_S , renders theoretical calculations based on perturbation theory relatively imprecise. The confinement of quarks and gluons inside hadrons also leads to uncertainty because the theoretical predictions cannot, in general, be tested directly against the experimental measurements but are subject to hadronization corrections. From an experimental standpoint, it has proven difficult to isolate gluon jets inside multi-jet events in an unbiased manner so as to determine gluon jet properties using model independent methods. Basic quark-gluon interactions such as the four-jet matrix element in e^+e^- annihilations have been relatively untested due to the lack of a data sample with sufficient statistics. Perturbation theory has essentially nothing to say about the properties of the hadronization process itself. It is for these reasons that QCD has remained relatively untested.

In the absence of precise theoretical predictions, experiment can play an important role in exploring the nature of strong interactions through a study of the phenomenology of quark and gluon hadronization, by providing detailed and model independent measurements of quark and gluon jet properties and by a quantitative test of the production matrix elements for multi-jet final-states. The e^+e^- collider LEP offers a unique opportunity for these investigations because of the very large data samples collected at the Z^0 peak and because of the excellent detector capabilities. Theoretical uncertainties are not as large at the Z^0 energy as they are at the lower energies of previous e^+e^- colliders because α_S , and thus unknown higher order terms, are smaller

for LEP. The hadronization correction is also smaller for LEP's larger energy because it decreases like the inverse power of the center-of-mass energy. The larger jet energies at LEP mean that gluon jets evolve to an advanced stage through multiple soft gluon emission so that their properties exhibit the full structure that can be expected perturbatively. The large data samples at LEP permit original analysis strategies to be developed, leading to new possibilities for conclusive tests of the theory. Thus, the physics potential for QCD studies at LEP is very high.

It was to initiate a program of research to investigate quark and gluon jets and the hadronization mechanism using Z^0 data that a proposal for funding was submitted to the Department of Energy in October 1991, for the benefit of John William Gary, Assistant Professor of Physics at the University of California, Riverside. This funding for a three year grant was requested under the Outstanding Junior Investigator program and received approval in June 1992. The program was based on analysis of the multihadronic Z^0 sample of the OPAL detector at LEP. In the current document, we submit a continuation request for OJI support for the coming year, covering the period from February 1, 1994 to January 31, 1995. In section 2, the goals of the proposed research program are restated. The progress made during 1993 towards the achievement of those goals is summarized in section 3. Section 4 states our goals for the upcoming year. Section 5 contains a summary. The budget request is given in section 6.

(2) Research program

The study of multihadronic final-states in e^+e^- annihilations has contributed much to the experimental verification of QCD. Examples include the first observation of jet structure in high energy collisions, the measurement of the gluon spin and the demonstration that the coupling strength of QCD decreases in value for smaller distance scales. Many important features of QCD have remained essentially untested, however, for the reasons outlined in the introduction. There are three related fields of study which we are pursuing, using novel techniques in part introduced by us. All three utilize the OPAL data statistics and detector capabilities to their full potential. They are structured so as to yield direct, model independent and definitive results: (1) quark-gluon jet differences using rare events with special geometric properties, such as three-jet events in which a high energy gluon jet recoils against two identified quark jets, (2) angular correlations between jets in four jet events, as a means to test the four-jet matrix element, determine the gauge group "color factors" and demonstrate the non-Abelian character of QCD in a quantitative manner, and (3) multi-particle correlations between identified large mass hadrons such as protons, Δ^{++} baryons, Λ hyperons and ϕ mesons, as indicators of the dynamics of the underlying QCD field.

The first major area of investigation in our program is the detailed measurement of differences between quark and gluon jets using model independent techniques. Despite the large numbers of three-jet events recorded at PEP, PETRA and TRISTAN, it proved difficult to establish whether differences were present between quark and gluon jets as expected from QCD. The studies at these lower energy colliders employed jets which did not have the same energy or event environment. Thus, quark jets in two-jet events were compared to gluon jets in three-jet events or else gluon jets in

three-jet events were identified by requiring that they have the least energy of the three jets. As a result, these studies were model dependent, largely inconclusive and sometimes contradictory. I introduced a new analysis strategy to study quark and gluon jet properties, utilizing rare events in which quark and gluon jets had the same energy and environment within an event. Two-fold symmetric three-jet events were employed, in which the angles between the highest energy jet and each of the two lower energy jets were the same. For the configuration chosen, the highest energy jet was known to be a quark or antiquark jet with high probability, because of the nature of the gluon radiation spectrum. In some cases, one of the two lower energy jets could be identified as a heavy quark jet by the presence of a high energy lepton. The lepton tag on the quark jet marked the other lower energy jet as a gluon jet. The properties of these anti-tagged gluon jets were compared to those of the unbiased sample of quark and gluon jets from the untagged sample. Since the quark and gluon jets being compared had the same energy, event environment and selection criteria, they could be compared directly, with no need for Monte Carlo calculations to establish the results. This analysis strategy was used in two OPAL physics publications [1, 2], both of which are entirely my work. It was observed that gluon jets were broader and yielded a softer particle energy spectrum than quark jets, in agreement with the expectations of QCD. The pursuit of the study of gluon jet properties using the innovative techniques introduced by these two papers continues to be a major element of our program, as presented in sections 3 and 4.

The second major area of investigation in our program is the study of angular correlations between jets in four jet events. The purpose of this study is to determine the color factors of QCD and test the four jet matrix element. Measurement of the color factors is equivalent to a direct observation of the triple gluon vertex and so this study also constitutes a quantitative test of the non-Abelian aspect of QCD.

This investigation comprises the principal thesis matter for Shun-Lung Chu, a UCR Ph.D. candidate for whom I am thesis advisor. Details of this analysis are presented in section 3.

The third major area of investigation in our program is the study of the transformation of the long distance QCD force field into hadrons. The essential tool for this study is correlations between two or more large mass particles such as protons, Δ^{++} baryons, Λ hyperons and ϕ mesons. Large mass hadrons preserve the momentum information of the particles produced in the breakup of the QCD field. As such, they map out the field which connects the quarks and gluons, acting as probes of how the QCD field hadronizes. Light particles such as π mesons arise primarily from resonance decays and do not preserve this information as well. Correlations between large mass hadrons, such as the location in phase space of an anti-baryon relative to a baryon that has been identified in an event, test mechanisms for how basic quantum numbers such as baryon number or strangeness are created from the QCD vacuum. Such information, for which little experimental data currently exist, should provide considerable information about the phenomenology of quark and gluon confinement and result in strong constraints on popular models of hadronization such as the string [3], cluster [4] and UCLA [5] models. We are presently working to reconstruct the Δ^{++} resonance in our data and to measure its decay properties, as discussed in section 3.

(3) Progress report to October 1993

In this section, we summarize the progress that has been made towards realizing the goals of our research program.

After the grant of the OJI award, an advertisement was issued for a postdoc position in my research group. This resulted in the recruitment of Dr. Paul Schenk, a recent Ph.D. recipient whose UCR contract began December 1, 1992. Dr. Schenk has a background in system management of distributed workstation systems and in e^+e^- physics at the Z^0 pole. He has become rapidly integrated into my OJI program. In addition to Dr. Schenk, a second postdoc, Charles Jui, and a UCR Ph.D. student, Shun-Lung Chu, are full time members of my research group. Dr. Schenk and Mr. Chu are compensated 50% from my OJI contract and 50% from funds provided to me by the University. Dr. Jui is compensated 50% from my University funds and 50% from the main UCR-OPAL contract with DOE.

Using OJI grant money and University funds, I purchased eleven HP PA-RISC workstations. These workstations form a Monte Carlo farm, known as the RSF or "Riverside Snake Farm," to produce large samples of simulated Z^0 hadronic decay events. This farm has been in operation for about one year and three months and has been essentially trouble free. Several million simulated multihadronic Z^0 decays have been generated with this facility. The generated samples have been extremely helpful to my research and to the OPAL Collaboration as a whole. Dr. Jui was instrumental in the set-up and initial operation of this farm. Currently, Drs. Jui and Schenk take on joint responsibility to manage this cluster, which constitutes a major contribution of my OJI program to OPAL. Dr Schenk presented a conference report on the architecture and operation of the RSF cluster at the Conference on Computing in High Energy Physics held at Florida State University in February 1993.

This past year, we continued our program to compare quark and gluon jet properties using the model independent techniques invented by us. We studied new ways to identify the quark jets in two-fold symmetric three-jet events, using reconstructed secondary vertices from heavy quark decay in place of the leptons used in the first analyses. Reconstruction of secondary vertices in jets permits bottom quark jets to be identified and the methods we developed in our earlier studies of two-fold symmetric three-jet events [1, 2] to be applied. The data sample in our new study is about seven times larger than that which we used previously, allowing more detailed and quantitative tests of quark and gluon jet differences. The paper containing this new analysis was recently published in *Zeitschrift für Physik C* [6]. This new work is entirely the product of my OJI program.

As an example of the new results, fig. 1 (a) shows the inclusive scaled energy distribution, $(1/n_{total}) dn_{total}/dx_E$, for particles assigned to the quark and gluon jets in our study. From comparison of these curves, a substantially softer particle energy spectrum of the gluon jets, relative to the quark jets, is quite clear. This feature is expected in QCD due to the larger color charge of gluons compared to quarks. The ratio of the gluon to the quark jet distribution is shown in fig. 1 (b), from which the softer particle energy spectrum of the gluon jets is again very clear. Shown in comparison to the data in fig. 1 (b) are the predictions of Monte Carlo calculations which incorporate perturbative QCD along with different assumptions about the hadronization process. The three models Jetset-Peterson [7], Herwig [8] and Cojets623 [9], all of which include differences between quark and gluon jets, provide adequate descriptions of the data, while the model Cojets612 [9], which does not contain significant quark and gluon jet differences, is in clear disagreement with the data, as expected. This illustrates the sensitivity of our analysis to differences between quark and gluon jet structure.

Figure 1: (a) Inclusive scaled particle energy distributions of the quark and gluon jets, corrected for quark and gluon jet misidentification. (b) Ratio of the two curves in (a).

Since the quark and gluon jets in our study have the same energy, while the particle energy spectrum of the gluon jets is observed to be softer, the gluon jets can be expected to exhibit a larger mean multiplicity. This is indeed the case, as is shown in figure 2: the difference in mean multiplicity between quark and gluon jets is determined to be $1.27 \pm 0.04 (\text{stat.}) \pm 0.06 (\text{syst.})$, which is the first significant difference between quark and gluon jet multiplicities ever reported.¹ Again the models, with the exception of Cojets612, provide a satisfactory description of the data, although the quark jet is better described by Jetset and Herwig than it is by Cojets623.

The results from this paper were chosen to be some of the principal ones from

¹Prior to the OPAL work, the only published value for this ratio was $1.29^{+0.21}_{-0.41} \pm 0.20$ from the HRS Collaboration [10]

Figure 2: (a) and (b): Multiplicity distributions of the quark and gluon jets, corrected for quark and gluon jet misidentification. The Monte Carlo results include detector simulation and the same selection criteria as the data, except the quark and gluon jets are identified using Monte Carlo information.

OPAL for 1993. Dedicated conference talks were given on this analysis at the DPF meeting held at Fermilab in November 1992 and at the plenary sessions of the La Thuile and Moriond Conferences in March 1993. No other single OPAL publication received as much attention during this period. The presentation at the DPF meeting mentioned above was given by my postdoc Charles Jui on my behalf. At the request of the OPAL physics coordinator, Dr. Jui also presented my results at a CERN seminar in February 1993. I presented these results myself in seminars at Caltech, UCLA and LBL given in May, June and September 1993, respectively, and at the Multiparticle Dynamics meeting held in Aspen in September 1993.

This past year, we also continued our study to measure the QCD color factors

using angular correlations in four jet events. This study leads to a quantitative demonstration of the non-Abelian character of QCD. The values of the color factors, denoted C_F , C_A and T_F , are physical manifestations of the underlying structure of the group in which a gauge theory is embedded. For QCD, based on $SU(3)$, the color factors are $C_F=4/3$, $C_A=3$ and $T_F=1/2$, while for the Abelian gluon theory, based on $SU(1)_1$, $C_F=1$, $C_A=0$ and $T_F=3$. The ratios of the color factors, C_A/C_F and T_F/C_F , are sufficient to distinguish between the different gauge groups.

A measurement of the color factor ratios C_A/C_F and T_F/C_F at e^+e^- colliders is possible through the study of processes at order α_s^2 or higher. The most straightforward case is the study of angular correlations between jets in four-jet events. Four jet production in e^+e^- annihilations occurs through double gluon bremsstrahlung, the triple gluon vertex and four quark production. These three processes lead to different angular correlations between the four jets while their relative contributions depend on the values of the color factors. Using distributions sensitive to the angular correlations, the relative contributions of the three different processes can be separated and the color factor ratios determined.

We choose three experimental variables for our analysis, each of which has a different dependence on the three processes leading to four-jet final states. These experimental variables are constructed from the angles between jets in four-jet events. The three variables are: (1) the cosine of the Bengtsson-Zerwas angle, $\cos \chi_{BZ}$ [11], (2) the modified Nachtmann-Rieter variable, $|\cos \theta_{NR}^*|$ [12], and (3) the cosine of the angle between the two lowest energy jets, $\cos \alpha_{34}$ [13]. The analysis is based upon a simultaneous fit of the theoretical predictions for χ_{BZ} , $|\cos \theta_{NR}^*|$ and $\cos \alpha_{34}$ to the measured distributions, after the data have been corrected for detector and hadronization effects and for background from two- and three-jet events. The color factor ratios C_A/C_F and T_F/C_F and the overall normalization are used as the fit

parameters. An innovative feature of our study is the use of calculated jet energies. By using jet energies calculated from the directions of the jets, we achieve superior jet energy resolution and more reliable results than are attainable using visible jet energies. Use of calculated jet energies is a standard technique in three-jet analyses, but ours is the first experimental study to introduce it to four-jet kinematics.

The preliminary results of this analysis are now in the form of an OPAL physics note draft. They should be available as an official OPAL result for presentation at conferences and seminars in the near future. A publication containing the final results is expected within a few months time. Full details will be contained in the thesis of Shun-Lung Chu, for whom this analysis is the principal Ph.D. subject matter.

The use of calculated jet energy in four-jet events is a new technique introduced in this study. As an example of the benefit of this technique, fig. 3 shows the measured distributions of $\cos \chi_{BZ}$ and $|\cos \theta_{NR}^*|$ in comparison to various Monte Carlo curves. The parton level Monte Carlo curve, shown by the histogram, is included to serve as a reference representing the ideal case of a perfect detector with no hadronization uncertainty. The uncorrected data spectra of $\cos \chi_{BZ}$ and $|\cos \theta_{NR}^*|$ are shown by the circular symbols while the corresponding Monte Carlo plots, including simulation of the detector and the same analysis procedures as the data, are shown by the square symbols. The distributions constructed using calculated jet energies, shown by the filled circles for the data and filled squares for the Monte Carlo, are in good agreement with the histograms representing the parton level Monte Carlo, while the distributions constructed using the traditional method of visible jet energies, shown by the open circles for the data and open squares for the Monte Carlo, show considerable distortion relative to the parton level reference curve. Thus we obtain much smaller hadronization and detector corrections by introducing calculated jet energies into our analysis. It is also seen from fig. 3 that the filled squares agree with the filled

Figure 3: Comparison of distributions, from both data and Monte Carlo, constructed using visible jet energies and calculated jet energies, for (a) $\cos \chi_{BZ}$ and (b) $|\cos \theta_{NR}^*|$.

circles better than the open squares agree with the open circles: thus we obtain a better description of the data by the detector level Monte Carlo using calculated jet energies instead of visible jet energies, again leading to smaller uncertainties in the data corrections.

Our preliminary results for the color factor ratios C_A/C_F and T_F/C_F are shown in fig. 4. The measured values, $C_A/C_F = 2.168 \pm 0.156(stat.) \pm 0.221(syst.)$ and $T_F/C_F = 0.416 \pm 0.092(stat.) \pm 0.222(syst.)$ (preliminary), are in good agreement with the $SU(3)$ values of QCD, which are $C_A/C_F = 9/4$ and $T_F/C_F = 3/8$, indicated by the filled star in fig. 4. Also shown in fig. 4 are the color factor ratios from other gauge groups than $SU(3)$. Of these groups, only the $U(1)_3$ Abelian gluon model and $SO(3)$ are realistic since it is only they which include three color degrees-of-freedom

Figure 4: Measured values of the color factor ratios C_A/C_F and T_F/C_F with 68% and 95% confidence-level contours. Expectations from various gauge models are also shown.

and which therefore describe the measured value of $R = \sigma(e^+e^- \rightarrow \text{hadrons})/\sigma(e^+e^- \rightarrow \mu^+\mu^-)$: both these groups are excluded by our analysis by more than four standard deviations.

The third major area in which we have invested effort this past year is the investigation of heavy baryon production in multihadronic Z^0 decays. This effort has concentrated on the Δ^{++} baryon since we find its production rate in the Monte Carlo to be very sensitive to the assumptions about the baryon production mechanism. Furthermore, the Δ^{++} is one of the most important hadrons which has never been observed in e^+e^- annihilations above the Υ region. The Δ^{++} is also interesting because it is a spin 3/2 particle. A measurement of its production rate would allow the suppression factor for spin 1 diquarks, relative to spin 0 diquarks, to be determined:

this would be the first such measurement for non-strange baryons. Our first goal is to measure and publish the total production rate and differential energy spectrum of the Δ^{++} and its anti-particle. Following this, we intend to investigate multi-particle correlations involving the Δ^{++} and other large mass hadrons. This investigation is expected to yield further, detailed information about the mechanism of quark and gluon confinement.

Figure 5 shows some preliminary results from this study. The points with errors

- Figure 5: Δ^{++} ($\bar{\Delta}^{--}$) mass peak for $0.1 < x_E$.

show the experimental data for proton-pion $p\pi^+$ mass combinations for which the proton has been identified using energy loss dE/dx information. The charge conjugate

states $\bar{p}\pi^-$ are also included. The p and π^+ are both required to emanate from the beam constrained primary event vertex point since the Δ^{++} decays strongly. For figure 5, the scaled energy, $x_E = 2 \cdot E_{p\pi^+}/E_{c.m.}$, is selected to be larger than 0.1. The shaded histogram in figure 5 shows the Monte Carlo prediction from Jetset with the Δ^{++} signal removed. Away from the region of the Δ^{++} mass, for values of $m_{p\pi^+}$ smaller than about 1.15 GeV/ c^2 or larger than about 1.35 GeV/ c^2 , the Monte Carlo and data are in good agreement, which demonstrates that the combinatoric background is well modeled. In the region of the Δ^{++} mass, for $m_{p\pi^+} \approx 1.15 - 1.35$ GeV/ c^2 , the data are in excess of the shaded Monte Carlo, which we interpret to be the first signal for Δ^{++} production ever observed in e^+e^- annihilations above the $\Upsilon(1S)$. Including the Δ^{++} in the Monte Carlo leads to the hatched histogram in figure 5, which agrees well with the measured distribution.

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