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STUDIES OF QCD B-PHYSICS AND JET HANDEDNESS AT SLD

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Abstract

We present tests of the flavor independence of strong interactions via preliminary measurements of the ratios $\alpha_s(b)\ /\alpha_s(udsc)$ and $\alpha_s(uds)\ /\alpha_s(bc)$ using data collected by the SLD experiment at SLAC during the 1992 SLD/SLC run. In addition, we have measured the difference in charged particle multiplicity between $Z^0 \to b\bar{b}$ and $Z^0 \to u\bar{u},\ d\bar{d},\ s\bar{s}$ events, and find that it supports the prediction of perturbative QCD that the multiplicity difference be independent of center-of-mass energy. We have also made a preliminary study of jet polarization and find, using a charge-signed definition, a small net handedness in our sample of hadronic jets.

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1. INTRODUCTION

One of the most important tests of QCD has been the measurement of the strong coupling α_s at different scales Q^2 and in different hard processes.[1] We have previously presented[2] measurements of $\alpha_s(M_Z^2)$ from the rate of production of multijet final states in hadronic decays of Z^0 bosons produced in e^+e^- annihilations. Here we apply the same techniques to samples of hadronic Z^0 events enriched in $Z^0 \rightarrow b\bar{b}$ and $Z^0 \rightarrow u\bar{u}$, $d\bar{d}$, $s\bar{s}$ decays, and measure the ratios $\alpha_s(b)\ /\alpha_s(udsc)$ and $\alpha_s(uds)\ /\alpha_s(bc)$, to test the *ansatz* of QCD that strong interactions are independent of flavor. The precision SLD vertex detector allows us to tag such samples with high efficiency and purity. We further exploit the SLD flavor-tagging capability to measure the difference in charged particle multiplicity between $Z^0 \rightarrow b\bar{b}$ and $Z^0 \rightarrow u\bar{u}$, $d\bar{d}$, $s\bar{s}$ events. We test the prediction of perturbative QCD, in the Modified Leading Logarithm Approximation, that this multiplicity difference is independent of center-of-mass energy. Finally, we present a preliminary study of the recently-revived notion of 'jet handedness,'[3] whereby a measure is defined for hadronic jets which may be related to the underlying polarization of the parton initiator of the jets.

2. THE SLD AND EVENT SELECTION

The SLAC Linear Collider (SLC) produces electron-positron annihilation events at the Z^0 resonance which are recorded by the SLC Large Detector (SLD). A unique feature of the SLC is its ability to deliver an intense beam of longitudinally polarized electrons. The data used in this analysis were taken during the 1992 SLC/SLD run, during which a mean electron beam polarization of magnitude 22% was attained, enabling the first measurement of the left-right Z^0 production cross-section asymmetry to be made.[4] For this analysis the data samples produced by left-, right-, and unpolarized electrons were combined.

SLD is a multi-purpose particle detector and is described in detail elsewhere.[5] Charged particles are tracked in the Central Drift Chamber (CDC), which consists of 80 layers of axial or stereo sense wires, and in the vertex detector (VXD), a device comprising 120 million silicon pixels.[6] Momentum measurement is provided by a uniform axial magnetic field of 0.6T. Particle energies are measured in the Liquid Argon Calorimeter (LAC),[7] and in the Warm Iron Calorimeter.[8] The LAC is segmented into approximately 40,000 projective towers and has a resolution of about 15% for the measured Z^0 mass.

Three triggers were used for hadronic events, one requiring a total LAC electromagnetic energy greater than 30 GeV, another requiring at least two well-separated tracks in the CDC, and a third requiring at least 8 GeV in the LAC as well as one track in the CDC. A selection of hadronic events was then made by two independent methods, one based on the topology of energy depositions in the LAC, the other on the number and topology of charged tracks measured in the CDC.

The analysis presented here uses charged tracks measured in the CDC. Spatial information from the VXD was included in the track fit for those tracks for which VXD hits were successfully linked, resulting in an improved determination of track parameters. A set of cuts was applied to the data to select well-measured tracks and events well contained within the detector acceptance. Tracks were required to have (i) a closest approach to the beam axis within 5 cm, and within 10 cm along the beam axis of the measured interaction point; (ii) a polar angle θ with respect to the beam axis with $|\cos\theta| < 0.80$, and (iii) a minimum momentum transverse to this axis of $p_{\perp} > 150$ MeV/c. Events were required to contain a minimum of five such tracks, a thrust axis[9] direction with respect to the beam axis, θ_T, within $|\cos\theta_T|$ < 0.71, and a minimum charged visible energy E_{vis} greater than 20 GeV, where all tracks were assigned the charged pion mass. From our 1992 data sample, a total of 6476 events survived these cuts. The acceptance for hadronic events satisfying the $|\cos\theta_T|$ cut was estimated to be above 96%, and the total residual contamination from background sources was estimated to be $0.3 \pm 0.1\%$, dominated by $\tau^+\tau^-$ events. With the selection criteria just described, distributions of single particle and event topology measures were found to be well described by Monte Carlo models of hadronic Z^0 boson decays[10),11)] combined with a simulation of the SLD.

3. FLAVOR TAGGING OF Z^0 DECAYS

Events were tagged using the distance of closest approach (DOCA) of charged tracks to the interaction point (IP), projected in the plane transverse to the beam (the x-y plane). In addition to the track selection cuts just described, further restrictions were imposed on tracks contributing to the tag to ensure good measurements of their DOCAs. Tracks were required to have hits in at least two layers of the VXD, at least 40 out of a possible 80 hits in the CDC, a $\chi^2/dof < 5.0$ in a track fit to the CDC hits, and not to form pairs consistent with K^0, Λ^0, or photon conversions. The error on the DOCA measurement arises from the intrinsic resolution of the VXD, multiple scattering and the IP measurement uncertainty. The IP was found by combining tracks from several events and fitting for a common origin. In 1992 the SLC beam interaction envelope measured less than 2 μm in x and y, and about 650 μm in z. The event-to-event location of the IP was stable to within 16 μm in x-y over periods of more than 200 hours. The average error on the DOCA of a track is therefore given by $< \sigma_{DOCA} > = 13 \oplus 70/(p\sqrt{sin^3\theta}) \oplus 16$ μm, where p is the track momentum in GeV, and the three terms derive, respectively, from the three sources just listed. Tracks with $\sigma_{DOCA} > 250\mu$m were not used in the tag.

For each event, tracks passing the above selection criteria were extrapolated near the IP, and their DOCAs were measured. A sign was applied to each DOCA by associating the track with the nearest jet axis, where jets were defined using the JADE algorithm at $y_c = 0.02$.[12] If the x-y projection of a track intersects the projection of the jet axis on the side opposite the IP from the jet direction, the DOCA is negative, otherwise it is positive. The normalized DOCA d is then formed by dividing the DOCA by its measurement error.

$Z^0 \rightarrow b\bar{b}$ events were tagged by requiring that they contain at least three tracks with $d \geq 3.0$, and light quark ($Z^0 \rightarrow u\bar{u},\ d\bar{d},\ s\bar{s}$) events by requiring no track with $d \geq 3.0$. 1054 b and 1799 light quark events were so tagged. The efficiencies ϵ of these procedures, and the purities p of the resulting tagged samples were estimated[13] using Monte Carlo simulations and found to be approximately $(\epsilon,p) = (71,80)$ and $(79,86)\%$ for the b and light quark samples, respectively.

4. MEASURING THE α_s RATIOS

A jet rates analysis[2] was performed on the two tagged samples and on the complete hadronic dataset using the JADE algorithm to obtain the ratios of 3-jet rates: $f_b^{meas} = R_3(b-tag)/R_3(all)$ and $f_{uds}^{meas} = R_3(uds-tag)/R_3(all)$ as a function of y_c. We adopt the convention[14] of the L3 collaboration and quote our results at $y_c = 0.05$, for which $\geq$ 4-jet production is a negligible fraction of the hadronic cross-section,[2] and the next-to-leading order corrections to 3-jet production[15] are about 0.5% and are neglected here. f_b^{meas} and f_{uds}^{meas} were each corrected for the difference in tagging efficiency between 2- and 3-jet events.

If the purity of the b-tag is $\mathcal{P}$ and the $Z^0 \rightarrow b\bar{b}$ branching fraction is R_b, then the ratio of the three-jet rate in b events to that in $udsc$ events is given by

$$f_b \equiv R_3(b)/R_3(udsc) = (f_b^{meas}(1-R_b) + \mathcal{P} - 1)/(\mathcal{P} - R_b f_b^{meas}).$$

The influence of the weak decays of B hadrons on $R_3(b)$ was investigated using Monte Carlo simulations and found to produce a negligible bias in f_b. However, due to the restricted phase space resulting from the large b-quark mass, gluon emission in $Z^0 \rightarrow b\bar{b}$ events relative to that in $Z^0 \rightarrow u\bar{u},\ d\bar{d},\ s\bar{s},\ c\bar{c}$ events has been calculated to be suppressed by a factor of about 0.95 at $y_c = 0.05$.[16] After applying this correction to f_b we equate it to $\alpha_s(b)/\alpha_s(udsc)$ and find:

$$\alpha_s(b)/\alpha_s(udsc) \quad = \quad 1.02 \pm 0.08 \text{ (stat.) } \pm 0.04 \text{ (syst.)} \quad \text{(PRELIMINARY)}$$

A similar procedure for f_{uds} yields:

$$\alpha_s(uds)/\alpha_s(bc) \quad = \quad 0.98 \pm 0.08 \text{ (stat.) } \pm 0.02 \text{ (syst.)} \quad \text{(PRELIMINARY)}$$

These ratios are consistent with the *ansatz* that strong interactions are flavor independent. Further studies of the systematic errors are in progress, but it is apparent that our measurements are statistically limited with the 1992 data sample of around 10,000 Z^0 decays. The result $\alpha_s(b)\ /\alpha_s(udsc)$ is in agreement with similar measurements made at PETRA and LEP.[17] No results on $\alpha_s(uds)\ /\alpha_s(bc)$ have been presented previously.

5. MEASUREMENT OF MULTIPLICITY IN $Z^0 \to b\bar{b}$ EVENTS

Predictions have been made recently of the difference in mean charged particle multiplicity, Δn_b, between $e^+e^- \to b\bar{b}$ and $e^+e^- \to u\bar{u},\ d\bar{d},\ s\bar{s}$ events.[18] Based on perturbative QCD in the Modified Leading Logarithm Approximation, Δn_b is predicted to be *independent* of centre-of-mass energy, and to be 5.5 charged tracks per event. The first prediction is estimated to be accurate to 0.1 tracks, and the second to about one charged track. We have tested these predictions by making an accurate measurement of Δn_b at $W = M_Z$.

Hadronic events were divided into two hemispheres by the plane perpendicular to the thrust axis. Using a similar technique as described in Section 3, a hemisphere was tagged as being of b-quark origin by requiring that it contain at least 2 tracks with $d \geq 3$. The tracks in the *opposite* hemisphere were then counted to give a less biased multiplicity. The mean multiplicity in this sample of opposite hemispheres was multiplied by 2 to give the mean charged multiplicity in the b-tagged sample $< n_{b-tag}^{meas} >$. The mean charged multiplicity in the sample of all events, $< n_{all}^{meas} >$, was also calculated. These quantities were related to the unknowns $< n_b >$ and $< n_{all} >$, the true mean multiplicities in b and *all* events, respectively, via coefficients determined from Monte Carlo simulations which include estimates of the purity and efficiency of the b-tag and the effects of detector acceptance and analysis cuts. Standard model branching ratios for Z^0 decays to the different quark flavors were assumed. The formalism for this procedure is described in more detail in Ref. 19. We find

$$< n_b > \quad = \quad 23.5 \pm 0.9 \quad \text{(PRELIMINARY)}$$

where the error is the sum in quadrature of the statistical and systematic errors.

In order to extract $\Delta n_b \equiv < n_b > - < n_{uds} >$ from $< n_b >$ and $< n_{all} >$, a further correction was applied for the charged multiplicity in $Z^0 \to c\bar{c}$ events, the assumption being that the mean lies between $< n_{uds} >$ and $< n_b >$. We find

$$\Delta n_b \quad = \quad 3.8 \pm 1.2 \pm 0.7 \quad \text{(PRELIMINARY)}$$

where the first error is the sum in quadrature of experimental statistical and systematic errors, and the second is from the uncertainty in the multiplicity in $Z^0 \to c\bar{c}$ events.

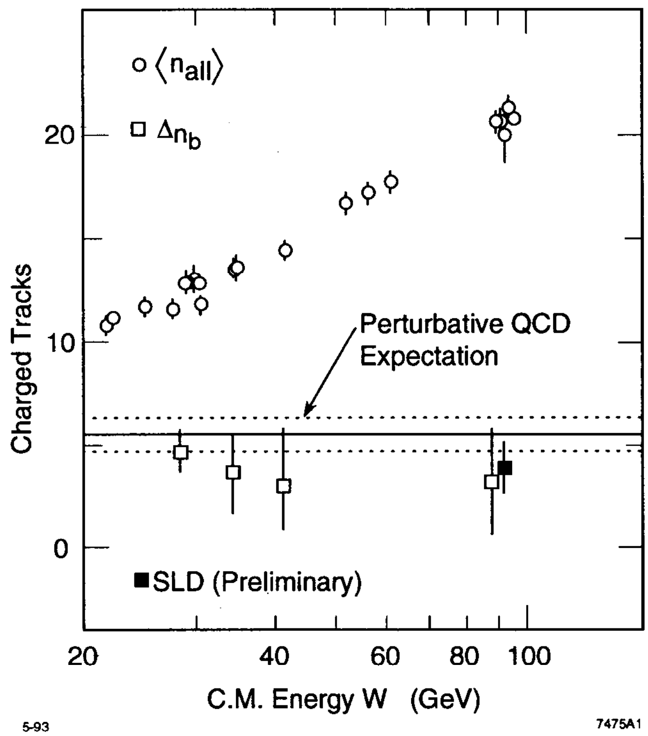

Figure 1. The mean charged particle multiplicity, $< n_{all} >$, and the b-quark multiplicity difference, Δn_b, measured in e^+e^- annihilation, as a function of center of mass energy W. The perturbative QCD prediction for Δn_b is shown, with an error band originating from the experimental uncertainty on the multiplicity in uds events at $W = \sqrt{e}\, m_b$.[18)]

Figure 1 shows, in the upper half, a compilation[18)] of measurements of the mean total charged multiplicity $< n_{all} >$ in e^+e^- annihilation events as a function of c.m. energy W. The growth of $< n_{ch} >$ is slightly faster than logarithmic with W. The lower half of Fig. 1 shows the present measurement of Δn_b, together with results from PEP, PETRA and MarkII/SLC.[18),19)] With the addition of the precise SLD measurement at $W = M_Z$, it can be seen that the data provide strong support for the energy independence of Δn_b and are in numerical agreement with the predicted value. This striking result may be interpreted to be due to coherence in gluon radiation in $b\bar{b}$ events.[18)] A qualitatively similar effect is also expected for $c\bar{c}$ events, and measurements of Δn_c would provide a powerful test of the MLLA calculations at the charm mass scale, thereby testing perturbative QCD close to the boundary of the confinement region.

6. JET HANDEDNESS

Efremov *et al* have speculated[3] that net polarization of hadronic jets may be observable via the triple scalar product T constructed from the momenta of the three fastest particles in each jet. The sign of the asymmetry

$$h_j = \frac{N_{T>0} - N_{T<0}}{N_{T>0} + N_{T<0}}, \tag{1}$$

is expected to be different for left- and right-handed jets and is called the jet handedness. They then assert that $h_j = \alpha\mathcal{P}_q$, where $\mathcal{P}_q$ is the underlying quark polarization and α is the (*a priori* unknown) analyzing power. Hadronic decays of Z^0 bosons are an ideal testing ground for the handedness method as, according to the standard model, the quark and antiquark from the Z^0 decay are highly polarized. However, because quarks (antiquarks) are produced left-(right-)handed, the measured handedness will be zero unless quark jets are measured separately from antiquark jets. Observation of handedness of opposite signs for tagged quark and antiquark jets would be a significant result. Furthermore, comparison with the assumed standard model (anti)quark polarization in Z^0 decay gives the analyzing power of this method. The analyzing power thus measured in e^+e^- annihilation could be utilized in handedness measurements in lepton-hadron and hadron-hadron collisions to deduce the polarization of quarks in hard scatterings.

SLD is uniquely placed to select samples of (right-)left-handed (anti)quark jets using the forward-backward asymmetry tag with high electron beam polarization. Without beam polarization, LEP has only the small natural forward-backward asymmetry of the Z^0, although preliminary results[20] suggest a small net charge-signed jet handedness, which might be expected from the net excess of down-over up-type quarks in Z^0 decays. We performed a handedness analysis similar to that of Ref. 20. We define $T = \vec{t}.(\vec{k_1^+} \times \vec{k_2^-})$, where $\vec{t}$ is the jet axis direction, and k_1^+ and k_2^- are the fastest positively and negatively charged particles, respectively, in the jet. We measure the asymmetry to be:

$$h_j \quad = \quad 5.9 \pm 3.4\% \quad \text{(PRELIMINARY)},$$

which provides an estimate of the upper limit of the analyzing power of this handedness method of $\alpha < 11.5\%$ at 95% confidence level. Studies are in progress to find definitions of T with higher analyzing power.

7. SUMMARY AND OUTLOOK

Using our 1992 data, we have presented tests of the flavor independence of strong interactions via preliminary measurements of the ratios $\alpha_s(b)\ /\alpha_s(udsc)$ and $\alpha_s(uds)\ /\alpha_s(bc)$. The goal for the 1993 SLD/SLC run is to integrate over 50,000 hadronic Z^0 decays.* This will reduce the statistical errors to below the expected size of the systematic errors, although these may also be reduced with further understanding of the detector performance. We have also measured the difference in charged particle multiplicity between $Z^0 \rightarrow b\bar{b}$ and $Z^0 \rightarrow u\bar{u},\ d\bar{d},\ s\bar{s}$ events which is presently limited in precision by the lack of knowledge of the multiplicity in $Z^0 \rightarrow c\bar{c}$ events. With the 1993 data we expect to make a first direct measurement of the $Z^0 \rightarrow c\bar{c}$ multiplicity. Finally we have studied jet handedness. With the achievement of an electron beam polarization in excess of 60%, the 1993 data will allow us to perform quark/antiquark jet separation with high efficiency using the natural quark forward-backward asymmetry enhanced by beam polarization. We shall therefore be able to look for jet handedness separately in samples enriched in left-handed quark and right-handed antiquark jets.

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* As of the end of May 1993, over 30,000 Z^0 decays have been recorded by SLD, and the electron beam polarization is > 60%.

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