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QCD Tests with SLD and Polarized Beams *

M. G. Strauss
University of Massachusetts, Amherst, Massachusetts 01003

On behalf of the SLD Collaboration
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94309

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Michael G. Strauss
University of Massachusetts
Amherst, Massachusetts 01003

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ABSTRACT

We present a measurement of the strong coupling α_s derived from multijet rates using data collected by the SLD experiment at SLAC and find that $\alpha_s(M_Z^2) = 0.118 \pm 0.002\,(\text{stat.}) \pm 0.003\,(\text{syst.}) \pm 0.010\,(\text{theory})$. We present tests of the flavor independence of strong interactions via preliminary measurements of the ratios $\alpha_s(b)\ /\alpha_s(udsc)$ and $\alpha_s(uds)\ /\alpha_s(bc)$. In addition, we have 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, and find that it supports the prediction of perturbative QCD that the multiplicity difference be independent of center-of-mass energy. Finally, we have made a preliminary study of jet polarization using the jet handedness technique.

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1 Introduction

The Standard Model of elementary particles comprises the theory of electroweak interactions and quantum chromodynamics (QCD), the theory of strong interactions. In recent years, the electroweak theory has been tested to high precision and proven to be quite successful.[1] Although not as accurately tested, QCD has also had many experimental confirmations, including multijet events, the running of the strong coupling α_s, and soft gluon coherence.[2] In this paper we present recent results from the SLD detector at SLAC which test QCD and probe the strong interaction. First, we present a measurement of the strong coupling $\alpha_s(M_Z)$ from the rate of production of multijet final states in hadronic decays of Z^0 bosons.[3] We employ six collinear and infrared safe jet algorithms to study the uncertainties arising from finite order perturbative QCD calculations, and we also compare our data with all-orders calculations in the next-to-leading logarithm approximation. Next, we apply a similar technique to samples of hadronic Z^0 events enriched in $Z^0 \to b\bar{b}$ and $Z^0 \to u\bar{u},\ d\bar{d},\ s\bar{s}$ decays, and measure the ratios $\alpha_s(b)\ /\alpha_s(udsc)$ and $\alpha_s(uds)\ /\alpha_s(bc)$, to test the QCD assumption 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 $Z^0 \to b\bar{b}$ and $Z^0 \to u\bar{u},\ d\bar{d},\ s\bar{s}$ events.[4] 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 concept of "jet handedness," whereby a measure is defined for hadronic jets which may be related to the underlying polarization of the parton initiator of the jets.[5]

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. During the 1992 SLC/SLD run, a mean polarization of 22% was attained. The first three topics discussed in this paper use this 1992 data, exclusively, and combine all data samples produced by left, right, and unpolarized electrons. During the 1993 SLC/SLD run, preliminary analysis measured a mean polarization of 62%, resulting in a more pronounced forward-backward Z^0 decay asymmetry. The jet handedness analysis uses this forward-backward asymmetry to tag quark and antiquark jets and uses data from both the 1992 and 1993 runs.

SLD is a multipurpose particle detector and is described in detail elsewhere.[6] 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 CCD based device with 120 million $22\times22\mu m^2$ pixels.[7] A conventional coil, producing a 0.6 Tesla magnetic field, provides a momentum measurement for charged tracks. Particle energies are measured in the Liquid Argon Calorimeter (LAC),[8] and in the Warm Iron Calorimeter.[9] The LAC is segmented into 40,000 projective towers and has a resolution of about 15% for the measured Z^0 mass.

Three triggers were used to select 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 and VXD. 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 a closest approach to the beam axis within 5 cm, and within 10 cm along the beam axis of the measured interaction point, a polar angle θ with respect to the beam axis with $|\cos\theta| < 0.80$, and 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 direction with respect to the beam axis, θ_T, within $|\cos\theta_T| < 0.71$, and a minimum charged visible energy 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. For the jet-handedness analysis, a subset of the 1993 data has been analyzed resulting in 20,662 events surviving 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 $0.3\pm0.1\%$, 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 Measurement of α_s from Jet Rates

Since the coupling of quarks to gluons is proportional to $\sqrt{(\alpha_s)}$, the rate of jet production can be used to measure α_s. In order to define jets, we applied several iterative clustering algorithms in which a measure y_{ij}, such as invariant mass-squared/s, is calculated for all pairs of particles i and j, and the pair with the smallest y_{ij} is combined into a single "particle." This process is repeated until all pairs have y_{ij} exceeding a value y_c, and the jet multiplicity of the event is defined as the number of particles remaining. Various recombination schemes and definitions of y_{ij} have been suggested.[12] We have applied the "E," "E0," "P," and "P0" variations of the JADE algorithm[13] as well as the "Durham" ("D") and "Geneva" ("G") algorithms, all of which are collinear and infrared safe.[12] The n-jet rate $R_n(y_c)$ is defined as the fraction of events classified as n-jet. The R_n distribution contains significant point-to-point correlations since every point contains one entry from every event. Consequently, a differential two-jet rate is defined as $D_2(y_c) \equiv (R_2(y_c) - R_2(y_c - \Delta y_c))/\Delta y_c$, which contains no correlations.[14] The measured jet rates were corrected for the effects of detector acceptance, inefficiency and resolution, particle interactions and decays within the detector, and bias from the analysis cuts using the SLD Monte Carlo simulation, as well as a hadronization correction estimated using JETSET 6.3.[10]

The corrected D_2 distributions were derived from the fully corrected jet rates and compared with QCD calculations employing the same jet algorithms, performed up to second order in perturbation theory, which have the general form: $R_3(y_c) = A(y_c)\alpha_s(\mu) + B(y_c, f)\alpha_s^2(\mu)$, and $R_4(y_c) = C(y_c)\alpha_s^2(\mu)$, where $\alpha_s = \alpha_s(\Lambda_{\overline{MS}}, \mu)$,[15] $\Lambda_{\overline{MS}}$ is the fundamental scale of strong interactions, and μ is the renormalization scale, often expressed in terms of the factor $f = \mu^2/s$. Here we have assumed the definition of $\Lambda_{\overline{MS}}$ for five active quark flavors. The explicit dependence of the next-to-leading coefficient B on f is an artifact of the truncation of the perturbation series at finite order. Therefore, if $\Lambda_{\overline{MS}}$ is extracted by fitting these calculations to the data, the variation of f must be taken into account as a contribution to the uncertainty in $\Lambda_{\overline{MS}}$. We used parameterizations of the coefficients $A(y_c)$, $B(y_c, f)$, $C(y_c)$ to derive $R_2 = 1 - R_3 - R_4$.[12] For each algorithm, $D_2^{\dagger}(y_c)$ was calculated and fitted to the fully corrected measured distributions by varying $\Lambda_{\overline{MS}}$ and minimizing χ^2.[16] The fits were restricted to the range of y_c for which the measured $R_4 < 1\%$, since in the second order calculation R_4 was evaluated only at leading order, and $R_{n>4}$ were not considered. The upper y_c fit boundary was chosen to be the kinematic limit for (massless) three-jet production, $y_c = 0.33$.

The fitted $\Lambda_{\overline{MS}}$ values were translated into $\alpha_s(M_Z^2)$.[15] The results are summarized in Fig. 1, where α_s and (χ^2_{dof}) are shown as functions of f in the range $10^{-5} \leq f \leq 10^1$. Several features are common to all algorithms: 1) α_s depends strongly on f; 2) across a range of f, the fit quality is reasonable and χ^2_{dof} changes slowly; 3) at low f, the fits are poor, χ^2_{dof} changes rapidly, and neither α_s nor its error can be interpreted meaningfully. The boundary between reasonable and poor fits is algorithm-dependent. We note also that for some algorithms reasonable fits can be obtained for $f \gg 1$, although such values are beyond the physical scale accessible in e^+e^- annihilation.

Figure 1 contains all of the information from the QCD fits to the data. In order to quote a single value of α_s for each algorithm, we adopt the following arbitrary procedure. We consider the range $0.002 \leq f \leq 4$. The exact interpretation of μ is renormalization scheme-dependent. However, the lower bound corresponds approximately to $\mu \geq m_b$, and restricts μ to the region in which five active quark flavors contribute to $\Lambda_{\overline{MS}}$, in addition to ensuring that the perturbative series for R_3 remains reasonably convergent for all algorithms. This excludes some small scales for which the fit quality is good, but includes the α_s minima for all algorithms except E. The upper bound restricts μ to a reasonable physical region, $\mu \leq 2\sqrt{s}$. Within this range, the fit quality is acceptable (Fig. 1(b)), the data show no strong preference for a particular scale, and we take the extreme of the α_s values as the uncertainty from the dependence on f. The large and different scale uncertainties may be interpreted as arising from uncalculated higher order contributions which are different for each algorithm. However, allowing for the scale uncertainties, the six α_s values are in agreement, which is a significant consistency check of QCD.

Experimental systematic errors were investigated by varying the cuts applied to the data and changing parameters in the simulation of the detector over large ranges.[17] In each case, the detector correction factors were reevaluated and the correction and fitting procedures repeated. In addition, the fit ranges were varied

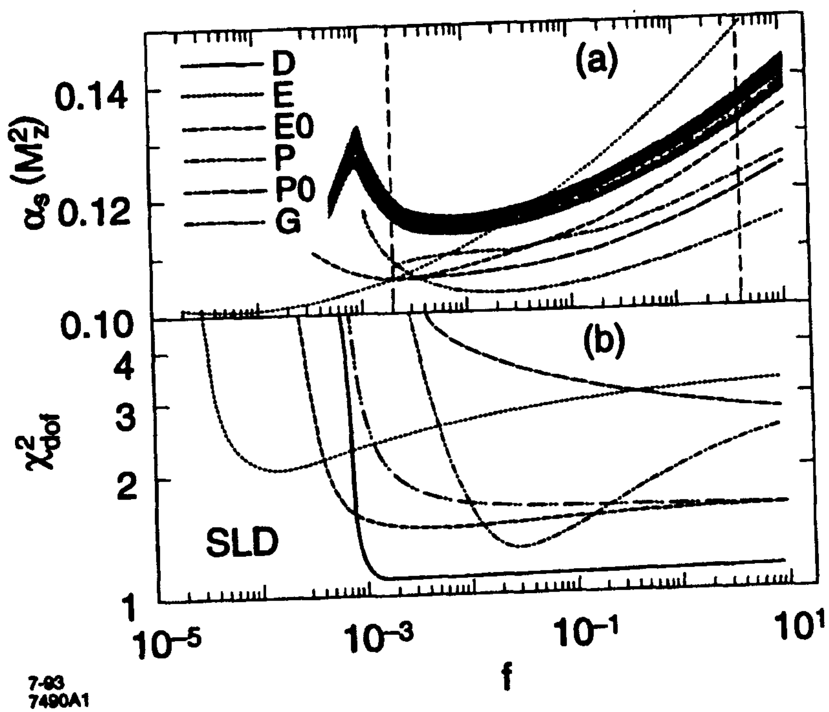

Figure 1: (a) $\alpha_s(M_Z^2)$ and (b) χ^2_{dof} from $O(\alpha_s^2)$ QCD fits (see text). The band indicates the size of statistical errors.

by deleting bins at the ends of the y_c regions. None of these effects changed the value of α_s by more than the statistical error. We conservatively estimate the systematic error to be ±0.003 for each algorithm. Hadronization uncertainties were studied by recalculating the hadronization correction factors using JETSET with values of the parton virtuality cutoff Q_0[10] in the range 0.5 to 2.0 GeV, and by using HERWIG,[11] which contains a different hadronization model.

In order to quote a single result, we calculated the mean and rms deviation of the six α_s values for each f in the range $0.002 \leq f \leq 4$. We then took the central value of the means in that range as our central result, the rms at the central value as the algorithm uncertainty, and the difference between the central value and the extreme as the scale uncertainty. This procedure corresponds to the conservative assumption that all six α_s at each f are completely correlated statistically, and yields:

$$\alpha_s(M_Z^2) \quad = \quad 0.118 \pm 0.002 \text{ (stat.)} \pm 0.003 \text{ (syst.)} \pm 0.010 \text{ (theory)}, \qquad (1)$$

where the theory uncertainty is the sum in quadrature of contributions from hadronization (±0.003), scale (±0.009), and algorithm (±0.003) uncertainties. This result is in good agreement with other measurements of $\alpha_s(M_Z^2)$.[2] Our theoretical uncertainty is slightly larger than that quoted by some of the LEP experiments because we considered a wider range of scales and more jet algorithms and added an additional algorithm uncertainty, which is not normally considered. The scale and algorithm uncertainties are correlated, but we consider the resulting estimate of uncalculated higher order contributions to be realistic.

Progress has recently been made in the form of "resummed" QCD calculations for event shape distributions in e^+e^- annihilation.[18] For the D algorithm, these techniques have been used to calculate jet rates at leading and next-to-leading order in $\ln(1/y_c)$, up to all orders in α_s.[19] The resulting all-orders calculation, valid in the region where $\alpha_s \ln(1/y_c) \leq 1$, may be combined with the fixed second order result[20] to yield improved predictions for multijet rates at low y_c. Several matching schemes have been proposed for this combination including "R-matching," "$\ln(R)$-matching," and "modified $\ln(R)$-matching."[21,22] For each scheme, D_2 was derived from the recalculated R_2 and fitted to the data in our full range $y_c \geq 0.01$. The resulting $\alpha_s(M_Z^2)$ and χ^2_{dof} values are shown in Fig. 2, labelled "ALEPH scheme," as a function of f. Results from both $\ln(R)$ matching schemes are similar, so we show only the modified scheme. The behavior is qualitatively similar to the second order result although $f \geq 0.1$ is needed to fit the data, and in this range the fitted α_s varies slowly with f.

We found, however, that the resummed calculations yield $R_2 > 1$ in some regions of phase space. This unphysical behavior gives rise to the peak at $f \sim 0.1$ in Fig. 2(a). For $y_c \leq 0.04$, the resummed R_2 remains below unity for $f \geq 0.2$, so we adopted a new procedure, using the matched calculation for $0.01 \leq y_c \leq 0.04$ and the $O(\alpha_s^2)$ calculation for $0.05 \leq y_c \leq 0.33$, giving α_s and χ^2_{dof} labelled "SLD scheme" in Fig. 2. With this procedure, we quote a single value of α_s by taking the mean in the range $1/4 \leq f \leq 4$, and the difference between the R- and $\ln(R)$-matching schemes as the *matching uncertainty.* This range excludes the unphysical $R_2 > 1$ region but includes the full measured variation of α_s up to $f = 4$; it is the same as that considered in Ref. 22 but larger than Ref. 21. We found:

$$\alpha_s(M_Z^2) \quad = \quad 0.126 \pm 0.002 \text{ (stat.)} \pm 0.003 \text{ (syst.)} \pm 0.006 \text{ (theory)}, \qquad (2)$$

where the theory uncertainty is the sum in quadrature of contributions from hadronization (± 0.003), scale (± 0.003), and matching (± 0.005) uncertainties. This is in good agreement with the $O(\alpha_s^2)$ result for the D algorithm. The scale uncertainty is considerably smaller, but there is extra uncertainty from the matching. The latter can be attributed to partly calculated, next-to-leading, and uncalculated subleading, logarithmic terms. Nevertheless, for the D algorithm the total theoretical uncertainty is smaller using the resummed calculation than the $O(\alpha_s^2)$ calculation. Further improvement in the accuracy of α_s determinations from jet rates must await better understanding of the remaining higher order contributions.

Since the resummed calculations have been performed only for the Durham algorithm and yield α_s in good agreement with the fixed order result, we quote the fixed order value based on all six algorithms as our final result: $\alpha_s(M_Z^2) = 0.118 \pm 0.002(\text{stat.}) \pm 0.003(\text{syst.}) \pm 0.010(\text{theory})$, in good agreement with other measurements.[2] This corresponds to $\Lambda_{\overline{MS}} \simeq 230 \pm 130$ MeV. The precision is limited by lack of knowledge of higher order contributions.

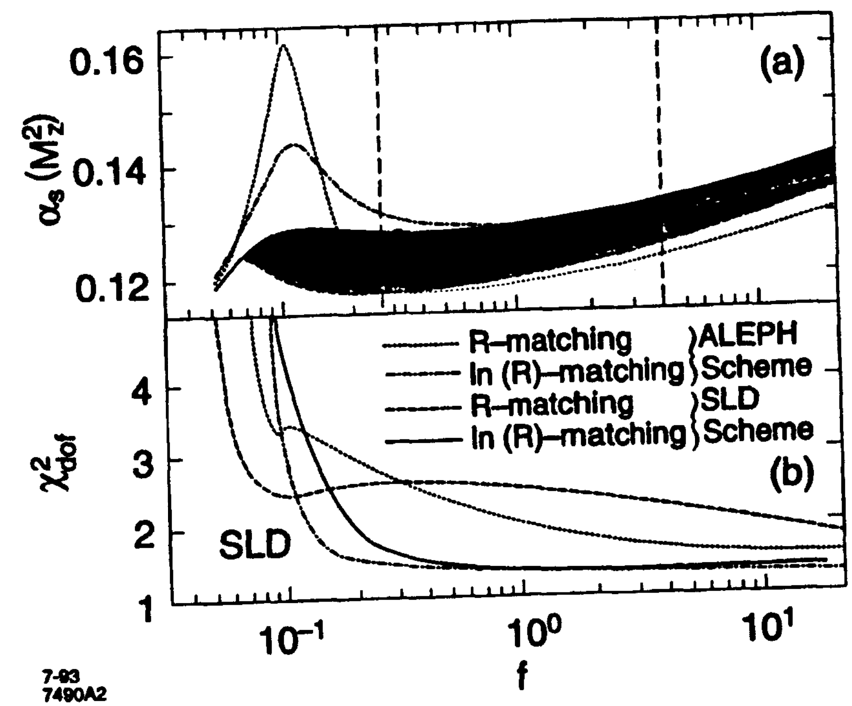

Figure 2: (a) $\alpha_s(M_Z^2)$ and (b) χ^2_{dof} from fits using resummed calculations for the D algorithm. The band shows the range of uncertainty from higher order effects (see text).

4 Flavor Tagging of Z^0 Decays

For our analysis of the ratios $\alpha_s(b)\ /\alpha_s(udsc)$ and $\alpha_s(uds)\ /\alpha_s(bc)$ and of 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, enriched samples of $Z^0 \to b\bar{b}$ and $Z^0 \to u\bar{u},\ d\bar{d},\ s\bar{s}$ decays must be obtained. These events were tagged using the signed 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 described in Section 2, further restrictions were imposed on tracks contributing to the tag to ensure good measurements of their DOCAs. Tracks were required to have at least one linked hit in 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, a DOCA<3mm, and error on the DOCA <250μm, a closest approach to the beam axis within 1 cm along the beam axis, 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 10 μm in x-y over periods of more than 200 hours. The average error on the DOCA of a track is therefore given by $<\sigma_{DOCA}>= 13 \oplus 70/(p\sqrt{sin^3\theta}) \oplus 10\ \mu$m, where p is the track momentum in GeV, and the three terms derive, respectively, from the three sources just listed.

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.[23] 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.

For the analysis testing the flavor independence of α_s, a sample of 1799 events enriched in light quark, ($Z^0 \to u\bar{u},\ d\bar{d},\ s\bar{s}$), was tagged by requiring that events contain no track with $d \geq 3.0$, and a sample of 1054 events enriched in $Z^0 \to b\bar{b}$ by requiring at least three tracks with $d \geq 3.0$. The efficiencies ϵ of these two tags, and the purities p of the resulting samples were estimated using Monte Carlo simulations of hadronic events, combined with a simulation of the SLD, to be approximately (ϵ,p) = (79,86) and (71,80)% for the light and b quark samples, respectively.[24]

In order to minimize bias, the analysis of multiplicity in $Z^0 \to b\bar{b}$ events tags hemispheres, rather than entire events. Each event is divided into two hemispheres separated by the plane perpendicular to the thrust axis. Hemispheres are tagged by requiring that two or more tracks in a given hemisphere pass all the above cuts and have $d > 3.0$. Monte Carlo (MC) studies indicate that this tag is 53% efficient at identifying hemispheres containing B hadrons, while providing an enriched sample of 69% purity. Bias is reduced by measuring the multiplicity in the hemisphere opposite to the tag.

5 Test of Flavor Independence of α_s

Using the methods described in Section 4, we tag samples of Z^0 decays enriched in $Z^0 \to u\bar{u},\ d\bar{d},\ s\bar{s}$ events, and $Z^0 \to b\bar{b}$ events. A jet rates analysis was performed on the two tagged samples and on the complete hadronic dataset using the JADE algorithm to obtain ratios of three-jet rates, $f_{uds}^{meas} = R_3(uds\text{-tag})/R_3(\text{all})$ and $f_b^{meas} = R_3(b\text{-tag})/R_3(\text{all})$, as functions of y_c. We quote our results at $y_c = 0.05$, for which $\geq$ 4-jet production is a negligible fraction of the hadronic cross section.[4]

The measured f_{uds}^{meas} and f_b^{meas} were corrected for the differences in tagging efficiency between two- and three-jet events, and were then corrected for tag purity. The ratio of the three-jet rate in b events to that in $udsc$ events is given by

$$f_b \equiv \frac{R_3(b)}{R_3(udsc)} = \frac{f_b^{meas}(1-R_b) + \mathcal{P}_b - 1}{(\mathcal{P}_b - R_b f_b^{meas})}, \tag{3}$$

where purity of the b-tag is $\mathcal{P}_b$ and the fraction of hadronic Z^0 decays to $b\bar{b}$ is R_b. By quoting our results as ratios, detector systematic errors mainly cancel, and theoretical errors are minimized. A similar equation holds for f_{uds}.

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 $Z^0 \to b\bar{b}$ events relative to that in $Z^0 \to u\bar{u},\ d\bar{d},\ s\bar{s},\ c\bar{c}$ events have been calculated to be suppressed by a factor of about 0.95 at $y_c = 0.05$.[25] After applying this correction to f_b, we equate it to $\alpha_s(b)\ /\alpha_s(udsc)$ and find:

$$\alpha_s(b)/\alpha_s(udsc) = 1.02 \pm 0.08\,(\text{stat.}) \pm 0.04\,(\text{syst.}) \quad (\text{PRELIMINARY}). \quad (4)$$

A similar procedure for f_{uds} yields:

$$\alpha_s(uds)/\alpha_s(bc) = 0.98 \pm 0.08\,(\text{stat.}) \pm 0.02\,(\text{syst.}) \quad (\text{PRELIMINARY}). \quad (5)$$

These ratios are consistent with the *ansatz* that strong interactions are flavor independent. The systematic errors are due to uncertainties in the sample purities and tag biases, and are dominated by limited Monte Carlo statistics. 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.[26]

6 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.[27] Based on perturbative QCD in the Modified Leading Logarithm Approximation, to $O([\alpha_s(W^2)]^{1/2}(M_Q^2/W^2))$, Δn_b is predicted to be *independent* of center-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 $W = M_Z$.

A $Z^0 \to b\bar{b}$ enriched sample was selected using the technique described in section 4. The tag selected 1650 out of 2 x 4351 = 8702 hemispheres in the SLD data sample.

In determining the total charged $Z^0 \to b\bar{b}$ multiplicity $< n_b >$, we minimized systematic error, such as those due to tracking efficiency and multiple scattering, by measuring $\delta n_b \equiv\ < n_b > - < n_{had} >$, and then adding back in the total hadronic charged multiplicity $< n_{had} >$, which has been accurately determined by other experiments. For hemispheres opposite tagged hemispheres, we find a mean multiplicity of 8.54 ± 0.09 tracks, while for all hemispheres in the hadronic sample we find a mean multiplicity of 7.96 ± 0.04 tracks. Following the procedure described in Ref. 27, we used the JETSET 6.3 Monte Carlo event generator, combined with a simulation of the SLD, to correct this raw multiplicity difference of 0.58 tracks per hemisphere for detector biases and sample impurities. The resulting multiplicity difference is 1.26 ± 0.22 tracks per hemisphere. Multiplying both mean value and uncertainty by two to provide an event, rather than hemisphere, multiplicity, we find that $\delta n_b = 2.5 \pm 0.4$ (stat.) tracks. As a check, the corrected total hadronic multiplicity is 20.62 ± 0.11 tracks per event, consistent with the world average of 20.95 ± 0.20.[28]

We have compared the fraction of tagged hemispheres $f_t^{data} = 1650/8702 = 0.190 \pm 0.005$ to the MC expectation $f_t^{MC} = 0.157$, assuming the world average value of $R_b = 0.220 \pm 0.003$.[29] If we conservatively assume that this difference is due entirely to extra $Z^0 \to udsc$ contamination in the tagged sample, the corresponding change in $< n_b >$ is 0.5 tracks. In addition, there is an uncertainty in the size of the MC correction of the raw multiplicity difference due to the absence of empirical knowledge of the momentum spectrum of the nonleading tracks in $Z^0 \to b\bar{b}$ events. For our cut of 0.20 GeV/c, we estimate this uncertainty to be ± 0.5 tracks. Finally, we include a systematic uncertainty of ± 0.2 tracks due to limited MC statistics. As mentioned above, detector effects are expected to add only a small contribution to the overall systematic error, as they largely cancel in the multiplicity difference $< n_b > - < n_{had} >$. Combining these sources of systematic error in quadrature,

$$\delta n_b = 2.5 \pm 0.4\ (\text{stat.}) \pm 0.7\ (\text{syst.})\ \text{tracks} \quad (\text{PRELIMINARY}). \quad (6)$$

Adding back in the world average total hadronic multiplicity $< n_{had} >= 20.95 \pm 0.20$ then yields

$$< n_b >= 23.5 \pm 0.4\ (\text{stat.}) \pm 0.7\ (\text{syst.})\ \text{tracks} \quad (\text{PRELIMINARY}). \quad (7)$$

In order to extract $\Delta n_b \equiv\ < n_b > - < n_{uds} >$ from $< n_b >$ and $< n_{had} >$, 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

$$\Delta n_b = 3.8 \pm 0.6 \pm 0.3 \quad (\text{PRELIMINARY}), \quad (8)$$

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

Figure 3 shows, in the upper half, a compilation[27] of measurements of the mean total charged multiplicity $< n_{had} >$ in e^+e^- annihilation events as a function of

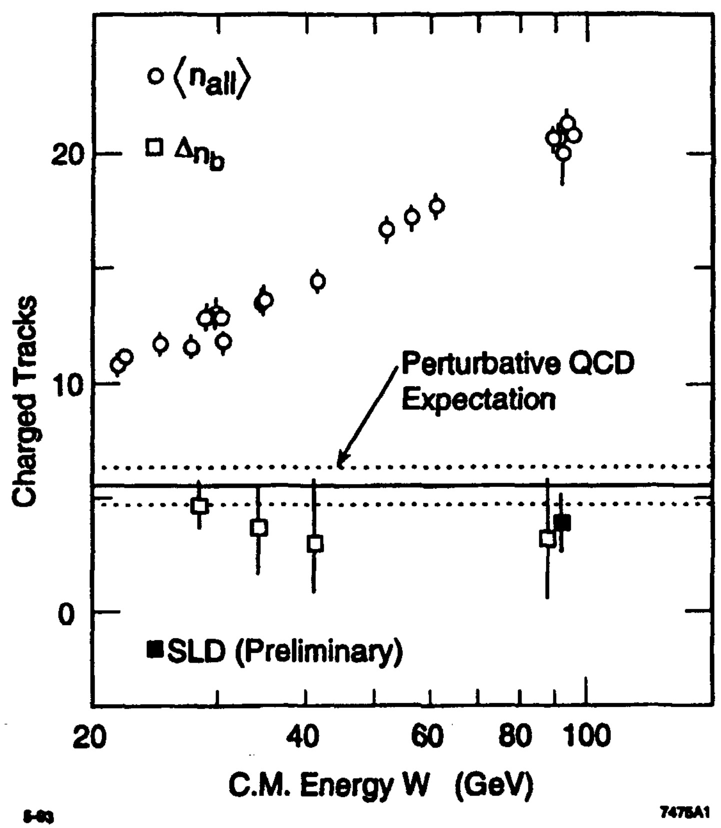

Figure 3: The mean charged particle multiplicity, $< n_{all} >$, and the b-quark multiplicity difference, Δn_b, measured in e^+e^- annihilation , as a function of center-of-mass energy W. The perturbative QCD prediction for Δn_b is shown, with an error band originating from the experimental uncertainty on the multiplicity in uds events at $W = \sqrt{e}\, m_b$.

center-of-mass energy W. The growth of $< n_{ch} >$ is slightly faster than logarithmic with W. The lower half of Fig. 3 shows the present measurement of Δn_b, together with results from PEP, PETRA, and MARK-II/SLC.[27,30] 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. 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.

It should be noted that several groups[31,32] have suggested that the nonleading multiplicity associated with heavy quark production at a given cms energy W should be equal to the total light quark event multiplicity at the reduced cms energy $(1-\langle x_Q \rangle)W$, where $x_Q = 2 \cdot E_B/W$ is the heavy hadron energy fraction after fragmentation. This hypothesis provides that the quantity $< n_b > - < n_{uds} >$ decrease with cms energy in proportion to $< n_{had}(W) >$, in contradiction with the perturbative QCD expectation. When the preliminary SLD result is included, however, the data are inconsistent with the energy dependence implied by this hypothesis at the level of 2.4 standard deviations.

7 Jet Handedness

The transport of parton polarization through the hadronization process is of fundamental interest in QCD, and it is presently an open question whether the spin of a parton produced in a hard collision is observable via the final state fragmentation products in its resulting jet. Efremov *et al*[5] have speculated that net polarization of hadronic jets may be observable via the triple scalar product Ω constructed from the momenta of three fast particles in each jet. For each jet a triple vector product, Ω, may be defined which might contain information on the longitudinal parton polarization:

$$\Omega = \frac{\vec{t} \cdot (\vec{k_1} \times \vec{k_2})}{|\vec{k_1} \times \vec{k_2}|}, \tag{9}$$

where $\vec{t}$ is a unit vector defining the jet axis and $\vec{k_1}, \vec{k_2}$ are the momenta of two particles in the jet, chosen by some prescription, for example, the two fastest particles. The sign of the asymmetry

$$H = \frac{N_{\Omega<0} - N_{\Omega>0}}{N_{\Omega<0} + N_{\Omega>0}}, \tag{10}$$

is expected to be different for left- and right-handed jets and is called the jet handedness. It can be asserted that $H = \alpha \mathcal{P}_q$, 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[33] 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. 33. Using equation (9), where $\vec{t}$ is the jet axis direction, and $\vec{k_1}$ and $\vec{k_2}$ are the momentum of the positive- and negative-charged particles, respectively, we measure the asymmetry to be:

$$H^{ch} \quad = \quad 2.4 \pm 1.1\% \quad \text{(PRELIMINARY)}, \tag{11}$$

which provides an estimate of the upper limit of the analyzing power of this handedness method of $\alpha^{ch} < 11\%$ at 95% confidence level. We have tested this method for intrinsic bias by performing the same analysis without charge ordering the fastest two particles, and using the Monte Carlo, where no effects from original parton spin are expected. In both cases, the measured handedness is consistent with zero, showing no intrinsic bias.

Using the forward-backward asymmetry provided by the SLC to select quark and antiquark events, we then defined Ω by considering the three fastest particles in each jet, taking the pair with the highest invariant mass and assigning k_1 as the faster particle irrespective of its charge. The handedness was then calculated separately for forward and backward jets in events produced with left- and right-handed electrons. The results are shown in Table 1.

p_e (%)	-62	$+62$
H^{pol}_{meas} forward	-2.1 ± 2.4	$+0.9 \pm 2.6$
H^{pol}_{meas} backward	-1.7 ± 2.4	-3.1 ± 2.7

Table 1: Measured handedness (%) in forward and backward jets in $Z^0 \to q\bar{q}$ events produced with electrons of polarization p_e. All results are preliminary.

With the present statistics, no evidence for a nonzero handedness is observed. We have derived the analyzing power of the polarized method, α^{pol}, where:

$$H^{pol}_{meas}(p_e) \quad = \quad \alpha^{pol}\, H^{pol}(p_e) \tag{12}$$

by combining the forward and backward results, correcting A_{FB} for the $|\cos\theta_T| < 0.71$ cut, and averaging the left- and right-handed electron polarization results and obtain:

$$\alpha^{pol} \quad = \quad 4.9 \pm 5.1(\text{stat.})\,\%, \quad \text{(PRELIMINARY)}, \tag{13}$$

which corresponds to an upper limit, at 95% confidence level, of $\alpha^{pol} < 15\%$.

8 Conclusions

The SLD has presented a number of tests of Quantum Chromodynamics. First, we have measured the strong coupling, $\alpha_s(M_Z^2) = 0.118 \pm 0.002$ (stat.) ± 0.003 (syst.) $\pm$ 0.010 (theory) which agrees with other measurements of α_s, as well as predictions of perturbative QCD. We have made a test of the flavor independence of α_s and made preliminary measurements of $\alpha_s(b)/\alpha_s(udsc) = 1.02 \pm 0.08$ (stat.) $\pm$

0.04 (syst.) and $\alpha_s(uds)/\alpha_s(bc) = 0.98 \pm 0.08$ (stat.) $\pm$ 0.02 (syst.). We have made a preliminary measurement of the difference in mean charged particle multiplicity between $e^+e^- \rightarrow b\bar{b}$ and $e^+e^- \rightarrow u\bar{u}$, $d\bar{d}$, $s\bar{s}$ events to be $\Delta n_b = 3.8 \pm 0.6$ (stat.) $\pm$ 0.3 (syst.) which is in agreement with the expectations of perturbative QCD and supports the notion that QCD remains asymptotically free down to the scale $Q^2 \simeq M_b^2$. Finally, we have searched for evidence of parton polarization in hadronic Z^0 decays using the jet handedness technique. We found no evidence, within statistical errors, of a nonzero handedness with our method. We set preliminary upper limits on the analyzing power of $\alpha^{ch} < 11\%$ and $\alpha^{pol} < 14\%$ for the charged and polarized methods, respectively.

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