SLAC-PUB-95-7083
November 1995

QCD TESTS IN ELECTRON-POSITRON SCATTERING

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Recent results on QCD tests at the Z^0 resonance are described. Measurements of Color factor ratios, and studies of final state photon radiation are performed by the LEP experiments. QCD tests using a longitudinally polarized beam are reported by the SLD experiment.

1 Color Factor Measurements

The dynamics of a gauge theory are completely defined by the commutation relations between its group generators. Combinatoric factors C_F, C_A, and T_F, called *color factors*, appear as characteristic constants of the gauge group. In perturbative calculations, C_F, C_A, and T_F determine the coupling strengths of gluon radiation from quarks, of the triple-gluon vertex, and of gluon splitting into a quark-antiquark pair, respectively. Measurements of the ratios between the color factors, C_A/C_F and T_F/C_F have been performed by LEP experiments using four-jet events.[1]. DELPHI, L3 and OPAL have reported new measurements.

Jet energy ordering is typically used to separate jets arising from primary and secondary partons. However, in only 42% of the events do the two highest-energy jets come from the primary quarks, resulting in low analyzing power and large systematic errors. DELPHI used lifetime and semileptonic tags to select two jets containing primary b-quarks.. To improve jet energy resolution, OPAL used only jet angles and solved the four-body kinematics of massless partons to reconstruct jet energies. To improve jet angular resolution, L3 used three different preclustering schemes based on the Durham and LUCLUS algorithms, and studied the dependence on jet resolution parameter using four different values of y_{cut} with the JADE algorithm

Fig. 1 shows the measured values of color factor ratios with 68% confidence-level contours and Table 1 summarizes the results. The measured values are in agreement with SU(3) expectations of $C_A/C_F = 9/4$ and $T_F/C_F = 3/8$. However, L3 observed an unexpected variation of C_A/C_F with y_{cut} which is larger than the estimated systematic errors.

OPAL reported evidence for the production of five-jet events, and measured the event rate, corrected for hadronization and detector effects, to be $R_5(y_c = 0.01) = (4.0 \pm 0.2 \pm 1.0)\%$. After examining 120 angular correlations between the five jets, five types of correlations were used to determine the color factor ratios C_A/C_F and $(C_A/C_F)^2$ at $\mathcal{O}(\alpha_s^3)$ for the first time.

Table 1: Color Factor Ratios

	C_A/C_F	T_F/C_F
DELPHI	$2.44 \pm 0.34 \pm 0.11$	$0.30 \pm 0.13 \pm 0.05$
L3	$1.85 \pm 0.12 \pm 0.36$	$0.28 \pm 0.05 \pm 0.13$
OPAL	$2.11 \pm 0.16 \pm 0.28$	$0.40 \pm 0.11 \pm 0.14$

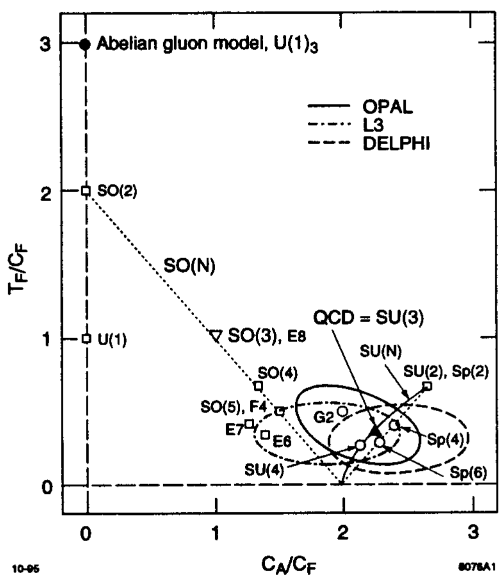

Figure 1: Measured values of C_A/C_F and T_F/C_F with 68% CL contour and expectations from various gauge theories.

2 Direct Photon Production

QCD shower models are very successful in simulating hadronic Z^0 decays, and they are also able to describe the general event shapes of events containing final state photon. However, it has been found that the predictions of the absolute cross section differ significantly among the different models[2].

Recently, matrix element calculations at $\mathcal{O}(\alpha\alpha_s)$ have been performed[3]. OPAL and DELPHI have compared the event properties of final state photon events with the matrix element calculations as implemented in the EEPRAD and GNJETS models.

The first order strong coupling used to describe the

Work Supported by the U.S. Department of Energy under Contract DE-AC03-76F00515

Presented at the International Europhysics Conference on High-Energy Physics (HEP '95), Brussels, Belgium, July 27-August 2, 1995

jet multiplicity was $\alpha_s^{(1)} = 0.186 \pm 0.020$ (DELPHI), and 0.18 ± 0.03 (OPAL). OPAL found that GNJETS describes the relative jet rate over the full range of the y_{cut} values between 0.02 and 0.2, while EEPRAD underestimates the relative 1-jet rate and correspondingly overestimates the relative 2-jet rate for $y_{cut} \geq 0.1$. Fig. 2 shows the relative jet rates compared to GNJETS by OPAL.

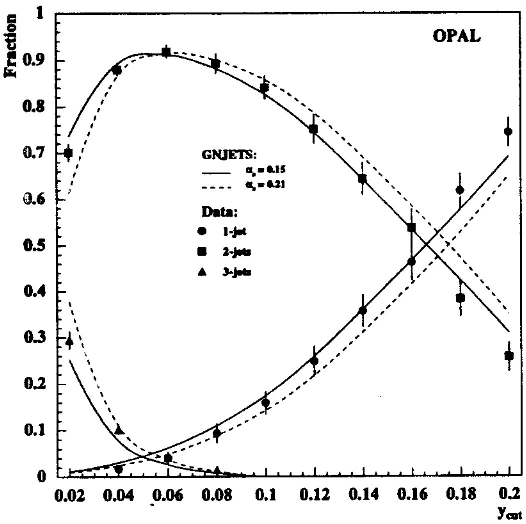

Figure 2: Relative jet rates compared to GNJETS

3 QCD Tests with Polarization

Since 1992 SLC has been running with a longitudinally polarized electron beam, and SLD has collected approximately 50,000 hadronic Z^0 decays in 1993 and 100,000 in 1994/5 with average beam polarizations of 63% and 77%, respectively. In the process $e^+e^- \to Z^0 \to q\bar{q}$, the forward-backward asymmetry A_{FB}, quark polarization P_q, and Z^0 polarization P_{Z^0} are greatly enhanced by the longitudinal beam polarization as shown in Table 2, and SLD has performed a variety of QCD tests exploiting these features.

Table 2: Expected Asymmetry and Polarization

	$P_{e^-} = -77\%$	$P_{e^-} = +77\%$
A_{FB} (u-type)	+0.42	−0.35
A_{FB} (d-type)	+0.58	−0.49
P_q at $\cos\theta = \pm 1$	∓ 0.83	± 0.70

3.1 Observation of leading particle effect

The large forward-backward quark production asymmetry can be used to study hadron production in quark and antiquark initiated jets separately. Each event was divided into two hemispheres by the plane perpendicular to the thrust axis $\vec{t}$, and tracks with $\vec{p} \cdot \vec{t} > 0$ were assumed to have come from a jet with polar angle $\theta_h = \cos^{-1}(t_z/|t|)$, where t_z is the component of the thrust axis along the electron beam direction. Hemispheres with $\cos\theta_h > 0.2$ produced with left-handed beam and those with $\cos\theta_h < -0.2$ produced with right-handed beam were tagged as quark jets. Hemispheres opposite quark-tagged jets were tagged as antiquark jets. The Standard Model at tree level predicts the purities of the quark- and antiquark-tagged samples to be 70%. A sample enriched in light quark (uds) events was selected using impact parameters of charged tracks. $\Lambda/\bar{\Lambda}$ were reconstructed by standard method, and protons and antiprotons were identified by the SLD Cherenkov Ring Imaging Detector (CRID).

Fig. 3 shows the differences between the baryon and antibaryon momentum spectra in quark-tagged jets normalized by their averages. While baryon and antibaryon productions are equal at low momentum, there is an excess of baryon production above about 12 GeV/c, providing direct evidence that faster baryons are more likely to contain the initial quark.

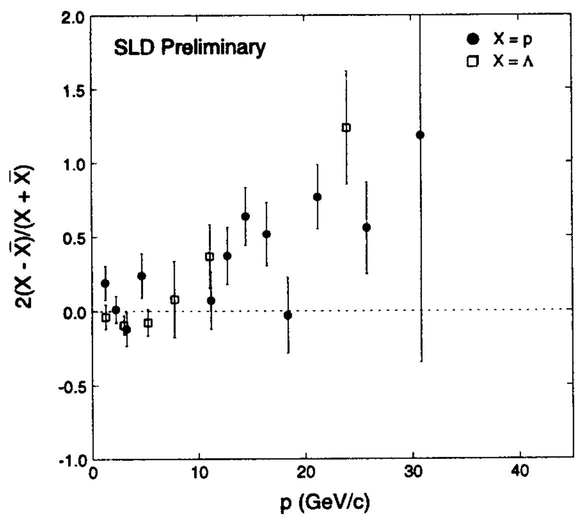

Figure 3: The difference between p and $\bar{p}$ (circles) and Λ^0 and $\bar{\Lambda^0}$ (squares) production spectra in quark-tagged jets.

3.2 Jet handedness

The transport of parton polarization in strong interactions is of fundamental interest, and the large quark polarization produced with the polarized beam is an ideal tool to study the spin transport. The results of the first search for jet handedness were reported in Ref. 4 based on the sample collected in 1993. Preliminary improved limits are presented based on the additional sample collected in 1994/5.

The simplest observable with the same transformation properties under parity inversion as spin has the form $\Omega \equiv \vec{t} \cdot (\vec{k}_1 \times \vec{k}_2)$, where $\vec{t}$ is a unit vector along the jet axis, corresponding to the spin direction of a longitudinally polarized parton, and $\vec{k}_1$ and $\vec{k}_2$ are the momenta of two particles in the jet chosen by some charge-independent prescription, such as $|\vec{k}_1| > |\vec{k}_2|$ [5]. A jet may be defined as left- or right-handed if Ω is negative or positive respectively, and the jet handedness H is defined as the asymmetry in the number of left- and right-handed jets: $H \equiv (N_{\Omega<0} - N_{\Omega>0})/(N_{\Omega<0} + N_{\Omega>0})$. Using the expected parton polarization P_q, the analyzing power α of the method is defined by $H = \alpha P_q$.

The observed H was consistent with zero, and the 95% upper limit of the analyzing power was determined to be $|\alpha| < 0.033$.

3.3 T-odd Triple Product

For polarized Z^0 decays to three hadronic jets one can define the triple product, $\vec{S_Z} \cdot (\vec{k_1} \times \vec{k_2})$, which correlates the Z^0 boson polarization vector $\vec{S_Z}$ with the normal to the three-jet plane defined by $\vec{k_1}$ and $\vec{k_2}$, the momenta of the highest- and the second-highest energy jets, respectively. The triple product is even under C and P reversals, and odd under T_N, where T_N reverses momenta and spin vectors without exchanging initial and final states. Since T_N is not a true time-reversal operation, a non-zero value does not signal CPT violation and is possible in a theory that respects CPT invariance.

The differential cross section for $e^+e^- \to q\bar{q}g$ for a longitudinally polarized electron beam and massless quarks may be written [6,8]

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\omega} = \frac{9}{16}[(1 - \frac{1}{3}\cos^2\omega) + \beta P_Z \cos\omega], \quad (1)$$

where ω is the polar angle of the vector normal to the jet plane, $\vec{k_1} \times \vec{k_2}$, w.r.t. the electron-beam direction. With $|\beta P_Z|$ representing the magnitude, the second term is proportional to the triple product, and appears as a forward-backward asymmetry of the jet-plane normal relative to the Z^0 polarization axis.

Recently Brandenburg, Dixon, and Shadmi have investigated Standard Model T_N-odd contributions at the Z^0 resonance[8]. The triple product vanishes identically at tree level, but non-zero contributions arise from higher-order processes: QCD rescattering of massive quarks[6], QCD triangle of massive quarks[7], and electroweak rescattering via W and Z exchange loops. Due to various cancellations, these contributions are found to be very small at the Z^0 resonance and to yield values of the correlation parameter $|\beta| < 10^{-5}$. Because of this background-free situation, measurement of the cross section (1) is sensitive to physics processes beyond the Standard Model that give $\beta \neq 0$.

Fig. 4 shows the corrected $\cos\omega$ distribution separately for left- and right-handed beam events in the 1994/5 data sample. A T_N-odd contribution would appear as a forward-backward asymmetry, of opposite sign between the left- and right-handed events. No asymmetry is apparent. A maximum-likelihood fit of Eq. 1 to the $\cos\omega$ distributions from the 1993 and 1994/5 samples yielded $\beta = 0.008 \pm 0.015$. The T_N-odd contribution is consistent with zero within the statistical error and the 95% C.L. limits are calculated to be $-0.022 < \beta < 0.039$.

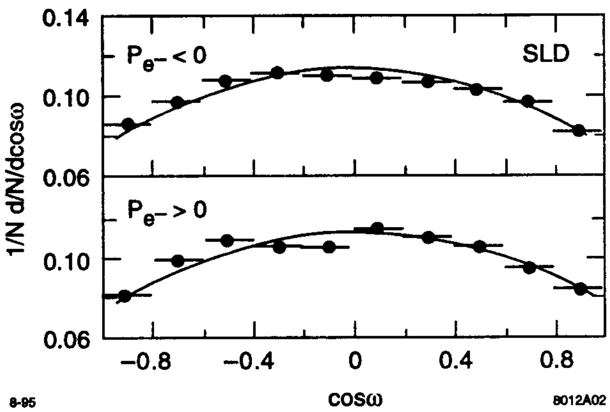

Figure 4: Polar-angle distribution of the jet-plane normal with respect to the electron-beam direction with (a) left-handed and (b) right-handed electron beam. The solid curve is the best fit to the combined data samples.

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