Measurement of the Charged Multiplicity of $Z^0 \rightarrow b\bar{b}$ Events

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Using an impact parameter tag to select an enriched sample of $Z^0 \to b\bar{b}$ events, we have measured the difference between the average charged multiplicity of $Z^0 \to b\bar{b}$ and $Z^0 \to$ hadrons to be $\bar{n}_b - \bar{n}_{\rm had} = 2.24 \pm 0.30({\rm stat}) \pm 0.33({\rm syst})$ tracks per event. From this, we have derived $\bar{n}_b - \bar{n}_{uds} = 3.31 \pm 0.41 \pm 0.79$. Comparing this measurement with those at lower center-of-mass energies, we find no evidence that $\bar{n}_b - \bar{n}_{uds}$ depends on energy. This result is in agreement with a precise prediction of perturbative QCD, and supports the notion that QCD remains asymptotically free down to the scale M_b^2.

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Heavy quark systems are a particularly good laboratory for detailed studies of the strong interaction and tests of the theory of quantum chromodynamics (QCD). The large quark mass $M_Q \gg \Lambda_{\rm QCD}$, where $\Lambda_{\rm QCD}$ is the QCD interaction scale, provides a natural cutoff in the parton shower evolution, which keeps the relevant space-time region compact enough to avoid the nonperturbative domain of the strong interaction. Recently it has been recognized that, within the context of perturbative QCD, this cutoff allows a stringent constraint to be placed on the difference in light hadron production between e^+e^- annihilation into heavy and light quarks [1]. In particular, it is expected that to $O([\alpha_s(W^2)]^{1/2}(M_Q^2/W^2))$ ($\simeq 0.1$ track at $W = M_Z$), the difference between the total mean charged multiplicity in light quark ($q = u,d,s$) events and the mean charged multiplicity of radiated "nonleading" hadrons in heavy quark ($Q = b,c$) events, excluding the decay products of the "leading" long-lived heavy hadrons, should be *independent* of center-of-mass-system (c.m.s.) energy W. This is a striking prediction, in that the total multiplicity is known to grow faster than logarithmically with W. Furthermore, to $O(\alpha_s(M_Q^2) \times \bar{n}_{uds}(M_Q))$ ($\simeq 1.2$ tracks for $Q = b$), this multiplicity difference should be equal to $\bar{n}_{uds}(\sqrt{e}M_Q)$, the mean charged multiplicity for e^+e^- annihilation to light quarks at the reduced c.m.s. energy $\sqrt{e}M_Q$, where $\ln e = 1$. A test of this hypothesis provides the opportunity to verify an accurate prediction of perturbative QCD, and to probe the validity of perturbative calculations down to the scale M_Q^2. In addition, this hypothesis is in direct contradiction with the hypothesis of flavor-independent fragmentation [2,3], which suggests that the nonleading multiplicity associated with heavy quark production at a given c.m.s energy W should be equal to the total light quark (u,d,s) event multiplicity at the reduced c.m.s. energy $(1 - \langle x_Q \rangle)W$, where $x_Q = 2E_Q/W$ is the heavy hadron energy fraction after fragmentation.

Recent tests of these hypotheses [1,4] made use of a measurement of the mean charged multiplicity of $Z^0 \to b\bar{b}$ events from the statistically limited data sample of the 1990 run of the Mark II detector at the SLAC Linear Collider (SLC), and were not able to demonstrate a clear preference for either. Here, we present a more accurate measurement based on the 1992 run of the SLC Large Detector (SLD) experiment, during which a total of 420 nb^{-1} of electron-positron annihilation data were recorded at a mean c.m.s. energy of 91.55 GeV.

The SLD is a multipurpose particle detector and is described elsewhere [5]. Charged particles are tracked and momentum analyzed in the central drift chamber (CDC), which consists of 80 layers of axial or stereo sense wires in a uniform axial magnetic field of 0.6 T. In addition, a silicon vertex detector (VXD) [6] provides an accurate measure of particle trajectories close to the beam axis. With the exception of the hadronic event trigger, this analysis relied exclusively upon the information from these two tracking systems.

While the multiplicity measurement relied primarily on information from the CDC, the more accurate impact parameter measurement provided by the addition of the VXD information to the CDC tracks was used to select a sample enriched in $Z^0 \to b\bar{b}$ events. All impact parameters used in this analysis were for tracks projected into the plane perpendicular to the beam axis, and were measured with respect to an average primary vertex (PV) derived from fits to events close in time to the event under study. The impact parameter d was derived by applying a sign to the distance of closest approach such that d is positive when the vector from the PV to the point at which the track intersects the thrust axis [7] makes an acute angle with respect to the track direction. Including the uncertainty on the average PV, the measured impact parameter uncertainty σ_d for the overall tracking system approaches 15 μm for high momentum tracks, and is 80 μm at $p_\perp\sqrt{\sin\theta}=1$ GeV/c, where $p_\perp$ is the momentum transverse to the beam axis, and θ the angle relative to the beam axis.

Events were classified as hadronic decays of the Z^0 provided that they contained at least 7 tracks which intersected a cylinder of radius $r_0=5$ cm and half length $z_0=10$ cm surrounding the average PV, a visible charged energy of least 20 GeV, and a thrust axis satisfying $|\cos\theta_{\rm thrust}|<0.7$. The resulting sample contained 5449 events. Backgrounds in this sample were estimated to be $\sim 0.1\%$.

For the purpose of multiplicity counting, a loose set of requirements was placed on reconstructed tracks, while stricter requirements were placed on tracks used to measure impact parameters. "Multiplicity quality" tracks were required to (i) have $p_\perp \geq 0.12$ GeV/c; (ii) have $|\cos\theta| \leq 0.8$; and (iii) intersect a cylinder of $(r_0,z_0)=(1.5,5.0)$ cm. "Impact parameter quality" tracks were required to (i) have $|\cos\theta| \leq 0.8$; (ii) intersect a cylinder of $(r_0,z_0)=(0.3,1.5)$ cm; (iii) have at least one VXD hit; (iv) have $\sigma_d < 250$ μm; and (v) have $\chi^2/N_{\rm DF}$ for the CDC-only and combined CDC-VXD fits of less than 5.0 and 10.0, respectively.

A $Z^0 \to b\bar{b}$ enriched sample was selected by dividing each event into two hemispheres separated by the plane perpendicular to the thrust axis, and requiring two or more impact parameter quality tracks in one hemisphere with normalized impact parameter $d/\sigma_d > 3.0$ [8]. Restricting the tag to tracks from a single hemisphere allowed potential tagging bias to be reduced by measuring the multiplicity in the hemisphere opposite to the tag. Monte Carlo (MC) studies indicate that this tag is 50% efficient at identifying hemispheres containing B hadrons in selected hadronic events, while providing an enriched sample of 72% purity. The tag selected 1829 hemispheres.

In determining the total charged $Z^0 \to b\bar{b}$ multiplicty $\bar{n}_b$, we minimized systematic errors by measuring $\delta\bar{n}_b \equiv \bar{n}_b - \bar{n}_{\rm had}$, and then adding back in the total hadronic charged multiplicity $\bar{n}_{\rm had}$, which has been accurately determined by other experiments [9]. In terms of the *uncorrected* mean reconstructed multiplicites $\bar{m}_h$ ($\bar{m}_t$) of the total hadronic (hemisphere opposite tag) samples [4],

$$\delta\bar{n}_b = (1-R_b)(\bar{n}_{dk}+\bar{n}_{nl}-\bar{n}_{udsc}),$$

where $\bar{n}_{nl}$ and $\bar{n}_{udsc}$ satisfy

$$\bar{m}_h = C_{h,udsc}(1-P_h)\bar{n}_{udsc} + C_{h,dk}P_h\bar{n}_{dk} + C_{h,nl}P_h\bar{n}_{nl},$$

$$2\bar{m}_t = C_{t,udsc}(1-P_t)\bar{n}_{udsc} + C_{t,dk}P_t\bar{n}_{dk} + C_{t,nl}P_t\bar{n}_{nl},$$

and where P_h and P_t are the fraction of $Z^0 \to b\bar{b}$ events in the hadronic and tagged samples, determined by MC studies to be 0.223 and 0.724, respectively. We have used the standard model value

$$R_b = \Gamma(Z^0 \to b\bar{b})/\Gamma(Z^0 \to \text{hadrons}) = 0.217$$

[10]. We have separated the $Z^0 \to b\bar{b}$ multiplicity into two components, one associated with the decay of the B hadrons (dk), and one associated with the remaining nonleading system (nl), in order to take advantage of measurements from the Υ_{4S} which constrain both the multiplicity and spectrum of B hadron decay products [11,12]. Here $\bar{n}_{dk}=10.88\pm0.22$ is twice the B hadron decay multiplicity from the Υ_{4S} [11], with an additional uncertainty of ± 0.10 tracks included to account for the uncertainty in the production fractions and decay multiplicities of the B_s and B baryons. The constants $C_{i,j}$ account for the effects of detector acceptance and inefficiencies, and biases introduced by the event and tagged sample selection criteria. The $C_{i,j}$ were evaluated, using a MC simulation of the detector, as the ratio of the number of multiplicity quality tracks to generated charged multiplicity tracks for the six subsamples. We have included in the generated multiplicity any charged track which is prompt, or is the decay product of a particle with mean lifetime less than 3×10^{-10} s.

Because of the exclusion of tracks with very low momentum of large $|\cos\theta|$, the constants $C_{i,j}$ are somewhat dependent on the model used to generate MC events; we have used JETSET 6.3 [13] with parameter values tuned to hadronic e^+e^- annihilation data [14]. The resulting values for the $C_{i,j}$ were 0.855, 0.905, and 0.810 for $C_{h,udsc}$, $C_{h,dk}$, and $C_{h,nl}$, and 0.870, 0.904, and 0.818 for $C_{t,udsc}$, $C_{t,dk}$, and $C_{t,nl}$, respectively.

The uncorrected mean charge multiplicity for all hadronic events was found to be $\bar{m}_h = 17.29\pm0.07$ tracks, while the mean charged multiplicity opposite tagged hemispheres was found to be $\bar{m}_t = 9.28\pm0.09$ tracks. Combining these values with the $C_{i,j}$ via the above relations yields $\delta\bar{n}_b = 1.94\pm0.30$(stat) tracks.

We have investigated a number of systematic effects which may bias the measured value of $\delta\bar{n}_b$. Dividing $\bar{m}_h$ by the overall reconstruction constant $C_{h,udscb}=0.855$ provides a measurement of the total hadronic multiplicity $\bar{n}_{\rm had}=20.21\pm0.08$(stat). This value is lower than the world average 20.95 ± 0.20 [9], indicating that the detector simulation overestimates the mean SLD tracking efficiency by $\sim 3.5\%$. We account for this by reducing all reconstruction constants $C_{i,j}$ by this amount, leading to a correction of $+0.10 \pm 0.10$ tracks in $\delta \bar{n}_b$. We have conservatively set the systematic error in the correction to be equal to the size of the correction itself.

After correcting for overall tracking efficiency, a comparison of the $p_\perp$ distribution between data and MC shows good agreement for the untagged sample, but an excess of $\sim 15\%$ for data tracks opposite tagged hemispheres with $p_\perp$ between 0.12 and 0.50 GeV/c, accounting for $\sim 3\%$ of all reconstructed tracks in this sample. Since there are currently no empirical constraints on the $p_\perp$ distribution of nonleading tracks in $Z^0 \to b\bar{b}$ events, we have assumed that this excess is due to improper modeling of the nonleading tracks by the JETSET MC, which to this point has been tuned only to the global features of inclusive $Z^0 \to$ hadrons data. We compensate for this discrepancy by applying a further correction to $\delta \bar{n}_b$ of $+0.20 \pm 0.20$ tracks, where again we conservatively assign an uncertainty equal in magnitude to the correction. In addition, we have studied the behavior of $\delta \bar{n}_b$ when numerous other experimental parameters, such as tracking and event selection requirements, were varied over wide ranges. As a result of these studies, we assign an additional systematic uncertainty of ± 0.15 tracks due to the uncertainty in charged-particle spectra modeling.

We have compared the fraction of tagged hemispheres $f_t^{\text{data}} = 1829/10898 = 0.168 \pm 0.004$ to the MC expectation $f_t^{\text{MC}} = 0.157$, assuming the world average value of $R_b = 0.220 \pm 0.003$ [15]. 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 $\delta \bar{n}_b$ is 0.21 tracks. Since impact parameter reconstruction errors tend to produce correlated changes in the $Z \to udsc$ and $Z^0 \to b\bar{b}$ tagging efficiencies, the true uncertainty is somewhat less than this. From MC studies of tracking errors which produce the observed difference in f_t, we estimate the systematic error due to the tagged sample purity to be ± 0.15 tracks.

An additional systematic error of ± 0.12 tracks arises from limited MC statistics. Combining these uncertainties in quadrature, and including the two corrections discussed above, we find

$$\delta \bar{n}_b = 2.24 \pm 0.30(\text{stat}) \pm 0.33(\text{syst}) \text{ tracks}.$$

The effects of initial state radiation, and the ~ 0.2 GeV difference between the mean c.m.s. energy of 91.55 GeV and the Z^0 peak, are small, and no correction has been made. Adding back in the world-average total hadronic multiplicity at the Z^0 peak $\bar{n}_{\text{had}} = 20.95 \pm 0.20$ [9] then yields

$$\bar{n}_b = 23.19 \pm 0.30(\text{stat}) \pm 0.37(\text{syst}) \text{ tracks}.$$

To test the energy independence of the difference between the total multiplicity in light quark events and the nonleading multiplicity in $Z^0 \to b\bar{b}$ events, we make use of lower c.m.s. energy measurements of the $e^+e^- \to b\bar{b}$ multiplicity from the SLAC PEP and DESY PETRA storage rings. Assuming the energy independence of the decay multiplicity of B hadrons produced in e^+e^- annihilation, it is equivalent to test the quantity $\Delta \bar{n}_b \equiv \bar{n}_b - \bar{n}_{uds}$. Results for this quantity for the various lower c.m.s. energy experiments are summarized in Ref. [1]. Applying the procedure presented in Ref. [1] to the SLD measurement to remove the contribution from $Z^0 \to c\bar{c}$, we arrive at the result

$$\Delta \bar{n}_b = 3.31 \pm 0.41(\text{stat}) \pm 0.53(\text{syst}) \pm 0.58(\bar{n}_c) \text{ tracks},$$

where we have constrained $\bar{n}_c$ to lie between $\bar{n}_{uds}$ and $\bar{n}_b$, yielding $\bar{n}_c = 21.9 \pm 2.0$ tracks.

Figure 1 shows $\bar{n}_{\text{had}}$ and $\Delta \bar{n}_b$ as functions of c.m.s. energy. The $\Delta \bar{n}_b$ data, with the additional lever arm provided by the SLD measurement, are seen to be consistent with the hypothesis of energy independence, in marked contrast to the steeply rising total multiplicity data [16]. Because of differing measurement techniques, results for $\Delta \bar{n}_b$ at PEP/PETRA energies are largely uncorrelated with those at the Z^0 peak. A linear fit to the $\Delta \bar{n}_b$ data yields a slope [tracks/ln W (GeV)] of -1.0 ± 1.1, consistent with 0 at 0.9 standard deviation. Also shown is the perturbative QCD expectation for the value of $\Delta \bar{n}_b$. Averaging the SLD result with previous measurements [1], we find that $\Delta \bar{n}_b^{\text{comb}} = 3.83 \pm 0.63$, within 1.1 standard deviations of the perturbative QCD expectation of $5.5 \pm 0.8 \pm 1.2(\text{theory})$ [1].

The hypothesis of flavor-independent fragmentation

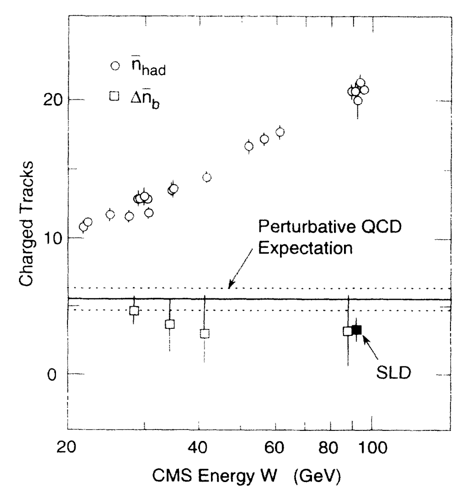

FIG. 1. Energy dependence of the total multiplicity [16] and the multiplicity difference $\Delta \bar{n}_b$ [1,16] between $e^+e^- \to b\bar{b}$ and $e^+e^- \to uds$ events. A linear fit to the energy dependence of $\Delta \bar{n}_b$ yields a slope of $s = -1.0 \pm 1.1$, consistent with the hypothesis of energy independence ($s = 0.0$). The horizontal lines are the expected value and 1σ range for $\Delta \bar{n}_b = \bar{n}_{dk} - \bar{n}_{uds}(\sqrt{e} M_b)$, given by lower-energy total multiplicity data in accordance with perturbative QCD (see text).

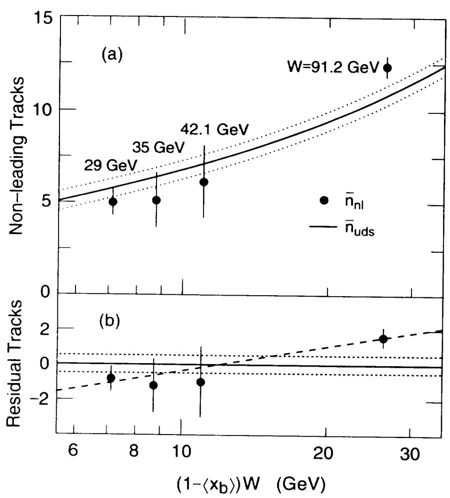

FIG. 2. (a) Nonleading multiplicity $\bar{n}_{nl}=\bar{n}_b-\bar{n}_{dk}$ in $e^+e^-\rightarrow b\bar{b}$ vs nonleading energy $(1-\langle x_b\rangle)W$ [16]. The solid line is a fit [4] to $e^+e^-\rightarrow uds$ multiplicity as a function of W. The error on this fit (dotted lines) is dominated by the uncertainty on the removal of the heavy quark $(Q=c,b)$ contribution to the measured $\bar{n}_{\text{had}}(W)$. (b) Residuals of (a).

[2,3], which provides that $\bar{n}_b(W)-\bar{n}_{dk}(W)=\bar{n}_{uds}([1-\langle x_Q\rangle]W)$, implies that $\Delta\bar{n}_b$ decreases with c.m.s. energy in proportion to $\bar{n}_{uds}(W)$ [1], in contradiction with the perturbative QCD expectation. Figure 2 shows a comparison between nonleading multiplicity $\bar{n}_b(W)-\bar{n}_{dk}(W)$ and $\bar{n}_{uds}([1-\langle x_Q\rangle]W)$, as a function of nonleading energy $[1-\langle x_Q\rangle]W$. When the SLD result is included, a linear fit to the residuals [Fig. 2(b)] yields a slope of $s=1.91\pm0.65$, inconsistent with the hypothesis of identical energy dependence $(s=0.0)$ at the level of 2.9 standard deviations.

In conclusion, we have measured the difference in the mean charged multiplicity between $Z^0\rightarrow b\bar{b}$ and $Z^0\rightarrow$ hadrons to be $\delta\bar{n}_b=2.24\pm0.30(\text{stat})\pm0.33(\text{syst})$ tracks per event, from which we calculate the multiplicity difference between $Z^0\rightarrow b\bar{b}$ and $Z^0\rightarrow uds$ to be $\Delta\bar{n}_b=3.31\pm0.41(\text{stat})\pm0.53(\text{syst})\pm0.58(\bar{n}_c)$ tracks. Comparing our measurement with similar results from lower energy e^+e^- annihilation data, we find no evidence that $\Delta\bar{n}_b$ depends on c.m.s. energy. This energy independence is in agreement with the precise perturbative QCD expectation, and indicates that QCD remains asymptotically free down to the scale M_b^2. Our measured value is in reasonable agreement with the less precise QCD prediction that $\Delta\bar{n}_b=\bar{n}_{dk}-\bar{n}_{uds}(\sqrt{e}M_Q)$. Including our measurement, the c.m.s. energy dependence of the nonleading multiplicity in e^+e^- annihilation to b quarks is inconsistent with that of the hypothesis of flavor-independent fragmentation at the level of 2.9 standard deviations.

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