MEASUREMENT OF $R_b$ AT SLD

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Abstract

We report a new measurement of $R_b = \frac{\Gamma_{Z^0\rightarrow b\bar{b}}}{\Gamma_{Z^0\rightarrow \text{hadrons}}}$ using a double tag technique where the $b$ selection is based on topological reconstruction of the mass of the $B$-decay vertex. The measurement was performed using a sample of 150k hadronic $Z^0$ events collected with the SLD at the SLAC Linear Collider during the years 1993-1995. The method utilizes the 3-D vertexing abilities of the SLD CCD pixel vertex detector and the small stable SLC beams to obtain a high $b$ tagging efficiency of 37% for a purity of 97.2%. The high purity reduces the systematics introduced by charm contamination and correlations with $R_c$. We obtain a result of $R_b = 0.2176 \pm 0.0033^{\text{stat.}} \pm 0.0017^{\text{syst.}} \pm 0.0008^{R_c}$.

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1 Introduction

The fraction $R_b$ of $Z^0 \to b\bar{b}$ events in the hadronic $Z^0$ decays is of special interest in the Standard Model (SM). Since this is a ratio between two hadronic rates, uncertainties from the unknown oblique or QCD corrections mostly cancel. Therefore, given the mass of the top (measured by CDF and D0 [2]) it provides through the $Zbb$ vertex radiative corrections a sensitive environment to detect a signal for physics beyond the SM. The LEP and SLD measurements on variety of $Z^0$ coupling parameters have provided precise confirmations of the SM predictions. Hence the current average value of $R_b$ measurements [1], which is more than 3$\sigma$ higher than the SM expectation, is very valuable window in the electroweak tests of the SM.

Our $b\bar{b}$ event selection utilizes a double tag technique where one attempts to identify separately the two $B$ hadrons in the event. It allows measurement of both the $R_b$ value and the efficiency for identifying a $b$ decay directly from the data. Most recent precise LEP [3] and SLD [4, 5] $R_b$ measurements have exploited the long lifetime of the $B$-hadrons to distinguish between the $b$ and the charm or lighter quark events. The elimination of charm is critical in obtaining precision $R_b$ measurements due to the dominance of charm decay modeling uncertainties in the overall $R_b$ uncertainty. LEP measurements are already systematically limited mainly by the charm contamination. Hence a new $b$ tag technology is required to improve the current level of precision. To increase significantly both the efficiency and the purity of $b\bar{b}$ identification our new measurement uses the CCD pixel vertex detector (VXD) to reconstruct the mass of the secondary vertex. In this paper we will show that using this mass tag we have obtained an $R_b$ measurement with the best total systematic uncertainty of all current $R_b$ measurements, and will, with data from future SLD runs, become the most precise single measurement of $R_b$.

2 SLD Detector

The SLD detector has been described in reference [6], and only components important to this analysis are briefly reviewed here. Charged particle tracking was performed using the Central Drift Chamber (CDC) [7] surrounded by a 0.6 $T$ solenoidal magnetic field. The vertex detector (VXD [8]) is of special importance for this measurement. It consists of 480 charged coupled devices (CCDs) with
2 hits in the angular region of $\cos \theta < 0.74$ and 1 hit within $\cos \theta < 0.8$. Each CCD is an array of $385 \times 578$ square pixels of size $22 \mu m \times 22 \mu m$. The CCDs are arranged in four concentric layers at a radii from 29.5 mm to 41.5 mm from the beam line. A typical tracks produces hits in two or three of these layers. SLC provides SLD with a small and very stable interaction point (IP) ($<\text{rms}>_{xyz} \approx 2.4 \times 0.8 \times 700 \mu m^3$). $\sigma_{IP}^{xy}$ measured with reconstructed tracks from $\sim$30 sequential hadronic $Z^0$ events is $7 \pm 2 \mu m$ and the z position measured on event-by-event basis is $\sigma_{IP}^z = 38 \mu m$. The impact parameter resolution in plane perpendicular to (containing) the beam axis is $\sigma_{r\phi} [\mu m] = 11 \oplus 70/p \sin^{3/2} \theta$ ($\sigma_{rz} [\mu m] = 37 \oplus 70/p \sin^{3/2} \theta$) where $p$ is in GeV/c. The energy deposition in the Liquid Argon Calorimeter (LAC) was used in the event trigger and in the calculation of the event thrust axis.

3 Analysis Method

3.1 Topological Vertexing

SLD has already presented a measurement of $R_b$ using the now standard lifetime double tag methods. The current analysis is performed in a similar manner except the $b$-tag on the track impact parameter to the interaction point is replaced by a $b$-tag using the reconstructed mass of the secondary vertex.

The identification of the vertices is performed using a topological vertexing procedure. It searches for 3-D high track overlapping density location from the single track probability (resolution) function. An event is divided into two hemispheres with the axis defined by the highest momentum jet. The vertex finding for a hemisphere is done using only tracks within the hemisphere, and the measured IP. A secondary (+tertiary) vertex is found in 45% (5%) of the $b$ hemispheres. The seed vertex (SV) is defined as the most significant non-primary vertex. Hence, a SV is identified in 50% of the $b$ hemispheres (and in 15% and 2% of the charm and the light quark hemispheres respectively). The tracks from a $b$ decay chain do not originate from a common vertex and will not necessarily be associated with the SV. All unassociated tracks are checked for consistency with the SV, looking at the point of closest approach with respect to the vertex flight direction.

To obtain the vertex mass, all tracks associated with the SV and consistent
with it are assigned the mass of a pion and used to calculate the invariant vertex mass. The mass distribution in our data compared to Monte Carlo (MC) is shown in Fig. 1a.

![Vertex Mass Diagram](image)

**Figure 1:** Vertex mass distribution (a), and the $P_t$ corrected mass distribution (b). The data is plotted with boxes where MC $b$, $c$, and $uds$ are represented by the open, hatched and cross hatched histograms respectively.

### 3.2 The Mass Tag

The MC reconstructed mass distributions show that a sharp cut-off just above the charm mass exists, beyond which almost only $b$ decays are found (see Fig. 1a). However since we are using charged track information to reconstruct the $B$ mass, only half of the reconstructed $b$ masses are beyond the natural charm edge. One
can still improve the $b$ tagging performance by including additional kinematic information to compensate for the loss of neutral particles energy information. Comparison between the direction of the SV displacement from the primary vertex (PV) and the direction of the sum of momenta of the associated charged tracks results in the missing transverse momentum. Including the transverse momentum $P_t$ as the minimum missing momentum we can define our tagging parameter $\mathcal{M}$ to be:

$$
\mathcal{M} \equiv \sqrt{P_t^2 + M(\text{tracks})^2} + |P_t| \leq M_B
$$

This procedure increases mass for the $b$ hemispheres significantly, especially affects those $B$s with small charged tracks invariant mass, while charm decays close to the full charm mass will gain relatively little. However, the errors in the derivation of either the PV or the SV may cause some low mass charm events or $uds$ events to gain enough $P_t$ to enter to the selected sample. Therefore, in order to prevent fluctuations in the $P_t$ distribution to contaminate our sample the following constraints are added: The contribution that is consistent with coming from the errors on one of the two vertices is subtracted from the missing $P_t$. The new $\mathcal{M}$ is limited to less than twice the original mass derived from charged tracks. The improvement of the tagging performance is demonstrated in Fig. [b].

### 3.3 $R_b$ Measurement

After partitioning events into hemispheres, $R_b$ is measured from $F_s$, the rate at which hemispheres pass the mass tag cut (single tags), and $F_d$, the rate at which both hemispheres in an event pass the mass tag cut (double tags).

$$
F_s = \epsilon_b R_b + \epsilon_c R_c + \epsilon_{uds}(1 - R_b - R_c),
$$

$$
F_d = (\epsilon_b^2 + \lambda_b(\epsilon_b - \epsilon_b^2))R_b + \epsilon_c^2 R_c + \epsilon_{uds}^2 (1 - R_c - R_b).
$$

Estimations for the light quarks and charm tagging rates ($\epsilon_{uds}, \epsilon_c$) and the hemisphere $b$-tagging efficiency correlation ($\lambda_b$) are derived from our Monte Carlo, where for $R_c$ we assume the SM value. Measuring the two tagging rates allows $\epsilon_b$, the hemisphere $b$-tagging efficiency, to be calculated directly from data simultaneously with $R_b$ itself:

$$
R_b = \frac{(F_s - R_c(\epsilon_c - \epsilon_{uds}) - \epsilon_{uds})^2}{F_d - R_c(\epsilon_c - \epsilon_{uds})^2 + \epsilon_{uds}^2 - 2F_s \epsilon_{uds} \lambda_b R_b (\epsilon_b - \epsilon_b^2)},
$$
\[ \epsilon_b = \frac{F_d - R_c \epsilon_c (\epsilon_c - \epsilon_{uds}) - F_s \epsilon_{uds} - \lambda_b R_b (\epsilon_b - \epsilon_b^2)}{F_s - R_c (\epsilon_c - \epsilon_{uds}) - \epsilon_{uds}}, \]

thus eliminating the influence of uncertainties in $b$ decay modeling except in the correlation term $\lambda_b$. The correlation which expresses the difference between the efficiency of tagging the two hemispheres in $b$ event ($\epsilon_b^{\text{double}}$) and $\epsilon_b^2$ is given by:

\[ \lambda_b = \frac{\epsilon_b^{\text{double}} - \epsilon_b^2}{\epsilon_b - \epsilon_b^2}. \quad (4) \]

### 3.4 $b$ Tag Performance

The $b$ hemisphere tagging efficiency and purity as a function of the cut on $M$ are shown in Fig. 2 along with the efficiencies estimated for charm and $uds$ hemispheres. At a mass cut of 2 GeV a $b$-tag efficiency of 37% and a $b$ purity of 97.2% is achieved. The measured $\epsilon_b$ from the data agrees with the MC estimate reasonably well. This far exceeds the performance we previously obtained using the impact parameter double tag ($\epsilon_b^{\text{lifetime}} = 31\%$, $\Pi_b^{\text{lifetime}} = 94\%$) \[5\].

From the single and double hemisphere $b$ tagging efficiencies we obtain the $b$ hemisphere efficiency correlation $\lambda_b = 0.47\%$.

A total of 71000 events passing the standard SLD hadronic events selection (see e.g. \[3\]) were included in this analysis to obtain $R_b = 0.2176 \pm 0.0033_{\text{stat.}}$. The $R_b$ measurement is performed also with different mass cut values and the variation in $R_b$ is found to be consistent with statistics.

### 3.5 Systematic Uncertainties

The systematic uncertainty is a combination of detector related effects such as tracking efficiency and resolution, as well as physics effect while the effect of $R_c$ uncertainty is treated separately. The physics systematic studies are similar to those of previous $R_b$ measurements at LEP and SLD \[3, 4\] and the error is a combination of uncertainties from the estimation of the correlations and the modeling of the charm and $uds$. The curves in Fig. 3 show all the detector, physics and $R_c$ systematic and the statistical uncertainties versus the $M$ cut. It demonstrates how charm systematics dominate for a loose $M$ cut, while after the natural charm mass cut-off the statistical uncertainty is the primary limitation. The contributions to the systematic uncertainty at the optimal cut are
Figure 2: As a function of the $M$ cut the purity of the $b$ sample ($\Pi_b$) and the efficiency for tagging light flavours ($\epsilon_c$, $\epsilon_{uds}$) are shown together with the $b$-tag efficiency ($\epsilon_b$) as measured in the data (black stars) and as estimated from MC (open circles).

summarized in Table [I]. At this cut the combined uncertainty from all systematic sources including detector, physics and $R_c$ is $\delta R_b/R_b = 0.83\%$.

4 Conclusions

The current world average $R_b$ measurement is more than $3\sigma$ higher than the SM expectation value. Previous LEP and SLD measurements were generally systematically limited mainly by the charm systematic uncertainty. High resolution topological vertexing and precision knowledge of the SLD interaction point allow a new high purity $b$-tag to provide a low systematic approach for precision $R_b$ measurement. Analyzing 1993 to 1995 data, SLD has measured a new
preliminary $R_b$ value:

$$R_b = 0.2176 \pm 0.0033_{\text{stat.}} \pm 0.0017_{\text{syst.}} \pm 0.0008_{R_c}$$

This value supersedes our previous $R_b$ measurement. With a new vertex detector and more data SLD is expected to perform a measurement of $R_b$ to a precision of < 1%.
Detector Systematics

| Systematic                  | $\delta R_b/R_b$ | Systematic                  | $\delta R_b/R_b$ |
|-----------------------------|------------------|-----------------------------|------------------|
| Efficiency Corrections      | 0.21%            | Beam Position Tails        | 0.08%            |
| Z Impact Resolutions        | 0.48%            |                             |                  |
| Total Detector Systematics  | 0.53%            |                             |                  |

Physics Systematics

| Systematic                  | $\delta R_b/R_b$ | Systematic                  | $\delta R_b/R_b$ |
|-----------------------------|------------------|-----------------------------|------------------|
| Correlation Systematics     | 0.37%            | Charm Systematics           | 0.36%            |
| Light Quark Systematics     | 0.19%            | $R_c = 0.171 \pm 0.014$     | 0.34%            |
| Total Physics (excluding $R_c$) Systematics | 0.55%            |                             |                  |

Table 1: Summary of contributions to the systematic error at $M_{J/\psi} = 2.0 \text{ GeV}$

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