SLAC-PUB-7481
July 17, 1997

A Measurement of R_b using a Vertex Mass Tag

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To be submitted to Physical Review Letters

Abstract

We report a new measurement of $R_b = \Gamma_{Z^o \to b\bar{b}}/\Gamma_{Z^0 \to hadrons}$ using a double tag technique, where the b hemisphere selection is based on the reconstructed mass of the B hadron decay vertex. The measurement was performed using a sample of 130k hadronic Z^0 events, collected with the SLD at the SLC. The method utilizes the 3-D vertexing abilities of the CCD pixel vertex detector and the small stable SLC beams to obtain a high b-tagging efficiency and purity. We obtain $R_b = 0.2142 \pm 0.0034_{stat.} \pm 0.0015_{syst.} \pm 0.0002_{R_c}$.

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We report a new measurement of R_b the fraction of $Z^0 \to b\bar{b}$ events in the hadronic Z^0 decays, collected with the SLD at SLC using a unique mass tag technique. The ratio R_b, is of special interest as a test of the Standard Model (SM), since it is sensitive to possible new physics effects modifying the $Zb\bar{b}$ vertex radiative corrections. The vertex corrections are isolated because R_b is a ratio between two hadronic rates, hence propagator (oblique) radiative and QCD corrections common to all quark flavors mostly cancel. Recent measurements yielded a world average R_b value 3σ higher than predicted by the SM [1]. Previous measurements [2] selected b events based upon mainly the long B hadron lifetime and were systematicaly limited by contamination due to the exponential tail of the charm lifetime distribution. To avoid this limitation our b-tag exploits the large B mass, since the mass distribution has a very small charm contamination beyond the charm mass cutoff. Taking advantage of SLD's precise 3-D vertexing capability and the small and stable SLC beam spot, we achieve a very efficient and pure b selection. We use a self-calibrating double tag technique [2], which allows one to measure both R_b and the b-tag efficiency, ϵ_b, simultaneously.

This measurement was performed using 130K $e^+e^- \to Z^0 \to q\bar{q}$ events collected during 1993-95. A detailed description of the detector can be found elsewhere [3]. The measurement primarily uses the information from charged particle tracks measured with the CCD pixel vertex detector (VXD) along with the Central Drift Chamber. The event selection and the determination of the thrust axis use the energy measured with the Liquid Argon Calorimeter.

The luminous region of the SLC interaction point (IP) has a size of about $(1.5 \times 0.8 \times 700)$ μm in (x,y,z). We use the average $\langle IP \rangle$ position of sequential hadronic events to determine the primary vertex (PV) in $r\phi$, the plane transverse to the beam direction. The longitudinal position of the PV is determined for each event individually [3]. This results in a PV with uncertainties of 7 μm transverse to the beam axis and 35 μm (52 μm for $b\bar{b}$ events) along it. The measured track impact parameter resolution 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 the track momentum expressed in GeV/c.

The hadronic event selection is based on charged track multiplicity and track visible energy requirements as described in Ref. [3]. The event selection is studied with Monte Carlo (MC) events generated by JETSET 7.4 [4], where the B hadron decays are simulated using a model tuned to current B and D decay data [5]. The thrust axis is used to divide the event into two hemispheres for independent tagging. In order to ensure that the jets (calculated from charged tracks using the JADE algorithm [6] with y_{cut}=0.02) are well contained within the acceptance of the VXD, the thrust is required to be within $|\cos\theta_{thrust}| < 0.71$. In addition we place a requirement that the event contains no more than three jets, to ensure the event hemisphere division is sensible and to reduce the contribution from events containing $g \to b\bar{b}$. A total of 72074 events remain after selection.

Well measured tracks [3] are used to search for secondary vertices (SV). The SV are found by searching for areas of high track overlap density from the individual track resolution functions, in 3-D co-ordinate space [7]. The vertexing is done in each hemisphere separately. The vertices are required to be separated from the PV by at least 1 mm and to contain at least two tracks each with a 3-D impact parameter $\geq 130\mu$m, ensuring they originate from a particle of relatively long lifetime. Secondary vertices are found in 50% of all b hemispheres, in 15% of the charm and $< 1\%$ of the light quark hemispheres [7].

Due to the cascade structure of the B decay, not all the tracks in the decay chain will come from a common vertex, thus the SV is incomplete. In attempt to obtain the invariant mass of the B hadron's charged tracks (M_{ch}) we would like to use all the decay tracks. We then form a full B decay candidate by attaching additional tracks to the SV which are consistent with the hypothesis of originating from the same SV. As demonstrated in Fig. 1(a), this is acomplished by forming a vertex axis, a straight line between PV and SV centroids. The 3-D distance of closest approach, T, and the distance from the PV along the vertex axis to this point, L, are calculated for all tracks not in the SV. Tracks with $T < 1$ mm. and $L/D > 0.25$ (where D is the distance from the PV to the SV) are attached to the SV forming the assembly of tracks for the B decay candidate. The invariant mass (M_{ch}) of the B candidate is obtained assuming each track has the mass of a charged π (Fig. 2(a)). Tagging hemispheres with M_{ch} beyond the charm mass cutoff (> 2 GeV/c^2), results in a b hemisphere tagging efficiency of 28% with a purity of 98%.

We improve the b tagging efficiency by applying a kinematic correction to the calculated M_{ch}. There is typically an acollinear angle between the SV flight path and the total momentum vector, usually due to the lack of information about the neutral particles in the decay. To gain back lost information we correct M_{ch} using the minimum missing momentum (P_t) transverse to the SV flight path that compensates for the acollinearity. To prevent udsc events gain an artificial P_t due to detector resolution effects, we replace the SV flight direction used in the P_t derivation with a vector tangent to the error boundaries of both the PV and the SV that minimizes the added P_t (see Fig. 1(b)). The ability to make this minimal correction is most effective at SLD due to the small and stable beamspot of the SLC and the high resolution vertexing. Given M_{ch} and P_t a lower bound for the mass of the B candidate is $\mathcal{M} = \sqrt{M_{ch}^2 + P_t^2} + |P_t|$, the P_t corrected mass. We further restrict $\mathcal{M}$ to be $\leq 2 \times M_{ch}$ to reduce the contamination from fake vertices in light quark events. As demonstrated in Fig. 2(b) using $\mathcal{M}$ as opposed to M_{ch} at a cut of 2 GeV/c^2 significantly raises our b-tag efficiency resulting in $\epsilon_b = 35.3\%$ while maintaining the same purity.

R_b and ϵ_b are measured by counting the fraction of tagged hemispheres, F_s, and the fraction of events with both hemispheres tagged, F_d:

$$\begin{aligned} R_b &= \frac{(F_s - R_c(\epsilon_c - \epsilon_{uds}) - \epsilon_{uds})^2}{F_d - R_c(\epsilon_c - \epsilon_{uds})^2 + {\epsilon_{uds}}^2 - 2F_s\epsilon_{uds} - \lambda_b R_b(\epsilon_b - {\epsilon_b}^2)}, \\ \epsilon_b &= \frac{F_d - R_c\epsilon_c(\epsilon_c - \epsilon_{uds}) - F_s\epsilon_{uds} - \lambda_b R_b(\epsilon_b - {\epsilon_b}^2)}{F_s - R_c(\epsilon_c - \epsilon_{uds}) - \epsilon_{uds}}. \end{aligned}$$

The only term dependent upon MC B production and decay modeling is the b hemisphere tagging correlation, $\lambda_b = \frac{{\epsilon_b}^{double} - {\epsilon_b}^2}{\epsilon_b - {\epsilon_b}^2} = 0.59\%$, where we have used the MC ϵ_b and ${\epsilon_b}^{double}$ (double tagging efficiency) to estimate λ_b. Estimations for the hemisphere tagging rates of light quarks, $\epsilon_{uds} = 0.06\%$ and charm, $\epsilon_c = 0.69\%$, are also derived from the MC, and we assume $R_c = \frac{\Gamma_{Z^0 \to c\bar{c}}}{\Gamma_{Z^0 \to q\bar{q}}} = 0.171$. For $\mathcal{M} > 2$ GeV/c^2 we measure a value of $R_b = 0.2142 \pm$

$0.0034_{stat.}$ after correcting by +0.0003 for the $e^+e^- \to \gamma \to b\bar{b}$ contribution as calculated by ZFITTER [8]. The value of $\epsilon_b = 35.3\% \pm 0.6\%$ as determined by the data is in good agreement with the MC estimation of 35.5%. As a cross check we repeated the measurement using different $\mathcal{M}$ cuts, and the measured R_b results are consistent for values of $0 < \mathcal{M}_{cut} < 3$ GeV/c^2 (see Fig. 3(a)).

The systematic uncertainty, given in detail in Table 1, is a combination of detector related effects and physics uncertainties in the simulation which affect our estimation of ϵ_c, ϵ_{uds} and λ_b. The physics systematic errors are assigned by comparing the nominal MC distributions with an alternative set of distributions which reflect the uncertainties in the world average measurements of the MC physics parameters [9]. The two significant sources of systematic errors from light quark events come from the uncertainties in long lived strange particle production and gluon splitting into heavy quark pairs. The effects of strange particle production are studied by varying the $s\bar{s}$ production probability in jet fragmentation. The $g{\to}b\bar{b}$ and $g{\to}c\bar{c}$ production rates are varied based upon the OPAL $g{\to}c\bar{c}$ measurement [10] and the theoretical prediction for the ratio $g{\to}b\bar{b}/g{\to}c\bar{c}$ [9].

The various charm hadron production rates and fragmentation parameters are varied within the present LEP measurement errors. Charm hadron fragmentation is studied by varying the average scaled energy $\langle x_E \rangle$ in the Peterson fragmentation function [11], as well as by studying the difference between Peterson model, and the Bowler model [12] with the same $\langle x_E \rangle$. Charm decay lifetimes are varied according to the world average measurement errors [13]. The charm decay charged multiplicity and K^0 production rate systematic uncertainties are based on measurements by Mark-III [14]. Charm decays with fewer neutral particles have higher charged mass and are therefore more likely to be tagged. Thus, an additional systematic uncertainty is estimated by varying the rates of charm decays with no π^0's by $\pm 10\%$.

The MC B decay modeling uncertainty enters via the λ_b estimation. It is studied by varying the B lifetime, Λ_b production rate, fragmentation function and the B decay charged multiplicity in a similar manner as for the charm systematic studies. Simulation errors which affect the tagging efficiency are studied by comparing data and MC b-tagging rate angular distributions and a systematic error is assigned to the difference. Hard gluon radiation effects are estimated from $\pm 30\%$ variation of the fraction of MC events where both B hadrons are contained within the same hemisphere and a hard gluon is in the other. Another systematic error is assigned to effects of B hadron momentum correlation between the two hemispheres mostly due to soft gluon radiation and fragmentation effects. This is estimated by comparing the B momentum correlation in HERWIG [15] and JETSET [4] event generators which in turn translate to a b-tagging efficiency correlation, as b-tagging efficiency is approximately proportional to the B momentum.

As a cross check we have performed a decomposition of the efficiency correlation where the goal is to obtain an independent set of components which represent all sources of correlation between the two b hemispheres. The components we have studied and their contributions are: the measurement of PV (-0.02%), the track resolution effect on the IP determination

(+0.04%), the detector non-uniformity via the tagging $\cos\theta$ dependence (+0.49%), the momentum distribution of the B hadrons in both hemispheres (+0.08%) and the effect of hard gluon emission forcing the two b jets into one hemisphere (+0.07%). The estimated λ_b and the sum of components are in a good agreement ((0.59 ± 0.11)% and 0.67% respectively for $\mathcal{M} > 2$ GeV/c^2).

A major source of detector systematic uncertainty is due to the discrepancy in track impact parameter resolution between data and MC, mainly along the beam axis. MC track z impact parameters are smeared with a random Gaussian of 20 μm $/\sin\theta$ width, as well as adjusted for z impact parameter mean position shifts to match the data. The full difference in R_b between the nominal and resolution corrected samples is conservatively taken as the resolution systematic error. The difference between data and MC charged track multiplicity as a function of $\cos\theta$ and momentum is attributed to a tracking efficiency correction. Both the tracking resolution and efficiency corrections require the use of a random number generator. The results with these corrections vary slightly for different random sequences. These fluctuations are included as an additional MC statistical uncertainty. The uncertainty of the primary vertex xy location simulation is estimated from the effect of adding an $\langle$IP$\rangle$ tail of a 100 μm width for 0.5% of the MC events. The MC shows that the ≤ 3 jets requirement in the event selection favors $b\bar{b}$ over other $q\bar{q}$ events which biases our measurement by +0.55%. We verified this bias in the data, by measuring R_b with and without applying the ≤ 3 jet criterion and found that our measured R_b value only changed by 0.0001, which is consistent with statistics, but nevertheless was included as systematic error. Another bias of $+0.26 \pm 0.12$% is introduced by the other event selection criteria, thus the combined bias is $+0.82 \pm 0.13$% which we correct for. The curves in Fig. 3(b) show all the detector, physics and R_c systematic and the statistical uncertainties versus the minimum $\mathcal{M}$ cut.

High resolution 3-D vertexing and precise knowledge of the SLC beam interaction point allow the reconstruction of the vertex mass, resulting in a highly efficient and pure b-tag with small systematic error on the R_b measurement. Analyzing the 1993-95 data, we have measured:

$$R_b = 0.2142 \pm 0.0034_{stat.} \pm 0.0015_{syst.} \pm 0.0002_{R_c}$$

after correcting by +0.0003 for the $e^+e^- \to \gamma \to b\bar{b}$ contribution. This value supersedes our previous R_b measurements [3]. A new high precision measurement has recently been reported by ALEPH [16], which also incorporates mass information to improve a lifetime probability tag. With the new SLD and LEP measurements the gap between the SM prediction of $R_b = 0.2155$ and the world average has narrowed.

We thank the personnel of the SLAC accelerator department and the technical staffs of our collaborating institutions for their outstanding efforts on our behalf. This work was supported by the U.S. Department of Energy and National Science Foundation, the UK Particle Physics and Astronomy Research Council, the Istituto Nazionale di Fisica Nucleare of Italy, the Japan-US Cooperative Research Project on High Energy Physics, and the Korea Science and Engineering Foundation.

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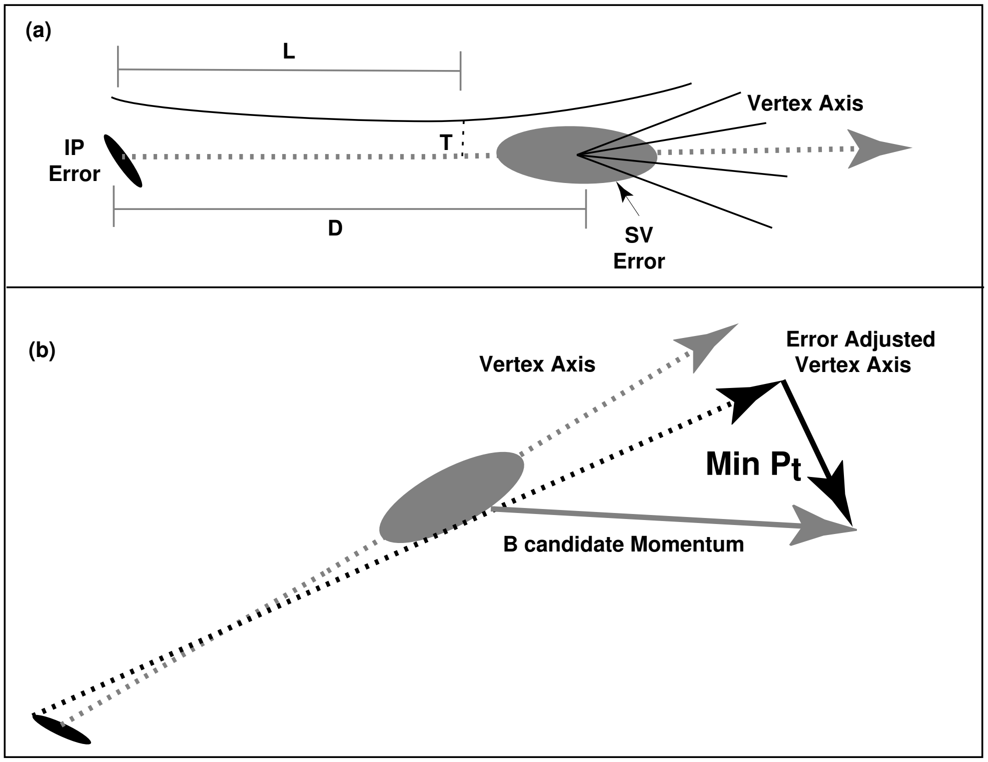

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Figure 1: (a) An illustration of the SV track attachment criteria. (b) Illustration of the min P_t derivation.

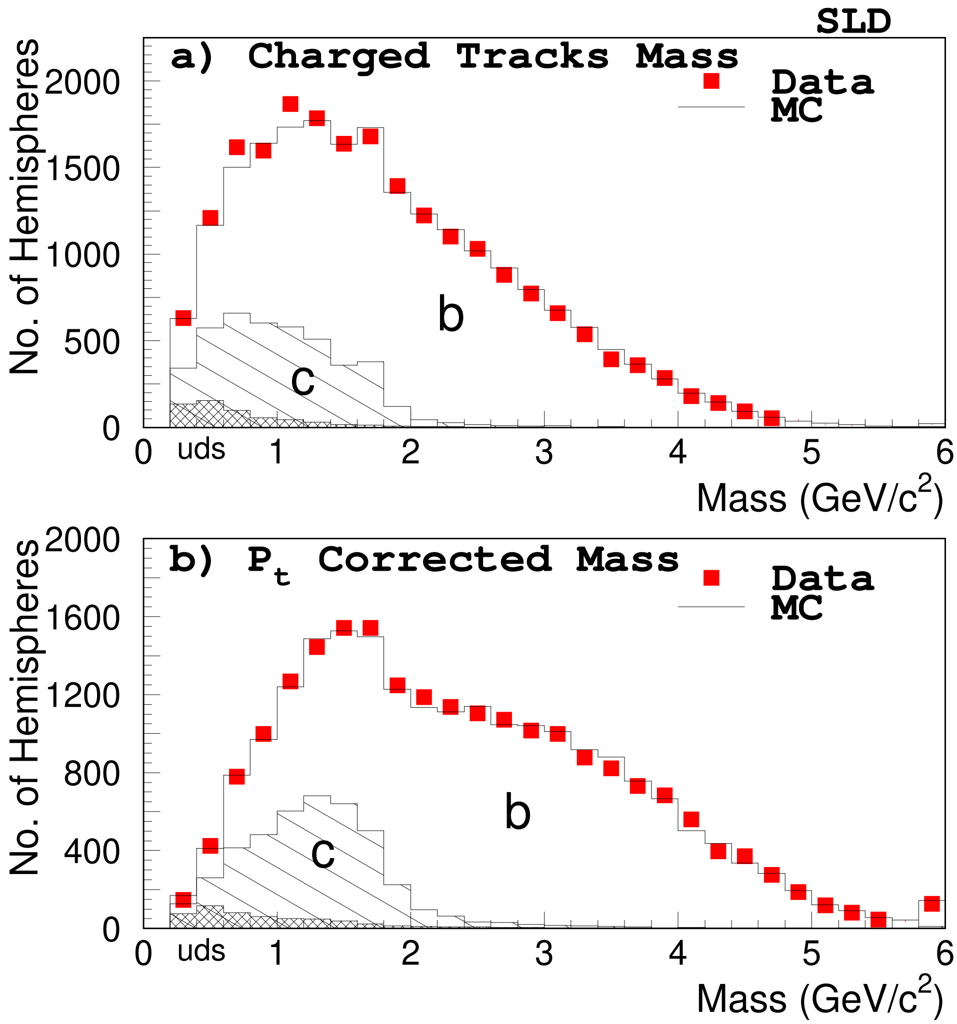

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Figure 2: Distribution of (a) M_{ch} and (b) P_t corrected mass,$\mathcal{M}$ for data (points) and MC breakdown of the b, c and uds contributions (open, hatched and crosshatched histograms respectively).

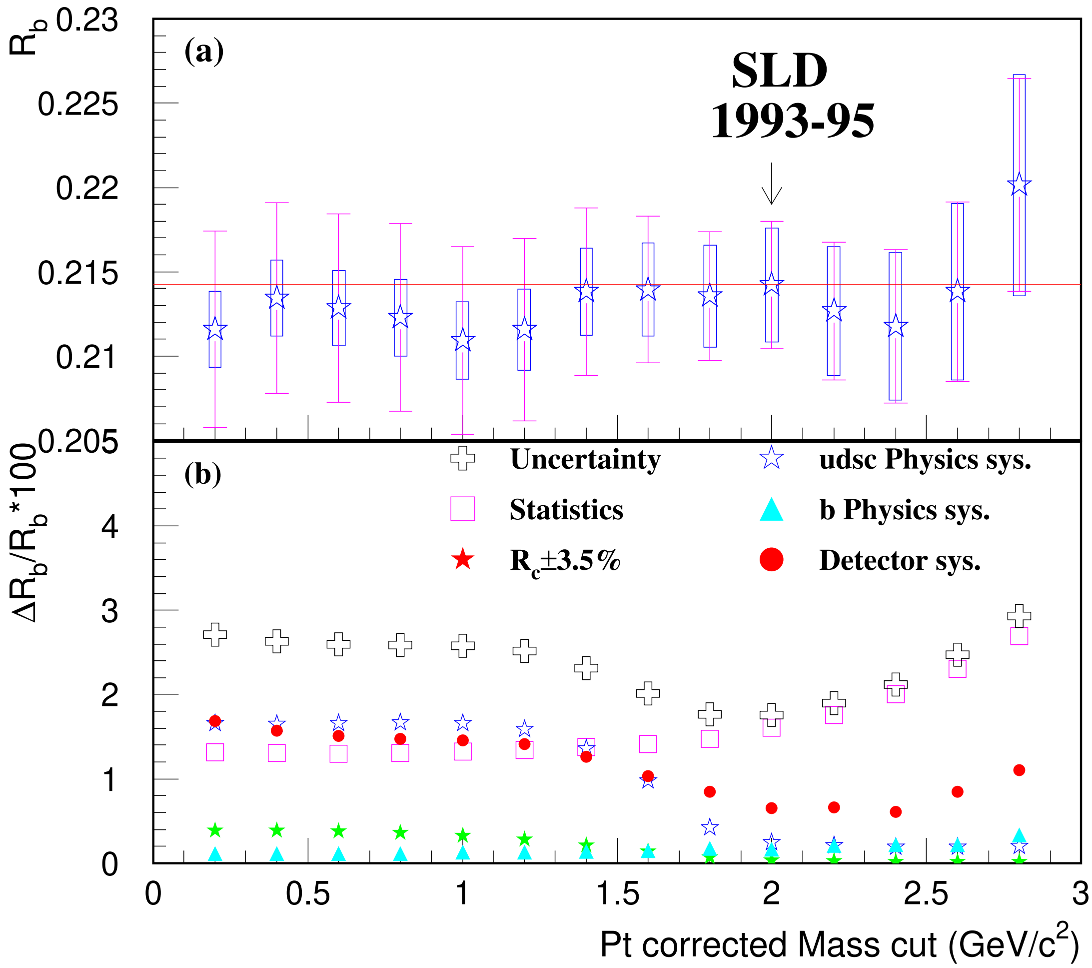

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Figure 3: (a) Variation of R_b with the $\mathcal{M}$ cut. The error bar show the total systematic plus statistical error (given with the boxes). (b) R_b statistical and systematic uncertainties versus $\mathcal{M}$ cut.

Light Quark Systematic (ϵ_{uds})	δR_b
$g \to b\bar{b}$ 0.31±0.11%	-0.00033
$g \to c\bar{c}$ 2.38±0.48%	-0.00004
K^0 production ±10%	-0.00003
Λ production ±10%	-0.00002
Total uds physics systematic	**0.00034**
Charm Systematic (ϵ_c)	δR_b
D^+ production 0.259 ± 0.028	-0.00011
D_s production 0.115 ± 0.037	-0.00005
c-baryon production 0.074 ± 0.029	0.00011
c-frag. $\langle x_E \rangle_D = 0.482 \pm 0.008$	-0.00006
c-frag. function shape	-0.00001
D^0 lifetime 0.415 ± 0.004 ps	-0.00003
D^+ lifetime 1.057 ± 0.015 ps	-0.00001
D_s lifetime 0.467 ± 0.017 ps	-0.00002
Λ_c lifetime 0.200 ± 0.011 ps	-0.00001
D^0 decay $\langle N_{ch} \rangle = 2.54 \pm 0.05$	-0.00006
D^+ decay $\langle N_{ch} \rangle = 2.50 \pm 0.06$	-0.00006
D_s decay $\langle N_{ch} \rangle = 2.65 \pm 0.33$	-0.00009
$D^0 \to K^0$ production 0.401 ± 0.059	+0.00015
$D^+ \to K^0$ production 0.646 ± 0.078	+0.00020
$D_s \to K^0$ production 0.380 ± 0.06	+0.00002
D^0 decay no-π^0 frac. 0.370 ± 0.037	+0.00005
D^+ decay no-π^0 frac. 0.499 ± 0.050	-0.00008
D_s decay no-π^0 frac. 0.352 ± 0.035	<0.00001
Total Charm Physics systematic	**0.00033**
B decay modeling (λ_b)	δR_b
B lifetime ±0.05 ps	0.00004
B decay $\langle N_{ch} \rangle = 5.73 \pm 0.35$	0.00003
b fragmentation	0.00019
Λ_b production fraciton 0.074 ± 0.03	0.00008
Hard gluon radiation	0.00008
B momentum correlation	0.00029
b-tag $\cos\theta$ dependency	0.00001
Total $b\bar{b}$ Physics systematic	**0.00038**
Detector Systematic	δR_b
Tracking resolution	0.00096
Tracking efficiency	0.00040
$\langle IP \rangle_{xy}$ smear	0.00010
MC statistics	0.00091
Event selection bias	0.00028
Total detector and MC	**0.00141**
$R_c = 0.171 \pm 0.006$	**0.00021**
Total (excl. R_c)	**0.00154**

Table 1: Summary of systematic uncertainties at $\mathcal{M} > 2.0$ GeV/c^2 cut.