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MEASUREMENT OF THE PROBABILITY FOR GLUON SPLITTING INTO $b\bar{b}$ IN Z^0 DECAYS

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ABSTRACT

We present a preliminary measurement of the rate of gluon splitting into bottom quarks, $g \to b\bar{b}$, in hadronic Z^0 decays collected by SLD between 1996 and 1998. The analysis was performed by looking for secondary bottom production in 4-jet events of any primary flavor. 4-jet events were identified, and a topological vertex-mass technique was applied to each jet in order to identify b or $\bar{b}$ jets. The upgraded CCD based vertex detector gives very high B-tagging efficiency, especially for B hadrons of the low energies typical of this process. The two most nearly collinear $b/\bar{b}$ jets were tagged as originating from $g \to b\bar{b}$. We measured the rate of secondary $b/\bar{b}$ production per hadronic event, $g_{b\bar{b}}$, to be $(3.07 \pm 0.71(\text{stat.}) \pm 0.66(\text{syst.})) \times 10^{-3}$ (preliminary).

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1 Introduction

The process of the splitting of a gluon into a heavy-quark pair is one of the elementary processes in QCD but is poorly known, both theoretically and experimentally.

The rate $g_{b\bar{b}}$ is defined as the fraction of hadronic events in which a gluon splits into a $b\bar{b}$ pair, $e^+e^- \to q\bar{q}g \to q\bar{q}b\bar{b}$. The value of $g_{b\bar{b}}$ is an infrared finite quantity, because the b-quark mass provides a natural cutoff, hence it can be safely computed in the framework of perturbative QCD [1]. However the rate is sensitive to α_S and to the b-quark mass, which results in a substantial theoretical uncertainty in the calculation of $g_{b\bar{b}}$. The limited accuracy of the $g_{b\bar{b}}$ prediction is one of the main sources of uncertainty in the measurement of the partial decay width $R_b = \Gamma(Z^0 \to b\bar{b})/\Gamma(Z^0 \to q\bar{q})$ [2, 3]. In addition, about 50% of the B hadrons produced at the Tevatron are due to the gluon splitting process, and a larger fraction is expected to contribute at the LHC. A better knowledge of this process can improve theoretical predictions of heavy-flavor production at such colliders.

This measurement is difficult experimentally. The cross section for $g \to b\bar{b}$ is very small even at Z^0 energies, since the gluon must have sufficient mass to produce the bottom-quark pair. There are huge backgrounds from $Z^0 \to b\bar{b}$ whose magnitude is about a hundred times larger than the $Z^0 \to q\bar{q}g \to q\bar{q}b\bar{b}$ process. Moreover the B hadrons from $g \to b\bar{b}$ have relatively low energy and short flight distance and are more difficult to distinguish using standard vertexing. So far, measurements of $g_{b\bar{b}}$ have been reported by DELPHI and ALEPH [4].

Here we present a new measurement of $g_{b\bar{b}}$ based on a 400k Z^0-decay data sample taken in 1996-98 at the Stanford Linear Collider (SLC), with the SLC Large Detector (SLD). In this period, Z^0 decays were collected with an upgraded vertex detector, wider acceptance and better impact parameter resolution, thus improving considerably the b-tagging performance.

2 The SLD Detector

A description of the SLD is given elsewhere [5]. Only the details most relevant to this analysis are mentioned here.

SLD is well-suited for the measurement of $g \to b\bar{b}$ due to two unique features. The first is that the SLC, the only linear collider in the world, provides a very small and stable beam spot. The SLC interaction point was reconstructed from tracks in sets of approximately thirty sequential hadronic Z^0 decays with an uncertainty of only 5μm transverse to the beam axis and 32μm (for $b\bar{b}$ events) along the beam axis. Second is the upgraded vertex detector (VXD3) [6], a pixel-based CCD vertex detector. VXD3 consists of 3 layers with 307M pixels and each layer is only 0.36% of a radiation length thick. The measured $r\phi$ (rz) track impact-parameter resolution approaches 11μm (23μm) for high momentum tracks, while multiple scattering contributions are $40\mu\text{m}/(p\sin^{3/2}\theta)$ in both projections (z is the coordinate parallel to the beam axis). With these features, topological vertex finding gives excellent b-tagging efficiency and purity. In particular, the efficiency is good even at low B-meson energies, which is especially important for detecting $g \to b\bar{b}$.

3 Flavor Tagging

Topologically reconstructed secondary vertices [7] are used by many analyses at the SLD for heavy-quark tagging. To reconstruct the secondary vertices, the space points where track density functions overlap are found in 3-dimensions. Only the vertices that are significantly displaced from the primary vertex (PV) are considered to be possible B- or D-hadron decay vertices. The mass of the secondary vertex is calculated using the tracks that are associated with the vertex. Since the heavy-hadron decays are frequently accompanied by neutral particles, the reconstructed mass is corrected to

account for this fact. By using kinematic information from the vertex flight path and the momentum sum of the tracks associated with the secondary vertex, we calculate the P_T-corrected mass M_{P_T} by adding a minimum amount of missing momentum to the invariant mass, as follows:

$$M_{P_T} = \sqrt{M^2{}_{VTX} + {P_T}^2} + |P_T|.$$

Here M_{VTX} is the invariant mass of the tracks associated with the reconstructed secondary vertex and P_T is the transverse momentum of the charged tracks with respect to the B-flight direction. In this correction, vertexing resolution as well as the PV resolution are crucial. Due to the small and stable interaction point at the SLC and the excellent vertexing resolution from the SLD CCD Vertex detector, this technique has so far only been successfully applied at the SLD.

4 Monte Carlo and data Samples

The measurement uses 400k $Z^0 \rightarrow$ hadron events collected between 1996 and 1998 with the requirement that the VXD3 was fully operational.

For the purpose of estimating the efficiency and purity of the $g \rightarrow b\bar{b}$ selection procedure, we made use of a detailed Monte-Carlo simulation of the detector. The JETSET 7.4 [8] event generator was used, with parameter values tuned to hadronic e^+e^- annihilation data [9], combined with a simulation of B hadron decays tuned to $\Upsilon(4S)$ data [10] and a simulation of the SLD based on GEANT 3.21 [11]. Inclusive distributions of single-particle and event-topology observables in hadronic events were found to be well described by the simulations [12]. Uncertainties in the simulation were taken into account in the systematic errors (Section 7).

Monte-Carlo events are reweighted to take into account current estimates for gluon splitting into heavy-quark pairs [4, 13]. JETSET with the SLD parameters predicts $g_{b\bar{b}} = 0.14\%$ and $g_{c\bar{c}} = 1.36\%$, and we reweighted them so that $g_{b\bar{b}} = 0.273\%$ and

$g_{c\bar{c}} = 2.58\%$. A Monte-Carlo production of about 1200k $Z \to q\bar{q}$ events, 1000k $Z \to b\bar{b}$ events and 480k $Z \to c\bar{c}$ events are used in order to better evaluate the efficiencies.

Besides the signal events, hereafter called B, two categories of background events exist:

- Events which do not contain any gluon splitting into heavy flavor at all, hereafter called Q events; and
- Events in which a gluon splits to a charm quark pair, named C events.

5 Analysis

The two B hadrons coming from the gluon tend to be produced in a particular topological configuration, which allows one to discriminate the signal from background. We select $g \to b\bar{b}$ events as follows:

- Require 4 jets in the events;
- Require b tags in two jets selected in a particular configuration; and
- Apply additional topological selections to improve the signal/background ratio.

Jets are formed by applying the Durham jet-finding algorithm [14] to energy-flow particles with $y_{cut} = 0.008$, chosen to minimize the statistical error. The overall 4-jet rate in the data is $(5.976 \pm 0.044)\%$, where the error is statistical only. In the Monte-Carlo simulation the 4-jet rate is $(5.678 \pm 0.002 \pm 0.068)\%$ where the first error is statistical and the second is due to the uncertainty in the simulation of heavy-quark physics. The 4-jet rates for the B, C and Q events predicted by the simulation are about 32%, 18% and 5.3%, respectively. The two jets forming the smallest angle in the event are considered as candidates for originating from the gluon splitting process

$g \to b\bar{b}$. The selected jets are labeled as jet 1 and jet 2, where jet 1 is more energetic than jet 2. The other two jets in the event are labeled as jets 3 and 4, where jet 3 is more energetic than jet 4.

Jets containing B-hadron decay products are then searched for by making use of the information coming from the vertex detector, using the topological vertex method. We require both jet 1 and jet 2 to contain a secondary vertex. No tag is applied to jet 3 and jet 4. After topological vertexing, about 300 events are selected. The selection efficiency for $g \to b\bar{b}$ is expected from the Monte Carlo simulation to be 6.6% while the signal/background ratio is 1/5. 67% of the background comes from $Z \to b\bar{b}$ events, 21% from $g \to c\bar{c}$ events and remaining 12% from $Z \to q\bar{q}$ $(q \neq b)$ events.

In order to improve the signal/background ratio, we use topological information. Firstly, many $Z^0 \to b\bar{b}$ background events have one b-jet which was split by the jet-finder into 2 jets so that the two found vertices are from different decay products from the same B decay. The two vertex axes tend to be collinear. Figure 1 shows the angular distribution between vertex axes in jet 1 and jet 2. Half of the $b\bar{b}$ background peaks at $\cos\theta_{12} \sim 1$. In order to remove $b\bar{b}$ events, we require $-0.2 < \cos\theta_{12} < 0.96$.

Secondly, the variable $|\cos\alpha_{1234}|$, where α_{1234} is the angle between the plane Π_{12} formed by jets 1 and 2 and the plane Π_{34} by jets 3 and 4, is used to suppress the $b\bar{b}$ background. Figure 2 shows the distribution of $|\cos\alpha_{1234}|$. This variable is similar to the Bengtsson-Zerwas angle [15], and is useful to separate $g \to b\bar{b}$ events because the radiated virtual gluon in the process $Z^0 \to q\bar{q}g$ is polarized in the plane of the three-parton event, and this is reflected in its subsequent splitting, by strongly favoring $g \to q\bar{q}$ emission out of this plane. Events with $|\cos\alpha_{1234}| > 0.8$ are rejected.

Thirdly, the b jets coming from a gluon tend to have lower energy than the other two jets in the event. Figure 3 shows the energy sum distribution of jets 1 and 2. We require the energy sum to be smaller than 36 GeV.

Finally, c jets have lower P_T-corrected mass than b jets. Figure 4 shows the greater of the P_T-corrected mass determined for jet 1 and jet 2 after the above cuts. Many

Source	Efficiency (%)
B	3.86 ± 0.52
C	0.10 ± 0.02
Q	0.73 ± 0.05

Table 1: Efficiencies after all cuts for the three categories. Errors are statistical only.

background events lie below 2.0 GeV. Hence we require M_{P_T} to be greater than 2.0 GeV.

6 Result

After requiring all the above mentioned cuts, 62 events are selected in the data. The number of background events is estimated, using the Monte Carlo simulation, to be 27.6, where 63% of the background comes from $Z \to b\bar{b}$ events, 27% from $g \to c\bar{c}$ events and the remaining 10% from $Z \to q\bar{q}$ $(q \neq b)$ events. Table 1 shows the tagging efficiencies for the three categories of events, where the errors are statistical only. From these efficiencies and the fraction of events selected in the data $f_d = (2.14 \pm 0.27) \times 10^{-4}$, the value of $g_{b\bar{b}}$ can be determined:

$$g_{b\bar{b}} = \frac{f_d - (1 - g_{c\bar{c}})\epsilon_Q - g_{c\bar{c}}\epsilon_C}{\epsilon_B - \epsilon_Q}. \tag{1}$$

We obtain

$$g_{b\bar{b}} = (3.07 \pm 0.71) \times 10^{-3}, \tag{2}$$

where the error is statistical only.

7 Systematic Errors

The efficiencies for the three event categories are evaluated using the Monte-Carlo

simulation. The limitations of the simulation in estimating these efficiencies lead to an uncertainty on the result. The error due to the limited Monte-Carlo statistics in the efficiency evaluation is $\Delta g_{b\bar{b}} = \pm 0.44 \times 10^{-3}$. This uncertainty comes mainly from the efficiency to tag Q events.

A large fraction of events remaining after the selection cuts contain B and D hadrons. The uncertainty in the knowledge of the physical processes in the simulation of heavy-flavor production and decays constitutes a source of systematic error. All the physical simulation parameters are varied within their allowed experimental ranges. In particular, the b and c hadron lifetimes as well as production rates are varied, following the latest recommendations of the LEP Heavy Flavour Working Group [16]. The uncertainties are summarized in Table 2.

The simulation of the signal events is based on the JETSET parton shower Monte Carlo, which is in good agreement with the theoretical predictions [1]. In order to estimate the uncertainty on this assumption, we have produced 10,000 $g \to b\bar{b}$ events using GRC4F [17] at the generator level. The signal tagging efficiency, ϵ_B, mainly depends on the energy of the gluon splitting into $b\bar{b}$. This efficiency function, computed with JETSET, is reweighted by the ratio of the GRC4F to JETSET initial energy distributions to obtain the average efficiency. A systematic error of $\Delta g_{b\bar{b}} = \pm 0.09 \times 10^{-3}$ is estimated from the difference in efficiency between the two Monte-Carlo models.

The dependence of the efficiency on the b-quark mass has also been investigated at the generator level. Events are generated using the GRC4F Monte Carlo, which is based on a matrix element calculation including b-quark masses. The variation of ϵ_B was computed for b-quark masses between 4.7 and 5.3 GeV/c^2. The resultant uncertainty is estimated to be $\Delta g_{b\bar{b}} = \pm 0.06 \times 10^{-3}$.

The uncertainty in the ratio of the $g \to c\bar{c}$ background events, $\Delta g_{c\bar{c}} = \pm 0.40\%$, gives an error $\Delta g_{b\bar{b}} = \pm 0.09 \times 10^{-3}$.

There is about a 5% discrepancy in the 4-jet rate between data and Monte Carlo at our y_{cut} value. The uncertainty due to the discrepancy is estimated by increasing

the number of background events in the Monte Carlo and is found to be $\Delta g_{b\bar{b}} = \pm 0.14 \times 10^{-3}$.

In the Monte-Carlo simulation charged tracks used in the topological vertex tag are smeared and rejected to reproduce better distributions in the data. Uncertainties in the efficiencies due to this smearing and rejection are assessed by evaluating the Monte-Carlo efficiencies without the smearing and rejection algorithm. The difference in the $g_{b\bar{b}}$ result is taken as systematic error. The errors on $g_{b\bar{b}}$ due to the tracking resolution and efficiency are then estimated to be $\Delta g_{b\bar{b}} = \pm 0.26 \times 10^{-3}$ and $= \pm 0.29 \times 10^{-3}$, respectively.

Table 2 summarizes the different sources of systematic error on $g_{b\bar{b}}$. The total systematic error is estimated to be the sum in quadrature, 0.66×10^{-3}.

8 Summary

A preliminary measurement of the gluon splitting rate to a $b\bar{b}$ pair in hadronic Z^0 decays collected by SLD has been presented. Excellent SLC and VXD3 performance provides advantages not only for the b-tag efficiency but also for the topological selections. The result is

$$g_{b\bar{b}} = (3.07 \pm 0.71(\text{stat.}) \pm 0.66(\text{syst.})) \times 10^{-3}(\text{preliminary}).$$

where the first error is statistical and the second includes systematic effects.

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Source	$\Delta g_{b\bar{b}}$ (10^{-3})
Monte Carlo statistics	± 0.44
B hadron lifetimes	± 0.01
B hadron production	± 0.07
B hadron fragmentation	± 0.12
B hadron charged multiplicities	± 0.11
D hadron lifetimes	± 0.01
D hadron production	± 0.03
D hadron charged multiplicities	± 0.08
Energy distribution of $g \to b\bar{b}$	± 0.08
b quark mass	± 0.06
$g_{c\bar{c}}$	± 0.09
4-jet rate discrepancy	± 0.14
IP resolution	± 0.09
Track resolution	± 0.26
Tracking efficiency	± 0.29
Total (Preliminary)	± 0.66

Table 2: Systematic uncertainties on $g_{b\bar{b}}$.

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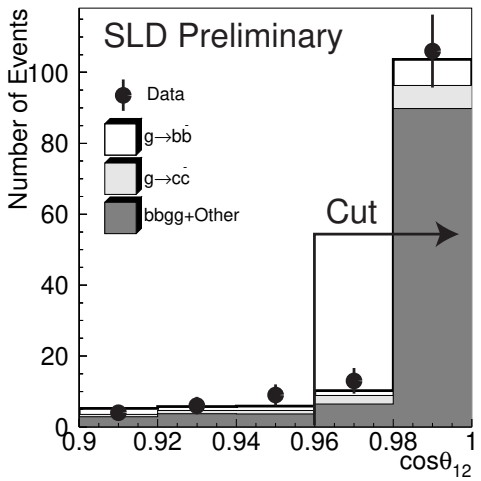

Figure 1: Angular distribution between vertex axes in jet 1 and jet 2 ($0.9 < \cos\theta_{12}$) (points). The simulated distribution is shown as a histogram.

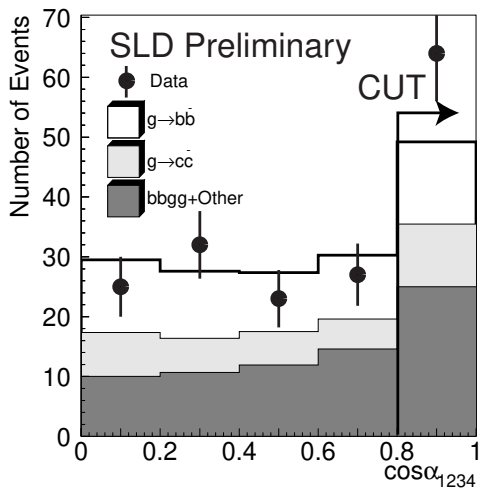

Figure 2: The distribution of the cosine of angle between the plane Π_{12} formed by jets 1 and 2 and the plane Π_{34} formed by jets 3 and 4, for data (points) and Monte Carlo simulation (histogram). We reject $|\cos\alpha_{1234}| > 0.8$

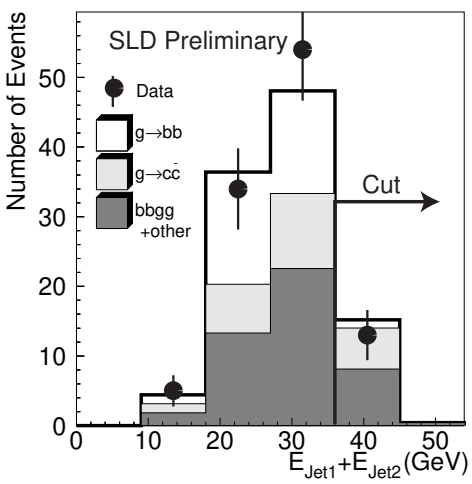

Figure 3: The distribution of the energy sum of jet 1 and jet 2.

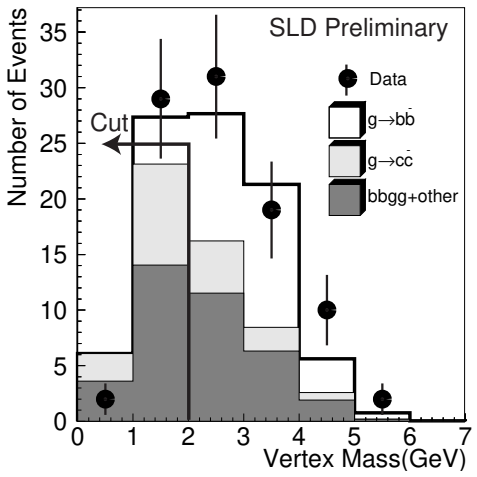

Figure 4: Maximum P_T-corrected mass distribution between jet 1 and jet 2 after jet-energy-sum cut. Points indicate data, open box signal, hatched boxes are backgrounds.