# Gluon splitting to $c\bar{c}$ and $b\bar{b}$ in hadronic $Z^0$ decays: Experimental results

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**Abstract**
Several measurements of the rates of gluon splitting to heavy quarks in hadronic $Z^0$ decays are presented and compared to theoretical predictions. Averages are calculated taking into account correlated sources of systematic uncertainties.

## 1. Introduction

In hadronic $Z^0$ decays, charm (c) or bottom (b) quark pairs are produced either directly, or by gluon splitting $g \to Q\bar{Q}$. The rate for the latter process per hadronic $Z^0$ decay is denoted $g_{Q\bar{Q}}$ ($Q = b, c$),

$$g_{Q\bar{Q}} = \frac{\Gamma\left(Z^0 \to q\bar{q}g,\ g \to Q\bar{Q}\right)}{\Gamma\left(Z^0 \to \text{hadrons}\right)}.$$

Theoretical calculations of the rates $g_{c\bar{c}}$ and $g_{c\bar{c}}$ are available [1, 2] and include the re-summation of large logarithmic terms. The predicted rates depend on the strong coupling constant and the heavy quark mass. However, as the tree-level part of the calculations is only performed up to leading order, no renormalisation scheme is defined, resulting in relatively large uncertainties on the predicted rates. Numerical values are given in [1, 2, 3], predicting rates in the range $g_{c\bar{c}}^{\text{theor}} = (1.05 - 2.54) \times 10^{-2}$ and $g_{b\bar{b}}^{\text{theor}} = (1.8 - 2.9) \times 10^{-3}$. Several experimental measurements of the rate of gluon splitting to charm and bottom quarks have been performed and will be summarised here, testing these predictions. Gluon splitting to heavy quarks is also an important source of background for the precise measurements of the partial decay width of the $Z^0$ to heavy quarks, $R_c$ and $R_b$ [4].

Experimentally, events with gluon splitting to heavy quarks are observed as events with three or four jets. In the latter case, the heavy quarks from gluon splitting are resolved in separate jets, while in the three-jet case, only one broad gluon jet is reconstructed. The other two jets correspond to the two primary quarks from the $Z^0$ decay.

In Section 2 and 3, experimental results are presented for $g_{c\bar{c}}$ and $g_{b\bar{b}}$, respectively. In Section 4, the averaging procedure developed for the use in this paper is described in more detail.

## 2. Gluon splitting to $c\bar{c}$ quark pairs

Results for gluon splitting to charm quarks are available from the ALEPH [5], L3 [6] and OPAL [7] collaborations. The new OPAL analysis supersedes previous results [8, 9]. The ALEPH and L3 results quoted here are preliminary.

ALEPH reconstructs $D^{\star\pm}$ mesons in the decay chain $D^{\star\pm} \to D^0\pi^\pm$, $D^0 \to K^\mp\pi^\pm$. These $D^{\star\pm}$ mesons originate from various sources, one of them being gluon splitting to $c\bar{c}$. The event is divided into two hemispheres, based on the thrust axis. The $D^{\star\pm}$ mesons from gluon splitting are preferentially found in the hemisphere with the larger invariant mass, with relatively small energies. In contrast, the mesons from direct $c\bar{c}$ production are found with about equal probability in both hemispheres and have larger energies.

The OPAL and the L3 analyses start with a selection of three-jet events. For the OPAL analysis, in each event a candidate gluon jet is selected. Within this jet, $D^{\star\pm}$ mesons or leptons from charm decays are identified, both originating with a high probability from gluon splitting to charm quark pairs. Optimised gluon-candidate selections are used for the lepton and the $D^{\star\pm}$ analysis, respectively.

The L3 collaboration identifies leptons from charm decays in the lowest-energetic jet. In an independent analysis, events from gluon splitting are selected with a dedicated neural network, based on event-shape observables.

The results of the individual analyses are shown in Figure 1. As the individual measurements are found to be consistent, their average is calculated using a common value for background from gluon splitting to $b\bar{b}$ and taking care of correlated systematic uncertainties. This is described in more

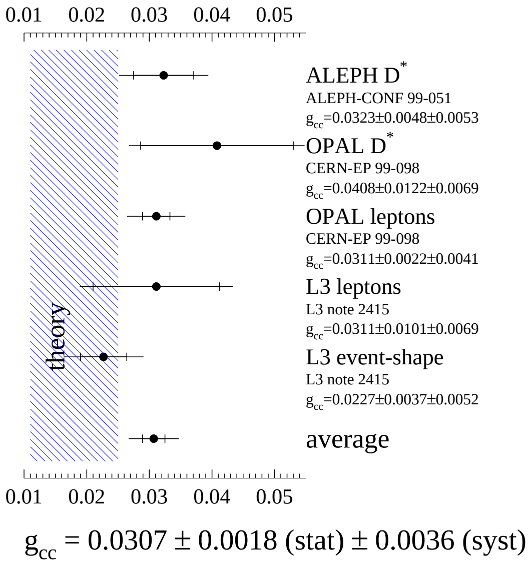


**Figure 1.** Experimental results for gluon splitting to charm quark pairs

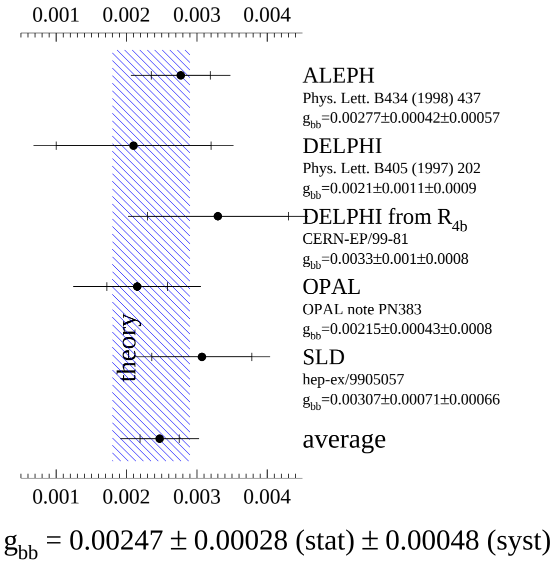


**Figure 2.** Experimental results for gluon splitting to bottom quark pairs

detail in Section 4. The result is:

$$g_{c\bar{c}} = 0.0307 \pm 0.0018(\mathrm{stat}) \pm 0.0036(\mathrm{sys})\,.$$

This is $1.3\sigma$ away from the upper edge of the theoretical prediction.

## 3. Gluon splitting to $b\bar{b}$ quark pairs

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New measurements of gluon splitting to bottom quark pairs are available from the DELPHI [10], OPAL [11] and SLD [12] collaborations in addition to older analyses by DELPHI [13] and ALEPH [14]. The OPAL and SLD results quoted here are preliminary.

The analyses performed by ALEPH and SLD, as well as the old DELPHI analysis, all follow similar strategies. Events with four jets are selected. Within these events, the signal is enriched by requiring two low-energetic jets, each one satisfying a b-tag requirement, with a small opening angle. The b-identification is based on vertexing information, sensitive to long-lived b-hadron decays.

The new DELPHI analysis is based on three-jet events, where the gluon decay products are not resolved in two separate jets. All three jets are required to have a b-tag. Using these events, the rate of events with four b-quarks $R_{4\mathrm{b}}$ is measured. A QCD prediction for $\frac{g_{b\bar{b}}}{R_{4\mathrm{b}}}$, which does only weakly depend on the b-quark mass and other parameters is used to extract the rate $g_{b\bar{b}}$ from this measurement of $R_{4\mathrm{b}}$.

OPAL selects four-jet events with two b-tagged jets that are close in phase-space. In addition, four-jet events with three b-tagged jets are selected. A simultaneous fit of the rates $g_{b\bar{b}}$ and $R_{4\mathrm{b}}$ is performed.

The results of these five analyses are shown in Figure 2 and are consistent with each other. Taking into account a common value for background from gluon splitting to charm quarks, and considering other correlated sources of systematic uncertainties, the result is:

$$g_{b\bar{b}} = 0.00247 \pm 0.00028(\mathrm{stat}) \pm 0.00048(\mathrm{sys})$$

consistent with theoretical predictions. The averaging procedure is described in the next Section.

It is also interesting to look at the rates of events with four bottom quarks, $R_{4\mathrm{b}}$. This quantity is measured by DELPHI and OPAL

$$\begin{aligned} R_{4\mathrm{b}}^{\mathrm{DELPHI}} &= (0.60 \pm 0.19 \pm 0.14) \times 10^{-3}\,, \\ R_{4\mathrm{b}}^{\mathrm{OPAL}} &= (0.53 \pm 0.20 \pm 0.23) \times 10^{-3}\,. \end{aligned}$$

The two measurements agree within errors.

## 4. Averaging procedure

To calculate the averages for $g_{c\bar{c}}$ and $g_{b\bar{b}}$, sources of systematic uncertainties that are correlated between the various measurements have to be considered.

For the $g_{c\bar{c}}$ measurements, the following sources of common systematic uncertainties are taken into account: gluon splitting to $b\bar{b}$, modelling of heavy quark fragmentation to hadrons, comparisons of various Monte Carlo generators for signal and background, dependence on $R_b$, and branching ratios for bottom and charm to leptons.

For the $g_{b\bar{b}}$ measurements the following sources of common systematic uncertainties are considered: gluon splitting to $c\bar{c}$, choice of Monte Carlo model for the signal, dependence on the b-quark mass, modelling of charm production and decays, and modelling of bottom production and decays.

For a given value of $g_{b\bar{b}}$ with error $\sigma$, the central values of the individual $g_{c\bar{c}}$ measurements are re-adjusted and new uncertainties from gluon splitting to $b\bar{b}$ are calculated. Then the weighted average of these $g_{c\bar{c}}$ measurements is calculated, with weights $w = \left(\sigma^2_{\rm stat} + \sigma^2_{\rm sys}\right)^{-1}$. The statistical and the uncorrelated systematic uncertainties of the individual measurements are added quadratically using these weights while the correlated systematic uncertainties are added linearly. An analogous procedure is then applied to $g_{b\bar{b}}$, with the new result for $g_{c\bar{c}}$ as input, and these two steps are iterated several times, until the results are stable.

To study correlations of $g_{c\bar{c}}$ and $g_{b\bar{b}}$, a symmetric error matrix is calculated using the ansatz:

$$\begin{pmatrix} \sigma^2_{g_{c\bar{c}}} & -\delta_{g_{c\bar{c}}}\sigma_{g_{b\bar{b}}} - \delta_{g_{b\bar{b}}}\sigma_{g_{c\bar{c}}} \\ -\delta_{g_{c\bar{c}}}\sigma_{g_{b\bar{b}}} - \delta_{g_{b\bar{b}}}\sigma_{g_{c\bar{c}}} & \sigma^2_{g_{b\bar{b}}} \end{pmatrix} .$$

Here $\sigma_{g_{c\bar{c}}}$ and $\sigma_{g_{b\bar{b}}}$ are the total uncertainties on $g_{c\bar{c}}$ and $g_{b\bar{b}}$, while $\delta_{g_{c\bar{c}}}$ is the contribution to $\sigma_{g_{c\bar{c}}}$ from gluon splitting to $b\bar{b}$ and $\delta_{g_{b\bar{b}}}$ is the contribution to $\sigma_{g_{b\bar{b}}}$ from gluon splitting to $c\bar{c}$. The sign reflects the fact that the measurements of $g_{b\bar{b}}$ and $g_{c\bar{c}}$ are anti-correlated.

## 5. Summary

Several new measurements of gluon splitting to heavy quarks have been presented. Averages of the experimental results for gluon splitting to charm quarks, $g_{c\bar{c}}$, and bottom quarks, $g_{b\bar{b}}$, are calculated taking into account correlations. The results are:

$$\begin{aligned} g_{c\bar{c}} &= 0.0307 \pm 0.0040 \\ g_{b\bar{b}} &= 0.00247 \pm 0.00056 \end{aligned}$$

with a correlation coefficient

$$C\left(g_{c\bar{c}}, g_{b\bar{b}}\right) = -0.43 \ .$$

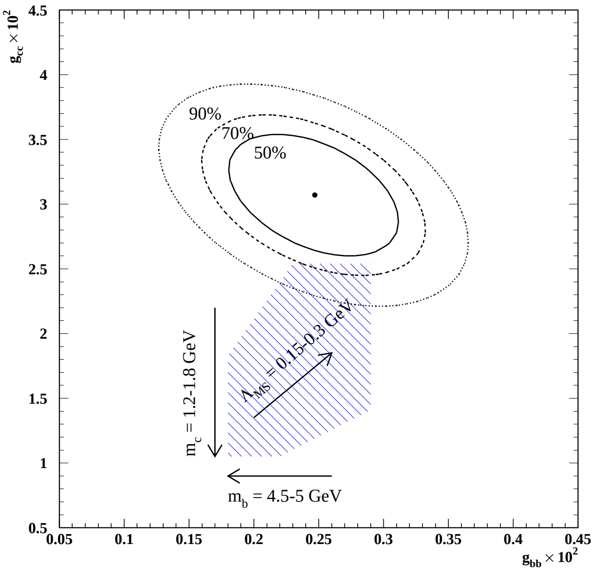


**Figure 3.** Areas allowed by theory and the measurements in the $g_{b\bar{b}} - g_{c\bar{c}}$ plane
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Figure 3 illustrates how this result is consistent with theoretical predictions at a confidence level of 70% for high values of the charm quark mass and the strong coupling constant.

## References


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