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A Measurement of the Gluon Splitting Rate into $c\bar{c}$ Pairs in Hadronic Z^0 Decays

The ALEPH Collaboration

Abstract

A measurement of the gluon splitting rate to a $c\bar{c}$ pair ($g_{c\bar{c}}$) is presented using data collected by ALEPH from 1991 to 1995 at the Z^0 resonance. The selection is based on a lepton tag and on the topological properties of the events. The result from electron and muon samples is: $g^e_{c\bar{c}} = (2.99 \pm 0.28(\mathrm{stat}) \pm 0.41(\mathrm{syst}))\%$ and $g^\mu_{c\bar{c}} = (2.90 \pm 0.38(\mathrm{stat}) \pm 0.74(\mathrm{syst}))\%$. The combined result is $g_{c\bar{c}} = (2.98 \pm 0.48)\,\%$.

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1 Introduction

This paper describes a measurement of the rate of $g \to c\bar{c}$ events in hadronic events at the Z^0 peak. The selection relies on tagging semileptonic decays of the c quarks from gluon splitting, and makes use of several discriminating variables related to the event topology.

The rate of gluon splitting to $c\bar{c}$ pairs is defined as

$$g_{c\bar{c}} = \frac{N(Z^0 \to q\bar{q}g, g \to c\bar{c})}{N(Z^0 \to hadrons)}. \tag{1}$$

The theoretical treatment of the production of heavy quarks from a gluon (*gluon splitting*) is described in a series of articles [1, 2, 3, 4] and the rate $g_{c\bar{c}}$ has been predicted to be in the range between 1.36% to 2.54%.

Measurements have been done using a D^* tag [5, 6], a lepton tag [5, 7] or event shape variables [7]. The lepton tag provides the most precise results.

2 Preselection

A selection is made on the full LEP I data (about 3.9 millions $e^+e^- \to Z^0$ events). The principle of the method is to look for leptons in the least energetic jet, since the "gluon jet", in signal events, is expected to be soft, further rejecting the background by means of a neural network.

The first step of the analysis selects events with a small value of the thrust [8]. Fig. 1 shows the different shapes of the thrust distribution for signal and background events. The thrust cut < 0.94 is chosen.

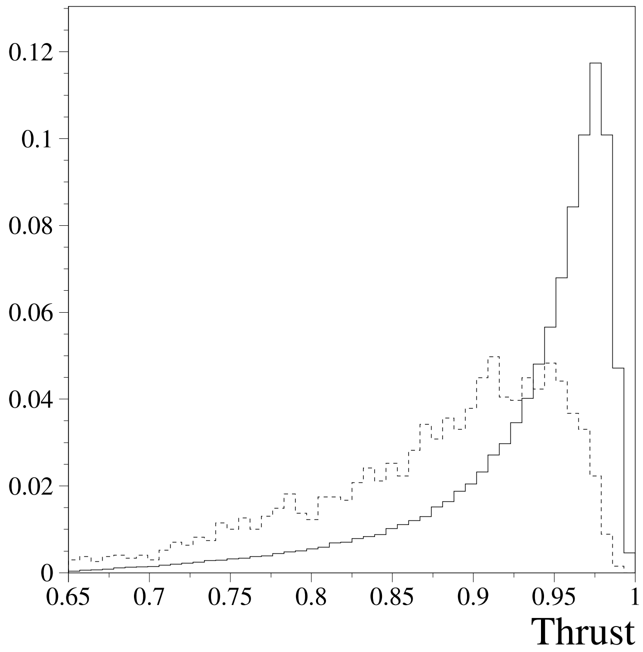


Figure 1: Thrust distributions in the Monte Carlo for signal (dotted line) and background (solid line) events.

The events which pass the thrust cut are forced to clusterize in exactly three jets. The clusterization algorithm chosen is JADE [9, 10] (with the "E scheme"). The jets are then ordered by decreasing momentum, and only events with a lepton in the third jet (identified as in [11, 12]) are retained.

The jet momenta are calculated neglecting mass effects and are given by:

$$p_i = E_{cm} \frac{\sin\psi_{jk}}{\sin\psi_{jk} + \sin\psi_{ij} + \sin\psi_{ik}}, \quad (2)$$

where $E_{cm} = 91.2\ GeV$ is the center-of-mass energy and ψ_{ij} is the angle between jets i and j. In this way the jet momenta are determined with a better resolution. Non-planar events, for which Eq. 2 does not hold, are rejected by requiring $\sin\psi_{12} + \sin\psi_{23} + \sin\psi_{31} > 358^o$. The jet momentum computed in this way is only used for ordering purposes.

Leptons with at least one VDET hit are selected. Furthermore, the distance of closest approach of the lepton track to the beam axis (d_0) is required to be less than 0.1 cm, to better reject the leptons from K or π decay (Section 4.6).

$g \rightarrow c\bar{c}$	2.96 %
$g \rightarrow b\bar{b}$	0.254 %
uds	58.8 %
c	16.5 %
b	21.4 %

Table 1: Flavour composition of the total sample before any cut.

	e	μ
$g \rightarrow c\bar{c}$	17.0 ± 0.3 %	12.8 ± 0.3 %
$g \rightarrow b\bar{b}$	3.4 ± 0.2 %	2.5 ± 0.1 %
uds	10.9 ± 0.3 %	27.6 ± 0.4 %
c	21.5 ± 0.4 %	20.0 ± 0.3 %
b	47.1 ± 0.4 %	37.0 ± 0.4 %

Table 2: Flavour composition of the preselected sample.

The preselection yields 13363 events, out of which 5639 contain an electron candidate and 7724 a muon candidate. The flavour composition of the preselected Monte Carlo sample is shown in table 2, which has to be compared to the initial composition shown in Table 1. The difference between the number of selected electrons and muons, and in the flavour composition of the events which contain them, are mostly due to the different contaminations of the electron and muon subsamples.

According to the Monte Carlo, about 56% of the muon candidates are coming directly from a heavy flavoured quark decay (*"prompt muons"*). Instead, 30% are coming from π or K decays, while 13% are hadrons which pass the standard identification criteria for prompt muons . In the electron sample the contamination is significantly lower: 69% of the candidates are prompt electrons, and the main contamination (26%) comes from photon conversions in the detector material.

3 Neural network

To discriminate between signal and background, a neural net is trained using as inputs the following variables:

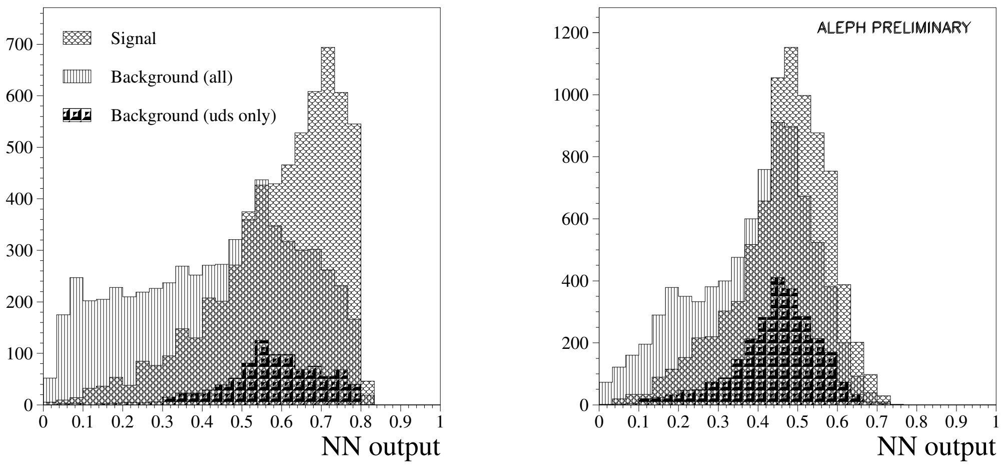
- the projection of the missing momentum along the axis of the lowest momentum jet ($\vec{P}_{miss} \cdot \vec{n}_3$);
- the b-tag probabilities [13] of the two hemispheres;
- the thrust of the event;
- the momentum of the tagged lepton;
- the b-tag probability of the tagged lepton in the third jet;

- the cosine of the angle between the tagged lepton and the LEP beam.

The $\vec{P}_{miss} \cdot \vec{n}_3$ variable is expected to be large for $c \to l$ decays, where the missing momentum due to the corresponding neutrino is mostly along the jet axis. The thrust of the event has already been used in the preselection, but after the cut it has still some discriminant power, since it distinguishes the events according to their sphericity. The b-tag probabilities, as well as the momentum of the lepton, are used to reject the background from primary b's. The cosine of the angle between the lepton track and the beam is a control variable to inform the net about the quality of the lepton candidate.

The neural network has been trained with half of the 8.7 million hadronic events of the LEP I Monte Carlo production and half of the 1.8 million $g \to c\bar{c}$ events of a dedicated signal Monte Carlo sample. The remaining statistics have been used to test the net, and then to extract the efficiencies of the final selection cuts (for this purpose additional samples of 5.1 million $b\bar{b}$ events and 2.3 millions $c\bar{c}$ events were also used).

The output of the electron and muon nets is shown in Fig. 2. The discriminant power of the two nets is quite different, due to the different flavour composition of the electron and muon samples (Table 2): the large number of non-prompt muons which pass the preselection leads to a larger number of uds events in the muon sample than in the electron sample.



(a) (b)

Figure 2: Output of the neural network for (a) electrons and (b) muons. (The signal area is normalized to the total background).

	e	μ
$g \to c\bar{c}$	25 %	18 %
$g \to bb$	4 %	2 %
uds	18 %	35 %
c	28 %	22 %
b	25 %	23 %

Table 3: Flavour composition of the selected sample, after the cut on the neural network output.

After the training, the net is applied to the real data, and a cut is performed (the output has to be higher than 0.55 for electrons and 0.45 for muons, values chosen to minimize the total error). This selects 2258 electrons and 3332 muons. Table 3 shows the final sample composition. The same cut is applied to the simulated events not used for the training to determine the efficiencies. The value of the gluon splitting rate is:

$$g_{c\bar{c}} = \frac{f \; - \; (1 - g_{b\bar{b}}) \; \epsilon_Q \; - \; g_{b\bar{b}} \; \epsilon_B}{\epsilon_C \; - \; \epsilon_Q}, \tag{3}$$

where f is the fraction of events selected; ϵ_Q, ϵ_C, ϵ_B are the efficiencies of the cut for events with, respectively, no gluon splitting, gluon splitting in $c\bar{c}$, and gluon splitting in $b\bar{b}$; they are reported in Table 4.

To extract $g_{c\bar{c}}$, $g_{b\bar{b}}$ is fixed to the last world average [14] $(2.54 \pm 0.51) \times 10^{-3}$. The results in the two channels are $g^e_{c\bar{c}} = (2.99 \pm 0.28)\%$ and $g^\mu_{c\bar{c}} = (2.90 \pm 0.38)\%$, where the quoted error only accounts for the statistical uncertainty on f.

	electrons (%)	muons (%)
f	0.0600 ± 0.0013	0.0885 ± 0.0015
ϵ_Q	0.0448 ± 0.0006	0.0742 ± 0.0008
ϵ_C	0.510 ± 0.006	0.471 ± 0.005
ϵ_B	0.88 ± 0.08	0.85 ± 0.07

Table 4: Fraction of events selected and selection efficiencies for the different event categories.

4 Systematic errors

The efficiencies for the background processes that appear in Eq. 3 are taken from simulated events. The sources of uncertainties on these parameters are discussed in this section, deriving estimates of the corresponding systematic uncertainties on $g_{c\bar{c}}$.

4.1 Monte Carlo statistics

The statistical uncertainties on the Monte Carlo efficiencies (Table 4) translates to $\Delta g^e_{c\bar{c}} = \pm 0.13\%$ and $\Delta g^\mu_{c\bar{c}} = \pm 0.21\%$.

4.2 Gluon splitting to $b\bar{b}$ pairs

Propagating the effect of the uncertainty in the $g_{b\bar{b}}$ value in Eq. 3 yields $\Delta g^e_{c\bar{c}} = \pm 0.10\%$ and $\Delta g^\mu_{c\bar{c}} = \pm 0.11\%$. This error is considered correlated when averaging the electron and the muon results.

4.3 Thrust cut

One of the main preselection requests is the thrust cut. The fraction of MC events fulfilling this request has been found to be slightly (but significantly) different than data, as shown in Table 5 on a year-to-year basis.

year	data (%)	MC (%)
1991	39.73 ± 0.10	39.96 ± 0.08
1992	39.60 ± 0.07	40.11 ± 0.04
1993	39.98 ± 0.06	40.09 ± 0.04
1994	40.00 ± 0.04	40.28 ± 0.03
1995	40.47 ± 0.06	40.32 ± 0.04

Table 5: Efficiency for the thrust cut.

Reweighting, year by year, the Monte Carlo efficiencies to the data efficiencies, a shift in the result is observed: $\Delta g^e_{c\bar{c}} = +0.07\%$ and $\Delta g^\mu_{c\bar{c}} = +0.11\%$. This shift is taken ad an error estimate, and considered as correlated for the two channels.

4.4 Heavy quark properties

The lifetimes of the b hadrons determine the impact parameter distribution of the decay products, which is the basis of the "anti-b tag" method used in this analysis [13]. Their values, with the current uncertainties, are shown in Table 6. The effect of these uncertainties is $\Delta g^e_{c\bar{c}} = \pm 0.05\%$ and $\Delta g^{\mu}_{c\bar{c}} = \pm 0.05\%$.

B hadron	Mean lifetime (ps)
B_d	1.55 ± 0.03
B_u	1.66 ± 0.03
B_s	1.47 ± 0.06
Λ_b	1.19 ± 0.05

Table 6: Lifetimes of the main b hadrons [14].

The semileptonic branching ratios of c and b hadrons affect the flavour composition of the leptonic samples. Their uncertainties and their influence on the result of the analysis are shown in Table 7.

	B.R. (%)	$\Delta g^e_{c\bar{c}}(\%)$	$\Delta g^{\mu}_{c\bar{c}}(\%)$
$b \to l$	10.58 ± 0.18	0.03	0.04
$b \to c \to l$	9.7 ± 0.5	0.07	0.09
$c \to l$	9.85 ± 0.32	0.21	0.19

Table 7: Effect of the uncertainties of the semileptonic branching ratios of the heavy quarks [14].

The energy spectra of leptons coming from $b \to l$, $c \to l$ and $b \to c \to l$ decays have been tuned and varied as in [12], and the effect has been propagated to the measured gluon splitting rate as shown in Table 8.

	$\Delta g^e_{c\bar{c}}(\%)$	$\Delta g^{\mu}_{c\bar{c}}(\%)$
$b \to l$	-0.01	< 0.01
$b \to c \to l$	$+0.02$	$+0.03$
$c \to l$	$+0.03$	$+0.12$

Table 8: Effect of reweighting the lepton energy spectra in the heavy hadron rest frame [12].

The x_E ($\equiv p_{had}/E_{beam}$) distribution of the heavy hadrons affects the decay length distribution of the heavy hadrons and the momenta of the decay products. The uncertainty coming from the limited knowledge of this quantity has been evaluated by varying $x_E^{(b)}$ and $x_E^{(c)}$ within their estimated errors: $< x_E^{(b)} >= 0.702 \pm 0.008$, $< x_E^{(c)} >= 0.484 \pm 0.008$ [14], obtaining $\Delta g^e_{c\bar{c}} = \pm 0.02\%$ and $\Delta g^{\mu}_{c\bar{c}} = \pm 0.04\%$, $\Delta g^e_{c\bar{c}} = \pm 0.05\%$ and $\Delta g^{\mu}_{c\bar{c}} = \pm 0.05\%$ respectively.

All these systematics are considered correlated between electrons and muons.

4.5 Lepton identification

The systematic error associated with the lepton identification efficiency is estimated by varying by 2% the efficiency in the simulation. The resulting effect is $\Delta g^e_{c\bar{c}} = \pm 0.19\%$ and $\Delta g^{\mu}_{c\bar{c}} = \pm 0.21\%$.

4.6 Fake leptons

The same procedure as in Ref. [12] has been used to correct the rate of fake and non-prompt leptons predicted by the simulation and to estimate the corresponding uncertainty.

A correction factor of 14% is applied to the rate of fake and non-prompt muons that fulfil the selection cuts in the simulation. Such a factor is varied by 5% in order to asses the corresponding systematic uncertainty, obtaining $\Delta g^{\mu}_{c\bar{c}} = \pm 0.49\%$.

For fake and non-prompt electrons, an uncertainty of 20% is assigned to the rate of misidentified hadrons, and an uncertainty of 5% to the rate of photon conversions, giving $\Delta g^{e}_{c\bar{c}} = \pm 0.09\%$.

4.7 Generators

A different modelling of the $g \to c\bar{c}$ process can give a different efficiency and hence a different measured value of $g_{c\bar{c}}$. The selection efficiency depends upon three variables: the energy (E_g) and effective mass (m^*_g) of the gluon and the angle of the charm with respect to the gluon direction, boosted in the gluon frame (θ^*). These have been compared between the JETSET [15] and HERWIG [16] Monte Carlo generators, and their effect on $g_{c\bar{c}}$ has been evaluated as in [17], giving $\Delta g^{e}_{c\bar{c}} = -0.05\%$ and $\Delta g^{\mu}_{c\bar{c}} = -0.11\%$ for the angular distribution; the effect of E_g and m^*_g (which are strongly correlated) is $\Delta g^{e}_{c\bar{c}} = +0.05\%$ and $\Delta g^{\mu}_{c\bar{c}} = +0.25\%$.

The errors are considered correlated for the electron and muon results.

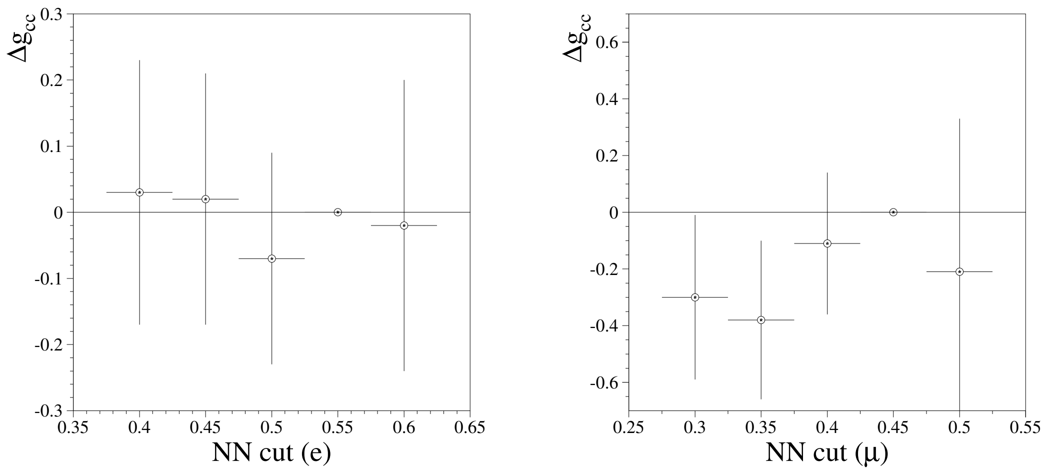
4.8 Mass of the charm quark

The mass of the charm quark has been varied between 1.0 and 1.4 GeV (as central value 1.2 GeV was chosen). The effect of m_c (correlated for electrons and muons) has been estimated as in section 4.7, comparing E_g and m^*_g between the different values of m_c. The result is $\Delta g^{e}_{c\bar{c}} = \pm 0.19\%$ and $\Delta g^{\mu}_{c\bar{c}} = \pm 0.24\%$.

5 Systematic checks

5.1 Stability of the NN cut

The stability of the results has been checked against the cut on the neural network output. Fig. 3 shows separately for electrons and muons the variation of the results versus the cut, together with the statistically uncorrelated error. No significant dependence is observed.



(a) (b)

Figure 3: $\Delta g_{c\bar{c}}$ versus the NN output cut, for electrons and muons. The errors are related to the difference of each point with respect to the cut used in the analysis.

5.2 Data/MC comparison of the shape of the NN output

Fig. 4 shows the contribution of the signal events to the shape of the output of the neural network. The normalization is such that the number of events in the first two bins is the same for data and simulation. Using the $g_{c\bar{c}}$ value obtained with this analysis by averaging the electron and muon results (Section 6), the Monte Carlo distribution is found to be consistent with the data.

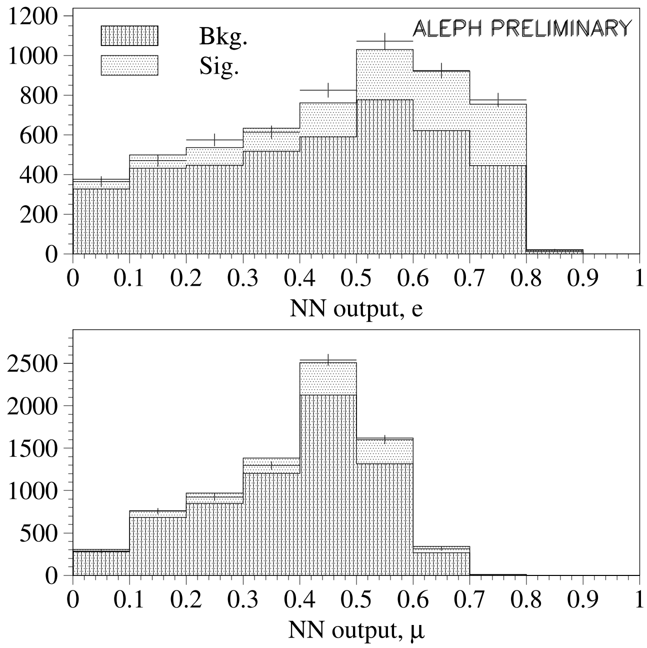


Figure 4: Data/MC comparison of the shape of the NN output; in the MC the contribution of the signal events is shown, using the $g_{c\bar{c}}$ value obtained in this analysis. The error bars are the quadratic sum of the errors for data and MC.

6 Results and conclusion

Considering the systematic uncertainties listed in Table 9, the results for the electron and muon samples are:

$$g^{e}_{c\bar{c}} = (2.99 \pm 0.28(\text{stat.}) \pm 0.41(\text{syst.}))\,\% \quad (4)$$

$$g^{\mu}_{c\bar{c}} = (2.90 \pm 0.38(\text{stat.}) \pm 0.74(\text{syst.}))\,\% \quad (5)$$

The two results are combined taking in account the correlations between systematics (using the Best Linear Unbiased Estimator technique [18]) giving the preliminary ALEPH result

$$g_{c\bar{c}} = (2.98 \pm 0.48)\,\%. \quad (6)$$

This result is in agreement with results of other collaborations [5, 6, 7] and with the present world average $g_{c\bar{c}} = (2.96 \pm 0.38)\%$ [14].

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Source of error	$\Delta g^{e}_{c\bar{c}}$ (%)	$\Delta g^{\mu}_{c\bar{c}}$ (%)
Statistical error	0.28	0.38
MC statistical	0.13	0.21
$g_{b\bar{b}}$	0.10	0.11
Thrust cut efficiency	0.07	0.11
BR($b \to l$)	0.03	0.04
BR($b \to c \to l$)	0.07	0.09
BR($c \to l$)	0.21	0.19
$b \to l$ spectrum	0.01	< 0.01
$b \to c \to l$ spectrum	0.02	0.03
$c \to l$ spectrum	0.03	0.12
Mean lifetimes of B hadrons	0.05	0.05
$< x_E^c >$	0.05	0.05
$< x_E^b >$	0.02	0.04
Lepton identification	0.19	0.21
Misidentifications	0.09	0.49
Generators, θ^*	0.05	0.11
Generators, E_g, m_g^*	0.05	0.25
m_c	0.19	0.24
Total systematics	0.41	0.74

Table 9: Summary of the uncertainties.

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