Measurement of the strong coupling constant $\alpha_s$ for bottom quarks at the $Z^0$ resonance

L3 Collaboration

B. Adeva a, O. Adriani b, M. Aguilar-Benitez c, H. Akbari d, J. Alcaraz e, A. Aloisio f,
G. Alveson f, M.G. Alviggi g, G. Ambrosi h, Q. An i, H. Anderhub j, A.L. Anderson k,
V.P. Andrei l, T. Angelov m, L. Antonov n, D. Antreasian p, P. Arce q, A. Arefiev r,
T. Azemoon s, T. Aziz t, P. V.K.S. Baba u, P. Bagnaia v, J.A. Bakken w, L. Baksay x, R.C. Ball y,
S. Banerjee z, J. Bao b, R. Barillere a, L. Barone q, R. Battiston s, A. Bay t, U. Becker u,
F. Behner v, J. Behrens w, S. Beisinger x, Gy. L. Benecke y, J. Berdugo z, P. Berges a,
B. Bertucci b, B.L. Betev c, A. Biland d, G.M. Bilei e, R. Bizzarri f, J.J. Blaising g, P. Blömeke h,
B. Blumenfeld d, G.J. Bobbink x, M. Bocciolini b, R. Bock w, A. Böhm v, B. Borgia q,
D. Bourilkov f, M. Bourquin t, D. Boutilny u, B. Bouwens x, E. Brambilla y, J.G. Branson γ,
I.C. Brock z, F. Bruyant c, C. Buisson aa, A. Bujak ab, J.D. Burger j, J.P. Burq aa, J. Busenitz z,
X.D. Cai b, M. Capell ac, M. Caria q, G. Carlino o, F. Carminati b, A.M. Cartacci b, M. Cerrada c,
F. Cesaroni q, Y.H. Chang j, U.K. Chaturvedi b, M. Chemarin aa, A. Chen ad, C. Chen ae,
G.M. Chen ae, H.F. Chen af, H.S. Chen ac, M. Chen i, M.L. Chen o, W.Y. Chen g, H. Chieffari c,
C.Y. Chien d, M. Chmeissani o, C. Civinini b, I, Clare j, R. Clare j, H.O. Cohn ag, G. Coignet u,
N. Colino a, V. Commacciolo w, G. Conforto b, A. Contin ma, F. Crijns ah, X.Y. Cui h, T.S. Dai j,
R. D’Alessandro b, R. de Asmundis c, A. Degré au, K. Deiters j, E. Dénes va, P. Denes l,
F. DeNotaristefani q, M. Dhina i, D. DiBitonto s, M. Diemoz o, H.R. Dimitrov t, C. Dionisi q,
M.T. Dova h, E. Drago c, T. Driever ah, D. Duchesneau p, P. Dunker x, I. Duran c,
H. El Mamouni aa, A. Engler β, F.J. Eppling j, F.C. Erné x, P. Extermann t, R. Fabbretti ai,
M. Fabre i, S. Falciano q, Q. Fan h, S.J. Fan aj, O. Fackler ac, J. Fay aa, T. Ferguson β,
G. Fernandez c, F. Ferroni na, H. Fesefeldt w, E. Fiandrini q, J. Field j, F. Filthaut ah,
G. Finocchiaro q, P.H. Fisher d, G. Forconi i, T. Foreman o, K. Freudenberg f, W. Frobel ak,
M. Fukushima i, A. Gailloud az, Yu. Gałaktionow n, E. Gallo b, S.N. Ganguli r, P. Garcia-Abia c,
S.S. Gau ad, D. Gele aa, S. Gentile q, M. Glaubman f, S. Goldfarb o, Z.F. Gong af, E. Gonzalez c,
A. Gordeev k, Y. Guo aj, O. Gurau p, H.R. Gustafson o, L.J. Gutay ab, H. Haan w,
A. Hasan h, D. Hauschildt γ, C.F. He aj, T. Hebbeker m, M. Hebert γ, G. Herten j, U. Herten w,
A. Hervé α, K. Hilgers v, H. Hofer i, H. Hoorani h, L.S. Hsu ad, G. Hu h, G.Q. Hu aj, B. Ille aa,
M.M. Ilyas h, V. Innocente r a, H. Janssen a, S. Jezquel u, B.N. Jin ac, L.W. Jones o, A. Kasser ak,
R.A. Khan h, Y. Kamyschov n, Y. Karyotakis ua, M. Kaur h, S. Khokhar h, V. Khoze k,
M.N. Kienzle-Focacci i, D. Kinnison an, D. Kirby ah, W. Kittel ah, A. Klimontov n,
A.C. König ab, O. Kornadt w, V. Koutsenko nj, J.W. Kraemer z, T. Kramer j, V.R. Krastev γ,
W. Krenz w, J. Krizmanic d, K.S. Kumar ao, V. Kumar h, A. Kunin ao, V. Lalieux i, G. Landi b,
K. Lanius a, D. Lanske w, S. Lanzano c, P. Lebrun aa, P. Lecomte i, P. Lecoq p, P. Le Couttre l,
D. Lee an, I. Leedom r, J.M. Le Goff a, L. Leistam a, R. Leiste ak, M. Lenti b, E. Leonardi q,
J. Lettry t, P.M. Levchenko k, X. Leytens x, C. Li af h, H.T. Li ac, J.F. Li h, L. Li ai, P.J. Li aj,
Q. Li h, X.G. Li ac, J.Y. Liao aj, Z.Y. Lin af, F.L. Linde ax, B. Lindemann w, D. Linthofer i,
R. Liu h, Y. Liu h, W. Lohmann ak, E. Longo o, Y.S. Lu ac, J.M. Lubbers a, K. Lübelsmeyer w,
We have measured the ratio of the strong coupling constants $\alpha_s$ for bottom quarks and light quarks at the $Z^0$ resonance, in order to test the flavour independence of the strong interaction. The coupling strength $\alpha_s$ has been determined from the fraction of events with three jets, measured for a sample of all hadronic events, and for inclusive muon and electron events. The b purity is evaluated to be 22% for the first data set and 87% for the inclusive lepton sample. We find

$$\frac{\alpha_s(b)}{\alpha_s(u,d,s,c)} = 1.00^{+0.05}_{-0.06} \text{ (stat.)} + 0.06 \text{ (syst.)}.$$

1. Introduction

Quantum chromodynamics, the theory of strong interactions, predicts the coupling constant $\alpha_s$ to be independent of the quark flavour.

For the light quark species, up, down and strange, this prediction is supported by the approximate isospin and SU(3) flavour symmetries. The relative coupling strengths for charm and bottom quarks have been measured in $e^+e^-$ annihilation at center of mass energies around 30 GeV [1,2], confirming the flavour independence of $\alpha_s$ within large uncertainties. Also the comparison of $\alpha_s$ values measured in charmonium and bottomonium decays [3] with those obtained for other processes involving only u, d and s quarks supports the flavour independence of the strong interaction. However, since these comparisons involve different energy scales and different systematic errors, the accuracy of such tests is limited. The flavour composition in hadronic events produced in $e^+e^-$ collisions at the $Z^0$ pole is different

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from that at lower center of mass energies. By comparing the corresponding 3-jet fractions one finds that the strong coupling constants for quarks with different electric charge (u, c and d, s, b) agree within 10% [4]. Here we present a precise measurement of the relative coupling strength for bottom quarks at the $Z^0$ resonance using the L3 detector at LEP.

The fraction of bottom events which we measured in hadronic decays of the $Z^0$ boson is in agreement with the standard model prediction of 22% [5,6]. Bottom quarks can be tagged via their semileptonic decays $b \rightarrow l + X$: because of the large mass of the $b$ quark, the leptons have large momentum $p$ and large transverse momentum $p_\perp$ with respect to the nearest jet. By selecting hadronic events containing electrons and muons with large values of $p$ and $p_\perp$ we obtain a sample of events with a high $b$ purity.

As the 3-jet rate ($\sigma_{3\text{-jet}}/\sigma_{\text{tot}}$) is a measure of $\alpha_s$, the comparison of the 3-jet fractions for event samples with different flavour composition provides a test of flavour independence. In this letter we determine the ratio of the 3-jet fraction for inclusive lepton events and of the 3-jet fraction for a sample of all hadronic events. In this double ratio, which is sensitive to the ratio of the coupling constants $\alpha_s(b)/\alpha_s(uds)$, most systematic uncertainties cancel.

The analysis is based on the events collected in 1990 ($\approx 5.5 \text{ pb}^{-1}$ of integrated luminosity) at center of mass energies in the range $88.2 < \sqrt{s} < 94.2 \text{ GeV}$.

2. The L3 detector

The L3 detector covers 99% of $4\pi$. The detector includes a central vertex chamber, a precise electromagnetic calorimeter composed of BGO crystals, a ring of scintillation counters, a uranium and brass hadron calorimeter with proportional wire chamber readout, and a high accuracy muon chamber system. These detectors are installed in a magnet with an inner diameter of 12 m, which provides a uniform field of 0.5 T along the beam direction.

The central tracking chamber is a time expansion chamber consisting of two cylindrical layers of 12 and 24 sectors, with 62 wires measuring the $R-\phi$ coordinate. The single wire resolution is 58 $\mu$m averaged over the entire cell. The double track resolution is 640 $\mu$m. The fine segmentation of the electromagnetic detector and the hadron calorimeter allows us to measure the axis of jets with an angular resolution of about $2.5^\circ$, and to measure the total energy of hadronic events from $Z^0$ decay with a resolution of 10% [7]. The muon detector consists of three layers of precise drift chambers. A detailed description of each detector subsystem, and its performance, is given in ref. [8].

For the present analysis, we use the data collected in the following ranges of polar angles:
- for the central chamber, $41^\circ < \theta < 139^\circ$,
- for the electromagnetic calorimeter, $42^\circ < \theta < 138^\circ$,
- for the hadron calorimeter, $5^\circ < \theta < 175^\circ$,
- for the muon chambers, $36^\circ < \theta < 144^\circ$.

3. Event selection

The primary trigger for hadronic events requires a total energy above 15 GeV in the calorimeters, while the trigger for muons requires the signal of one of the 16 scintillation counter $\phi$ sectors to be in coincidence with a track in the muon chambers. The two triggers are in a logical OR with a charged track trigger and a scintillation counter multiplicity trigger. The combined trigger efficiency exceeds 99.9% for hadronic events, with or without leptons.

The selection of $e^+e^- \rightarrow$ hadrons events is based on the energy measured in the electromagnetic and hadronic calorimeters:

$$0.6 < E_{\text{vis}}/\sqrt{s} < 1.4,$$
$$|E_{\parallel}|/E_{\text{vis}} < 0.40,$$
$$E_{\perp}/E_{\text{vis}} < 0.50,$$
$$N_{\text{cluster}} > 12.$$

$E_{\text{vis}}$ is the total energy observed in the detector, $E_{\parallel}$ and $E_{\perp}$ are the parallel and transverse energy imbalances with respect to the beam direction. $N_{\text{cluster}}$ is the number of clusters, groups of neighbouring hits in the calorimeters with an energy exceeding 100 MeV. The algorithm normally reconstructs one cluster for each particle produced near the interaction point. The cut on the number of clusters rejects low multiplicity events ($e^+e^-, \mu^+\mu^-, \tau^+\tau^-$). Applying the same cuts to simulated events, we estimate the acceptance to be 97%.

Events of the type $Z^0 \rightarrow b\bar{b}$ are selected identifying
the muons or electrons coming from the semileptonic
decay of the b quark.

Muons are identified and measured in the muon
chamber system. A muon track must consist of track
segments in at least two of three layers of the muon
spectrometer. To reject the punch-through back-
ground, we require that the reconstructed track points
to the interaction region.

Electrons are identified using the BGO, the central
tracking chamber and the hadron calorimeter. We re-
quire the lateral showed shape of the cluster in the
BGO to be consistent with that of an electromagnetic
shower. The energy in the hadron calorimeter behind
this cluster must be small, and the centroid of the
cluster must be matched to a track in the vertex
chamber. The selection for both inclusive muon and
electron events is described in detail in ref. [ 5 ].

Leptons coming from b semi-leptonic decays have
a large momentum and a large transverse momentum
with respect to the b quark direction. Therefore we
require the muons and electrons to have a momentum
greater than 4 GeV and 3 GeV respectively, and a
transverse momentum with respect to the axis of the
nearest jet greater than 1.5 GeV for muons and 1
GeV for electrons. For this selection jets are recon-
structed using the algorithm described in ref. [7]: the
measured momentum of the lepton is excluded in the
calculation of the jet direction. From 110,000 had-
ronic events we select approximately 1800 muon and
1100 electron events.

Monte Carlo distributions were generated by the
program JETSET 7.2 [9] with parton shower and
string fragmentation. For the heavy quarks we use the
Peterson fragmentation function [10] with parame-
ters adjusted to match our measured inclusive muon
data [5]. The generated events were passed through
the L3 detector simulation [11] which includes the
effects of energy loss, multiple scattering, interac-
tions and decay sin the detector materials and beam
pipe. From Monte Carlo studies we estimate the b
purity to be 86% for the muon sample and 88% for
the electron sample. The error on these numbers is
estimated to be ±5% [5].

4. Determination of the 3-jet rate

In order to determine the number of jets in the se-
lected samples of hadronic and inclusive lepton
events, we use the JADE algorithm [12]. For each
pair of "particles" (calorimetric clusters and muons)
i and j we calculate the scaled invariant mass squared
\( y_{ij} = 2E_i E_j / E_{\text{vis}}^2 \cdot (1 - \cos \theta_{ij}) \),
where \( E_i \) and \( E_j \) are the particle energies and \( \theta_{ij} \) is the angle between particles
i and j. The pair for which \( y_{ij} \) is smallest is replaced
by a pseudoparticle k with four-momentum \( p_k = p_i + p_j \). This procedure is repeated until all \( y_{ij} \) exceed the
jet resolution parameter \( y_{\text{cut}} \). The remaining pseudo-
particles are called jets.

We determine the 3-jet rate

\[ f_3 = \frac{N_{3\text{-jet}}}{N_{\text{tot}}} \]

(where \( N \) is the number of events) at nine equidis-
stant values of \( y_{\text{cut}} \) ranging from 0.02 to 0.10, for the
total hadronic sample

\[ f_3(\text{had}) = \frac{N_{3\text{-jet}}(\text{had})}{N_{\text{tot}}(\text{had})} \]

and for the inclusive muon and electron samples
separately

\[ f_3(\mu) = \frac{N_{3\text{-jet}}(\text{incl. muons})}{N_{\text{tot}}(\text{incl. muons})} \]
\[ f_3(e) = \frac{N_{3\text{-jet}}(\text{incl. electrons})}{N_{\text{tot}}(\text{incl. electrons})} \]

From these quantities we compute the ratios \( f_3(\mu) / f_3(\text{had}) \) and \( f_3(e) / f_3(\text{had}) \) for each value of \( y_{\text{cut}} \).

In order to correct the two ratios we use the Monte
Carlo JETSET 7.2. The corrected ratios are obtained
by multiplying with a \( y_{\text{cut}} \) dependent factor

\[ C = C_d \cdot C_h \cdot C_b \]

The factors \( C_d \) take into account the detector effects
and are evaluated from the parton shower Monte
Carlo before and after including detector resolution
and acceptance: they range from 0.90 to 1. The fac-
tors \( C_b \) are due to fragmentation effects and are given
by the ratio of \( f_3(\text{incl. lepton}) / f_3(\text{had}) \) before and after had-
ronization: this gives a correction of typically 3%. The
numbers \( C_h \) have been evaluated using the first order
QCD matrix element, including mass effects, assum-
Table 1
Measured 3-jet rates for the inclusive muon and the inclusive electron samples for the nine different values of $Y_{cut}$. The ratios have been corrected for detector acceptance and resolution, for hadronization and bottom mass effect. The first error is statistical, the second is systematic.

<table>
<thead>
<tr>
<th>$Y_{cut}$</th>
<th>$f_3(\mu)/f_3(\text{had})$</th>
<th>$f_3(e)/f_3(\text{had})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.02</td>
<td>0.94 ± 0.03 ± 0.05</td>
<td>0.94 ± 0.04 ± 0.05</td>
</tr>
<tr>
<td>0.03</td>
<td>0.98 ± 0.04 ± 0.05</td>
<td>0.99 ± 0.05 ± 0.06</td>
</tr>
<tr>
<td>0.04</td>
<td>0.99 ± 0.04 ± 0.05</td>
<td>1.00 ± 0.05 ± 0.06</td>
</tr>
<tr>
<td>0.05</td>
<td>0.99 ± 0.04 ± 0.05</td>
<td>1.02 ± 0.06 ± 0.07</td>
</tr>
<tr>
<td>0.06</td>
<td>1.00 ± 0.05 ± 0.06</td>
<td>1.02 ± 0.07 ± 0.07</td>
</tr>
<tr>
<td>0.07</td>
<td>0.97 ± 0.05 ± 0.06</td>
<td>1.03 ± 0.07 ± 0.08</td>
</tr>
<tr>
<td>0.08</td>
<td>0.95 ± 0.06 ± 0.06</td>
<td>1.02 ± 0.08 ± 0.08</td>
</tr>
<tr>
<td>0.09</td>
<td>0.92 ± 0.06 ± 0.07</td>
<td>1.02 ± 0.09 ± 0.09</td>
</tr>
<tr>
<td>0.10</td>
<td>1.00 ± 0.07 ± 0.07</td>
<td>1.04 ± 0.09 ± 0.09</td>
</tr>
</tbody>
</table>

5. Results and conclusions

The two ratios for muons and electrons are finally combined in order to calculate the ratio between the 3-jet fraction for bottom events and for all other flavours. Assuming that there is no difference in the strong interaction for the quarks $u$, $d$, $s$ and $c$, we can write

$$f_3(e + \mu) = \frac{(1 - p^{e+\mu})f_3^{udsc} + p^{e+\mu}f_3^b}{(1 - p^{\text{had}})f_3^{udsc} + p^{\text{had}}f_3^b},$$

where $p^{e+\mu}$ is the combined $b$ purity for the two samples of inclusive lepton events ($87 \pm 5\%$) and $p^{\text{had}}$ is the percentage of $b$ in hadronic events ($22 \pm 0.5\%$).

In first order QCD, the 3-jet rate is proportional to $\alpha_s$:

$$f_3 = A(Y_{cut})\alpha_s.$$

The function $A(Y_{cut})$ has been calculated in ref. [16]. From the ratio $f_3(b)/f_3(udsc)$ we can then determine the relative coupling strength for $b$ and the other quarks: fig. 1 shows the ratio $\alpha_s(b)/\alpha_s(udsc)$ as a function of $Y_{cut}$.

![Fig. 1. Measured $\alpha_s(b)/\alpha_s(udsc)$ ratios, for the inclusive lepton sample (muons and electrons), as a function of the jet resolution parameter $Y_{cut}$. The error includes the statistical and the systematic contributions.](image_url)
where the systematic error includes also the small contributions from the errors on the $p^{e+\mu}$ and $p^{\text{had}}$ fractions. This result is consistent with the flavour independence predicted by QCD. The precision is significantly better than that previously achieved [2].

Acknowledgement

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References