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

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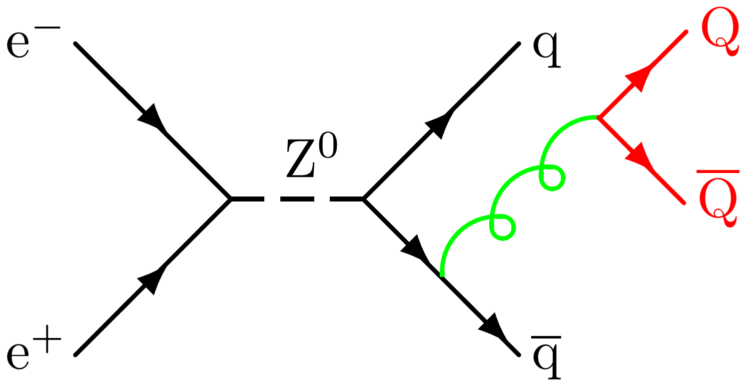
Introduction

Gluon splitting to heavy quarks



$Q = \mathrm{b}$ or c

Production rate

$$g_{Q\overline{Q}} = \frac{\Gamma\left(Z^0 \to q\bar{q}g, g \to Q\overline{Q}\right)}{\Gamma_{\mathrm{hadr}}}$$

- $g_{Q\overline{Q}}$ is sensitive to α_s and m_Q

$\rightarrow$ **measurements of $g_{Q\overline{Q}}$ are interesting tests of QCD**

Theoretical predictions

- theoretical calculations are available (tree-level + leading logarithmic terms)
- the leading logarithmic terms are large
- no full next-to-leading order calculation is available

$\longrightarrow$ **the quark mass m_{Q} is not defined in some renormalisation scheme**

$\longrightarrow$ **relatively large uncertainties in the prediction of $g_{\mathrm{Q\overline{Q}}}$**

Predicted gluon splitting rates

$$g_{c\overline{c}} = (1.05 - 2.55) \times 10^{-2}$$

$$g_{b\overline{b}} = (1.8 - 2.9) \times 10^{-3}$$

These are small rates compared to direct $c\overline{c}$ and $b\overline{b}$ production

$$R_c = \frac{\Gamma\left(Z^0 \to c\overline{c}\right)}{\Gamma_{\mathrm{hadr}}} = 0.1694 \pm 0.0038$$

$$R_b = \frac{\Gamma\left(Z^0 \to b\overline{b}\right)}{\Gamma_{\mathrm{hadr}}} = 0.21680 \pm 0.00073$$

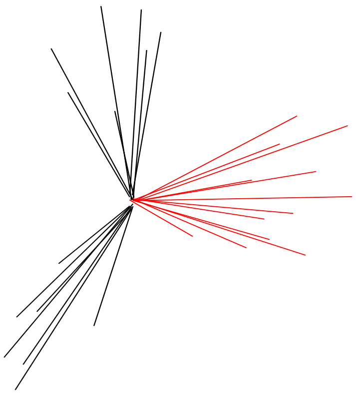
but they have some impact on the precision measurements of R_b and R_c

$$\Delta R_c(g_{Q\overline{Q}}) = 0.0006$$

$$\Delta R_b(g_{Q\overline{Q}}) = 0.00028$$

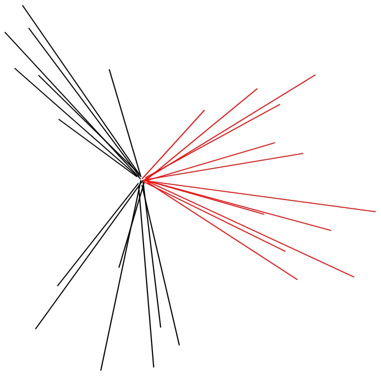
The R_b and R_c results shown here are the results presented at the 1999 winter conferences

Experimental signature for $\mathbf{g \rightarrow c\bar{c}}$



three jets, one of the jets (low-energy, broad) with charm decay products

Experimental signature for $\mathbf{g \rightarrow b\bar{b}}$



four jets, two of the jets (low-energy, close in phase-space) with bottom decay products

The main source of background is from direct $c\bar{c}$ and $b\bar{b}$ production with the radiation of hard gluons.

In addition $g \rightarrow c\bar{c}$ is background for $g \rightarrow b\bar{b}$ and vice versa.

Gluon splitting to $\mathbf{c\bar{c}}$

There are new results from ALEPH, L3 and OPAL (supersedes the old OPAL analysis).

The analyses are based on

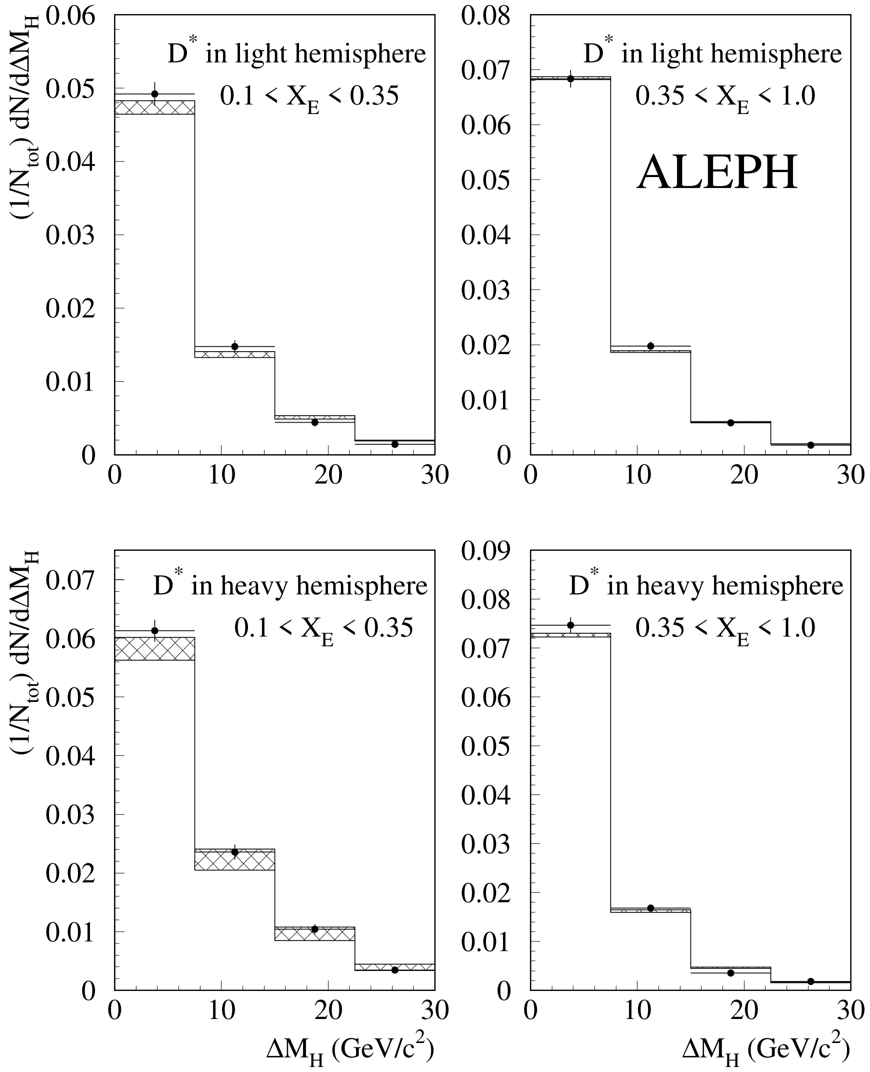
- $D^{\star\pm} \rightarrow D^0\pi^\pm$, $D^0 \rightarrow K^\mp\pi^\pm$ reconstruction (OPAL, ALEPH)
- electron and muon identification (L3 and OPAL)
- event shape variables (L3)

Additional selection criteria are used, like jet masses, jet energies, hemisphere masses, ...

The ALEPH $g_{c\bar{c}}$ analysis

- reconstruct $D^{\star\pm}$ mesons in the decay chain $D^{\star\pm} \to D^0\pi^\pm$, $D^0 \to K^\mp\pi^\pm$
- define two event hemispheres using the thrust axis

  $D^{\star\pm}$ mesons from gluon splitting are preferentially found in the heavy hemisphere
- study the hemisphere mass difference $\Delta M_{\mathrm{H}} = M_{\mathrm{Heavy}} - M_{\mathrm{Light}}$ and the mean scaled $D^{\star\pm}$ energy x_E
- extract $g_{c\bar{c}}$ in a simultaneous fit to ΔM_{H} and x_E



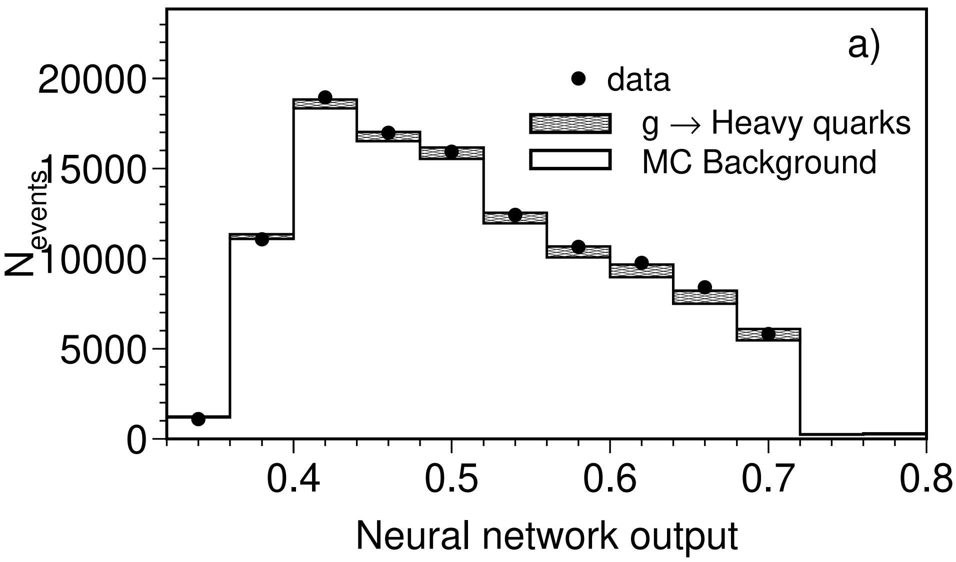
- the $g_{c\bar{c}}$ signal is preferentially in the heavy hemisphere, at low x_E
- the signal-to-background ratio improves with increasing ΔM_{H}

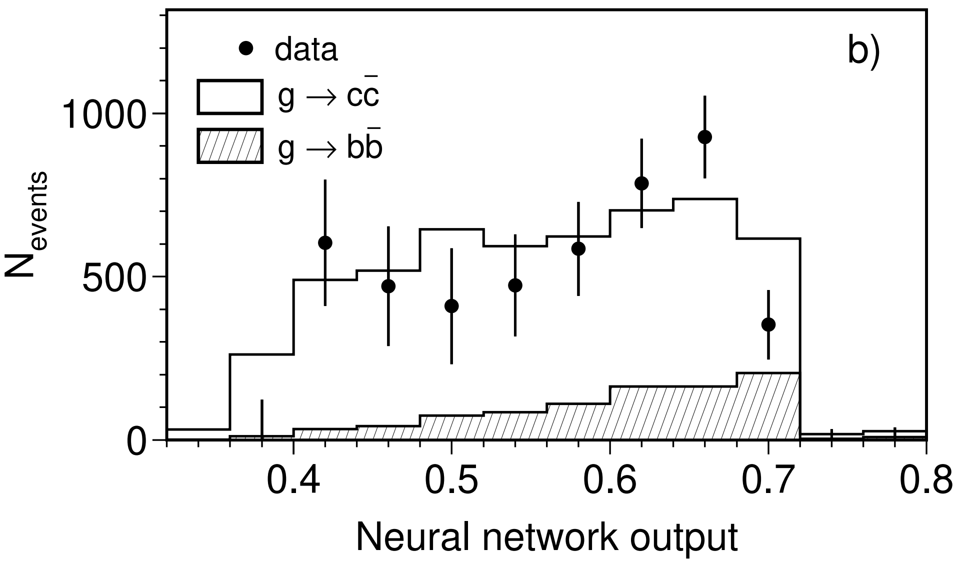
The L3 event shape analysis

- select three-jet events ($E_1 > E_2 > E_3$)
- reject events with primary $\mathrm{b\bar{b}}$ production
- use a neural network to identify gluon splitting to heavy quarks

  The input variables are

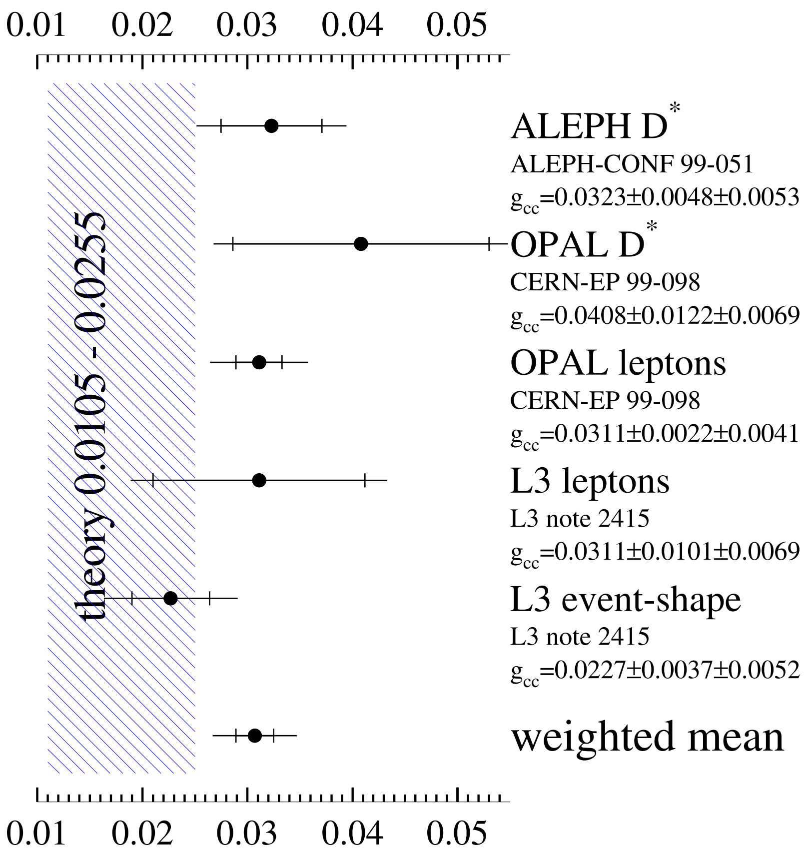
  - the jet mass difference
    $\Delta m = m_3 + m_2 - m_1$
  - the energy-flow in jet 2 inside an 8 degree half-angle cone $\frac{E_{\mathrm{cone}}}{E_{\mathrm{jet}}}$
  - Three different kinds of Fox-Wolfram moments





- L3 chooses a cut on the neural network output $O > 0.59$
- they find 1700 ± 300 signal events after background subtraction

Experimental results for gluon splitting to $c\bar{c}$



$$g_{cc} = 0.0307 \pm 0.0018\,(\mathrm{stat}) \pm 0.0036\,(\mathrm{syst})$$

- the measurements are consistent
- the average is $1.3\,\sigma$ away from theory
- the systematic uncertainties are dominant

Note: $g_{b\bar{b}} = (2.47 \pm 0.55) \times 10^{-3}$ is used for this average.

Gluon splitting to $b\bar{b}$

New results from DELPHI, OPAL, SLD, in addition to older ALEPH and DELPHI analyses.

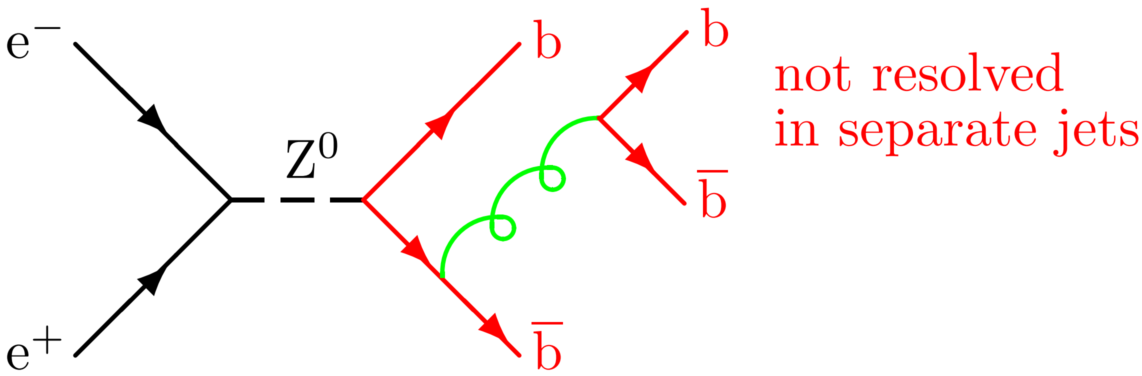
- ALEPH, DELPHI, SLD: four jet events, two low-energetic b-jets with a small opening angle
- DELPHI: three-jet events with a vertex tag in each jet, to measure $b\bar{b}b\bar{b}$ events.

$$R_{4b} = \frac{\Gamma\left(Z^0 \to b\bar{b}b\bar{b}\right)}{\Gamma_{hadr}}$$

- OPAL: four-jet events with two b-jets that are close in phase space, and four jet-events with three b-jets. Simultaneous fit of $g_{b\bar{b}}$ and R_{4b}.

The DELPHI $b\bar{b}b\bar{b}$ analysis

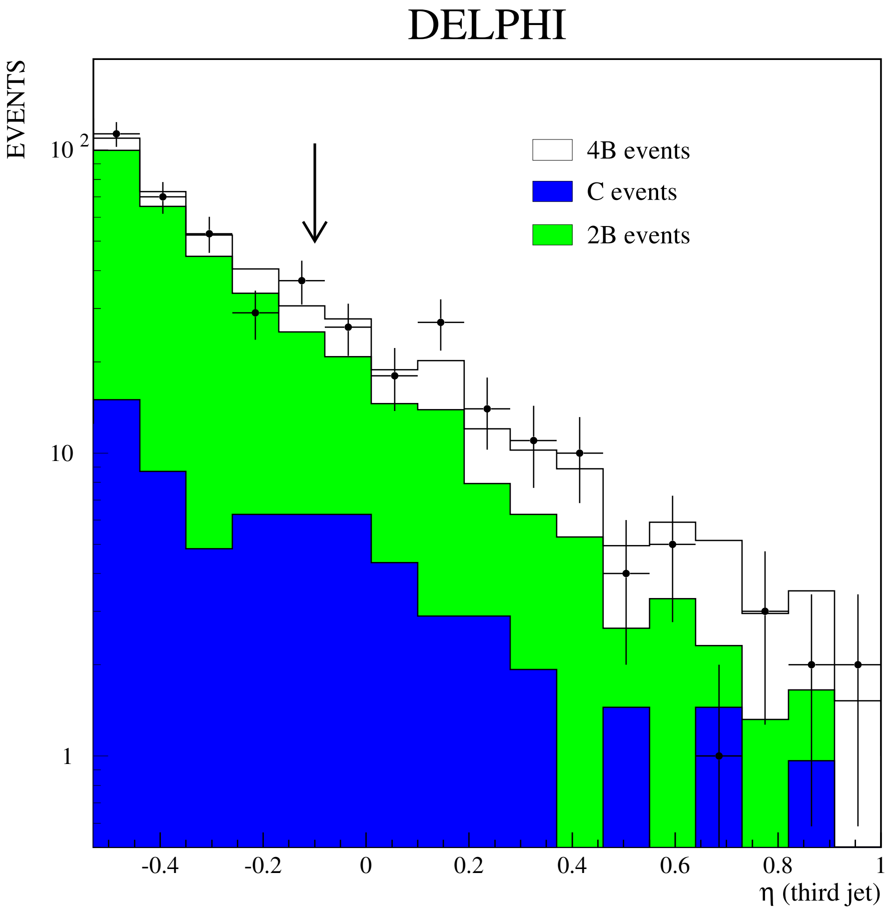
Events with two $b\bar{b}$ quark pairs



- tree level calculations are available
- the predicted ratio

$$\frac{g_{b\bar{b}}}{R_{4b}} = \frac{\Gamma\left(Z^0 \to q\bar{q}g, g \to b\bar{b}\right)}{\Gamma\left(Z^0 \to b\bar{b}b\bar{b}\right)} = 5.457$$

is used to extract $g_{b\bar{b}}$ from R_{4b}



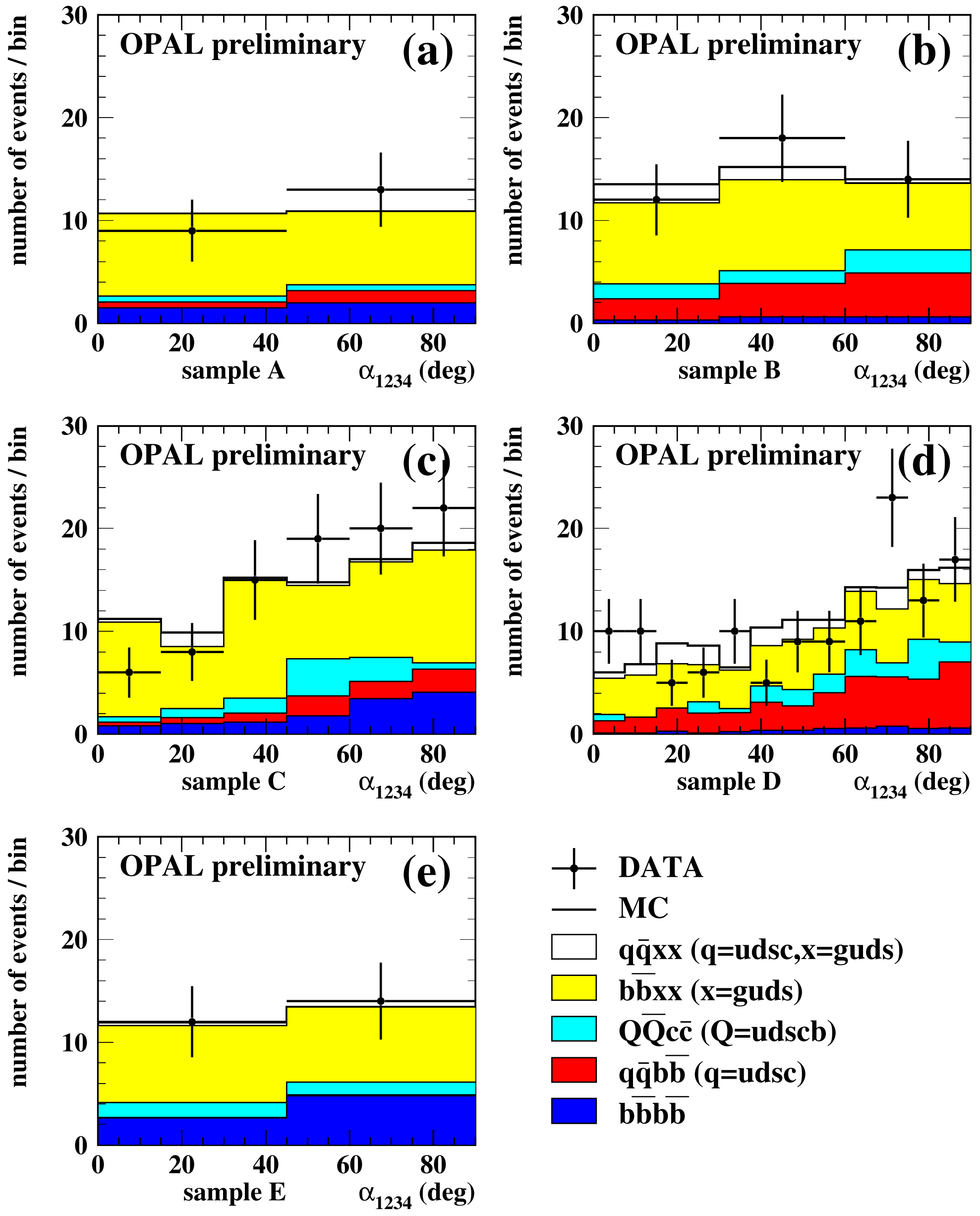
4B: $Z^0 \to b\bar{b}b\bar{b}$

C: $Z^0 \to b\bar{b}g,\ g \to c\bar{c}$ **2B:** $Z^0 \to b\bar{b}g$

- the $b\bar{b}b\bar{b}$ signal is enhanced for a high b-tagging probability η of the jet with the lowest b-tagging probability

The OPAL $g_{\mathrm{b\bar{b}}}$ analysis

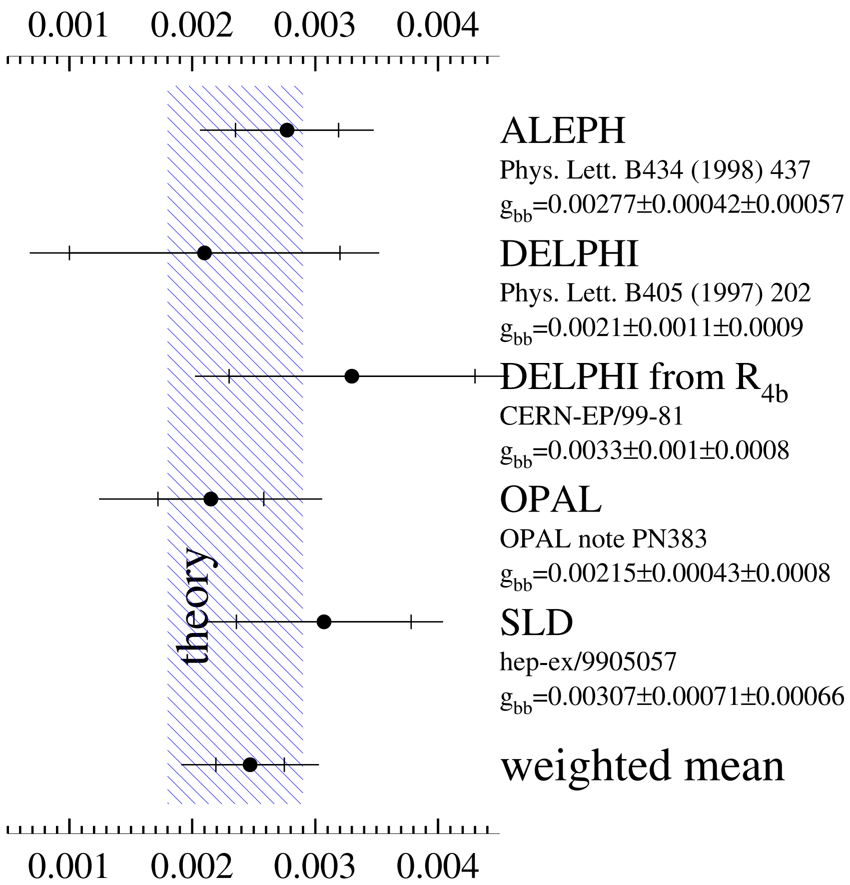
- select four-jet events
- require a b-tag for the two jets i and j that have the smallest jet resolution $y^{ij} = \frac{\min(E_i^2, E_j^2)(1-\cos\theta_{ij})}{(\sum_k E_k)^2}$
- subdivide the event sample further, depending on the event topology and whether b-tags are found in the other jets
- set up an independent selection of four-jet events with at least three b-tagged jets
- consider some angle α_{1234} between jet-jet planes
- extract $g_{\mathrm{b\bar{b}}}$ and R_{4b} in a simultaneous fit



- five statistically independent event samples
- (a), (c), (e) are enriched in $b\bar{b}b\bar{b}$ events
- (b), (d) are depleted in $b\bar{b}b\bar{b}$ events

Stefan Schmitt, Tampere EPS-HEP, July 1999

Experimental results for gluon splitting to $b\bar{b}$



$$g_{bb} = 0.00247 \pm 0.00028\ (\mathrm{stat}) \pm 0.00048\ (\mathrm{syst})$$

- the measurements are consistent
- they are consistent with the prediction
- dominated by systematic uncertainties

Note: the value $g_{c\bar{c}} = (3.07 \pm 0.40) \times 10^{-2}$ is used for this average.

Measurements of $\mathrm{b\bar{b}b\bar{b}}$ events

DELPHI (CERN-EP/99-81)

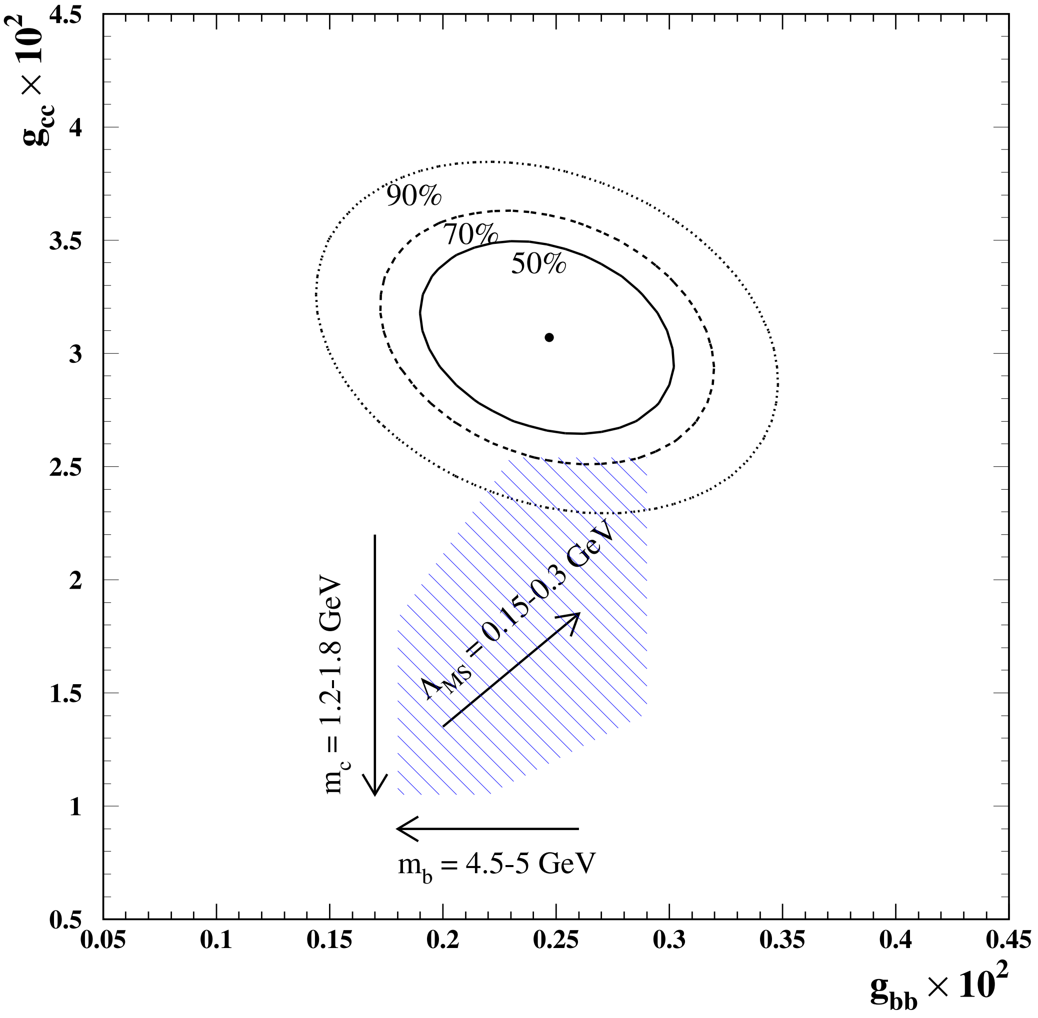
$$R_{4\mathrm{b}} = (0.60 \pm 0.19 \pm 0.14) \times 10^{-3}$$

OPAL (OPAL note PN383)

$$R_{4\mathrm{b}} = (0.53 \pm 0.20 \pm 0.23) \times 10^{-3}$$

- the measurements are consistent
- there is no theoretical prediction besides the tree-level calculation
- the results are compatible with the naive expectation $R_{4\mathrm{b}} \approx R_{\mathrm{b}} \times g_{\mathrm{b\bar{b}}}$

Two-dimensional comparison of $g_{c\bar{c}}$ and $g_{b\bar{b}}$



- the measurements of $g_{c\bar{c}}$ and $g_{b\bar{b}}$ are anti-correlated
- only the upper edge of the theory prediction (small m_c, large $\Lambda_{\overline{MS}}$) is inside the 70% confidence contour

Summary

- five new LEP and one new SLD measurement of gluon splitting to heavy quarks
- the averages are dominated by systematic uncertainties
- the experimental results are consistent
- gluon splitting to $c\bar{c}$ is $1.3\,\sigma$ away from the theoretical prediction
- gluon splitting to $b\bar{b}$ fits to the theoretical prediction

Averaging the $g_{c\bar{c}}$ and $g_{b\bar{b}}$ measurements

- every experiment is weighted according to the total uncertainty
- several sources of systematic uncertainties are treated as correlated between the experiments

The results are

$$
\begin{aligned}
\frac{g_{c\bar{c}}}{10^{-2}} = 3.07 \pm 0.17\,(\mathrm{stat}) \quad & \pm \quad 0.19\,(\mathrm{sys,uncorr}) \\
& \pm \quad 0.30\,(\mathrm{sys,corr}) \\
& \pm \quad 0.08\,(\mathrm{sys},\mathrm{g}_{b\bar{b}}) \\
\frac{g_{b\bar{b}}}{10^{-3}} = 2.47 \pm 0.28\,(\mathrm{stat}) \quad & \pm \quad 0.25\,(\mathrm{sys,uncorr}) \\
& \pm \quad 0.39\,(\mathrm{sys,corr}) \\
& \pm \quad 0.13\,(\mathrm{sys},\mathrm{g}_{c\bar{c}})
\end{aligned}
$$

The following sources of systematic uncertainties are treated as correlated for $g_{c\bar{c}}$

	ALEPH $D^\star$	OPAL $D^\star$	OPAL leptons	L3 leptons	L3 event-shape
b,c fragm	0.0024	0.0025	0.0007	0.0006	0.0011
MC model	0.0072	0.0025	0.0017	0.0022	0.0021
R_b	—	0.0001	0.0001	0.0010	0.0033
$\mathrm{Br}(X \to \ell)$	—	—	0.0025	0.0050	—

The following sources of systematic uncertainties are treated as correlated for $g_{\mathrm{b\overline{b}}}$

	ALEPH	DELPHI	OPAL	SLD	DELPHI $R_{4\mathrm{b}}$
MC-model	0.00031	0.00040	0.00036	0.00008	0.00026
b mass	0.00017	0.00010	0.00010	0.00006	—
c physics	0.00011	—	0.00011	0.00009	0.00025
b physics	0.00018	0.00040	0.00031	0.00018	0.00020