Gluon splitting to $b\bar{b}$ e $c\bar{c}$ at the Z resonance

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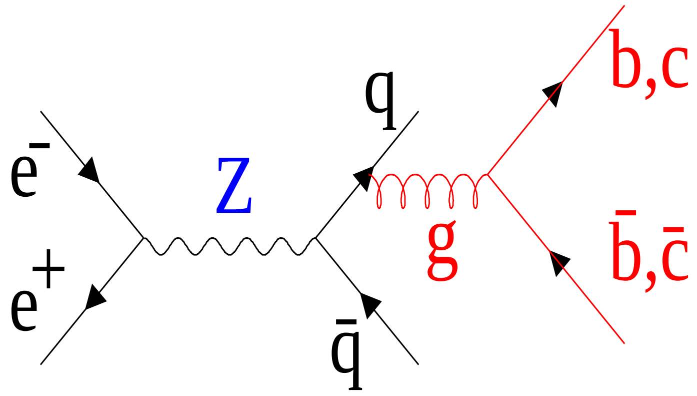
- The process
- Theoretical estimates and Monte Carlo models
- Experimental measurements of $g \to c\bar{c}$
- Experimental measurements of $g \to b\bar{b}$
- Combined estimates

The physical process

- *Gluon splitting* is the process



$$g_{Q\bar{Q}} = \frac{\Gamma(g \to Q\bar{Q})}{\Gamma(Z \to q\bar{q})}$$

Q = heavy quarks (b, c); q = all families

- Theoretical predictions give

$\Lambda_5^{\overline{MS}}$(MeV)	$\alpha_s(M_Z)$	$g_{c\bar{c}}(\%)$	$g_{b\bar{b}}(10^{-3})$
150	0.112	$1.35^{+0.48}_{-0.30}$	$2.0^{+0.2}_{-0.2}$
300	0.125	$1.85^{+0.69}_{-0.44}$	$2.6^{+0.3}_{-0.3}$

- Monte Carlo models give predictions in agreement with theoretical calculations

	$g_{c\bar{c}}(\%)$	$g_{b\bar{b}}(10^{-3})$
JETSET 7.4	1.701 ± 0.013	1.60 ± 0.04
HERWIG 5.9	0.923 ± 0.005	2.27 ± 0.01
ARIADNE	2.177 ± 0.015	3.26 ± 0.06

- Monte Carlo based upon Parton Shower models are in better agreement than Matrix Element ones.

- A good experimental knowledge of $g_{b\bar{b}}$ and $g_{c\bar{c}}$ rates is important for
  - Test of QCD parameters.
  - Decrease the error on R_b.
  - Future experiments at hadron colliders: at LHC energies more than 50% of $b\bar{b}$ events will be produced *via* gluon splitting.

$g_{c\bar{c}}$: Available experimental measurements

- OPAL : measurement using energy spectra of D^*.

- ALEPH : measurement with mass difference between hemispheres in events with D^*.

- OPAL and L3: search for leptons in three jet events.

- L3 : event–shape variables as inputs in a neural network

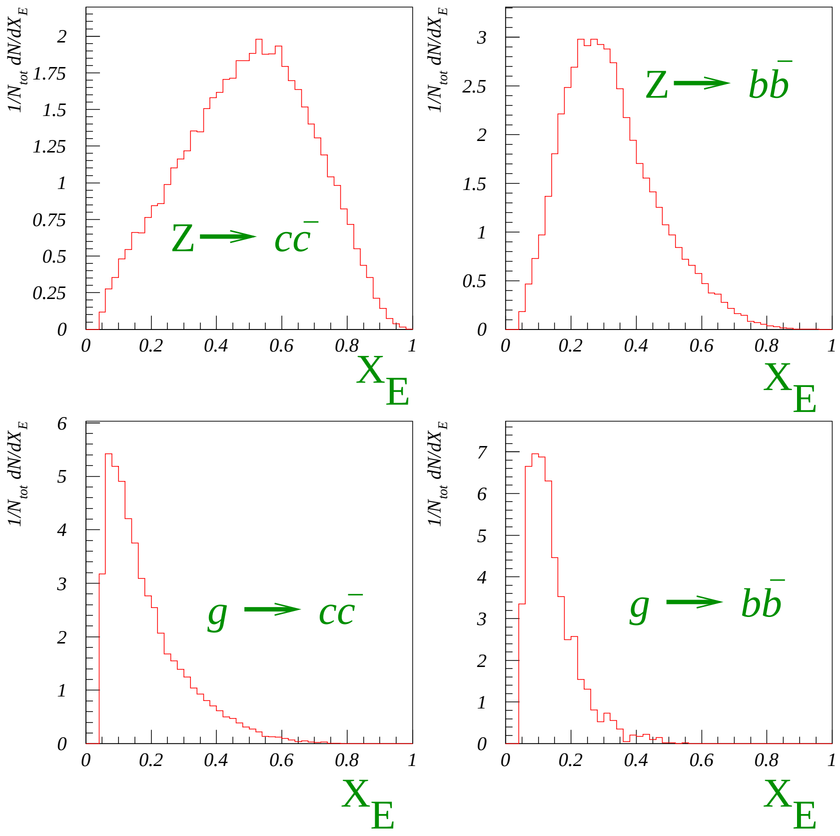
$g_{c\bar{c}}$: methods based on D^* reconstruction

Those methods search for the inclusive decay chain

$$D^{*+} \rightarrow D^0\pi^+ \qquad (68\%)$$
$$D^0 \rightarrow K^-\pi^+ \qquad (4\%)$$

The main advantages are:

- $M(D^*) - M(D^0) \sim M(\pi)$, so phase space accessible to background is small.
- It is easily possible to distinguish between the process that generated D^* from energy spectra: $X_E = \frac{E_{D^*}}{E_{Beam}}$.



Measurements with D^*

- OPAL:
  - Fit to the X_E distribution:

    OPAL D^* $\quad g_{c\bar{c}} = (4.4{\pm}1.4\ (\mathrm{stat}){\pm}1.5\ (\mathrm{syst}))\%$

  - Systematic errors mainly from bottom quarks rejection and uncertainty in heavy flavour fragmentation functions.

- ALEPH:
  - Fit to the shape of mass difference between hemispheres:

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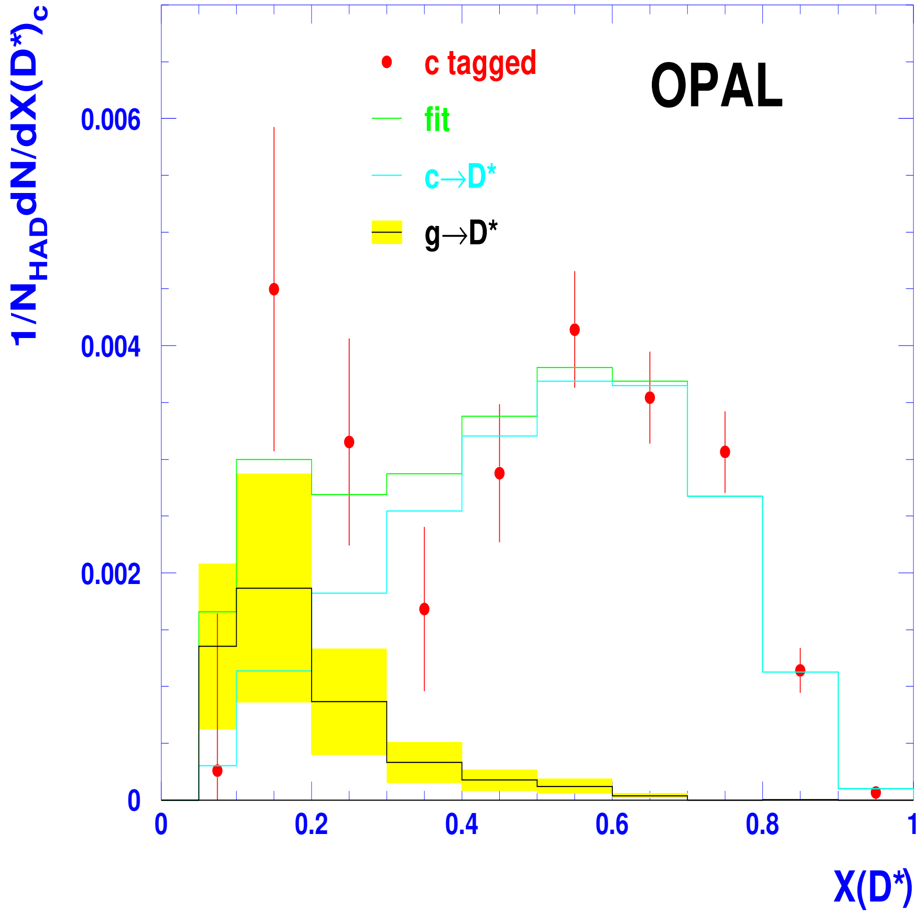
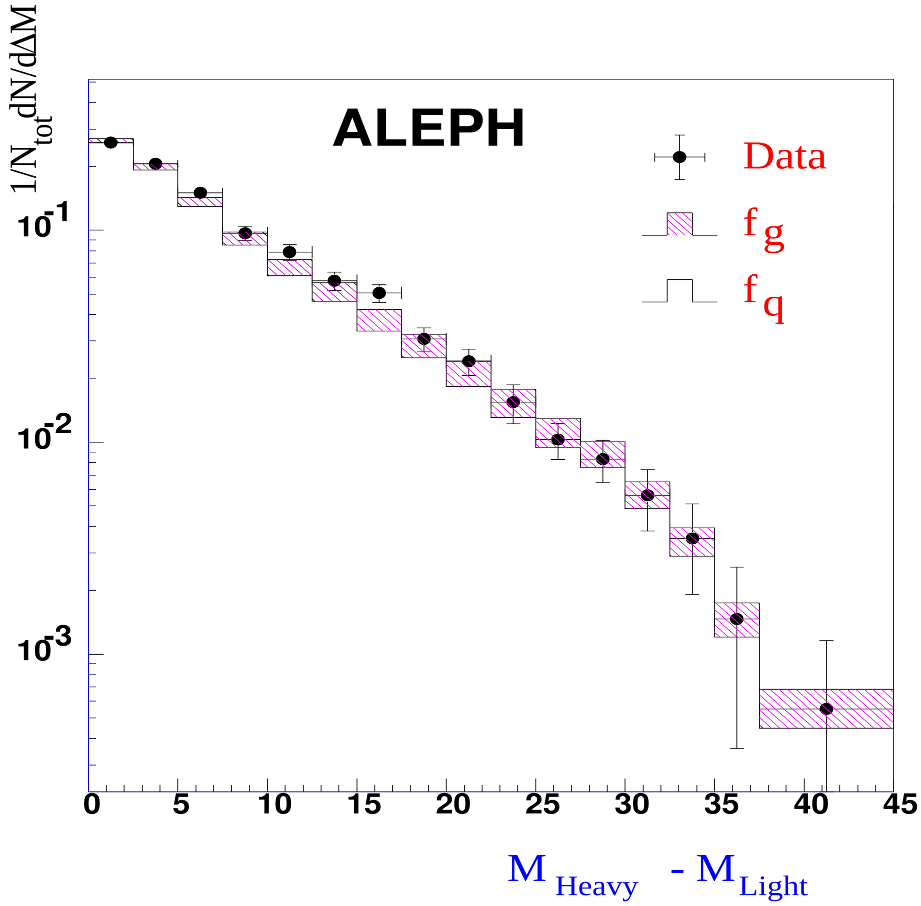
    ALEPH D^* $\quad g_{c\bar{c}} = (2.65{\pm}0.74\ (\mathrm{stat}){\pm}0.51\ (\mathrm{syst}))\%$

  - Systematic errors mainly from QCD parameters (quark masses, Λ_{QCD}) and uncertainty in heavy flavour fragmentation functions.


OPAL
c tagged
fit
c→D*
g→D*
1/N_HAD dN/dX(D*)_c
0.006
0.004
0.002
0
0
0.2
0.4
0.6
0.8
1
X(D*)


ALEPH
Data
f_g
f_q
1/N_tot dN/dΔM
10^-1
10^-2
10^-3
0
5
10
15
20
25
30
35
40
45
M_Heavy - M_Light

Measurements with leptons

- Those methods select events with $g \to c\bar{c} \to Xl\nu$.
- The two c quarks from $g \to c\bar{c}$ are clustered in the same jet in 3 jet events (JADE, $y_{cut} = 0.03$).
- Due to phase space limitations, this jet is likely to be the least energetic one.

Background:

- $Z \to b\bar{b}$ and $Z \to c\bar{c}$ decays ☞ rejected with b antitag and subtracted
- $g \to b\bar{b}$ ☞ subtracted using theoretical input $R \equiv \frac{g_{b\bar{b}}}{g_{c\bar{c}}}$
- photon conversions ☞ subtracted
- Dalitz decays of π^0 and η ☞ subtracted
- Fake leptons ☞ subtracted

OPAL and L3 results

- OPAL estimates 325 e and 175 μ from $g \to c\bar{c}$ after background subtraction

  OPAL leptons $g_{c\bar{c}} = (2.27 \pm 0.28\ (\mathrm{stat}) \pm 0.41\ (\mathrm{syst}))\%$

- L3 estimates 75 e and 51 μ from $g \to c\bar{c}$ after background subtraction

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  L3 leptons $g_{c\bar{c}} = (2.68 \pm 0.64\ (\mathrm{stat}) \pm 0.59\ (\mathrm{syst}))\%$

The main systematic errors for both analysis are

- semileptonic BR of heavy quarks
- fragmentation models for heavy quarks
- fake leptons

L3 – Neural Networks

- Neural network in 3–jet events. The inputs are:
  - Mass differences in jets
  - Fox-Wolfram moments
  - Energy in a $8°$ cone around the second most energetic jet
- Cut on number of tracks displaced from the primary vertex

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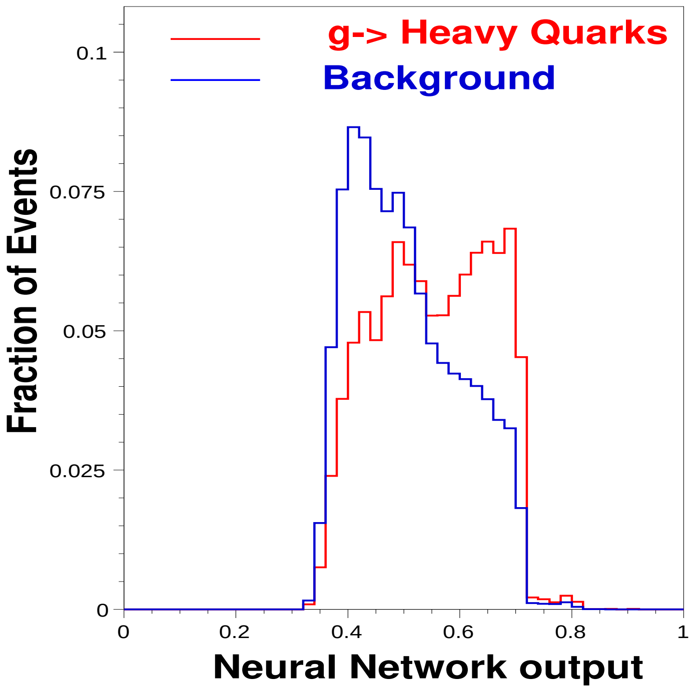
L3 NN $\quad g_{c\bar{c}} = (2.05 \pm 0.19\ (\mathrm{stat}) \pm 0.48\ (\mathrm{syst}))\%$

Main systematic errors:

- subtraction of $g \to b\bar{b}$ events
- R_b
- detector calorimetric response



$g_{b\bar{b}}$: Available measurements

- Indirect estimate of $g_{b\bar{b}}$: given $R \equiv \frac{g_{b\bar{b}}}{g_{c\bar{c}}} = (0.13 \pm 0.04)$ (theoretical error) and $g_{c\bar{c}} = (2.4 \pm 0.5)\%$

$$\Downarrow$$

$$g_{b\bar{b}} = (3.1 \pm 1.1) \times 10^{-3}$$

- Experimental measurements have been presented by DELPHI and ALEPH. They use:
  - 4 jet events: good rejection of background, clustering optimized to force the two b quarks from splitting in 2 jets.
  - lifetime tags.
  - topological cuts.
- Alternative approach: use $Z \to b\bar{b}b\bar{b}$ events
  - Requiring at least 3 good b jets rejects background without other efforts
  - Unfortunately, also on signal the statistics go down.

  ALEPH and DELPHI tried this approach.

DELPHI $g_{b\bar{b}}$ (2b)

- 4 Jets using DURHAM ($y_{cut} = 0.017$) $\Rightarrow$15% efficiency on $g \rightarrow b\bar{b}$, 2% on background.

- Jets are ordered in relative angle: the closer two are expected to come from $g \rightarrow b\bar{b}$ in signal events. The event is discarded is these jets are the most energetic.

- Cut on lifetime of the first two jets.

- Cuts on topological variables (rapidity of the first jet with respect to thrust axis, acoplanarity).

⇨ The analysis uses only 1994 data ($\sim 1.4 \times 10^6$ events); the cuts select 22 events, with a purity of 40%.

⇨ The efficiency on signal events is $\epsilon = 0.31\%$.

The result is

DELPHI 2b $\quad g_{b\bar{b}} = (2.1 \pm 1.0\ (\mathrm{stat}) \pm 0.9\ (\mathrm{syst})) \times 10^{-3}$

➪ Systematic errors:

- Monte Carlo statistics $\rightarrow 0.6 \times 10^{-3}$
- Model dependence (comparison Matrix Element – Parton Shower) $\rightarrow 0.4 \times 10^{-3}$
- Topological cuts $\rightarrow 0.4 \times 10^{-3}$
- Lifetime tag efficiencies $\rightarrow 0.4 \times 10^{-3}$

DELPHI $g_{b\bar{b}}$ (4b)

- 3 Jets using Durham ($y_{cut} = 0.06$)
- Jets are ordered in lifetime: the first one contains more tracks from b decay.
- Cut on probability of each jet to come from b.

➩ 140 events selected from 2×10^6(1994+1995)
➩ The efficiency on signal events is $\epsilon = 3.2\%$.

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DELPHI 4b $\quad g_{b\bar{b}} = (3.0 \pm 1.0\ (\mathrm{stat}) \pm 0.8\ (\mathrm{syst})) \times 10^{-3}$

Errors from

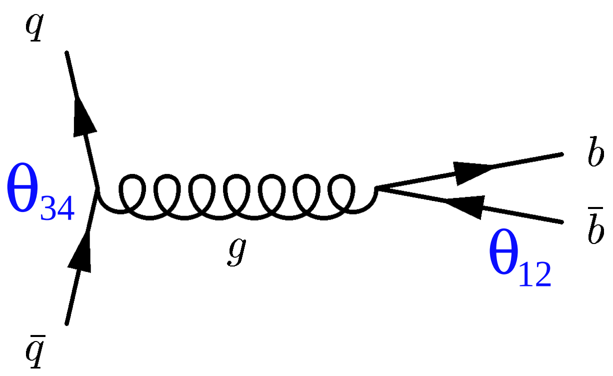
- Signal simulation $\rightarrow 0.30$.
- Data/MC discrepancy in 3-jet rate $\rightarrow 0.40$.
- $g_{c\bar{c}} \rightarrow 0.56$.

ALEPH $g_{b\bar{b}}$ (2b)

- 4 Jets using DURHAM, ($y_{cut} = 0.006$)
  $\Rightarrow$ 50% efficiency on $g \to b\bar{b}$, 10% on background.
- Jets are ordered in decreasing lifetime $\Rightarrow$ in signal events B hadrons are in jet 1 and 2.
- Cut on lifetimes of first two jets.
- Small angle between the first two jet and large angle between the second pair.
- Jets from gluon splitting must have low momentum, while jets from primary quarks can have high momentum.

➩ 222 events over 3.7×10^6 are selected, with a purity of about 45% .

➩ The efficiency on signal events is $\epsilon = 0.96\%$.



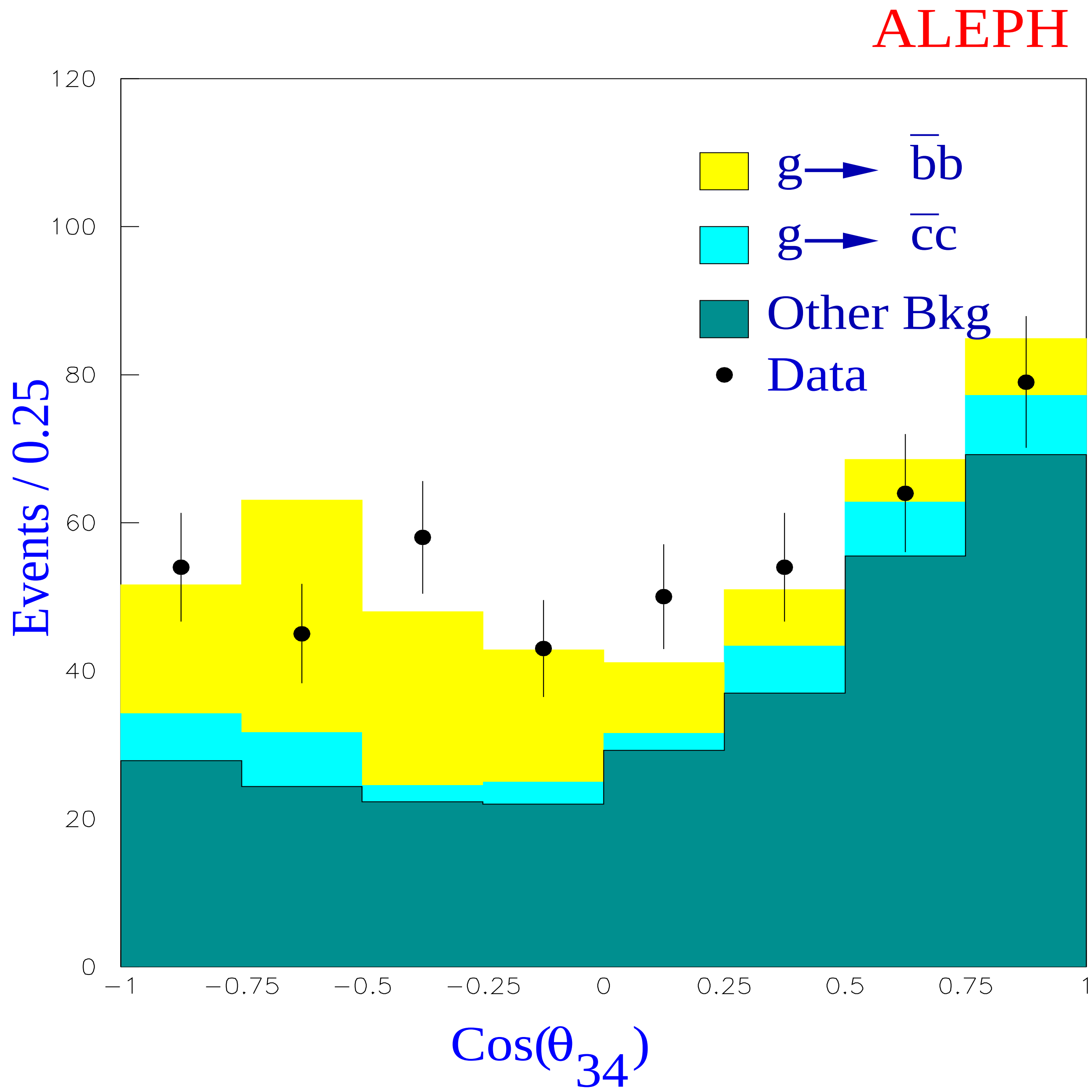
The measured value is:

ALEPH $g_{b\bar{b}} = (2.77 \pm 0.42\ (\mathrm{stat}) \pm 0.57\ (\mathrm{syst})) \times 10^{-3}$

Systematics take into account:

- Monte Carlo statistics $\rightarrow$ 0.26.
- $B\&C$ hadrons physics uncertainties $\rightarrow$ 0.32.
- Experimental error on $g_{c\bar{c}}$ $\rightarrow$ 0.11.
- Model dependence on signal simulation (JETSET – HERWIG) $\rightarrow$ 0.31.
- b quark mass $\rightarrow$ 0.17.
- Detector simulation $\rightarrow$ 0.10.

Data composition of selected events



ALEPH $g_{b\bar{b}}$ (4b)

- Same 4 jets than $2b$ analysis.
- Cut on lifetime of the first 3 jets.

  259 events are selected (32 in common with $2b$ analysis)

ALEPH 4b $\quad g_{b\bar{b}} = (3.6 \pm 0.6\ (\text{stat}) \pm 0.8\ (\text{syst})) \times 10^{-3}$

- Main systematic errors:
  - Monte Carlo statistics $\rightarrow$ 0.42.
  - $B\&C$ hadrons physics uncertainties $\rightarrow$ 0.56.
  - Model dependence on signal simulation (JETSET – HERWIG) $\rightarrow$ 0.40.

Combined estimations

I combined $g_{b\bar{b}}$ and $g_{c\bar{c}}$ measurements using BLUE technique, taking into account:

- The correlations between different measurements of the same quantity.
- The fact that $g_{b\bar{b}}$ is a input to $g_{c\bar{c}}$ measurements, and *vice-versa*.

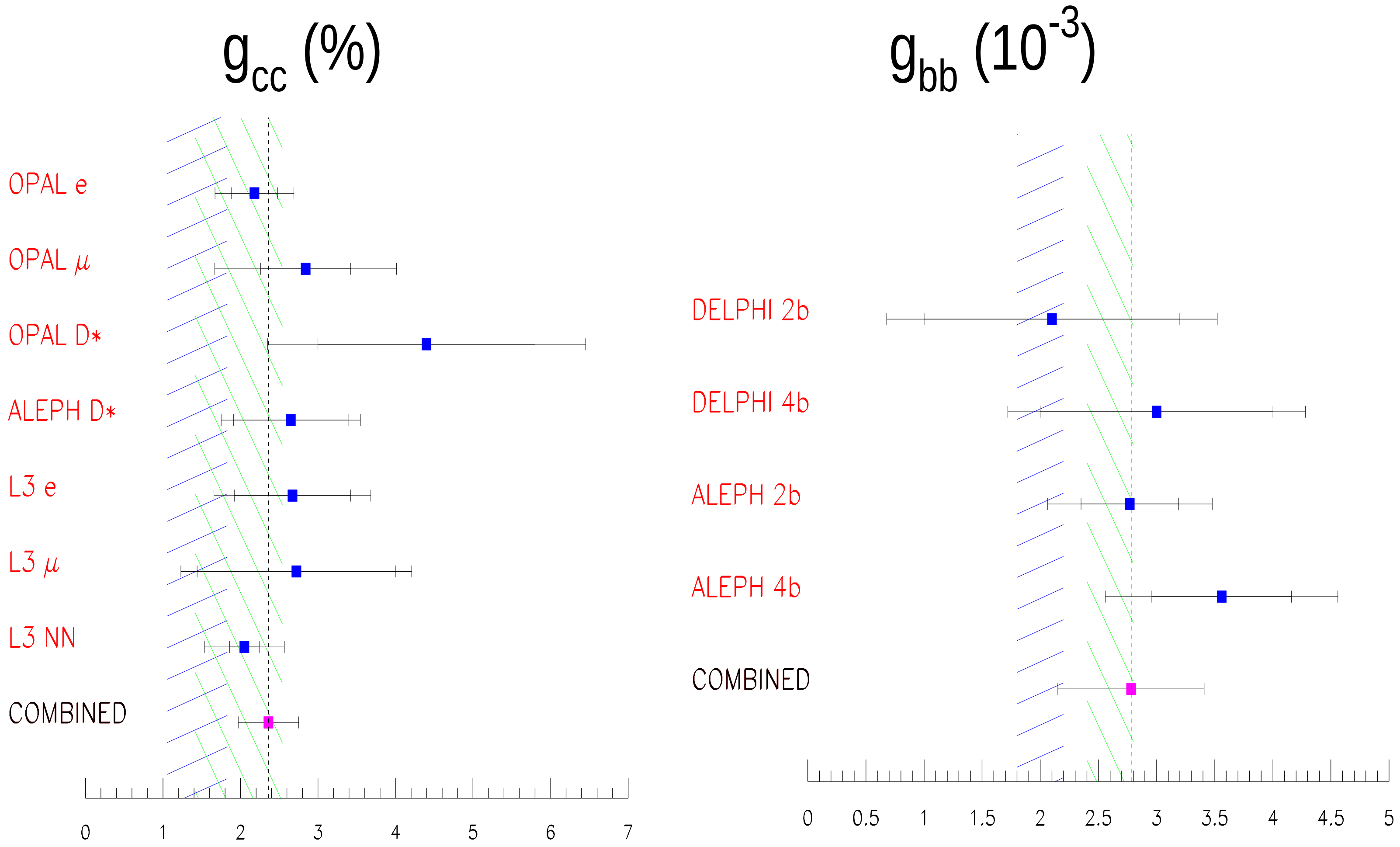
I used an iterative method, giving:

$$g_{c\bar{c}} = (2.36 \pm 0.39)\%$$

$$g_{b\bar{b}} = (2.78 \pm 0.63) \times 10^{-3}$$

Weights from BLUE

	$g_{c\bar{c}}$		$g_{b\bar{b}}$		
	OPAL e	47.5%	DELPHI $2b$	13%	
	OPAL μ	6.0%	DELPHI $4b$	15%	NEW
	OPAL D^*	3.3%	ALEPH $2b$	65%	FINAL
	ALEPH D^*	2.7%	ALEPH $4b$	6%	FINAL
NEW	L3 e	0.6%			
NEW	L3 μ	0.4%			
NEW	L3 NN	39.5%			


g_{cc} (%)
OPAL e
OPAL μ
OPAL D*
ALEPH D*
L3 e
L3 μ
L3 NN
COMBINED
0 1 2 3 4 5 6 7
g_{bb} (10^{-3})
DELPHI 2b
DELPHI 4b
ALEPH 2b
ALEPH 4b
COMBINED
0 0.5 1 1.5 2 2.5 3 3.5 4 4.5 5

Conclusions

- The value for the gluon splitting rates agree with standard model predictions. In particular, both $g_{b\bar{b}}$ and $g_{c\bar{c}}$ seem to privilege high values of $\Lambda_5^{\overline{MS}}$.
- The combined value for Winter Conferences for R_b is 0.2170 ± 0.0009. Using the value for $g_{b\bar{b}}$ here presented R_b can be rescaled to 0.2171 ± 0.0008.
- While $g_{c\bar{c}}$ precision was already comparable with theoretical errors, the new measurement of $g_{b\bar{b}}$ by ALEPH is for the first time precise enough

$$\Downarrow$$

I propose to use from now on the combined value $g_{b\bar{b}} = (2.78 \pm 0.63) \times 10^{-3}$ as input for heavy flavour measurements.