Gluon splitting to $c\bar{c}$ at the Z^0 resonance

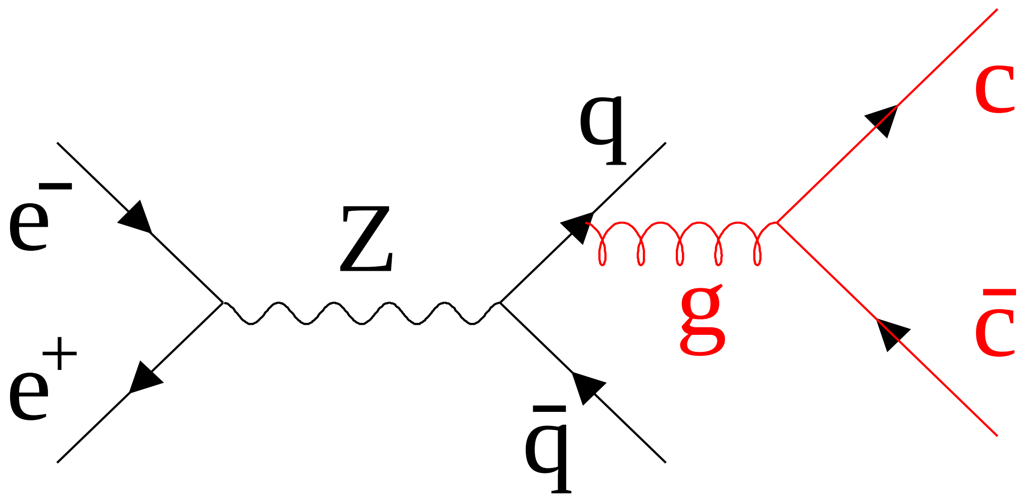
Andrea Giammanco

INFN Pisa & Scuola Normale Superiore Pisa
on behalf of ALEPH Collaboration

- The process
- Theoretical estimates
- Previous measurements
- New ALEPH measurement
- Combined estimates

The physical process:

$$Z^0 \to q\bar{q}\, g \quad , \quad g \to c\bar{c}$$



$$\boxed{g_{c\bar{c}} = \frac{\text{N. of events with } g\to c\bar{c}}{\text{Total number of } Z \to q\bar{q}}}$$

Theoretical predictions

- The heavy quark mass provides a natural infrared cut-off
- Tree level + leading logarithmic calculations are available
- The leading logarithmic terms are large
- No next-to-leading order calculation is available

Theoretical calculations predict:

$$g_{c\bar{c}} = 2.3 \times 10^{-2} \quad (m_c = 1.2\ \text{GeV}, \alpha_s = 0.120)$$
$$g_{c\bar{c}} = 1.7 \times 10^{-2} \quad (m_c = 1.5\ \text{GeV}, \alpha_s = 0.120)$$
$$g_{c\bar{c}} = 2.0 \times 10^{-2} \quad (m_c = 1.2\ \text{GeV}, \alpha_s = 0.118)$$

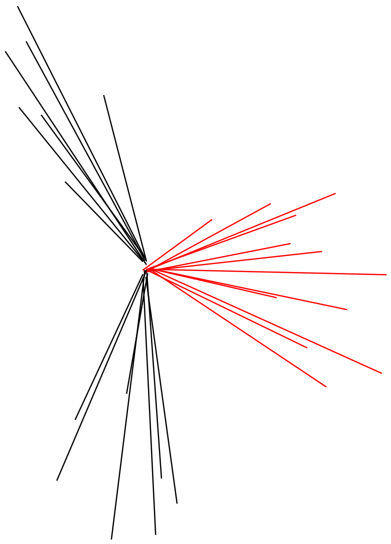
(15 – 30% uncertainty due to the truncation of the perturbation series)

References:

M.H. Seymour, *Heavy quark pair multiplicity in e^+e^- events*, 1995, Nuclear Physics B 436, 163–183

D.J. Miller, M.H. Seymour, *Secondary heavy quark pair production in e^+e^- annihilation*, Phys.Lett. **B435** (1998) 213

Experimental signature for $g \to c\bar{c}$:



three jets; the c decay products mainly in the lowest momentum jet.

Backgrounds:

For $Z^0 \to q\bar{q}g, g \to Q\bar{Q}$, the main background is $Z^0 \to Q\bar{Q}g, g \to q\bar{q}$.

$g \to b\bar{b}$ is also a background for $g \to c\bar{c}$.

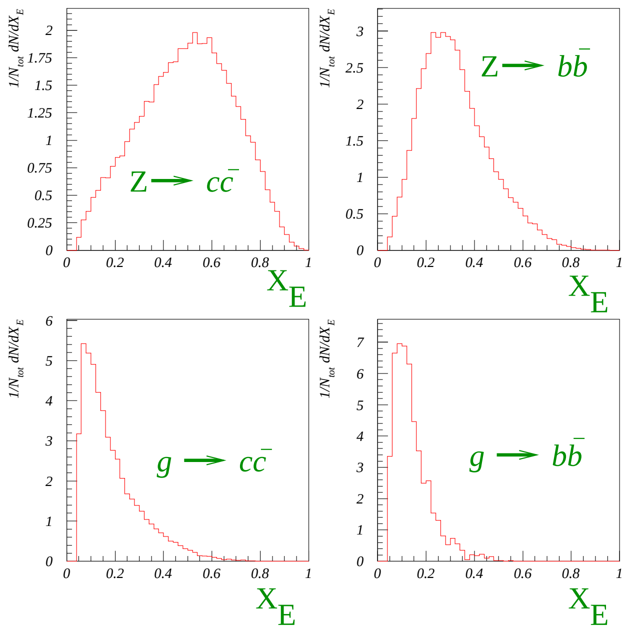
Measurement strategies

- Look for D^*(OPAL,ALEPH).
- Combination of event-shape variables (L3).
- Look for leptons in 3 jet events (OPAL,L3,ALEPH).

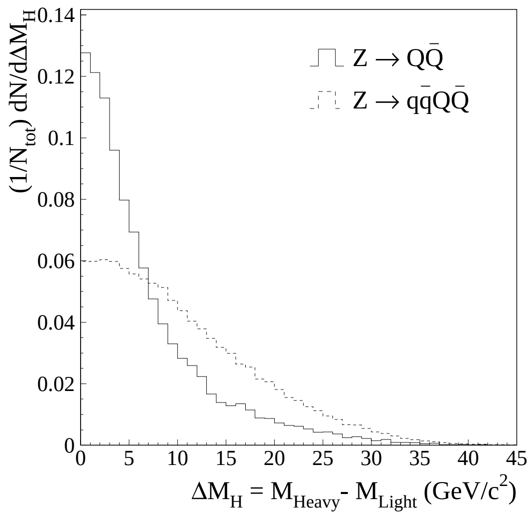
Methods based on D^* reconstruction

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

- energy spectra of D^*



- mass difference between hemispheres in events with D^* (ALEPH).

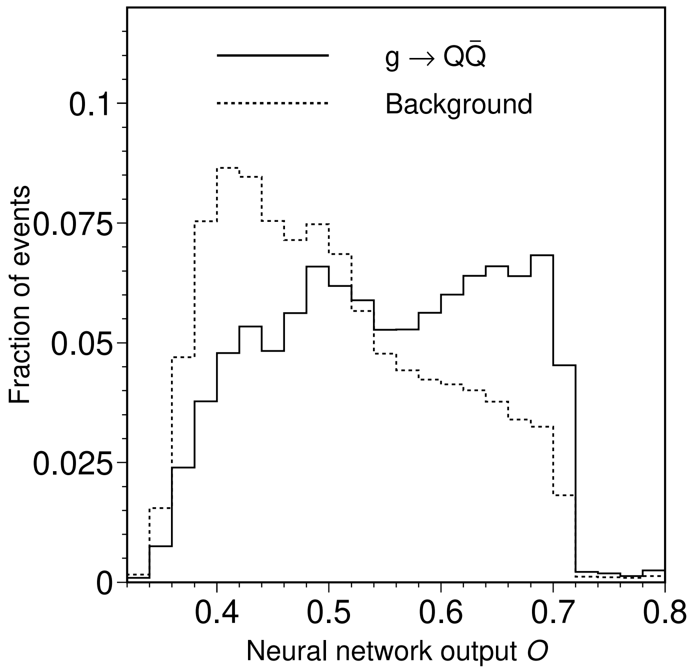


Exp	Fit to	$g_{c\bar{c}} \pm (stat) \pm (syst)$	Main systematics
OPAL	X_E	$(4.08 \pm 1.22 \pm 0.79)\%$	b rejection, fragmentation
ALEPH	ΔM_H	$(3.23 \pm 0.48 \pm 0.53)\%$	m_Q,Λ_{QCD}, fragmentation

Event shape analysis

L3 selects 3 jet events, then:

- enriches in heavy quarks looking for secondary vertices
- uses a Neural Network with:
  - $\Delta M \equiv M_3 + M_2 - M_1$ (energy ordering)
  - three different Fox-Wolfram moments



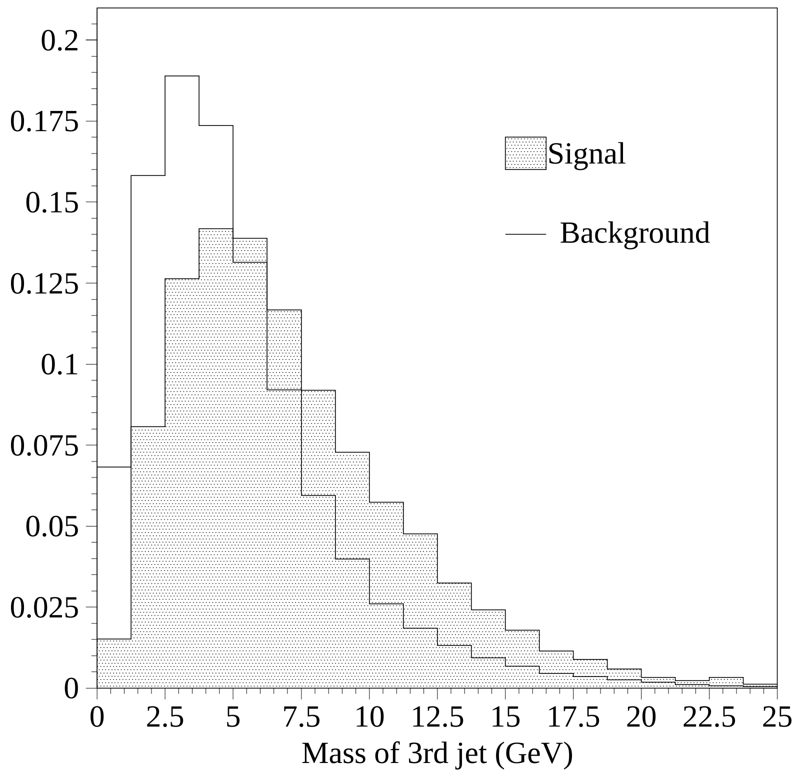
$$g_{c\bar{c}} = (2.27 \pm 0.30(stat) \pm 0.59(syst))\%$$

Main systematic errors:

- subtraction of $g_{b\bar{b}}$ events
- R_b uncertainty
- detector calorimetric response

Measurements with leptons

- $g \longrightarrow c\bar{c} \longrightarrow Xl\nu$.
- The two c quarks from $g \longrightarrow c\bar{c}$ are mostly clustered in the same jet in 3 jet events.
- This jet is likely to be the least energetic one.
- Further signal/bkg discrimination is provided by the properties of this jet; in OPAL and L3 analyses the invariant mass is used.



Measurements with leptons

- OPAL estimates 688 e and 836 μ from $g \longrightarrow c\bar{c}$ in the selected sample after background subtraction, out of 4.4×10^6 hadronic events, yielding

$$g^e_{c\bar{c}} = (3.03 \pm 0.28(stat) \pm 0.41(syst))\%$$
$$g^\mu_{c\bar{c}} = (3.53 \pm 0.37(stat) \pm 0.79(syst))\%$$

- L3 estimates 75 e and 51 μ from $g \longrightarrow c\bar{c}$ in the selected sample after background subtraction, out of 1.7×10^6 hadronic events, yielding

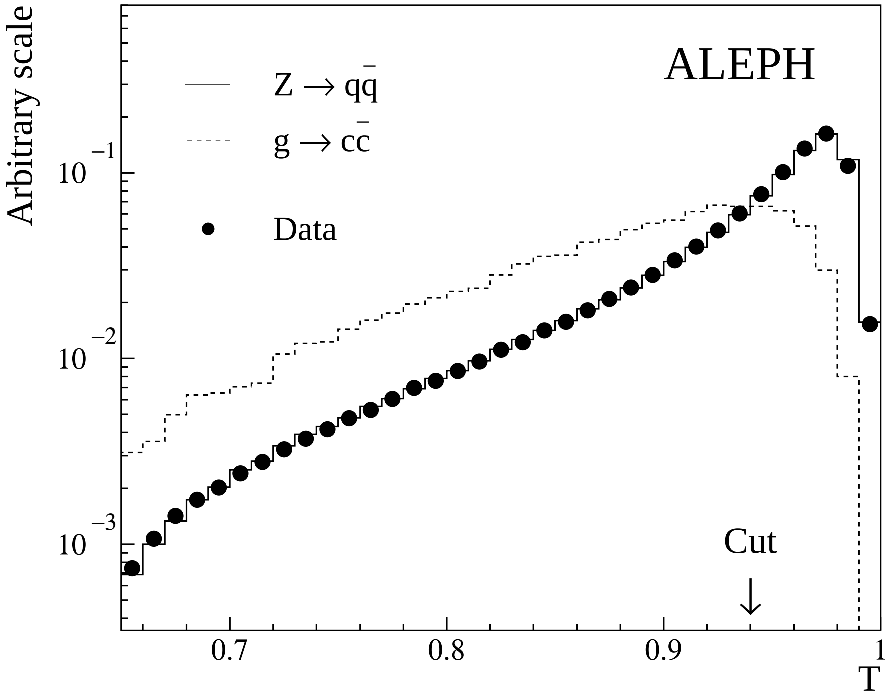
$$g^e_{c\bar{c}} = (3.14 \pm 1.14(stat) \pm 0.85(syst))\%$$
$$g^\mu_{c\bar{c}} = (3.06 \pm 1.76(stat) \pm 0.83(syst))\%$$

Main systematic errors for both analyses:

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

New ALEPH analysis

- cut on the thrust of the event



- clusterization **forced** into three jets of the remaining events
- energy ordering of the jets
- request of a lepton in the third (least energetic) jet
- further signal/background discrimination by means of a neural network

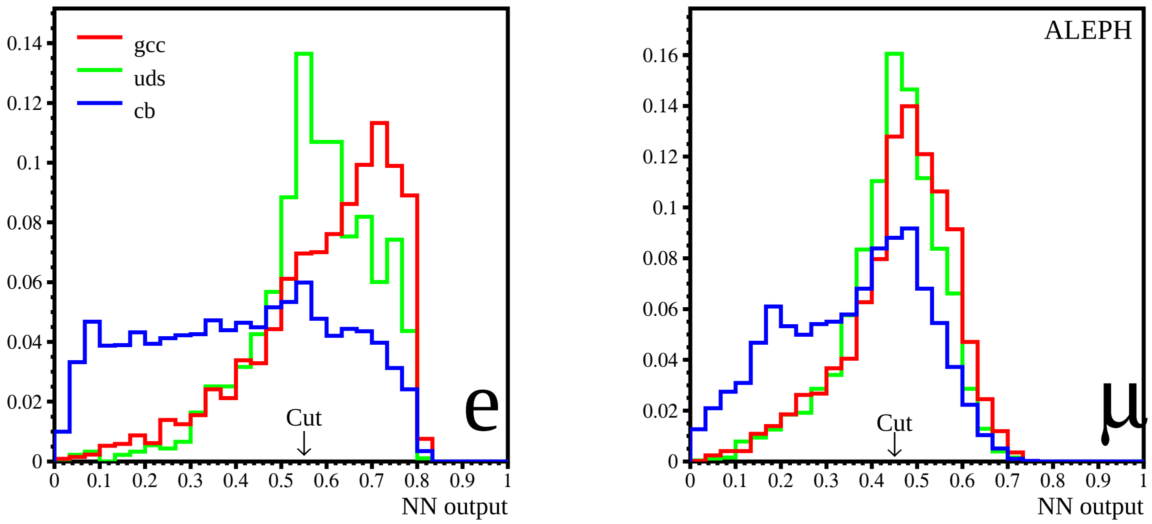
New ALEPH analysis

After the preselection, events are analyzed by two independent neural networks (one for e, the other for μ) based on:

- kinematics of the lepton
- presence of secondary vertices in the event
- $P^3_{\mathrm{miss}} = \vec{P}_{\mathrm{miss}} \cdot \vec{n}_3$ (missing momentum along the third jet)

The mass of the third jet is not used, since the simulation of soft jets with our jet definition was found to be inadequate.

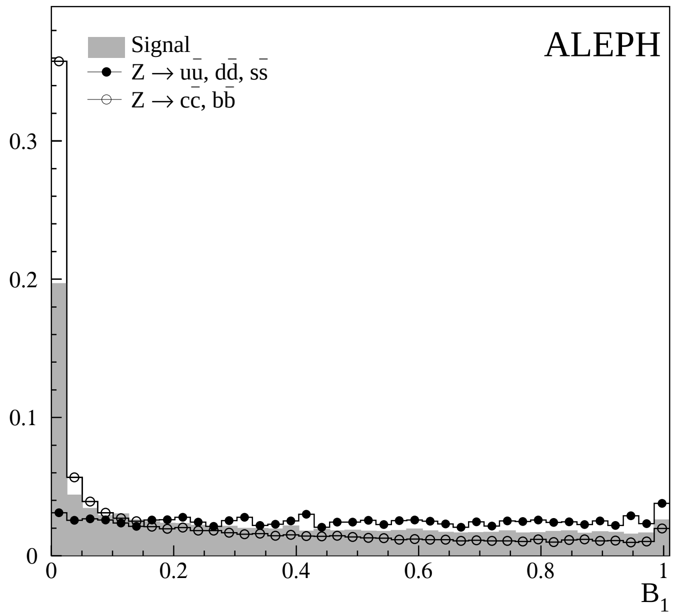
NN outputs for $g \to c\bar{c}$, uds, cb events:



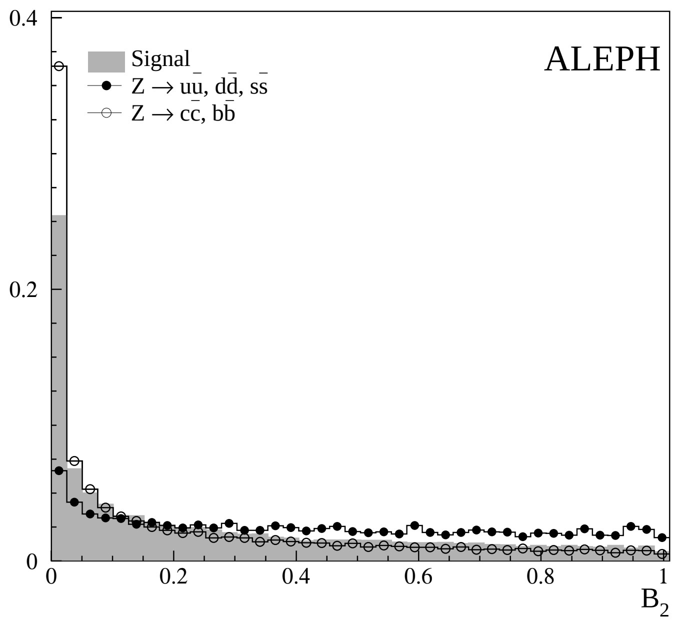
(a) (b)

New ALEPH analysis: most important NN inputs

b-tagging variable (based on vertices):

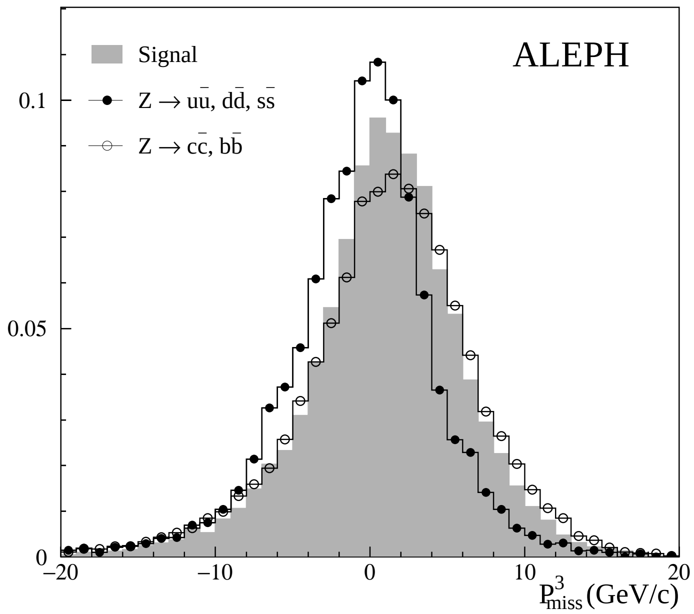


Light hemisphere

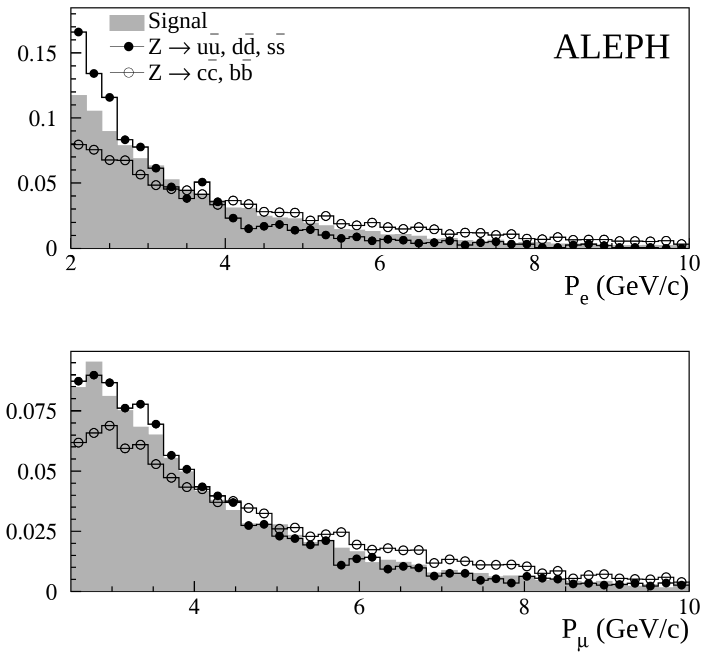


Heavy hemisphere

New ALEPH analysis: most important NN inputs



Missing momentum along the third jet



Lepton momentum (e and μ)

New ALEPH analysis

ALEPH selects 2258 e and 3332 μ of which 565 e and 600 μ are estimated to come from $g \to c\bar{c}$, out of 3.9×10^6 hadronic events, yielding

$$g^e_{c\bar{c}} = (3.32 \pm 0.28(stat) \pm 0.42(syst))\%$$
$$g^\mu_{c\bar{c}} = (2.99 \pm 0.37(stat) \pm 0.72(syst))\%$$

Systematic errors:

Source of error	$\Delta g^e_{c\bar{c}}$ $(\times 10^{-2})$	$\Delta g^\mu_{c\bar{c}}$ $(\times 10^{-2})$
Statistical error	0.28	0.38
Statistics of the simulation	0.13	0.21
$g_{b\bar{b}}$	0.09	0.10
Thrust cut efficiency	0.07	0.11
BR$(b \to l)$	0.05	0.06
BR$(b \to c \to l)$	0.02	0.03
BR$(c \to l)$	0.23	0.20
$b \to l$ spectrum	0.01	< 0.01
$b \to c \to l$ spectrum	0.02	0.02
$c \to l$ spectrum	0.03	0.12
Lifetimes of b hadrons	0.03	0.03
$\langle x_E^{(c)} \rangle$	0.04	0.05
$\langle x_E^{(b)} \rangle$	0.02	0.03
Lepton identification	0.18	0.01
Lepton background	0.09	0.50
Generators, θ^*	0.06	0.12
Generators, $E_{\rm g}, m^*_{\rm g}$	0.05	0.26
$m_{\rm c}$	0.19	0.24
Total systematic error	0.42	0.72

Combined estimations

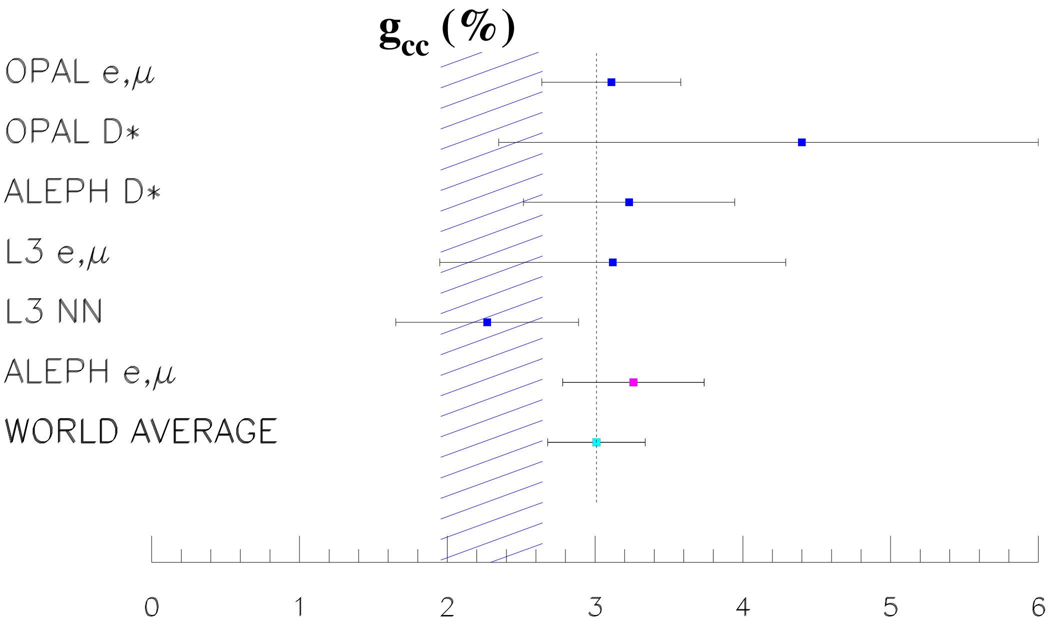
$g_{c\bar{c}}$ and $g_{b\bar{b}}$ measurements are combined taking into account:

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

An iterative method is used:

1. Combine measurements of $g_{c\bar{c}}$ and $g_{b\bar{b}}$ separately to obtain $g_{c\bar{c}}^{best}$ and $g_{b\bar{b}}^{best}$
2. Use $g_{c\bar{c}}^{best}$ and $g_{b\bar{b}}^{best}$ to obtain a new estimate from each measurement:
$$g_{c\bar{c}}^{i} = A_i - B_i \times g_{b\bar{b}}^{best}$$
$$g_{b\bar{b}}^{i} = C_i - D_i \times g_{c\bar{c}}^{best}$$
3. Iterate until convergence (three iterations are enough).

Results



Hatched area: theoretical prediction ±15%.

Uncertainties due to m_c and α_s are not shown.

New World Average:

$$g_{c\bar{c}} = (3.01 \pm 0.33)\%$$

(not yet official)

Weights of the single measurements

OPAL e	22.6%
OPAL μ	3.0%
OPAL D^*	1.0%
L3 e	2.3%
L3 μ	0.4%
L3 ev.sh.	22.2%
ALEPH D^*	14.4%
ALEPH e	29.5%
ALEPH μ	4.6%

Summary

- A new ALEPH analysis is available.
- All measurements are dominated by systematic uncertainties.
- All results are consistent.
- $g_{c\bar{c}}$ average is 2σ far from the theoretical prediction, and tends to favour low m_c or high α_s. But large uncertainties affect the predicted value.