Recent Results of Electroweak Measurements with Heavy Flavours

Results from LEP and SLD

Status at Brussels and Beijing conferences

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Thanks

The work reported here is the analysis of many people in the LEP and SLD collaborations.

The laborious task of ensuring that results are combined consistently and correctly is performed by the LEP electroweak heavy flavour group, currently:

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and from the SLD heavy flavour group:

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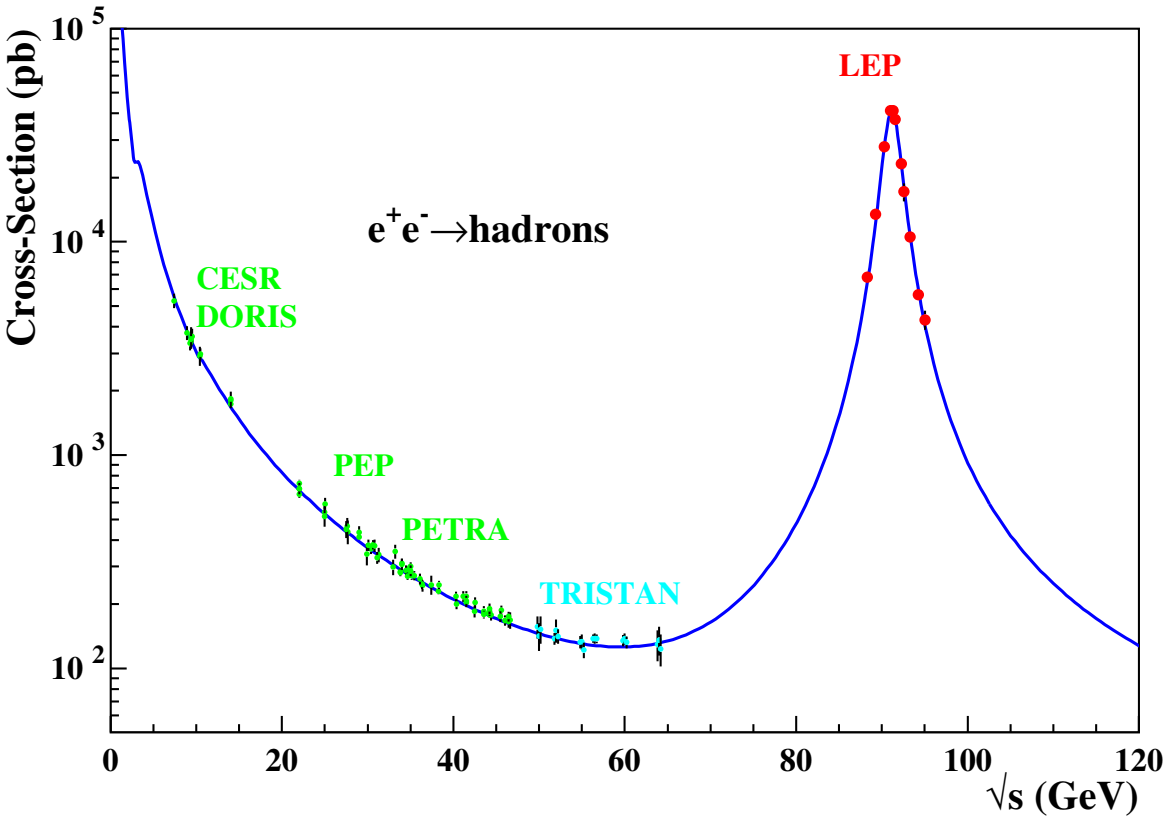
B. Schumm.

Outline

- Introduction
- b tags and R_{b}
  - Lifetime tags
- c tags and R_{c}
  - Reconstructed particle tags
- Asymmetries
- Summary

Focus on measurements of R_{b} and R_{c}

Z Physics



Tree-level cross-section:

$$\sigma_f(s) = \sigma_f^0 \frac{s\Gamma_{Z^0}^2}{(s - m_{Z^0}^2)^2 + s^2\Gamma_{Z^0}^2/m_{Z^0}^2} + [\gamma] + [\gamma/Z^0]$$

where:

$$\sigma_f^0 = 12\pi\Gamma_e\Gamma_f/m_{Z^0}^2\Gamma_{Z^0}^2$$

Partial decay widths:

$$\Gamma_f = \frac{G_\mu m_{Z^0}^3}{6\pi\sqrt{2}}(v_f^2 + a_f^2)N_{col}$$

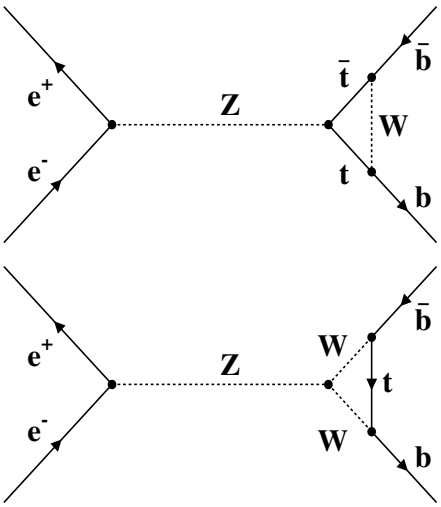
Heavy Quark Partial Widths

In practice, we measure

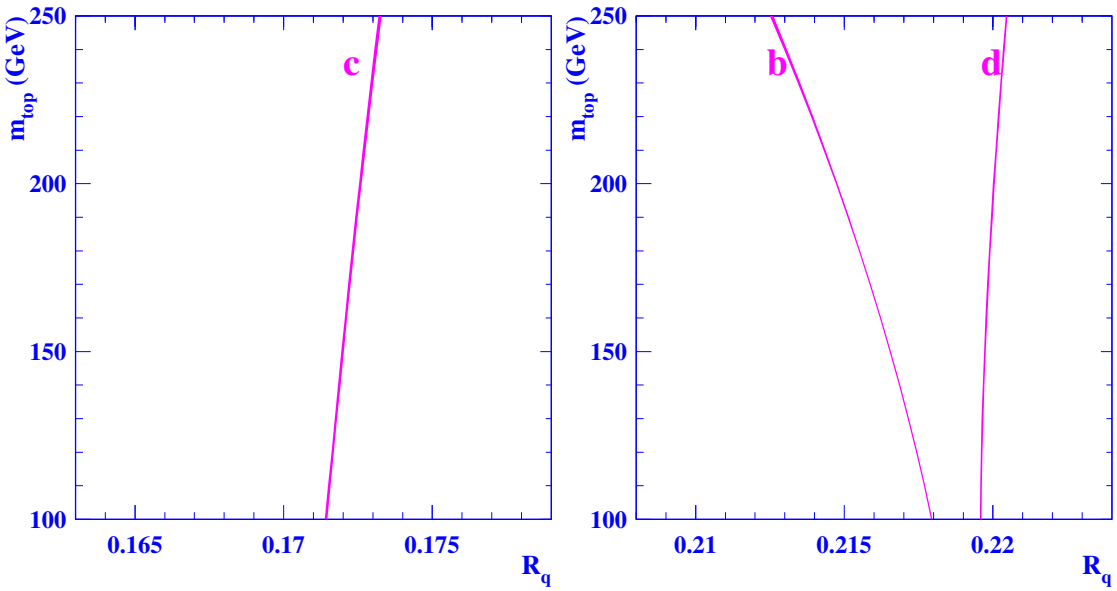
$$R_{\mathrm{Q}} \equiv \frac{\Gamma(\mathrm{Z}^0 \to \mathrm{Q}\overline{\mathrm{Q}})}{\Gamma(\mathrm{Z}^0 \to \mathrm{hadrons})}$$

Radiative corrections largely cancel in this ratio (propagator corrections, ISR...)

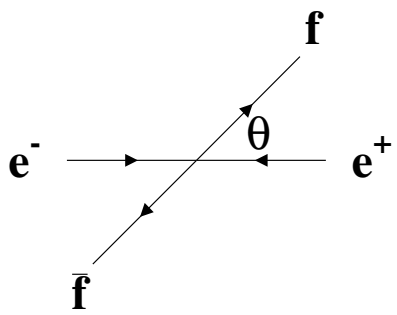
Special corrections for the Zbb vertex don't cancel:



Implication:



Heavy Quark Asymmetries



$$\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta} \propto 1+\cos^2\theta+\frac{8}{3}A^f_{\mathrm{FB}}\cos\theta$$

$$A^f_{\mathrm{FB}} = \frac{\sigma_{\mathrm{F}}-\sigma_{\mathrm{B}}}{\sigma_{\mathrm{F}}+\sigma_{\mathrm{B}}}$$

$$A^f_{\mathrm{FB}} \approx A^{f,0}_{\mathrm{FB}} \equiv \frac{3}{4}\mathcal{A}_e\mathcal{A}_f \qquad \text{when } \sqrt{s} = m_{\mathrm{Z}^0}$$

$$\mathcal{A}_f = 2\frac{v_f a_f}{(v_f^2+a_f^2)}$$

$$\frac{v_f}{a_f} = (1-4|Q_f|\sin^2\theta^{\mathrm{eff},f}_{\mathrm{W}})$$

Leptons define $\sin^2\theta^{\mathrm{lept}}_{\mathrm{eff}}$. Small corrections for quarks.

$$\begin{aligned}\mathcal{A}_{\mathrm{e}} &\approx 0.14\\ \mathcal{A}_{\mathrm{c}} &\approx 0.7\\ \mathcal{A}_{\mathrm{b}} &\approx 0.9\end{aligned}$$

($\Longrightarrow A^{\mathrm{b}}_{FB}$ sensitive to $\sin^2\theta^{\mathrm{lept}}_{\mathrm{eff}}$)

At SLD also left-right forward-backward asymmetries:

$$\frac{[\sigma_{\mathrm{L}}(\mathrm{F})-\sigma_{\mathrm{L}}(\mathrm{B})]-[\sigma_{\mathrm{R}}(\mathrm{F})-\sigma_{\mathrm{R}}(\mathrm{B})]}{[\sigma_{\mathrm{L}}(\mathrm{F})+\sigma_{\mathrm{L}}(\mathrm{B})]+[\sigma_{\mathrm{R}}(\mathrm{F})+\sigma_{\mathrm{R}}(\mathrm{B})]} = \frac{3}{4}\mathcal{P}_{\mathrm{e}}\mathcal{A}_{\mathrm{q}}$$

Heavy Quark Tags

Tags for heavy quarks rely on:

- Lifetimes
- Specific decay modes
- High mass – hard fragmentation

Three main types of tag for electroweak analyses:

- Lifetime tags **b**
  - Impact parameter methods
  - Secondary vertex reconstruction
- Reconstructed particle tags **c**
  - Fully/partially reconstructed hadrons
  - Transition pion tag
- Leptons **b,c**

Impact Parameter Probability b Flavour Tag

- Construct "no-lifetime" probability for tracks with physics-signed impact parameter $b > 0$:

$$\mathcal{P}_T = \int_b^\infty \mathcal{R}(x)\mathrm{d}x$$

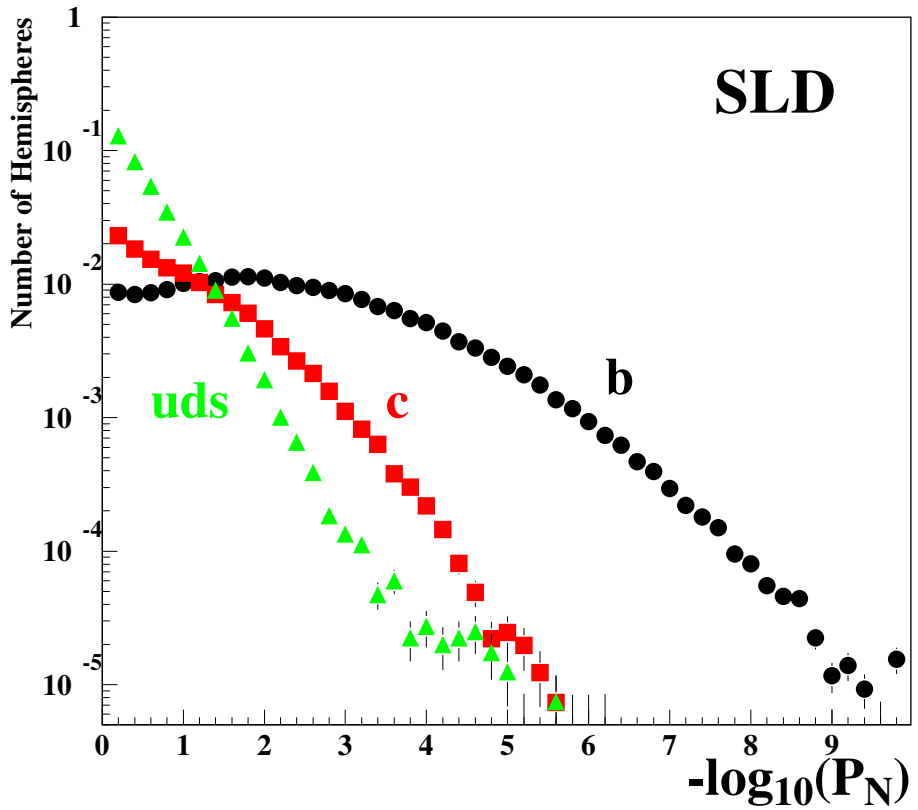
resolution function $\mathcal{R}$ measured from $b < 0$ distribution

- Construct joint probability for "no-lifetime" in the hemisphere:

$$\mathcal{P}_N \equiv \Pi \sum_{j=0}^{N-1} \frac{(-\ln \Pi)^j}{j!}$$

where

$$\Pi \equiv \prod_{i=1}^{N} (\mathcal{P}_T)_i$$

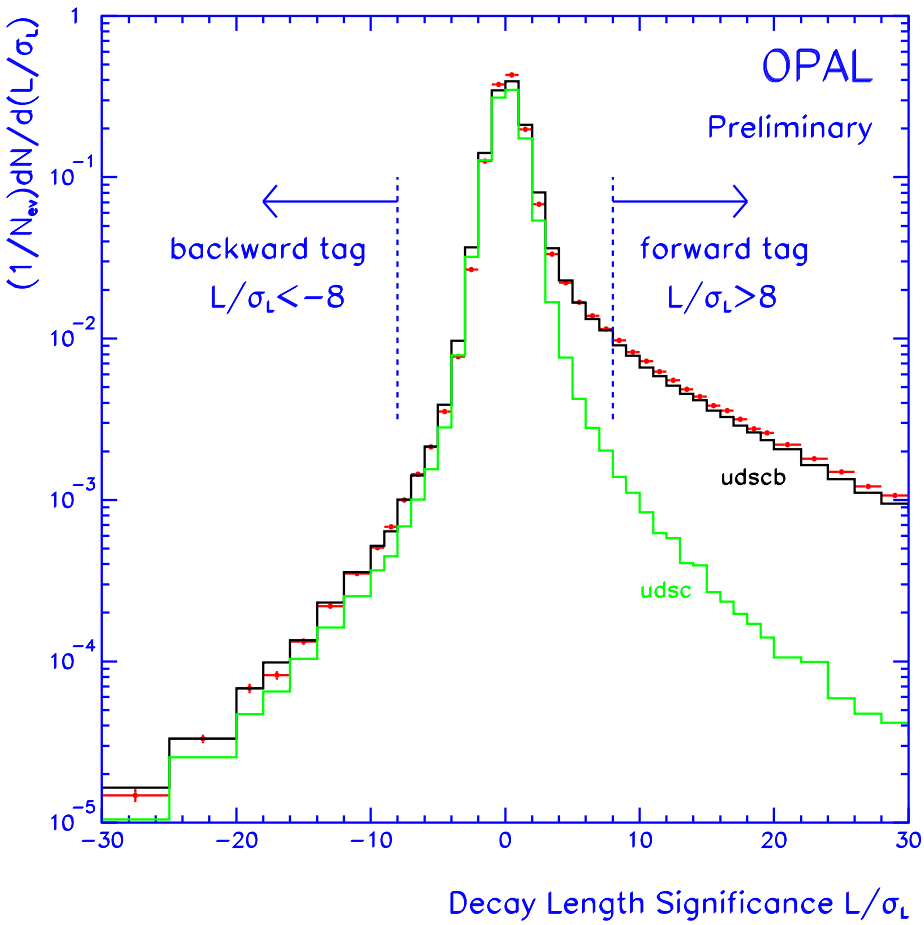


Used by ALEPH, DELPHI, SLD

Secondary Vertex b Flavour Tag

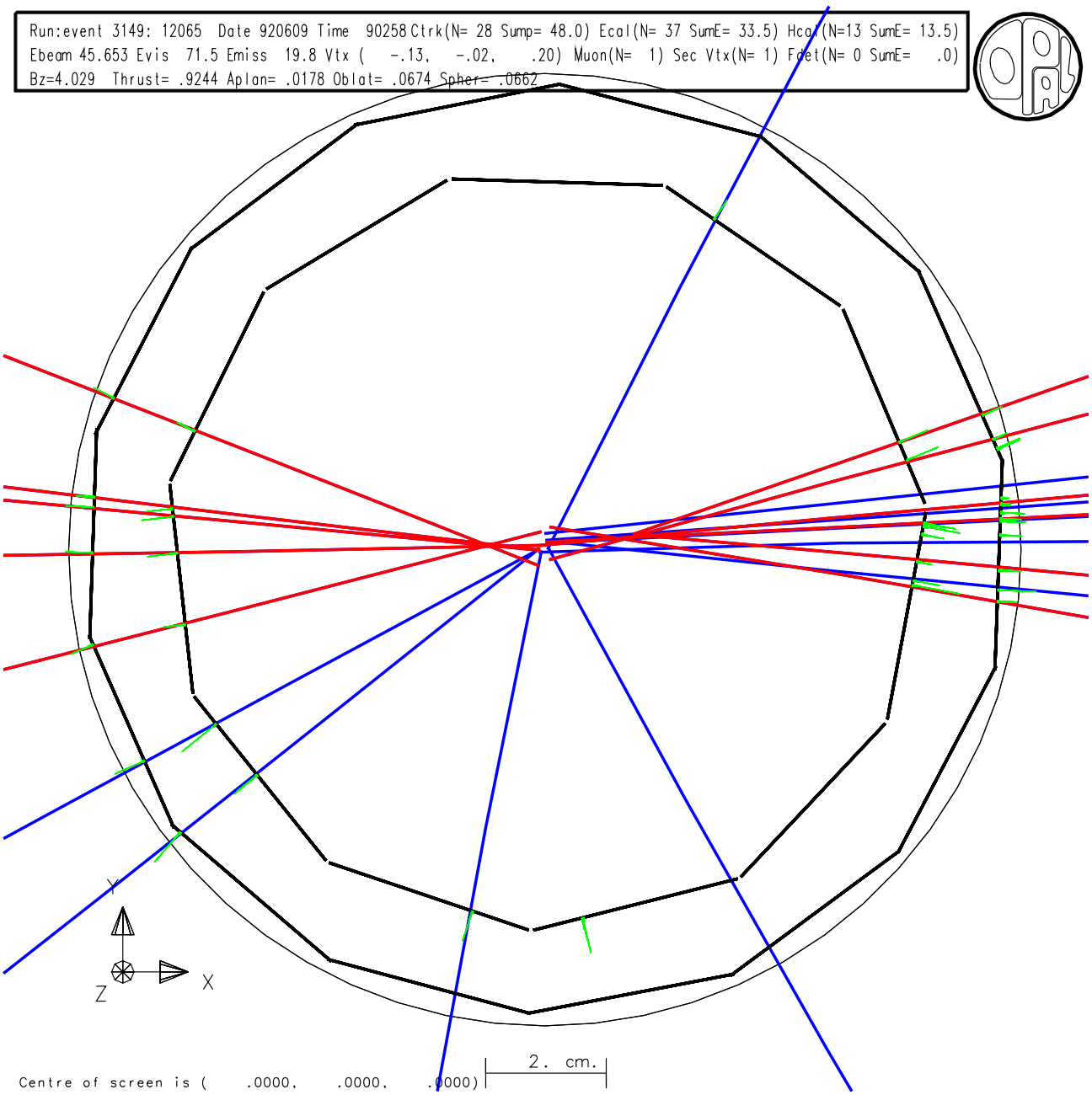
Used by OPAL

- Reconstruct secondary vertices from tracks in each jet
- Reject vertices with fewer than four tracks
- Construct physics signed decay length significance



- Folded tag: subtract statistically backwards vertices from forwards vertices $\longrightarrow$ reduces resolution uncertainties

Double Lifetime Tagged Event



Lifetime Tag Performance

Very high purities essential particularly for R_{b} analysis

	ε^{b}	b purity
ALEPH	26%	96%
DELPHI	21%	92%
OPAL*	23%	94%
SLD	31%	94%

(* includes high-p_t lepton tag)

ε^{b} : tag efficiency for a b hemisphere, determined from data

R_{b} Analyses: Double Tagging

Look for b tags separately in two thrust hemispheres of event

Number of tagged hemispheres N_{t}:

$$\frac{N_{\mathrm{t}}}{2N_{\mathrm{had}}} = \varepsilon^{\mathrm{b}} R_{\mathrm{b}} + \varepsilon^{\mathrm{c}} R_{\mathrm{c}} + \varepsilon^{\mathrm{uds}}(1 - R_{\mathrm{b}} - R_{\mathrm{c}})$$

Number of double-tagged events N_{tt}:

$$\frac{N_{\mathrm{tt}}}{N_{\mathrm{had}}} = C_{\mathrm{b}}(\varepsilon^{\mathrm{b}})^2 R_{\mathrm{b}} + (\varepsilon^{\mathrm{c}})^2 R_{\mathrm{c}} + (\varepsilon^{\mathrm{uds}})^2(1 - R_{\mathrm{b}} - R_{\mathrm{c}})$$

- Solve for R_{b} and ε^{b}, from N_{t}, N_{tt}, N_{had}
  $\Longrightarrow$ Removes need to know ε^{b}
- Take R_{c}, C_{b}, ε^{c}, $\varepsilon^{\mathrm{uds}}$ from external knowledge
- Statistical error dominated by N_{tt}
- Systematic error dominated by ε^{c}, C_{b}
- Tune to give best overall error: statistics vs. systematics
- R_{c} dependence handled in averaging procedure

Hemisphere Correlations

b-tagging efficiencies in 2 hemispheres are correlated:

- hard gluon radiation: $\mathrm{b\overline{b}}$ vs. gluon ($-$)
- gluon radiation: $p(\mathrm{b})$ and $p(\overline{\mathrm{b}})$ correlated ($+$)
- detector non-uniformity: e.g. ends ($+$)
- primary vertex effects ($+/-$)

Evaluated with a mixture of simulation and data:

- Find an event variable ν which reflects the property causing the correlation, e.g.
  θ, ϕ of thrust axis for geometrical correlations
- Measure fraction $f_{1,2}(\nu)$ of single tagged hemispheres as function of this variable on both sides (1,2) of event
- Evaluate correlation from

$$\frac{< f_1(\nu) f_2(\nu) >}{< f_1(\nu) >< f_2(\nu) >}$$

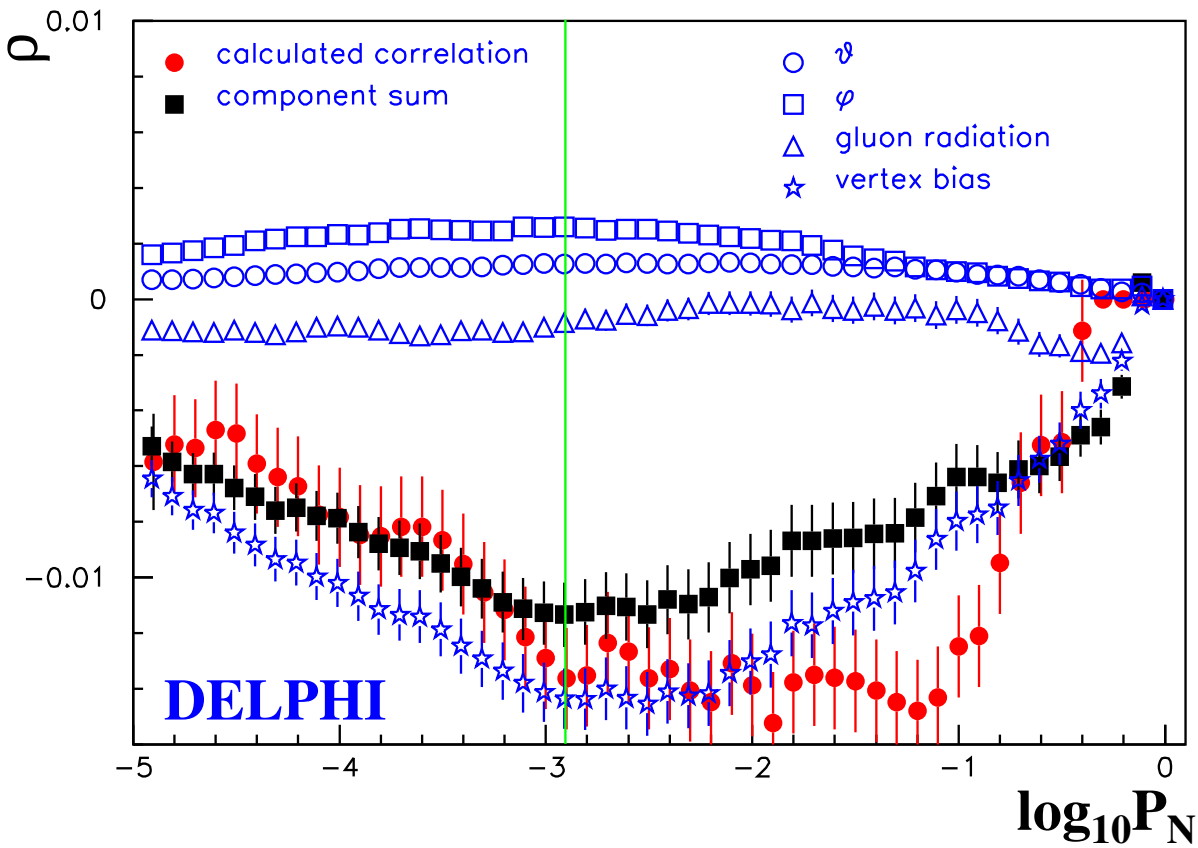
- Corrections from Monte Carlo for residual effects of background on correlation estimate

Total efficiency correlation ρ:

$$\rho = \frac{(C_b - 1)\varepsilon^{\mathrm{b}}}{(1 - \varepsilon^{\mathrm{b}})}$$

typically:

- ρ –1% to –2% for IP probability tag
- ρ +0.2% for secondary vertex tag



Systematics from statistics, residual MC-data differences

Latest Results with Double Lifetime Tag

Lifetime tags require excellent vertex/tracking detectors

Hadronic Z^0 decay samples with silicon vertex detectors:

	LEP	SLD
1991	$\sim$ 0.2 M	
1992	0.7 M	
1993	0.7 M	50 k
1994	1.7 M	100 k
1995	0.7 M	

Latest double-lifetime tag results from:

DELPHI	(91-93 prel)	$0.2210 \pm 0.0016 \pm 0.0020$
OPAL	(92-94 prel)	$0.2197 \pm 0.0014 \pm 0.0022$
SLD	(93-94 prel)	$0.2171 \pm 0.0040 \pm 0.0037$
ALEPH	(92)	$0.2192 \pm 0.0022 \pm 0.0026$

(excluding errors from R_c dependence)

Best measurements are at 1.2% precision level

Systematic errors now rather important

Summary of Systematic Uncertainties

Compare precise lifetime-dominated measurements

	ALEPH	DELPHI	OPAL	SLD
detector/MC statistics	0.0015	0.0009	0.0012	0.0025
efficiency correlation	0.0016	0.0011	0.0007	0.0010
c production fractions	0.0009	0.0016	0.0009	0.0013
c decay multiplicity	0.0006	0.0010	0.0010	0.0018
c lifetimes	0.0005	0.0006	0.0004	0.0003
c fragmentation	0.0001	0.0005	0.0008	0.0012
gluon splitting	0.0003	0.0003	0.0005	0.0004
light quark bkgd	0.0002	0.0006	0.0003	0.0001
total systematic	0.0026	0.0027	0.0022	0.0037
statistical	0.0022	0.0017	0.0014	0.0040

Some small systematics not shown, nor is R_c dependence

Systematic errors dominated by charm modelling

Some scope for improving these at LEP

c Production Fractions

- Tagging probability of different c hadron species differs (lifetime)
- From D^+ to Λ_c^+, typically factor four difference

R_b results use averages derived from CLEO/ARGUS and 1992 PDG branching ratios (%):

$$\mathrm{D}^0 : \mathrm{D}^+ : \mathrm{D}_\mathrm{s}^+ : \Lambda_\mathrm{c}^+ =$$
$$55.7 : 24.8 : 12.0 : 7.5$$

("Λ_c^+" includes all c baryons)

Variations according to CLEO/ARGUS errors (%):

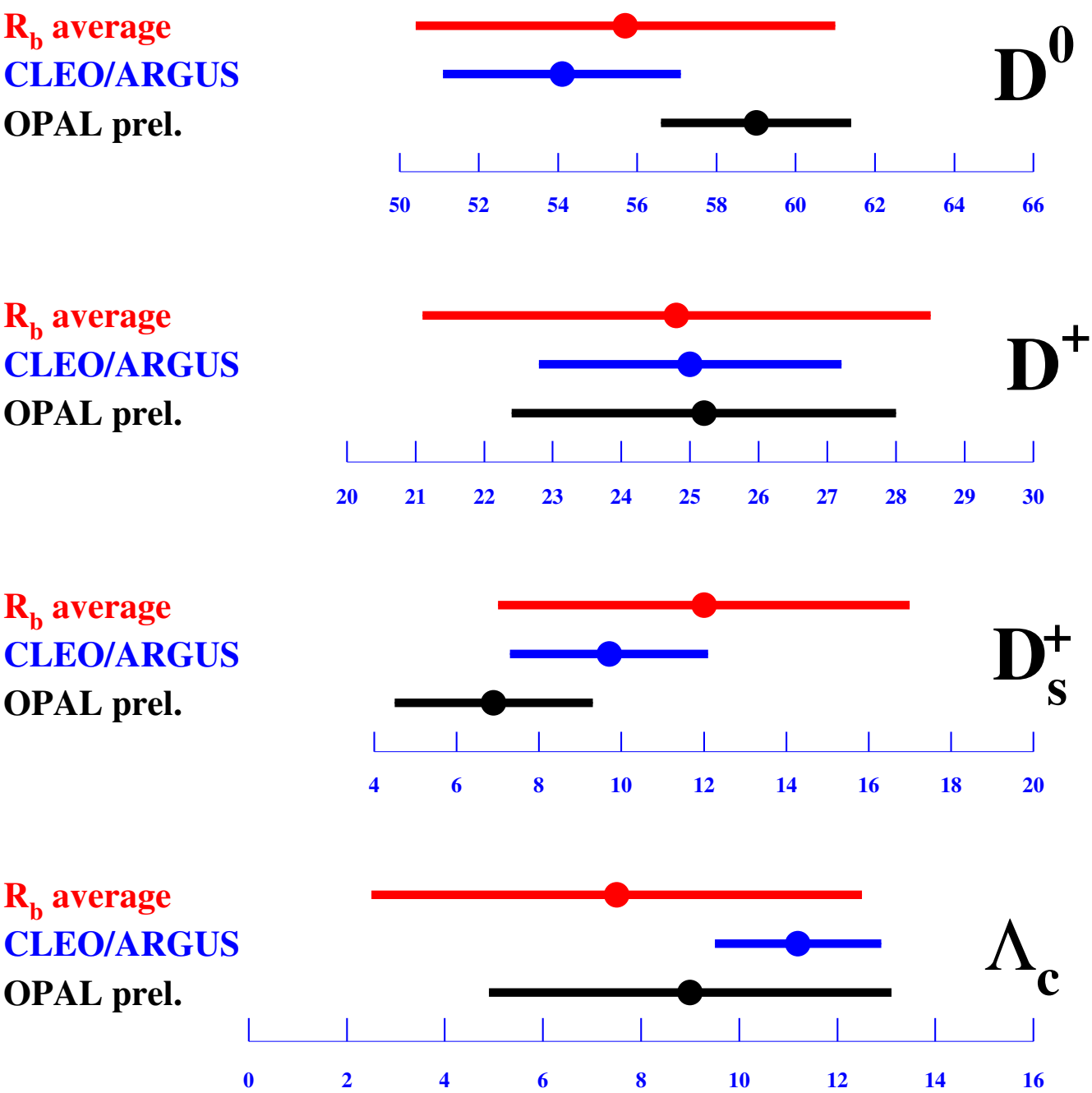
$$\mathrm{D}^0 \pm 5.3; \mathrm{D}^+ \pm 3.7; (\mathrm{D}^0 + \mathrm{D}^+) \pm 7.0; \mathrm{D}_\mathrm{s}^+ \pm 5.0$$

Latest CLEO/ARGUS/1994 PDG numbers are:

$$\mathrm{D}^0 : \mathrm{D}^+ : \mathrm{D}_\mathrm{s}^+ : \Lambda_\mathrm{c}^+ =$$
$$54.1 \pm 3.0 : 25.0 \pm 2.2 : 9.7 \pm 2.4 : 11.2 \pm 1.7$$

New numbers from LEP (OPAL preliminary) are:

$$\mathrm{D}^0 : \mathrm{D}^+ : \mathrm{D}_\mathrm{s}^+ : \Lambda_\mathrm{c}^+ =$$
$$59.0 \pm 2.4 : 25.2 \pm 2.8 : 6.9 \pm 2.4 : 9.0 \pm 4.1$$

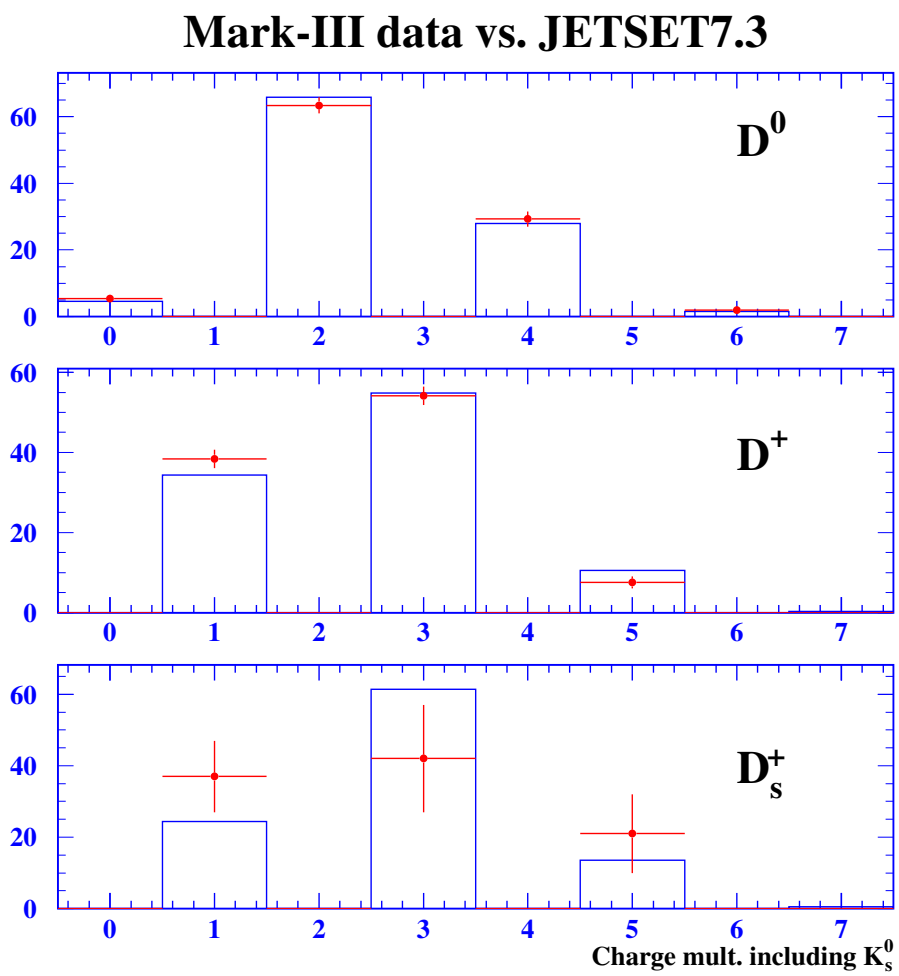

R_b average
CLEO/ARGUS
OPAL prel.
D^0
50 52 54 56 58 60 62 64 66
R_b average
CLEO/ARGUS
OPAL prel.
D^+
20 21 22 23 24 25 26 27 28 29 30
R_b average
CLEO/ARGUS
OPAL prel.
D_s^+
4 6 8 10 12 14 16 18 20
R_b average
CLEO/ARGUS
OPAL prel.
Λ_c
0 2 4 6 8 10 12 14 16

c Decay Multiplicity

MARK III measurements (Phys.Lett.B263(1991)1)

- D^0,D^+,D_s^+ mean charged decay multiplicities and distributions
- $B(\mathrm{D} \to \mathrm{K}^0(\mathrm{or}\ \overline{\mathrm{K}}^0)X)$

Add a large error on mean charge multiplicity for unmeasured Λ_c^+ (± 0.5 on mean about JETSET prediction)



c Lifetimes

Take PDG (1992) values and error ranges:

$$\begin{aligned}
\tau(\mathrm{D}^0) &= 0.420 \pm 0.008\ \mathrm{ps} \\
\tau(\mathrm{D}^+) &= 1.066 \pm 0.023\ \mathrm{ps} \\
\tau(\mathrm{D}_\mathrm{s}^+) &= 0.450 \pm 0.030\ \mathrm{ps} \\
\tau(\Lambda_\mathrm{c}^+) &= 0.191 \pm 0.015\ \mathrm{ps}
\end{aligned}$$

PDG 1995 values:

$$\begin{aligned}
\tau(\mathrm{D}^0) &= 0.415 \pm 0.004\ \mathrm{ps} \\
\tau(\mathrm{D}^+) &= 1.057 \pm 0.015\ \mathrm{ps} \\
\tau(\mathrm{D}_\mathrm{s}^+) &= 0.467 \pm 0.017\ \mathrm{ps} \\
\tau(\Lambda_\mathrm{c}^+) &= 0.206 \pm 0.012\ \mathrm{ps}
\end{aligned}$$

Very similar, with smaller errors.

Other charm baryons? Even shorter life times than Λ_c^+

c Fragmentation

For R_{b} results and averages:

$$< x_E^{\mathrm{c}} >= 0.51 \pm 0.02$$

where $x_E \equiv E_{\mathrm{hadron}}/E_{\mathrm{beam}}$ is that of *produced* D or D^{*+} (P-wave mesons ignored)

Recent measurements looking consistently at *weakly decaying* c hadrons give:

$$\begin{aligned} < x_E(\mathrm{D}^0) > &= 0.489^{+0.008+0.011}_{-0.009-0.009} \\ < x_E(\mathrm{D}^+) > &= 0.481^{+0.013+0.012}_{-0.012-0.010} \end{aligned}$$

(OPAL preliminary)

Good consistency (shift by ∼0.03 to find $< x_E(\mathrm{D}/\mathrm{D}^{*+}) >$)

Uncertainty can be improved in future.

Gluon Splitting $g \to c\bar{c}$, $g \to b\bar{b}$

Theoretical prediction (M.H.Seymour Nucl.Phys.B436(1995)163):

$$n_{g\to c\bar{c}} = (1.3 \pm 0.4)\%$$
$$n_{g\to b\bar{b}} = (0.18 \pm 0.05)\%$$

per hadronic Z^0 decay

Can we test this experimentally?

Measurements at LEP (OPAL, Phys Lett.B353(1995)595):

$$n_{g\to c\bar{c}} = (2.38 \pm 0.48)\%$$

giving, assuming $n_{g\to b\bar{b}}/n_{g\to c\bar{c}} = 0.132 \pm 0.047$

$$n_{g\to b\bar{b}} = (0.30 \pm 0.12)\%$$

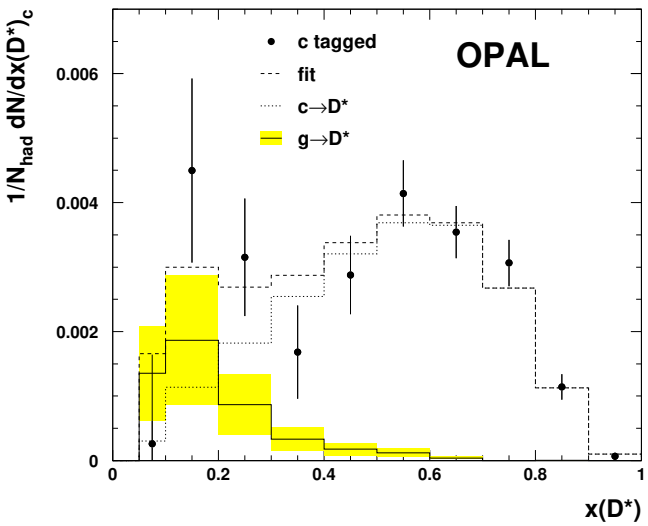
Measurements reported here use JETSET prediction:

$$n_{g\to c\bar{c}} \simeq 1.6\%$$
$$n_{g\to b\bar{b}} \simeq 0.16\%$$

and apply a $\pm$50% uncertainty

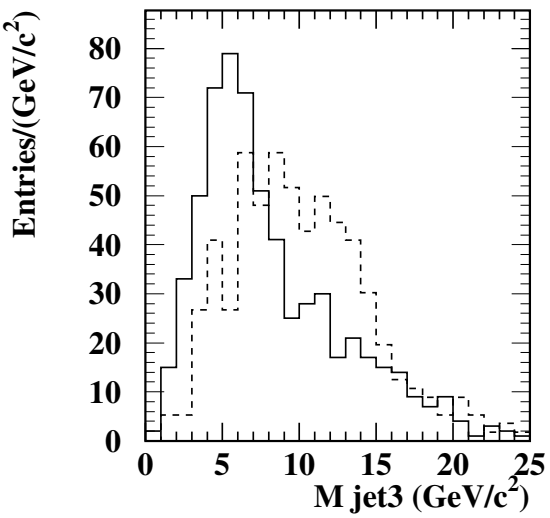
The OPAL Measurements of $g \to c\bar{c}$

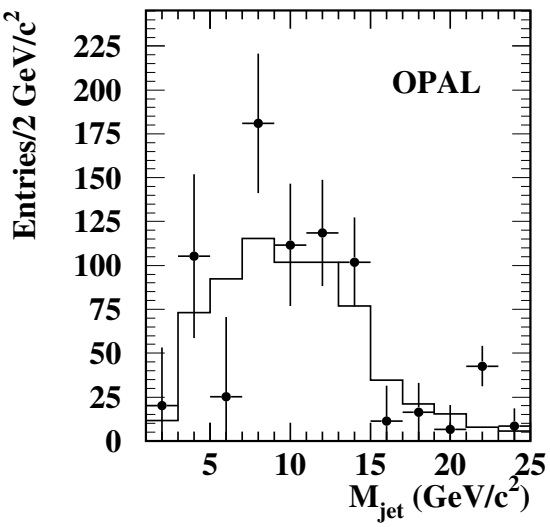
From low-momentum tail of D^* mesons from non-$b\bar{b}$ events:



From 3-jet events

- Require no significantly displaced reconstructed secondary vertex in event ($b\bar{b}$ event veto)
- Search for leptons in third jet, look at jet mass distribution





Combined result: $n_{g \to c\bar{c}} = 2.38 \pm 0.48$

Energy Dependence of $\mathrm{b\overline{b}}$ Fraction

The measured ratio

$$\frac{\sigma(\mathrm{e^+e^-} \to \mathrm{b\overline{b}})}{\sigma(\mathrm{e^+e^-} \to \mathrm{hadrons})}$$

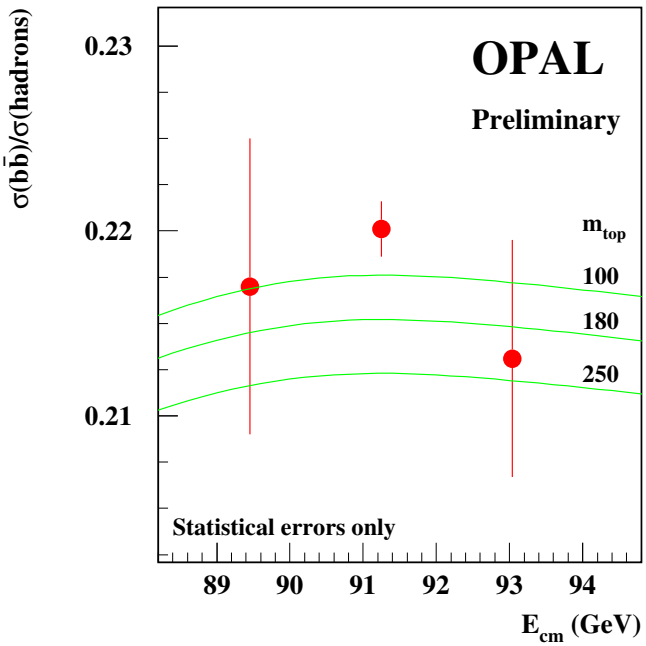
differs slightly from R_b, and varies slowly with centre-of-mass energy

Measured 2 GeV above & below Z^0 peak by DELPHI, OPAL

OPAL: Full double-tag analysis at each energy separately

DELPHI: Derive ε^b from on-peak sample, use MC to map energy dependence of ε^b, ε^c, ε^uds efficiency corrections to off-peak energies

Results:



DELPHI

$$\frac{R_\mathrm{b}(89.49\ \mathrm{GeV})}{R_\mathrm{b}(91.25\ \mathrm{GeV})} = 0.982 \pm 0.015$$

$$\frac{R_\mathrm{b}(93.08\ \mathrm{GeV})}{R_\mathrm{b}(91.25\ \mathrm{GeV})} = 0.997 \pm 0.016$$

compared to SM predictions 0.997, 0.998

A Different Technique: Multivariate Analysis

DELPHI

Combines 13 microvertex and event shape variables for each hemisphere of an event

Divides hemispheres into six categories

Advantages compared to conventional double tag:

- All efficiencies and backgrounds estimated from data
- Degeneracy of solutions: has to be broken
  - One degeneracy removed by measuring b tag performance by cutting hard on other hemisphere
  - Remaining degeneracy broken by using R_{c} as input
- Systematic errors from physics modelling reduced
- Systematic errors from detector modelling similar
- Systematic errors from testability of method on simulated data

Disadvantages:

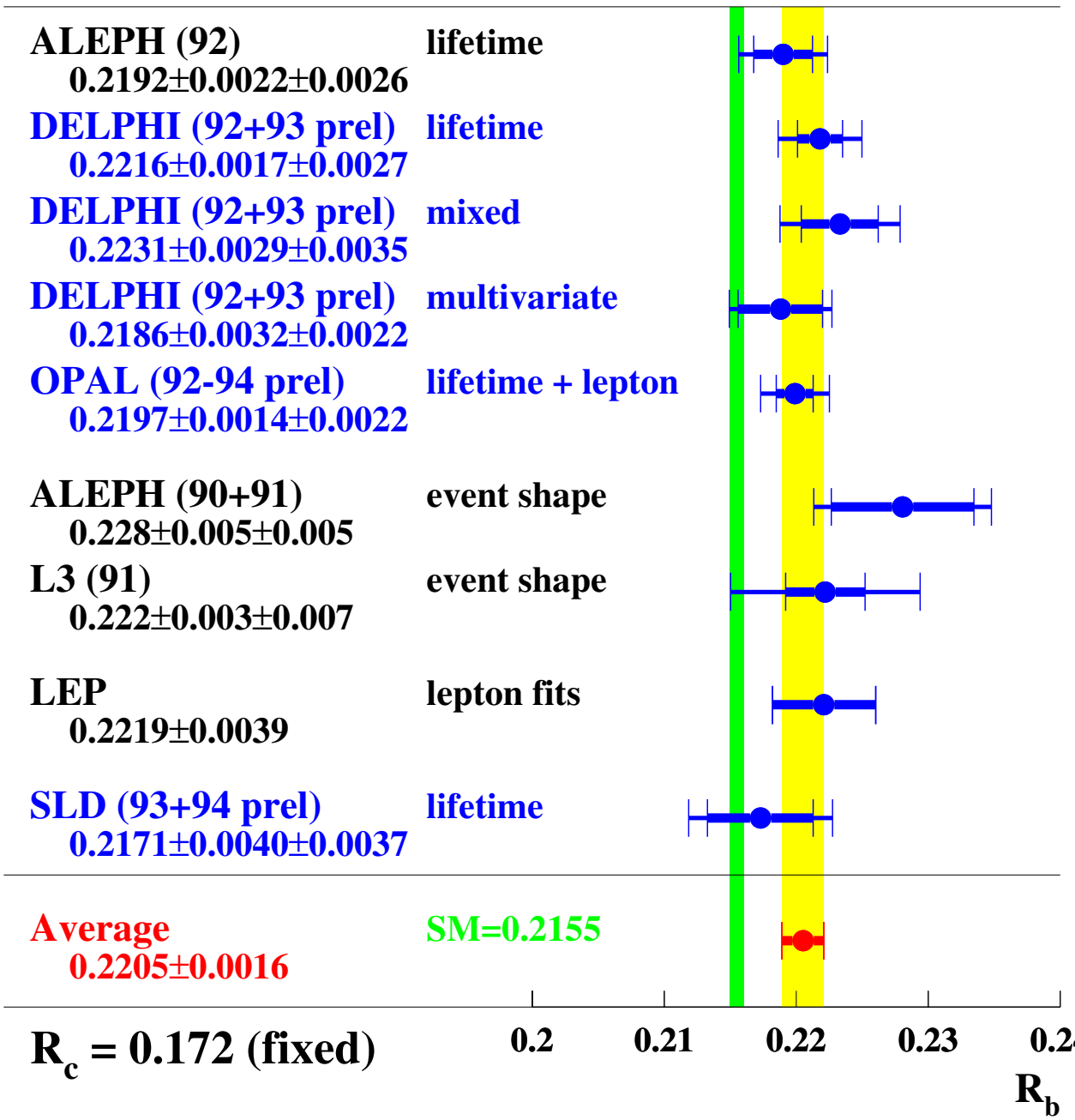
- Statistical uncertainty increased over conventional double-tag
- Correlation matrix between hemispheres from simulation
- Systematic errors from hemisphere correlations increase

Result:

$$R_{\mathrm{b}} = 0.2186 \pm 0.0032 \pm 0.0022$$

from 1991 to 1993 data (R_{c} fixed)

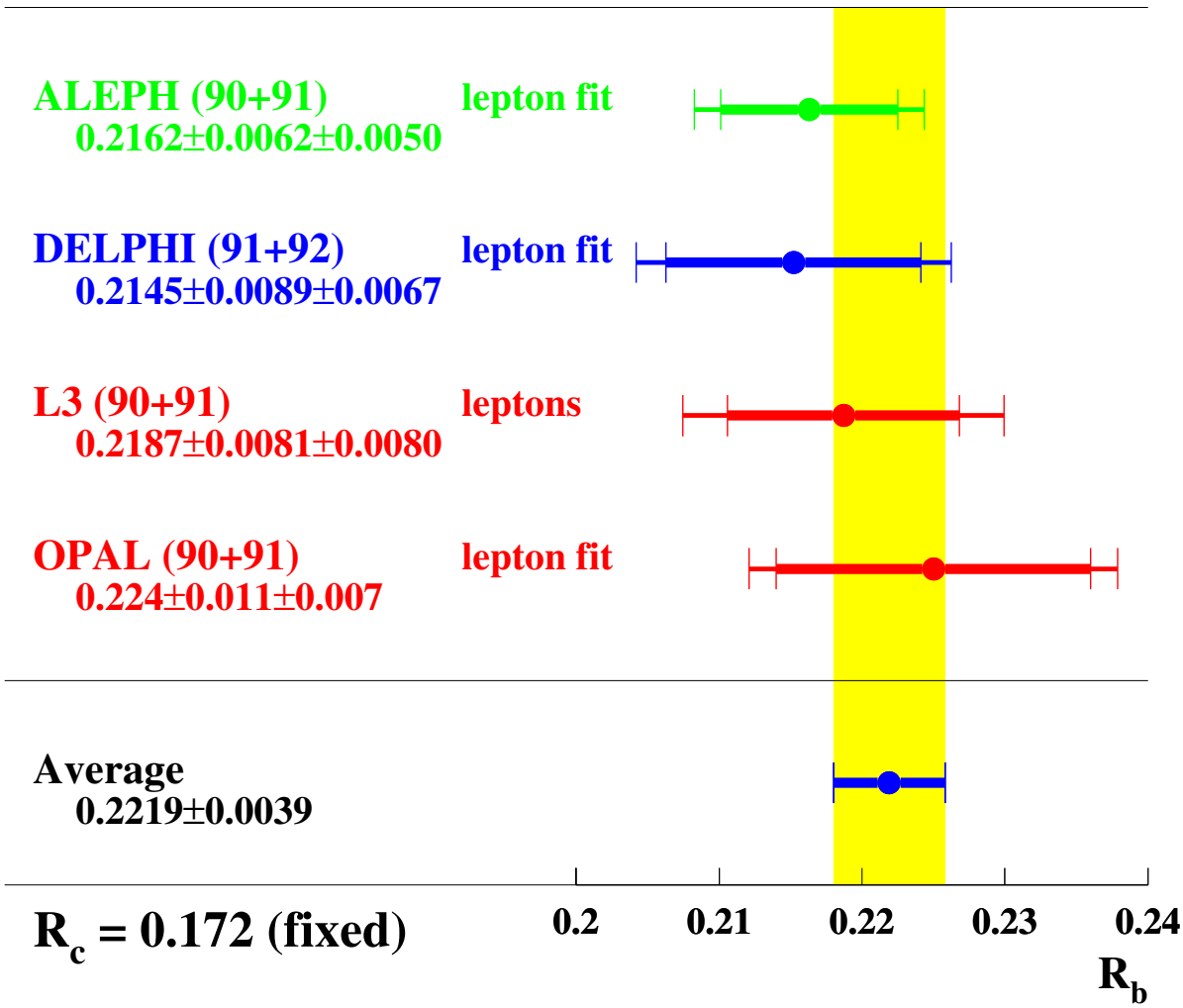
R_b Results



Small corrections have been applied to plotted results for consistency with LEP HF EW WG recommendations

Photon correction of +0.0003 already applied to average

Lepton Fit Results for R_b



Correlations large in lepton fits, particularly between R_b and semileptonic branching ratios.

Reconstructed Particles for c Tagging

Tag decaying c-flavoured hadrons, from:

- $\mathrm{Z}^0 \to \mathrm{c}\overline{\mathrm{c}}$
- $\mathrm{Z}^0 \to \mathrm{b}\overline{\mathrm{b}}$, $\mathrm{b} \to \mathrm{c}$
- $g \to \mathrm{c}\overline{\mathrm{c}}$

Usually take from lower energies:

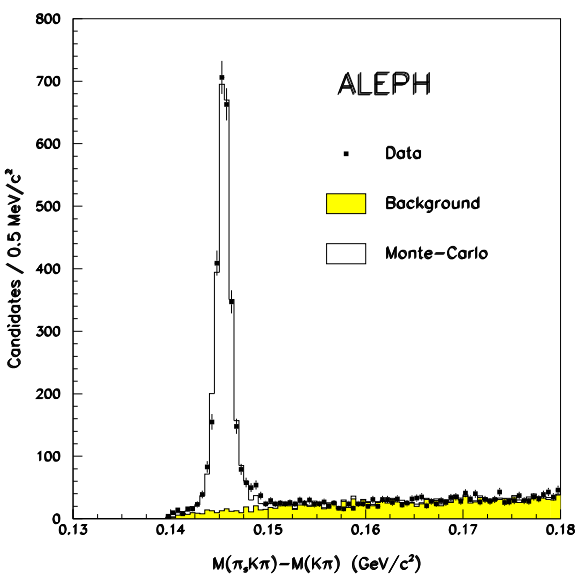
- hadronization fractions $f(\mathrm{c} \to \mathrm{D}^0)$ etc.
- decay branching ratios $B(\mathrm{D}^0 \to \mathrm{K}\pi)$ etc.

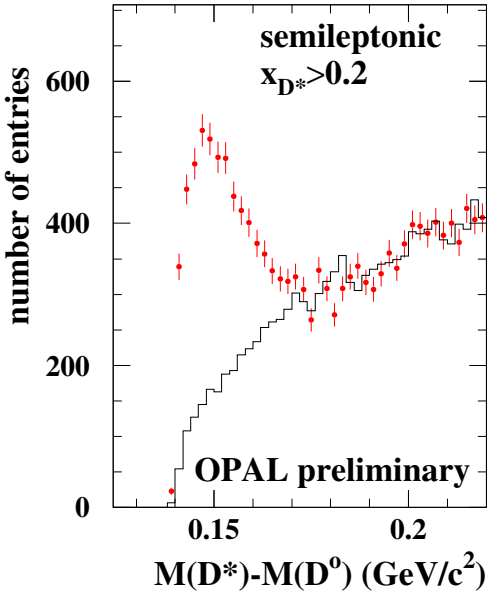
for $\mathrm{c}\overline{\mathrm{c}}$ events

D^* Mesons and Transition Pions

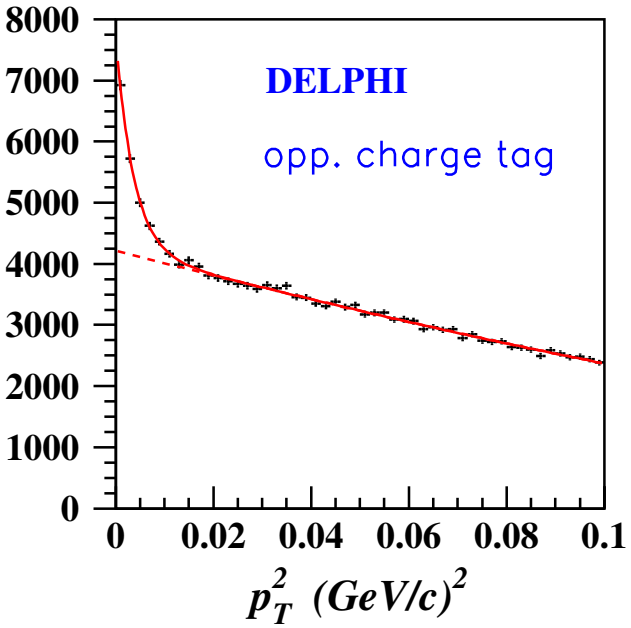
Fully and partially-reconstructed D^* mesons

$\mathrm{D}^* \to \pi \mathrm{D}^0$, $\mathrm{D}^0 \to \mathrm{K}\pi$ or $\mathrm{D}^0 \to \mathrm{K}\ell\nu X$

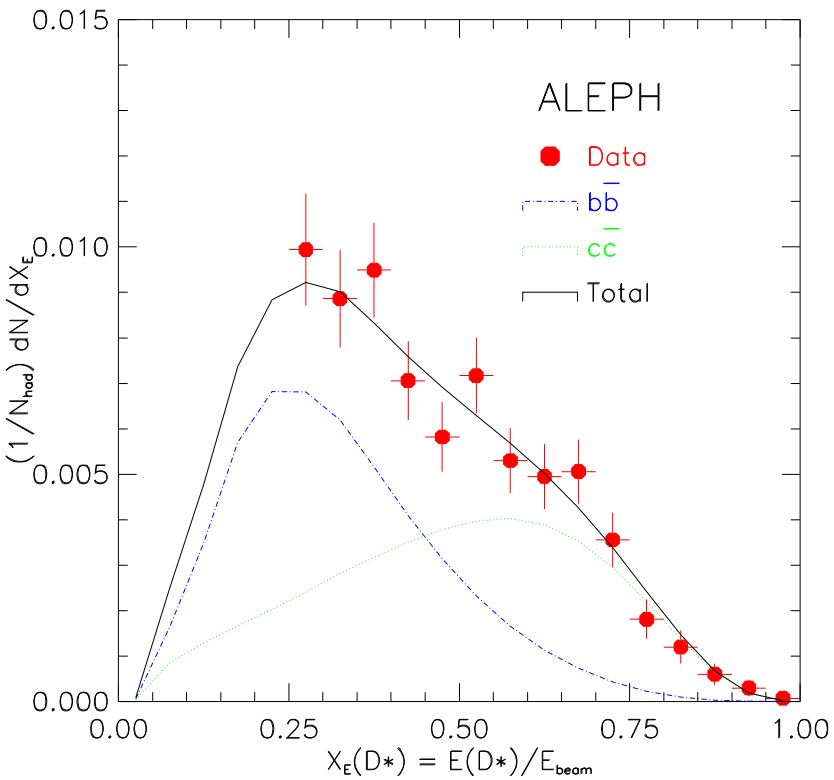




Inclusive transition π tag:



Flavour Separation Techniques

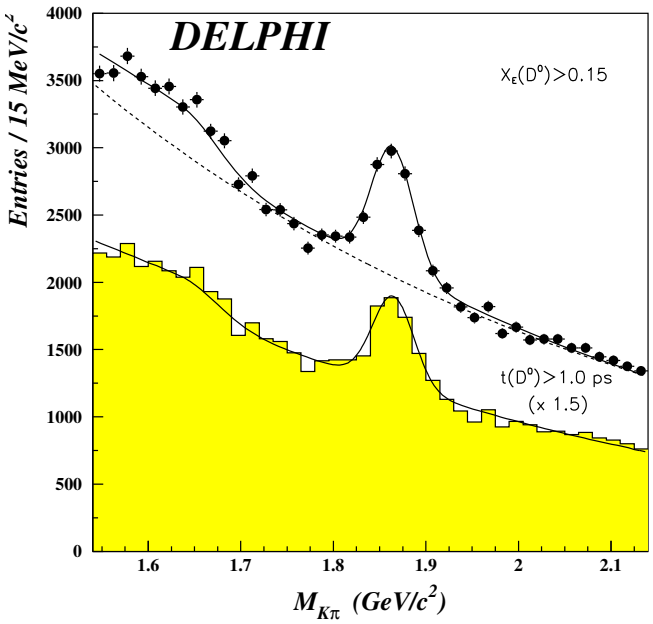


Flavour separation techniques for statistical separation of b and c components:

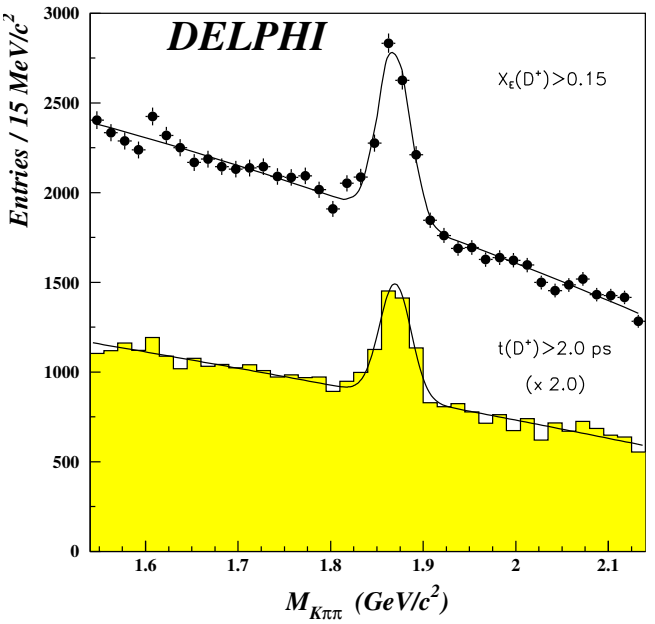
- Momentum of decaying hadron
- Lifetime of tagged particle
- Lifetime information in rest of event
- Event shapes
- Presence of leptons

Fully Reconstructed Hadrons

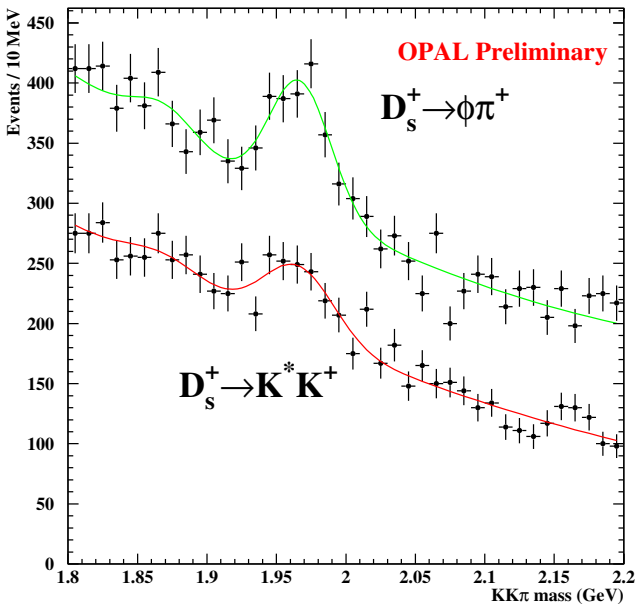
$D^0 \to K\pi$



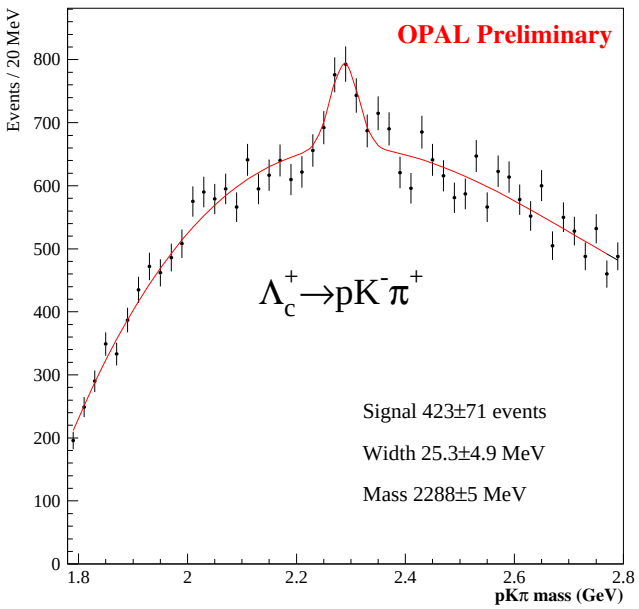
$D^+ \to K\pi\pi$



$D_s^+ \to KK\pi$



$\Lambda_c^+ \to pK\pi$:



R_c Measurements

Measuring R_c:

- Single-tag D^* or D^+/D^0
  - Need $f(c \to D)$ and decay BRs from lower energy
- Double-tag - either two π_s or D^* opposite π_s
  - Can measure $f(c \to D^*) \cdot B(D^* \to D^0\pi)$
  - Still need $B(D^0 \to K\pi)$ – known rather better
- Total rate of D^0, D^+, D_s^+ and Λ_c^+
  - Saturates $Z^0 \to c\bar{c}$ (unobserved baryons small)
  - Removes need for f's (measured simultaneously)
  - Needs reference decay branching ratios
  - Poor signal/background $\Longrightarrow$ large statistical errors
- Common systematic error from b/c separation in all above
- Lepton fits – decay modelling systematics

Statistics insufficient for clean double-tag as used for R_b

R_c from the Total Rate of c Hadrons

OPAL have preliminary measurements of:

$$
\begin{aligned}
R_c f(c \to D^0) B(D^0 \to K^- \pi^+) &= 0.383 \pm 0.025 \pm^{0.029}_{0.028} \\
R_c f(c \to D^+) B(D^+ \to K^- \pi^+ \pi^+) &= 0.371 \pm 0.042 \pm^{0.033}_{0.029} \\
R_c f(c \to D_s^+) B(D_s^+ \to \phi \pi^+) &= 0.040 \pm 0.013 \pm 0.007 \\
R_c f(c \to \Lambda_c^+) B(\Lambda_c^+ \to p K^- \pi^+) &= 0.056 \pm 0.026 \pm 0.014
\end{aligned}
$$

- Sum these, using measured reference BRs from lower energy:

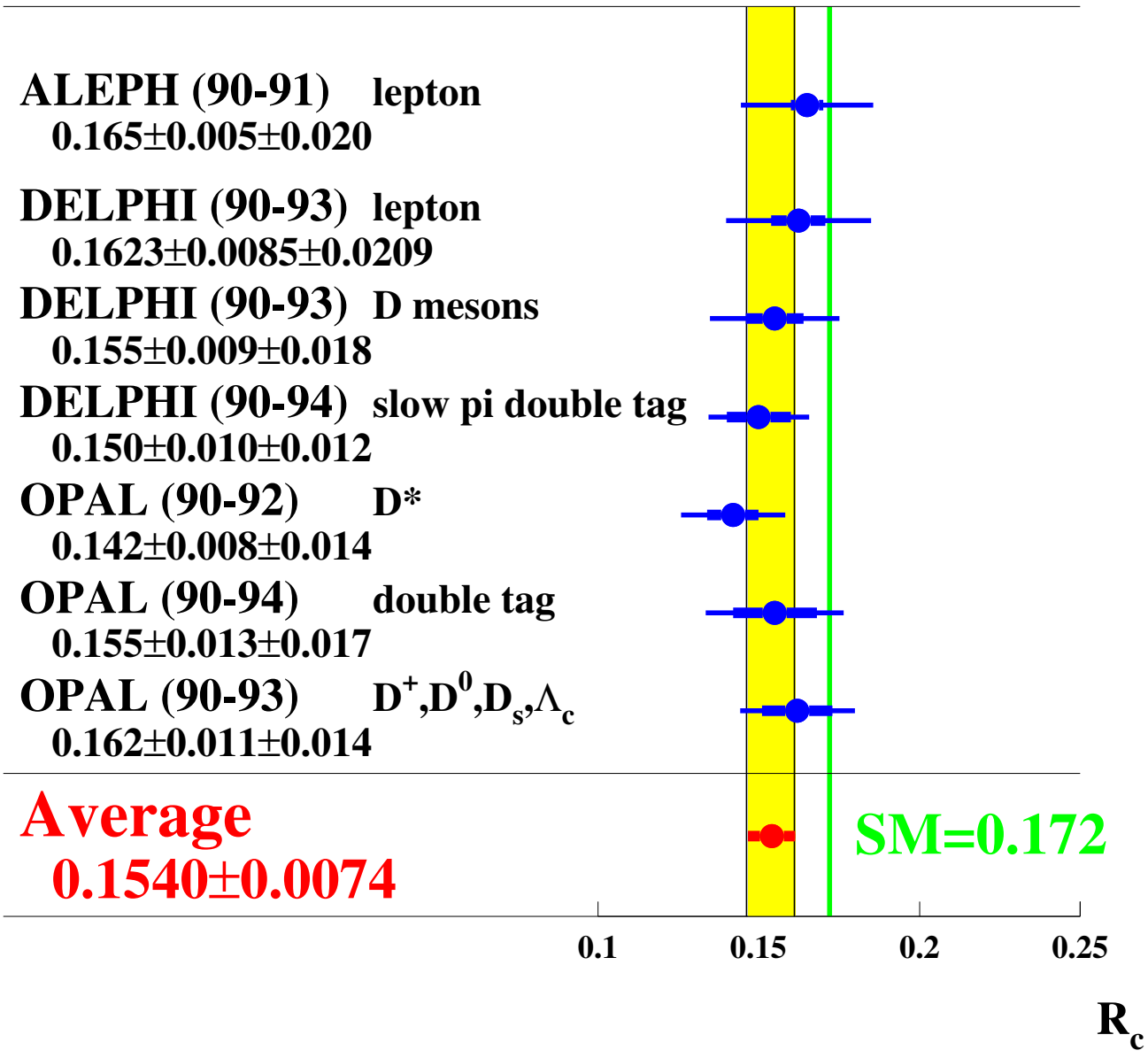
$$
\begin{aligned}
B(D^0 \to K^- \pi^+) &= 4.01 \pm 0.14\% \\
B(D^+ \to K^- \pi^+ \pi^+) &= 9.1 \pm 0.6\% \\
B(D_s^+ \to \phi \pi^+) &= 3.5 \pm 0.4\% \\
B(\Lambda_c^+ \to p K^- \pi^+) &= 4.4 \pm 0.6\%
\end{aligned}
$$

- Correct for unmeasured Ξ_c and Ω_c decays

Result: $R_c = 0.162 \pm 0.011(stat) \pm^{0.013}_{0.012} (sys) \pm 0.005(BR)$

Main other systematics from b/c separation (b lifetime, b and c fragmentation) and pure experimental effects (dE/dx,...)

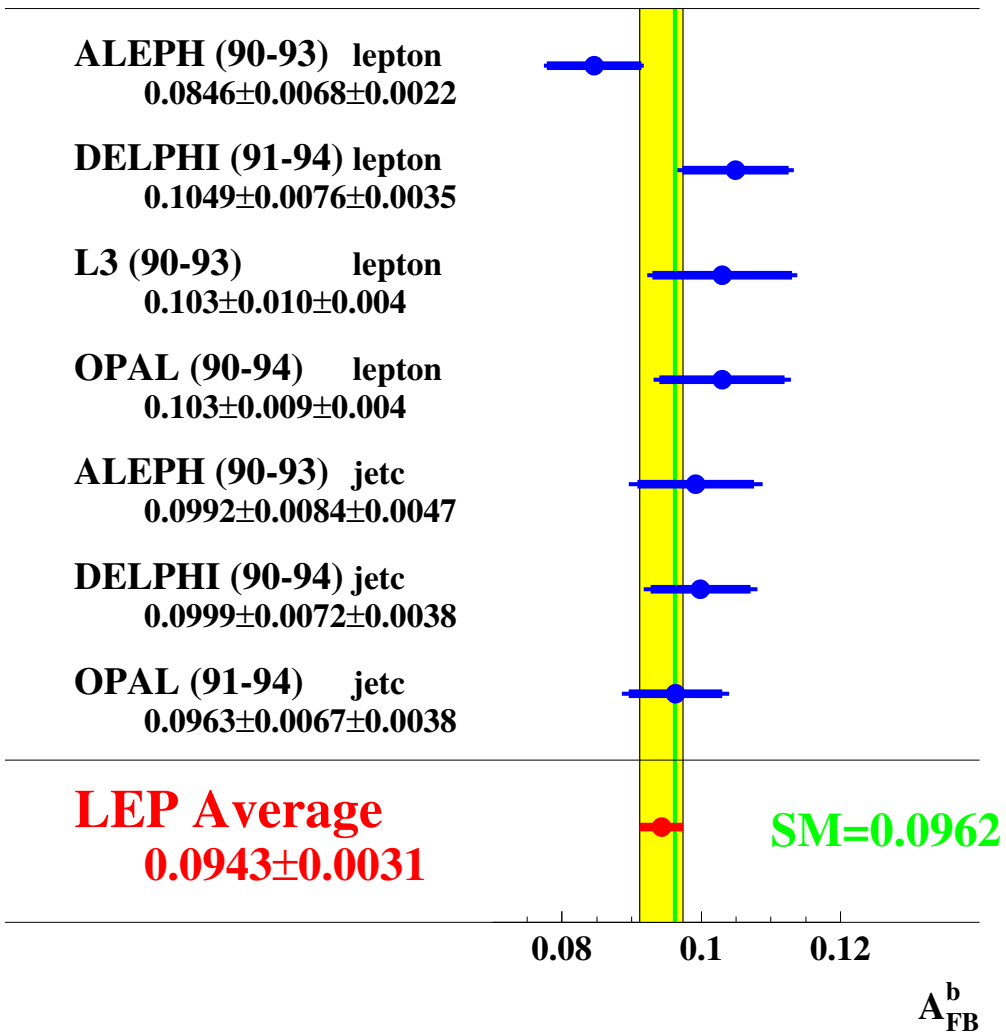
R_c Results

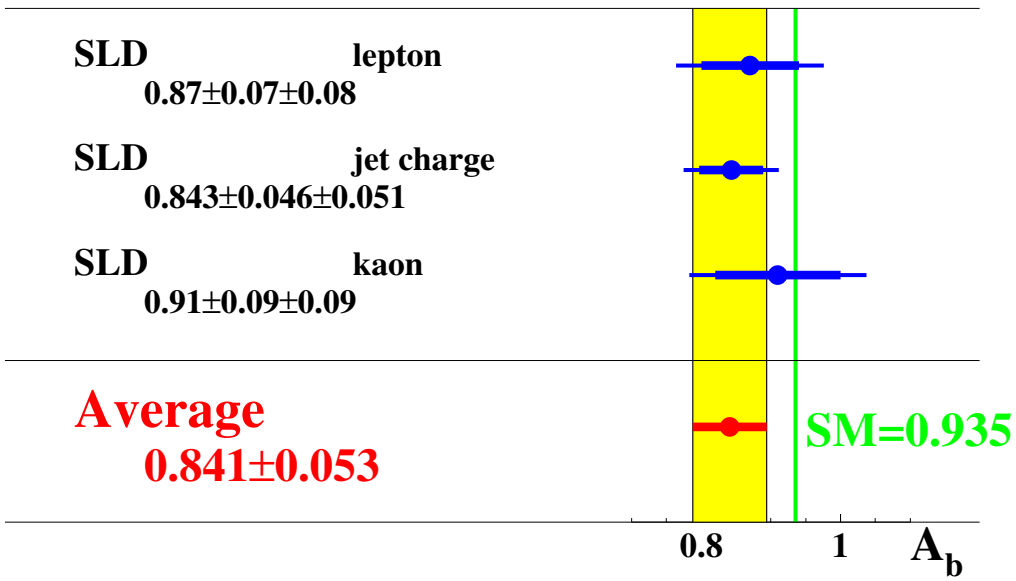


Small corrections have been applied to plotted results for consistency with LEP HF EW WG recommendations

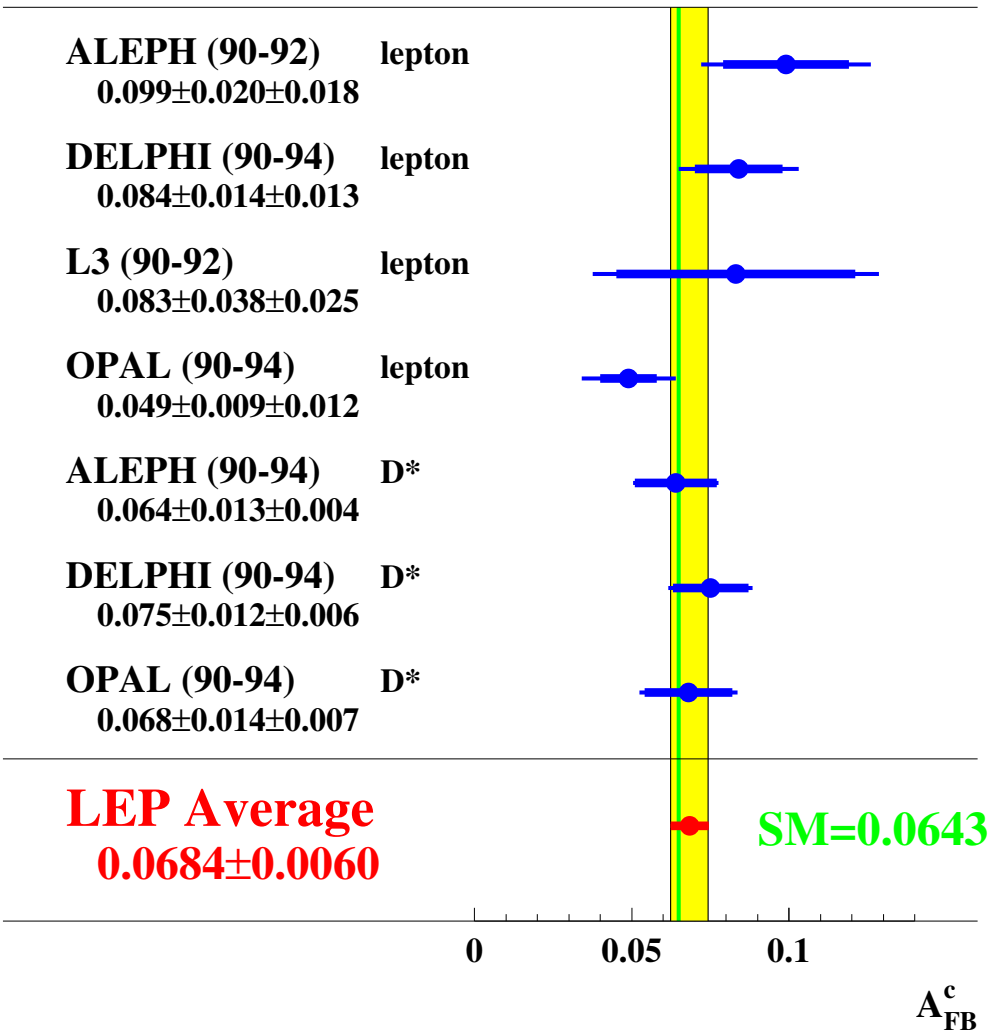
Photon correction of -0.0003 already applied to average

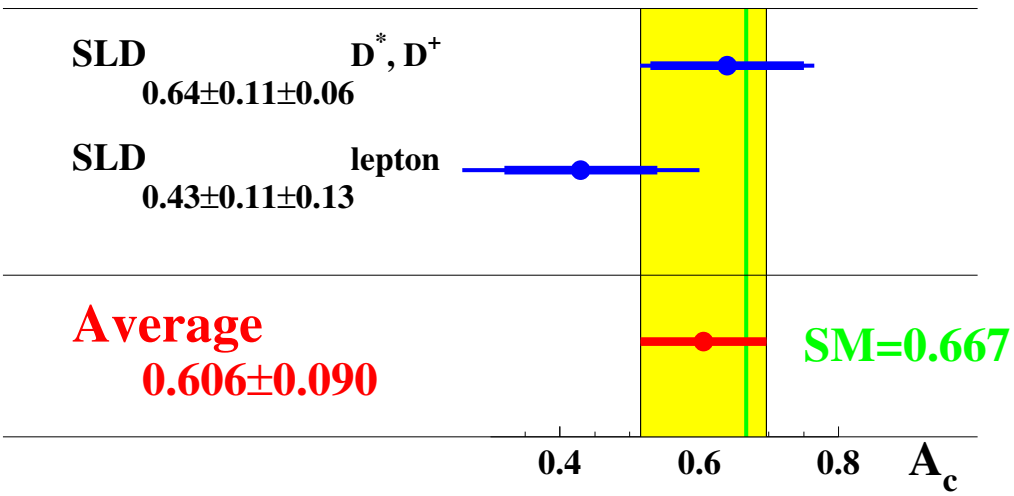
A_{FB}^{b} and $\mathcal{A}_b$ results





A_{FB}^{c} and $\mathcal{A}_c$ results





$\mathcal{A}_{\rm b}$ and $\mathcal{A}_{\rm c}$

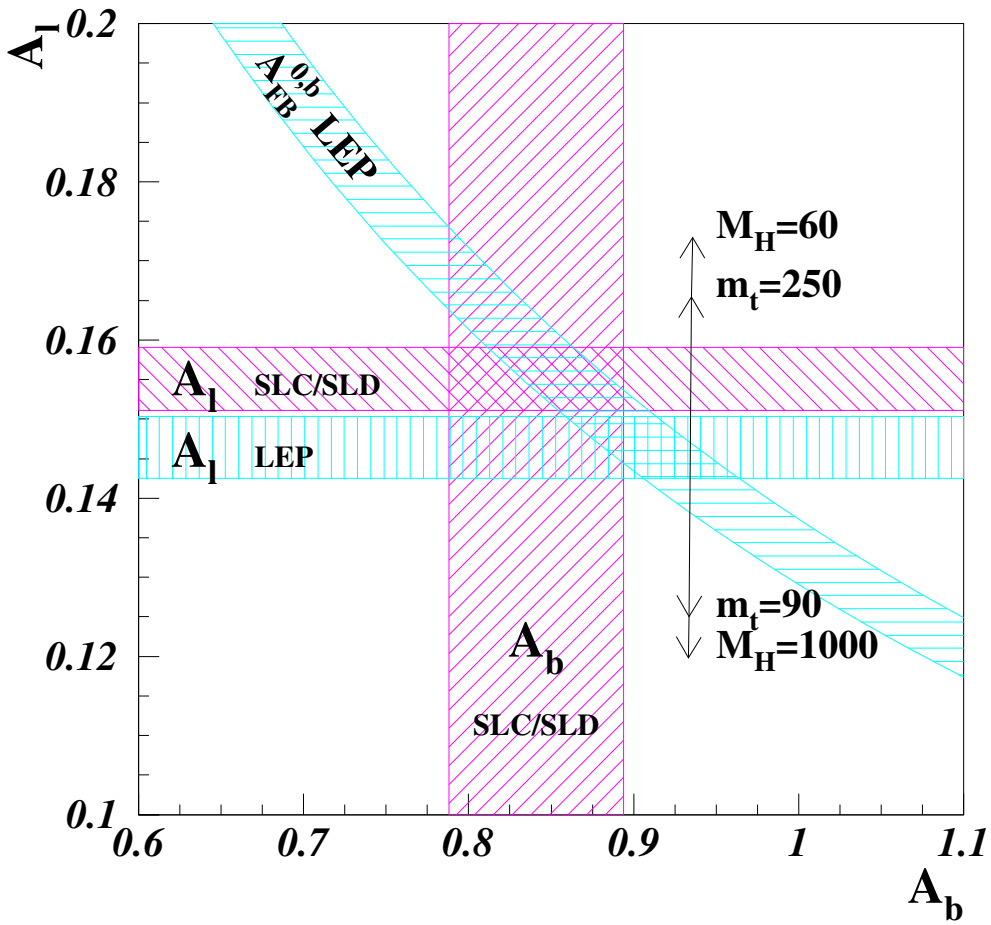
Recall: $A_{\rm FB}^{f,0} \equiv \frac{3}{4}\mathcal{A}_{\rm e}\mathcal{A}_f$

	$\mathcal{A}_{\rm b}$	$\mathcal{A}_{\rm c}$
SLD Average	0.841 ± 0.053	0.606 ± 0.090
LEP (a)	0.910 ± 0.037	0.660 ± 0.056
Combined (b)	0.871 ± 0.027	0.635 ± 0.046
SM (c)	0.935	0.667

(a) Using $\mathcal{A}_\ell = 0.1464 \pm 0.0039$ from $A_{\rm FB}^{\ell,0}$ and τ pol

(b) Using $A_{\rm LR}$ in addition

(c) $m_{\rm Z^0} = 91.1884$ GeV, $m_{\rm top} = 180$ GeV, $m_{\rm H} = 300$ GeV



Combining Correlated Measurements

Heavy flavour electroweak analyses often:

- measure several parameters simultaneously (e.g. asymmetries)
- depend on other unmeasured widths, branching ratios, etc.

Heavy flavour group combination procedure:

- Provides standard ranges for external inputs which lead to systematic errors
- Takes into account correlated errors, statistical and systematic
- Takes into account dependencies on external parameters of each measurement
- Overall χ^2 minimization using full covariance matrix between measurements
- Provides full correlation matrix for final fit results

Checks include:

- Consistency with simple one-parameter averages
- Effect of varying details of correlation assumptions small

Combined LEP and SLD Results

(includes preliminary results)

$$
\begin{aligned}
R_{\mathrm{b}} &= 0.2219 \pm 0.0017 \\
R_{\mathrm{c}} &= 0.1540 \pm 0.0074 \\
A_{\mathrm{FB}}^{\mathrm{b},0} &= (9.97 \pm 0.31)\% \\
A_{\mathrm{FB}}^{\mathrm{c},0} &= (7.29 \pm 0.58)\% \\
\mathcal{A}_{\mathrm{b}} &= 0.841 \pm 0.053 \\
\mathcal{A}_{\mathrm{c}} &= 0.606 \pm 0.090 \\
\mathrm{Br}(\mathrm{b} \to \ell) &= (11.12 \pm 0.23)\% \\
\mathrm{Br}(\mathrm{b} \to \mathrm{c} \to \ell^{+}) &= (7.76 \pm 0.36)\% \\
\overline{\chi} &= 0.1145 \pm 0.0061
\end{aligned}
$$

With a χ^2/dof of $55.1/(74-9)$, χ^2 probability 80%

If R_{c} fixed to Standard Model $R_{\mathrm{c}} = 0.172$

$$
R_{\mathrm{b}}(R_{\mathrm{c}} = 0.172) = 0.2205 \pm 0.0016
$$

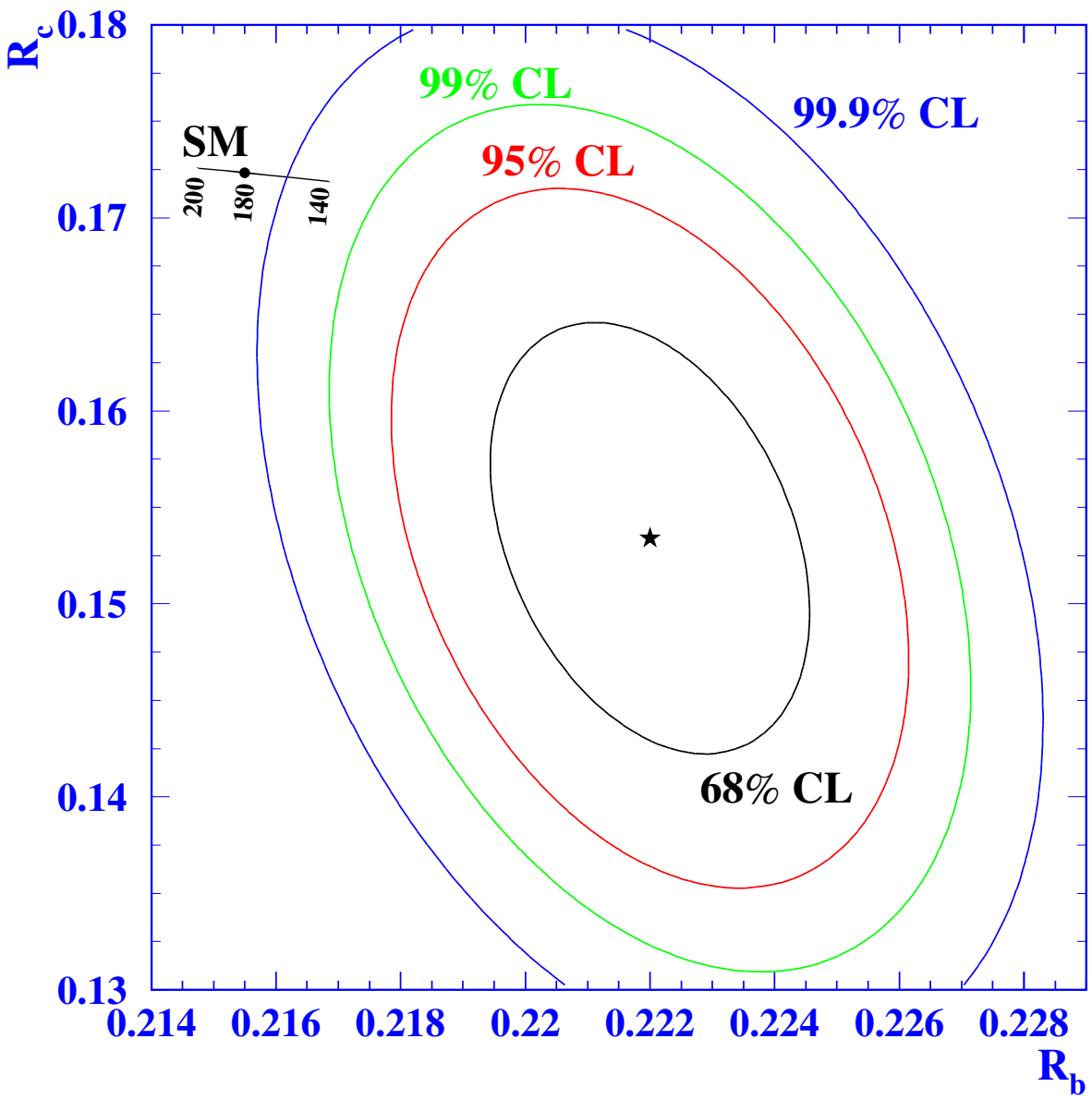
Correlation matrix:

	R_{b}	R_{c}	$A_{\mathrm{FB}}^{\mathrm{b},0}$	$A_{\mathrm{FB}}^{\mathrm{c},0}$	$\mathcal{A}_{\mathrm{b}}$	$\mathcal{A}_{\mathrm{c}}$
R_{b}	1.00	–0.35	0.01	0.06	–0.07	0.05
R_{c}	–0.35	1.00	0.08	–0.06	0.07	–0.06
$A_{\mathrm{FB}}^{\mathrm{b},0}$	0.01	0.08	1.00	0.11	0.06	–0.03
$A_{\mathrm{FB}}^{\mathrm{c},0}$	0.06	–0.06	0.11	1.00	–0.02	0.07
$\mathcal{A}_{\mathrm{b}}$	–0.07	0.07	0.06	–0.02	1.00	0.07
$\mathcal{A}_{\mathrm{c}}$	0.05	–0.06	–0.03	0.07	0.07	1.00

Only significant correlation is that between R_{b} and R_{c}

Size of R_{b}–R_{c} correlation slightly lower than in previous averages, as flavour separation techniques improve

Comparison with Standard Model: R_c vs. R_b

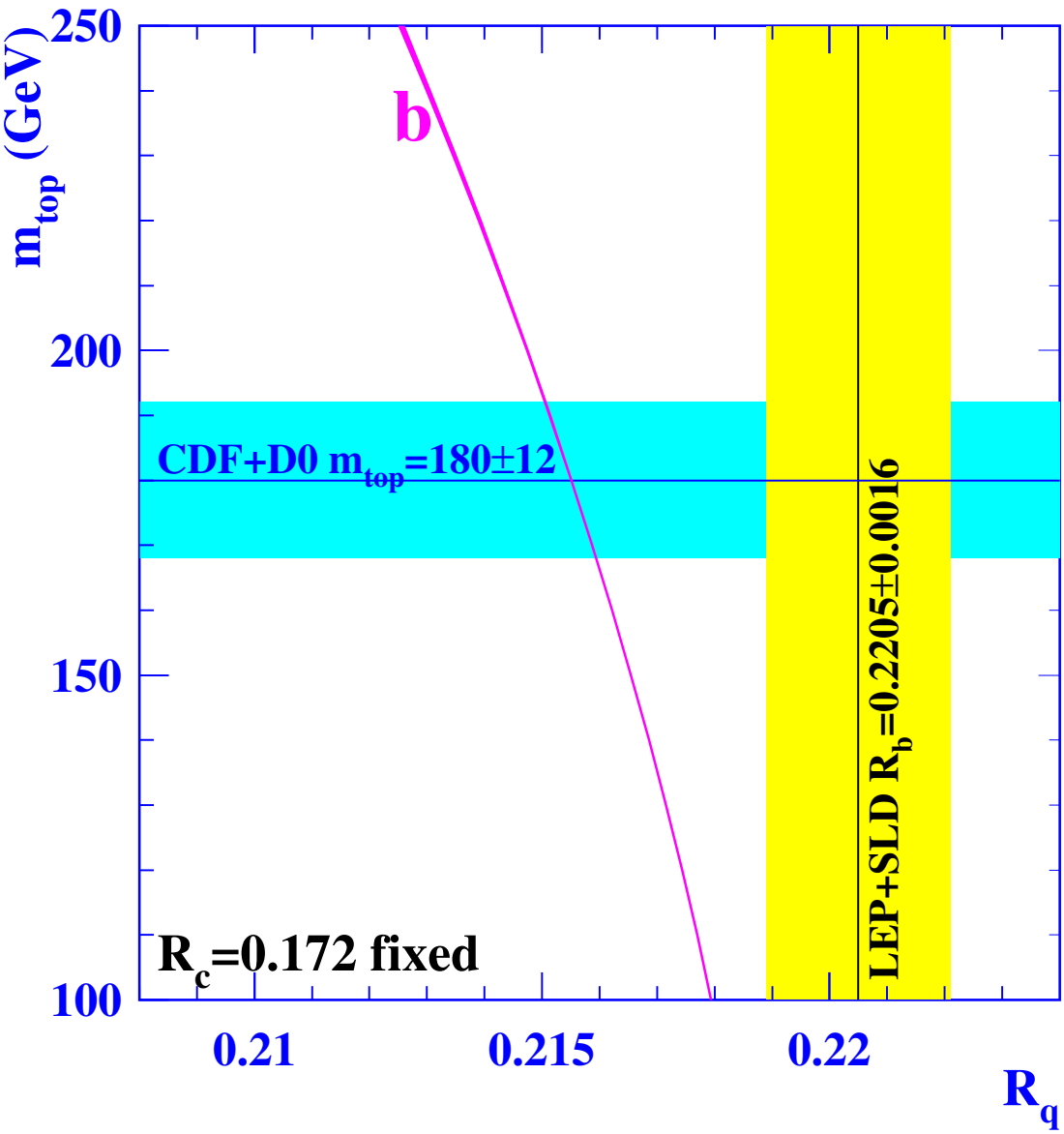


$\Delta\chi^2$ between best fit with Standard Model R_b and R_c

($m_{top} = 180$ GeV, $R_b = 0.2155$, $R_c = 0.172$),

and best overall fit, is 16.0

Comparison with Standard Model: R_c Fixed



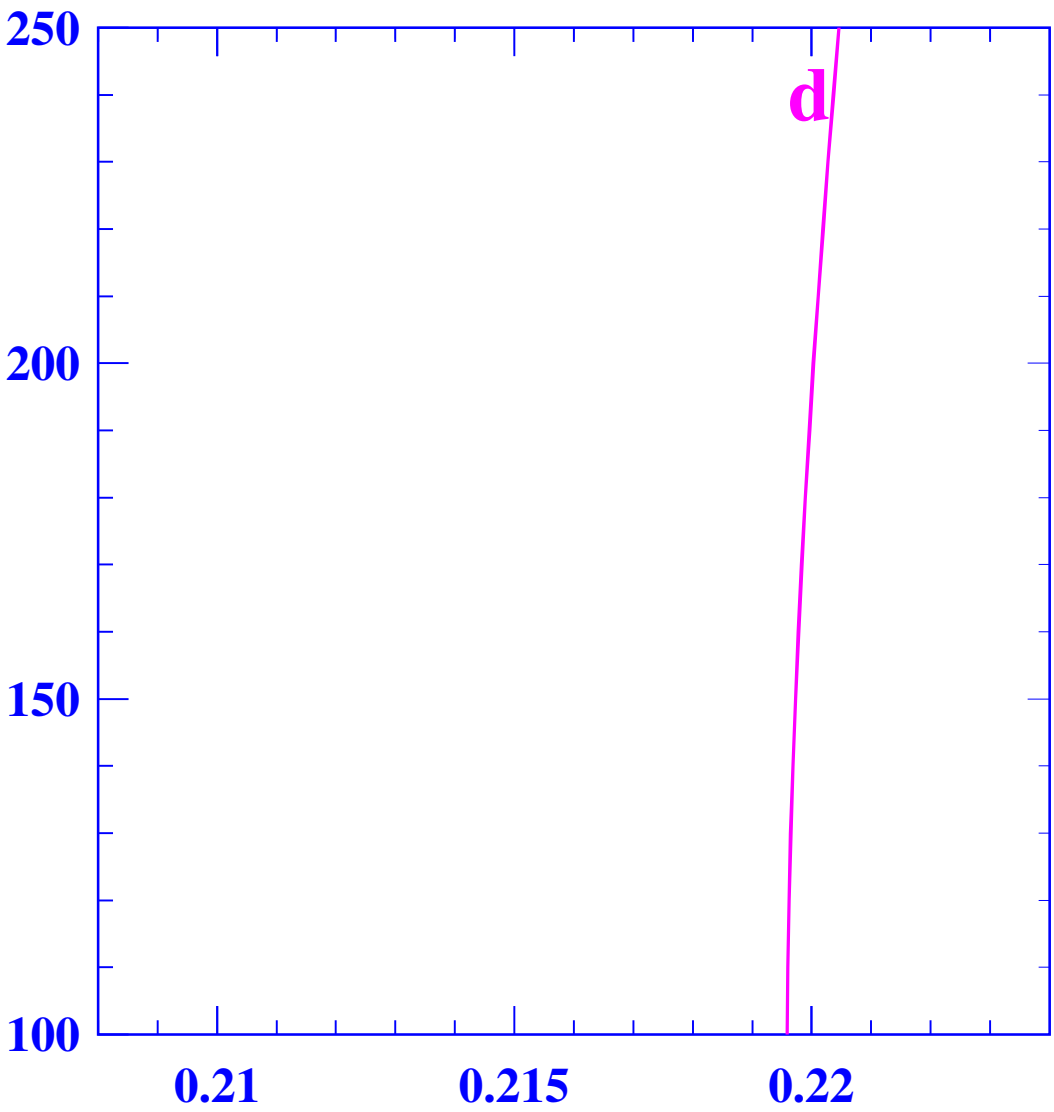
Standard Model predictions from ZFITTER 4.9:

m_{Z^0} =91.1888 GeV, 60 GeV < m_H < 1000 GeV,

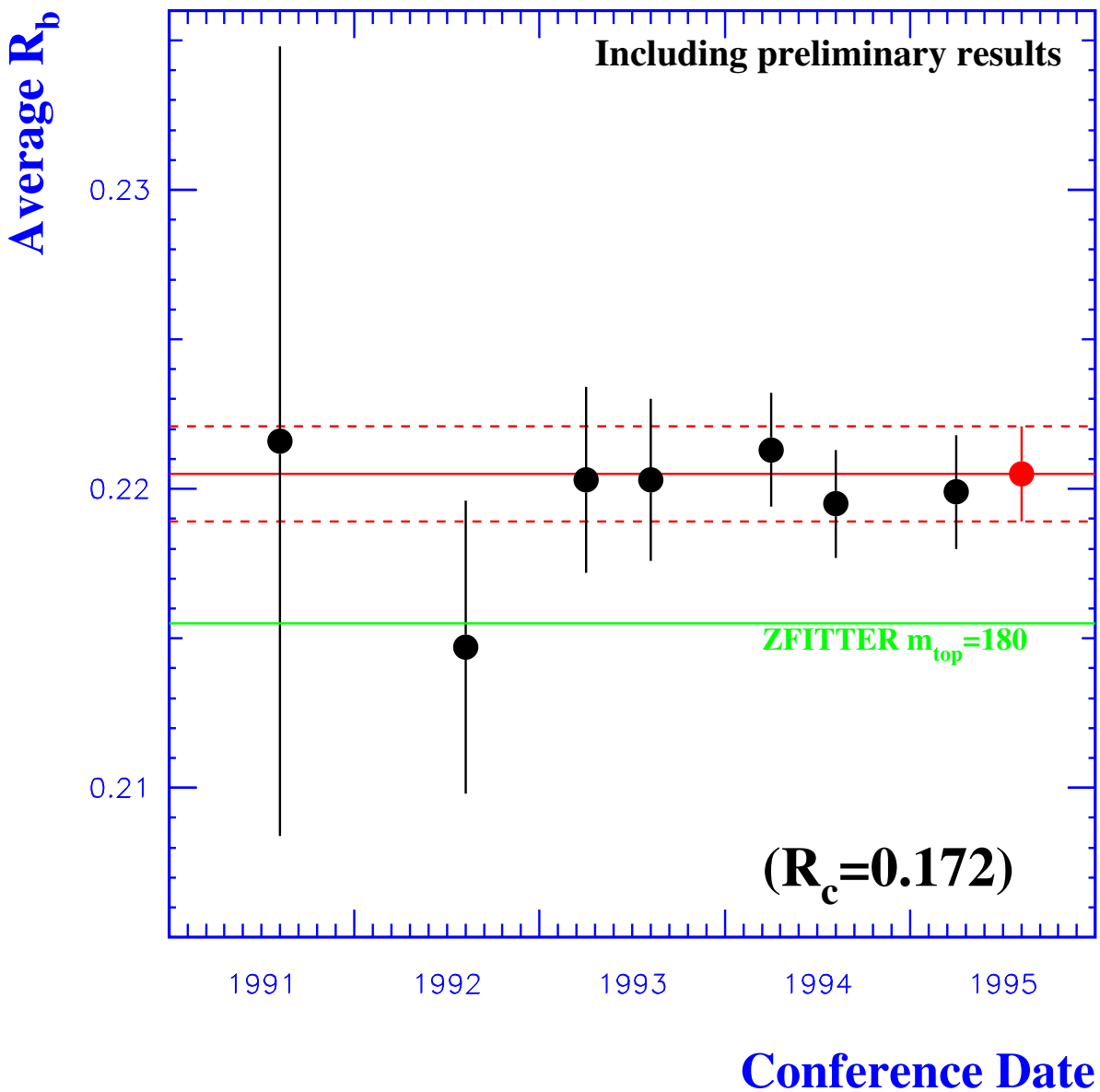
$\alpha_s(m_{Z^0})$=0.12, $\alpha(m_{Z^0})$=1/128.867

For $m_{\rm top} = 180 \pm 12$ GeV, Standard Model prediction

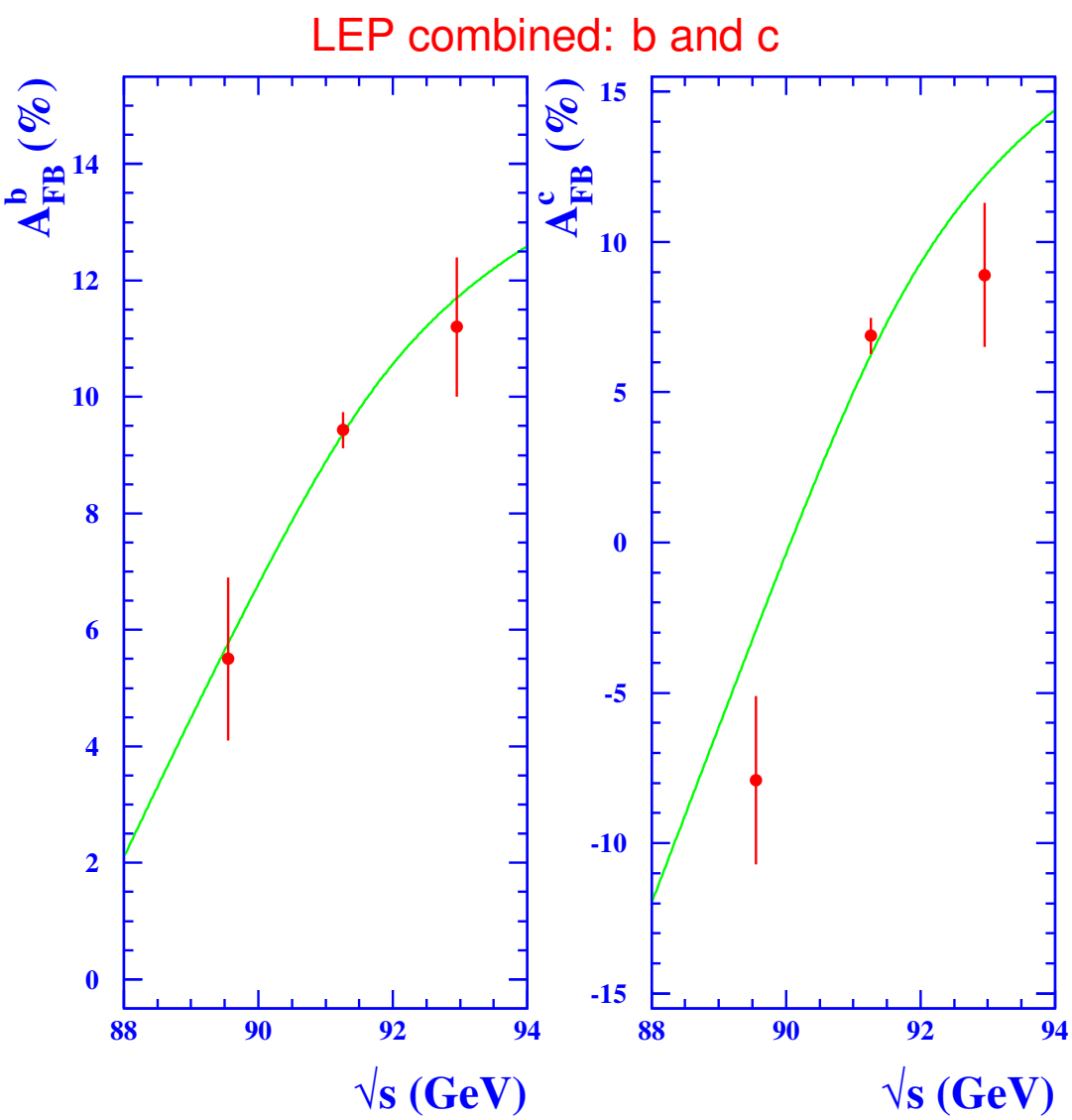
$R_{\rm b} = 0.2155 \pm 0.0005$


250
200
150
100
0.21
0.215
0.22
d

Time Evolution of World Average R_b

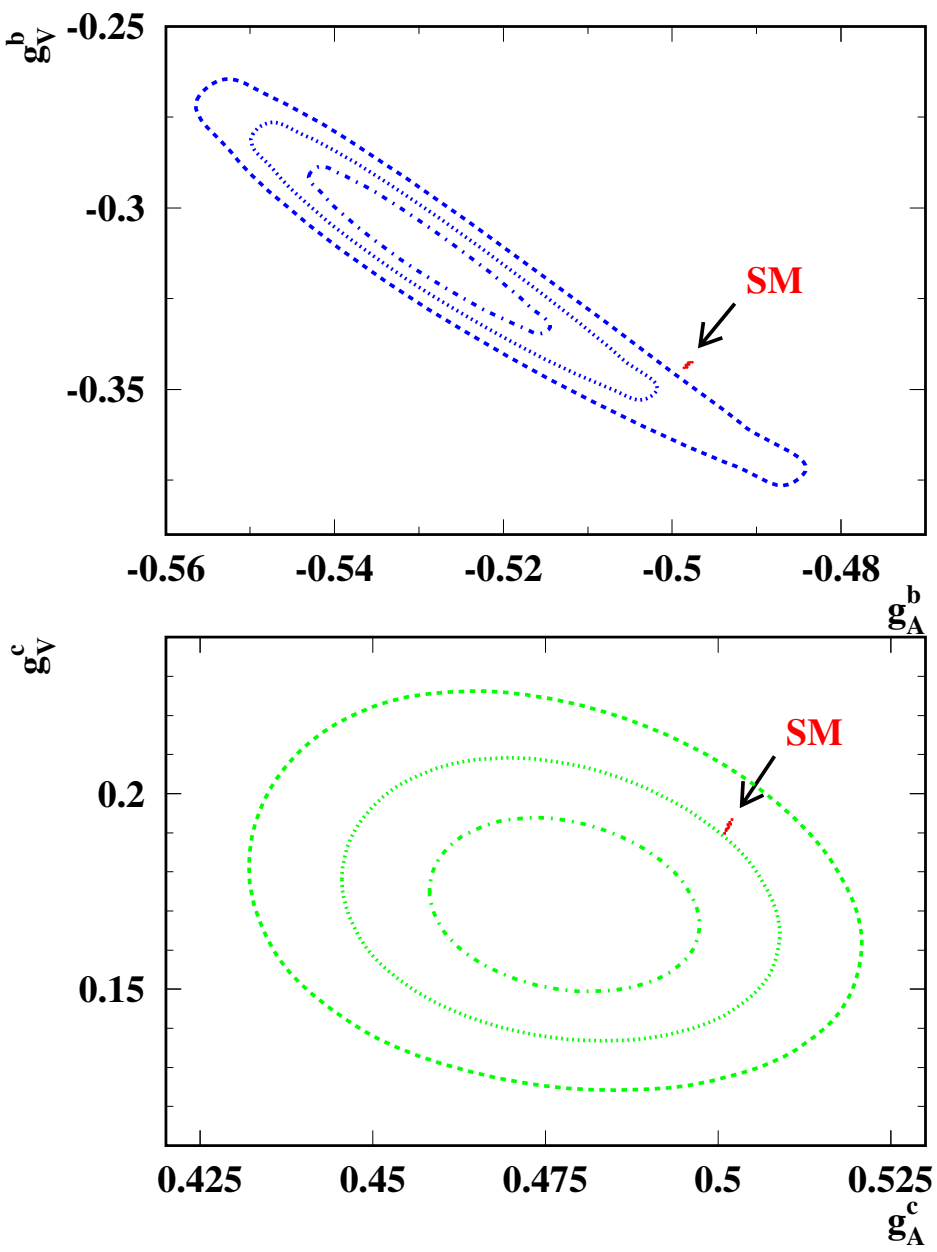


Energy dependence of asymmetries



Heavy quark couplings

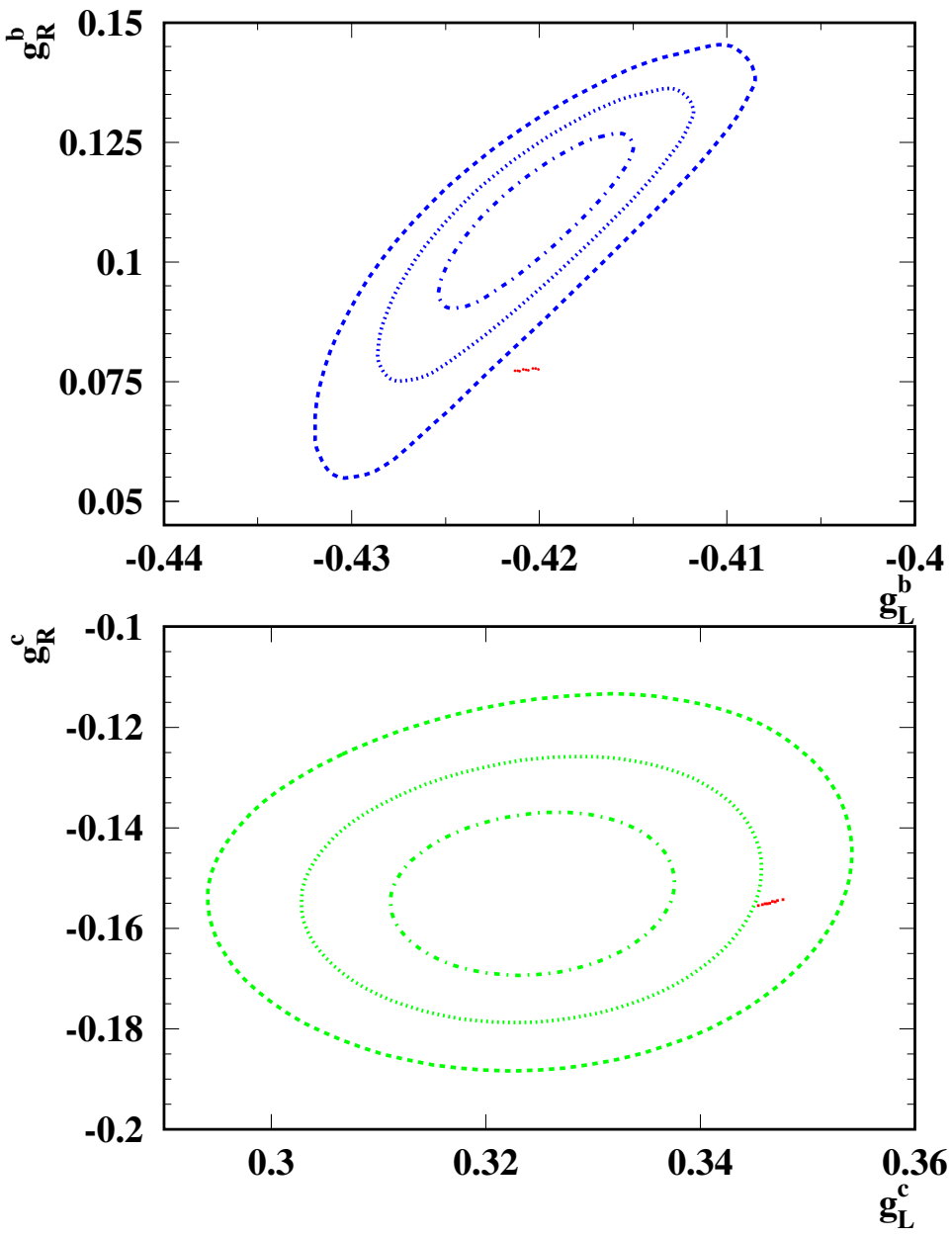
- $\Gamma_f \propto v_f^2 + a_f^2$, (take $\Gamma_{\rm had}$ from measurement)
- $\mathcal{A}_f \implies v_f/a_f$



LEP+SLD, $\Gamma_{\rm had}$ from measurement

- Contours are 68%, 95% and 99.7%.
- $\alpha_s(m_{Z^0}) = 0.123 \pm 0.006$

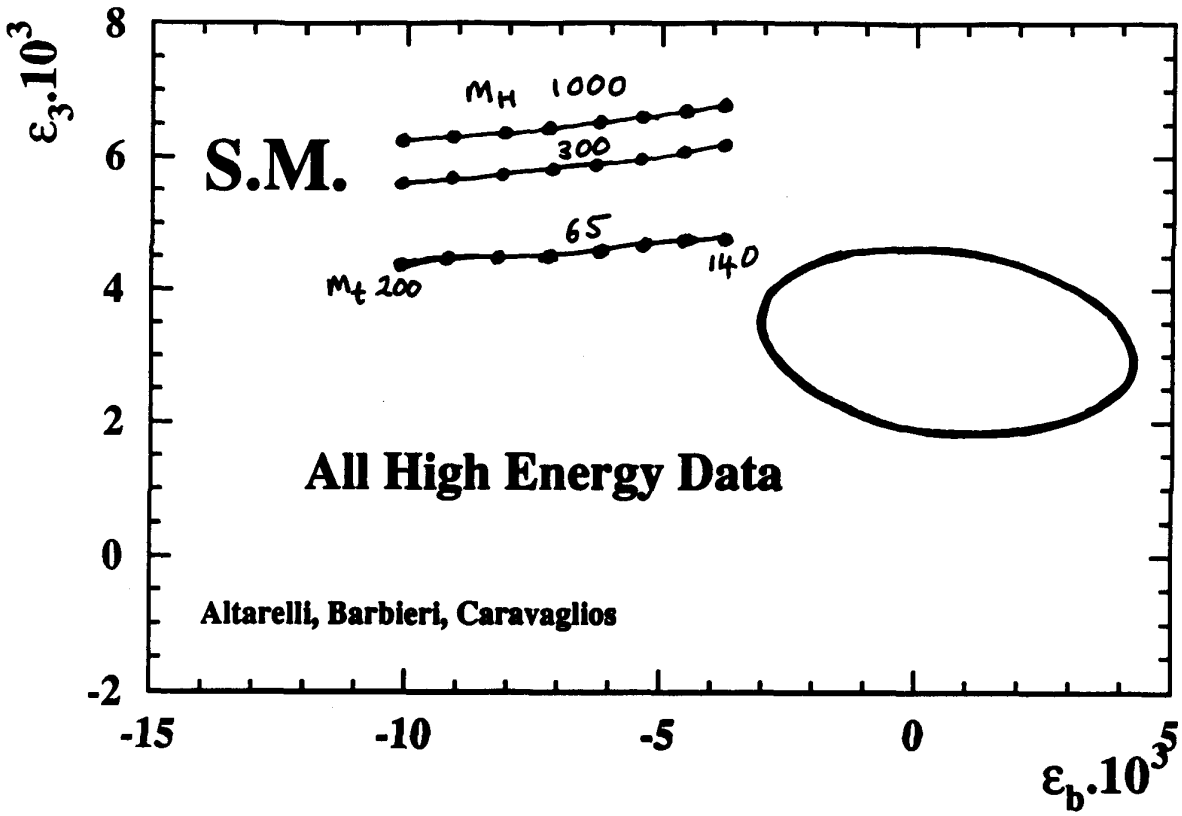
Heavy quark couplings

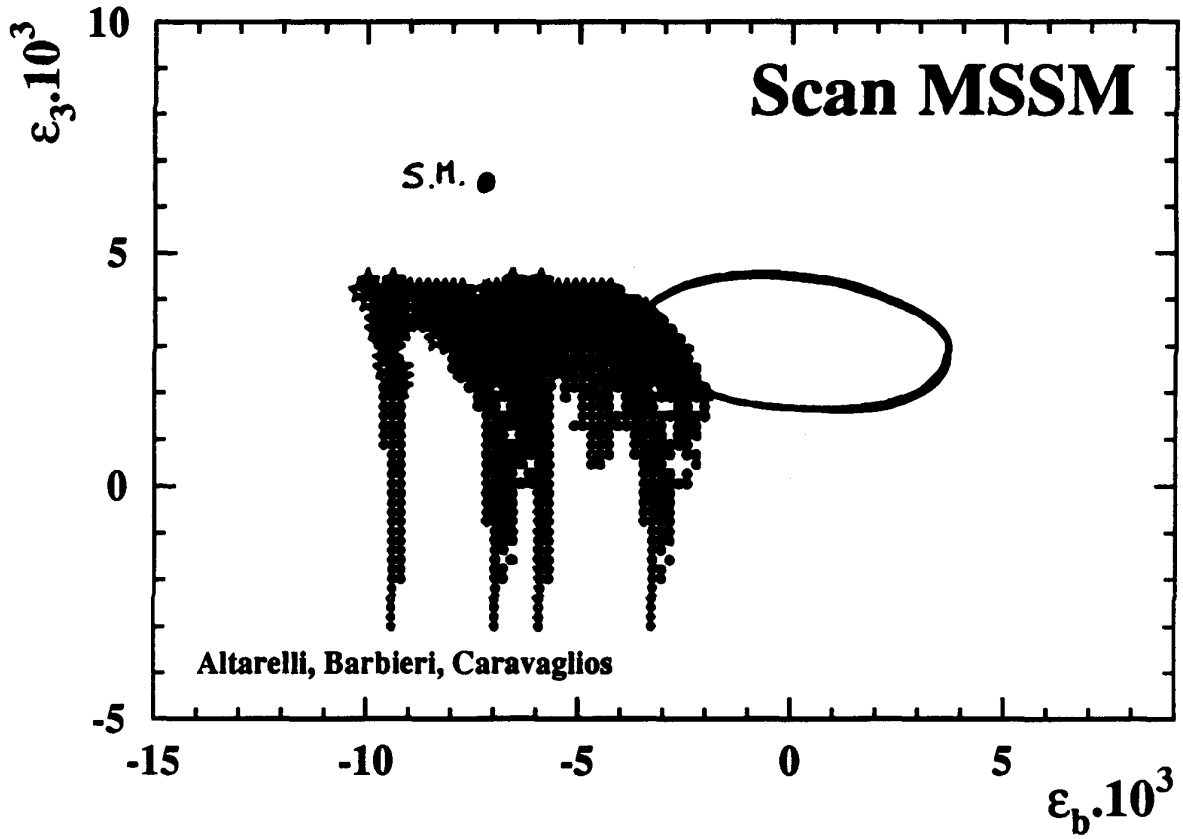


LEP + SLD, Γ_{had} from measurement

- Contours are 68%, 95% and 99.7%.

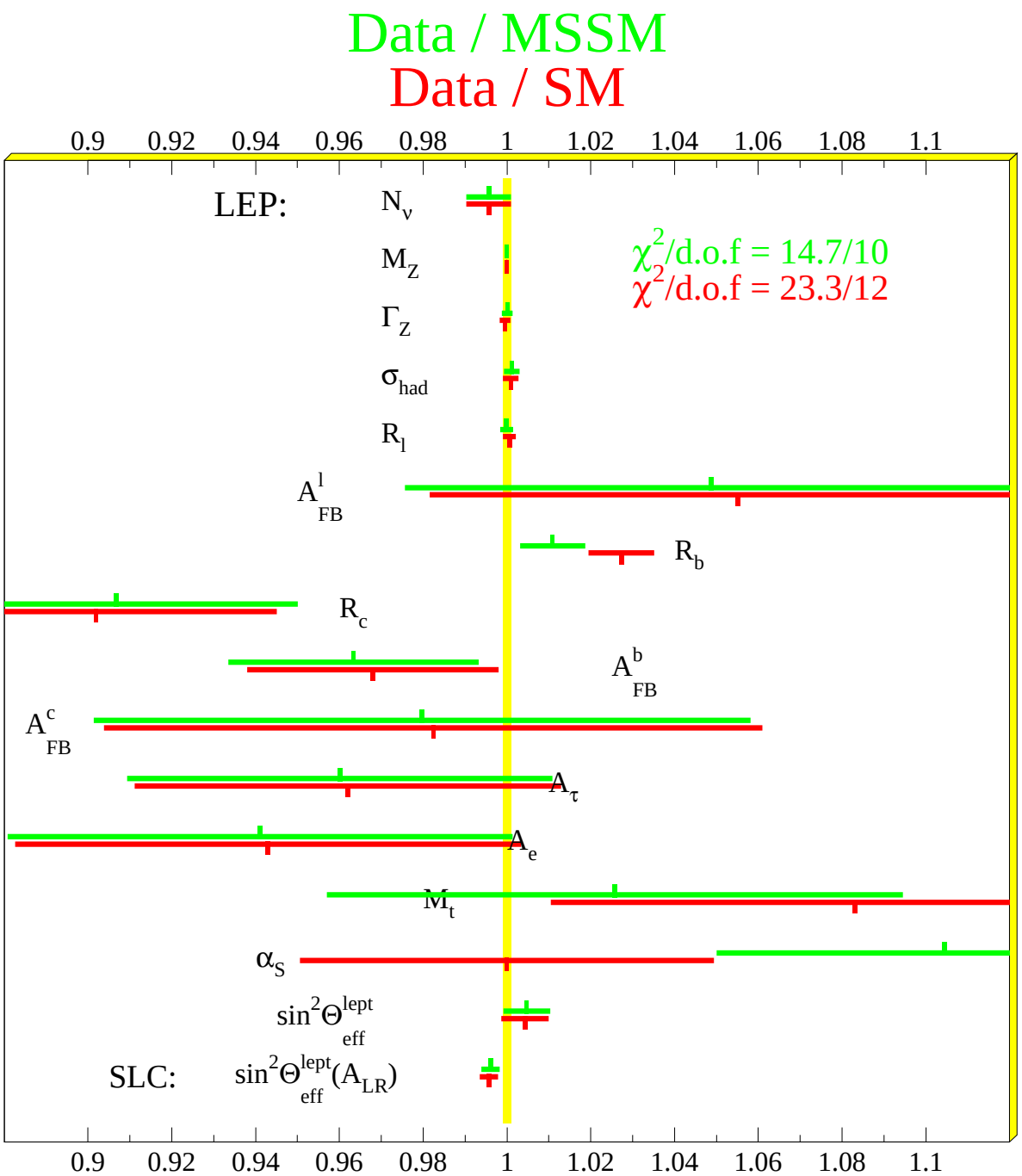
Epsilon analyses





Comparison with MSSM

de Boer et. al.



Summary

- Precision of measurements continues to improve
- World average values (including preliminary results):

$$R_{\mathrm{b}} = 0.2219 \pm 0.0017$$
$$R_{\mathrm{c}} = 0.1540 \pm 0.0074$$

  or with R_{c} fixed $R_{\mathrm{b}}(R_{\mathrm{c}}= 0.172) = 0.2205 \pm 0.0016$

- Measured R_{b} 3σ above Standard Model prediction
- Measured R_{c} is 2.5σ below SM prediction
- Together R_{b}, R_{c} consistent with SM at 0.1% level
- Asymmetries consistent with SM predictions
- First hint of new physics from precision measurements?

Plenty more LEP-I data to be analysed