Measurements of R_b with Lifetime Tags

Results from LEP and SLD

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

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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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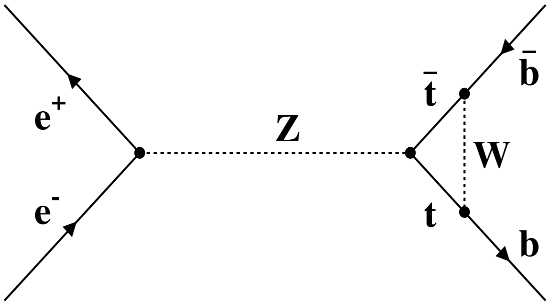
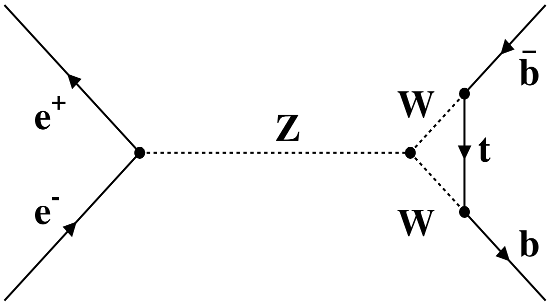
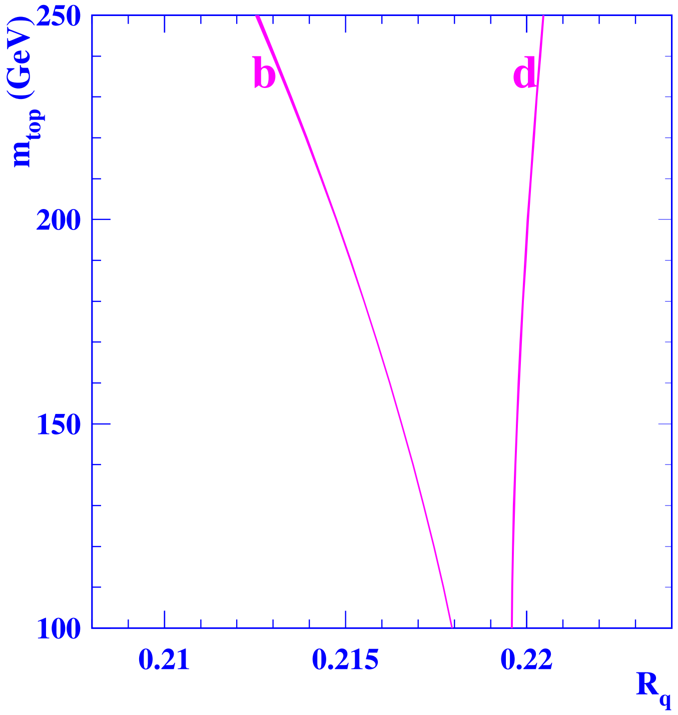
Why is R_b Interesting?

- It can be measured precisely because of the high b mass and long lifetime

- It has special vertex corrections in the Standard Model







- New physics coupling to mass might show up here first?

- Is R_b still high?

  Glasgow: $R_b = 0.2192 \pm 0.0018$

  Standard Model ($m_{top} = 180$): $R_b = 0.2155$

Double-Tagging Method

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}:

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

- 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
  (neglect C_{c}–1, C_{uds}–1)
- Statistical error dominated by N_{tt}
- Systematic error dominated by ε^{c}, C_{b}
- R_{c} dependence handled in averaging procedure

Impact Parameter Probability b Flavour Tag

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

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

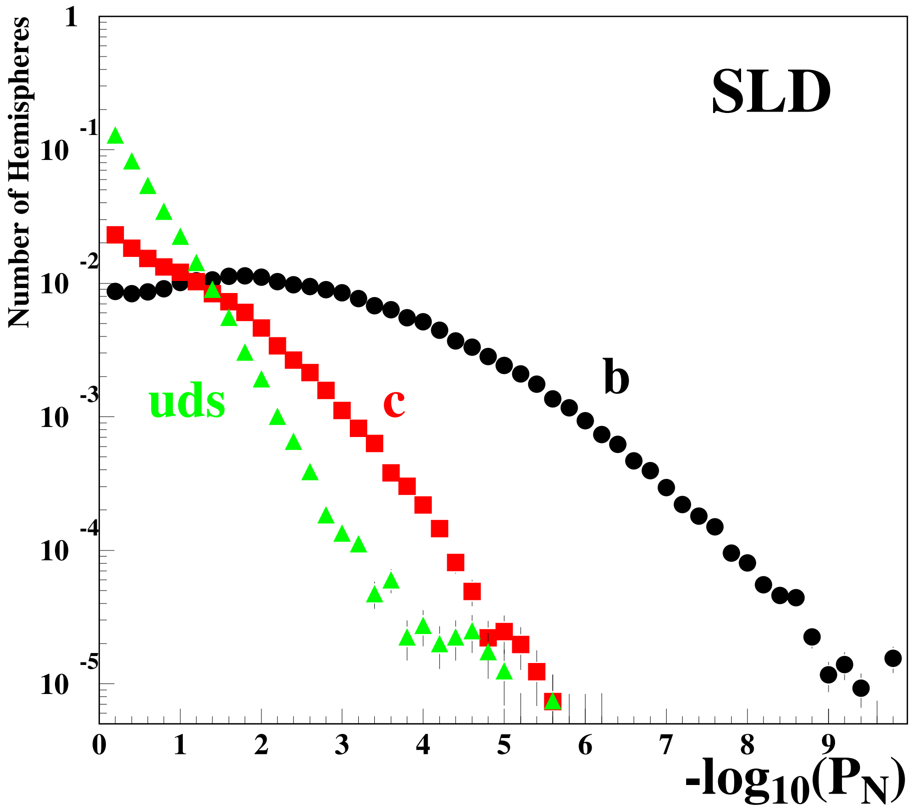
resolution function $\mathcal{R}$ measured from $b < 0$ distribution

- 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

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

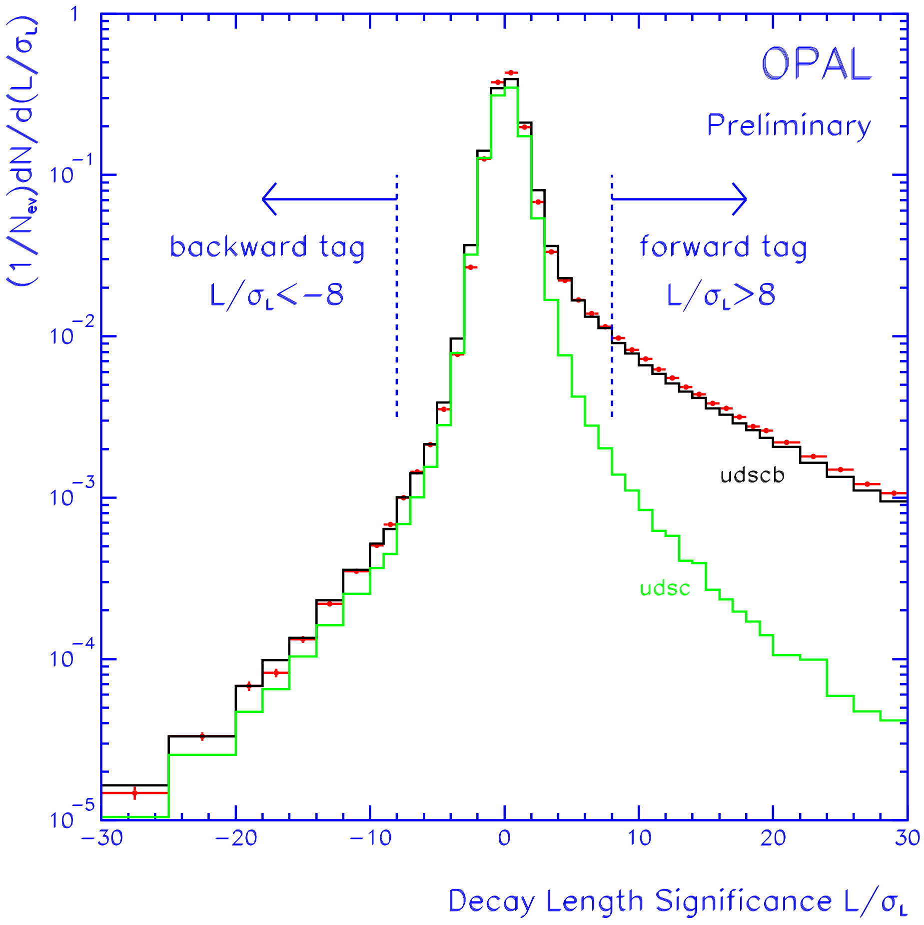


Used by ALEPH, DELPHI, SLD

Secondary Vertex b Flavour Tag

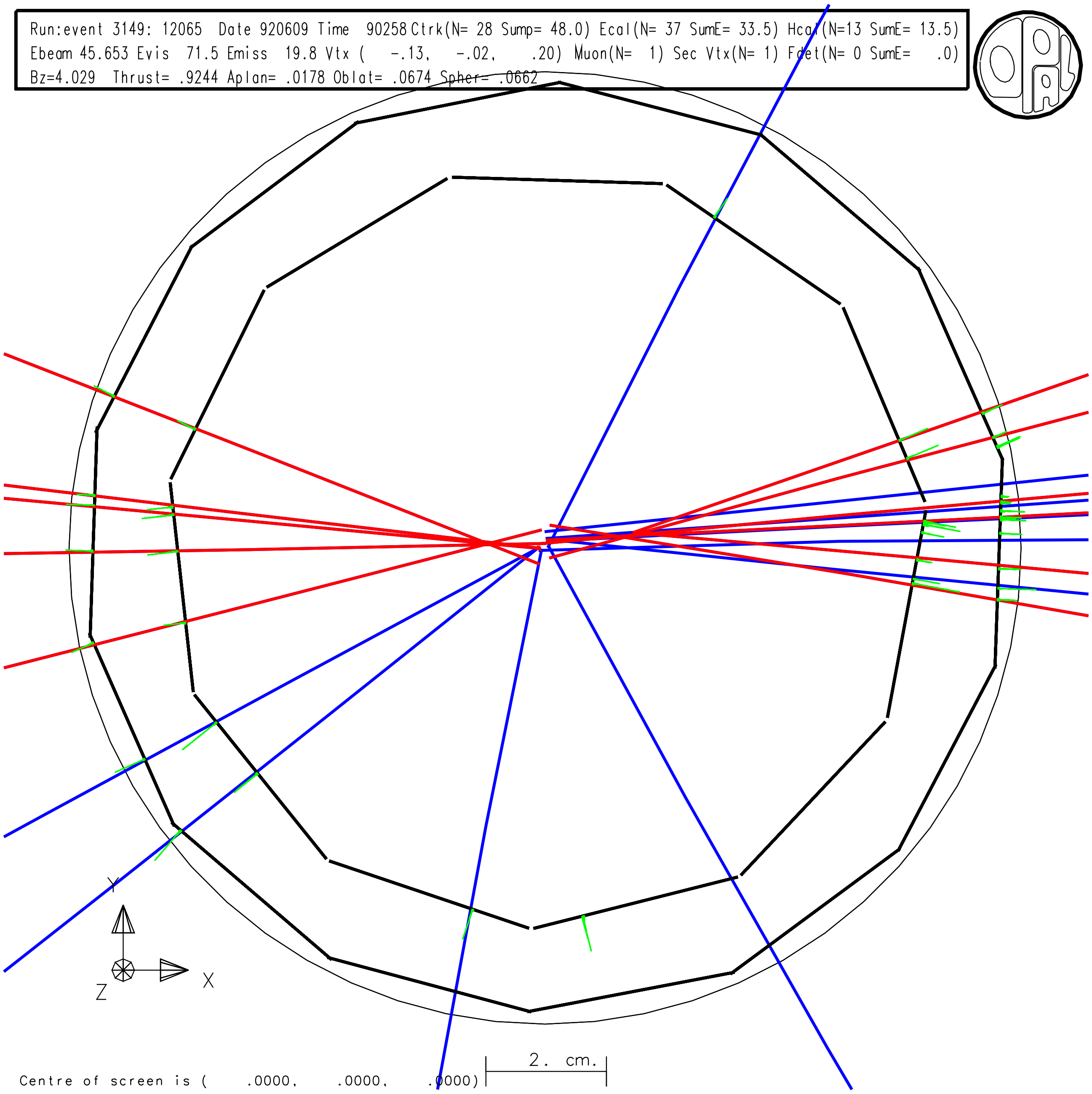
Used by OPAL

- 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 for this 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

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
  - thrust for momentum 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

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

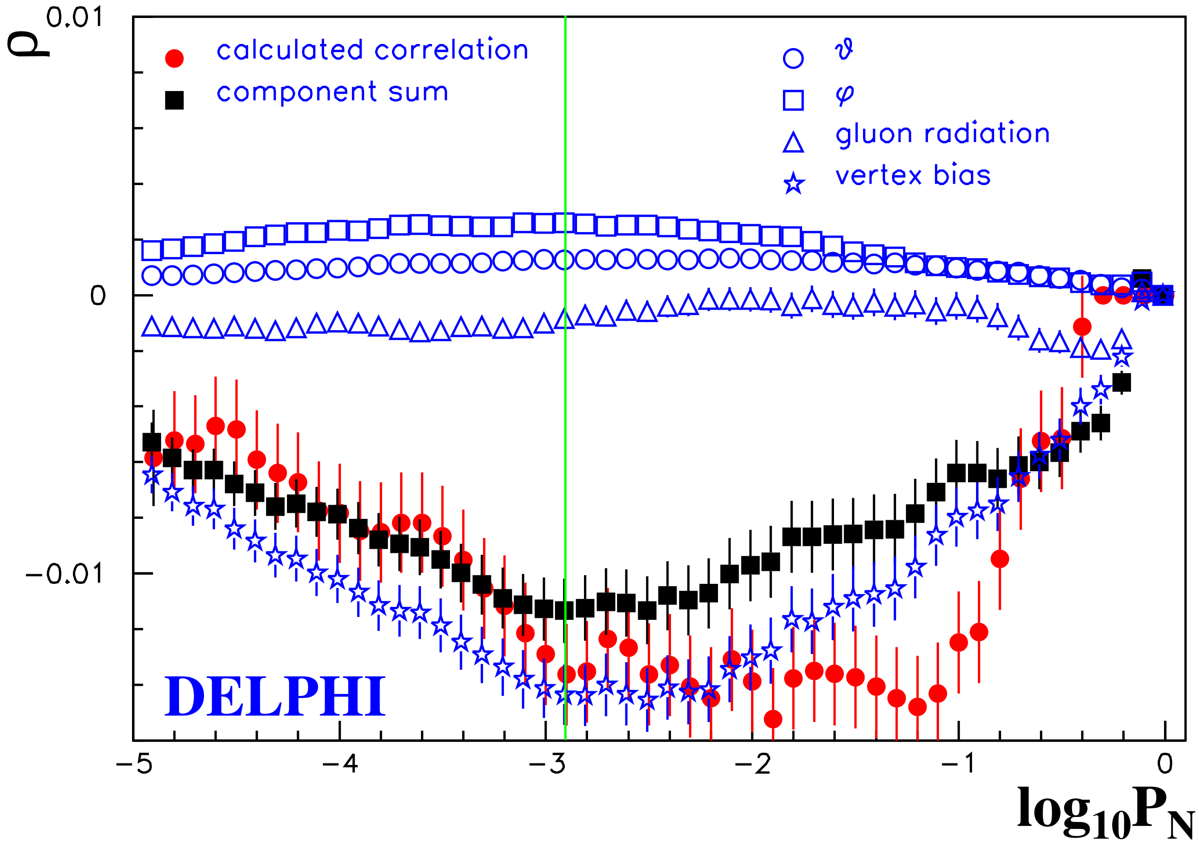
- Corrections from Monte Carlo for residual effects of background on correlation estimate

Total efficiency correlation ρ:

$$\rho = \frac{(C_b(\varepsilon^{\mathrm{b}})^2 - \varepsilon^{\mathrm{b}})}{(\varepsilon^{\mathrm{b}} - (\varepsilon^{\mathrm{b}})^2)}$$

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	0.05
1994	1.7 M	0.1

At this conference, 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

Charm Systematics

Production fractions

- Tagging probability of different c hadron species differs (lifetime)
- From D^+ to Λ_c^+, typically factor four difference
- Take from CLEO and ARGUS measurements

$$f(\mathrm{D}^0) : f(\mathrm{D}^+) : f(\mathrm{D}_s^+) : f(\Lambda_c^+) =$$
$$0.557 : 0.248 : 0.120 : 0.075$$

- Variations according to CLEO/ARGUS errors

$$\begin{array}{llll} f(\mathrm{D}^0) & \pm 0.053; & f(\mathrm{D}^+) & \pm 0.037; \\ f(\mathrm{D}^0 + \mathrm{D}^+) & \pm 0.070; & f(\mathrm{D}_s^+) & \pm 0.050 \end{array}$$

- LEP measurements now competitive: consistent with above numbers (see talk by M.Hauschild)

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)

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

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

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

per hadronic Z^0 decay

Can we test this experimentally?

Measurements at LEP (OPAL Collab., CERN-PPE/95-058 & Z.Phys.C67(1995)27): (see T.Behnke talk)

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

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

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

Measurements reported here use JETSET prediction:

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

and apply a $\pm$50% uncertainty

Energy Dependence

The measured ratio

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

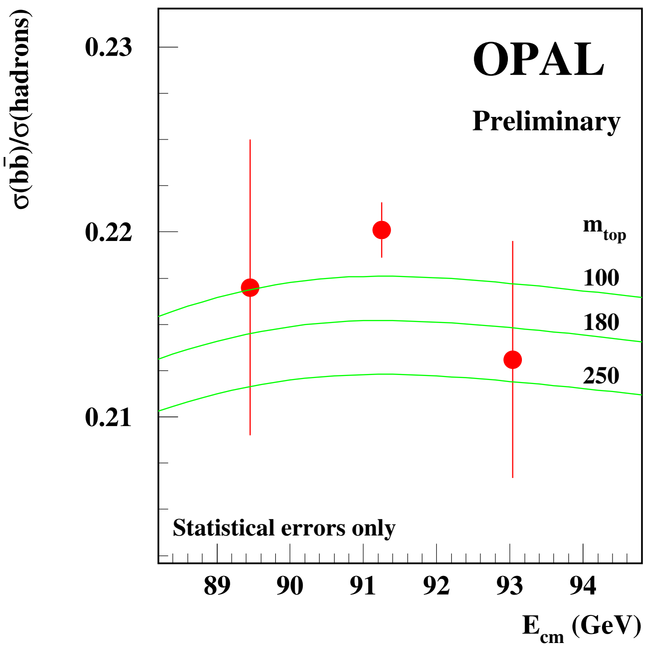
differs slightly from R_b, and varies slowly with centre-of-mass energy

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:



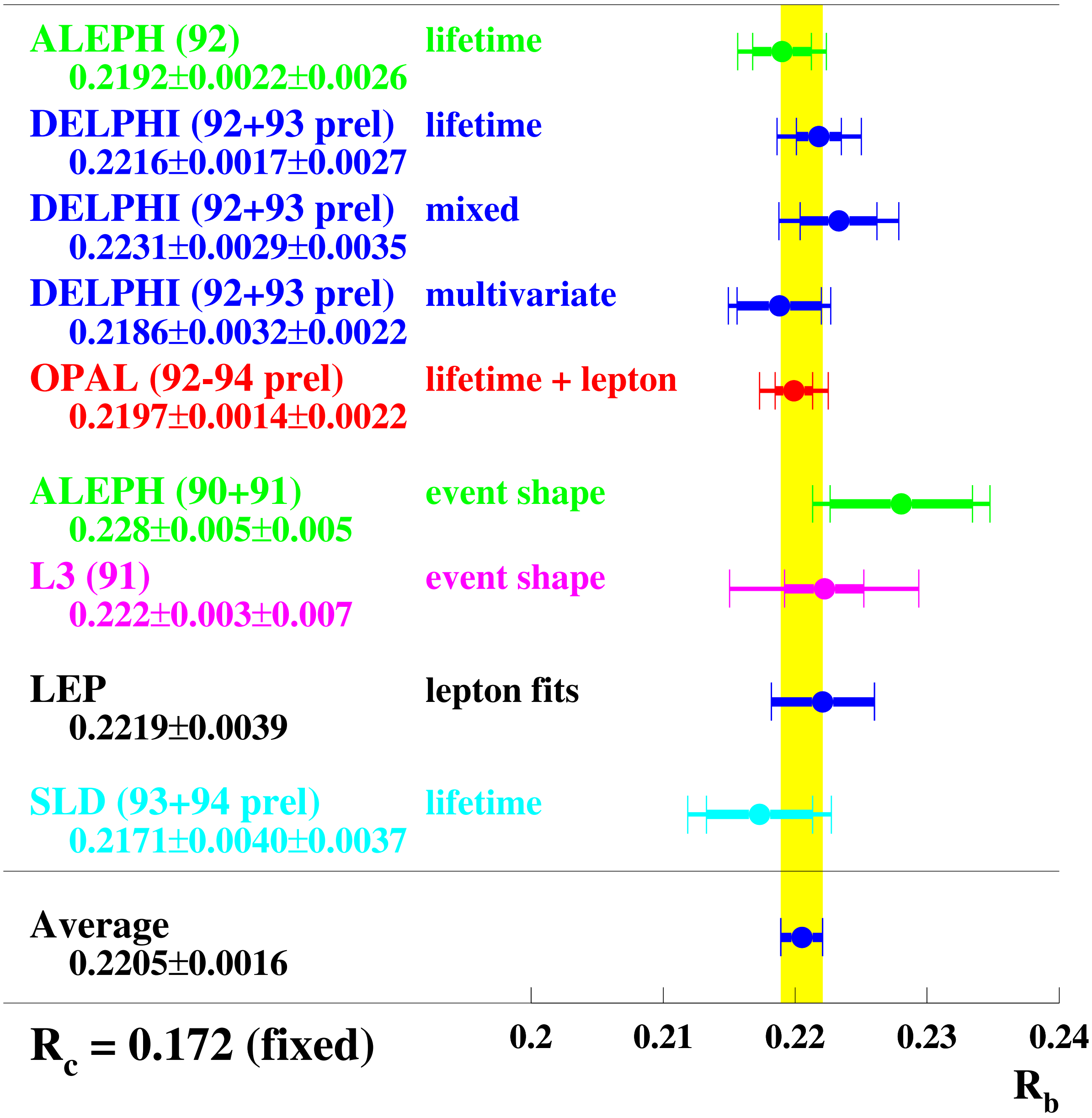
DELPHI

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

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

compared to SM predictions 0.997, 0.998

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

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)

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

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

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

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

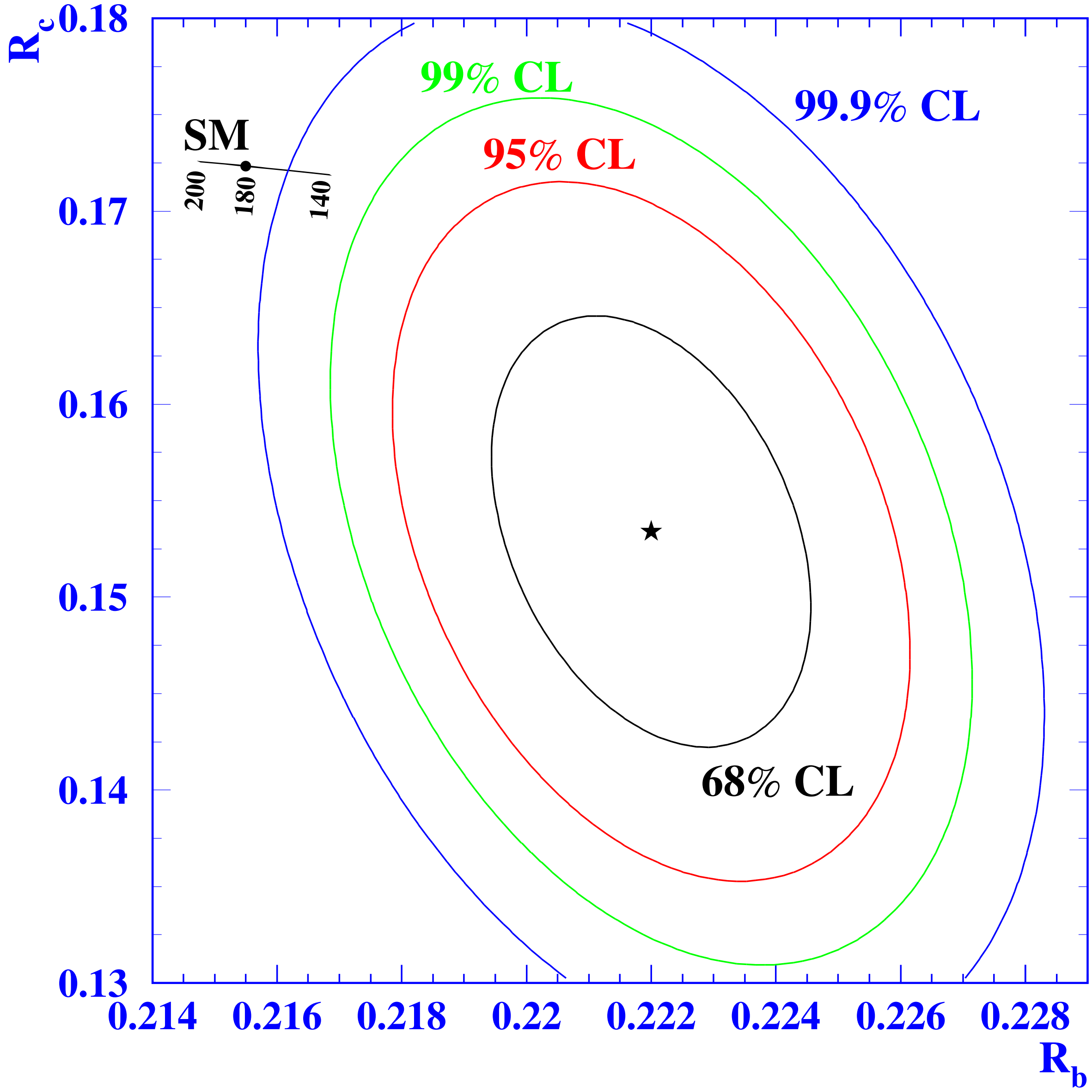
Correlation matrix:

	R_b	R_c	$A_{FB}^{b,0}$	$A_{FB}^{c,0}$	$A_{FB,pol}^{b}$	$A_{FB,pol}^{c}$
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
$A_{FB}^{b,0}$	0.01	0.08	1.00	0.11	0.06	–0.03
$A_{FB}^{c,0}$	0.06	–0.06	0.11	1.00	–0.02	0.07
$A_{FB,pol}^{b}$	–0.07	0.07	0.06	–0.02	1.00	0.07
$A_{FB,pol}^{c}$	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

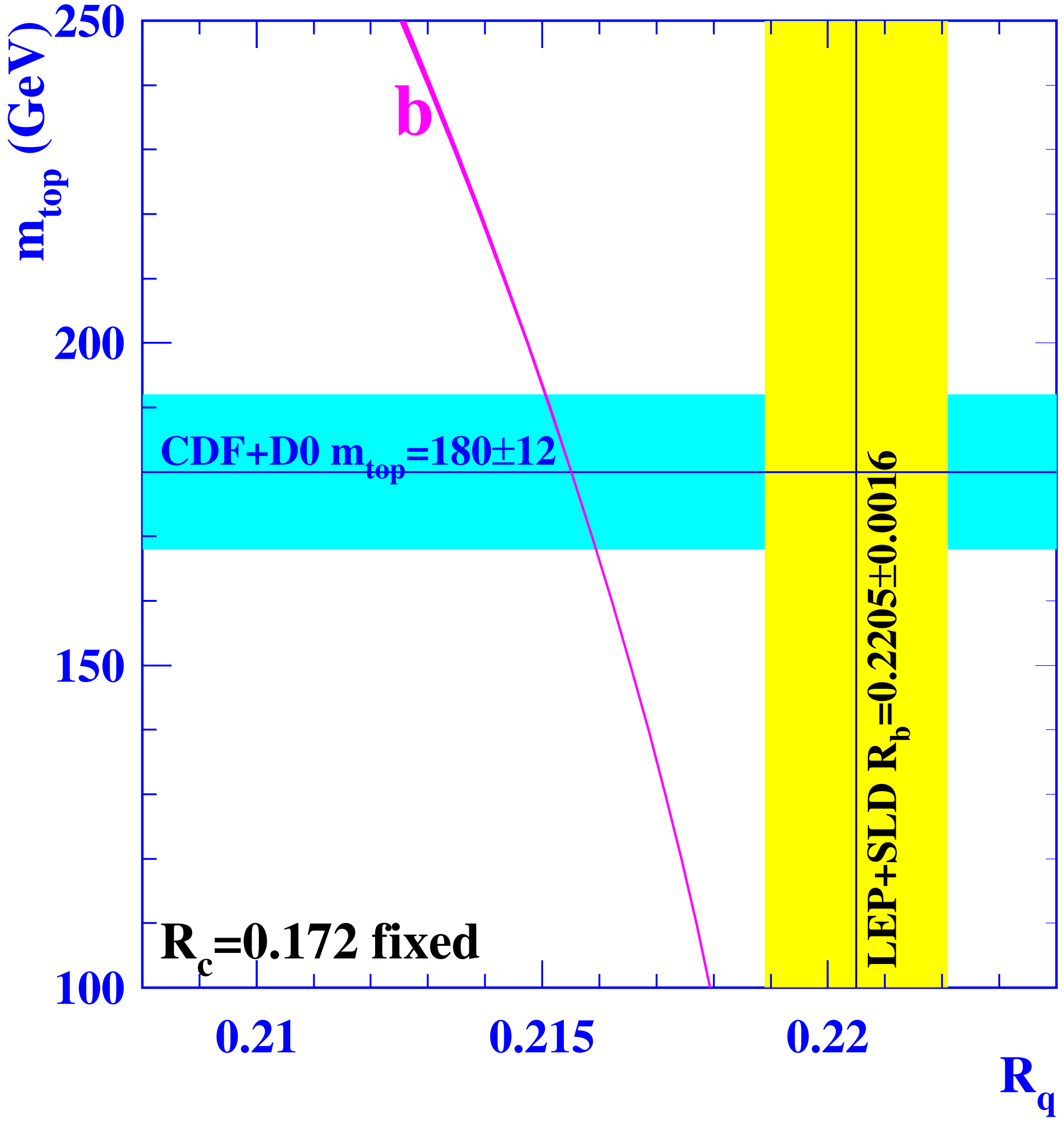


$\Delta\chi^2$ between best fit with Standard Model R_b and R_c

($m_{top} = 180$ 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:

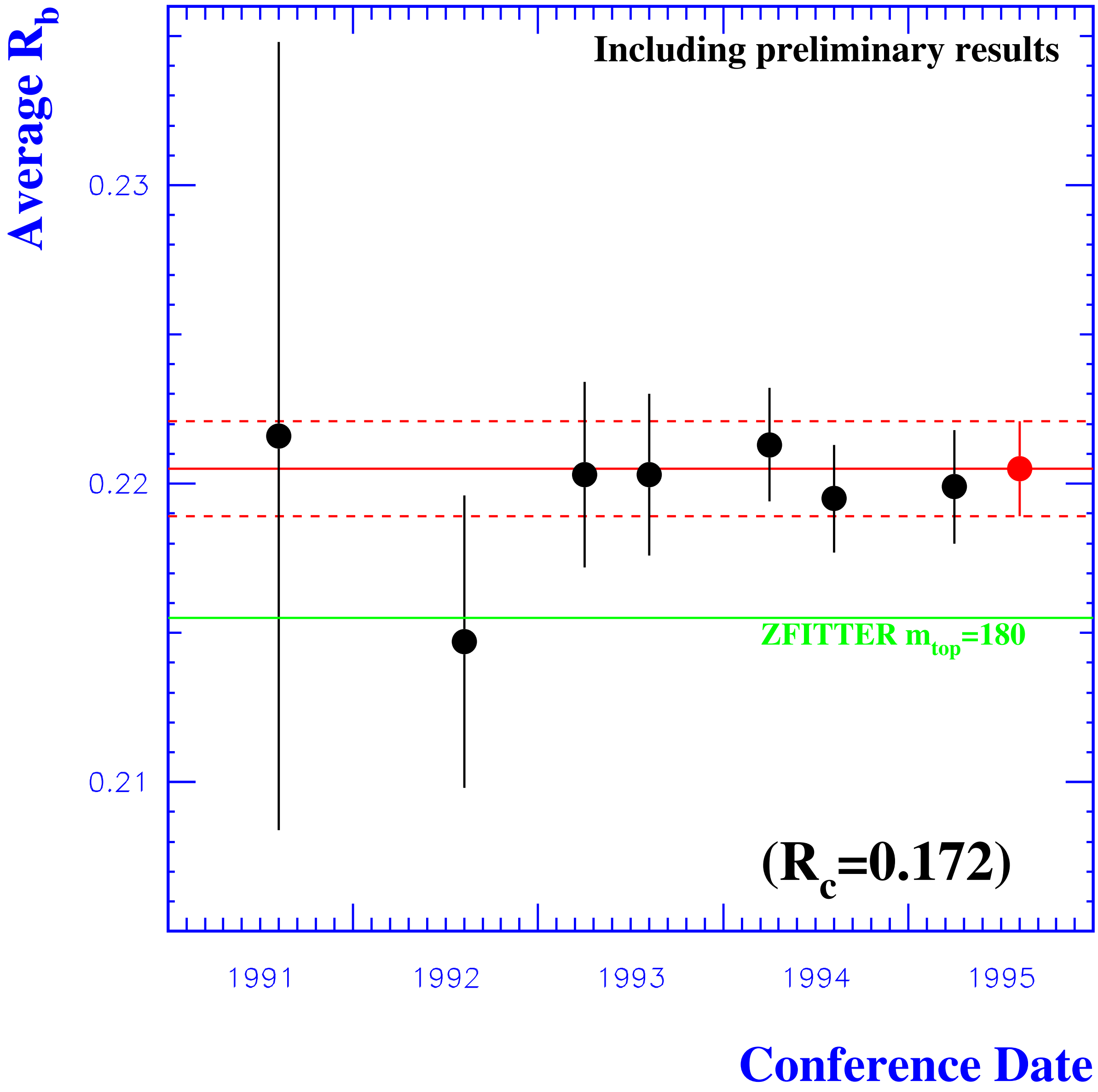
m_{Z^0}=91.1888 GeV, 60 GeV < m_H < 1000 GeV,

$\alpha_s(m_{Z^0})$=0.12, $\alpha(m_{Z^0})$=1/128.67

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

$R_b = 0.2155 \pm 0.0005$

Time Evolution of World Average R_b



Summary

- Precision of measurements of R_{b} and R_{c} continues to improve

- R_{b} results dominated by double-lifetime tags

- Potential to improve charm uncertainties using LEP data

- World average values (including preliminary results):

$$
\begin{aligned}
R_{\mathrm{b}} &= 0.2219 \pm 0.0017 \\
R_{\mathrm{c}} &= 0.1540 \pm 0.0074
\end{aligned}
$$

  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} and R_{c} consistent with SM at 0.1% level