The Current Status of the R_b and R_c "Puzzle"

XXXIst Rencontres de Moriond

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Many thanks to: LEP electroweak working group
LEP and SLD heavy flavour groups

Introduction

The partial width of the Z^0 into a quark-antiquark pair is given by

$$\Gamma_{f\bar{f}} = \frac{G_\mu M_Z^3}{6\pi\sqrt{2}}(v_f^2 + a_f^2)N_{\rm col}\ .$$

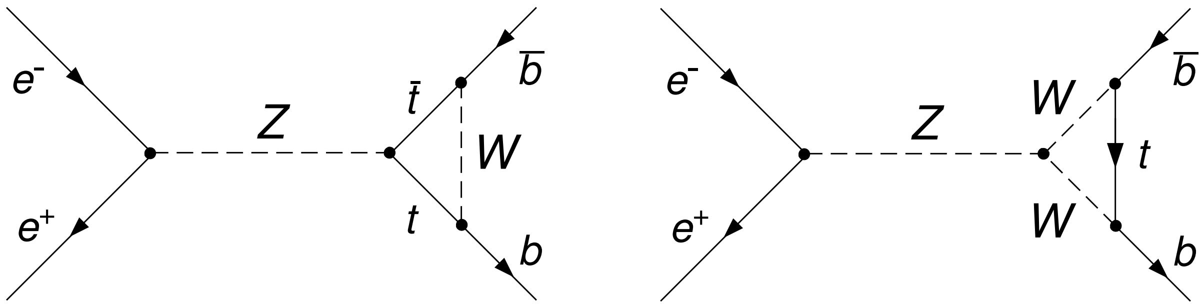
Measured $\Gamma_{f\bar{f}}$ is modified by oblique, initial-state, and QCD radiative corrections.

Experimentally, the quantity

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

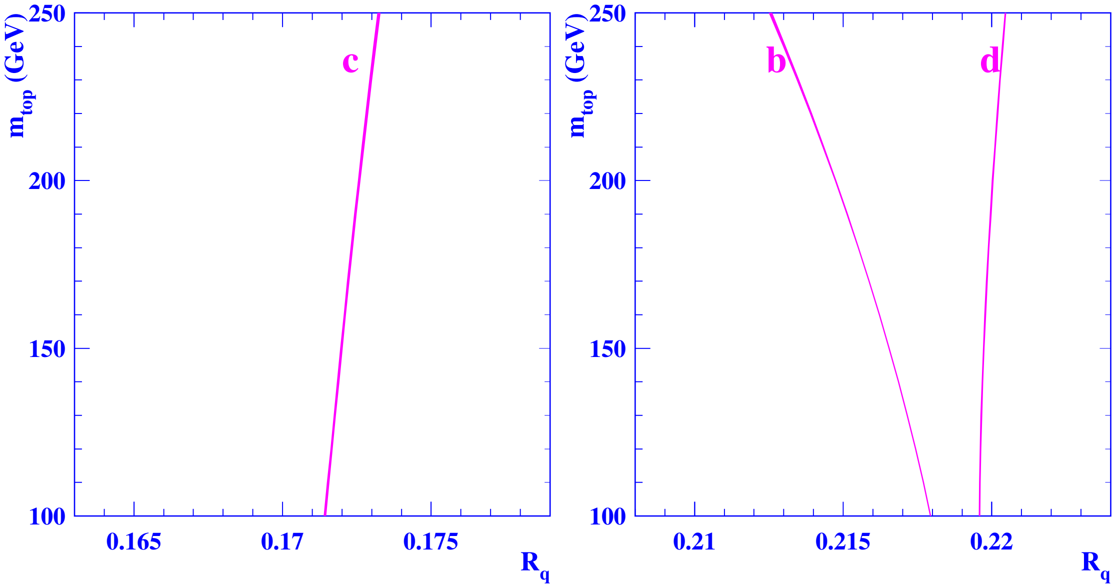
is more readily accessible, and has the added advantage that the radiative corrections essentially cancel, leaving final-state vertex corrections as a possible window on new physics.

This is particularly important in the case of $R_{\rm b}$:



where the vertex loops induce a large dependence on the top quark mass (and possibly other heavy particles which can modify the coupling)

Introduction



The Situation as of Summer 1995:

Together, the values of R_b (3σ high) and R_c (2.5σ low) were only consistent with the Standard Model at the 0.1% level

(overheard) comments:

"R_c is wrong"

"R_b is *interesting*"

Since then:

Experimentalists have tried to improve the measurements

Theorists have been furiously writing papers

Outline

This talk will include

- R_c :
  - D counting $\star$
  - D^{*+} production
  - D^{*+} Double-Tag measurements $\star$
- R_b :
  - Lifetime Double-Tag measurements
  - “Super” Tags $\star$
- New World Average Values $\star$
- Discussion

All of these methods use the heavy quark masses and long lifetimes as tools for flavor separation

Focus on strengths, weaknesses, and possible biases

$\star$ = New Measurement

R_c from D Counting

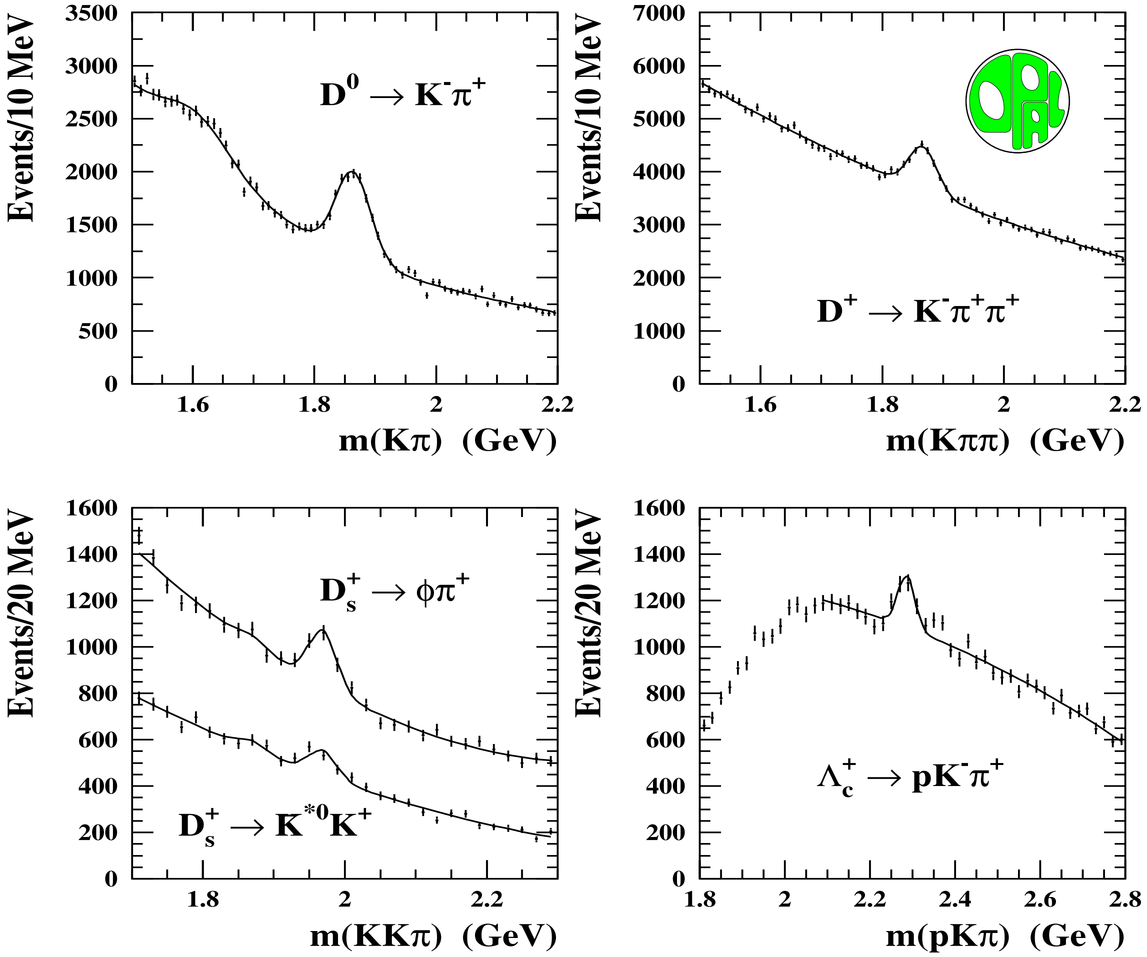
Simple Assumption: All charm quarks end up in weakly decaying hadrons, or

$$P_{c\to \mathrm{D}^0} + P_{c\to \mathrm{D}^+} + P_{c\to \mathrm{D_s}^+} + P_{c\to \Lambda_c} \times (1 + S_{\mathrm{c\ baryon}}) = 1$$

Method: R_c can be measured from the total production rates of

$$\mathrm{D}^0,\ \mathrm{D}^+,\ \mathrm{D}_s^+,\ \text{and}\ \Lambda_c$$

in $Z^0 \to c\bar{c}$ events (b/c separation needed)



R_c from D Counting

Advantages:

+ "LEP Only" Measurement

  Only small external dependence on charm Branching Ratios

+ Complete Picture of charm production

+ Allows verification of low energy measurements of D production

+ Well-established techniques, controllable errors

Disadvantages:

− Low efficiency + Large background $\longrightarrow$ large Statistical error

Dominant systematic errors are from:

c fragmentation, and particle-id uncertainties

Results:

OPAL ('91-'93)

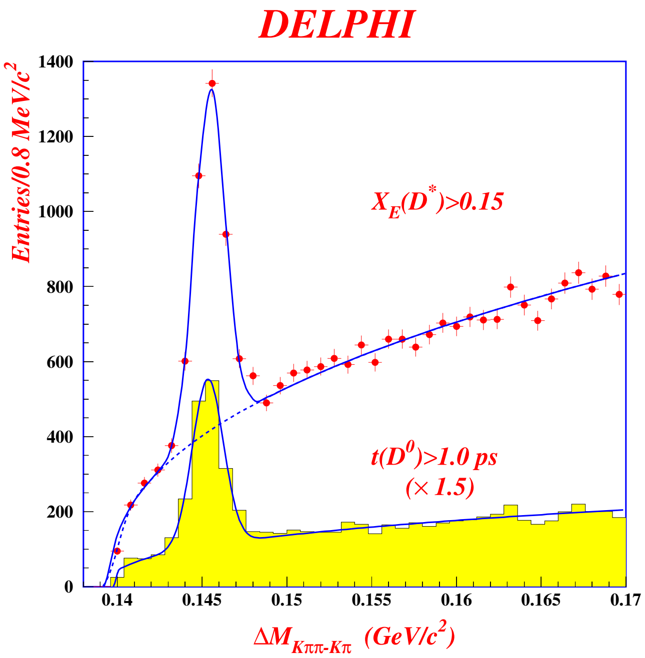
$$\Gamma_{c\bar{c}}/\Gamma_{\rm had} = 0.166 \pm 0.011(stat)^{+0.013}_{-0.012}(syst) \pm 0.005(br)$$

DELPHI ('91-'93)$\star$

$$\Gamma_{c\bar{c}}/\Gamma_{\rm had} = 0.164 \pm 0.011(stat) \pm 0.018(syst) \pm 0.005(br)$$

R_c from D^* Production

Since $D^{*+} \to \pi D^0$ has a distinctive kinematic signature, a pure sample of D^{*+} decays can be isolated.



Method: For a specific D^0 final state X, this technique measures (after b/c separation)

$$\frac{\Gamma_{c\bar{c}}}{\Gamma_{\rm had}} \times P(c \to D^{*+} \to \pi^+ D^0) \times B(D^0 \to X)$$

$\Longrightarrow$ External input required to obtain R_c.

$$P(c \to D^{*+} \to \pi^+ D^0) \times B(D^0 \to X)$$

can be obtained from lower energy data or from LEP

R_c from D^* Production

Advantages:

+ (Relatively) High-Purity samples
+ Well-established techniques, controllable errors
+ Also measures rate for $g \rightarrow c\bar{c}$

Disadvantages:

– External Input required to obtain R_c

Dominant systematic errors are from:

c fragmentation, $P(c \rightarrow D^{*+} \rightarrow \pi D^0)$, and D^0 decay BRs

Results:

OPAL ('90-'92)

$$\Gamma_{c\bar{c}}/\Gamma_{\mathrm{had}} = 0.148 \pm 0.008(stat) \pm 0.009(syst) \pm 0.011(br)$$

Using PDG '95 $B(D^0 \rightarrow K\pi)$ and

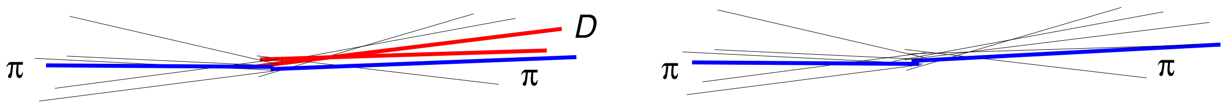
low energy	$P(c \rightarrow D^{*+} \rightarrow \pi^+ D^0)$	$=$	0.178 ± 0.013
(compare LEP ave	$P(c \rightarrow D^{*+} \rightarrow \pi^+ D^0)$	$=$	0.168 ± 0.007)

R_c from D^* Double-Tag

The branching fraction $c \to D^{*+} \to \pi D^0$ is sufficiently large ($\sim 20\%$) to consider a D^{*+} *Double Tag* to measure R_c

$$\Longrightarrow \pi_s \text{ has } \sim 0\, p_T \text{ with respect to } D^{*+} \text{ or jet}$$

Methods:



Inclusive π_s-Exclusive D^{*+} Inclusive π_s-Inclusive π_s

Neglecting backgrounds for simplicity (and after b/c separation),

$$N_{(\pi \text{or } D)} \propto \frac{\Gamma_{c\bar{c}}}{\Gamma_{\text{had}}} \cdot P(c \to D^{*+} \to \pi^+ D^0) \cdot \varepsilon_{(\pi \text{ or } D)}$$

$$N_{\pi,(\pi \text{ or } D)} = N_{(\pi \text{ or } D)} \cdot [P(c \to D^{*+} \to \pi^+ D^0) \cdot \varepsilon^c_\pi]$$

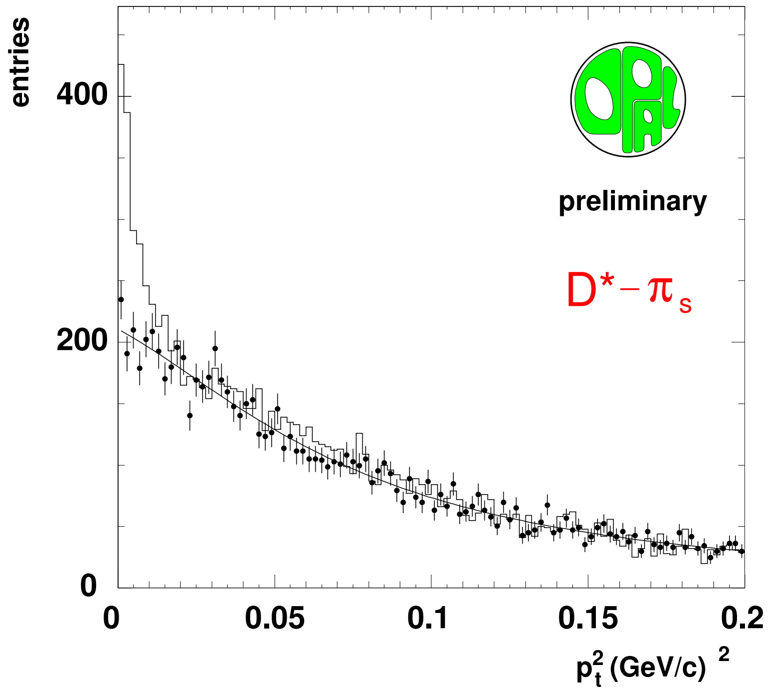
So, R_c and $P(c \to D^{*+} \to \pi^+ D^0)$ can be measured simultaneously from

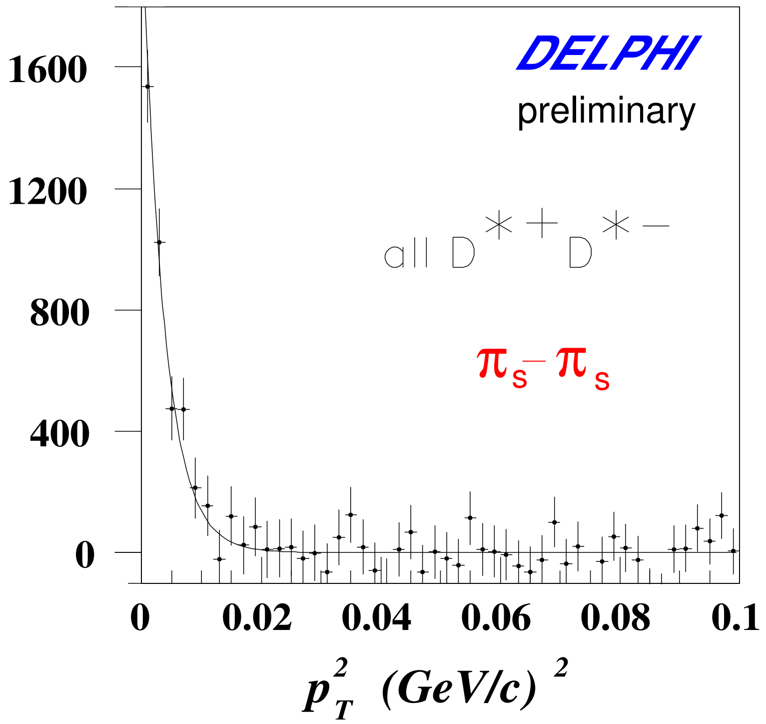
$$\frac{\Gamma_{c\bar{c}}}{\Gamma_{\text{had}}} \propto N_{(\pi \text{ or } D)}$$

$$P(c \to D^{*+} \to \pi^+ D^0) = \frac{N_{\pi,(\pi \text{ or } D)}}{N_{(\pi \text{ or } D)} \varepsilon^c_\pi}$$

(of course, the actual analyses are substantially more complicated)

R_c from D^* Double-Tag





R_c from D^* Double-Tag

Advantages:

+ "LEP Only" measurements

Disadvantages:

– MC still required for efficiencies ($D^* - \pi_s$ analyses)

– Large backgrounds under π_s signal

Dominant systematic errors are from:

background subtraction, ε_π, b/c separation

Results:

OPAL ('92-'94) ($D^{*+} - \pi_s$ Double tag)

$$P(c \to D^{*+} \to \pi^+ D^0) = 0.162 \pm 0.014(stat) \pm 0.013(syst)$$

DELPHI ('91-'94) ($\pi_s - \pi_s$ Double tag)⋆

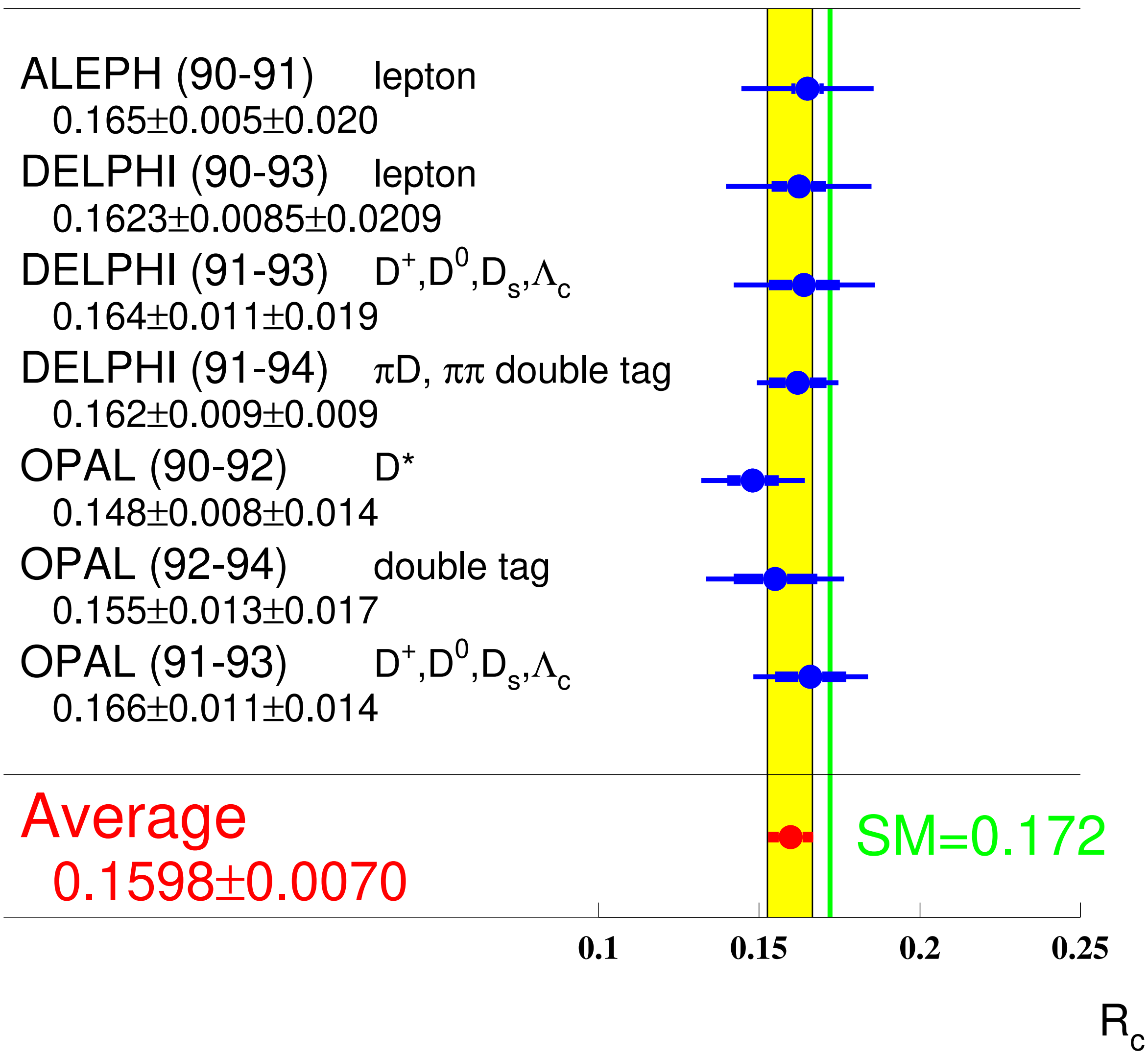
$$P(c \to D^{*+} \to \pi^+ D^0) = 0.166 \pm 0.009(stat) \pm 0.013(syst)$$

$$\Gamma_{c\bar{c}}/\Gamma_{\rm had} = 0.158 \pm 0.009(stat) \pm 0.014(syst)$$

DELPHI ('91-'94) ($D^{*+} - \pi_s$ Double tag)⋆

$$P(c \to D^{*+} \to \pi^+ D^0) = 0.162 \pm 0.016(stat) \pm 0.009(syst)$$

R_c Results



$\gamma - Z$ interference correction (-0.0003) applied to average

Results have been corrected to PDG '95 $B(D^0 \to K\pi)$, low energy $P(c \to D^{*+} \to \pi^+ D^0) = 0.178$ where needed

R_b with Lifetime Tags

b hadrons have high masses and long lifetimes

$\Longrightarrow$ b events can be more easily isolated from all other flavors

$\Longrightarrow$ High Purity, High Efficiency tags

Measurements based on lifetime tags currently dominate the precision of R_b

Method:

Apply a b tag to each thurst hemisphere of an event.

Number of tagged hemispheres N_t:

$$\frac{N_t}{2N_{had}} = \varepsilon^b R_b + \varepsilon^c R_c + \varepsilon^{uds}(1 - R_b - R_c)$$

Number of double-tagged events N_{tt}:

$$\frac{N_{tt}}{N_{had}} = \mathcal{C}_b(\varepsilon^b)^2 R_b + (\varepsilon^c)^2 R_c + (\varepsilon^{uds})^2(1 - R_b - R_c)$$

- Solve for R_b and ε^b, from N_t, N_{tt}, N_{had}
  $\Longrightarrow$ ε^b Measured from data
- Take R_c, $\mathcal{C}_b$, ε^c, ε^{uds} from MC $\Longrightarrow$ High Purity tags
- Assume (hemisphere tag correlations)$\times\varepsilon^2$ are small for uds, c
- Statistical error $\propto N_{tt} \propto (\varepsilon^b)^2$ $\Longrightarrow$ High ε^b tags

b Tags: Lifetime Probability

ALEPH and DELPHI form a “no-lifetime” probability for tracks with physics signed impact parameter $b > 0$:

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

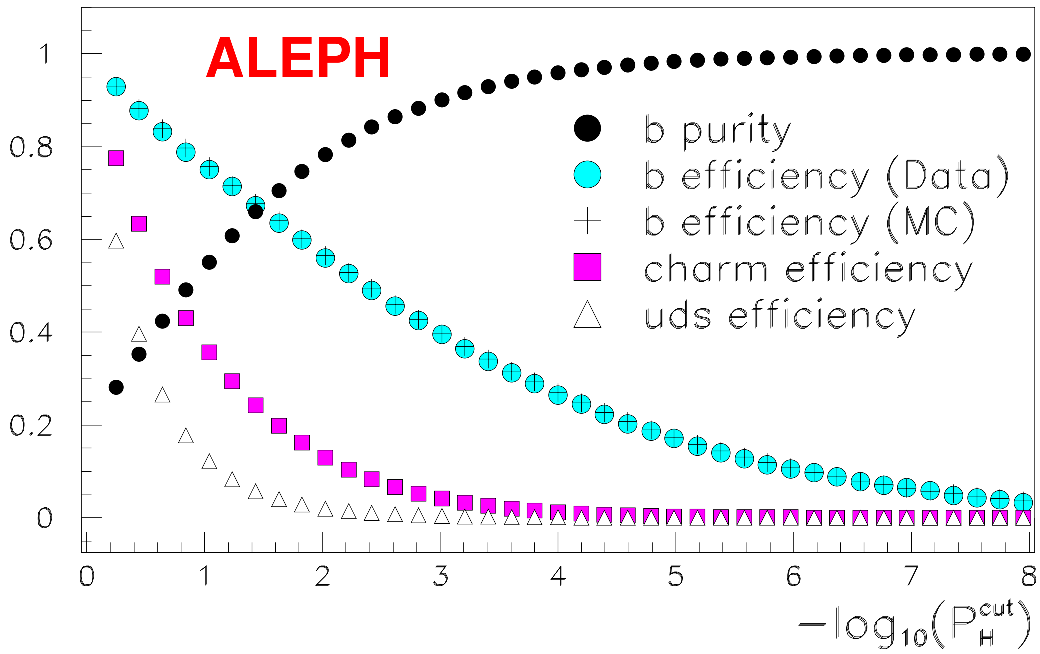
resolution function $\mathcal{R}$ measured from $b < 0$ distribution

The joint probability for “no-lifetime” in the hemisphere is then:

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

where

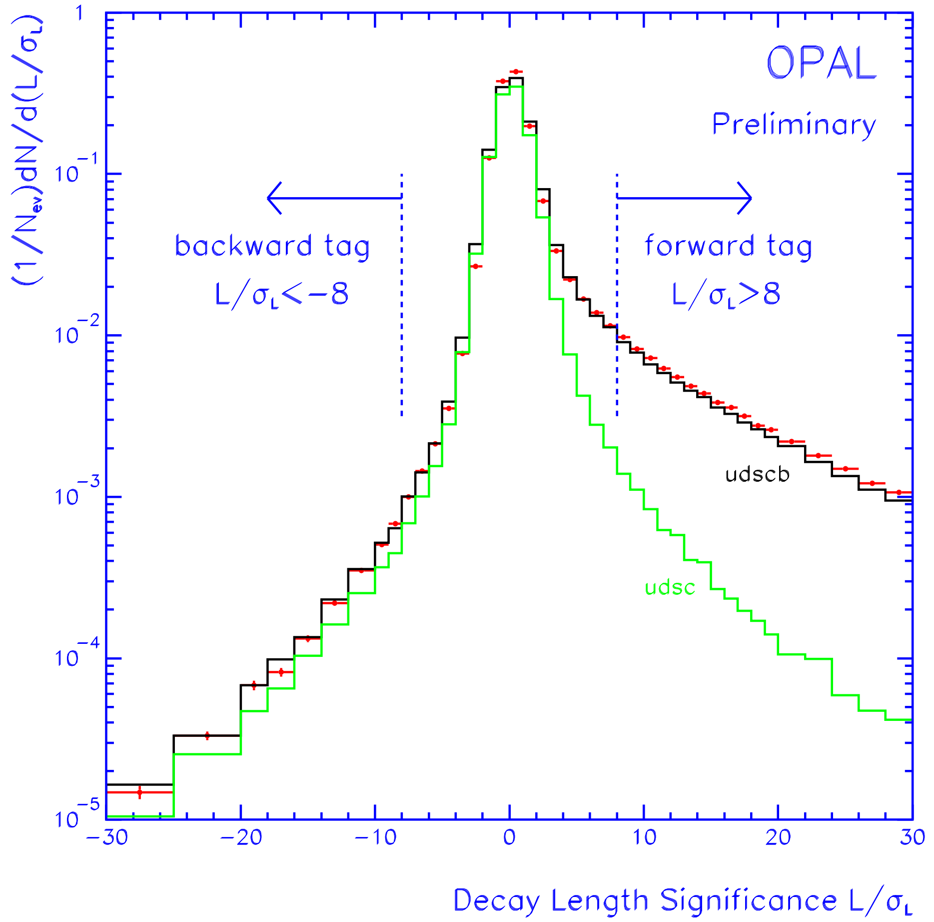
$$\Pi \equiv \prod_{i=1}^{N} (\mathcal{P}_T)_i$$



b Tags: Secondary Vertices

Used by OPAL

- Reconstruct high-multiplicity secondary vertices from tracks in each jet
- Construct physics signed decay length significance



- Folded tag: subtract statistically backwards vertices from forwards vertices to reduce resolution uncertainties

R_{b} with Lifetime Tags

Advantages:

+ Most important quantities (ε^{b}) derived directly from data

Disadvantages:

– MC (external values) still required for ε^{c} and $\mathcal{C}_{\mathrm{b}}$

Dominant systematic errors are from:

ε^{c} and $\mathcal{C}_{\mathrm{b}}$

Results:

ALEPH ('92)

$$\Gamma_{\mathrm{b\bar{b}}}/\Gamma_{\mathrm{had}} = 0.2192 \pm 0.0022(stat) \pm 0.0026(syst)$$

DELPHI ('91-'93)

$$\Gamma_{\mathrm{b\bar{b}}}/\Gamma_{\mathrm{had}} = 0.2219 \pm 0.0018(stat) \pm 0.0028(syst)$$

OPAL ('92-'94)

$$\Gamma_{\mathrm{b\bar{b}}}/\Gamma_{\mathrm{had}} = 0.2197 \pm 0.0014(stat) \pm 0.0022(syst)$$

Not including systematic error from R_{c}

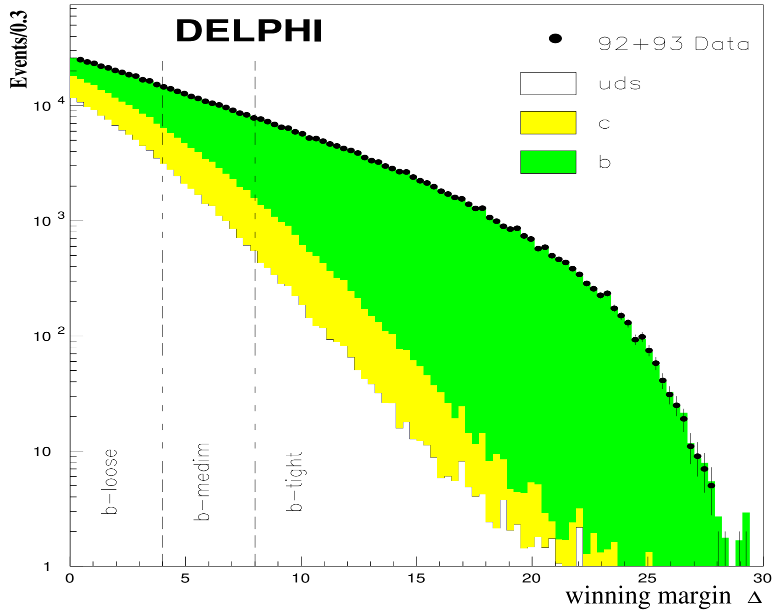
R_b with "Super" Tags

"Super" Tags attempt to use as much of the information in each event to discriminate between b and other flavors

Method (DELPHI):

- 6 "tags": *uds-tight*, *uds-loose*, *c*, *b-loose*,*b-medium*, *b-tight*,
- based on 13 (mostly vertex-related) variables combined into a joint-probability
- The tag "clarity" for each hemisphere is given by the "winning margin"

$$\Delta = \mathcal{L}_{first} - \mathcal{L}_{second}\ (\mathrm{or},\ \mathcal{L}_b - \mathcal{L}_{other})$$



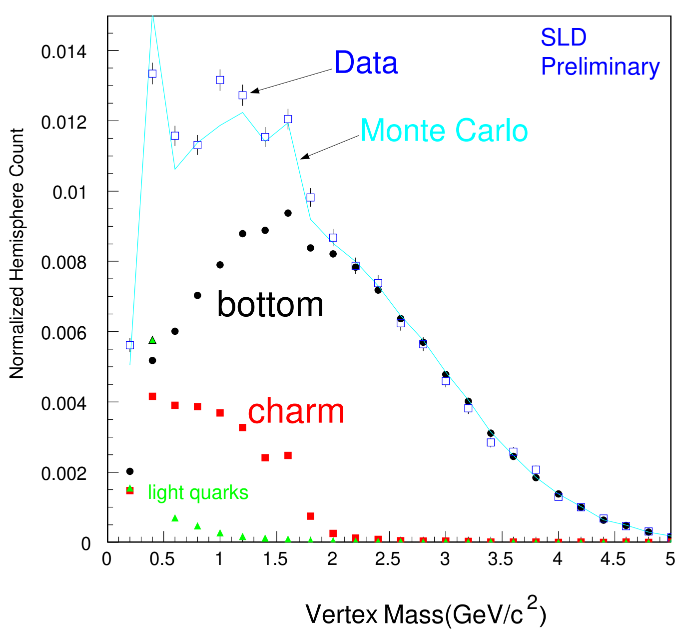
- Taking $\Delta \to \infty$ and looking at the *opposite* hemisphere allows a simultaneous measurement of tag efficiencies, backgrounds, and R_b.

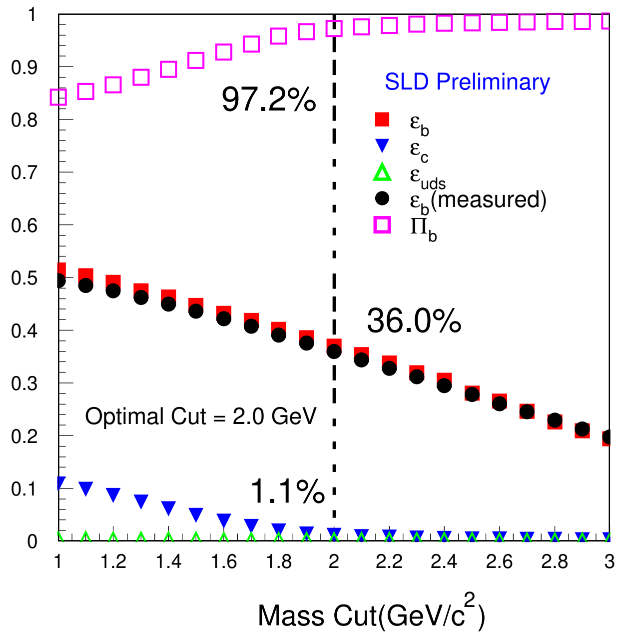
R_b with "Super" Tags

Method (SLD):

Based on a "Super" vertex detector/beam spot combination...

- Topological vertex reconstruction to assign each track to either the primary event vertex or a secondary decay vertex
- Vertex "Mass" is used to separate b from other flavors





R_{b} with "Super" Tags

Advantages:

+ (DELPHI) ALL important quantities (ε^{b}) derived directly from data
+ (SLD) charm contamination $\longrightarrow$ zero
+ Potentially much smaller dependence on MC, external inputs

Disadvantages:

– (DELPHI) Complicated, difficult to check directly

– (SLD) ???

Dominant systematic errors are from:

(DELPHI) MC statistics to determine $\mathcal{C}_{\mathrm{b}}$, Fit method

(SLD) MC statistics, detector

Results:

DELPHI ('91-'93)

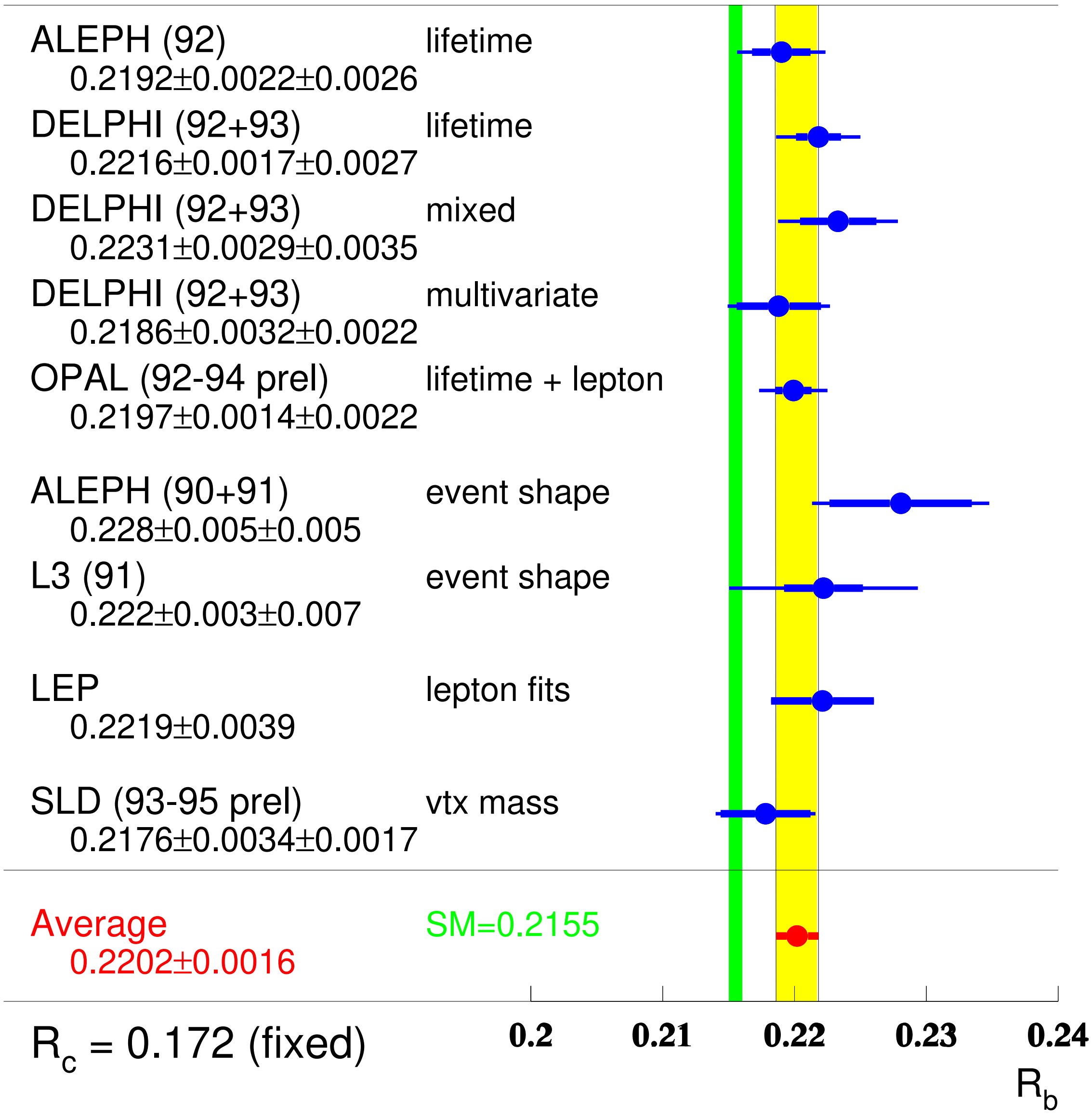
$$\Gamma_{\mathrm{b\bar{b}}}/\Gamma_{\mathrm{had}} = 0.2194 \pm 0.0032(stat) \pm 0.0022(syst)$$

SLD ('93-'95)$\star$

$$\Gamma_{\mathrm{b\bar{b}}}/\Gamma_{\mathrm{had}} = 0.2176 \pm 0.0034(stat) \pm 0.0017(syst)$$

Not including systematic error from R_{c}

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

LEP HQEW Averaging Procedure

Heavy flavour electroweak analyses often:

- measure several parameters simultaneously (A^b_{FB}, χ, etc.)
- depend on other widths, branching ratios, etc.

The LEP Heavy Flavour group combination procedure handles all correlations and dependences on external inputs (and their errors) consistently.

The results are derived from a 10-parameter overall χ^2 minimization fit using the full covariance matrix between measurements

(See P.S. Wells' talk, $R_{\rm b}/R_{\rm c}$ Workshop next week)

Checks include:

- Internal consistency with simple one-parameter averages
- Varying the details of correlation assumptions only has a small effect

Combined LEP and SLD Results

$$
\begin{aligned}
\boldsymbol{R_\mathrm{b}} &= \mathbf{0.2211 \pm 0.0016} \\
\boldsymbol{R_\mathrm{c}} &= \mathbf{0.1598 \pm 0.0070} \\
A_\mathrm{FB}^{\mathrm{b},0} &= (10.0 \pm 0.28)\% \\
A_\mathrm{FB}^{\mathrm{c},0} &= (7.59 \pm 0.51)\% \\
A_\mathrm{FB,pol}^{\mathrm{b}} &= 0.842 \pm 0.053 \\
A_\mathrm{FB,pol}^{\mathrm{c}} &= 0.618 \pm 0.090 \\
\mathrm{BR(b \to \ell)} &= (11.12 \pm 0.23)\% \\
\mathrm{BR(b \to c \to \ell^+)} &= (7.81 \pm 0.42)\% \\
\overline{\chi} &= 0.1221 \pm 0.0052 \\
P(c \to D^{+*} \to \pi D^0) &= 0.168 \pm 0.007
\end{aligned}
$$

With a χ^2/dof of $40.8/(76-10)$

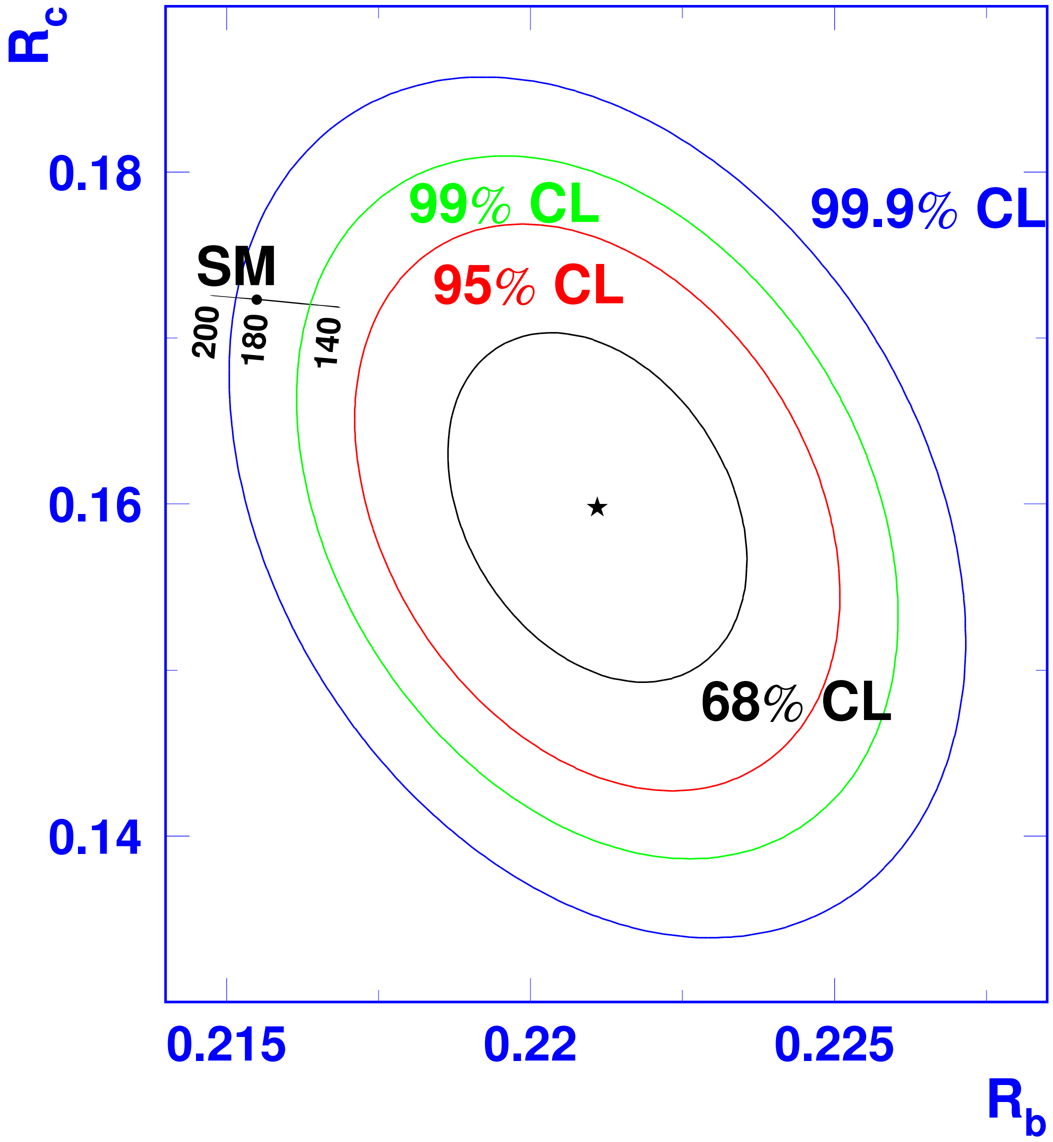
If R_c fixed to Standard Model $R_\mathrm{c} = 0.172$

$$\boldsymbol{R_\mathrm{b}(R_\mathrm{c} = 0.172) = 0.2202 \pm 0.0016}$$

Correlation matrix:

$$
\begin{array}{l}
R_\mathrm{b} \\
R_\mathrm{c} \\
A_\mathrm{FB}^{\mathrm{b},0} \\
A_\mathrm{FB}^{\mathrm{c},0} \\
A_\mathrm{FB,pol}^{\mathrm{b}} \\
A_\mathrm{FB,pol}^{\mathrm{c}} \\
P_{c \to D^*}
\end{array}
\begin{pmatrix}
1.00 & -.30 & .00 & .01 & -.05 & .04 & .11 \\
-.30 & 1.00 & .06 & -.01 & .06 & -.06 & -.40 \\
.00 & .06 & 1.00 & .12 & .06 & .02 & -.07 \\
.01 & -.01 & .12 & 1.00 & .00 & .05 & -.04 \\
-.05 & .06 & .06 & .00 & 1.00 & .07 & -.04 \\
.04 & -.06 & .02 & .05 & .067 & 1.00 & .04 \\
.11 & -.40 & -.07 & -.04 & -.04 & .04 & 1.00
\end{pmatrix}
$$

Standard Model Comparison: R_c vs. R_b



$\Delta\chi^2$ between best fit with Standard Model R_b and R_c ($m_\mathrm{top} = 180$ GeV, $R_\mathrm{b} = 0.2155$, $R_\mathrm{c} = 0.172$), and best overall fit, is 11.0

Hemisphere correlations

Reminder:

$$R_{\mathrm{b}} \approx \mathcal{C}_{\mathrm{b}} \frac{N_t^2}{4 N_{\mathrm{tt}} N_{\mathrm{had}}}$$

$$\lambda_b \equiv (\mathcal{C}_{\mathrm{b}} - 1)\varepsilon^{\mathrm{b}}/(1-\varepsilon^{\mathrm{b}})$$

	$\mathcal{C}_{\mathrm{b}}$	λ_b	ε^{b}	$\mathcal{C}_{\mathrm{b}} - 1$
OPAL (92–94)	1.006 ± 0.003		23%	$+0.6 \pm 0.3\%$
ALEPH (92)		$-2.0 \pm 0.3\%$	26%	$-5.7 \pm 0.8\%$
DELPHI (91)		$-0.1 \pm 0.4\%$	24%	$-0.4 \pm 1.3\%$
DELPHI (92)		$-0.3 \pm 0.2\%$	20%	$-1.0 \pm 0.7\%$
DELPHI (93)		$-1.3 \pm 0.2\%$	21%	$-4.8 \pm 0.6\%$
SLD (93–95)		$+0.5 \pm 0.2\%$	36%	$-0.9 \pm 0.4\%$

Size of correlations dominated by effects of $g \longrightarrow b\bar{b}$ events

Estimates of error due to $\mathcal{C}_{\mathrm{b}}$ dominated by statistics (Monte Carlo or data)

$\Longrightarrow$ assume uncertainty not correlated between measurements

Varying assumptions on correlated uncertainty due to $\mathcal{C}_{\mathrm{b}}$

has a tiny effect on R_{b}

Hemisphere correlations area of intense study

Common systematic errors - I

Representative table of significant contributions to total error.

“Value and range” correspond to PDG ’92, “New value” is either PDG ’95 or unofficial LEP average.

“Pull” is (Average – Standard Model) / (Error from this source).

Error source	Value and range	New value	R_b pull	R_c pull
Decay model $b \to \ell$	ACCMM$^{+\mathrm{ISGW}}_{-\mathrm{ISGW**}}$		–47	–34
Decay model $c \to \ell$	CL1 $^{+\mathrm{CL2}}_{-\mathrm{CL3}}$		–88	∞
BR($c \to \ell$)	(9.8 ± 0.5)%		+21	+5
BR($b \to \bar{c} \to \ell^-$)	(1.3 ± 0.5)%		–161	+168
$\langle x_E(\mathrm{b})\rangle$ (if not in fit)	0.70 ± 0.02	0.695 ± 0.010 LEP	–129	+16
$\langle x_E(\mathrm{c})\rangle$ (if not in fit)	0.51 ± 0.02	0.515 ± 0.013 LEP	–100	+13
b fragmentation model	Peterson, Kartvelishvelli, Collins–Spiller		∞	+67
c fragmentation model	”		–135	–8
BR($D^0 \to K^-\pi^+$)	(3.84 ± 0.13)%	PDG’95	+61	+9
BR($D^+ \to K^-\pi^+\pi^+$)	(9.1 ± 0.6)%	PDG’95	+168	+25
BR($D_s{}^+ \to \phi\pi^+$)	(3.5 ± 0.4)%	PDG’95	+178	+34
BR($\Lambda_c \to pK^-\pi^+$)	(4.4 ± 0.6)%	PDG’95	+198	+30
c baryon/Λ_c	1.15 ± 0.05		∞	–94

Common systematic errors - II

Error source	Value and range	New value	R_b pull	R_c pull
D^0 fraction in $\mathrm{c\bar{c}}$ events	0.557 ± 0.053	0.583 ± 0.035 LEP	–132	∞
D^+ fraction	0.248 ± 0.037	0.233 ± 0.024 LEP	–11	+55
$(\mathrm{D}^0 + \mathrm{D}^+)$ fraction	0.80 ± 0.07		–19	+124
$\mathrm{D_s}$ fraction	0.12 ± 0.05	0.097 ± 0.022 LEP	–18	+119
Λ_c fraction	0.08 ± 0.05	0.076 ± 0.033 LEP	–198	∞
D^0 lifetime (ps)	0.420 ± 0.008	0.415 ± 0.004 PDG'95	–35	–76
D^+ lifetime (ps)	1.066 ± 0.023	1.057 ± 0.015 PDG'95	–31	–52
$\mathrm{D_s}$ lifetime (ps)	$0.450^{+0.030}_{-0.026}$	0.467 ± 0.017 PDG'95	–44	–96
Λ_c lifetime (ps)	$0.191^{+0.015}_{-0.012}$	0.206 ± 0.012 PDG'95	–323	–30
B decay multiplicity	5.5 ± 0.5 OPAL	5.7 ± 0.3 OPAL, DELPHI	–263	+52
D decay multiplicity	2.53 ± 0.06		–15	+101
$\mathrm{BR(D \rightarrow K_s{}^0X)}$	0.46 ± 0.06		+17	–109
$N(\mathrm{g \rightarrow b\bar{b}})$	$(0.16 \pm 0.08)\%$		–41	∞
$N(\mathrm{g \rightarrow c\bar{c}})$	$(1.6 \pm 0.8)\%$ theory	$(2.38 \pm 0.48)\%$ OPAL	–28	–24
Rate long-lived light h	JETSET$\pm 10\%$		–26	+118
Light quark frag.	JETSET $\pm$ small		+20	–72

Conclusions

$R_{\rm c}$:

- Much experimental effort has been put into improving the $R_{\rm c}$ measurements

    better statistical precision

    better understanding of external inputs ($P_{c\rightarrow D^*}$)

$\Longrightarrow$ Small shift ($+0.8\sigma$) in central value, smaller errors

- More “inclusive” tags on the horizon

$R_{\rm b}$:

- Much thought has been put into understanding correlations, systematic errors

    No glaring problems found

- New, more powerful tags promise further improvement

$R_{\rm b}$ is still high

I will leave it to our theoretical colleagues for an interpretation...