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Production of Heavy Quarks in Z^0 decays at LEP:

Measurement of R_b and R_c with OPAL.

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with special thanks to: – Dave Charlton (CERN)
– Ties Behnke (CERN)

R_{b} and R_{c} in the Standard Model

- Definition: $R_{\mathrm{q}} = \dfrac{\Gamma(\mathrm{Z}^0 \to \mathrm{q}\bar{\mathrm{q}})}{\Gamma(\mathrm{Z}^0 \to \mathrm{hadrons})}$

- Lowest order:

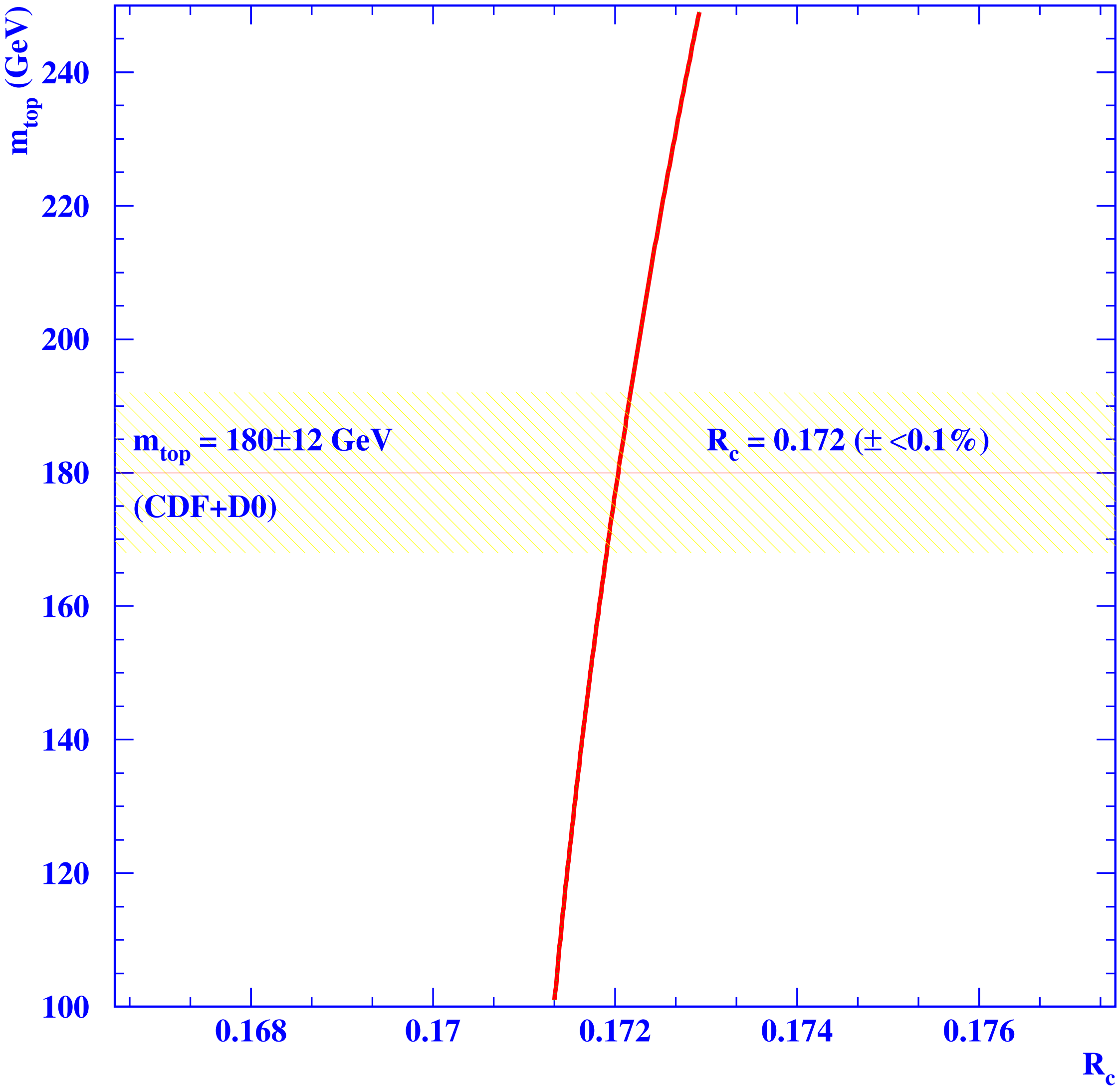
$$\Gamma(\mathrm{Z}^0 \to \mathrm{q}\bar{\mathrm{q}}) = \frac{G_\mu m_{\mathrm{Z}}{}^3}{2\pi\sqrt{2}} \left(g_V^q{}^2 + g_A^q{}^2 \right)$$

$$\text{with:} \quad \left\{ \begin{array}{ll} g_A^q & = I_3^q \\ g_V^q & = I_3^q - 2Q^q \sin^2\theta_W \end{array} \right.$$

- Higher order terms: rad. corrections (esp. QCD) affect Γ but $\sim$ cancel in ratio. $\Rightarrow R_{\mathrm{q}}$ precisely constrained theoritically.

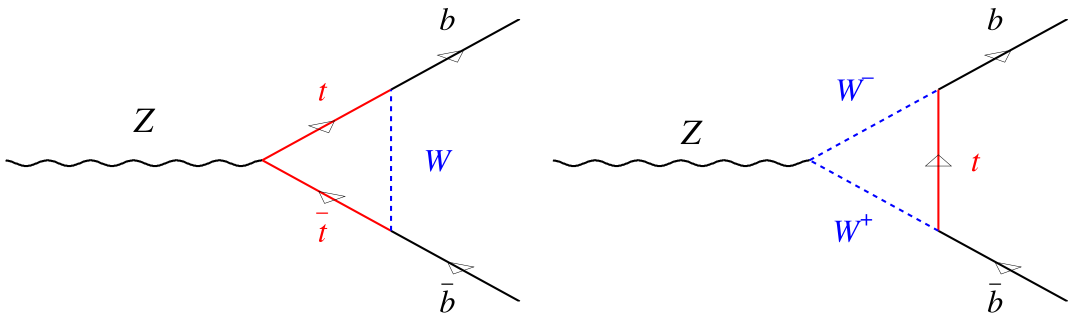
- Specific EW corrections to $\mathrm{Zb\bar{b}}$ vertex involving virtual top makes R_{b}:
  - more sensitive to m_{top}
  - potentially sensitive to new physics...

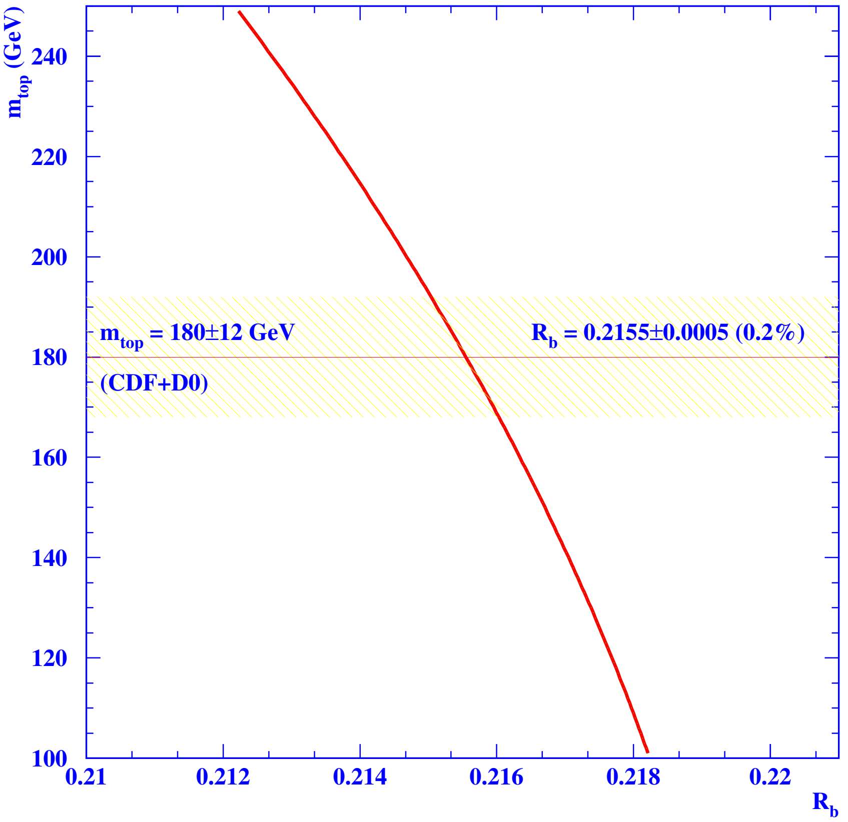
R_{c}: (nearly) no dependence on m_{top}, m_{H}, α_s...



$\Rightarrow$ in SM, R_{c} constrained to better than 0.1%.

R_{b}: additional top contribution





$\Rightarrow$ more sensitive to m_{top} and to new physics?

R_{b} measurement

Method now well established and widely used:

1. Tag b-hadron decays inclusively using, e.g., their long lifetime ($\sim$ 1.5 ps) $\Rightarrow$decay length $\sim$ 2–3 mm.

2. Get tagging efficiency ϵ_{b} from the data using flavour correlation between two hemispheres of the same event: $\Rightarrow$ "double tagging" method.

$$\frac{N_{\mathrm{hemi}}^{\mathrm{tag}}}{2N_{\mathrm{had}}} = \epsilon_{\mathrm{b}} R_{\mathrm{b}} + \epsilon_{\mathrm{c}} R_{\mathrm{c}} + (u, d, s) ... (1)$$

$$\frac{N_{\mathrm{event}}^{2-\mathrm{tag}}}{N_{\mathrm{had}}} \approx {\epsilon_{\mathrm{b}}}^2 R_{\mathrm{b}} + {\epsilon_{\mathrm{c}}}^2 R_{\mathrm{c}} + ... \qquad (2)$$

$$\frac{(2)}{(1)} \Rightarrow \epsilon_{\mathrm{b}} \approx 2\frac{N_{\mathrm{event}}^{2-\mathrm{tag}}}{N_{\mathrm{hemi}}^{\mathrm{tag}}} + ... \quad \text{and } (1) \Rightarrow R_{\mathrm{b}}$$

OPAL specific

Can use any "standard" b-tagging method, but need:

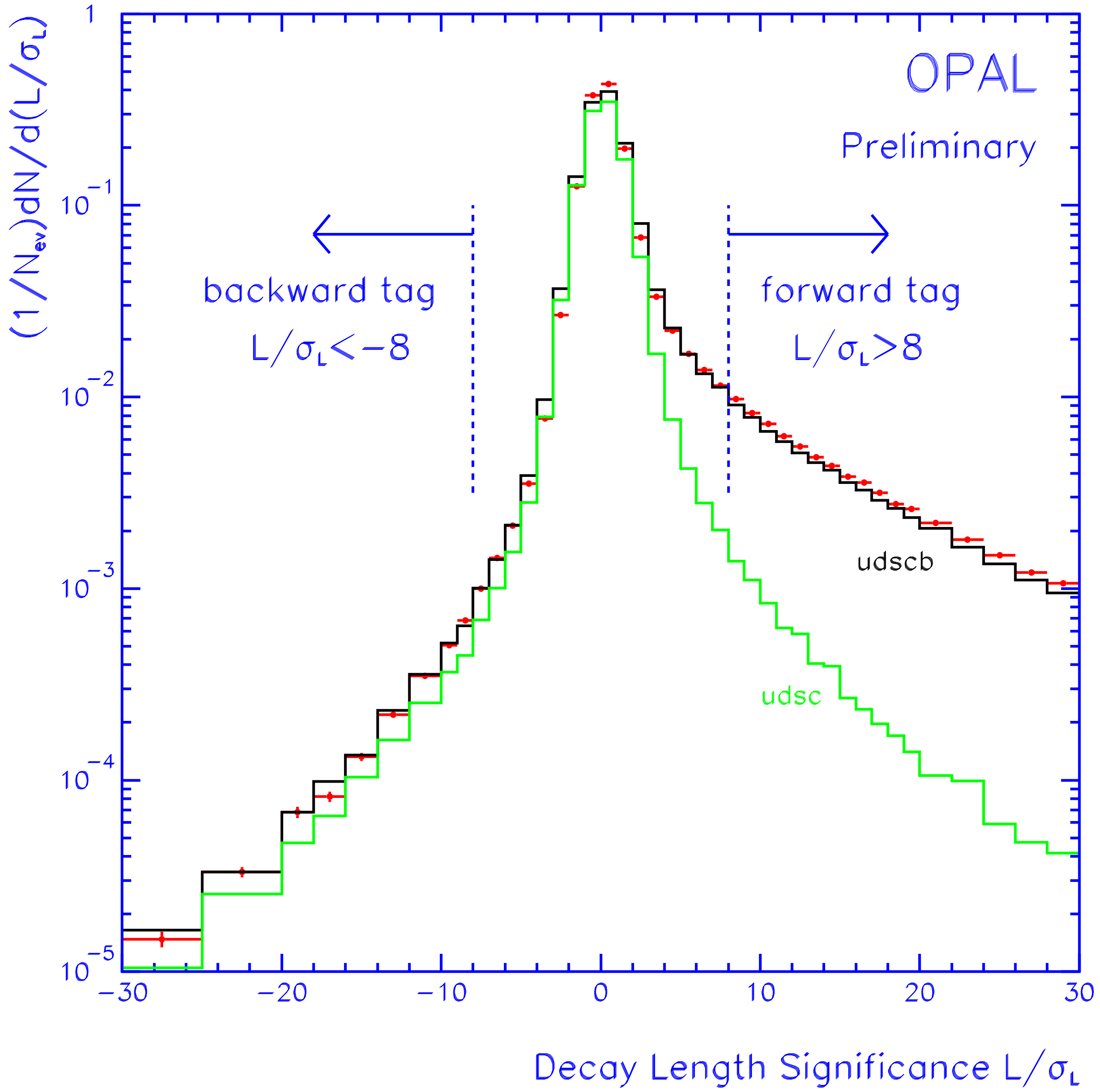
- high efficiency: statistical error on R_{b} varies as $\sim \frac{1}{\sqrt{N_{\mathrm{event}}^{2-\mathrm{tag}}}}$ i.e. $\sim \frac{1}{\epsilon_{\mathrm{b}}}$.
- high b-purity: main systematic error comes from c contribution.

$\Rightarrow$ tag = lifetime .OR. high p_t lepton

$$\left\{ \begin{array}{l} \mathrm{L}/\sigma_{\mathrm{L}} \;\; > 8 \\ \\ \text{electron (muon) with:} \left\{ \begin{array}{ccc} p & > & 2\ (3)\ \mathrm{GeV}/c \\ p_t & > & 1.1\ (1.2)\ \mathrm{GeV}/c \end{array} \right. \end{array} \right.$$

$\Rightarrow \epsilon_{\mathrm{b}} = 23\ \%$, b purity $= 94\ \%$

Lifetime tag at OPAL



$\Rightarrow \epsilon_{\mathrm{b}} = 23\ \%$, b purity $= 94\ \%$

OPAL results for R_{b}

- Published measurement (92 and 93 data):

$$R_{\mathrm{b}} = 0.2171 \pm 0.0021(\mathrm{stat}) \pm 0.0021(\mathrm{syst})$$

- Preliminary updated measurement (including 94 data):

$$R_{\mathrm{b}} = 0.2197 \pm 0.0014(\mathrm{stat}) \pm 0.0022(\mathrm{syst})$$

  Tot. error = 1.2 %, now systematic limited.

- Note: $R_{\mathrm{c}} = 0.172$ standard model value used, and dependence on R_{c} not considered in systematic.

$$\frac{\Delta R_{\mathrm{b}}}{R_{\mathrm{b}}} = -0.084 \quad \frac{\Delta R_{\mathrm{c}}}{R_{\mathrm{c}}}$$

OPAL result for R_{b}:
Main systematic uncertainties

Charmed hadron fraction	± 0.00094
Charmed decay multiplicity	± 0.00076
c-quark fragmentation	± 0.00075
Charmed hadron lifetime	± 0.00041
Tracking resolution	± 0.00083
Efficiency correlation	± 0.00072
Total	± 0.00220

R_{c} dependence

ΔR_{c}(-9 %)	+0.00150 (+0.7%)

$\Rightarrow$ Precision on R_{b} measurement now limited by knowledge of R_{c}...

R_c measurement

R_c much more difficult to measure than R_b:

1. No efficient and pure inclusive tag available
$\Rightarrow$ need to (fully) reconstruct charmed meson/baryon decays.

simplest case: $D^{*+} \rightarrow D^0 \pi^+_{slow}$ (68%)
$\hookrightarrow K^- \pi^+$ (4%)

small BRs $\Rightarrow$ low c-tag efficiency: $\epsilon^{tag}_{D^*} < 1\%$

2. several sources of c-quarks:

$Z^0 \rightarrow c\bar{c}$	$f_c \sim \frac{1}{2}$
$Z^0 \rightarrow b\bar{b}$ $\hookrightarrow$ c	$f_b \sim \frac{1}{2}$
$Z^0 \rightarrow q\bar{q}g$ $\hookrightarrow$ $c\bar{c}$	small

$\Rightarrow$ need to separate c $\rightarrow$D/ b $\rightarrow$c $\rightarrow$D

3. to extract R_c use:

$$\frac{N^{\mathrm{obs}}_{\mathrm{D}^*}}{2N_{\mathrm{had}}} = \mathrm{B}(\mathrm{c}{\rightarrow}\mathrm{D}^*) \times \epsilon^{\mathrm{tag}}_{\mathrm{D}^*} \times \frac{1}{\mathrm{f_c}} \times R_\mathrm{c}$$

And thus need:

- $N^{\mathrm{obs}}_{\mathrm{D}^*}$: observed number of D^*.
- $\epsilon^{\mathrm{tag}}_{\mathrm{D}^*}$: tagging efficiency (from MC)
- $\mathrm{f_c}$: c-purity (b/c separation techniques)

AND

- $\mathrm{B}(\mathrm{c}{\rightarrow}\mathrm{D}^*)$: hadronisation fraction.

Until recently, $\mathrm{B}(\mathrm{c}{\rightarrow}\mathrm{D}^*)$ only measured at lower energy experiments ($\Upsilon(4s)$, PEP, PETRA) and assumed to be valid at LEP.

$$\mathrm{B}(\mathrm{c}{\rightarrow}\mathrm{D}^*) = 0.250 \pm 0.020$$

D^* reconstruction at OPAL

❒ Increase $\epsilon_{D^*}^{tag}$ using many modes:

$D^{*+} \rightarrow D^0 \pi^+$

$\hookrightarrow$	$K^- \pi^+$	"3 prong"	(4%)
$\hookrightarrow$	$K^- \pi^+ \pi^0$	"satellite"	(13%)
$\hookrightarrow$	$K^- \pi^+ \pi^- \pi^+$	"5 prong"	(8%)
$\hookrightarrow$	$K^- e^+ \nu_e$	"electron"	(4%)
$\hookrightarrow$	$K^- \mu^+ \nu_\mu$	"muon"	(3%)

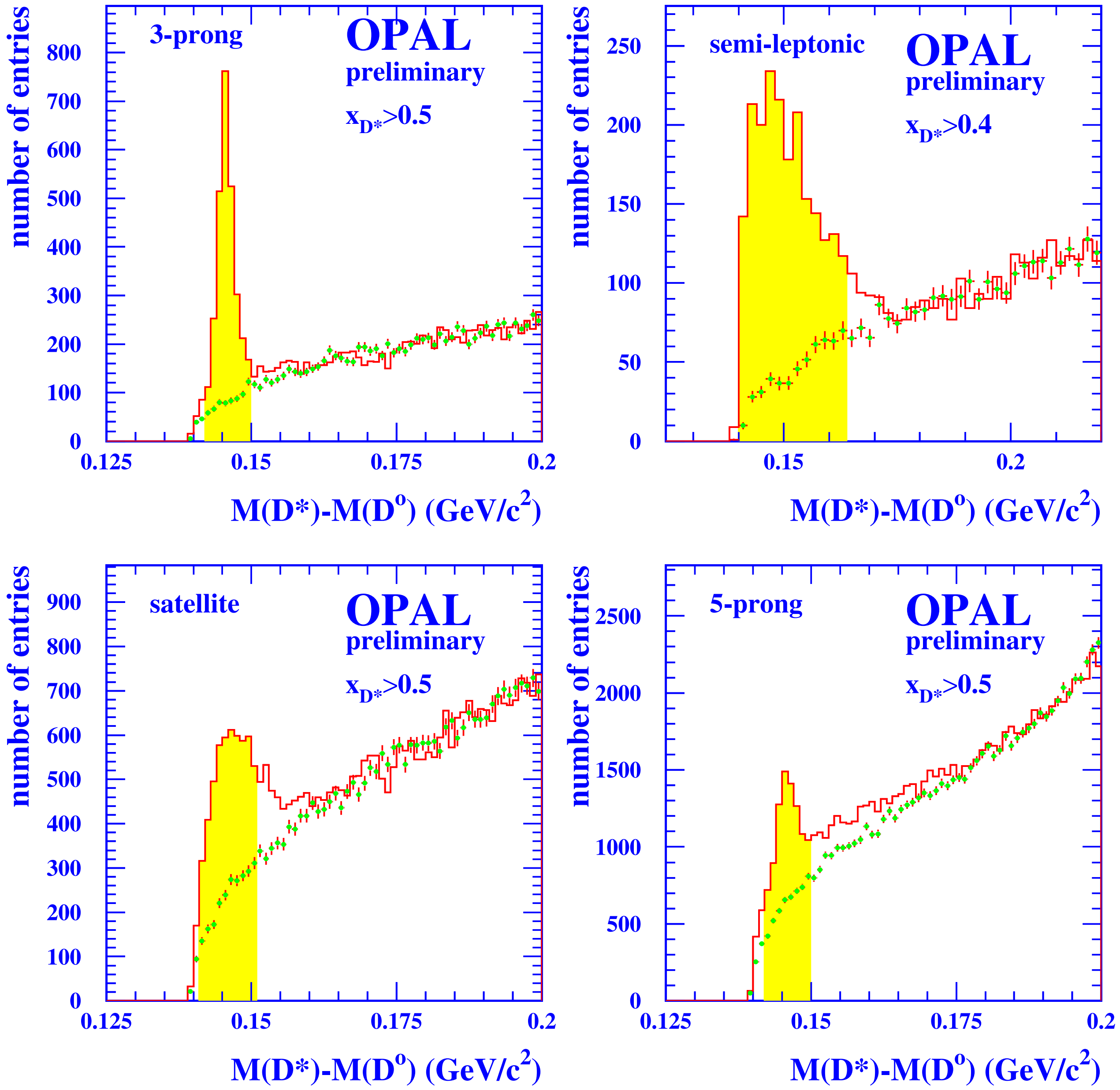
❒ D^* selection based mainly on invariant mass:

- $\Delta M = M(D^*) - M(D^0)$

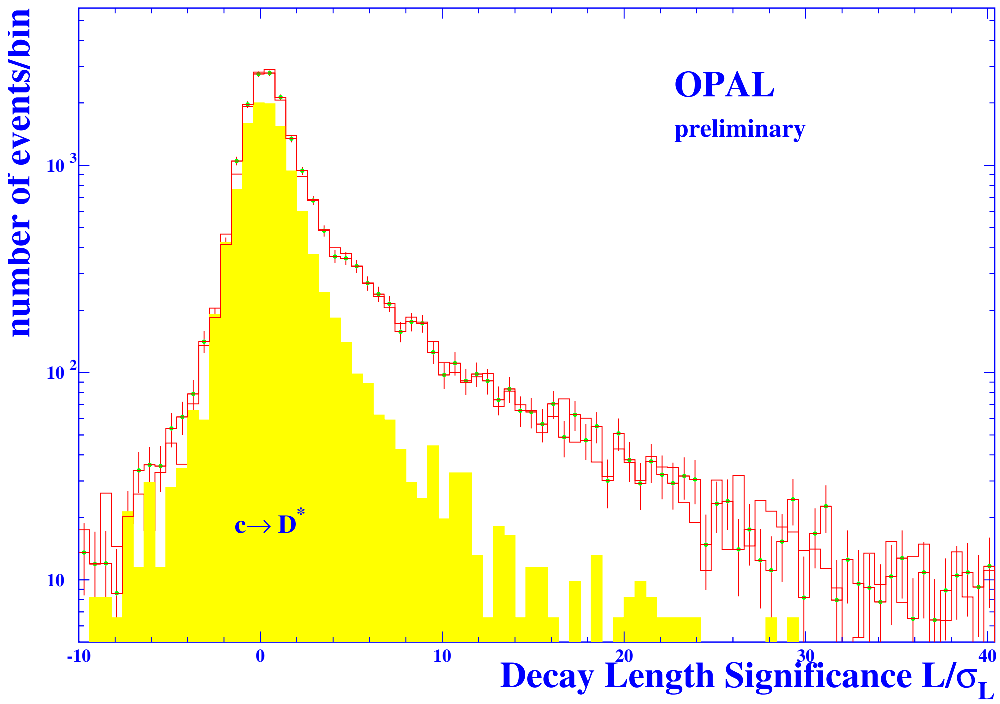
❒ background from data: wrong charge combination, reflected pion...

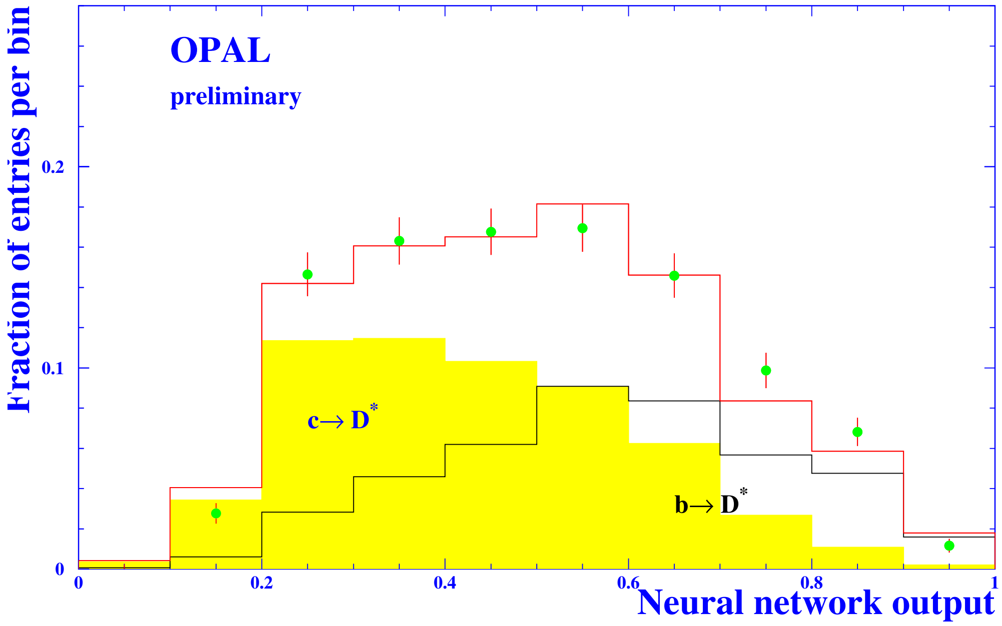
❒ $\epsilon_{D^*}^{tag}$ (including BR) $\sim 6.5\%$.

D* reconstruction at OPAL



2. c →D/ b →c →D separation





⇒ fit to extract f_c.

Measurement of B(c→D*) at LEP

- Lower energy measurements give:

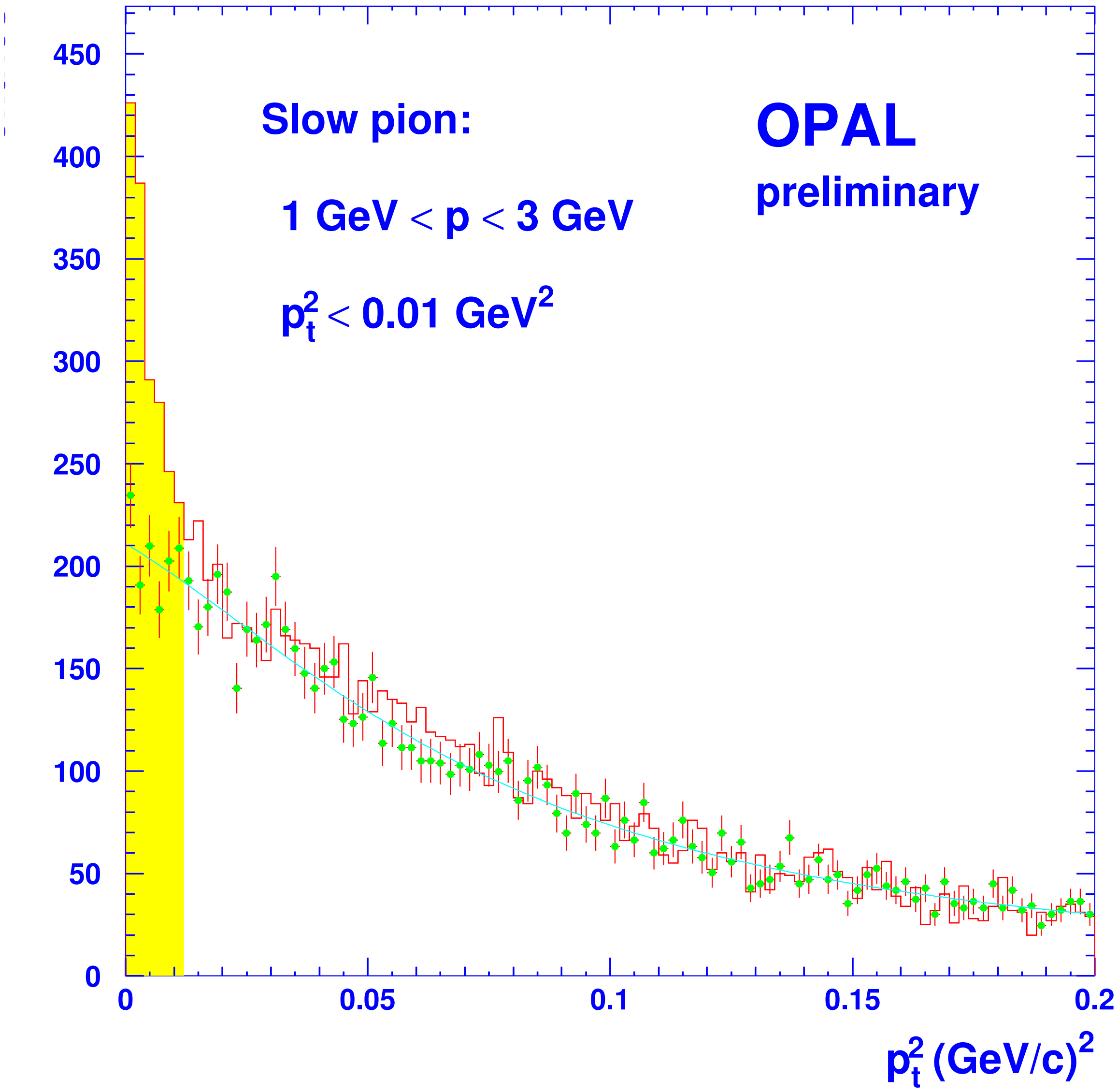
$$\mathrm{B(c{\rightarrow}D^*)} = 0.250 \pm 0.020$$

- Recent first measurement by OPAL using "double-tagged" events:

$$N_{\mathrm{D^*,D^*}} = N_{\mathrm{D^*}}\left[\mathrm{f_c B(c{\rightarrow}D^*)}\epsilon^{\mathrm{c}}_{\mathrm{D^*}} + \mathrm{f_b B(b{\rightarrow}D^*)}\epsilon^{\mathrm{b}}_{\mathrm{D^*}}\right]$$

- Insufficient statistic to fully reconstruct 2 D* in same event ⇒
  - One D* fully reconstructed ($\mathrm{D^0{\rightarrow}K^-\pi^+}$)
  - Second D* tagged inclusively by a slow-pion ($\epsilon^{\mathrm{tag}}_{\mathrm{D^*(\pi)}} \sim 35\%$)

<u>Slow pion inclusive tag at OPAL</u>



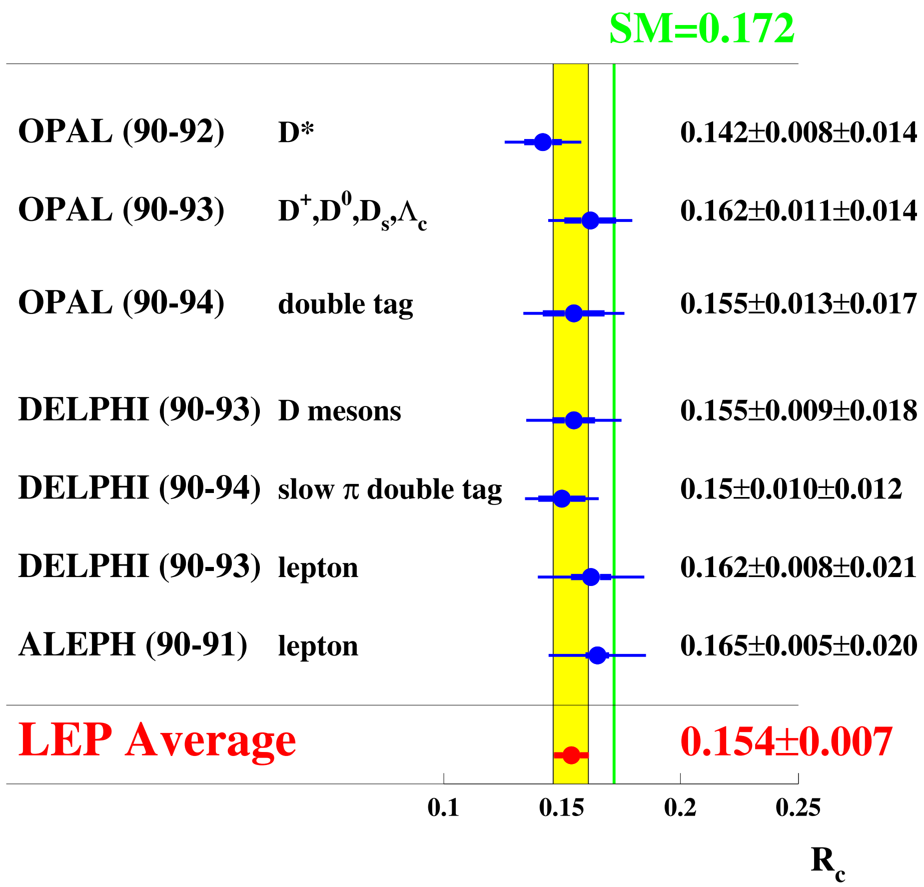
$\Rightarrow$B(c$\rightarrow$D*) $= 0.237 \pm 0.020_{stat} \pm 0.018_{syst}$
compatible with lower energy measurements.

Status of R_c measurement at LEP

Published OPAL measurement with D*:

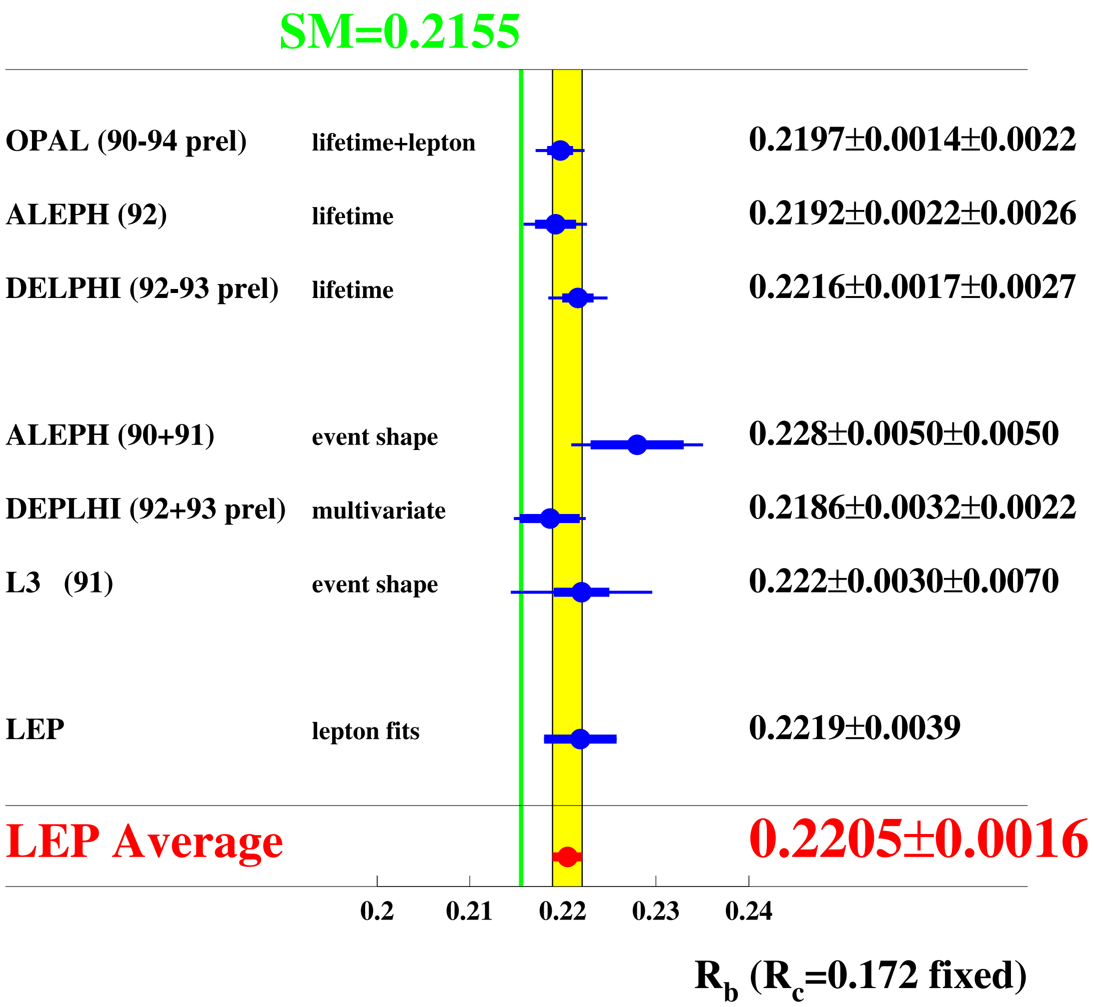
$$R_c = 0.142 \pm 0.008_{stat} \pm 0.014_{syst}$$

$\Rightarrow$ tot. error $\sim 10\%$, systematic limited...



$\Rightarrow$ LEP Average $\sim 2.5\ \sigma$ lower than SM.

Status of $R_{\rm b}$ measurement at LEP



$\Rightarrow$ $R_{\rm b}$ now measured at $\pm 0.7\%$ (syst)

$\Rightarrow$ LEP Average $\sim$ 3 σ <u>above</u> SM ($R_{\rm c}$=0.172)

$\sim$ 4 σ above SM ($R_{\rm c}$=0.154)

Conclusion

- important weight of R_{b} and R_{c} OPAL measurement in LEP averages.

- error on R_{b} now <u>well below 1%</u> and will decrease further with the inclusion of 94 data by other LEP exp. but already systematic limited:

$$
\begin{aligned}
R_{\mathrm{b}} &= 0.2205 \pm 0.0016 \; (R_{\mathrm{c}} = 0.172) \\
R_{\mathrm{b}} &= 0.2219 \pm 0.0017 \; (R_{\mathrm{c}} = 0.154 \pm 0.007)
\end{aligned}
$$

- R_{b} (R_{c}) still compatible with SM ?

$$
R_{\mathrm{b}}{}^{SM} = 0.2155 \pm 0.0005 \quad (m_{\mathrm{top}} = 180 \pm 12\,\mathrm{GeV})
$$

Comparison with SM (R_c fixed)