Heavy-Quark Electroweak Measurements Using Leptons

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Outline

Introduction

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- Cross-section Measurements
- Asymmetry Measurements
- Branching ratio Measurements

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Measured Quantities

$$R_b = \frac{\Gamma(Z^0 \to b\bar{b})}{\Gamma(Z^0 \to \text{hadrons})}$$

$$R_c = \frac{\Gamma(Z^0 \to b\bar{b})}{\Gamma(Z^0 \to \text{hadrons})}$$

$$\frac{d\sigma(e^+e^- \to b\bar{b})}{d\cos\theta} \propto 1 + \cos^2\theta + \frac{8}{3} A_{FB}^{b} \cos\theta$$

$$\frac{d\sigma(e^+e^- \to c\bar{c})}{d\cos\theta} \propto 1 + \cos^2\theta + \frac{8}{3} A_{FB}^{c} \cos\theta$$

Introduction

Semileptonic decays of b/c hadrons produce leptons with large p and p_t — Can be used to *tag* $Z^0 \to b\bar{b}$ and $Z^0 \to c\bar{c}$ events.

Efficiency lower than lifetime tags, limited by

$$\mathrm{Br}(b \to \ell^-) \sim \mathrm{Br}(c \to \ell^+) \sim 10\%.$$

Additional information from p, p_t spectra and charge.

Wide variety of possible measurements:

- Contributions from $b \to \ell^-$, $c \to \ell^+$, and $b \to c \to \ell^+$ can be separated by fitting (p, p_t) distribution. This gives measurements of $R_b \mathrm{Br}(b \to \ell^-)$, $R_b \mathrm{Br}(b \to c \to \ell^+)$, and $R_c \mathrm{Br}(c \to \ell^+)$.
- Lepton momentum spectrum also tells the quark fragmentation $\langle x_b \rangle$ and $\langle x_c \rangle$.
- Lepton charge tells the quark charge, and thus the forward-backward asymmetries: A^b_{FB} and A^c_{FB}.
- The average B^0-$\overline{B}^0$ mixing $\overline{\chi}$ can be measured from the fraction of like-sign dilepton events.

Measurement technique depends on what to measure. Cross-section? Asymmetry? Mixing? Everything?

Measurements Overview

Cross-section measurements

R_b, R_c, branching ratios, mixing etc.

ALEPH	90–91	Z. Phys. C62 (1994) 179
DELPHI	91–92	Z. Phys. C66 (1995) 323
L3	90–91	Preliminary (Glasgow '94)
OPAL	90–91	Z. Phys. C60 (1993) 199

New ALEPH R_c measurement:

ALEPH	92–94	Preliminary **NEW**

Will be presented by I. Khokhlov.

Asymmetry measurements A^b_{FB}, A^c_{FB} and $\overline{\chi}$

ALEPH	90–95	CERN-PPE/96-072 **NEW**
DELPHI	91–94	Preliminary (Brussels '95)
L3	90–93	Preliminary (Glasgow '94)
OPAL	90–95	Preliminary **NEW**

Branching ratio measurements

$\mathrm{Br}(b \to \ell^-)$, $\mathrm{Br}(b \to c \to \ell^+)$ or $\mathrm{Br}(c \to \ell^+)$

ALEPH	92–93	Preliminary
DELPHI	91–95	Preliminary **NEW**
L3	91–92	Preliminary **NEW**

Will be presented by J. Alcaraz in Pa-05.

Cross-Section Measurements

Basic Idea

Fitting (p, p_t) spectra of inclusive leptons gives:

$$R_{\mathrm{b}}\mathrm{Br}(\mathrm{b} \to \ell^-),\ R_{\mathrm{b}}\mathrm{Br}(\mathrm{b} \to \mathrm{c} \to \ell^+),\ \text{and}\ R_{\mathrm{c}}\mathrm{Br}(\mathrm{c} \to \ell^+).$$

Dilepton events give additional constraint — Possible to measure R_{b}, R_{c}, $\mathrm{Br}(\mathrm{b} \to \ell^-)$, and $\mathrm{Br}(\mathrm{b} \to \mathrm{c} \to \ell^+)$ at once.

$\mathrm{Br}(\mathrm{c} \to \ell^+)$ difficult due to poor separation between $\mathrm{b} \to \mathrm{c} \to \ell^+$ and $\mathrm{c} \to \ell^+$ decays.

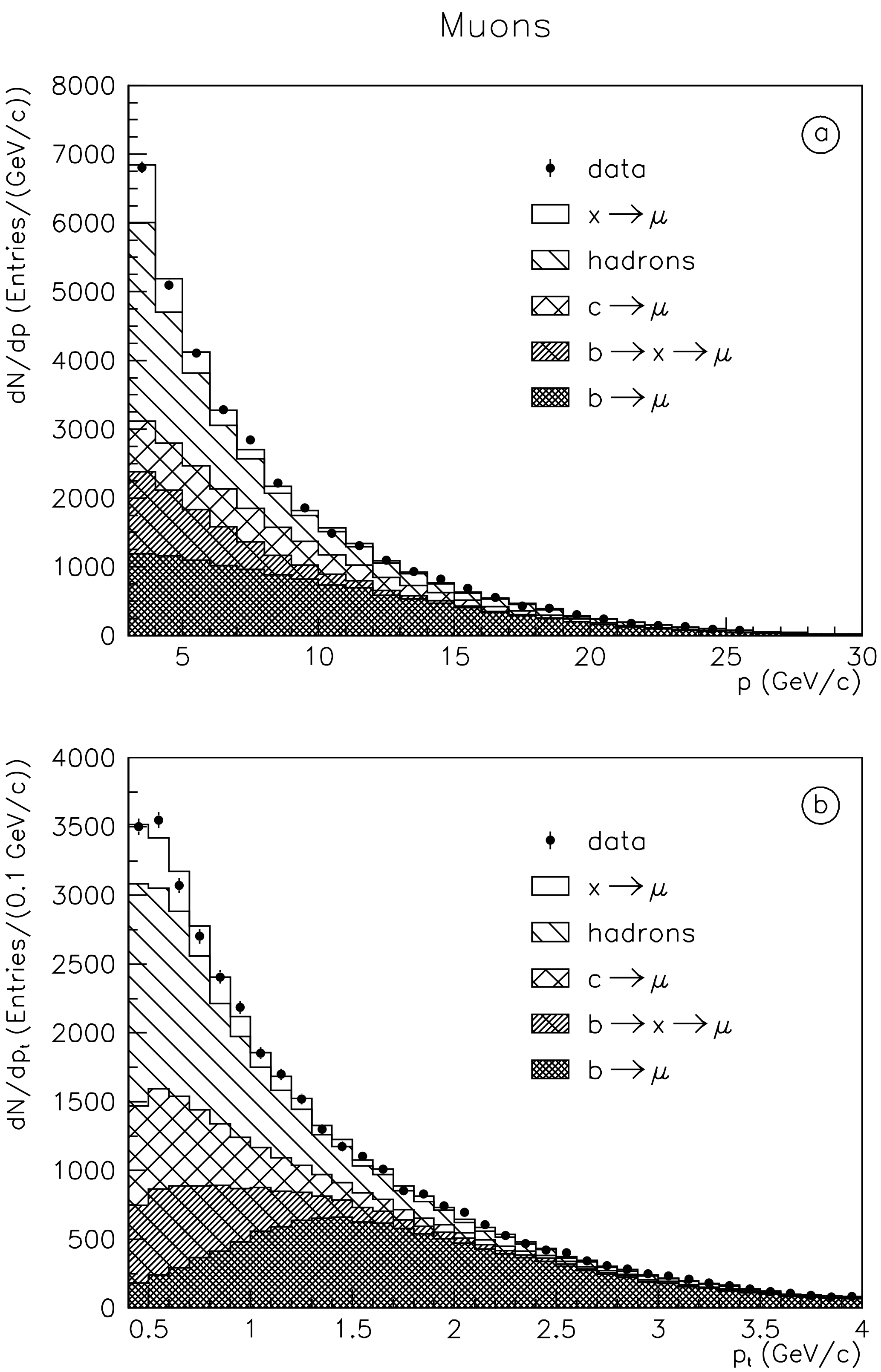
$\overline{\chi}$ and $\langle x_{\mathrm{b}} \rangle$ major systematics — Fit them together.

Measurements

Expt.	Data	R_{b}	R_{c}	A_{FB}^{b}	A_{FB}^{c}	$\mathrm{Br}(\mathrm{b} \to \ell^-)$	$\mathrm{Br}(\mathrm{b} \to \mathrm{c} \to \ell^+)$	$\langle x_{\mathrm{b}} \rangle$	$\langle x_{\mathrm{c}} \rangle$	$\overline{\chi}$
ALEPH	90–91	y	y	y	y	y	y	y	y	y
DELPHI	91–92	y	y	-	-	y	y	y	-	y
L3	90–91	y	-	-	-	y	-	-	-	-
OPAL	90–91	y	-	-	-	y	y	y	-	y

ALEPH measured asymmetries as well.

No recent updates.
Only 12% of the LEP-1 data analysed.



(p, p_t) distributions for muons in 1993 DELPHI data.

Z. Phys. C66 (1995) 323

Results

R_b	ALEPH	0.219	$\pm$	0.006	$\pm$	0.005
	DELPHI	0.2145	$\pm$	0.0089	$\pm$	0.0067
	L3	0.2133	$\pm$	0.0079	$\pm$	0.0078
	OPAL	0.222	$\pm$	0.011	$\pm$	0.007
R_c	ALEPH	0.165	$\pm$	0.005	$\pm$	0.020
	DELPHI	0.1623	$\pm$	0.0085	$\pm$	0.0209
A_{FB}^{b}	ALEPH*	0.090	$\pm$	0.013	$\pm$	0.003
A_{FB}^{c}	ALEPH	0.111	$\pm$	0.021	$\pm$	0.018
$\overline{\chi}$	ALEPH*	0.114	$\pm$	0.014	$\pm$	0.008
	DELPHI	0.154	$\pm$	0.020	$\pm$	0.015
	OPAL	0.143	$\pm$	0.022	$\pm$	0.007

Results of the cross-section type measurements as quoted by each experiment.

ALEPH* A_{FB}^{b} and χ results have been superseded.

New ALEPH R_c Measurement

Preliminary, Pa10-016

Basic Idea

Fit (p, p_t) distribution of electrons to separate b, c, and uds contributions.

Distribution for bottom events measured using lifetime-tagged events — Measurement insensitive to bottom physics.

Distributions for charm and uds events taken from MC.

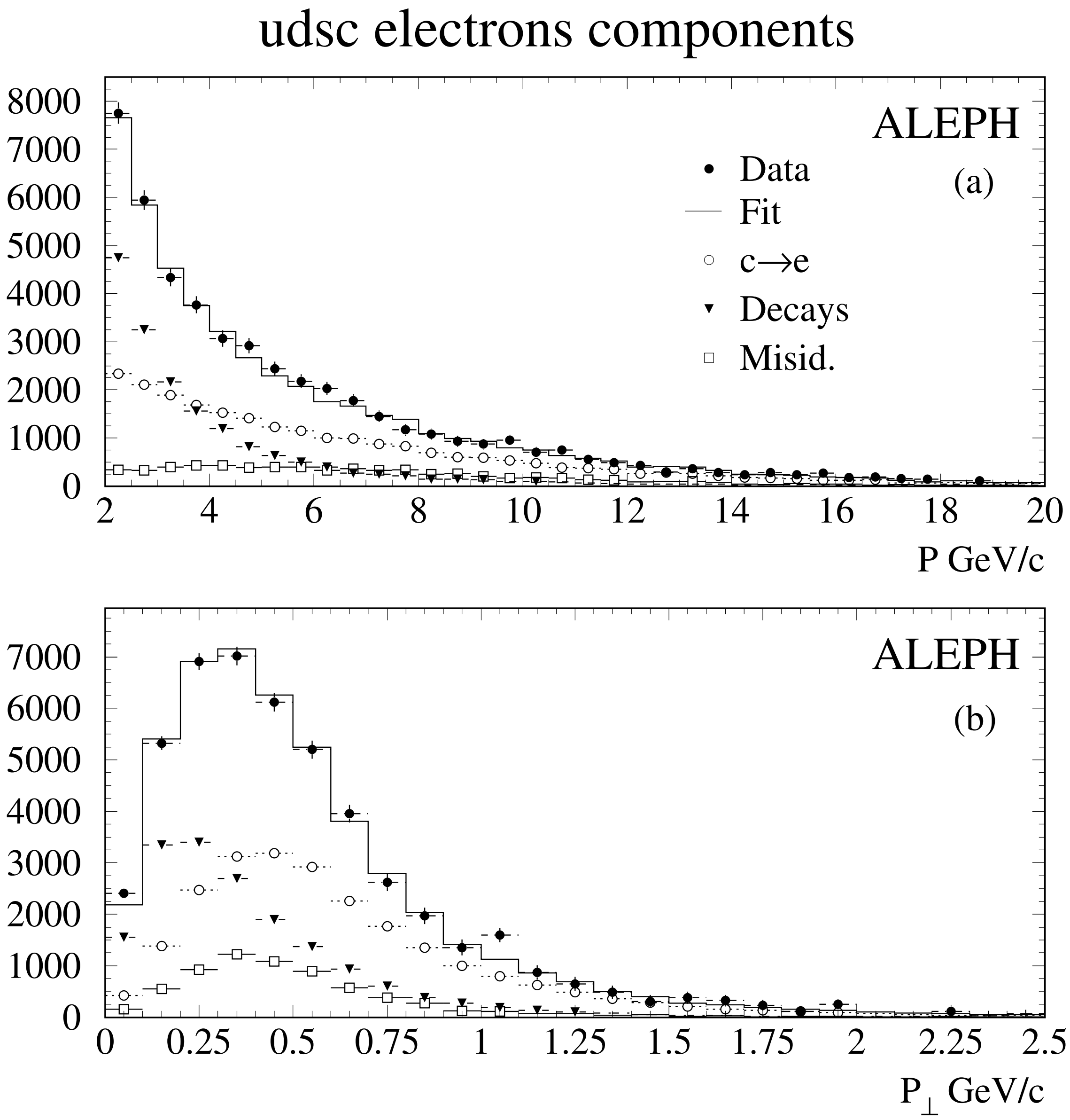
Charm fragmentation and photon conversion background allowed to float in the fit to reduce systematics.

Result

$$R_c = 0.1649 \pm 0.0070_{\mathrm{stat}} \pm 0.0066_{\mathrm{syst}} \pm 0.0084_{\mathrm{Br}(c\to\ell+)}$$

Systematics

- charm decay modelling
- electron background



Momentum and transverse momentum of leptons after subtracting $\mathrm{b} \to \ell^-$ component.

ALEPH Preliminary, Pa10-016

Asymmetry Measurements

Basic Idea

Lepton charge tells the charge of the decaying quark.
b/c separation by fitting (p, p_t) distribution.

$A^{\mathrm{b}}_{\mathrm{FB}}$ and $A^{\mathrm{c}}_{\mathrm{FB}}$ can be measured from the asymmetry of the lepton charge.

Observed $\mathrm{Z^0} \to \mathrm{b\bar{b}}$ asymmetry $A^{\mathrm{b,obs}}_{\mathrm{FB}}$ has to be corrected for the $\mathrm{B^0}$-$\overline{\mathrm{B}}^0$ mixing:

$$A^{\mathrm{b}}_{\mathrm{FB}} = \frac{A^{\mathrm{b,obs}}_{\mathrm{FB}}}{1 - 2\overline{\chi}}.$$

$\overline{\chi}$ can be measured from like-sign dilepton events.

Fitting $A^{\mathrm{b}}_{\mathrm{FB}}$ and $\overline{\chi}$ together cancels part of systematics.

Measurements

Expt.	Data	$A^{\mathrm{b}}_{\mathrm{FB}}$	$A^{\mathrm{c}}_{\mathrm{FB}}$	$\overline{\chi}$	
ALEPH	90–95	y	-	y	NEW
DELPHI	91–94	y	peak	-	
L3	90–93	y	peak	y	
OPAL	90–95	y	y	y	NEW

New updates from ALEPH and OPAL using full LEP-1 statistics. 81% of LEP-1 data used.

New ALEPH $A_{\mathrm{FB}}^{\mathrm{b}}$ Measurement

CERN-PPE/96-072, submitted to Phys. Lett. B

Basic Idea

Count electrons and muons in hadronic Z^0 decays with $p > 3\,\mathrm{GeV}/c$ and $p_t > 1.25\,\mathrm{GeV}/c$.

Fit $\cos\theta$ distribution (signed by the lepton charge) to get observed asymmetry:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta} = C(1 + \cos^2\theta + \frac{8}{3}A_{\mathrm{FB}}^{\mathrm{obs}}\cos\theta).$$

Correct for $\mathrm{c} \to \ell^+$ and other backgrounds to get $A_{\mathrm{FB}}^{\mathrm{b,obs}}$.

Average mixing $\overline{\chi}$ is obtained from numbers of like-sign and opposite-sign dilepton events.

Solve

$$A_{\mathrm{FB}}^{\mathrm{b,obs}} = (1 - 2\overline{\chi})(f_{\mathrm{b}}^{\mathrm{rs}} - f_{\mathrm{b}}^{\mathrm{ws}})A_{\mathrm{FB}}^{\mathrm{b}}$$

to get $A_{\mathrm{FB}}^{\mathrm{b}}$.

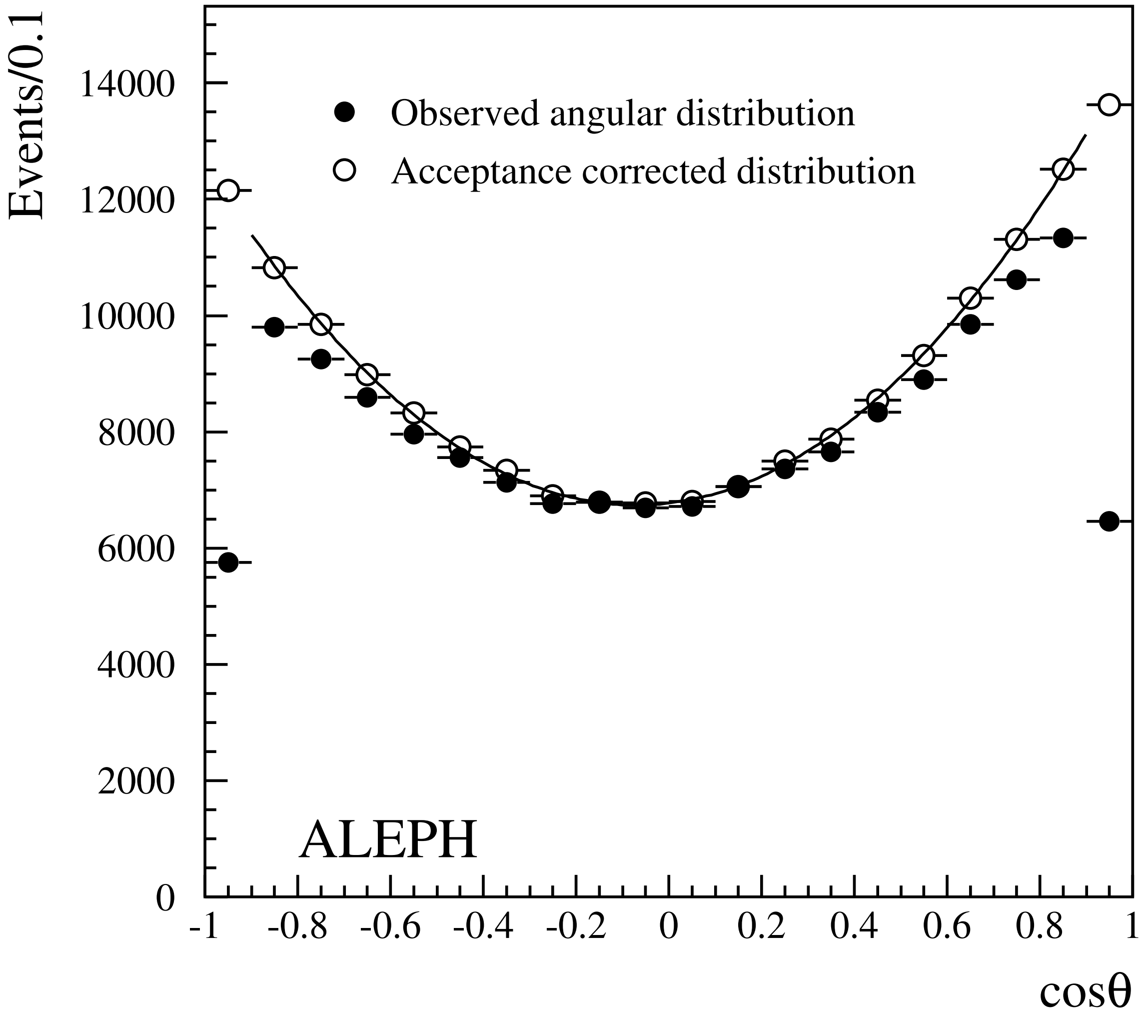
Results

$$\begin{aligned} \overline{\chi} &= 0.1246 \pm 0.0051_{\mathrm{stat}} \pm 0.0052_{\mathrm{syst}} \\ A_{\mathrm{FB}}^{\mathrm{b}} &= 0.1008 \pm 0.0043_{\mathrm{stat}} \pm 0.0028_{\mathrm{syst}} \end{aligned}$$

Systematics

$A_{\mathrm{FB}}^{\mathrm{b}}$ — c fragmentation, $\mathrm{c} \to \ell^+$ modelling, R_{c} and $\overline{\chi}$

$\overline{\chi}$ — b/c hadron decay modelling



Polar angle distribution in the on-peak data before/after acceptance correction.

CERN-PPE/96-072, submitted to Phys. Lett. B

New OPAL $A_{\mathrm{FB}}^{\mathrm{b}}$ and $A_{\mathrm{FB}}^{\mathrm{c}}$ Measurement

Preliminary, Pa05-007

Update based on Z. Phys. C70 (1996) 357

Basic Idea

To measure both $A_{\mathrm{FB}}^{\mathrm{b}}$ and $A_{\mathrm{FB}}^{\mathrm{c}}$, try to separate $\mathrm{b} \to \ell^-$, $\mathrm{b} \to \mathrm{c} \to \ell^+$ and $\mathrm{c} \to \ell^+$ contributions instead of just counting high-p_t leptons.

In addition to p and p_t, use:

- kinematic variables of the jet, e.g., sub-jet energy
- lifetime information, e.g., decay length significance
- electron identification variables (for electrons)

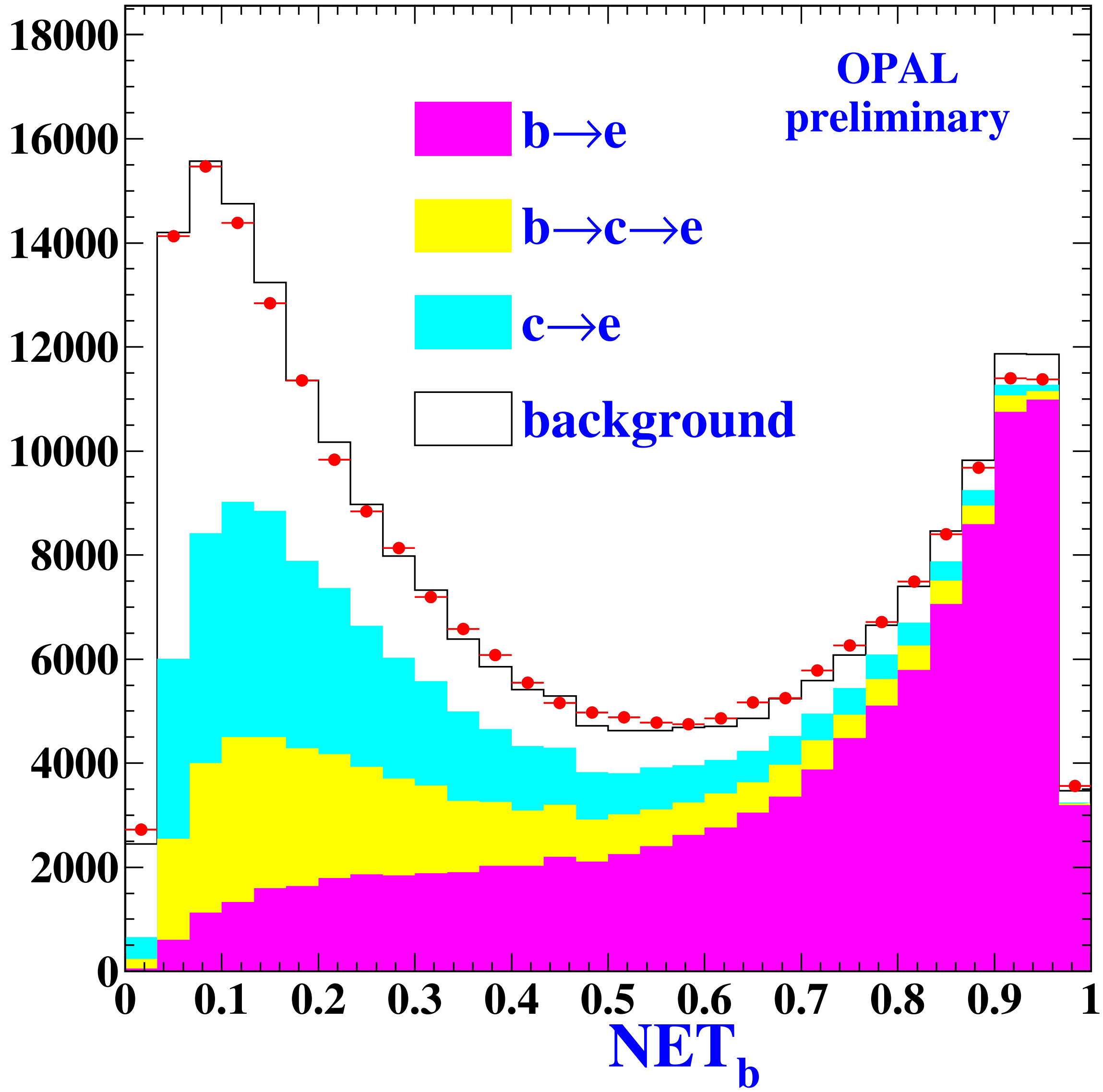
to improve the separation.

Use Artificial Neural Networks (**ANN**) to construct two variables optimized for separating $\mathrm{b} \to \ell^-$ and $\mathrm{c} \to \ell^+$ from other components.

Benefits of ANN

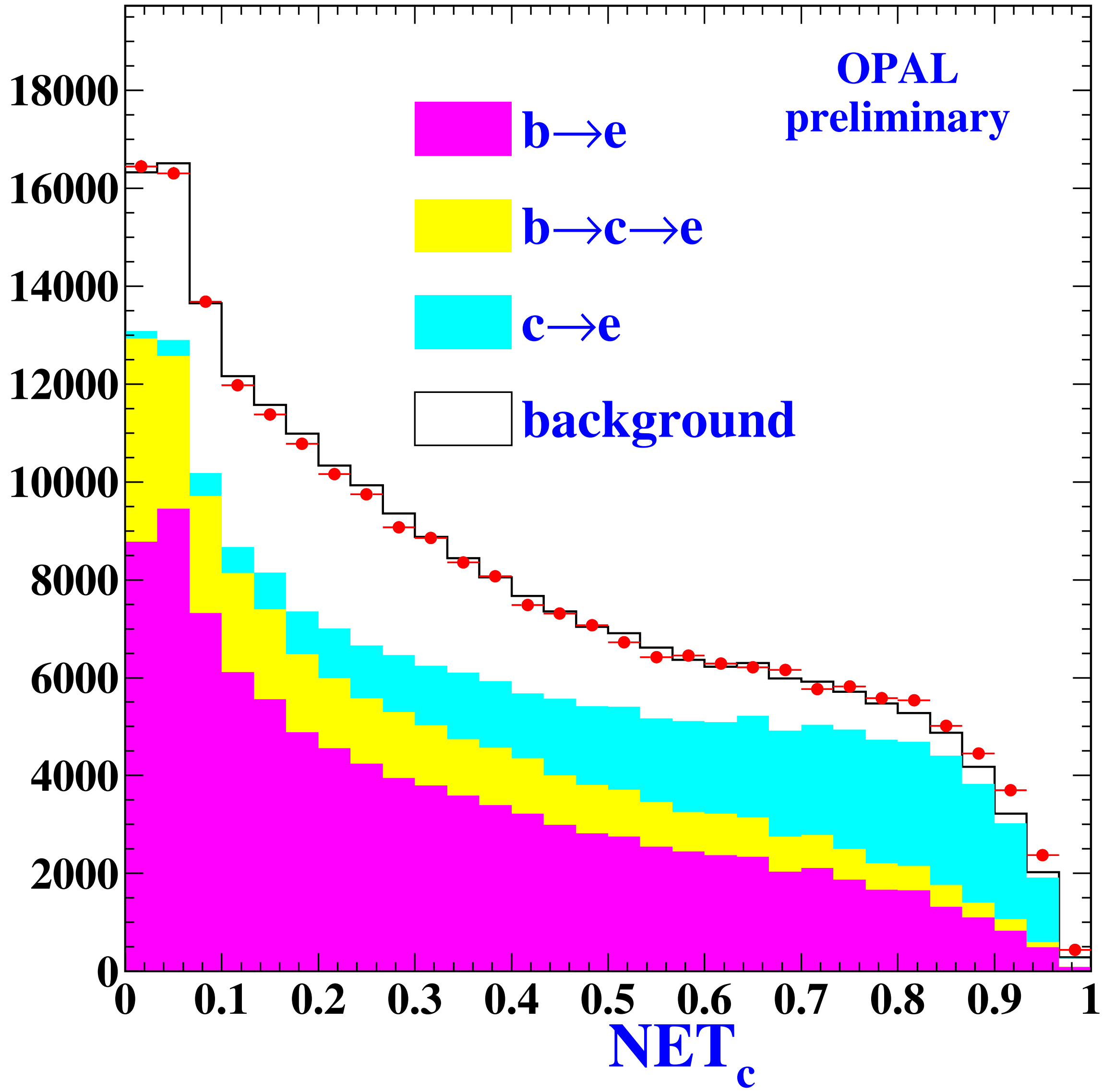
- optimum separation between lepton sources
- reduction of fit dimensionality
- robustness against systematic uncertainties

Improved accuracy of $A_{\mathrm{FB}}^{\mathrm{c}}$.



Output of ANN designed for separating $b \to e^-$.

OPAL Preliminary, Pa05-007



Output of ANN designed for separating $c \to e^+$.

OPAL Preliminary, Pa05-007

Fitting Method

Simultaneously fit:

- differential asymmetries of single lepton events in bins of ANN outputs and $|\cos\theta|$
- like-sign fraction of dilepton events

to obtain A^{b}_{FB}, A^{c}_{FB} and $\overline{\chi}$.

Fraction of hadronic background left free in the fit to reduce the systematic error.

Results

$A^{b}_{FB}(\%)$	$A^{c}_{FB}(\%)$	$\sqrt{s}$ (GeV)
$3.4 \pm 1.7 \pm 0.2$	$-6.8 \pm 2.4 \pm 0.5$	89.49
$8.92 \pm 0.44 \pm 0.20$	$5.88 \pm 0.59 \pm 0.56$	91.24
$10.5 \pm 1.4 \pm 0.4$	$15.4 \pm 2.0 \pm 1.0$	92.57

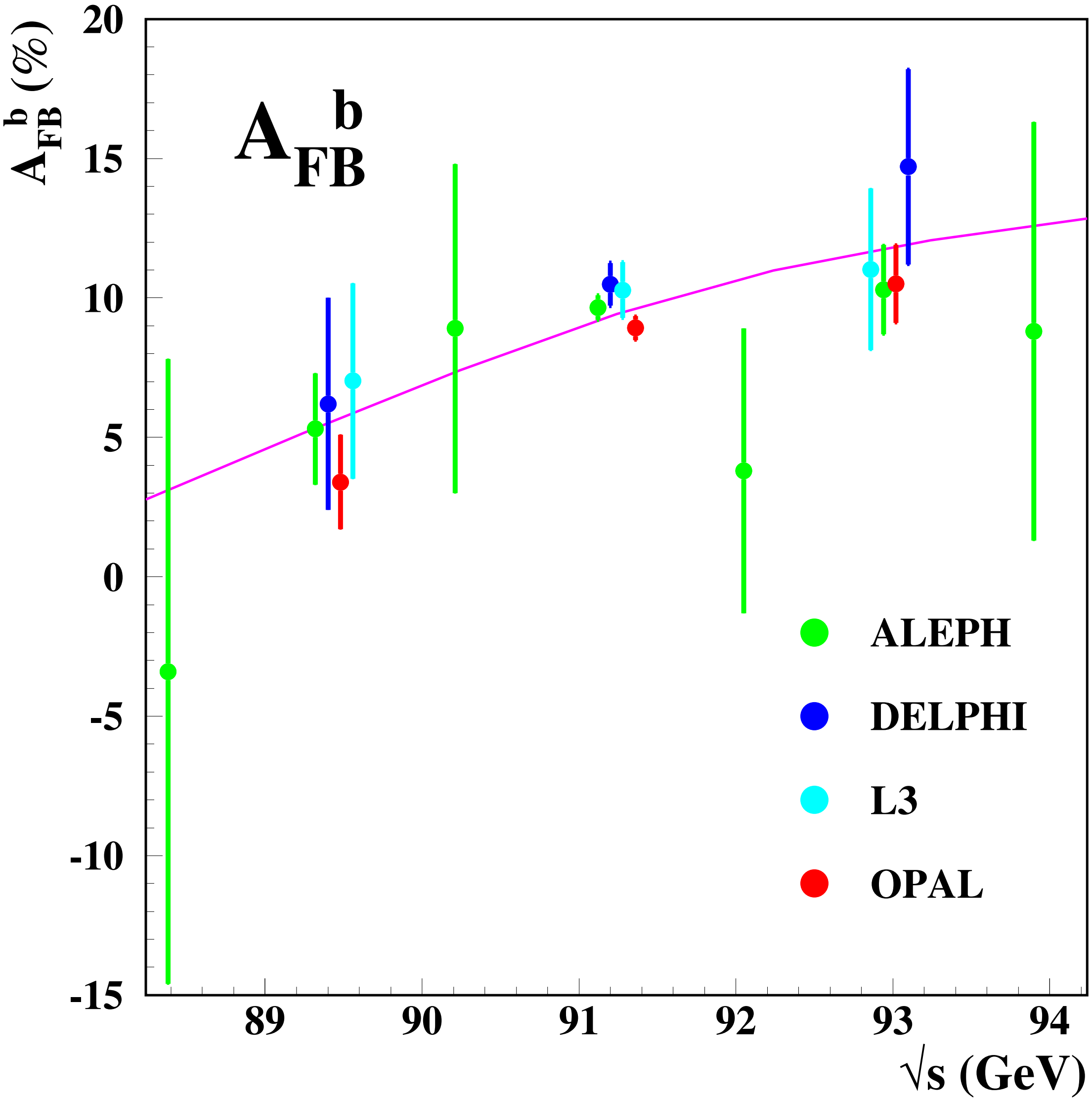
Systematics

A^{b}_{FB} — c fragmentation

A^{c}_{FB} — $b \to \ell^-$ decay modelling, bkgd. asymmetry

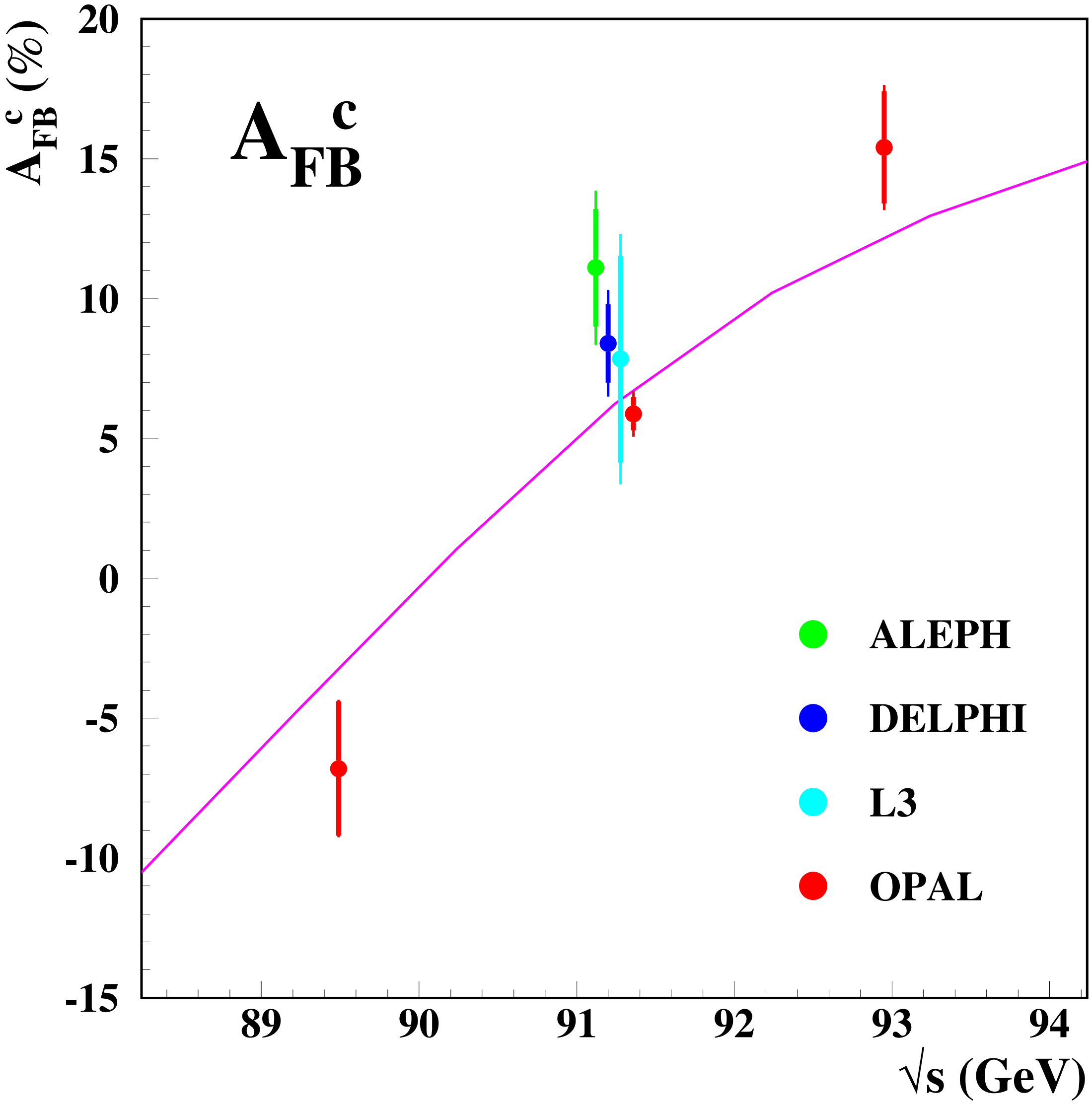
$\overline{\chi}$ — b fragmentation, $\mathrm{Br}(b \to c \to \ell^+)$, $c \to \ell^+$ decay modelling

B Asymmetry Results



$A_{\mathrm{FB}}^{\mathrm{b}}$ vs. $\sqrt{s}$ measured by the LEP experiments

C Asymmetry Results



$A^{c}_{\mathbf{FB}}$ vs. $\sqrt{s}$ measured by the LEP experiments

Branching Ratio Measurements

Two new measurements.

Will be presented by J. Alcaraz in Pa-05.

L3 $\mathrm{Br}(b \to \ell^-)$ measurement

CERN-PPE/96-49, submitted to Z. Phys. C

$$\begin{aligned} \mathrm{Br}(b \to e(\mu)\nu X) &= (10.85 \pm 0.12 \pm 0.47)\% \\ \mathrm{Br}(b \to \nu X) &= (23.08 \pm 0.77 \pm 1.24)\% \\ \mathrm{Br}(b \to \tau\nu X) &= (1.7 \pm 0.5 \pm 1.1)\% \end{aligned}$$

$\mathrm{Br}(b \to e\nu X)$ and $\mathrm{Br}(b \to \mu\nu X)$ measured by counting leptons.

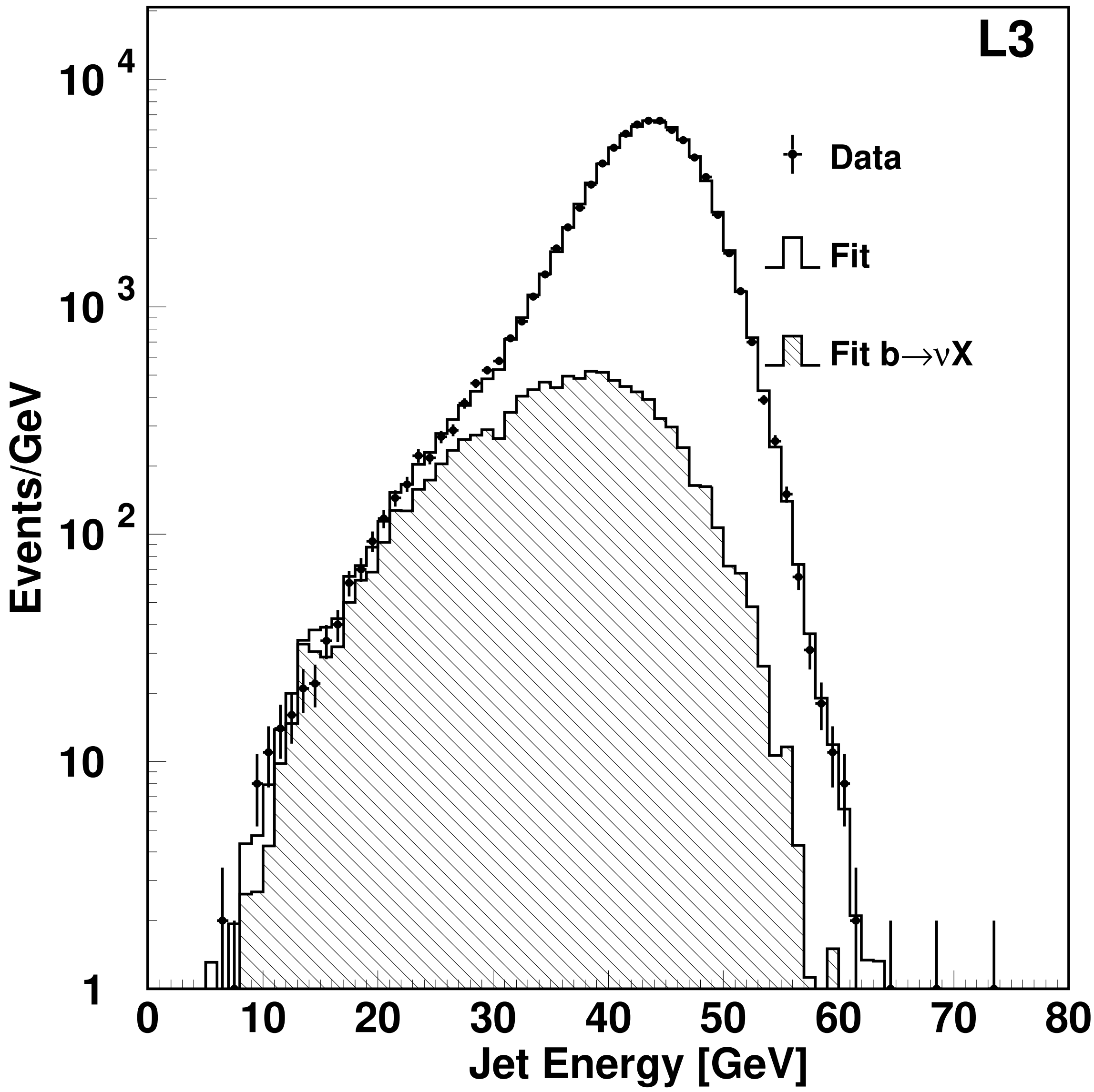
$\mathrm{Br}(b \to \nu X)$ measured by jet-energy spectrum in lifetime-tagged events.

DELPHI $\mathrm{Br}(c \to \ell^+)$ measurement

Preliminary, Pa01-063

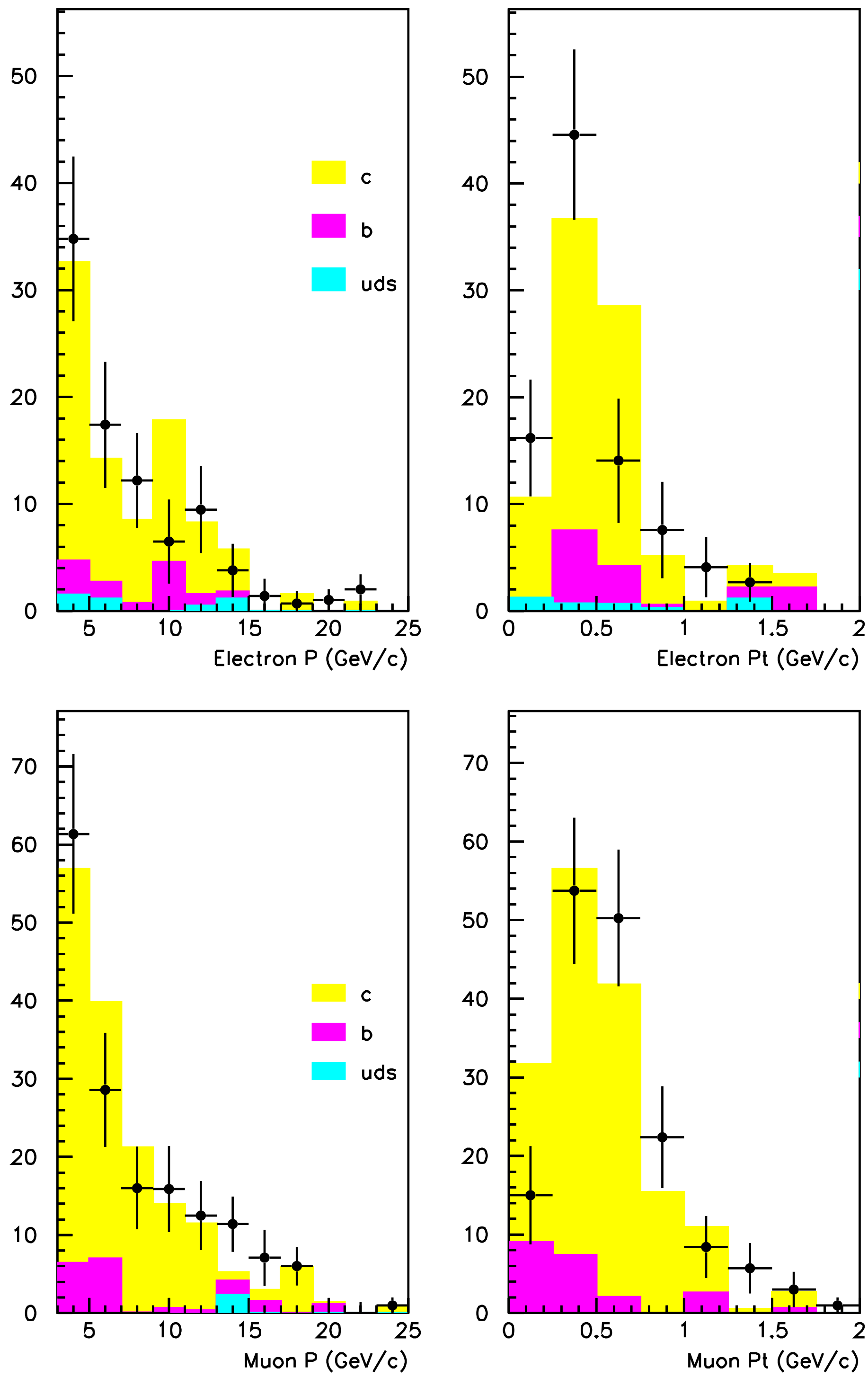
$$\mathrm{Br}(c \to \ell^+) = (9.8 \pm 1.0 \pm 0.6)\%$$

Measured from the yield of leptons opposite to exclusively reconstructed D^* and D^0.



Jet energy in lifetime-tagged sample.

L3, CERN-PPE/96-49



Momentum and transverse momentum of leptons opposite to reconstructed D mesons.

DELPHI Preliminary, Pa01-063

Combined Results

Combine results from lepton measurements.

Consistent treatment of physics inputs proposed by the Heavy-Flavour subgroup of the LEP Electroweak Working Group:

D. Abbaneo, P. Antilogus, P. Arce, T. Behnke, D. Bloch, I.C. Brock, D.G. Charlton, M. Elsing, A. Halley, M. Hildreth, R.W.L. Jones, C. Mariotti, K. Moenig, A. Nippe, F. Palla, A. Passeri, P. Perret, R. Tenchini, I. Tomalin, P.S. Wells.

Measurement results corrected according to the recommendation and combined with correlated errors taken into account.

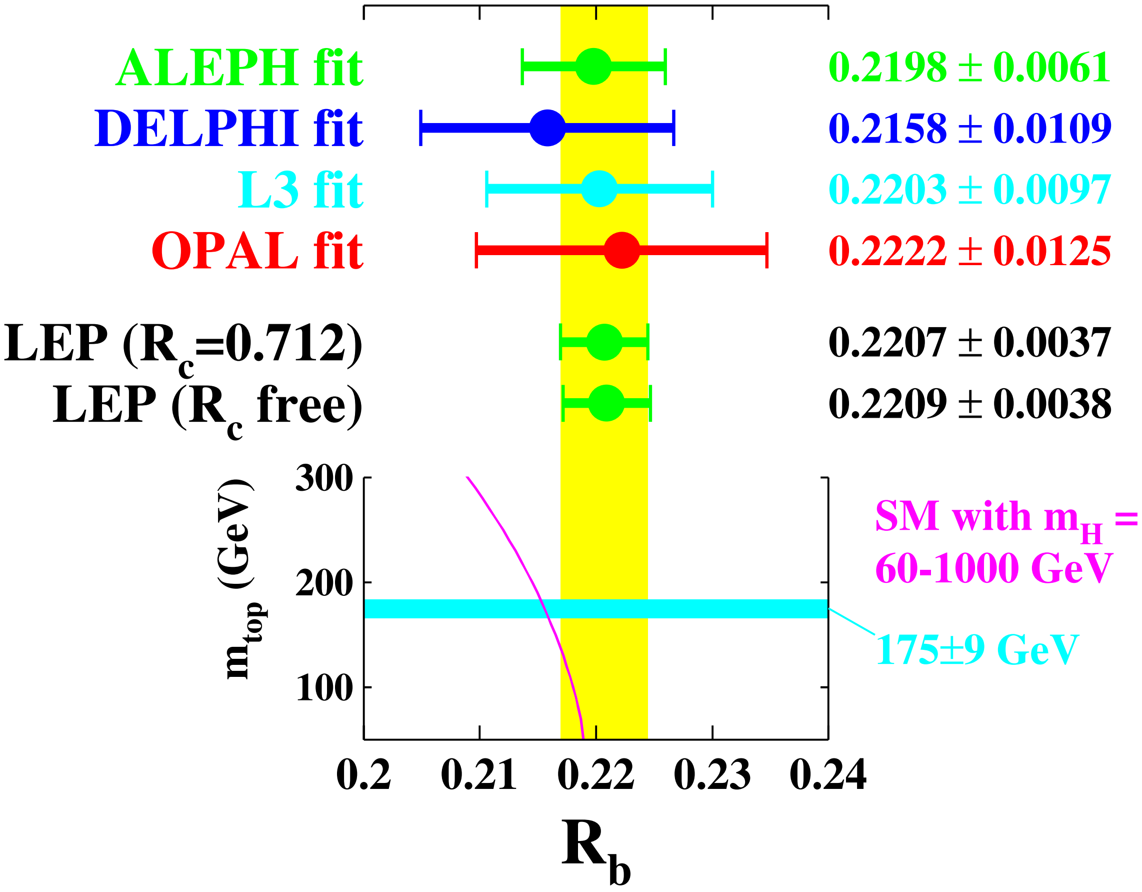
Combination method will be presented by K. Moenig.

Fit tried:

- For all LEP measurements with and without $\boldsymbol{R_c}$ constrained to the SM prediction $(= \mathbf{0.172})$. Little difference found.
- For each LEP experiment (with $\boldsymbol{R_c} = \mathbf{0.172}$). $\mathbf{Br(b \to c \to \ell^+) = (8.10 \pm 0.36)}$ used for L3 fit (obtained from the LEP-wide fit).

Results follow ...

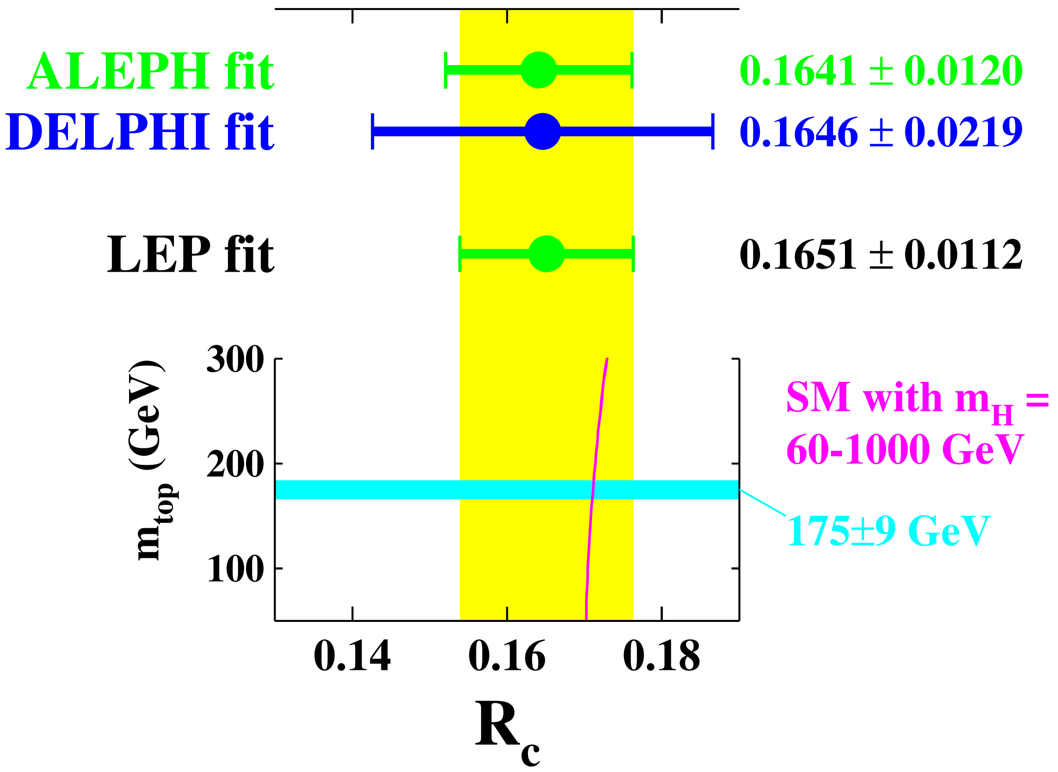
R_b Result



Fit results of R_b using lepton measurements compared with the SM expectation

- Good agreement among experiments.
- Accuracy not high compared with lifetime-tag measurements.
- Slightly higher than the SM prediction, but consistent.

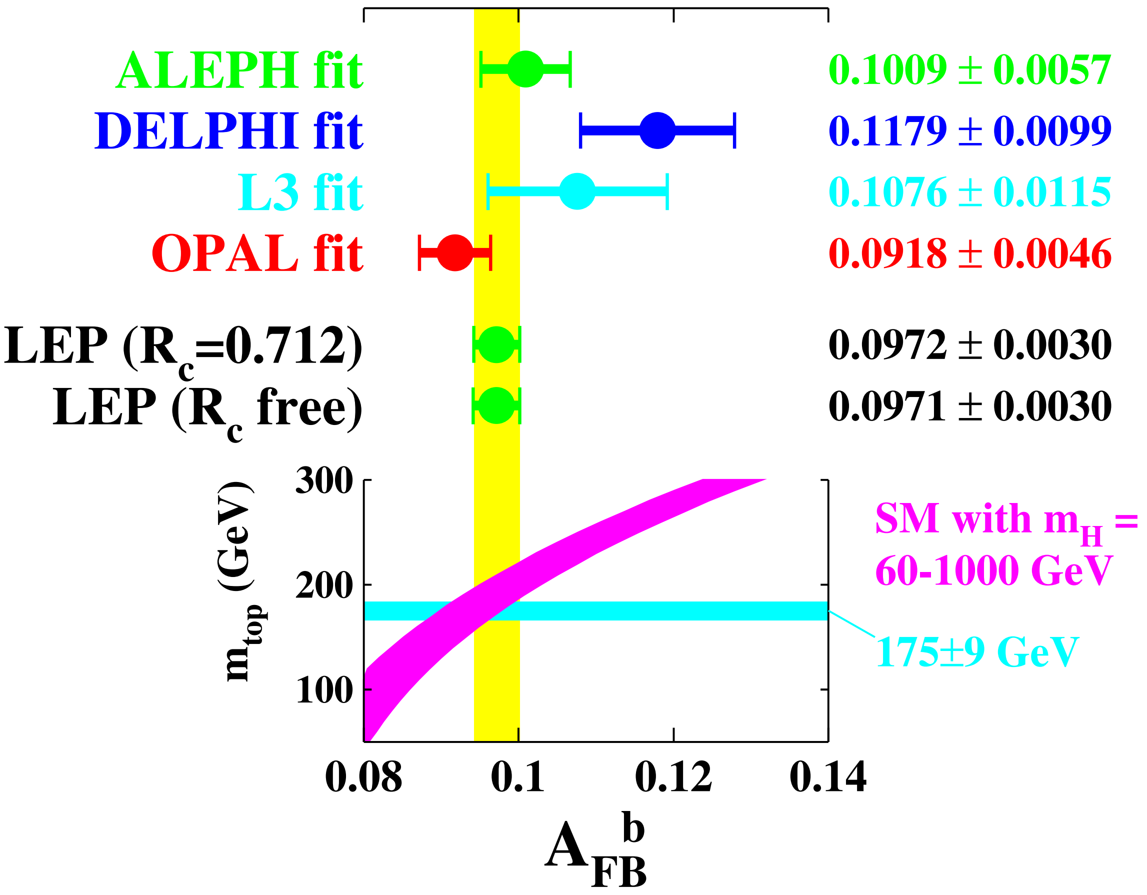
R_c Result



Fit results of R_c using lepton measurements compared with the SM expectation

- Only ALEPH and DELPHI measured R_c.
- Accuracy not high. Measurements using charmed hadron reconstruction do better.
- Consistent with the SM prediction.

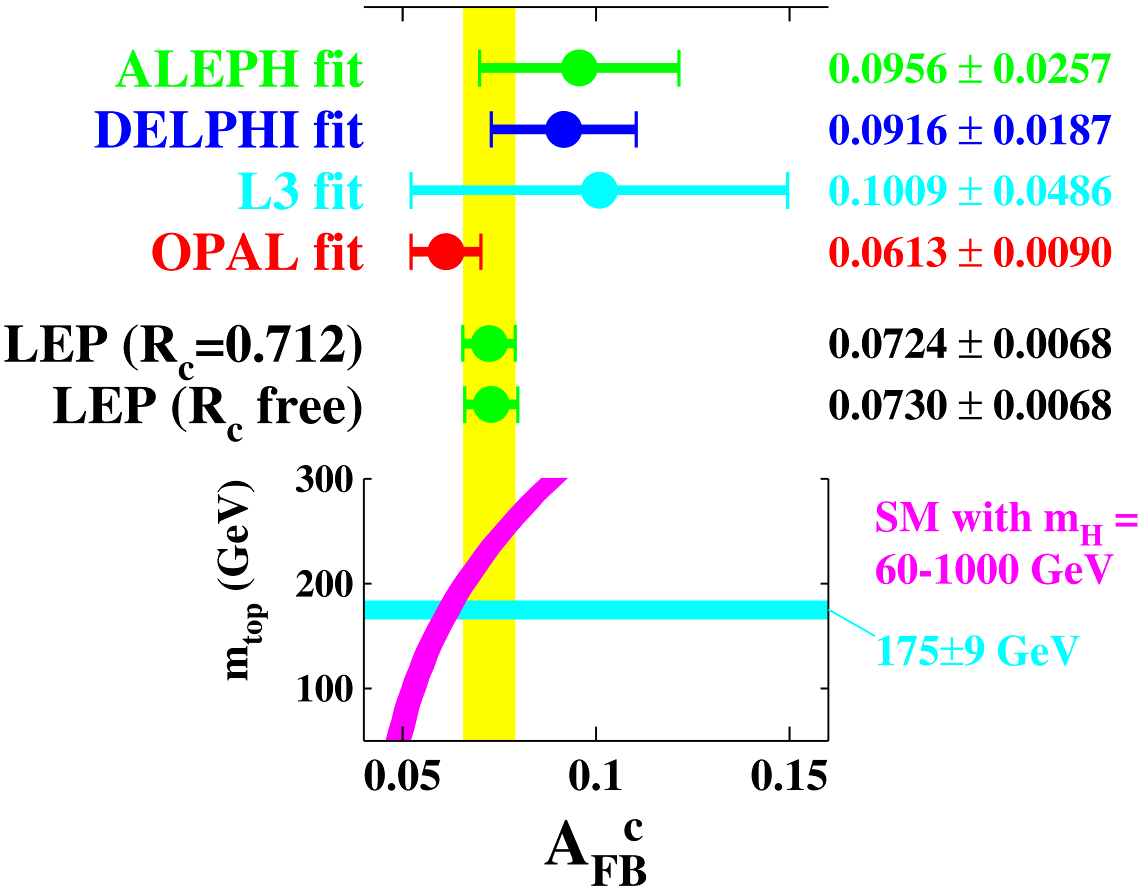
A_{FB}^{b} Result



Fit results of A_{FB}^{b} using lepton measurements compared with the SM expectation

- DELPHI fit high because it includes an old $\overline{\chi}$ measurement which is high (0.149 compared with 0.122 from the LEP fit).
- Good accuracy. Error larger than all LEP heavy flavour fit (including non-lepton measurements) by only 30%.
- Consistent with $m_{top} \sim 180\ \mathrm{GeV}$.

A^c_{FB} Result



Fit results of A^c_{FB} using lepton measurements compared with the SM expectation

- Good agreement among experiment.
  NB: Positive correlation with A^b_{FB}.
- Good accuracy. Error larger than all LEP heavy flavour fit by 40%.
- Consistent with m_{top} around $200\ \mathrm{GeV}$.

Summary

- The cross-section ratios R_b, R_c, and the forward-backward asymmetries A_{FB}^b, A_{FB}^c have been measured at Z^0 using leptons with large p and p_t.
- Fitting all LEP measurements using leptons gives:

$$\begin{aligned} R_b &= 0.2209 \pm 0.0038 \\ R_c &= 0.1651 \pm 0.0112 \\ A_{FB}^b &= 0.0971 \pm 0.0030 \\ A_{FB}^c &= 0.0730 \pm 0.0068 \end{aligned}$$

- High accuracies achieved for A_{FB}^b and A_{FB}^c.
- Recent update using improved flavour-separation technique proved successful.
- Results consistent with the SM predictions with currently measured top quark mass, providing significant constraint esp. by A_{FB}^b.
- Still more LEP-1 data waiting to be analysed.