Measurement of R_b with a Double-Tagging Method

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Representing the OPAL Collaboration

Outline:

- Introduction
- Tag Description
  - Secondary Vertex Tag
  - Lepton Tag
- Results
- Systematic Errors
  - Correlation Studies

The Bottom Line:

OPAL $R_b = 0.2178 \pm 0.0011(\mathrm{stat}) \pm 0.0013(\mathrm{syst})$

Introduction/Motivation

Why Measure R_b?

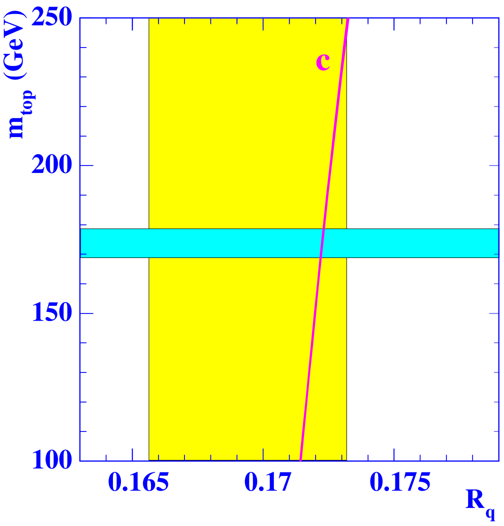
A measured value of $\Gamma_{f\bar{f}} \equiv \Gamma(Z^0 \to f\bar{f})$ is modified by oblique, initial-state, and QCD radiative corrections away from its tree-level value $\Gamma^0_{f\bar{f}}$.

Experimentally, the quantity

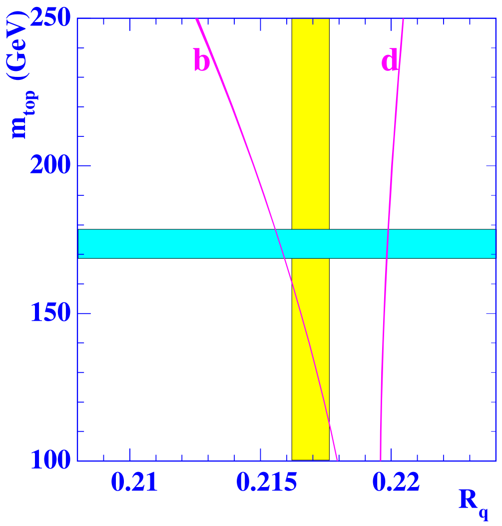
$$R_{\mathrm{Q}} \equiv \frac{\sigma(e^+e^- \to \mathrm{Q\overline{Q}})}{\sigma(e^+e^- \to \mathrm{hadrons})}$$

is more readily accessible, and has the added advantage that these 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_{b}, where the vertex loops induce a large dependence on the top quark mass (and possibly other heavy particles which can modify the coupling)



$R_c^{SM} = 0.1722$

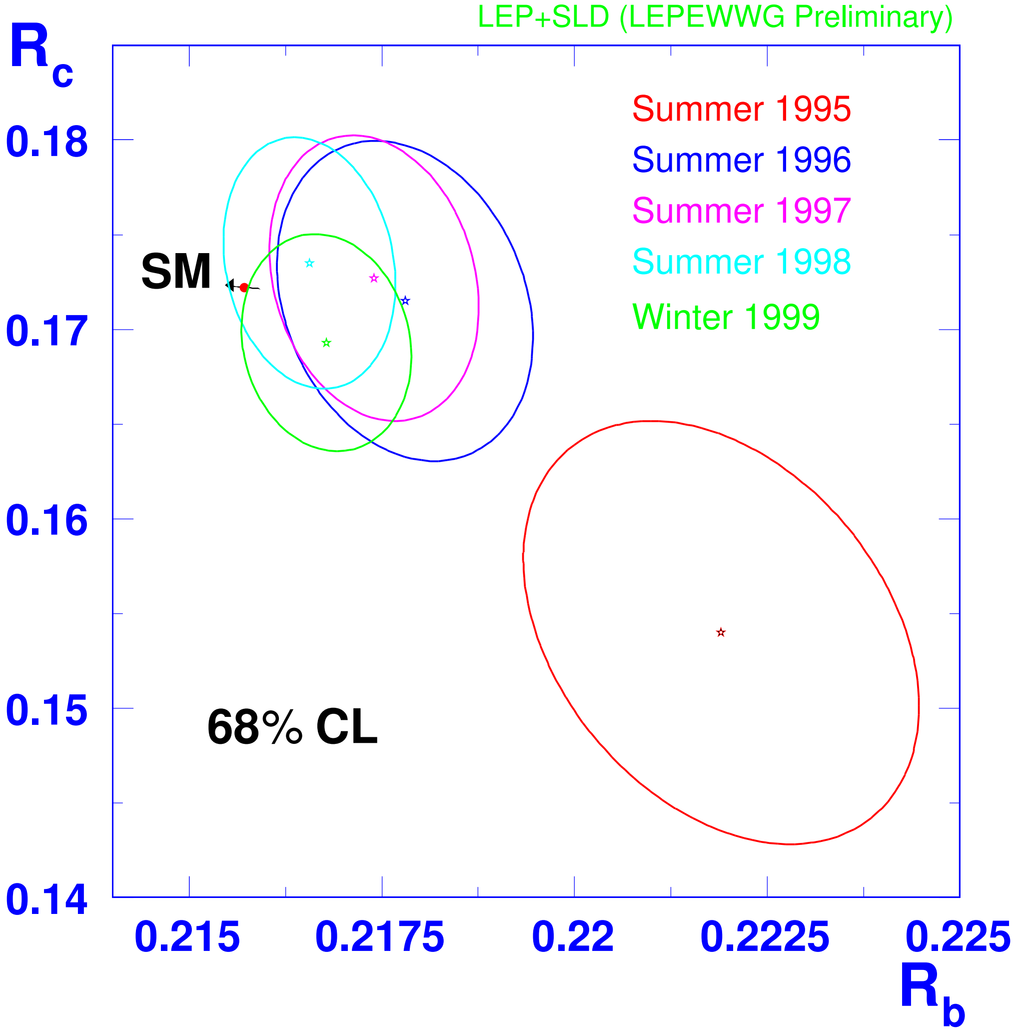


$R_b^{SM} = 0.2155$

- One of the keystones of EW Physics at the Z^0

Alternate Motivation

Original Vertex-Tag Measurements were far from SM:



- Summer 1995:

$$R_b = 0.2219 \pm 0.0017 \qquad R_b(\mathrm{SM},\ m_t = 180) = 0.2155$$
$$R_c = 0.1540 \pm 0.0074 \qquad R_c(\mathrm{SM},\ m_t = 180) = 0.1720$$

- Now (Moriond 1999):

$$R_b = 0.21680 \pm 0.00073$$
$$R_c = 0.1694 \pm 0.0038$$

- Constant Refinement of Techniques

Analysis Method

Double Tag Analysis with Vertex and Lepton Tags

Number of tagged hemispheres $N_{\rm t}$:

$$\frac{N_{\rm t}}{2N_{\rm had}} = \varepsilon_{\rm b}R_{\rm b} + \varepsilon_{\rm c}R_{\rm c} + \varepsilon_{\rm uds}(1 - R_{\rm b} - R_{\rm c})$$

Number of double-tagged events $N_{\rm tt}$:

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

Relevant Points:

- Solve for $R_{\rm b}$ and $\varepsilon_{\rm b}$, from $N_{\rm t}$,$N_{\rm tt}$, $N_{\rm had}$

  $\Longrightarrow$ $\varepsilon_{\rm b}$ Measured from data

- Take $R_{\rm c}$, $C_{\rm b}$, $\varepsilon_{\rm c}$, $\varepsilon_{\rm uds}$ from Monte Carlo

  $\Longrightarrow$ High Purity tags

  $\Longrightarrow$ Only large sources of Systematic Error

- Assume $(C-1) \times \varepsilon^2$ is small for uds, c

- Statistical error $\propto N_{\rm tt} \propto (\varepsilon_{\rm b})^2 \Longrightarrow$ High $\varepsilon_{\rm b}$ tags

Tags based on large mass of b, hard fragmentation, lifetime information

Standard Event Selection $\oplus$ Acceptance Cuts:

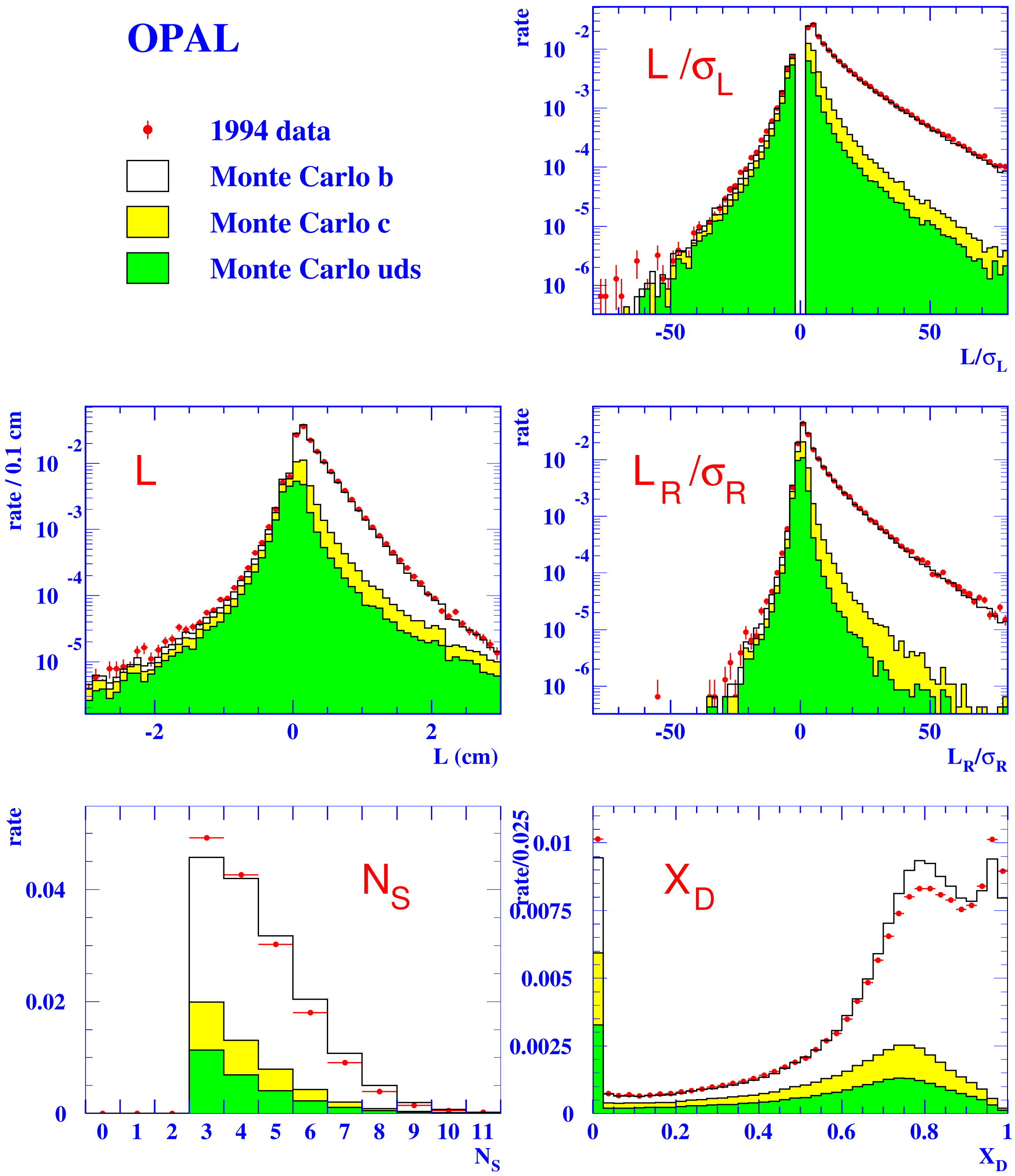
1.9×10^6 Hadronic events selected from 1992-1995

Vertex Tag

- Separate Primary Vertex found in each event hemisphere
- Then, Secondary Vertices sought in each Jet

  $\geq$ 3 tracks per vertex required
- Found vertices fed to a NNET to enhance b purity:

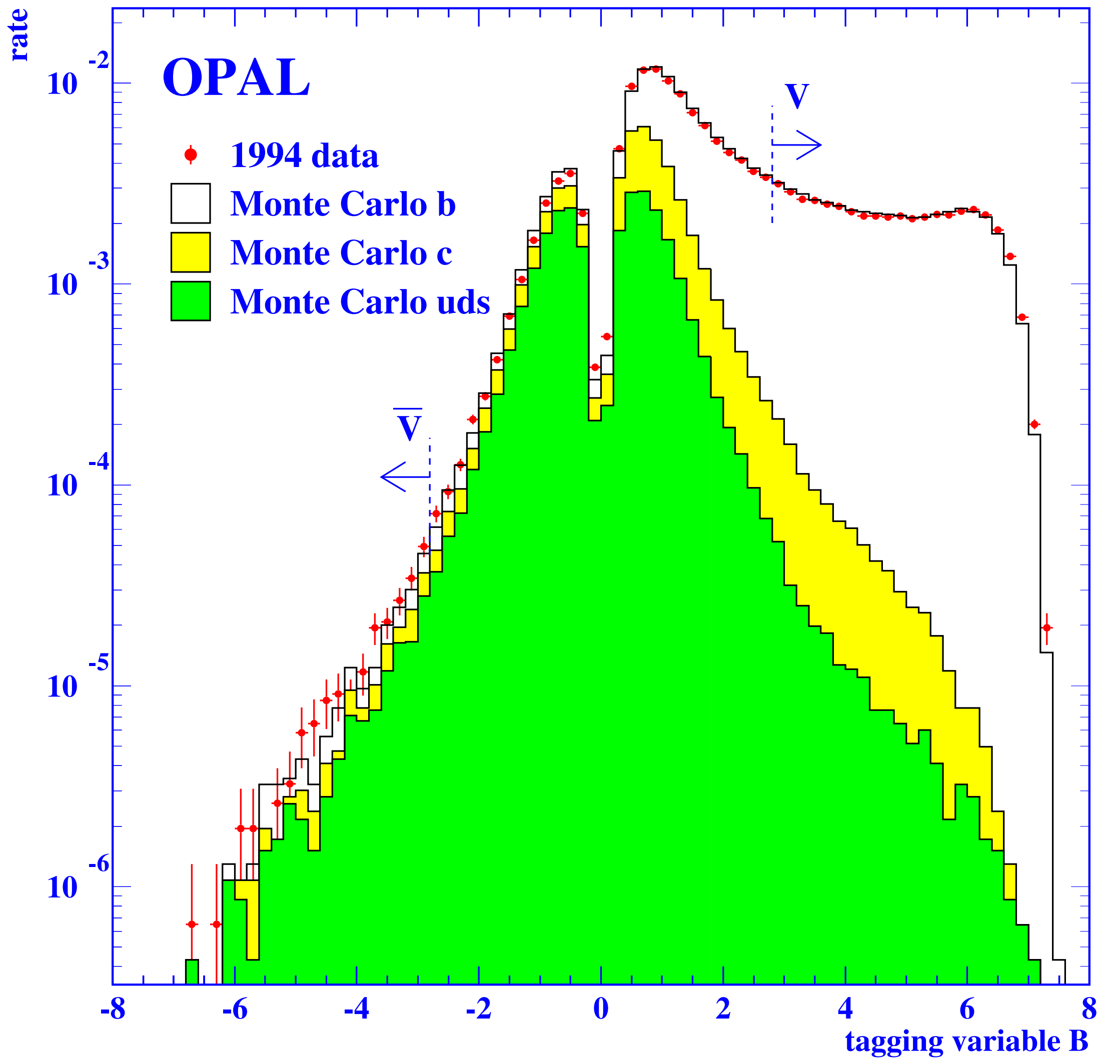
  NNET inputs:



(Small Data/MC discrepancies completely covered by systematic errors)

Vertex Tag Performance

NNET Tagging Variable B signed by decay length:



- **Folded Tag ($N(B > 2.8) - N(B < -2.8)$) is used**

  $\Rightarrow$ reduces tracking systematics

- At the chosen working point, $\epsilon^{\mathrm{b}} \sim 21\%$, Purity $\sim 98\%$

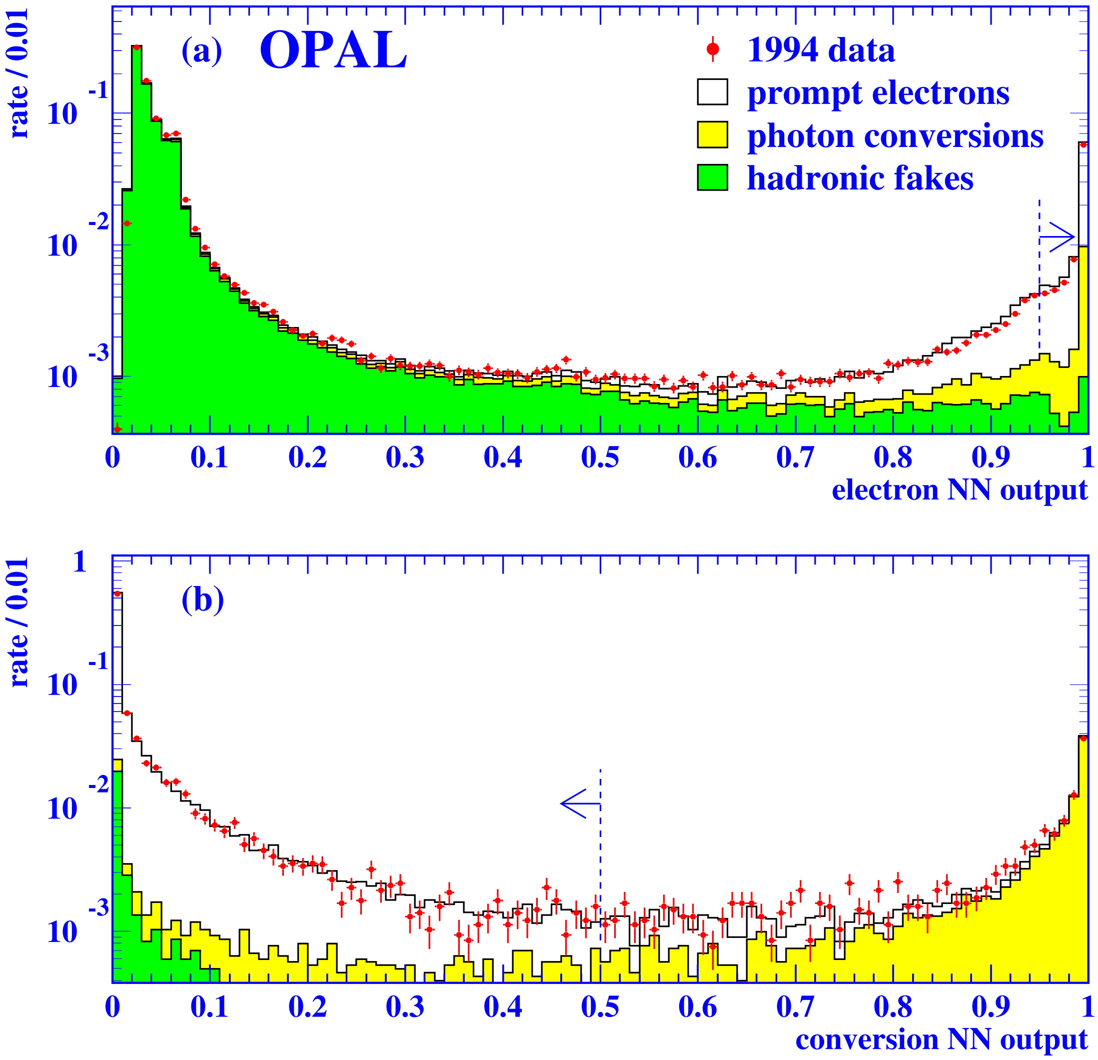
$[|B| = -\ln(1 - \mathrm{NNetB})]$

Lepton Tag

Standard Lepton ID

Electrons:

NNETs based on p, $\mathrm{d}E/\mathrm{d}x$, ECAL response, and isolation



- 26185 tagged electrons, $\sim$ 1900 of which are background

Muons:

Track Matching to Muon Detector Segments and $\mathrm{d}E/\mathrm{d}x$

- 21558 tagged muons, $\sim$ 3300 of which are background

At the chosen working point, $\epsilon^{\mathrm{b}} \sim 5\%$, Purity $\sim 93\%$

Results

Separate R_b measurement for each year:

	Vertex	Lepton	Combined
1992	0.2169 ± 0.0033	0.2156 ± 0.0174	0.2164 ± 0.0027
1993	0.2182 ± 0.0030	0.2495 ± 0.0199	0.2182 ± 0.0025
1994	0.2176 ± 0.0021	0.2113 ± 0.0110	0.2194 ± 0.0018
1995	0.2120 ± 0.0027	0.2171 ± 0.0160	0.2157 ± 0.0023
Combined	0.2163 ± 0.0013	0.2184 ± 0.0074	0.2178 ± 0.0011

Dependence on R_c :

$$\frac{\Delta R_\mathrm{b}}{R_\mathrm{b}} = -0.056 \frac{\Delta R_\mathrm{c}}{R_\mathrm{c}^\mathrm{SM}}$$

Sensitivity to Systematic Errors:

$$\frac{\Delta R_\mathrm{b}}{R_\mathrm{b}} = -0.059 \frac{\Delta \epsilon^\mathrm{c}}{\epsilon^\mathrm{c}} - 0.010 \frac{\Delta \epsilon^\mathrm{uds}}{\epsilon^\mathrm{uds}} + \frac{\Delta C^\mathrm{b}}{C^\mathrm{b}}$$

★ OPAL Result:

$$R_b = 0.2178 \pm 0.0011(\mathrm{stat}) \pm 0.0013(\mathrm{syst})$$

Systematic Errors

Source	$\Delta\epsilon^{c}/\epsilon^{c}$ (%)	$\Delta\epsilon^{uds}/\epsilon^{uds}$ (%)	ΔR_{b}
Tracking resolution	1.24	4.0	0.00017
Tracking efficiency	0.80	4.0	0.00014
Silicon hit matching efficiency	0.82	2.8	0.00009
Silicon alignment	0.58	2.1	0.00008
Electron identification efficiency	1.11	0.5	0.00015
Muon identification efficiency	0.64	0.2	0.00009
c quark fragmentation	2.26	-	0.00028
c hadron production fractions	3.66	-	0.00046
c hadron lifetimes	0.55	-	0.00007
c charged decay multiplicity	1.09	-	0.00014
c neutral decay multiplicity	2.39	-	0.00030
Branching fraction $B(\mathrm{D} \to \mathrm{K}^{0})$	1.20	-	0.00015
c semileptonic branching fraction	2.44	-	0.00031
c semileptonic decay modelling	2.34	-	0.00029
Gluon splitting to $\mathrm{c\bar{c}}$	0.34	6.3	0.00018
Gluon splitting to $\mathrm{b\bar{b}}$	0.50	9.3	0.00027
K^{0} and hyperon production	-	0.3	0.00001
Monte Carlo statistics (c, uds)	0.66	2.5	0.00010
Subtotal $\Delta\epsilon^{c}$ and $\Delta\epsilon^{uds}$	6.65	13.3	0.00090
Electron identification background			0.00039
Muon identification background			0.00041
Efficiency correlation ΔC^{b}			0.00066
Event selection bias			0.00033
Total			0.00129

- Physics Systematics limited by Tag Performance
- Lepton ID Systematics limited by Detector Modelling
- Correlation Systematics limited by Physics Understanding

Hemisphere Correlations

Potentially Large Source of Error: $\frac{\Delta R_{\rm b}}{R_{\rm b}} = \frac{\Delta C^{\rm b}}{C^{\rm b}}$

Three sources of efficiency correlations:

- Correlations from Primary Vertex Position

  MC studies

- Geometrical correlations from Detector Acceptance

  Measured from Data

- “Kinematic” correlations between hemispheres from QCD

  MC studies, cross check with Data

★ Total Correlation, taken from MC, is $1 + (0.93 \pm 0.17)\%$
calculated with 7×10^6 Fully Simulated $\mathrm{b\overline{b}}$ events

First two sources not controversial:

- $C^{\rm b}_{\rm pri-vtx} - 1 \leq 0.02\%$ estimated from MC
- $C^{\rm b}_{\rm geom} - 1 = 0.71 \pm 0.03\%$ measured in Data
  - separate measurements for each year, from

$$C^{\rm b}_{\rm geom} = \frac{\langle \epsilon^{\rm b}(\cos\theta_{\rm B}, \phi_{\rm B})\epsilon^{\rm b}(\cos\theta_{\bar{\rm B}}, \phi_{\bar{\rm B}})\rangle}{\langle \epsilon^{\rm b}(\cos\theta_{\rm B}, \phi_{\rm B})\rangle\langle \epsilon^{\rm b}(\cos\theta_{\bar{\rm B}}, \phi_{\bar{\rm B}})\rangle}$$

Kinematic Correlations I

Since p_{B} and $p_{\bar{\mathrm{B}}}$ are correlated, $\epsilon^{\mathrm{b}}(p_{\mathrm{B}})$ should be correlated with $\epsilon^{\mathrm{b}}(p_{\bar{\mathrm{B}}})$

Start with theory – The predicted correlation between p_{B} and $p_{\bar{\mathrm{B}}}$ is

$$C_{p_{\mathrm{B}}} = \frac{\langle p_{\mathrm{B}}\, p_{\bar{\mathrm{B}}}\rangle}{\langle p_{\mathrm{B}}\rangle\langle p_{\bar{\mathrm{B}}}\rangle} = 1 + (0.80 \pm 0.01)\%$$

from JETSET, agrees with calculations by Nason & Oleari (PLB 407 ('97) 57)

IF the *only* C^{b} was from same hemisphere effects, we would measure

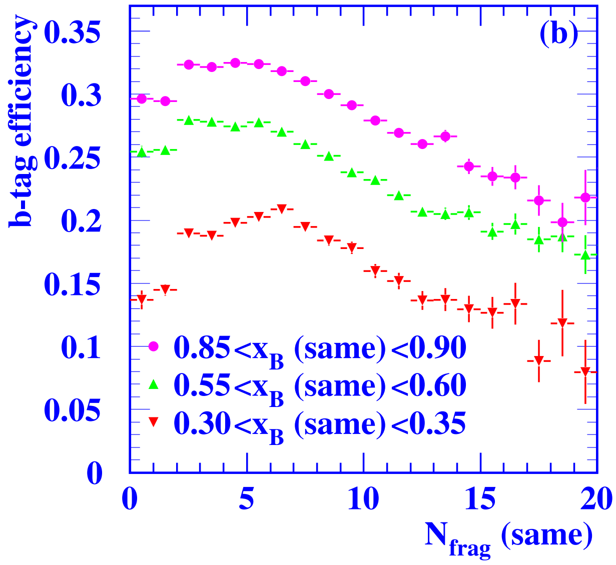
$$C_p^{\mathrm{b}} = \frac{\langle \epsilon^{\mathrm{b}}(p_{\mathrm{B}})\, \epsilon^{\mathrm{b}}(p_{\bar{\mathrm{B}}})\rangle}{\langle \epsilon^{\mathrm{b}}(p_{\mathrm{B}})\rangle\langle \epsilon^{\mathrm{b}}(p_{\bar{\mathrm{B}}})\rangle} = 1 + (0.55 \pm 0.03)\% \Rightarrow \text{too big}$$

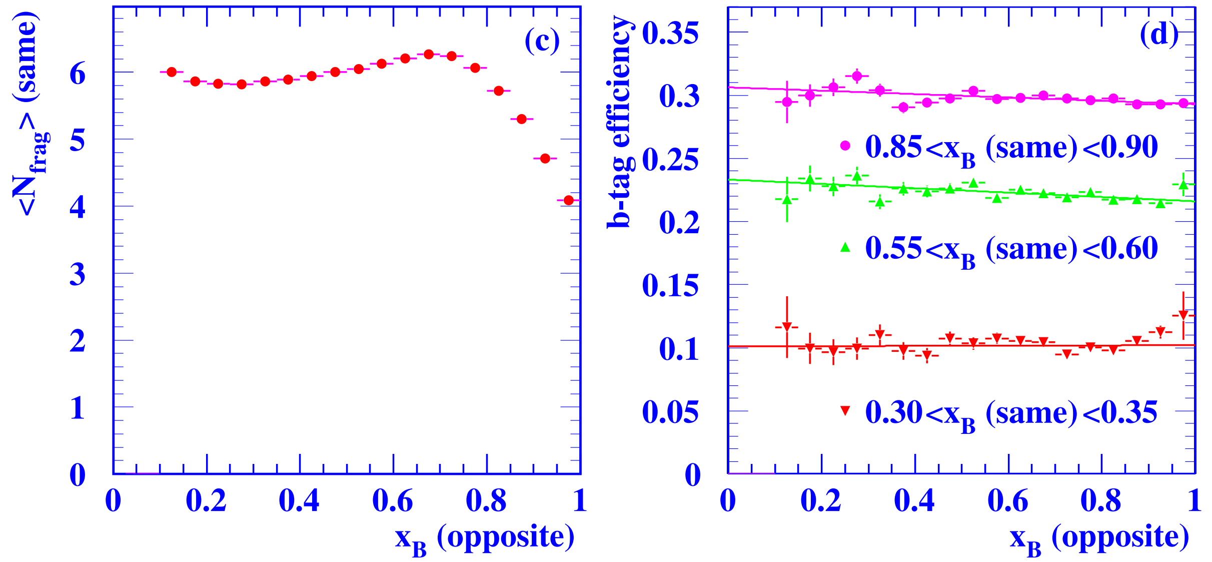
Cross-Hemisphere Correlations

Eg., Number of fragmentation tracks (N_{frag}) influences tag efficiency

Correlated across hemispheres by (E, p) Conservation

ϵ^{b} is really $\epsilon^{\mathrm{b}}(p_{\mathrm{B}}, p_{\bar{\mathrm{B}}})$





Kinematic Correlations II

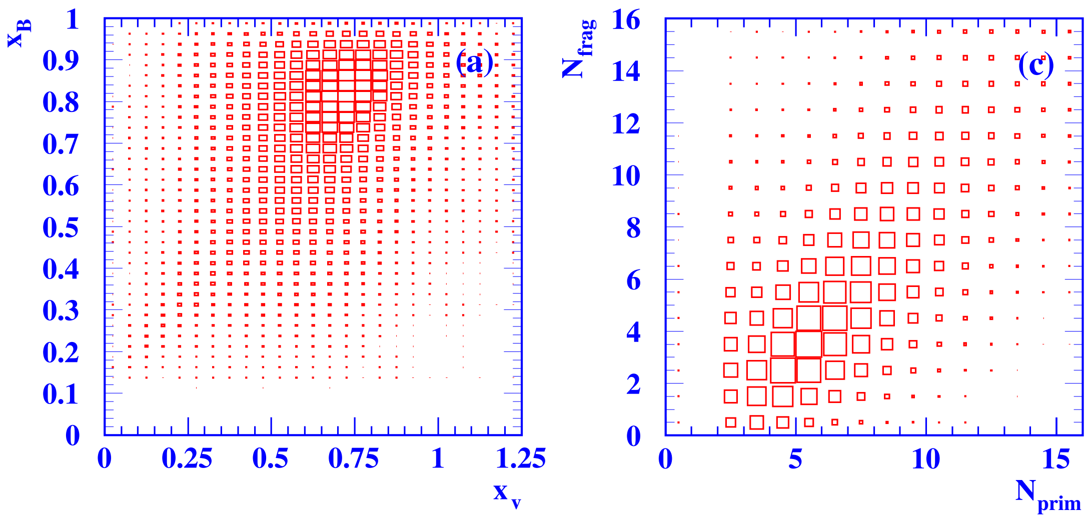
So, the full correlation is actually given by

$$C^{\mathrm{b}}_{p,\bar{p}} = \frac{\langle \epsilon^{\mathrm{b}}(p_{\mathrm{B}}, p_{\bar{\mathrm{B}}})\epsilon^{\mathrm{b}}(p_{\bar{\mathrm{B}}}, p_{\mathrm{B}})\rangle}{\langle \epsilon^{\mathrm{b}}(p_{\mathrm{B}}, p_{\bar{\mathrm{B}}})\rangle\langle \epsilon^{\mathrm{b}}(p_{\bar{\mathrm{B}}}, p_{\mathrm{B}})\rangle} = 1 + (0.06 \pm 0.03)\%$$

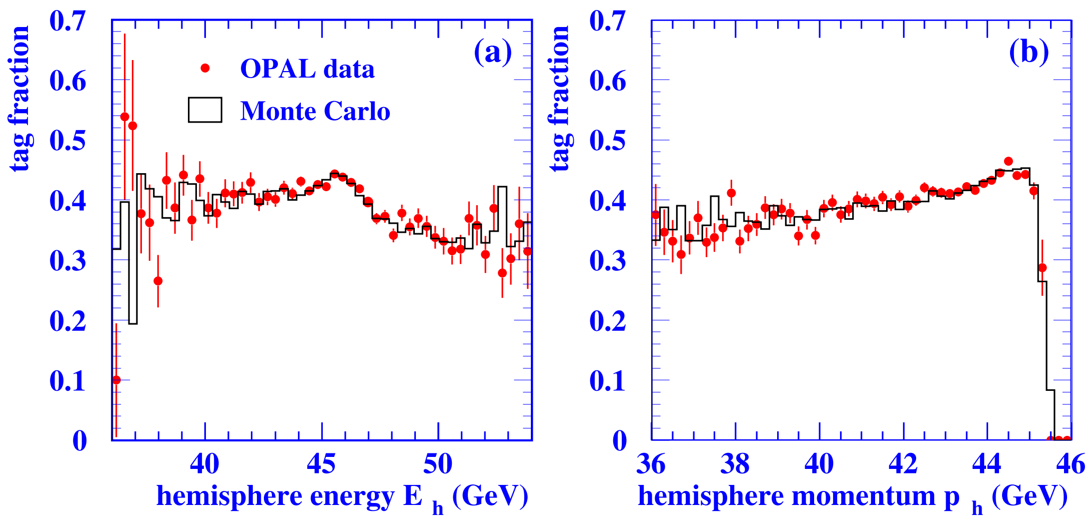
$\Rightarrow$ Total Correlation reduced by Cross-Correlations

Verification of Correlation Effects with Data Estimators:

Vertex Momentum (x_{v}) and Number of tracks from primary vertex (N_{prim})



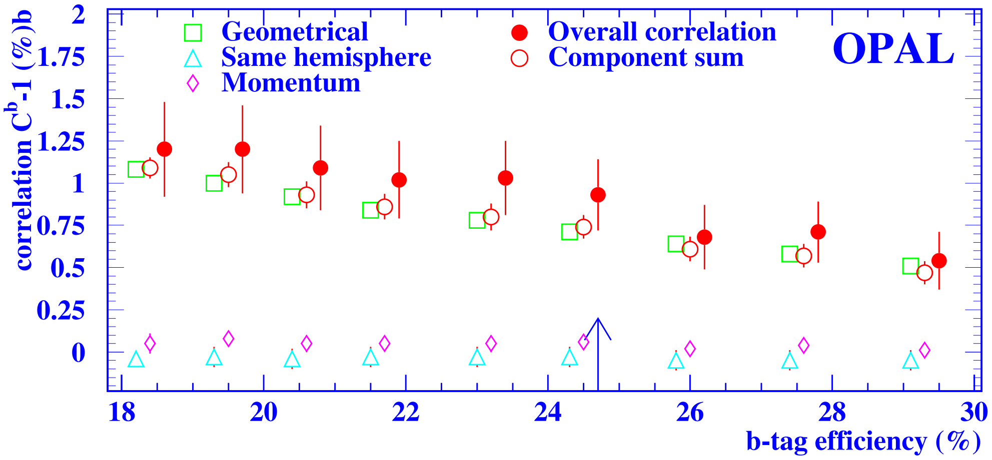
Measured Hemisphere Energy (E_{h}) and Momentum (p_{h})



- *Size* of correlations reproduced in Data and MC
- *Sensitivity* of estimators verified by reweighting MC Correlations
- Systematic Error from MC reweighting $\oplus$ stat. error

Conclusions

Correlations Well-Understood:



OPAL's Final Word on R_b from LEP1...