Investigation on the b-quark mass

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Review of

#1_223, DELPHI: "Three- and four-jet heavy b-quark production rates in e^+e^- annihilation at the Z peak"

#1_384, ALEPH: "Investigations on the b-quark mass from hadronic Z decays"

Introduction

❶ Why measure the b-quark mass?

- One of the fundamental parameters of the QCD Lagrangian

❷ Quark mass definition is not unique

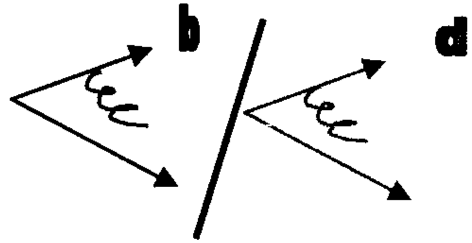
- Pole mass scheme $\mathbf{M_b}$
- Running mass scheme ($\overline{MS}$) $\mathbf{m_b}$

$$M_b^2 = m_b^2(\mu)\left[1+\frac{\alpha_s(\mu)}{2\pi}\left(\frac{16}{3}-4\log\frac{M_Z^2}{\mu^2}\right)\right]+O(\alpha_s^2)$$

❸ Mass effects at the Z

- **$m^2_b/(y_{cut}\ m^2_Z)$ ~ few % for jet quantities**
- b-mass extracted from the ratio $R_{b/l}(X)$ of any infrared-safe observable X computed for b quarks and light quarks (l) *assuming α_s universality*

$R_{b/l}$ (X)=



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Introduction (cont'd)

Experimental method

- Select $e^+e^- \to q\bar{q}$ events
- Tag events of different flavours
- Measure $R_{b/l}$ (X)
- Correct for hadronization, detector, flavour and tag bias
- Extract m_b from

$$R_{b/l}(X) = 1 + \frac{m_b^2}{M_Z^2}\left[b_0(X, m_b) + \frac{\alpha_s(\mu)}{2\pi} b_1(X, m_b) \right]$$

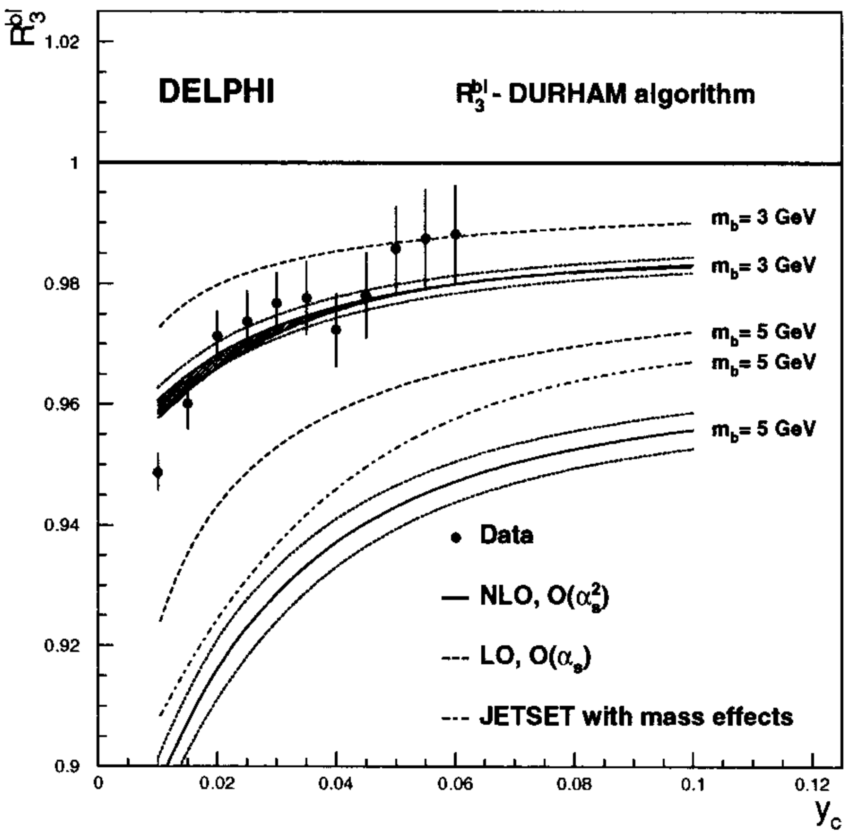
[redacted]

[redacted]

Introduction (cont'd)

- **First NLO calculations from Rodrigo *et al.* in 1997 for the 3 jet rate, later Nason & Oleari, Brandenburg *et al.***
- **Firstly measured by DELPHI in 1997**
  - Use 3 jet rate ratio and 1992→1994 data
- **Also measured by SLD**
  - **in agreement with DELPHI**
  - **but found a large jet algorithm dependence**

3 Jet Rate Ratio vs y_{cut}



ALEPH Analysis

- Use 1.1 M hadronic Z decays in 1994 (+3.3 Million MC)
- Jet reconstruction with Durham E-scheme
- Variables studied:
  - **Three jet rate @ y_{cut}=0.02**
  - **First 2 moments of:**
    - **Thrust**
    - **C Parameter**
    - **y_3 distribution (Durham)**
    - **Total Jet Broadening (B_{tot})**
    - **Wide Jet Broadening (B_w)**

For m_b extraction use:

Rodrigo *et al*

PROGRAMS

ZBB4 for b

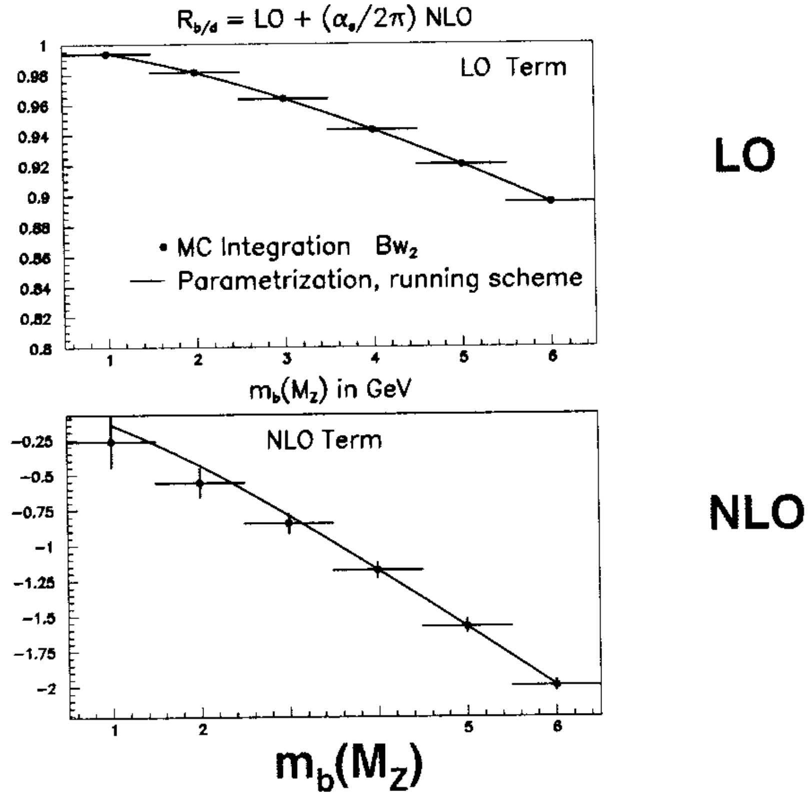
EVENT for uds

ALEPH Analysis (cont'd)

- **Using ZBB4 and EVENT MC to extract LO+NLO predictions:**

$$\frac{1}{\sigma}\frac{d\sigma_{b,l}}{dX} = \alpha_s A_{b,l}(X) + \alpha_s^2 B_{b,l}(X)$$

$$R_{b/l} = \frac{A_b}{A_l} + \alpha_s \frac{B_b A_l - B_l A_b}{A_l^2}$$



$$\text{LO,NLO} = c_1 + c_2 \frac{m_b^2}{M_Z^2} + c_3 \log\frac{m_b^2}{M_Z^2}$$

ALEPH Analysis (cont'd)

- **Perturbative predictions: $1-R_{b/l}$ (%)**

Hadr. corr larger than mass effect and/or big NLO (T_1 … B_{W1})

Correlated variables (Y_{31} … $R_{2jet}(0.02)$)

Variable	Had $_{b/l}$	LO run	NLO run	LO pole	NLO pole
T_1	1.142	3.6	1.9	7.6	-0.7
T_2	1.139	1.7	[redacted]	4.3	3.6
C_1	1.175	4.4	2.2	9.1	-1.1
C_2	1.181	2.1	[redacted]	5.2	4.3
B_{T1}	[redacted]	11.7	0.6	18.8	-7.4
B_{T2}	[redacted]	3.6	[redacted]	8.0	[redacted]
B_{W1}	1.142	11.7	-8.5	18.8	-18.3
Y_{31}	1.029	3.2	0.7	7.1	-2.1
Y_{32}	0.990	1.5	0.3	3.2	-0.7
$R_{2jet}(0.02)$	0.989	2.0	0.5	5.6	-0.4
B_{W2}	1.093	3.6	1.6	8.0	-1.3

ALEPH (cont'd)

- *b-tag* : Lifetime+Mass Tag
- *l-tag* :Discriminant variable based on 5 variables per hemisphere:
  - Lifetime
  - $2p/\sqrt{s}$ of fastest particle
  - Visible energy
  - p_T π-soft
  - p_T(lepton) if any
- Chose cuts such that TAG corrections be small

  $P_{bb}, \varepsilon_b \approx$ 83%,87%

  $P_{ll}, \varepsilon_l \approx$ 83%,97%

ALEPH Analysis (cont'd)

- **Experimental systematics**
  - Tags varied by 2 x effect:
    changes in purities by ≈ 5%
  - Vary $g \to bb$, $g \to cc$ rates
    $\Delta\, m_b(R_{3jet}) \approx 400$ MeV
    $\Delta\, m_b(Bw2) \approx 170$ MeV

- **Hadronization systematics**
  - JETSET Q_0 up to 4 GeV (retuned)
  - HERWIG -JETSET difference
  - JETSET massive matrix elements matching
    $\Delta\, m_b(R_{3jet}) \approx 700$ MeV
    $\Delta\, m_b(Bw2) \approx 100$ MeV

ALEPH Analysis (cont'd)

- **Theoretical systematic errors on $m_b(M_Z)$**
  - Scale variation: $0.1 < \mu/m_Z < 2$
    - $\Delta m_b(R_{3jet})$= 200 MeV
    - $\Delta m_b(Bw2)$= 118 MeV
  - $\Delta \alpha_s$=0.004
    - Δm_b =20 MeV
  - Evaluate pole mass,translate to $m_b(m_b)$ and then up to $m_b(M_Z)$

M_b(pole mass)

↓ $O(\alpha_s)$

$m_b(m_b)$

↓ running

$\tilde{m}_b(M_Z)$

$\Delta m_b(R_{3jet})$= -372 MeV
$\Delta m_b(Bw2)$= -57 MeV

ALEPH Analysis (cont'd)

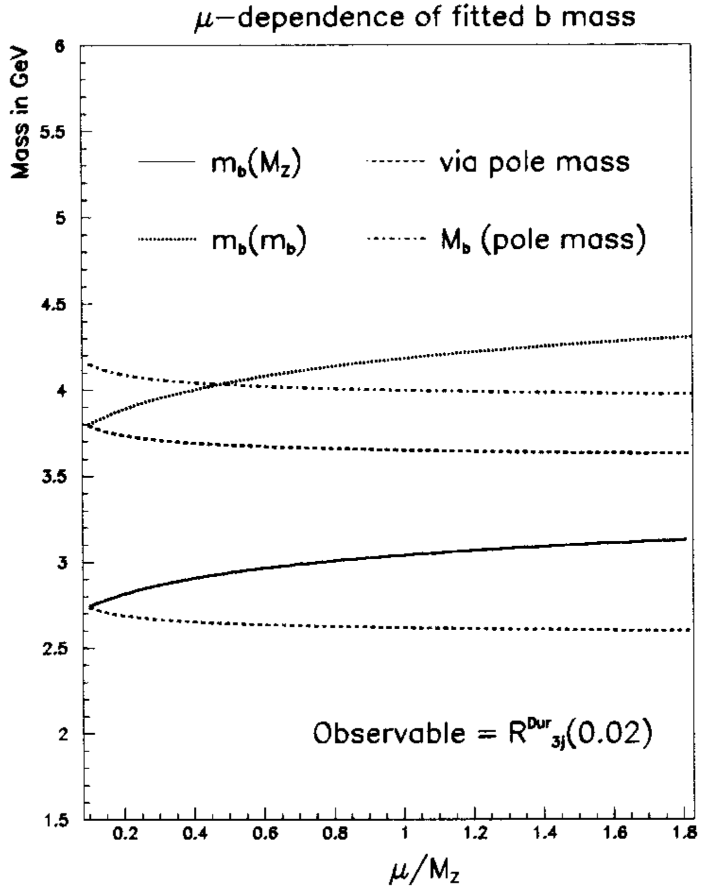
R$_{3jet}$

$$m_b(M_Z) = 3.04^{+0.37}_{-0.34}(stat)$$
$$^{+0.44}_{-0.39}(syst)$$
$$^{+0.72}_{-0.59}(had)$$
$$^{+0.20}_{-0.42}(theo)$$
$$= 3.04 \pm 0.92 \text{ GeV}$$

Bw2

$$m_b(M_Z) = 3.78 \pm 0.14(stat)$$
$$\pm 0.17(syst)$$
$$\pm 0.10(had)$$
$$^{+0.12}_{-0.13}(theo)$$
$$= 3.78 \pm 0.27 \text{ GeV}$$

3 Jet Mass vs μ/M_Z



ALEPH Analysis (cont'd)

Variable	$R_{b/l}$ (part)	$m_b(M_Z)$ (GeV)
T_1	0.904±0.003	4.48±0.09
T_2	0.901±0.006	4.84±0.20
C_1	0.890±0.002	4.41±0.06
C_2	0.887±0.004	4.69±0.12
[redacted]	[redacted]	[redacted]
Y_{32}	0.981±0.015	$3.51^{+1.50}_{-0.95}$
B_{T1}	0.832±0.001	3.94±0.03
B_{T2}	0.825±0.003	3.57±0.06
B_{W1}	0.903±0.002	4.74±0.05
B_{W2}	0.928±0.004	3.78±0.14
$R_{3jet}(0.02)$	0.969±0.007	$3.04^{+0.37}_{-0.34}$

Large scatter in b-quark mass already seen by SLD from different jet algorithms

uncontrolled biases from hadronization and/or NNLO?

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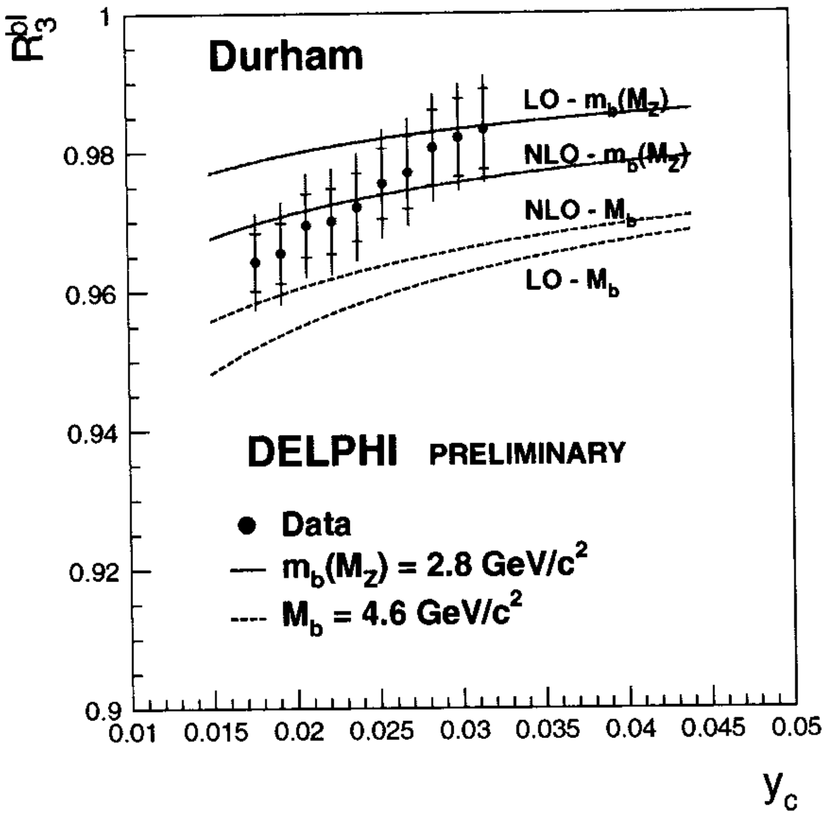
DELPHI Analyses

- **Two new analyses on 3 jet rate on 94+95 data**
  - Two jet algorithms: Durham and <u>Cambridge</u> (smaller NLO corrections and more stable against y_{cut})
  - Use <u>improved</u> tag (vertex + shape) and compare with old to establish tag systematic

$P_{bb,}\varepsilon_b \approx$ 86%,53% $P_{ll,}\varepsilon_l \approx$80%,60%

3 Jet Rate Ratio vs y_{cut}

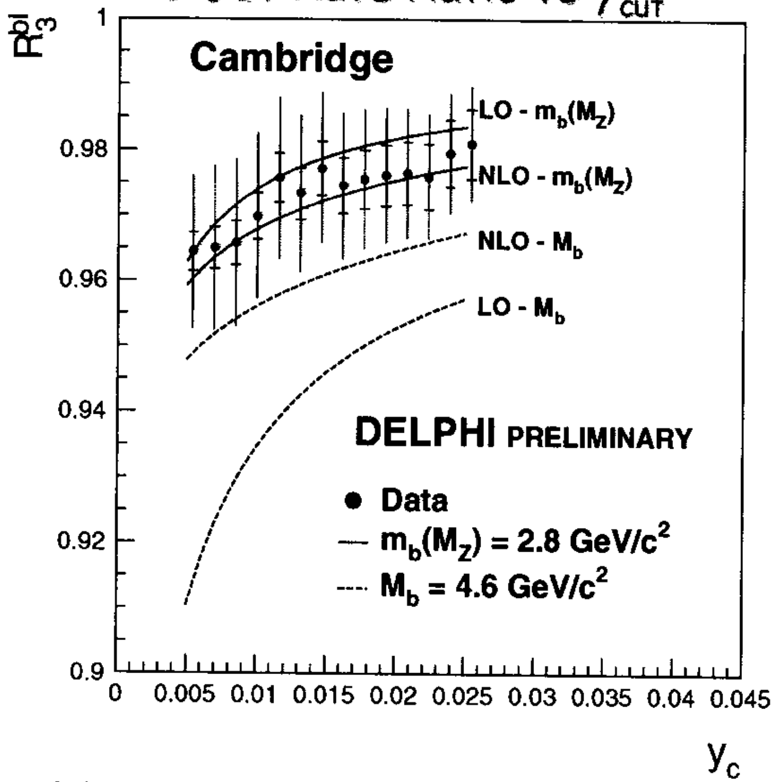


Consistent results with old measurement

DELPHI Analyses (cont'd)

- **Experimental systematics**
  - Compare 2 Tags
  - Vary purities by 1%
- **Hadronization systematics**
  - JETSET $\Delta Q_0 = 0.2$ GeV + other parameters by 2σ
  - HERWIG - JETSET
- **Theoretical error**
  - Scale: $0.1 < \mu/m_z < 1$
  - $\frac{1}{2}(m_b - \tilde{m}_b)$

3 Jet Rate Ratio vs y_{cut}



$$m_b(M_Z) \equiv \frac{1}{2}(m_b + \tilde{m}_b) = 2.61 \pm 0.18(stat)^{+0.45}_{-0.49}(had) \pm 0.04(syst) \pm 0.07(theo)$$

$$= 2.61 \pm 0.52\ \text{GeV}$$

Comparison

Errors on $m_b(M_Z)$ (GeV)

	$m_b(m_Z)$	Stat*	Syst♠	Had	Scale	Scheme	
Aleph 3jet Durham (0.02)	**3.04**	+0.30 -0.28	+0.49 -0.44	+0.72 -0.59	0.20	-0.37	**0.92**
[illegible]							
Aleph Bw2	**3.78**	0.12	0.19	0.10	0.12	-0.06	**0.27**
[illegible]							

* Statistical errors are only from Data

♠Systematic error includes limited MC statistics

Summary and conclusions

- ALEPH: a large set of observables used to extract the running b-quark mass
  - Very nice agreement with DELPHI using the 3-jet rate
  - Wide spread in the found b-quark masses might indicate uncontrolled biases from hadronization and/or NNLO
- DELPHI: Cambridge jet algorithm
  - Very good agreement with NLO calculations of the running b-quark mass
  - Very nice theoretical errors but still suffers from hadronization systematics