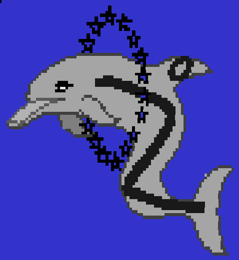
Measurement of b-quark mass effects for multi-jet events at LEP



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Introduction (I)

- **Over recent years mass effects in multi-jet event topologies were observed and confirmed at LEP and SLC by various experiments (ALEPH, DELPHI, OPAL, SLD).**

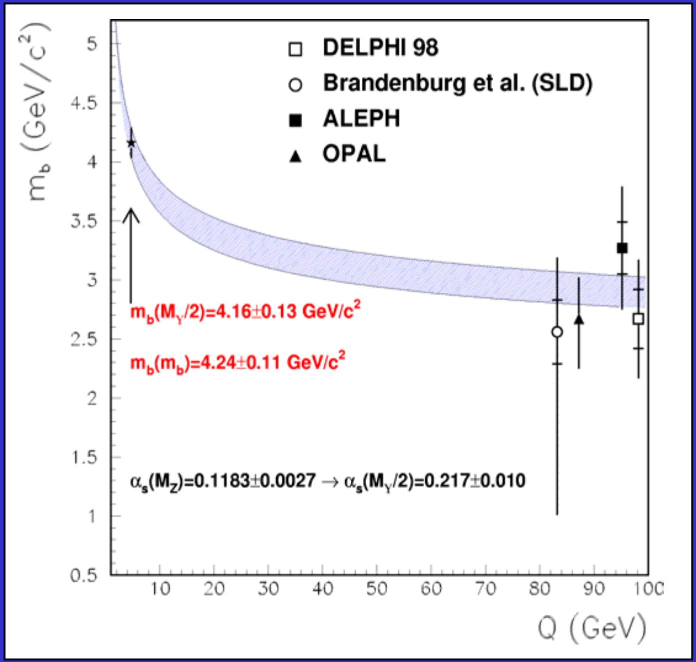
- **The availability of new massive NLO calculations for three-jet event observables (G. Rodrigo et al., W. Bernreuther et al., P. Nason et al.) and improved b-tagging techniques enabled the understanding of these effects in terms of QCD and allowed for:**

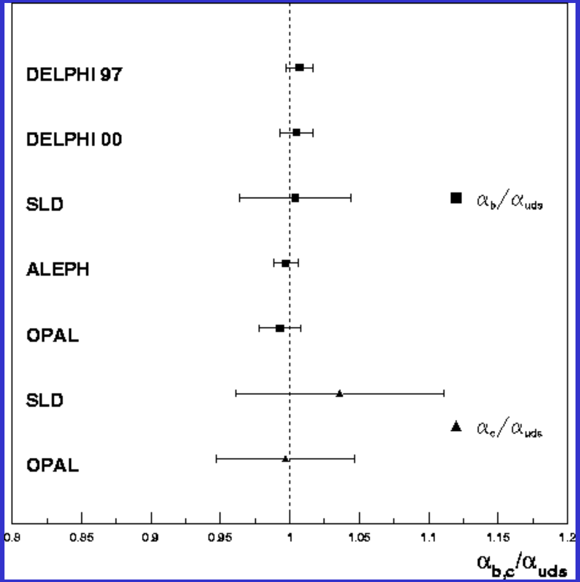
  - **Determinations of the *b*-quark mass at M_Z (~17% precision)**
  - **Flavour independence tests of α_S → $\alpha_S^b / \alpha_S^\ell$ (~1%precision)**
  - **More precise determination of α_S (2%-3% impact for some observables)**

Some Previous Experimental Results

$m_b(M_Z)$ →

LEP:	DELPHI (1998)	$\sigma \sim 0.5$ GeV/c²
	ALEPH (2000)	$\sigma \sim 0.5$ GeV/c²
	OPAL (2001)	$\sigma \sim 0.4$ GeV/c²
SLC:	Bradenburg et al. SLD (1999)	$\sigma \sim 1$ GeV/c²





← Flavour Independence of α_S

LEP:	DELPHI (1998)	$\sigma \sim 1\%$
	ALEPH (2000)	$\sigma \sim 1\%$
	OPAL (1999)	$\sigma \sim 1\%$
SLC:	SLD (1999)	$\sigma \sim 5\%$

Introduction (II)

Relevant results achieved ..but.., still some interesting questions remained to be answered !!

- **Can precision be improved ?**
  - **Use of new observables**
  - **Better understand of fragmentation**
  - **Tagging for *b*- and *l*-quarks**
  - **Gluon splitting**
- **Role of the quark masses parameter in the QCD generators**
- **Can these studies be extended to other multi-jet topologies ?**
- **Mass scheme dependence: pole mass (M_b) and running mass $m_b(M_Z)$ in $\overline{MS}$**
- **Could one single experiment cover more than one energy point for $m_b(\mu)$?**

Prior step of the analysis: The quark mass definition

- Quarks are not observed as free particles in nature.

Confined inside hadrons ⇒ NOT A TRIVIAL DEFINITION!

- Theoretical convention is needed to define quark masses (mandatory at NLO)
- The two most commonly used mass definitions are:

Pole mass: M_q Pole of the renormalized quark propagator

$$\frac{i}{\not{p}-m-i\Sigma(p,m)} \qquad p-m-i\Sigma(p,m)\Big|_{p^2=M_q^2}=0 \qquad \Sigma(p,m) = \text{quark self energy}$$

Gauge and scheme independent

Non-perturbative corrections give an ambiguity of order Λ_{QCD} *Infrared renormalon*

Running mass: $m_q(\mu)$ renormalized mass in the $\overline{\text{MS}}$ scheme.

Scheme and scale dependent.

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

Definition of the observable and theoretical calculations

Jet clustering algorithms:
DURHAM
CAMBRIDGE ...New...

$$R_3^{b\ell}(y_c) = \frac{\Gamma_{3j}^{Z^0\to b\bar{b}g}(y_c)/\Gamma_{tot}^{Z^0\to b\bar{b}}}{\Gamma_{3j}^{Z^0\to \ell\bar{\ell}g}(y_c)/\Gamma_{tot}^{Z^0\to \ell\bar{\ell}}}$$

Event flavour (b, $\ell = uds$) is defined by the quarks coupled to the Z^0

Cancel hadronization and detector corrections

Cancel EW corrections

LO, NLO and NLL calculations for $R_{3,4}^{b\ell}$ with massive and massless quarks

G.Rodrigo et al., Phys.Lett.B79 (1997) 193
M. Bilenky et al.,Phys.Rev.D60 (1999) 114006
Z. Nagy, Z, Trocsanyi, Phys.Rev.D59 (1999) 014020
F. Krauss, G. Rodrigo CERN-TH-2003-42

- In terms of the pole mass: $R_{3,4}^{b\ell}(M_b)$
- In terms of the running mass: $R_{3,4}^{b\ell}(m_b(\mu))$

- Test prediction: Th-Exp
- Extract M_b and $m_b(M_Z)$
- Extract α_s^b/α_s^ℓ

Experimental Process (Delphi)

Raw Data

Hadron Selection

Hadronic Sample: $Z^0 \rightarrow q\bar{q}$

Tagging

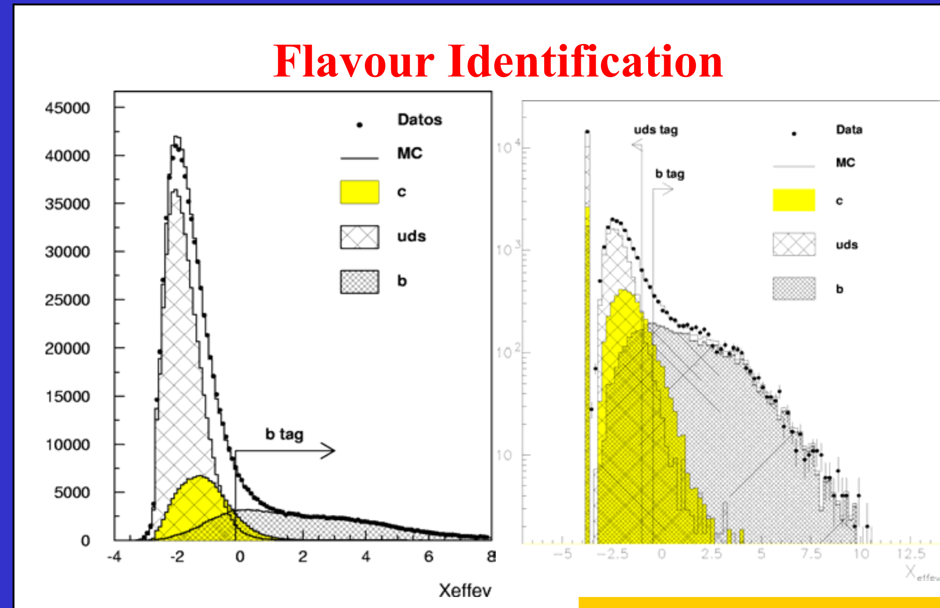
b-Sample | ***ℓ-Sample***

Jet reconstruction

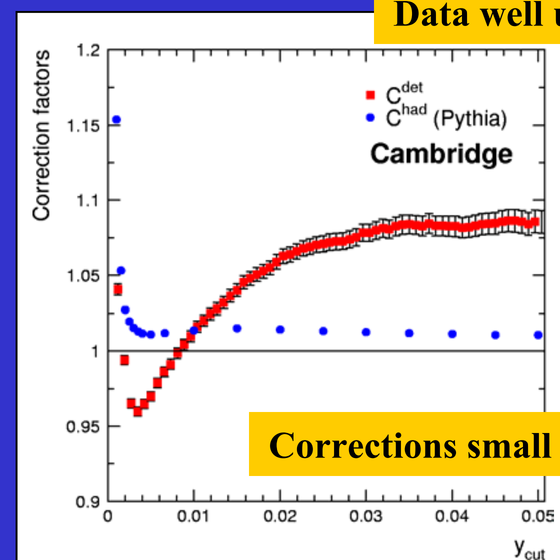
$R_n^{b\ell}$ (detector)

Detector and Fragmentation corrections

$R_n^{b\ell}$ (parton)

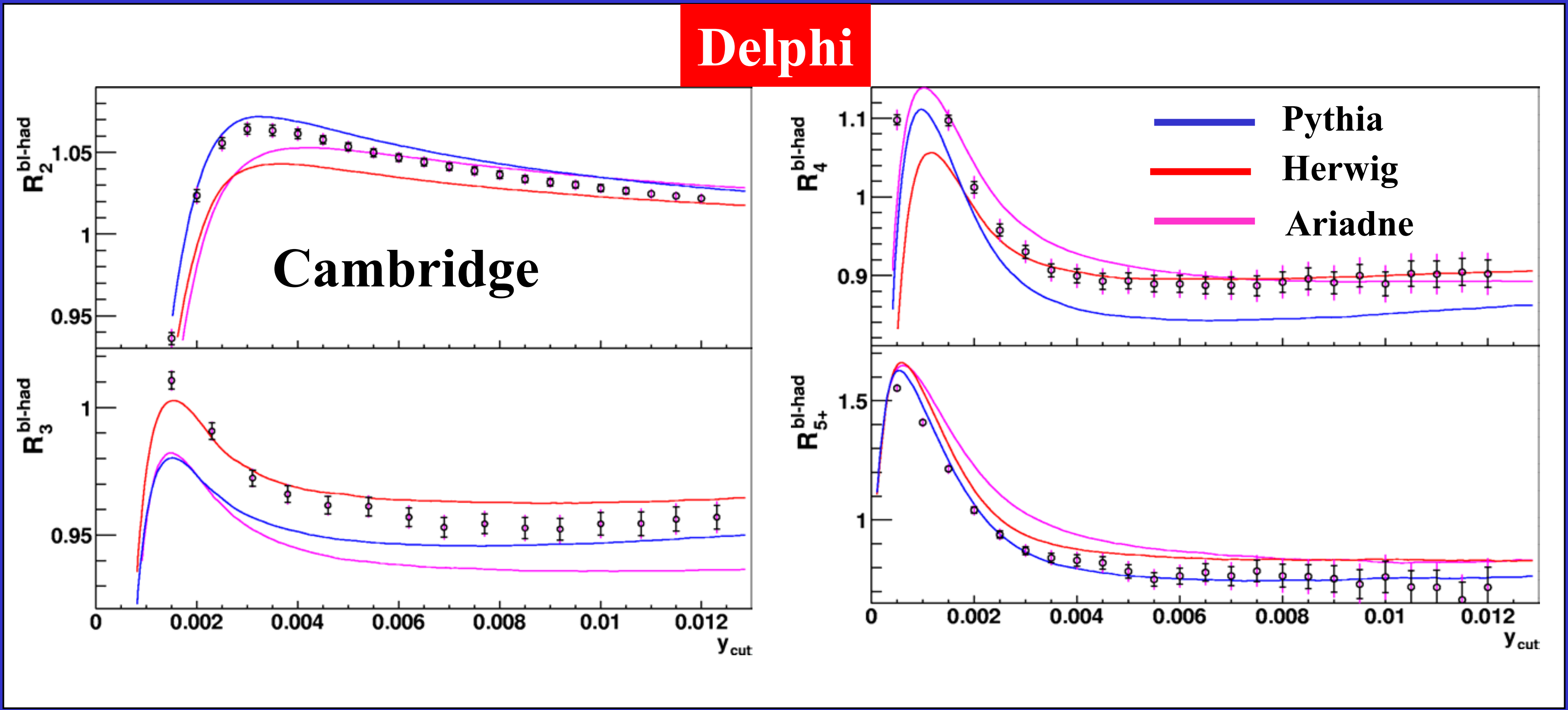


Data well understood



Corrections small and stable

$R_n^{b\ell}$ at Hadron Level: Data vs. Generators



No Generator describes particularly well data for all multijet topologies

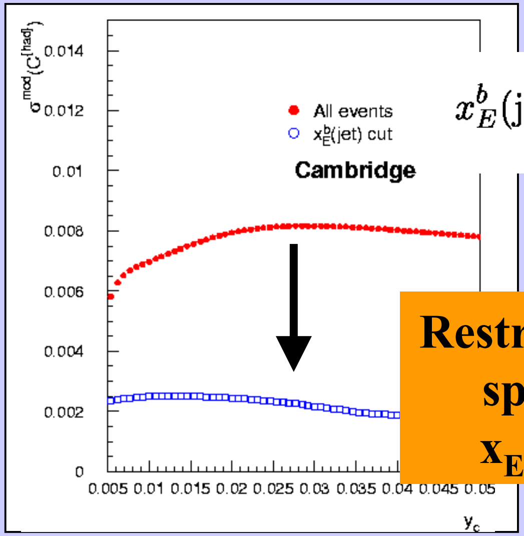
Hadron Correction (3-jets mainly)

- **Fragmentation Models Considered:**
  (Last versions with mass effects improved)
  - String+Peterson (Pythia)
  - String+Bowler (Pythia)
  - Cluster (Herwig)

Tuning

$$\sigma^{had}(y_c) = \sqrt{\sigma^{mod}(y_c)^2 + \sigma^{tun}(y_c)^2 + \sigma^{mass}(y_c)^2}$$

Fragmentation model



$$x_E^b(\text{jet}) = 2\,\frac{E_{b-\text{jet}}}{E_{CM}}$$

Restrict the phase space region $x_E{}^b(\text{jet})>0.55$

b **mass parameter uncertainty**

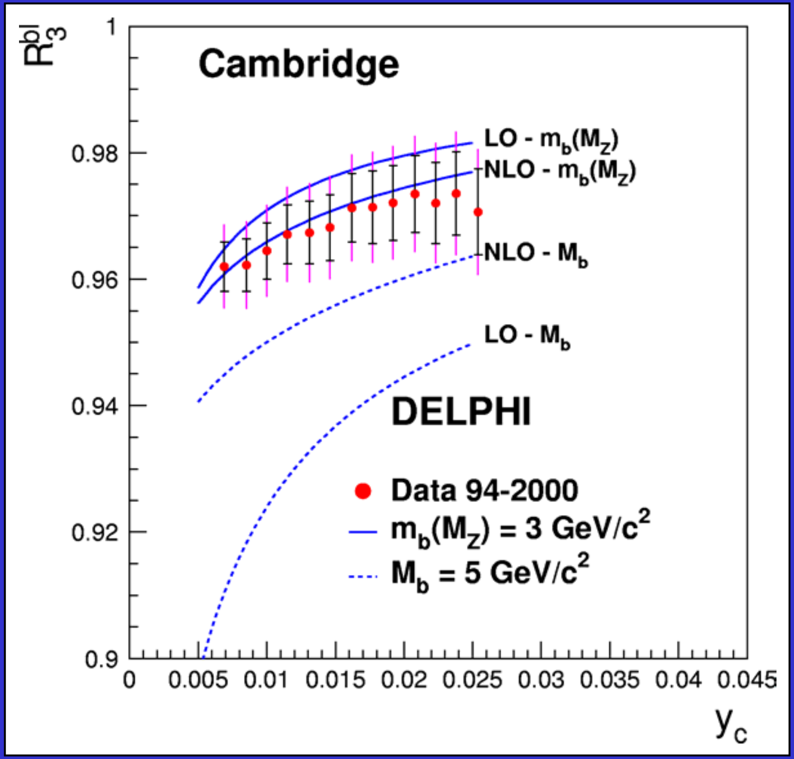
Which mass and which value of M_b should be used in the generator ?

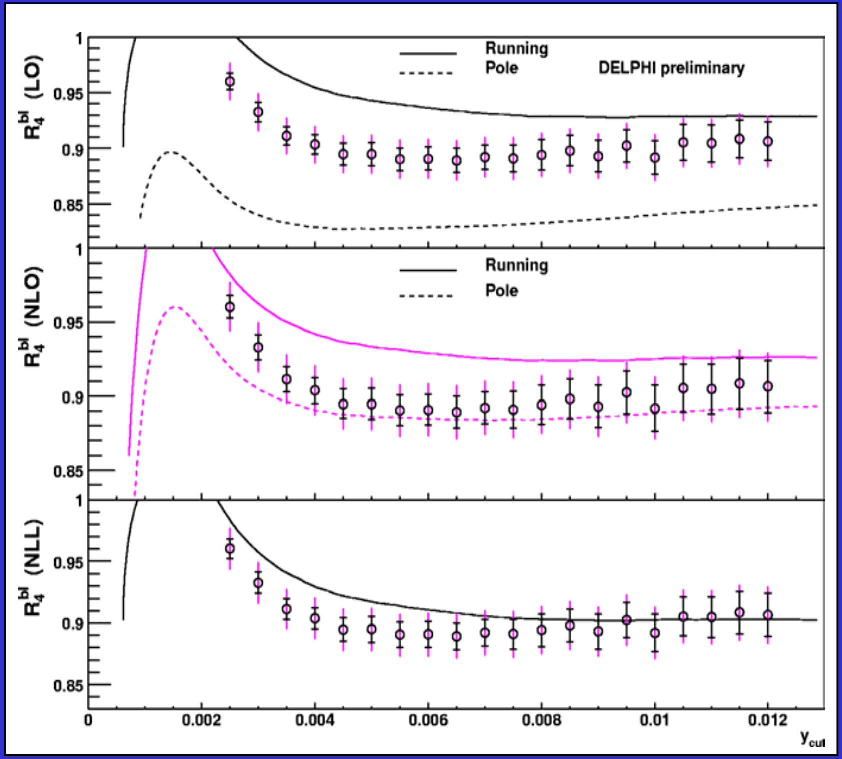
It should be the pole mass:

$$M_b = 4.98 \pm 0.13\ \text{GeV}/c^2$$

M. Eidemüller, Phys. Rev. D67 (2003) 113002

$R^{b\ell}_{3,4}$ corrected at parton level





3-jet analysis Calculations

LO: Leading Order massive

NLO: Next to Leading Order Massive

4-jet analysis Calculations

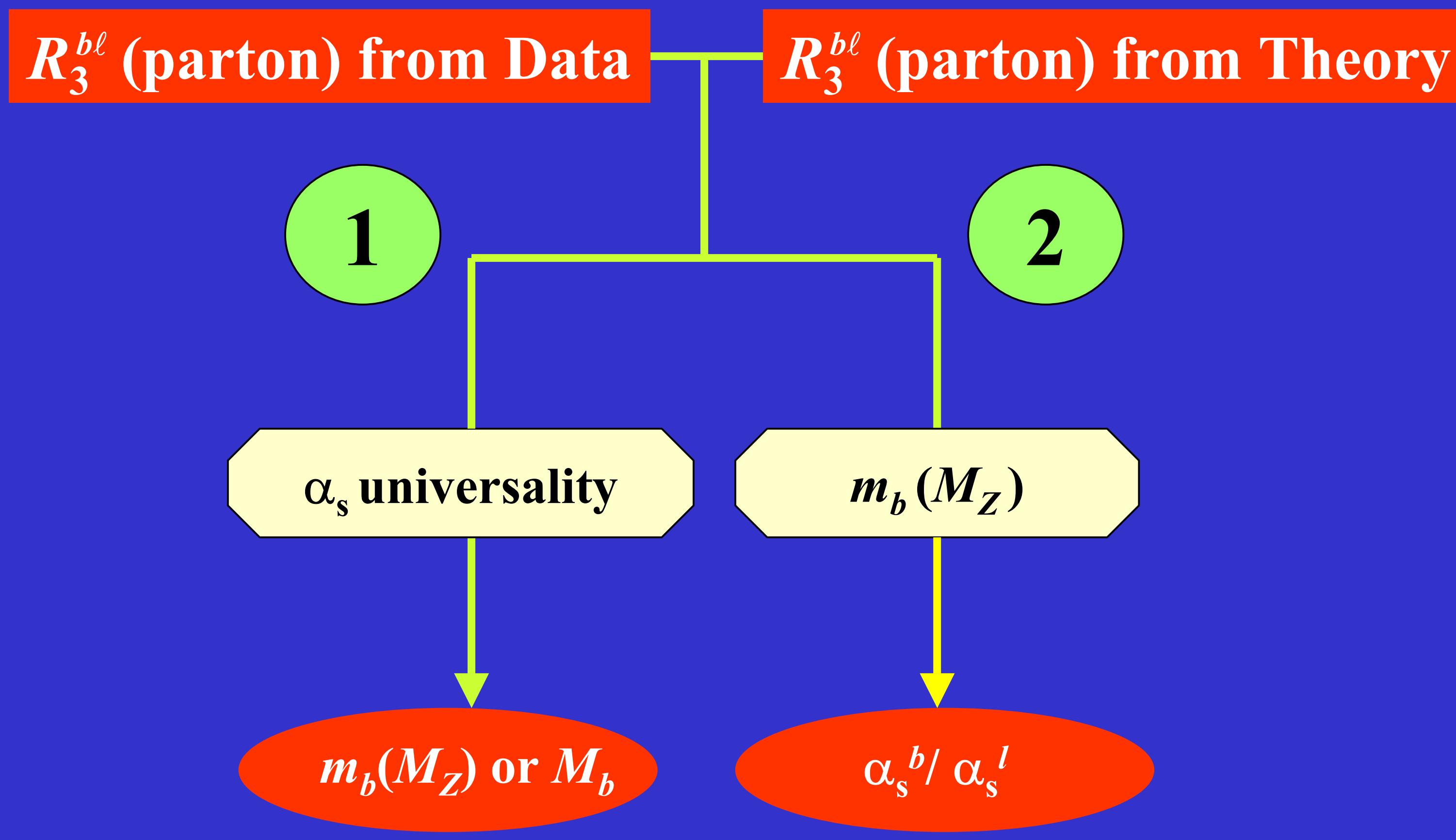
LO: Leading Order Massive

NLO: Leading Order Massive + Next to Leading Order massless

NLL: Next to Leading Log Masive approximation (on going..)

Extracting QCD parameters

- Only for $R_3^{b\ell}$ as NLO calculation exist.



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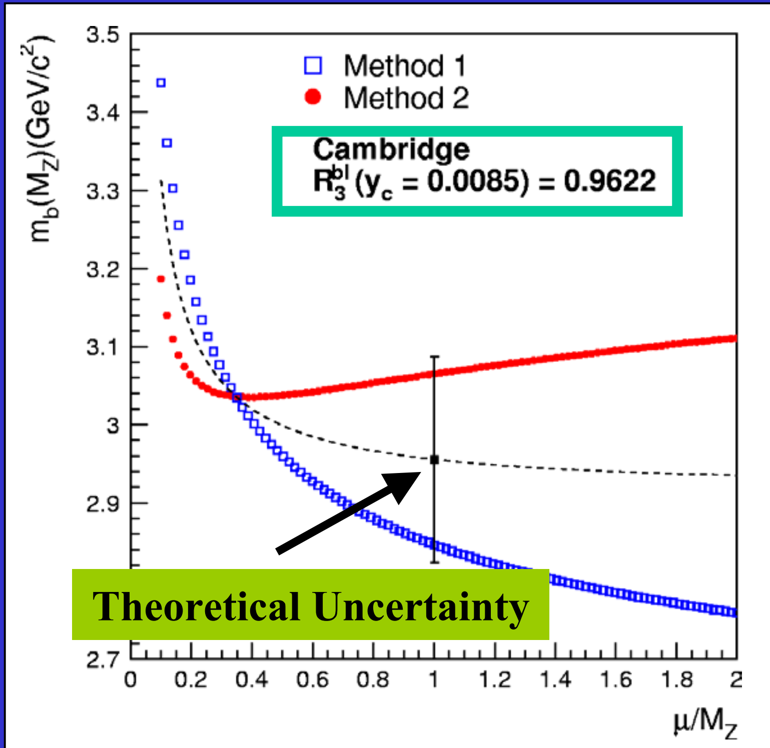
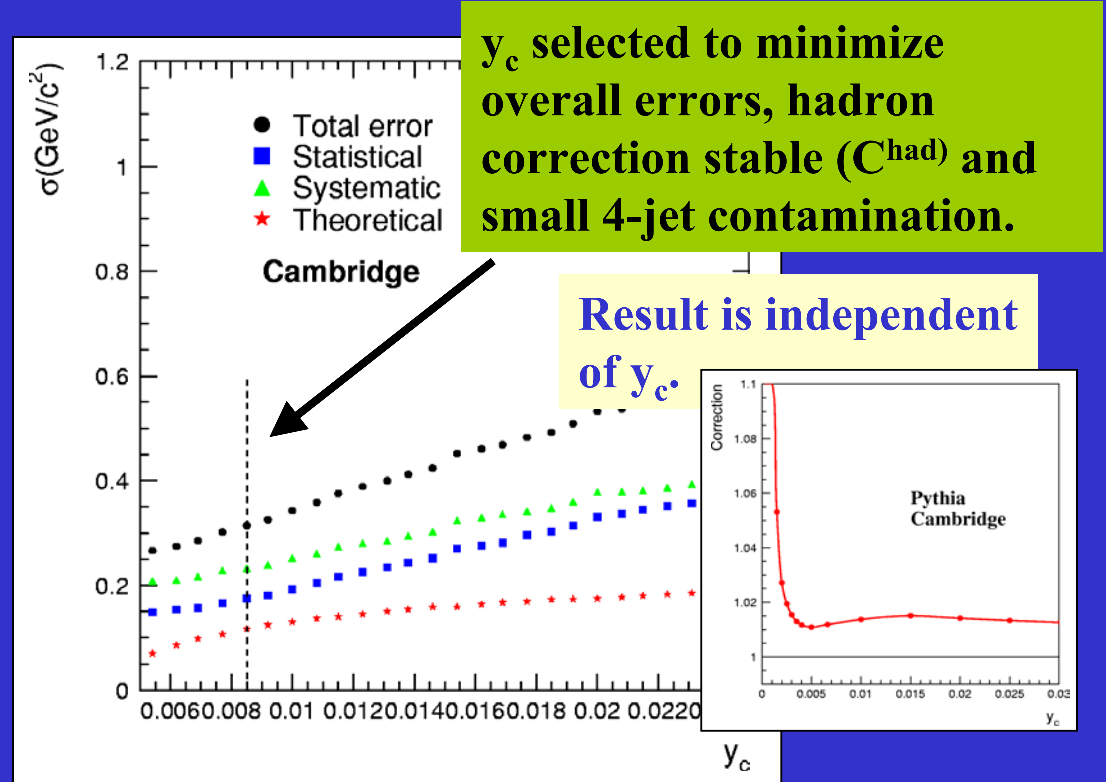
b-quark mass determination





Durham $m_b(M_Z) = 3.23^{+0.24}_{-0.25}\ (\text{stat})^{+0.19}_{-0.20}\ (\text{had})^{+0.22}_{-0.23}\ (\text{exp}) \pm 0.24\ (\text{theo})\ \text{GeV}/c^2$

Cambridge $m_b(M_Z) = 2.96^{+0.17}_{-0.18}\ (\text{stat}) \pm 0.19\ (\text{had}) \pm 0.14\ (\text{exp}) \pm 0.12\ (\text{theo})\ \text{GeV}/c^2$

Durham $M_b = 4.48^{+0.30}_{-0.32}\ (\text{stat})^{+0.36}_{-0.39}\ (\text{syst}) \pm 0.13\ (\text{theo})\ \text{GeV}/c^2$

Cambridge $M_b = 4.26^{+0.22}_{-0.23}\ (\text{stat})^{+0.30}_{-0.31}\ (\text{syst}) \pm 0.44\ (\text{theo})\ \text{GeV}/c^2$

2

Universality of α_s: α_s^b/α_s^l

$$\alpha_s^b/\alpha_s^\ell = R_3^{b\ell}(y_c) - H(m_b(M_Z), y_c) + \mathcal{O}(\alpha_s)$$

Experimental result (→ $R_3^{b\ell}(y_c)$)

From NLO calculation (→ $H(m_b(M_Z), y_c)$)

$$\bar{r}_b\left(b_0(\bar{r}_b, y_c) + \frac{\alpha_s(\mu)}{\pi}\bar{b}_1(\bar{r}_b, y_c, \mu)\right)$$

$$\bar{r}_b(\mu) = m_b^2(\mu)/M_Z^2$$

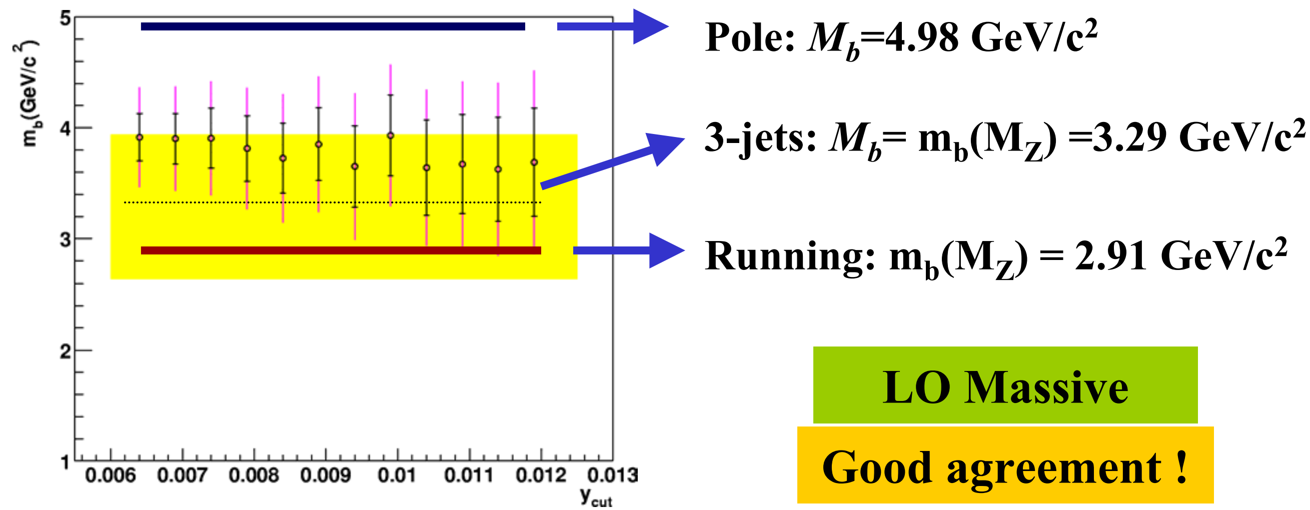
$m_b(m_b) = 4.24 \pm 0.11\ \mathrm{GeV}/c^2$

Durham $\alpha_s^b/\alpha_s^\ell = 0.989^{+0.006}_{-0.005}\ (\mathrm{stat}) \pm 0.007\ (\mathrm{syst}) \pm 0.005\ (\mathrm{theo})$

Cambridge $\alpha_s^b/\alpha_s^\ell = 0.996 \pm 0.004\ (\mathrm{stat}) \pm 0.006\ (\mathrm{syst}) \pm 0.003\ (\mathrm{theo})$

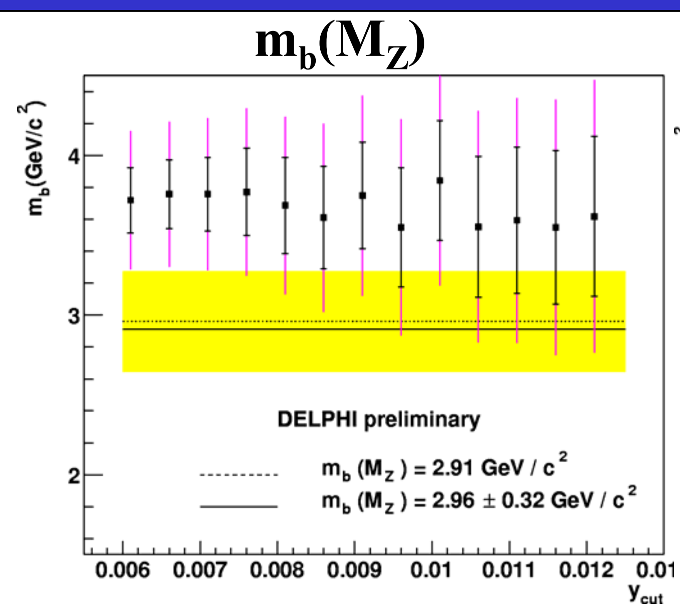
Consistency: $R_4^{b\ell}$ vs. $R_3^{b\ell}$

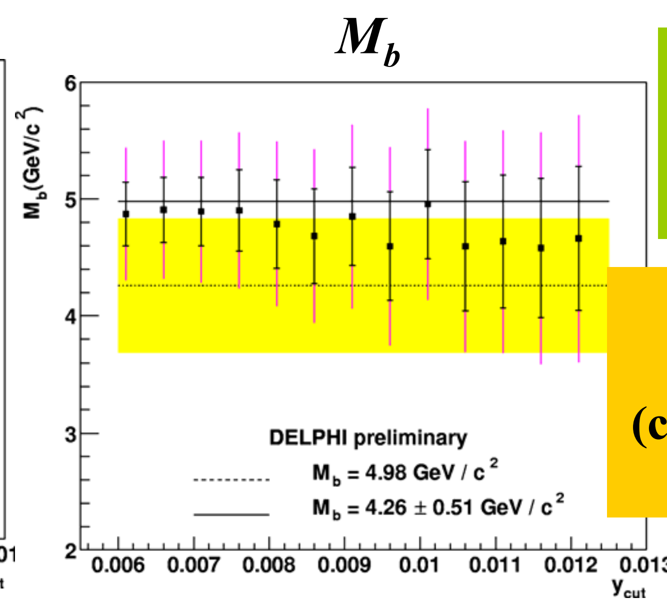
- Mass effects for $R_4^{b\ell}$ only at LO
- NLO approximation for $R_4^{b\ell}$: LO massive + NLO massless



LO Massive

Good agreement !





LO Massive + NLO Massless

Reasonable agreement ! (calculations are not comparable)

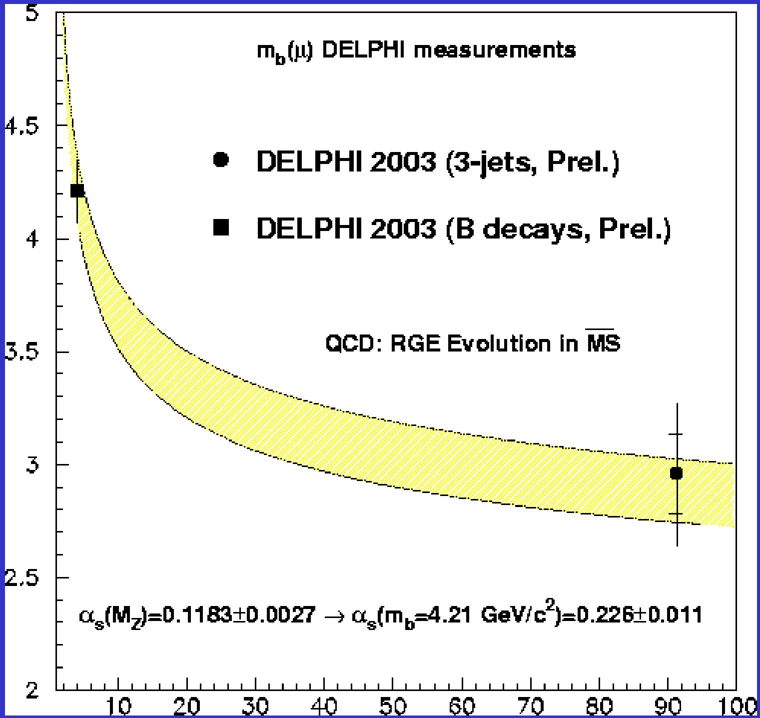
Comparison with DELPHI analysis at threshold

Measurement of moments of inclusive spectra in Semileptonic B-decays in DELPHI (EPS contribution):

$$m_b(m_b) = 4.21 \pm 0.14 \text{ GeV}/c^2$$

First time one single experiment measures $m_b(\mu)$ at two different energy regimes

To understand data as a whole and at the same time, the evolution of $m_b(\mu)$ needs to be as predicted by the RGE in the $\overline{\text{MS}}$-scheme



Summary

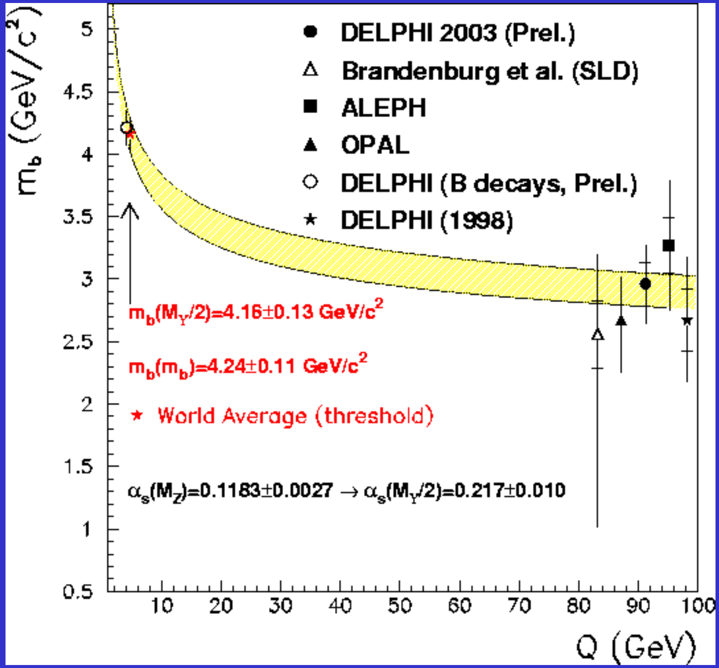
- A new analysis for $R_3^{b\ell}$ is being presented with considerably improved understanding of the systematic uncertainties of previous analyses.
- A consistent picture of $R_4^{b\ell}$ with respect to $R_3^{b\ell}$ is observed but the lack of appropriate theoretical calculations limits the results.

Running Mass: (Cambridge)

$$m_b(M_Z) = 2.96^{+0.31}_{-0.32}\ \mathrm{GeV}/c^2$$

Pole Mass: (Durham)

$$M_b = 4.48^{+0.49}_{-0.52}\ \mathrm{GeV}/c^2$$



- For the first time one single experiment can measure $m_b(\mu)$ at two different energy scales