# STUDY OF HARD GLUON RADIATION IN B FINAL STATES AND A DETERMINATION OF $m_b$ AT $M_Z$

J. Fuster

DELPHI collaborators: P. Bambade, M.J. Costa, P. Tortosa.

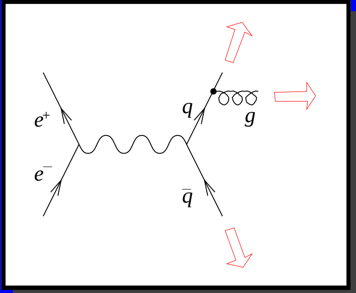
Special thanks to: G. Dissertori, G. Rodrigo, A. Santamaría

ISMD02
J. Fuster
IFIC, Univ. València–CSIC
Alushta, 11 Sept. 2002

# Contents

- Old DELPHI results
  - $R_3^{b\ell}$ using DURHAM
  - $m_b$, $M_b \leftrightarrow$ flavour independence of $\alpha_s$
- Other experimental results
  - SLD, Brandenburg et al.
  - OPAL
  - ALEPH
- The new analyses of $R_3^{b\ell}$ and $R_4^{b\ell}$ show a better understanding of:
  - Jet reconstruction algorithm: CAMJET
  - $x_E^b(jet)$ distribution, Pythia (Peterson, Bowler), Herwig
  - Mass parameters in the generators: $M_b^{const} \leftrightarrow M_b$
  - $b$- and $\ell$-tagging
  - $g \to b\bar{b}$ and $g \to c\bar{c}$
- Results

# Observables sensitive to mass effects




- Due to the mass effect, massive quarks radiate less gluons than light quarks.
- For inclusive observables, at LEP/SLC energies, the $b$-quark mass effect can be neglected, as it goes like $m_b^2/M_Z^2 \leq 0.3\%$.
- BUT, for more exclusive observables, like jet rates:
  - jet resolution parameter, $y_c << 1$.
  - new scale, $E_c = M_Z\sqrt{y_c}$.
  - $(m_b^2/M_Z^2)/y_c$ terms give sizeable effects.


G.Rodrigo et al. Phys. Rev. Lett. 79 (1997) 189

W. Bernreuther et al. Phys. Rev. Lett. 79 (1997) 193

P. Nason, C. Oleari, Phys. Lett. B407 (1997) 57

M. S. Bilenky et al. Phys Rev D60 (1999) 114006


- Calculations inculding mass effects at NLO have been performed for the $b/\ell$ ratios.

$$R^{b\ell}(O) = \frac{O_b}{O_\ell} = \quad 1 + r_b\left(b_I(O,r_b) + \frac{\alpha_s}{\pi} b_{II}(O,r_b)\right) + \mathcal{O}(\alpha_s^2)$$

where $r_b = (\frac{m_b}{M_Z})^2$ and $O$ = Event shapes, $R_3$ (infrared safe).

- $\alpha_s$ universality $\Leftrightarrow m_b$.

# DELPHI Old Result

The observable was originally calculated at NLO as:

$$R_3^{b\ell}(y_c) = \frac{R_3^b}{R_3^\ell} = \frac{\Gamma_{3j}^{Z^0\to b\bar{b}g}(y_c)/\Gamma_{tot}^{Z^0\to b\bar{b}}}{\Gamma_{3j}^{Z^0\to \ell\bar{\ell}g}(y_c)/\Gamma_{tot}^{Z^0\to \ell\bar{\ell}}} = 1 + r_b\left(b_I(R_3^{b\ell}, r_b) + \frac{\alpha_s}{\pi} b_{II}(R_3^{b\ell}, r_b)\right) + \mathcal{O}(\alpha_s^2)$$

with $r_b = (\frac{M_b}{M_Z})^2$ and $M_b$ the $b$ pole mass

- However two theoretical scenarios to describe $R_3^{b\ell}(y_c)$ based on the quark mass definition were studied: the b pole mass ($M_b$) and the b running mass ($m_b(\mu)$).
- Although at infinite orders both mass definitions should be equivalent for a fixed order calculation they lead to different predictions for $R_3^{b\ell}(y_c) \Leftrightarrow M_b$ and $m_b(M_Z)$.
- They can be related through

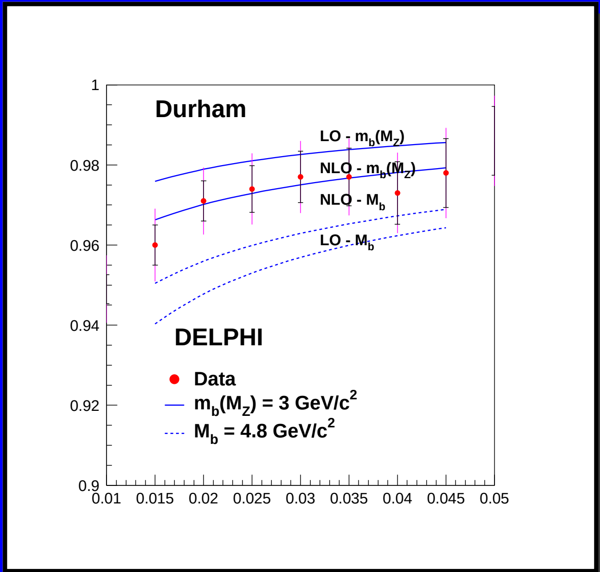
  1) At scale $\mu$ : $M_b^2 = m_b^2(\mu)\left[1 + \frac{2\alpha_s(\mu)}{\pi}\left(\frac{4}{3} - \log\frac{m_b^2(\mu)}{\mu^2}\right)\right] + \mathcal{O}(\alpha_s^2)$

  2) At scale $M_b$ : $m_b(M_Z) \Leftrightarrow m_b(M_b)$ (RGE) $\Leftrightarrow \frac{M_b}{m_b(M_b)} = 1 + \frac{4}{3}\frac{\alpha_s(M_b)}{\pi} + \mathcal{O}(\alpha_s^2)$

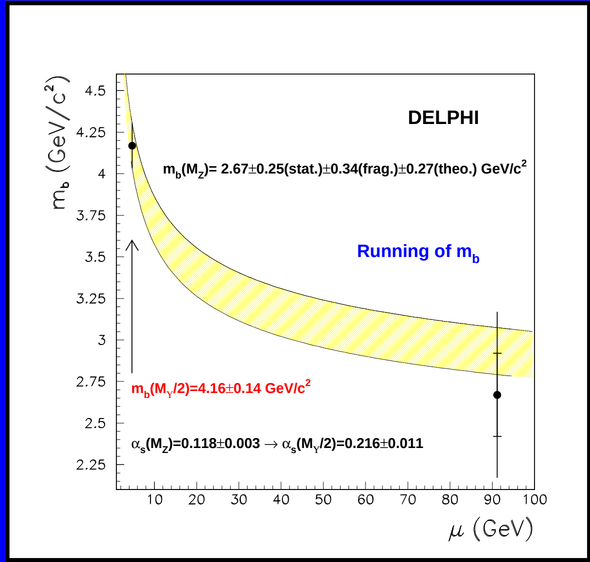
  Differences in the result due to the use of either 1) or 2) might be considered as an estimation of the contribution of the higher order terms.

# DELPHI Old Result

$R_3^{b\ell}$




$m_b(\mu)$




Experimental result: $R_3^{b\ell}(0.02) = 0.971 \pm 0.004\ \text{(stat.)} \pm 0.007\ \text{(frag.)} \pm 0.003\ \text{(simu.)}$

In terms of $m_b$ $\Rightarrow$ $m_b(M_Z) = 2.67 \pm 0.25\ \text{(stat.)} \pm 0.34\ \text{(frag.)} \pm 0.27\ \text{(theo.)}$

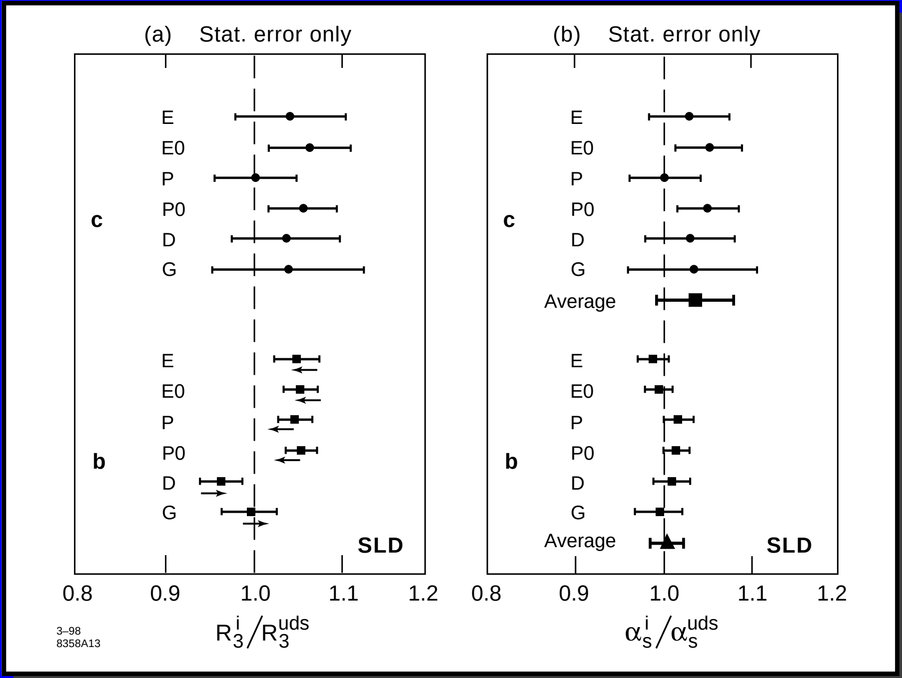
Change of $m_b(\mu)$ $\Rightarrow$ $m_b(M_Z) - m_b(M_\Upsilon/2) = -1.49 \pm 0.52\ \text{GeV}$

or, $\alpha_s^b/\alpha_s^{uds}$ $\Rightarrow$ $\alpha_s^b/\alpha_s^{uds} = 1.007 \pm 0.005\ \text{(stat.)} \pm 0.007\ \text{(frag.)} \pm 0.005\ \text{(theo.)}$

# SLD, Brandenbrurg et al. results

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

- $R_3^q$ is the fraction of $q$-events classified as 3 or more jets.
- Jet cluster algorithms used: E, E0, P, P0, Durham (D) and Geneva (G).
- Jade family algorithms: $R_3^{bl} > 1$
- Durham and Geneva: $R_3^{bl} < 1$
- NLO massive calculations used: W. Bernreuther, A. Brandenburg, P. Uwer, only running mass scheme is considered.

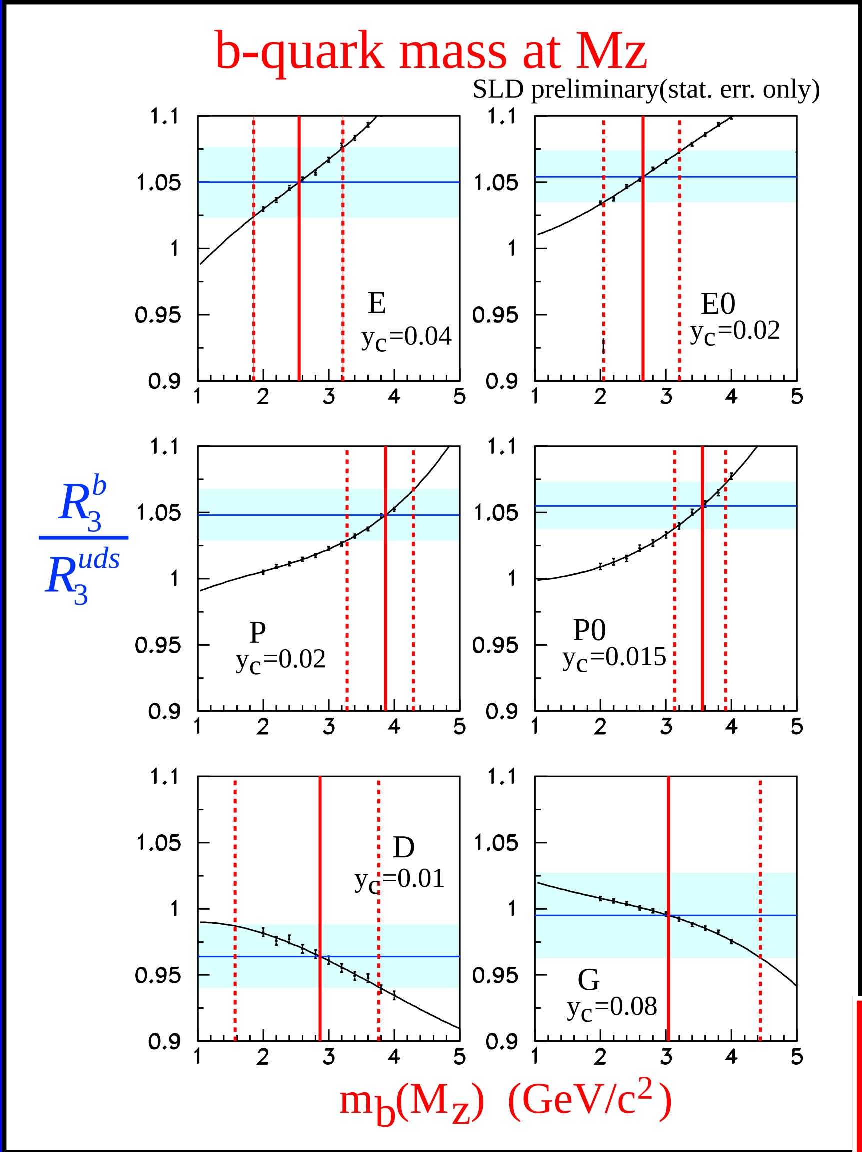



$\alpha_s^c/\alpha_s^{uds} =$

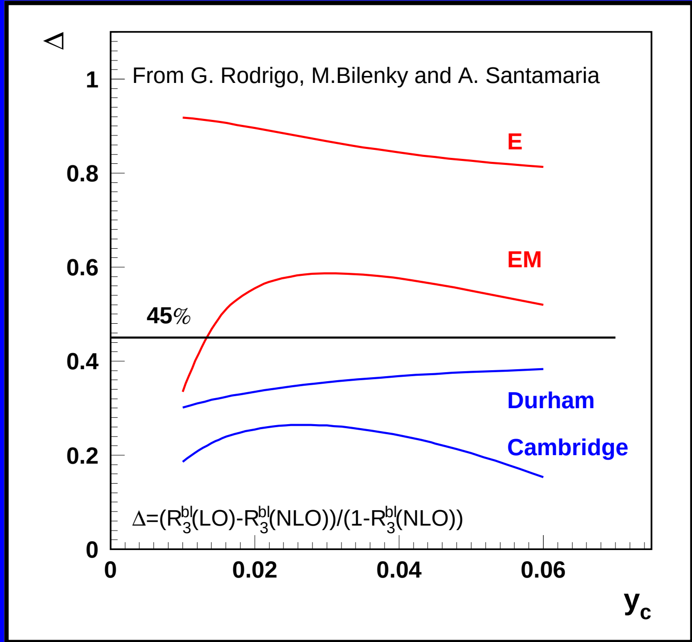
$1.036 \pm 0.043(stat)^{+0.041}_{-0.045}(syst)^{+0.020}_{-0.018}(theo)$

$\alpha_s^b/\alpha_s^{uds} =$

$1.004 \pm 0.018(stat)^{+0.026}_{-0.031}(syst)^{+0.018}_{-0.029}(theo)$




- $m_b(M_Z)$: 2.3 to 4.1 GeV, with r.m.s = 0.7 GeV.
- A consistent $m_b(M_Z)$ value can be obtained provided that there exist additional uncertainties at the level of 2% on $R_3^{b\ell}$ ($\sim 0.5\ GeV$).




$$m_b(M_Z) = 2.56 \pm 0.27(stat)^{+0.28}_{-0.38}(syst)^{+0.49}_{-1.48}(theo)\ \text{GeV/c}^2$$

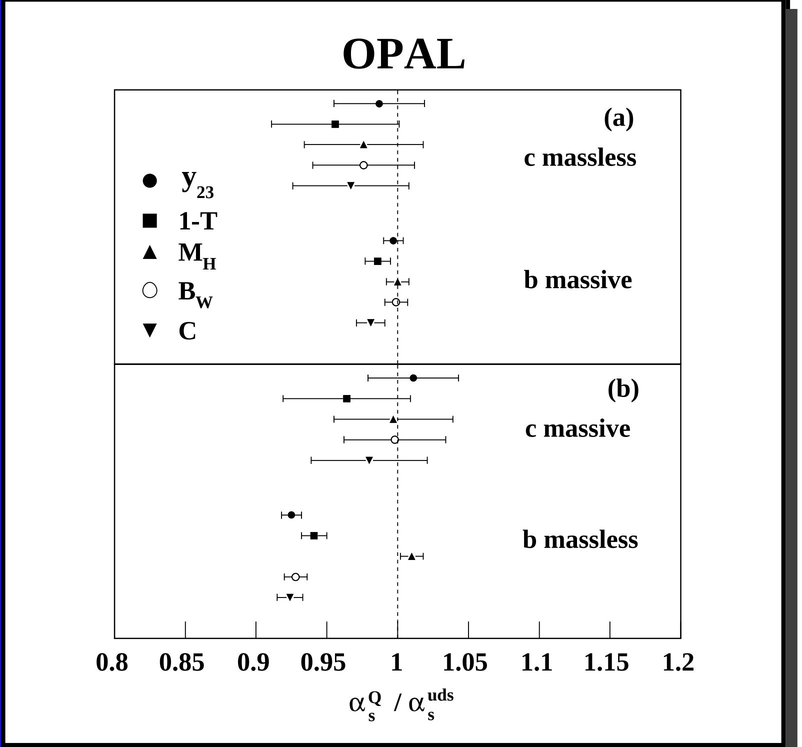
# OPAL results

- Observables used: $y_{23}$, $1-T$, $M_H$, $B_W$ and $C$ for $\ell$, $c$ and $b$ tagged samples.

- 3 parameter ($\alpha_s^{uds}$, $\frac{\alpha_s^c}{\alpha_s^{uds}}$, $\frac{\alpha_s^b}{\alpha_s^{uds}}$) fit:

$$\left(\frac{1}{\sigma_{tot}}\frac{d\sigma}{dy}\right)^{q-tag} = f_\ell^{q-tag} R(y)^\ell \left(\frac{1}{\sigma_{tot}}\frac{d\sigma}{dy}\right)^{\ell,th} + f_c^{q-tag} R(y)^c \left(\frac{1}{\sigma_{tot}}\frac{d\sigma}{dy}\right)^{c,th} + f_b^{q-tag} R(y)^b \left(\frac{1}{\sigma_{tot}}\frac{d\sigma}{dy}\right)^{b,th}$$

- $l$-th: Ellis, Ross and Terrano, masless O($\alpha_s^2$).
- $c$-th, $b$-th: P.Nason and C.Oleari, massive O($\alpha_s^2$) with $M_c$=1.35 GeV and $M_b$=5 GeV, pole mass.
- Mass effects for $b$ quarks $\sim$ 7%.

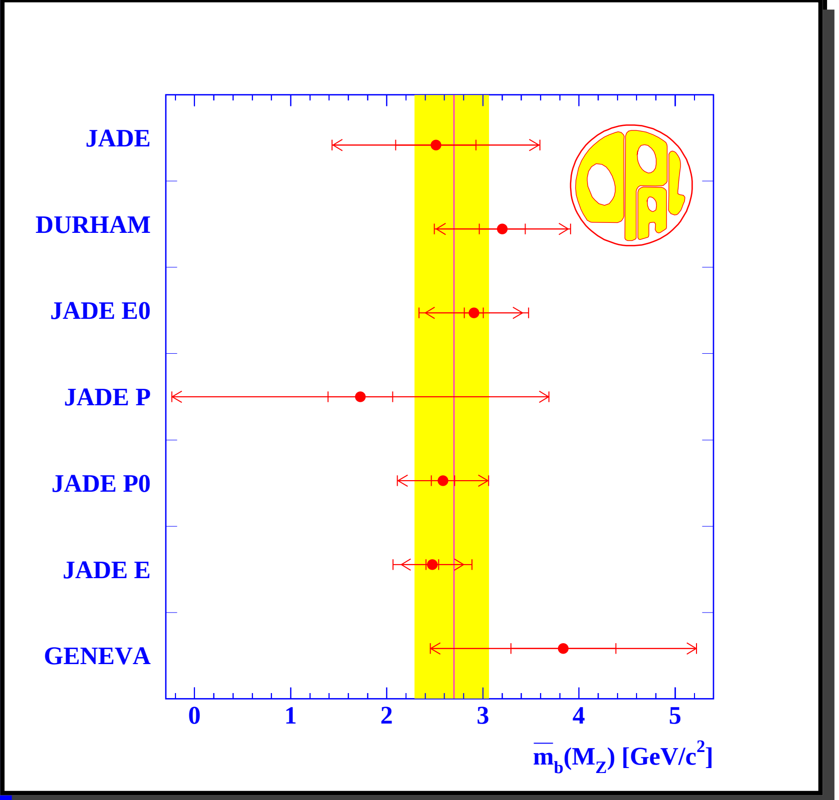



$$\alpha_s^c/\alpha_s^{uds} = 0.997 \pm 0.038(stat) \pm 0.030(syst) \pm 0.012(theo)$$
$$\alpha_s^b/\alpha_s^{uds} = 0.993 \pm 0.008(stat) \pm 0.006(syst) \pm 0.011(theo)$$

# OPAL results

$$B_3^{b\ell}(y_c) = \frac{R_3^b}{R_3^\ell} = \frac{\Gamma_{3j}^{Z^0\to b\bar{b}g}(y_c)/\Gamma_{tot}^{Z^0\to b\bar{b}}}{\Gamma_{3j}^{Z^0\to \ell\bar{\ell}g}(y_c)/\Gamma_{tot}^{Z^0\to \ell\bar{\ell}}}$$

- $R_3^q$ is the fraction of $q$-events classified as 3 jets.
- Jet cluster algorithms used: E, E0, P, P0, Durham (D) and Geneva (G).
- NLO massive calculations used: W. Bernreuther, A. Brandenburg, P. Uwer.

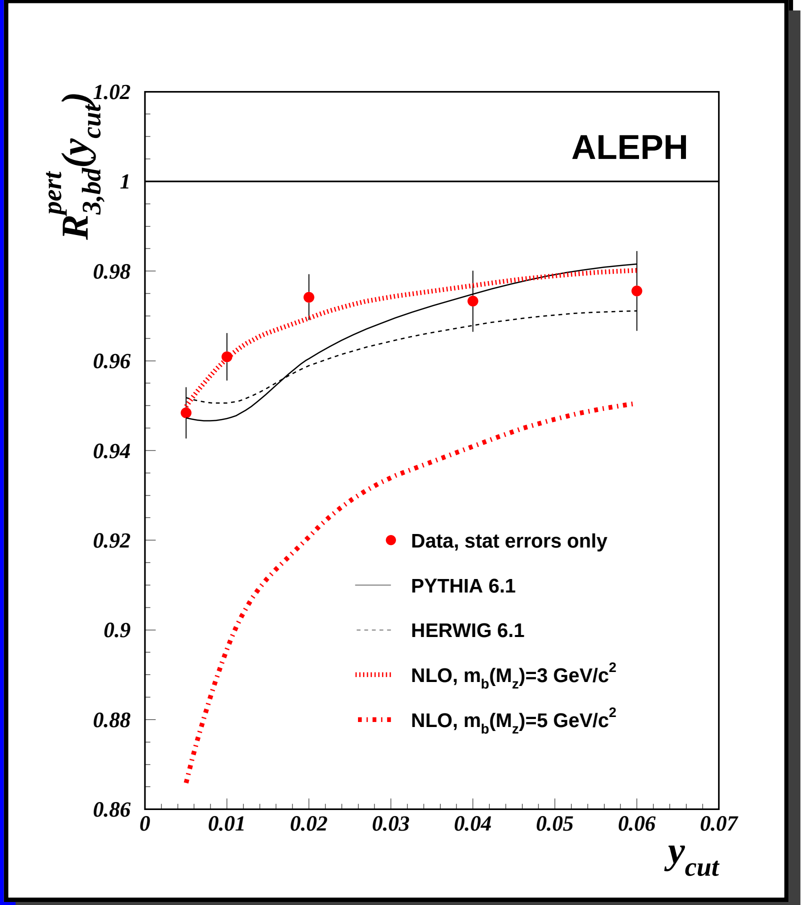



$$m_b(M_Z) = 2.67 \pm 0.03(stat)^{+0.29}_{-0.37}(syst) \pm 0.19(theo)\ \mathrm{GeV/c^2}$$

# ALEPH results

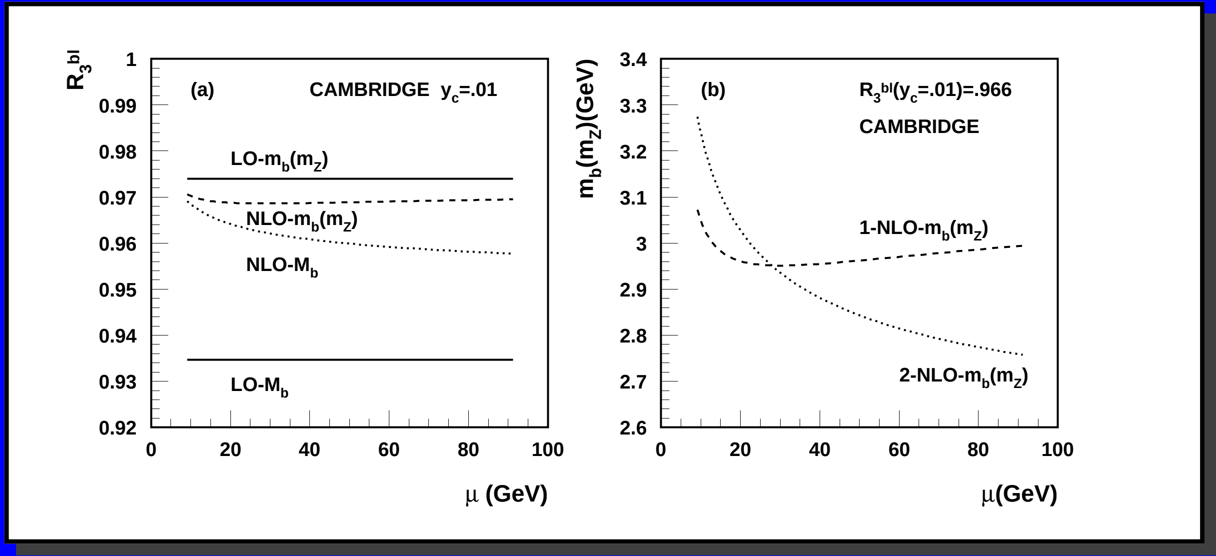
$$R^{b-all}(O) = O_b/O_{all} \to R^{b\ell}(O)$$

- $O$: $R_3$ (Durham), $T_1$, $T_2$, $C_1$, $C_2$, $y_{3_1}$, $y_{3_2}$, $B_{T_1}$, $B_{T_2}$, $B_{W_1}$, $B_{W_2}$.
- Requirements for $O$: Small NLO and hadronization corrections with respect to the mass effect and uncertainty at the 1% level $\Rightarrow$ Only $R_3$ and $y_{3_1}$.
- $y_{3_1}$ gives the smallest hadronization correction and systematic uncertainties $\Rightarrow$ it is the one used.

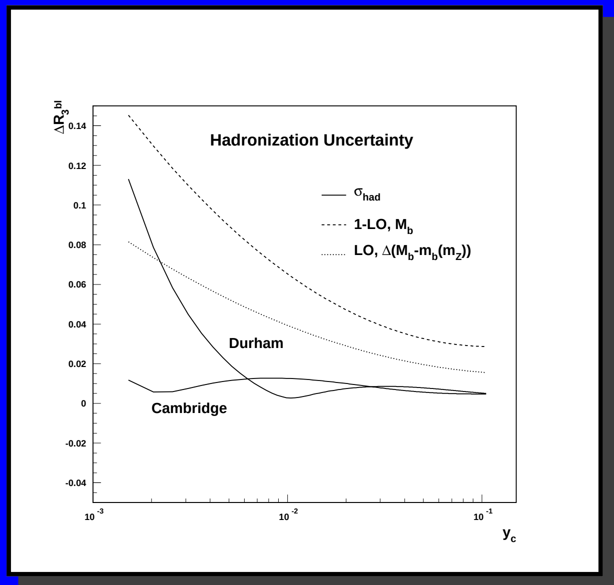



$$m_b(M_Z) = 3.27 \pm 0.22(stat) \pm 0.22(exp) \pm 0.38(had) \pm 0.16(theo)\ \text{GeV/c}^2$$
$$\alpha_s^b/\alpha_s^{uds} = 0.997 \pm 0.004(stat) \pm 0.004(exp) \pm 0.007(had) \pm 0.003(theo)$$

# Reducing theoretical uncertainty: Cambridge

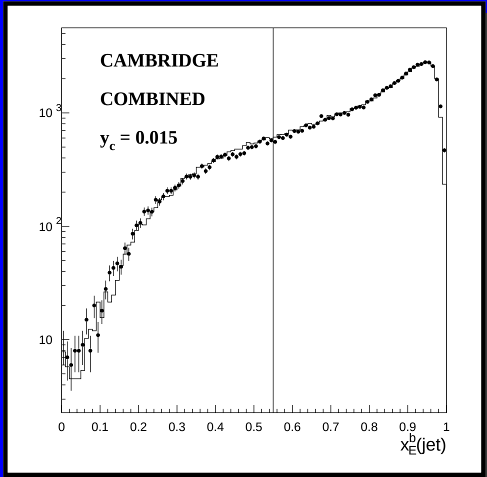



- Using Cambridge
  - Reduces the scale dependece ($\mu$).
  - Reduces the mass ambiguity, Ex: $R_3^{b\ell}$(Durham): $\sim$270 MeV $\Rightarrow$ $R_3^{b\ell}$(Cambridge): $\leq$100 MeV.
  - Allows for extending the analysis towards small $y_c$, i.e., increasing the sensitivity to $m_b$

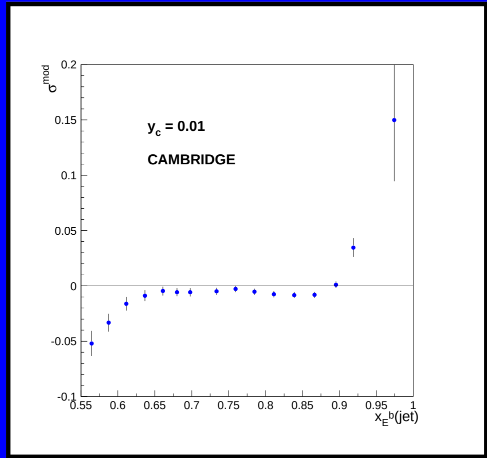


# Reducing fragmentation uncertainty: $x_E^b(jet)$

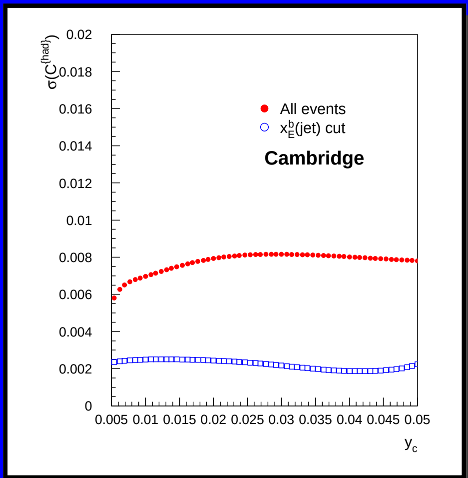
Data Distribution for $x_E^b(jet)$




$\sigma^{mod}$ vs. $x_E^b(jet)$




$\sigma^{mod}$ vs. $y_c$



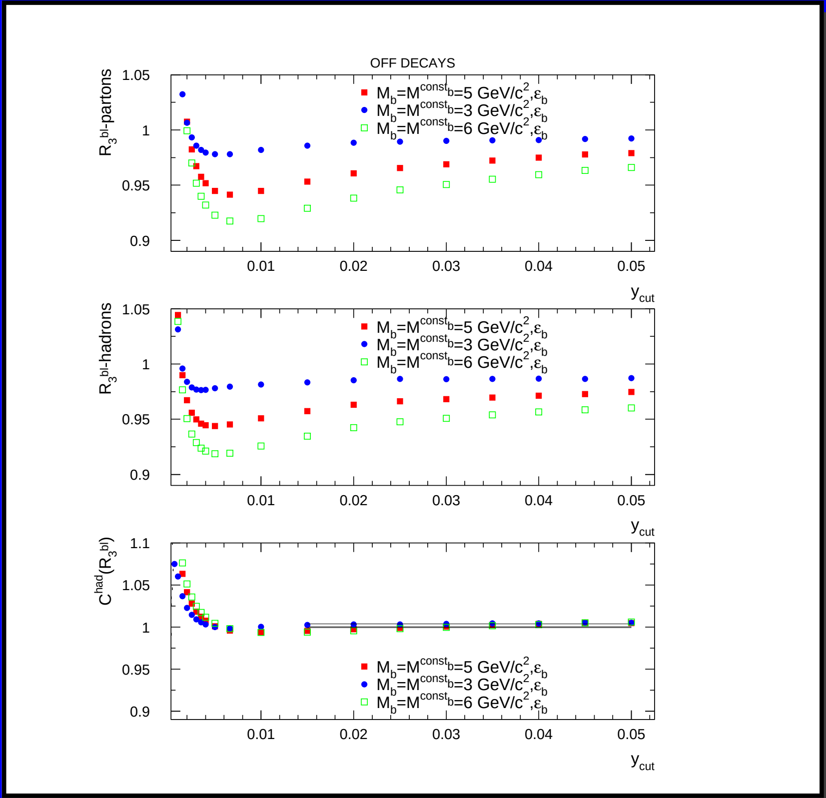

- Uncertainty on the fragmentation model:
  - 2 known models: string and cluster.
  - Ex: For $R_3^{b\ell}$ is taken as:

    $$\sigma^{mod} = \sigma(C^{had}_{Herw} + C^{had}_{Pyt-Pet} + C^{had}_{Pyt-Bow})$$

  - Using $x_E^b(jet) > 0.55$ for Cambridge $\sigma^{mod}(y_c = 0.02) = 0.002$.

# Masses in Pythia Generator

Hadronization Corr. depending on $M_b$




$b$-mass values used in Pyhtia:

- $M_b$ for partons
- $M_b^{const}$ for hadronization and unknown Bs
- $M_B$ Known B-hadrons

In the program they are independent of each other.
If not connected the hadronization correction depends on $M_b$.
If connected, as it should, the hadronization correction doesn't depend on $M_b$

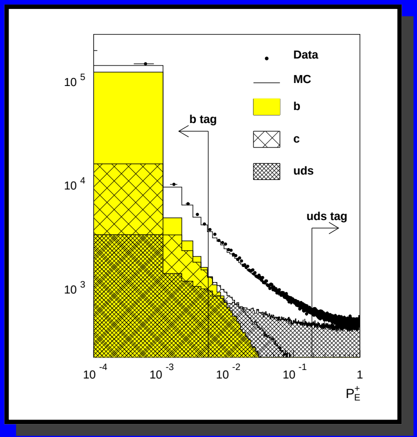
Use Pole mass $M_b \sim$4.94 GeV/c$^2$ in the generator:

$$m_B = M_b + \Lambda + \mathcal{O}(1/M_b) \text{ with } \Lambda = 350 \pm 122 \text{ MeV}$$

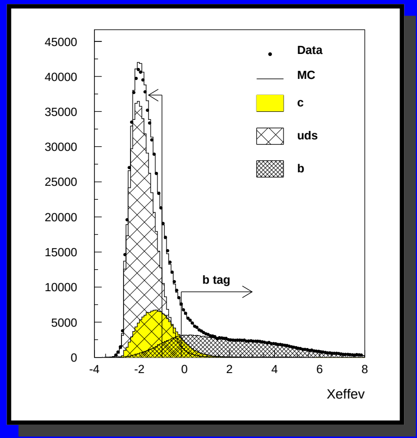
Uncertainity of $M_b$ in the PS should be 122 MeV $\leq \sigma \leq \Lambda_{QCD} \sim$ 220 MeV

# Understanding $b$- and $\ell$- tagging: IP vs. Combined

Data Distribution for $P_E^+$

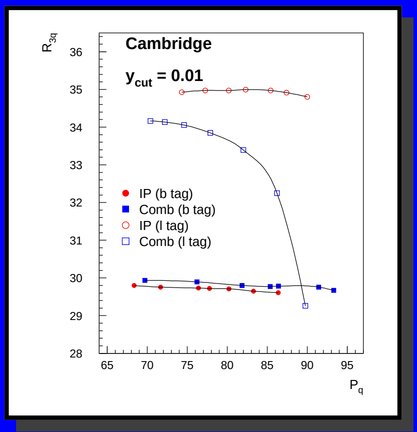



Data Distribution for $X_{effev}$

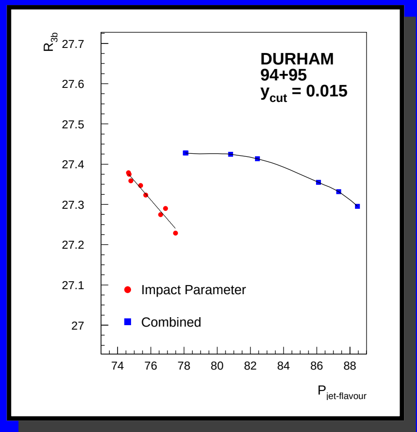



$b$-events are identified using Combined $b$-tagging with $P_b = 86\%$

$b$- and $\ell$- event identification




$b$/gluon-jet identification

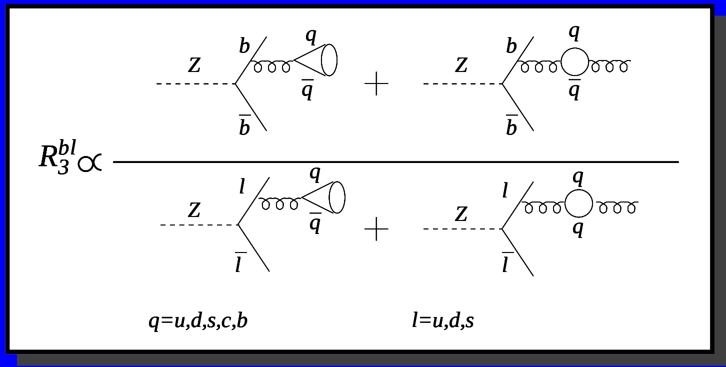



$\ell$-events are identified using Impact Parameter with $P_\ell = 82\%$

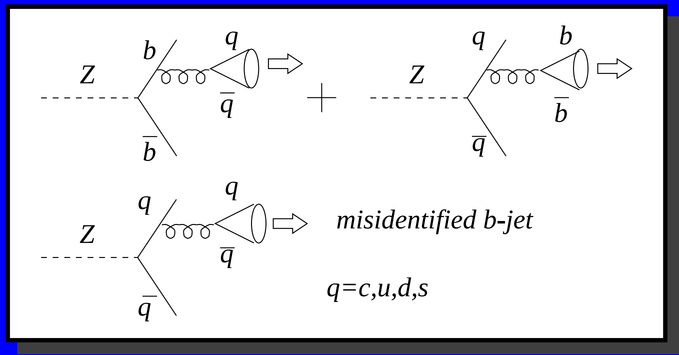
# Four partons final state influence to $R^3_{b\ell}$

- In theory, i.e., the calculation:
  - the event flavour is defined as that of the quark coupling to the $Z$,
  - divergencies are cancelled in the usual way,
  - the observable is well defined:

$$\lim_{m_b \to 0} R_3^{b\ell} = 1$$




- In practice, the event flavour is experimentally tagged. Receiving contributions from:
  - all three-jet final state toplogies with $b$'s in the final state,
  - all three-jet events with misidentified flavour tagged.



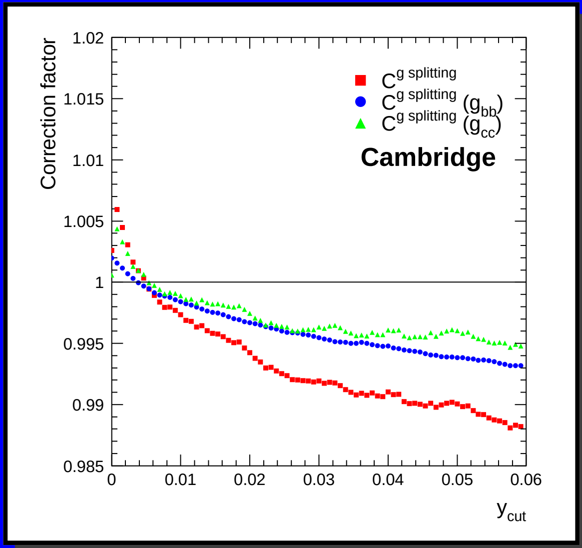
# Gluon splitting: $g \to b\bar{b}$, $g \to c\bar{c}$

The MC, DELSIM, is used to reconstruct the original observable $R_3^{b\ell}$ starting from the tagged events and the assumptions considered for the gluon splitting probabilities have an impact.

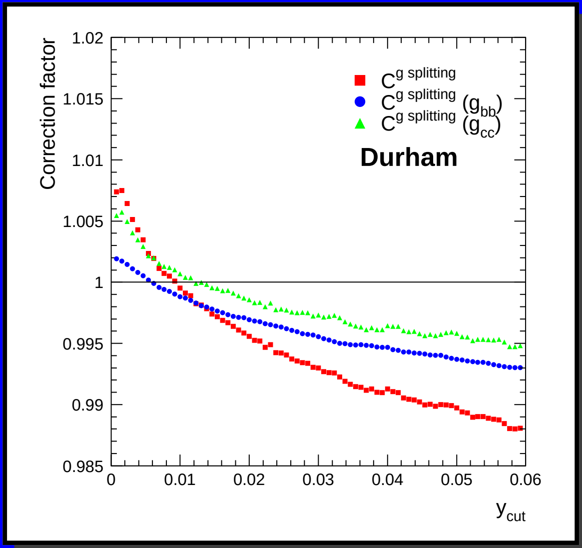
Furthermore DELSIM results need to be reweighted to account for latest measured values of $g_{b\bar{b}}$ and $g_{c\bar{c}}$:

$$g_{b\bar{b}} : 0.00155 \to 0.00254 \pm 0.0051 \;\text{ and }\; g_{c\bar{c}} : 0.0155 \to 0.0296 \pm 0.0038$$

Correction Factors to DELSIM

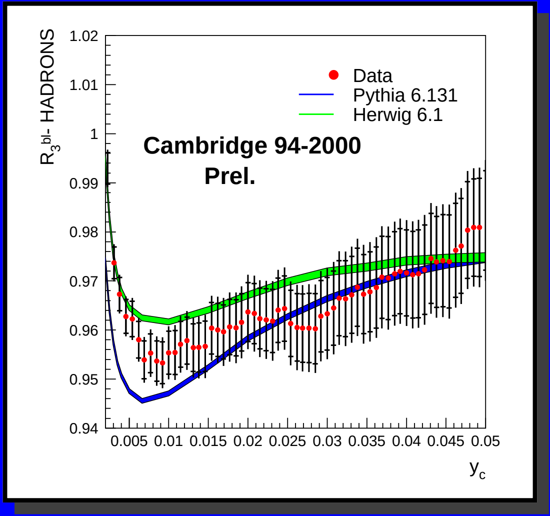


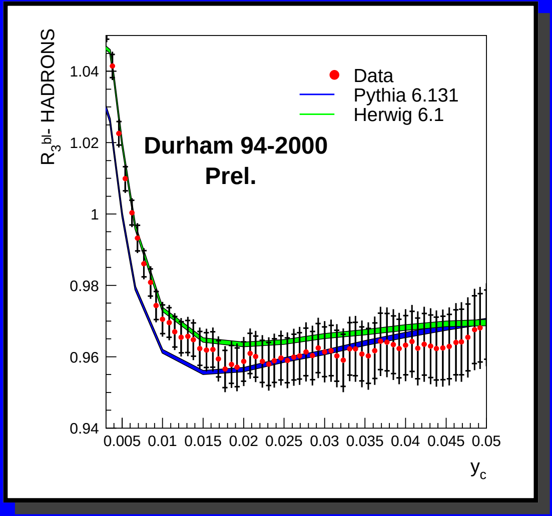

Correction Factors to DELSIM




- $R_{b\ell}^3$ using Cambridge is less sensitive to the choice of the gluon splitting values.

# Results for $R^3_{b\ell}$ at hadron level



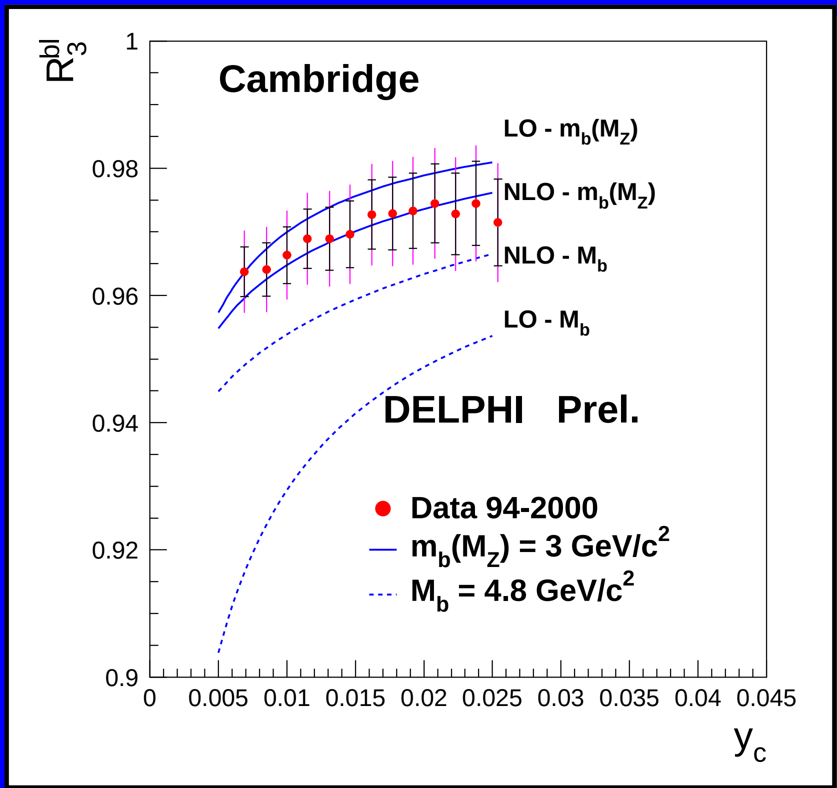

- For large $y_c$ both generators, Pythia and Herwig, describe well the data
- For low $y_c$ Herwig seems to describe data better

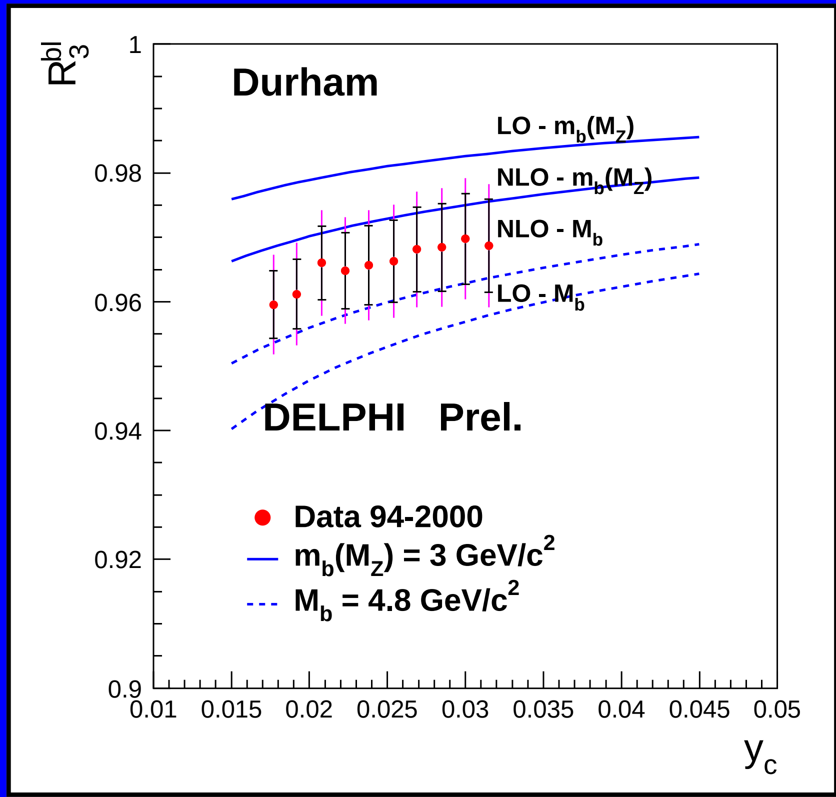
However, $R_3^{b\ell}$ and/or other observables depend on $M_b$ if B-hadron masses and $b$-parton masses are connected:

$$m_B = m_0 + \sum_i M_i + k m_d^2 \sum_{i<j} \frac{< \sigma_i \sigma_j >}{M_i M_j}$$

From data a value of $M_b$ in the generator can then be derived. The uncertainity (still under study) on $m_b$ could then be in the order of 100-150 MeV/$c^2$.

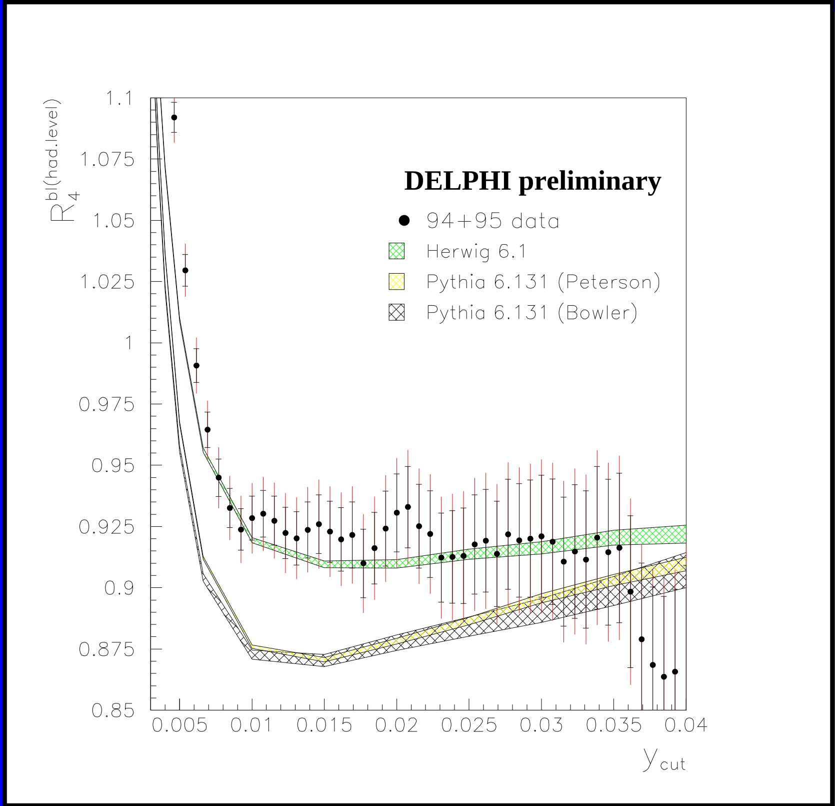
# Results for $R^3_{b\ell}$ at parton level

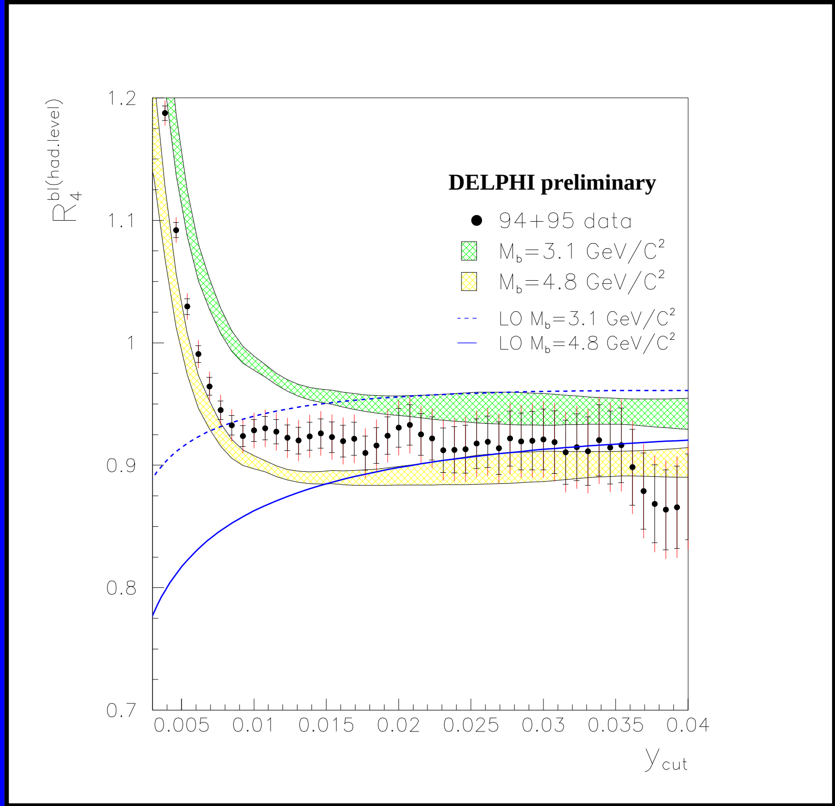



| | | |
|---|---|---|
| Cambridge | $R_3^{b\ell}(0.009)$ | $= 0.964 \pm 0.004\,(\text{stat.}) \pm 0.007\,(\text{syst.})$ |
| Durham | $R_3^{b\ell}(0.02)$ | $= 0.963 \pm 0.006\,(\text{stat.}) \pm 0.008\,(\text{syt.})$ |

# First look into $R^4_{b\ell}$

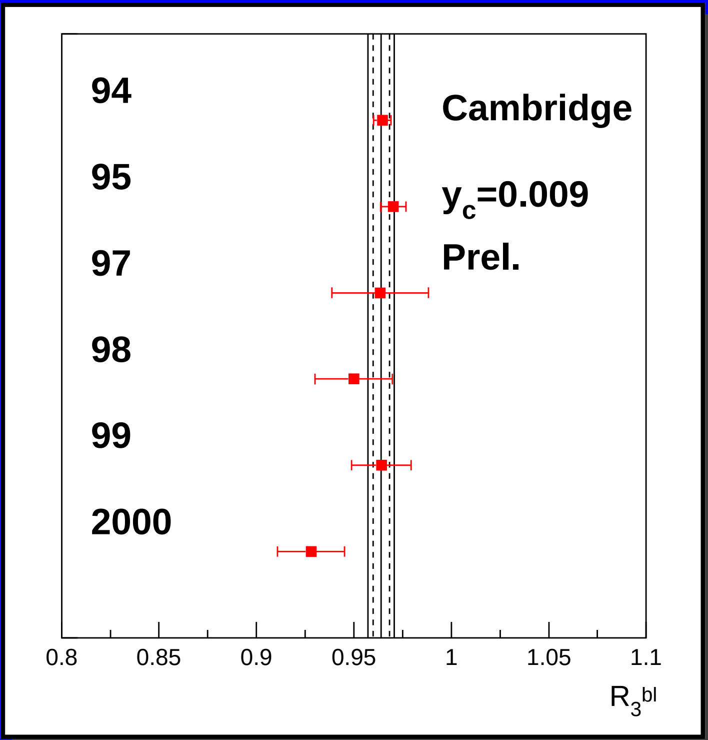


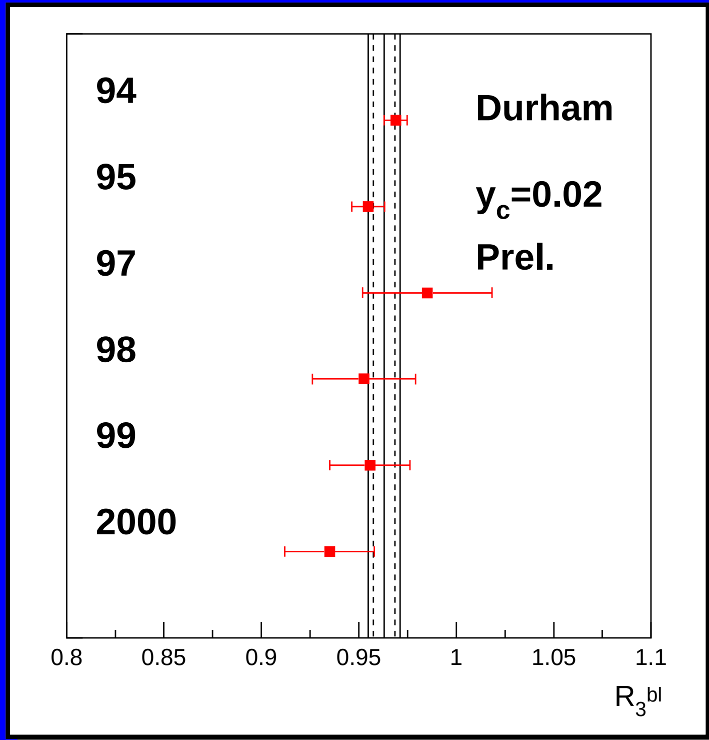




Similar results to $R^3_{b\ell}$:

- Herwig seems to describe data better at hadron level
- Data are contained between LO predictions for $3\ \mathrm{GeV/c^2} \leq \mathrm{m_b} \leq 4.8\ \mathrm{GeV/c^2}$

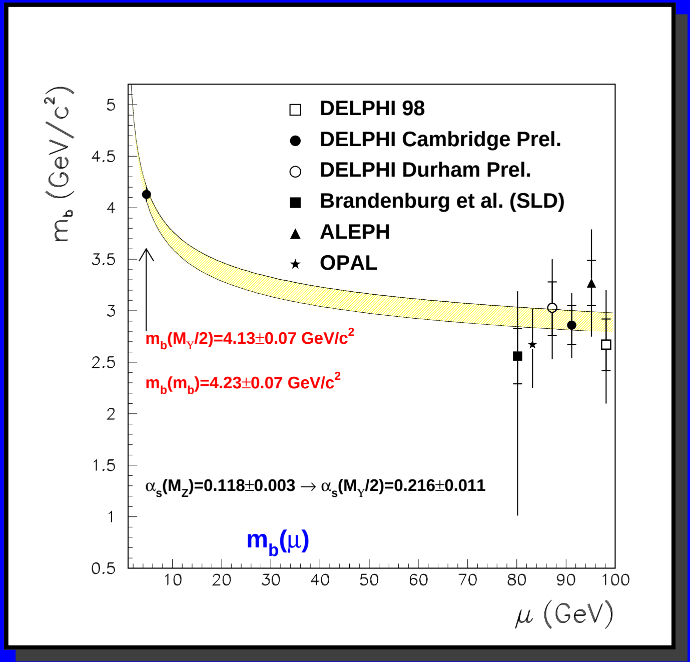
# Stability of $R^3_{b\ell}$




| | | |
|---|---|---|
| Cambridge | $m_b(M_Z)$ | $= 2.82 \pm 0.19\ (\text{stat.}) \pm 0.32\ (\text{syst.}) \pm 0.06\ (\text{theo.})$ |
| Durham | $m_b(M_Z)$ | $= 2.99 \pm 0.26\ (\text{stat.}) \pm 0.35\ (\text{syst.}) \pm 0.28\ (\text{theo.})$ |
| Cambridge | $\alpha_s^b/\alpha_s^\ell$ | $= 1.001 \pm 0.004\ (\text{stat.}) \pm 0.007\ (\text{syst.}) \pm 0.002\ (\text{theo.})$ |

# $m_b(M_Z)$ and $M_b$




A net change of $m_b(\mu)$ is observed at $m_Z$ when compared to measurments at $\Upsilon$:

$$m_b(M_\Upsilon/2) - m_b(M_Z) = 1.31 \pm 0.37\,\mathrm{GeV/c^2}$$

| Durham | $m_b(M_Z)(\mathrm{GeV/c^2})$ | $M_b(\mathrm{GeV/c^2})$ |
|---|---|---|
| $NLO$ | 2.99 | 4.12 |
| $LO$ | 4.04 | |

| Cambridge | $m_b(M_Z)(\mathrm{GeV/c^2})$ | $M_b(\mathrm{GeV/c^2})$ |
|---|---|---|
| $NLO$ | 2.82 | 4.21 |
| $LO$ | 3.19 | |

- $m_b(M_Z)$ values in agreement with QCD prediction and $\Upsilon$ determinations.
- $M_b$ low values obtained when compared to QCD prediction and $\Upsilon$ determinations.
- With Cambridge, data can be reasonably described at LO.
- If the role of $M_b$ in the generator is better understood a total uncertainity on $m_b$ in the order of $0.25 - 0.30\ \mathrm{GeV/c^2}$ can be achieved.