b QUARK MASS MEASUREMENT AT HIGH ENERGIES

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QCD@WORK

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Theoretical considerations on quark masses

- Free quarks are not observed in nature $\rightarrow$ they can only be determined indirectly through their influence on hadron properties.
- Quark masses are additional couplings in the QCD Lagrangian.
- The two most common quark mass definitions are:
  - M_q: Pole mass. Pole of the perturbative quark propagator (gauge and scheme independent).
  - $m_q(\mu)$: Running mass. Renormalized mass in the $\overline{MS}$ scheme.

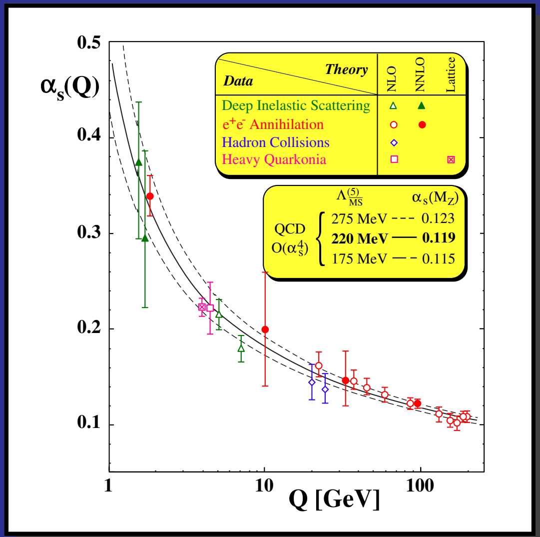
$$\boxed{\frac{M_b}{m_b(M_b)} = 1 + \frac{4}{3}\frac{\alpha_s(M_b)}{\pi} + 12.4\left(\frac{\alpha_s(M_b)}{\pi}\right)^2 + \mathcal{O}(\alpha_s^3)}$$

- At infinite orders both definitions are equivalent but not for a fixed order calculation $\Rightarrow$ They have different convergence properties.
- NLO calculations are needed to distinguish M_b from $m_b(\mu)$.

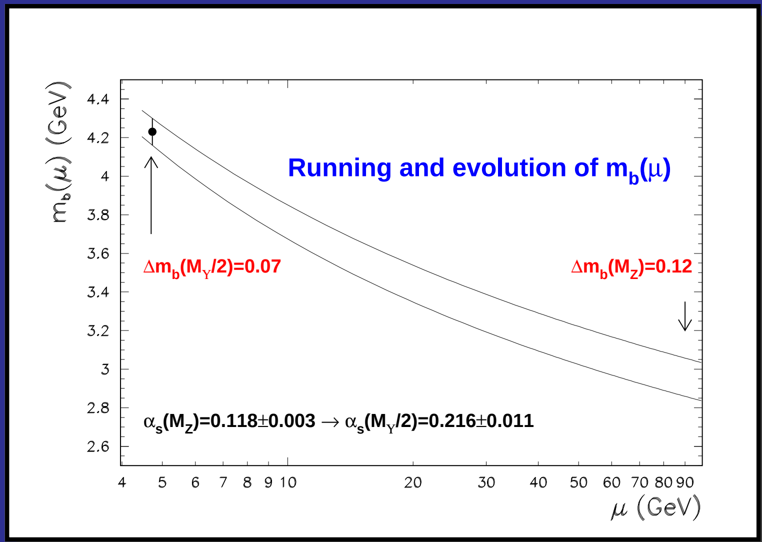
Motivations to measure the b-quark mass at M_Z

- Direct and independent determination of the b mass at high energy (test of QCD).
- In the case of $m_b(\mu)$, test of the evolution with the scale, as has been already measured for α_s.

Running of $\alpha_s(\mu)$



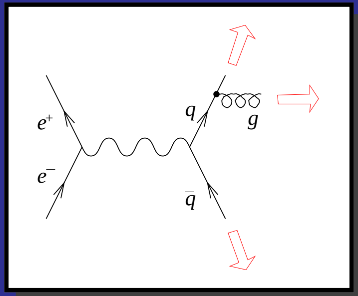
Running of $m_b(\mu)$



- $m_b(M_Z)$ is a basic input parameter to test $m_b - m_\tau$ unification predicted by GUT models at $M_{GUT} \sim 10^{16}$ GeV.

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

W. Bernreuther et al. Rev. Lett. 79

P. Nason, C. Oleari, Phys. Lett. B407

- Recent calculations of mass effects at NLO have been performed for the b/ℓ ratios.

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

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

- α_s universality $\Leftrightarrow$ M_b and $m_b(M_Z)$.

Data Analysis

- Data sample of hadronic Z^0 decays used:

-LEP: 1991-1995 $\sim 4 \cdot 10^6$

-SLC: 1993-1995 $\sim 0.15 \cdot 10^6$

- Need to tag the b and ℓ intiated events samples:

- Purities: $\sim (80 - 90)\%$.

- Working point: small corrections and biases.

- Measure O_b and O_ℓ or O_{all}:

  O good observable $\Leftrightarrow$ small NLO and fragmentation corrections.

- Event shapes.

- $R_3 \rightarrow$ Jet reconstruction algorithms.

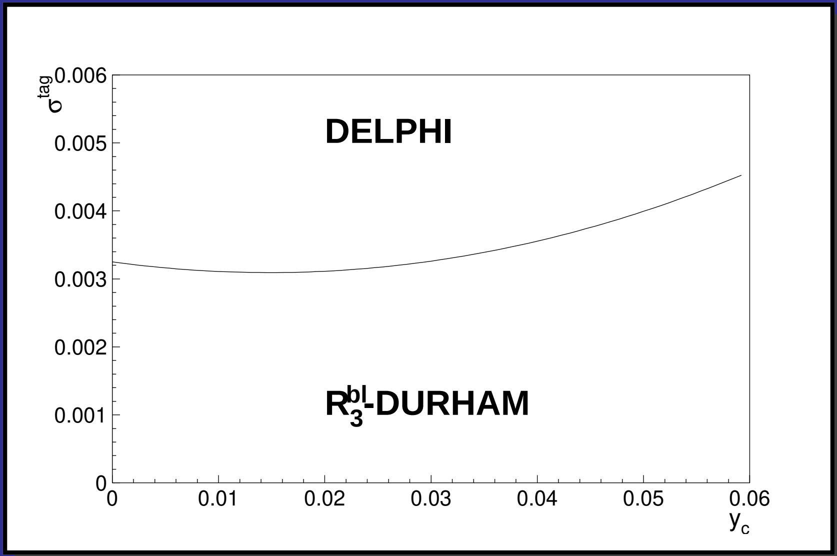
- Simulated data is used to correct for detector and tag effects and the hadronization process:

- Detector and tag effects $\sim 9\%$.

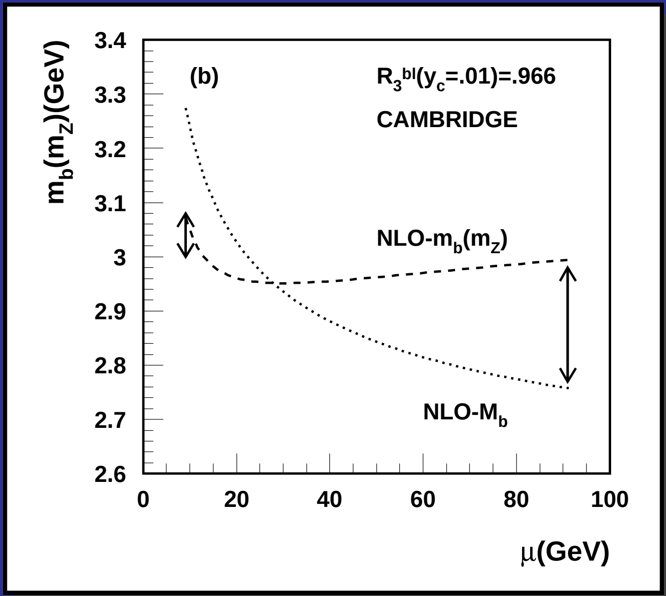
- Hadroniztion process $\sim 1\%$.

Systematic Uncertainties

- Imperfections of the detector modelling and physics modelling uncertainties:
  - Detector: resolution, tracking ϵ, ...
  - Physics processes: particle decays, fragmentation, g splitting, ...
  - Example: DELPHI, $R_3^{b\ell}$(Durham): $\sigma^{tag}(y_c = 0.02) = 0.003$.

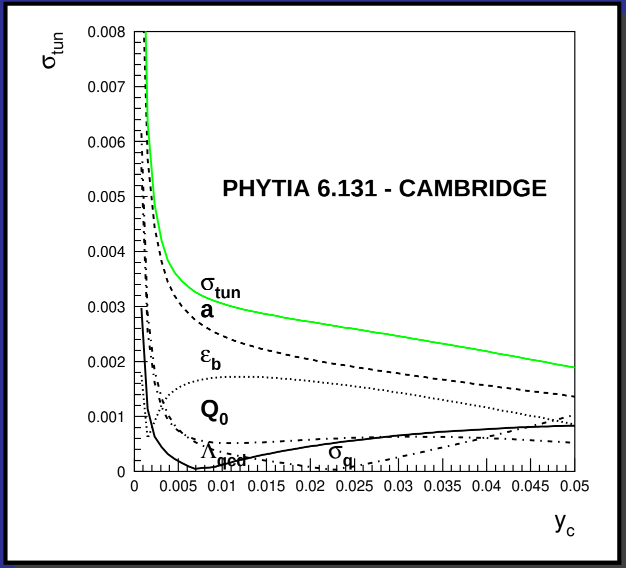


- Theoretical
  - Scale dependece (μ) .
  - Mass ambiguity: fit either $m_b(M_Z)$ directly or M_b and evolve this to $m_b(M_Z)$.
  - Ex: $R_3^{b\ell}$(Durham): 270 MeV $\rightarrow$ $R_3^{b\ell}$(Cambridge): 120 MeV.



- Hadronization process: 2 sources of error, $\sigma^{had} = \sqrt{(\sigma^{tun})^2 + (\sigma^{mod})^2}$.

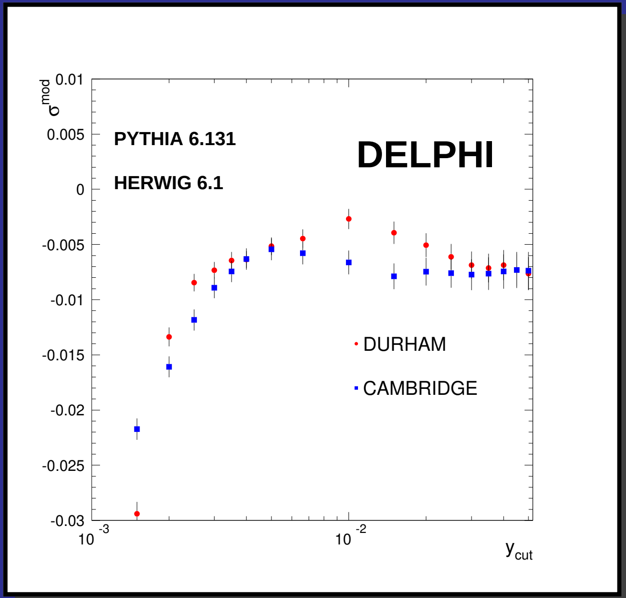
- Uncertainty on the fragmentation parameters:
  - Ex: Obtained from a $\pm 2\sigma$ variation of the string model fragmentation tuned parameters of PYTHIA.
  - Ex: DELPHI, $R_3^{b\ell}$(Cambridge): $\sigma^{tun}(y_c = 0.01) = 0.003$.



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

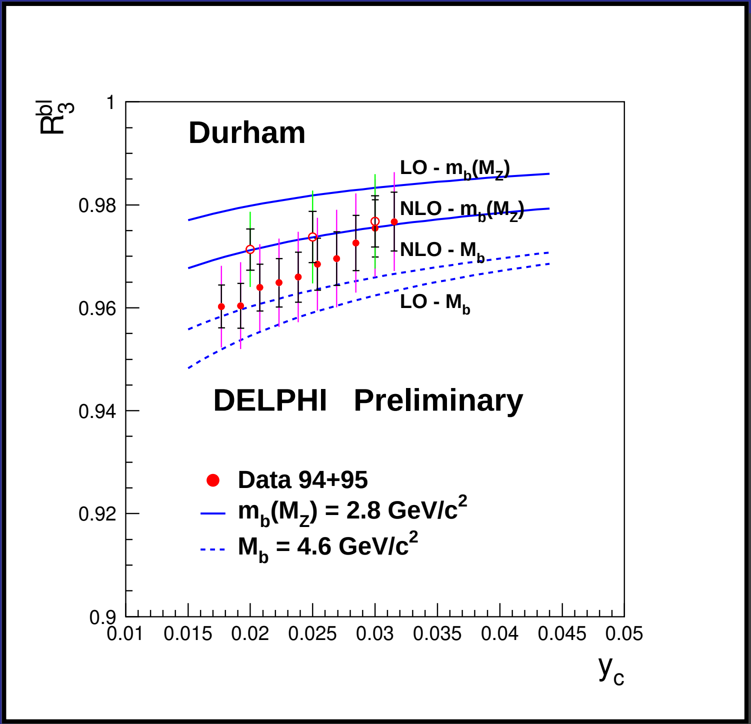
$$\sigma^{mod} = \frac{1}{2}(C^{had}_{Herw} - C^{had}_{Pyt})$$

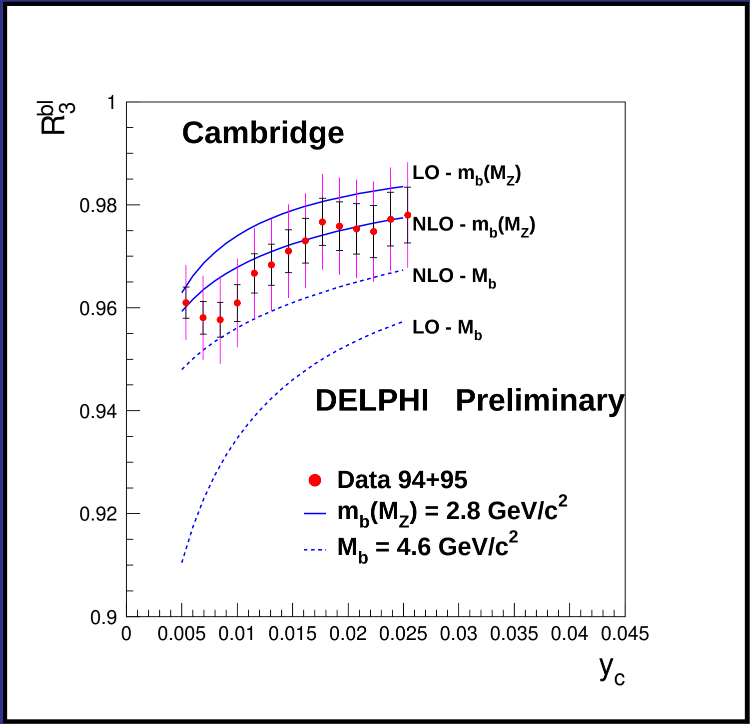
  - For Durham $\sigma^{mod}(y_c = 0.02) = 0.006$.



DELPHI results

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

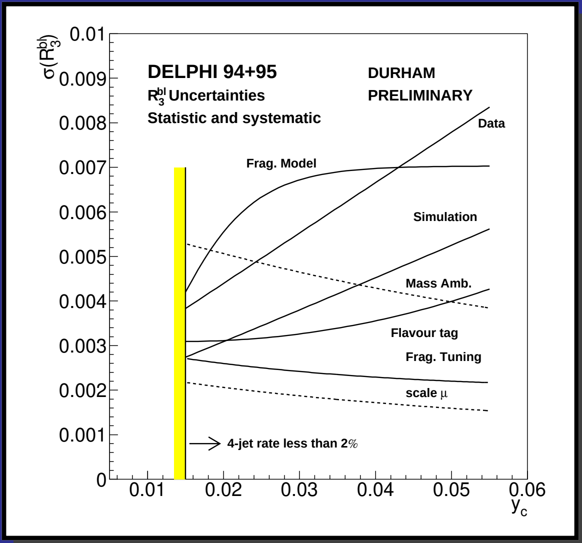


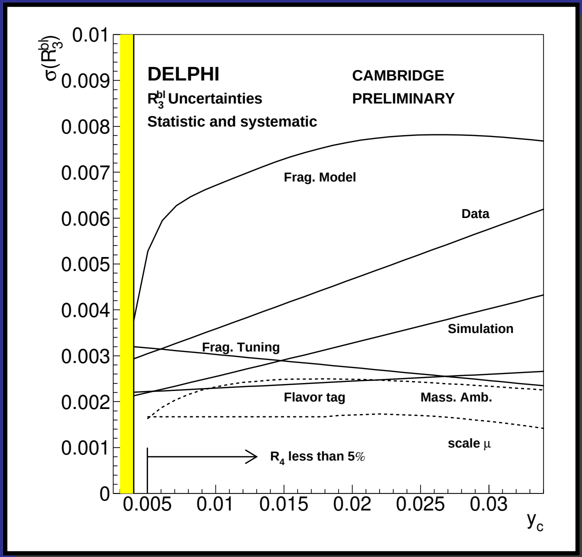


DUR. $m_b(M_Z) = 2.67 \pm 0.25(stat) \pm 0.34(had) \pm 0.27(theo)$ GeV/c^2

CAM. $m_b(M_Z) = 2.61 \pm 0.18(stat) \pm 0.47(had) \pm 0.18(tag) \pm 0.12(theo)$ GeV/c^2

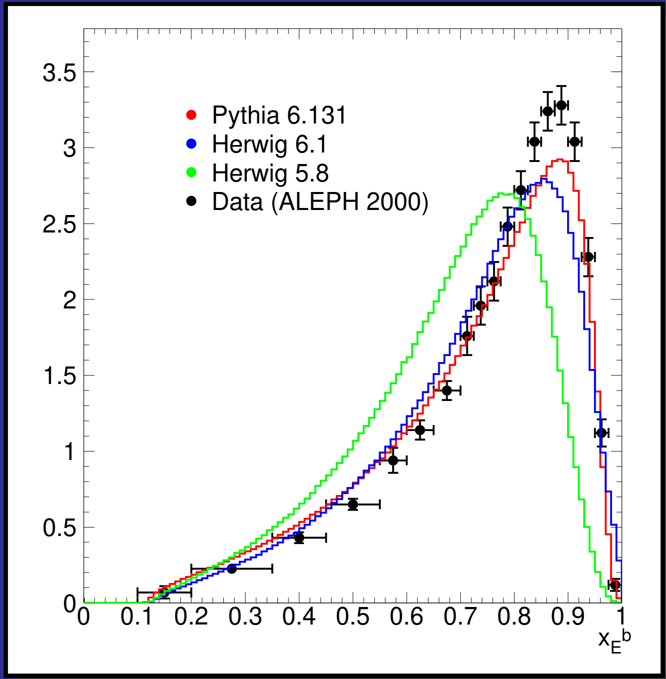
DELPHI results





- The σ^{theo} is smaller for Cambridge.
- The σ^{had} is the dominant error for both algorithms.
- Work is going on to reduce σ^{had} by studying the b fragmentation.

y_c	Alg.	$R_3^{b\ell}$	σ^{stat}	σ^{had}	σ^{tag}
0.02	DUR.	0.962	0.005	0.007	0.004
0.01	CAM.	0.961	0.005	0.007	0.003

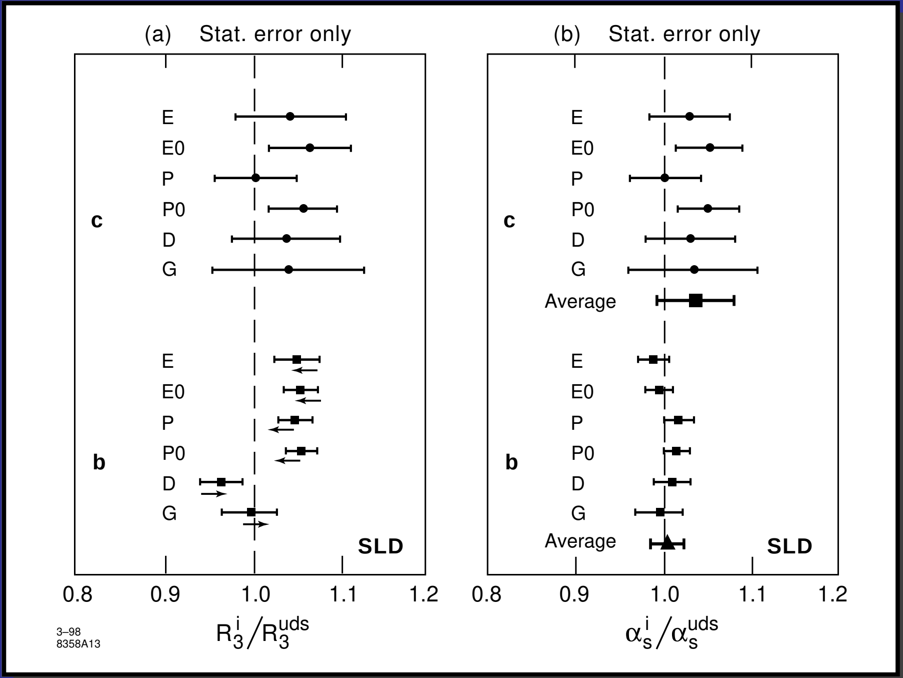


- The new generators Herwig 6.1 and Pythia 6.131 (both tuned by DELPHI) have been used $\Rightarrow$
  - $\Delta R_3^{b\ell} \sim 0.6\%$.
  - For Cambridge, σ^{had}: 0.012 $\rightarrow$ 0.007 $\rightarrow$ 0.004, with respect to the previous analysis.

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.

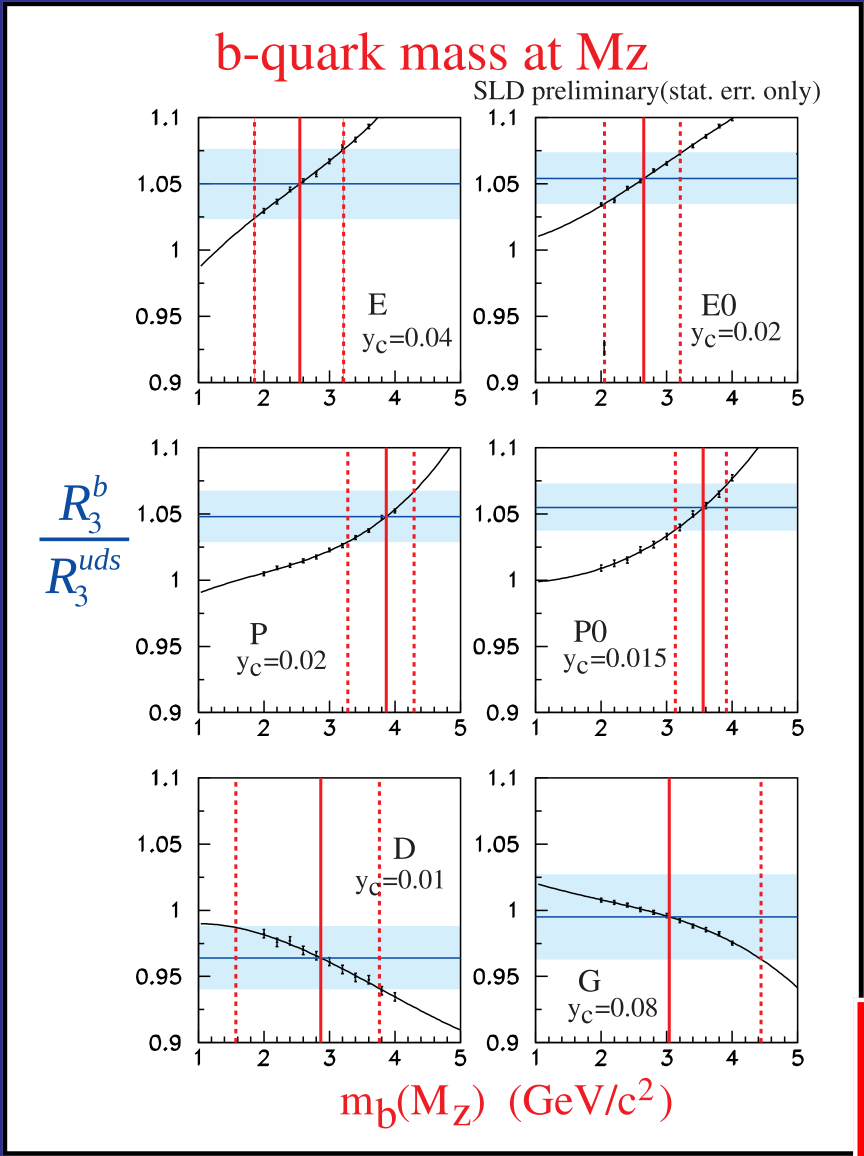


$\alpha_s^c/\alpha_s^{uds} =$

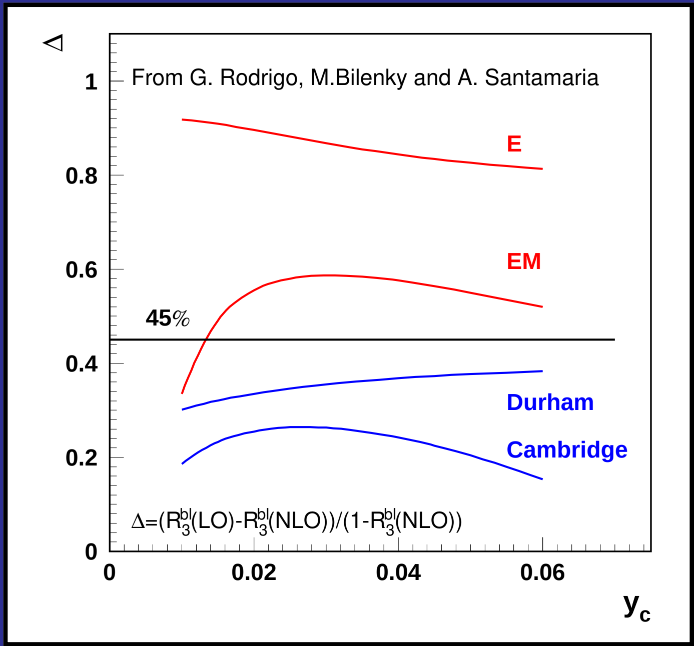
$1.036 \pm 0.043(stat)^{+0.041}_{-0.045}(syst)^{+0.020}_{-0.018}(theo)$

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

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



- $m_b(M_Z)$: 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 $R_3^{b\ell}$ ($\sim 0.5\ GeV$).



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

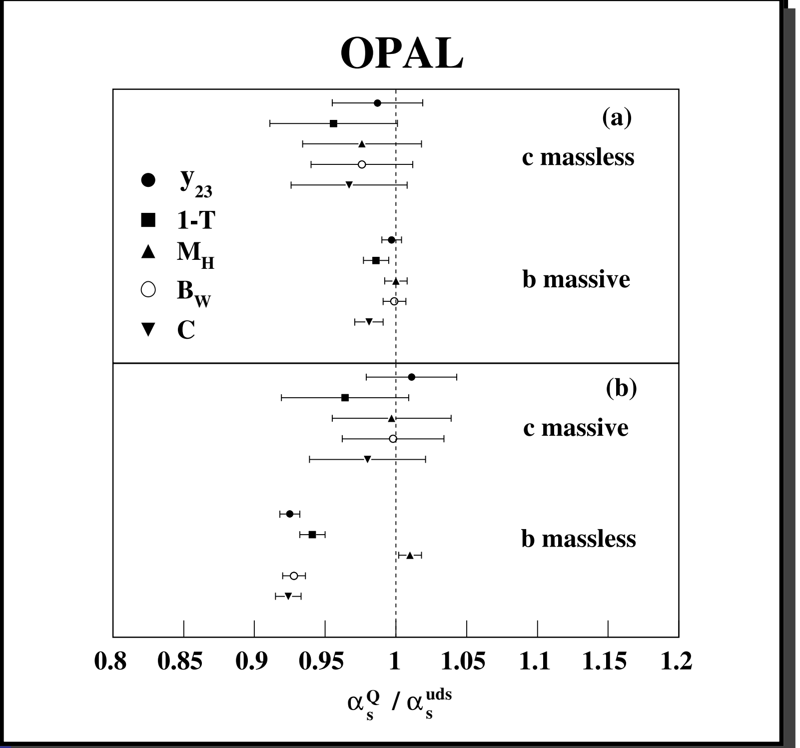
OPAL results

- Observables used: y_{23}, $1-T$, M_H, B_W and C for ℓ, 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(α_s^2).
- c-th, b-th: P.Nason and C.Oleari, massive O(α_s^2) with M_c=1.35 GeV and M_b=5 GeV, pole mass.
- Mass effects for b quarks $\sim 7\%$.

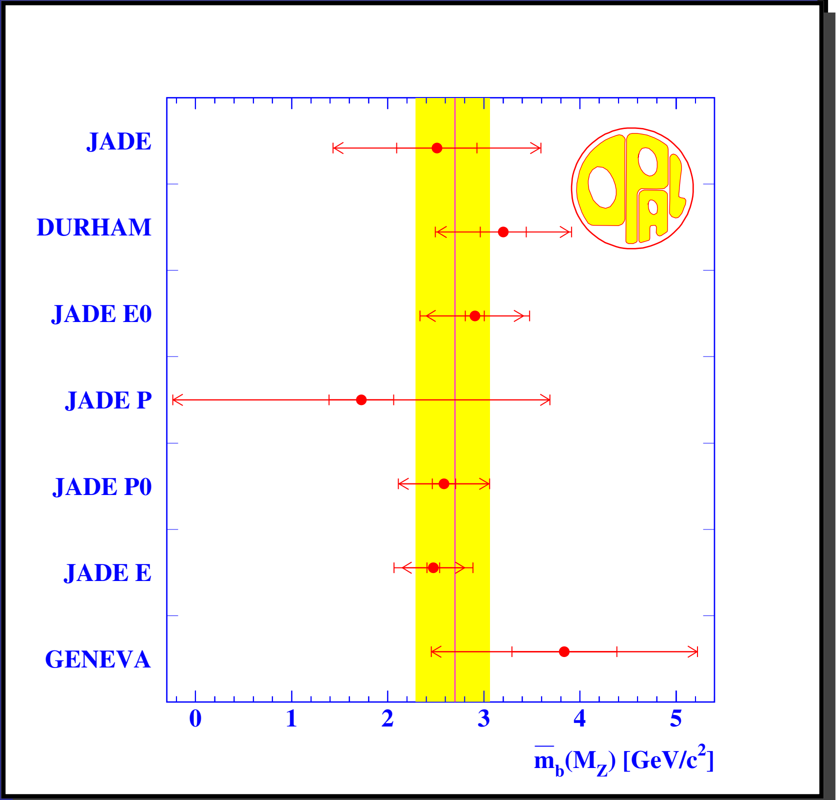


$$\alpha_s^c/\alpha_s^{uds} = 0.997 \pm 0.038(stat) \pm 0.030(syst) \pm 0.012(theo)$$
$$\alpha_s^b/\alpha_s^{uds} = 0.993 \pm 0.008(stat) \pm 0.006(syst) \pm 0.011(theo)$$

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 or more jets.
- Jet cluster algorithms used: E, E0, P, P0, Durham (D) and Geneva (G).
- NLO massive calculations used: W. Bernreuther, A. Brandenburg, P. Uwer.

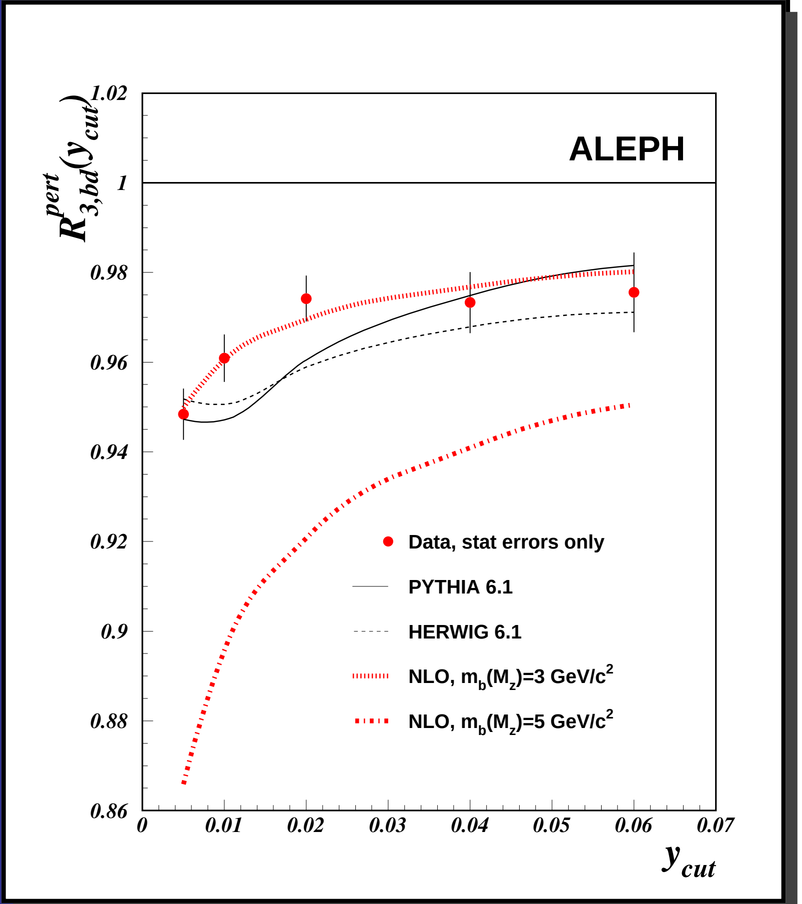


$$m_b(M_Z) = 2.67 \pm 0.03(stat)^{+0.29}_{-0.37}(syst) \pm 0.19(theo)\ \mathrm{GeV/c^2}$$

ALEPH results

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

- 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.

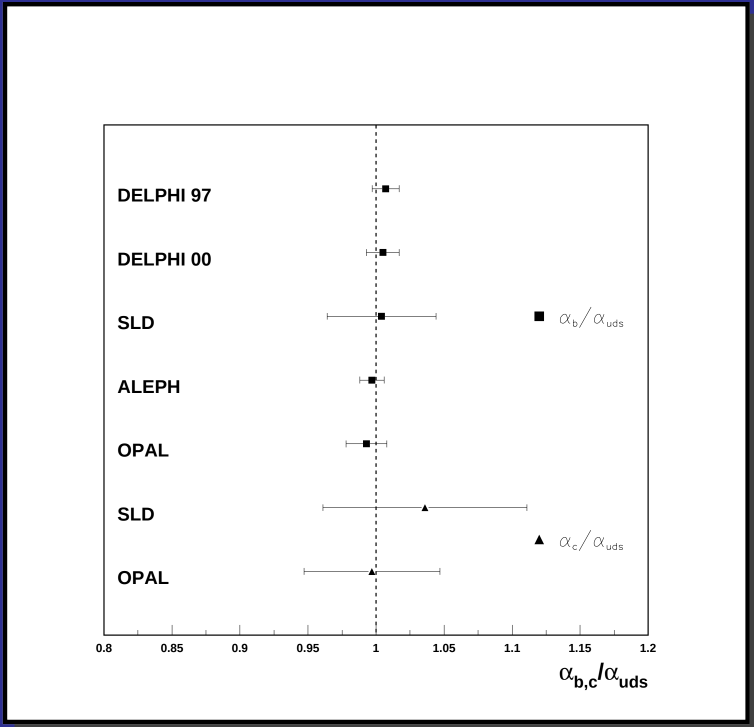


$$m_b(M_Z) = 3.27 \pm 0.22(stat) \pm 0.22(exp) \pm 0.38(had) \pm 0.16(theo)\ \mathrm{GeV/c^2}$$

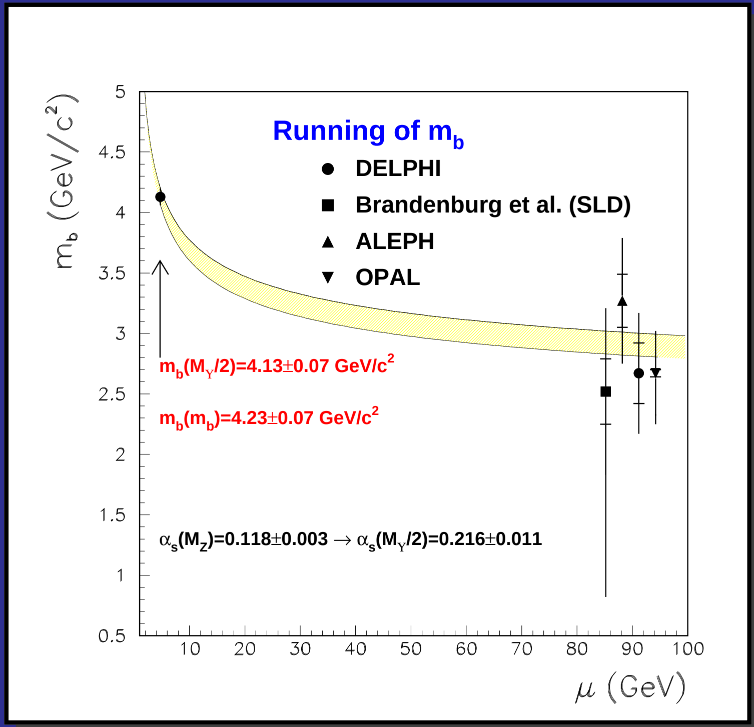
$$\alpha_s^b/\alpha_s^{uds} = 0.997 \pm 0.004(stat) \pm 0.004(exp) \pm 0.007(had) \pm 0.003(theo)$$

Summary

α_s universality



$m_b(M_Z)$ running



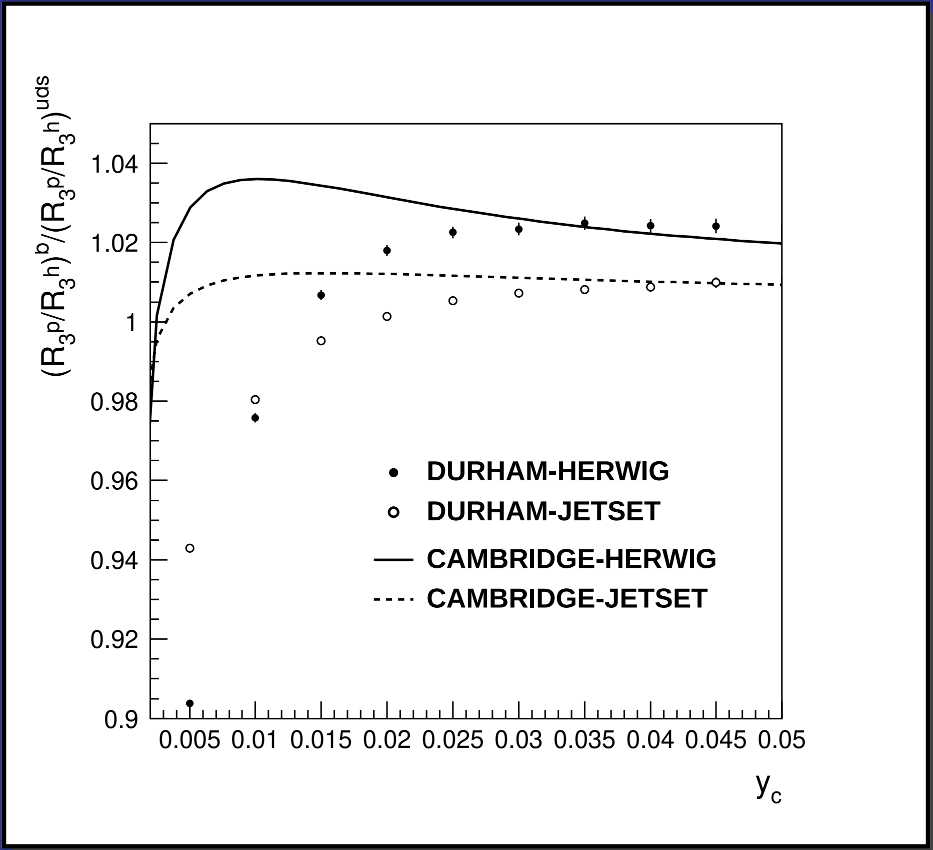
ALEPH (Pole-mass)	$M_b = 4.7 \pm 0.67(stat + exp + had + theo)$ GeV/c^2
DELPHI (Pole-mass)	$M_b = 4.2 \pm 0.61(stat + exp + had + theo)$ GeV/c^2

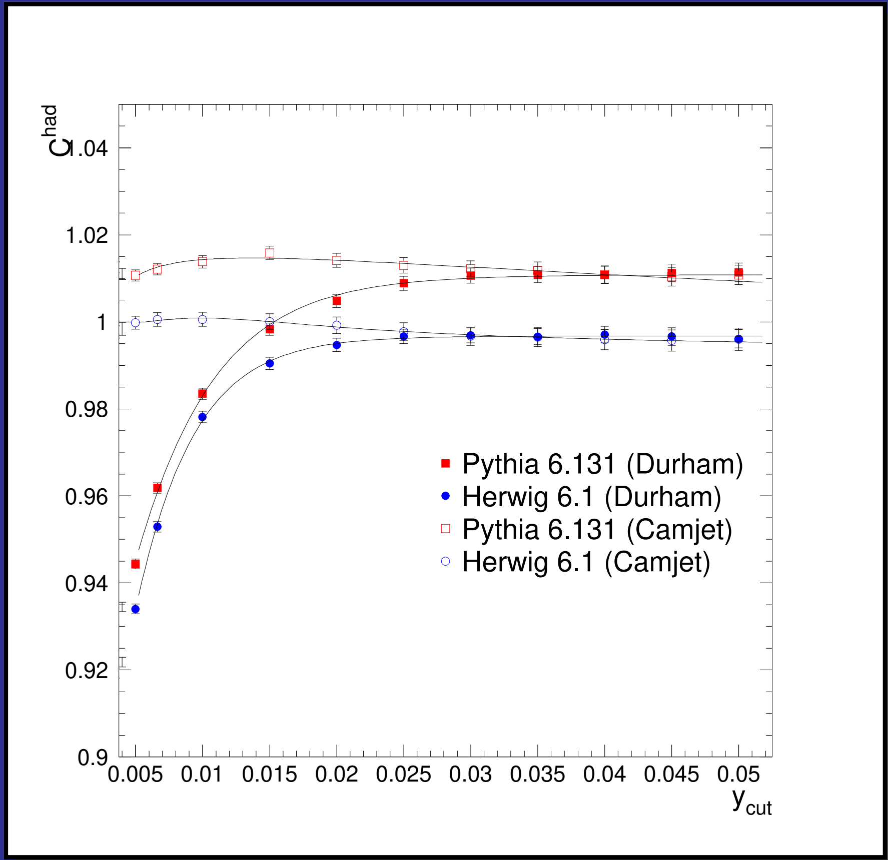
Conclusions

- b mass effects have been observed at LEP and SLC energies.
- NLO massive calculations are needed to understand the data and have allowed to:
  - Test flavour independence of α_s (assuming a value for $m_b(M_Z)$ or M_b).
  - Measure the b-quark at the M_Z scale (assuming α_s universality).

  with a precision of 1% using 3-jet observables like jet rates and event shapes.
- Not all observables are as convenient (theoretical and hadronization properties).
- The dominant error on all performed measurements is due to the uncertainty on the fragmentation process.
- The new tuned generators Herwig 6.1 (cluster) and Pythia 6.131 (string) used in DELPHI reduce the σ^{mod} for $R_3^{b\ell}$(Cambridge) with respect to older ones (Herwig 5.8 and Jetset 7.4).
- Big improvements have been achieved in the Monte Carlo generators to reproduce the observed mass effects.
- A better understanding of the b fragmentation function could allow a further improvement on the measurement.

New fragmentation corrections used

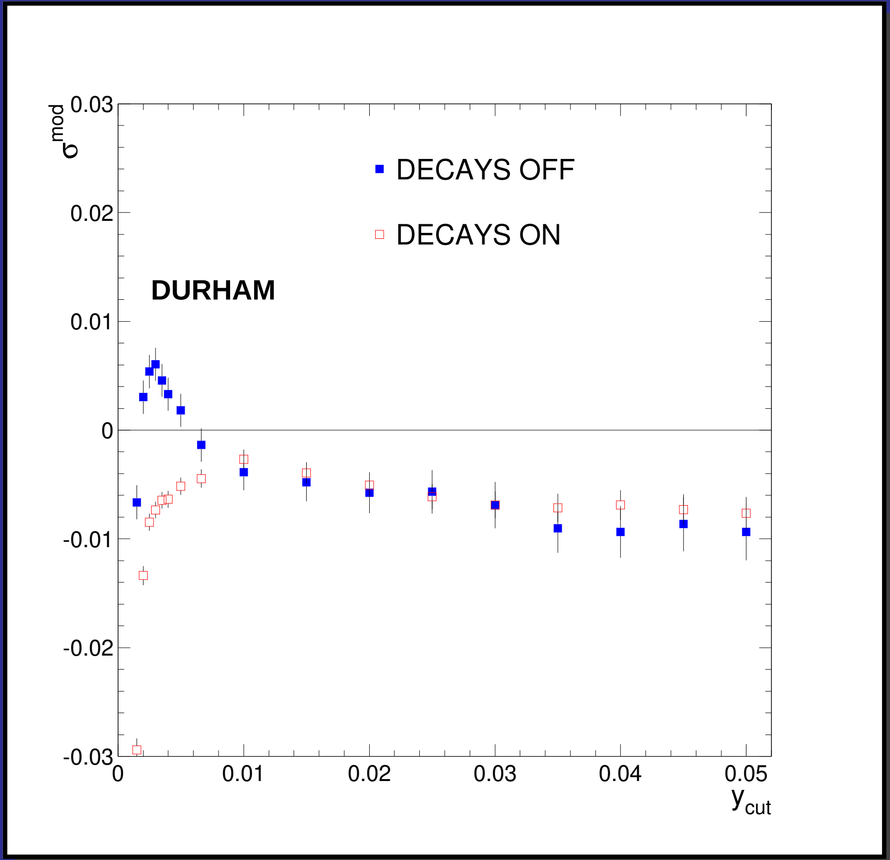


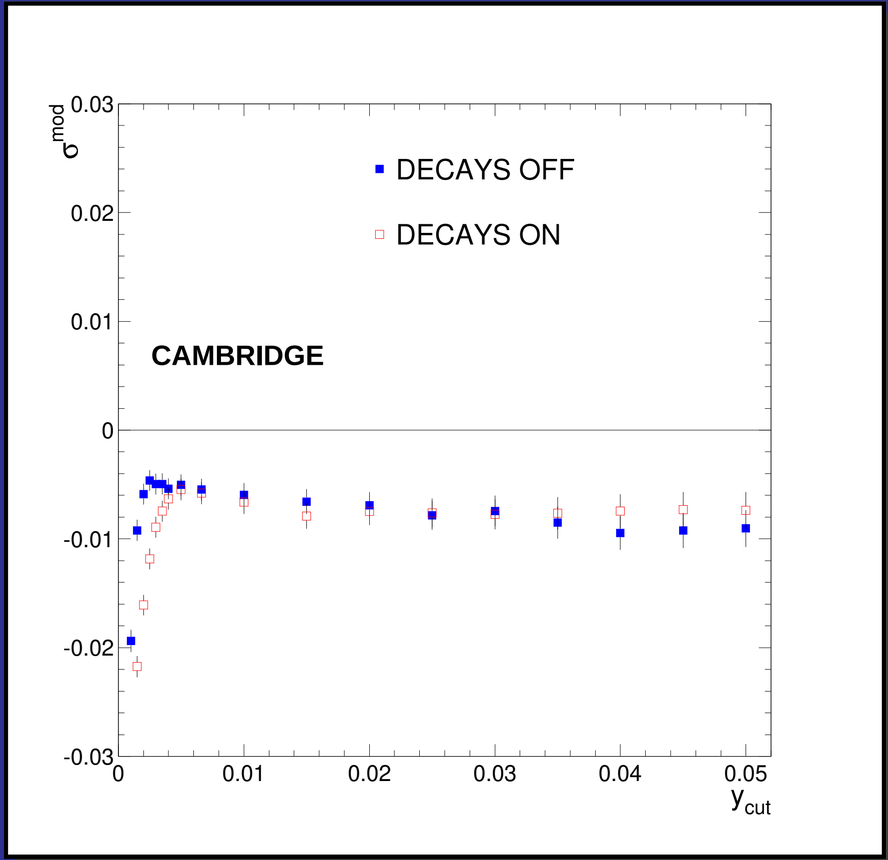


- Jetset and Pythia give the same C^{had}.
- Herwig 6.1 goes in the opposite direction of Herwig 5.8.

Influence of the decay model on σ^{mod}

$$\sigma^{mod}(y_c) = \sqrt{\sigma^{frag-mod}(y_c)^2 + \sigma^{dec-mod}(y_c)^2}$$





- $\sigma^{dec-mod}(y_c)$ is negligible for the interested region of y_c.