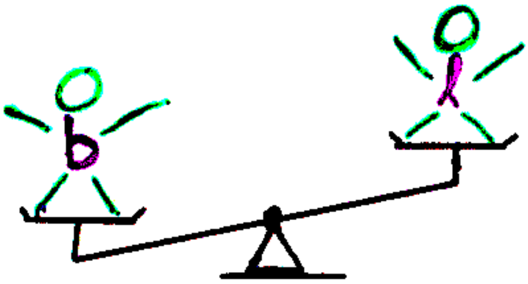
Experimental observation of quark mass effects in e^+e^- annihilation



O. Biebel
MPI Physik
12.02.01

- Introduction: Successes of QCD
- Quark mass effects ?
- Quark mass effects !
- Determination of b quark mass at m_Z

Introduction

- QCD very successful in describing strong interaction:
  - ▶ Colour factors C_A, C_F, T_R
  - ▶ non-abelian gluon self coupling
  - ▶ running of strong coupling α_S

    meanwhile: $\delta\alpha_S(M_Z) \simeq 2.5\%$

all thoroughly scrutinized by experiments

- a few missing pieces:

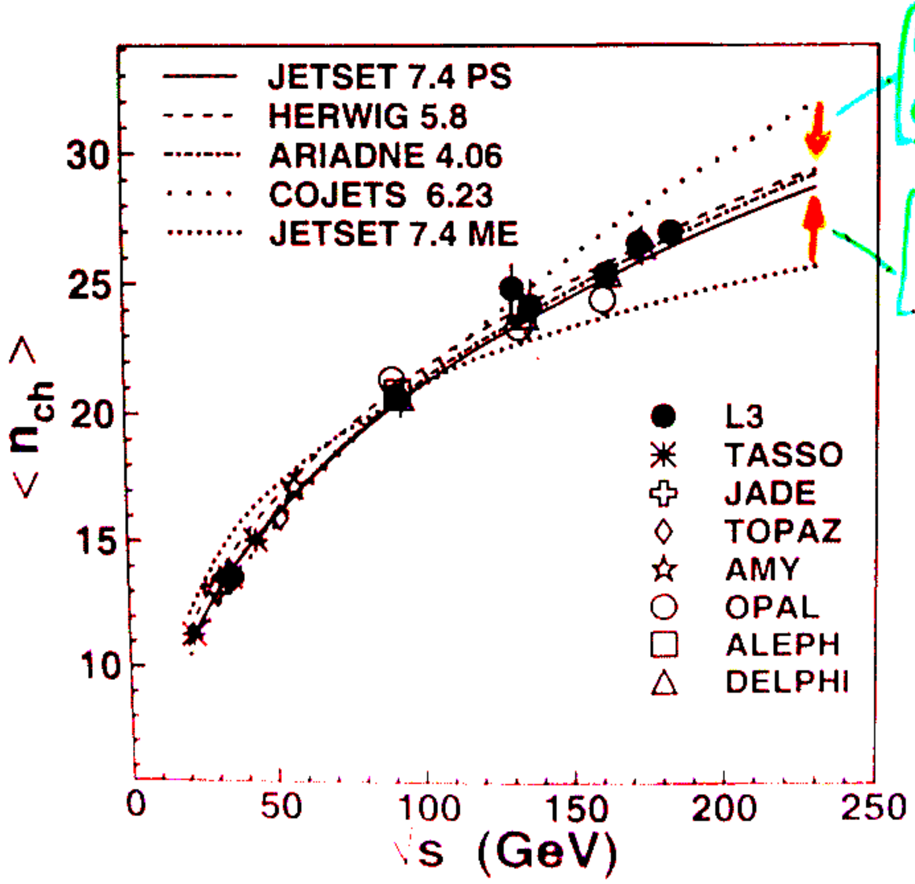
  effects due to finite quark masses:

  - ▶ "dead-cone" effect in $Q \to Q + g$
  - ▶ parton multiplicity: $Q\bar{Q}$ vs. $q\bar{q}$
  - ▶ running of quark masses (i.e. renormalized quark masses)

Successes of QCD

e.g. :
- gluon coherence
- LLA parton shower
- ...

average charged particle multiplicity :



[need colour coherence !

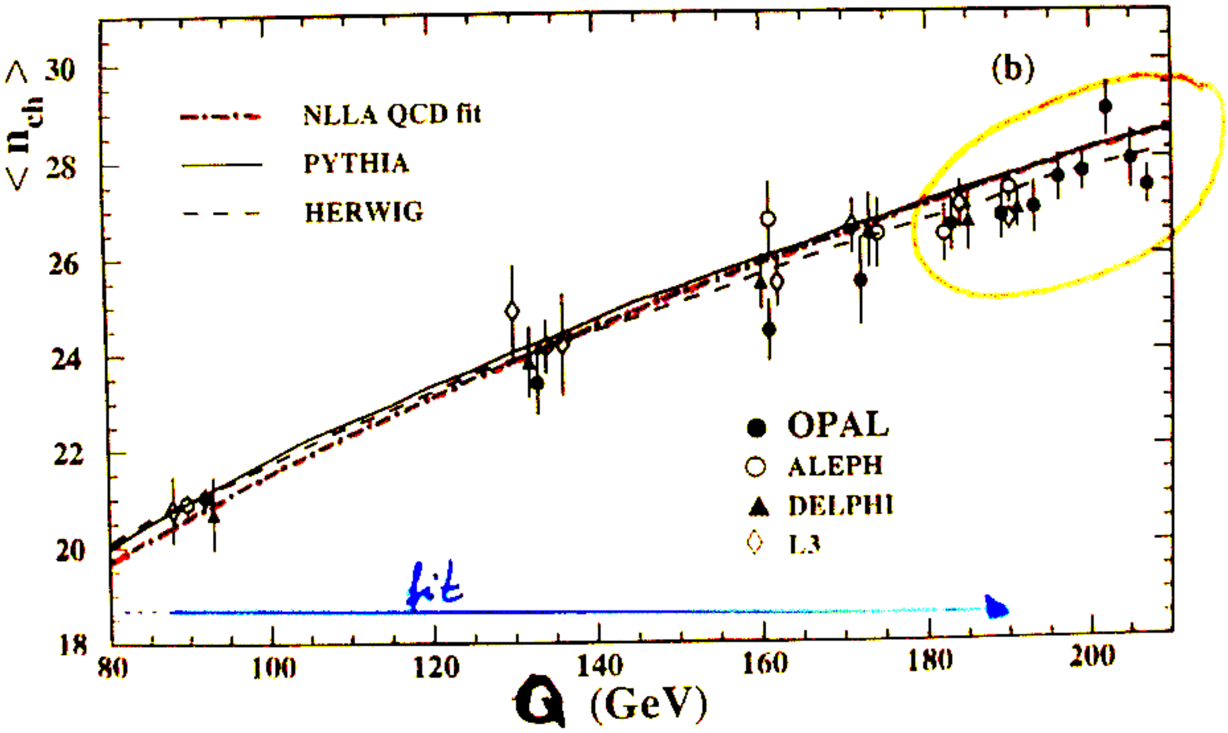
[need parton shower !

Quark mass effects? … multiplicity

NLLA : $\langle n_{ch}\rangle \sim (\alpha_s(Q))^b \cdot \exp\left[\frac{c}{\sqrt{\alpha_s(Q)}} \cdots\right]$

fit to exp. data $Q = 12 \ldots 189$ GeV:

→ NLLA overshoots data at high Q

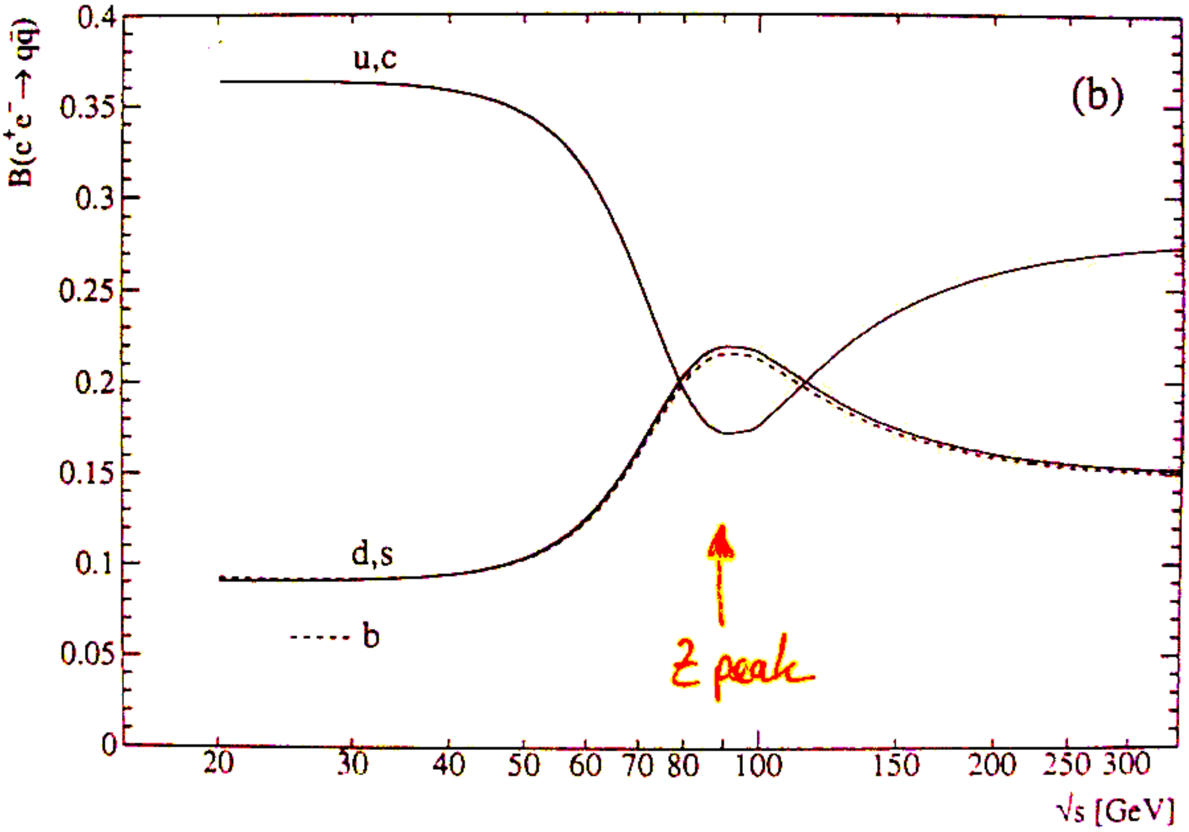


→ higher order terms missing?

→ impact of high precision Z peak data with large b-quark contrib.?

Branching ratio

$BR(e^+e^- \to \gamma/Z \to q\bar{q})$



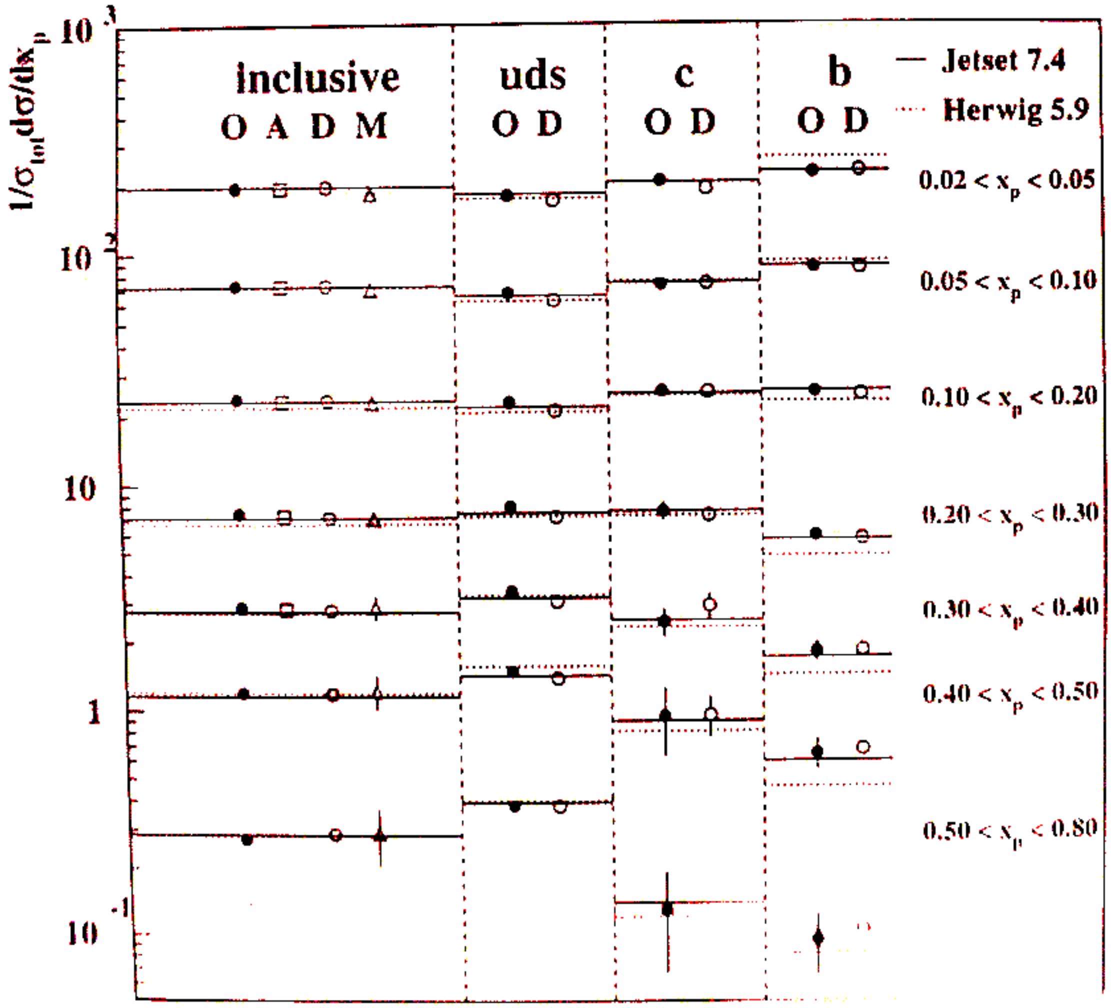
(ZFITTER program)

Quark mass effects? — fragmentation fct.s

expect.: higher q mass → harder fragmentation

observ.: heavy quark: soft fragmentation

at Z peak:



low ($x_p = \frac{2p}{E_{cm}}$)

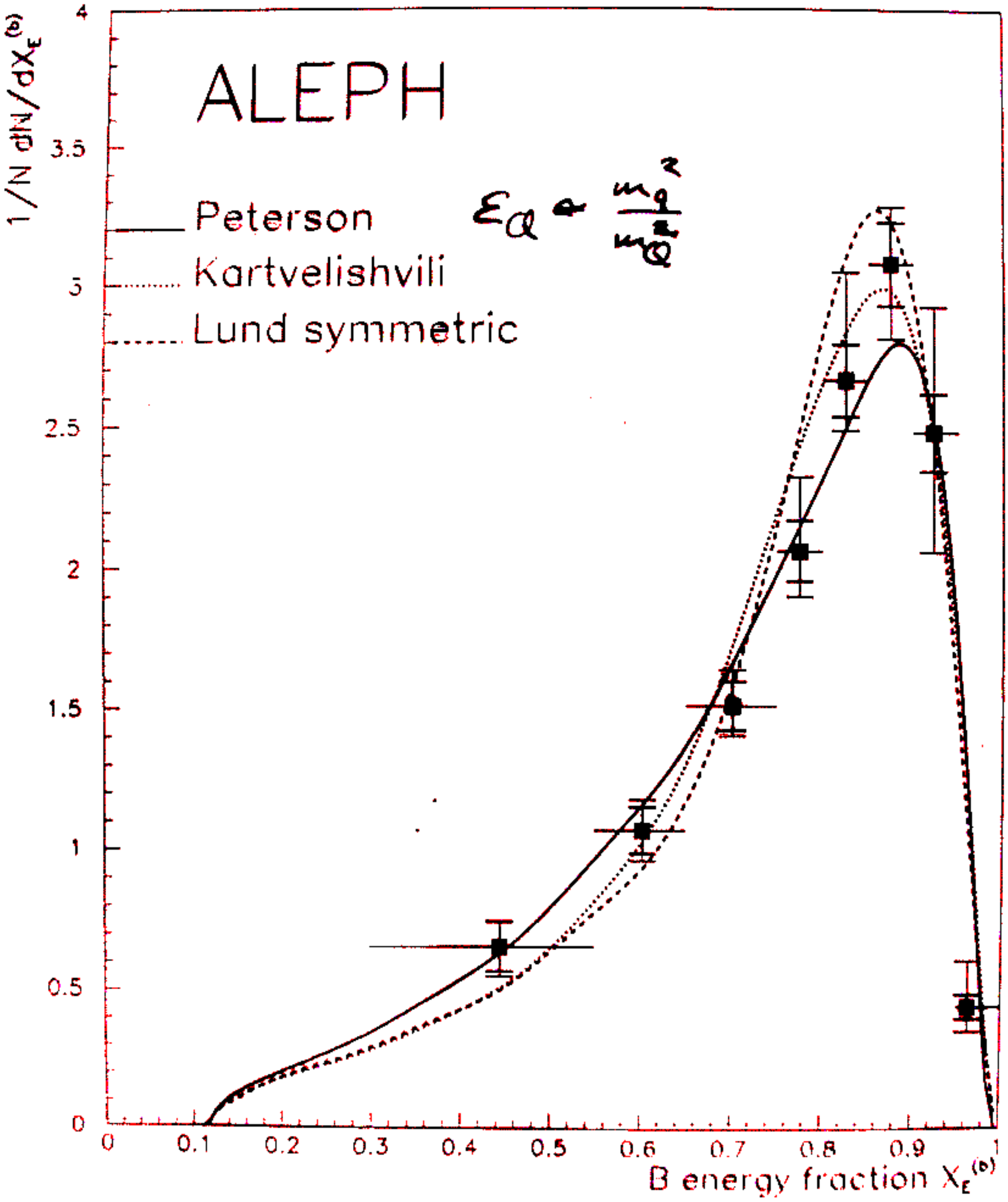
↓

high momentum

→ due to chain decays b → c → s ?

b fragmentation function

$\langle x_E^{(b)} \rangle = 0.715 \pm 0.015$



$\varepsilon_Q \propto \frac{m_q^2}{m_Q^2}$

$x_E = \frac{2E_{hadron}}{E_{cm}}$

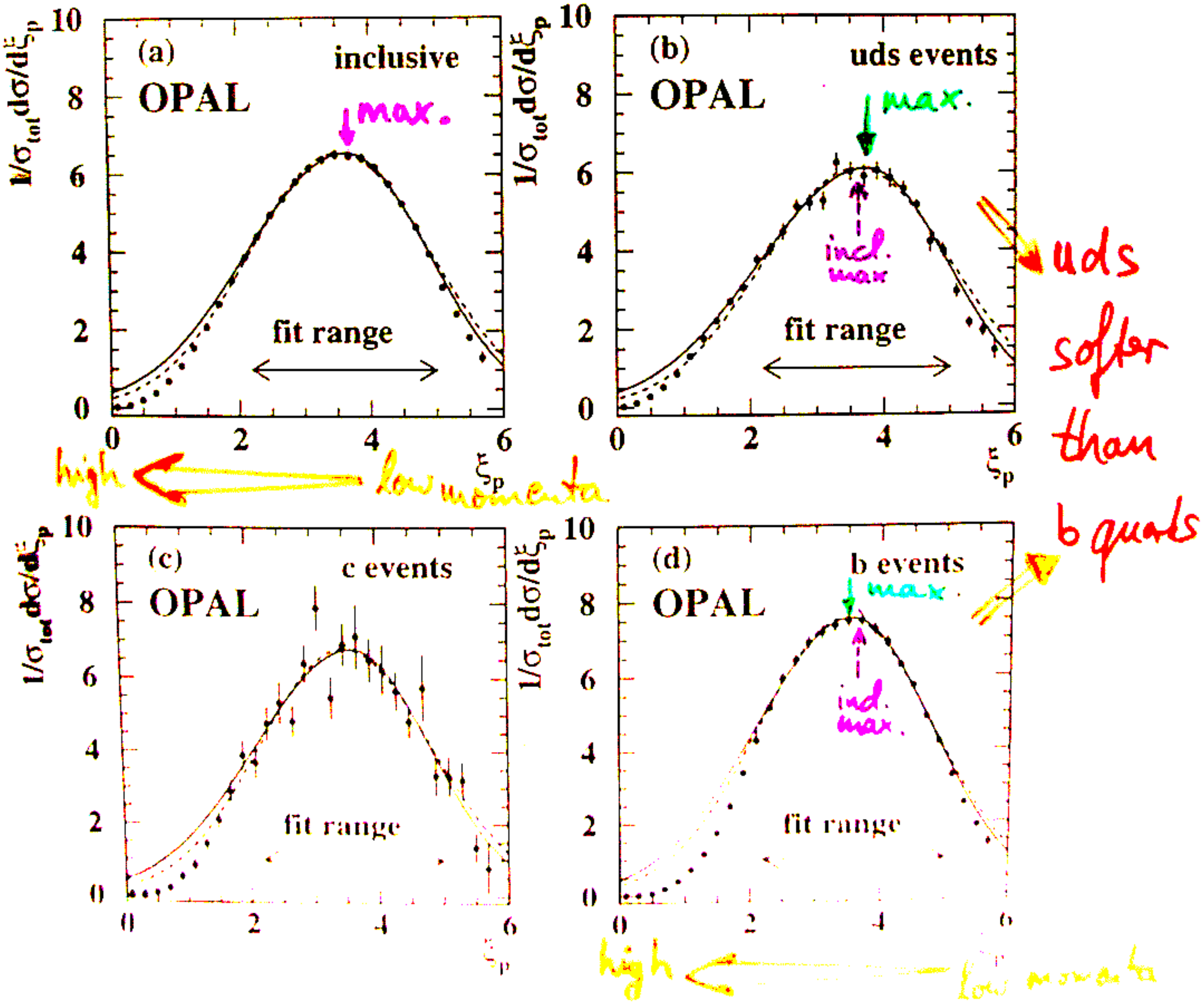
ALEPH
PL B 357, 699

Figure 7: The acceptance corrected $x_E^{(b)}$ spectrum of the leading b-meson for $f_{B^{**}}=27.9\%$ and $f_{D^{**}}=30\%$, compared with the predictions of different fragmentation models. The smaller error bar is statistical. The larger one is the sum of statistical + systematic errors. The errors shown do not account for the point-to-point correlations induced by the deconvolution process.

Quark mass effects? — $\ln \frac{1}{x_p}$ distributions

small x_p fragmentation: $\xi_p = \ln \frac{1}{x_p}$

NLLA: distorted Gaussian shape
(= limiting spectrum of MLLA)
around maximum



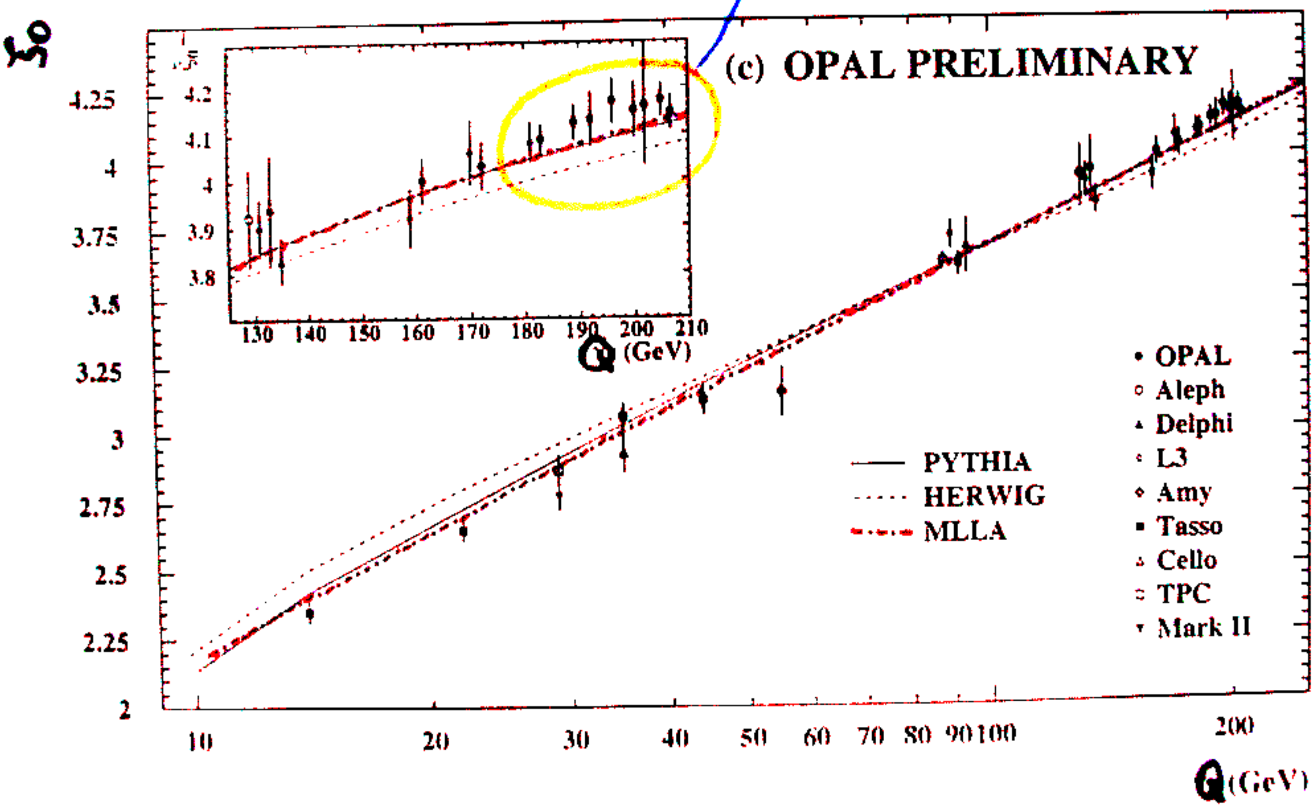
uds softer than b quarks

Quark mass effects? — position of max

MLLA: position of max $\xi_0 = Y \cdot \left(\frac{1}{2} + * \sqrt{\alpha_s(Y)} + \ldots\right)$
$(Y = \ln(Q/2Q_0))$

fit to exp. data $Q = 14 \ldots 189$ GeV:

→ MLLA undershoots data at high Q



→ higher order terms missing?

→ impact of high precision Z peak data with large b-quark contrib.?

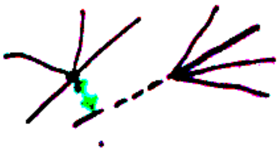
Quark mass effects?

- massless QCD works fine in principle
- some experimental evidence for quark mass effects
- a few concrete examples
    - multiplicity differences : b vs. light
light vs. light
    - flavour (in-)dependence of strong coupling
    - b quark mass at Z mass scale

Experimental identification of quarks

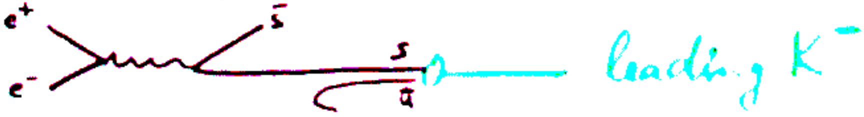
- b quarks
  - semi-leptonic decays : e , μ
  - decay vertices

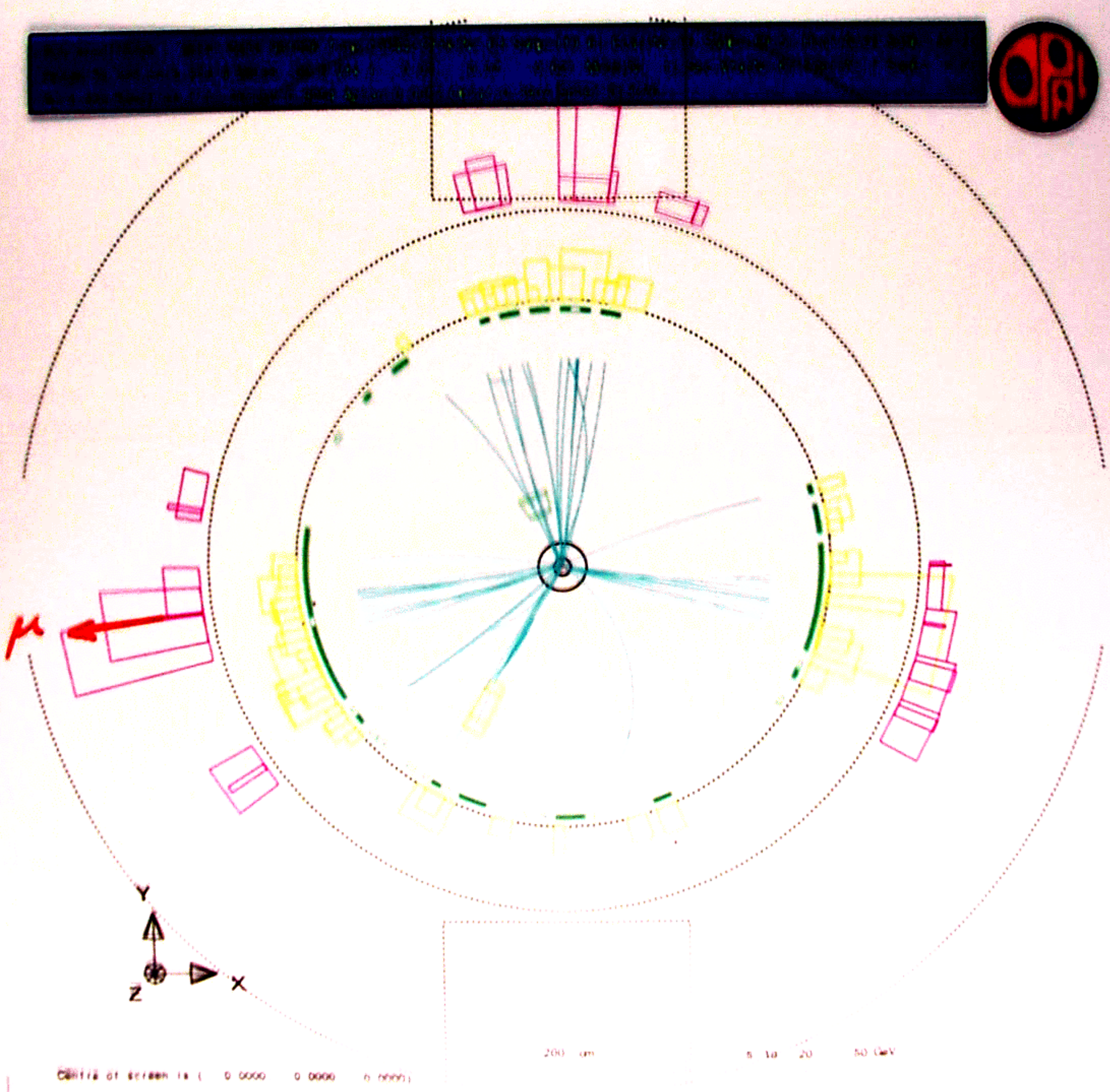
  - impact parameter



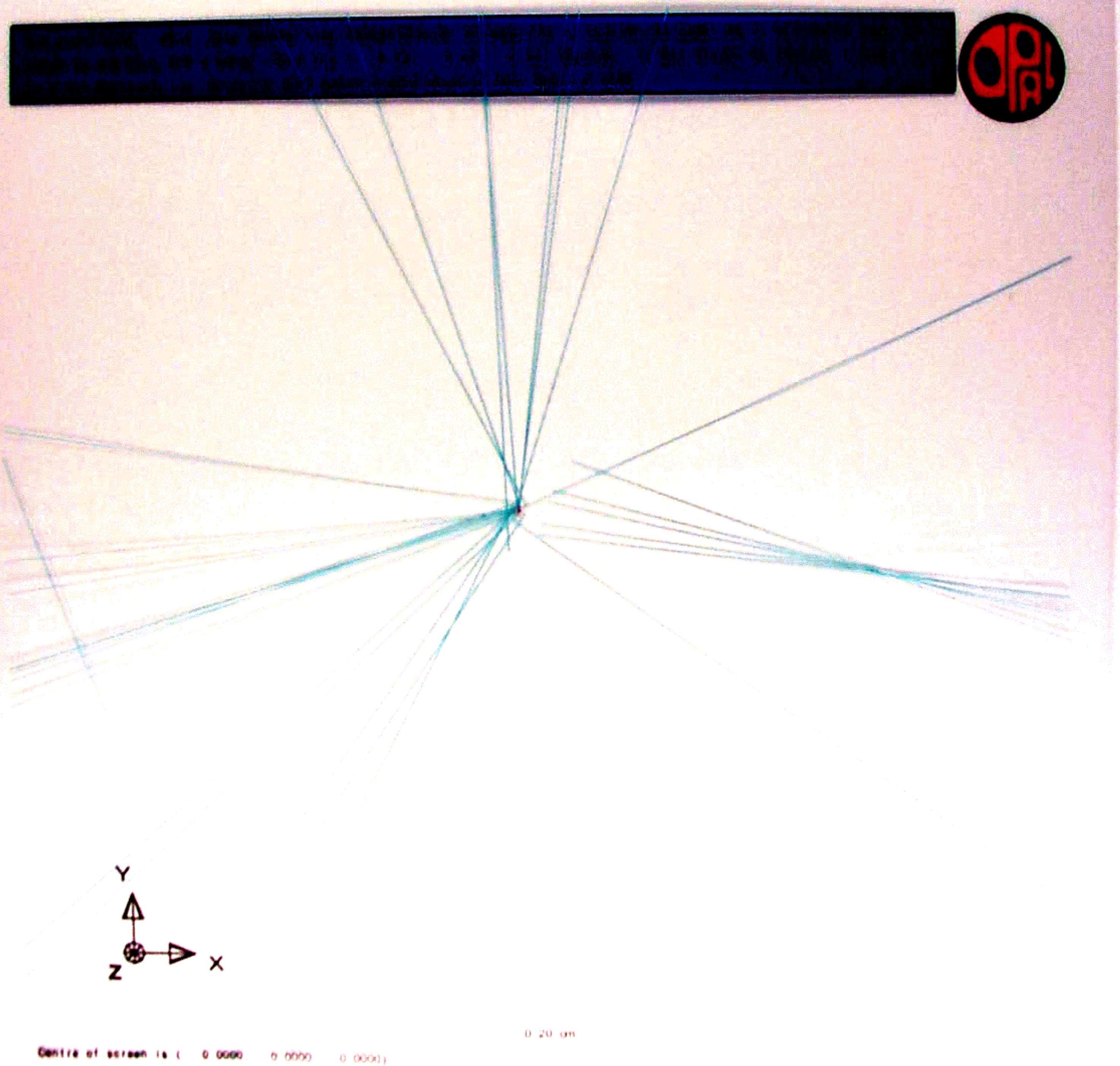
- c quarks
  - $D^{*\pm}$ decays
  - semi-leptonic decays : e , μ
  - decay vertices
  - impact parameter
- u, d, s quarks
  - leading particle effect

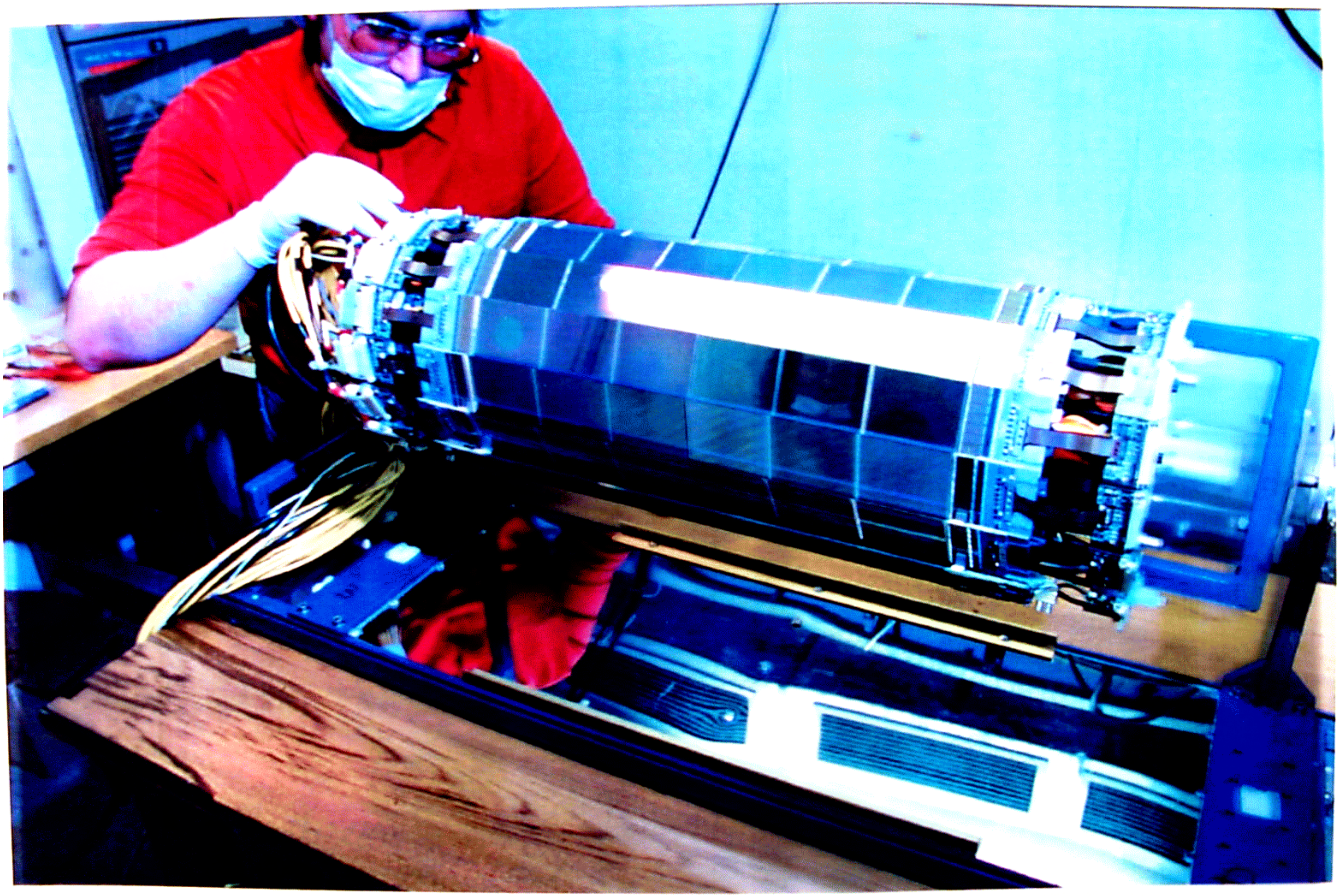
e.g.



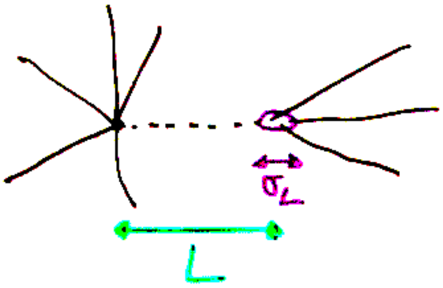

μ
Y
Z
X
200 cm
5 10 20 50 GeV
Centre of screen is (0.0000 0.0000 0.0000)

x500 zoomed

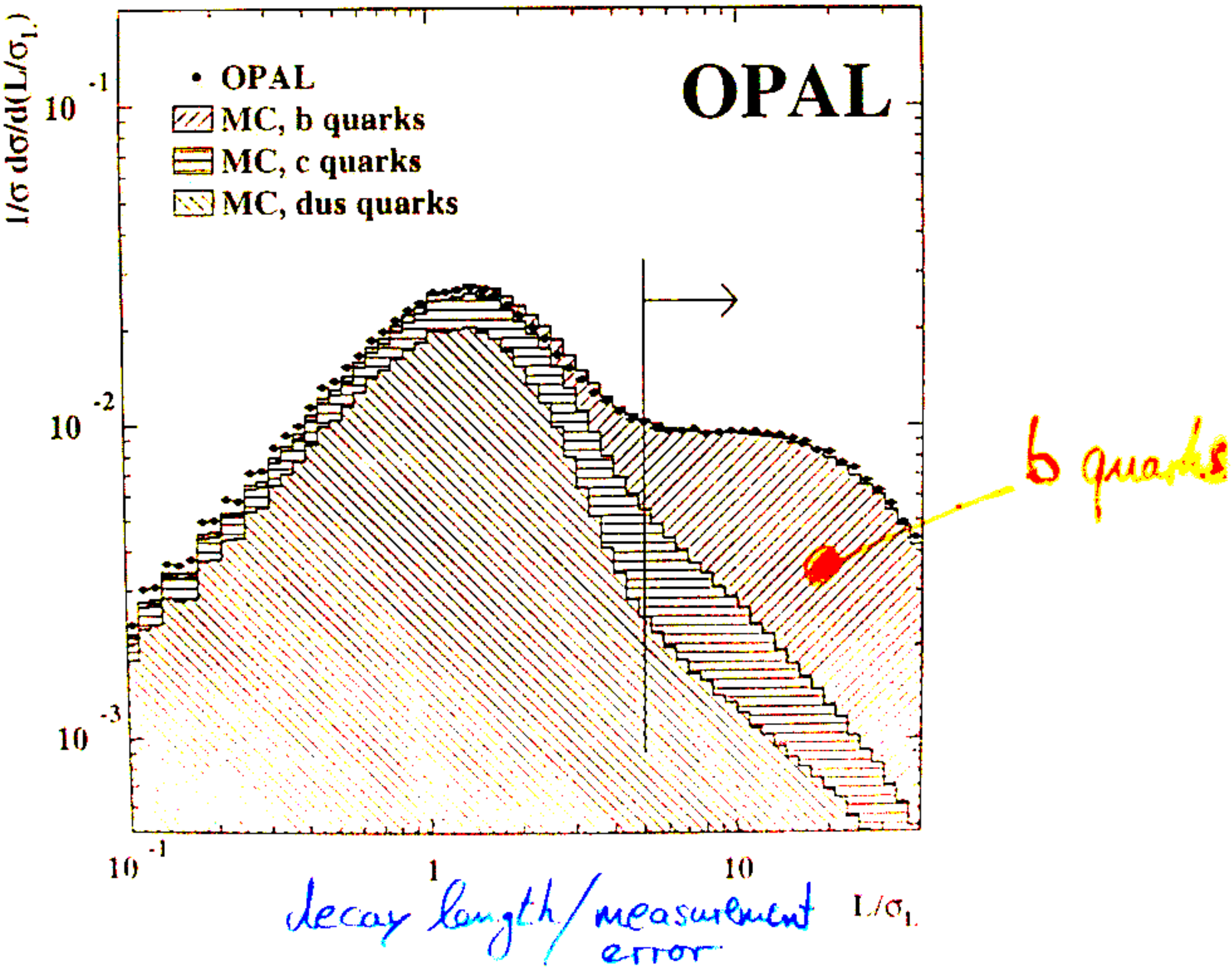




b quark tagging by vertices

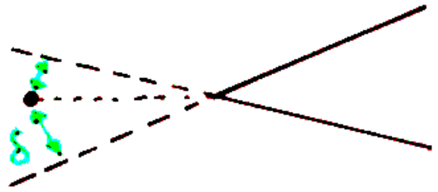


decay length significance : L/σ_L

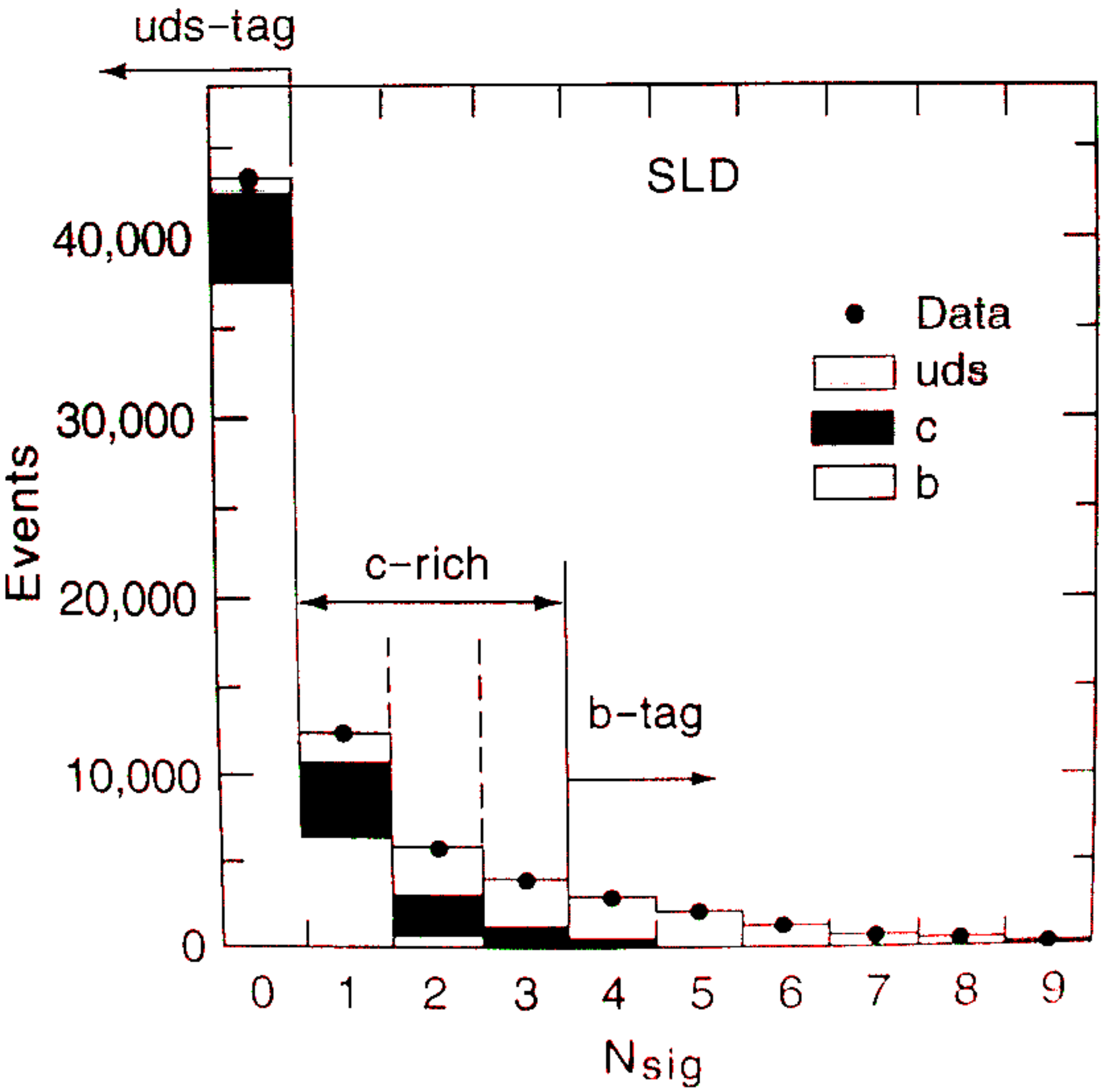


⟹ Efficiency typ 70%
Purity typ 90%

b quark tagging by impact parameter



N_{sig} = no. of tracks with significant impact parameter δ



Quark mass effects ! – $\langle n_{Q\bar{Q}}\rangle$ vs. $\langle n_{q\bar{q}}\rangle$

- **Flavour Independent Fragmentation** (Kisselev et al. ZP C41, 521)

$$\langle n_{Q\bar{Q}}(Q)\rangle = 2\cdot\langle n_B^{decay}\rangle \; +$$

$$+\iint dx_B\, dx_{\bar{B}}\, \underbrace{f(x_B)\cdot f(x_{\bar{B}})}_{\text{b fragment. fct.}}\cdot \underbrace{\left\langle n_{q\bar{q}}\left(Q\cdot\left[1-\frac{x_B+x_{\bar{B}}}{2}\right]\right)\right\rangle}_{\text{light flavour mult. at reduced energy}}$$

$$\Rightarrow \boxed{\langle n_{Q\bar{Q}}(Q)\rangle \xrightarrow{Q\to\infty} \langle n_{q\bar{q}}(Q)\rangle}$$

- **QCD: MLLA calculation** (eg. in Khoze, Ochs, et al. MPI-PhT/2000-35)

$$\langle n_{Q\bar{Q}}(Q)\rangle = 2\cdot\langle n_B^{decay}\rangle \; + \langle n_{q\bar{q}}(Q)\rangle - \langle n_{q\bar{q}}(m_b\sqrt{e})\rangle$$

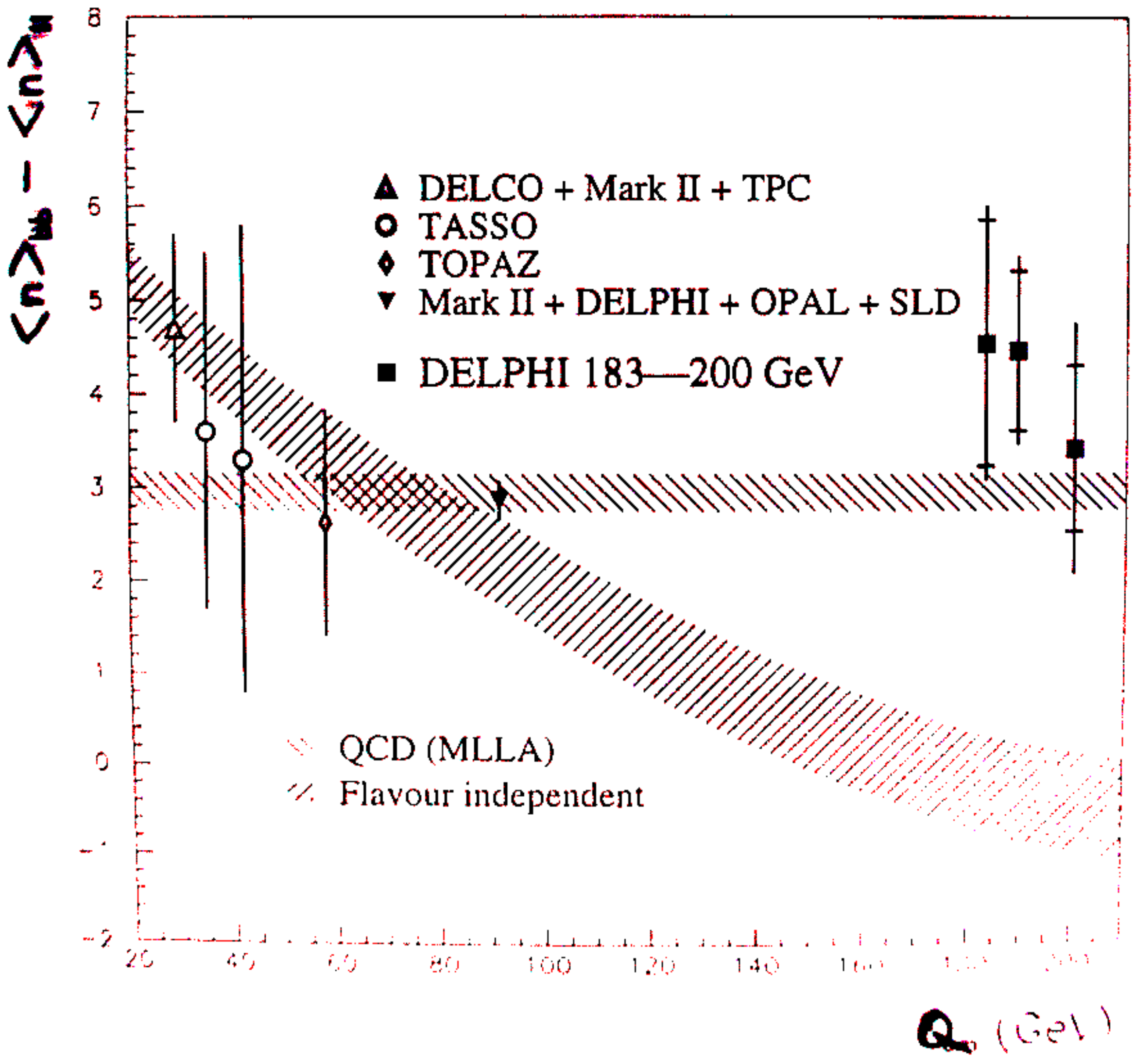
$$\Rightarrow \boxed{\delta_{Q\ell} \equiv \langle n_{Q\bar{Q}}(Q)\rangle - \langle n_{q\bar{q}}(Q)\rangle \approx \text{const.}(Q)}$$

$$= 2\cdot\langle n_B^{decay}\rangle - \langle n_{q\bar{q}}(m_b\sqrt{e})\rangle \approx 3.6 \ldots 5.5$$

eg. Schumm et al. PRL 69, 3025; Petrov et al. ZP C66, 453

Quark mass effects! — $\langle n_{a\bar{a}} \rangle$ vs. $\langle n_{q\bar{q}} \rangle$

- QCD: $\delta_{b\ell} \approx 3$ und const.(Q)!
- + $\delta_{b\ell}$ value depends on m_b



$\Rightarrow$ QCD ✓

Quark mass effects! — $\langle n_{d\bar{d}}\rangle$ vs. $\langle n_{s\bar{s}}\rangle$?

- very difficult to distinguish between light flavours u, d, s
- leading particle effect (at Z peak):

K^0_S : $s + (d)$

$K^\pm$: $s + (u)$

$\pi^\pm, K^\pm, \overset{(-)}{p}$: $u + d + s$

- take care of bias due to leading particle
- statistical unfolding

$$\Rightarrow \left\{ \begin{aligned} \langle n_s\rangle - \langle n_d\rangle &= -1.4 \pm 2.0 \\ \langle n_s\rangle - \langle n_u\rangle &= 2.3 \pm 1.5 \\ \langle n_d\rangle - \langle n_u\rangle &= 3.7 \pm 2.5 \end{aligned} \right.$$

(OPAL, CERN-EP/[illegible]
accept. EPJC

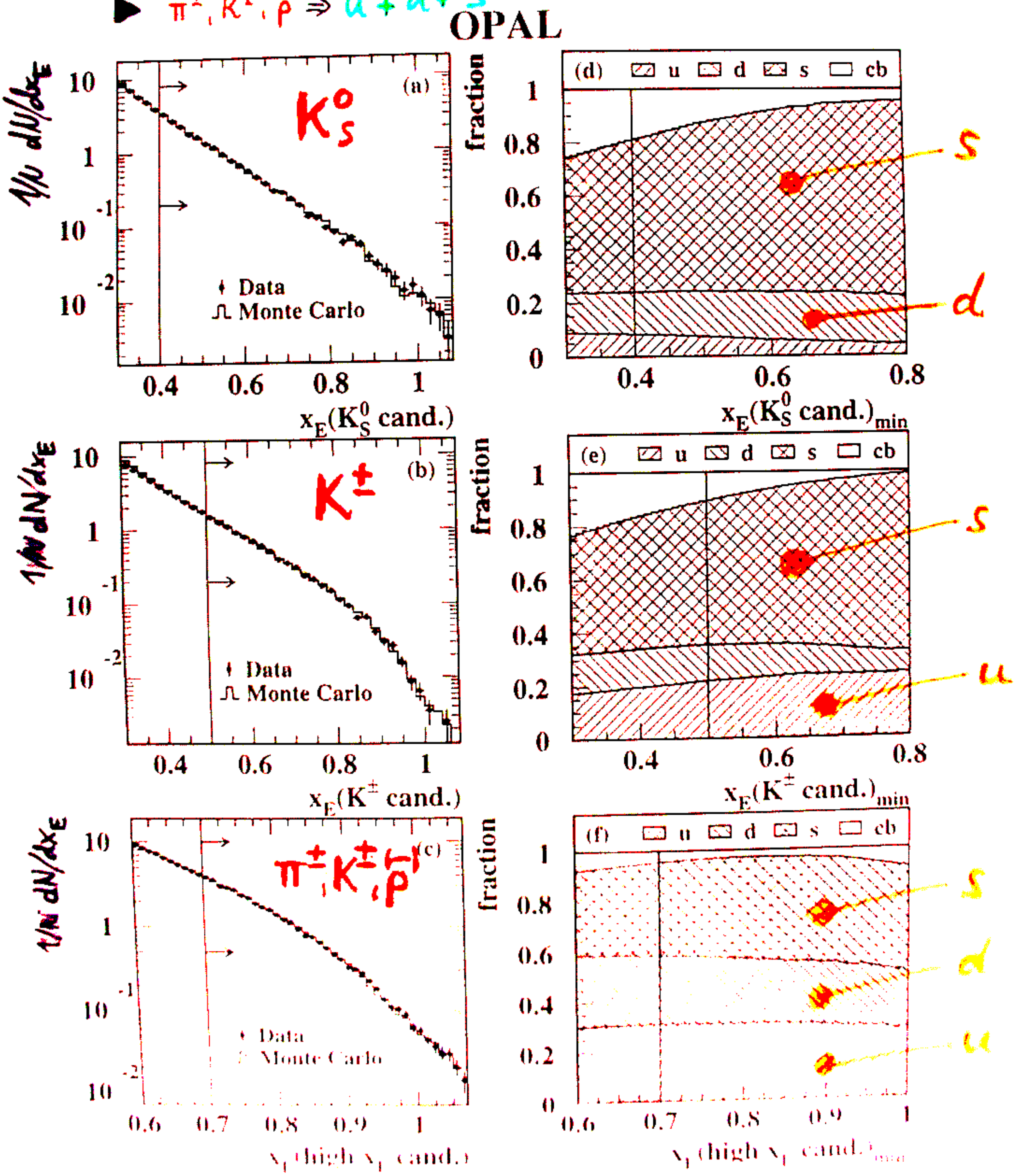
⇒ large errors

⇒ only a single energy $Q = 91$ GeV

light quark tagging by leading particle effect

- $K^0_s \Rightarrow s + (d)$
- $K^\pm \Rightarrow s + (u)$
- $\pi^\pm, K^\pm, \overset{(-)}{p} \Rightarrow u + d + s$

} statistical unfolding



Quark mass effects! — flavour (in-)dependence

- u, d, s multiplicities ⟶ flavour-depend. coupling

$$\langle n_{q\bar{q}} \rangle \sim \left(\alpha_s^{NLLA}(M_Z)\right)^b \cdot \exp\left[\frac{c}{\sqrt{\alpha_s^{NLLA}(M_Z)}} + \dots\right]$$

⇒ α_s^{NLLA} for flavour $q = u, d$, or s

- ratios of $\alpha_s^q / \alpha_s^{q'}$ for better comparison

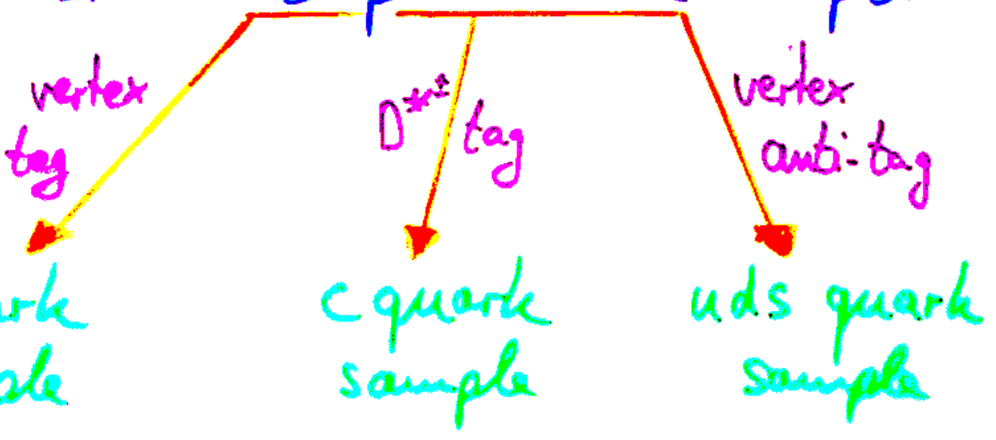
$$\Rightarrow \left\{ \begin{array}{l} \alpha_s^u / \alpha_s^d = 0.88 \pm 0.08 \\ \alpha_s^s / \alpha_s^d = 0.96 \pm 0.06 \\ \alpha_s^s / \alpha_s^u = 1.09 \pm 0.06 \end{array} \right.$$

⇒ flavour independence ≈ OKAY

but hadron decays may interfere

Quark mass effects! – flavour (in-)dependence

- high statistics Z peak data sample



b quark sample

c quark sample

uds quark sample

- flavour dependent investigation of
  - ▶ event shapes $(1-T, M_H, B_W, C, y_3)$
  - ▶ jet rates $(E, E0, P, P0, D, G, \ldots)$
- … and flavour dependent determination of α_s
  - ▶ massless $\mathcal{O}(\alpha_s^2)$ QCD (ERT, NP B178, 421 and others)
  - ▶ massive QCD predictions (full $\mathcal{O}(\alpha_s^2)$ since 1997 available)

c quark tagging by $D^{*\pm}$ decays

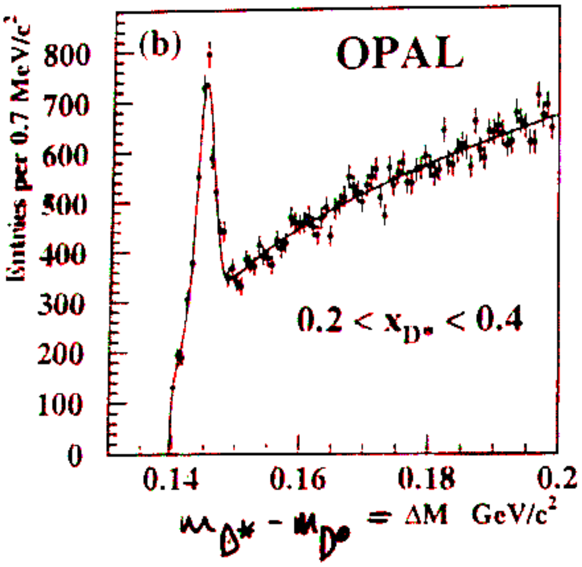
- $D^{*+} \to D^0 \pi^+$
  - $\to K^- \pi^+$
  - $\to K^- \pi^+ \pi^0$
  - $\to K^- \pi^+ \pi^- \pi^+$
  - $\to K^- e^+ \nu_e$
  - $\to K^- \mu^+ \nu_\mu$
- + c.c.

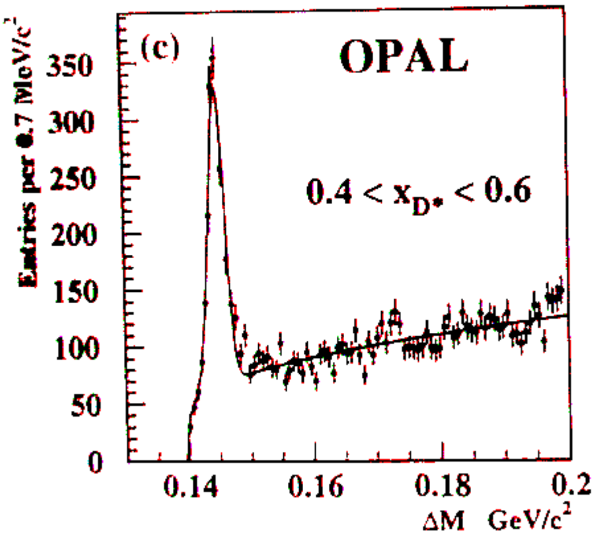
$\Downarrow$

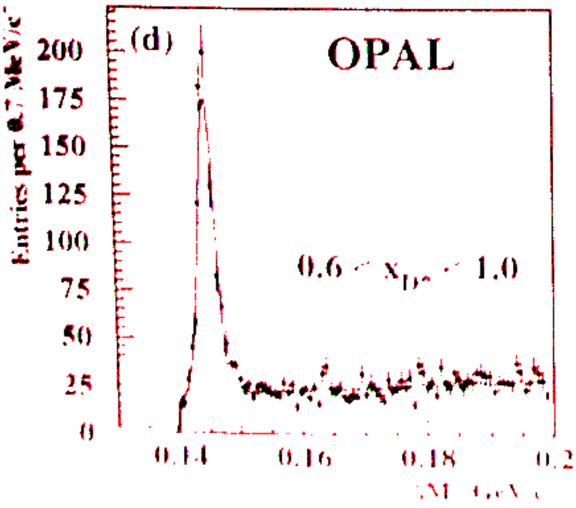
Efficiency typ. 2%

Purity typ. 60%

(but ~23% $b \to c \to D^*$)







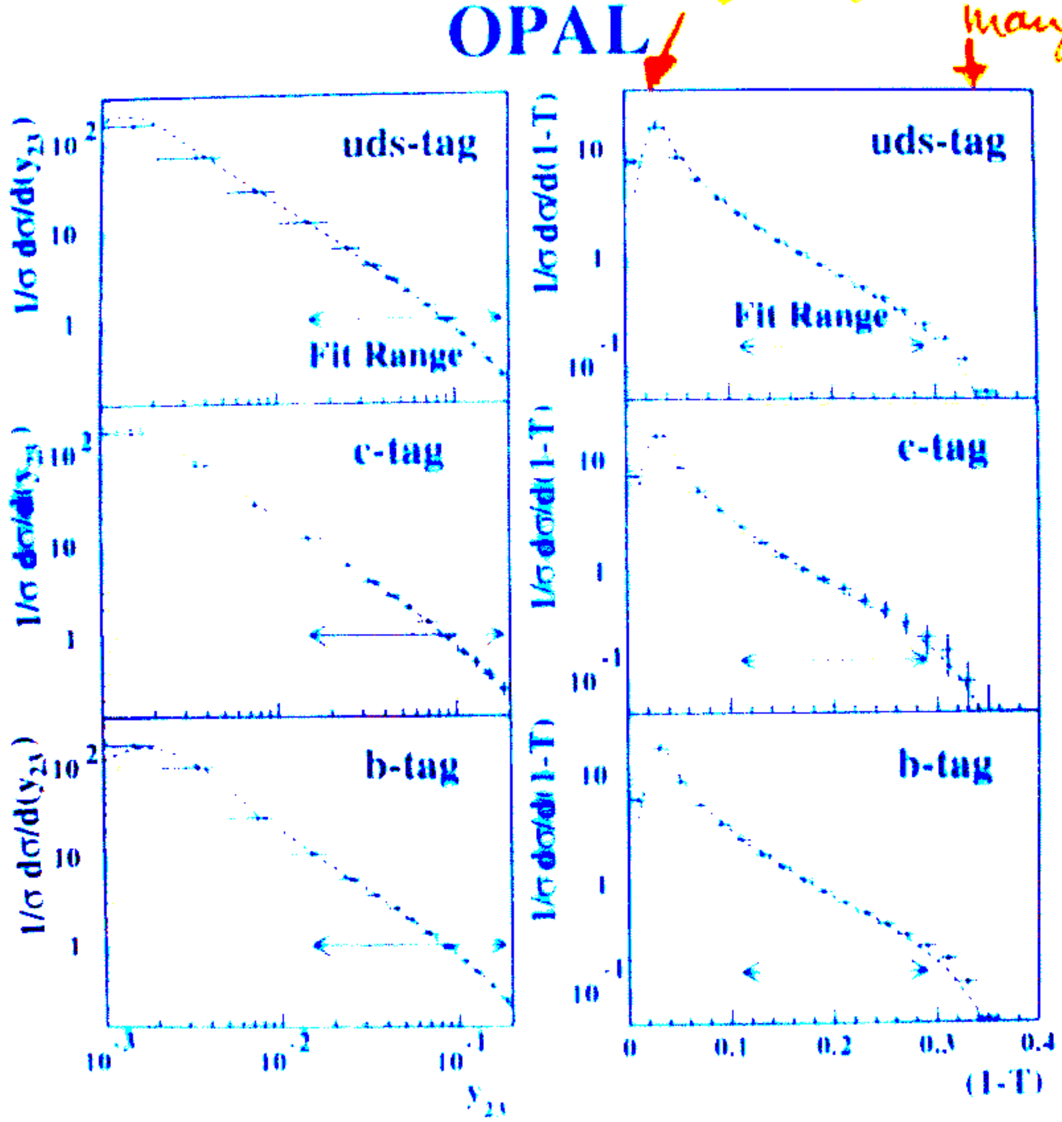
Massive QCD predictions

- LO calculations:
  - Joffe PL B78 (1978) 277
  - Kramer et al ZP C4 (1980) 149
  - Laermann et al PL B89 (1980) 225
  - Niles PRL 45 (1980) 319
- NLO (without loops):
  - Ballestrero et al. PL B294 (1992) 425
  - Ballestrero et al. NP B415 (1994) 265
  - Ballestrero et al. PL B323 (1994) 53
- full NLO calculation:
  - Bernreuther et al. PRL 79 (1997) 189 ($\overline{MS}$ mass)
  - Rodrigo et al. PRL 79 (1997) 193 (pole mass)
  - Nason et al. NP B521 (1998) 237 (pole mass)

Quark mass effects! — flavour (in-)dependence

2 jet regime

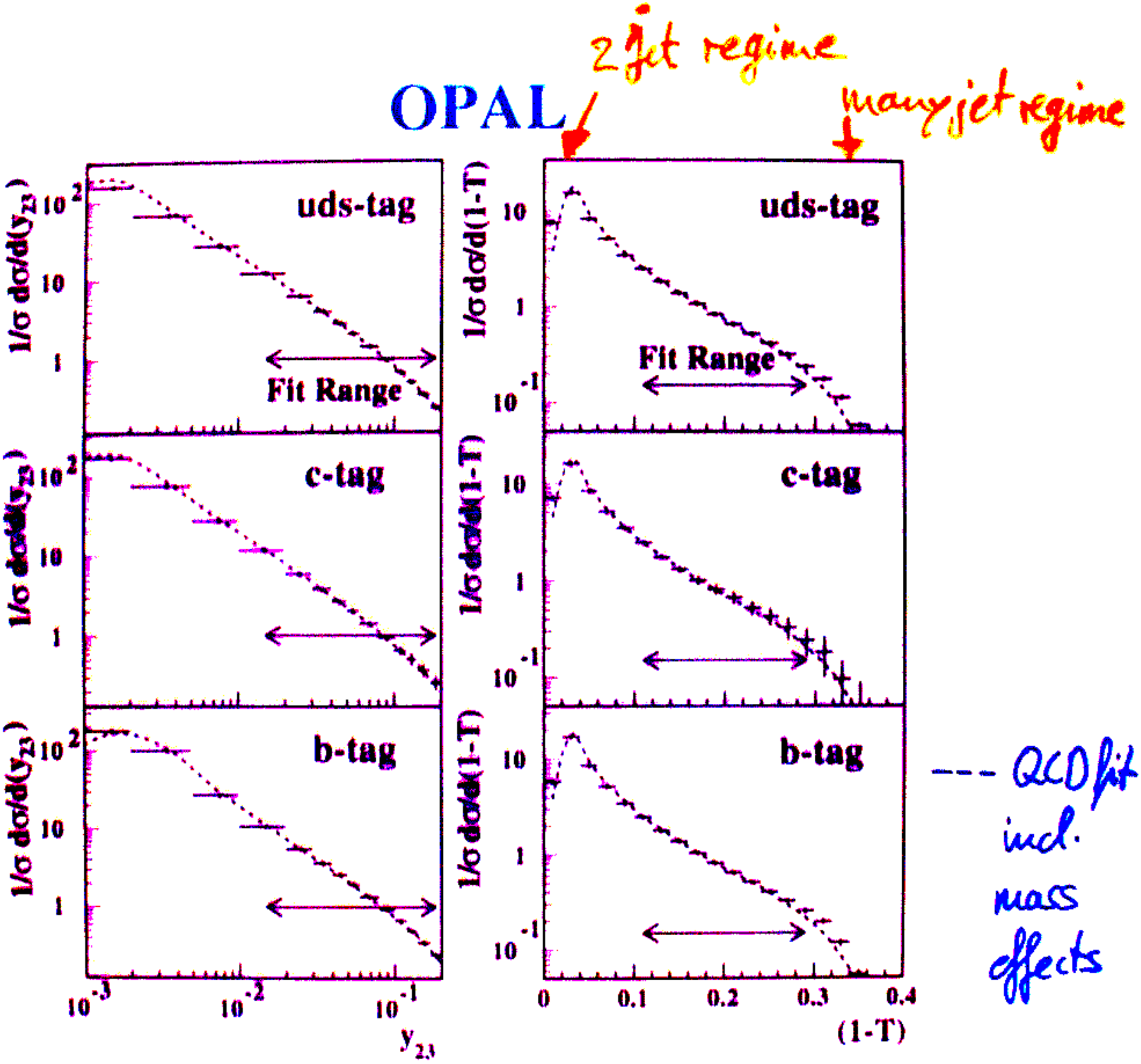
many jet regime



--- QCD fit incl. mass effects

Notice:
- small statistical uncertainties
- tiny mass effects

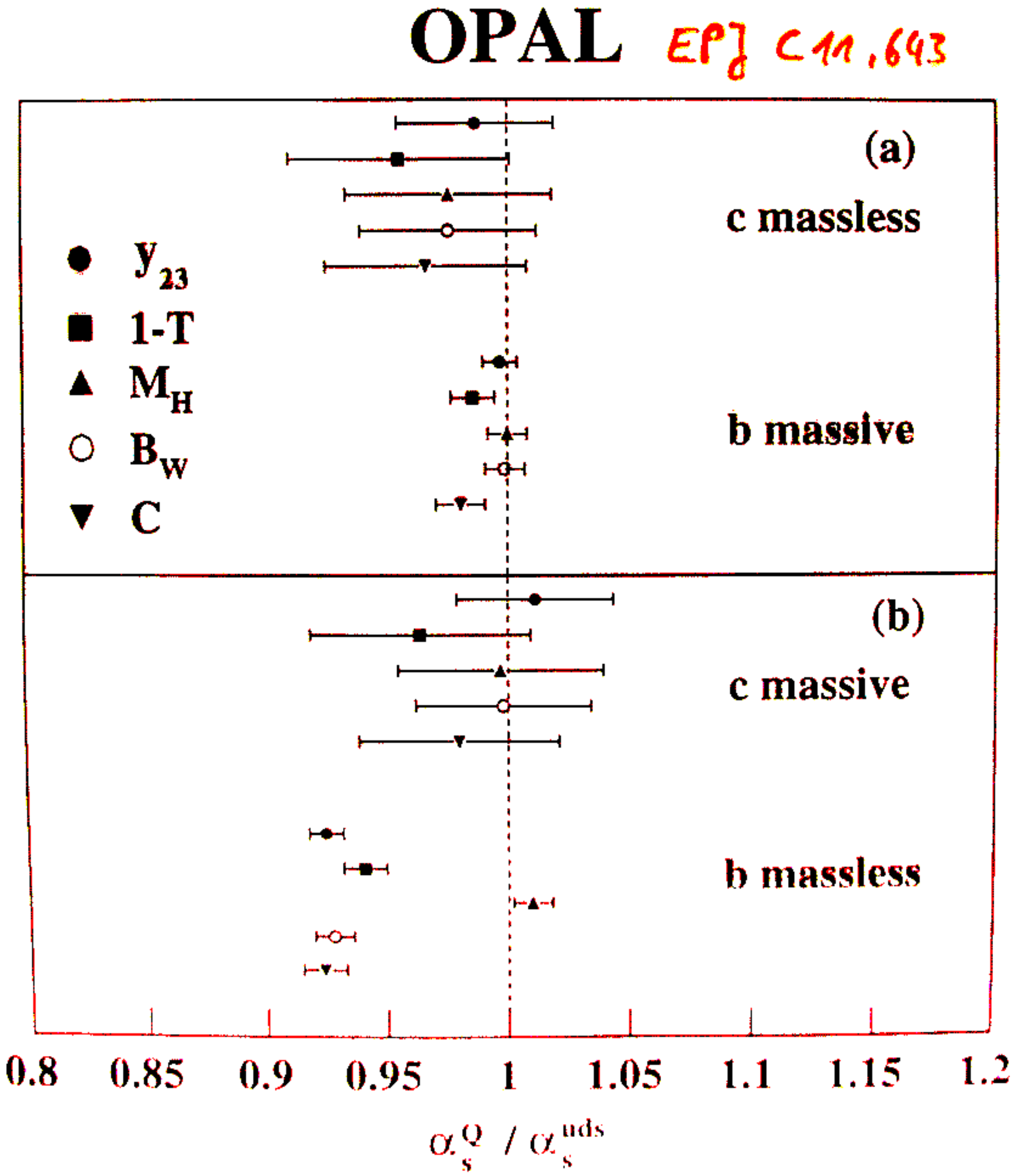
Quark mass effects! – flavour (in-)dependence



Notice:
- small statistical uncertainties
- tiny mass effects

Quark mass effects! — flavour (in-)dependence

- results of fits :



EPJ C11, 643

⇒ 2 - 7% mass effects for c & b

Quark mass effects! — flavour (in-)dependence

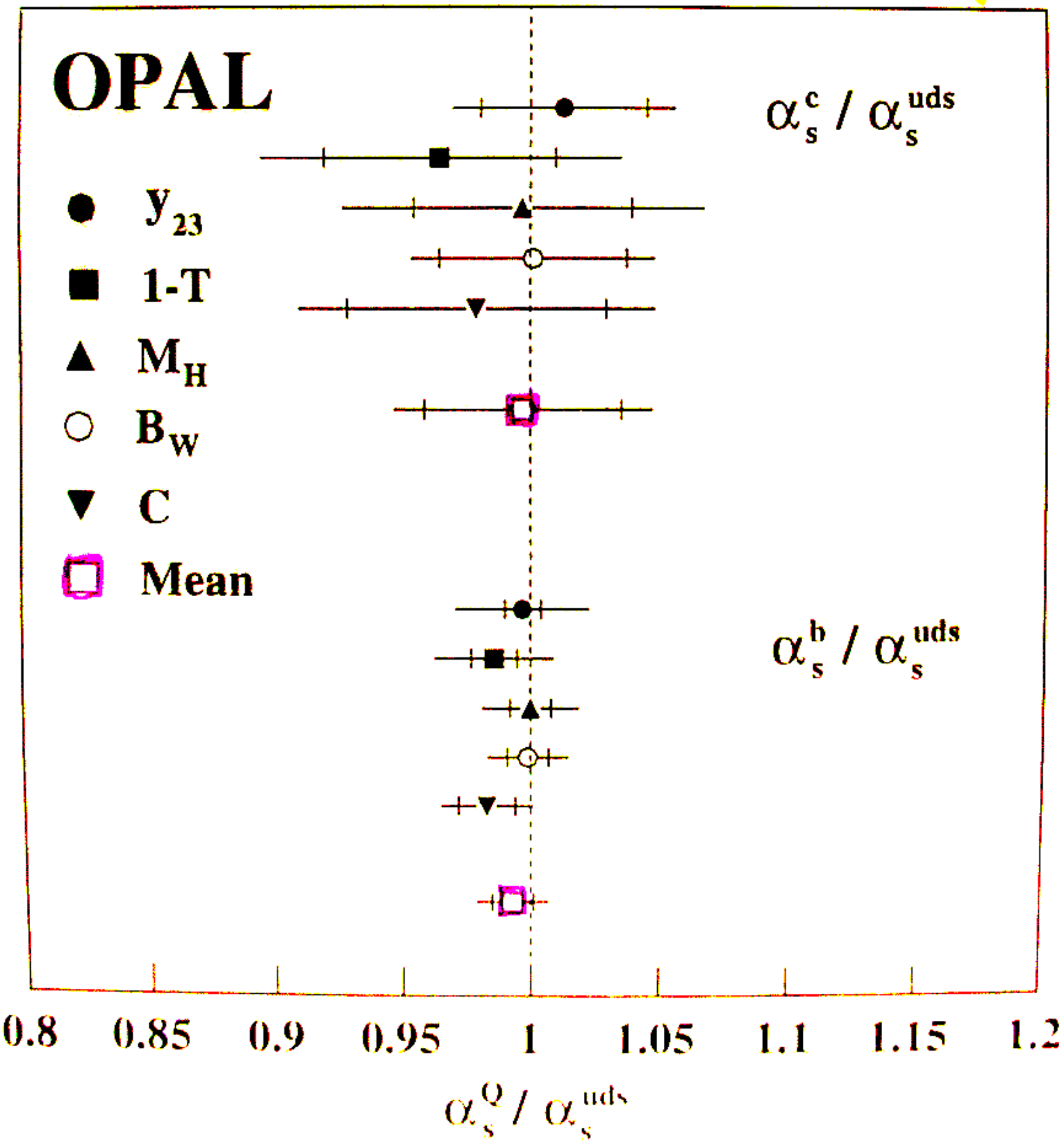
- Flavour independent coupling:

$\alpha_s^c/\alpha_s^{uds} = 0.977 \pm 0.050$ (5% precis.)

$\alpha_s^b/\alpha_s^{uds} = 0.993 \pm 0.015$ (1.5% precis.!)

when quark masses considered!

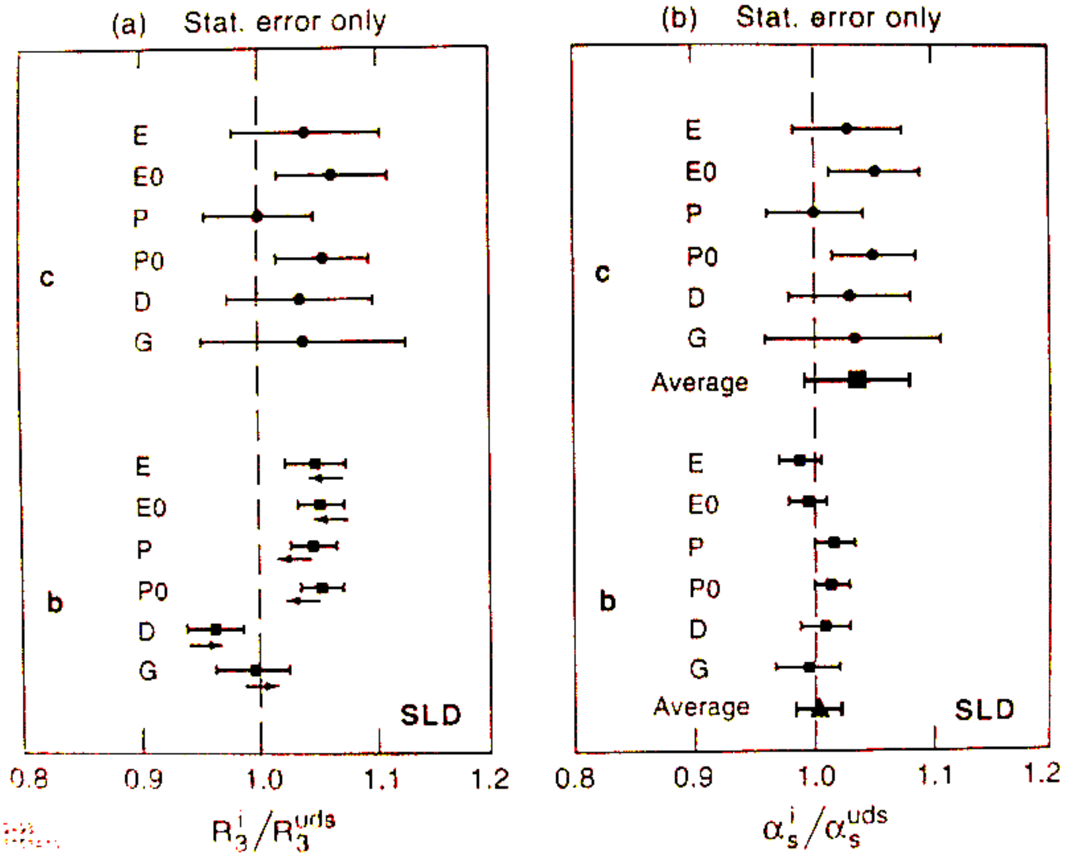
EPJ C11, 643



Quark mass effects! – Flavour (in-)dependence

- Flavour independent coupling when quark masses considred

precision: $\delta_c = 6\%$, $\delta_b = 4\%$



$$\frac{\# \; Q \to Q + g}{\# \; q \to q + g}$$

Figure 6. (a) The measured ratios R_3^i/R_3^{uds}, and (b) the corresponding translated ratios $\alpha_s^i/\alpha_s^{uds}$ (i = c, b). The arrows in (a) indicate the range of the theoretical prediction described in the text for values of the b-quark mass in the range $2.5 \le m_b(M_Z) \le 3.5$ GeV/c^2, with the arrow pointing towards the lower mass value.

Determination of b quark mass

- Some theoretical issues on quark masses:
  - ▶ NLO calculations use different mass definitions
    - ■ **pole mass M_b**
      - ○ from pole in quark propagator $\frac{1}{q^2-M^2}$
      - ⊕ independent of renormalization scheme
      - ⊖ on-shell quark propagator has no pole (quarks are confined, though not free observ.)
      - ○ mass only in pert. theory defined
      - ⊖ suffers non pert. infrared effects in QCD
    - ■ **renormalized mass m_b** (eg. $\overline{MS}$: $\overline{m}_b$)
      - ⊖ depends on renormalization scheme
      - ○ mass is scale dependent → running
      - ⊕ theoretically well-defined concept (all α_s)
      - ⊕ ≡ mass in Lagrangian (current mass)
  - ▶ both masses are related in pert. theory (relation known in $\mathcal{O}(\alpha_s^3)$ Chetyrkin et al. 9911434 Melnikov et al. 9912391)

Determination of b quark mass

- assume flavour independent coupling (=QCD)

$$\frac{\alpha_s^b}{\alpha_s^{uds}} \equiv 1 \longrightarrow M_b \quad \text{or} \quad \bar{m}_b(Q)$$

- sensitive observable:

$$R_3^{bl} \equiv \frac{R_3^b(y_{cut})}{R_3^{udsc}(y_{cut})} \quad \text{ratio of 3-jet rates}$$

(also called r^b and B_3)

with a simple relation with $\bar{m}_b$ (M_b):

$$R_3^{bl} = a_0 + a_2 \cdot \bar{m}_b^2 \quad (+ \text{ negligible } \ln \bar{m}\text{-terms})$$

- NLO calculations of R_3^{bl} vs $\bar{m}_b$ (M_b)

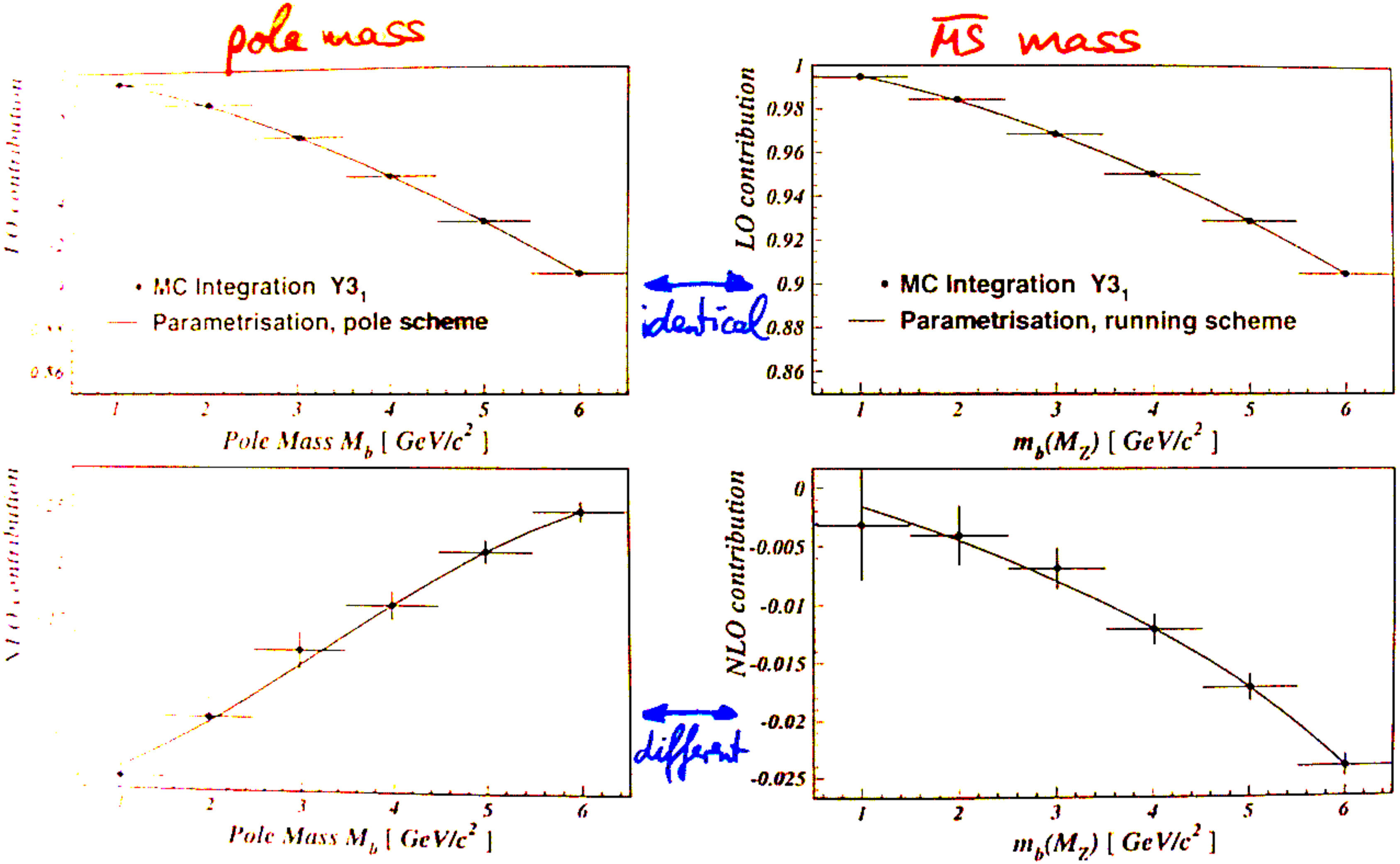
for many jet finders:

JADE, E0, E, P0, P, Durham, Geneva, Cambridge

[+ program zbb4 of Nason & Oleari to integrate massive matrix element for every observable]

Determination of b quark mass

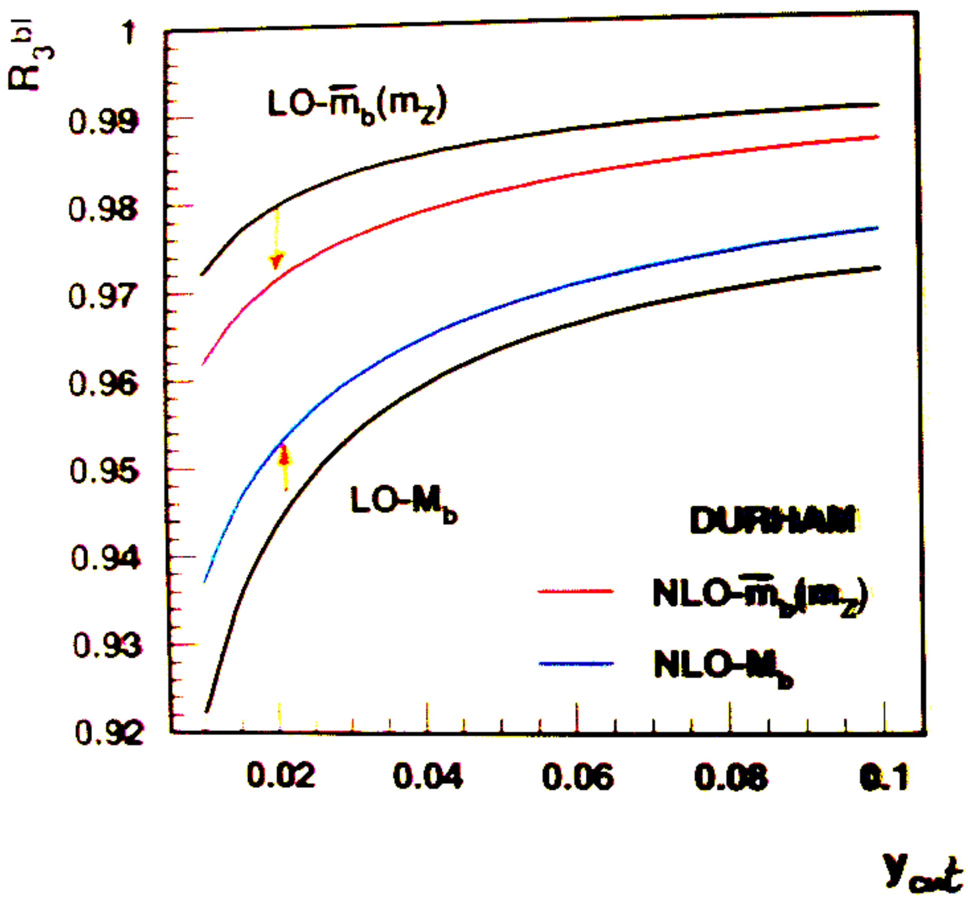
LO + NLO calculation for $R^{b\ell} = \frac{\langle Y_3^b \rangle}{\langle Y_3^d \rangle}$ using ZBB4:

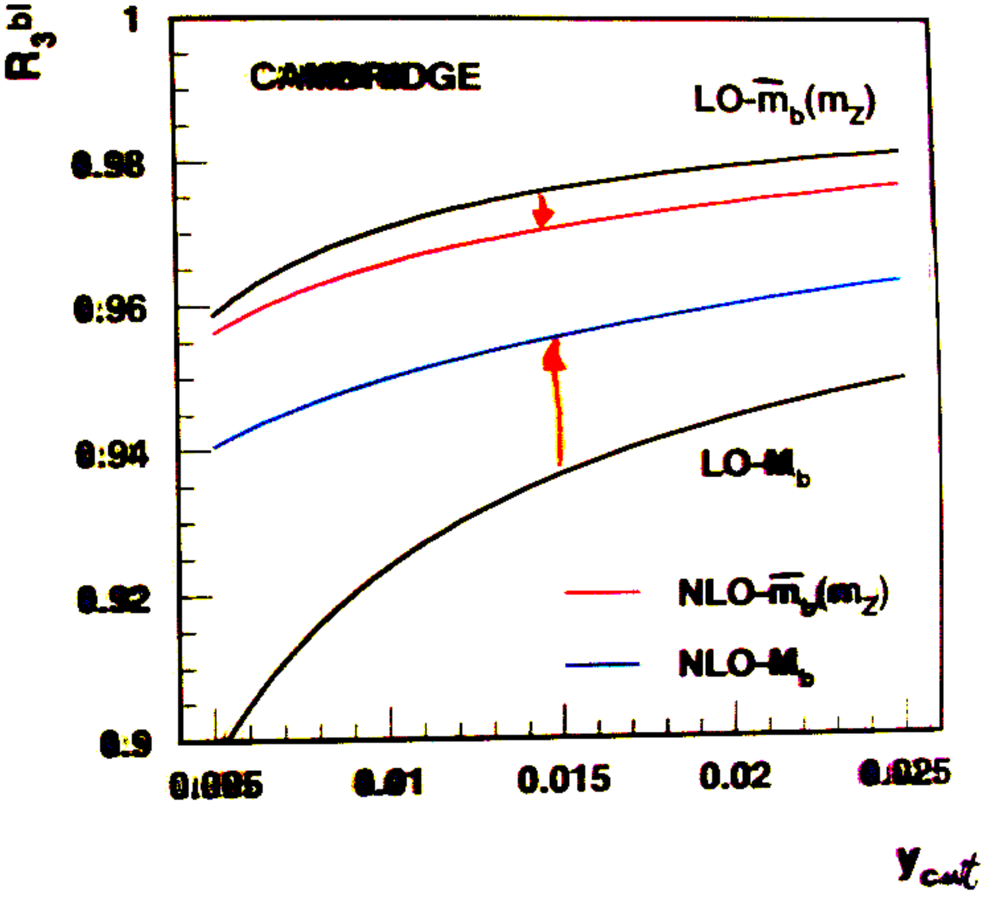


⇒ NLO contribution typ. ≤ 3%

Determination of b quark mass

Comparison M_{Pole} vs. $\overline{MS}-\overline{m}_b$: $M_{Pole} = 5\,\mathrm{GeV}$; $\overline{m}_b(m_Z) = 3\,\mathrm{GeV}$





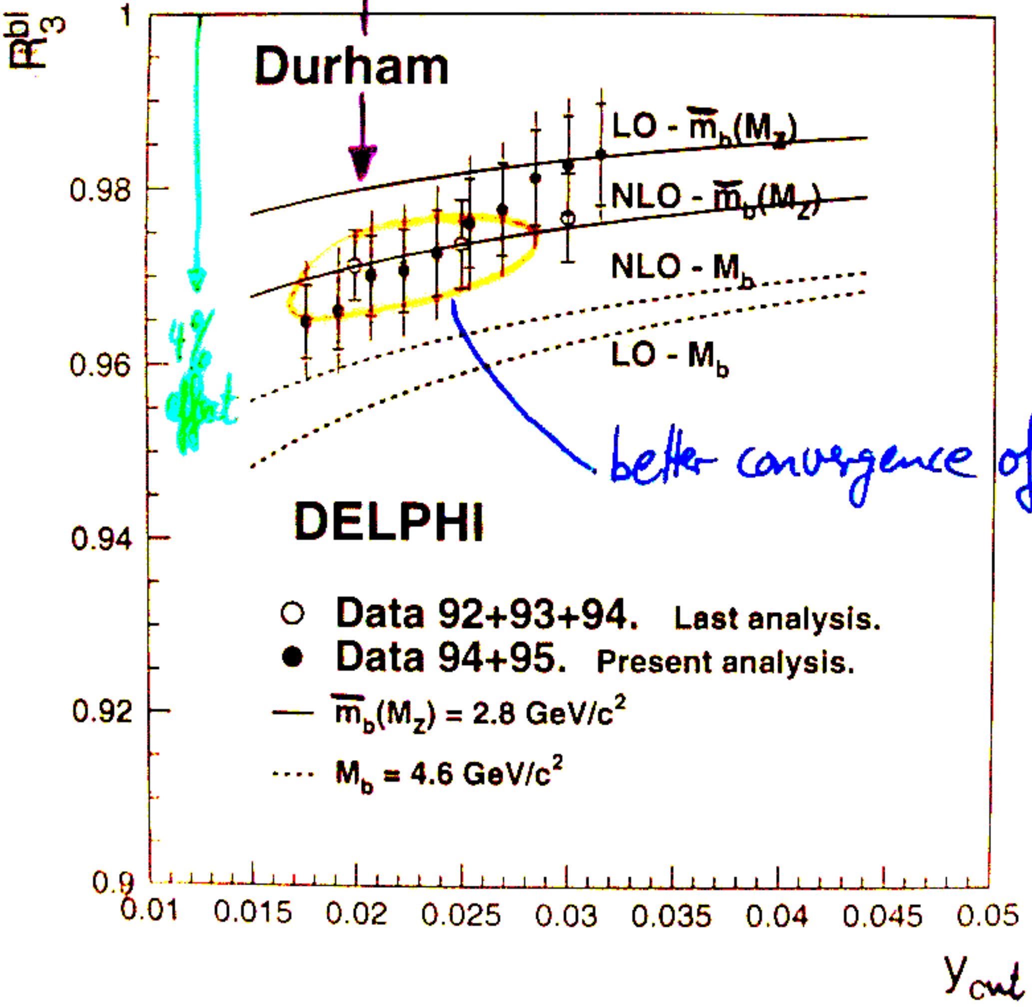
$\Rightarrow$ large differences NLO-M_b $\Leftrightarrow$ NLO-$\overline{m}_b(m_Z)$ $\longrightarrow$ theory uncertainty?

Determination of b quark mass

- data vs. theory

→ determine $\overline{m}_b\,(M_b)$ at a fixed y_{cut}

$y_{cut} = 0.02 \rightarrow \overline{m}_b(m_Z) = 2.8$ GeV



4% effect

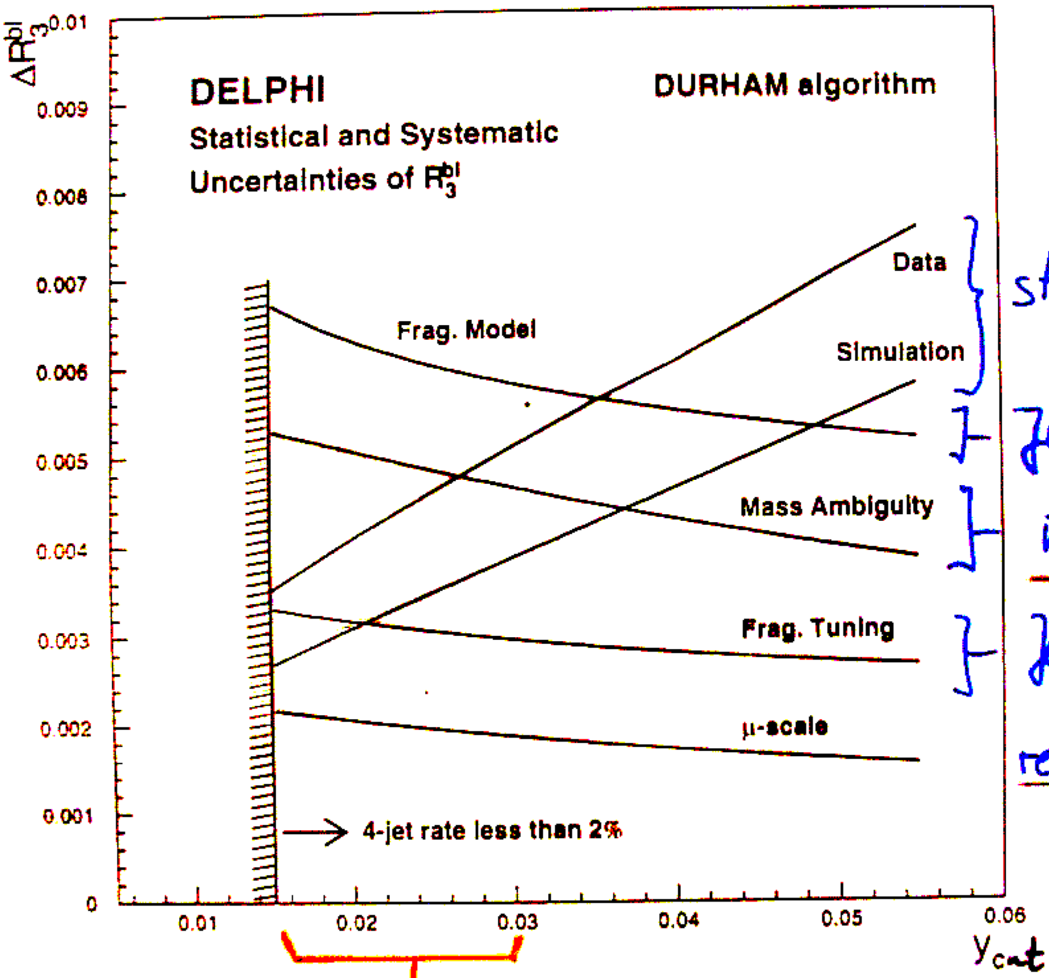
better convergence of $\overline{m}_b$ than M_b?

DELPHI-2000-121
CONF 420
(ICHEP 2000)

Figure 3: Corrected data values of $R_3^{b\ell}$ using DURHAM algorithm compared with the theoretical predictions from reference [10] at LO and NLO in terms of the pole mass $M_b = 4.6$ GeV/c^2 (dashed lines) and in terms of the running mass $m_b(M_Z) = 2.8$ GeV/c^2 (solid lines)

Determination of b quark mass

- choice of y_{cut} to extract $\overline{m}_b$



statistics

JETSET vs. HERWIG

$\overline{m}_b$ vs. M_b

JETSET parameters

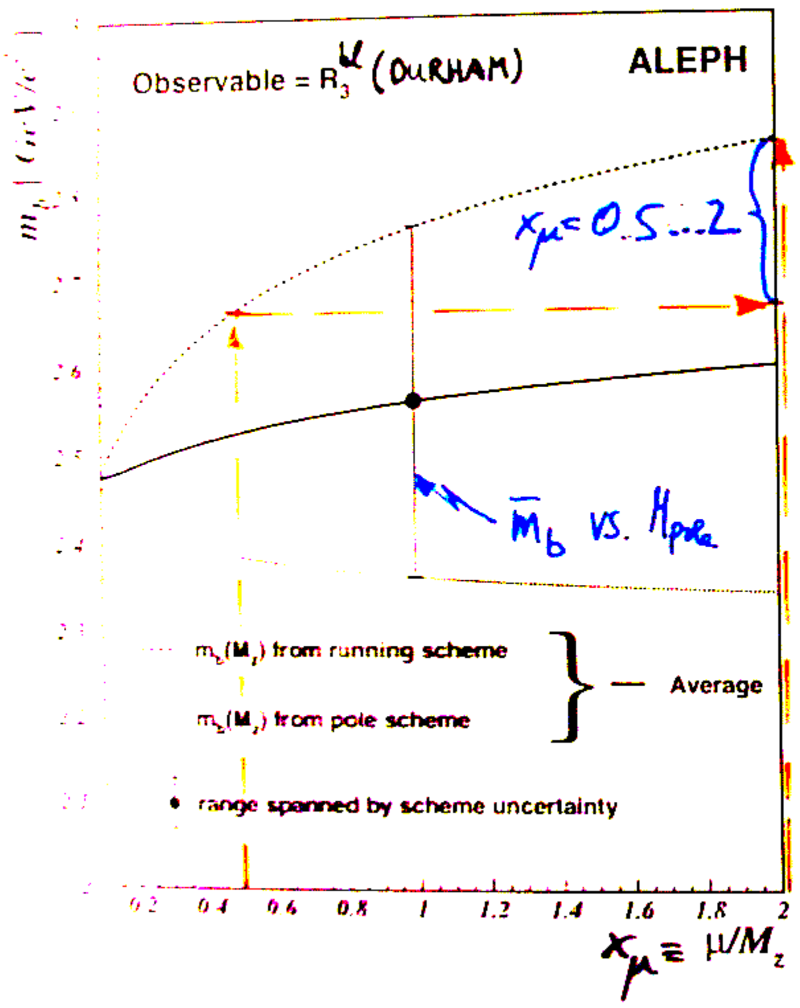
renormalization scale

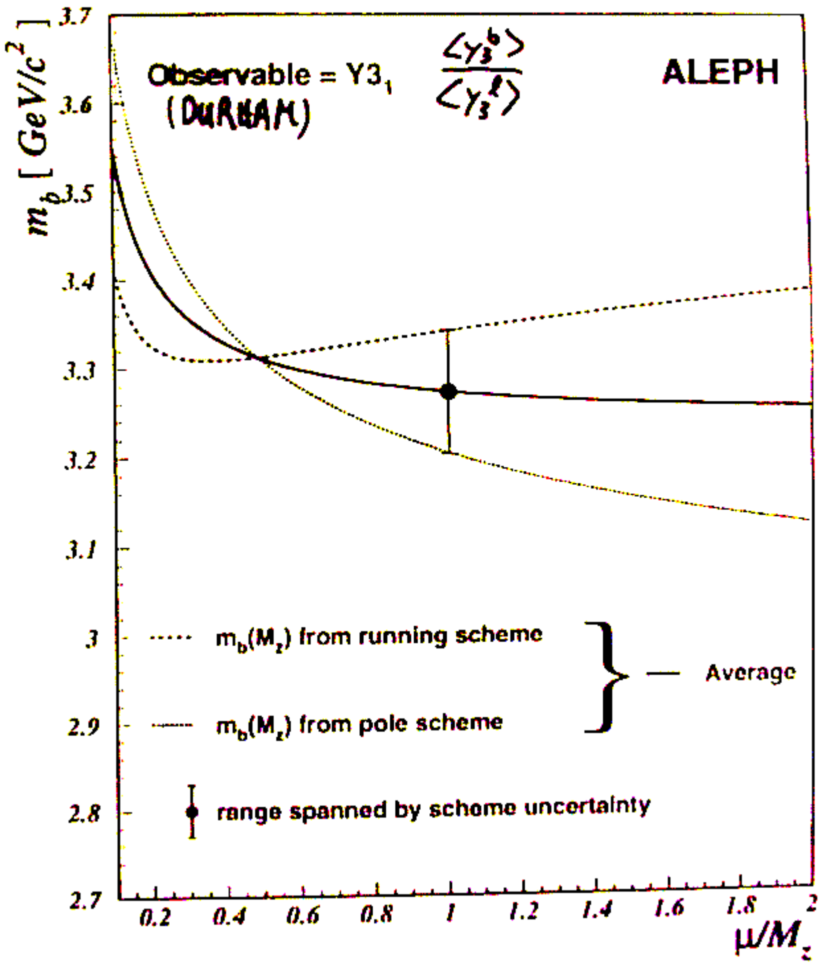
all choices
in this range
OKAY

(DELPHI : $y_{cut} = 0.02$)

Determination of b quark mass

- renormalization scale dependence

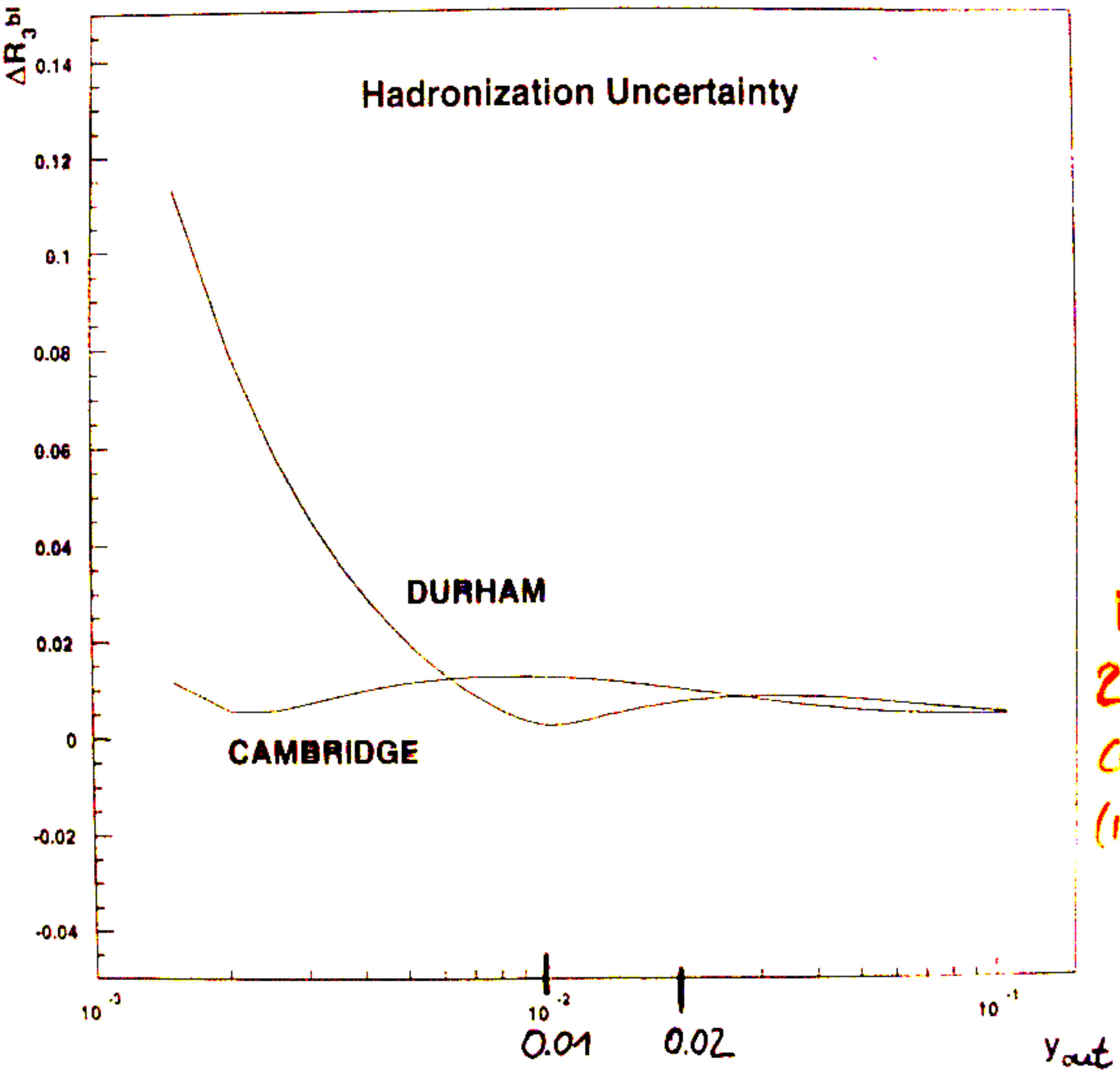




CERN-EP/2000-093

Determination of b quark mass

- Jet finders show different sensitivity to hadronization



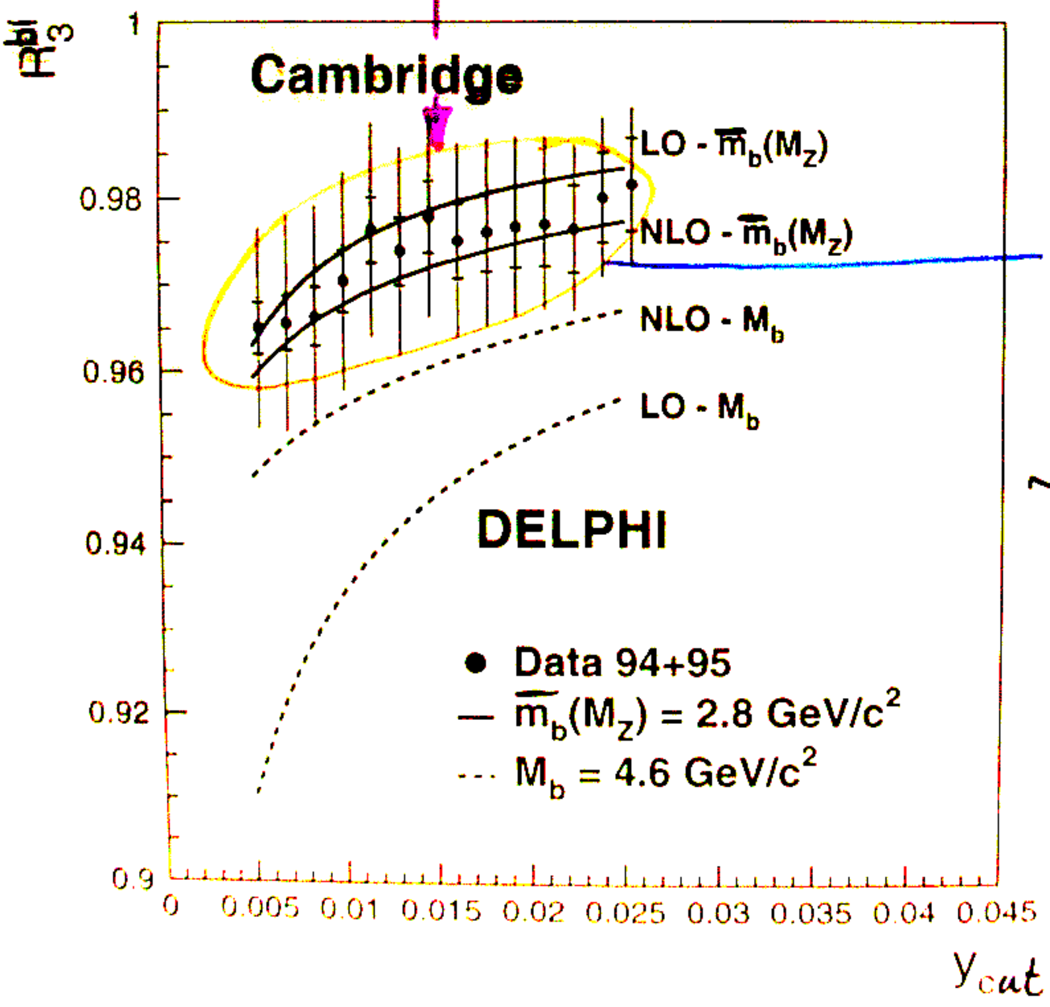
DELPHI
2000-131
CONF 421
(ICHEP 2000)

⇒ Cambridge allows for smaller y_{cut}

⇝ reduced statistical uncertainty

Determination of b quark mass

$y_{cut} = 0.015 \longrightarrow \overline{m}_b(m_Z) = 2.6$ GeV



data prefer $\overline{m}_b$ over M_b.

→ due to nonperturb. effects of M_b?

Determination of b quark mass

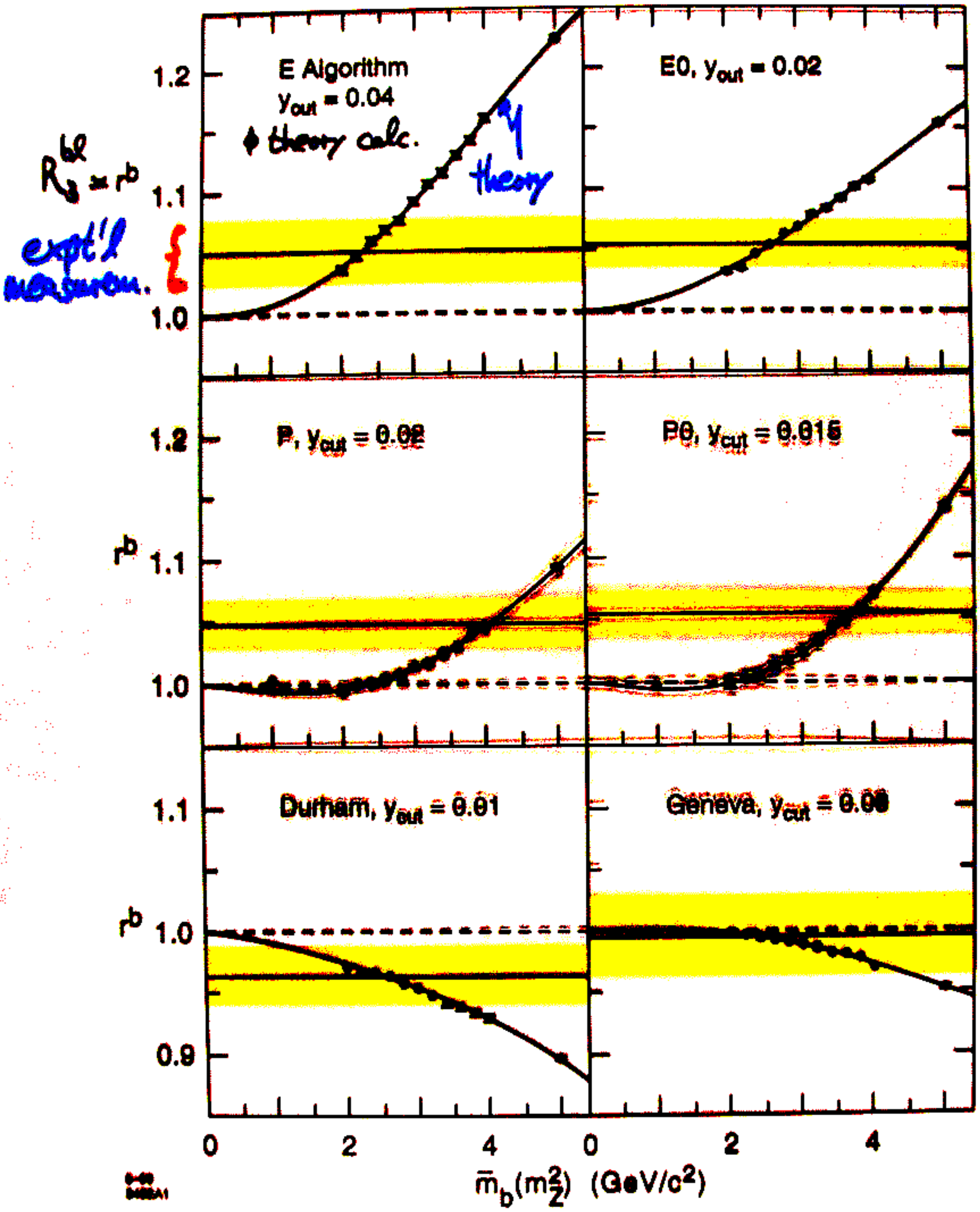


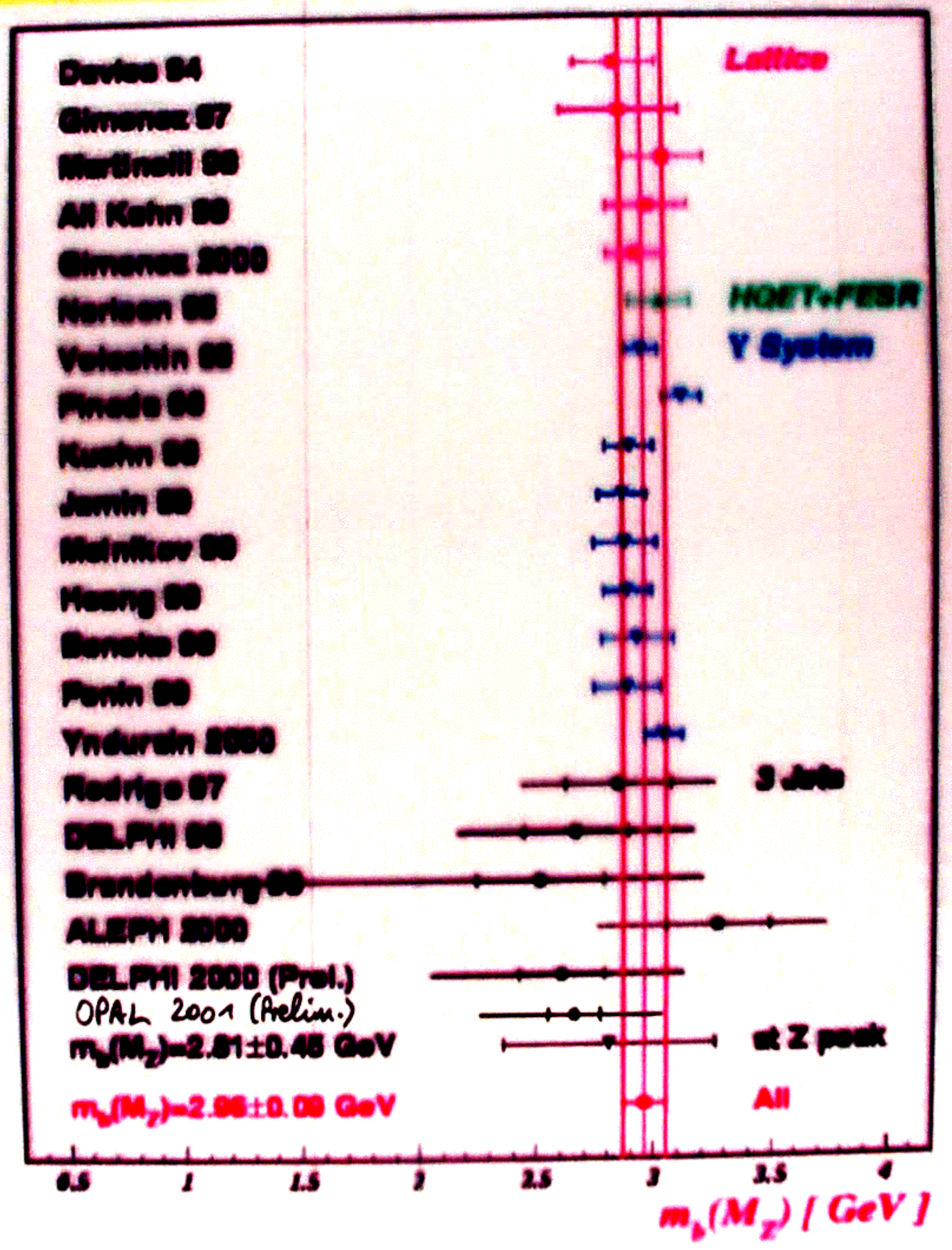
Fig. 26. At fixed y_{cut} the theoretically expected dependence of the 3-jet rate ratio, $r_b \equiv R_3^b/R_3^{uds}$, for bottom and light quarks on the bottom quark mass is shown for various jet finders as points with error bars and parameterised by a curve. The gray bands represent the experimentally measured values of the ratio and the respective statistical errors as obtained by the SLD collaboration. The figure is taken from [156].

Brandenburg et al. PL B468, 168

Summary of m_b measurements

Compilation by Gimenez et al. and J. Fuster

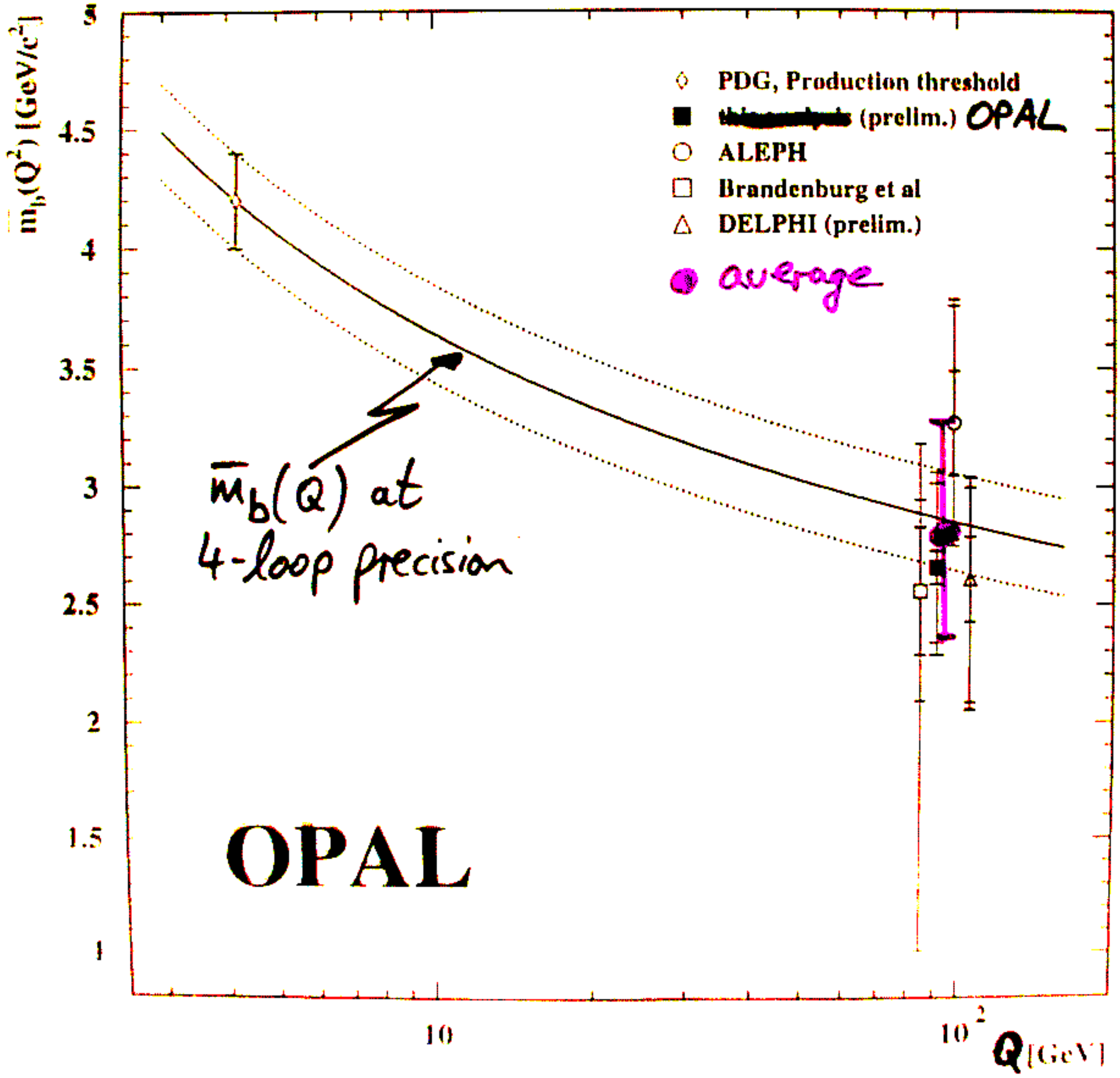
Averaging method by M.Schmelling



Determination of b quark mass

- Compilation of $\bar{m}_b(m_Z)$ determinations

⇒ $\boxed{\bar{m}_b(m_Z) = 2.80 \pm 0.45 \text{ GeV}}$



⇒ $\bar{m}_b(\bar{m}_b) = 4.11 \pm 0.66$ GeV

$\bar{m}_b^{PDG} - \bar{m}_b(m_Z) = 1.40 \pm 0.49$ GeV (>0 ; 3σ)

Summary

- Quark mass effects start getting important in experimental studies
  - ▶ multiplicity
  - ▶ hard & soft fragmentation
  - ▶ flavour (in-) dependence
- NLO calculations on the market since about 4 years
  - ▶ flavour independence
  - ▶ determination of b quark mass
- (too?) many quark mass definitions
  - ▶ $\overline{m}_b$ vs. M_{Pole} a liable test of higher orders?
  - ▶ choice of renormalization scale a significant uncertainty
- running of $\overline{MS}$ b quark $\overline{m}_b(m_Z) = 2.80 \pm 0.45$ (tot
  - ▶ intermediate determination wishful to prove running unambiguously