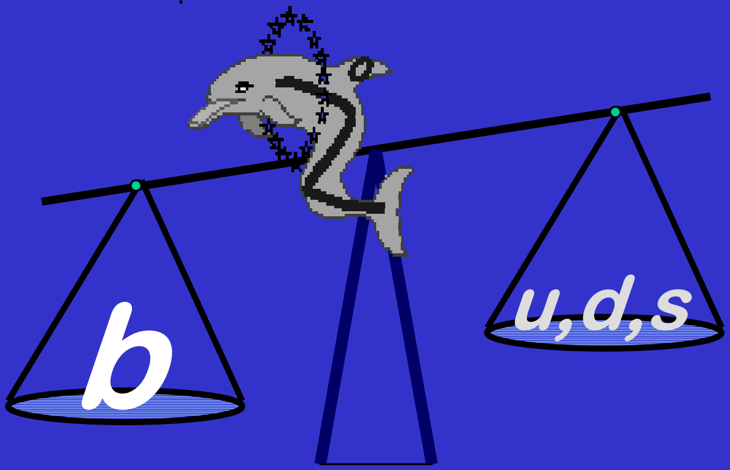
b-mass studies at LEP



Pablo Tortosa

XXXIXth Rencontres de Moriond

March 28th-April 4th 2004

Theoretical introduction

- **The Standard Model has a set of free parameters.**
- **QCD Lagrangian:**

$$\mathcal{L}_{QCD} = -\frac{1}{4}(\partial^{\mu} G^{\nu}_{a} - \partial^{\nu} G^{\mu}_{a})(\partial_{\mu} G^{a}_{\nu} - \partial_{\nu} G^{a}_{\mu}) + \sum_{f} \bar{q}^{\alpha}_{f} \, (i\gamma^{\mu}\partial_{\mu} - \boxed{m_f}) \, q^{\alpha}_{f}$$

$$-\boxed{g_s} G^{\mu}_{a} \sum_{f} \bar{q}^{\alpha}_{f} \gamma_{\mu} \left(\frac{\lambda^{a}}{2}\right)_{\alpha\beta} q^{\beta}_{f} - \frac{\boxed{g_s}}{2} f^{abc} (\partial^{\mu} G^{\nu}_{a} - \partial^{\nu} G^{\mu}_{a}) G^{b}_{\mu} G^{c}_{\nu} - \frac{\boxed{{g_s}^2}}{4} f^{abc} f_{ade} G^{\mu}_{b} G^{\nu}_{c} G^{d}_{\mu} G^{e}_{\nu}$$

$\alpha_s = {g_s}^2/4\pi$ and quark masses are not predicted by the SM

They need to be determined experimentally!

Quark mass definitions

- 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

Gauge and scheme independent

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

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

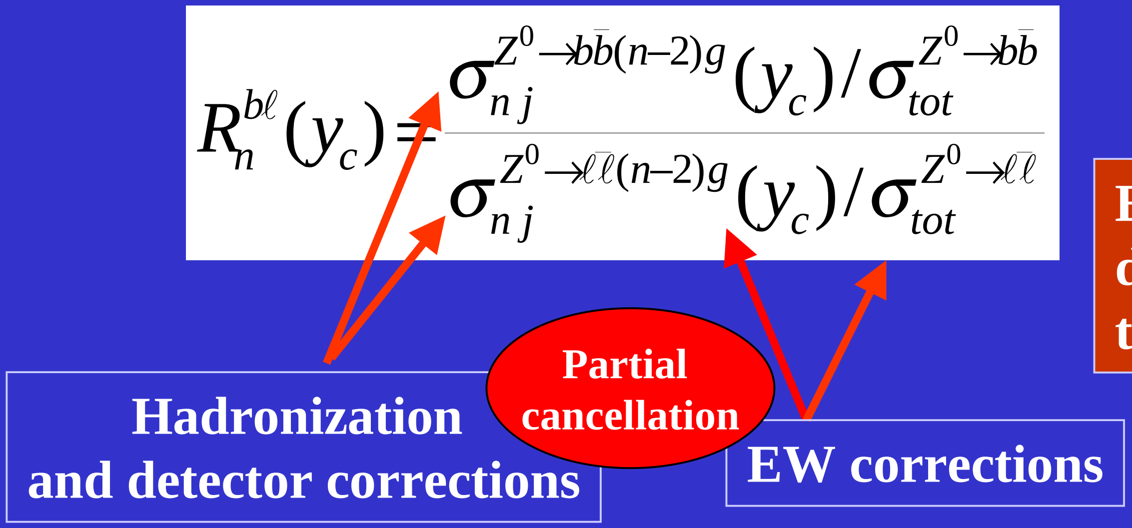
Running mass: $m_q(\mu)$ Renormalized mass in the $\overline{\mathrm{MS}}$ scheme.

Scheme and scale dependent.

- Additional mass definitions at threshold: $m_b^{\mathrm{kin}}(\mu)$ ...

Definition of the observable and theoretical calculations

Jet clustering algorithms:
DURHAM
CAMBRIDGE



$$R_n^{b\ell}(y_c) = \frac{\sigma_{n\,j}^{Z^0\to b\bar{b}(n-2)g}(y_c)/\sigma_{tot}^{Z^0\to b\bar{b}}}{\sigma_{n\,j}^{Z^0\to \ell\bar{\ell}(n-2)g}(y_c)/\sigma_{tot}^{Z^0\to \ell\bar{\ell}}}$$

Hadronization and detector corrections

Partial cancellation

EW corrections

Event flavour (b, ℓ = *uds*) is defined by the quarks coupled to the Z^0

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: $R_{3,4}^{b\ell}(m_b(\mu))$**

- **Extract M_b and $m_b(M_Z)$**
- **Extract α_s^b/α_s^ℓ**

Experimental Process (Delphi)

Raw Data

Hadron Selection

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

Tagging

***b*-Sample** **ℓ-Sample**

Jet reconstruction

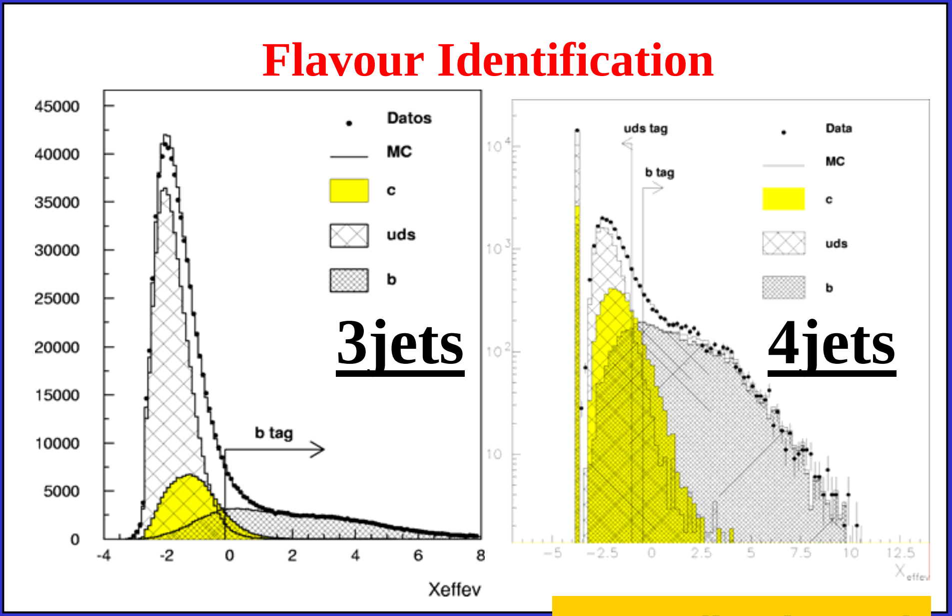
$R_n^{b\ell}$ (detector)

Detector corrections

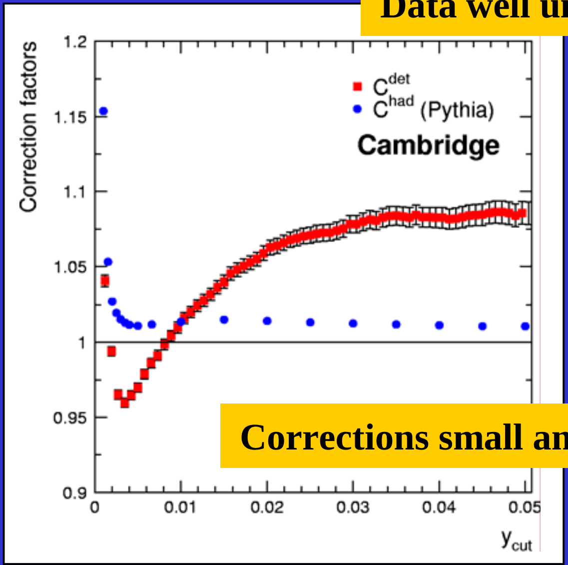
$R_n^{b\ell}$ (hadron)

Fragmentation corrections

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



Data well understood

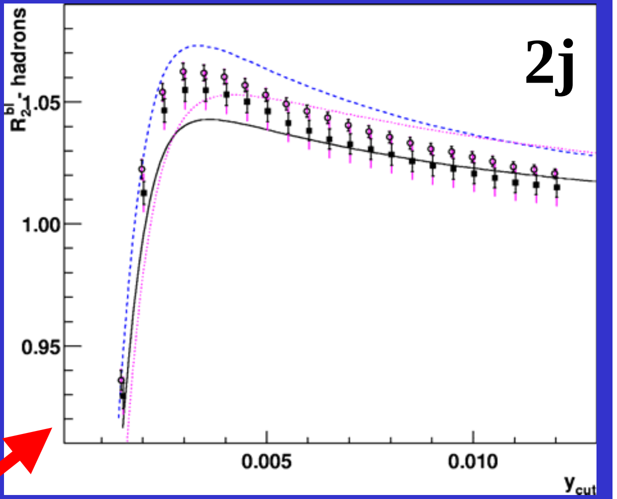


Corrections small and stable

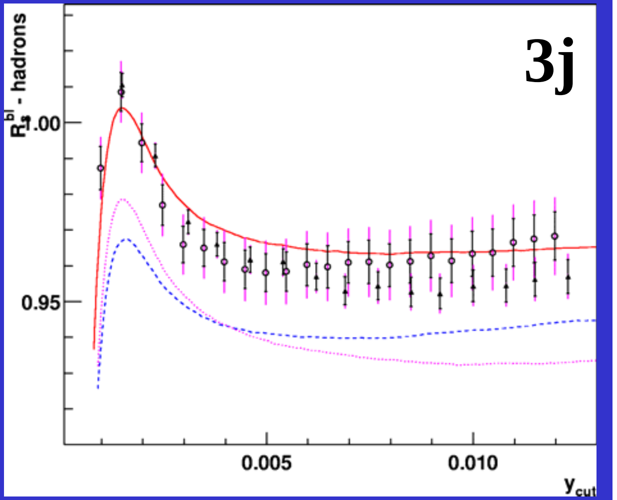
Experimental Process (Delphi)

- **2-3jets: Measure double rates simultaneously (n-jet AND inclusive sample) Smaller uncertainty.**

$$R_3^{b\ell-part}(y_c) = \frac{\left[c_B^{\ell} g_{3B}^{\ell}(y_c) + c_B^{c} g_{3B}^{c}(y_c)\right] - \left[P_{\ell} g_{3L}^{\ell}(y_c) + c_L^{c} g_{3L}^{c}(y_c)\right] R_3^{b\ell-det}(y_c)}{c_L^{b} g_{3L}^{b}(y_c) R_3^{b\ell-det}(y_c) - P_b g_{3B}^{b}(y_c)}$$



Useful cross-check of flavour tagging



- **4-jets: Measure only 4-jet sample with double tag. Take normalization from R_b, R_c**

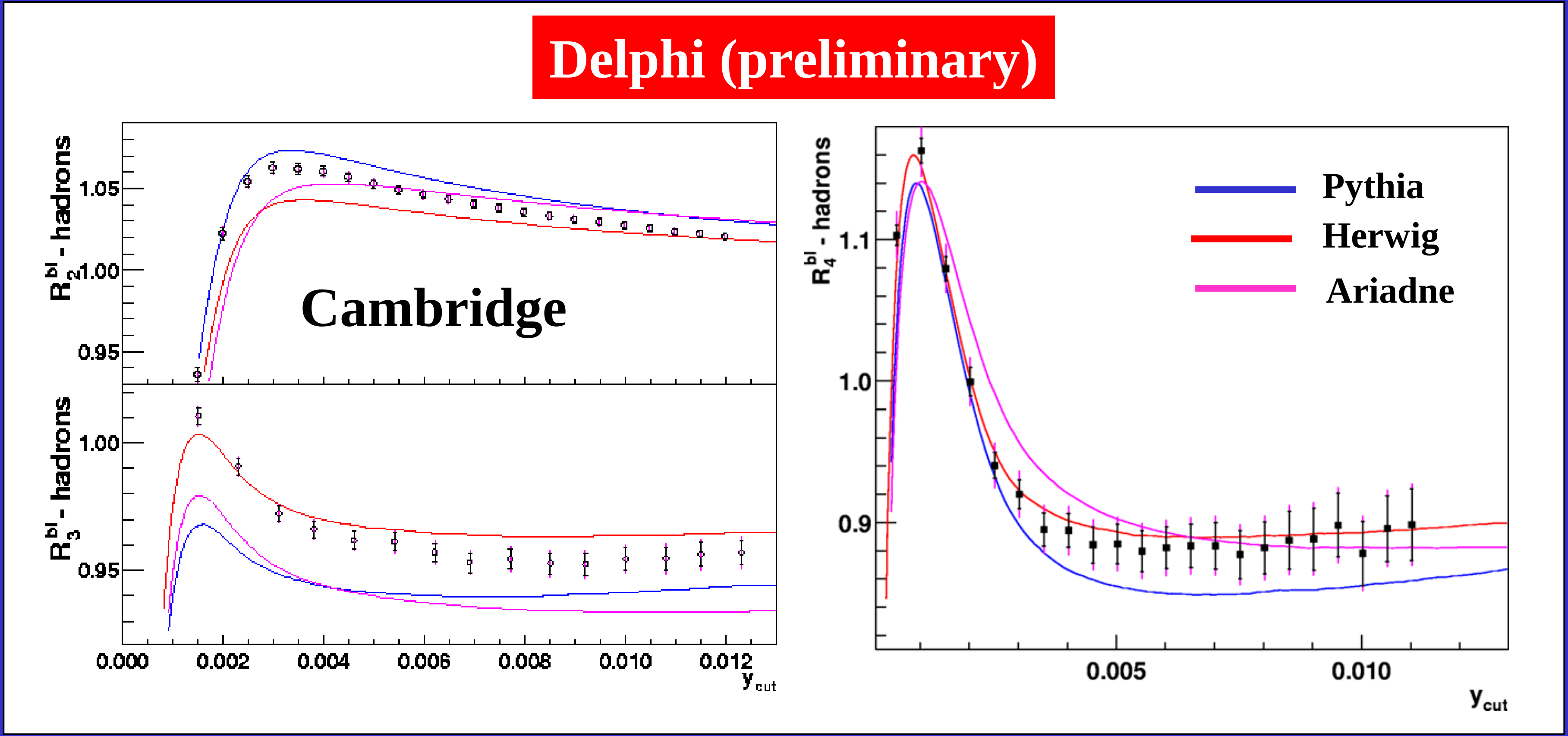
$$\begin{aligned}
\mathbf{N_4} &= \left\{N_4^b \varepsilon_h^b + (N_4 - N_4^b)\varepsilon_h^{\not{b}}\right\} \\
\frac{1}{2}\mathbf{N_{4}}_{B} &= \left\{N_4^b \varepsilon_h^b \varepsilon_B^b + (N_4 - N_4^b)\varepsilon_h^{\not{b}} \varepsilon_B^{\not{b}}\right\} \\
\mathbf{N_{4}}_{BB} &= \left\{N_4^b \varepsilon_h^b \varepsilon_{BB}^b + (N_4 - N_4^b)\varepsilon_h^{\not{b}} \varepsilon_{BB}^{\not{b}}\right\}
\end{aligned}$$

▶

$$R_4^{b\ell} = \left(\frac{1 - R_b - R_c}{R_b}\right)\frac{N_4^b}{N_4^{\ell}}$$

+ equations for LIGHT quarks

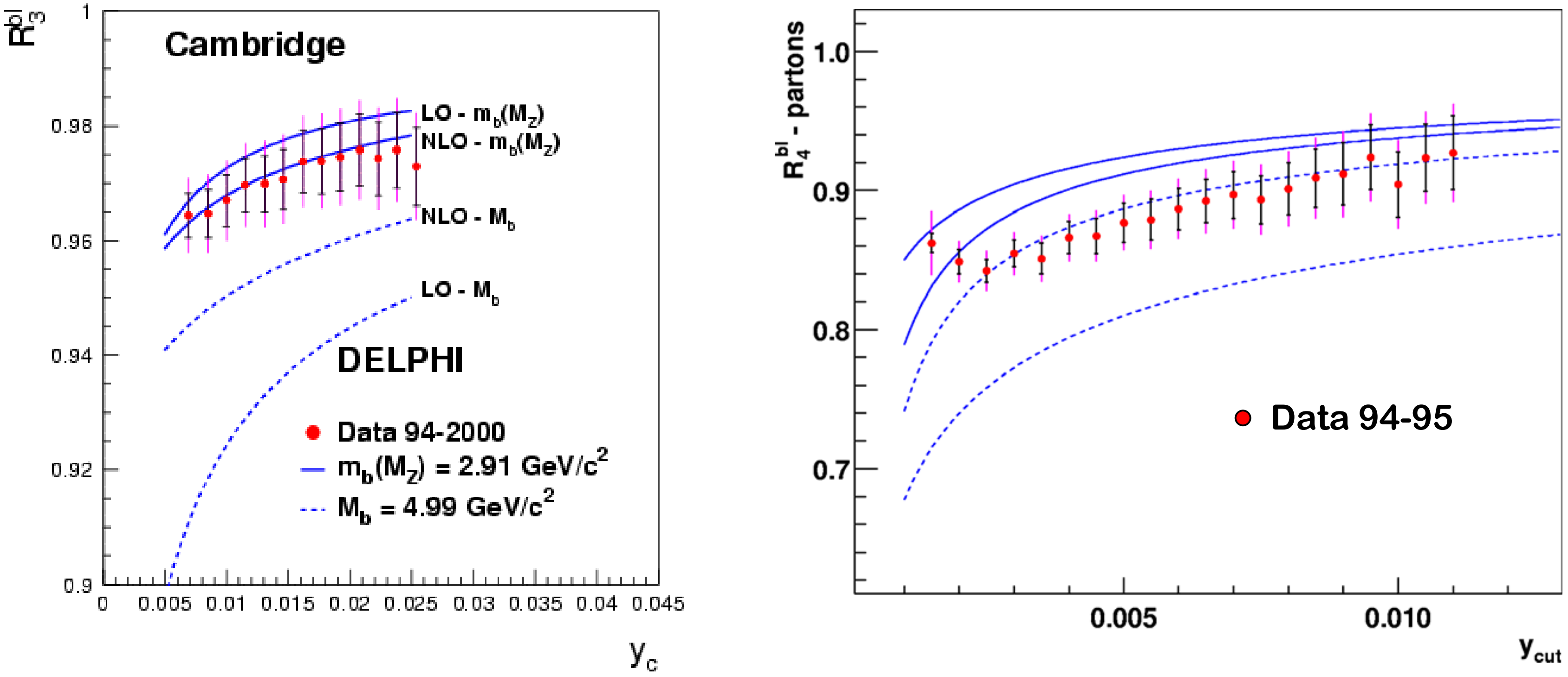
$R_n^{b\ell}$ at Hadron Level: Data vs. Generators



No Generator describes particularly well data for all multijet topologies

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

Delphi (preliminary)



3-jet analysis Calculation

Massive NLO

4-jet analysis Calculations

Massive LO

+

Massless NLO

Hadron Correction (3-jets mainly)

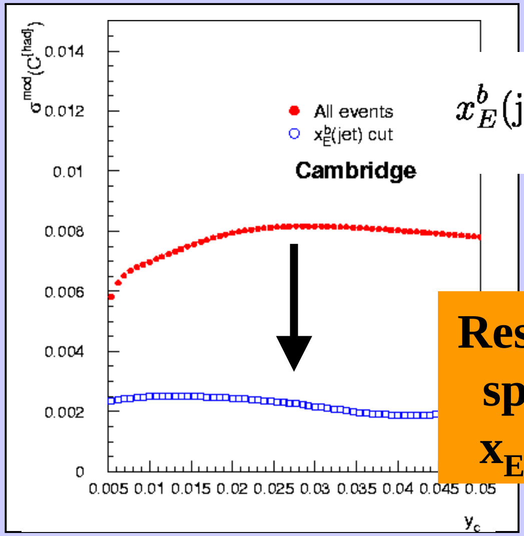
- **Fragmentation Models considered:**
  (Last versions with mass effects improved)

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

b mass parameter uncertainty

Consistent with Pole mass (Pythia)

$M_b = 4.99 \pm 0.13$ GeV/c^2

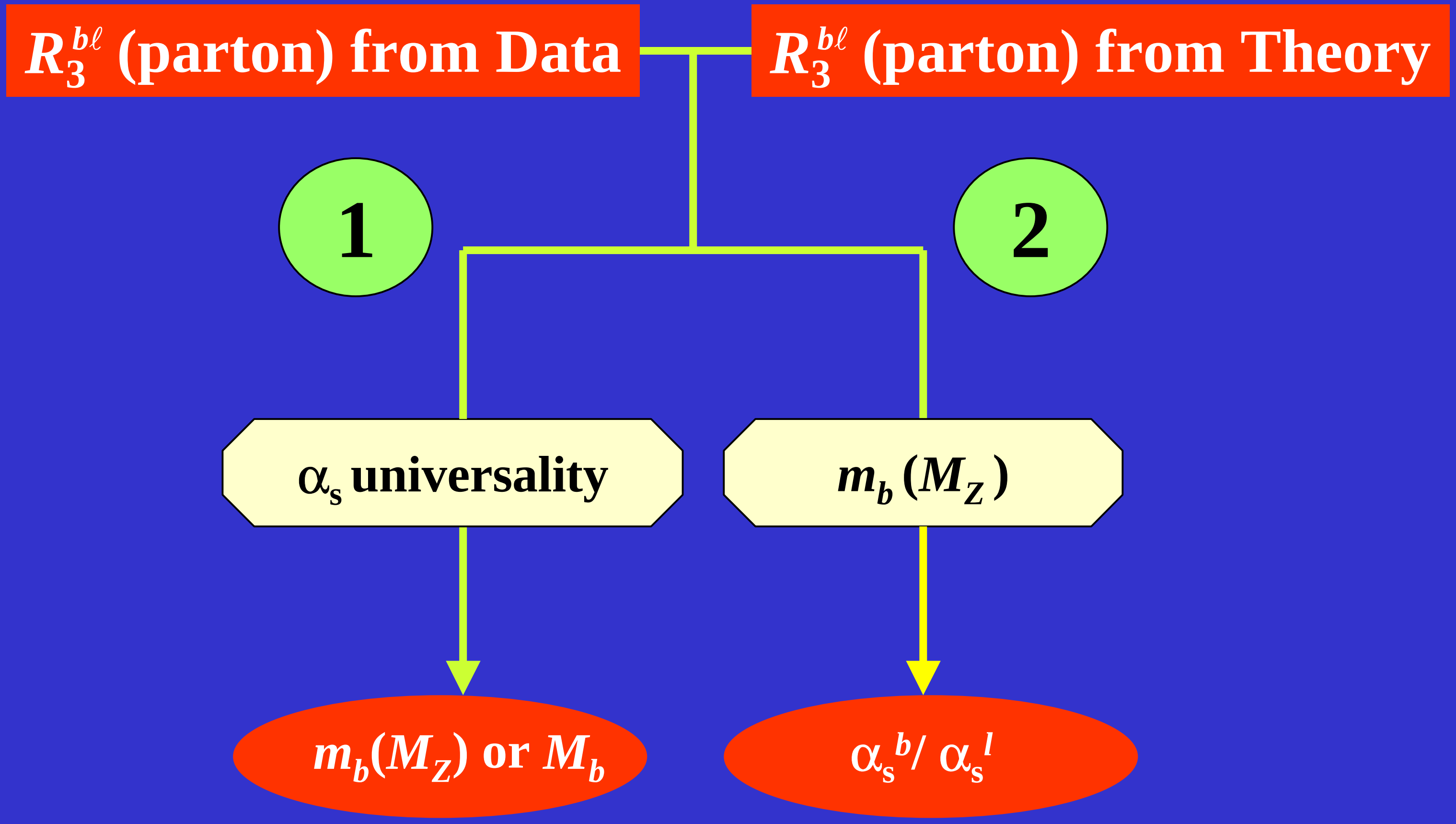
A.X.El-Khadra et al.,
Ann.Rev.Nucl.Part.Sci 52 (2002) 201

From low energy measurements

Mass result depends on value, dominant uncertainty on m_b

Extracting QCD parameters

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



$R_3^{b\ell}$ (parton) from Data

$R_3^{b\ell}$ (parton) from Theory

1

2

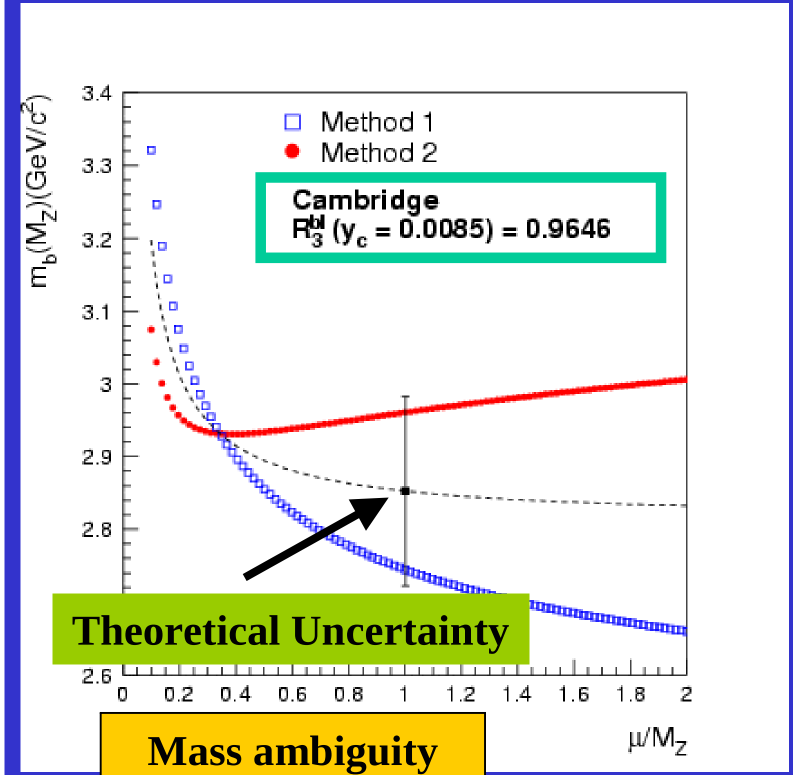
α_s universality

$m_b(M_Z)$

$m_b(M_Z)$ or M_b

α_s^b / α_s^l

b-quark mass determination (preliminary)



Theoretical Uncertainty

Mass ambiguity

Running mass $m_b(M_Z)$

Durham

3.20 ± 0.26 (stat) ± 0.19 (exp) ± 0.20 (had) ± 0.24 (theo) GeV/c^2

Cambridge

2.85 ± 0.19 (stat) ± 0.13 (exp) ± 0.20 (had) ± 0.12 (theo) GeV/c^2

Pole mass M_b

Durham

4.47 ± 0.32 (stat) ± 0.24 (exp) ± 0.80 (had) ± 0.04 (theo) GeV/c^2

Cambridge

4.19 ± 0.23 (stat) ± 0.17 (exp) ± 0.85 (had) ± 0.13 (theo) GeV/c^2

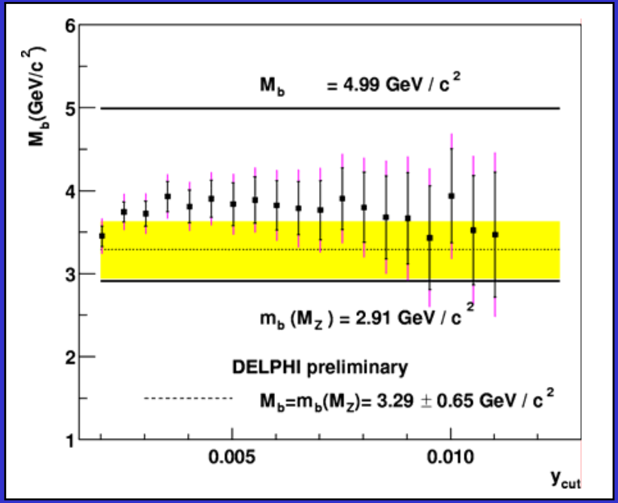
α_s universality

Durham $\alpha_s^b/\alpha_s^\ell = 0.990 \pm 0.006\ (\text{stat}) \pm 0.006\ (\text{syst}) \pm 0.005\ (\text{theo})$

Cambridge $\alpha_s^b/\alpha_s^\ell = 0.999 \pm 0.004\ (\text{stat}) \pm 0.005\ (\text{syst}) \pm 0.003\ (\text{theo})$

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

- Only Massive LO for $R_4^{b\ell}$
- NLO approximation for $R_4^{b\ell}$: LO massive + NLO massless



Only experimental uncertainties at LO

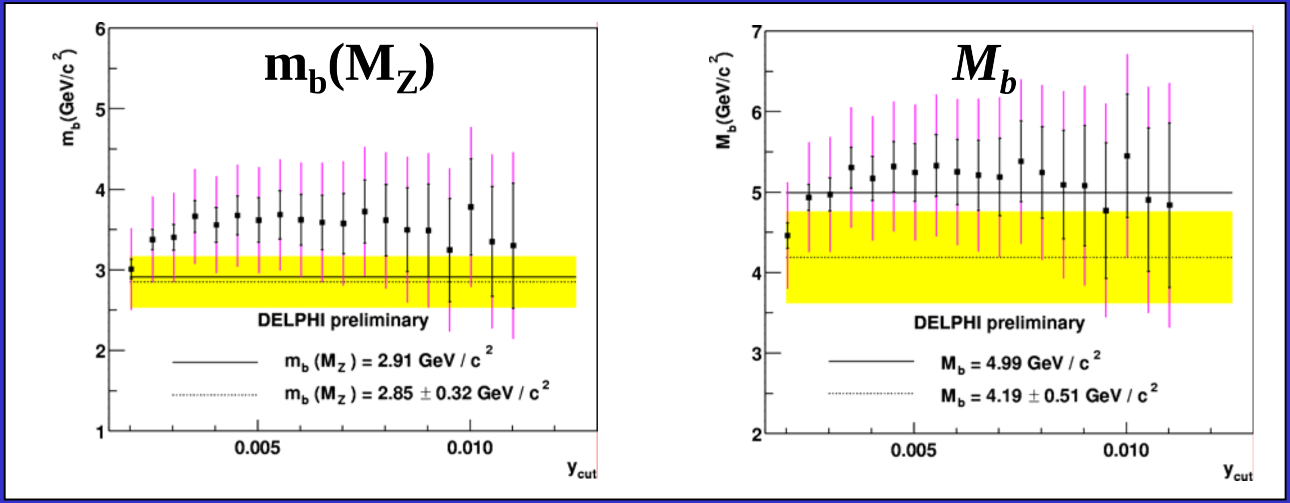
LO Massive

Good agreement !

+

NLO Massless

Good agreement !
(calculations are not comparable)



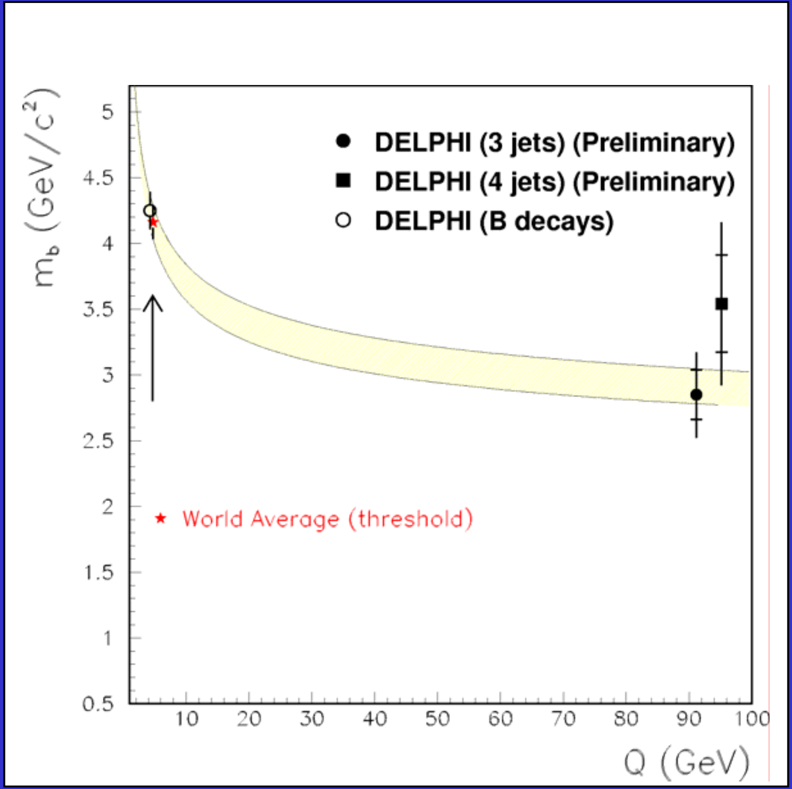
Comparison with DELPHI analysis at threshold

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

m_b^{kin} (1 GeV) → $m_b(m_b) = 4.26 \pm 0.13$ GeV/c^2

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

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



Summary

- New analysis for $R_3^{b\ell}$: considerable improvement of syst. uncertainties
  Mass extraction depends on M_b input in Pythia

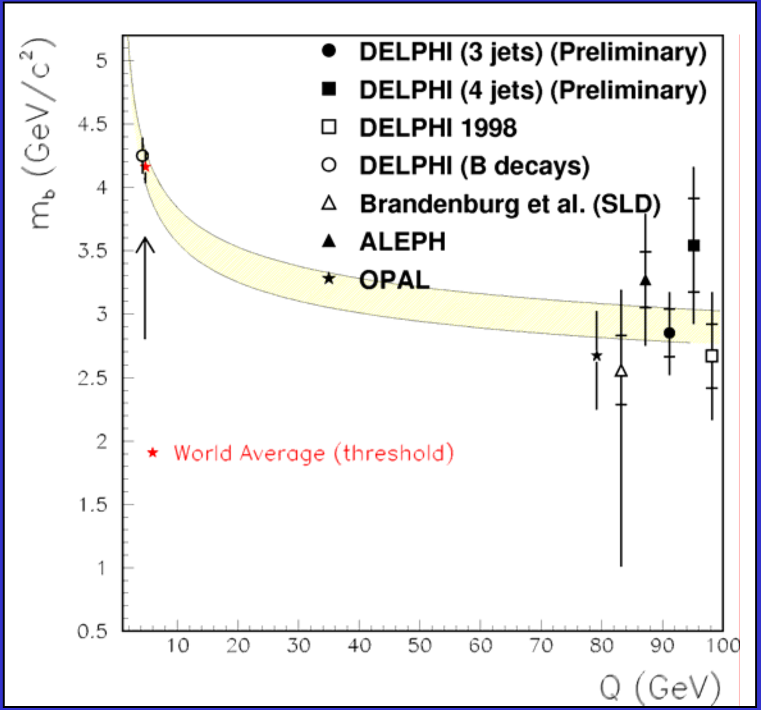
- Uncertainties from $R_4^{b\ell}$ slightly higher, mass extraction limited by theoretical calculations ~ 400 MeV.

<u>Running observed</u>,
Most of dependence on M_b input in generator cancels in the difference mb(mb)-mb(MZ)

Running Mass: (Cambridge)

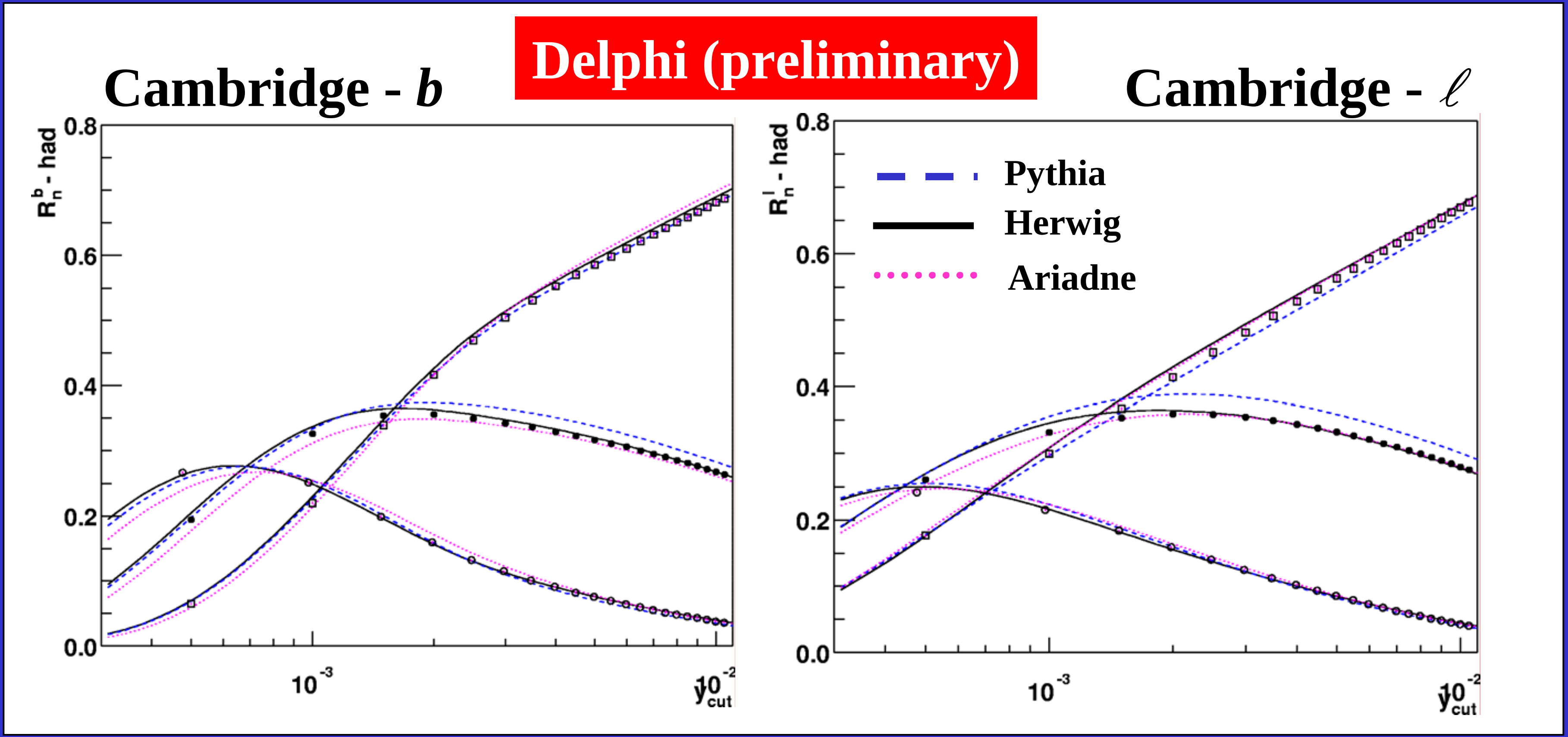
$$m_b(M_Z) = 2.85 \pm 0.33\ \mathrm{GeV/c^2}$$

4 jets → $(3.54 \pm 0.62\ \mathrm{GeV/c^2})$



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

R_n^q at Hadron Level: Data vs. Generators



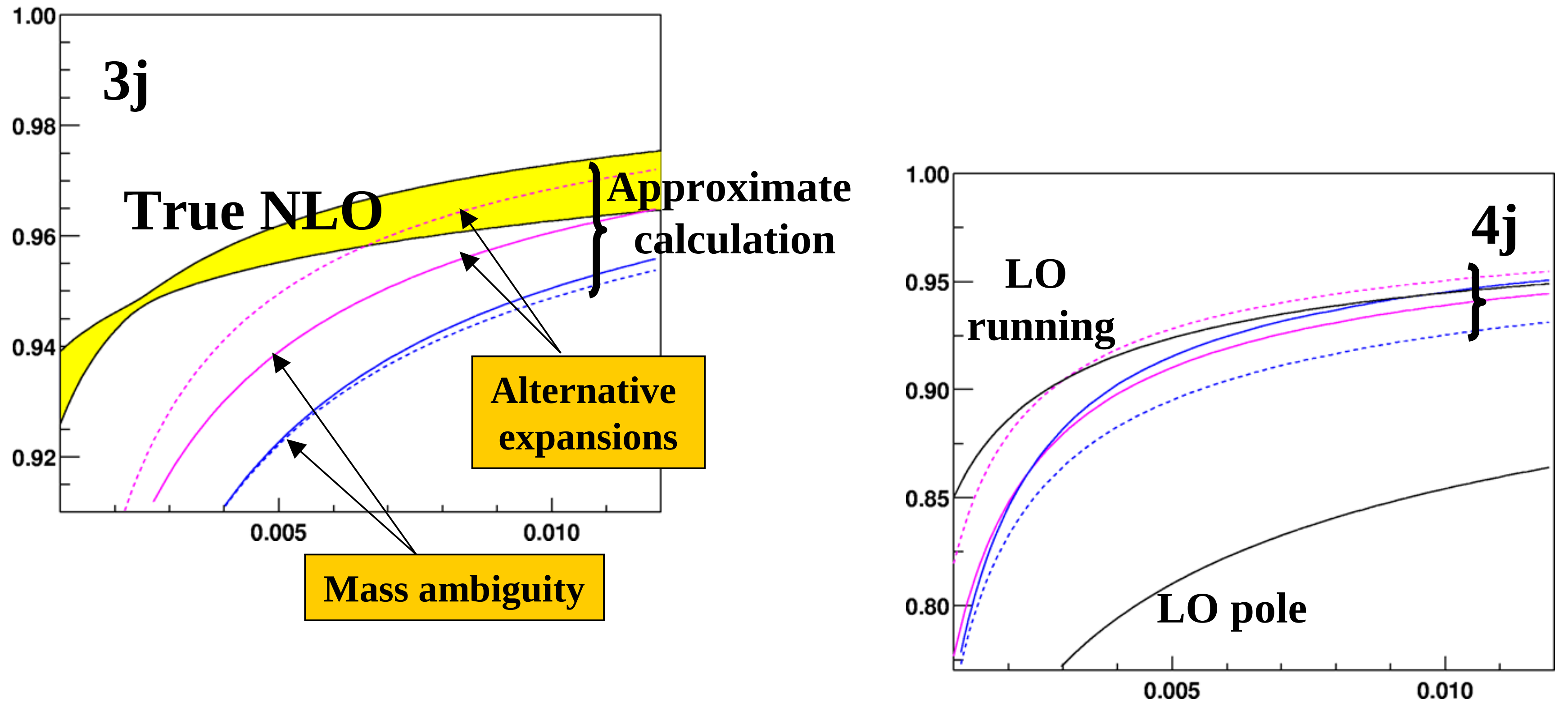
Delphi (preliminary)

Cambridge - *b*

Cambridge - ℓ

No Generator describes all multijet topologies

Theoretical uncertainty for Massless NLO



Uncertainty estimated as maximum spread with Massless NLO ~ 400 MeV

Conservative: test in 3-jet calculation gives 2*x* true uncertainty