B-quark mass determination from three jet rates at the ILC

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ILD Software & Analysis, 10th February 2021

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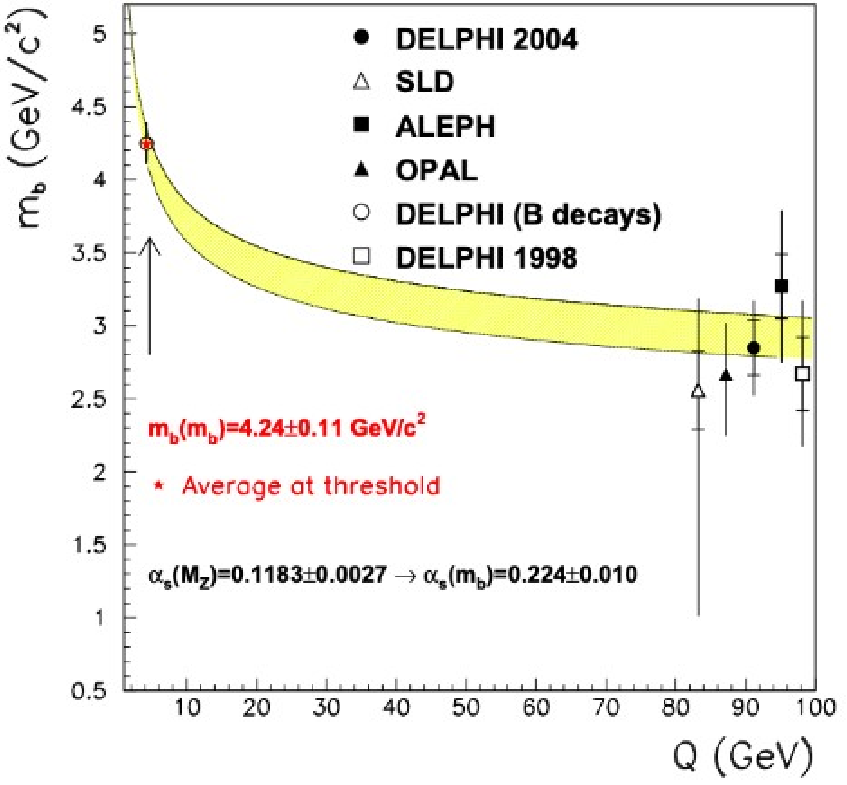
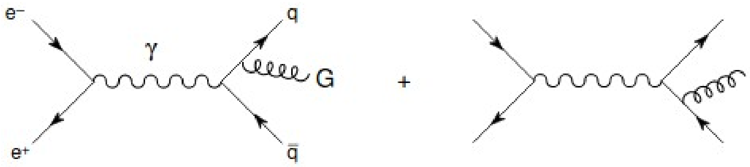
A running mass

- Quarks are confined in colorless hadrons → not seen as free particles.
- Therefore, quark masses are not observables: **are running parameters**
  - Similarly as the coupling constants (alpha_s)
  - The mass is only defined within a given renormalization scheme (and calculation order)
- The quark masses are inferred from hadronic observables and their theoretical predictions
  - Inclusive cross sections
  - **Three jet rates**
- **The running quark mass has been very precisely measured in the past**
- **Measurements at different scales in the MSbar scheme**
  - **More limited precision at higher energies**

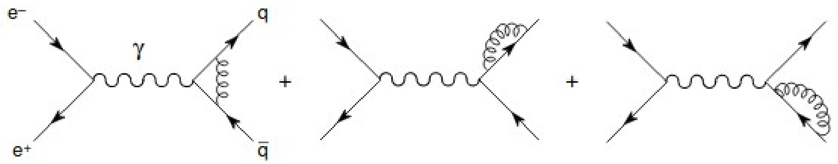


mb(mb) at high energies – Z pole

- LEP/SLD manage to determine the mass at the Z-pole with the highest precision studying jet observables
  - 3/4 jet rates – [Rodrigo, Santamaria, Bilenky] [Bernreuther, Brandenburg, P. Uwer] , [Nason, Oleari]



+ virtuals



- QCD radiation in the final state creates divergences (soft/collinear)
  - We need a jet-definition: an algorithm to decide how to avoid Infrared divergences
  - JADE / DURHAM / CAMBRIDGE jet algorithms
- The qqbar+jet cross section definition depends on the jet algorithm

$$R_3^{flav} = \frac{\Gamma^{3\,jet}_{flav}(y_{cut})}{\Gamma flav},$$

JADE/DURHAM/CAMBRIDGE
ycut= resolution parameter

Total width

mb(mb) at high energies – Z pole

- The observable:

$$R_3^{b\ell} = \frac{\Gamma^b_{3j}(y_c)/\Gamma^b}{\Gamma^\ell_{3j}(y_c)/\Gamma^\ell}$$

- l= uds
- The double ratio
  - Cancel most of the EW corrections and large logarithms of the b-mass
  - Reduces of the common systematic uncertainties (hadronization effects)
  - ratio allows to cancel large logarithms of the b-mass

- At NLO QCD

$$R_3^{b\ell} = 1 + \frac{\alpha_S(\mu)}{\pi} a_0(y_{cut}) + \bar{r}_b(\mu)\left(b_0(\bar{r}_b, y_{cut}) + \frac{\alpha_S(\mu)}{\pi}\bar{b}_1(\bar{r}_b, y_{cut}, \mu)\right),$$

where $\bar{r}_b(\mu) = m_b^2(\mu)/s$ and $\bar{b}_1(\bar{r}_b, y_{cut}, \mu) = b_1(\bar{r}_b, y_{cut}) + 2b_0(\bar{r}_b, y_{cut})(4/3 - \log\bar{r}_b + \log(\mu^2/s))$.

- Using the Msbar instead of the pole mass scheme improves the convergence of the perturbative predictions

mb(mb) at high energies – Z pole

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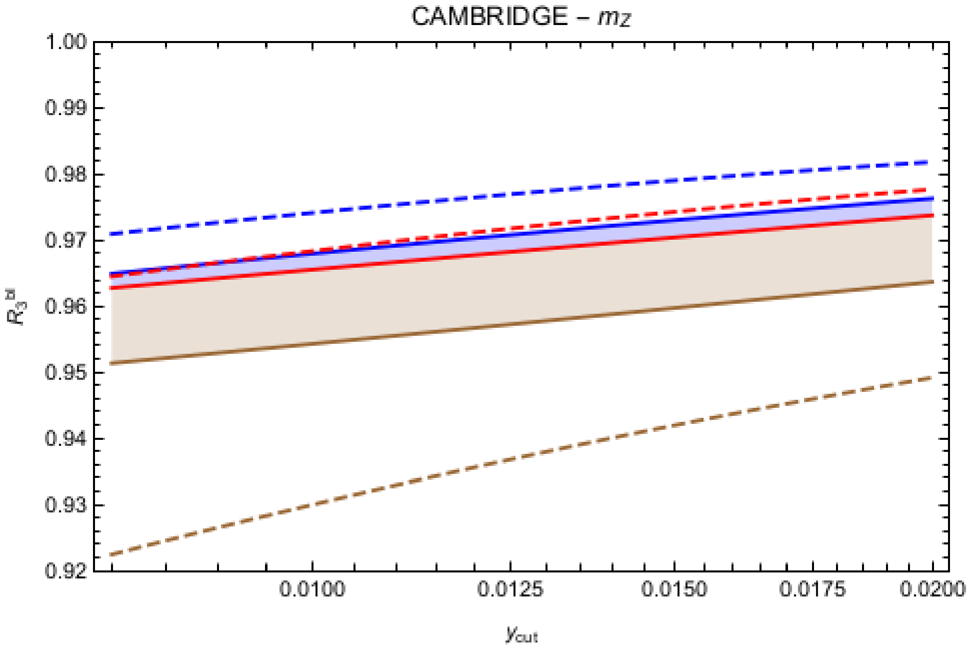
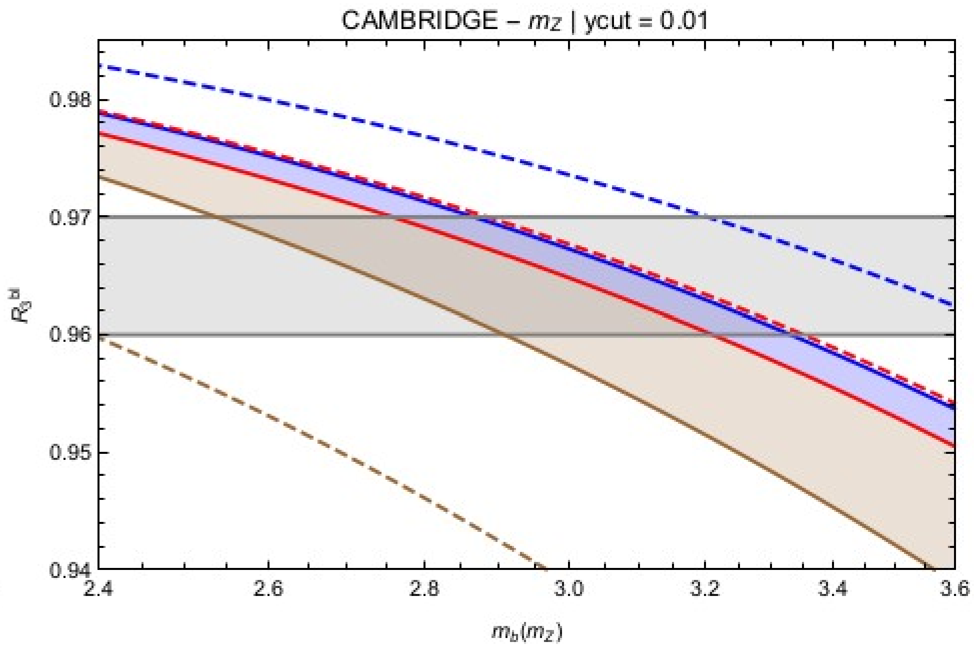




- The dashed lines are LO, and the solid lines are NLO. The **brown lines** correspond to the theory predictions in terms of the **pole mass** and μ = cme. The **blue** and **red** lines represent the theory predictions with the **running mass** and renormalization scales at **μ = 2 cme** and **μ = cme/2**, respectively. The theory uncertainty is estimated from the spread of the results, and is given by the shadowed band at NLO.

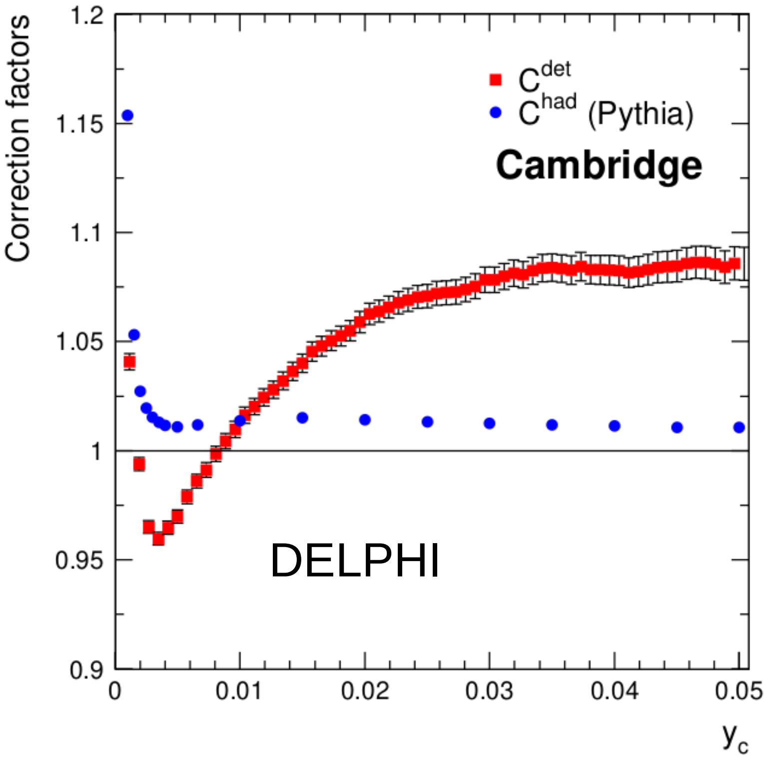
- The horizontal band represents an Ansatz for the experimental measurement.

Snapshot of the DELPHI measurement

$$m_b(M_Z) = 2.85 \pm 0.18\ (\text{stat}) \pm 0.13\ (\text{exp}) \pm 0.19\ (\text{had}) \pm 0.12\ (\text{theo})\ \text{GeV}/c^2$$

- **Statistical uncertainty:** associated to the luminosity and selection efficiency (flavour tagging)
- **Experimental uncertainties:** detector effects, flavour tagging efficiency/purity
- **Hadronization uncertainties:** modeling of the parton shower + hadronization (including mass effects on the hadronization)
  - Includes a $O(\lambda_{QCD})$~150 MeV uncertainty related to the intrinsic Msbar – pole conversion and renormalons

$$R_3^{bl}(parton) = C^{had}\, C^{det}\, R_3^{bl}(reco)$$



hep-ex/0603046

Snapshot of the DELPHI measurement

$$R_3^{bl}(parton) = C^{had}\, C^{det}\, R_3^{bl}(reco)$$

▶ C^{had} → corrects from parton level to hadron level

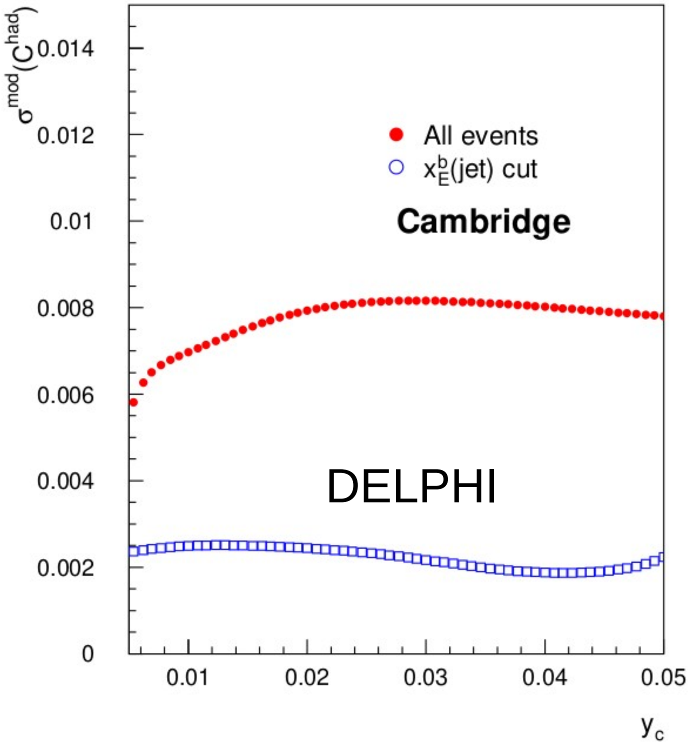
- Hadronization uncertainty was negligible as soon as a minimal energy of the B-hadron is required (xbE)
- LEP: 0.2% on Chad → comparing different Had. Algorithms and tunes

▶ C^{det} → corrects from reco level to parton level

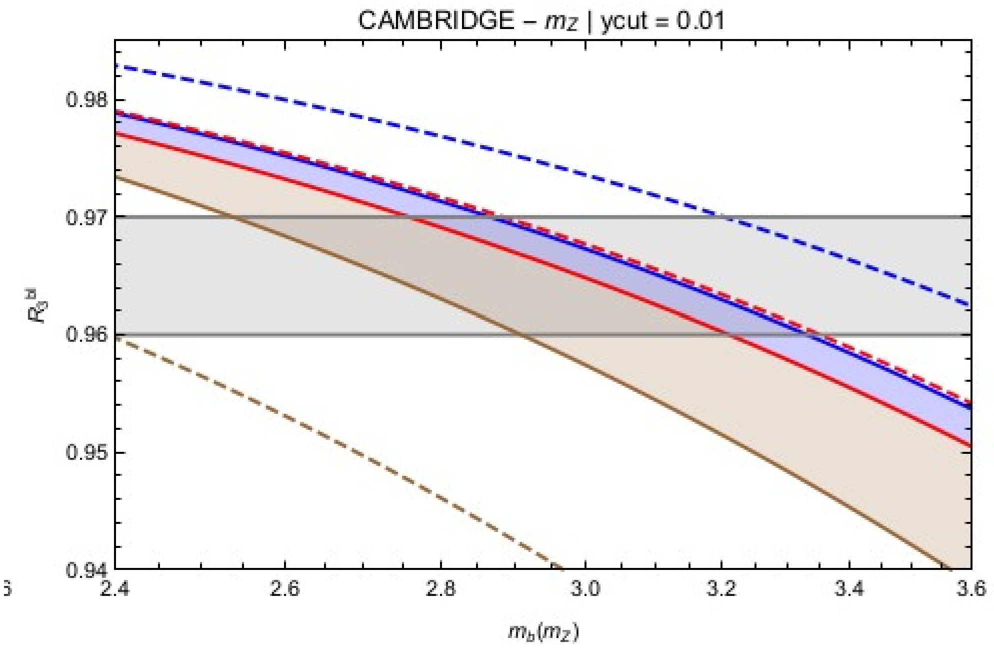
- Main uncertainties coming from flavour selection efficiency, detector acceptance, etc
- Flavour tagging efficiency and purity

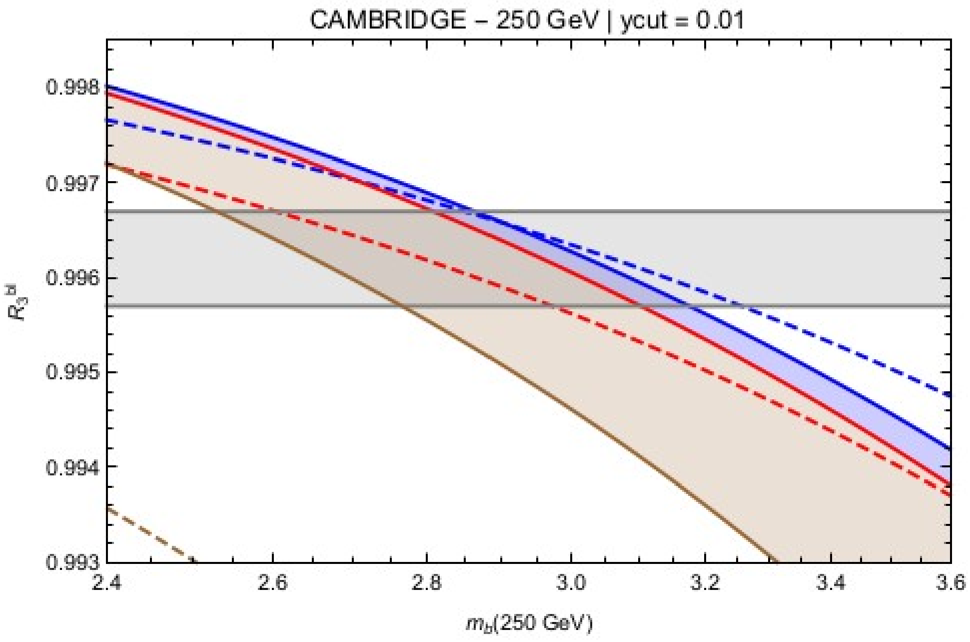
	b-quark		light quarks	
Experiment	Eff. [%]	Pur. [%]	Eff. [%]	Pur. [%]
DELPHI [19]	47%	86%	51%	82%

- The efficiency defines our statistical uncertainty
- The purity limited the accuracy on the efficiency determination



ILC prospects: Z-Pole vs 250GeV





Sensitivity of the observable

$$\Delta R_3^{b\ell} \sim \frac{2(1-R_3^{b\ell})}{m_b(\mu)} \Delta m_b(\mu) \, .$$

The sensitivity at 250GeV is ~5 times worst

ILC prospects: Z-Pole vs 250GeV

- ILC can operate at the Z-pole
  - GigaZ with ~x100 more Z→ bbar than LEP
- ILC will operate at 250 GeV
  - 2000fb-1 with shared luminosity of two polarization scenarios
  - ~3M of bbar pairs
  - Limited sensitivity…
  - Contamination from radiative return backgrounds and diboson backgrounds
  - **Very challenging measurement**

Signal (250GeV)

Polarization	$\sigma_{e^-e^+\to q\bar{q}}(E_\gamma < 50\,GeV)$[fb]		
	$b\bar{b}$	$c\bar{c}$	$q\bar{q}\ (q = uds)$
$e^-_L e^+_R$	5970.9	8935.2	19347.6
$e^-_R e^+_L$	1352.1	3735.1	5920.4

Channel	$\sigma_{e^-_L e^+_R\to X}$ [fb]	$\sigma_{e^-_R e^+_L\to X}$ [fb]
$X = Z\gamma \to \gamma q\bar{q}(E_\gamma > 50GeV)$	94895.3	60265.3
$X = WW \to q_1\bar{q}_2q_3\bar{q}_4$	14874.4	136.4
$X = ZZ \to q_1\bar{q}_1q_2\bar{q}_2$	1402.1	605.0
$X = HZ \to q_1\bar{q}_1q_2\bar{q}_2$	346.0	222.0

bkg (250GeV)

ILC250 prospects

- We study the experimental viability of the R3bl at ILC250 and ILC-GigaZ
  - We only have samples for the 250GeV
- We used old samples DBD (the 2020 samples were still not validated)
- e+e- → qq at LO and for massless quarks (including the b-quark)
  - The mass effects are wrongly implemented: only appear during the PS and Hadronization process
  - Including higher QCD orders and mass effects is an ongoing activity of the Whizard experts in contact with our team.
- With these samples we cannot get a reliable R3bl prediction
  - But we can estimate the efficiency of selection and flavour tagging
  - And the optimization of the background rejection

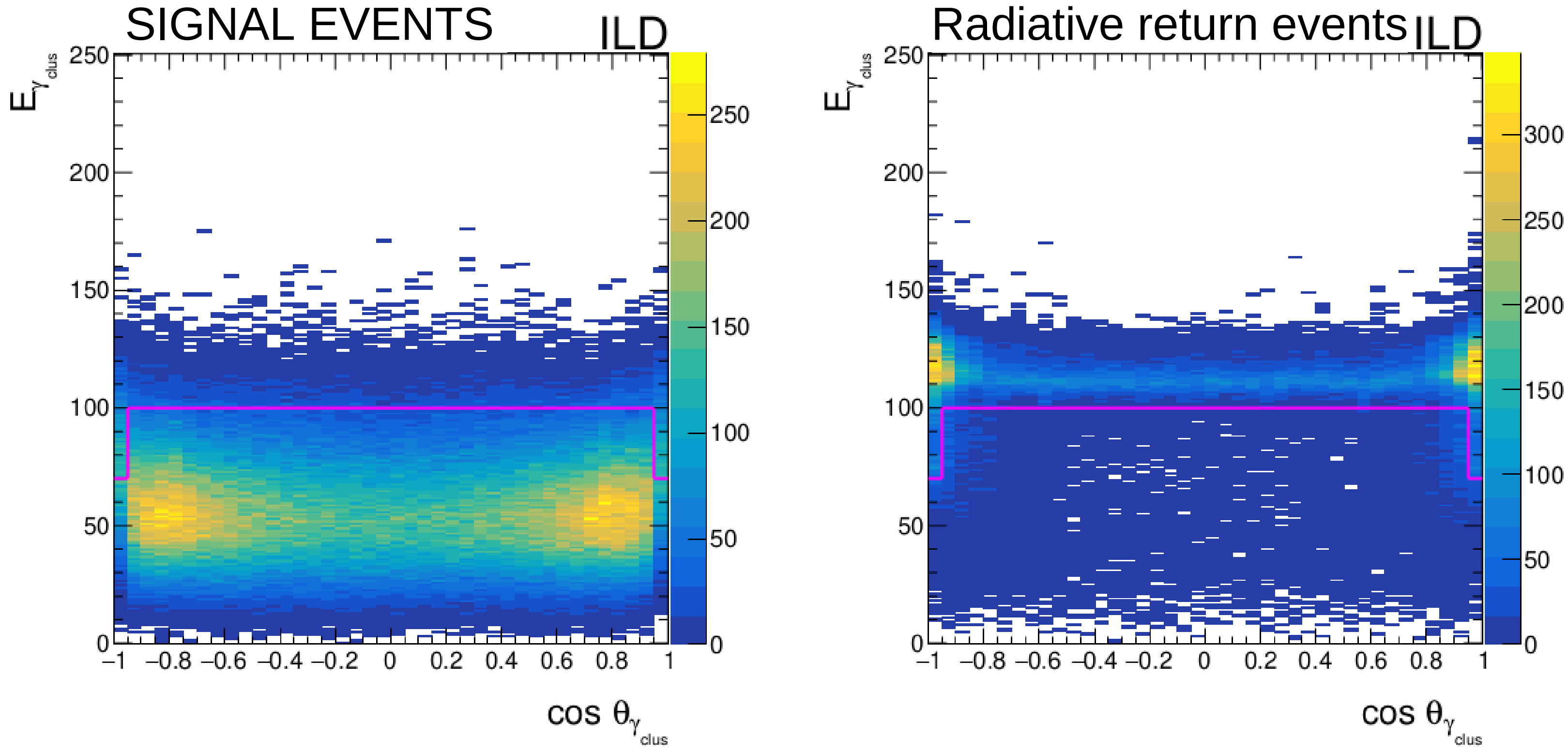
ILC250: Event Selection

- We follow the same recipe & techniques than for the AFBb studies (Bilokin, Poeschl, Richard, A.I)
- Start with a preselection of quarks in the final state.
- We force our events to be reconstructed as 2 jets
  - ee_gen_kt, R=1.25
- Cut 1: removal of radiative return events with “undetected” photon
  - Cut in the invariant mass of the system (mjj>130GeV)+ cut in the energy of the lost ISR photon (Kreco<50GeV)

$$|\vec{k}| \approx K_{reco} = \frac{250\,\mathrm{GeV} \cdot \sin\Psi_{acol}}{\sin\Psi_{acol} + sin\theta_1 + sin\theta_2}.$$

ILC250: Event Selection

- Cut 2: veto of events in which the ISR photon was reconstructed and identified inside the detector

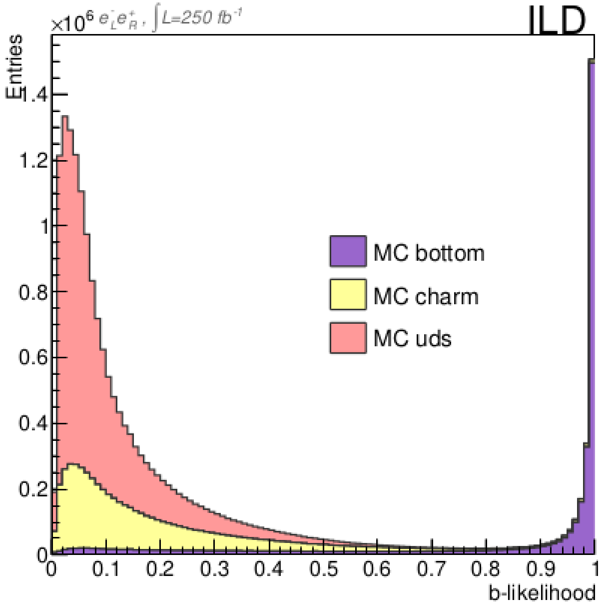


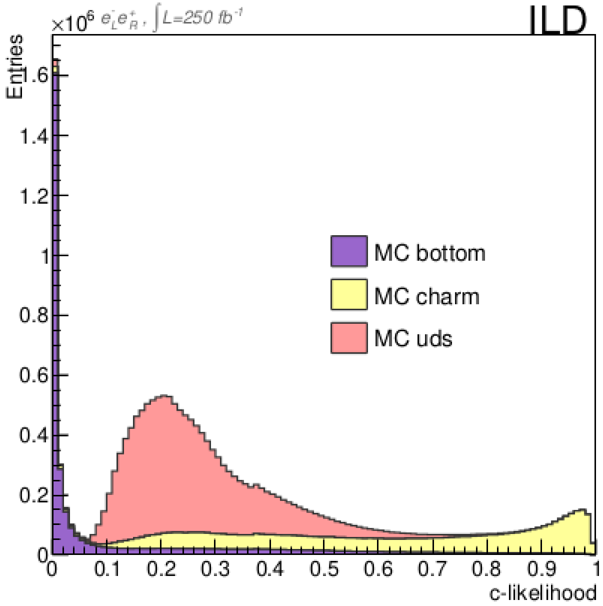
ILC250: Event Selection

▶ Cut 3: flavour tagging (double tagging)

- b-quark selection: btag>0.85
- l-quark selection: btag<0.4 & ctag<0.25

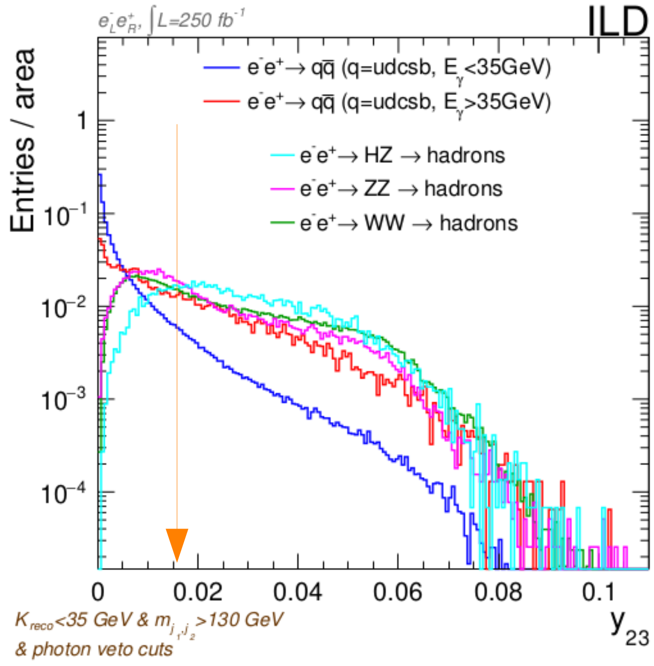
	b-quark		light quarks	
Experiment	Eff. [%]	Pur. [%]	Eff. [%]	Pur. [%]
DELPHI [19]	47%	86%	51%	82%
ILD (this note)	80%	98.7%	58%	96.1%

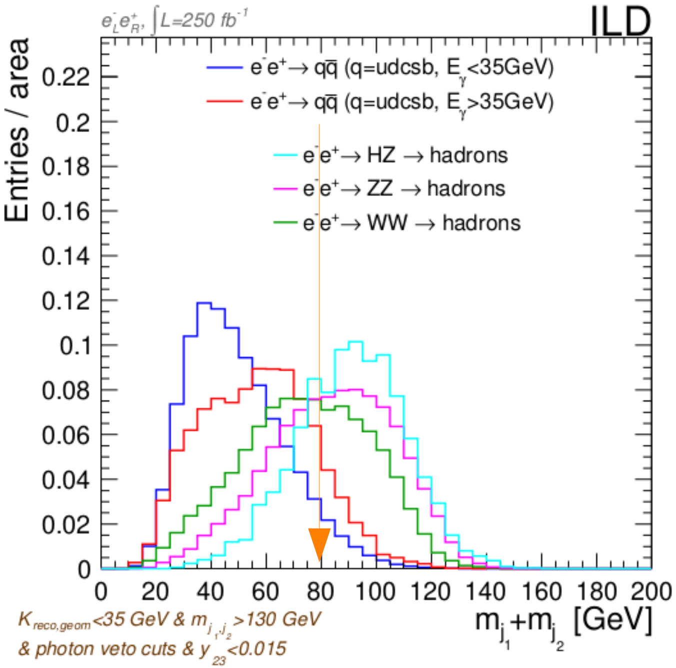




ILC250: Event Selection

- ▶ Is this enough? For the AFBb analysis we add another set of aggressive cuts on jet variables (y23, mass of the jets) to remove the remaining backgrounds.
- ▶ Undesirable here since y23 and mass of the jets are tightly connected to the R3bl observable





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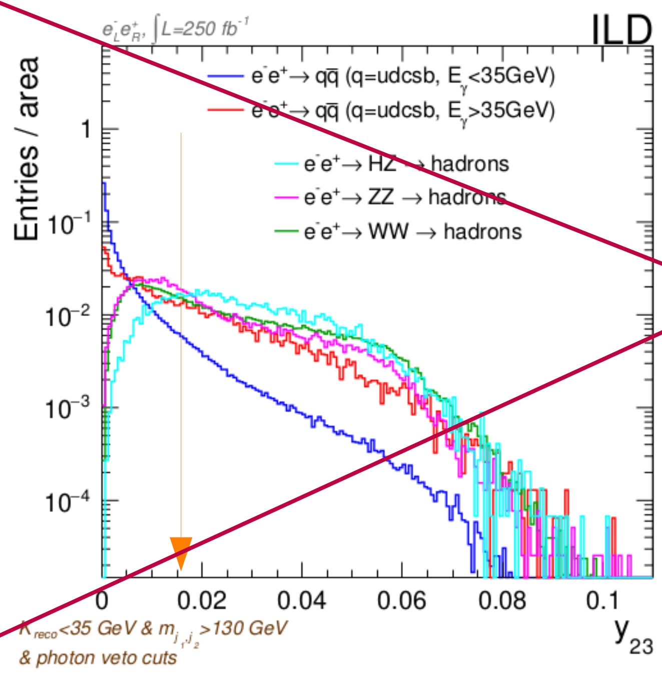
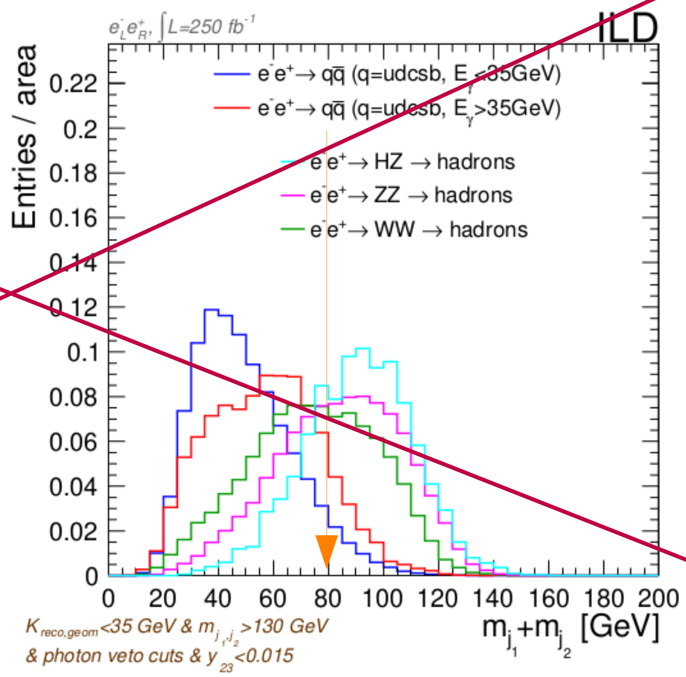
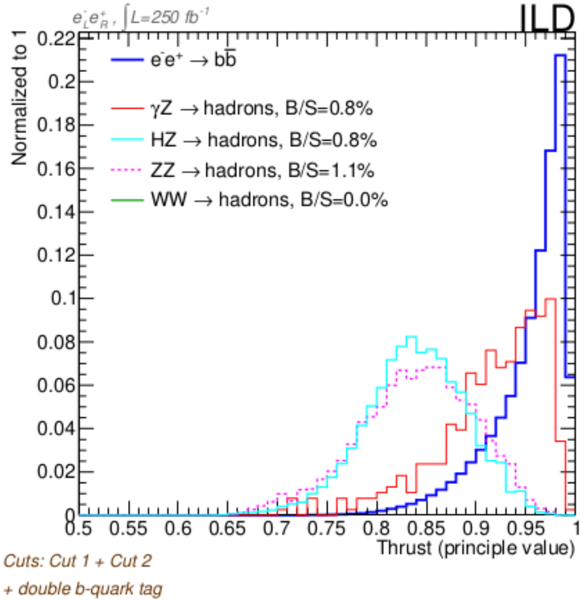
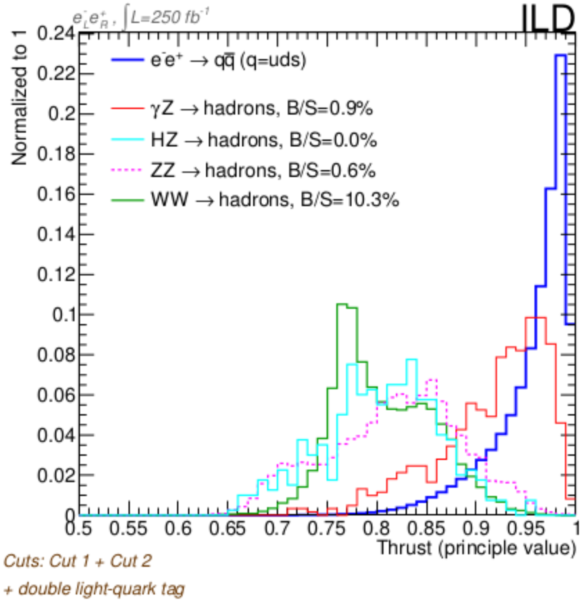




ILC250: Event Selection

- Let's take a look at the Thrust (principle axis)
- Left polarization case: the WW bkg adds a large contribution to the light quark selection

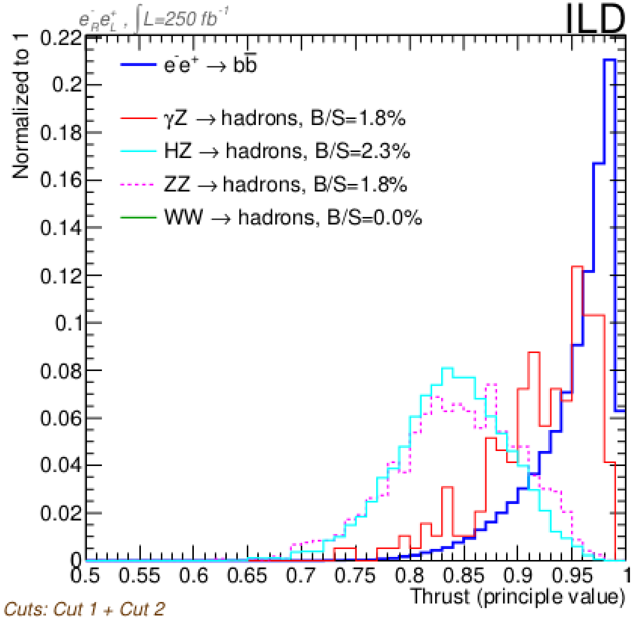




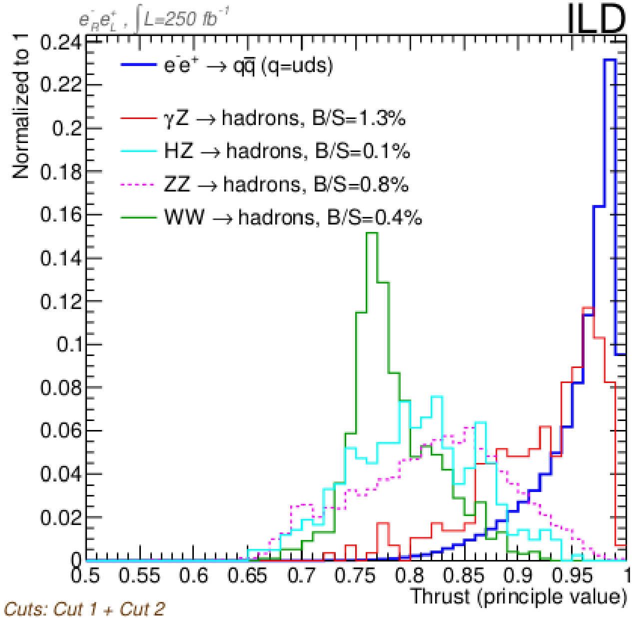
- We can remove large part of the WW background if T>0.8
  - Which seems a harmless cut

ILC250: Event Selection

- Let's take a look at the Thrust (principle axis)
- Right polarization case:
  - Smaller bkg contribution



Cuts: Cut 1 + Cut 2
+ double b-quark tag



Cuts: Cut 1 + Cut 2
+ double light-quark tag

ILC250: Event Selection

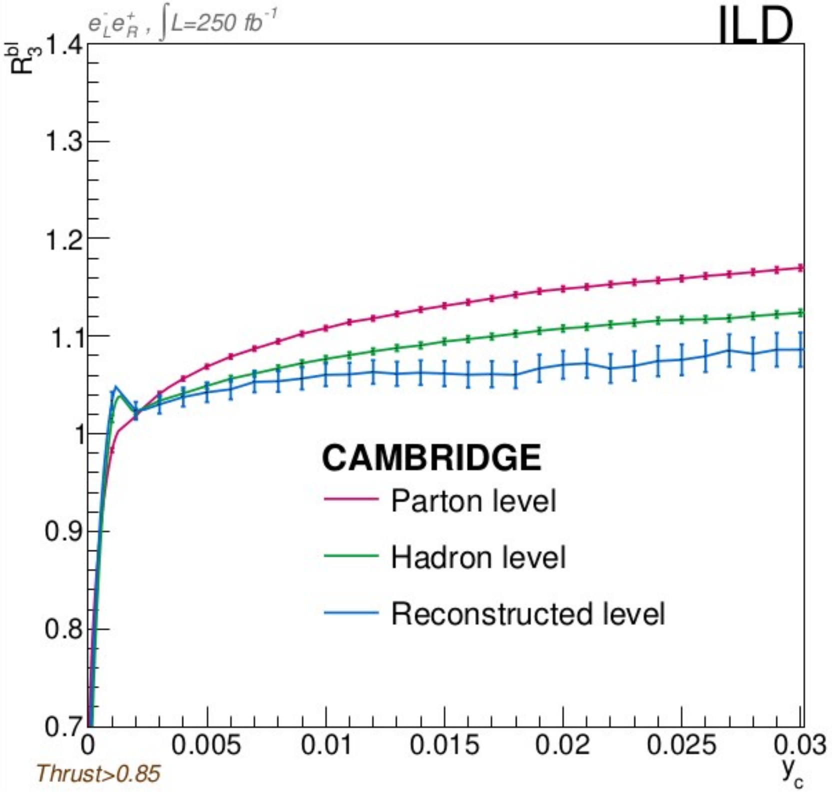
$e^-_L e^+_R$					
		B/S [%]			
	Signal Eff [%]	Rad. Return	WW	ZZ	HZ
T>0.8					
R_3^ℓ	16.5%	1.4%	5.1%	0.3%	0.0 %
R_3^b	37.8%	1.2%	0.0%	0.6%	0.6 %
T>0.85					
R_3^ℓ	16.2%	1.3%	2.3%	0.2%	0.0 %
R_3^b	36.9%	1.2%	0.0%	0.3%	0.3 %

$e^-_R e^+_L$					
		B/S [%]			
	Signal Eff [%]	Rad. Return	WW	ZZ	HZ
T>0.8					
R_3^ℓ	16.7%	1.5%	0.1%	0.5%	0.0
R_3^b	37.3%	1.9%	0.0%	1.4%	1.8
T>0.85					
R_3^ℓ	16.4%	1.4%	0.0%	0.3%	0.0
R_3^b	36.5%	1.8%	0.0%	0.9%	1.0

ILC250: final selection

- We construct the R3q observables by **reclustering all available PFOs using the CAMBRIDGE** algorithm with ycut=0.01

- The mass effects are not implemented in the current MC
- But we can estimate the difference between steps:
  - Hadron Level / Parton shower = Chad
  - Reco Level After Selection / Hadron Level = Cdet



ILC250: final selection

- R3q ~ 0.3 Rq
  - With the estimated efficiencies
  - and for 2000fb-1 H20 scenario we calculate

$$\Delta m_b(-+) = \pm 0.85(stat.) \quad \text{GeV}$$
$$\Delta m_b(+-) = \pm 1.53(stat.) \quad \text{GeV}$$

ILC 250 Estimation of uncertainties: Chad

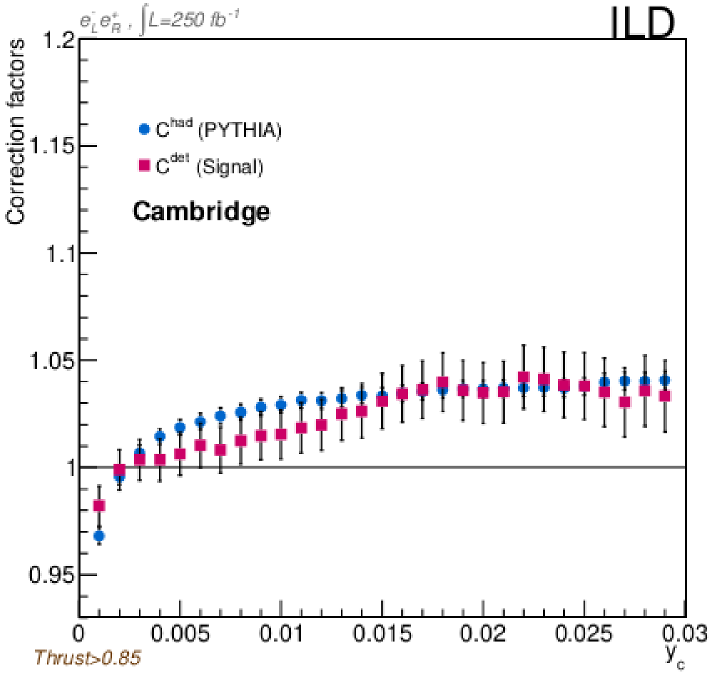
$$R_3^{b\ell}\Big|_{parton} = C_{had} \times C_{det} \times R_3^{b\ell}\Big|_{reco}$$

DELPHI PAPER

- C^{had} → corrects from parton level to hadron level
  - Hadronization uncertainty was negligible as soon as a minimal energy of the B-hadron is required (xbE)
  - LEP: 0.2% on Chad → comparing different Had. Algorithms and tunes

ILD 250GeV

- Not different PS/Fragmentation alogrithms compared (only pythia)
- Higher energy of b-hadrons and more data…
- **We assume that we could improve the uncertainty by a factor two.**

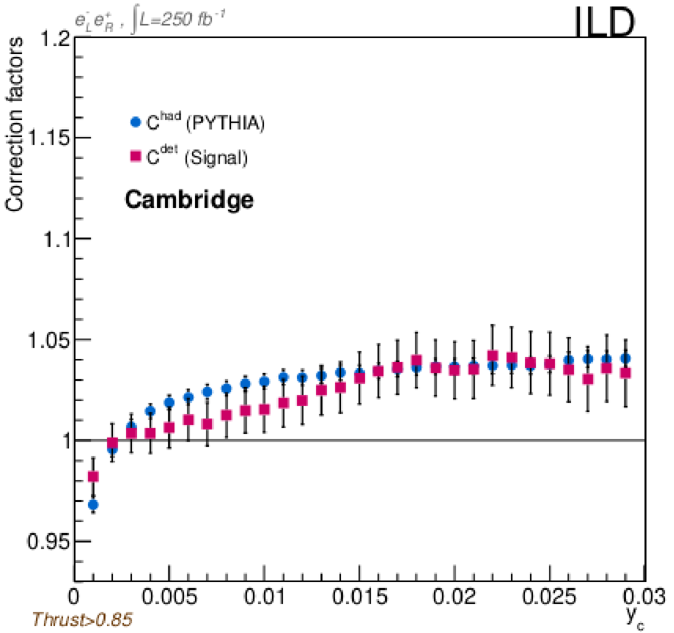


ILC 250 Estimation of uncertainties: Cdet

$$R_3^{b\ell}\Big|_{parton} = C_{had} \times C_{det} \times R_3^{b\ell}\Big|_{reco}$$

$$R_3^q(y_{cut})\Big|_{reco} = \frac{\varepsilon_{sel} \cdot \left[\varepsilon_q^2 \sigma_{q\bar{q}}^{3\,jet}(y_{cut}) + \varepsilon_{q'}^2 \sigma_{q'\bar{q}}^{3\,jet}(y_{cut})\right] + \varepsilon_{bkg}\sigma_{bkg}^{3\,jet}(y_{cut})}{\varepsilon_{sel} \cdot \left[\varepsilon_q^2 \sigma_{q\bar{q}} + \varepsilon_{q'}^2 \sigma_{q'\bar{q}}\right] + \varepsilon_{bkg}\sigma_{bkg}}.$$

- ▶ We have estimations for all values in the right-side formula
- ▶ The Flavour tagging efficiency can be **measured** at following Double tagging methods
  - 0.1-0.5% level (as in the AFBb analysis)
- ▶ The BKGs can be reduced to small contributions, however the uncertainty of such contributions is unknow
  - We assume O(1%) uncertainty on epsilon_bkg x sigma_bkg



ILC 250 Estimation of uncertainties

C_{had} Systematic Unc.		
Source	**Estimation**	comments
hadronization modelling	0.1 %	Assumed to be half the uncertainty evaluated for LEP
C_{det} Systematic Unc. ($e^-_L e^+_R$)		
flavour tagging	0.07 %	assuming flavour tagging uncertainties as estimated in [36]
pre-selection efficiency	0.06 %	as estimated in [36]
$Z\gamma/WW/HZ/ZZ$ modelling	0.20 %	assuming modelling uncertainties at the per cent level. It assumes a moderate cut in the thrust of the event which may required further studies to reject possible biases on the observable due to this cut.
total	**0.22 %**	dominated by the WW contamination to R_3^ℓ
C_{det} Systematic Unc. ($e^-_R e^+_L$)		
flavour tagging	0.06 %	assuming flavour tagging uncertainties as estimated in [36]
pre-selection efficiency	0.06 %	as estimated in [36]
$Z\gamma/WW/HZ/ZZ$ modelling	0.1 %	Assuming modelling uncertainties at the per cent level. No specific cuts are needed for the removal of the backgrounds.
total	**0.13 %**	dominated by the ZZ and radiative return contamination to R_3^b

ILC 250 Estimation of uncertainties

$$\Delta R_3^{b\ell} \sim \frac{2(1-R_3^{b\ell})}{m_b(\mu)} \Delta m_b(\mu) \; .$$

$$\Delta m_b(-+) = \pm 0.85(stat.) \pm 0.34(had.) \pm 0.75(exp.) \pm 0.07(th.) \text{ GeV}$$
$$\Delta m_b(+-) = \pm 1.53(stat.) \pm 0.34(had.) \pm 0.44(exp.) \pm 0.07(th.) \text{ GeV}$$

ILC GigaZ Estimation of uncertainties

$$\Delta R_3^{b\ell} \sim \frac{2(1-R_3^{b\ell})}{m_b(\mu)} \Delta m_b(\mu)\ .$$

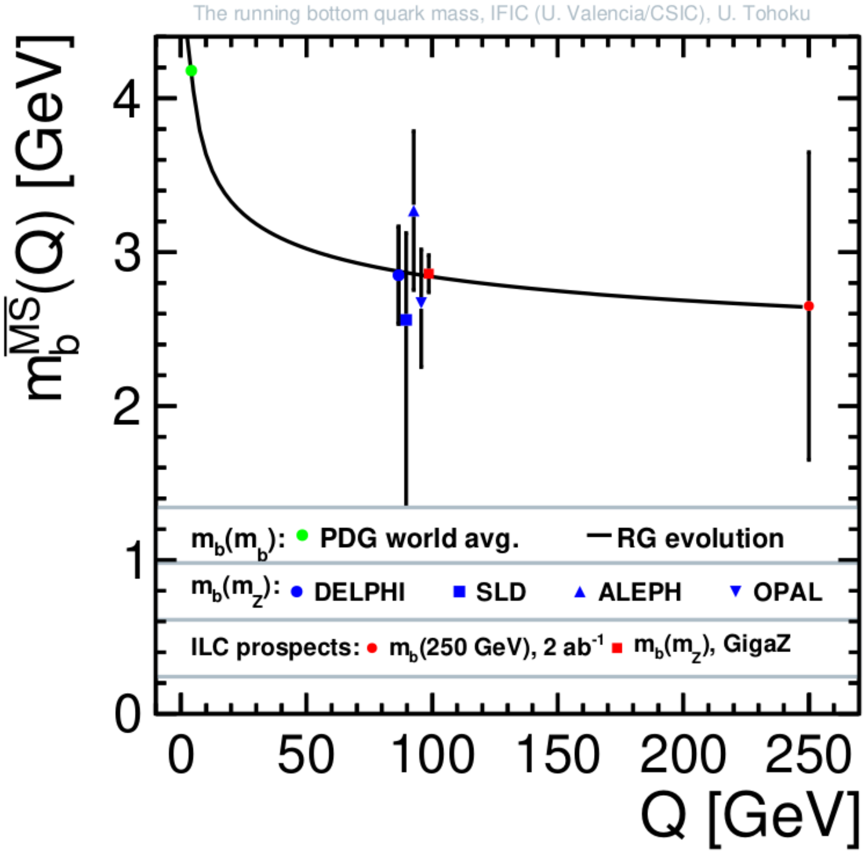
$$\Delta m_b(m_Z) = 0.12 = 0.02(stat.) \pm 0.09(had.) \pm 0.02(exp.) \pm 0.06(th.)\ \text{GeV}$$

- We recover large the large sensitivity
- We no longer have the problem of radiative return and diboson backgrounds
- ILD superior flavour tagging will reduce the experimental uncertainties
- Assumed same efficiencies at 250 GeV and GigaZ
  - Make negligible the experimental uncertainties in a first approximation
- Hadronization still dominates → even assuming that we will be twice smarter than LEP (with 100 times more data)

ILC Prospects

- The ILC250 measurement is very challenging and show limited sensitivity
  - However it will add an extra point at never probed energies

- A measurement at GigaZ would allow to test the hypothesis of SM running of the mass at ~5 sigmas



Summary & plans

- Seidai Taraifune just defended his Master these based on this work
- We are sending an abstract to LCWS
  - Presenter Seidai
- We plan to make this work public through an ILD public note
  - Contacting the PSB just after this talk

- This work has triggered the discussion with Whizard experts
  - Towards NLO QCD samples
  - With non massless quarks

mb(mb) at high energies – Z pole

experiment	$m_b(m_Z)$ [GeV]
DELPHI	2.67 ± 0.25 (stat.) ± 0.34 (frag.) ± 0.27 (th.)
SLD	2.56 ± 0.27 (stat.) $^{+0.28}_{-0.38}$ (syst.) $^{+0.49}_{-1.48}$ (th.)
ALEPH	3.27 ± 0.22 (stat.) ± 0.22 (exp.) ± 0.38 (had.) ± 0.16 (th.)
OPAL	2.67 ± 0.03 (stat.) $^{+0.29}_{-0.37}$ (syst.) ± 0.19 (th.)
DELPHI	2.85 ± 0.18 (stat.) ± 0.13 (exp.) ± 0.19 (had.) ± 0.12 (th.)
DELPHI	3.76 ± 0.32 (stat.) ± 0.17 (syst.) ± 0.22 (had.) ± 0.90 (th.)

Table 1: Measurements of the bottom-quark $\overline{MS}$ mass at the scale $\mu = m_Z$, from three and four-jet rates with bottom quarks in e^+e^- collisions at the Z-pole at LEP and SLD.