Bottom-quark fragmentation and impact on the top mass reconstruction

GENNARO CORCELLA

INFN - Laboratori Nazionali di Frascati

1. **Introduction**
2. **QCD calculations and Monte Carlo codes for b-fragmentation in top events**
3. **Hadronization models and fits to LEP and SLD data**
4. B**-hadron spectrum in top decay**
5. **Systematic error on the top mass measurement**
6. **Conclusions**

Based on work by G.C., F.Mescia, V. Drollinger, A.D. Mitov, M. Cacciari, LEP, SLD, ATLAS and CMS top/heavy-quark working groups

Work in progress with F.Mescia and K.Tywoniuk

Reliable description of multiple radiation in top production and decay and of b-quark fragmentation is fundamental in the measurements of the top properties

Monte Carlo event generators (HERWIG/PYTHIA) widely used to simulate top production and decay and bottom-quark hadronization

LHC and Tevatron inclusive analyses (dilepton, lepton+jets and all-hadrons) propagate the uncertainty on b-fragmentation to the systematic error due to b-jet energy scale and b-tagging efficiency:

$\Delta m_t(\mathrm{bfrag}) \simeq 250 - 430$ MeV ; $\Delta m_t(\mathrm{tot}) \simeq 920$ MeV (TOPLHCWG)

$J/\psi+$ **lepton final states (10^3/year in high-luminosity phase)**

$t \to bW$; $b \to B \to J/\psi\ X$; $J/\psi \to \mu^+\mu^-$; $W \to \ell\nu_\ell$

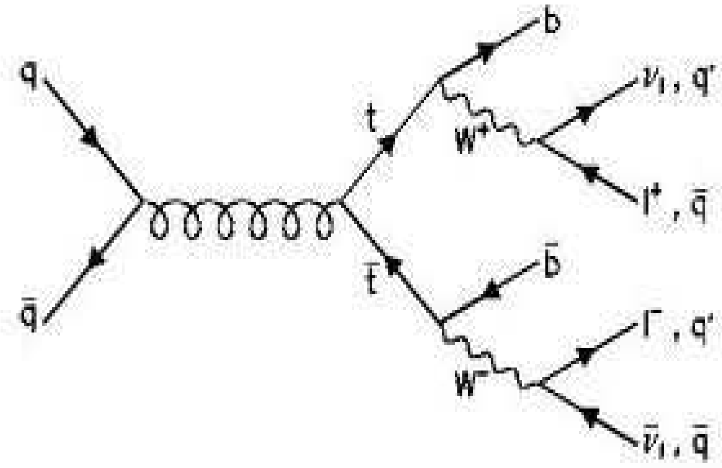
A. Kharchilava, PLB 476 (2000) 73, R. Chierici and A. Dierlamm, CMS Note 2006/058

$m_{3\ell}^{\max} = 0.56\ m_t - 25.3$ GeV Systematics (theo + exp): $\Delta m_t(\mathrm{syst}) \simeq 1.47$ GeV

b-**fragmentation (PYTHIA+Peterson model):** $\Delta m_t(\mathrm{frag}) \simeq 0.51$ GeV

Several calculations and tools are available for bottom fragmentation in top decays, but not unique strategy for the systematic error: comparing two tuned codes/computations, one program varying fragmentation parameters, etc.

Top production and decays at hadron colliders, e.g. in $q\bar{q}$ annihilation



Perturbative QCD allows one to calculate the parton-level (b-quark) spectrum

Phenomenological hadronization models are given in terms of non-perturbative fragmentation functions

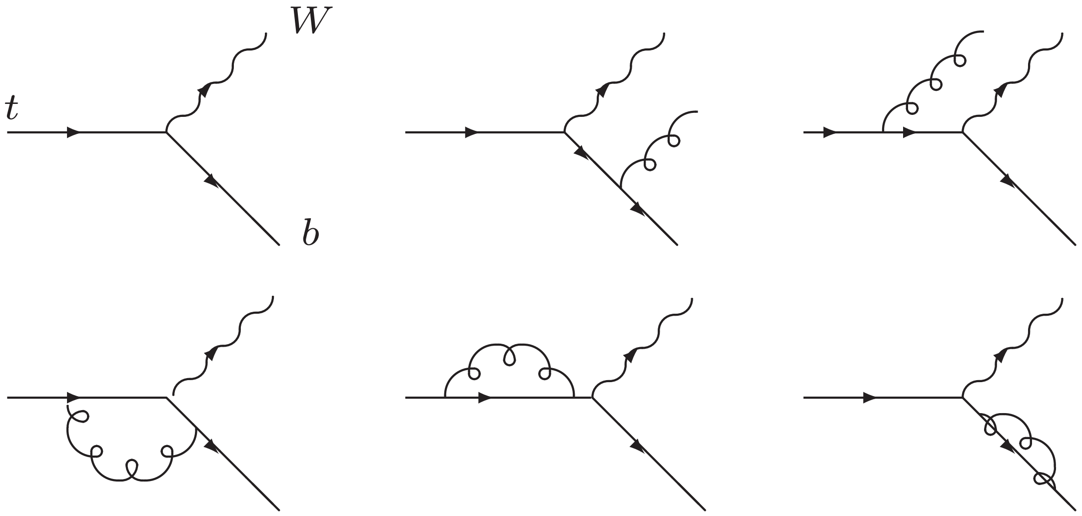
$$\sigma(t \to WB) = \sigma(t \to Wb) \otimes D_{np}(b \to B)$$

$D_{np}(b \to B)$ **contains parameters to be fitted to experimental data**

Narrow-width approximation:

$$\frac{d\sigma_{\rm had}}{dx_B}(t \to B) \simeq \frac{d\Gamma_{\rm had}}{dx_B}(t \to B) \quad ; \quad \frac{d\Gamma_{\rm had}}{dx_B}(t \to B) = \frac{d\Gamma_{\rm part}}{dx_b}(t \to b) \otimes D_{np}(b \to B)$$

Top decay at NLO:



$t(q) \to b(p_b)W(p_W)\,\big(g(p_g)\big)$

$x_b = \frac{1}{1-m_W^2/m_t^2}\,\frac{2p_b\cdot p_t}{m_t^2}$

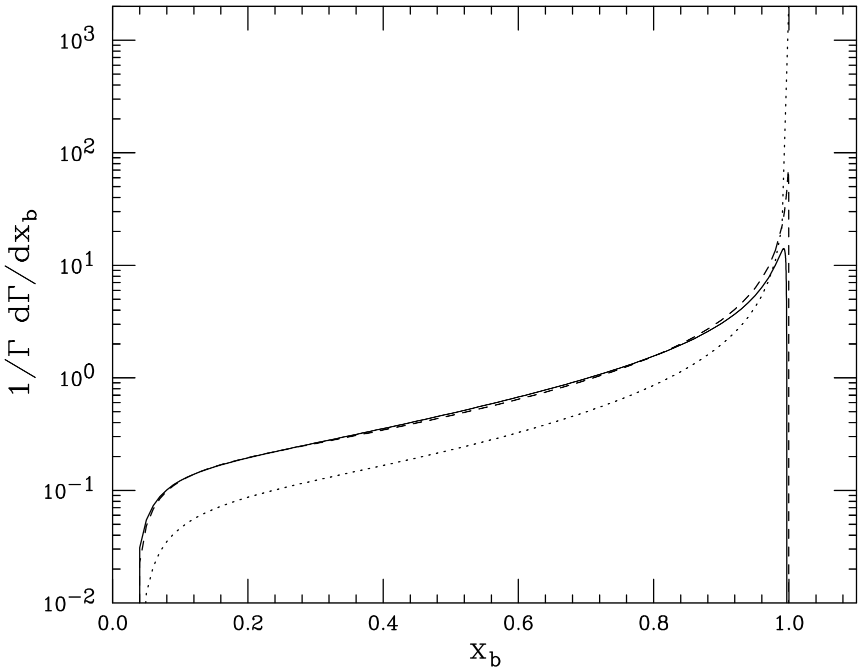
$$\frac{1}{\Gamma_0}\frac{d\Gamma}{dx_b} = \delta(1-x_b) + \frac{\alpha_S(\mu)}{2\pi}\left[P_{qq}(x_b)\ln\frac{m_t^2}{m_b^2} + A(x_b)\right] + \mathcal{O}\left[\left(\frac{m_b}{m_t}\right)^p\right]$$

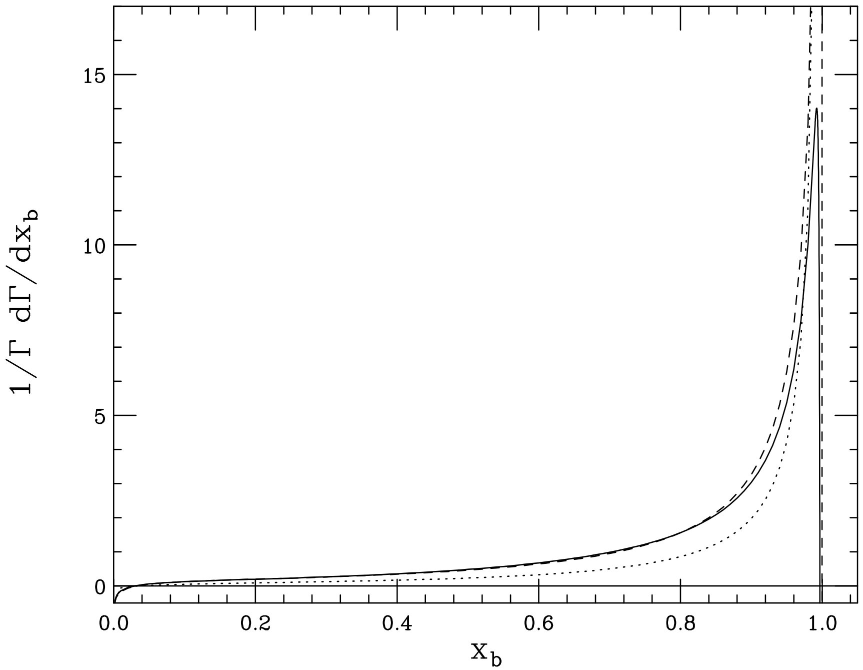
$$P_{qq}(x_b) = C_F\left(\frac{1+x_b^2}{1-x_b}\right)_+ \;;\; \int_0^1 dx_b f(x_b)[g(x_b)]_+ = \int_0^1 dx_b[f(x_b)-f(1)]g(x_b)$$

Mass logarithms and large-x_b terms need resummation (soft/collinear radiation)

b-quark energy spectrum in top decay

m_t=175 GeV, m_b=5 GeV, m_W=80.425 GeV, $\mu_F = \mu = m_t$, $\mu_0 = \mu_{0F} = m_b$, $\Lambda_{\overline{\rm MS}}$=200 GeV





Solid: soft and collinear resummation Dashes: only collinear resummation

Dots: massive NLO without resummation

Resummations in the NLL approximation:

Collinear: $\alpha_S \ln(m_t^2/m_b^2)$, $\alpha_S^2 \ln(m_t^2/m_b^2)$, $\ldots$ $\alpha_S^n \ln^n(m_t^2/m_b^2)$, $\alpha_S^n \ln^{n-1}(m_t^2/m_b^2)$, $\ldots$

Soft $[1/(1-x_b)_+ \to \ln N]$: $\alpha_S \ln^2 N, \alpha_S \ln N, \ldots \alpha_S^n \ln^{n+1} N, \alpha_S^n \ln^n N, \ldots$

Monte Carlo generators for high-energy colliders

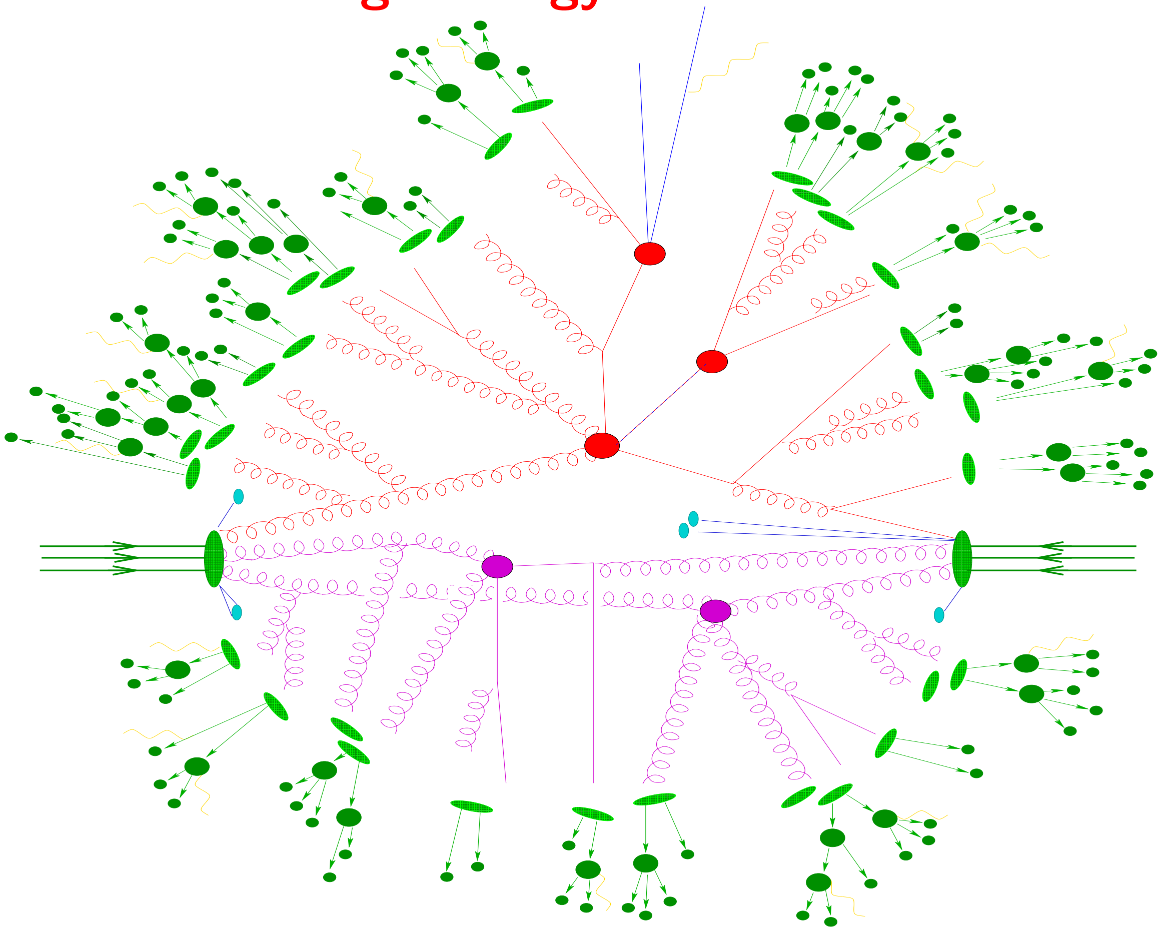


Figure by Frank Krauss

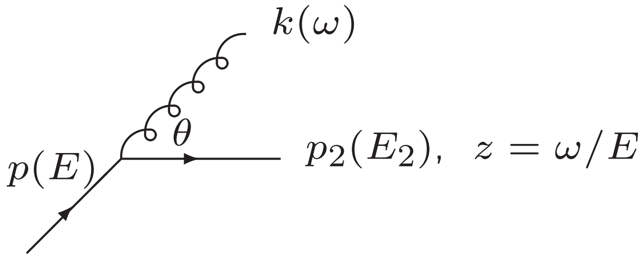
Hard $2 \to 2$ subprocess: leading-order (LO) matrix element

Parton showers in the soft or collinear approximation

Matrix-element corrections for hard and large-angle parton radiation

Models for hadronization and underlying event

Parton shower algorithms



$$dP = \frac{\alpha_S}{2\pi}\, \hat{P}(z) dz\, \frac{dQ^2}{Q^2}\, \Delta_S(Q^2_{\rm max}, Q^2)$$

Q^2: **ordering variable**

$\Delta_S(Q^2_{\rm max}, Q^2)$ **Sudakov form factor: no radiation in** $[Q^2, Q^2_{\rm max}]$

$$\Delta_S(Q^2_{\rm max}, Q^2) = \exp\left[-\frac{\alpha_S}{2\pi}\int_{Q^2}^{Q^2_{\rm max}} \frac{dQ'^2}{Q'^2}\int_{z_{\rm min}}^{z_{\rm max}} dz \hat{P}(z)\right]$$

HERWIG : $Q^2 = E^2(1-\cos\theta) \simeq E^2\theta^2/2$ **Soft approximation: angular ordering**

PYTHIA (up to 6.2 version): $Q^2 = p^2$

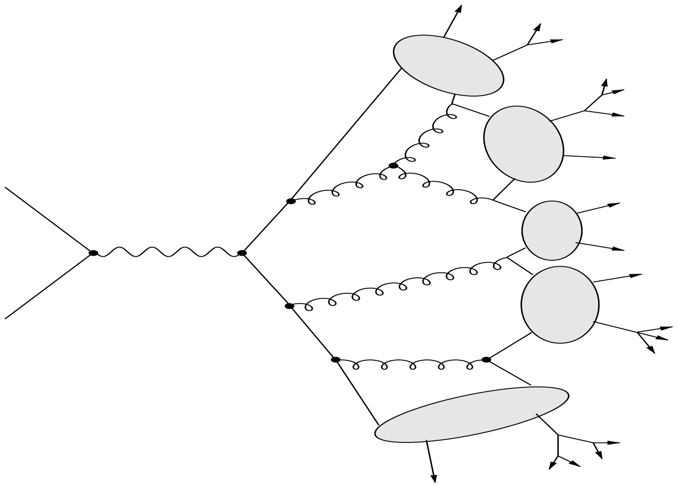
It includes angular ordering only by an additional veto

PYTHIA 6.3 and 8: $Q^2 = k_T^2$

Showers are equivalent to LO+LL resummation, with the inclusion of some NLLs
$(\Lambda_{\overline{\rm MS}} \to \Lambda_{\rm MC} = \Lambda_{\overline{\rm MS}} \exp(4K\beta_0))$

Hadronization: NP fragmentation functions and Monte Carlo models

$$D_{\rm K}(x,\alpha) = (1+\alpha)(2+\alpha)x(1-x)^{\alpha} \;\; ; \;\; D_{\rm P}(x,\epsilon) = \frac{N_P}{x\left[1-1/x-\epsilon/(1-x)\right]}$$



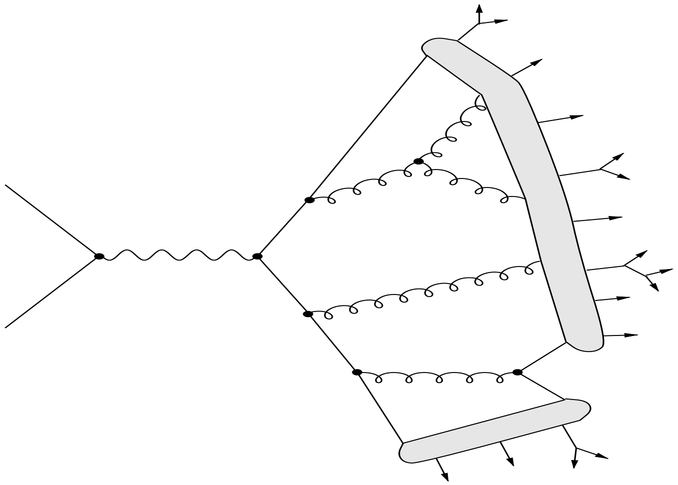
HERWIG: cluster model

Perturbative evolution ends at $Q^2 = Q_0^2$

Angular ordering ⇒ colour preconfinement

Forced gluon splitting $(g \to q\bar{q})$

Colour-singlet clusters decay into the observed hadrons



PYTHIA: string model

q and $\bar{q}$ move in opposite directions

The colour field collapses into a string with uniform energy density

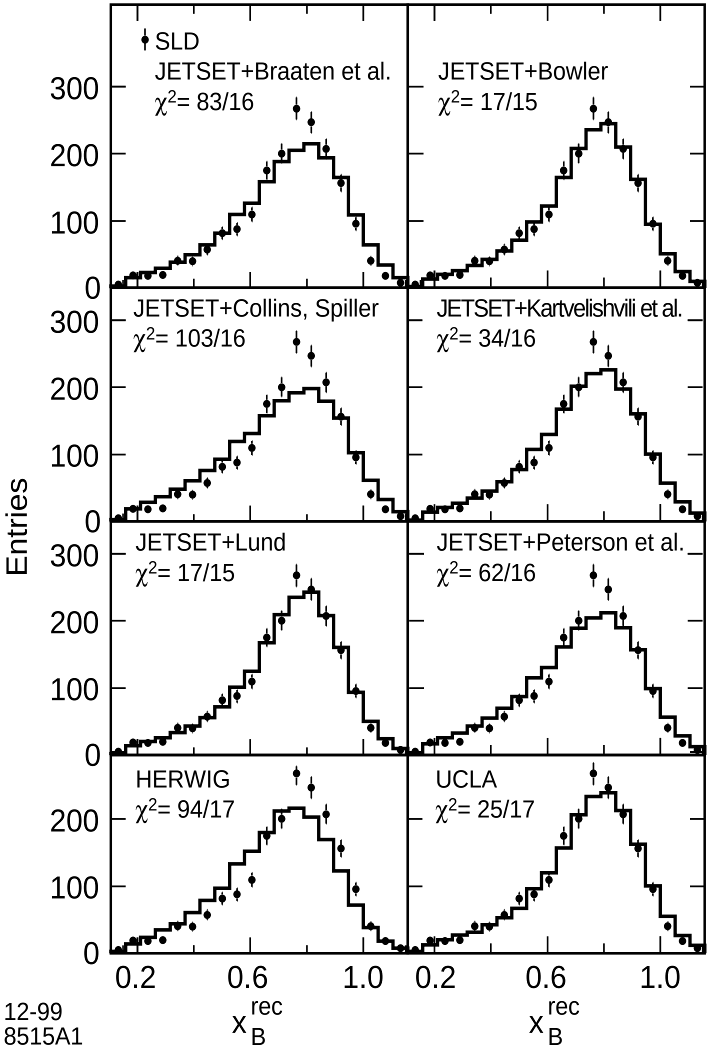
$q\bar{q}$ pairs are produced

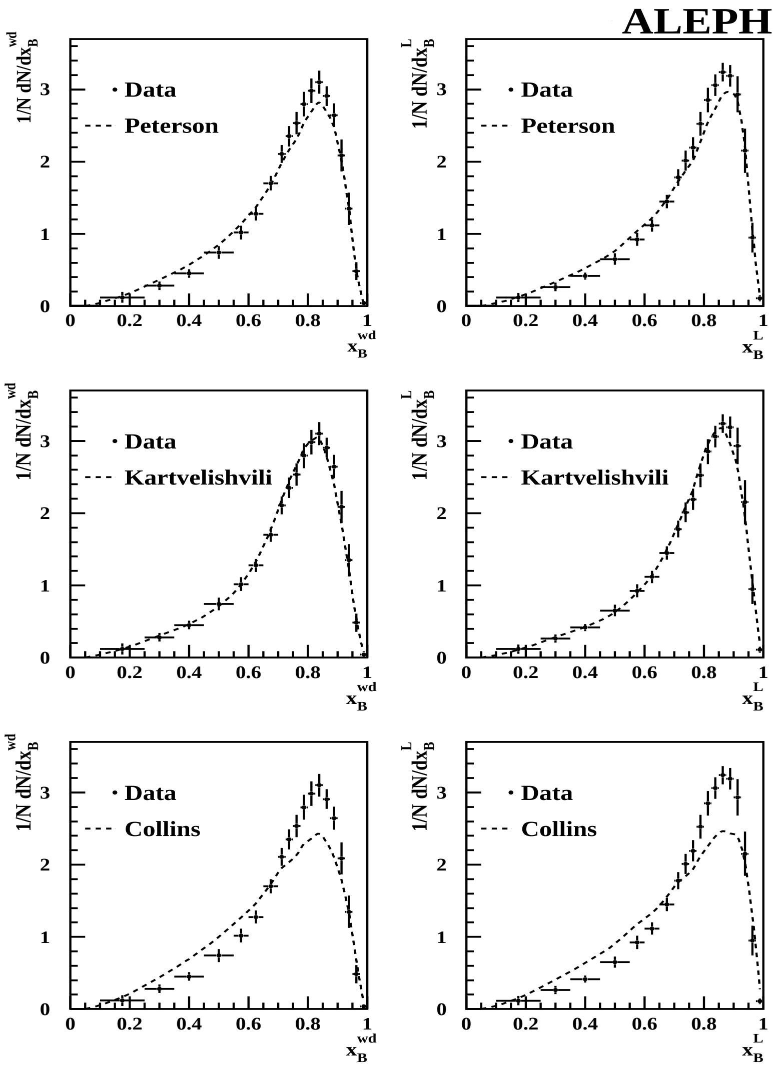
The string breaks into the observed hadrons

Possible interface with NP fragmentation functions

Tuning involves hadronic and perturbative parameters: Q_0, $\Lambda_{\rm MC}$, m_g, etc. and relies on precise e^+e^- data (LHC data in future?)

Bottom-quark fragmentation at the Z^0 pole





LEP tuning of PYTHIA+Peterson used in $J/\psi + \ell$ analysis

Best-fit parameters not the same, e.g. $\epsilon_b = 0.0033$ (ALEPH), 0.0055 (SLD); $\alpha_K = 11.9$ (OPAL), 13.7 (ALEPH), 10.0 (SLD)

G. C. and V. Drollinger, NPB (2005): weakly-decaying B-hadron data from OPAL (mesons and baryons), ALEPH (only mesons) and SLD (mesons and baryons)

HERWIG	PYTHIA
CLSMR(1) $=$ 0.4 (0.0)	
CLSMR(2) $=$ 0.3 (0.0)	PARJ(41) $=$ 0.85 (0.30)
DECWT $=$ 0.7 (1.0)	PARJ(42) $=$ 1.03 (0.58)
CLPOW $=$ 2.1 (2.0)	PARJ(46) $=$ 0.85 (1.00)
PSPLT(2) $=$ 0.33 (1.00)	
χ^2/dof $=$ 222.4/61 (739.4/61)	χ^2/dof $=$ 45.7/61 (467.9/61)

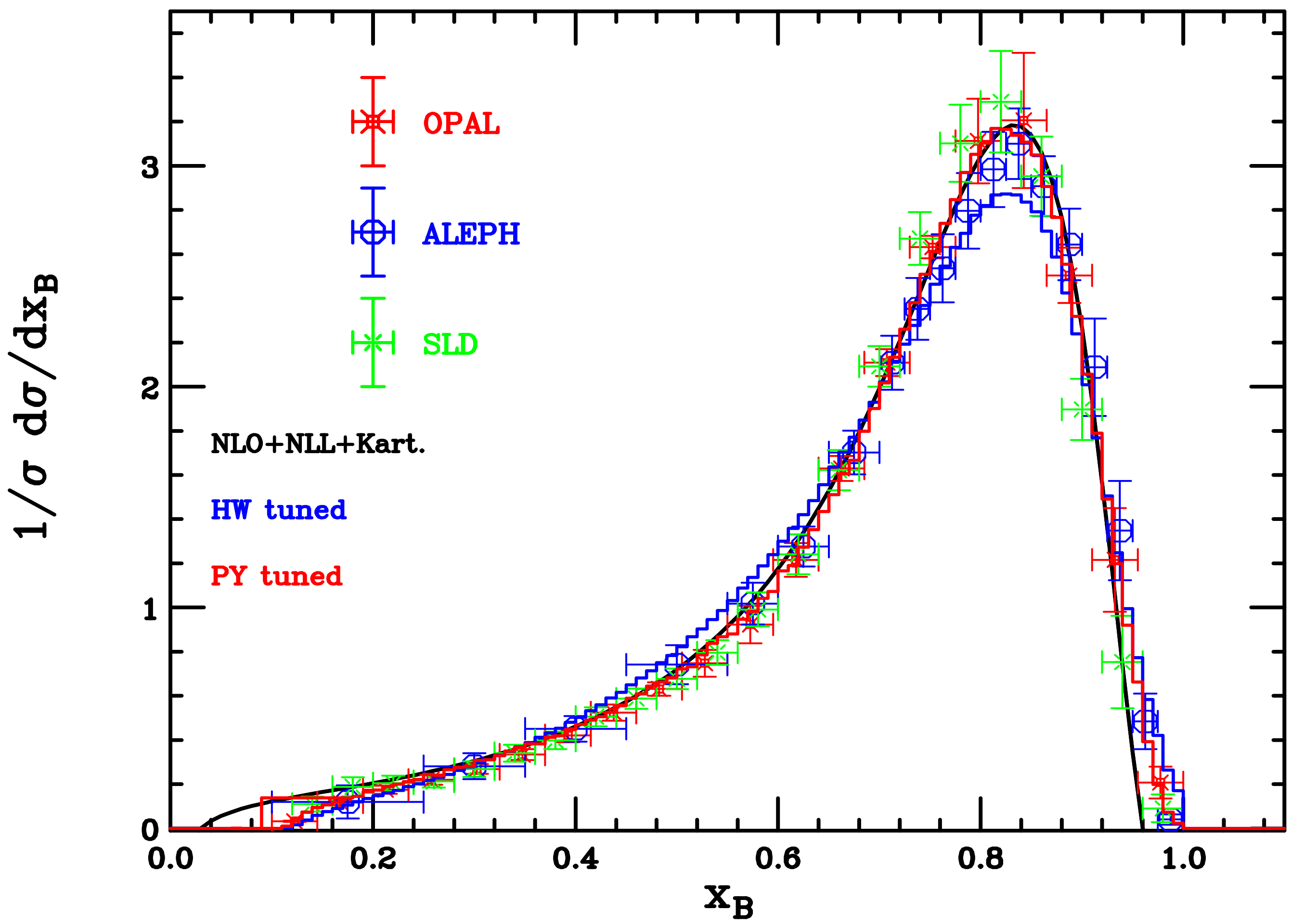
Lund/Bowler fragmentation function (PYTHIA):

$$f_B(z) \propto \frac{1}{z^{1+brm_b^2}}(1-z)^a \exp(-bm_T^2/z)$$

HERWIG tuned parameters describe hadron gaussian smearing **(CLSMR)**, baryon/meson **(CLPOW)** and decuplet/octet **(DECWT)** ratios, mass spectrum of b-like clusters **(PSPLT)**

Our PYTHIA tuning in ATLAS jet-energy measurement (EPJ C73 (2013) 2304) and as a cross-check for top analyses

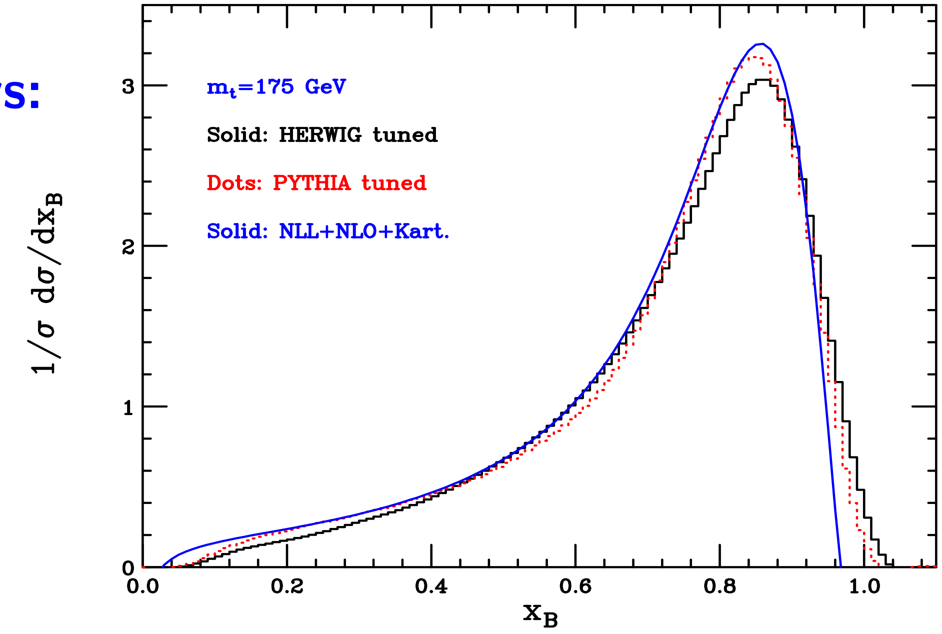
Comparing tuned HERWIG and PYTHIA and resummed calculations



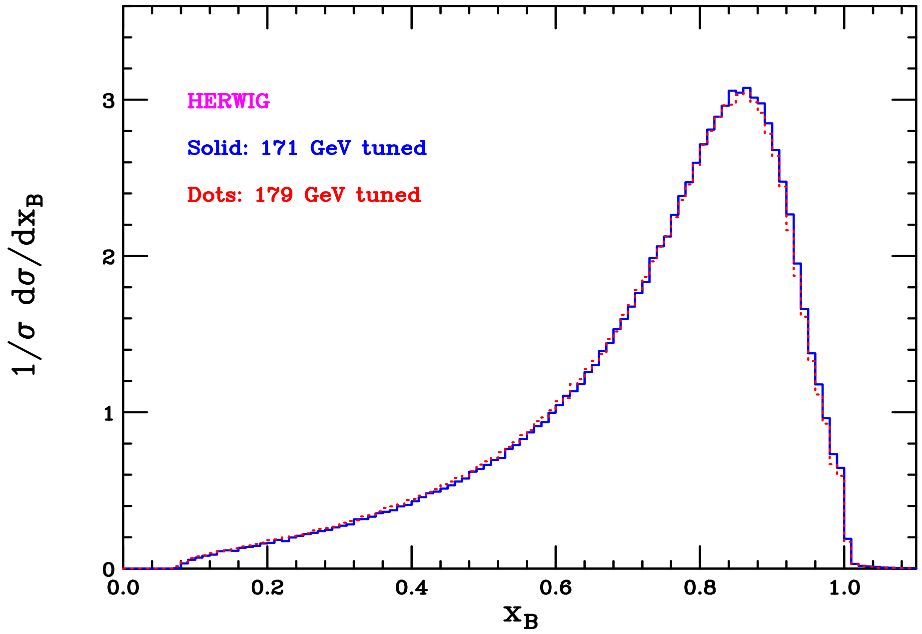
NLO+NLL: M.Cacciari and S.Catani, NPB617 (2001) 253-290

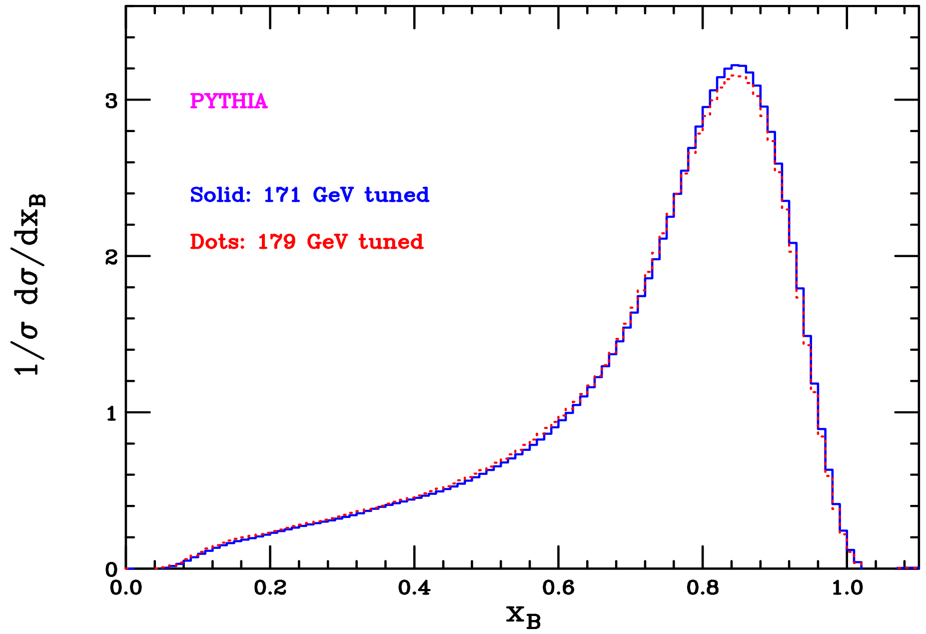
Best fit $(0.18 \leq x_B \leq 0.94)$**:** $\alpha = 17.178 \pm 0.303, \quad \chi^2/\mathrm{dof} = 46.2/53$

B-hadron spectrum in top decays:



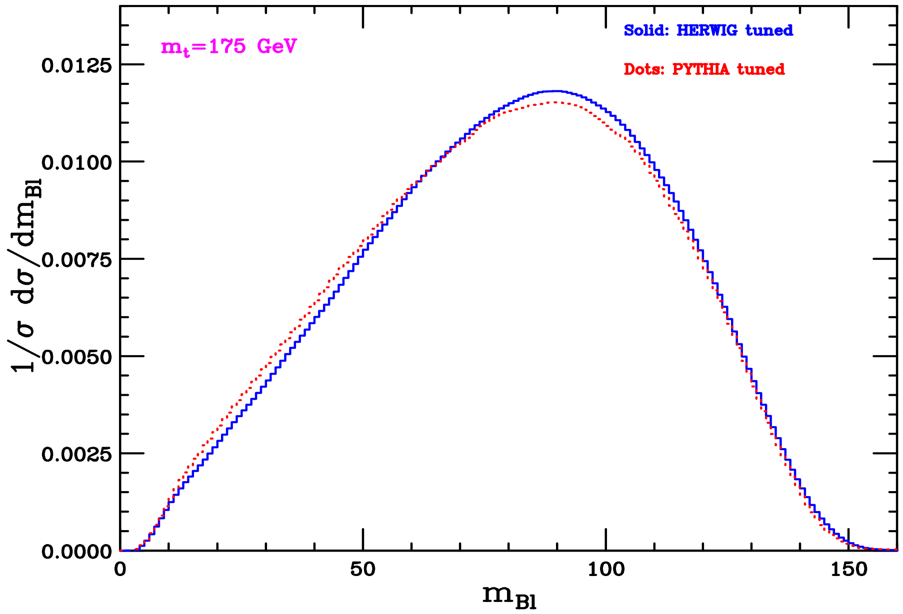
Mild dependence on the top mass in both HERWIG and PYTHIA:

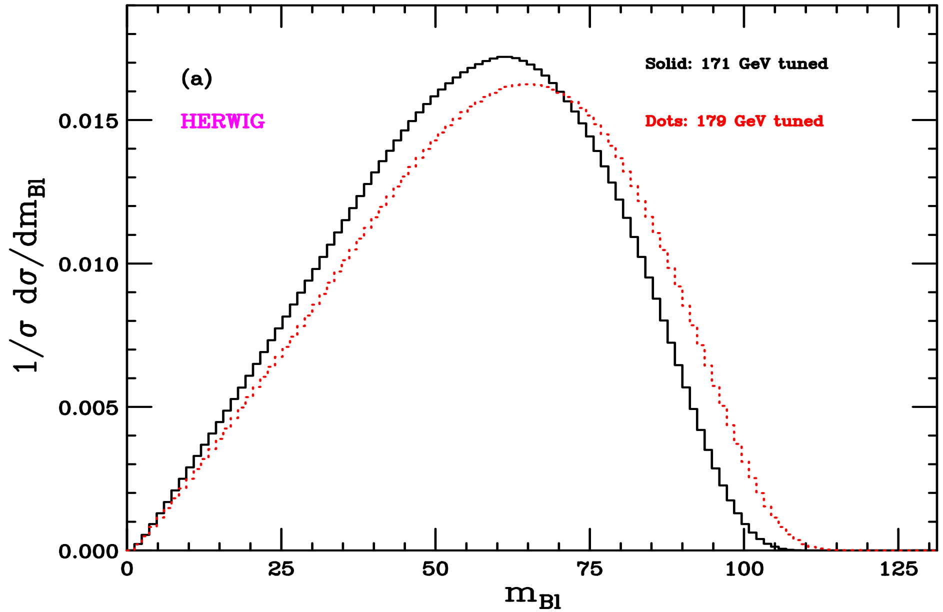


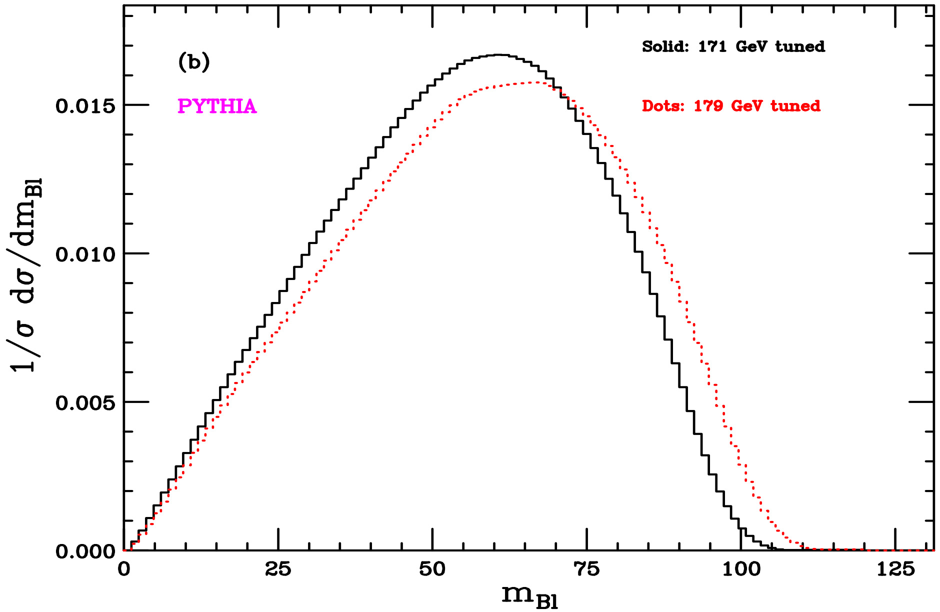


Discussion with CMS/ATLAS folks: x_B hard to measure experimentally

B-lepton invariant mass according to tuned HERWIG and PYTHIA







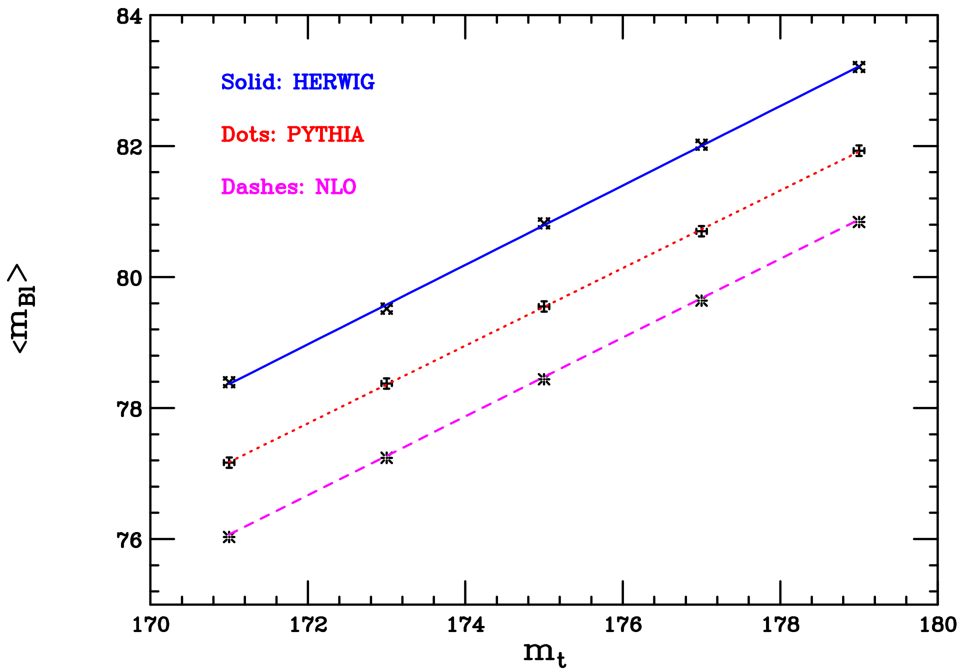
Linear fits to extract m_t from $m_{B\ell}$

HERWIG: $\langle m_{B\ell}\rangle_{\rm H} \simeq -25.31\ {\rm GeV} + 0.61\ m_t$; $\delta = 0.043$ GeV

PYTHIA: $\langle m_{B\ell}\rangle_{\rm P} \simeq -24.11\ {\rm GeV} + 0.59\ m_t$; $\delta = 0.022$ GeV

NLO: $\langle m_{B\ell}\rangle_{\rm NLO} \simeq -26.7\ {\rm GeV} + 0.60\ m_t$; $\delta = 0.004$ GeV

S.Biswas, K.Melnikov and M.Schulze, JHEP 1008 (2010) 048: $m_{B\ell}$ at NLO

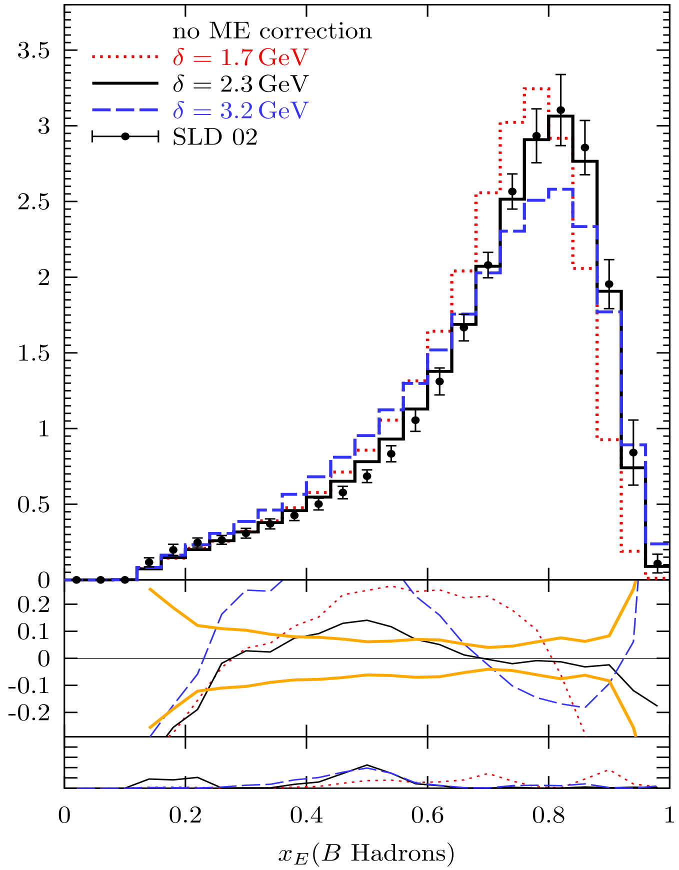


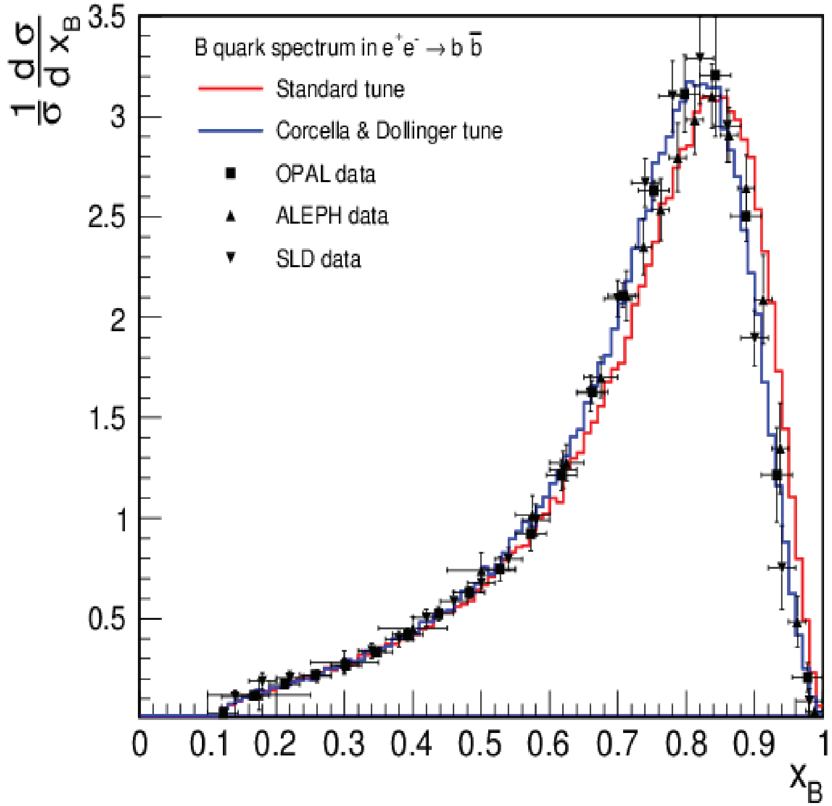
$\Delta\langle m_{B\ell}\rangle_{\rm H,P} \simeq 1.2$ GeV ; $\Delta\langle m_{B\ell}\rangle_{\rm H,NLO} \simeq 2.2$ GeV ; $\Delta\langle m_{B\ell}\rangle_{\rm P,NLO} \simeq 1.1$ GeV

NLO+showers for top decays or C++ codes may shed light on this discrepancy

HERWIG++ : improved fragmentation model and mass-dependent splitting functions

$$P_{qq}(z) = C_F \left[\frac{1+z^2}{1-z} - \frac{2m^2}{Q^2 z(1-z)} \right]_+$$





Left: HERWIG++ vs. SLD data on B-hadron energy fraction (δ: shower cutoff)

Right: tuning PYTHIA 8 (C++) to LEP and SLD data (K.Tywoniuk, preliminary)

Conclusions and outlook

Bottom fragmentation in top decays is a source of uncertainty on the measurement of the top properties in inclusive (b-tagging and b-energy scale) and exclusive analyses ($J/\psi + \ell$)

LO+shower codes and NLO+NLL calculations for b-fragmentation, tuning hadronization models to e^+e^- data

Predictions for top decays yielded by the different codes exhibit some discrepancies, mostly driven by unsatisfactory tunings

Preliminary results with object-oriented codes exhibit a better description of b-quark fragmentation in e^+e^- collisions after the tuning

Perspectives:

Comparing tuned PYTHIA and HERWIG++ can be a valuable way to estimate b-hadronization systematics

Extending the analysis to NLO+showers tools (POWHEG and aMC@NLO with off-shell effects) and ultimately NNLO calculations

Tuning fragmentation parameters directly to LHC data ($t\bar{t}$, $b\bar{b}$, $Z/\gamma + b$) and comparison with e^+e^- fits to test factorization and quality of hadronization models