A Comparison of Bottom Production in Different Event Generators

J.R. Cudell[1], O. Di Rosa[2], I. ten Have[3], A. Nisati[4], R. Odorico[5], T. Sjöstrand[1]

[1]CERN, CH-1211 Geneva 23, Switzerland
[2]LAA Project, CERN, CH-1211 Geneva 23, Switzerland
[3]University of Glasgow, Glasgow, United Kingdom
[4]INFN, Rome, Italy
[5]Università di Bologna and INFN, Bologna, Italy

Abstract:
We study some of the uncertainties attached to the prediction of bottom production at LHC energies by comparing the answers of five different Monte Carlo event generators. The input parameters are set to be as close as possible, so that the resulting discrepancies are mostly due to different algorithms for perturbative QCD, fragmentation and decay. We show that the answers differ by at least a factor 3 after the perturbative description and 10 after fragmentation and decay.

The bottom quark is one of the main sources of prompt leptons at high energy hadron colliders. These leptons constitute a non-negligible background to planned LHC searches, for the top quark, Higgses, weak bosons, or more exotic particles. The optimization of experimental cuts requires the evaluation of this background via Monte Carlo simulations, and it is an important question to see how reliable the present event generation algorithms are.

It is well known that higher order corrections to b production are large. The exact $\mathcal{O}(\alpha_S^3)$ calculations [1] show enhancement factors of around 3, compared to the lowest order results, at LHC energies. In part this is due to the fact that higher orders include contributions for which a vector particle is exchanged in the t channel; these terms remain constant as the centre of momentum energy $\sqrt{\hat{s}}$ increases. An enhancement also comes from the rise of the gluon structure function at low x and from the big colour factors associated with $gg \to gg \to b\bar{b}g$. The size of yet higher order contributions is unknown.

Many of the event generators on the market do not make use of exact higher order matrix elements, but instead combine lowest order $2 \to 2$ hard scatterings with a parton shower picture for initial and final state radiation. Since both the exact matrix element and the parton shower approaches have limitations, it is interesting to see how well they compare, and also how big is the spread between programs of the same class.

We thus propose to compare five Monte Carlo simulations against one another and against the analytical results of Nason, based on [1]. The present study does not evaluate the uncertainties resulting from the input physical parameters,

Table 1: Physics input for the comparison of the various Monte Carlos.

parameter	value	exceptions
process	pp collisions	
$\sqrt{s}$	16 TeV	
structure functions	DFLM set 2 [2]	COJETS
α_S	1-loop, $n_f = 4$	HERWIG 4.6
$\Lambda_{QCD}(GeV)$	260 MeV	
α_S scale	$m_b^2 + p_\perp^2$	
m_b	4.75 GeV	
top quarks	assumed absent	

such as the quark masses or the structure functions, but concentrates on those discrepancies that are related to the different algorithms used. Accordingly, input parameters have been standardized as much as possible, as is summarized in Table 1.

The five Monte Carlo generators used are COJETS 6.11 [3], EUROJET [4], HERWIG 4.6 [5], ISAJET 6.24 [6] and PYTHIA 5.4 [7].

The last three use similar showering algorithms, in which the incoming partons at the hard scattering are evolved backward to the incoming hadrons, and the outgoing partons are evolved forward to the fragmentation region. Here the programs use distinct fragmentation algorithms, respectively cluster, independent and string fragmentation. Note that in its latest version, HERWIG uses a 2 loop expression for α_S with a Q^2-dependent number of flavours. When appropriate, we shall quote the results of HERWIG 4.3, which is entirely comparable with ISAJET and PYTHIA in this respect.

COJETS proceeds from a different point of view, in which the parton showers are evolved forward from the protons to the hard scattering. This means that, contrary to the programs above, structure function parametrizations are only used at the initial low Q_0^2 scale where the showers are begun, with subsequent evolution calculated by the program itself. Since the evolution in COJETS is leading log, while DFLM contains next-to-leading corrections, utilization of DFLM with COJETS would lead to inconsistent results, which is why COJETS has been used with the leading log EHLQ set 1 [8] instead. COJETS uses independent fragmentation.

Finally, EUROJET is a matrix element Monte Carlo, which includes all $2 \to 2$ and $2 \to 3$ tree level diagrams. It does not include the loop corrections to $2 \to 2$ but, with a judicious choice of parton separation cutoffs, it is possible to reproduce the b rate of Nason *et al.* reasonably well. EUROJET contains no parton showering. It uses independent fragmentation.

In our comparisons, we choose to concentrate on inclusive $p_\perp$ distributions at various stages of b production.

- Born level $q\bar{q}, gg \to b\bar{b}$ flavour creation results. Here only the hard scattering tree level cross-section enters, and thus all programs should agree.
- Results after the full perturbative QCD treatment, with shower or higher order matrix elements. Here one is sensitive to the QCD treatment, in particular to the details of the shower schemes.
- The muon distributions, which are sensitive to the full machinery, including fragmentation and decays.

Finally, we show that some related distributions can clearly distinguish between matrix element and shower Monte Carlos.

The results of the first, Born level, comparison are shown in Fig. 1. Results

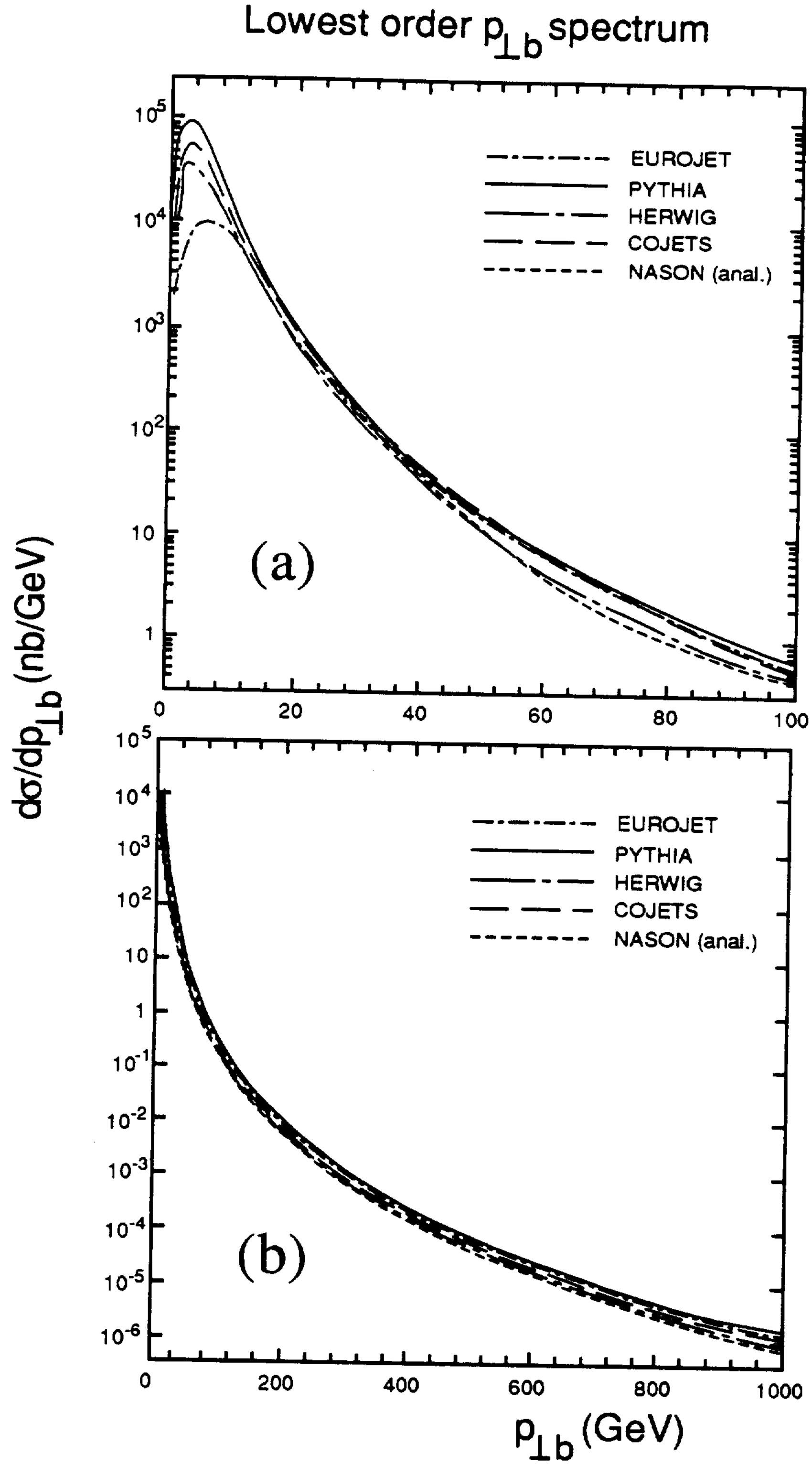

Figure 1: Inclusive $b+\overline{b}$ transverse momentum distribution for $2 \rightarrow 2$ flavour creation only ($q\overline{q} \rightarrow b\overline{b}$ and $gg \rightarrow b\overline{b}$) at (a) low and (b) high transverse momentum $p_{\perp}$.

are calculated using samples of roughly 10^4 events, except COJETS which uses much bigger statistics, and statistical fluctuations have been smoothed by hand. The differences between the lowest order calculations are understood as follows. HERWIG 4.6 and PYTHIA differ only because they are using 2 vs. 1 loop expressions for α_S: HERWIG 4.3 (after errors in the colour factors in that version have been corrected) is in perfect agreement with PYTHIA. Also the analytical curve is based on a 2-loop expression for α_S, and is in good agreement with HERWIG 4.6. The additional discrepancy between programs at low $p_\perp$ is probably entirely related to structure functions: in this region many events are produced from partons which have x values below the stated region of validity of structure function parametrizations. In EUROJET the structure functions $f(x)$ are assumed to vanish in this x region, while PYTHIA extrapolates from the lower bound of the parametrizations under the assumption that $xf(x)$ is fix. Finally, as was pointed out before, COJETS uses leading-log evolved structure functions, and its results are thus similar to those obtained using EHLQ [8] in the other Monte Carlos.

The second test compares the $b + \bar{b}$ sample when the full perturbative QCD machinery is used in programs, Fig. 2. The parton shower curves include both flavour creation and flavour excitation, while the analytic curve and EUROJET take only flavour creation into account. The flavour excitation graphs $q+b \to q+b$ and $g + b \to g + b$ appear when branchings $g \to b\bar{b}$ are allowed to build up b structure functions inside the incoming hadrons. The $2 \to 3$ matrix elements include the contributions from initial $g \to b\bar{b}$ branchings, which is why it would be doublecounting also to include b structure functions in the matrix elements approach. At first glance, no doublecounting issues are involved in the parton shower approach, but actually the definition of heavy flavour structure functions is delicate [9], so that some doublecounting may still appear. Uncertainties are particularly important for $p_\perp \to 0$, where the naive cross-section is divergent. In the parton shower programs, flavour excitation gives a major contribution to the b cross-section, overshooting that of flavour creation by a factor 2 to 4.

One can see from Fig. 2 that various showering algorithms disagree by a factor 5 to 10. It is worth noting that the prediction of HERWIG 4.3 is in good agreement with that of PYTHIA, so that the discrepancy shown in the figure can be traced back to the use of a 2 loop expression in α_S. However, the parton shower programs cannot reproduce the analytical results of [1]. This is particularly obvious from Fig. 3, which shows the ratio of the full to the lowest order result: while the analytic formulae give a ratio that is essentially flat as a function of $p_\perp$, the shower programs give a ratio that tends to drop with $p_\perp$. There are two main reasons for the latter behaviour.

1. A b quark originally produced at a given $p_\perp$ will be degraded towards a smaller $p_\perp$ by final state gluon emission in the shower. Contributions from $b \to bg$ branchings also appear in the $2 \to 3$ matrix elements but, since at most one gluon may be emitted here, the true size of the effect is underestimated. In matrix element programs, the same effect could partly be taken into account by the proper choice of perturbative [10] and nonperturbative fragmentation function(s).
2. In the shower evolution, a gluon may branch into a $b\bar{b}$ pair. Again contributions of this type appear in the $2 \to 3$ matrix elements, but again the full shower description involves a larger number of gluons, and therefore an increased probability for one of them to branch into $b\bar{b}$ (see also [11]). Since the full energy of the original jet is shared between many partons, the additional production is concentrated towards smaller $p_\perp$.

Although the final answer is not at hand, there are good physics reasons to be

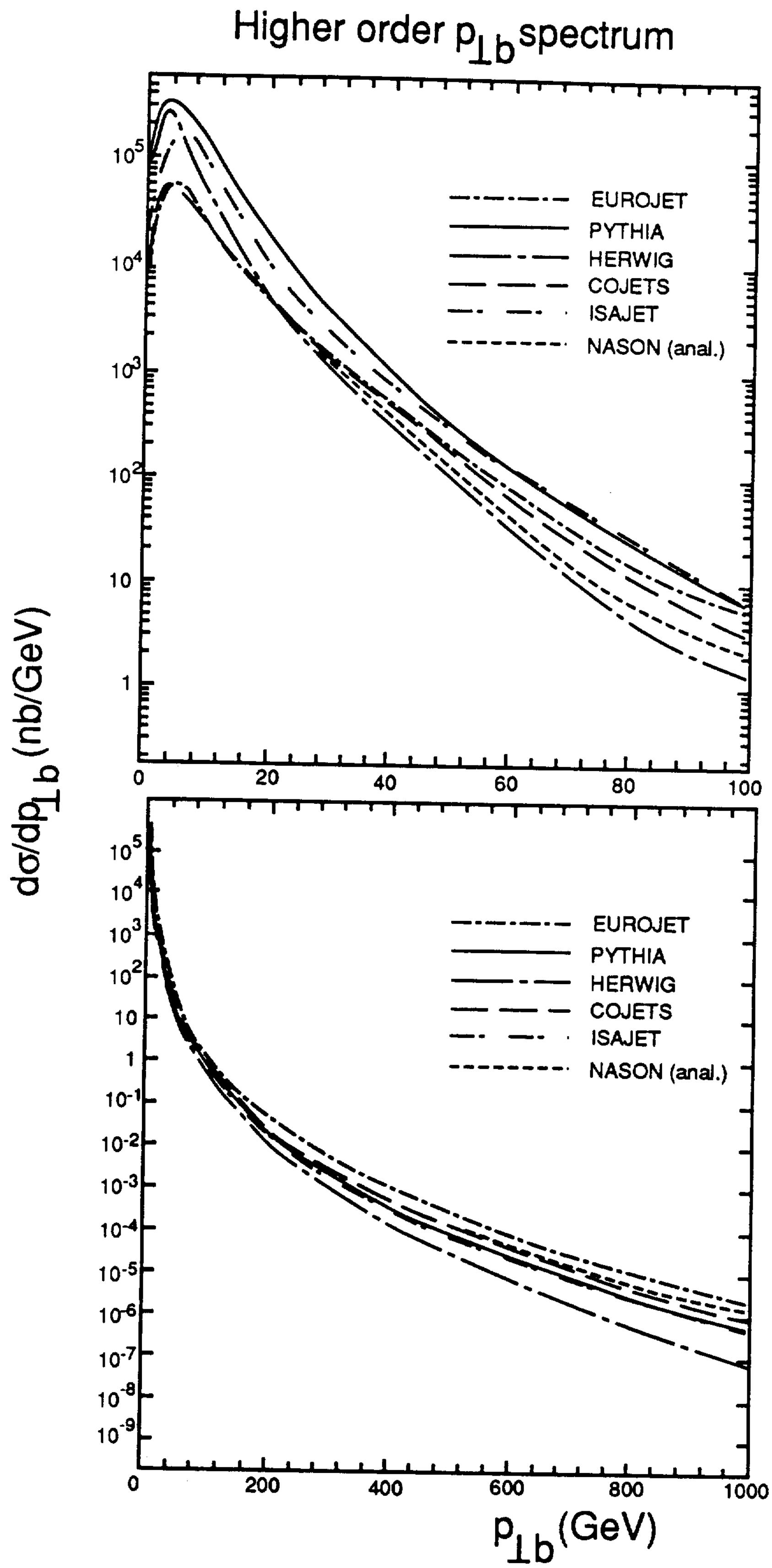

Figure 2: Inclusive $b + \bar{b}$ transverse momentum distribution after the full perturbative treatment, i.e. shower or higher order matrix elements, at (a) low and (b) high transverse momentum $p_\perp$.

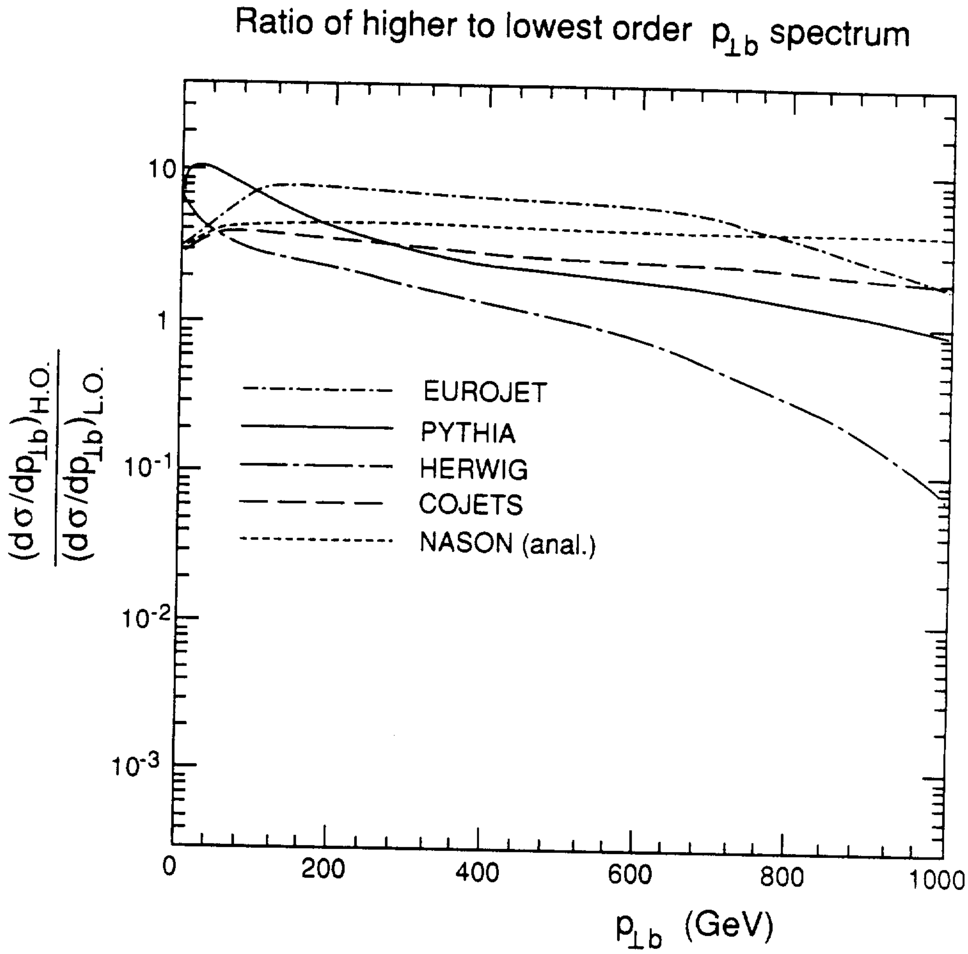

Figure 3: Ratio of the inclusive $p_\perp$ distribution of $b + \bar{b}$ quarks in the full treatment, shower or higher order matrix elements, to those of lowest order flavour creation, i.e. the ratio of Figs. 2(b) and 1(b).

wary of the results of the $\mathcal{O}(\alpha_S^3)$ analytic calculations, and to believe that the ratio in Fig. 3 should indeed drop with $p_\perp$. However, the large spread between the shower programs indicates that, also in this approach, the answer is not well known.

Finally, we can also test the fragmentation and decay algorithms by looking at muon distributions. Fig. 4(a) shows the spectrum of the muons from primary $b/\bar{b}$ decays, and again there is a disagreement, of about a factor 10 (the size of the statistical sample is not entirely appropriate to make this statement more precise). It is interesting to compare the primary μ spectrum of Fig. 4(a) with that of all the other muons produced in the shower, from charm and secondary b decays ($b \to c \to \mu$, $b \to \tau \to \mu$), Fig. 4(b). For the latter, the disagreement between the programs is slightly smaller, which leads to an interesting difference: while COJETS and PYTHIA predict most high-$p_\perp$ muons to come from primary b decays, by a wide margin, HERWIG gives about equal importance to primary b decays and to the other sources. We do not know whether this comes from differences in the charm production in the shower or from differences in bottom and charm decays.

All the previous curves have been quite similar in shape, if not in magnitude.

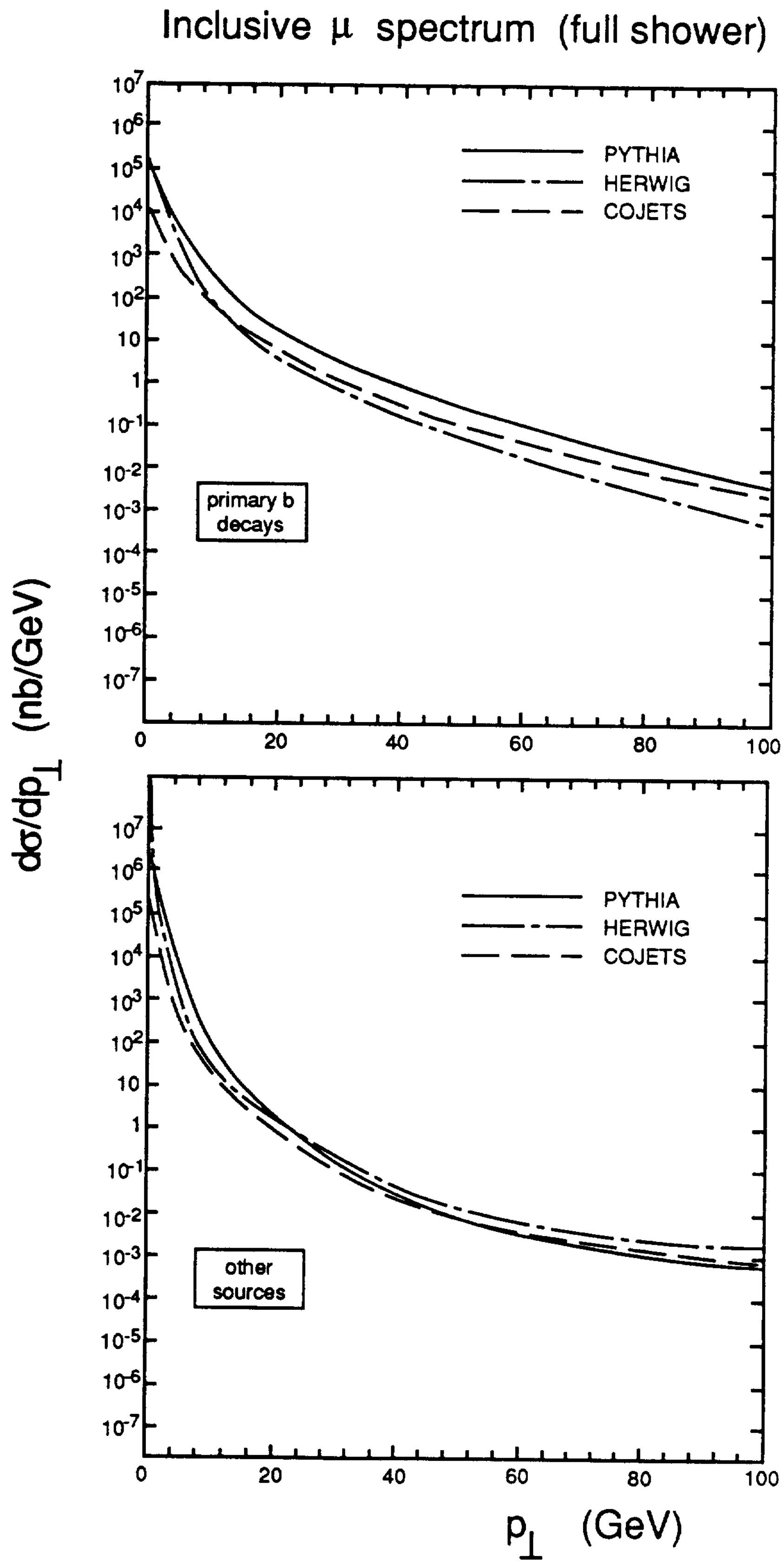

Figure 4: Inclusive muon $p_\perp$ distributions, after full perturbative QCD, fragmentation and decay treatment. The direct muons from $b+\bar{b}$ are shown in (a), whereas (b) shows the muons coming from other sources (from secondary b decays, or from charm production).

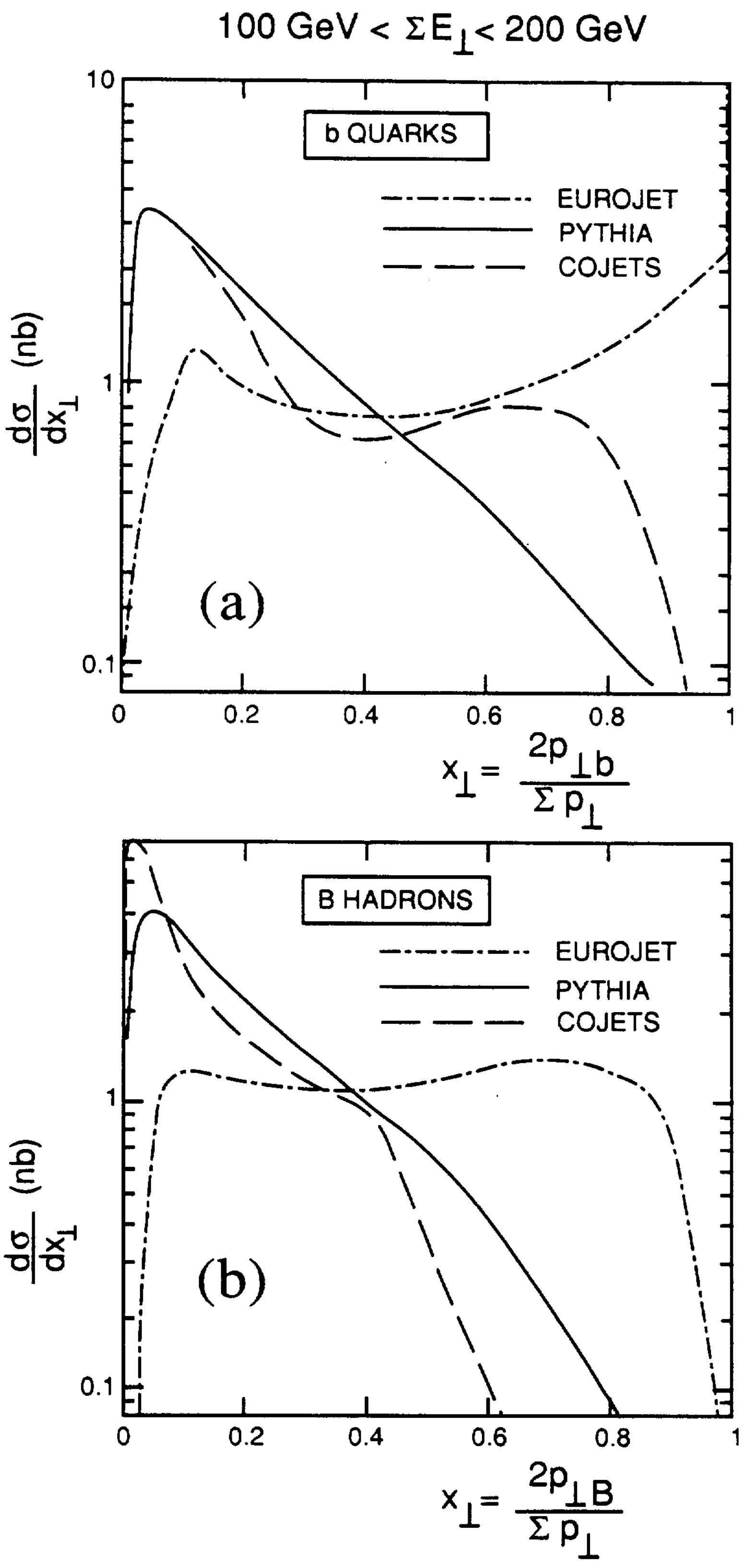

Figure 5: Inclusive transverse momentum fraction $x_\perp$ for (a) $b + \bar{b}$ quarks after perturbative treatment and (b) bottom hadrons after fragmentation. The total (parton level) transverse energy of the event is constrained to lie between 100 and 200 GeV.

One can, however, find distributions which differ drastically. One of these is shown in Fig. 5. It gives the prediction of three Monte Carlos for the $x_\perp$ distribution, first at the quark level, then at the hadron level. The $x_\perp = 2p_{\perp(b,B)}/\sum p_\perp$ variable tests both the perturbative description and the fragmentation. At the hard scattering level, for flavour creation, one has $x_\perp \equiv 1$, and also $2 \to 3$ matrix elements tend to be peaked near $x_\perp = 1$, cf. the EUROJET curve in Fig. 5(a). As noted above, in the shower description original b quarks are degraded in momentum due to gluon emission, and new $b\bar{b}$ pairs are created at smaller $x_\perp$ values by gluon branchings; therefore the shower description gives an $x_\perp$ spectrum concentrated at smaller values. Since the shower cutoff scale is higher in COJETS than in PYTHIA, more of the original peak at $x_\perp = 1$ survives; once fragmentation is included, Fig. 5(b), this peak disappears completely, however. If Figs. 5(a) and 5(b) are compared, one should also note that independent fragmentation gives a significant shift of the spectrum towards smaller $x_\perp$ values, an effect that is almost absent in the string fragmentation picture.

In conclusion, even before considering ambiguities from the choice of scales or from structure functions, one has to realize that different theoretical and phenomenological estimates of the same background lead to uncertainties of the order of a factor 10, and that the actual shape of distributions can be very sensitive to the fragmentation description, i.e. to theoretically less well controlled parts of Monte Carlos. A minimum requirement on programs would be that they can describe existing data, both from $p\bar{p}$ colliders and from e^+e^- annihilation; in particular, LEP may be expected to contribute significantly to our current understanding.

The main lesson is that, currently, no single treatment of b production can be trusted on its own.

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