HERWIG for Top Physics at the Linear Collider

G. Corcella*, E.K. Irish* and M.H. Seymour†

*Department of Physics and Astronomy, University of Rochester, Rochester, NY 14627, U. S. A.
†Rutherford Appleton Laboratory, Chilton, Didcot, Oxfordshire. OX11 0QX, U. K.

Abstract. We discuss recent improvement in the treatment of gluon radiation in top production and decay in e^+e^- processes according to the HERWIG event generator and show studies on the top mass reconstruction at the future Linear Collider.

For the sake of performing precision measurements of top quark properties at the future Linear Collider, trustworthy Monte Carlo simulations of multiparton radiation in top production and and decay will be essential. According to the standard algorithm of the HERWIG event generator [1], we shall refer to hereinafter, multiple radiation is treated in the soft or collinear approximation and no emission is permitted in the so-called 'dead zones', which correspond to hard and large-angle parton radiation. The HERWIG algorithm can be improved by applying matrix-element corrections: the dead zone is populated by the use of the exact first-order matrix element ('hard correction') and the $\mathcal{O}(\alpha_S)$ result is used in the already-filled region any time an emission is the 'hardest so far' ('soft correction') [2].

One of the new features of HERWIG 6 [3] consists of the implementation of matrix-element corrections to top decays, which have been shown to have a relevant effect on jet observables at the threshold for top pair production [4]. As pointed out in [5], matrix-element corrections to top production in e^+e^- annihilation, implemented following [6], still needed improvement, since mass effects are not systematically included in the dead zone boundary and in the soft correction.

In Fig. 1 we plot the total and HERWIG phase space for the process $e^+e^- \to q(p_1)\bar{q}(p_2)g(p_3)$, considering massless quarks and top quarks at $\sqrt{s} = 500$ GeV, in terms of the energy fractions $x_1 = 2p_1 \cdot q/q^2$ and $x_2 = 2p_2 \cdot q/q^2$, with $q = p_1+p_2+p_3$. We see that once we account for mass effects, the dead zone includes both a large- and a small-angle region of the physical phase space, the latter corresponding to the neighbourhood of the $x_1 = x_2 = 1$ point, which, on the contrary, would be entirely inside the HERWIG region if we neglected m_t^2/s terms. Since the soft singularity is not completely inside the HERWIG region, the total emission into the dead zone,

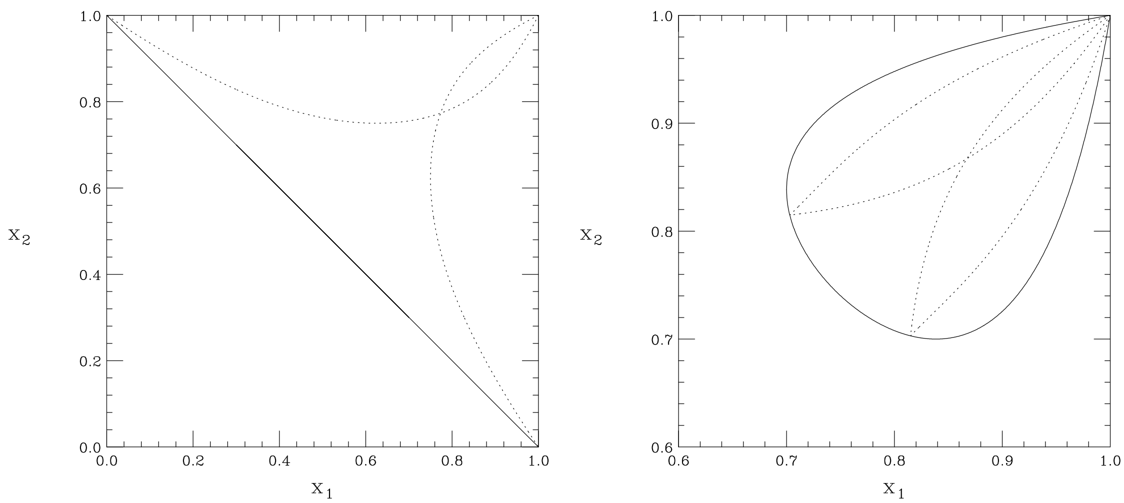

FIGURE 1. Total (solid) and HERWIG (dotted) phase-space limits for massless quarks (left) and for $t\bar{t}$ production (right) at $\sqrt{s} = 500$ GeV.

naïvely calculated, would be infinite. As we did for the top-decay case [4], we avoid the soft singularity by setting a cutoff $E_{\rm min}$ on the energy of gluons which are radiated in the dead zone and check that phenomenological observables are weakly dependent on the value of $E_{\rm min}$. We choose $E_{\rm min} = 2$ GeV as the cutoff default value.

We consider $e^+e^- \to t\bar{t}$ processes at $\sqrt{s} = 500$ GeV and 1000 GeV and cluster final-state partons into three jets by the use of the Durham algorithm [7], assuming that both W's decay leptonically. We set the cuts $E_T > 10$ GeV and $\Delta R > 0.7$ on transverse energy and invariant opening angle of clustered jets. In Fig. 2 we plot the distributions of y_3, the threshold value of the Durham variable for all events to be three-jet-like, according to HERWIG 6.2, the latest public version, and 6.3, the new version in progress which will fully include mass effects in matrix-element corrections to top production. We investigate the options to fill either the small- and large-angle dead zone or only the large-angle region. The impact of the full implementation of m_t^2/s effects is a suppression of emission, which is more visible at $\sqrt{s} = 1000$ GeV, as the radiation in the top-production stage gets more important. Filling the small-angle region as well results in more events at intermediate values of y_3. We checked that once the centre-of-mass energy is increased so that terms m_t^2/s are negligible, the 6.3 results reproduce the 6.2 ones.

Matrix-element corrections to $W \to q\bar{q}'$ decays in the top decay, not yet included in [3], turn out to be a straightforward extension of the corrections to $Z \to q\bar{q}$ processes in the massless approximation $m_{q,q'} \ll m_{W,Z}$. We found little impact on generic jet observables at the Linear Collider, even at the top threshold, where the radiation in the production phase is negligible. In fact, the already-existing jets associated with the b quarks from the top decay and with the W-decay products, even in the soft or collinear approximation, make the detection of hard and large-angle gluon radiation in the W decay pretty difficult. Systematic and detailed

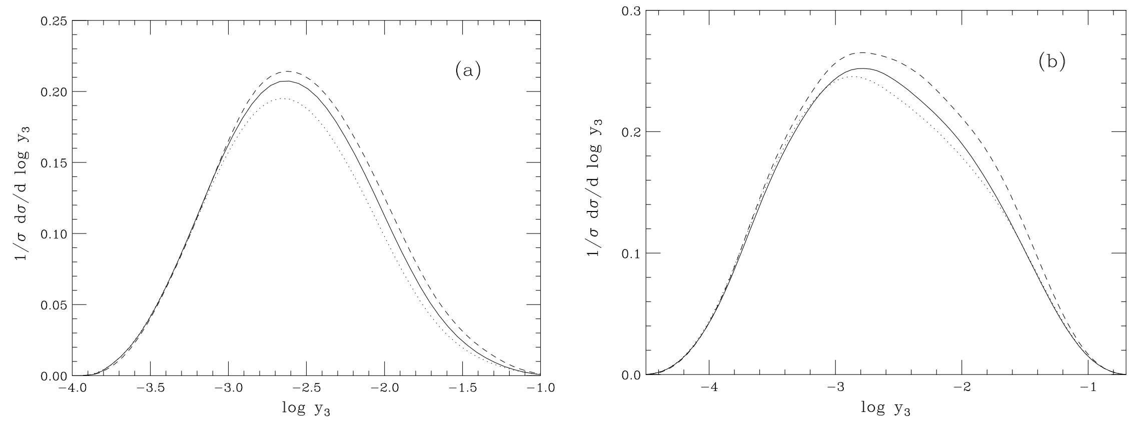

FIGURE 2. y_3 distributions at $\sqrt{s} = 500$ GeV (a) and $\sqrt{s} = 1000$ GeV (b) according to HERWIG 6.2 (dashed line) and 6.3, once we populate either the small- and large-angle (solid) or only the large-angle region (dotted) of the dead zone.

analyses to find out possible variables which might be sensitive to matrix-element corrections to W decays are in progress.

We finally wish to report on studies on the top mass reconstruction in the dilepton channel. We consider the b-lepton invariant mass $m_{b\ell}$ and the b energy E_b, where the b quark is considered together with its gluon radiation, as possible variables which may allow a fit of the top mass. Being a Lorentz-invariant observable, the $m_{b\ell}$ distribution is independent of the centre-of-mass energy and, as already pointed out in [8] for the purpose of hadron collisions, of the hard-scattering process as well. In fact, within the statistical Monte Carlo fluctuations, we find the same results for different values of $\sqrt{s}$. On the contrary, E_b is not Lorentz-invariant, hence it will be sensitive to the boost from the top rest frame, where the top decay is performed, to the laboratory frame. At the threshold for $t\bar{t}$ production, the dependence of E_b on the top mass will be emphasized, as the $t\bar{t}$ pair is produced almost at rest. Fig. 3 shows that the $m_{b\ell}$ distribution is shifted towards larger values as the top mass is increased. Moreover, the half-maximum width σ_b of the E_b distribution shows a strong dependence on the top mass at $\sqrt{s} = 370$ GeV, since the distribution gets narrower as the top mass approaches the threshold value $\sqrt{s}/2$. If we try to parametrize the relation of the average value $\langle m_{b\ell}\rangle$ and σ_b in terms of m_t, we find that the best fits are a straight line for $\langle m_{b\ell}\rangle$ and a parabola for σ_b:

$$\langle m_{b\ell}\rangle = \quad 0.756\ m_t - 37.761\ \mathrm{GeV}\ ; \tag{1}$$

$$\sigma_b = -0.081\ m_t^2 + 26.137\ m_t - 2048.968\ \mathrm{GeV}\ . \tag{2}$$

Inverting Eqns. (1) and (2) to extract m_t, we conclude that if $\Delta\langle m_{b\ell}\rangle$ and $\Delta\sigma_b$ are the uncertainties on measurements of the invariant mass and of the half-maximum width, they will result in an error $\Delta m_t \approx 1.32\ \Delta\langle m_{b\ell}\rangle$ and $\Delta m_t \approx 0.35 - 0.65\ \Delta\sigma_b$, where the latter uncertainty refers to the range 171 GeV $\lesssim m_t \lesssim$ 179 GeV. The b energy looks therefore to be a quite promising observable with which to extract m_t,

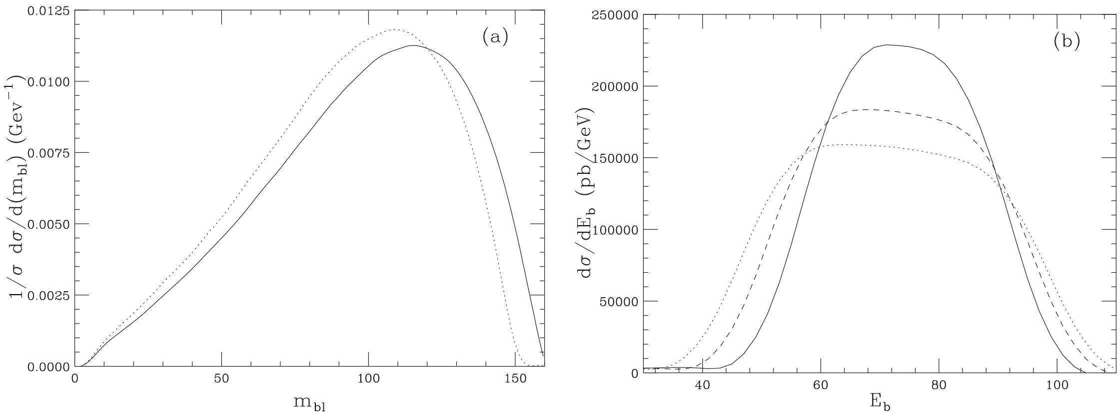

FIGURE 3. (a): Distribution of the invariant mass $m_{b\ell}$ for $m_t = 171$ GeV (dotted line) and $m_t = 179$ GeV (solid). (b): b energy $\sqrt{s} = 370$ GeV for $m_t = 179$ (solid), 175 (dashed) and 171 (dotted) GeV.

although we would need to know the experimental accuracy on the masurement of σ_b in order to estimate the foreseen uncertainty on m_t. Furthermore, we expect that E_b and σ_b will be sensitive to the beam energy smearing, which has not been accounted for in the plots of Fig. 3. The implementation of beamsstrahlung in HERWIG, via an interface with the CIRCE program [9], is under way.

In summary, we discussed recent progresses in the implementation of matrix-element corrections to the HERWIG simulation of top production and decay at the Linear Collider and showed studies on the top mass reconstruction, for which purpose the b energy is expected to be an interesting variable for e^+e^- collisions slightly above the top threshold.

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REFERENCES

1. Marchesini, G., et al., *Comput. Phys. Commun.* **67**, 465 (1992);
   Marchesini, G., and Webber, B.R., *Nucl. Phys.* **B231**, 1 (1984).
2. Seymour, M.H., *Comput. Phys. Commun.* **90**, 95 (1995).
3. Corcella, G., et al., hep-ph/0011363, submitted to *JHEP*.
4. Corcella, G., and Seymour, M.H., *Phys. Lett.* **B442**, 417 (1998).
5. Corcella, G., and Seymour, M.H., hep-ph/9911335, Talk given at *ECFA/DESY Linear Collider Workshop*, Frascati, Italy, 8-10 November 1998, LC-TH-1999-011.
6. Seymour, M.H., *Z. Physik* **C 56** 161 (1992).
7. Catani, S., Dokshitzer, Yu. L., Olsson, M., Turnock, G., and Webber, B.R., *Phys. Lett.* **B269**, 432 (1991).
8. Corcella, G., Mangano, M.L., and Seymour, M.H., *JHEP* **07** 004 (2000).
9. Ohl, T., *Comput. Phys. Communq.* **101**,269 (1997).