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Simulations of Top Production and Decay at the Linear Collider*

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Abstract

We review the present status of simulations of top production and decay in the HERWIG Monte Carlo event generator. We show the phenomenological impact of the recently-implemented matrix-element corrections to top decays for e^+e^- collisions at 360 GeV and discuss possible further improvements for studies of future experiments at the Linear Collider.

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1 Introduction

The study of the top quark phenomenology will be among the main topics of interest for the future experiments at the Linear Collider. In order to perform such analyses, it will be essential to have reliable Monte Carlo simulations of top production and decay. Standard event generators [1,2] simulate parton showers in the soft/collinear approximation, leaving empty regions in the phase space ('dead zones') where, according to the exact matrix element, the radiation should be suppressed but not completely absent. Parton showers need therefore to be supplemented by matrix-element corrections.

As far as the HERWIG parton shower is concerned, matrix-element corrections to e^+e^- annihilation [3], deep inelastic scattering [4], top decays [5] and Drell–Yan processes [6] have been implemented following the general prescriptions given in [7]. In section 2 we shall review the HERWIG parton shower algorithm for top production and decay in e^+e^- collisions and discuss the recent implementation of matrix-element corrections to top decays. In section 3 we shall show some phenomenological results at the Linear Collider, for a centre-of-mass energy of 360 GeV. In section 4 we shall make some concluding remarks on the results and possible improvements of this work.

2 The HERWIG parton shower algorithm for top production and decay in e^+e^- collisions

For the emission of one more parton (gluon) in top production in e^+e^- annihilation ($e^+e^- \to t\bar{t}g$) and top decay ($t \to bWg$), the elementary probability implemented in the HERWIG event generator is the general result for parton radiation in the soft/collinear limit [8]:

$$dP = \frac{dq^2}{q^2}\,\frac{\alpha_S}{2\pi}\,P(z)dz\,\frac{\Delta_S(q^2_{\rm max},q_c^2)}{\Delta_S(q^2,q_c^2)}\ . \tag{1}$$

The shower is ordered according to the variable $q^2 = E^2\xi$, E being the energy of the parton that splits and $\xi = p_1 \cdot p_2/(E_1E_2)$, where p_1 and p_2 are the momenta of the two outgoing partons; z is the energy fraction of the emitted parton (gluon) relative to the incoming one. In the massless approximation, $\xi = 1 - \cos\theta$, θ being the emission angle, in such a way that ordering according to q^2, in the soft limit, results in angular ordering. $\Delta_S(q^2,q_c^2)$ is the Sudakov form factor, expressing the probability that no resolvable radiation is emitted from a parton whose upper limit on emission is q^2, with q_c^2 being a cutoff on transverse momentum. The ratio of Sudakov form factors in (1) sums up all virtual contributions and unresolved emissions.

The parton shower variables z and ξ are frame-dependent, nevertheless it is possible to prove that colour coherence implies that the values $q_{\rm max}$ of any pair of colour-connected partons are related via $q_{i{\rm max}}q_{j{\rm max}} = p_i \cdot p_j$, which is Lorentz-invariant. For top production, as for most of the HERWIG processes, symmetric limits are chosen, i.e. $q_{i{\rm max}} = q_{j{\rm max}} = \sqrt{p_i \cdot p_j}$ and the energy of the parton which initiates the cascade is equal to $E_i = q_{i{\rm max}}$. Ordering according to q^2 leads to the condition $\xi < 1$. The phase space region $1 < \xi < 2$ is not populated at all by the parton shower algorithm. In [3]

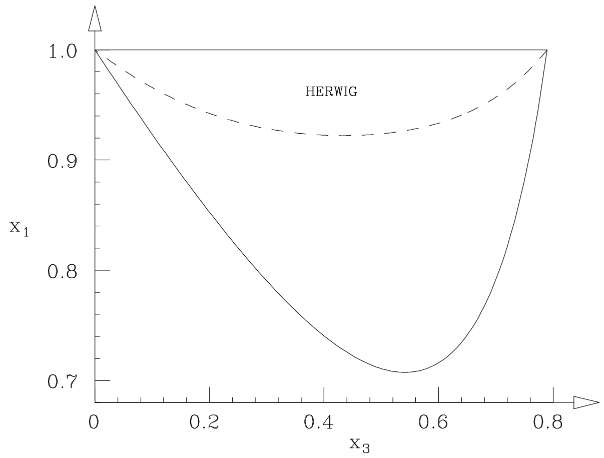

Figure 1: The total and HERWIG phase space in terms of x_1 and x_3. The soft singularity $x_3 = 0$ is not completely inside the HERWIG region.

matrix-element corrections are implemented to $e^+e^- \to q\bar{q}$ processes: the 'dead zone' of the phase space is populated according to a probability distribution obtained from the exact $\mathcal{O}(\alpha_S)$ matrix-element calculation of the process $e^+e^- \to q\bar{q}g$ ('hard correction') and the emission in the already-populated region is corrected using the exact amplitude for every emission that is the hardest so far ('soft correction').

Top decays are treated in a somewhat different way in HERWIG, since the top quark rest frame is chosen to perform such a decay [9]. This means that $E_t = m_t = q_{t\max}$ and $E_b = p_t \cdot p_b / m_t$. Being at rest, the top quark is not allowed to radiate gluons in the decay stage, while the b quark emits soft gluons for $\xi < 1$, i.e. $0 < \theta < \pi/2$. The result is that the soft phase space is not completely populated by HERWIG as all the soft gluons which should be emitted in the backward hemisphere $\pi/2 < \theta < \pi$ are missed. For e^+e^- annihilation we have two back-to-back partons, q and $\bar{q}$, that are capable of emitting soft gluons for $\xi < 1$, in such a way that each of them radiates in the region the other is missing out and the whole of the soft phase space is filled. In [9] it is shown that, though neglecting the soft radiation in the backward hemisphere, the total energy loss due to gluon radiation is roughly right. However, we may have serious problems when dealing with angular differential distributions.

For the reasons previously mentioned, the implementation of matrix-element corrections to top decays is not a straightforward extension of the method applied for the purpose of other processes. In order to avoid the soft singularity, we set a cutoff on the energy of backward gluons, whose default value is $E_{\min} = 2$ GeV. In [5] we calculated the phase space limits for the decay $t(q) \to b(p_2)W(p_1)g(p_3)$ with respect to the variables

$$x_1 = 1 - \frac{2p_2 \cdot p_3}{m_t^2}, \qquad (2)$$

$$x_3 = \frac{2p_3 \cdot q}{m_t^2}. \qquad (3)$$

In Fig. 1 we plot the total and the HERWIG phase space. The differential width reads:

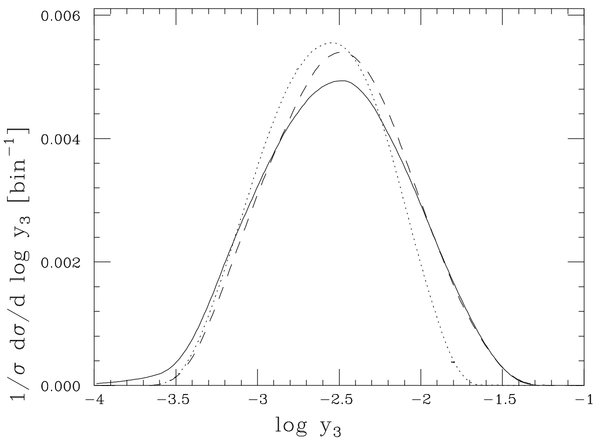

Figure 2: y_3 distributions according to HERWIG 6.1 (dashed line), HERWIG 6.0 (dotted) and according to the exact $\mathcal{O}(\alpha_S)$ calculation (solid).

$$\begin{aligned}\frac{1}{\Gamma_0}\frac{d^2\Gamma}{dx_1\,dx_3} &= \frac{1}{(1-a)\left(1+\frac{1}{a}-2a\right)}2\,\frac{\alpha_s}{2\pi}\,C_F\frac{1}{x_3^2(1-x_1)}\Big\{(1+\tfrac{1}{a}-2a)\big[(1-a)x_3-(1-x_1)(1-x_3)-x_3^2\big] \\ &\quad +(1+\tfrac{1}{2a})x_3(x_1+x_3-1)^2+2x_3^2(1-x_1)\Big\}, \qquad (4)\end{aligned}$$

where Γ_0 is the width of the Born process $t\to bW$ and $a=m_W^2/m_t^2$. The integral of the differential width over the 'dead zone' is divergent, because of the soft divergence. We use the differential width (4) to generate events in the missing backward phase space and in the already-populated forward hemisphere for every hardest-so-far emission capable of being the hardest so far. Both hard and soft corrections should be applied only for gluon energies larger than the cutoff value.

3 Phenomenological results at the Linear Collider

In order to test the reliability of the HERWIG algorithm provided with matrix-element corrections we wish to compare its phenomenological results with the ones obtained by calculating the exact first-order matrix element of the process:

$$e^+e^-\to t\bar{t}\to (bW^+)(bW^-)g. \qquad (5)$$

It is interesting to perform such an analysis at the centre-of-mass energy $\sqrt{s}=360$ GeV, slightly above the threshold for $t\bar{t}$ production, in such a way that all the gluon emission is associated to top decays, the available phase space for radiation in the production stage being too small. In the last public version HERWIG 5.9 some bugs were found in the treatment of top decays, therefore, if we wish to investigate the effect of the implemented matrix-element corrections, it is better to compare the new version HERWIG 6.1 to an intermediate version, which we call HERWIG 6.0, where all the bugs are supposed to be fixed.

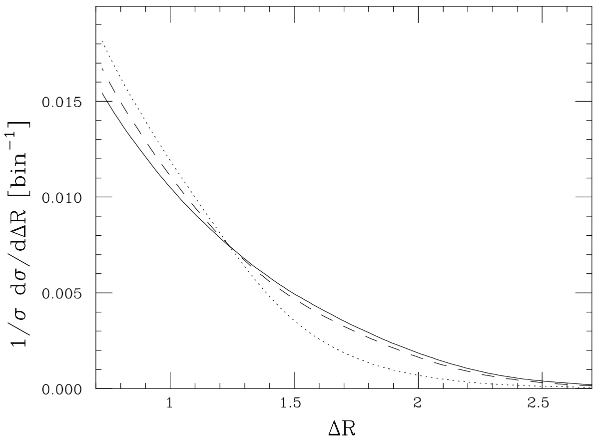

Figure 3: Invariant opening angle distributions according to HERWIG 6.1 (dashed line), HERWIG 6.0 (dotted line) and according to the exact $\mathcal{O}(\alpha_S)$ matrix element (solid).

We study three-jet events according to the Durham k_T algorithm [10] and plot the differential distributions with respect to the threshold variable y_3 and the minimum invariant opening angle $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$ using HERWIG 6.1 and 6.0 and the exact $\mathcal{O}(\alpha_S)$ for a value $\alpha_S = 0.145$ of the strong coupling constant. We also set the cuts $E_T > 10$ GeV and $\Delta R > 0.7$ on the resolved jets. Such an analysis was already performed in [11] and serious discrepancies were found when comparing the exact results with the ones obtained by the using of HERWIG before the implementation of matrix-element corrections to top decays.

In Figs. 2 and 3 we observe a remarkable impact of matrix-element corrections: HERWIG 6.1 generates more events at large y_3 with respect to the 6.0 version, which can be explained as due to the hard corrections which allow hard and large-angle gluon radiation. We also get a suppression at small y_3, which compensates the enhancement at large y_3, the total amount of radiation being roughly right even before matrix-element corrections. The soft corrections, applying the matrix-element distribution instead of the parton shower one in the already-populated forward region for every hardest-so-far emission, is responsible of the suppression at small y_3. The agreement between HERWIG 6.1 and the exact calculation is pretty good at large y_3, as it should be since the fixed-order calculation is reliable only if we are far from the soft and collinear divergences, which correspond to small y_3, where, on the contrary, parton showers are more trustworthy. Similar comments hold for the ΔR plots as well. In [5] we also showed that the dependence on the chosen value of the cutoff $E_{\rm min}$ is negligible after we apply the experimental cuts.

4 Conclusions

We have reviewed the HERWIG parton shower model for top production and decay in e^+e^- annihilation and the main features of the method of matrix-element corrections, recently implemented to the simulation of top decays. We studied three-jet events at

$\sqrt{s}$ = 360 GeV using HERWIG before and after matrix-element corrections to top decays, and the exact first-order calculation. The results showed a marked effect of the improvement to the treatment of top decays and a good agreement with the $\mathcal{O}(\alpha_S)$ calculation in the phase space region where such an agreement is to be expected. We therefore feel confident that the new version HERWIG 6.1 should be a reliable Monte Carlo event generator to simulate top quark decay at the future Linear Collider.

For the sake of completeness, we have however to say that the implementation of matrix-element corrections to the process $e^+e^- \to q\bar{q}g$ still needs some improvement since, in the determination of the phase space limits and in the application of the soft corrections, the $q\bar{q}$ pair is treated as if it was massless, which might not be a good approximation for the purpose of the top quark. We have been working on fully including these mass effects. Furthermore, it will be very interesting to investigate the impact of matrix-element corrections to top decays on the top mass reconstruction at the Linear Collider. This is in progress as well.

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