Improving multiparton Monte Carlo tools in hadronic collisions⋆

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Abstract. Recent work on leading order multiparton calculations for hadronic collisions is reviewed, with special emphasis on the `ALPGEN` event generator. Some problems connected with the interface of the partonic events generated via matrix elements with the showering are addressed.

1 Introduction

In high energy hadronic collisions multijet final states characterize a large class of important phenomena both within and beyond the SM. These multiparticle final states can originate from hard QCD radiation processes, decay of SM massive particles (W, Z, top quark, Higgs boson), decay of heavy supersymmetric or more exotic particles. In general there are two different approaches to simulate multijet final states: the first one consists in generating the simplest possible final state by means of matrix elements and producing additional jets by parton showering (`HERWIG` [1], `ISAJET` [2], `PYTHIA` [3]).

This procedure works well in the soft/collinear regions but fails to describe configurations with several widely separated jets. A complementary strategy is to generate high-multiplicity partonic final states by means of exact matrix elements and eventually pass the generated events to further showering. Even if it is a leading-order (LO) approach, this procedure can become very difficult because of the complexity of the matrix element calculations with many external legs and of the phase-space integration. Recently there has been extensive activity in developing several parton-level Monte Carlo (MC) event generators, such as `ACERMC` [4], `ALPGEN` [5], `AMEGIC++` [6], `CompHEP` [7], `GRACE` [8], `HELAC/PHEGAS/JETI` [9], `MADEVENT` [10]. In this contribution the state of the art of the `ALPGEN` generator is reviewed, paying attention to the latest improvements. The general problem of interfacing a LO partonic event generator with the parton shower is addressed, reviewing some recent work on the subject.

2 The `ALPGEN` event generator

The `ALPGEN` library is a collection of MC codes dedicated to many processes relevant to high energy hadron–hadron

collisions. The calculations are based on partonic events generated by means of exact LO matrix elements, obtained with the `ALPHA` algorithm [11] for assigned kinematics, spin, flavour and colour configurations. The generated unweighted events, stored according to the Les Houches Accord #1 [12] format, are ready for the `HERWIG/PYTHIA` evolution from partons to hadrons. Up to now the available final states in the `ALPGEN` package are:

– $W + N$ jets, $Z/\gamma^* + N$ jets, $N \leq 6$,
– $WQ\bar{Q} + N$ jets, $Z/\gamma^*Q\bar{Q} + N$ jets ($Q = c, b, t$), $N \leq 4$,
– $W + c + N$ jets, $N \leq 5$,
– $n\,W + m\,Z + p\,\text{Higgs} + N$ jets, $n + m + p \leq 8$, $N \leq 3$,
– $m\,\gamma + N$ jets, $N + m \leq 8$ and $N \leq 6$,
– $Q\bar{Q} + N$ jets, ($Q = c, b, t$), $N \leq 6$,
– $Q\bar{Q}Q'\bar{Q}' + N$ jets, ($Q, Q' = b, t$), $N \leq 4$,
– N jets, $N \leq 6$,
– $Q\bar{Q}H + N$ jets, ($Q = b, t$), $N \leq 4$.

The limitations in the maximum number of jets is only due to the setting of internal parameters in the `ALPHA` code, which could be changed to accomodate a larger number of final-state particles. While in the first version of `ALPGEN` the top quarks were considered as real particles, they are now (`v1.3`, in the $Q\bar{Q}$ and $Q\bar{Q}H$ processes) allowed to decay in the three final state fermions ($t \rightarrow Wb \rightarrow bf\bar{f}'$) with exact matrix element, thus retaining all the spin correlations among the top decay products. The decay is calculated in the approximation of on-shell top quark and W boson, in order to avoid the inclusion of non-resonant diagrams while preserving the gauge invariance of the calculations. The same strategy has been implemented for the decay of the gauge boson in the `vbjets` code, the `ALPGEN` directory dedicated to multiboson plus jets production, where the matrix element for the vector boson decay into a fermionic pair has been introduced in the zero width approximation. The generation of multiboson final states requires a careful treatment of the widths in the propagators of the unstable particles, because they generally break gauge invariance, giving rise to a bad high energy behaviour of the cross Sect. [13]. The strategy adopted

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⋆ Based on work done in collaboration with M.L. Mangano, M. Moretti, R. Pittau and A.D. Polosa.

in `ALPGEN` is to calculate the matrix element with the bosonic widths set to zero, removing the events containing a vector boson with a propagator mass M_0 such that $|M_0^2 - M^2| < s_0$, with

$$\int_{-\infty}^{M^2-s_0} ds \frac{1}{(s-M^2)^2} = \int_{-\infty}^{M^2} ds \frac{1}{(s-M^2)^2 + \Gamma^2 M^2}$$

and

$$|M_0 - M| \leq \frac{\Gamma}{\pi}.$$

For all other processes that do not involve the presence of several gauge bosons, the fixed-widths prescription is used. The Higgs bosons are treated as stable particles. Their decay to fermion pairs or to four fermions will be implemented in a future release of the programme.

3 Matching partonic event generators to parton shower

In order to simulate the real hadronic final states, the partonic events have to be passed through a MC parton shower. However, in this interface there is some ambiguity in the cuts implemented at the partonic level. They are unphysical, in the sense that the final jet cross-section should be independent of their choice, provided that they are not harder than the cuts applied to the real jets. However, starting with looser partonic cuts increases the probability of obtaining n jets from $n + m$ partons after parton showering (giving rise to the double-counting problem), as can be seen in Fig. 1, which shows the jet rates with the constraint $E_T^{jet} > E_T^{cut}$ for the hardest jet in $W + 3$ jets events at Tevatron, versus the parton separation ΔR_{part} imposed at the level of ME generation. The jets are reconstructed with the cone algorithm and the cross sections are normalized to the result obtained with $\Delta R_{\mathrm{part}} = 0.7$. The increasing ratio for smaller ΔR_{part} is due to both the collinear divergence of the matrix element for $\Delta R_{\mathrm{part}} \to 0$ and the increasing double counting for smaller ΔR_{part}. A first approximation to the solution of the problem could consist in requiring a jet matching for every parton [14]. With this recipe the shapes of the $W + 3$ jets example above become flatter, as diplayed in Fig. 2, but still showing a residual dependence on the parameter ΔR_{part}. The general problem of matching multiparton matrix element calculations with parton showers has been extensively studied in the literature and for $e^+ e^-$ collisions a solution (CKKW) has been proposed and tested on LEP data [15], which avoids double counting and shifts the dependence on the resolution parameter beyond next-to-leading logarithmic (NLL) accuracy. The method consists in separating arbitrarily the phase-space regions covered by matrix element and parton shower, and use, for all parton multiplicities, vetoed parton showers together with reweighted tree-level matrix elements by means of suitable Sudakov form-factor combinations. The necessary steps for the implementation of the procedure can be summarized as follows:
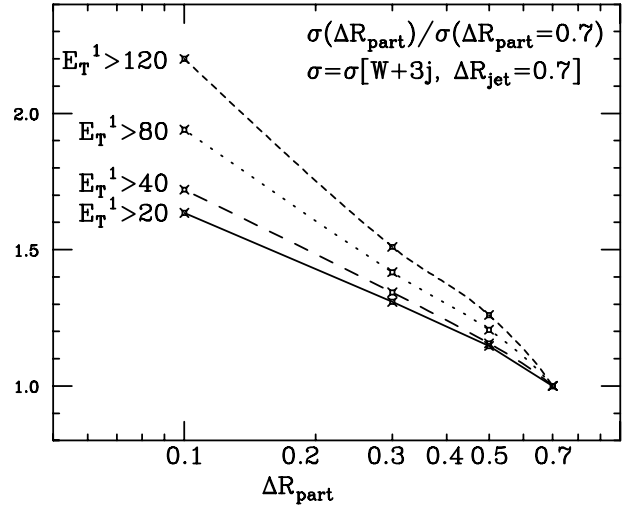

Fig. 1. The rate for $p\bar{p} \to W + 3$ jets at Tevatron as a function of the partonic separation cut ΔR_{part} normalized to the cross section for $\Delta R_{\mathrm{part}} = 0.7$
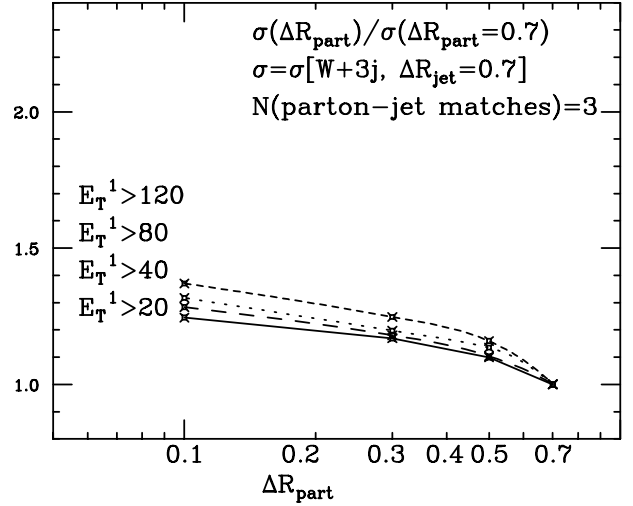

Fig. 2. The same as in Fig. 1, requiring a jet matching for every parton [14]

- select the jet multiplicity n according to the jet rates obtained with matrix elements with resolution $y_{ij} > y_{cut}$, defined according to the k_T-algorithm [16] ($y_{ij} = 2\min(E_i^2, E_j^2)/\hat{s}(1 - \cos\vartheta_{ij})$);
- generate n parton momenta according to the matrix element with fixed $\alpha_s(y_{cut})$ and reweight the event with the probability of no further branching by means of Sudakov form factors;
- build a "PS history" by clustering the partons to determine the values at which 1,2,...,n jets are resolved. In so doing a tree of branchings is constructed and the nodal scales characteristic of each branching are used to reweight the event with running α_s;
- apply a coupling constant reweighting factor $\alpha_s(y_i)$ / $\alpha_s(y_{cut}) \leq 1$ for every branching of the "PS history", where y_i is the nodal scale;
- after successful unweighting, use the n-parton kinematics as initial condition for the shower, vetoing all branchings such that $y_{ij} > y_{cut}$.

The extension of the procedure to hadronic collisions has been proposed in [17]. Recent detailed results of the implementation of the procedure with the programs HERWIG, PYTHIA and SHERPA have been presented in [18]. The implementation in ALPGEN is currently under investigation.

Preliminary studies regarding the partonic steps with ALPGEN have been presented in [19]. In the case of hadronic collisions there is a certain degree of arbitrariness, such as the choice of the Sudakov form factors, the choice of the scale of α_s (LO or NLO), the treatment of the highest-multiplicity matrix element, the choice of the clustering scheme, the use of flavour or colour information to define the tree and the related reweighting factors, the treatment of gauge bosons.

All these uncertainties entail that a large degree of tuning on the data (possibly process-dependent) will be needed, and further work remains to be done to find what the correct prescriptions are. The α_s reweighting of the partonic events could be important on its own, because it should effectively give, in a gauge-invariant way, the bulk of the NLO QCD corrections. This could be tested in cases where multijet NLO calculations are available.

4 Summary

The MC simulation of hard multiparticle final states at hadronic colliders is a very important issue. Thanks to recent efforts by different groups, several multiparton event generators based on exact matrix elements are now available; they were thoroughly cross-checked during the MC workshops held at FNAL and CERN during 2003. These programs generate samples of unweighted events in a standardized format (the LesHouches Accord # 1) which can be passed to the parton shower-based MC programs to go from the partons to the real final-state hadrons. The matching between a LO multijet event generator and the parton shower MC suffers from the serious problems of double-counting and dependence on the parton-level cuts. For the case of e^+e^- collisions the problem has been solved beyond NLL accuracy with the CKKW algorithm. This can be extended to hadronic collisions, but the proof is still pending. However, recently, there has been an intense activity in its implementation on existing MC event generators going through many subtleties involved in the CKKW algorithm for hadronic collisions.

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