Production of gauge bosons plus jets in hadronic collisions * †

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A computational strategy and a collection of codes are presented for studying multiparticle final states in hard hadronic collisions.

1. Introduction

Multijet final states are characteristic of a large class of important phenomena present in high-energy hadronic collisions. QCD interactions generate multijet final states via radiative processes at high orders of perturbation theory (pure QCD processes). Heavy particles in the Standard Model (SM), such as $W$ and $Z$ bosons or the top quark, $t$, decay to multiquark configurations (eventually leading to jets) via electroweak (EW) interactions (mixed EW-QCD processes).

In addition to the above SM sources, particles possibly present in theories beyond the SM are expected to decay to multiparton final states, and therefore to lead to multijets. Typical examples are the cascade decays to quarks and gluons of supersymmetric strongly interacting particles, such as squarks and gluinos (SUSY-QCD processes).

In addition to fully hadronic multijet final states, a special interest exists in final states where the jets are accompanied by gauge bosons. For example

$$p^- p \rightarrow Z + \text{jets} \rightarrow \nu \bar{\nu} + \text{jets}$$  \hspace{1cm} (1)

is an important background to SUSY searches. Likewise,

$$p^- p \rightarrow W + 4 \text{jets} \rightarrow \ell \bar{\nu}_\ell + 4 \text{jets}$$  \hspace{1cm} (2)

provides the leading source of backgrounds to the identification and study of top quark pairs in hadronic collisions.

Several parton-level Monte Carlo (MC) event generators exist in the literature (such as VECBOS 1, MADGRAPH 2, CompHEP 3, GRACE 4, PAPAGENO 5) and studies can be performed by assuming that hard partons can be identified with jets, and that the jets’ momenta are equal to those of the parent partons. This simplification gives rough estimates, but cannot be used in the context of realistic detector simulations, for which a representation of the full structure of the final state (in terms of hadrons) is required.

This full description can be obtained by merging the partonic final states with shower MC programs where partons are perturbatively evolved through emission of gluons, and subsequently hadronized.

However, this merging is not always possible, since common parton-level MC’s sum and average over flavours and colours, and do not usually provide sufficient information on the flavour and colour content of the events.

In this contribution we review a strategy for the construction of event generators for multijet final states, based on the exact leading-order evaluation of the matrix elements for assigned flavour and colour configurations, and the subsequent shower development and transition into a fully hadronized final state.

We also present ALPGEN 6, a collection of codes realized within the framework of the presented approach.

As a case study, we then focus on the production of $WQ\bar{Q}+n$ jet final states 7 (with $Q$ being a massive quark, and $n \leq 4$) and present results for several production rates and distributions of
interest at the LHC and at the TEVATRON.

2. The computational strategy

There are two main sources of problems: the matrix-element evaluation and the reconstruction of the colour flow. To illustrate our solutions we take, for simplicity, the case of multiguon processes, as the extensions to cases with quarks and EW particles follow the same pattern.

The process \(gg \to 10\ g\) has \(5 \times 10^9\) contributing Feynman diagrams. To efficiently carry out the computation, an algorithm is therefore needed which does not make explicit use of Feynman diagrams. Fortunately, such an algorithm exists [6]. The key ingredient is the use of a recursive procedure to determine the matrix element directly from the effective action.

To better illustrate the problem with the color flow, we take again the case of multiguon production. The scattering amplitude for \(n\) gluons with momenta \(p_i^g\), helicities \(\epsilon_i^g\) and colours \(a_i\) (with \(i = 1, \ldots, n\)), can be written as

\[
M(\{p_i\}, \{\epsilon_i\}, \{a_i\}) = \sum_{P(2,3,\ldots,n)} \text{tr}(\lambda^{a_1}, \lambda^{a_2} \ldots \lambda^{a_n})
\]

where the sum extends over all permutations \(P_i\) of indices \((2, 3, \ldots, n)\), and the functions \(A(\{P_i\})\) (known as dual or colour-ordered amplitudes) are gauge invariant, cyclically-symmetric functions of the gluons’ momenta and helicities.

Each dual amplitude \(A(\{P_i\})\) corresponds to colour flows from one gluon to the next, according to the ordering specified by the permutation of indices. Furthermore, each different colour ordering corresponds to a different shower evolution of the event, once the hadronization programs are turned on. Therefore, any realistic event generator should keep track, event by event, of the colour flow (and flavour content) to perform a reliable simulation of the subsequent evolution into fully hadronized final states.

More details on our algorithm for the colour reconstruction can be found in ref. [10].

3. The ALPGEN project

ALPGEN [3] is a collection of codes for the generation of multi-parton processes in hadronic collisions implementing the computational strategy described in the previous section.

The processes currently available in the package are:

1) \(p \bar{p} \to WQ\bar{Q} + n\) jets \((n \leq 4)\)
2) \(p \bar{p} \to Z/\gamma^* Q\bar{Q} + n\) jets \((n \leq 4)\)
3) \(p \bar{p} \to W + n\) jets \((n \leq 6)\)
4) \(p \bar{p} \to Z/\gamma^* + n\) jets \((n \leq 6)\)
5) \(p \bar{p} \to n_z Z + n_w W + n_h H + n\) jets \((n_z + n_w + n_h + n \leq 8, n \leq 3)\)
6) \(p \bar{p} \to Q\bar{Q} + n\) jets \((n \leq 6)\)
7) \(p \bar{p} \to Q\bar{Q} Q' + n\) jets \((n \leq 4)\)
8) \(p \bar{p} \to HQ + n\) jets \((n \leq 4)\)

\(Q\) and \(Q'\) being massive quarks. Anywhere, except for processes 5), \(W\) and \(Z/\gamma^*\) are considered off-shell, meaning that the corresponding produced final state is a pair of leptons.

The documentation and the codes can be found at [http://mlm.home.cern.ch/mlm/alpgen/](http://mlm.home.cern.ch/mlm/alpgen/).

4. Results

We show a few illustrative examples obtained with ALPGEN for the process \(p \bar{p} \to Wb\bar{b} + n\) jets. At the LHC one gets the partonic rates of Table 1. The numbers in the first column refer to the sub-processes given in ref. [2]. The qualitatively new processes appearing when \(N_j\) increases are large and are responsible for the growth of the partonic rates when going from \(N_j = 2\) to \(N_j = 3\).

In Figure 3 we show a comparison between the \(p_T\) distributions of jets at the TEVATRON before and after the perturbative phase of the shower evolution performed by HERWIG [11]. A good matching of the jet spectra is achieved when using generation (parton level) cuts loser than jet-defining cuts. Finally, we address the issue of the ability of the shower MC to correctly predict the rate for hard radiation leading to extra final-state jets. In Figure 4 we compare the jet rates eval-
Table 1
Partonic rates in pb at the LHC, as a function of the total number of jets $N_J$ (including $b$ and $\bar{b}$).

| Process | $N_J = 2$ | $N_J = 3$ | $N_J = 4$ | $N_J = 5$ | $N_J = 6$ |
|---------|-----------|-----------|-----------|-----------|-----------|
| 1       | 2.60(1)   | 0.63(1)   | 0.144(3)  | 0.036(2)  | 0.008(1)  |
| 2       | –         | 2.97(1)   | 2.11 (2)  | 1.08(2)   | 0.47(2)   |
| 3+4     | –         | –         | 0.288(1)  | 0.24(1)   | 0.13(2)   |
| 5       | –         | –         | –         | 0.030(1)  | 0.031(4)  |
| 6       | –         | –         | –         | –         | 0.0010(3) |
| Total   | 2.60(1)   | 3.60(1)   | 2.54(2)   | 1.38(2)   | 0.64(3)   |

The jet defining cuts are $p_T > 20$ GeV, $|\eta| < 2.5$ and $\Delta R_{ij} > 0.4$.

Figure 1. Inclusive $p_T$ distributions of jets at the parton level, with separation cut $\Delta R > 0.7$ (solid curves), and of fully-showered $R_{jet} = 0.7$ jets (dashed curves). These last are obtained starting from a full sample of $\Delta R > 0.4$ partonic events.

Figure 2. $p_T$ distributions of jets at the TEVATRON: Matrix Element versus Parton Shower.

5. Summary
The formalism we have outlined allows us to compute several complex multiparton processes. ALPGEN is a collection of codes realized within the framework of the presented approach. It can be used to perform realistic studies of multipartonic processes at TEVATRON and LHC.

ALPGEN is ready-to-use and available at http://mlm.home.cern.ch/mlm/alpgen/.

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