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Event Generators — New Developments [⋆]

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1 Introduction: event generators

As in the past, Monte Carlo event generators will play a vital rôle for the physics analysis of events at present and future hadron colliders like the Tevatron, HERAII and, of course, the LHC. The particular advantages of the simulation of single events with a multi-purpose event generator like HERWIG [1,2] or Pythia [3] are all related to the fact that a fully exclusive final state is obtained. This allows to run the output through the same analysis tools as the data that was measured, thereby allowing to apply e.g. the same physical cuts as those applied to the data *after* the generation of events. This means that the events generated by the Monte Carlo program are treated in exactly the same way as the data from the measurement.

In this overview we revisit the basic facts and features of multi-purpose event-generators. In the following we consider some recent approaches to a significant improvement of the quality of event generators with the help of matrix elements: methods to match the results of matrix element calculations with those of the parton shower approach are discussed in Sec. 2. Finally, in Sec. 3 we describe the ongoing development of Herwig++ .

1.1 An event generator for e^+e^--collisions

The basic steps of the event generation in a Monte Carlo program for e^+e^- collisions are sketched in Fig. 1 (left). The incoming e^+e^--pair generates a quark-antiquark-pair ($t\bar{t}$ in this example) via the exchange of a vector boson (γ or Z^0). This central production mechanism is usually referred to as the 'hard process'. The incoming and outgoing electrically charged lines may additionally radiate soft photons. Following the hard production process the coloured particles are subject to parton shower evolution: they radiate a number of partons, mainly gluons. Technically this means that large logarithms from those regions in phase space that are enhanced by soft and/or collinear emissions are resummed. From the point of view of the final state this means

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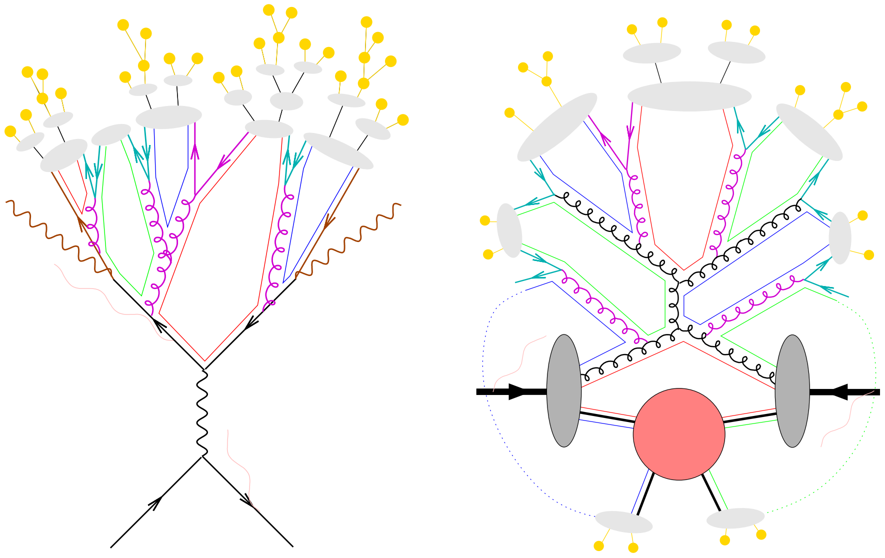

Fig. 1. An event generator for e^+e^--collisions (left) and the more complicated event structure in a $p\bar{p}$-collision (right)

that the coloured particles will be surrounded by a cloud of more coloured particles that will form a jet in the final state. The parton shower evolution is a complete perturbative description and is terminated at a low scale μ_0 of the order of Λ_{QCD}. The colour structure is kept track of in the large-N_c approximation. This means that the colour of gluons can be represented by a colour-anticolour-pair as if it was a $q\bar{q}$-pair.

Following the perturbative description of the parton shower evolution the partonic final state is converted into an exclusive hadronic final state by means of a hadronization model. Aside from two other models, the Field-Feynman-type fragmentation model [4] and the Lund string fragmentation [5], implemented in `Pythia`, the *cluster hadronization model* [6,7] is a very popular one and implemented in present `HERWIG`. In order to convert the partons in the final state into hadrons, the gluons in the final state are split nonperturbatively into $q\bar{q}$-pairs with colours according to the colour structure of the gluons. Eventually, pairs of matching colour partners can be found in the final state, being paired up into colourless clusters that carry the sum of the momenta of the constituent partons. These clusters can undergo further decays and are then converted into hadrons that carry the appropriate quantum numbers and momenta weighted according to available phase space and angular momentum. These possibly unstable hadrons decay according to well-known branching ratios such that the majority of hadrons in the final state will be low-mass pions and kaons.

1.2 Additional complications in $p\bar{p}$ collisions

In proton-antiproton collisions the above picture is significantly complicated by the presence of coloured particles in the initial state (cf. Fig. 1, right). In addition, the initial state particles of the hard process have to carry momentum fractions of the initial state hadrons according to the parton distribution functions (pdfs). Then, these coloured initial state partons typically radiate coloured particles as well, as described by a so-called backward evolution which technically differs from the final-state evolution by the presence of pdfs.

Apart from this initial state radiation the remnant particles in the initial state might undergo further interactions, in the so-called *soft underlying event*. Note that, as depicted in Fig. 1 (right), the colour structure is connected to the colour structure of the final state partons. The final state arising from the underlying event was modeled according to a simple model from UA5 [8] in recent HERWIG, used to describe the $p_\perp$-distribution of minimum bias events. Recently [3,9], multiple interactions above some hard scale are taken to model the interaction of the beam remnants.

The multi-purpose models based on such kind of model have proven to describe the data at LEP very well in general. However, there are certainly observables where an increased accuracy reached by a MC model as described above is highly desirable. Obviously the modelling of the hadronization gives some room for improvement when observables that depend on long-range effects are considered. In general, the modelling of the hadronization is not affected by the large scales in the problem. As shown in Fig. 2, the cluster mass distribution obtained in the cluster hadronization model of HERWIG is independent of the centre-of-mass energy of the hard process. This property is well-known as colour pre-confinement in QCD.

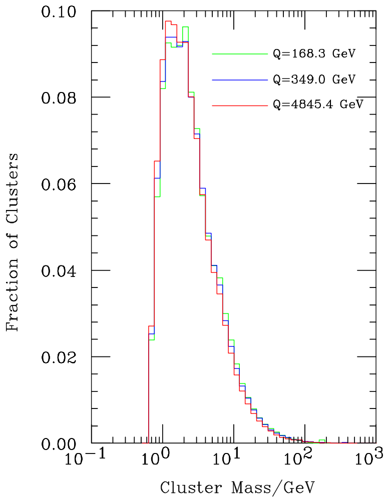

Fig. 2. The cluster mass distribution is independent of the hard scale

2 Matrix elements and parton showers

For hard scales the situation that was described above is quite different. If one considers observables where large transverse scales play a dominant role, the modelling of jets with the parton shower alone fails. Of course, the parton shower, based on the universal soft and collinear behaviour of matrix elements in QCD is obviously only valid in this kinematical domain of the coloured particles in the process.

However, it has the advantage of describing at least the leading contributions correctly to all orders. In Fig. 3 this situation is clarified for the case of multi-jet production. Only the top two rows on the diagonal are well-described by the parton shower approximation. In the following, several attemps to take the advantages of both, fixed order approximation and the parton shower, into account for the description of different observables are discussed. The aim is to keep the accuracy of fixed order calculations as well as the possibility to produce an undetermined and possibly large number of partons in the soft and collinear domain of the phase space of an observable, where the parton shower approximation is assumed to hold.

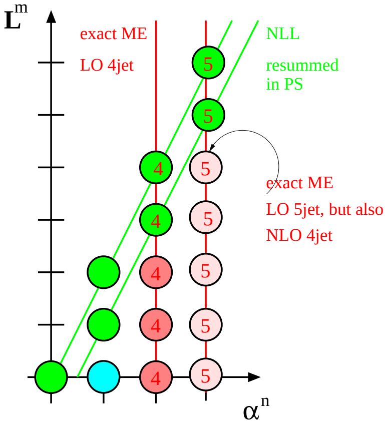

Fig. 3. Different orders in the LL approximation and in α_S

2.1 Matrix element corrections

In the simplest cases the above extensions are important in the decay $t \to Wb$ or the production of vector bosons in hadronic collisions where an extra gluon is radiated. Usually the g is generated from parton shower radiation. Even though the largest part of the matrix element (ME) is described well in this approximation, this approach fails when the gluon initiates an extra high-$p_\perp$ jet. Here, one can improve the description of the final state tremendously by considering matrix element corrections [10,11].

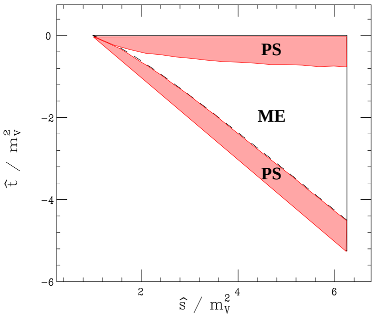

Fig. 4. The phase space for Wg production

In Fig. 4 the phase space for Wg-production in hadron-hadron collisions is shown. The regions 'PS' are covered by the parton shower while a hard gluon emission is typically from the region 'ME' that is not even covered by the HERWIG parton shower in this case. Therefore this region is often denoted as 'dead region'. When the phase space distribution of the hardest gluon emission is generated from the full matrix element rather than from the parton shower, a significant part of high-$p_\perp$ radiation is added to the parton shower result, as is shown in Fig. 5 for the Tevatron. The $p_\perp$-distribution for Z-production is shown in the right panel of the same figure, together with experimental data from CDF.

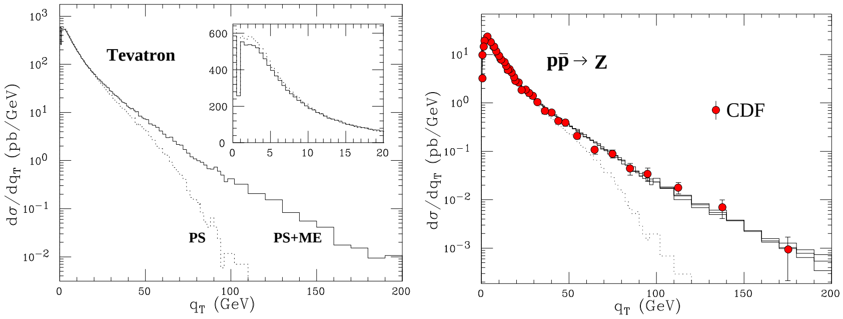

Fig. 5. $p_\perp$-distribution for Wg production with and witout ME corrections (left). $p_\perp$-distribution for Zg production in comparison to CDF data (right)

In conclusion we note that the contributions from the matrix elements are clearly important and the parton shower approximation might not be sufficient for observables in which large transverse momenta play a rôle.

2.2 Matching LO matrix elements with parton showers

[12,13] can be considered as the first systematic approach that has been implemented into an event generator for multi-jet production. The algorithm is suitable for an undetermined number of partons in the final state. The number of hard jets that can be desribed correctly by this approach is in principle only limited by the capabilities to calculate the matrix elements for these processes.

The algorithm generates momenta for a given n-gluon final state according to the exact matrix element. The number of gluons has been preselected according to a known rate with a (Durham) jet resolution cut y_1. The final state particles are then successively clustered backwards until only the LO configuration survives. This gives a resolution scale at each node where two particles were clustered, allowing to calculate a weight from the Sudakov form factors, telling that these final states are actually unresolved down to the given scales, and a weight taking into account the correct values of the strong coupling. This particular final state is then accepted according to the calculated weight and a (vetoed) parton shower evolution is applied to the resulting legs in between the appropriate scales. [12] have proven that the final rate is then independent of the cut parameter y_1 and correct up to NLLA. Results for a typical 4-jet variable, the Bengtsson-Zerwas angle, are displayed in Fig. 6 and show that this algorithm, implemented into the event generator APACIC++ [14] gives results to a high precision. We note, that this approach has been generalized to $p\bar{p}$ collisions recently [15]. Another implementation of these ideas is realized in the dipole cascade [16].

The success of this approach raises the question of appropriate matrix element generators that allow for a generation of multijet final states to a very high precision, to be combined with the benefits of the Monte Carlo event generator to generate additional LL QCD-radiation and to produce an exclusive final state. Two recent examples are AMEGIC++ [17] and `MadEvent` [18]. The latter allows for a rather robust generation of final states with a large number of jets while the former aims for high precision at the same time. Both are multi-purpose programs that do not require any user interaction apart from entering the desired process, of course. Even this task can in principle be done automatically. Other examples of multi-purpose matrix element generators are `AlpGen` [19] and `CompHEP`[20].

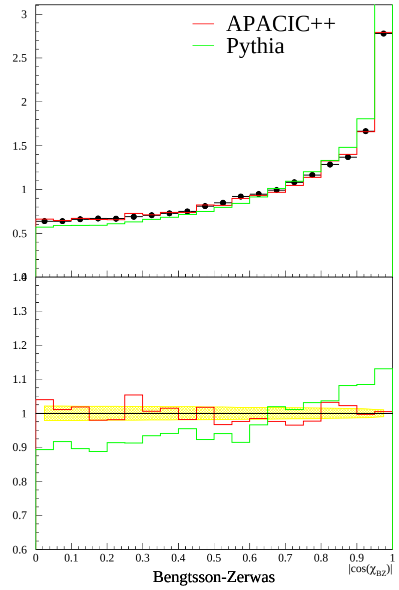

Fig. 6. Begtsson-Zerwas angle at LEP, compared to `Pythia` and APACIC++

2.3 Matching parton showers with NLO matrix elements

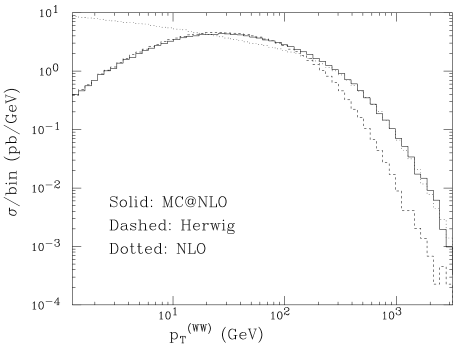

Fig. 7. Results from [23] for W-pair production

In addition to aiming for a large number of jets in the final state, improved precision is achieved by taking into account NLO matrix elements as well. The challenge is to correctly match up the emission of an extra gluon from the real correction with the the parton shower emission. Three groups have investigated this problem in different ways. [21] and [22] have used the phase space slicing method to separate hard and soft (unresolvable) emissions with good success in the description of e.g. the differential jet shape at HERA. [23], however, argue that their results suffer from an inconsistency: they do not reproduce the perturbative orders at any point in phase space correctly. In contrast, the latter use a subtraction method that suits the needs of the Monte Carlo program which does not have to be modified to a large extent. The implementation `MC@NLO` [24] generates results for

W-pair production that show the desired features (Fig. 7): at high $q_\perp$ the program matches up the NLO result while at low $q_\perp$ the soft and collinear divergences are properly resummed by the Monte Carlo program. The group [26] has achieved important theoretical results as well as matching of NLO matrix elements to parton showers for certain processes.

3 Development of Herwig++

In this final section the status of the development of the new Monte Carlo event generator Herwig++ is outlined. As the name might suggest, Herwig++ is a new C++ version of the well-known event generator HERWIG. However, Herwig++ will not be a plain 'rewrite' of the same program but will have some new features added. There are several major motivations for a complete rewrite in another programming language.

First of all, the existing Fortran code has been constantly developed throughout nearly twenty years and is maintained by a large number of authors making it increasingly difficult to maintain the program efficiently and to guarantee the safety of code, i.e. it is in principle possible that one author modifies parts of the program which he did not intend to touch at all. In addition, more and more users wish to modify the code themselves, adding for example matrix elements they obtained from new models. Aside from others, these examples clearly show the requirements that a new version of the program should fulfil. The object oriented features of C++ perfectly match these requirements.

Some major arguments in favour of such a rewrite are:

- The experimental collaborations start to write new (and to rewrite existing) analysis software entirely in C++. Since the program will be used by people working in these collaborations it is much more likely that a succesful process of bug report and handling is achieved when the users actually know the language a program is written in very well.
- Benefit along similar lines is achieved since C++ has become the standard programming language in the UNIX/LINUX world, which is clearly dominating in the HEP world.
- Object oriented code is much easier to maintain since parts of the code are *encapsulated* and therefore the modification of one part of the program cannot affect another part of the program.
- The maintenance is easier for similar reasons. Even after a long period one might modify the code for a specific process without having to know all the details of the remainder of the program.
- For similar reasons it will be easy to implement code for new physics processes. The user does not have to be worried about modifying code he did not intend to.

Apart from a different programming language, Herwig++ will also depend on parts of the new program Pythia7 [27], a similar project for the well-known

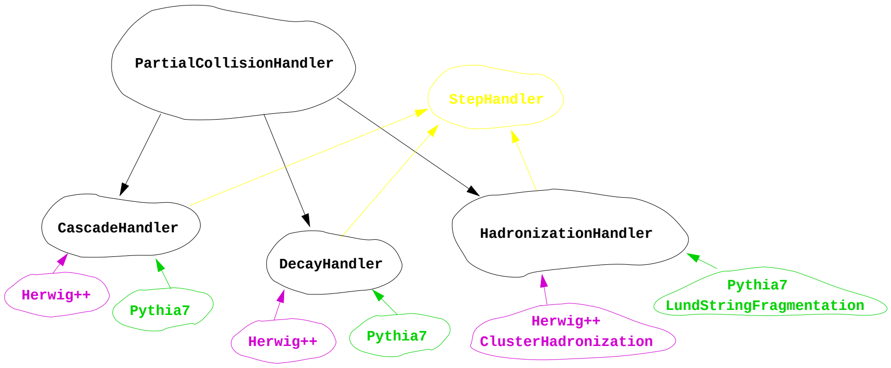

Fig. 8. The PartialCollisionHandlers in Herwig++ and their interplay with Pythia7

program Pythia. One must note that Pythia7 consists of two major pieces. First of all a library of very general classes was developed that contains many useful features. On top of this library there will be the physics implementation of the event generator Pythia. Upon the start of the Herwig++ project the library part of Pythia7 was already completed and it was decided to build the physics implementation of Herwig++ on top of this library. The way in which Herwig++ hooks into the structure of Pythia7 is sketched in Fig. 8. Even though these classes were designed very properly and the whole approach was intended to be as general as possible, one might expect the disadvantage that the two models are not completely independent anymore. However, on the other hand, users of both models might benefit from the common environment in several ways. Among these benefits there are the possibility to use parts of both programs, e.g. Herwig++'s parton shower together with the Lund string fragmentation from Pythia7. Furthermore, one might have a common graphical user interface.

In summary, the idea is to have a large and flexible, object-oriented implementation of the physics models that are implemented so far in the Fortran version HERWIG with the possibility of a straightforward extension and adaptation to future requirements. In the following, two major physics improvements in the parton shower will be described in greater detail.

3.1 New parton shower variables

One major improvement of the parton shower in Herwig++ will be the usage of a new set of evolution variables [?,28]. The previous HERWIG evolved partons in an angular variable ξ, suffering from complicated 'dead' cones and an overlap in the soft region of the 'final state+gluon' phase space. It is possible to overcome these problems with a new evolution variable $\tilde{q}^2$. Based on a Sudakov basis p, n with $p^2 = m^2, n^2 = 0$ we decompose the partons' momenta in the shower as shown in Fig. 9

$$q_i = \alpha_i p + \beta_i n + \boldsymbol{q}_i.$$

The vector p is the momentum of the jet's parent particle and n defines a backward direction in a suitable way. The longitudinal splitting is then defined relative to the p-direction,

$$\alpha_i = z_i \alpha_{i-1}.$$

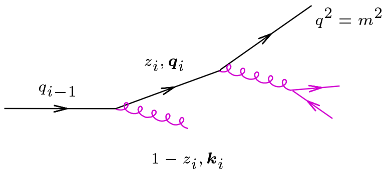

Fig. 9. Kinematics of the parton shower

The evolution variable

$$\tilde{q}^2 = \frac{\boldsymbol{p}^2}{z^2(1-z)^2} + \frac{m^2}{z^2}, \tag{1}$$

with the argument of running α_S chosen according to $\alpha_\mathrm{S}(z^2(1-z)^2\tilde{q}^2)$, determines the transverse momenta via $\boldsymbol{p}_i$,

$$\boldsymbol{q}_i = \boldsymbol{p}_i + z_i \boldsymbol{q}_{i-1}, \qquad \boldsymbol{k}_i = -\boldsymbol{p}_i + (1-z_i)\boldsymbol{q}_{i-1}\,. \tag{2}$$

Having chosen an azimuthal angle φ still randomly or as a result of planned azimuthal spin correlations [29] we can reconstruct the kinemaics recursively from the onshellness of the final state particles in the shower. Note that angular ordering is satisfied in terms of

$$\tilde{q}_{i+1} < z_i \tilde{q}_i, \qquad \tilde{k}_{i+1} < (1-z_i)\tilde{q}_i\,. \tag{3}$$

Technically, the new evolution variables only lead to a reinterpretation of the well-known Sudakov form factors, i.e. the branching probability for parton a splitting to partons bc is still given in terms of the usual splitting function as

$$dP(a \to bc) = \frac{d\tilde{q}^2}{\tilde{q}^2}\frac{C_i \alpha_\mathrm{S}}{2\pi} P_{ba}(z)\,dz \tag{4}$$

where C_i is a colour factor. Considering the two processes $e^+e^- \to q\bar{q}g$ and $t \to Wbg$ in Fig. 10 it is clear that a smooth coverage of the soft region can be achieved by choosing appropriate limiting values for the parton shower. This allows for the generation of soft radiation without double counting.

3.2 Multiscale shower

The next major improvement of the parton shower will be the implementation of a *multiscale parton shower* algorithm that takes the evolution of unstable particles and their widths properly into account. In order to outline the basic features of such a showering algorithm let us briefly recapitulate the treatment of the parton shower evolution of the t-quark in recent `HERWIG`. In Fig. 11 (left) we have a $t\bar{t}$-pair produced at a scale $\hat{s}$. First there will be the evolution

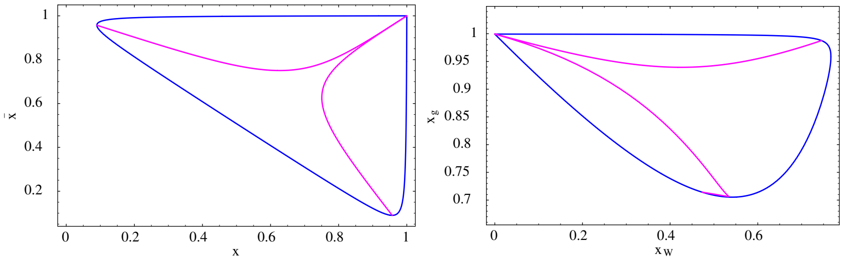

Fig. 10. Phase space covered by the parton shower in $e^+e^- \rightarrow q\bar{q}g$ (left) and $t \rightarrow Wbg$ (right)

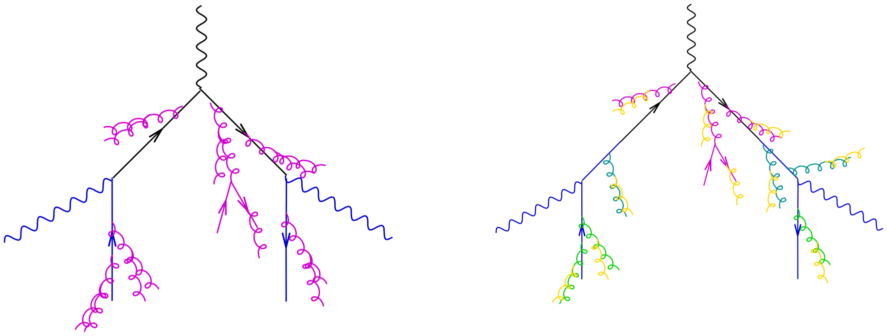

Fig. 11. Treat of QCD radiation in recent `HERWIG` (left) and the new multiscale shower algorithm (right)

of the top-quarks between the scales ($\hat{s} \rightarrow \mu_0$) with subsequent decays of the t-quarks, ($t \rightarrow Wb, \bar{t} \rightarrow W\bar{b}$) and finally the parton shower evolution of the b ($\bar{b}$) within ($m_t \rightarrow \mu_0$). In both cases we have QCD-radiation down to a lowest resolution scale μ_0, ignoring the finite width Γ_t of the t-quark.

In the Multiscale Shower, cf. Fig. 11 (right), on the other hand, the t-quarks will only be evolved down to their width ($\hat{s} \rightarrow \Gamma_t$) before they decay. Next, they decay ($t \rightarrow Wb$, $\bar{t} \rightarrow W\bar{b}$) and a (DIS-like) backward-evolution ($m_t \rightarrow \Gamma_t$) from t, $\bar{t}$ is generated to take into account that the t quarks are actually off-shell, quite in contrast to the description of the hard matrix elements, where they are assumed to be on-shell. Next, the b, $\bar{b}$ are evolved ($m_t \rightarrow \Gamma_t$) down to the lowest scale taken into account so far. Finally, the evolution from ($\Gamma_t \rightarrow \mu_0$) is generated *globally*. In case also the b were unstable, the last global evolution would have been going down to only Γ_b and the algorithm would have carried on as in the t-case.

In conclusion, the multiscale shower algorithm will be suitable for a description of the QCD evolution in complicated decay chains, as they might become important e.g. for supersymmetric particles. The algorithm is general enough to deal with arbitrary width and masses, assuming the usual collinear factorization. The classes for the multiscale shower are already implemented in Herwig++ and the shower algorithms are designed appropriately even though the 'concrete' code is not yet completed. Old HERWIG results should be reproduces with a simple set of switches. Furthermore, we note that also different types of radiation are foreseen in the shower design even though their physical relevance remains to be clarified.

3.3 Status of the program

As to the remaining parts of the program, we briefly summarize their status of development. The partonic decays are clearly interwoven with the parton shower as it should be clear from the previous section. In order to be able to treat the emission of multiple gluons with high precision, if needed, we have implemented and tested an interface to the matrix element generator AMEGIC++ for the case of the top quark decay. The vast amount of hadronic decays will be treated as in HERWIG in a first version. This may be very useful for testing purposes since as a first step we want to reproduce results from HERWIG with Herwig++. In addition, interfaces to existing decay tables e.g. from EvtGen and geant4 are foreseen. Hard processes will be treated in a similar way: the important 2 → 2 matrix elements will be hard-wired into the code while we will have the option to have interfaces to matrix element generators like AMEGIC++ in order to treat multijet production with high precision if desired. Again, the object oriented approach will allow users a safe implementation of their own matrix elements. In fact, this will be encouraged and one might possibly think of a kind of library here. Finally, the cluster hadronization model of recent HERWIG has been implemented and tested successfully along the lines of the existing Fortran code.

In conclusion, a running version for e^+e^- collisions with similar features as in recent HERWIG will appear quite soon. Further stages of development include the complete implementation and testing of the multiscale shower algorithm and the quickest possible extension towards the description of hadronic collisions. The final aim is, of course, to provide a full featured version in time for the advent of LHC.

Acknowledgments

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