Event generator for the LHC

T. Gleisberg\textsuperscript{a}, S. Höche\textsuperscript{a}, F. Krauss\textsuperscript{a}, A. Schälicke\textsuperscript{b}, S. Schumann\textsuperscript{a}, J. Winter\textsuperscript{a}

\textsuperscript{a}Institut für theoretische Physik, TU Dresden, D-01062 Dresden, Germany
\textsuperscript{b} DESY Zeuthen, Platanenallee 6, 15738 Zeuthen

In this contribution the new event generation framework \texttt{SHERPA} will be presented. It aims at the full simulation of events at current and future high-energy experiments, in particular the LHC. Some results related to the production of jets at the Tevatron will be discussed.

1. INTRODUCTION

The observation and interpretation of multi-particle, multi-jet final states will be in the centre of the physics programme at the LHC. They serve as signals or backgrounds for new physics; as an example consider the production and decay of heavy SUSY particles. This shift of focus towards higher multiplicities translates directly into new challenges for the simulation of such events and necessitates the construction of new simulation tools; for an overview on currently available tools cf. [1].

The multi-purpose event generator \texttt{SHERPA} \cite{s} is one of these new tools, which are currently under construction. Others, namely \texttt{PYTHIA7} \cite{pythia7}, \texttt{PYTHIA8} \cite{pythia8} and \texttt{HERWIG++} \cite{herwig++} are complete rewrites of the well-established codes \texttt{PYTHIA} \cite{pythia} and \texttt{HERWIG} \cite{herwig}, extending or improving their physics content. To exemplify this, consider the new parton showering algorithms \cite{apacic++}, that are or will be included. All these new codes are written in the object-oriented programming language C++; in the beginning it was planned that at least the successors of \texttt{PYTHIA} and \texttt{HERWIG} would be based on the same underlying machinery and a repository of common classes, CLHEP \cite{clhep}, which is also used in experiments. However, this turned out to be not feasible, and \texttt{PYTHIA8} and \texttt{SHERPA} are relying on their own framework.

2. PRESENTING SHERPA

It is fair to state that, at the moment, \texttt{SHERPA} is the one of the new simulation tools, which is most advanced when it comes to the ability to actually generating events. Currently, the following physics modules are implemented:

- PDFs:
  Various PDFs - CTEQ \cite{cteq} and MRST \cite{mrst} in their original form as well as many other PDFs through the LHAPDF library \cite{lhapdf} - are interfaced.

- Matrix elements:
  \texttt{AMEGIC++} \cite{amegic++} is a matrix element generator to describe hard scattering processes and decays at the tree level. Apart from the full SM \texttt{AMEGIC++} contains the full MSSM \cite{mssm} in the notation of \cite{mssm1,mssm2} and an ADD model of large extra dimensions \cite{add} with its implementation described in \cite{add1}. SUSY particle spectra are provided through the SUSY Les Houches accord interface \cite{shac}.

- Parton showers:
  For multiple QCD bremsstrahlung, i.e. the emission of secondary partons, \texttt{SHERPA} relies on \texttt{APACIC++} \cite{apacic++}, which uses, similar to \texttt{PYTHIA7}, an ordering by virtuality supplemented with an explicit angular veto to ensure a proper treatment of quantum coherence. The merging of the hard matrix elements for multijet production and the subsequent parton shower is
achieved according to the merging procedure proposed in [25,26] and implemented in [27].

- Multiple parton interactions:
  A first simulation of the “hard” underlying event in the spirit of [28] but supplemented with parton showering has been implemented and tested. A more involved model is currently in preparation.

- Hadronisation:
  The translation of the emerging partons into primordial hadrons is taken care of by the Lund string model [29]. This, as well as subsequent hadron decays are realized by an interface to the corresponding PYTHIA routines. However, a new version of cluster fragmentation [30] is ready to be fully implemented in the near future.

3. RESULTS

3.1. Matrix elements

AMEGIC++ automatically constructs Feynman diagrams and helicity amplitudes [31,32] for a given set of processes. For the helicity amplitudes, the formulation of [33] is employed. Having constructed them, AMEGIC++ simplifies and combines them by factoring out common parts and then writes the results out in library files to be compiled and linked with the core program. This leads to a drastic reduction of computing time. For the Monte-Carlo integration over phase space, the multi-channel approach of [34,35] is being used. For each Feynman diagram, suitable phase space mappings are constructed and also written out as library files. During integration, the weight optimisation procedure selects successful channels having a large impact on the integration. In AMEGIC++, after a number of integration steps, these winning channels are then further optimised by employing VEGAS [36] to select random numbers for them.

AMEGIC++ has exhaustively been tested for a large number of production cross sections for six-body final states at an $e^+e^-$-collider [37] and various processes at the LHC, see [38]. As an example for the latter, consider the processes $pp \rightarrow e^{-}\nu_{e} + n\text{jets} + X$ and $pp \rightarrow e^{-}\nu_{b}b + n\text{jets} + X$ at the LHC. Cross sections for these processes, obtained through ALPGEN [39], COMPHEP [40], MADEVENT [41], and AMEGIC++ can be found in Table 3.1.

In these comparisons, AMEGIC++ proved to work for up to eight external particles, and, thus, SHERPA includes a state-of-the-art matrix element generator, one of the key elements of modern event generators.

3.2. Merging of matrix elements and the parton shower

In order to fully exploit the power of such multi-particle matrix elements, they have to be combined with the parton shower which models subsequent, secondary emission of softer QCD quanta. There are different ways to do so, among them MC@NLO [43]. An alternative approach [25,26] is to combine tree-level matrix elements for different jet multiplicities. This is done by defining two disjoint regions of jet production and evolution, separated by a jet measure defined according to the $k_\perp$ algorithm [44,45,46].

Then the matrix elements are reweighted with suitable Sudakov form factors such that the corresponding matrix element becomes “exclusive”, and the parton showers are vetoed such that no extra jet is produced in the showering. This approach guarantees independence of the jet separation definition at leading logarithmic order. The algorithm has been implemented in full generality in SHERPA [27], forming one of its cornerstones. The approach and its implementation in SHERPA has been tested by comparing both with data and other codes, in a number of processes, cf. for example [51,52,53]. The findings in these comparisons were:

- Self-consistency:
  Varying the $k_\perp$ cut in the internal jet definition for the merging and the maximal number of jets taken care off by the matrix elements, the approach has been found to be extremely stable and independent of the jet

1For details of the calculational setup and more results, cf. the MC4LHC homepage [38].

2There exist some variations of this approach [47,48,49,50] with different technical realisations of the same idea.
### Scale-independence:

The shapes of characteristic distributions such as the transverse momentum of jets etc. are surprisingly stable (deviations of the order of 20% and less) under global variations of the renormalisation and factorisation scale in the matrix elements, Sudakov weights and the parton shower. The total cross section, being calculated at leading order only, however, depends much stronger on these choices.

### Comparison with NLO results:

The shapes of distributions obtained by SHERPA are in excellent agreement with those obtained by full NLO calculations.

In this presentation, the merging approach will be applied to the case of jet production at Tevatron, Runs I and II. At Run I, the D0 collaboration measured the ratio of the three-to-two jet rate $R_{32}$, using the midpoint algorithm with different $E_{\perp}$ of the jets and in different regions of pseudorapidity of the jets [54]. The stability of the results obtained by SHERPA under variations of renormalisation and factorisation scales $\mu_{R,F}$ is demonstrated in Fig. 1. In Fig. 2 the SHERPA results are contrasted with those of a full NLO calculation [55]. In all these figures $R_{32}$ is plotted against $H_T$, the scalar sum of the transverse momenta of all hard objects in the detector. Jets are defined by $E_{\perp} > 40$ GeV, $|\eta| \leq 3$ and $R = 0.7$. Again, stability of the results obtained by SHERPA under scale variations is found; the agreement with a full NLO calculation for the result is remarkable. These findings, however, are a continuation of what has been found before for other processes.

At Run II, the D0 collaboration measured the angular decorrelation in the azimuthal plane of the two leading jets in jet production [56]. In Fig. 3 the results of SHERPA are contrasted with the experimental findings. Again, SHERPA is capable of precisely reproducing the QCD radiation pattern in these events.

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**Table 1:** Compilation of results for cross sections for $pp \rightarrow e^- \bar{\nu} e + n$ jets + $X$ and $pp \rightarrow e^- \nu b \bar{b} + n$ jets + $X$ at the LHC.

| X-sections (pb) | Number of jets |
|----------------|---------------|
| $e^- \nu + n$ QCD jets |
| 0 | 1 |
| 3904(6) | 3892(5) | 3808(3) |
| 1013(2) | 1012(2) | 1011(2) |
| 1 | 2 |
| 9.34(4) | 9.415(5) | 9.32(3) |
| 9.85(6) | 9.91(2) | 9.74(1) |
| 6.82(6) | 6.80(2) | 6.87(5) |
| Alpgen | CompHEP | MadEvent |
| 3974.4(3) | 3964.4(4) | 391(1) |
| 135.5(3) | 137.5(5) | 54(1) |

**X-sections (pb)**

| $e^- \nu + b \bar{b}$ |
|------------------------|
| 0 | 1 |
| 3 | 4 |
| 9.37(1) | 9.86(2) | 6.87(5) |
| 9.85(5) | 9.91(2) | 6.80(2) |
| 6.82(6) | 6.87(5) | 6.87(5) |
| Alpgen | CompHEP | MadEvent | Sherpa |
| 9.34(4) | 9.415(5) | 9.32(3) | 9.37(1) |
| 9.85(6) | 9.91(2) | 9.74(1) | 9.86(2) |
| 6.82(6) | 6.80(2) | 6.87(5) | 6.87(5) |
Figure 1. $R_{32}$ in dependence of $H_T$ for different global factors on the renormalisation and factorisation scale.

Figure 2. $R_{32}$ in dependence of $H_T$ as described by SHERPA and a full NLO calculation.

Figure 3. The azimuthal decorrelation of the two leading jets in the transversal plane. The four curves correspond to four different bins of $p_\perp$ of the leading jet.

4. CONCLUSIONS

In this publication the event generator SHERPA has been presented. Results have been presented for the working of its internal matrix element generator AMEGIC++, a state-of-the-art tool. The implementation of the merging procedure is a key ingredient of the SHERPA event generator. Results for jet production at the Tevatron prove that the merging of tree-level matrix elements and parton showers is work in a systematically correct manner. Further tests, especially in the simulation of more processes, are ongoing. The results obtained so far indicate that SHERPA is perfectly suitable to meet the enhanced demands of the community to reliably simulate physics processes at the next generation of collider experiments.

ACKNOWLEDGEMENTS

Financial support by BMBF, DESY and GSI is gratefully acknowledged.

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