Proceedings of the DIS'2004, Štrbské Pleso, Slovakia

MONTE CARLO MODELS AT THE LHC

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In this contribution the new event generation framework SHERPA will be presented, which aims at a full simulation of events at current and future high-energy experiments. Some first results exemplify its capabilities.

Experiments at particle colliders are the most prominent way of testing the basic structure of matter at shortest distances and the dynamics underlying the interactions of its fundamental constituents at the energy frontier. These tests, however, become increasingly precise; the number of processes as well as the complexity of the phenomena involved require an increasingly careful planning of the experimental strategy and more and highly sophisticated analysis tools. In order to compare theoretical predictions with actual experimental results, simulation programs, also known as event generators, have become one of the most central tools. Over the past decades, these programs have been significantly improved in terms of physics content and they have grown to highly evolved computer code. In view of the next generation of collider experiments it is apparent that also the development of event generators have to keep pace with the new great challenges posed by them. Apart from physics issues, reflecting the rising complexity of the experiments, transparency and maintenance of these codes start to become an important issue.
In order to meet these increasingly demanding requirements, a number of new codes are being constructed at the moment. These include the completely new write-ups in C++ of the well-known Fortran programs Herwig [1]and Pythia [2].Both Herwig++ [3] and Pythia7 [4] rely on a common event generation framework called ThePEG [5] and concentrate on the specific implementation of physics models for different aspects of event simulation. ThePEG, in turn, incorporates the organisation and structure of event generation itself. Another, completely independent approach is represented by the package SHERPA [6], also written in C++. In the remainder of this contribution, this new event generator will be presented in more detail; for details concerning the status of the two other C++-based event generators, cf. the respective presentations by L. Lönnblad and S. Gieseke.
One of the construction paradigms of SHERPA is the clear separation of specific physics implementation and the more abstract rules defining the interplay of the different physics modules. To exemplify this, consider the case of potentially different codes for the description of hard scattering matrix elements. The SHERPA framework provides an interface called Matrix_Element_Handler to steer these codes. In turn, this interface is used by different phases of event generation, like, e.g., the

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generation of the signal process or the simulation of the hard underlying event. However, in the following the focus will be on physics issues only. In its current version, SHERPA-1.0.4., the following physics modules are implemented:

- Interface to various PDFs: CTEQ [7] and MRST [8] in their original form as well as many other PDFs through the LHAPDF interface in its version 1 [9].
- AMEGIC++ [10] as generator for the matrix elements for hard scattering processes and decays as well as an internal library of analytical expressions for some very constrained set of $2 \to 2$ processes. AMEGIC contains the full MSSM, where SHERPA provides an interface to Isajet [11] for the SUSY particle spectra[a]. AMEGIC++ has exhaustively been tested for a large number of production cross sections for six-body final states at an e^+e^--collider [13] and various processes at the LHC [14].
- For multiple QCD bremsstrahlung, i.e. the emission of secondary partons, SHERPAs own parton shower module APACIC++ [15] is invoked[b]. The merging of the hard matrix elements for multijet production and the subsequent parton shower is achieved according to the merging procedure proposed in [16], heavy quarks are treated with corresponding Sudakov form factors [17].
- Multiple parton interactions, giving rise to the "hard" underlying event, are currently being implemented. The corresponding module will be part of the next release of SHERPA.
- Hadronisation of the resulting partons and subsequent hadron decays so far are realized by an interface to the corresponding Pythia routines. However, a new version of cluster fragmentation [18] is ready to be fully implemented in the near future.

As a first example of the capabilities of the SHERPA framework, the production of single electroweak gauge bosons, i.e. W or Z-bosons, is considered in this presentation. The idea underlying the merging prescription [16]is to separate the phase space for parton emission in two regions, one for jet production, described by appropriate matrix elements, and one for jet evolution, modelled by the parton shower. The first step is realized by reweighting the matrix elements with Sudakov form factors and by applying suitable dynamical scales for the strong coupling constant; the second step translates into vetoing hard parton emission in the subsequent parton shower. A systematic check of this procedure therefore consists of three steps:

1. In a first step, the reweighting part is taken as a scale-setting prescription and the thus modified matrix elements are compared with suitable higher order calculations. For this, the computer program MCFM has been used [19]. In Fig. 1 the results for the $p_\perp$ spectra of the first (left panel) and of the first and second jet (right panel) for Wj and Wjj exclusive final states are compared. Both the NLO calculation and the LO results are for "exclusive" jets - for the

[a] The inclusion of the corresponding Les Houches accord interface [12] is in preparation.

[b] In addition to the published version, it has been supplemented by parton showers in the initial state, enabling SHERPA to also simulate events with hadronic initial states.

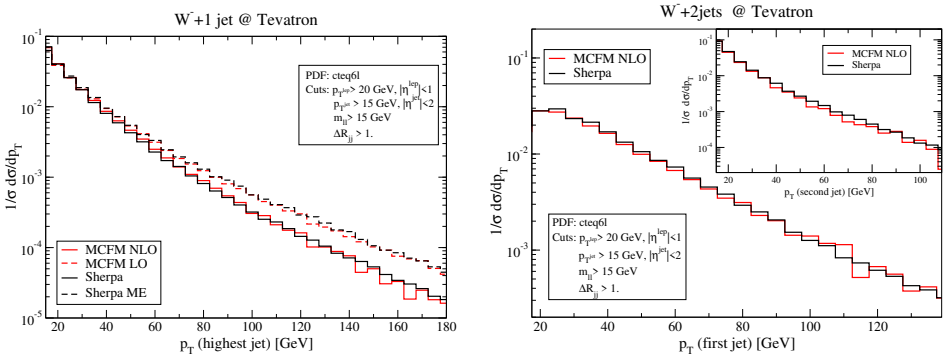

Figure 1. $p_\perp$ spectra of the first (left panel) and of the first and second jet (right panel) of the corresponding NLO calculations for exclusive Wj and Wjj final states and of the reweighted LO matrix elements of `SHERPA` in $p\bar{p}$ collisions at Tevatron are compared.

NLO calculation this translates into constraining the phase space of real parton emission, whereas for the reweighted LO results a suitable choice of scale of the Sudakov form factors has to be applied (the corresponding minimal $p_\perp$ of the jet). In contrast Fig. 2 shows results for inclusive final states, i.e., the phase space for the real correction in the NLO calculation is not restricted. For the reweighted LO matrix elements then the choice of scale for the Sudakov form factors is dynamical, namely the actual $p_\perp$ of the jet or the softer of the two jets, respectively. This difference also explains the relative effect of the higher order correction. The results show an impressive agreement, supporting the idea that reweighting the matrix elements at LO takes proper care of higher order corrections. This statement, however, has to be taken with a grain of salt: The agreement is for shapes only but not for their total normalisation. To have also the normalisation correct, one has to apply a constant K-factor given by the ratio of LO and NLO total cross section.

2. In a next step the way the parton shower is added, including the veto procedure, is controlled. It is important to check that the result for sufficiently inclusive observables is independent on the separation scale between matrix element and parton shower regime[c]; also the independence on the number of extra parton emissions handled by the matrix elements is of relevance. `SHERPA` passes these checks, as can be seen from Figs. 3 and 4, where the former exhibits the $p_\perp$ spectrum of the W-boson at Tevatron, Run II, whereas in the latter its η spectrum is depicted, using matrix elements with up to three extra jets. In both figures, different minimal $p_\perp$ between jets or jets and the beam are applied. Also, in all plots there is a second, dashed black line showing the results for a cut of 20 GeV and for up to two extra jets.

3. Finally the results are compared with experimental data from Tevatron, Run

[c] Of course, if correlations sensitive to quantum mechanics are considered, one has to ensure that the matrix elements dominate in the relevant region.

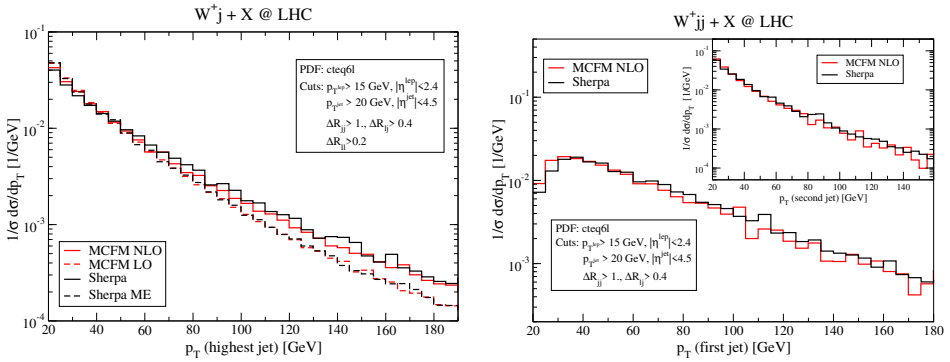

Figure 2. $p_\perp$ spectra of the first (left panel) and of the first and second jet (right panel) of the corresponding NLO calculations for inclusive Wj and Wjj final states and of the reweighted LO matrix elements of SHERPA in $p\bar{p}$ collisions at Tevatron are compared.

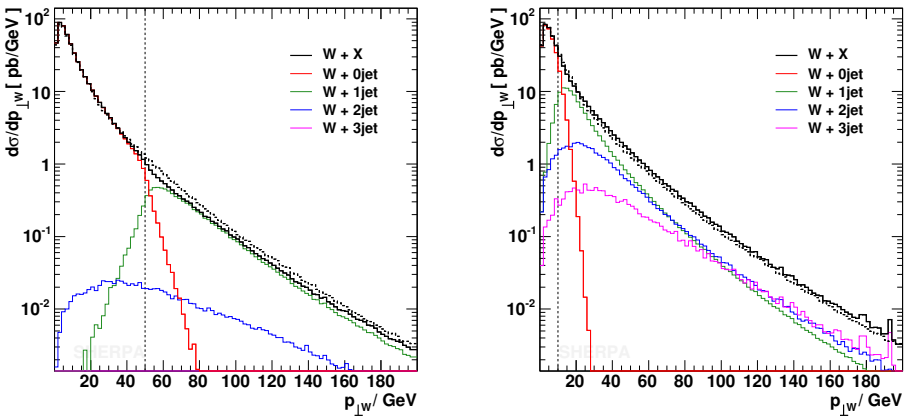

Figure 3. $p_\perp$ spectrum of the W at Tevatron, Run II; separation cuts are 50 GeV (left) and 10 GeV (right), solid lines are for individual contributions (up to three extra jets) and for the total result, the dashed line is for W plus up to two extra jets with a cut of 20 GeV.

I. In the left panel of Fig. 5 the $p_\perp$ distribution of the Z is displayed [20], whereas in the right panel the $p_\perp$ distribution of the W-boson is shown [21]. In both cases, SHERPAs results are rescaled by a constant K-factor.

Taken together, these results prove that the merging as implemented in SHERPA is working in a systematically correct manner; further tests include, e.g., the sensitivity of results to the choice of scale, the quality in describing more complicated correlations, for instance of different jets and the simulation of more processes. This programme currently is being worked on, first preliminary results are very encouraging. This indicates that SHERPA is perfectly suitable to meet the enhanced demands

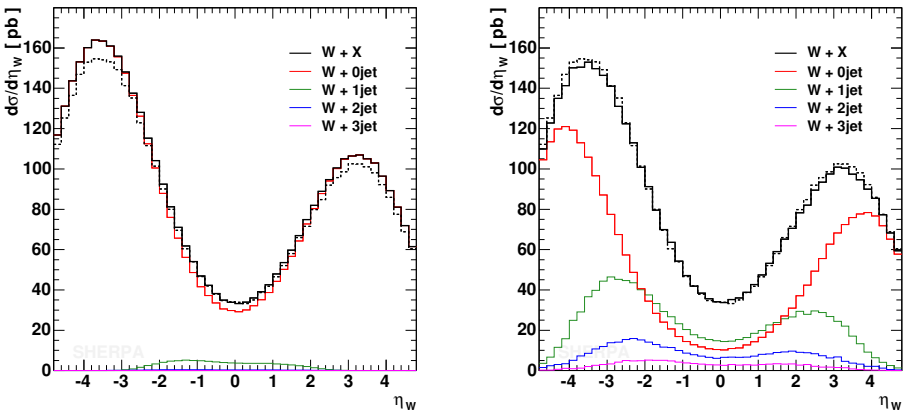

Figure 4. η spectrum of the W at Tevatron, Run II; separation cuts are 50 GeV (left) and 10 GeV (right), solid lines are for individual contributions (up to three extra jets) and for the total result, the dashed line is for W plus up to two extra jets with a cut of 20 GeV.

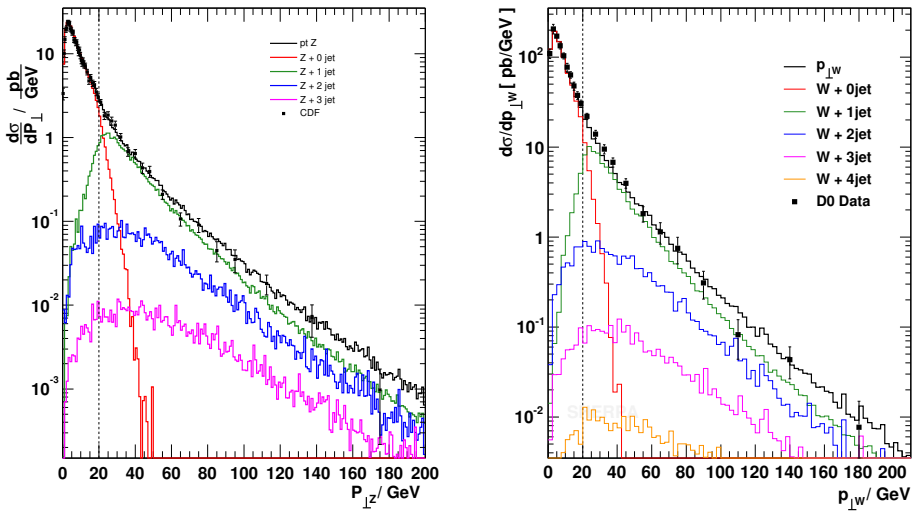

Figure 5. p_perp distribution of the Z (left panel) and of the W (right panel) at Tevatron, Run I, compared with predictions by SHERPA, which have been rescaled by a constant K-factor.

of the community to reliably simulate physics processes at the next generation of collider experiments.

Acknolwedgments

The authors gratefully acknowledge financial support by BMBF, DFG, and GSI. F.K. wishes to thank the organisers of DIS2004 for the extremely pleasant and fruitful atmosphere.

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