Chapter 1

Soft Interactions in Herwig

S. Gieseke, P. Kirchgäßer & F. Loshaj
Karlsruhe Institute of Technology, Institute for Theoretical Physics
Wolfgang-Gaede-Str. 1, 76131 Karlsruhe, Germany

We introduce a new model for soft interactions in the Monte Carlo event generator Herwig. We add a new model for the simulation of diffractive final states, based on the cluster hadronization model in Herwig. The soft component of the Multiple partonic interaction model is replaced by a refined model for soft gluon production. With these two components we are for the first time able to give a full simulation of minimum-bias events at hadron colliders. We briefly describe the models and present a few results obtained with it.

1. Introduction

The underlying event plays an important rôle in the simulation of particle collisions at hadron colliders. The most important input for the simulation of the underlying event is the usage of a multiple partonic interaction (MPI) model that is capable to produce jets at large transverse momentum via the simulation of multiple semi-hard partonic scatters.\[1,4,5-7\]

In Herwig, the MPI model has been implemented following the JIMMY model[3] and extending it with a soft component[5,7]. Here, the soft component adds additional gluons with low transverse momentum according to a Gaussian in $p_T^2$ that is also found in experimental data on the transverse momentum of very soft particles, i.e. particles with transverse momenta lower than a few GeV. These soft gluons clearly have to be seen as a technical vehicle to simulate soft physics rather than perturbative quanta of strong interactions. They help us to connect the event on the parton level to the hadronization stage of the event. At this point, the colour structure of the event, given by the connections of individual gluons to the colour lines of partons from other events or the event remnants is most important.
for the further evolution of the event. Given the lack of a first-principles approach to these soft interactions they were modeled as a random assignment of either a colour connection as in a hard event, i.e. with colour exchange, or as a peculiar event where the produced gluons are disrupted from the colour structure of the remainder of the event. The weight towards one or the other structure was left as a tuning parameter and fixed with a rather large probability to produce colour disrupted events.

This modeling of soft events was intended as a smooth interpolation of the hard events into the soft region with the main motivation to avoid unphysical boundary effects in the simulation of MPI events, serving as the underlying event in hard events. At the same time it also allowed for a glimpse into the regime of minimum-bias (MB) events where no hard scatter was present. The model has turned out to be fairly stable whenever a not too soft selection as a minimum transverse momentum of at least 500 MeV or the requirement of a handful of charged particles in the event has been made. At the same time, the model obviously failed when it was applied to less restricted minimum-bias events. This is easily explained as a result of i) the rather poor modeling of soft particle production and ii) the overall lack of a description of diffractive events. These two points have now been addressed in our recent work that we report on at this conference.

A particularly clear failure can be observed in Fig. 1. The observable $\Delta \eta_F$ describes the largest rapidity gap in the detector from any given track towards the end of the detector. This gap will be large for diffractive events where the final state of one system disappears into the beam pipe while the other system leaves tracks in the detector. The observed bump in the Herwig simulation is a result of e.g. events with disrupted colour connections that result in large rapidity gaps.

2. The new model for soft interactions

This failure led us to further studies of the simulation of soft physics with our event generator with the conclusion that we need to replace the production of soft particles with a new, more sophisticated model and that we need a model for diffractive final states to complement this soft model.

The latter model is, despite the hadronic nature of diffractive interactions, formulated as a model of (non-perturbative) parton production that can be used to produce low-mass diffractive final states by means of the cluster hadronization model in Herwig. We make use of a Regge factorized ansatz for the diffractive cross section with an exponentially falling $t$ depen-
Rapidity gap size in $\eta$ starting from $\eta = \pm 4.9$, $p_T > 200$ MeV
d$\sigma/d\Delta\eta F [mb]$

Fig. 1. Distribution of events with large rapidity gap, as measured by ATLAS.

dence and a power-like $M$ dependence, where $t, M$ are the commonly known momentum transfer and diffractive mass of the system. Once given these kinematics per event, we can generate the production of a quark-diquark system with the given $t, M$ that will then hadronize into the desired diffractive final state. For very low masses we directly produce a $\Delta$ resonance.

The model for soft particle production is much more detailed and is based on the model for so-called multi-peripheral particle production\textsuperscript{11} Again, we translate the model into our space of partonic degrees of freedom, where we produce soft gluons approximately flat in rapidity, i.e. according to the multi-peripheral kinematics. In order to be able to hadronize this final state and to avoid high-mass clusters in the system we have to add a quark pair to the system and then produce the soft gluons ordered in rapidity as depicted in Fig. 2. One such ladder is the result of one soft interaction according to our MPI model. Le where we previously produced a single pair of gluons we now produce a whole ladder of soft gluons cf. Fig. 3. The number of gluons depends on the available phase space in rapidity and is chosen to keep the number of soft gluons approximately constant per rapidity interval. The transverse momenta are chosen according to a Gaus-
sian, as in the previous model for soft interactions. A detailed description of the model is given in.
interactions, i.e. the number of ladders. The number of particles within the single ladder depends on the available rapidity span and needs a single normalization factor that will as well mildly rise with $\sqrt{s}$. Furthermore we have to adjust the fraction of diffractive events.

Some results of these tunes are shown in Fig. 4. We find that the rapidity distribution of charged particles in minimum-bias events is very well reproduced also for events with a significant fraction of diffraction, the data is taken from ATLAS. These observables have been used to tune the model parameters. In Fig. 5 we show transverse momentum distributions of charged particles in minimum-bias events that are also very well described in the regime of soft particle production as measured by ATLAS. Our tune has been focused on this regime and the extension of this plot into the harder regime has to be properly adjusted for in the semi-hard events from the MPI that have not been adjusted in our study. Once again, the results turn out very nicely and show that we have much improved the description of this observable.

Last but not least, we consider the rapidity gap fraction measurement that has initially motivated the extension of our model. With this observable we have adjusted the relative weight of the diffractive vs. non-diffractive contributions to the total cross section. In Fig. 6 we show the result in comparison to CMS data. We find that with the new model the bump disappears, as we do not have any more artificial rapidity gaps as a result of unphysical colour assignments to the soft final states. In Fig. 7...
Fig. 5. Transverse momentum distributions in MB interactions as measured by ATLAS\cite{ATLAS} compared to simulations with the old and new MB models in Herwig.

we also show the individual contributions from the diffractive matrix elements vs the hard and soft MPI contribution, called MinBias in the plot. The MPI contribution shows the exponential-like fall off for small rapidity gaps which is hardened a bit by the MPI interactions. The diffractive contribution is fairly flat throughout the considered range in $\Delta\eta_F$.

4. Conclusion

We have presented the new model for soft interactions in Herwig. The model adds diffractive final states to the simulation of minimum-bias events and allows for the production of rapidity ordered gluons with very small transverse momentum. We can improve all considered observables related to minimum-bias and diffractive events significantly with this model. This model is only the first of a number of steps to improve the modeling of soft physics in Herwig.

This work was supported in part by the European Union as part of the FP7 Marie Curie Initial Training Network MCnetITN (PITN-GA-2012-315877)

References

1. M. Bähr et al., Herwig++ Physics and Manual, *Eur. Phys. J.* C58, 639–707 (2008). doi: 10.1140/epjc/s10052-008-0798-9.
2. T. Sjöstrand, S. Mrenna, and P. Skands, A Brief Introduction to PYTHIA
Fig. 6. The $\Delta \eta^F$ distribution as measured by CMS compared to the new model of soft interactions in Herwig.

8.1, *Comput. Phys. Commun.* **178**, 852–867 (2008). doi: 10.1016/j.cpc.2008.01.036.
3. T. Gleisberg et al., Event generation with SHERPA 1.1, *JHEP*. **0902**, 007 (2009). doi: 10.1088/1126-6708/2009/02/007.
4. J. Butterworth, J. R. Forshaw, and M. Seymour, Multiparton interactions in photoproduction at HERA, *Z.Phys.* **C72**, 637–646 (1996). doi: 10.1007/s002880050286.
5. M. Bahr, J. M. Butterworth, S. Gieseke, and M. H. Seymour. Soft interactions in Herwig++. In *Proceedings, 1st International Workshop on Multiple Partonic Interactions at the LHC (MPI08): Perugia, Italy, October 27-31, 2008*, pp. 239–248 (2009). URL http://inspirehep.net/record/821555/files/arXiv:0905.4671.pdf.
6. M. Bähr, J. M. Butterworth, and M. H. Seymour, The Underlying Event and the Total Cross Section from Tevatron to the LHC, *JHEP*. **0901**, 065 (2009). doi: 10.1088/1126-6708/2009/01/065.
7. M. Bähr, S. Gieseke, and M. H. Seymour, Simulation of multiple partonic interactions in Herwig++, *JHEP*. **0807**, 076 (2008). doi: 10.1088/1126-6708/2008/07/076.
8. S. Gieseke, F. Loshaj, and M. Myska. Towards Diffraction in Herwig. In *Proceedings, 7th International Workshop on Multiple Partonic Interactions*
Rapidity gap size in $\eta$ starting from $\eta = \pm 4.9$, $p_T > 200$ MeV
d$\sigma$/d$\Delta$ $\eta$ $F$ [mb]

\begin{tabular}{ccccccccc}
0 & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 \\
0.6 & 0.8 & 1 & 1.2 & 1.4 & \\
\end{tabular}

$\Delta$ $\eta$ $F$
MC/Data

Fig. 7. The diffractive and non-diffractive contributions to the $\Delta$ $\eta$ $F$ distribution compared to ATLAS data.

at the LHC (MPI@LHC 2015): Miramare, Trieste, Italy, November 23-27, 2015, pp. 53-57 (2016). URL https://inspirehep.net/record/1421665/files/arXiv:1602.04690.pdf.

9. S. Gieseke, F. Loshaj, and P. Kirchgaeer, Soft and diffractive scattering with the cluster model in Herwig, Eur. Phys. J. C77(3), 156 (2017). doi: 10.1140/epjc/s10052-017-4727-7.

10. G. Aad et al., Rapidity gap cross sections measured with the ATLAS detector in $pp$ collisions at $\sqrt{s} = 7$ TeV, Eur. Phys. J. C72, 1926 (2012). doi: 10.1140/epjc/s10052-012-1926-0.

11. M. Baker and K. A. Ter-Martirosian, Gribov’s Reggeon Calculus: Its Physical Basis and Implications, Phys. Rept. 28, 1–143 (1976). doi: 10.1016/0370-1573(76)90002-8.

12. G. Aad et al., Charged-particle multiplicities in $pp$ interactions measured with the ATLAS detector at the LHC, New J. Phys. 13, 053033 (2011). doi: 10.1088/1367-2630/13/5/053033.

13. V. Khachatryan et al., Measurement of diffraction dissociation cross sections in $pp$ collisions at $\sqrt{s} = 7$ TeV, Phys. Rev. D92(1), 012003 (2015). doi: 10.1103/PhysRevD.92.012003.