Herwig 7.2 Release Note

Johannes Bellm\textsuperscript{1}, Gavin Bewick\textsuperscript{2}, Silvia Ferrario Ravasio\textsuperscript{2}, Stefan Gieseke\textsuperscript{3}, David Grellscheid\textsuperscript{4}, Patrick Kirchgaesser\textsuperscript{3}, Mohammad R. Masouminia\textsuperscript{2}, Graeme Nail\textsuperscript{5}, Andreas Papaefstathiou\textsuperscript{7}, Simon Platter\textsuperscript{6}, Michael Rauch\textsuperscript{4}, Christian Reuschle\textsuperscript{1}, Peter Richardson\textsuperscript{2,7}, Michael H. Seymour\textsuperscript{8}, Andrzej Siódmok\textsuperscript{9}, and Stephen Webster\textsuperscript{2}

\textsuperscript{1} Department of Astronomy and Theoretical Physics, Lund University,
\textsuperscript{2} IPPP, Department of Physics, Durham University,
\textsuperscript{3} Institute for Theoretical Physics, Karlsruhe Institute of Technology,
\textsuperscript{4} Department of Informatics, University of Bergen,
\textsuperscript{5} Higgs Centre for Theoretical Physics, University of Edinburgh,
\textsuperscript{6} Particle Physics, Faculty of Physics, University of Vienna,
\textsuperscript{7} CERN, PH-TH, Geneva,
\textsuperscript{8} Particle Physics Group, Department of Physics and Astronomy, University of Manchester,
\textsuperscript{9} The Henryk Niewodniczański Institute of Nuclear Physics in Cracow, Polish Academy of Sciences.

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Abstract A new release of the Monte Carlo event generator Herwig (version 7.2) is now available. This version introduces a number of improvements, notably: improvements to the simulation of multiple-parton interactions, including diffractive processes; a new model for baryonic colour reconnection; spin correlations in both the dipole and angular-ordered parton showers; improvements to strangeness production; an improved choice of evolution variable in the angular-ordered parton shower; support for generic Lorentz structures in BSM models.

1 Introduction

Herwig is a multi purpose particle physics event generator. The current version series, Herwig\textsuperscript{7} \cite{1}, is based on a major development of the Herwig++ \cite{2–7} branch. It fully supersedes the Herwig++ 2.x and HERWIG 6.x versions. Building on the technology and experience gained with the higher-order improvements provided by Herwig 7.0 \cite{1} and 7.1 \cite{8}, a major follow-up release, Herwig 7.2 is now available. The new version includes several improvements to the soft components of the simulation, amongst other changes and physics capabilities, which we will highlight in this release note. Please refer to the Herwig++ manual \cite{2}, the Herwig 7.0 \cite{1} as well as this release note when using the new version of the program. Studies or analyses that rely on a particular feature of the program should also reference the paper(s) where the physics of that feature was first described. The authors are happy to provide guidance on which features are relevant for a particular analysis.

1.1 Availability

The new version, as well as older versions of the Herwig event generator can be downloaded from the website \url{https://herwig.hepforge.org/}. We strongly recommend using the bootstrap script provided for the convenient installation of Herwig and all of its dependencies, which can be obtained from the same location. On the website, tutorials and FAQ sections are provided to help with the usage of the program. Further enquiries should be directed to herwig@projects.hepforge.org. Herwig is released under the GNU General Public License (GPL) version 3 and the MCnet guidelines for the distribution and usage of event generator software in an academic setting, see the source code archive or \url{http://www.montecarlonet.org/}.

1.2 Prerequisites and Further Details

Herwig 7.2 is built on the same backbone and dependencies as its predecessors Herwig 7.0 and 7.1, and uses the same method of build, installation and run environment. No major changes should hence be required in comparison to a working Herwig 7.1 installation. Some of the changes, though, might require different compiler versions. The tutorials at \url{https://herwig.hepforge.org/tutorials/} have been extended and adapted to the new version and serve as the primary reference for physics setups and as a user manual until a comprehensive replacement for the detailed manual \cite{2} is available.
2 Angular-Ordered Parton Shower

A major restructuring of the angular-ordered parton shower has been performed in order to simplify the code, remove unused levels of abstraction and unused options. This is intended to improve the maintainability of the code and make new developments easier.

In addition we have changed the default interpretation of the ordering variable. When a final-state splitting $i \to j, k$ is generated, we can define the ordering scale in three different ways:

$$\hat{q}^2 = \frac{q_i^2 - m_i^2}{z(1-z)}; \quad (1)$$
$$= \frac{p_{T}^2 + (1-z)m_j^2 + zm_k^2 - z(1-z)m_i^2}{z^2(1-z)^2}; \quad (2)$$
$$= \frac{2q_j \cdot q_k + m_j^2 + m_k^2 - m_i^2}{z(1-z)}; \quad (3)$$

where $z$ is the light-cone momentum fraction carried by the particle $j$. $p_T$ is the transverse momentum of the splitting. When multiple emissions occur just one definition can be employed and this choice will also determine which quantity is preserved. We call this choice the “recoil scheme”. By default, the scale is now expressed in terms of the dot-product of the emitted particles, i.e. Eq. (3), as discussed in Ref. [9]. We also include a veto on the masses of final-state jets, as suggested in Ref. [9], and we adopt the tuned parameter obtained in Ref. [9]. All of the choices for the interpretation of the evolution variable and tunes from Ref. [9] are available using the snippets

EvolutionScheme-*.in Tune-*.in

where * can be DotProduct-Veto, DotProduct, $p_T$ or Q2. This new recoil scheme, together with the veto on the final-state jets, allows a better description of the double-logarithmically enhanced region, without overpopulating the tail of the distributions, as can be seen in Fig. 1 where the thrust distribution at the Z pole is compared to LEP data. The $q^2$-preserving scheme (blue) yields a good description of the tail, while the $p_T$-preserving (red) one performs better in the $T \approx 1$ region, however the dot-product-preserving (red) one performs better in the double-logarithmically enhanced region, without the amplitude and conjugate amplitude vectors at the level of the hard process which is evolved to higher multiplicities using the soft-collinear approximation. They can be enabled using the dipole shower with any of the Matchbox generated processes and the

Matchbox/CMEC.in

snippet.

3 Colour Matrix Element Corrections

General colour matrix element corrections for the dipole shower as presented in [11] and earlier outlined in [12] are now available in the new release. The colour matrix element corrections change the radiation pattern of the dipole shower for subsequent emissions by including a correction factor

$$w_{ij,k} = -\frac{\text{Tr}[T_{ij} \cdot T_k M_n]}{T_{ij} \text{Tr}[M_n]} \quad (4)$$

along with each dipole splitting kernel $V_{ij,k}$, where $M_n$ is the $n$-parton ‘colour density operator’ initialized by

4 Spin Correlations

Herwig7 has always included spin correlations between production and decay of particles, and in both perturbative and non-perturbative decays. We have now completed the inclusion of spin correlations in all stages of the event generation by incorporating the correlations into both the angular-ordered and dipole parton showers. An example of these correlations is shown in Fig. 2 and this work is described in more detail in Ref. [13].
5 Perturbative Decays

The classes implementing perturbative decays, in both the Standard Model and for BSM models, have been restructured. This allows the several previous implementations of hard radiation corrections in these decays, in both the POWHEG and matrix element correction schemes, to be combined and generalised. This now allows us to apply POWHEG-style hard corrections to a much wider range of decays, in particular in BSM models, and also include hard QED radiation. This restructuring also allows these decays, and the POWHEG corrections, to be used with both parton shower modules.

6 Baryonic Colour Reconnection

While the plain Colour Reconnection model [14] is an integral part of the description of general properties of Minimum Bias (MB) data, the description of flavour specific observables remained difficult. With Herwig 7.1.5 we introduced a new Colour Reconnection model that reconnects clusters based on geometrical properties. We also allow multiple mesonic clusters to form a baryonic type cluster if certain requirements are met. This gives an important lever on the baryon to meson ratio and proved to be a good starting point for the description of flavour observables. Additionally we allow non-perturbative $g \to s \bar{s}$ splitting for an additional source of strangeness. With the new model, the whole range of MB data can be described with similarly good quality and the description of hadronic flavour observables improves significantly. An example of the strangeness production is shown in Fig. 3, where we see a greatly improved description of ALICE data with either of the shower models. For more details on the implementation and the details of the model, we refer to [16].

7 BSM Physics

We have made significant improvements to the handling of models in the Universal FeynRules Output (UFO) format. Previously we could only handle vertices that had the perturbative form of the interaction, for example $(p_1 - p_2)^0$ for vector-scalar-scalar interactions, where $p_{1,2}$ are the four momenta of the scalar particles.

We now make use of the sympy package [17] to allow us to write code capable of evaluating the HELAS building blocks for arbitrary Lorentz structures. This allows Herwig to be used to simulate a much wider class of BSM models with, for example, spin $\frac{3}{2}$ particles, colour flows involving $\varepsilon$ tensors and sextet particles, and many four-point interactions now supported. Splitting functions for the production of electromagnetic radiation are now also created by default for BSM particles.

Figure 3. The $K$ to $\pi$ ratio in inelastic events in comparison with ALICE data [15].
The kinematics of the soft model have been modified to use the algorithm described in [21], resulting in a disappearance of the unphysical correlation found in [23]. Related to the kinematics of the soft ladders is the distribution that is used to generate the transverse momenta. Here, we allow switching between different schemes and we found that it is beneficial to produce the hardest parton in the ladder according to the old distribution used in [2] and the rest of the partons flat below this maximal value.

The variable $p_T$ which splits the hard from the soft scatterings was found to give a good description of data at high energies if a power law was used to parametrize the energy dependence. At small centre-of-mass energies ($\lesssim 200$ GeV), this power-law generated values for $p_T^\text{min}$ for which the eikonal model could not be solved. A comprehensive tuning effort showed that a power-law with an offset can be used to describe the data and solve the model at any sensible energy.

A ‘dummy’ matrix element is used to start the production of minimal bias events. In this version, the processes handled by the ME are restricted to extract valence quarks only. The amount of forced splittings in the backward evolution to the incoming beams is therefore strongly reduced.

We have replaced the cross-section reweighter, which was previously used, and modified the matrix element used in minimum bias runs to reweight the cross section, such that the eikonalized cross sections are produced. This has the advantage of generating unit weights at the production level.

Another change that is more on the technical side is the introduction of the parameter that controls the ratio of the diffractive cross-section as part of the inelastic cross-section, named DiffractionRatio. It was previously a combination of the CSNorm parameter and the construction of the matrix element weight. The new parameter allows a more controlled and physically motivated tuning.

It was found that changed starting conditions for the showering of the gluons, in particular the recoil partner and scale choice, are beneficial for the description of charged multiplicities over rapidity. The default choice is the same as used previously in the showering of NLO matched samples and external LHE files. In Fig. 4 we illustrate the effect for the choices that choose the evolution partner randomly (Rand) or according to the maximal angle (Max) and allow the shower starting scale choice to be chosen according to the partner (Partner) or differently (Different).

The combination of all the changes described here required a retuning of the MPI model. Details are outlined in [20].

9 Other Changes

Besides the major physics improvements highlighted in the previous sections, we have also made a number of smaller changes to the code and build system which we will summarize below. Please refer to the online documentation for a fully detailed description or contact the authors.

9.1 SaS Parton Distribution Functions

As version 6 of the LHAPDF [24] package does not contain any parton distributions for the partons inside resolved photons the FORTRAN code and an interface to the Schuler-Sjöstrand [25] parton distribution functions for the photon have been included to allow the simulation of resolved photon processes.

9.2 FxFx

The FxFx merging module was introduced in [1] to provide support of the NLO multi-jet merging method.
of [26], via Les Houches-accord event (LHE) files generated by MadGraph 5/aMC@NLO [27].

In Herwig 7.2 this functionality is available by default, being compiled with the main part of the code. The framework also provides an interface for merging of tree-level events generated either by MadGraph 5/aMC@NLO or AlpGen via the MLM technique [28, 29], replacing all the functionality that first appeared in [6]. The relevant input files for the FxFx merging and tree-level merging are now LHE-FxFx.in and LHE-MGMerging.in respectively. We emphasize that it is essential to include the MC@NLO matching settings for MadGraph 5/aMC@NLO when performing the FxFx merging, as given in LHE-MC@NLO.in. These settings should not be included when merging tree-level events. The tree-level merging functionality via MadGraph 5/aMC@NLO events uses the event tags in the appropriately-generated LHE files and requires the option MergeMode to be set to TreeMG5, as is done by default in LHE-MGMerging.in. To enable merging with events generated via AlpGen, MergeMode should be switched to Tree.

We note that the FxFx functionality has been tested thoroughly only for $W + \text{jets}$ and $Z + \text{jets}$ events in [30], where it was compared against LHC data at 7 and 8 TeV. We also note that no tuning was performed in Herwig using events generated via this interface.

### 9.3 Default PDF

The default parton distribution function has been changed from that of MMHT 2014 [31] to CT14 [32].

### 9.4 Minor improvements and bug fixes

A number of minor changes and bug fixes are worth noting, in particular, there have been new options for the physics simulation besides the ones described in the previous text:

- major updates in the Tests directory to improve both the generation of input files and add new Rivet analyses.
- a number of changes have been made to ensure that the Herwig code compiles with the Intel and Clang compilers. A number of changes have also been made to ensure compilation with recent gcc compilers, including gcc9.
- The deprecated UA5 soft underlying event model has been removed.
- The input files for a number of old tunes have been removed.
- The cut-off for photon radiation from leptons has been reduced to $10^{-6}$ GeV.
- Support for fixed target collisions has been included, together with an example input file.
- The analytic calculation of the partial width for $V \to SS$ decays has been corrected.
- The setting of masses in UFO models where one parameter sets the masses of many particles has been fixed.
- An effective vertex for the processes $h^0 \to Z^0\gamma$ has been added so the $Z^0$ mass is correctly generated in this decay.
- Fix to the MEvv2fs class so that more than one four-point vertex is allowed.
- A missing $t$-channel diagram has been added to the MEvv2fs class.
- Changes to avoid 0/0 have been made in the VVVDecayer class.
- An option to use the internal Standard Model Higgs boson vertices for UFO models which do not implement the full Higgs sector has been added.
- Several bugs in the presence of space-like off-shell incoming legs have been fixed in ThePEG’s StandardXComb and Herwig’s Tree2toNPhasespace classes.
- The option of an asymmetric splitting of the colour flows for the $q \to gg$ branching in the dipole shower has been added.
- Additional kernels are implemented for the $\bar{q}$ shower to incorporate the Catani-Marchesini-Webber (CMW) scheme as part of a linear scheme. By default, the scheme is absorbed in a change of the nominal value of the strong coupling $\alpha_S(M_Z)$. A similar scheme has been available for the dipole shower since Herwig 7.1.
- The dipole shower has been tuned using the method described in [33].

Technical issues which have been addressed include:

- The old ClassTraits mechanism used by ThePEG has been replaced by the new DescribeClass mechanism consistently in all the Herwig code.
- Changes to the templates for dimension-full quantities to improve the maintainability of this code. Regrettably this is incompatible with gcc 4.8 and therefore gcc 4.9 is now the oldest supported version of gcc.
- A number of changes have been made to ensure the bootstrap script works with python3, however a number of our dependencies do not yet support python3 and therefore the code still uses python2.
- The generation of trial values of the scale and light-cone momentum fraction in the angular-ordered parton shower has been restructured to improve performance.
- The calculation of the cross section in Matchbox processes has been restructured to reduce calls to the parton distribution functions, and hence improve performance.
- Changes have been made to improve the detection of recent boost versions at compile time.
- A number of changes have been made to our test suite to include more Rivet analyses and improve the output of the results.

### 9.5 Build and external dependencies

Since version 7.1, Herwig has enforced the use of a C++11 compliant compiler, and C++11 syntax and standard library functionality is used widely within the code. The herwig-bootstrap script is able to provide
such a compiler along with a full Herwig plus dependencies build. herwig-bootstrap will also enforce the newest versions of external amplitude providers; specifically we now use:

- OpenLoops [34] versions $\geq 2.0.0$ with the Collier library [35] for tensor reduction (should older versions of OpenLoops be required, the input files require the additional option set OpenLoops:UseCollier off), and
- GoSam versions $\geq 2.0.4$ to pick up the correct normalization for loop induced processes outside of specialized setups.

A number of changes have also been implemented to reduce run-time load for allocating and de-allocating various containers, and to reduce overall memory consumption.

### 9.6 Licensing

While older versions were licensed under the GNU General Public License GPL version 2, since version 7.1, Herwig has been distributed with the GPL version 3. The MCnet guidelines for the distribution and usage of event generator software in an academic setting apply as before, and both the legally binding GPL license and the MCnet guidelines are distributed with the code.

### 10 Example Results

Herwig 7.2 has been thoroughly validated against a wide range of existing data, as implemented in the Rivet and FastJet frameworks [36, 37]. Parameter tuning has been performed using Professor [38].

Here, we illustrate some examples of the fact that we can simulate LHC events with any combination of LO or NLO matrix elements, matched with the angular-ordered or dipole showers using either additive (MC@NLO-like) or multiplicative (POWHEG-like) methods, as well as multi-jet merging, for Z boson production. In Fig. 5, we show the results in comparison with ATLAS data [39]. The upper plot shows that, as would be hoped, merging with multi-jet matrix elements enables a good description of the data over a wide range of jet multiplicities. The lower plot shows that even for more inclusive quantities, such as the total scalar sum of final state transverse momentum, $H_T$, (lower) in comparison with ATLAS data [39].

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### 11 Summary and Outlook

We have described a new release, version 7.2, of the Herwig event generator. This new release contains a number of improvements to both perturbative and non-perturbative simulation of collider physics and will form the basis of further improvements to both physics and technical aspects.
References

1. J. Bellm et al., Herwig 7.0/Herwig++ 3.0 release note, Eur. Phys. J. C76 (2016) 196, [1512.01178].
2. M. Bähr et al., Herwig++ Physics and Manual, Eur. Phys. J. C55 (2008) 639–707, [0803.0883].
3. M. Bähr et al., Herwig++ 2.2 Release Note, 0804.3053.
4. M. Bähr et al., Herwig++ 2.3 Release Note, 0812.0529.
5. S. Gieseke et al., Herwig ++ 2.5 Release Note, 1205.9402.
6. K. Arnold et al., Herwig++ 2.6 Release Note, 1310.6877.
7. J. Bellm et al., Herwig++ 2.7 Release Note, 1604.06792.
8. J. Bellm et al., Herwig 7.1 Release Note, 1705.06919.
9. G. Bewick, S. Ferrario Ravasio, P. Richardson and M. H. Seymour, Logarithmic Accuracy of Angular-Ordered Parton Showers, 1904.11866.
10. DELPHI collaboration, P. Abreu et al., Tuning and test of fragmentation models based on identified particles and precision event shape data, Z. Phys. C73 (1996) 11–60.
11. S. Plätzer, M. Sjödahl and J. Thorén, Color matrix element corrections for parton showers, JHEP 11 (2018) 009, [1808.00332].
12. S. Plätzer and M. Sjödahl, Subleading Nc improved Parton Showers, JHEP 07 (2012) 042, [1201.0260].
13. P. Richardson and S. Webster, Spin Correlations in Parton Shower Simulations, 1807.01955.
14. S. Gieseke, C. Rühr and A. Siödmok, Colour reconnections in Herwig++, Eur. Phys. J. C72 (2013) 2803–2819, [1204.0885].
15. ALICE collaboration, J. Adam et al., Measurement of pion, kaon and proton-proton production in proton-proton collisions at √s = 7 TeV, Eur. Phys. J. C75 (2015) 226, [1504.00024].
16. S. Gieseke, P. Kirchgaefler and S. Plätzer, Baryon production from cluster hadronisation, Eur. Phys. J. C78 (2018) 99, [1710.10906].
17. A. Meurer et al., Sympy: symbolic computing in python, PeerJ Computer Science 3 (Jan., 2017) e103.
18. ATLAS collaboration, G. Aad et al., Charged-particle multiplicities in pp collisions measured with the ATLAS detector at the LHC, New J. Phys. 13 (2011) 053032, [1202.5104].
19. J. Bellm, C. B. Duncan, S. Gieseke, M. Myska and A. Siödmok, Spacetime Colour Reconnection in Herwig 7, accepted for publication in Eur. Phys. J. C (2019), [1909.08850].
20. J. Bellm, S. Gieseke and P. Kirchgaefler, Improving the description of multiple interactions in Herwig, 1911.13149.
21. S. Jadach, Rapidity generator for Monte-Carlo calculations of cylindrical phase space, Comput. Phys. Commun. 9 (1975) 297–304.
22. M. Baker and K. A. Ter-Martirosian, Gribov’s Reggeon Calculus: Its Physical Basis and Implications, Phys. Rept. 28 (1976) 1–143.
23. M. Azarkin, P. Kotko, A. Siödmok and M. Strikman, Studying minijets and MPI with rapidity correlations, Eur. Phys. J. C79 (2019) 180, [1806.09016].
24. A. Buckley et al., LHAPDF6: parton density access in the LHC precision era, Eur. Phys. J. C75 (2015) 132, [1412.7420].
25. G. A. Schuler and T. Sjöstrand, Parton distributions of the virtual photon, Phys. Lett. B376 (1996) 193–200, [hep-ph/9601282].
26. R. Frederix and S. Frixione, Merging meets matching in MC@NLO, JHEP 12 (2012) 061, [1209.6215].
27. J. Alwall et al., The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations, JHEP 07 (2014) 079, [1405.0301].
28. M. L. Mangano, M. Moretti, F. Piccinini, R. Pittau and A. D. Polosa, ALPGEN, a generator for hard multiparton processes in hadronic collisions, JHEP 0307 (2003) 001, [hep-ph/0206293].
29. M. Mangano, Merging multi-jet matrix elements and shower evolution in hadronic collisions, http://mml.web.cern.ch/mml/talks/land-alpgen.pdf (2004).
30. R. Frederix, S. Frixione, A. Papaefstathiou, S. Prestel and P. Torrielli, A study of multi-jet production in association with an electroweak vector boson, 1511.00847.
31. L. A. Harland-Lang, A. D. Martin, P. Motylinski and R. S. Thorne, Parton distributions in the LHC era: MMHT 2014 PDFs, Eur. Phys. J. C75 (2015) 204, [1412.3988].
32. S. Dulat et al., The CT14 Global Analysis of Quantum Chromodynamics, 1506.07443.
33. J. Bellm and L. Gellersen, High dimensional parameter tuning for event generators, 1908.10811.
34. F. Cascioli, P. Maihöfer and S. Pozzorini, Scattering Amplitudes with Open Loops, Phys. Rev. Lett. 108 (2012) 111601, [1111.5206].
35. A. Denner, S. Dittmaier and L. Hofer, Collier: a fortran-based Complex One-Loop Library in Extended Regularizations, Comput. Phys. Commun. 212 (2017) 220–238, [1604.06792].
36. A. Buckley et al., Rivet user manual, Comput. Phys. Commun. 184 (2013) 2803–2819, [1003.0694].
37. M. Cacciari, G. P. Salam and G. Soyez, FastJet User Manual, Eur. Phys. J. C72 (2012) 1896, [1111.6097].
38. A. Buckley, H. Hoeth, H. Lackner, H. Schulz and J. E. von Seggern, Systematic event generator tuning for the LHC, Eur. Phys. J. C65 (2010) 331–357, [0907.2973].
39. ATLAS collaboration, M. Aaboud et al., Measurements of the production cross section of a Z boson in association with jets in pp collisions at √s = 13 TeV with the ATLAS detector, Eur. Phys. J. C77 (2017) 301, [1702.05726].