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Herwig 7.2 Release Note

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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, Herwig7 [1], is based on a major development of the Herwig++ [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 [1] and 7.1 [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 [2], the Herwig 7.0 [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 `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 `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 `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 [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:

$$\begin{aligned}\tilde{q}^2 &= \frac{q_i^2 - m_i^2}{z(1-z)}; &(1)\\ &= \frac{p_T^2 + (1-z)m_j^2 + zm_k^2 - z(1-z)m_i^2}{z^2(1-z)^2}; &(2)\\ &= \frac{2q_j \cdot q_k + m_j^2 + m_k^2 - m_i^2}{z(1-z)}; &(3)\end{aligned}$$

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`, `pT` 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 scheme, together with the veto (green), gives the best agreement with data over the whole range.

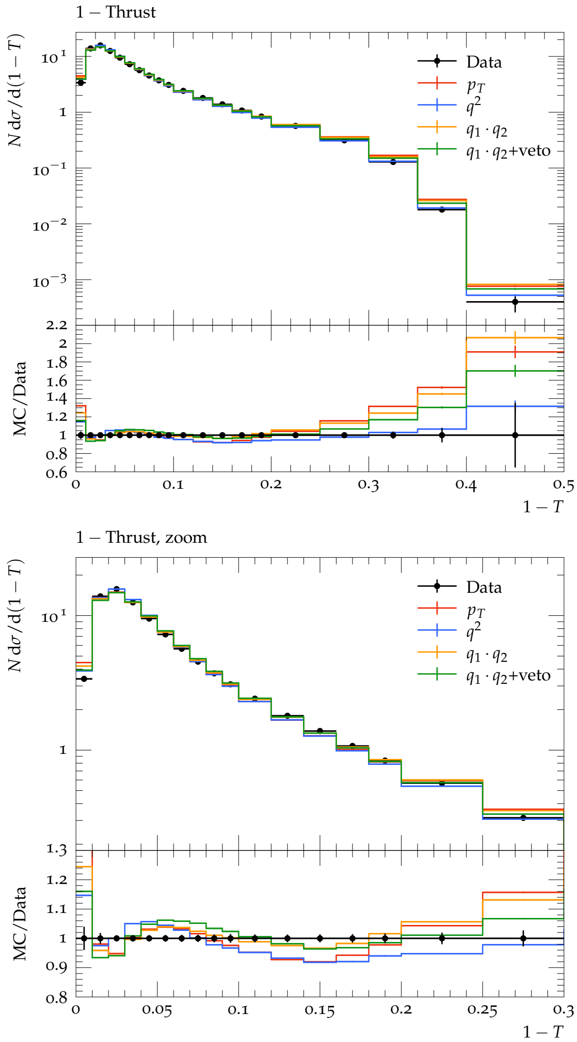

Figure 1. The thrust at the Z-pole compared with data from the DELPHI [10] experiment. In the right panel a zoom for small $1-T$ values is shown.

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

$$w_{ij,k} = -\frac{\mathrm{Tr}[\mathbf{T}_{ij} \cdot \mathbf{T}_k\ \mathbf{M}_n]}{\mathbf{T}_{ij}^2 \mathrm{Tr}[\mathbf{M}_n]} \tag{4}$$

along with each dipole splitting kernel $V_{ij,k}$, where $\mathbf{M}_n$ is the n-parton 'colour density operator' initialized by 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.

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].

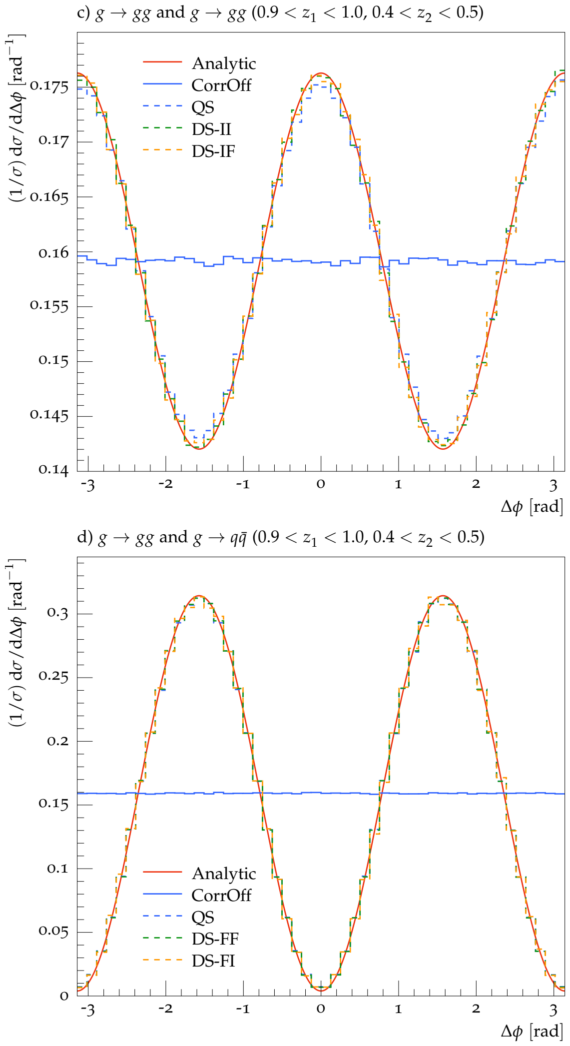

Figure 2. Examples of the spin correlations in the parton shower for $g \to gg$ with subsequent $g \to gg$ and $g \to q\bar{q}$ branching. For details, see Ref. [13].

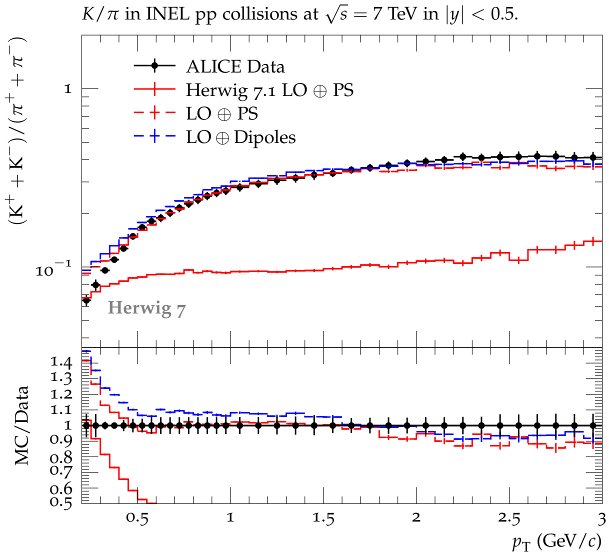

Figure 3. The K to π ratio in inelastic events in comparison with ALICE data [15].

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 $(p_1 - p_2)^\mu$ 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 ε 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.

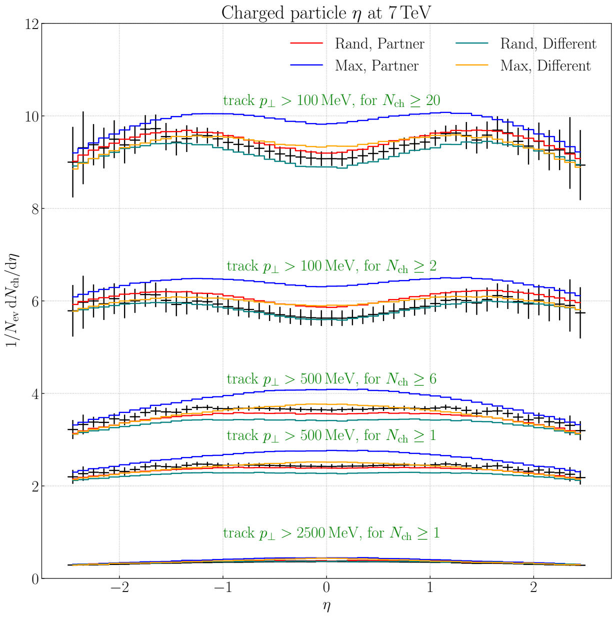

Figure 4. The charged-particle multiplicity is plotted against the rapidity for multiple cuts (green labels) on the hardest track transverse momentum and number of charged particles. Data is taken from [18]. This observable is sensitive to the choices that are employed as the starting conditions of the parton shower process. The four choices are described in Sec. 8. While height differences are easily modified in the tuning process, shape differences prefer choices with a random colour partner for gluons in the hard process.

8 Modifications to multi parton interactions

While the space-time picture [19] is not included in the release various changes have been made to the handling of multiple parton interactions. The changes made are described in detail in [20]. Here, we give a summary of the findings and the implications for the newly released version.

The kinematics of the soft model have been modified to use the algorithm described in [21][1], 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 $p_\perp^{\min}$ 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 $p_\perp^{\min}$ 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

[1] The previous version of Herwig made use of algorithms described in [22].

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-MCatNLO.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 + jets and Z + 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 MEvv2vs class so that more than one four-point vertex is allowed.
- A missing t-channel diagram has geen added to the MEfv2fs 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 asymetric splitting of the colour flows for the $g \to gg$ branching in the dipole shower has been added.
- Additional kernels are implemented for the $\tilde{q}$ 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 mupliticities. The lower plot shows that even for more inclusive quantities, such as the total scalar transverse momentum, the multijet effects are important.

A wide range of further plots can be found at https://herwig.hepforge.org/plots/herwig7.2.

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.

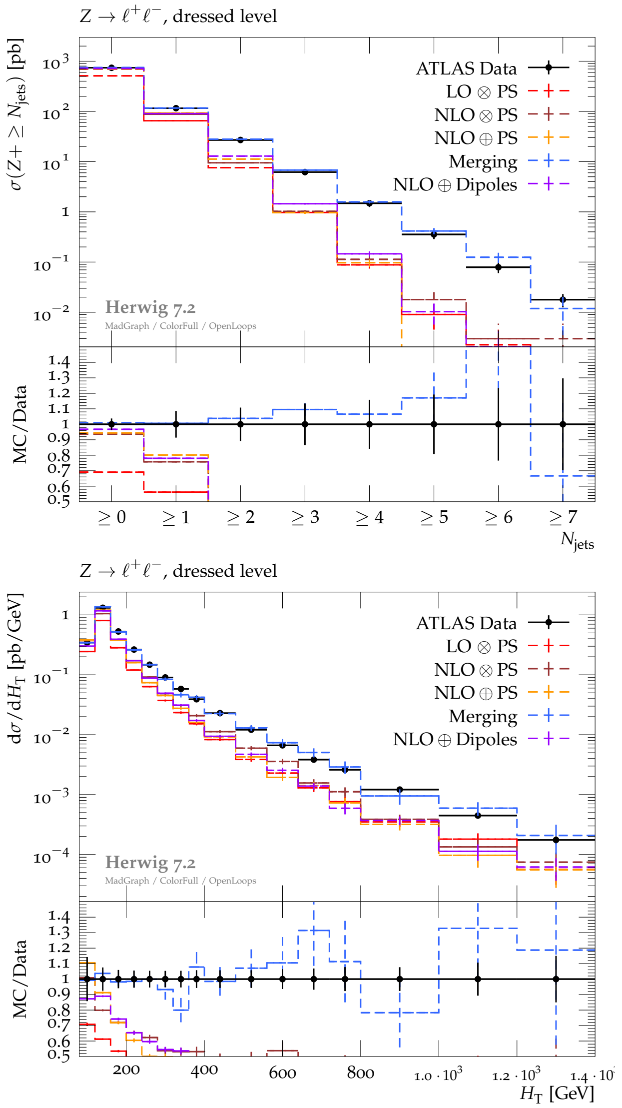

Figure 5. The cross section for Z production in association with N_{jets} jets (upper) or differentially with respect to the total scalar sum of final state transverse momenta, H_T, (lower) in comparison with ATLAS data [39].

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