Status of Herwig 7 and Heavy Flavours

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The Herwig family is one of three multipurpose event generators.

Herwig++ has seen a ten-year development to meet a milestone intended to succeed the FORTRAN HERWIG program.

This milestone evolved over time as the experimental and phenomenological needs did.

On top of its first definition (= at least as good as HERWIG), precision has become the key goal.

Herwig++ 3.0 → Herwig 7.0

[Herwig collaboration – EPJ C76 (2016) 665]
Introducing Herwig 7

**NLO matched to parton showers as default** for the hard process.

- Fully automated, only linking external codes to calculate amplitudes.
- Run in a single program, no event files to move around.
- Subtractive (MC@NLO-type) and multiplicative (POWHEG-type) matching.

**NLO multijet merging** with the dipole shower.

**Two showers:** Angular-ordered and dipole shower.

Facilities for **parton shower variations and reweighting.**

Many more things, visit [https://herwig.hepforge.org](https://herwig.hepforge.org)

A collaborative effort:

Johannes Bellm, Stefan Gieseke, David Grellscheid, Patrick Kirchgæßer, Frasher Loshaj, Graeme Nail, Andreas Papaefstathiou, Simon Plätzer, Radek Podskubka, Michael Rauch, Christian Reuschle, Peter Richardson, Peter Schichtel, Michael H. Seymour, Andrzej Siódmok and Stephen Webster
Fast cutoff of the resummation is crucial to produce 'controllable' uncertainties:

Need to reflect reliability of showering and to preserve relevant hard process properties.

Comparable between the two shower algorithms.
Shower reweighting

On-the fly shower reweighting available for both shower's scale variations.

Fills HepMC multi-weight vectors, dedicated validation and performance studied.

Weighted version of the “Sudakov veto algorithm” allowing for an unprecedented shower flexibility.

\[ S_R = \Delta_R(\mu|Q)\delta(q - \mu) + R(q)\Delta_R(q|Q)\theta(\mu < q < Q) \]

\[ w_{\text{veto}} = \frac{1 - \frac{P}{R}}{1 - \epsilon} \]

\[ w_{\text{accept}} = \frac{P}{\epsilon R} \]

More applications to follow, can also deal with negative “probabilities”.

[Bellm, Plätzer, Richardson, Siodmok, Webster – PRD 94 (2016) 034028]
Under the hood

Use run-time interfaces to external codes to evaluate amplitudes. Automatically build up fixed-order or matched NLO cross sections.

Output: HepMC, Rivet, built-in analyses.
Operating Herwig 7

read snippets/PPCollider.in

set Factory:OrderInAlphaS 1
set Factory:OrderInAlphaEW 2
do Factory:Process p p -> e+ e- j

read Matchbox/MadGraph-OpenLoops.in

read Matchbox/MCatNLO-DefaultShower.in

← Choose collider setup.
← Choose process.
← Choose amplitude providers.
← Choose shower and matching.
NLO merging in Herwig 7.1

NLO multijet merging with the dipole shower, inspired by “unitary” merging algorithms.

→ No strict unitarization, only cancel log-enhanced contributions
→ Catching cross section changes due to finite real emission contributions
→ Standard NLO matching below merging scale
Recent development & phenomenology applications

Current focus on (theory) development and extensive phenomenology.

- Spin correlations in the dipole shower
- Mass effects in the dipole shower
- Matching systematics in top pair production
- Colour matrix element corrections
- Colour reconnection & rearrangement
- Loop induced processes, mixed expansions
- VBF and VBS processes
- New tuning efforts, string hadronization interface
- Dipole shower off-shell/smeared tops handling
- Top quark mass interpretation

Next release: Herwig 7.2

- Timeline/content currently under discussion, manual in progress
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Revised treatment of massive quark evolution in dipole shower, and evolution of decay systems. Matching now available for production and decays, and angular ordered and dipole shower.

Use the pt relevant to quasi-collinear limit, with smooth massless limit.

Significant improvement to b-quark fragmentation function.

\[
\begin{align*}
q_i &= z q_{ij} + \frac{w \cdot s_{ijk} + m_i^2 - z^2 m_{ij}^2}{2 q_{ij} \cdot n_k} n_k + \sqrt{w} n_{\perp}, \\
q_j &= (1 - z) q_{ij} + \frac{w \cdot s_{ijk} + m_j^2 - (1 - z)^2 m_{ij}^2}{2 q_{ij} \cdot n_k (1 - z)} n_k - \sqrt{w} n_{\perp}.
\end{align*}
\]
Spin correlations & gluon branchings

Spin correlations are now available for both showers:

→ Top decays
→ Shower branchings in general

Gluon to b branching performs well on ATLAS data:

Study NLO matching in detail using Herwig shower modules and Matchbox.
Top ‘particle’ interpretation does not apply, always accompanied by gluon cloud.

Top mass is a scheme dependent parameter in perturbative calculations, scheme of parton showers is unclear, even in presence of NLO matching.

Relate to pole mass, for definiteness:

\[ m_t^{\text{MC}} = m_t^{\text{pole}} + \Delta_m^{\text{pert}} + \Delta_m^{\text{non-pert}} + \Delta_m^{\text{MC}} \]

Perturbative shift: Scheme definition

Hadronization contributions

Modeling uncertainties

Effect of parton shower cutoff \( Q_0 \) crucial to identify contributions.
Consider **two-jetiness in e+e- as a benchmark**: EFT calculation, direct QCD analysis (coherent branching), and actual event generator (Herwig 7) at hand.

Boosted regime for quasi-collinear shower approximation to be valid, observable insensitive to decay details. No finite lifetime effects (yet).

Effective theory and direct QCD calculation agree on cutoff-dependent shift of peak, massless calculation identifies large-angle soft contribution compensated by hadronization and ultracollinear radiation affecting the mass scheme.

**Parton shower unitarity** transfers IR cutoff effect to effectively change pole of heavy quark propagator.

\[
m_t^{\text{CB}}(Q_0) = m_t^{\text{pole}} - \frac{2}{3} Q_0 \, \alpha_s(Q_0) + \mathcal{O}(\alpha_s^2)
\]

Recover the pole mass in absence of a cutoff.
Comparison to Herwig 7 AO Shower

Massless and massive coherent branching calculation and **Herwig 7 angular ordered** shower in full agreement in the log-enhanced peak region, NLL accurate.

Cutoff shifts peak in absence of compensating change in hadronization.

Similar observations in endpoint of lepton/b-jet mass observed. **Detailed analysis of hadronization effects now underway.**
**Colour reconnection & soft modelling**

**Improvements to soft MPI, including soft diffraction.**

Significant development on colour reconnection and baryon production, theoretical progress and links to soft gluon evolution.

**Kinematic dependence of strange production.**

[Gieseke, Kirchgässer, Loshaj – EPJ C77 (2017) 156]

[Duncan, Kirchgässer – EPJ C79 (2019) 61]
Thank you!
Complex processes require more fine-grained workflow and parallelization.

Can use as 'old' Herwig++ but also much more flexible:

Build of event generator separated from grid adaption and running
   → Cheaper parameter variations to just apply to event generation

Grid adaption parallelized in separate jobs (no IPC required):
   → Herwig build --maxjobs=6 LHC-Matchbox.in
   → Herwig integrate --jobid=3 LHC-Matchbox.run ...

Multicore capabilities for event generation:
   → Herwig run -N 24000000 --jobs=24 LHC-Matchbox.run