Recent Developments in H7

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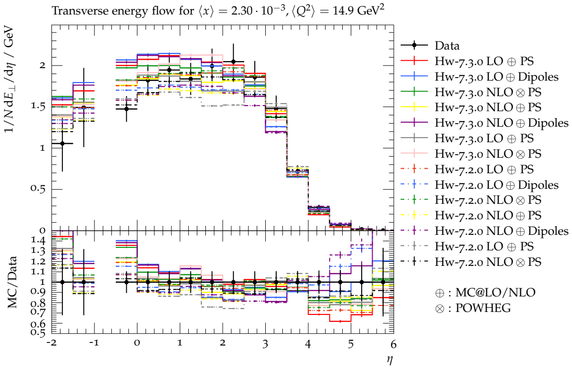
On behalf of the Herwig Collaboration

Herwig 7 Overview

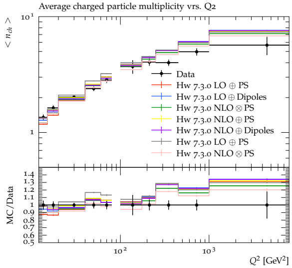
(1992-2013) (2003-2014) (2015-present)

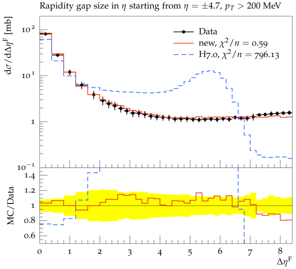
- LO and NLO ME, internally or through Matchbox
- MC@NLO and POWHEG Matchings
- QTilde and Dipole shower modules
- QCD jet-merging with Dipole
- QCD jet-merging with QTilde through FxFX plus EW matching (work in progress)
- Cluster and String hadronisation models
- Applications in DIS, photo-production and heavy ion collisions



DIS, Photoproduction and Diffraction in Herwig 7

- Key focus on the precision of DIS measurements [D'Errico1, Richardson, '12]
  - LO neutral- and charged-current DIS process
  - Jet Merging in DIS with Matchbox
  - NLO DIS will be addressed
- Photoproduction [Helenius, Meinzinger, Plätzer, Richardson, '24]
  - Direct and resolved photoproduction (limited)
  - Diffractive photoproduction needs to be developed
  - Photoproduction with Matchbox needs to be developed
  - Challenges with NLO ME, MPI and photon PDFs
- Diffractive jets in Herwig [Gieseke, Loshaj, Kirchgaeber, '17]
  - Both diffractive jets and soft diffractive events via DIS
  - Based on cluster model and soft MPI
  - Tuned with minimum-bias measurements
- Improvements needed for accurate simulation
  - Modelling hadronization and parton showers
  - Incorporating higher-order corrections
  - Addressing soft QCD and EW effects
- Key parameters and tuning for specific EIC applications



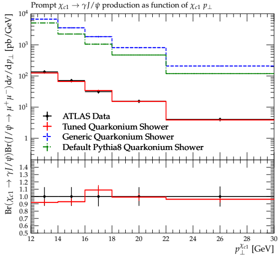


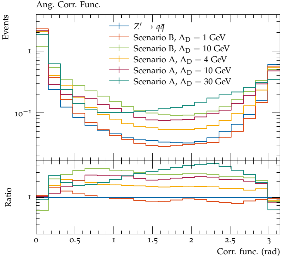
Herwig 7 News

- The current version (Herwig-7.3.0):
  - EW shower
  - HQET in hadronisation and decay
  - Dot-preserving scheme for PS evolution scale
  - Dynamic approach to cluster splitting
  - Globally tuned with a new strategy

- The new version (Herwig-7.4) is being finalised:
  - Generalized angular-ordered PS; BSM parton showers
  - Quarkonium production in AO shower
  - Coherence general tune
  - Implementation of the HV Model; Dark parton showers
  - New dynamic cluster hadronisation approach
  - New colour-reconnection for baryonic sector

- Future developments (Herwig-7.5):
  - Implementation of a NLL Dipole shower
  - Improved coherence evolution for AO parton shower
  - Improved photoproduction in Herwig 7
  - Automated BSM UFO ME Integration in Matchbox
  - Further improvements in Hadronisation

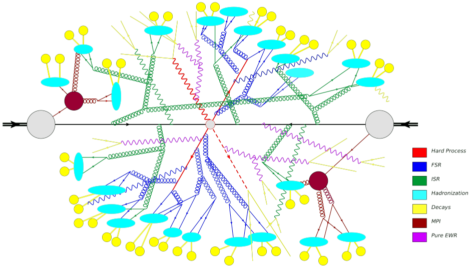


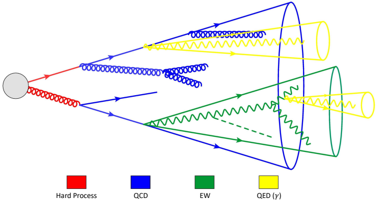


Angular-Ordered Parton Shower

Pros:

- Respects QCD coherence via angular ordering.
- Soft gluon emissions are properly resummed.
- Built-in `LL+NLL` accuracy.
- EW interactions can be interleaved with QCD.
- Control over colour flow and spin correlations.
- Naturally suppresses wide-angle emissions (empty dead zone).
- Matching with `MC@NLO` and `POWHEG`.
- Modularity and intuitive UI.





Cons:

- More complex kinematics reconstruction.
- Interfacing with dipole-based ME corrections.
- Handling NNLL effects is non-trivial.

Many recent developments in the AO PS of Herwig 7.

EW Parton Shower

Motivation:

- At TeV scales, EW corrections can become large as Sudakov logarithms $\sim \alpha \log^2(Q^2/M_W^2)$.
- Precise predictions for HE-LHC and FCC require consistent inclusion of EW radiation in event generators.

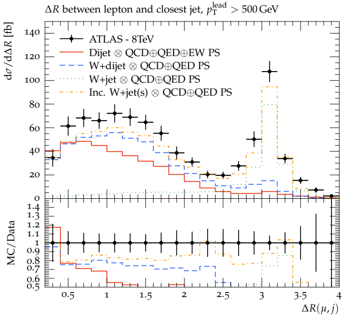
EW PS in Herwig 7:

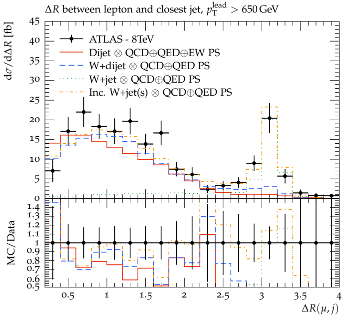
- Fully automated **EW shower** for ISR/FSR: emission of $W^\pm/Z^0/\gamma/H$ bosons. [AM, Richardson, '22]
- Incorporates **spin correlations** and helicity structure.
- Coherent with QCD shower and preserves AO.

[AM, Seymour, Sule, to appear soon]

Impact:

- BSM searches and precision observables.
- Realistic simulation of weak boson emissions, EW jets, and boosted topologies. [Darvishi, AM, '22]





BSM Parton Shower

Motivation:

– Realistic event generation requires consistent parton-shower evolution for non-SM radiation patterns.

Generalised PS in Herwig 7: [Lee, AM, Seymour, Yang, '23]

– Imports BSM sector directly from the `UFO`.

– CP-odd/event couplings and FCNC splittings.

– Intuitive UI, compatible with the existing `UFO` libraries.

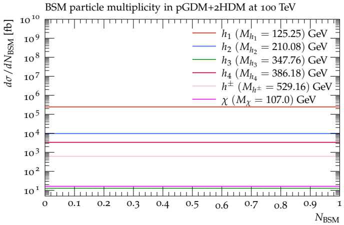
Impact:

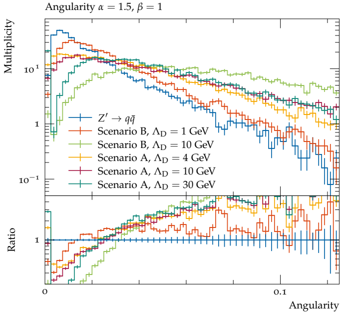
– Allows for the study of BSM sectors, less accessible though explicit production scenarios.

[Buckley, Cazzaniga, De Cosa, Huang, Kar, Kulkarni, AM, Plätzer, Sinha, Stafford, in progress]

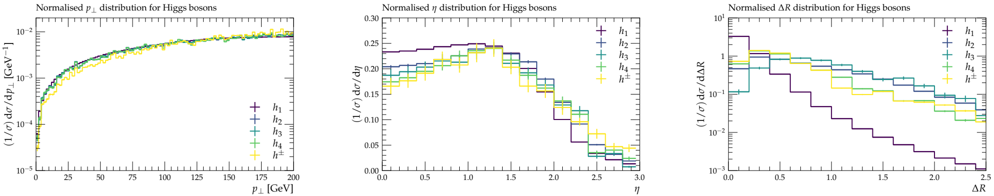
– Accurate simulation of exotic sectors and BSM signatures.

[Darvishi, AM, Seymour, Sule, in progress]



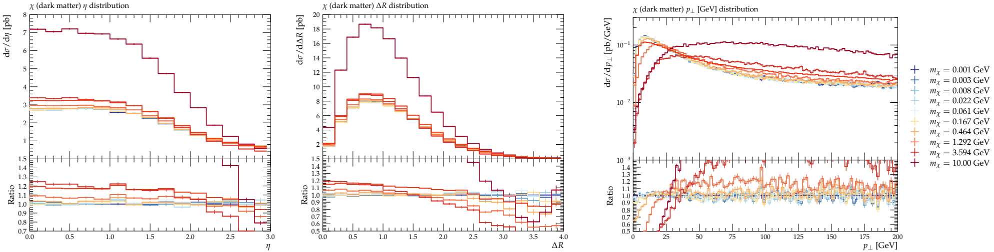


BSM Parton Shower Phenomenology



Normalised signature of 2HDM+CS Higgs sector

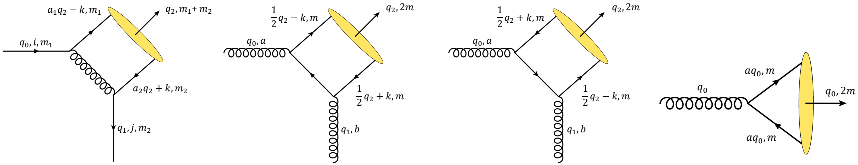
[Darvishi, Grzadkowski, ’22]



DM signature for different DM masses

[Darvishi, AM, Seymour, Sule, in progress]

Quarkonium Parton Shower



Motivation:

- Heavy quarkonia (J/ψ, Υ, B_c, χ_Q) are key probes of QCD and hadronisation.
- Their production spans non-trivial scales: hard scattering, parton shower, and non-perturbative bound-state formation.
- NRQCD factorisation predicts **colour-singlet** (CS) and **colour-octet** (CO) mechanisms.

Why a dedicated PS? [AM, Richardson, to appear soon]

- Standard showers treat quarkonia as point-like particles.
- Quarkonium-specific emissions (${}^1P_1$, ${}^3P_J$, ${}^1D_2$, ...) require matrix-element level control.
- Octet transitions must be modelled as $g \to \mathcal{O}^{(8)}$, respecting NRQCD long-distance dynamics.

Relevance:

- Accurate p_T spectra, polarisation predictions, and feed-down chains.
- Essential for heavy-flavour jets, exotic decay chains, and BSM signatures involving quarkonia.

Shower Implementation

30 quarkonium splitting classes:

- 5 CS $g \to g\mathcal{O}$ classes ($^1S_0$, $^3S_1$ and $^3P_{0,1,2}$)

  `GtoG1S0SplitFn`, `GtoG3S1SplitFn`, `GtoG3P0SplitFn`, `GtoG3P1SplitFn`, `GtoG3P2SplitFn`

- 8 generic CS $q \to q'\mathcal{O}$ classes ($^1S_0$, $^3S_1$, $^3P_{0,1,2}$ and $^3D_{1,2,3}$)

  `QtoQP1S0SplitFn`, `QtoQP3S1SplitFn`, `QtoQP3P0SplitFn`, `QtoQP3P1SplitFn`, `QtoQP3P2SplitFn`, `QtoQP3D1SplitFn`, `QtoQP3D2SplitFn` `QtoQP3D3SplitFn`,

- 10 same-flavour CS $q \to q\mathcal{O}$ classes ($^1S_0$, $^1P_1$, $^2D_1$, $^3S_1$, $^3P_{0,1,2}$, and $^3D_{1,2,3}$)

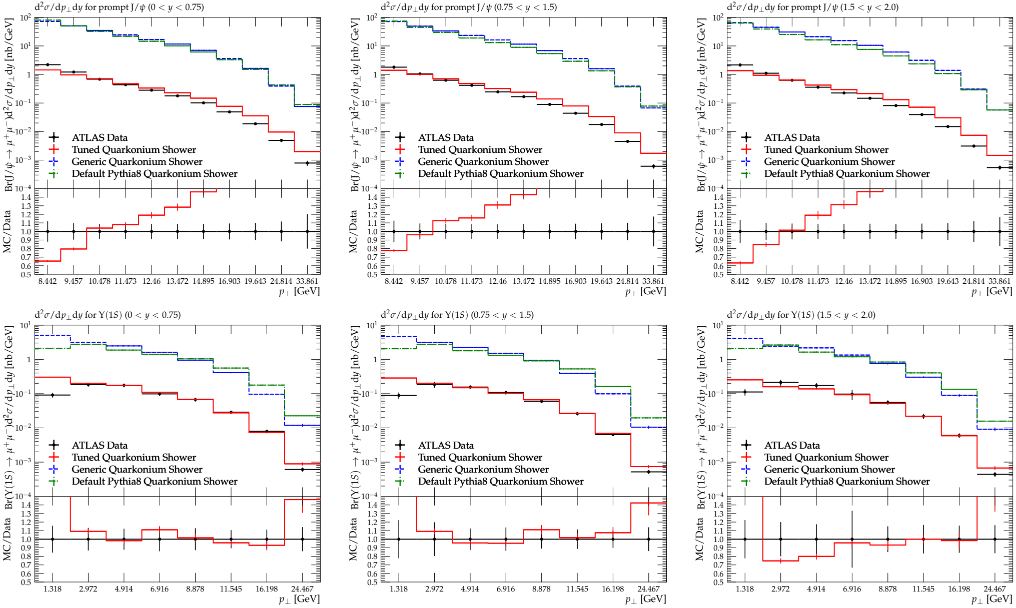
  `QtoQ1S0SplitFn`, `QtoQ1P1SplitFn`, `QtoQ3S1SplitFn`, `QtoQ3P0SplitFn`, `QtoQ3P1SplitFn`, `QtoQ3P2SplitFn`, `QtoQ1D2SplitFn`, `QtoQ3D1SplitFn`, `QtoQ3D2SplitFn`, `QtoQ3D3SplitFn`

- 3 diquark splitting classes ($^1S_0$: $q \to \bar{q} + (qq)_1$, $q \to \bar{q}' + (qq')_0$ and $q \to \bar{q}' + (qq')_1$)

  `QtoQPBarQQP0SplitFn`, `QtoQBarQQ1SplitFn`, `QtoQPBarQQP1SplitFn`

- 4 CO $g \to (\bar{q}q)$ splitting classes ($^3S_1$ and $^3P_{0,1,2}$)

  `Gto3S1OctetSplitFn`, `Gto3P0OctetSplitFn`, `Gto3P1OctetSplitFn`, `Gto3P2OctetSplitFn`



Prompt production of J/ψ and Υ states. [AM, Richardson, to appear soon]

Angular-Ordered Dark Showers in Herwig 7

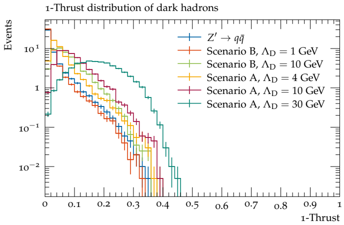
- Hidden Valley models predict dark showers with distinct jet-like signatures.
- First implementation of dark-sector showers using the angular-ordered approach.
- Handles an SU(N_C) dark sectors with $2 \leq N_f \leq 9$.
- Flexible dark cluster hadronisation.

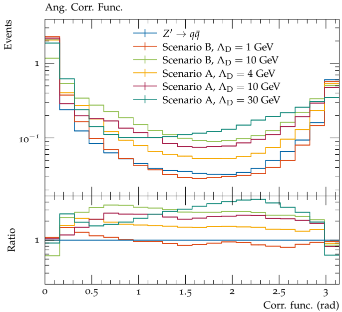
Phenomenology:

- Benchmarks with $1 \leq \Lambda_D \leq 30$ GeV.
- Variables: thrust, angularities, energy correlations $\rightarrow$ probe dark radiation patterns.
- Demonstrated sensitivity to hadronisation and shower parameter variations.

Impact:

- Provides an independent cross-check of dark shower phenomenology.
- Lays groundwork for systematic uncertainty assessment in dark sector searches.





[Kulkarni, AM, Plätzer, Stafford, '24]

A New Cluster Hadronisation Model

- Traditional cluster models rely on ad-hoc kinematic choices; correlations are poorly described.
- Infrared colour evolution motivates viewing cluster fission as a continuation of perturbative dynamics. [Plätzer '22]

New Cluster Model Developments:

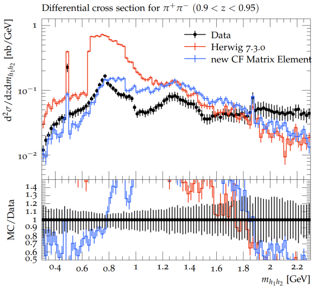
- Re-interprets cluster fission as a *partonic 2 $\rightarrow$ 4 process* with factorised kinematics.
- ME-inspired sampling for cluster masses and decay angles.
- Clear separation between perturbative cluster fission (CF) and non-perturbative cluster decay (CD).

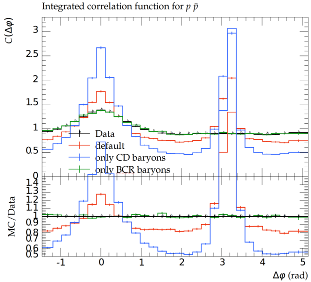
Phenomenology:

- Baryon–antibaryon angular correlations and di-hadron mass spectra match LEP and Belle data.
- New decay kinematics improves description of p_T in/out distributions and angularities.

Impact:

- Better theoretical control of hadronisation uncertainties.
- Basis for future dynamic Colour Reconnection models.





[Kiebacher, Gieseke, Plätzer, '24]

Summary

- Significant extensions of the **angular-ordered parton shower framework**:
  - BSM and dark-sector radiation patterns.
  - Quarkonium parton shower.
  - Improved coherence and colour structure.
- First implementation of **dark showers and hadronisation** in an angular-ordered framework.
- New **cluster hadronisation model:** physically motivated fission and improved baryon correlations.
- Ongoing validation and tuning for precision phenomenology.
- These upgrades extend Herwig's reach across BSM, dark sector, and QCD phenomenology.
- All developments presented here will be available in the public release of Herwig-7.4.0, **hopefully very soon.**
- Dedicated improvements for DIS and photoproduction processes are planned for Herwig-7.5.0.

For more details, please visit:
herwig.hepforge.org

Thank You!