Recent Developments in

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On behalf of the Herwig Collaboration

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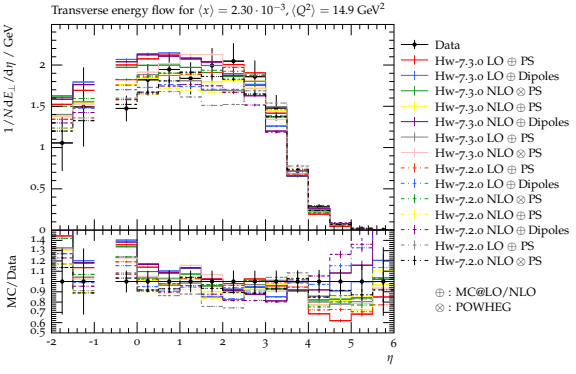
IP3

Herwig 7 Overview

HERWIG → **Herwig++** → **Herwig7**

(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

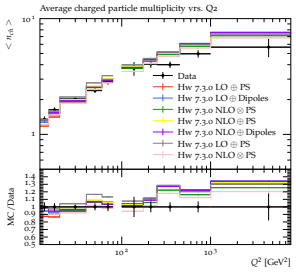


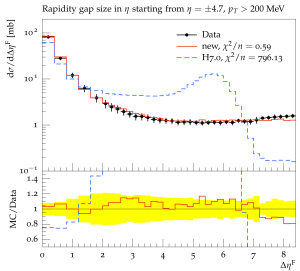
DIS, Photoproduction and Diffraction in Herwig 7

- Key focus on the precision of DIS measurements

  [D'Errico1, Richardson, EPJC (2012) 72:2042]

  - LO neutral- and charged-current DIS process
  - Jet Merging in DIS with Matchbox
  - NLO DIS will be addressed
- Photoproduction through Internal ME
  - 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, EPJC 77 (2017) 3, 156]
  - 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

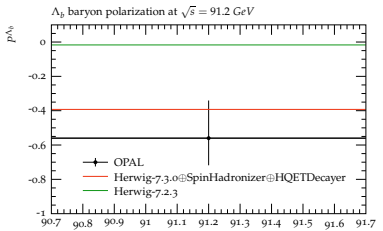


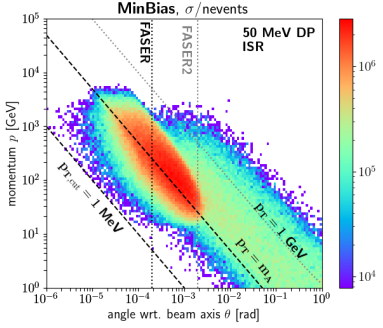


Herwig 7 News

- Recent developments (Hw-7.3.0):
  - EW shower
  - HQET in hadronisation and decay
  - Dot-preserving scheme for PS evolution scale
  - Separation of ISR and FSR phase-spaces
  - Dynamic approach to cluster splitting
  - Tuning efforts and strategies

- On-going developments (Hw-7.4.0):
  - Generalized angular-ordered PS; BSM showers
  - Quarkonium production in AO shower
  - Implementation of a NLL Dipole shower
  - Coherence interleaving of interactions
  - Implementation of the Hidden Valley Model
  - New dynamic cluster hadronisation approach
  - New colour-reconnection for baryonic sector
  - Dark photon production though EW shower





EW Parton Shower

- One of the key components of all multi-purpose event generators → process-independent parton shower.
- The current meta for parton showers is the *QCD plus QED* schemes → satisfactory results for now.
- At higher energies, EW bosons will start behaving as massless partons.
- Such an expectation is supported by the LHC observations.

[1507.04548, 1807.08639]

- The corresponding EW virtual corrections are large and have negative signs.

[hep-ph/0005316]

- This justifies making an effort to introduce a process-independent EW PS and upgrade the PS picture to a *QCD plus QED plus EW* scheme.
- A few attempts have been made:

[hep-ph/0206293, 1305.6837, 1401.5238, 1403.4788, 2002.09248, 2108.10786]

Generic Helicity-Dependent Splitting Functions

- Quark splittings (IS and FS)

$$q \to q' W^{\pm}, \quad q \to q Z^0, \quad q \to q H$$

- Gauge boson splittings (FS only)

$$W^{\pm} \to W^{\pm} Z^0, \quad W^{\pm} \to W^{\pm} \gamma,$$

$$Z^0 \to W^+ W^-, \quad \gamma \to W^+ W^-,$$

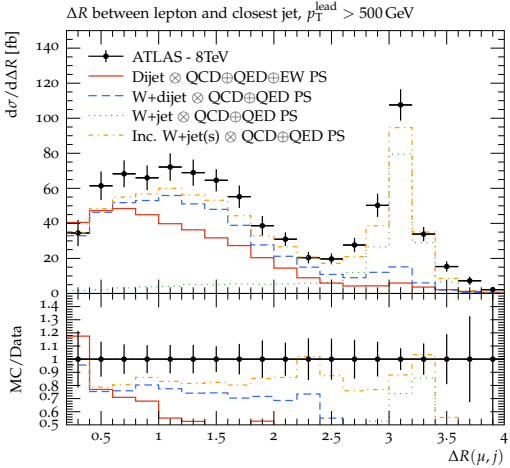
$$W^{\pm} \to W^{\pm} H, \quad Z^0 \to Z^0 H$$

- Calculation of helicity-dependent splitting functions in the quasi-collinear limit
- Comprehensive performance and physics tests

[Richardson, AM, JHEP 04 (2022) 112]

- Started to look at the phenomenology of EW radiations

[Darvishi, AM, Nucl.Phys.B 985 (2022) 116025]



Angular-Ordered Parton Shower in Herwig 7

- By nature, AO effects are of NLL accuracy
- Governed by an AO evolution scale, $\tilde{q}^2$
- 3 evolution scales to “rule them all”
- Definition of these evolution scales will determine the kinematics and the phase-space of the shower.

[Marchesini, Webber, 1988]

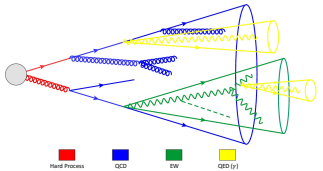
[Gieseke, Stephens, Webber, 2003]

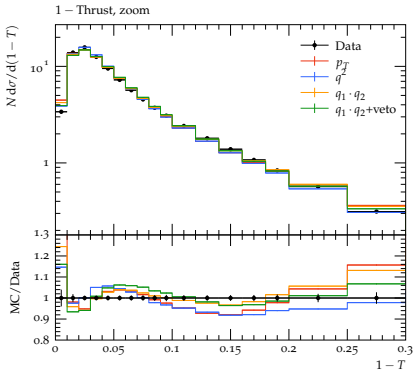
[Reichelt, Richardson, Siodmok, 2017]

[Bewick et al, JHEP 04 (2020); JHEP 01 (2022) 026]

- The choice of the preserved quantity will determine the interpretation of $\tilde{q}^2$.
- Going to a default QCD⊕QED⊕EW setting
- Critical question: will QTilde shower remain coherent after interleaving QCD and EW interactions?

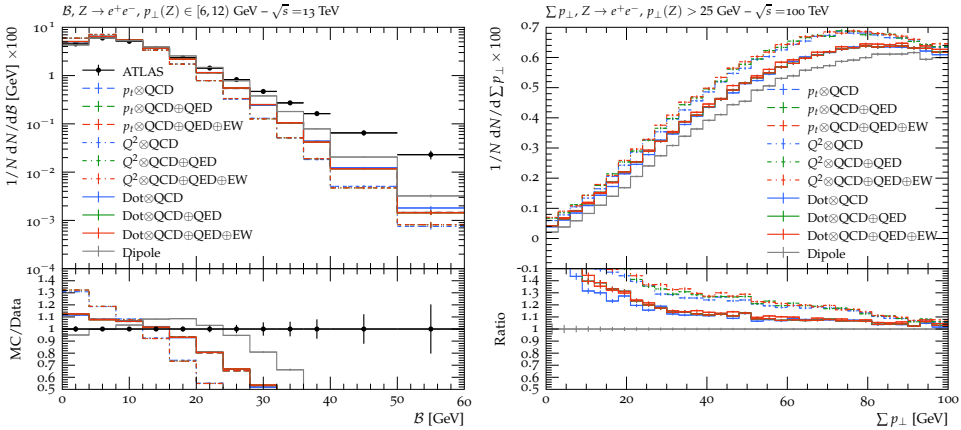
[Seymour, Sule, AM, work in progress]





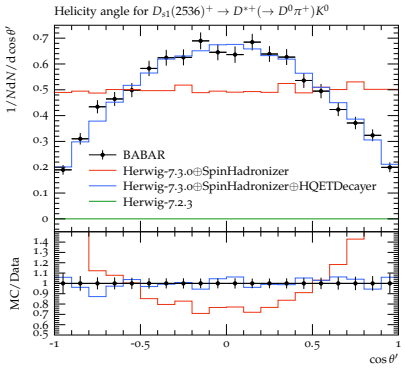
– Grouping of the predictions depends on the evolution scheme and not the shower interactions, even for the zoomed phase-space at 100 TeV.

[Seymour, Sule, AM, work in progress]



– A simultaneous IS+FS tune to jet/event shapes and groomed jets will decrease the discrepancy between AO and Dipole.

Heavy Quark Effective Theory in Cluster Hadronisation



[Richardson, AM, ArXiv:2312.02757]

– Passing through the polarization of heavy hadrons at the end of parton shower.

- For $m_Q \gg \Lambda_{\mathrm{QCD}}$, the light degrees of freedom become insensitive to m_Q. For the iso-spin heavy hadron multiplet $(H,\, H^\star)$ we can have:

$$\Gamma(H \to X) \gg \Delta m \gg \gamma(H \to H^\star X)$$

- Heavy quarks act as non-recoiling sources of colour.
- A **spin-flavor symmetry** appears for heavy quarks.
- A net polarization of the initial heavy quark may be detected, either in a polarization of the final ground state or in the decay products of the **excited heavy mesons** and **heavy baryons**.
- **Falk-Peskin "no-win" theorem**:

[Falk, Peskin, Phys.Rev.D 49 (1994) 3320-3332]

No polarization information would be found in non-excited mesons.

Kinematic Optimization in Cluster Hadronisation

`Static` vs `Dynamic` kinematic thresholds in cluster splitting:

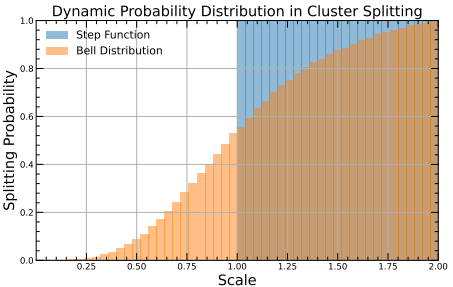
$$\texttt{Static}: \quad M > M_1 + M_2, \quad M_1 > m + m_1, \quad M_2 > m + m_2$$

$$\texttt{Dynamic}: \quad M^2 > M_1^2 + M_2^2, \quad M_1^2 > m^2 + m_1^2 + \delta_{\text{th}}, \quad M_2^2 > m^2 + m_2^2 + \delta_{\text{th}}$$

Probability of cluster splittings for heavy clusters:

$$P_{\text{cluster}} = \frac{1}{1 + \left| \frac{M - \delta}{M_{\text{th}}} \right|^r} > \text{Rand}(0,1)$$

[Richardson, AM, ArXiv:2312.02757]



General Tune for Herwig-7.3.0

- First general tune of Herwig 7.3.0 since the 7.2.0 release.
- Fitting to LEP mesurments, for over 9,000 data bins.
- Tune weighted around both light and heavy hadron production rates and multiplicities, prioritising more dominant processes.
- Initial attempts to use Professor II yielded inconsistencies.
- We resorted to a multi-layered, brute-force approach to minimizing the χ^2 parameter.
- 5 consecutive runs, making the parameter range smaller, focusing on the best tune in the previous run. Each run for 5000 samples.

Tuned Parameter	Herwig-7.3.0	Herwig-7.2.0
`ClMaxLight` [GeV]	3.234	3.649
`ClPowLight`	2.646	2.780
`PSplitLight`	0.723	0.899
`PwtSquark`	0.357	0.292
`PwtDIquark`	0.365	0.298
`SngWt`	0.880	0.740
`DecWt`	0.346	0.620
`ProbabilityPowerFactor`	3.346	–
`ProbabilityShift`	6.044	–
`KineticThresholdShift` [GeV]	-1.532	–
`AlphaIn`	0.119	0.126
`pTmin` [GeV]	0.747	0.958

- χ^2 improved by 8.88% (compared to Herwig 7.2.0 tune).
- χ^2 improved by 48.5% (compared to the untuned Herwig-7.3.0).

[Richardson, AM, ArXiv:2312.02757]

Reconstruction of Cluster Hadronisation

- Too late for Herwig-7.3.0 → Herwig-7.4.0

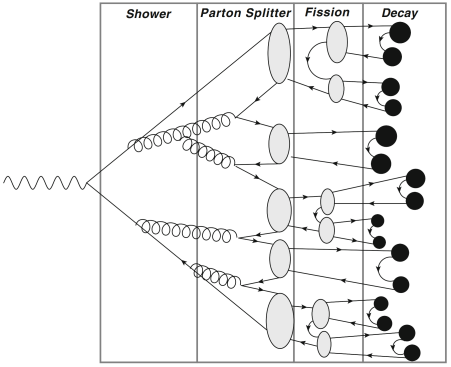
- Dynamic hadronization model and the possibility to extract hadronization corrections in a clean way
  [Gieseke, Kiebacher, Plätzer, Samitz]

- Structural work on Matchbox and the merging to have more flexible solutions and less negative weights
  [Plätzer, Siódmok, Whitehead]

- Ongoing work on hadronization and colour reconnection
  [Gieseke, Kiebacher, Plätzer]

- KrKNLO matching scheme
  [Sarmah, Plätzer, Siódmok, Whitehead]

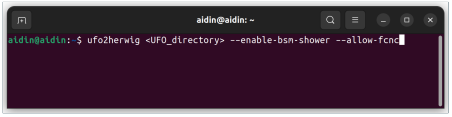
- Coherence AO parton shower tune [Seymour, Sule, AM]



Plot from [arXiv:1811.10336]

Generalised Parton Shower in Herwig 7

- Supports a broad range of BSM scenarios using UFOs
- Manages interactions involving and couplings, crucial for BSM physics
- Enhances simulation accuracy by addressing unique kinematic properties of BSM particles
- Provides computational efficiency
- Allows rigorous validation against experimental data, ensuring practical reliability
- Low-mass BSM bosons can be produced during the PS process




```
######################################################
## BSM Particles
######################################################
read FRModel.model

cd /Herwig/NewPhysics

# Particle property
cd /Herwig/FRModel/Particles
```

```
create Herwig::ZeroZeroOneEWSplitFn h3hmWpSplitFnEW
set h3hmWpSplitFnEW:InteractionType EW
set h3hmWpSplitFnEW:ColourStructure EW
set h3hmWpSplitFnEW:CouplingValue.Im 0.0640873328870152
set h3hmWpSplitFnEW:CouplingValue.Re 0.31615273869493926
cp /Herwig/Shower/SudakovCommon h3hmWpSudakovEW
set h3hmWpSudakovEW:SplittingFunction h3hmWpSplitFnEW
set h3hmWpSudakovEW:Alpha /Herwig/Shower/AlphaEW
do /Herwig/Shower/SplittingGenerator:AddFinalSplitting h3->h-,W+; h3hmWpSudakovEW

create Herwig::ZeroZeroOneEWSplitFn h3h1Z0SplitFnEW
set h3h1Z0SplitFnEW:InteractionType EW
set h3h1Z0SplitFnEW:ColourStructure EW
set h3h1Z0SplitFnEW:CouplingValue.Im 0.0
set h3h1Z0SplitFnEW:CouplingValue.Re -0.10889984429545985
cp /Herwig/Shower/SudakovCommon h3h1Z0SudakovEW
set h3h1Z0SudakovEW:SplittingFunction h3h1Z0SplitFnEW
set h3h1Z0SudakovEW:Alpha /Herwig/Shower/AlphaEW
do /Herwig/Shower/SplittingGenerator:AddFinalSplitting h3->h1,Z0; h3h1Z0SudakovEW
```

BSM Splitting Functions

- Scalar splittings

$$\phi \to \phi' \phi'', \qquad f \to f' \phi, \qquad V \to V' \phi$$

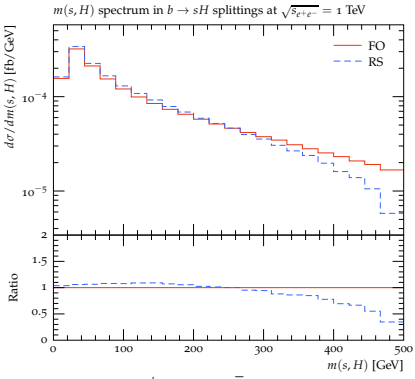
- Vector boson splittings

$$\phi \to \phi' V, \qquad f \to f' V, \qquad V \to V' V''$$

- Charged Higgs bosons and FCNCs can be treated.

- Separation of CP-even scalar and CP-odd pseudo-scalar scalars couplings.

[Lee, Seymour,Yang, AM, arXiv:2312.13125]



FO: $e^+e^- \to s\bar{b}H$(MG5)

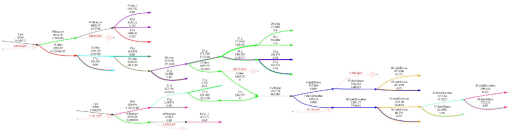
RS: $e^+e^- \to b\bar{b}$(MG5) $+ b \to sH$(Hw7)

Dark Showers

- Dark Shower Developments in Herwig 7:

  An implementation of the hidden valley model with a SU(3) dark interaction tree, dark quarks and wrapped with dark cluster hadronisation and decay

  [Papaefstathiou, Plätzer, Siódmok, Suchita, Stafford, AM]

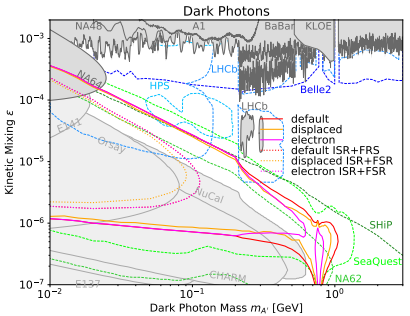


- Dark-photon production in Herwig 7:

  Inclusion of light dark portal model in AO shower as a mechanism for producing dark photons in ISR/FSR

  Also, dark bremsstrahlung can also be interpreted as a form of ISR/FSR

  [Kling, Plätzer, Reimitz, AM]



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

Thank You!