What's New in

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Evolution of Herwig

Hadron **E**mission **R**eactions **W**ith **I**nterfering **G**luons
HERWIG 5.1: [G. Marchesini et al, 1992]
`FORTRAN` code, latest version 6.521 (March 11th, 2013)
Gluon+quark AO parton shower ⊕ Simple cluster hadronisation model

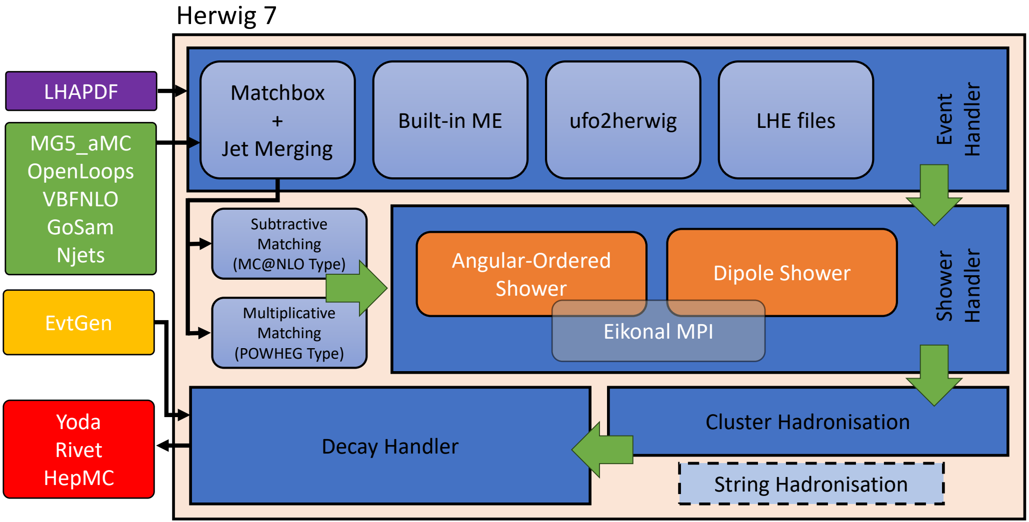
Herwig++: [S. Gieseke et al, 2003]
`C++` code, latest version 2.7.1 (July 7th, 2014)
Modular Structure, Efficiency and Speed, User Interface
Improved Physics, Better Soft Physics, ME Corrections
Improved Hadronisation, Precision Calculations

The final evolution of Herwig++ (Herwig++ 3.0)
Fully replaced both HERWIG and Herwig++
The Physics of Herwig 7: [J. Bellm et al, 2015]
Built on ThePEG: **T**oolkit for **H**igh **E**nergy **P**hysics **E**vent **G**eneration
Herwig 7.3.0 December 2023 – Herwig 7.4.0 Summer 2026

HERWIG (1992-2013)
↓
Herwig++ (2003-2014)
↓
Herwig 7 (2015)

The Physics of Herwig 7: [arXiv: 2512.16645]
Herwig 7.3 release note: [arXiv: 2312.05175]

Under the Hood

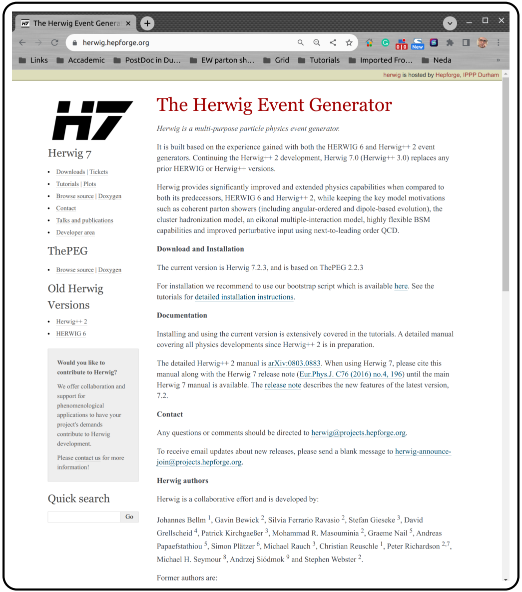


Herwig 7; What it does?

– An outstanding list of features:

Angular ordered parton shower (QCD+QED+EW)
Colour dipole parton shower (QCD)
Automated matching and merging
Colour reconnection models
Colour ME corrections
Cluster and String hadronization model
Underlying event
Flavour mass schemes
Built-in HQET for hadronisation and decay
Electroweak corrections (including a EW PS)
Multiparton hard interactions
Jet structure
Forward physics
BSM physics (including a brand-new BSM PS)
Import UFO models
Shower with LHE samples
Complex decay chains for unstable particles
Interfacing with (many) external programs
Parallel simulations
Built-in interface to Rivet and HepMC
Modularity and extensibility
User-friendly interface
Easy to build and use

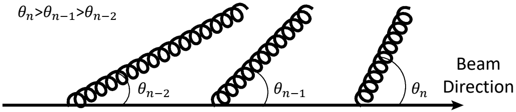
Many more features are being developed



Outlook

1. **Angular-ordered parton shower** in Herwig 7 [arXiv:0803.0883]
2. **EW parton shower** [arXiv:2108.10817]
   – Massive boson emission at high energy, precision in multi-boson processes.
   – Longitudinal Modes: Dawson and Gauge-Invariant Pictures [AM, Richardson, to appear soon]
   – Implemented in Herwig 7.3.0. [arXiv:2312.05175]
   – Phenomenological consequences [arXiv:2012.14746, arXiv:2112.15487]
3. **Generalised (BSM) parton shower** [arXiv:2312.13125]
   – Extend shower kernels to *all possible* $1 \to 2$ quasi-collinear splittings (BSM-capable).
   – Parton shower as a Sub-GeV DM Generator [Darvishi, AM, Seymour, to appear soon]
4. **New BSM interactions; the Hidden Valley model** [arXiv:2408.10044]
   – Add new splittings and *interleave* with SM ones;
   – Case study: **dark sector showers** and hadronisation.
5. **Quarkonium Parton Shower** [arXiv:2508.06307]
6. **HQET and Hadronisation/Decay of Excited Heavy Hadrons** [arXiv:2312.02757]
7. **Tuning Herwig 7: The QCD Coherence Tune** [AM, Seymour, Sule, to appear soon]
   – Interleaving QCD and EW emissions should preserve QCD coherence.
   – Tested via coherence-sensitive observables (jet/event shapes) in large-M, high-lumi limits.
   – Defined a *"coherence tune"* for QCD+QED+EW PS.

Angular Ordering from QCD Coherence



– In the soft limit, emission amplitude from a colour dipole (ij):

$$\mathcal{M}_{ij}(k) \;\propto\; g_s \left(\frac{p_i}{p_i \cdot k} - \frac{p_j}{p_j \cdot k} \right); \qquad |\mathcal{M}(k)|^2 \propto \underbrace{[\cos\phi_{ik} - \cos\phi_{jk}]}_{\text{interference term}} [\phi_{ik} \approx \phi_{jk}] \theta_k > \theta_{ij} 0$$

– ϕ_{ik} is the polar opening angle between the emitted gluon k and leg i,

$$\cos\phi_{ik} = (\vec{p}_i \cdot \vec{k}) / (|\vec{p}_i||\vec{k}|)$$

– Large-angle soft gluons only see the *total colour charge* of the dipole $\Rightarrow$ destructive interference outside θ_{ij}:

$$\text{Quasi-collinear soft limit} \quad \Rightarrow \quad p_{T,n}^2 \;\simeq\; z_n(1-z_n)\, E^2 \theta_n^2$$

– Successive emissions (in backward ISR evolution) must satisfy:

$$\theta_n > \theta_{n-1} > \theta_{n-2} > \ldots \quad \equiv \quad y_n > y_{n-1} > y_{n-2} > \ldots \quad \text{with} \quad y_k = \frac{1}{2} \ln \frac{E_k + p_{k,\parallel}}{E_k - p_{k,\parallel}}$$

Angular Ordering Evolution Scales

– **$\mathbf{p_T}$-preserving** (HERWIG, Herwig++): [NPB 310 (1988) 461-526; arXiv:hep-ph/0311208]

$$\tilde{q}^2_{\tilde{ij}\to i,j} = \frac{|p_T|^2 - z m_2^2}{(1-z)^2} \quad \rightarrow \quad p_T^2 = z^2(1-z)^2\tilde{q}^2 + m_0^2 z(1-z) - m_1^2(1-z) - m_2^2 z$$

– **$\mathbf{q^2}$-preserving** (Herwig-7.0): [arXiv:1708.01491]

$$\tilde{q}^2_{\tilde{ij}\to i,j} = \frac{q_0^2 - m_0^2}{z(1-z)} \quad \rightarrow \quad p_T^2 = z^2(1-z)^2\tilde{q}^2 + m_0^2 z(1-z) - q_1^2(1-z) - q_2^2 z$$

– **dot-product preserving** (Herwig-7.3): [arXiv:1904.11866, arXiv:2107.04051]

$$\tilde{q}^2_{\tilde{ij}\to i,j} = \frac{2q_1\cdot q_2 + m_1^2 + m_2^2 - m_0^2}{z(1-z)}, \qquad \tilde{q}^2 > 2\max\left(\frac{m_1^2}{z^2}, \frac{m_2^2}{(1-z)^2}\right)$$

$$p_T^2 = z^2(1-z)^2\tilde{q}^2 - q_1^2(1-z)^2 - q_2^2 z^2 + z(1-z)\left[m_0^2 - m_1^2 - m_2^2\right]$$

– For heavy quark radiation,

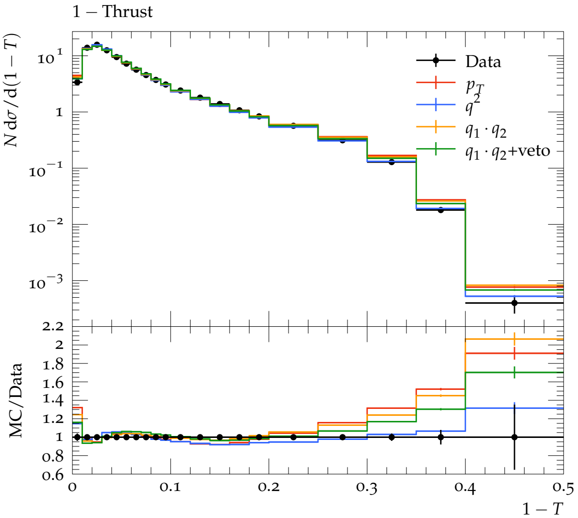
$$p_T \geq (1-z)m_Q \quad \rightarrow \quad \theta > m_Q/E \quad \rightarrow \quad p_T^{\mathrm{cuttoff}} \sim \mathcal{O}(m_c)$$

For 3rd generation quarks, a small fraction of the events end up in the dead zone any way, but these are subleading and don't impact the logarithmic accuracy.

Angular Ordering from QCD Coherence

The AOC is:

- A *physical consequence* of **gauge invariance** & **colour coherence**.
- Is realised in PS by ordering in an evolution variable $\tilde{q}$ that is *monotonic with emission angle* in the soft limit.
- The choice of $\tilde{q}^2$ definition:
  - Mapping between $\tilde{q}$ and θ for hard/massive splittings.
  - Phase-space coverage (dead zones).
  - Logarithmic accuracy.
- Built-in **LL+NLL accuracy**.
- Only required calculating the helicity-dependent splitting kernels.



[Plots from arXiv:1904.11866]

EW Parton Shower

- One of the key components of all multi-purpose event generators: **process-independent parton shower**.
- Current meta: QCD+QED showers $\to$ satisfactory for most present analyses.
- At $\sqrt{s} \gg m_W$, W/Z, Higgs, and heavy quarks behave quasi-massless $\Rightarrow$ **partonic degrees of freedom**.
- Expectation supported by LHC observations of EW radiation.
  [arXiv:1507.04548, arXiv:1807.08639]
- EW virtual corrections grow $\sim \alpha_W \ln^2(s/m_W^2)$ and are negative. [arXiv:hep-ph/0005316]
- Motivates **process-independent EW PS** $\to$ upgrade to QCD+QED+EW scheme.
- Few existing implementations:
  [arXiv:1305.6837, arXiv:1401.5238, arXiv:1403.4788, arXiv:2002.09248, arXiv:2108.10786]
- Became available since Herwig-7.3.0. [arXiv:2312.05175]

Parton Shower Kinematics in Herwig7

- A shower branching is denoted as $\widetilde{ij} \to i + j$ with.
- Differential cross-section for the production of the children:

$$d\sigma_{i+j} \simeq \frac{\alpha_{\rm int}(\tilde{q}^2)}{2\pi} \frac{d\tilde{q}^2}{\tilde{q}^2}\, dz\, P_{\widetilde{ij}\to i+j}(z,\tilde{q})\, d\sigma_{\widetilde{ij}}$$

- The **helicity-dependent splitting function** can be written as

$$P_{\widetilde{ij}\to i+j}(z,\tilde{q}) \;=\; \sum_{\lambda_{\widetilde{ij}},\lambda_i,\lambda_j} \left| H_{\widetilde{ij}\to i+j}(z,\tilde{q};\lambda_{\widetilde{ij}},\lambda_i,\lambda_j) \right|^2$$

- The **helicity amplitude** for the splitting: $H_{\widetilde{ij}\to i+j}(z,\tilde{q};\lambda_{\widetilde{ij}},\lambda_i,\lambda_j) \;=\; g_{\rm int} F^{\widetilde{ij}\to i+j}_{\lambda_{\widetilde{ij}},\lambda_i,\lambda_j}$
- The **vertex function** $F^{\widetilde{ij}\to i+j}_{\lambda_{\widetilde{ij}},\lambda_i,\lambda_j}$ explicitly depends on Feynman rules of the splitting legs.
- $g_{\rm int}$ is the relevant coupling (QCD, QED, EW, BSM).
- *Quasi*-collinear approximation: $\tilde{q}^2_{\widetilde{ij}\to i+j} \gg m_i^2, p_\perp^2, \quad m_i \to 0, \quad p_\perp \to 0, \quad \frac{m_i}{p_\perp} = \text{const.}$
- Rescaling: $m_i \to \lambda m_i,\ p_\perp \to \lambda p_\perp$.

EW Splitting Functions

– Implementing IS and FS EW parton shower in Herwig 7. [arXiv:2108.10817]

– The viable EW splittings are:

  ▷ 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)

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

  ▷ EW decays (already included in Herwig)

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

– Going to a full IS+FS EW PS requires incorporating EW PDFs and folding QCD and EW effects into a unified set of evolution equations → only relevant in the massless EW theory.

Helicity-dependent $\mathrm{q} \to \mathrm{q}'\mathrm{V}$ Splitting Functions

– Incoming/Outgoing fermion spinors: [arXiv:2108.10817]

$$u_{\pm\frac{1}{2}}(p) = \begin{pmatrix} \delta_{+\frac{1}{2}} \frac{m_0}{\sqrt{2p}}\lambda \\ \delta_{-\frac{1}{2}} \sqrt{2p}\left(1 + \frac{m_0^2\lambda^2}{8p^2}\right) \\ \delta_{+\frac{1}{2}} \sqrt{2p}\left(1 + \frac{m_0^2\lambda^2}{8p^2}\right) \\ \delta_{-\frac{1}{2}} \frac{m_0}{\sqrt{2p}}\lambda \end{pmatrix}, \qquad \bar{u}_{\pm\frac{1}{2}}(q_1) = \left[A_\pm,\ B_\pm,\ C_\pm,\ D_\pm\right]$$

$$A_+ = D_- = \sqrt{2zp}\left(1 + \frac{m_0^2\lambda^2}{8p^2}\right),\ B_+ = -C_-^* = \frac{e^{-i\phi}p_\perp\lambda}{\sqrt{2zp}},\ C_+ = B_- = \frac{m_1}{\sqrt{2zp}}\lambda,\quad D_+ = -A_-^* = \frac{e^{-i\phi}p_\perp m_1\lambda^2}{(2zp)^{3/2}}$$

– Gauge boson polarisation vectors:

$$\epsilon^\mu_{\lambda_2=\pm1}(q_2) = \left[0; -\frac{\lambda_2}{\sqrt{2}}\left(1 - \frac{p_\perp^2\lambda^2e^{i\lambda_2\phi}\cos\phi}{2p^2(1-z)^2}\right), -\frac{i}{\sqrt{2}} + \frac{\lambda_2 p_\perp^2\lambda^2 e^{i\phi}\sin\phi}{2\sqrt{2}p^2(1-z)^2}, -\frac{\lambda_2 p_\perp\lambda e^{i\lambda_2\phi}}{\sqrt{2}(1-z)p}\right]$$

$$\begin{aligned}\epsilon^\mu_{\lambda_2=0}(q_2) = \Bigg[&\frac{p(1-z)}{\lambda m_2} + \frac{p_\perp^2 + m_0^2(1-z)^2 - m_2^2}{4p(1-z)m_2}\lambda; \cos\phi\left(\frac{p_\perp}{m_2} - \frac{m_2 p_\perp\lambda^2}{2p^2(1-z)^2}\right), \\ &-\sin\phi\left(\frac{p_\perp}{m_2} - \frac{m_2p_\perp\lambda^2}{2p^2(1-z)^2}\right), \frac{p(1-z)}{\lambda m_2} - \frac{p_\perp^2 - m_0^2(1-z)^2 - m_2^2}{4p(1-z)m_2}\lambda\Bigg]\end{aligned}$$

Longitudinal vectors in a shower: why a scheme?

- For a massive vector boson, the longitudinal polarisation vector is gauge dependent:

$$\epsilon_L^\mu(p) \;\rightarrow\; \epsilon_L^\mu(p) + \alpha\,\frac{p^\mu}{m_V}\,.$$

- In the broken SM, the p^μ-contraction **does not vanish diagram-by-diagram**.
- The broken-theory Ward identity relates it to the corresponding would-be Goldstone amplitude (and Yukawa terms for massive fermions).
- A shower needs **a local longitudinal splitting current** that is numerically stable *and* consistent with these identities (before phase-space integration/diagram sums).
- Practical options:
  - ▷ **Dawson's approach:** define a finite longitudinal basis by subtracting the p^μ/m_V piece at current level. [Nucl.Phys.B249(1985)42, arxXiv:2108.10817]
  - ▷ **GI completion:** keep the Dawson remainder *and* add the uniquely fixed Goldstone-matching term $\Rightarrow$ Ward-identity consistent longitudinal current. [AM, Richardson, to appear soon]
- Expectation: Dawson $\simeq$ GI at high $\tilde{q}$, while differences appear at low $\tilde{q}$ in symmetry-breaking/Yukawa-sensitive channels.

$q \to q'V$ Splitting Function in Dawson's Picture

$$P^{\mathrm{T}}_{q\to q'V}(z,\tilde{q}) = \frac{1}{1-z}\Bigg[\left({g_L}^2\rho_{-1,-1} + {g_R}^2\rho_{1,1}\right)\left\{(1+z^2)\left(1+\frac{m_0^2(1-z)-m_2^2}{z(1-z)^2\tilde{q}^2}\right) - \frac{{m_1}^2(z+1)}{z(1-z)\tilde{q}^2}\right\}$$
$$+\frac{m_0^2}{\tilde{q}^2}\left(g_L^2\rho_{1,1}+g_R^2\rho_{-1,-1}\right) - \frac{2m_0m_1}{z\tilde{q}^2}g_Lg_R\left(\rho_{1,1}+\rho_{-1,-1}\right)\Bigg]$$

– **Dawson Picture**:

$$F^{q\to q'V}_{L;\mathrm{Dawson}} = \frac{m_2^2}{\tilde{q}^2(1-z)^3}\left(g_R^2\,\rho_{++}+g_L^2\,\rho_{--}\right)$$

– **GI Picture**: [AM, Richardson, to appear soon]

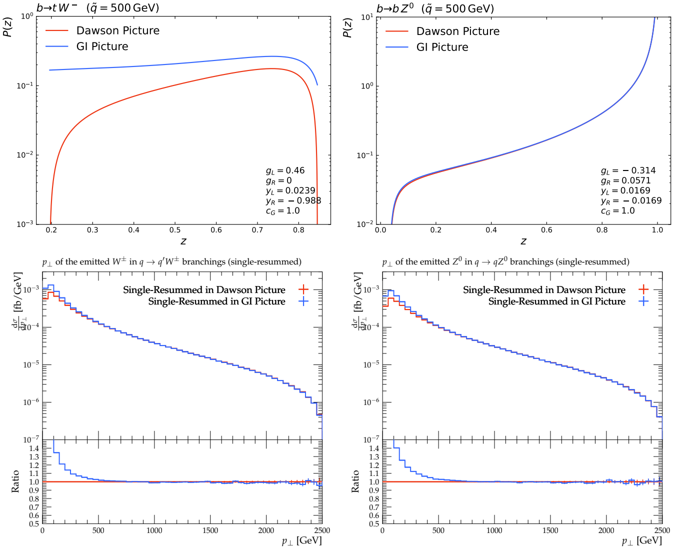
$$F^{q\to q'V}_{L;\mathrm{GI}} = \frac{m_2^2}{\tilde{q}^2(1-z)^3}\left(g_R^2\,\rho_{++}+g_L^2\,\rho_{--}\right)$$
$$-\frac{\sqrt{2}\,c_G\,m_2}{\tilde{q}^2z(1-z)^2}\left[\left(g_R\,\rho_{++}\,y_L+g_L\,\rho_{--}\,y_R\right)m_0z+\left(g_R\,\rho_{++}\,y_R+g_L\,\rho_{--}\,y_L\right)m_1\right]$$
$$+\frac{c_G^2}{2\tilde{q}^2z(1-z)}\left[\left(\rho_{--}\,y_L^2+\rho_{++}\,y_R^2\right)\left(m_0^2+m_1^2-m_2^2+\tilde{q}^2z(1-z)^2\right)+4\,m_0m_1\,y_Ry_L\left(\rho_{--}+\rho_{++}\right)\right]$$

– **GI massless limit**:

$$F^{q\to q'V}_{\mathrm{GI,massless}}(z) = \left(g_L^2\,\rho_{--}+g_R^2\,\rho_{++}\right)\frac{1+z^2}{1-z}+c_G^2\left(y_L^2\,\rho_{--}+y_R^2\,\rho_{++}\right)\frac{(1-z)^2}{1-z}$$

Dawson vs GI: Kernel-Level Comparison

- $b \to tW$: GI adds Goldstone/Yukawa matching; dominated by y_t and the large m_t insertion $\Rightarrow$ sizeable enhancement.
- $b \to bZ$: matching is controlled by $y_b \ll 1$ and no large mass splitting $\Rightarrow$ much smaller effect (visible mainly in longitudinal-sensitive regions).
- **Single-step:** isolates the *unitarised one-emission* prediction, so Dawson$\leftrightarrow$GI differences can be traced to the longitudinal current.
- A larger local longitudinal rate in GI also strengthens the **Sudakov suppression** $\Rightarrow$ non-monotonic accepted shifts.



[AM, Richardson, to appear soon]

Implementation

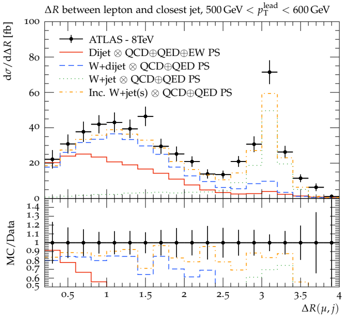
- The implementation has been rigorously validated.
  [arXiv:2108.10817]

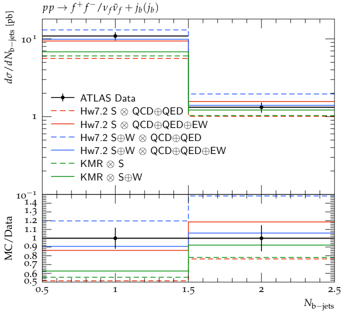
- New Classes:
  `HalfHalfOneEWSplittingFunction`
  `HalfHalfZeroEWSplittingFunction`
  `OneOneOneEWSplittingFunction`
  `OneOneZeroEWSplittingFunction`

- To set up the `QCD⊕QED⊕EW` PS:

```
cd Herwig/Shower/
set ShowerHandler:Interactions ALL
set <kernel>:LongitudinalEWScheme Dawson
```

- Options: `ALL`, `QEDQCD`, `QCD`, `QED` and `EWOnly`.
- Options: `Dawson` or `GaugeInvariant`.
- We have tested the performance and physics of this new PS and have done several phenomenological studies.
  [arXiv:2012.14746, arXiv:2112.15487]
- More studies are in progress.





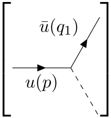
Generalised BSM Parton Shower in Herwig

- **Universal framework:** PS kernels extended to *all possible* $1 \to 2$ quasi-collinear splittings from UFO models. [arXiv:2312.13125]

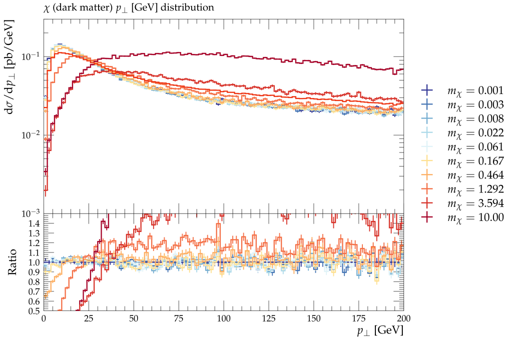
```
ufo2herwig <UFO_directory> -enable-bsm-shower -allow-fcnc
```

- **Model-inclusive:** Works for SM, EW, and a wide range of BSM scenarios.
- **Practical advantage:** Light BSM states can be generated in the shower without higher-order ME corrections.

- Updated SM splittings / Included BSM Splittings:
  - Scalars: $\phi \to \phi'\phi''$, $\quad f \to f'\phi$, $\quad V \to V'\phi$
  - Vectors: $\phi \to \phi' V$, $\quad f \to f'V$, $\quad V \to V'V''$
- Accommodating CP-even/CP-odd couplings and FCNCs splittings.

$-i\mathcal{M}$ 

$= \bar{u}(q_1)\big[-i(\kappa + \tilde{\kappa}\gamma_5)\big]u(p)$



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

Dark Sector Showers in Herwig

Extending Herwig AO parton shower to simulate *dark sector QCD-like showers* with full interleaving with SM radiation (a darkly-interacting copy of SU(3) QCD shower). [arXiv:2408.10044]

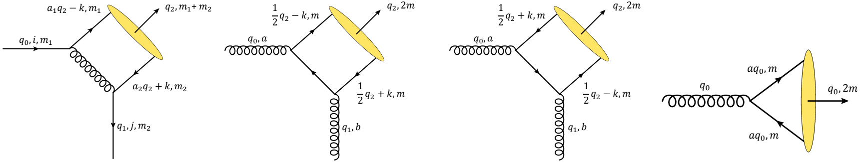
Key Ingredients:

- Introduce **dark gauge group** $SU(N_d)$ with confinement scale Λ_d.
- Implement all $1 \to 2$ **dark splittings** using same quasi-collinear AO formalism as SM.
- Include *dark hadronisation* model: cluster formation $\to$ dark hadrons.
- Interleave dark shower with QCD/EW showers while preserving coherence.

Phenomenology:

- Benchmarked with $Z' \to q_d\bar{q}_d$ at LHC energies.
- Dark jets can mimic QCD jets, but differ in:
  - Jet mass and shape distributions,
  - Multiplicity of soft constituents,
  - Sensitivity to Λ_d.
- Attempting a Herwig 7 vs Pythia8 cross-tune.
- Possibility of looking into other phenomenology.

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?

- 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: [AM, Richardson, arXiv:2508.06307]

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

NRQCD Framework

Quarkonium production amplitude (NR limit $k \sim m_Q v$, $v \ll 1$):

$$\mathcal{M}(p) = \sum_{L_Z, S_Z} \int \frac{\mathrm{d}^3\mathbf{k}}{(2\pi)^3}\, \psi_{LL_Z}(\mathbf{k})\, \underbrace{\big\langle L\, L_Z;\, S\, S_Z \,\big|\, J\, J_Z \big\rangle\, \Gamma_{S\, S_Z}(p,k)}_{\text{short-distance amplitude} \,\equiv\, \mathcal{A}(p,k)}$$

$$\text{hard QCD at } \mu_F \gtrsim m_Q \xrightarrow{\mathcal{A}(p,k)} Q\bar{Q}\ (S, L;\ \text{spin/colour proj.}) \xrightarrow{\text{LDMEs}} H\big(n^{2S+1}L_J\big)$$

Factorisation principle:

– Non-perturbative Bethe–Salpeter wavefunction $\psi_{LL_Z}(\mathbf{k})$:

$$\int \frac{\mathrm{d}^3\mathbf{k}}{(2\pi)^3}\, [k^\alpha k^\beta \cdots]\, \psi_{LL_Z}(\mathbf{k}) \ \propto\ \frac{R^{(L)}(0)}{\sqrt{4\pi}}\, \epsilon^{[\alpha\beta\cdots]}(P, L_Z)$$

– Wavefunction at the origin (NRQCD LDMEs):

$$\langle 0|\mathcal{O}_c^H(^nL_J)|0\rangle \ \propto\ \frac{1}{4\pi}\, |R^c_{^nL_J}(0)|^2 \quad (\text{S: } |\mathrm{R}(0)|^2,\ \text{P: } |R'(0)|^2,\ \text{D: } |R''(0)|^2)$$

Spin–colour projections:

– Angular-momentum coupling via Clebsch–Gordan: $\big\langle L\, L_Z;\, S\, S_Z \,\big|\, J\, J_Z \big\rangle$.

– Colour projectors: singlet $\delta_{ij}/\sqrt{N_c}$, octet $(\lambda^a)_{ij}/\sqrt{2}$.

– Perturbative short-distance piece: $\mathcal{A}(p,k) = \big\langle LL_Z; SS_Z \big| JJ_Z \big\rangle\, \Gamma_{SS_Z}(p,k)$.

Colour-Singlet Splittings

Production amplitudes: [AM, Richardson, arXiv:2508.06307]

$$\mathcal{M}(q \to q'\,\mathcal{O}_1({}^nL_J)) = \frac{g_s^2\,C_F\,\langle\mathcal{O}_1({}^nL_J)\rangle\,\delta_{ij}}{\sqrt{N_C}\,\left(q_0^2 - a_1^2 M^2\right)}\,\bar{u}_j(q_1,m_2)\,\gamma^\nu\,\Pi_{nS}\,\gamma^\mu\,u_i(p,m_1)\,[\cdots]$$

- C_F: colour factor.
- $\langle\mathcal{O}_1\rangle$: NRQCD LDME $\propto |R_{{}^nL_J}(0)|^2$ or derivatives.
- Π_{nS}: spin projection operator, e.g. γ^5 for ${}^1S_0$, $\not\epsilon$ for ${}^3S_1$.

$$\mathcal{M}(g \to g\,\mathcal{O}_1({}^nL_J)) = \frac{g_s^2\,\delta^{ab}\,\langle\mathcal{O}_1({}^nL_J)\rangle}{4m\sqrt{2N_C m}\,q_0^2}\,\mathrm{Tr}\Big[\left(\tfrac{1}{2}\not q_2 + \not k + m\right)\left(\gamma^5 \text{ or } -\not\epsilon\right)\left(\tfrac{1}{2}\not q_2 - \not k + m\right)[\cdots]\Big]$$

- δ^{ab}: colour-singlet projection after summing gluon colours.

From amplitude to splitting kernel:

$$F_{q\to q'\mathcal{O}_1}(z,q_0^2) = \frac{1}{2}\sum_{\text{spins,colours}} |\mathcal{M}|^2 \quad\Rightarrow\quad P_{q\to q'\mathcal{O}_1} = \int \mathrm{d}z\,\mathrm{d}q_0^2\,\frac{\mathrm{d}\phi}{2\pi}\,F(z,q_0^2)$$

Implemented in Herwig 7 for S-, P-, D-wave states up to ${}^3D_J$.

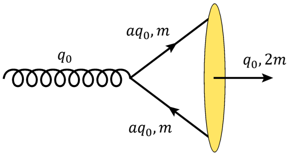
Colour-singlet $q \to q' \, \mathcal{O}_1(^nL_J)$ configurations:

State	Herwig Class	Main Processes
$^1S_0$	`QtoQ1S0SplitFn`, `QtoQP1S0SplitFn`	$c \to c{+}\eta_c$, $b \to b{+}\eta_b$; $c \to b{+}B_c^+$, $b \to c{+}B_c^-$
$^3S_1$	`QtoQ3S1SplitFn`, `QtoQP3S1SplitFn`	$c \to c + J/\psi$, $b \to b + \Upsilon$; $c \to b + B_c^{*+}$, $b \to c + B_c^{*-}$
$^1P_1$	`QtoQ1P1SplitFn`	$c \to c + h_c$, $b \to b + h_b$
^3P_J	`QtoQ3P0/1/2SplitFn`, `QtoQP3P0/1/2SplitFn`	χ_{cJ}, χ_{bJ}; B_c P-wave excitations $(J = 0, 1, 2)$
$^1D_2$	`QtoQ1D2SplitFn`	$b \to b + \eta_{b2}$; $c \to c + \eta_{c2}$
^3D_J	`QtoQ3D1/2/3SplitFn`, `QtoQP3D1/2/3SplitFn`	$\psi(3770)$, $\psi_2(1D)$, $\psi_3(1D)$; $\Upsilon_J(1D)$; B_c D-wave excitations

Colour-singlet $g \to g \, \mathcal{O}_1(^nL_J)$ configurations:

State	Herwig Class	Main Processes
$^1S_0$	`GtoG1S0SplitFn`	$g \to g + \eta_c$, $g \to g + \eta_b$
$^3S_1$	`GtoG3S1SplitFn`	$g \to g + J/\psi$, $g \to g + \Upsilon$
$^1P_1$	`GtoG1P1SplitFn`	$g \to g + h_c$, $g \to g + h_b$
^3P_J	`GtoG3P0/1/2SplitFn`	χ_{cJ}, χ_{bJ} $(J = 0, 1, 2)$
$^1D_2$	`GtoG1D2SplitFn`	$g \to g + \eta_{c2}$, $g \to g + \eta_{b2}$
^3D_J	`GtoG3D1/2/3SplitFn`	$\psi(3770)$, $\psi_2(1D)$, $\psi_3(1D)$; $\Upsilon_J(1D)$

Colour-Octet Branching Probability



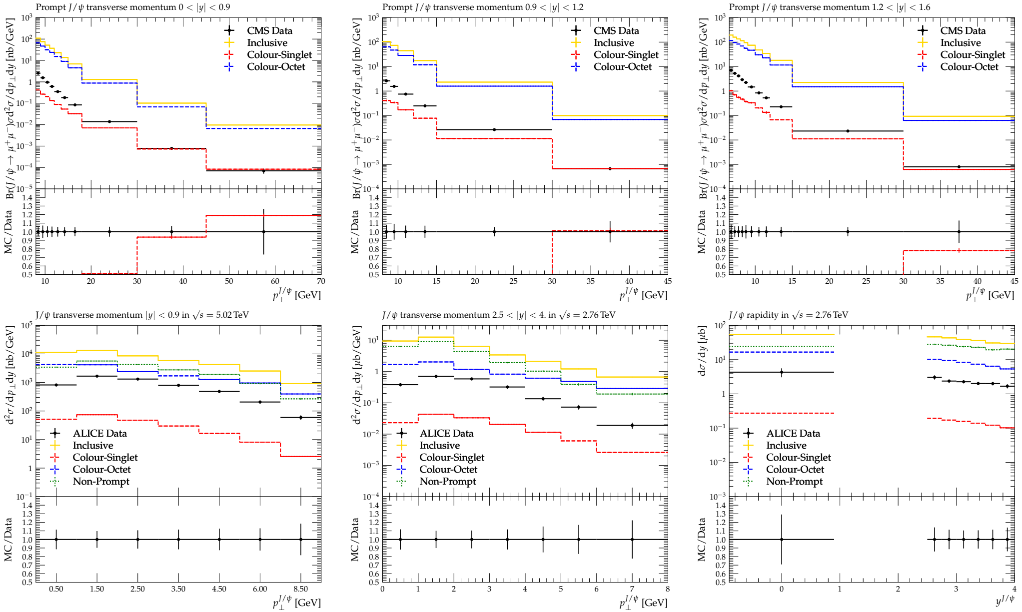
- High-p_T quarkonium production is dominated by CO fragmentation.
- $g \to Q\bar{Q}[n^{(8)}]$ is the leading production mechanism.
- Non-perturbative LDMEs govern the transition from $Q\bar{Q}[n^{(8)}]$ to the physical $\mathcal{O}^{(8)}$ state.
- This process is sufficient at LO, and no explicit inclusion of $g \to g\mathcal{O}^{(8)}$ or $g \to gg\mathcal{O}^{(8)}$ are required.
- The $g \to \mathcal{O}^{(8)}$ transition is modelled via a fixed probability per unit evolution time.
- This probability is governed by the LDME:

$$P_{g\to\mathcal{O}^{(8)}(^nS_J)} = \frac{\pi\,\alpha_s(4m^2)}{24m^3}|\mathcal{M}(g \to \mathcal{O}(^nS_J))|^2$$

- $|\mathcal{M}(g \to \mathcal{O}(^nS_J))|^2$ is treated here as a tuneable non-perturbative parameter.

Impact

[AM, Richardson, arXiv:2508.06307]



Tuning the CS Parameters

- Use experimental decay widths to extract $|R_{^nL}(0)|^2$.
- Apply known QCD radiative corrections.
- Cross-check with potential model predictions for higher states.

$$\Gamma\big(\mathcal{O}_1(^3S_1)\to\ell\ell\big) = \frac{16\pi\alpha_{\rm em}^2}{9}\,\frac{|R_{^3S_1}(0)|^2}{4\pi(2m)^2}\left(1-\frac{16}{3}\frac{\alpha_S(m^2)}{\pi}\right),$$

$$\Gamma\big(\mathcal{O}_1(^1S_0)\to\gamma\gamma\big) = \frac{48\pi\alpha_{\rm em}^2}{81}\,\frac{|R_{^1S_0}(0)|^2}{4\pi(2m)^2}\left(1-3.4\frac{\alpha_S(m^2)}{\pi}\right),$$

$$\Gamma\big(\mathcal{O}_1(^1S_0)\to gg\big) = \frac{32\pi\alpha_S^2(m^2)}{3}\,\frac{|R_{^1S_0}(0)|^2}{4\pi(2m)^2}\left(1+4.4\frac{\alpha_S(m^2)}{\pi}\right),$$

$$\Gamma\big(\mathcal{O}_1(^3S_1)\to 3g\big) = \frac{160(\pi^2-9)\alpha_S^3(m^2)}{81}\,\frac{|R_{^3S_1}(0)|^2}{4\pi(2m)^2}\left(1-4.9\frac{\alpha_S(m^2)}{\pi}\right),$$

$$\Gamma\big(\mathcal{O}_1(^3S_1)\to 3\gamma\big) = \frac{64(\pi^2-9)\alpha_{\rm em}^3}{2187}\,\frac{|R_{^3S_1}(0)|^2}{4\pi(2m)^2}\left(1-12.6\frac{\alpha_S(m^2)}{\pi}\right),$$

$$\Gamma\big(\mathcal{O}_1(^3S_1)\to gg\gamma\big) = \frac{128(\pi^2-9)\alpha_{\rm em}\alpha_S^2(m^2)}{81}\,\frac{|R_{^3S_1}(0)|^2}{4\pi(2m)^2}\left(1-1.7\frac{\alpha_S(m^2)}{\pi}\right).$$

- Only the above CS states have measured partial widths. [AM, Richardson, ‘25]
- The rest are taken from potential models. [Eichten, Quigg, ‘19]

Tuning the CS Parameters

Type	Structure	$\lvert R_{n\,S}(0)\rvert^2$
$c\bar{c}$	^1S	**1.0285**
$c\bar{c}$	^1P	**0.0013**
$c\bar{c}$	^1D	0.0329
$c\bar{c}$	^2S	**0.4262**
$c\bar{c}$	^2P	0.1767
$c\bar{c}$	^2D	0.0692
$c\bar{c}$	^3S	0.5951
$c\bar{c}$	^3P	0.2106
$c\bar{c}$	^3D	0.1074
$c\bar{c}$	^4S	0.5461
$c\bar{c}$	^4P	0.2389
$c\bar{c}$	^5S	0.5160

Type	Structure	$\lvert R_{n\,S}(0)\rvert^2$
$b\bar{b}$	^1S	**3.2250**
$b\bar{b}$	^1P	1.6057
$b\bar{b}$	^1D	0.8394
$b\bar{b}$	^2S	**0.5974**
$b\bar{b}$	^2P	1.8240
$b\bar{b}$	^2D	1.5572
$b\bar{b}$	^3S	**1.1136**
$b\bar{b}$	^3P	1.9804
$b\bar{b}$	^3D	2.2324
$b\bar{b}$	^4S	1.2863
$b\bar{b}$	^4P	2.1175
$b\bar{b}$	^4D	2.8903
$b\bar{b}$	^5S	1.7990
$b\bar{b}$	^5P	2.2430
$b\bar{b}$	^5D	3.5411
$b\bar{b}$	^6S	1.6885
$b\bar{b}$	^6P	2.3600
$b\bar{b}$	^7S	1.6080

Type	Structure	$\lvert R_{n\,S}(0)\rvert^2$
$b\bar{c}$	^1S	1.9943
$b\bar{c}$	^1P	0.3083
$b\bar{c}$	^1D	0.0986
$b\bar{c}$	^2S	1.1443
$b\bar{c}$	^2P	0.3939
$b\bar{c}$	^2D	0.1989
$b\bar{c}$	^3S	0.9440
$b\bar{c}$	^3P	0.4540
$b\bar{c}$	^4S	0.8504

[Eichten, Quigg, '19]
[AM, Richardson, '25]

Table: Non-perturbative singlet wavefunctions, given in GeV^3 units.

Tuning the CO Parameters

– Fit $|\mathcal{M}(g \to \mathcal{O}(^nS_J))|^2$ values to reproduce all available quarkonium production data.
– Constrain octet LDMEs using multiple processes, where possible.

Process	Type	Structure	$\lvert\mathcal{M}(g \to \mathcal{O}(^nS_J))\rvert^2$
$g \to J/\psi$	$c\bar{c}$	$^1S_3$	1.09×10^{-4}
$g \to \psi(2S)$	$c\bar{c}$	$^1S_3$	6.23×10^{-5}
$g \to \chi_{c0}$	$c\bar{c}$	$^1S_3$	5.99×10^{-5}
$g \to \chi_{c1}$	$c\bar{c}$	$^1S_3$	1.80×10^{-4}
$g \to \chi_{c2}$	$c\bar{c}$	$^1S_3$	2.99×10^{-4}
$g \to \Upsilon$	$b\bar{b}$	$^1S_3$	7.08×10^{-4}
$g \to \Upsilon(2S)$	$b\bar{b}$	$^1S_3$	3.68×10^{-4}
$g \to \Upsilon(3S)$	$b\bar{b}$	$^1S_3$	2.19×10^{-4}
$g \to \chi_{b0}$	$b\bar{b}$	$^1S_3$	3.10×10^{-4}
$g \to \chi_{b1}$	$b\bar{b}$	$^1S_3$	9.30×10^{-4}
$g \to \chi_{b2}$	$b\bar{b}$	$^1S_3$	1.55×10^{-3}
$g \to \chi_{b0}(2P)$	$b\bar{b}$	$^1S_3$	3.10×10^{-4}
$g \to \chi_{b1}(2P)$	$b\bar{b}$	$^1S_3$	9.30×10^{-4}
$g \to \chi_{b2}(2P)$	$b\bar{b}$	$^1S_3$	1.55×10^{-3}
$g \to \chi_{b0}(3P)$	$b\bar{b}$	$^1S_3$	3.10×10^{-4}
$g \to \chi_{b1}(3P)$	$b\bar{b}$	$^1S_3$	9.30×10^{-4}
$g \to \chi_{b2}(3P)$	$b\bar{b}$	$^1S_3$	1.55×10^{-3}

Table: Tuned octet parameters. [AM, Richardson, '25]

Diquark	$\lvert R_{^nS}(0)\rvert^2$
cc (^1S)	1.9943
bb (^1S)	0.3083
bc (^1S)	0.0986

Table: Non-perturbative singlet wavefunctions $|R_1(0)|^2$ for S-state diquarks, given in GeV^3 units.

[Falk, Luke, Savage, Wise, '93]

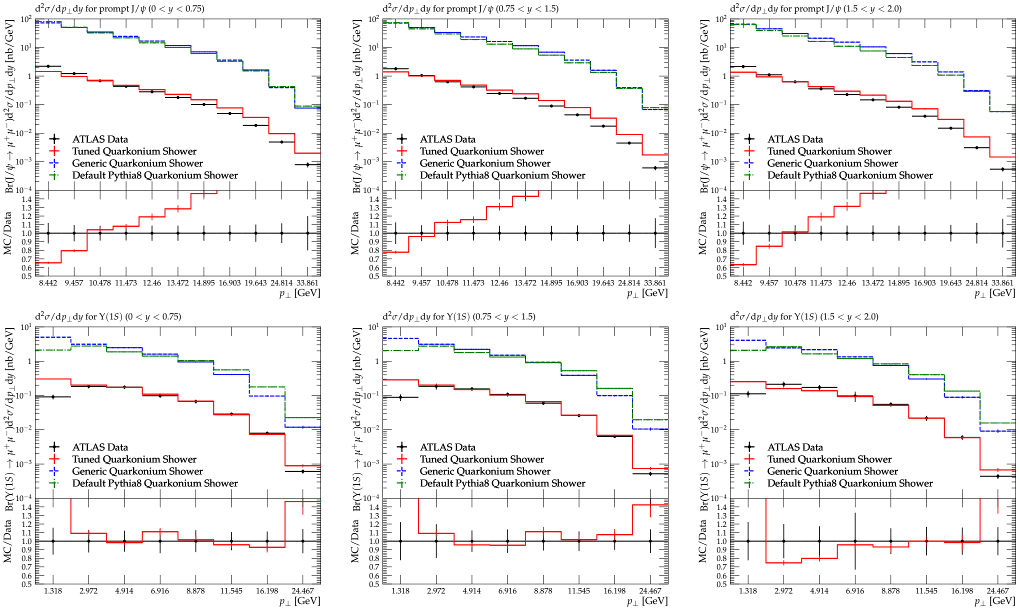


Figure: Prompt production of J/ψ and Υ states. [arXiv:2508.06307, arXiv:2312.05203]

HQET in Cluster Hadronisation

– Passing through the polarisation 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:

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

$$\gamma(H^\star \to HX) \propto \Phi^{H^\star \to HX}_{\mathrm{phase-space}} \times |\mathcal{M}(H^\star \to HX)|^2 \sim \mathcal{O}(m_Q^{-(2+n)}), \quad n \geq 1$$

- Heavy quarks act as non-recoiling sources of colour at the end of PS.
- A **spin-flavor symmetry** appears for heavy quarks.
- A net polarisation of the initial heavy quark may be detected, either in a polarisation 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 polarisation information would be found in non-excited mesons. This could be realised for other possible cases, i.e.

$$\Delta m \gg \Gamma \gg \gamma \qquad \text{or} \qquad \Delta m \gg \gamma \gg \Gamma$$

Polarization of Excited Heavy Mesons

- Considering charm mesons with a left handed c quark, $j_Q = -1/2$.
- Colour magnetic interaction becomes decoupled, leaving the spin-orientation of the light degrees independent of the charm quark and distributed uniformly:

$j_q^{(3)}$	-3/2	-1/2	1/2	3/2
Probability	$\frac{1}{2}\omega_{\frac{3}{2}}$	$\frac{1}{2}(1-\omega_{\frac{3}{2}})$	$\frac{1}{2}(1-\omega_{\frac{3}{2}})$	$\frac{1}{2}\omega_{\frac{3}{2}}$

- ω_j is the likelihood of fragmentation leading to a state with maximum value $|j_q^{(3)}|$.
- Coherent linear superposition of the charmed state helicity probabilities $P_{H^\star}(j_q + j_Q)$:

$j^{(3)}$	-2	-1	0	$+1$	$+2$
D	–	–	$\frac{1}{4}$	–	–
$D^\star$	–	$\frac{1}{2}$	$\frac{1}{4}$	0	–
D_1	–	$\frac{1}{8}(1-\omega_{\frac{3}{2}})$	$\frac{1}{4}(1-\omega_{\frac{3}{2}})$	$\frac{3}{8}(1-\omega_{\frac{3}{2}})$	–
$D_2^\star$	$\frac{1}{2}\omega_{\frac{3}{2}}$	$\frac{3}{8}(1-\omega_{\frac{3}{2}})$	$\frac{1}{4}(1-\omega_{\frac{3}{2}})$	$\frac{1}{8}\omega_{\frac{3}{2}}$	0

Polarization of Excited Heavy Mesons

- To evaluate the parameter ω_j:

$$\frac{d\Gamma(H^\star \to H\pi)}{d\cos\theta} \propto \int d\phi \sum_j P_{H^\star}(j) \left|Y_j^\ell(\theta,\phi)\right|^2$$

$$\frac{1}{\Gamma}\frac{d\Gamma(D_2^\star \to D\pi)}{d\cos\theta} = \frac{1}{4}\left[1 + 3\cos^2\theta - 6\omega_{\frac{3}{2}}\left(\cos^2\theta - \frac{1}{3}\right)\right]$$

- Comparing to the avaiable experimental data, $\omega_{\frac{3}{2}} < 0.24$ with in 90% CL.
- Default value in Herwig is set $\omega_{\frac{3}{2}} = 0.20$.
- Generalise for the possible spin polarisations of excited charmed mesons: [arXiv:2312.02757]

$\hat{\rho}$	$\rho_{0,0}$	$\rho_{1,1}$	$\rho_{2,2}$	$\rho_{3,3}$	$\rho_{4,4}$
D	1	–	–	–	–
$D^\star$	$\frac{1}{2}(1-\rho_Q)$	$\frac{1}{2}$	$\frac{1}{2}(1+\rho_Q)$	–	–
D_1	$\frac{1}{16}[1-\rho_Q+\omega_{\frac{3}{2}}(3-5\rho_Q)]$	$\frac{1}{4}(1-\omega_{\frac{3}{2}})$	$\frac{1}{16}[1-\rho_Q+\omega_{\frac{3}{2}}(3+5\rho_Q)]$	–	–
$D_2^\star$	$\frac{1}{4}\omega_{\frac{3}{2}}(1-\rho_Q)$	$\frac{3}{16}(1-\rho_Q)-\frac{1}{8}\omega_{\frac{3}{2}}(1-\rho_Q)$	$\frac{1}{4}(1-\omega_{\frac{3}{2}})$	$\frac{3}{16}(1+\rho_Q)-\frac{1}{8}\omega_{\frac{3}{2}}(1+\rho_Q)$	$\frac{1}{4}\omega_{\frac{3}{2}}(1+\rho_Q)$

Polarization of Heavy Baryons

– For ground state heavy baryons, $j_q = 0$ so the initial polarization will be preserved without dilution.

– Considering charm baryons with a left handed c quark, $j_Q = -1/2$.

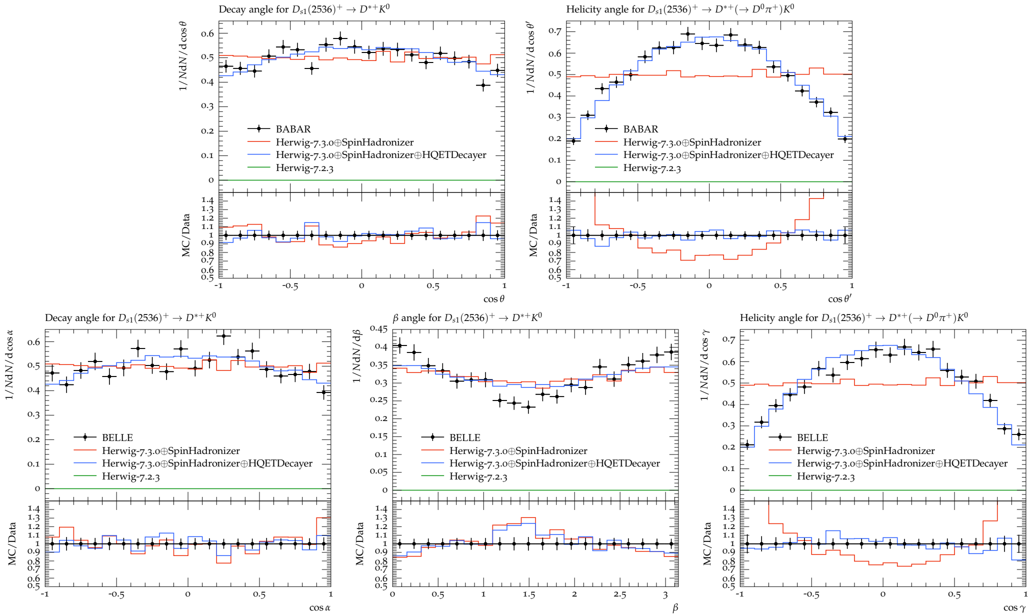
– $\omega_1 = 2/3$.

– ω_a is the rate of spin-0 to spin-1 diquark production, which we take to be $\omega_a = 1$.

$j^{(3)}$	$-3/2$	$-1/2$	$+1/2$	$+3/2$
Λ_c	–	$\frac{1}{1+\omega_a}$	0	–
Σ_c	–	$\frac{(1-\omega_1)\omega_a}{3(1+\omega_a)}$	$\frac{\omega_1\omega_a}{3(1+\omega_a)}$	–
$\Sigma_c^\star$	$\frac{\omega_1\omega_a}{2(1+\omega_a)}$	$\frac{2(1-\omega_1)\omega_a}{3(1+\omega_a)}$	$\frac{\omega_1\omega_a}{6(1+\omega_a)}$	0

– Generalise for the possible spin polarisations of charmed baryons: [arXiv:2312.02757]

$\hat{\rho}$	$\rho_{0,0}$	$\rho_{1,1}$	$\rho_{2,2}$	$\rho_{3,3}$
Λ_c	$\frac{1}{2}(1-\rho_Q)$	$\frac{1}{2}(1+\rho_Q)$	–	–
Σ_c	$\frac{1}{2}(1-\rho_Q)+\omega_1\rho_Q$	$\frac{1}{2}(1+\rho_Q)-\omega_1\rho_Q$	–	–
$\Sigma_c^\star$	$\frac{3}{8}\omega_1(1-\rho_Q)$	$\frac{1}{2}(1-\rho_Q)-\frac{1}{8}\omega_1(3-5\rho_Q)$	$\frac{1}{2}(1-\rho_Q)-\frac{1}{8}\omega_1(3+5\rho_Q)$	$\frac{3}{8}\omega_1(1+\rho_Q)$



Efficiency-corrected decay rates of D_{s1}^+ meson.

[arXiv:2312.02757]

Coherence in Angular-Ordered Showers

- QCD coherence = destructive interference of large-angle soft gluons.
- AO in Herwig guarantees this for pure QCD.
- AO applied to QED/EW as well; each progenitor carries three evolution scales:

$$\tilde{q}_S^2 \text{ (QCD)}, \; \tilde{q}_{em}^2 \text{ (QED), and } \tilde{q}_{ew}^2 \text{ (EW)}$$

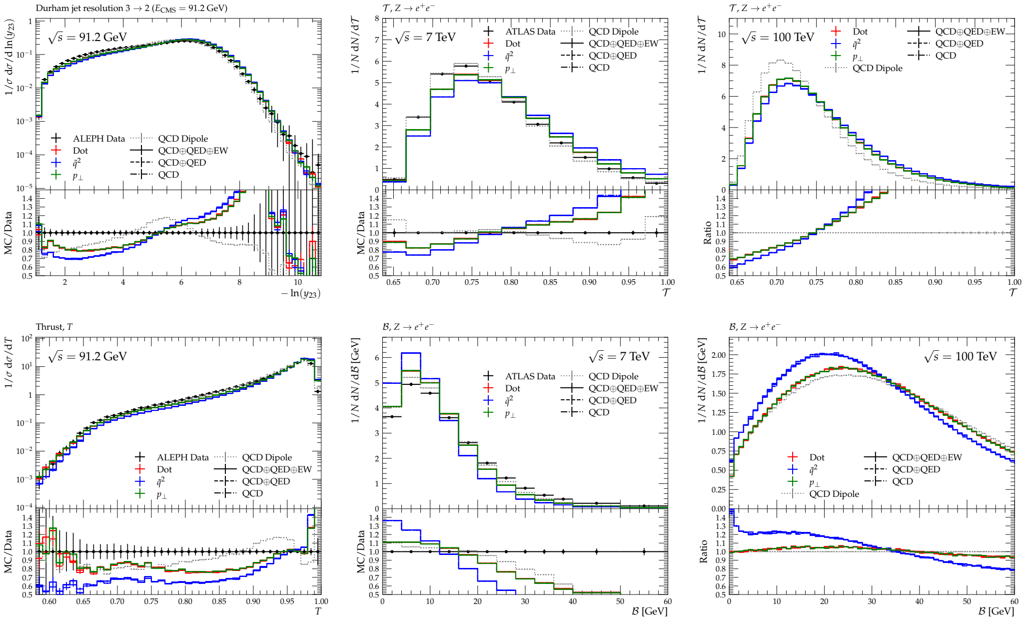
- This is a conservative choice $\Rightarrow$ **more restrictive than true QED/EW coherence**
- Concern: interleaving QED/EW emissions with QCD *might* upset this picture.
- Loss of coherence would mean overcounting wide-angle radiation, distorting jets, event shapes, and precision predictions.

Findings:

- No evidence that interleaving spoils QCD coherence.
- But misalignments with data persist in coherence-sensitive observables.

Approach: [AM, Seymour, Sule, work in progress]

- Use *coherence-sensitive observables*: jet shapes, event shapes.
- Compare pure QCD AO PS vs QCD+QED+EW AO PS.
- Develop a new *coherence tune* $\Rightarrow$ improved phenomenology.



[AM, Seymour, Sule, work in progress]

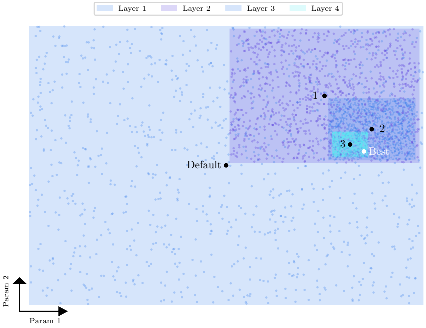
Tuning Strategy

- Direct *evaluate-and-select* strategy adopted due to high parameter dimensionality (14 parameters).
- Bounded hypercube defined around nominal settings using Latin-hypercube sampling.
- Avoided emulator (PROFESSOR II) due to degeneracies and extrapolation issues in high-dimensional space.
- Iterative process: generate ensemble $\rightarrow$ compute χ^2 $\rightarrow$ select minimum χ^2 point $\rightarrow$ recenter and shrink hypercube.
- Repeated three times to converge to a stable basin without emulator-induced bias.
- Robust χ^2 calculation using bin-weighted uncertainties with a 5

$$\chi^2(\vec{\theta}) = \sum_{h\in\mathcal{H}} w_h \sum_{b\in h} \frac{[D_{hb} - T_{hb}(\vec{\theta})]^2}{\Sigma_{hb}^2}$$

where $\Sigma_{hb}^2 = \max\left(\sigma_{hb}^{\text{data}}, 0.05 \cdot D_{hb}\right)^2$.

- Tune simultaneously constrains perturbative (shower) and non-perturbative (hadronisation) parameters.



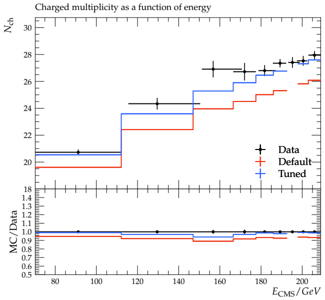
[AM, Seymour, Sule, to appear soon]

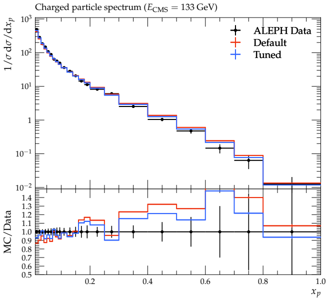
Coherence Tune for Herwig 7

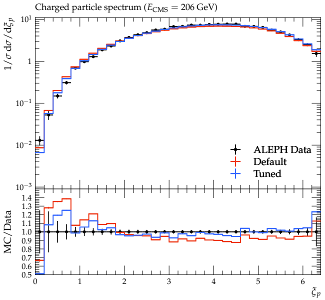
Parton-shower parameters			
Parameter	Herwig-7.3.0	Coherence Tune	Scan Range
`AlphaQCDFSR:AlphaIn`	0.115809	0.112624	[0.10, 0.13]
`AlphaQCDISR:AlphaIn`	0.115809	0.114178	[0.10, 0.13]
`PTCutOff:pTmin`	0.938419	0.956510	[0.8, 1.2] GeV
`ShowerHandler:IntrinsicPtGaussian`	2.007500	2.166640	[0.0, 5.0] GeV
Cluster-hadronisation parameters			
`ClusterFissioner:ClMaxLight`	2.915694	2.833051	[2.5, 4.0]
`ClusterFissioner:ClPowLight`	2.596680	2.467103	[0.5, 3.0]
`ClusterFissioner:PSplitLight`	0.975635	0.877047	[0.5, 2.0]
`ClusterFissioner:ProbabilityPowerFactor`	4.864188	5.983814	[1.0, 10.0]
`ClusterFissioner:ProbabilityShift`	−0.158672	−0.395582	[−10.0, 10.0]
`ClusterFissioner:KineticThresholdShift`	0.197088	0.259519	[−10.0, 10.0]
`SMHadronSpectrum:PwtSquark`	0.203449	0.302658	[0.1, 1.5]
`SMHadronSpectrum:PwtDIquark`	0.861184	0.633981	[0.1, 1.5]
`SMHadronSpectrum:SngWt`	0.439219	0.359488	[0.0, 1.0]
`SMHadronSpectrum:DecWt`	0.496738	0.382421	[0.0, 1.0]

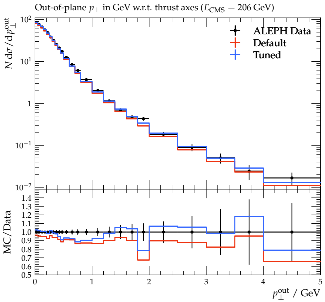
- χ^2 reduced by $\sim$ **44%** relative to Herwig-7.3.0 defaults.
- Tune spans 14 parameters: 4 parton-shower + 10 cluster-hadronisation parameters.

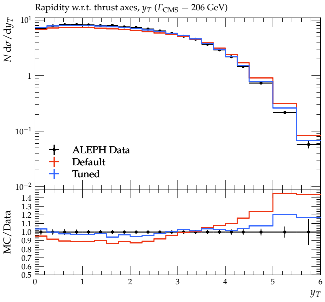
Tuning Impact

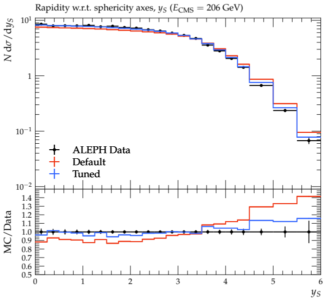












Summary

A **process-independent**, **spin-aware** framework extending Herwig 7 from QCD to a unified **QCD⊕QED⊕EW** event generator, with validated phenomenology and clear upgrade paths.

- **Electroweak parton shower:** LO, process-independent **AO EW PS** with **helicity-dependent** kernels (T/L), interleaved with QCD/QED and maintaining **coherence** via dedicated tuning.
- **BSM automation:** generalised **UFO-based** shower infrastructure for **all** $1 \to 2$ **quasi-collinear splittings**, supporting CP structures, FCNC splittings, and model-independent radiation of massive weakly-interacting states.
- **Heavy flavour & hadronisation (HQET):** `SpinHadronizer` + HQET-inspired strong/radiative decayers, improved cluster splitting kinematics and tuned parameters ⇒ better heavy-hadron predictions.
- **Quarkonium shower:** complete process-independent implementation covering **103** spin-colour-flavour configurations (CS/CO, $S/P/D$ waves, diquarks) with simple normalisation to PDG/experimental inputs.
- **Dark sector:** AO shower extended to **dark QCD-like** radiation with interleaving and hadronisation; pathway to exotic interactions (e.g. dark photon ISR/FSR).

Impact: A coherent, extensible platform for **precision SM** and **BSM** collider phenomenology, with validated observables and near-term deliverables.

"The Physics of Herwig 7", arXiv:2512.16645

Herwig-7.4.0 is coming!

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

Thank You!