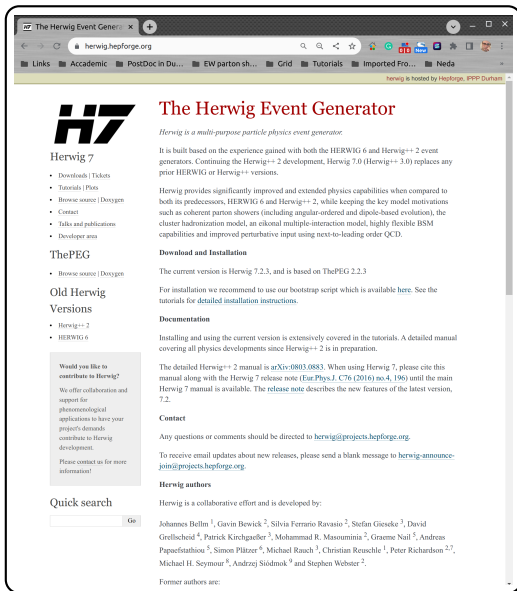


Herwig 7; What it does?

- 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



The screenshot shows the website for The Herwig Event Generator. The browser address bar shows herwig.hepforge.org. The page features the Herwig logo (H7) and the title "The Herwig Event Generator". Below the logo, there is a list of links: Downloads | Tickets, Tutorials | Plots, Browse source | Doxygen, Contact, Talks and publications, and Developer area. The main content area is divided into sections: ThePEG (with a link to "Browse source | Doxygen"), Old Herwig, and Versions (listing Herwig++ 2 and HERWIG 6). A call-to-action box asks "Would you like to contribute to Herwig?" and offers collaboration and support for phenomenological applications. There is also a "Quick search" field with a "Go" button. The page includes a "Documentation" section with a detailed Herwig++ 2 manual reference and a "Contact" section with an email address herwig@projects.hepforge.org. The "Herwig authors" section lists the collaborative effort and names of the authors: Johannes Bellm¹, Gavin Bewick², Silvia Ferrario Ravasio², Stefan Gieseke³, David Greifeisheid⁴, Patrick Kirchgaesser³, Mohammad R. Masouminia², Graeme Neil⁵, Andreas Papaefstathiou⁶, Simon Plattner⁶, Michael Rauch¹, Christian Reuschle¹, Peter Richardson^{2,7}, Michael H. Seymour⁸, Andrzej Siodmok⁹, and Stephen Webster². A note mentions "Former authors are:".

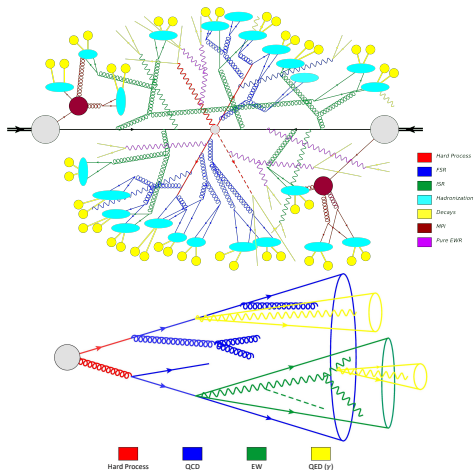
Angular-Ordered Parton Shower

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:

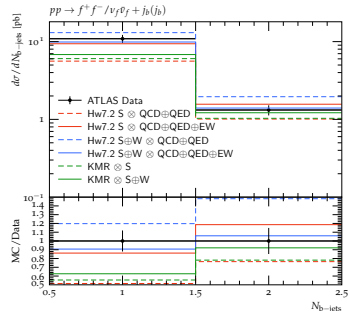
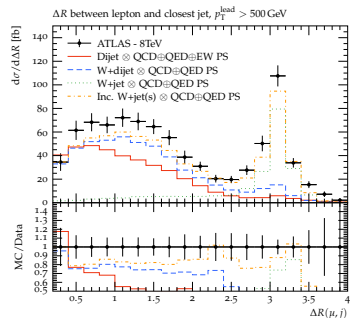
- At TeV scales, EW corrections can become large as Sudakov logarithms $\sim \alpha \log^2(Q^2/M_W^2)$.
- Precise predictions for HE-LHC and FCC require consistent inclusion of EW radiation in event generators.

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.

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.

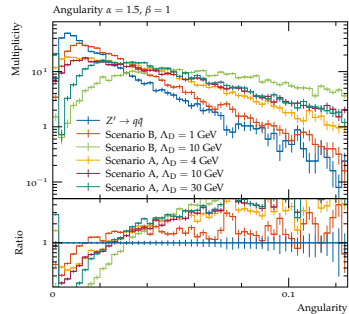
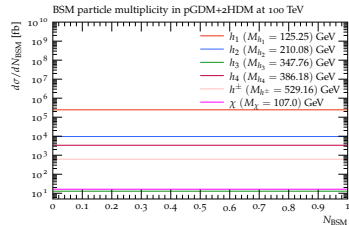
Dark PS in Herwig 7: [\[Kulkarni, AM, Plätzer, Stafford, '24\]](#)

- Implementation of the Hidden Valley Model in Herwig 7.
- A copy of QCD parton shower, with dark colour charges.
- Wrapped with a complete dark hadronisation handler.

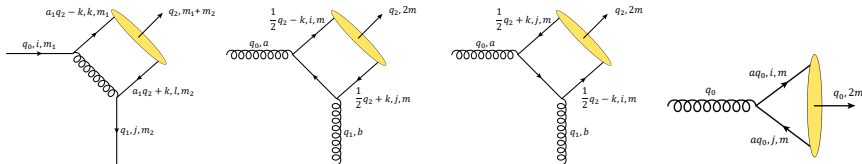
Impact:

- Accurate simulation of exotic sectors and BSM signatures. [\[Darvishi, Sule, AM, in progress\]](#)
- Enables comparison with other HV implementations, e.g. from Pythia8 to appropriate HV benchmarks.

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



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?

- 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 $g \rightarrow \mathcal{O}^{(8)}$, 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.

NRQCD Framework

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

$$A(P) = \sum_{L_Z, S_Z} \int \frac{d^3 \mathbf{k}}{(2\pi)^3} \psi_{LL_Z}(\mathbf{k}) \langle L L_Z; S S_Z | J J_Z \rangle \mathcal{M}(P, k)$$

Factorisation principle:

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

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

- Wavefunction at the origin:

$$\langle 0 | \mathcal{O}^H(^n S_J) | 0 \rangle \propto \frac{1}{4\pi} |R_H^{(^n S_J)}(0)|^2$$

Spin–colour projections:

- Spinor structures encoded via Clebsch–Gordan projections: $\langle L L_Z; S S_Z | J J_Z \rangle$
- Perturbative short-distance coefficient: $\mathcal{M}(P, k) = S_\Gamma \Gamma(P, k)$.

Colour-Singlet Branching Probability

- CS production amplitudes:

$$\mathcal{M}(q \rightarrow q' \mathcal{O}({}^n S_J)) = \frac{g_s^2 C_F \mathcal{O}_n \delta_{ij}}{\sqrt{N_C} (q_0^2 - a_1^2 M^2)} \bar{u}_j(q_1, m_2) \gamma^\nu \Pi_{n_S} \gamma^\mu u_i(p, m_1) \\ \times \left[g_{\mu\nu} - \frac{(q_1^\mu + a_2 q_2^\mu + k^\mu)(q_1^\nu + a_2 q_2^\nu + k^\nu) + (q_0^2 - a_1^2 M^2) g_{\mu\nu}}{(q_1 \cdot n + a_2 q_2 \cdot n + k \cdot n)(k^2 + q_1^2 + 2a_2 q_1 \cdot q_2 + 2q_1 \cdot k + 2a_2 q_2 \cdot k + 2a_2 q_1 \cdot q_2)} \right]$$

$$\mathcal{M}(g \rightarrow g \mathcal{O}({}^n S_J)) = \frac{g_s^2 C_F \mathcal{O}_n \delta^{ab}}{4m\sqrt{2}N_C m q_0^2} \text{Tr} \left[\left(\frac{1}{2} \not{q}_2 + \not{k} + m \right) \left(-\not{\epsilon}(q_2) \right) \left(\frac{1}{2} \not{q}_2 - \not{k} + m \right) \right. \\ \left. \times \left(-\frac{\not{\epsilon}_0^a \left(\not{q}_1 + \frac{1}{2} \not{q}_2 + \not{k} - m \right) \not{\epsilon}_1^b}{(q_1 + \frac{1}{2} q_2 + k)^2 - m^2} + \frac{\not{\epsilon}_1^b \left(\not{q}_1 + \frac{1}{2} \not{q}_2 - \not{k} + m \right) \not{\epsilon}_0^a}{(q_1 + \frac{1}{2} q_2 - k)^2 - m^2} \right) \right]$$

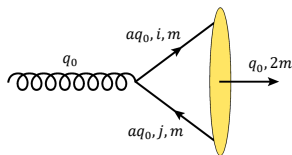
- The spin-squared/averaged and colour-averaged splitting function:

$$F_{q \rightarrow q' \mathcal{O}({}^n S_J)}(z, q_0^2) = \frac{1}{2} \sum_{\text{spins}} |\mathcal{M}(q \rightarrow q' \mathcal{O}({}^n S_J))|^2$$

- Branching probability:

$$P_{q \rightarrow q' \mathcal{O}({}^n S_J)} = \int dz dq_0^2 \frac{d\phi}{2\pi} F_{q \rightarrow q' \mathcal{O}({}^n S_J)}(z, q_0^2)$$

Colour-Octet Branching Probability



- High- p_T quarkonium production is dominated by CO fragmentation.
- $g \rightarrow Q\bar{Q}[n^{(8)}]$ 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 $g \rightarrow g\mathcal{O}^{(8)}$ or $g \rightarrow gg\mathcal{O}^{(8)}$ are required.
- The $g \rightarrow \mathcal{O}^{(8)}$ transition is modelled via a fixed probability per unit evolution time.
- This probability is governed by the LDME:

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

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

Shower Implementation

30 quarkonium splitting classes:

- 5 CS $g \rightarrow g\mathcal{O}$ classes (1S_0 , 3S_1 and $^3P_{0,1,2}$)
GtoG1S0SplitFn, GtoG3S1SplitFn, GtoG3P0SplitFn, GtoG3P1SplitFn,
GtoG3P2SplitFn
- 8 generic CS $q \rightarrow q'\mathcal{O}$ 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 $q \rightarrow q\mathcal{O}$ 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 ($^1S_0: q \rightarrow \bar{q} + (qq)_1$, $q \rightarrow \bar{q}' + (qq')_0$ and $q \rightarrow \bar{q}' + (qq')_1$)
QtoQPBarQQP0SplitFn, QtoQPBarQQ1SplitFn, QtoQPBarQQP1SplitFn
- 4 CO $g \rightarrow (\bar{q}q)$ splitting classes (3S_1 and $^3P_{0,1,2}$)
Gto3S1OctetSplitFn, Gto3P0OctetSplitFn, Gto3P1OctetSplitFn,
Gto3P2OctetSplitFn

Impact

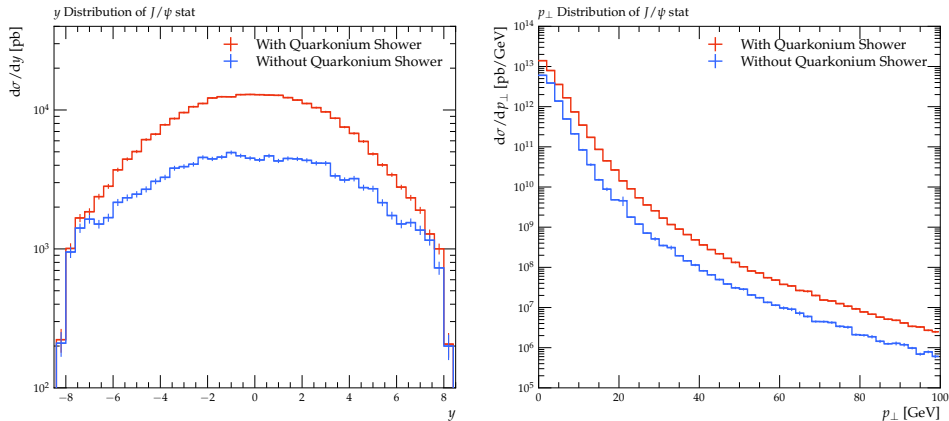


Figure: Inclusive (prompt + non-prompt) production of J/ψ quarkonia with/without the quarkonium parton shower for 10^8 events, for the un-tuned quarkonium shower.

Tuning The Non-Perturbative Parameters

$$\Gamma(\mathcal{O}(^n S_J) \rightarrow \ell^+ \ell^-) = \frac{16\pi\alpha_{\text{em}}^2}{9} \frac{|R_{nS}(0)|^2}{4\pi(2m_Q)^2} \left(1 - \frac{16}{3} \frac{\alpha_s(m_Q)}{\pi}\right), \quad \Gamma(J/\psi \rightarrow \ell^+ \ell^-) = (5.971 \pm 0.032)\%$$

Type	Structure	$ R_{nS}(0) ^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	$ R_{nS}(0) ^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	$ R_{nS}(0) ^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, to appear soon]

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

Tuning The Non-Perturbative Parameters

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

Diquark	$ R_{n_S}(0) ^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]

Table: Tuned octet parameters for selected states using all available experimental data. [AM, Richardson, to appear soon]

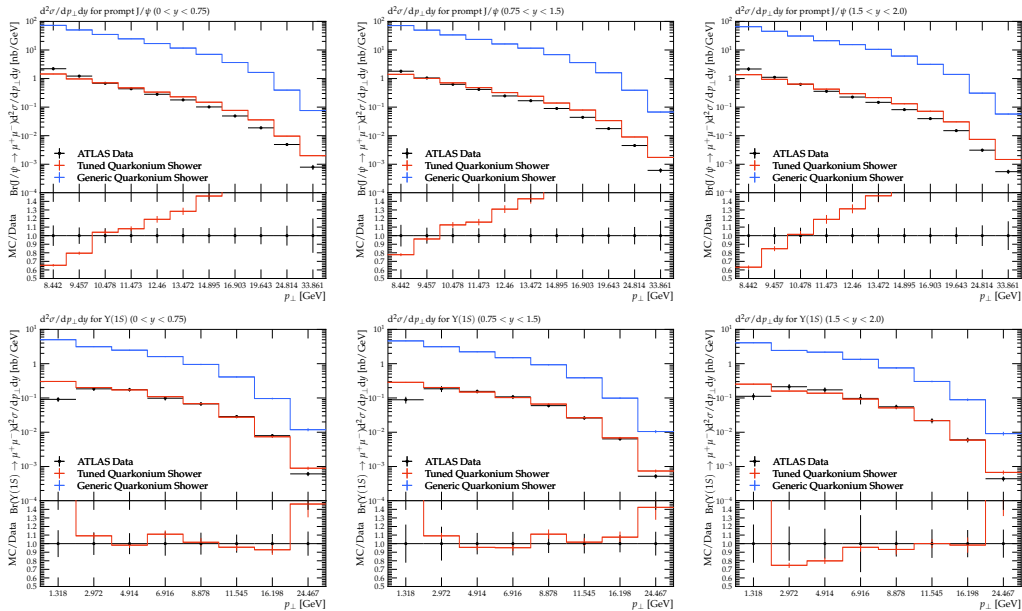


Figure: Prompt production of J/ψ and Υ states.

[AM, Richardson, to appear soon]

Final Remarks

- A complete, automated, and process-independent quarkonium parton shower has been implemented in Herwig 7.
- Defines **30** new splitting classes to cover **103** unique spin-colour-flavour configurations.
- Supports CS q - and g -initiated splittings, as well as CO transitions via gluon fragmentation.
- Handles S -, P -, and D -wave transitions across all relevant quantum numbers.
- Handles diquark for all possible configurations.
- Requires only a simple multiplicative normalisation to PDG rates (for CS) and experimental cross-sections (for CO).
- Provides a robust platform for studying quarkonium dynamics in collider physics and Monte Carlo event generators.
- Quarkonium parton shower will become available with the Herwig-7.4.0 release.

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

Thank You!