Herwig 7.3.0;
Recent Developments in the Herwig 7 Event Generator

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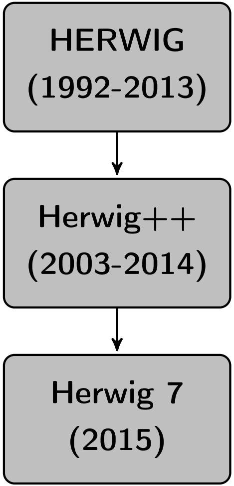
On behalf of the Herwig Collaboration

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 Hadronization, Precision Calculations

The final evlution of Herwig++ (Herwig++ 3.0)
Fully replaced both HERWIG and Herwig++
Herwig-7.0.0: [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 realease: any days now!



Structure of the code

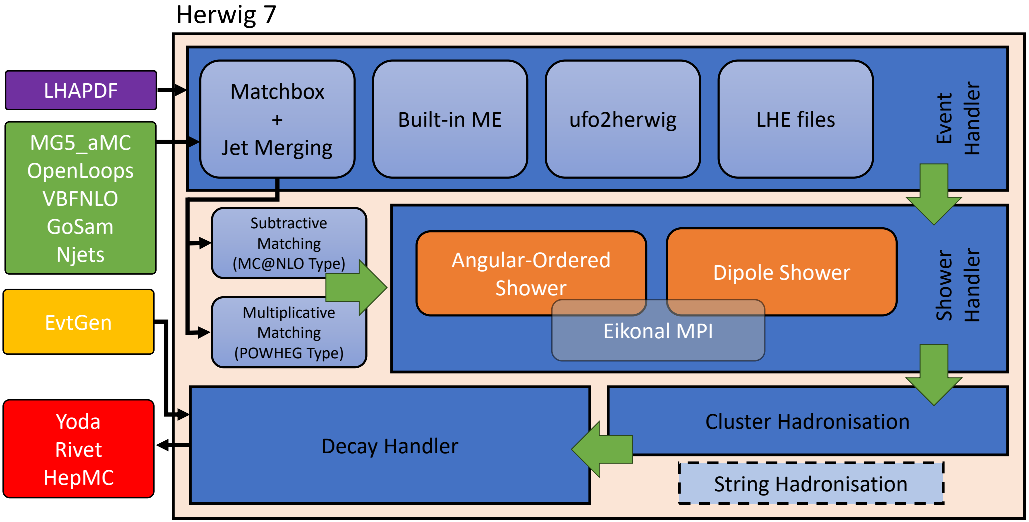
List of dependecies:

- PDF providers:
  LHAPDF
- ME providers:
  MadGraph, OpenLoops, GoSam, VBFNLO, NJet, Hjets++
- Analysis tools:
  Yoda, Rivet, HepMC
- Utilities:
  EvtGen, FastJet
- Helpers:
  Boost, GSL

Table: Herwig 7 as it stands today:

Language	**Files**	**Lines of code**
C++	1163	264809
C/C++ Header	1275	84613
Fortran 77	80	26405
m4	28	22619
Python	25	9142
Bourne Shell	5	15773
make	127	4083
Java	21	3213
Other	29	2525
SUM	2732	**433179**

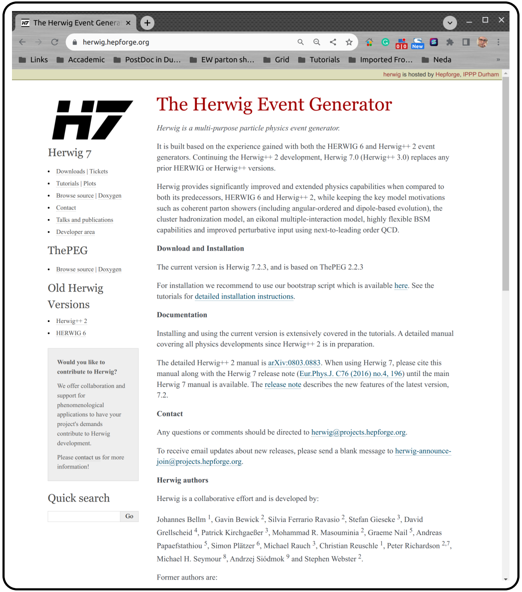
Under the Hood



Herwig 7; What it does?

– An outstanding list of features:

Angular ordered parton shower
Colour dipole parton shower
Automated matching and merging
Colour reconnection models
Colour ME corrections
Cluster hadronization model
(String plug-in being developed)
Underlying event
Flavour mass schemes
Built-in HQET for hadronisation and decay
Electroweak corrections
Multiparton hard interactions
Jet structure
Forward physics
BSM physics (BSM PS is developed)
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



The News!

– New features in Herwig-7.3.0:

- Implementation of electoweak parton shower [Richardson, AM]
- HQET in hadronisation and decay of heavy hadrons [Richardson, AM]
- AO parton showers for ISR with a new recoil scheme [Bewick, Ravasio, Richardson, Seymour]
- A new geneal tune for PS and cluster hadronization model [Richardson, AM]
- Kinematci optimisations

– Coming soon:

- Reconstruction of the cluster hadronisation [see Stefan Kiebacher's talk] [Gieseke, Kiebacher, Plätzer]
- Developments on the string hadronisation [Sarmah, Siódmok]
- KrKNLO Matching [Sarmah, Plätzer, Siódmok, Whitehead]
- Generalized angular-ordered parton showers; BSM parton shower [Lee, AM, Seymour]
- NLL dipole shower [Duncan, Holguin, Plätzer]
- Dark parton shower & hadronisation [Kulkarni, AM, Papaefstathioi, Plätzer, Siódmok, Stafford]
- ISR and FSR of dark photons at the LHC [Kling, AM, Plätzer, Reimitz]

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

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

- Gauge boson splittings (FS only)

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

- The helicity amplitudes for the splitting can then be written as

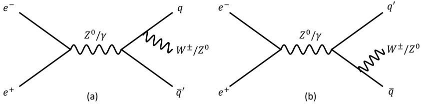
$$H_{p_0 \to p_1 p_2}(z, \tilde{q}; \lambda_0, \lambda_1, \lambda_2) = g \sqrt{\frac{2}{\tilde{q}_0^2 - m_0^2}} F^{p_0 \to p_1 p_2}_{\lambda_0, \lambda_1, \lambda_2}$$

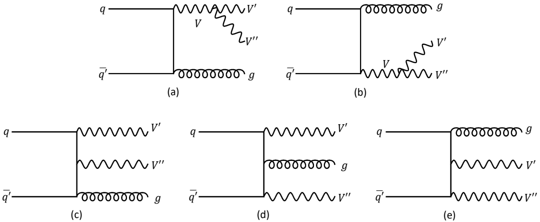
- The vertex function $F^{q \to q' V}_{\lambda_0, \lambda_1, \lambda_2}$ is determined through Feynman rules only.
- The splitting function becomes

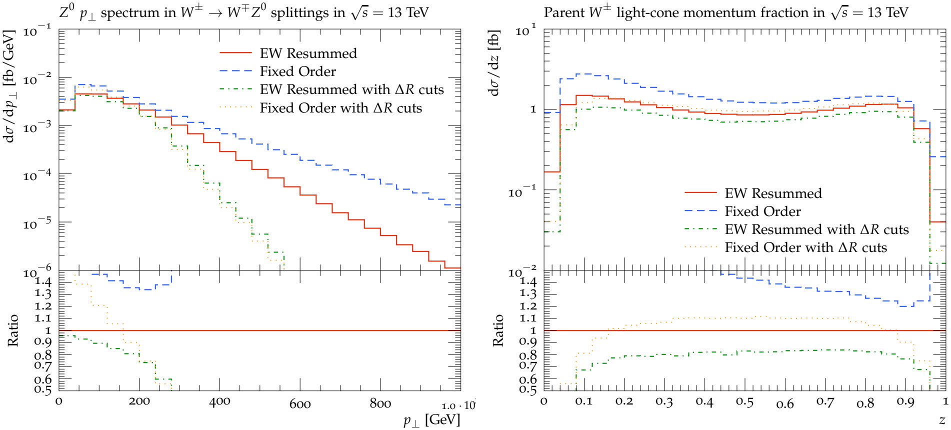
$$P_{p_0 \to p_1 p_2}(z, \tilde{q}) = \sum_{\text{spins}} \left| H_{p_0 \to p_1 p_2}(z, \tilde{q}; \lambda_0, \lambda_1, \lambda_2) \right|^2$$

Performance Tests

- In EW resummed computations we use the internal MEs `MEee2gZ2qq`, `MEWjet`, `MEZjet` and `MEGammajet`.
- The corresponding MEs for the FO calculations are generated by MadGraph5.
  [arXiv:1405.0301]
- The produced events are analysed by Rivet.
  [arXiv:1003.0694]
- Various cuts has been applied.







$W^\pm \to W^\pm Z^0$ EW branching in Herwig 7 for $\sqrt{s} = 13$ TeV, with/without ΔR cuts.

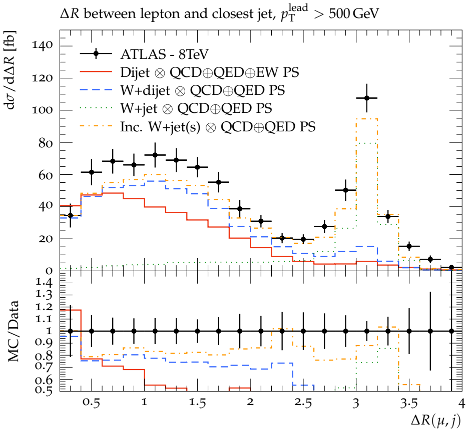
$$\Delta R_{W^\pm,V} > 1, \qquad \Delta R_{W^\pm,jet} < 1, \qquad \Delta R_{V,jet} < 1.$$

Physics Test

- The angular distribution of $W^{\pm}$ bosons accompanied with high transverse momentum jets at $\sqrt{s} = 8$ TeV. The data is from ATLAS [arXiv:1609.07045].

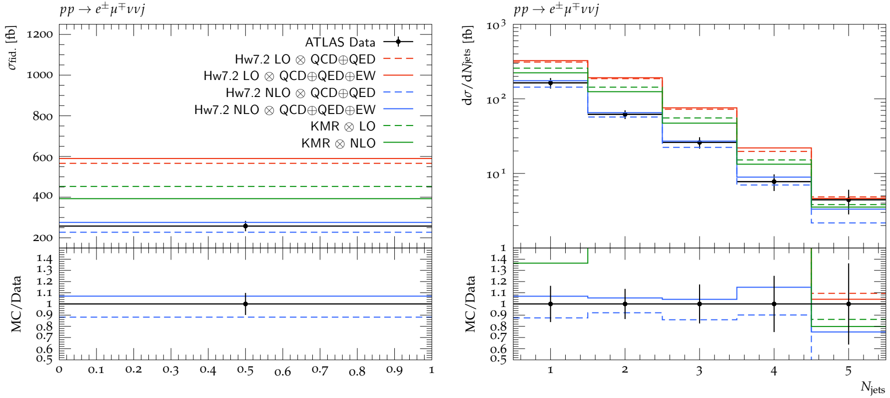
- Pure QCD di-jet event showered with EW PS $\rightarrow$ red solid histograms

- Explicit (prompt) $W^{\pm}$ plus jets $\rightarrow$ orange dashed-dotted histograms



Rich Phenomenology of EW Corrections

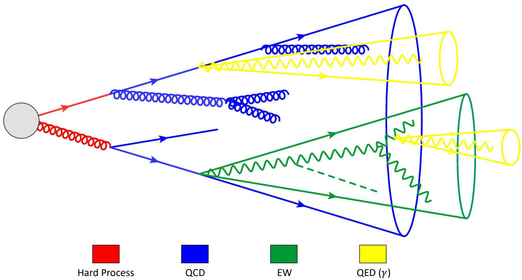
[Darvishi, AM, Nucl.Phys.B 985 (2022) 116025]



EW real and virtual corrections in production of $W^{\pm}W^{\mp}$ + jets at the LHC.

Angular-Ordered Parton Shower in Herwig

- Going to a defualt `QCD⊕QED⊕EW` meta
- By nature, AO effects are of `NLL` accuracy
- Goverend by an AO evolution scale, $\tilde{q}^2$
- 3 evolution scales to "rule them all"
- Definition of these evolution scales will determain the kinematics and the phase-space of the shower.
- The choice of the preserved quantity will determine the interpretation of $\tilde{q}^2$.



– **$\mathbf{p_T}$-preserving**: The choice to preserve the transverse momentum of each emission

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

[Marchesini, Webber, 1988; Gieseke, Stephens, Webber, 2003]

⊕ Always gives a physical solution for the transverse momentum.

⊗ Gives too much hard radiation in the parton shower, as the virtuality of the parent parton can arbitrarily grow after multiple emissions.

– **$\mathbf{q^2}$-preserving**:

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

[Reichelt, Richardson, Siodmok, 2017]

⊕ Excelent predictions.

⊕ A nearly empty dead zone!

⊗ Does not guarantee a physical solution for p_T^2.

⊗ Vetoing non-physical emissions resulted in an incorrect LL evolution.

– **dot-product preserving**:

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

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

[Bewick, Ravasio, Richardson, Seymour, JHEP 04 (2020); JHEP 01 (2022) 026]

⊕ Condition for $p_T^2 > 0$

$$\tilde{q}^2 > 2\max\left(\frac{m_1^2}{z^2}, \frac{m_2^2}{(1-z)^2}\right)$$

⊕ Large virtualities can be safely vetoed.

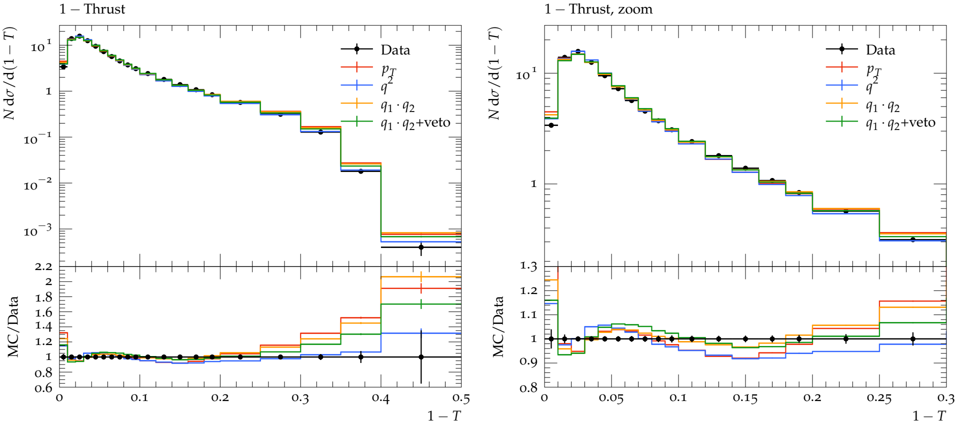
⊗ The inclusion of the masses is required to give the correct propagator.

⊗ For heavy quark radiation,

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

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.

[Bewick, Ravasio, Richardson, Seymour, JHEP 04 (2020)]



The thrust at the Z-pole compared with data from the DELPHI experiment.

Heavy Quark Effective Theory in Cluster Hadronisation

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

- For $m_Q \gg \Lambda_{\rm QCD}$, 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 color at the end of PS.
- 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. This could be realized for other possible cases, i.e.

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

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

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

- ω_j is the likelihood of fragmentation leading to a state with a maximum value of $|j_q^{(3)}|$, for a system with light degrees of freedom with spin j_q. [Richardson, AM]
- $\omega_{\frac{3}{2}} = 1/5$ and $\omega_1 = 2/3$.

HQET and the Decay Modes of the Excite Heavy Mesons

- Improving the **strong isospin-conserving** decay modes
  - $J^P = 0^-, 1^-$ doublet; D and $D^\star$
  - $J^P = 1^+, 2^+$ doublet; D_1 and $D_2^\star$
  - $J^P = 0^+, 1^+$ doublet; $D_0^\star$ and D_1'
- The **electromagnetic** and **strong isospin-violating** decay modes
  - Particular importance where the strong isospin conserving decays are either **not allowed** or **kinematically suppressed**.
  - D^* and B^* mesons, where the strong decays are kinematically suppressed and radiative modes are important.
  - D_s^{*+}, D_{s0}^{*+} and $D_{s1}^+(2460)$ mesons, where both radiative and isospin-violating decay modes are important as the strong isospin conserving DK modes are kinematically forbidden.
  - the B_s^{*0} where only the radiative mode is kinematically allowed.
  - The D_s system is the most complicated as there are many excited mesons below the strong decay threshold.
- Has been used for heavy baryon decays since Herwig++.

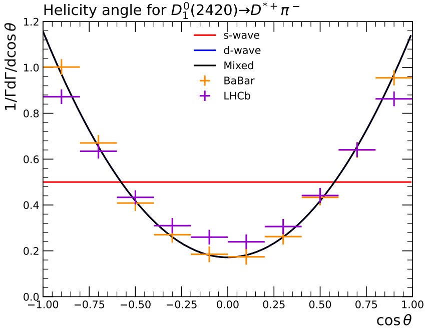
Decay Modes

For 2-body decay modes:

$$\mathcal{M}(D^\star \to D\pi) = -\frac{2g}{f_\pi}\left(m_D m_{D^\star}\right)^{\frac{1}{2}} p_0 \cdot \epsilon_0$$

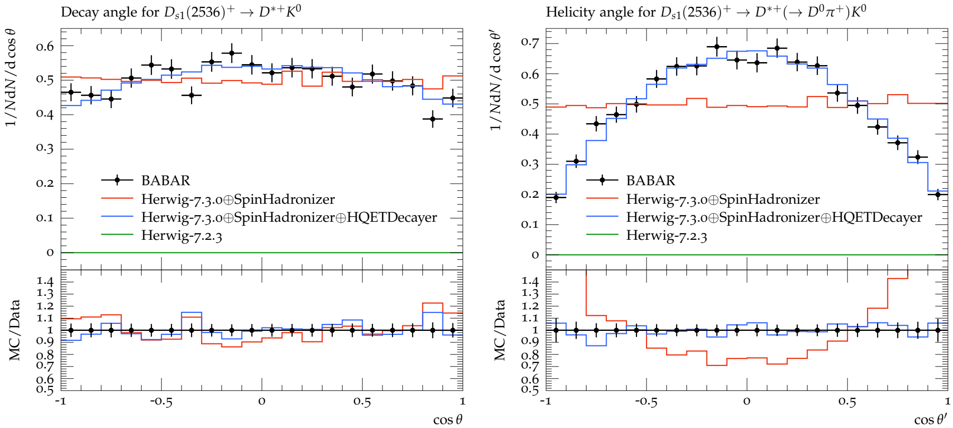
$$\Gamma(D^\star \to D\pi) = \frac{1}{8\pi\ m_{H^\star}^2}\left|\mathcal{M}(D^\star \to D\pi)\right|^2 p_{\rm CM}$$

$$\Gamma(D^\star \to D\pi) = \frac{g^2}{6\pi f_\pi^2}\frac{m_D}{m_{D^\star}} p_{\rm cm}^3$$



Parameter	Fitted Value
f_π	0.130 ± 0.001 [GeV]
g	0.565 ± 0.006

HQET in Herwig 7



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

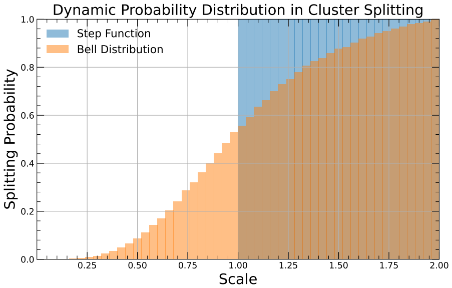
Kinematic Optimization in Cluster Hadronisation

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

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

Probability of cluster splittings for heavy clusters:

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



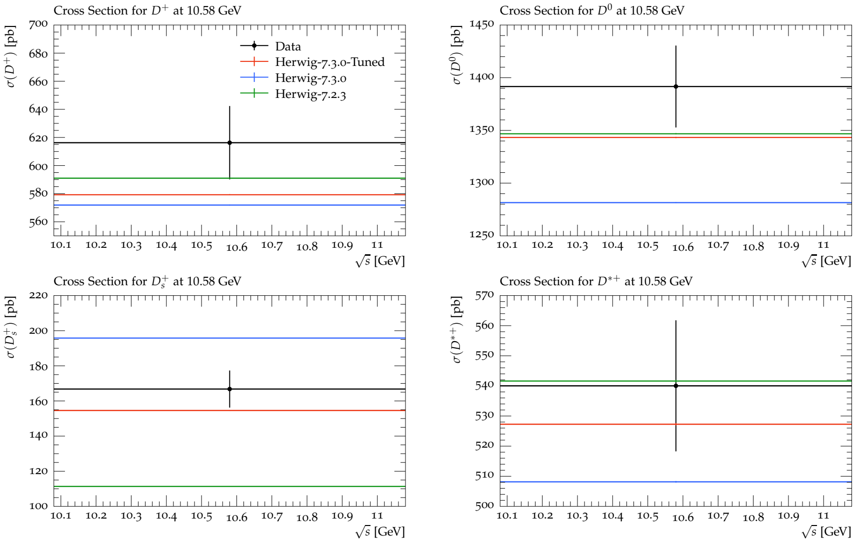
General Tune for Herwig-7.3.0

- 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.
- 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).

General Tune for Herwig-7.3.0

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

The values of tuned parameters in Herwig 7.3.0 compared to Herwig 7.2.0.



Comparison of heavy meson production rates at LEP, from various experimental data sets.

A Sneak Peek

Reconstruction of Cluster Hadronisation

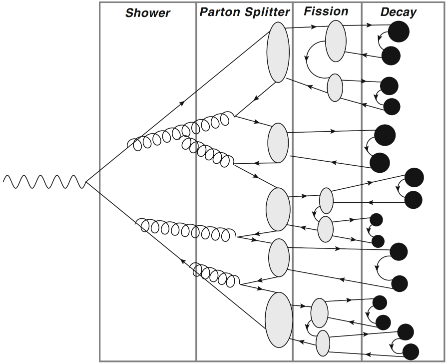
- Too late for Herwig-7.3.0 → Herwig-7.3.1
  - Dynamic hadronization model and the possibility to extract hadronization corrections in a clean way

    [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

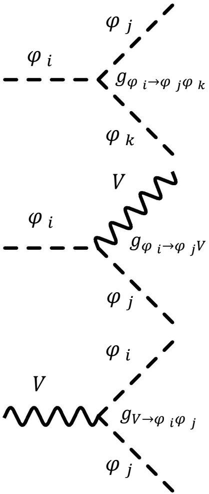
    [Gieseke, Kiebacher, Plätzer]
  - KrKNLO matching scheme

    [Sarmah, Plätzer, Siódmok, Whitehead]
- For more details see Stefan Kiebacher's talk.



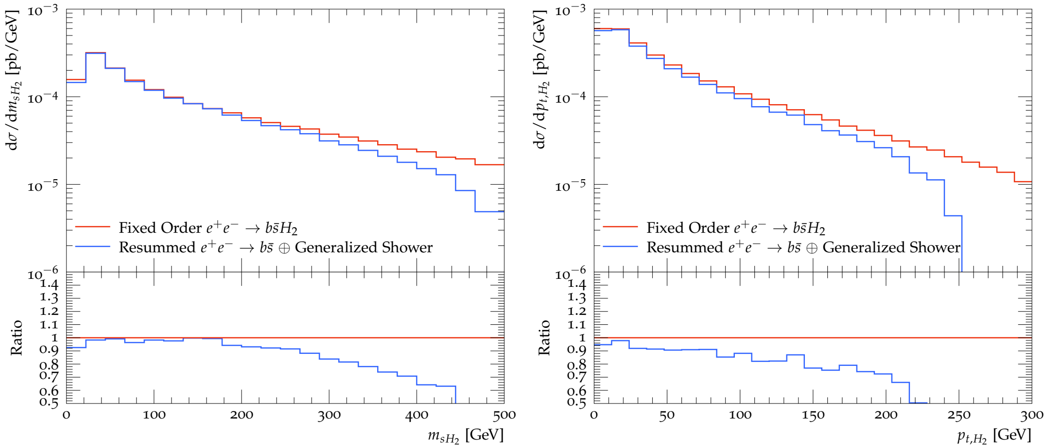
Plot from [arXiv:1811.10336]

Generalized Parton Showers in Herwig 7



- Introducing model-independent generalized radiations of massive weakly-interacting particles in AO PS.
  - `QCD⊕QED⊕EW` PS
  - `ufo2herwig`
- Collecting "all possible" spin-unaveraged splitting functions in quasi-collinear limit:
  - Spin-0 → Spin-0, Spin-0
  - Spin-0 → Spin-0, Spin-1
  - Spin-1 → Spin-0, Spin-0
- CP-odd couplings and FCNC splittings. [Lee, AM, Seymour]
- Also possible to add exotic interactions (currently only model-dependent).
  - ◇ Dark photon production in IS and FS radiations [Kling, AM, Plätzer, Reimitz]
  - ◇ Dark parton shower and dark hadronisation [Kulkarni, AM, Papaefstathioi, Plätzer, Siódmok, Stafford]
- Available with future releases.

Performance Test



$b \to sH_2$ splitting (FCNC process) for the general 2HDM with $M_{H_2} = 10$ GeV for $\sqrt{s} = 1$ TeV at LEP. (RS) ME($e^+e^- \to b\bar{b}$) + PS and (FO) ME($e^+e^- \to b\bar{b}H_2$) with out PS.

Herwig-7.3.0

Herwig-7.3.x, x>0

Thank You!

Under Development

- Heavy Quark Systems:
  - Hadrons with dual heavy quarks
  - Efficient generation of g $\rightarrow$ heavy quark pairs within the shower
- Collision and Cross-Section Models:
  - Photon-photon collision simulation
  - Diffractive cross-sections employing multi-channel eikonal models
- Reconnection and Reweighting:
  - Extended Color Reconnection model
  - Hard process reweighting in Matchbox
- Hadronization Models:
  - String model tuning for hadronization
  - Introduction of new model tunes
- Baryon Physics:
  - W-heavy baryon studies
  - Enhanced baryon decay algorithms
- Advanced Showering Mechanisms:
  - Two-particle correlation effects
  - New recoil schemes in dipole showers
  - Reconstruction of the dipole parton shower and dipole boosts
- Specialized Physics:
  - Sphaleron-related physics
  - Mambo phase space studies
  - Investigation of QCD instantons
- Precision Parton Shower:
  - EW Matching and Merging
  - EW coherence