BSM Parton Shower in

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On behalf of the Herwig Collaboration

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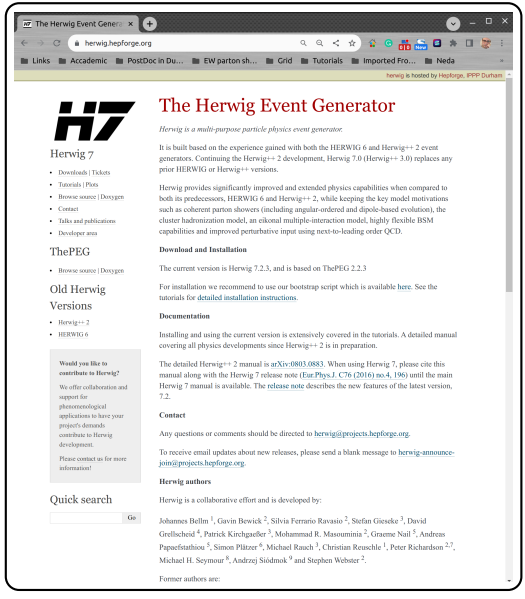
Durham University

IP3

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
```



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+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+QED+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]

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

– Gauge boson splittings (FS only)

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

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

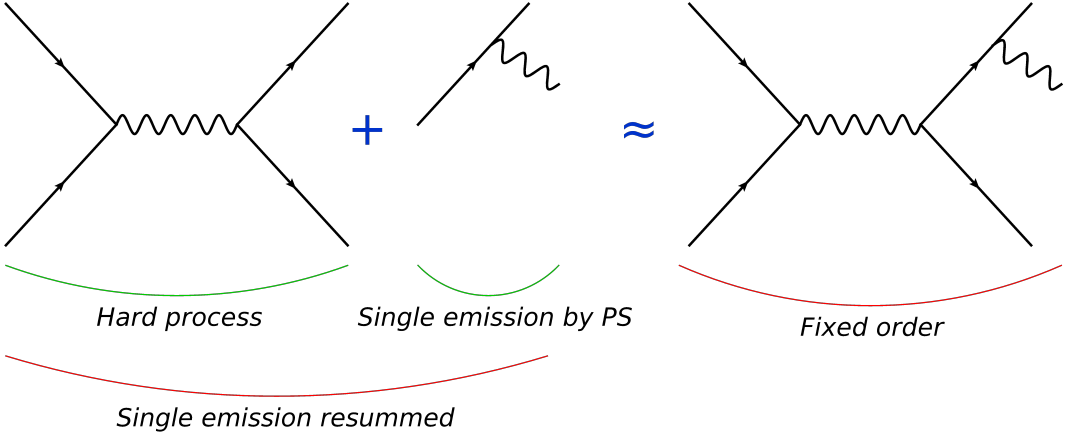
$$H_{p_0 \to p_1 p_2}(z, \tilde{q}; \lambda_0, \lambda_1, \lambda_2) = g \sqrt{\frac{2}{\tilde{q}_0^2 - m_0^2}} F^{p_0 \to p_1 p_2}_{\lambda_0, \lambda_1, \lambda_2}$$

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

– The splitting function becomes

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

Performance Tests

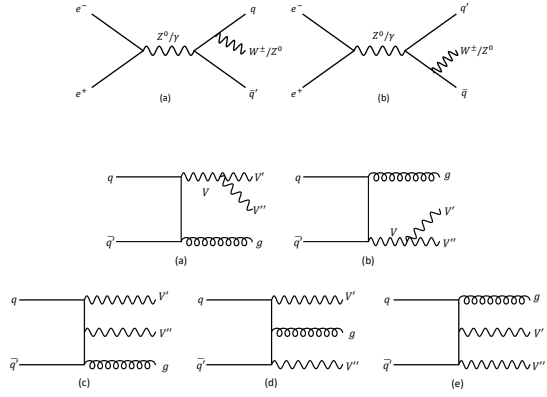


Performance Tests

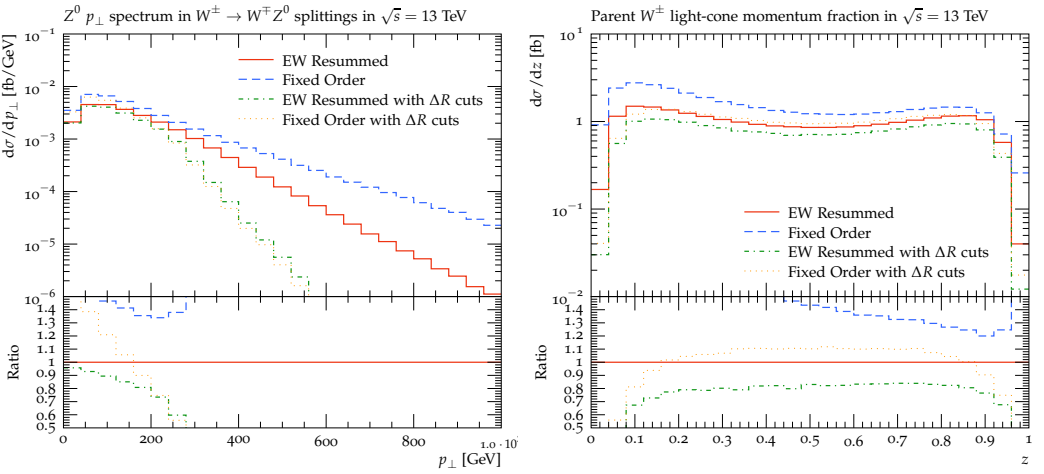
- In EW resummed computations we use the internal MEs `MEee2gZ2qq`, `MEWjet`, `MEZjet` and `MEGammajet`.
- The corresponding MEs for the FO calculations are generated by MadGraph5.

  [arXiv:1405.0301]
- The produced events are analysed by Rivet.

  [arXiv:1003.0694]
- Various cuts has been applied.



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



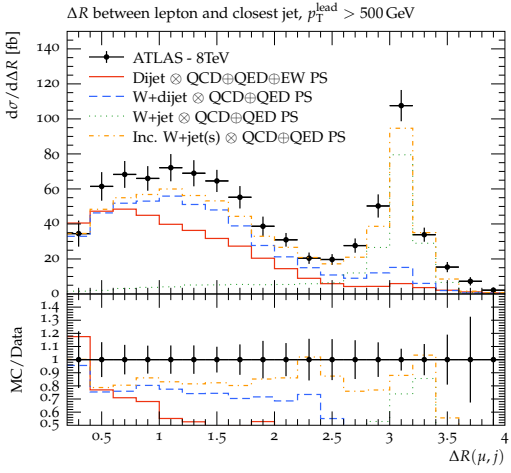
$W^\pm \to W^\pm Z^0$ EW branching in Herwig 7 for $\sqrt{s} = 13$ TeV, with/without ΔR cuts.

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

Physics Test

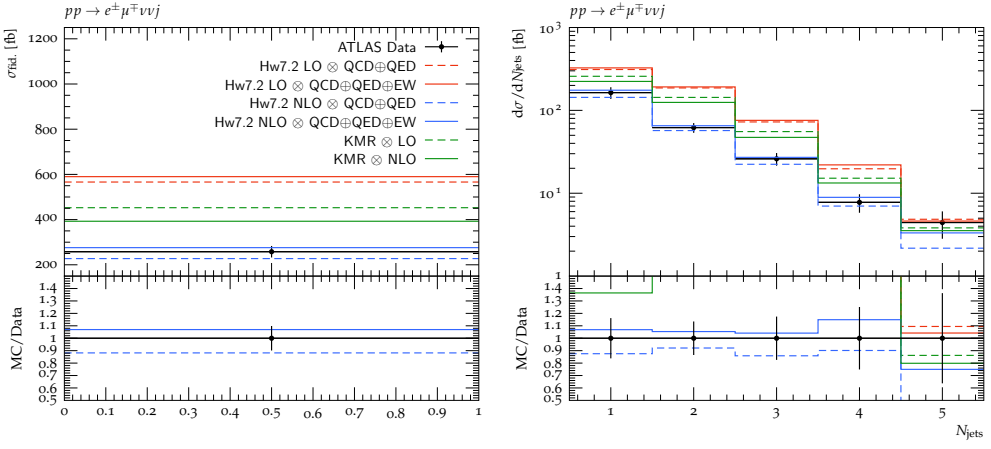
[Richardson, AM, JHEP 04 (2022) 112]

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



Rich Phenomenology of EW Corrections

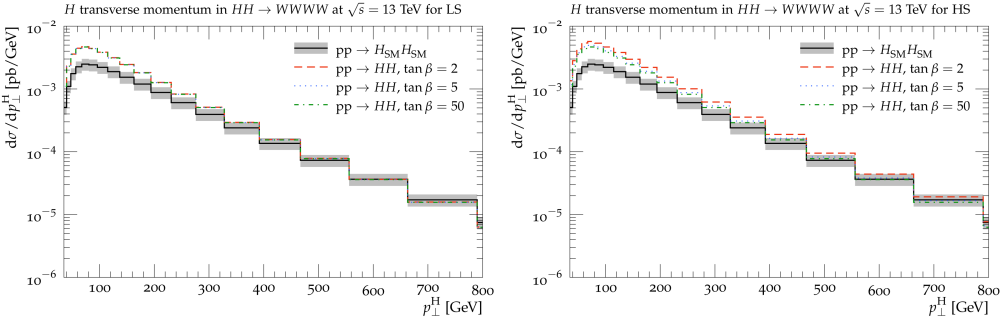
[Darvishi, AM, Nucl.Phys.B 985 (2022) 116025]



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

Rich Phenomenology of EW Corrections

[Darvishi, AM, Phys.Rev.D 103 (2021) 9, 095031]



Differential cross-section of $W^{\pm}$-quadruplet productions through double SM-like Higgs boson events in MS-2HDM [Darvishi, Pilaftsis, Phys.Rev.D 99 (2019) 11, 115014].

Generalised Parton Shower in Herwig

- **Model independence and flexibility:** Supports a broad range of BSM scenarios using Universal `FeynRules` Output (UFO).
  [Alloul, Christensen, Degrande, Duhr, Fuks, Comput.Phys.Commun. 185 (2014) 2250-2300]
- **Complex particle interactions:** Manages interactions involving and couplings, crucial for BSM physics.
- **Kinematic features of BSM radiation:** Enhances simulation accuracy by addressing unique kinematic properties of BSM particles.
- **Efficiency in simulations:** Provides computational efficiency, critical for exploring extensive BSM parameter spaces.
- **Validation and compatibility:** Allows rigorous validation against experimental data, ensuring practical reliability.
- **Computational advantages:** Low mass BSM bosons can be produced during the PS process without considering higher-order corrections to the MEs or BSM hard processes.

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.

$$-i\mathcal{M}\left[\begin{array}{l}\bar{u}(q_1)\\ \\ u(p)\end{array}\right] = \bar{u}(q_1)\big[-i(\kappa + \tilde{\kappa}\gamma_5)\big]u(p)$$

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

Interfacing to BSM Models

– Translate a `UFO` into a `Herwig` model file:

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

– Model properties written into "FRModel.model" file:

```
read FRModel.model
```

– For example, if the model has a $H^+H^-H_1$ vertex:

```
create Herwig::ZeroZeroZeroEWSplitFn hphph1SplitFnEW
```

– Automatically sets up the interaction type:

```
set hphph1SplitFnEW:InteractionType EW
set hphph1SplitFnEW:ColourStructure EW
```

– Extracts coupling values from the model, explicitly:

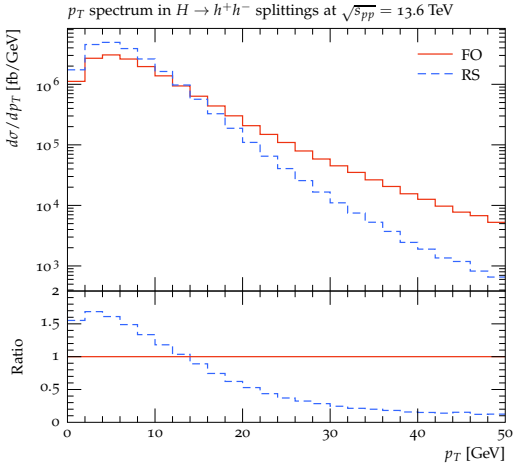
```
set hphph1SplitFnEW:CouplingValue.Im 3261.0203694564357
set hphph1SplitFnEW:CouplingValue.Re 0.0
```

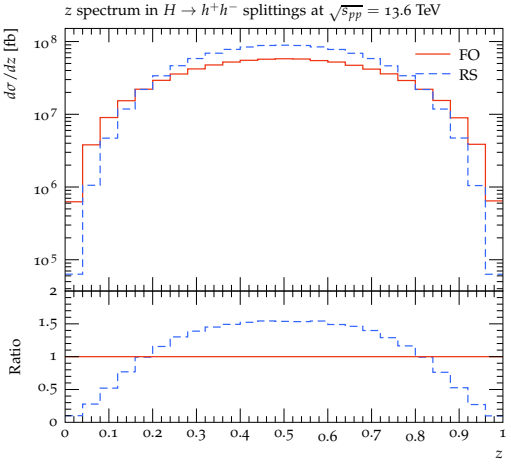
– Adds the splitting to the AO shower algorithm:

```
do SplittingGenerator:AddFinalSplitting h+->h+,h1; hphph1SudakovEW
```

Performance Tests

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



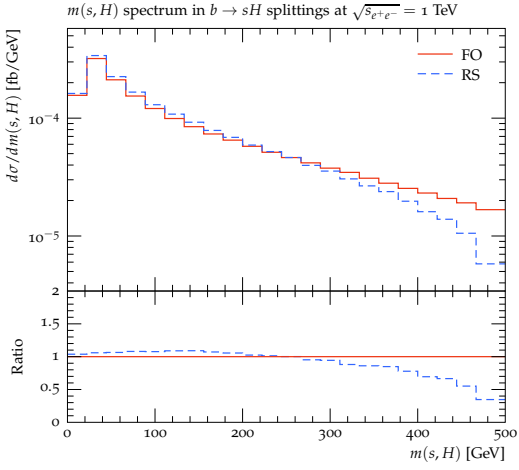


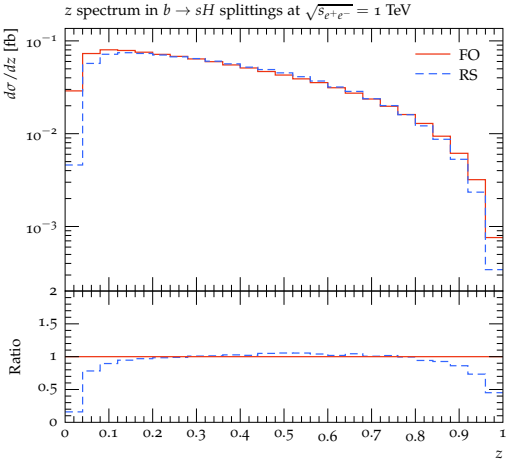
BSM $H \to h^+h^-$ branching in general 2HDM with $m(H, h^+) = 10$ GeV.

FO: $pp \to h^+h^- j$(MG5), RS: $pp \to Hj$(MG5) $+ H \to h^+h^-$(Hw7)

Performance Tests

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



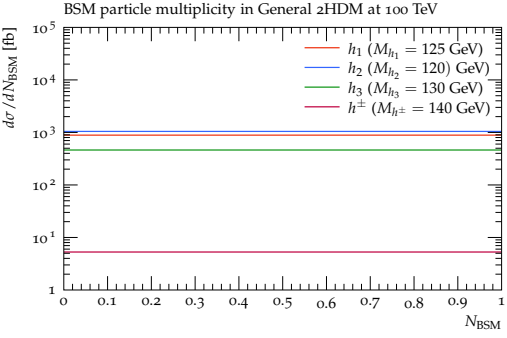


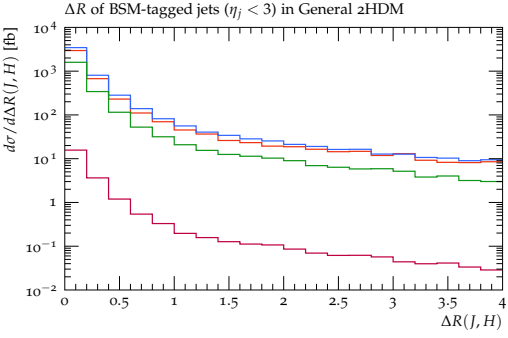
BSM $b \to sH$ FCNC branching in general 2HDM with $m(H) = 10$ GeV.

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

Phenomenology of BSM parton shower

[Darvishi, Lee, AM, Work in progress]

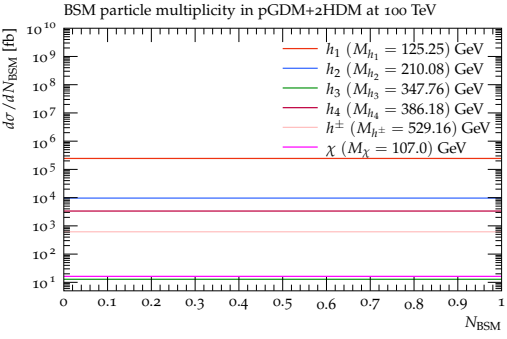


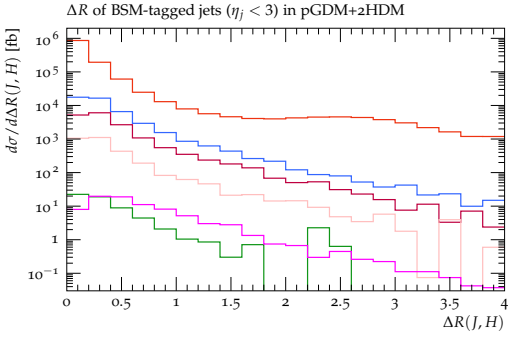



```
read General-2HDM.model
set EventGenerator:EventHandler:LuminosityFunction:Energy 100000.0*GeV
insert SubProcess:MatrixElements[0] MEQCD2to2 #(i.e. a purely SM ME)
set /Herwig/Cuts/Cuts:MHatMin 5000.*GeV
set /Herwig/Shower/ShowerHandler:Interactions ALL #(i.e. QCD+QED+EW)
```

Phenomenology of BSM parton shower

[Darvishi, Lee, AM, Work in progress]






```
read pGDM+2HDM.model
set EventGenerator:EventHandler:LuminosityFunction:Energy 100000.0*GeV
insert SubProcess:MatrixElements[0] MEQCD2to2 #(i.e. a purely SM ME)
set /Herwig/Cuts/Cuts:MHatMin 5000.*GeV
set /Herwig/Shower/ShowerHandler:Interactions ALL #(i.e. QCD+QED+EW)
```

[Darvishi, Grzadkowski, JHEP 06 (2022) 092]

Summary & Outlook

- Implementation of fully process-independent QCD+QED+EW AO parton shower.
  [Richardson, AM, JHEP 04 (2022) 112]
- Introducing model-independent generalized radiations of massive weakly-interacting particles in AO PS. [Lee, Seymour,Yang, AM, arXiv:2312.13125]
  - Expanded QCD⊕QED⊕EW PS
  - Updated ufo2herwig
- Collecting "all possible" spin-unaveraged splitting functions in quasi-collinear limit by adding
  - Spin-0 → Spin-0, Spin-0
  - Spin-0 → Spin-0, Spin-1
- CP-even/CP-odd couplings and FCNC splittings.
- Becomes available with the upcoming Herwig 7.4.0 release.

▷ Planned extension to include upto spin-2 particle splittings.

▷ Also possible to add exotic interactions (currently only model-dependent).
  - ◇ Dark photon production in IS and FS radiations
    [Kling, Plätzer, Reimitz, AM]
  - ◇ Dark parton shower and dark hadronisation (Hidden Valley model)
    [Kulkarni, Papaefstathioi, Plätzer, Siódmok, Stafford, AM]

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

Thank You!