Karlsruhe Institute of Technology

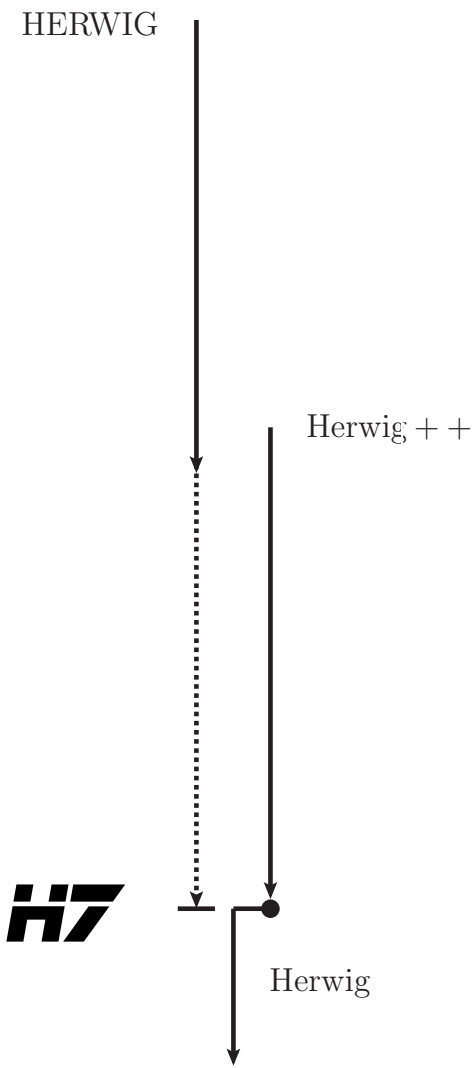
Herwig

on behalf of the Herwig 7 team

Michael Rauch | MC4BSM 2016, Jul 2016

INSTITUTE FOR THEORETICAL PHYSICS

Herwig Evolution



HERWIG:
Fortran code, last version 6.521
(1992-2002)
[Marchesini, Webber, Abbiendi, Corcella, Knowles, Moretti, Odagiri, Richardson, Seymour, Stanco]

Herwig++:
C++ rewrite , last version 2.7.1 (2004-2014)
[Bähr, Gieseke, Gigg, Grellscheid, Hamilton, Latunde-Dada, Plätzer, Richardson, Seymour, Sherstnev, Tully, Webber]
intended to fully replace Fortran version

experimental and phenomenological evolution over time
$\Rightarrow$ precision as key goal

Herwig++ 3.0 $\rightarrow$ **Herwig 7.0**

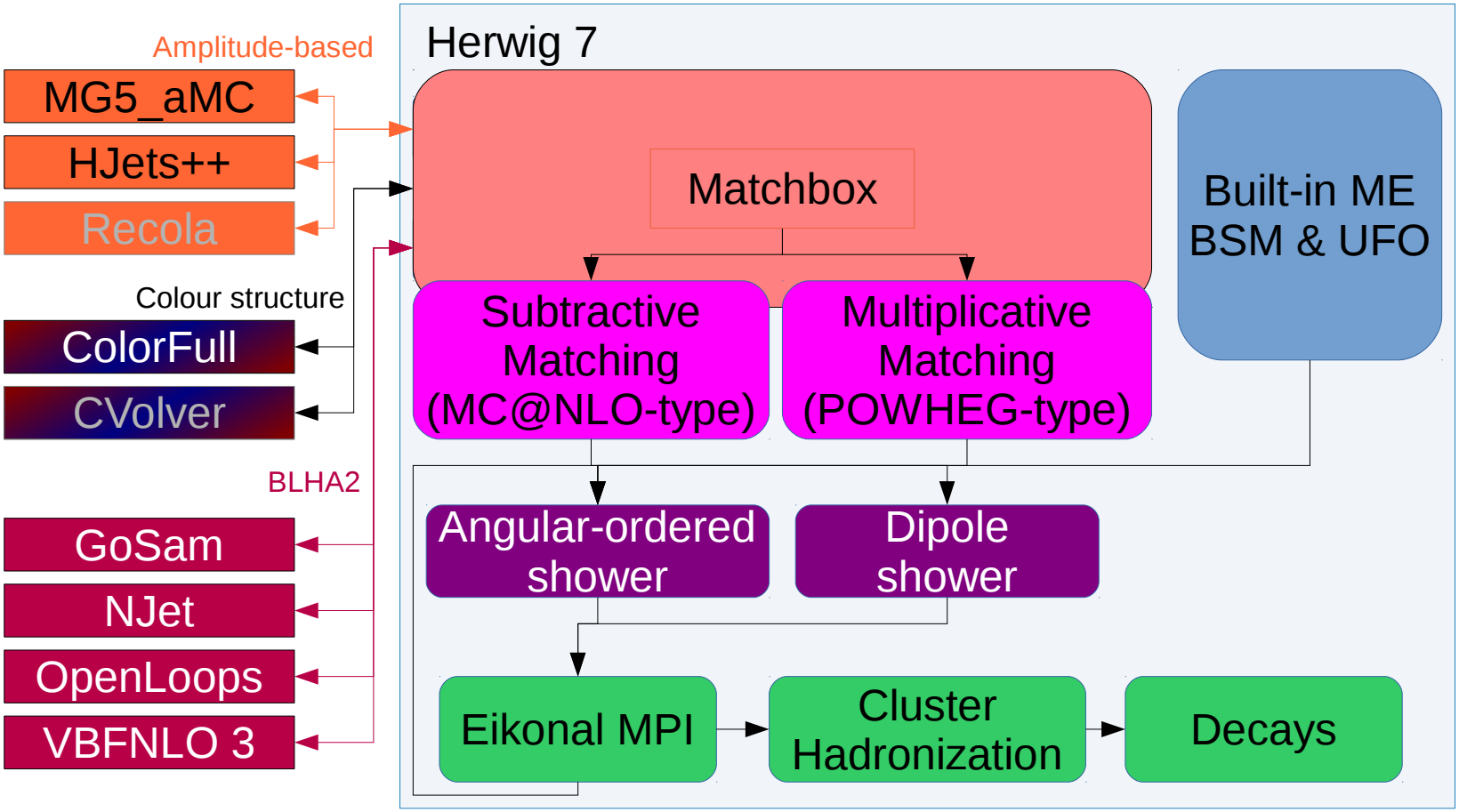
[Bellm, Gieseke, Grellscheid, Plätzer, MR, Reuschle, Richardson, Schichtel, Seymour, Siódmok, Wilcock, Fischer, Harrendorf, Nail, Papaefstathiou, D. Rauch]

Features

Main features of Herwig 7:

- NLO matched to parton showers as new default
  - Matching/merging mechanism fully generic, fully automated
  - Two matching schemes implemented
    - subtractive (MC@NLO-type)
    - multiplicative (Powheg-type)
  - performed by Matchbox module
    [work led by S. Plätzer with substantial contributions by J. Bellm, A. Wilcock, MR, C. Reuschle]
  - matrix elements in general from external providers via linked library
- Two parton-shower implementations
  - Angular-ordered shower
  - Dipole shower
- Spin correlations and QED radiation in angular-ordered shower [Richardson]
  last missing feature from Fortran HERWIG
- Parton-shower uncertainties [Bellm, Nail, Plätzer, Schichtel, Siódmok]
- Parton-shower reweighting [Bellm, Plätzer, Richardson, Siódmok, Webster]
- Improved documentation, much more user-friendly input files

Structure


Amplitude-based
MG5_aMC
HJets++
Recola
Colour structure
ColorFull
CVolver
BLHA2
GoSam
NJet
OpenLoops
VBFNLO 3
Herwig 7
Matchbox
Built-in ME
BSM & UFO
Subtractive
Matching
(MC@NLO-type)
Multiplicative
Matching
(POWHEG-type)
Angular-ordered
shower
Dipole
shower
Eikonal MPI
Cluster
Hadronization
Decays

Input

New-style input files

- common code fragments separated into snippets
- include with simple `read <file>` statement
- small complete input file example:

```
read Matchbox/PPCollider.in                          ← collider setup

cd /Herwig/MatrixElements/Matchbox                   ← process setup
set Factory:OrderInAlphaS 0
set Factory:OrderInAlphaEW 2
do Factory:Process p p -> e+ e-
read Matchbox/MadGraph-OpenLoops.in                  ← amplitude provider

read Matchbox/FiveFlavourScheme.in                   ← additional options
read Matchbox/MCatNLO-DefaultShower.in               ← e.g. shower and matching

do /Herwig/MatrixElements/Matchbox/Factory:ProductionMode
cd /Herwig/Generators
saverun LHC EventGenerator
```

Installation and Usage

- Simple installation via bootstrap script

  ```
  ./herwig-bootstrap <installation directory>
  ```

  by default also installs external matrix providers (GoSam, HJets++, MadGraph5_aMC@NLO, NJet, OpenLoops, VBFNLO) simultaneously

- Simple running

  ```
  Herwig build LHC.in
  Herwig integrate LHC.run
  Herwig run LHC.run
  ```

- lots of parallelization

  - grid adaption parallel with separate jobs (no IPC)

    ```
    Herwig build LHC.in -z1
    for i in `seq 0 <maxjobs>`; do
      <qsub> Herwig integrate LHC.run --jobid=$i; done
    ```

  - parallel running on multi-core machines

    ```
    Herwig run --jobs=8 LHC.run
    ```

- live documentation via sphinx sites at

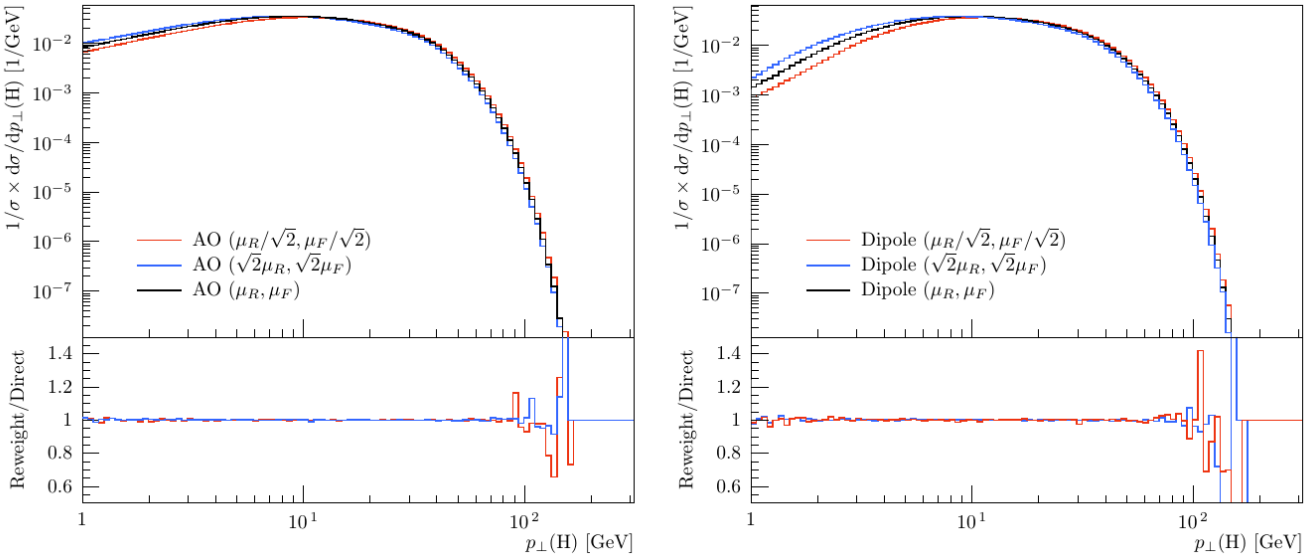
  ```
  https://herwig.hepforge.org
  ```

Parton-Shower Reweighting

Run-time improvement via parton-shower reweighting

[Bellm, Plätzer, Richardson, Siódmok, Webster]

Transverse momentum of Higgs boson in $pp \to gg \to H$, $\sqrt{S} = 13$ TeV

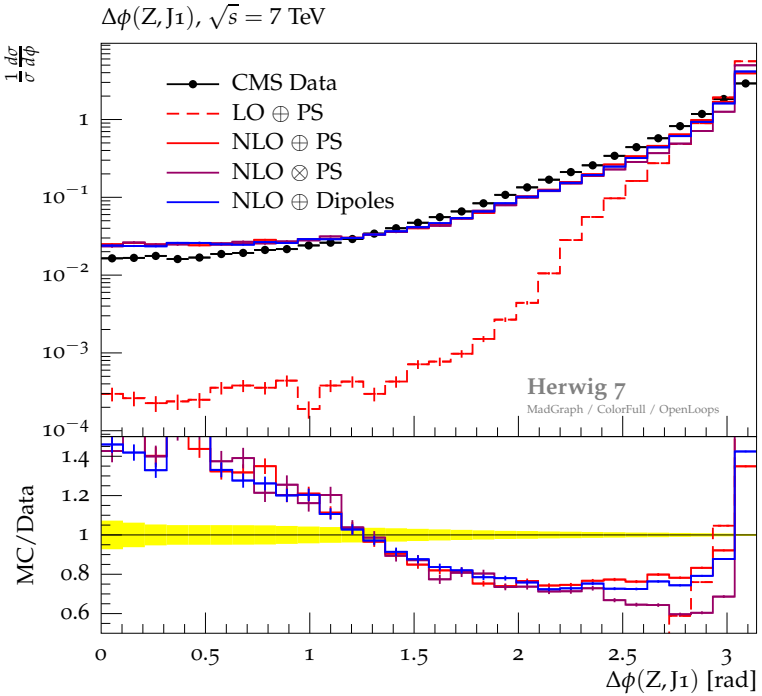


- excellent agreement between individual runs for different scales and reweighting
- significant speed improvements: time in seconds for 10 000 events

Shower	Hadron-ization & Decays	No MPI			MPI					
					Primary			All		
		Direct	Reweight	Frac. Diff.	Direct	Reweight	Frac. Diff.	Direct	Reweight	Frac. Diff.
AO	Off	79.8	94.2	-0.18	384.4	249.1	0.35	416.7	375.1	0.09
	On	183.2	128.3	0.30	738.7	364.3	0.51	751.4	482.3	0.35
Dipole	Off	99.6	52.8	0.47	435.4	161.9	0.63	462.7	213.6	0.54
	On	271.8	108.2	0.60	831.7	286.6	0.65	859.2	340.1	0.60

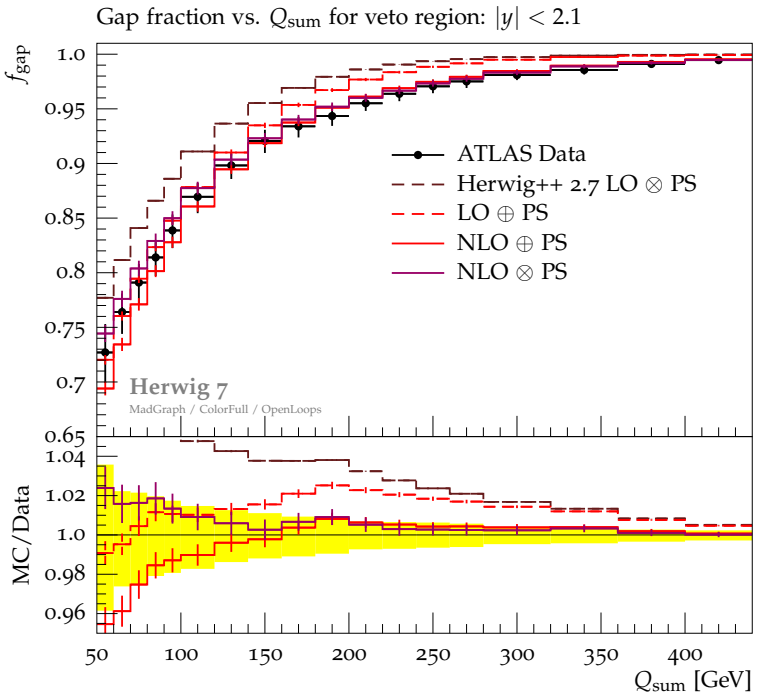
Physics Results (1)

$pp \to Z +$ jets (CMS, 7 TeV)



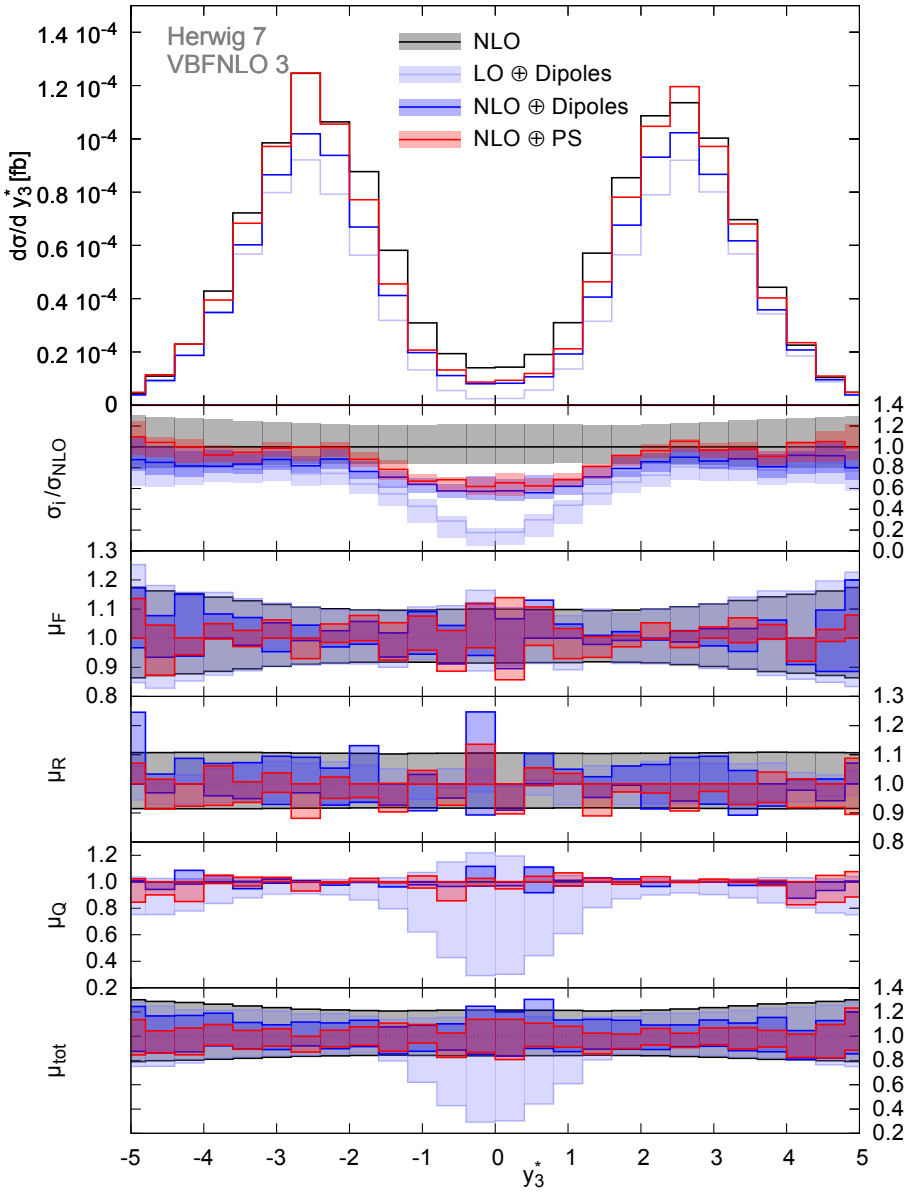
- $\Delta\phi \sim \pi$: LO kinematics
- $\Delta\phi < \pi$: Z recoiling against additional jet(s)
- agreement between parton showers/matching schemes $\to$ important cross-check

$pp \to t\bar{t}$ (ATLAS, 7 TeV)



- jet activity in $t\bar{t}$ events
- gap fraction: event fraction with $\sum p_T$ of additional jets $< Q_{\text{sum}}$
- $\to$ improved description

Physics Results (2)



[MR, Plätzer]

Parton-shower effects and matching systematics in

$pp \to W^+W^-jj \to e^+\nu_e\mu^-\bar{\nu}_\mu jj$

via vector-boson fusion

Rapidity of third jet relative to two tagging jets

$$y_3^* = y_3 - \frac{y_1+y_2}{2}$$

central rapidity gap is important feature of process

$\to$ stabilized at NLO

$\to$ good agreement between both parton showers

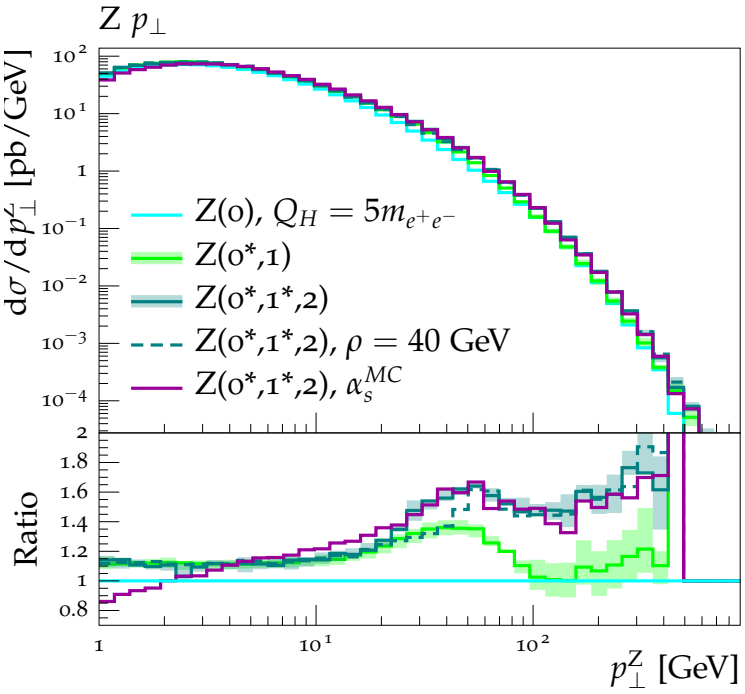
Merging

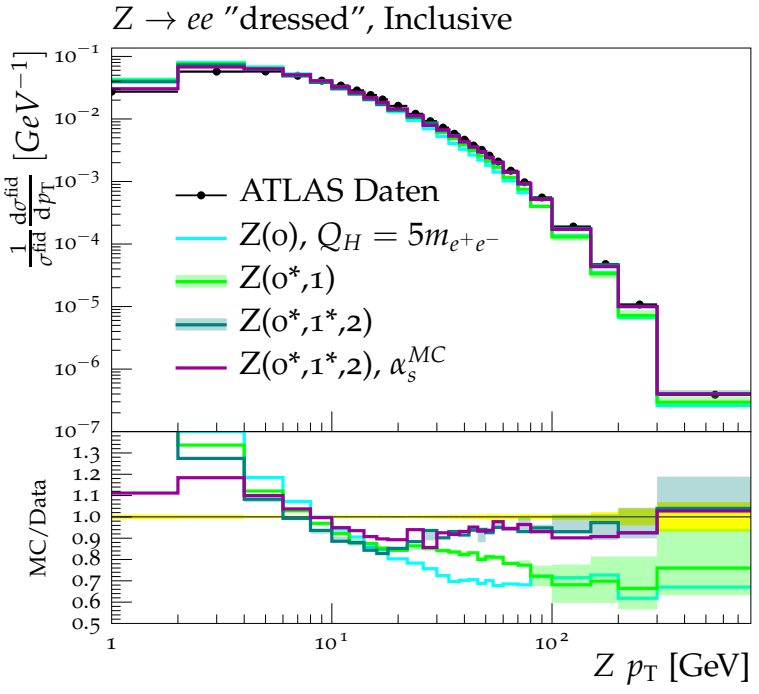
Outlook: Combination of different jet multiplicities

[Bellm, Gieseke, Plätzer]

part of next release → Herwig 7.1

Example: $pp \to e^+e^- + X$





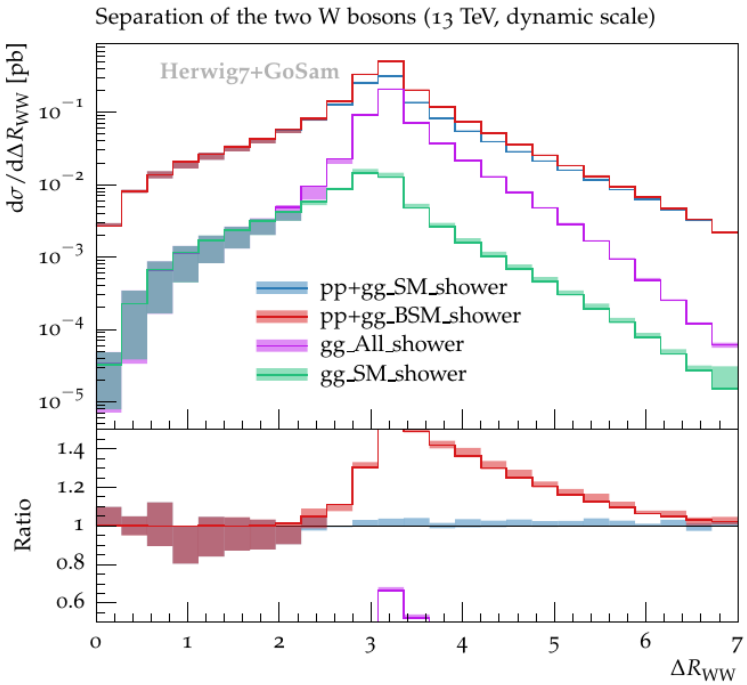
[ATLAS Collaboration, JHEP 1409 (2014) 145]

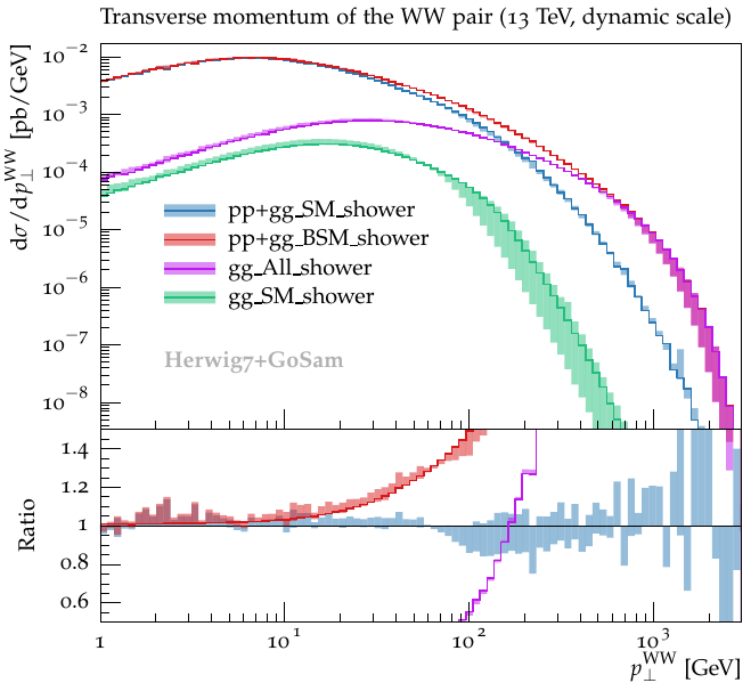
- $Z(0*, 1*, 2) \to Zj$@NLO in hard region
- soft region stable

BSM in Herwig (1)

- BSM capabilities of external matrix providers, e.g.
  - VBFNLO: dimension-6 and 8 operators and unitarization in VBF processes
  - GoSam: dim-8 operators affecting *ggWW* vertex in $pp \to W^+W^- \to e^+\nu_e\mu^-\bar{\nu}_\mu$, e.g. $\mathcal{O}_1 = \frac{c_1}{\Lambda^4} G^a_{\mu\nu} G^{a,\mu\nu} W^i_{\rho\sigma} W^{i,\rho\sigma}$, $\frac{c_{1,2,3}}{\Lambda^4} = 0.1\text{TeV}^{-4}$

[Bellm, Gieseke, Greiner, Heinrich, Plätzer, Reuschle, v. Soden-Fraunhofen]





- large (hard-veto) scale-variation uncertainties where real-emission or dim-8 operator dominates (small $\Delta R_{WW} < \pi$, large p_T^{WW})
- $\to$ LO+PS accuracy

BSM in Herwig (2)

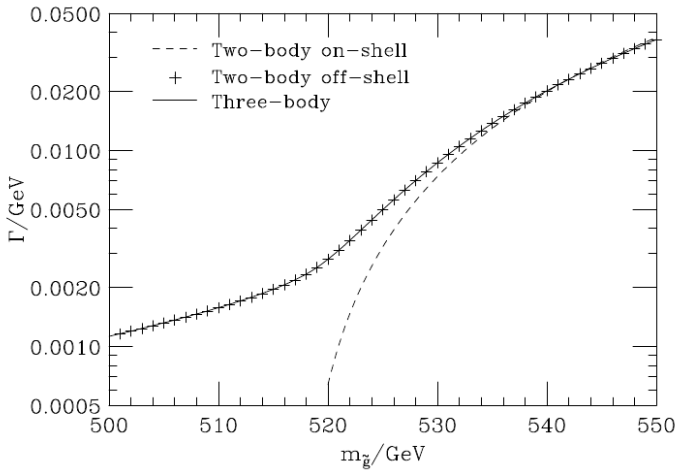
- BSM capabilities of external matrix providers
- Reading in Les Houches Event (LHE) files
  - partonic events from external matrix-element generator
  - input through ThePEG `LesHouchesReader` class
  - handles positive and negative weights $\rightarrow$ NLO-safe

BSM in Herwig (3)

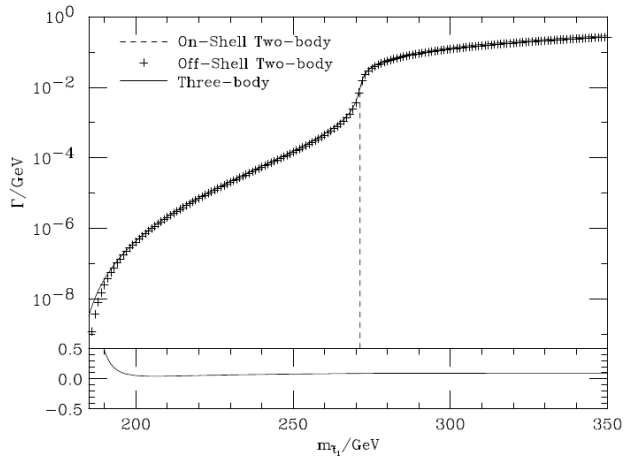
- BSM capabilities of external matrix providers
- Reading in Les Houches Event (LHE) files
- Internal helicity amplitudes
  - Two different sources:
    - internal models, e.g.
      MSSM, NMSSM, RPV SUSY, ADD and RS gravitons, UED, leptoquarks, sextet, ...
    - Universal FeynRules Output (UFO)
  - automatic determination of matrix elements
    - decays:
      $1 \to 2$, $1 \to 3$ (and some $1 \to 4$) processes
    - production:
      $2 \to 2$
      in preparation: $2 \to N$ @NLO via Matchbox [Bellm, Grellscheid]
      using MadGraph5_aMC@NLO matrix elements
    - including spin correlations
  - automatic simulation of all possible decay modes
    without need to explicitly specify decay chains

BSM in Herwig (4)

- BSM capabilities of external matrix providers
- Reading in Les Houches Event (LHE) files
- Internal helicity amplitudes
  - Two different sources:
    - internal models, e.g.
      MSSM, NMSSM, RPV SUSY, ADD and RS gravitons, UED, leptoquarks, sextet, ...
    - Universal FeynRules Output (UFO)
  - automatic determination of matrix elements for
    $2 \to 2$, $1 \to 2$, $1 \to 3$ (some $1 \to 4$, $2 \to N$ in preparation) including spin correlations
  - automatic simulation of all possible decay modes without need to explicitly specify
  - simulation of finite-width effects via weight factor $w = \frac{1}{\pi} \int \mathrm{d}m^2 \frac{m\Gamma(m)}{\left(m^2 - M^2\right)^2 + \left(m\Gamma(m)\right)^2}$



$\tilde{g} \to \bar{b}\tilde{b}_1 \to \bar{b}b\tilde{\chi}_2^0$

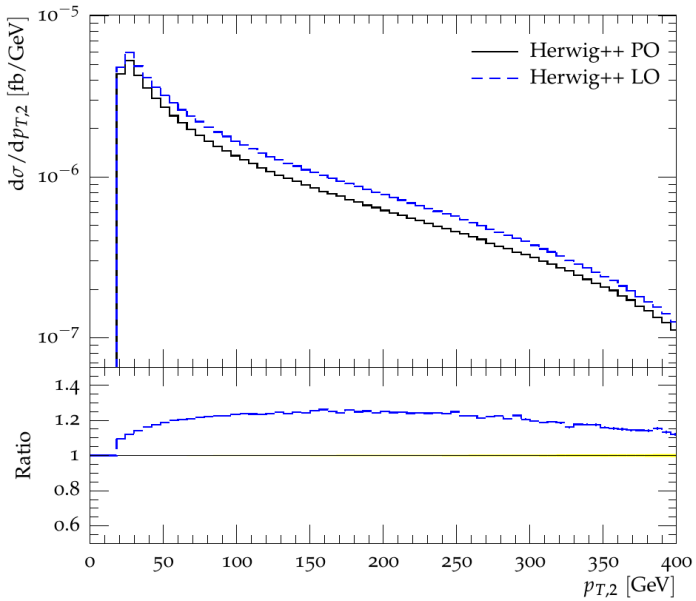


$\tilde{t}_1 \to t\tilde{\chi}_1^0 \to W^+ b\tilde{\chi}_1^0$

[Gigg, Richardson]

BSM in Herwig (5)

- BSM capabilities of external matrix providers
- Reading in Les Houches Event (LHE) files
- Internal helicity amplitudes
  - Two different sources:
    - internal models
    - Universal FeynRules Output (UFO)
  - automatic determination of matrix elements for $2 \to 2$, $1 \to 2$, $1 \to 3$ (and some $1 \to 4$) processes, including spin correlations
  - simulation of finite-width effects via weight factor
  - improved simulation of hard radiation in decays



use Powheg-inspired matrix-element corrections

available for $1 \to 2$ decays involving:

- scalar, fermion, vector, uncoloured tensor particles
- colour singlets, (anti)fundamental and adjoint reps of $SU(3)$

$\tilde{u}_L \to u\tilde{\chi}_1^0$ [Richardson, Wilcock]

Summary & Outlook

Herwig 7

- Fully automated NLO plus parton-shower calculations by default
  - Two matching algorithms
  - Two parton showers
- Flexible, easy-to-use tool for both SM and BSM simulations
- New models easily added via UFO
- Further development:
  - NLO multi-jet merging
  - NLO EW corrections
  - Loop-induced processes
  - automated $2 \to N$ @NLO for BSM models from UFO input
  - ...

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https://herwig.hepforge.org/