



Herwig 7: overview and recent developments

on behalf of the Herwig 7 team

Andrzej Siodmok | QCD@LHC, 22 Aug 2016

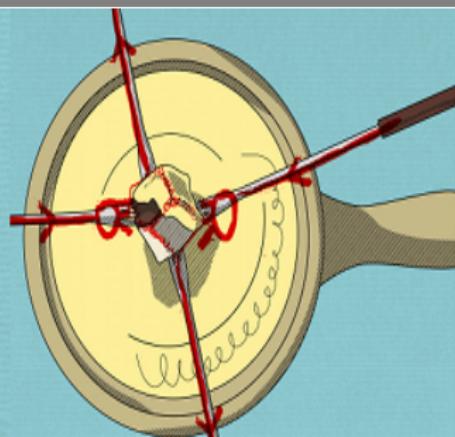
THEORETICAL PHYSICS DEPARTMENT, CERN

QCD@LHC

22ND-26TH AUGUST

INTERNATIONAL CONFERENCE ZURICH

2016



herwig.hepforge.org

Herwig Evolution

HERWIG

HERWIG (Hadron Emission Reactions With Interfering Gluons):
Fortran code, last version 6.521
(1992-2002)

[Marchesini, Webber, Abbiendi, Corcella, Knowles, Moretti, Odagiri, Richardson, Seymour, Stanco]

Herwig++

Herwig++ (C++ rewrite, 2004):

[Bähr, Gieseke, Gigg, Grellscheid, Hamilton, Latunde-Dada, Plätzer, Richardson, Seymour, Sherstnev, Tully, Webber]

last version 2.7.1 (2014)

[Bellm, Gieseke, Grellscheid, Papaefstathiou, Platzer, Richardson, Rohr, Schuh, Seymour, AS, Wilcock, Zimmermann]

intended to fully replace Fortran version

experimental and phenomenological evolution over time
⇒ precision as key goal

Herwig++ 3.0 →

Herwig 7.0

Evolution of fHERWIG/Herwig++



Herwig

subsumed as “7 > 6.5”. “Better than fHERWIG in any aspect plus more”.

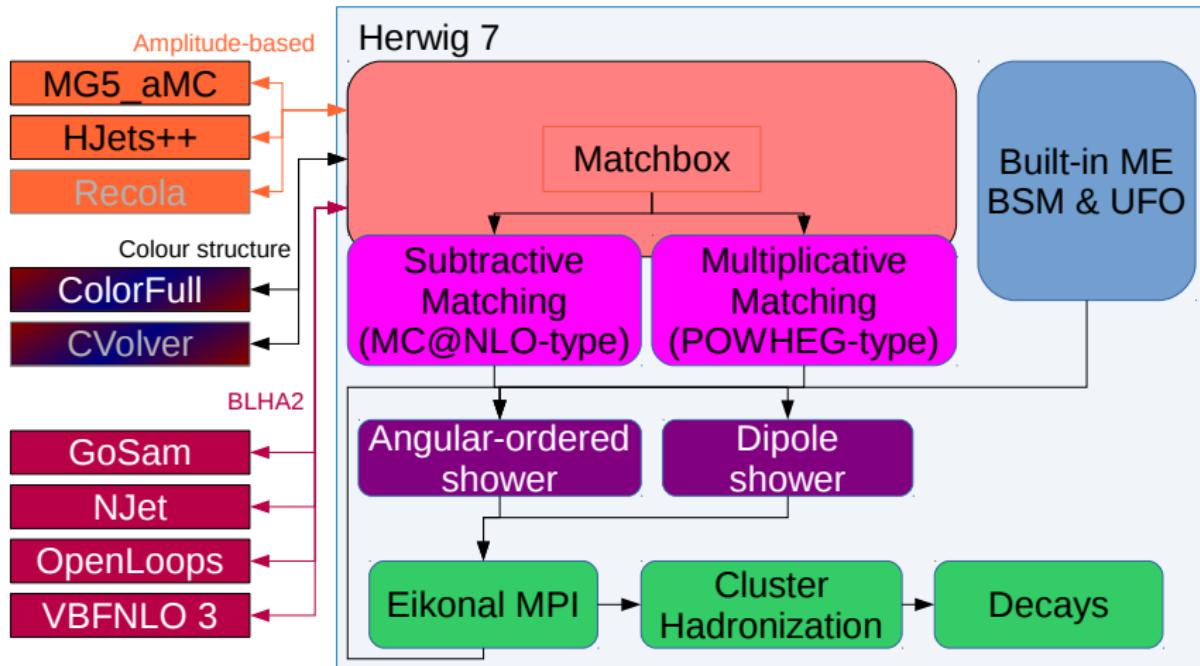
[Bellm, Gieseke, Grellscheid, Plätzer, Rauch, Reuschle, Richardson, Schichtel, Seymour, AS, Wilcock, Fischer, Harrendorf, Nail, Papaefstathiou, D. Rauch]

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, M. Rauch, 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, AS]
- Parton-shower reweighting [Bellm, Plätzer, Richardson, AS, Webster]
- Third matching scheme: KrkNLO [Jadach, Nail, Placzek, Sapeta, AS, Skrzypek]
- Improved documentation, much more user-friendly input files

Structure



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
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

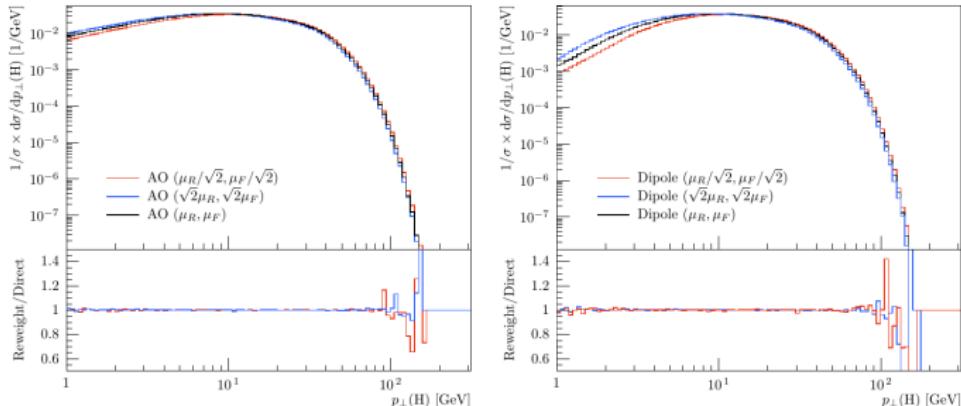
<https://herwig.hepforge.org>

Parton-Shower Reweighting

Run-time improvement via parton-shower reweighting

[Bellm, Plätzer, Richardson, AS, Webster, Phys.Rev. D94 (2016)]

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

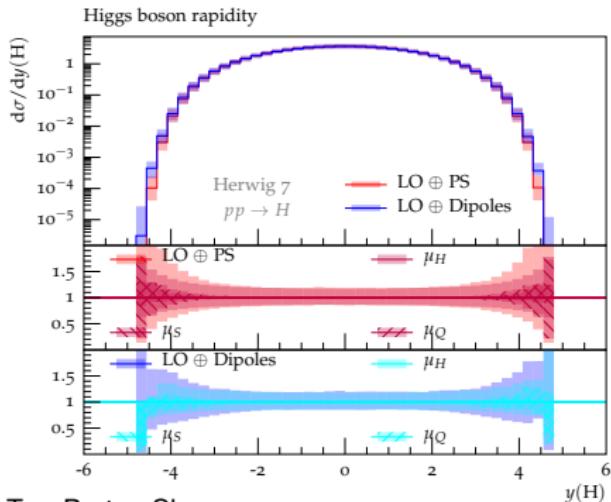


- excellent agreement between individual runs for different scales and reweighting
- significant speed improvements:** time in seconds for 10 000 events

Shower	Hadronization & Decays	No MPI			MPI					
		Direct	Reweight	Frac. Diff.	Primary	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

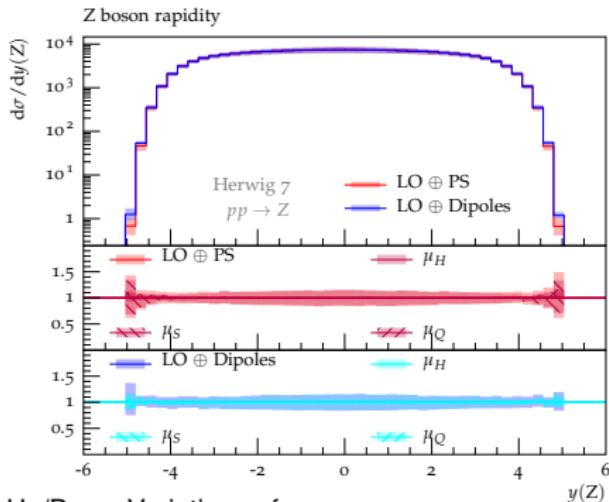
Parton-shower uncertainties

[Bellm, Nail, Plätzer, Schichtel, AS]



Two Parton Showers:

- Angular-ordered Parton Shower (PS)
- p_T -ordered Dipole Shower



Up/Down Variations of:

- μ_H - argument of PDF, α_S in hard matrix element
- μ_S - argument of PDF, α_S in the shower
- μ_Q - shower starting/veto scale
- μ_{IR} - shower cutoff

Parton-shower uncertainties: Profile scales

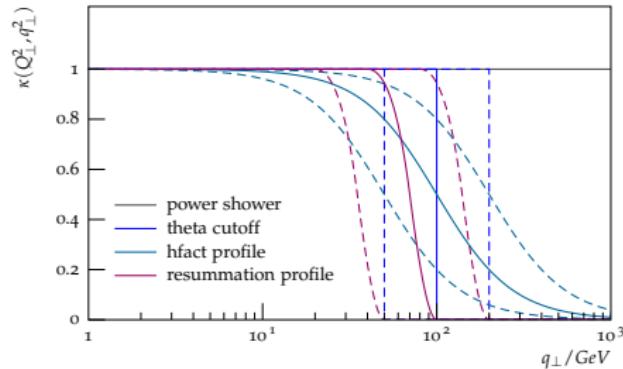
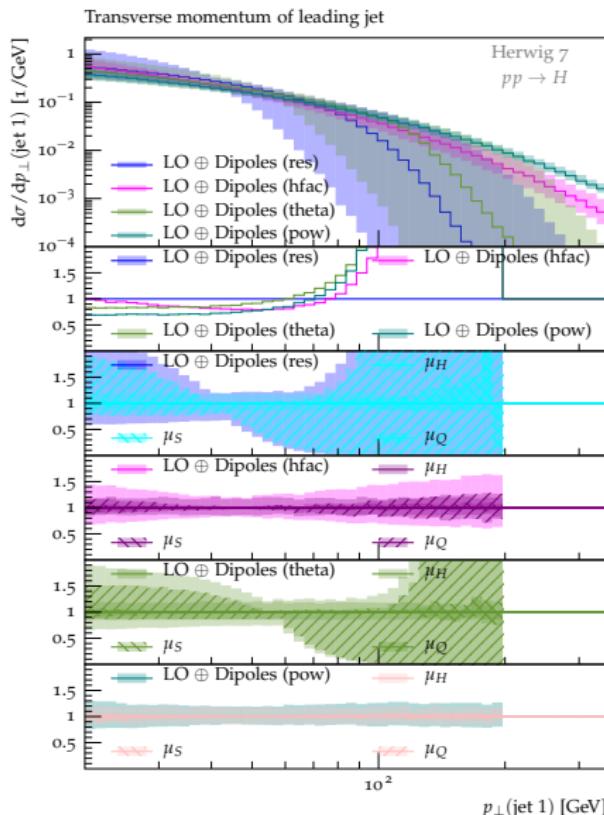


Figure: Profile Scales with $Q_{\perp} = 100$ GeV

Power

$$\kappa(Q, q) = 1$$

Theta

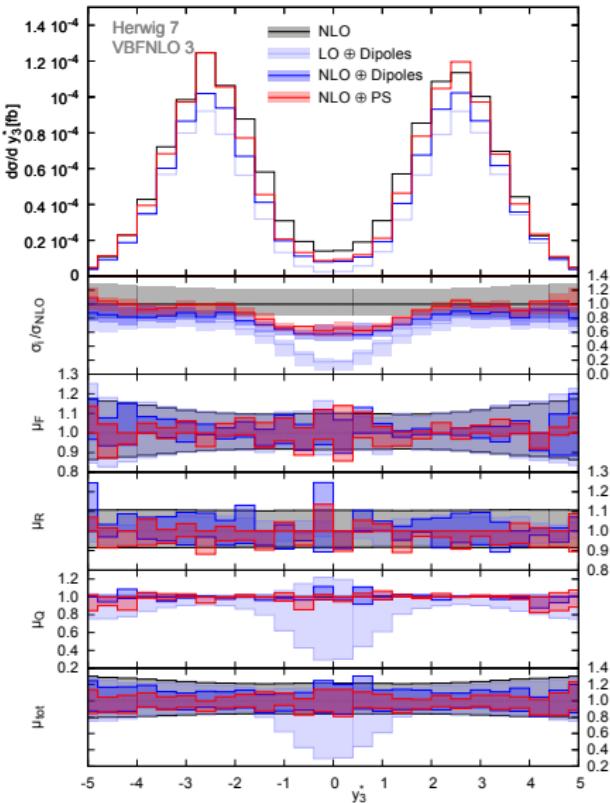
$$\kappa(Q_{\perp}^2, q_{\perp}^2) = \theta(Q^2 - q^2)$$

HFact

$$\kappa(Q_{\perp}^2, q_{\perp}^2) = \left(1 + \frac{q^2}{Q^2}\right)^{-1}$$

Resummation

Parton-shower Effects in VBF WW production



[Rauch, Plätzer, arXiv:1605.07851]

Parton-shower effects and matching systematics in

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

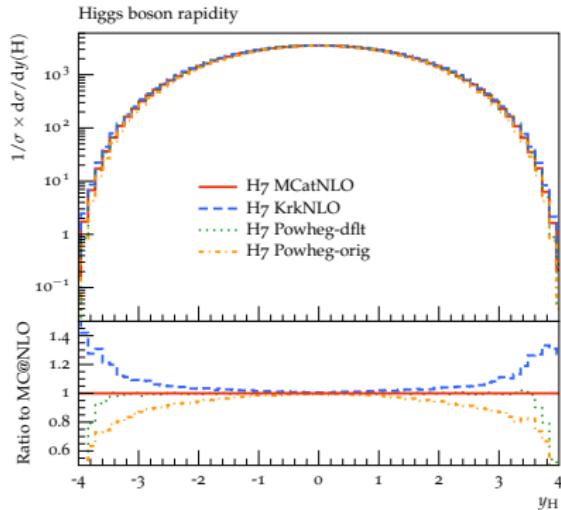
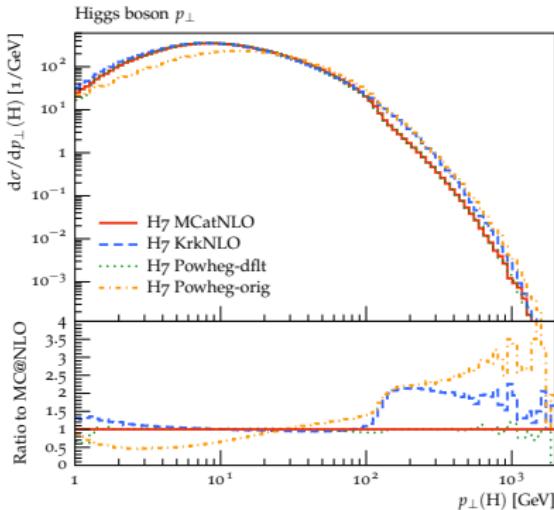
→ stabilised at NLO

→ good agreement between both parton showers

Matching: MC@NLO, Powheg and KrkNLO

- NLO matched to parton showers as new default. Matching mechanism fully generic, fully automated for two showers and two matching schemes [subtractive (MC@NLO-type) multiplicative (Powheg-type)]
 - performed by Matchbox module
- [work led by S. Plätzer with substantial contributions by J. Bellm, A. Wilcock, M. Rauch, C. Reuschle]
- matrix elements in general from external providers via linked library
- Also a new matching method KrkNLO available in H7 (see KrkNLO talk on Thursday)

[Jadach, Nail, Placzek, Sapeta, AS, Skrzypek, arXiv:1607.06799]



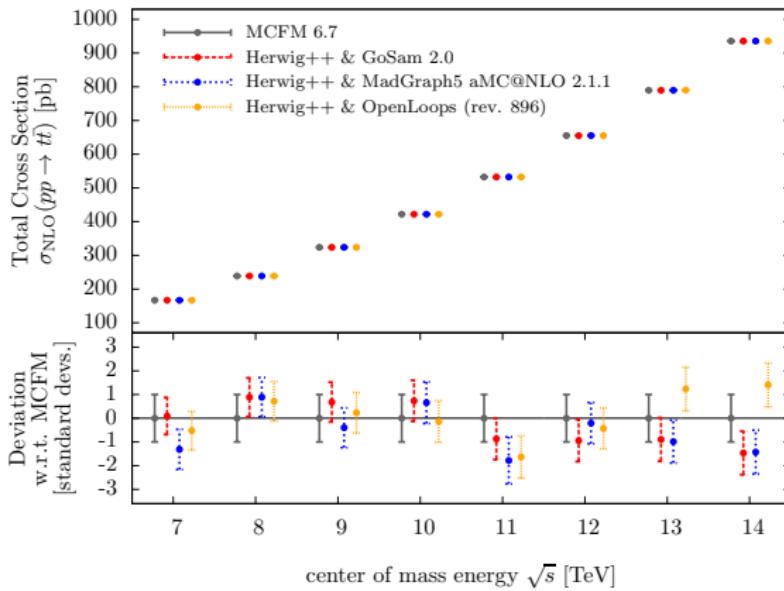
ttbar@NLO

fixed order

[J. Bellm, S. Gieseke, D. Rauch, CR, S. Plätzer, P. Richardson, A. Wilcock; in prep.]

Plots by D. Rauch (pre-release: H7 Matchbox)

Comparison of Total Cross Sections for $pp \rightarrow t\bar{t}$ at NLO



center of mass energy \sqrt{s} [TeV]

- Compare against MCFM
- Various one-loop providers (tree-level always MG5@MC@NLO)
- Fixed scale $\mu = \mu_F = \mu_R = 80$ GeV; CT10nlo, $\alpha_s(M_Z)|_{\text{CT10nlo}}$; $M_t = 173.5$ GeV, on-shell

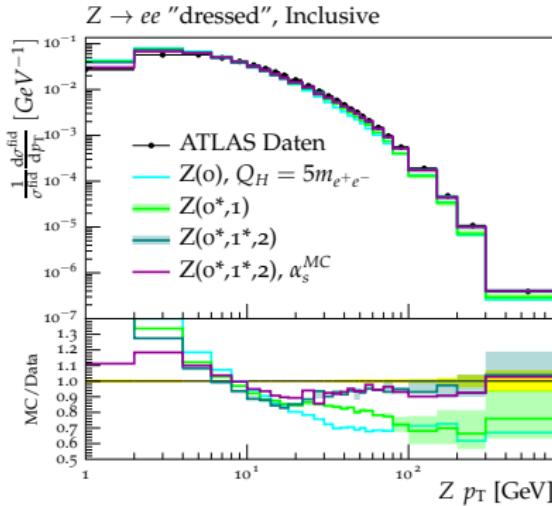
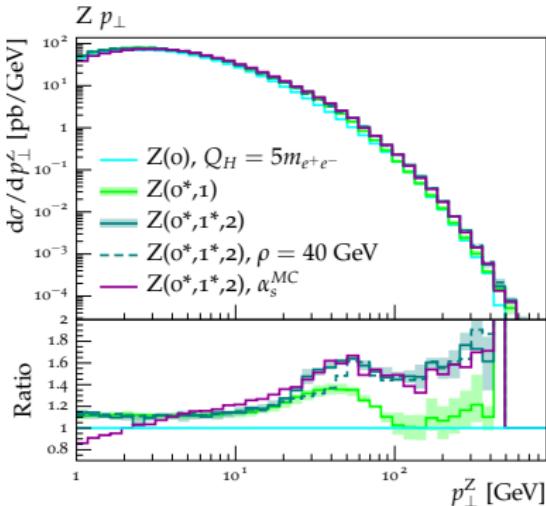
Merging

Outlook: Combination of different jet multiplicities.

Modified unitarized merging algorithm with the dipole shower. Part of next release → Herwig 7.1

[Bellm, Gieseke, Plätzer] based on [Plätzer & Lönnblad, Prestel – 2012]

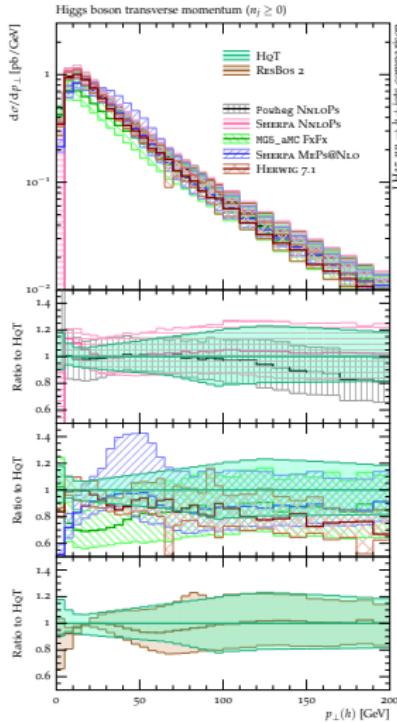
Example: $pp \rightarrow e^+e^- + X$



[ATLAS Collaboration, JHEP 1409 (2014) 145]

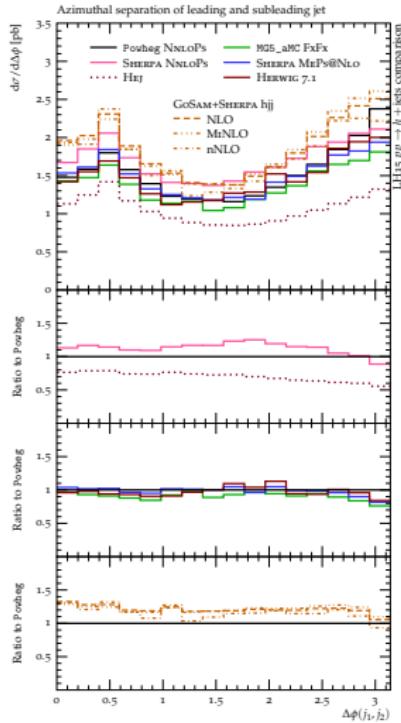
- $Z(0^*, 1^*, 2) \rightarrow Zj@NLO$ in hard region
- soft region stable

LH2015: Physics at TeV Colliders SM WG Report



Higgs p_T . NLO merging schemes, NNLO+PS and analytic resummed results agree in general within the uncertainties.

[arXiv:1605.04692]

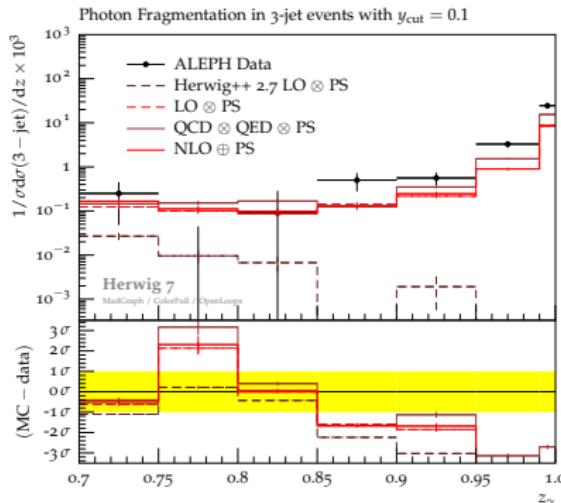
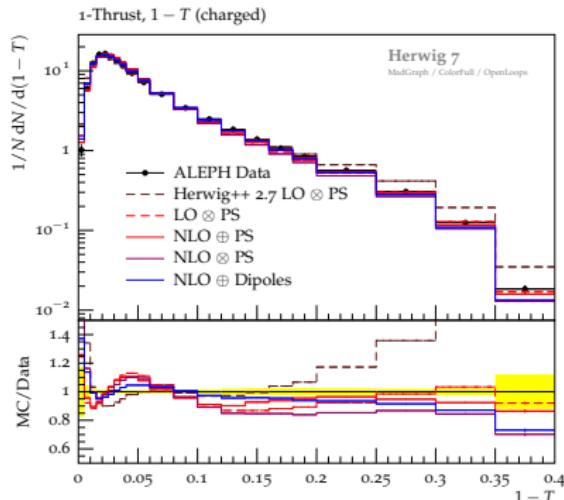


Azimuthal difference of 2 hardest jets in H+jets. NLO merged samples describe the 2nd emission with NLO accuracy and nicely agree.

[arXiv:1605.04692]

Data Comparisons LEP

[Eur.Phys.J. C76] & [<https://herwig.hepforge.org/>]

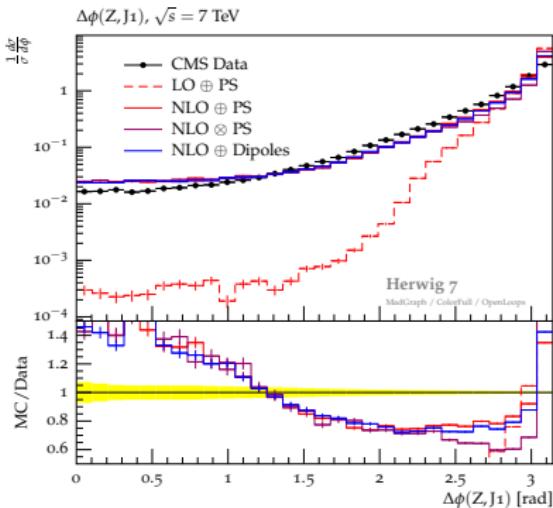


- Thrust distribution at LEP.
ALEPH_1996_S3486095 [Phys. Rept. 294 (1998) 1-165].
- Herwig++: Too many hard events (regardless of NLO matching).
- Improvements to the angular-ordered parton shower in H7: All matching variants give a similarly good description of the data.

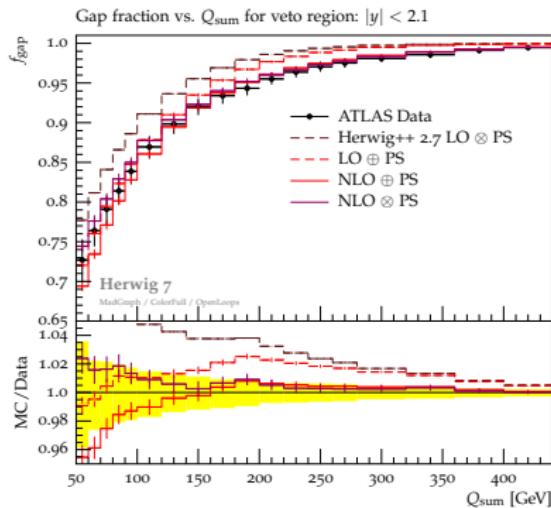
- Photon fragmentation in three-jet events at LEP.
ALEPH_1996_S3196992 [Z. Phys. C69 (1996) 365-378].
- Events at $z_\gamma = 1$ are isolated photons, events at lower z_γ are from hard collinear photon emission off final state quark jets.
- Herwig++: No component at large z_γ at all.
- Including photon emission in the angular-ordered parton shower in H7: All variants are much closer to the data.

Data Comparisons LHC

[Eur.Phys.J. C76] & [<https://herwig.hepforge.org/>]



- Separation in azimuthal angle between Z boson and hardest jet, in $Z + \text{jets}$ at 7 TeV LHC.
CMS_2013_I1209721 [[Phys. Lett. B722 \(2013\) 238-261](#)].
- $\Delta\phi \sim \pi$: The Z gains transv. momentum from recoiling against a single hard parton (LO conf.).
- $0 < \Delta\phi < \pi$: Z recoils against two or more jets.
- Need NLO corrections: Cross-checking the two NLO matching schemes and the two shower variants in H7 (both w/ subtr. matching).



- Fraction of events with less than Q_{sum} transverse energy in $|y| < 2.1$, in $t\bar{t}$ events at 7 TeV LHC.
ATLAS_2012_I1094568 [[Eur. Phys. J. C72 \(2012\) 2043](#)].
- Herwig++: Far too little jet activity (too many gap events).
- H7: LO plus angular-ordered shower is closer to the data at small Q_{sum} , but not at high Q_{sum} . However, both NLO matching schemes describe the data well.

Data Comparisons: Soft QCD

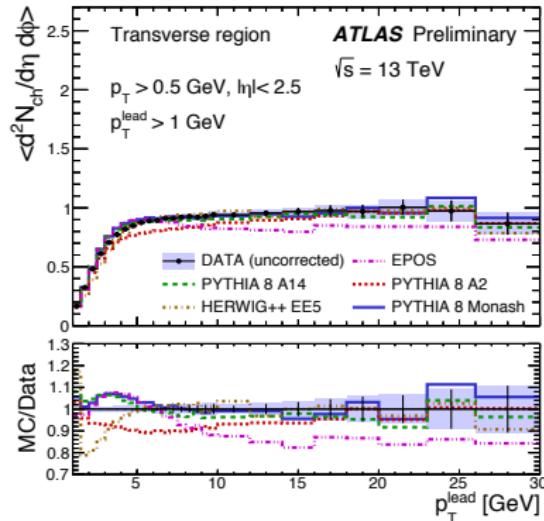
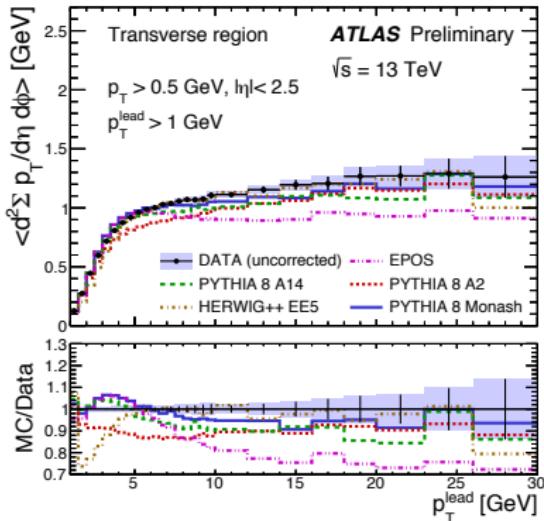
Multiple Partonic Interactions model in H7 is almost the same as in Herwig++. The main difference is a new tune, however also like in Herwig++ based on ideas from [Seymour, AS, JHEP 1310 (2013) 113]

Outlook New colour re-connection models, baryonic clusters, fix to soft MPI (improves low p_T^{lead})

[Gieseke, Myska, Kirchgaesser, Platzer, Richardson, Seymour, AS]

Underlying event@13TeV

[Talk by A. Salzburger & ATL-PHYS-PUB-2015-019]

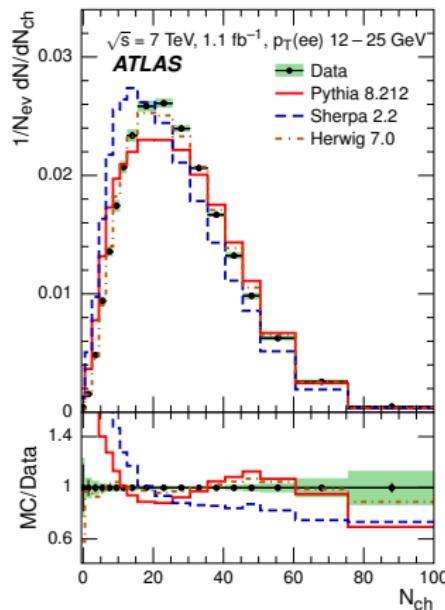


[All see talk by A. Mehta for CMS]

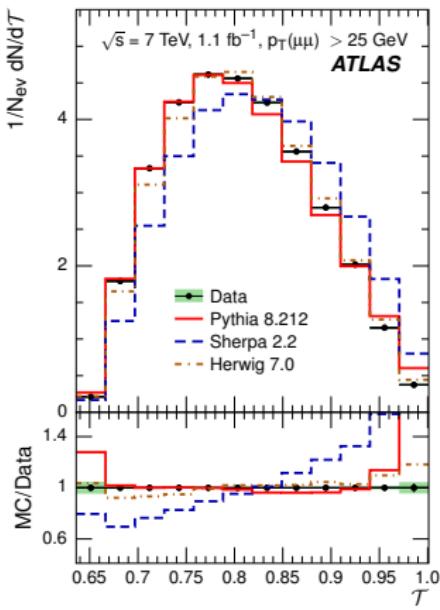
Data Comparisons: Soft QCD Underlying Event

Collaborations starts to use H7. The first time in Measurement of event-shape

observables in $Z \rightarrow e^+ e^-$ by ATLAS [Talk by A. Salzburger & Eur.Phys.J. C76, (2016), 375]



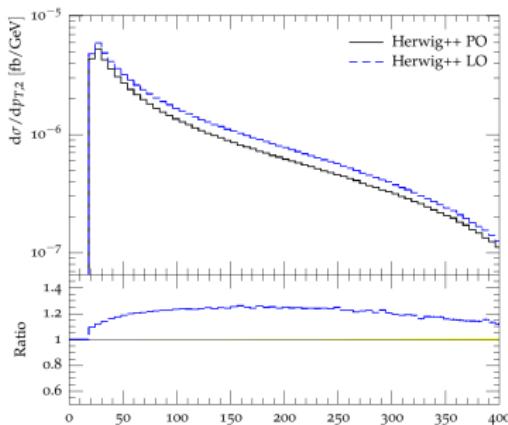
Distribution of charged-particle multiplicity for $Z \rightarrow e^+ e^-$.



Transverse thrust T distribution of charged particles for $Z \rightarrow e^+ e^-$.

BSM in Herwig

- 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 $2 \rightarrow 2$, $1 \rightarrow 2$, $1 \rightarrow 3$ (and some $1 \rightarrow 4$) 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 $1 \rightarrow 2$ decays involving:

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

$$\tilde{u}_L \rightarrow u\tilde{\chi}_1^0$$

[Richardson, Wilcock]

Summary & Outlook



- 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 $2 \rightarrow N$ @NLO for BSM models from UFO input
 - work on soft QCD: new colour re-connection models, baryonic clusters ...
 - fully exploit phenomenology potential (for example q/g discrimination) and continue on uncertainties.
 - ...

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<https://herwig.hepforge.org/>



Thank you for your attention!