Herwig 7 Status and Prospects

on behalf of the Herwig 7 team

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QCD@LHC, TU Dresden, 27/08/18

Outline

- Introduction
- Main building blocks:
  - Parton Shower (status and the recent progress)
  - Matching and Merging (status and the recent progress)
  - Underlying Event & Hadronization (status and the recent progress)
- Conclusions & Future Plans

What does Herwig stand for?

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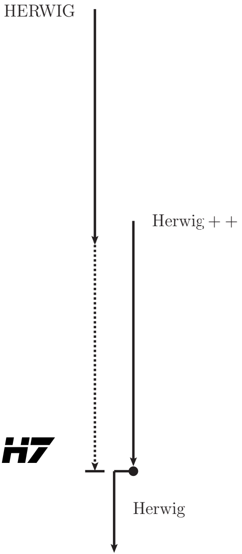
Hadron Emission Reactions With Interfering Gluons

Herwig Evolution



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++ (C++, improved physics, 2004):
[Bähr, Gieseke, Gigg, Grellscheid, Hamilton, Latunde-Dada, Plätzer, Richardson, Seymour, Sherstnev, Tully, Webber]
last version 2.7.1 (2014)
[Bellm, Gieseke, Grellscheid, Papaefstathiou, Plätzer, Richardson, Rohr, Schuh, Seymour, AS, Wilcock, Zimmermann]
intended to fully replace Fortran version

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

Herwig 7.0

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

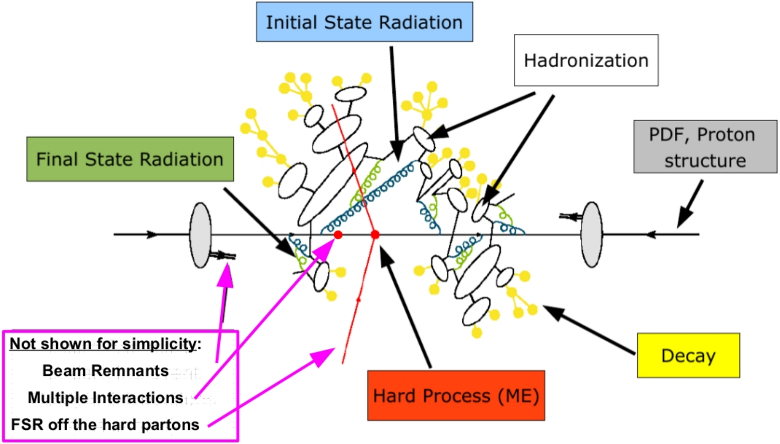
τ(HERWIG) $\sim$ τ(Herwig++) $\gtrsim$ 15 years.

Herwig 7

- New major release Herwig++ 3.0 $\rightarrow$ Herwig 7.0
- Evolution of fHERWIG/Herwig++ subsumed as “7 $>$ 6.5”.
  “Better than fHERWIG in any aspect plus more”.
- “NLO for all hard processes.”

[J. Bellm et.al., Eur.Phys.J. C76 (2016), 196]

Building blocks



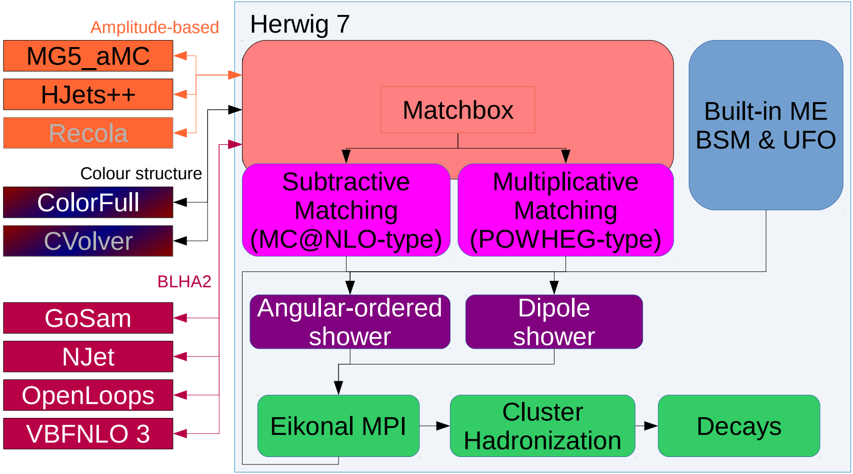
taken from Stefan Gieseke©

Features

Main features of Herwig 7:

- Two parton-shower implementations
  - Angular-ordered shower
  - Dipole shower
- 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
- NLO merging with the dipole shower [Bellm, Gieseke , Plätzer]
- Spin correlations and QED radiation in angular-ordered shower [Richardson, Webster]
  last missing feature from Fortran HERWIG
- Simulation of QED Radiation in Particle decays using the YFS Formalism [Hamilton, Richardson]
- Parton-shower variations [Bellm, Nail, Plätzer, Schichtel, AS]
- Parton-shower reweighting [Bellm, Plätzer, Richardson, AS, Webster]
- Developments at the soft front [Gieseke, Kirchgaeßer, Plätzer, Seymour, AS]
- Third matching scheme: KrkNLO [Jadach, Nail, Placzek, Sapeta, AS, Skrzypek]
- Improved documentation, much more user-friendly input files
- Many many more... for example Quark and Gluon Jets with Herwig 7 [Reichelt, Richardson, AS]

Structure



Fully automated, so that users can choose their process and everything is set up for them!

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

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https://herwig.hepforge.org

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Herwig 7 Tutorials

Bootstrap installation

To ensure a consistent and working setup, we highly recommend that you install Herwig and all its dependencies using the bootstrap script we provide.

- Using the Herwig bootstrap script

Manual installation

Should the options provided by the bootstrap script be insufficient for your purposes, or if a manual installation is required for a different reason, we provide detailed instructions below:

- System Requirements
- Prerequisites of the Herwig program
- Manual installation of the Herwig program

Getting started

Your first run of Herwig. Look at a simple event and understand the event record.

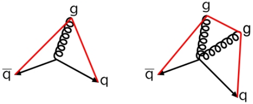
- The first run
  - Make yourself comfortable
  - First events
  - A first look at the output

Parton-showers in Herwig 7: Status

Angular-ordered Parton Shower

- Angular-ordered
- Colour coherence by construction
- No full coverage of phase-space (fixed by Hard Matrix corrections)

Catani-Seymour Dipole Shower



- p_T-ordered
- Colour coherence
- Full phase space
- Catani-Seymour dipoles

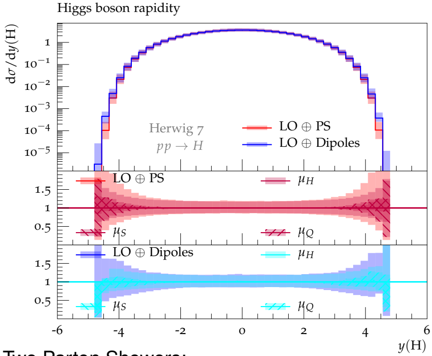
Main parameters:

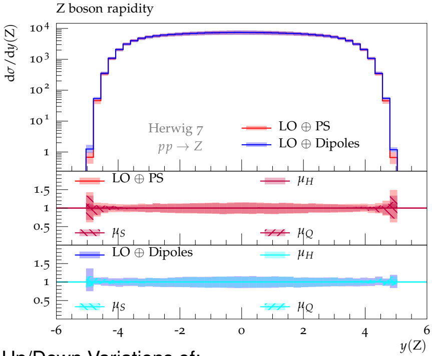
- $\alpha_s(M_Z)$.
- $\mu_{\rm IR}$ the cut-off in the parton shower and μ_Q - shower starting/veto scale.
- μ_S - argument of α_S and PDF in the shower.
- kinematic reconstruction (formally subleading but important!)

[see D. Reichelt's talk]

Parton-shower Variations

[Bellm, Nail, Plätzer, Schichtel, AS Eur.Phys.J. C76 (2016) no.12, 665]





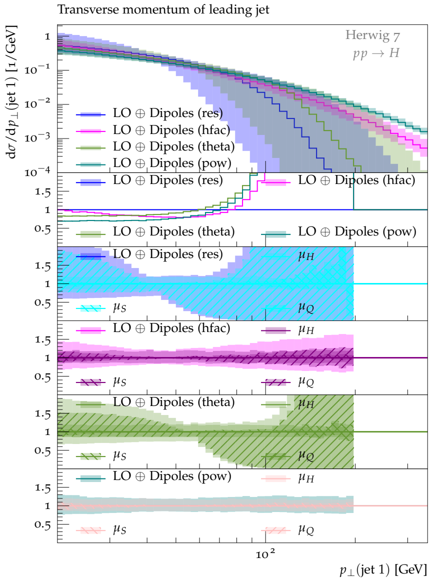
Two Parton Showers:

- 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
- $\mu_{\rm IR}$ - shower cutoff

Parton-shower Variations: Profile scales



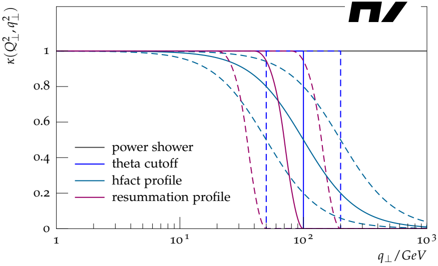


Figure: Profile Scales with $Q_\perp = 100$ GeV

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

$\kappa(Q_\perp^2, q_\perp^2) = 1$ below $(1 - 2\rho)\, Q_\perp$,
0 above $Q_\perp$, and quadratically interpolating in between.

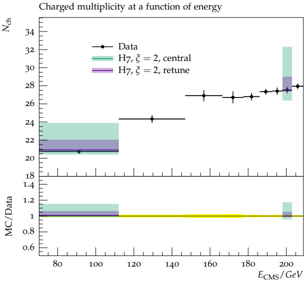
Tuning vs. Variations

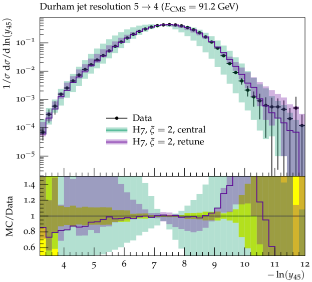
[Part of Les Houches proceedings, Bellm, Hoang, Lönnblad, Plätzer, Prestel, Samitz, AS]

To assess the effect of the correlation between infrared cut-offs and hadronization parameters with variations of α_s:

1. The central tune. This is simply chosen to be the default value. Its scale variation band (the envelope of the tune) is estimated by shifting $\alpha_s(M_z) \to \alpha_s(\{\frac{1}{\xi}, 1, \xi\}M_z) \to \alpha'_s(M_z)$, with $\xi = 2$ without additional retuning for each $\alpha'_s(M_z)$ variation.
2. Two more tunes, called “retune” and the corresponding scale variation band, are obtained by the same $\alpha_s(M_z)$ variation as for ”central“ tune but this time we also retune to ALEPH data for each $\alpha'_s(M_z)$ variation.

For some observables it seems like the uncertainties shrink dramatically.





But there are also some surprises.

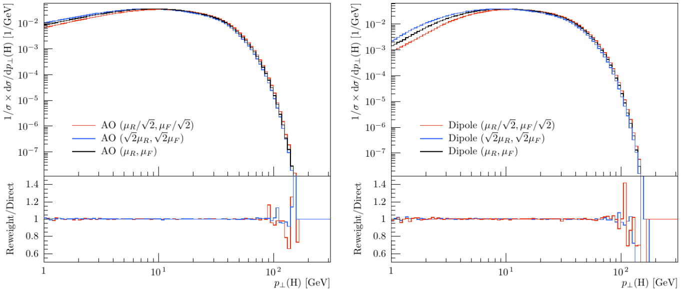
[See AS talk on Thursday and related talk by Andre Hoang]

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 $pp \to gg \to H$, $\sqrt{S} = 13$ TeV



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

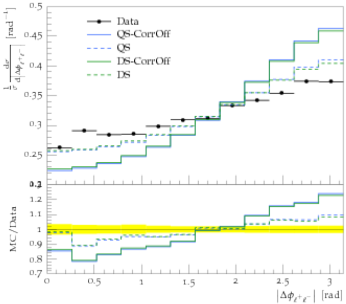
Shower	Hadron-ization & Decays	No MPI			MPI					
					Primary			All		
		Direct	Reweight	Frac. Diff.	Direct	Reweight	Frac. Diff.	Direct	Reweight	Frac. Diff.
AO	Off	79.8	94.2	-0.18	384.4	249.1	0.35	416.7	375.1	0.09
	On	183.2	128.3	0.30	738.7	364.3	0.51	751.4	482.3	0.35
Dipole	Off	99.6	52.8	0.47	435.4	161.9	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

Parton-showers in Herwig 7: Recent Developments

- **Spin correlations** in both the angular-ordered and dipole shower algorithms and between the PS and hard production and decay processes.

[P. Richardson, S. Webster arXiv:1807.01955]

CMS data on the azimuthal separation of the leptons, in $pp \to t\bar{t}$ events

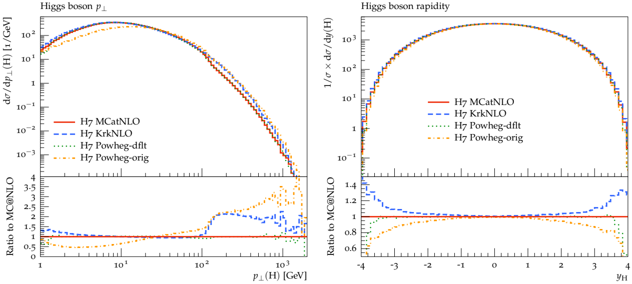


- **Colour Rearrangement for Dipole Showers** [J. Bellm Eur.Phys.J. C78 (2018) no.7, 601]
- **Colour Matrix Element Corrections** - full color structure for parton emissions in PS [S. Plätzer, M. Sjödahl, J. Thorén - see the Talk by Malin]
- **Amplitude level PS evolution** [M. De Angelis, J. Forshaw, S. Plätzer, see talk by Matthew]

Matching and Merging: status

- 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 matched to the Dipole Shower is available in H7
  - Very simple. [Jadach, Nail, Placzek, Sapeta, AS, Skrzypek, Eur.Phys.J. C77 (2017) no.3, 164]
  - Price to pay: new pdf sets in MC scheme, we provide them based on standard MSbar sets.



  - So far implemented in Herwig for Z/H.

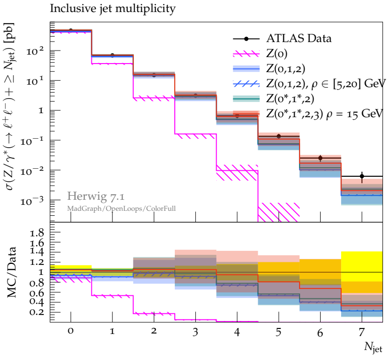
Matching and Merging: recent developments

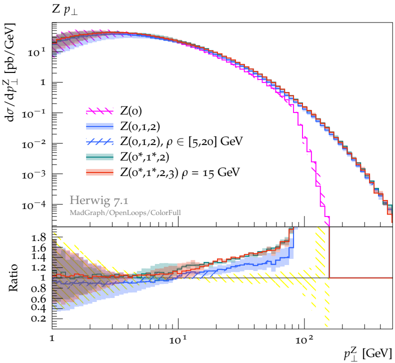
NLO Merging to Parton Shower Combination of different jet multiplicities.

Modified unitarized merging algorithm with the dipole shower

[Bellm, Gieseke, Plätzer EPJC 78 (2018)no.3,244] based on [Plätzer & Lönnblad, Prestel – 2012]

Example:

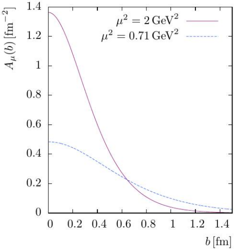




The uncertainty bands are produced by synchronized variation of the renormalization and factorization scale in the shower and ME calculation

Underlying event: - status (key components)

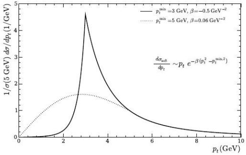
Matter distribution (μ^2)



Based on electromagnetic form factor

(radius of the proton free parameter)

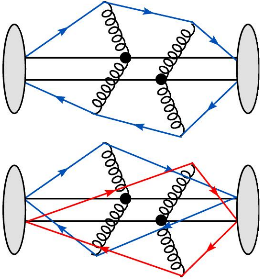
Extension to soft MPI ($p_t < p_t^{\min}$)



Gaussian extension below $p_t^{\min}$

Energy dependent $p_t^{\min}$

Colour structure (p_{reco}, p_{CD})



Possibility of change of color structure (color reconnection)

The least understood part of modeling

Main parameters:

- μ^2 - inverse hadron radius squared (parametrization of overlap function)
- $p_t^{\min}$ - transition scale between soft and hard components $\Rightarrow p_t^{\min} = p_{t,0}^{\min}\left(\frac{\sqrt{s}}{E_0}\right)^b$
- p_{reco} - colour reconnection

[Gieseke, Röhr, AS, EPJC C72 (2012)]

Underlying event: recent developments

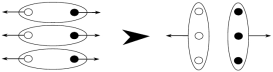
Baryonic Colour Reconnection

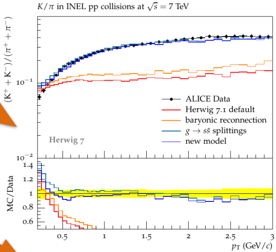
[Gieseke, Kirchgaeßer, Plätzer EPJC 78 (2018) no.2, 99]

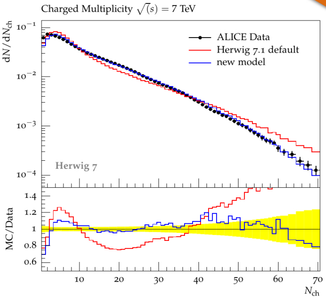
Idea:

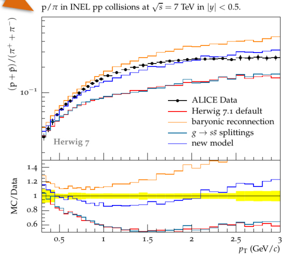
– Allow gluon to strange-pairs

– Allow recombination of mesonic to baryonic clusters with probability derived in proximity in momentum space.







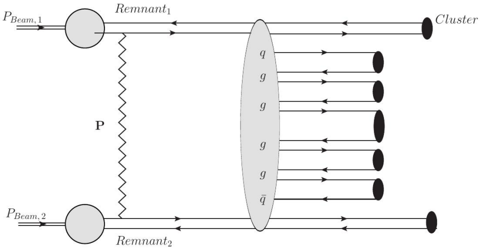


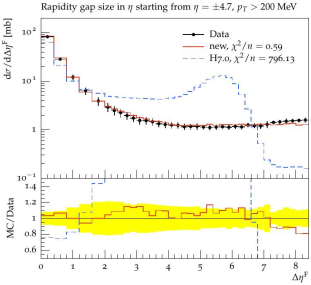
[ALICE, EPJ C75 (2015) 226]

Underlying event: Recent Developments

Soft Physics

- Inclusion of diffractive topologies
- New soft peripheral MPI model
- The rapidity bump disappears

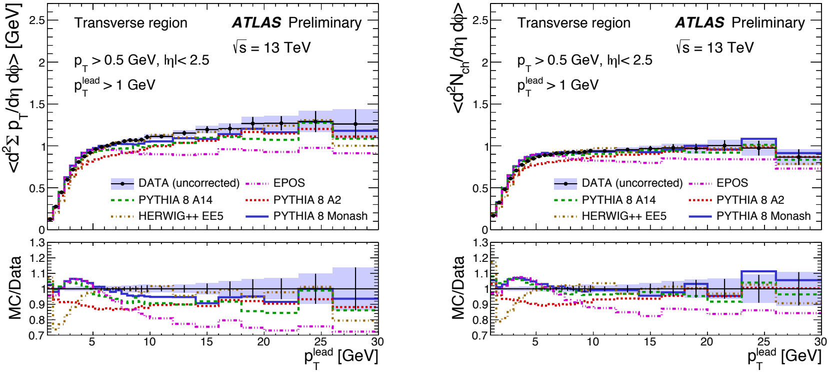




[S. Gieseke, F. Loshaj, P. Kirchgaeßer Eur.Phys.J. C78 (2018) no.2, 99]

Data Comparisons: Soft QCD

Underlying event@13TeV
This is prediction since the model was not tuned to 13 TeV data sets

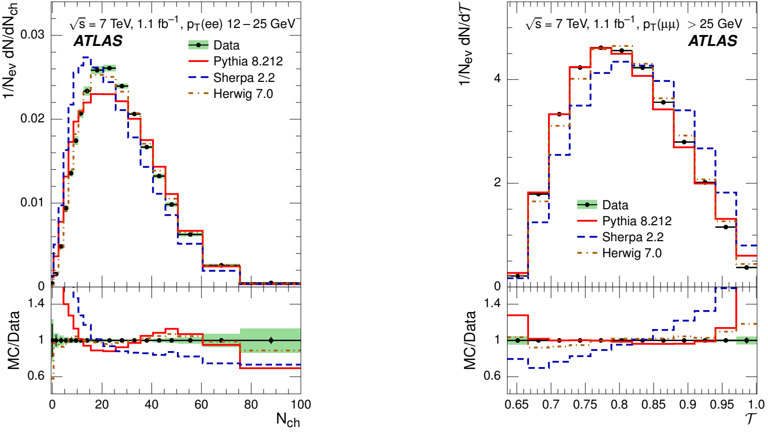


A lot of progress in Soft Physics → important to use up-to-date models and tunes!
More is comming:

- Colour Reconnection from Soft Gluon Evolution [S. Gieseke, P. Kirchgaeßer, S. Plätzer, AS - see Patrick's talk]
- Space-time Colour Reconnection [Bellm, Blok, Duncan, Gieseke, Myska, AS]

Data Comparisons: Soft QCD Underlying Event

Collaborations starts to use H7. The first time in Measurement of event-shape observables in $Z \to e^+e^-$ by ATLAS [Eur.Phys.J. C76, (2016), 375]

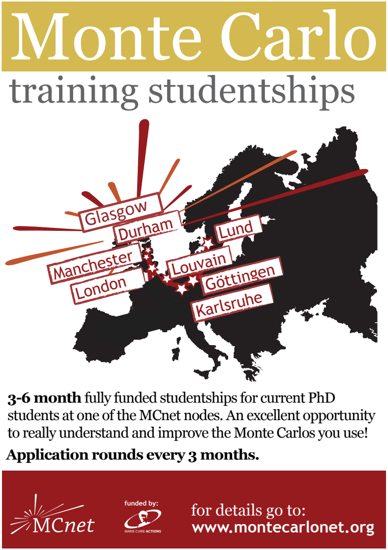


Distribution of charged-particle multiplicity for $Z \to e^+e^-$.

Transverse thrust $\mathcal{T}$ distribution of charged particles for $Z \to e^+e^-$.

Summary & Outlook

- Fully automated NLO plus parton-shower calculations by default
  - Two matching algorithms
  - Two parton showers
- NLO multi-jet merging
- Flexible, easy-to-use tool for both SM and BSM simulations
- Spin Correlations in Parton Shower Simulations
- Further development:
  - Parton Shower and Matching Uncertainties in Top Quark Pair Production with Herwig 7 - very soon [K. Cormier, S. Plätzer, Ch. Reuschle, P. Richardson, S. Webster]
  - more on NLO EW corrections (Recola together with an extension to mixed QCD+QED corrections in the Matchbox), QED radiation in the Dipole Shower...
  - Loop-induced processes [Reuschle, Richter, Papaefstathiou, Plätzer]
  - work on soft QCD: new colour re-connection models, ... [see previous slides :)]
  - fully exploit phenomenology potential (for example q/g discrimination [Reichelt, Richardson, AS - Eur.Phys.J. C77 (2017) no.12, 876]),BSM [Richardson] and continue on uncertainties.
  - Heavy Ion collisions via PISTA: Posterior Ion STActing [see, J. Bellm, Ch. Bierlich arXiv:1807.01291]
  - . . .



MC*net* projects

Pythia+Vincia

Herwig

Sherpa

MadGraph

“Plugin” − Ariadne+HEJ

CEDAR − Rivet+Professor

+Contur+hepforge+...

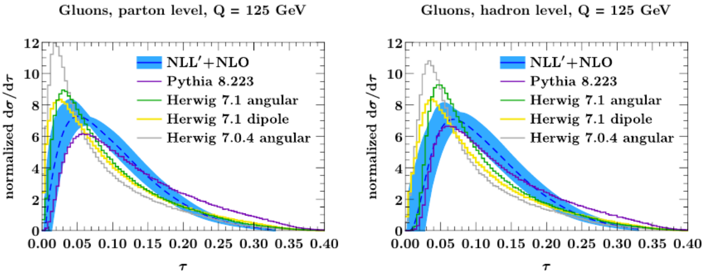
Thank you for your attention!

Comparison with a recent resummation results

"A case study of quark-gluon discrimination at NNLL0 in comparison to parton showers"
[J. Mo, F.Tackmann, W. Waalewijn, 1708.00867]

Thrust - similar to general angularity (1,2) but not restricted to particles in a jet.

$$T = \max_{\hat{t}} \frac{\sum_i |\hat{t} \cdot \vec{p}_i|}{\sum_i |\vec{p}_i|}, \quad \tau = 1 - T$$



"This highlights the substantial improvement in the description of gluon jets in the latest version of Herwig"
[D. Reichelt, P. Richardson, AS, Eur.Phys.J. C77 (2017) no.12, 876]