Herwig 7

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Outline

- Introduction
- Current Status
- BSM in Herwig
- Conclusions & Future Plans

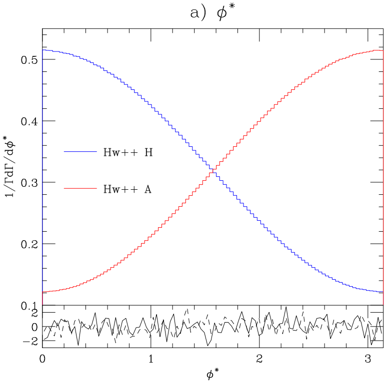
Introduction

- HERWIG was originally designed as a program for understanding hadronic physics.
- Strong emphasis on the accurate simulation of QCD.
- From HERWIG 6 strong emphasis on the study of BSM:
  - SUSY (including RPV and ϵ^{ijk} colour flows);
  - Spin Correlations;
  - RS, ...
- Starting in 2000 major rewrite in C++ (Herwig++)
- The old code was becoming impossible to maintain and a lot of physics we wanted to implement, e.g. QCD radiation from squarks and gluinos, was impossible to implement.

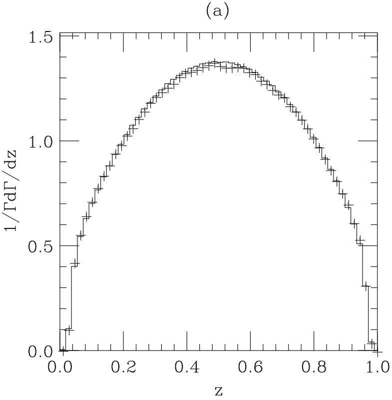
Introduction

- While still emphasising the simulation of QCD including BSM was an important design feature:
  - Better handling of weird colour structures;
  - Coding of Feynman rules rather than matrix elements;
  - automatic calculation of $1 \to 2$, $1 \to 3$ decays (some $1 \to 4$) and $2 \to 2$ scattering processes;
  - Use helicity amplitudes (based on HELAS formalism);
  - Consistently include spin correlations.
- Made adding new models much easier.
- Sophisticated simulation of BSM processes.

Tau Decays



$h^0, A^0 \to \tau^+\tau^- \to \pi^+\bar{\nu}_\tau\pi^-\nu_\tau$



$\tilde{\tau}_L \to \tau^-\tilde{\chi}_1^0 \to \pi^-\pi^0\nu_\tau\tilde{\chi}_1^0$

- Correlations possible due to consistent implementation of BSM physics and τ decays.

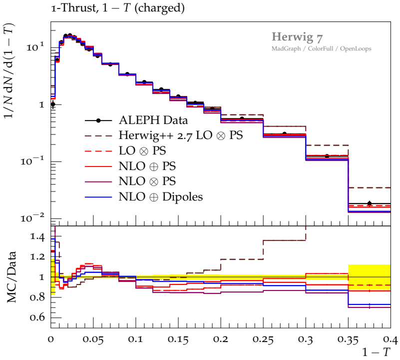
Herwig 7

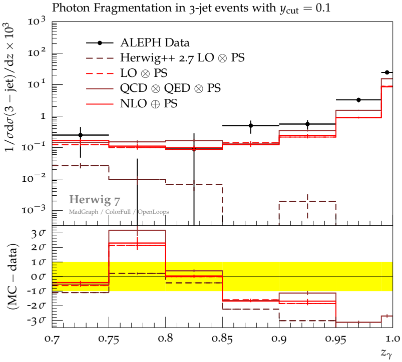
- For the last 10 years we have been working towards a goal of a release that met a (moving) definition intended fully replace the FORTRAN HERWIG program.
- Over time that has evolved as the needs of the experimental and phenomenological communities have developed over the last ten years.
- Precision is now the key and matching to higher orders absolutely essential.

Herwig 7.1

- Focus on Standard Model physics.
- Default is to have NLO matrix elements matched to the parton shower.
- Fully automated, so that users can choose their process and everything is set up for them.
- Both multiplicative (POWHEG) and additive (MC@NLO) type matching
- Option of two different parton showers, angular-ordered and dipole.
- NLO merging with the dipole shower
- Much better documentation
- Finally completely replaces FORTRAN HERWIG.

NLO Matching

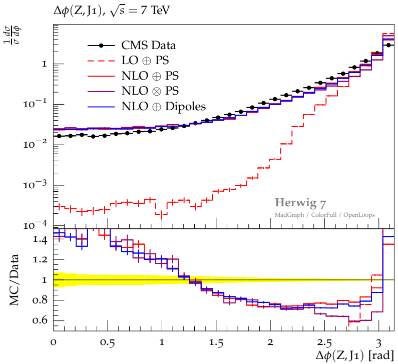


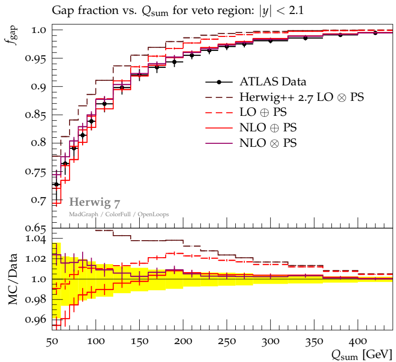


Herwig 7.0 at LEP – new tune available with the release.
Several improvements to angular ordered shower.

Tons of plots using all combinations at: `https://herwig.hepforge.org/plots/herwig7.0/`

NLO Matching





Z+jet events from CMS and top pairs from ATLAS.
Matchbox using MadGraph, ColorFull and OpenLoops.

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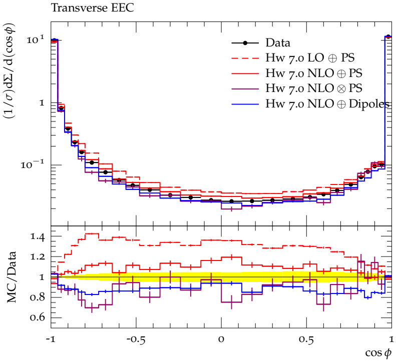
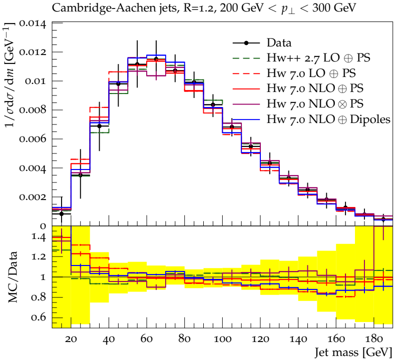
NLO Matching





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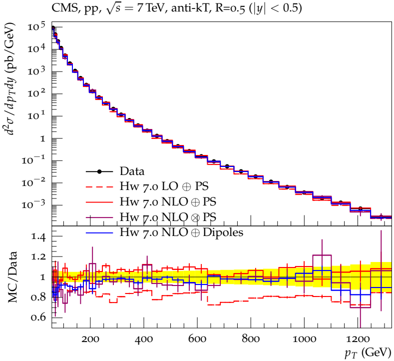

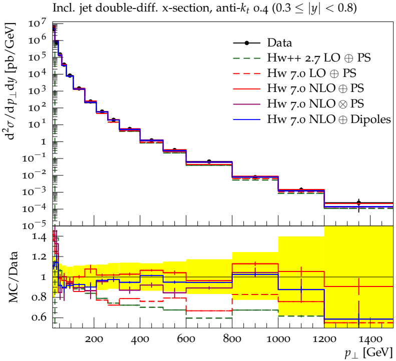

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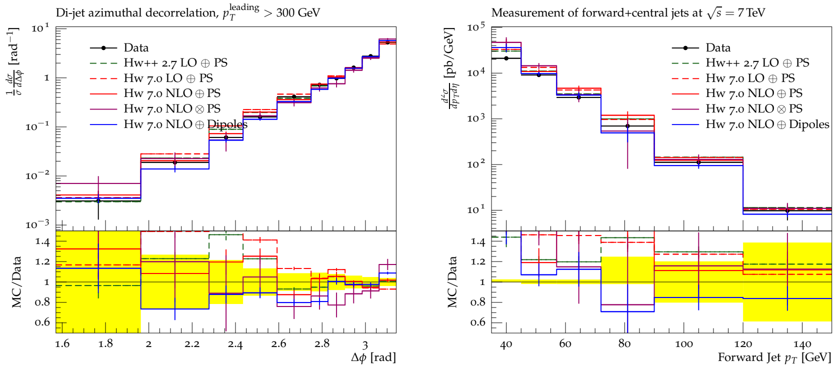

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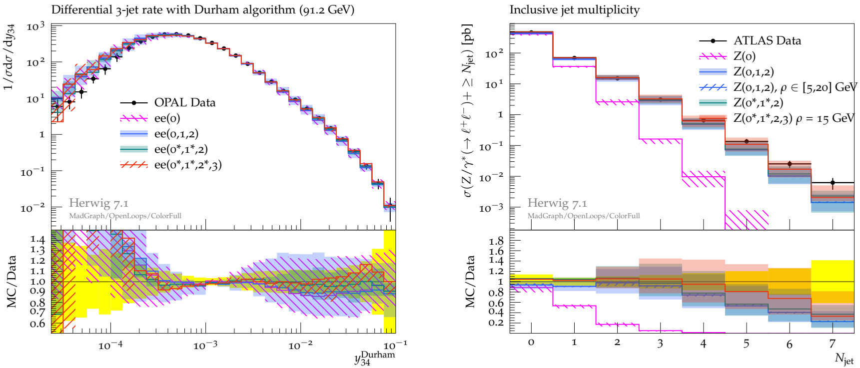
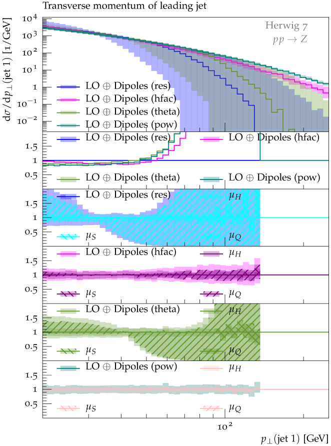
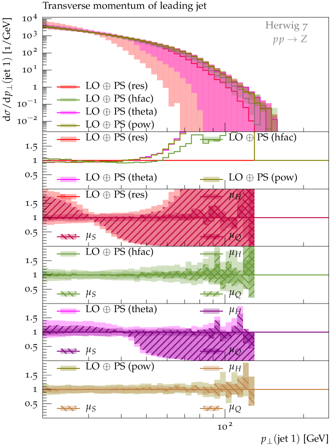
NLO Merging



J. Bellm, S. Gieseke, S. Plätzer Eur.Phys.J. C78 (2018) no.3, 244

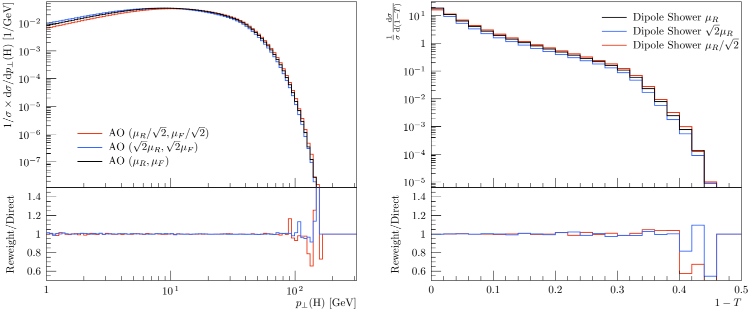
Uncertainities





Eur.Phys.J. C76 (2016) no.12, 665 Bellm et.al.

Reweighting



Bellm et. al. Phys.Rev. D94 (2016) no.3, 034028

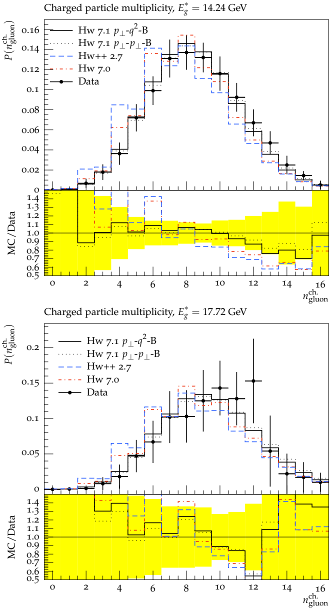
Quark-Gluon discrimination

- Lot of study as part of the 2015 Les Houches workshop

  Gras et. al., JHEP 1707 (2017) 091.
- Finally some real data we can compare do, not just neutral net/BDT outputs,

  ATLAS, Eur. Phys. J. C76(6), 322 (2016).
- Improvements to the non-perturbative modeling and tuning in Herwig 7.1

  Reichelt, PR and Siodmok, arXiv:1708.01491



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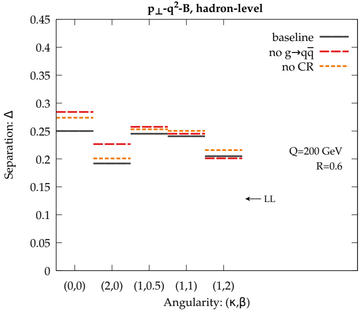
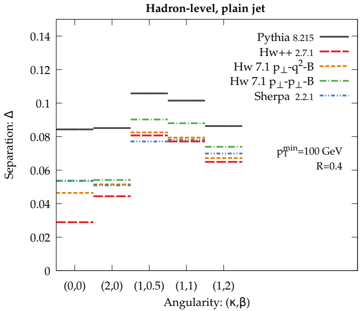
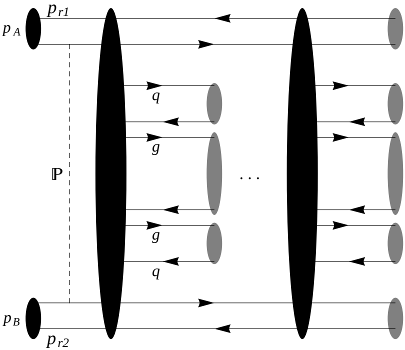
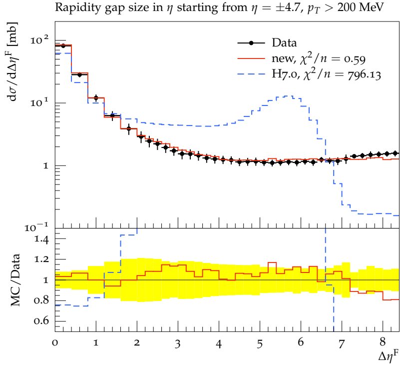




Soft Physics

- Inclusion of diffraction
- New soft model.

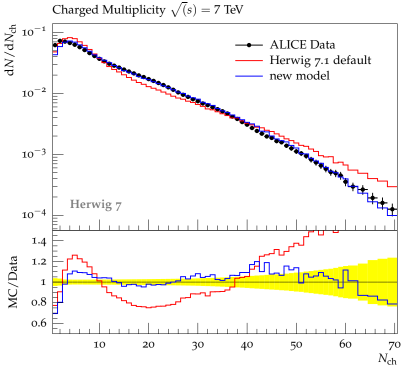




S. Gieseke, F. Loshaj, P. Kirchgaeßer Eur.Phys.J. C77 (2017) no.3, 156

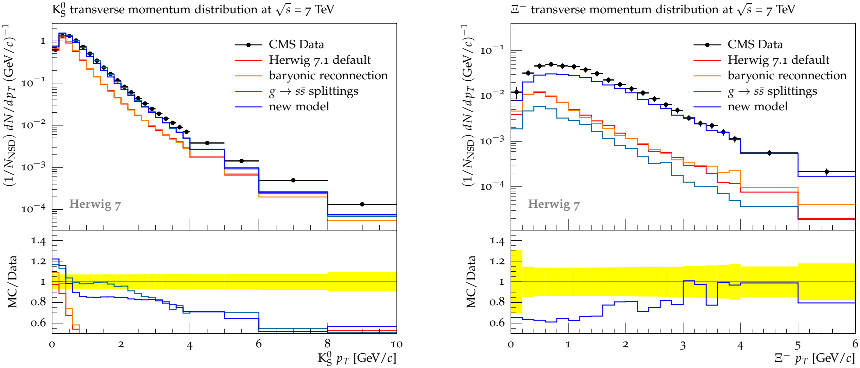
Baryonic Colour Reconnection

- Allow recombination of mesonic clusters to give baryonic ones.
- Based on proximity in momentum space
- Include non-perturbative $g \to s\bar{s}$ splitting in the cluster model.



S. Gieseke, P. Kirchgaeßer, Simon Plätzer Eur.Phys.J. C78 (2018) no.2, 99

Baryonic Colour Reconnection



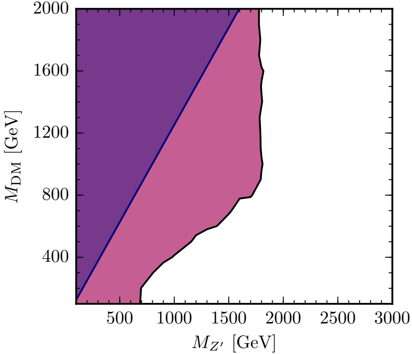
S. Gieseke, P. Kirchgaeßer, Simon Plätzer Eur.Phys.J. C78 (2018) no.2, 99

BSM in Herwig

- Most of the work over the last 10 years has focused on simulation of Standard Model processes.
- Still a number of BSM improvements:
  - Handling of colour sextets;
  - More BSM models;
  - full correlations (i.e. including in shower);
  - use τ decay currents for nearly degenerate BSM decays.
- Major improvement with the ability to use models in the UFO format
  - python ufo2herwig program converts UFO to C++ code implementing the model.
  - can then be used like an internal model with simulation of production, decay and QCD radiation from the BSM particles.
- Most models can be used but limited to the perturbative spin and colour structures.

Contour

- One important use case for Herwig
- Uses:
  - UFO interface;
  - ability to generate inclusive signals.



J. Butterworth, D. Grellscheid, M. Krämer, B. Sarrazin, D. Yallup arXiv:1606.05296

Future

- The type of BSM we need to simulate has changed.
  - Previously complete models with vertices having the perturbative form.
  - Now simplified models and effective theories.
- Next minor release, 7.1.4, will include some improvements
  - Some effective vertices, mainly for SSS, VSS, VVS, and VVVS for models with different Higgs couplings
- Next major release, 7.2, handling of general Lorentz structures for the vertices and more colour structures.

Example: SUSY model with goldstino and gravitino

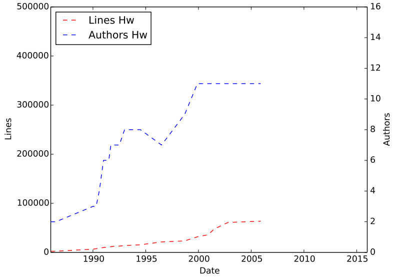
- Model with:
  - spin-$\frac{3}{2}$ particles;
  - complicated Dirac structures;
  - $\epsilon^{\alpha\beta\gamma\delta}$ in many vertices;
- Tough test for automatic parsing of the vertices.
- Excellent agreement with MC5-aMCNLO.

Process	σ/pb		Ratio	Fractional Difference	χ
	Hw 7	Mad			
$gu \to \tilde{u}_1 gld$	$(27.20200 \pm 0.0040) \times 10^{-1}$	$(27.21160 \pm 0.0079) \times 10^{-1}$	0.9996	-0.0002	-1.0852
$gu \to \tilde{u}_1 grv$	$(18.53800 \pm 0.0030) \times 10^{-1}$	$(18.53830 \pm 0.0044) \times 10^{-1}$	1.0000	-0.0000	-0.0564
$gu \to \tilde{u}_4 gld$	$(28.13400 \pm 0.0040) \times 10^{-1}$	$(28.13260 \pm 0.0085) \times 10^{-1}$	1.0000	0.0000	0.1495
$gu \to \tilde{u}_4 grv$	$(19.48900 \pm 0.0030) \times 10^{-1}$	$(19.49400 \pm 0.0048) \times 10^{-1}$	0.9997	-0.0001	-0.8891
$gs \to \tilde{d}_2 gld$	$(1.11250 \pm 0.0002) \times 10^{-1}$	$(1.11264 \pm 0.0003) \times 10^{-1}$	0.9999	-0.0001	-0.4102
$gs \to \tilde{d}_2 grv$	$(1.08280 \pm 0.0002) \times 10^{-1}$	$(1.08255 \pm 0.0003) \times 10^{-1}$	1.0002	0.0001	0.7631
$gs \to \tilde{d}_5 gld$	$(1.22070 \pm 0.0002) \times 10^{-1}$	$(1.22098 \pm 0.0003) \times 10^{-1}$	0.9998	-0.0001	-0.7607
$gs \to \tilde{d}_5 grv$	$(1.22890 \pm 0.0002) \times 10^{-1}$	$(1.22904 \pm 0.0003) \times 10^{-1}$	0.9999	-0.0001	-0.4333
$gc \to \tilde{u}_2 gld$	$(7.69000 \pm 0.0010) \times 10^{-2}$	$(7.68954 \pm 0.0020) \times 10^{-2}$	1.0001	0.0000	0.2080
$gc \to \tilde{u}_2 grv$	$(7.61300 \pm 0.0010) \times 10^{-2}$	$(7.61320 \pm 0.0017) \times 10^{-2}$	1.0000	-0.0000	-0.1001
$gc \to \tilde{u}_5 gld$	$(8.06500 \pm 0.0010) \times 10^{-2}$	$(8.06697 \pm 0.0021) \times 10^{-2}$	0.9998	-0.0001	-0.8579
$gc \to \tilde{u}_5 grv$	$(8.12600 \pm 0.0010) \times 10^{-2}$	$(8.12763 \pm 0.0018) \times 10^{-2}$	0.9998	-0.0001	-0.7919
$gb \to \tilde{d}_3 gld$	$(5.65120 \pm 0.0008) \times 10^{-2}$	$(5.64113 \pm 0.0014) \times 10^{-2}$	1.0018	0.0009	6.2993
$gb \to \tilde{d}_3 grv$	$(6.21400 \pm 0.0010) \times 10^{-2}$	$(6.20548 \pm 0.0013) \times 10^{-2}$	1.0014	0.0007	5.1251
$gb \to \tilde{d}_6 gld$	$(4.94500 \pm 0.0008) \times 10^{-2}$	$(4.95255 \pm 0.0012) \times 10^{-2}$	0.9985	-0.0008	-5.1105
$gb \to \tilde{d}_6 grv$	$(5.20610 \pm 0.0008) \times 10^{-2}$	$(5.21305 \pm 0.0012) \times 10^{-2}$	0.9987	-0.0007	-4.8722
$g\bar{d} \to \tilde{d}_1^* gld$	$(2.12470 \pm 0.0003) \times 10^{-1}$	$(2.12507 \pm 0.0005) \times 10^{-1}$	0.9998	-0.0001	-0.5958
$g\bar{d} \to \tilde{d}_1^* grv$	$(2.01050 \pm 0.0003) \times 10^{-1}$	$(2.01034 \pm 0.0005) \times 10^{-1}$	1.0001	0.0000	0.2877
$g\bar{d} \to \tilde{d}_4^* gld$	$(2.32600 \pm 0.0004) \times 10^{-1}$	$(2.32610 \pm 0.0006) \times 10^{-1}$	1.0000	-0.0000	-0.1367
$g\bar{d} \to \tilde{d}_4^* grv$	$(2.27300 \pm 0.0004) \times 10^{-1}$	$(2.27331 \pm 0.0005) \times 10^{-1}$	0.9999	-0.0001	-0.4704
$g\bar{u} \to \tilde{u}_1^* gld$	$(1.71460 \pm 0.0003) \times 10^{-1}$	$(1.71493 \pm 0.0004) \times 10^{-1}$	0.9998	-0.0001	-0.6189
$g\bar{u} \to \tilde{u}_1^* grv$	$(1.65060 \pm 0.0003) \times 10^{-1}$	$(1.65038 \pm 0.0004) \times 10^{-1}$	1.0001	0.0001	0.4498
$g\bar{u} \to \tilde{u}_4^* gld$	$(1.79670 \pm 0.0003) \times 10^{-1}$	$(1.79669 \pm 0.0004) \times 10^{-1}$	1.0000	0.0000	0.0188
$g\bar{u} \to \tilde{u}_4^* grv$	$(1.75910 \pm 0.0003) \times 10^{-1}$	$(1.75882 \pm 0.0004) \times 10^{-1}$	1.0002	0.0001	0.5742
$g\bar{s} \to \tilde{d}_2^* gld$	$(9.70200 \pm 0.0010) \times 10^{-2}$	$(9.70334 \pm 0.0024) \times 10^{-2}$	0.9999	-0.0001	-0.5159
$g\bar{s} \to \tilde{d}_2^* grv$	$(9.59600 \pm 0.0010) \times 10^{-2}$	$(9.59757 \pm 0.0022) \times 10^{-2}$	0.9998	-0.0001	-0.6553
$g\bar{s} \to \tilde{d}_5^* gld$	$(1.06630 \pm 0.0002) \times 10^{-1}$	$(1.06679 \pm 0.0003) \times 10^{-1}$	0.9995	-0.0002	-1.4664
$g\bar{s} \to \tilde{d}_5^* grv$	$(1.09190 \pm 0.0002) \times 10^{-1}$	$(1.09190 \pm 0.0002) \times 10^{-1}$	1.0000	-0.0000	-0.0032
$g\bar{c} \to \tilde{u}_2^* gld$	$(7.69000 \pm 0.0010) \times 10^{-2}$	$(7.68954 \pm 0.0020) \times 10^{-2}$	1.0001	0.0000	0.2080
$g\bar{c} \to \tilde{u}_2^* grv$	$(7.61300 \pm 0.0010) \times 10^{-2}$	$(7.61320 \pm 0.0017) \times 10^{-2}$	1.0000	-0.0000	-0.1001
$g\bar{c} \to \tilde{u}_5^* gld$	$(8.06500 \pm 0.0010) \times 10^{-2}$	$(8.06697 \pm 0.0021) \times 10^{-2}$	0.9998	-0.0001	-0.8579
$g\bar{c} \to \tilde{u}_5^* grv$	$(8.12600 \pm 0.0010) \times 10^{-2}$	$(8.12763 \pm 0.0018) \times 10^{-2}$	0.9998	-0.0001	-0.7919
$g\bar{b} \to \tilde{d}_3^* gld$	$(5.65120 \pm 0.0008) \times 10^{-2}$	$(5.64113 \pm 0.0014) \times 10^{-2}$	1.0018	0.0009	6.2993
$g\bar{b} \to \tilde{d}_3^* grv$	$(6.21400 \pm 0.0010) \times 10^{-2}$	$(6.20548 \pm 0.0013) \times 10^{-2}$	1.0014	0.0007	5.1251
$g\bar{b} \to \tilde{d}_6^* gld$	$(4.94500 \pm 0.0008) \times 10^{-2}$	$(4.95255 \pm 0.0012) \times 10^{-2}$	0.9985	-0.0008	-5.1105

15

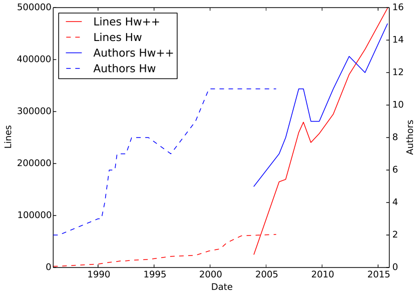
Long Term future

- We are now as far from the start of the redevelopment of Herwig as that was from the start of the project.



Long Term future

- We are now as far from the start of the redevelopment of Herwig as that was from the start of the project.
- The number of lines is again about a factor of 10 more than when the framework was designed.



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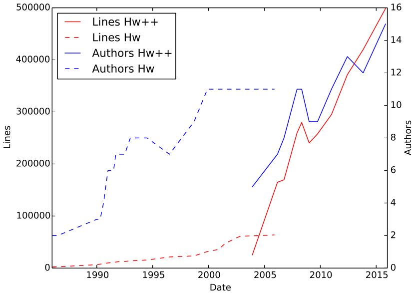

- Not as bad as for FORTRAN as the structure was better in the first place but clearly for the next stage of development some significant restructuring of parts of the code will be required.

Conclusions

- The HERWIG project has taken over 30 years to reach the current state-of-the-art.
- It has been a constant series of incremental developments combined with occasional major changes in how we simulate events such as the move to NLO.
- Hopefully the next thirty years will see as much development.
- However not obvious that much more is currently needed for BSM signals.