Herwig++ & BSM Physics

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MC4BSM

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Fortran Herwig

- Hadron Emission Reactions With Interfering Gluons.
- First versions: Late 1980's.
- From the Abstract of v5.1 (1991*), described as:
  - '...a general-purpose particle physics event generator, which includes the simulation of hard lepton-lepton, lepton-hadron and hadron-hadron collisions in one package [...] uses the parton-shower approach for ISR and FSR QCD radiation, including colour coherence effects and azimuthal correlations both within and between jets'.

* Marchesini, Webber, Abbiendi, Knowles, Seymour, Stanco, Comput. Phys. Commun. 67, 465 (1992).

Fortran Herwig

- From the same 1991 publication:

Program Summary

Title of the Program: HERWIG

Catalogue Number:

Program obtainable from: CPC Program Library, Queen's University of Belfast, N. Ireland (see application form in this issue).

Computers on which the program is operable: VAX. Only minor modifications are needed to run on any machine running standard FORTRAN 77.

!

FHerwig ➠ Herwig++

2003: Herwig++ v1.0: e^+e^- only.

Motivation: '[...] FHerwig has reached the limit of reasonable maintenance [...]'.

2008: Herwig++ v2.3: Hadron collisions.

'[...] provides a much more flexible structure for further development [...]' &
'[...] includes several features more advanced FHerwig.'

2011: Herwig++ v2.5.2: Further development, extensive use in collider experiments.

Hw++: Technical Description

- A general-purpose Monte Carlo event generator for lepton-lepton, lepton-hadron, hadron-hadron colliders.
- A complete redesign from ground up w.r.t. FHerwig.
- Based on ThePEG — the Toolkit for High Energy Physics Event Generation, a framework for implementing Monte Carlo event generators.
- ThePEG provides all parts of the event generator infrastructure that do not depend on the physics models.
  ➠ A collection of modular building blocks.
- Specific physics models of Herwig++ are implemented on top of these.

Main Physics Features

SM/BSM physics including correlations between the production and decay of the SM/BSM particles.

cluster model of the hadronization of jets based on non-perturbative gluon splitting

Initial/Final-state QCD evolution, taking account soft gluon interference (angular ordering).

Eikonal model for multiple partonic scatterings: the underlying event.

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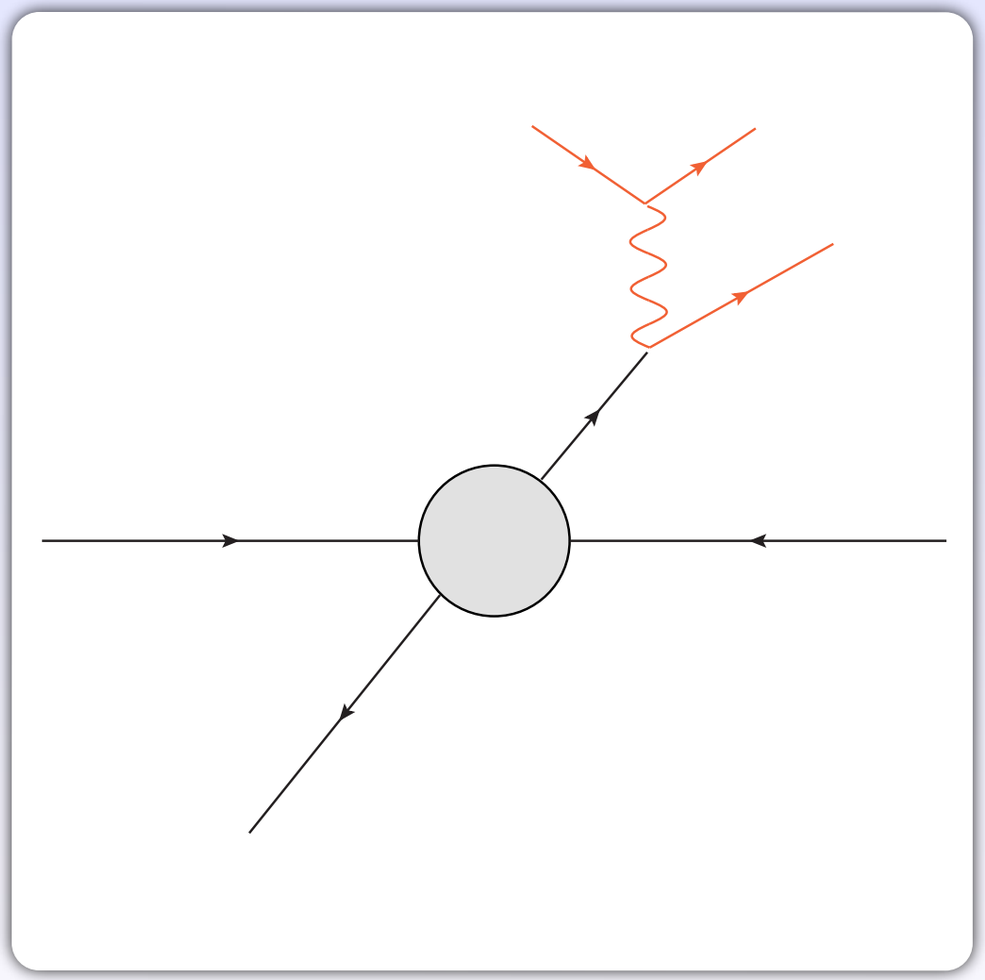

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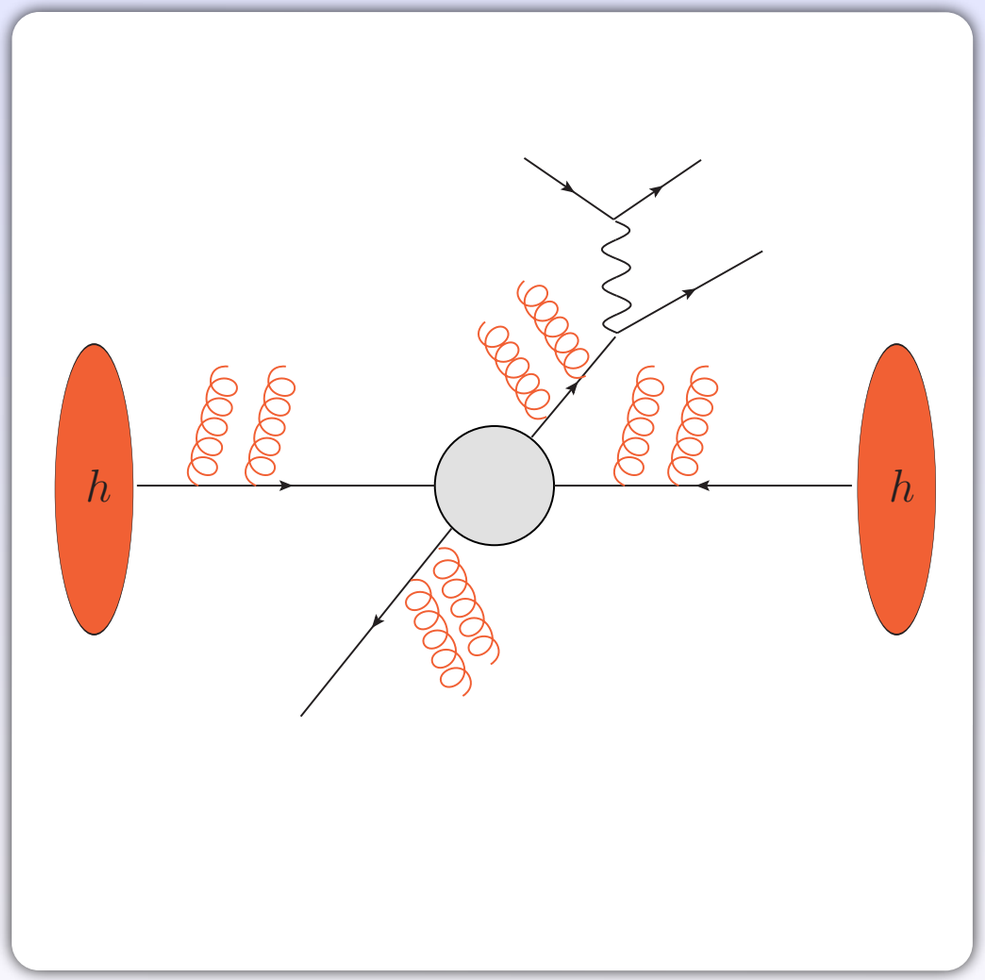

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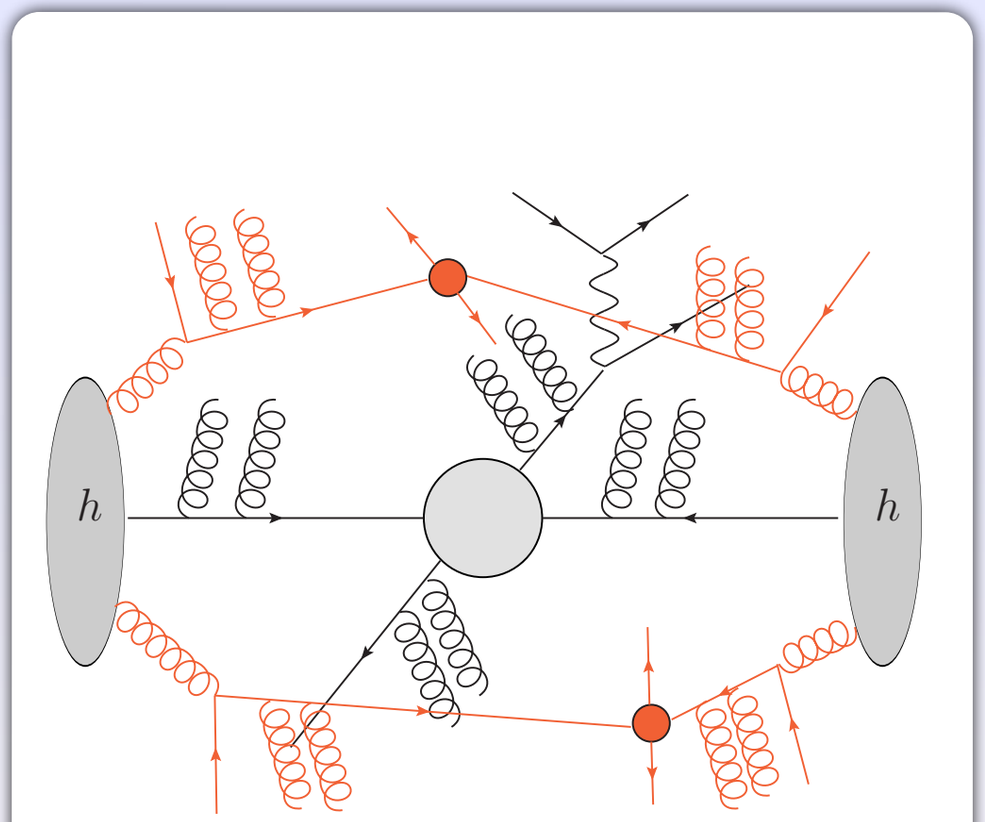

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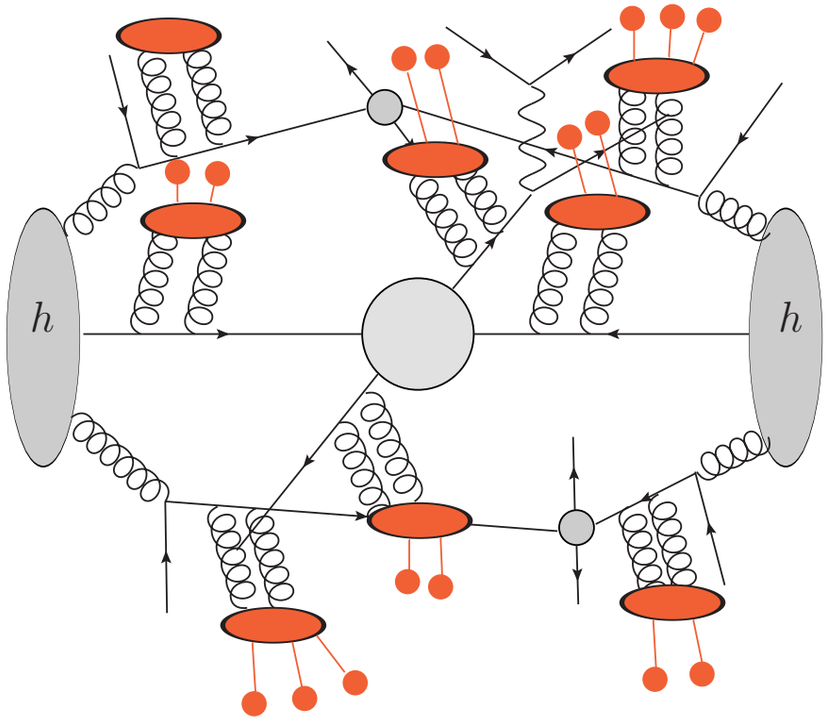

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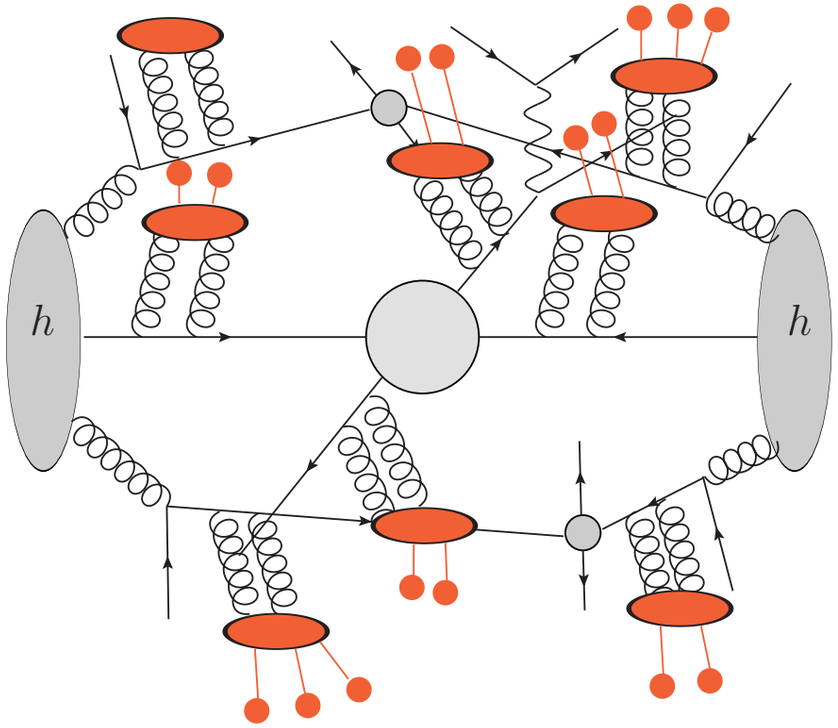
Main Physics Features

Hard Processes



Hadronization

ISR/FSR

Underlying Event

‘Other’ Features...

- Full spin correlations between the production and decay of particles (including taus).
- Colour reconnection model (extension of cluster model of hadronization).
- MC@NLO compatibility/POWHEG Matrix Elements.
- New colour evolution method in the Parton Shower for more proper treatment of wide-angle radiation (1103.4811, A. Schofield, M.H. Seymour).
- ... + Many more.

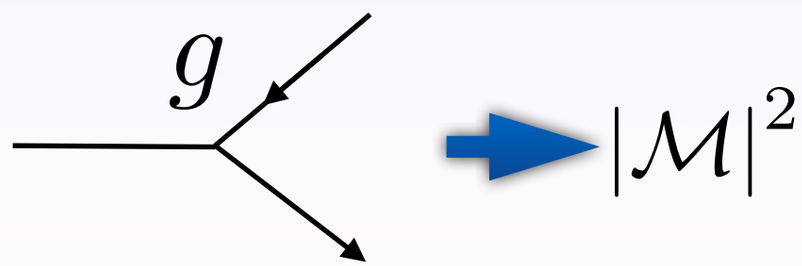
Hard processes in Hw++

1 Hard-coded Matrix Elements → $|\mathcal{M}|^2$

2 Input through Les Houches-accord event files. (e.g. MadGraph)

```
<event>
 8   0  0.4965114E-04  0.5000000E+03  0.7957747E-01  0.1023679E+00
       -2   -1    0    0    0  501  0.00000000000E+00  0.00000000000E+00  0.22355011895E+03  0.22355011895E+03  0.00000000000E+00 0. -1.
        2   -1    0    0  502    0  0.00000000000E+00  0.00000000000E+00 -0.14041414125E+04  0.14041414125E+04  0.00000000000E+00 0.  1.
  9000008    2    1    2  502    0 -0.15674549041E+02  0.40804737723E+02 -0.98365659989E+03  0.11071129113E+04  0.50616990604E+03 0.  0.
 -9000008    2    1    2    0  501  0.15674549041E+02 -0.40804737723E+02 -0.19693469370E+03  0.52057862017E+03  0.47990426971E+03 0.  0.
        2    1    3    3  502    0 -0.34214394313E+01 -0.19624325218E+03 -0.42456593633E+03  0.46773855365E+03  0.00000000000E+00 0.  1.
  9000006    1    3    3    0    0 -0.12253109610E+02  0.23704798991E+03 -0.55909066356E+03  0.63937435766E+03  0.19968803406E+03 0.  0.
       -2    1    4    4    0  501 -0.98735012733E+02  0.17645304792E+02  0.99155735033E+02  0.14103836113E+03  0.00000000000E+00 0. -1.
  9000006    1    4    4    0    0  0.11440956177E+03 -0.58450042516E+02 -0.29609042873E+03  0.37954025904E+03  0.19968803406E+03 0.  0.
</event>
```

3 Automatic construction of 2->2 Matrix Elements.



① Hard-coded Matrix Elements

- An option is to implement the MEs explicitly by hand.
- Tedious even if one has the calculation (e.g. the colour structure may be non-trivial).
- Existing: Mostly Standard Model and LO, some POWHEG processes.

Hard-coded MEs: A sample

$e^+e^- \to \ell^+\ell^-$

⚛ $e^+e^- \to Z/\gamma \to q\bar{q}$

$e^+e^- \to VH$

$\gamma\gamma \to f\bar{f}$

$\gamma\gamma \to WW$

$\gamma h \to \text{jets}$

$hh \to \gamma\gamma$

$hh \to \gamma\text{jet}$

$hh \to Q\bar{Q}$

$hh \to VV$

⚛ $hh \to H$

$hh \to H\text{jet}$

$hh \to Q\bar{Q}H$

⚛ $hh \to VH$

$hh \to Z'$

+Transplanckian Scattering
(eikonal limit: see hep-ph/0112161)

⚛ = also POWHEG

V = W or Z
H = Higgs Boson
h = hadron

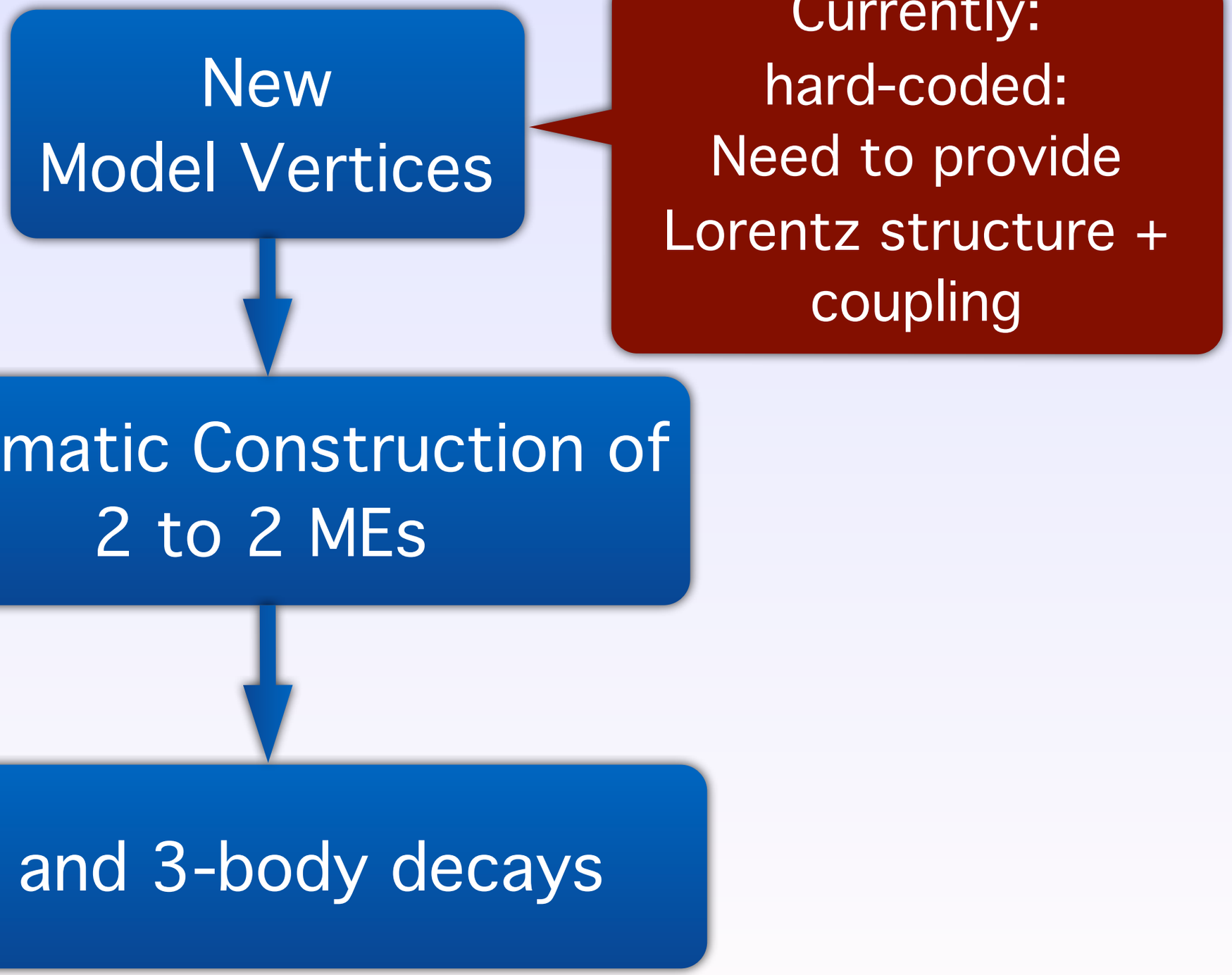
SM

BSM

2 Les Houches-accord event files

- Input through Les Houches accord event files, e.g. generated in MadGraph.
- Standard options of the Les Houches-accord interface: e.g. handles positive and negative weights (e.g. for MC@NLO).
- Showering/Hadronization/Multiple interactions and Analysis, as you would with internal MEs.

3 Automatic construction of 2->2 MEs

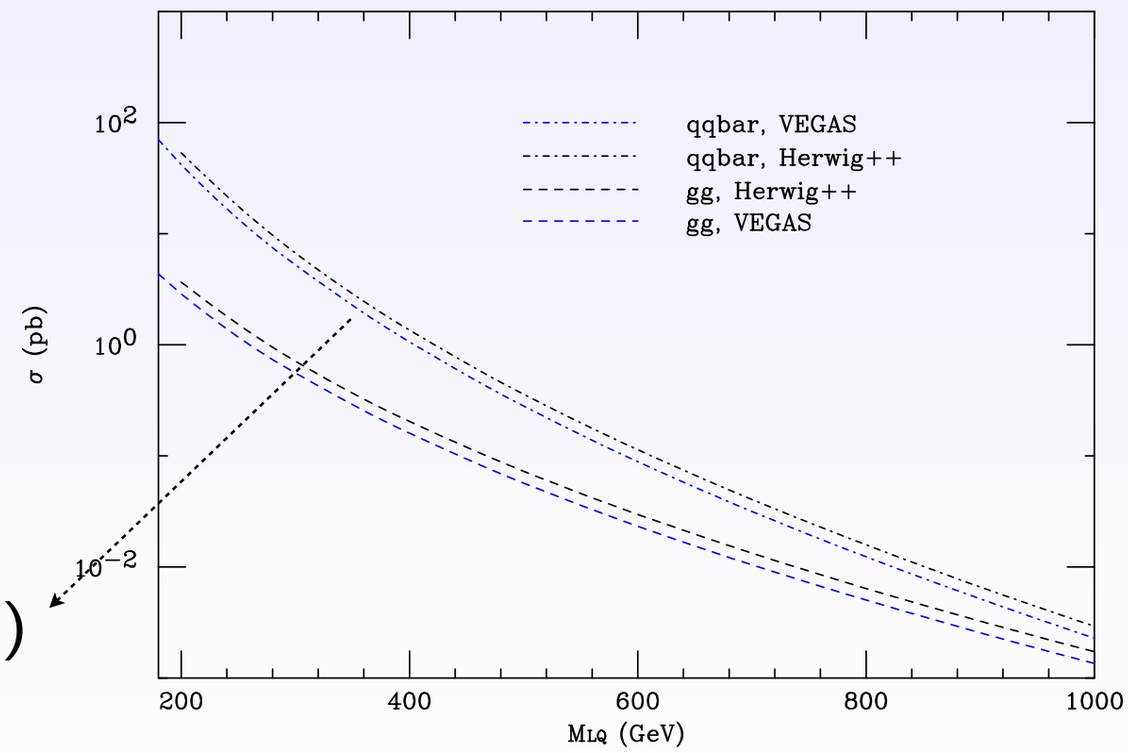


Available Models

- Version 2.5.2 (a sample):
  - ADD/UED/RS extra dimensions.
  - SUSY with Les Houches Accord Reader (SLHA): MSSM and NMSSM (e.g. 1111.3365, D. Grellscheid, J. Jaeckel, V. V. Khoze, P. Richardson, C. Wymant)
  - Third-generation leptoquarks (e.g. 1010.3962, B. Gripaios, A.P., K. Sakurai, B. Webber).

Example from Pheno Study:
Cross section VS leptoquark mass @ LHC14

(discrepancy due to differences in α_S)

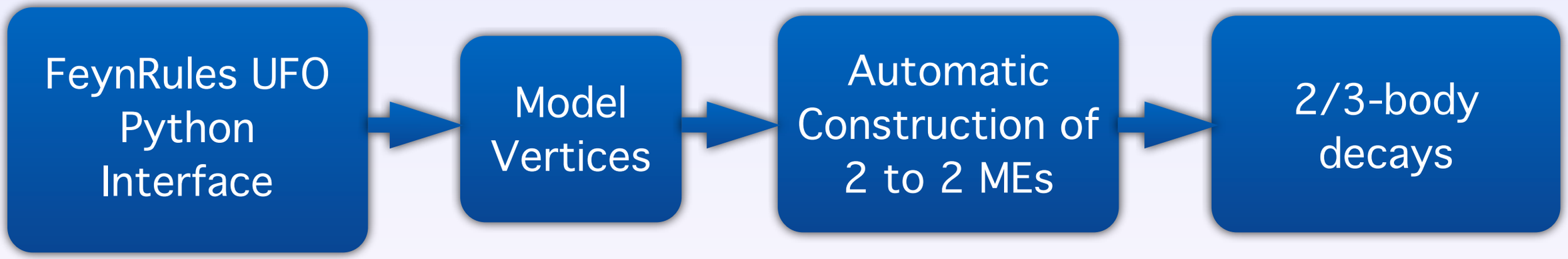


Upcoming Model Vertices

- Models for the top-antitop asymmetry@ Tevatron.
- Sextet diquarks (1108.6154, P.Richardson, D. Winn).
- ...+ More.

FeynRules UFO Python interface*

- Automatically converts a model in UFO file format into a Herwig++ model.
- The rest of the machinery remains unchanged:



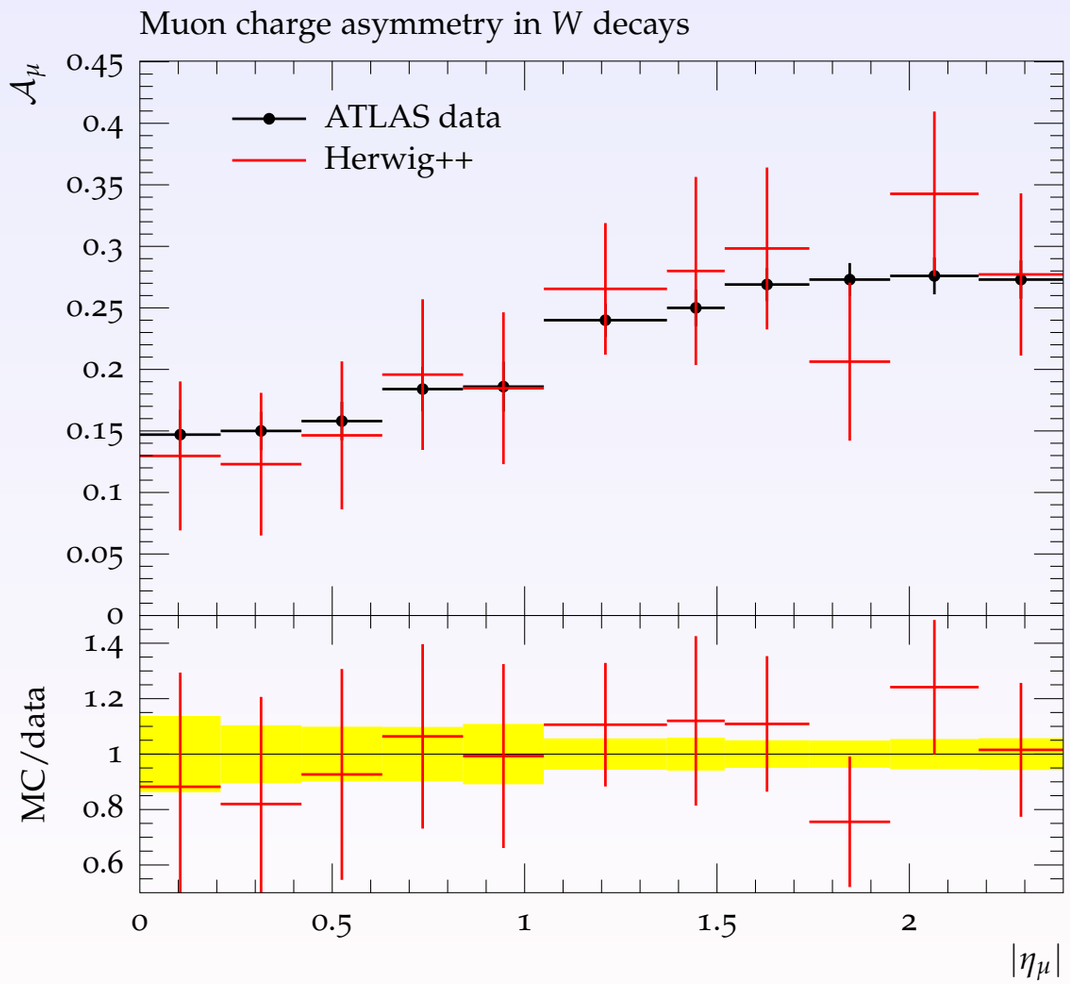
- Implementation almost complete, some testing required. Soon in a public release!

*See other talks/tutorials.

Output and Analysis

- Internal Analyses easy to implement and flexible.
- Interface to HepMC format: online or offline analysis.
- Enables analysis through Rivet.

e.g. (randomly chosen)
Muon charge asymmetry in W decays:



‘Other’ Upcoming Features

- Multi-Jet matching via CKKW/MLM.
- More (and automated: MatchBox) NLO processes.
- Dipole Shower.
- ... + More!

Finally...

- Herwig++ provides a modern, flexible framework for both experimentalists and theorists to use in their searches for new physics.
- Download and further info:
  - http://herwig.hepforge.org
- Feedback is very welcome:
  - herwig@projects.hepforge.org

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Supplementary Slides

Colour Reconnection in Herwig++ (I)

- Starting with the clusters that are produced generically by virtue of pre-confinement, the cluster creation procedure is slightly modified.
- This is done by allowing pairs of clusters to be ‘reconnected’: the coloured constituent of cluster A and the anti-coloured constituent of cluster B form a new cluster, as do the remaining two partons.

Colour Reconnection in Herwig++ (II)

- Algorithm:
  - loop over all other existing clusters and choose the one where a reconnection of the two clusters would result in the smallest sum of cluster masses.
  - if such a reconnection possibility is found, accept it with certain probability.

FHerwig VS Herwig++ shower

- The Herwig shower includes soft gluon interference effects (colour coherence), via angular ordering of emissions in the PS.

- Herwig++ improves upon the success of FHerwig in a number of ways, e.g.:
  - Covariant formulation of the showering algorithm (invariant under boosts along jet axis).
  - Heavy quark fragmentation through use of mass-dependent splitting functions/kinematics.