Herwig++ for BSM

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[on behalf of the Herwig++ team]

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Herwig++ details

- General purpose MC event generator
  - Uses ThePEG (Toolkit for High Energy Physics Event Generation)
  - Native matrix elements and interfaces
  - POWHEG and MC@NLO matching
  - Angular ordered and dipole showers, cluster hadronization, underlying event...
- Major new release coming soon (more on that later)
- Currently $\sim$ 15 collaboration members in CERN, Durham, Karlsruhe, Manchester
- More info at arXiv:0803.0883 and download at http://herwig.hepforge.org

Outline

Hard processes in Herwig++

Simulation of BSM hard processes can be done by:

1. Reading in LHE files
2. Using internal helicity amplitudes with:
   - Hand-coded models
   - Universal FeynRules Output

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1. Les Houches event files

- Generate partonic events in LHA format using an external matrix element generator
- Input through ThePEG `LesHouchesReader` class
- Handles positive and negative fixed weights - NLO compatible

2. Internal simulation

Automatic determination of MEs for $2 \to 2$, $1 \to 2$, $1 \to 3$ (and some $1 \to 4$) processes, including spin correlations

- Based on implementation of the HELAS formalism
- Interactions are coded as `Vertex` classes which evaluate e.g $\bar{\psi} c \gamma^{\mu} \left[g_L P_L + g_R P_R \right] \psi \epsilon_{\mu}$
- Inherit from existing Lorentz structures

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Hand-code models by implementing:

- Input file specifying particle content
- Model class that stores/calculates parameters of the model
- Vertex classes with the new coupling information
- E.g. MSSM, NMSSM, RPV SUSY, ADD and RS gravitons, UED, leptoquarks, sextet...

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UFO model converter

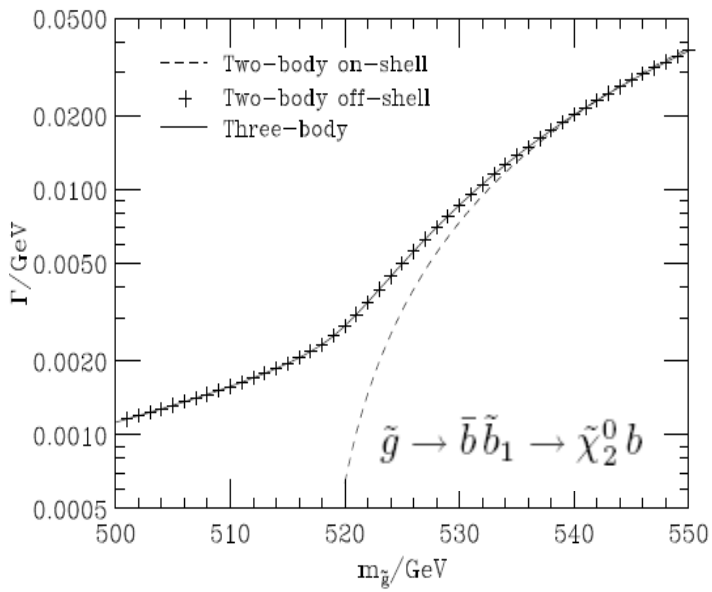
- Automatically convert models in UFO format into a Herwig++ model
- `$ufo2herwig /path/directoryName`

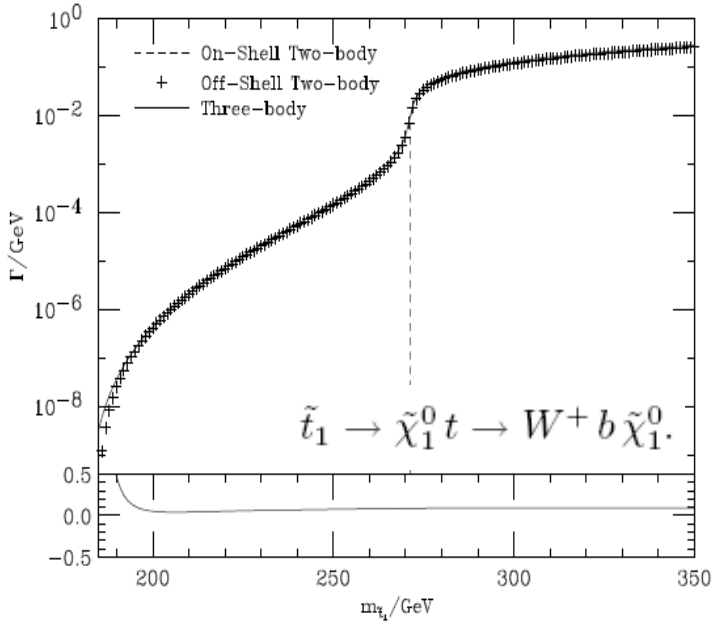
Decays of BSM particles

Finite width effects

- NWA used to separate production and decay
- Often need to include finite width effects
- Distribute masses of outgoing particles in hard processes and decays using a weight factor [arXiv:0805.3037]

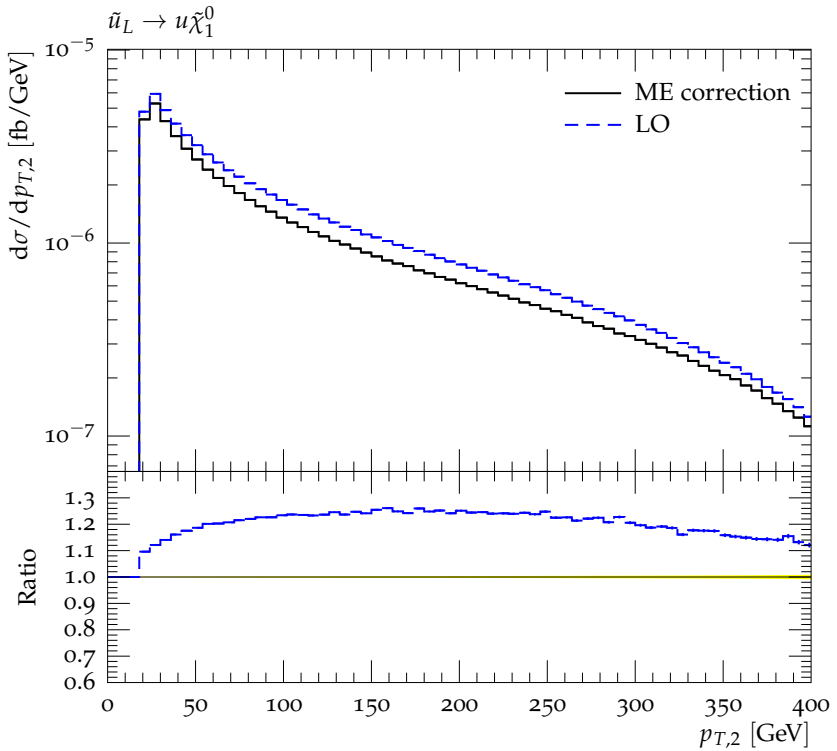
$$w = \frac{1}{\pi} \int dm^2 \frac{m\Gamma(m)}{(m^2 - M^2)^2 - m^2\Gamma^2(m)}$$





Decays of BSM particles

- Improve simulation of hard radiation using POWHEG inspired ME correction [arXiv:1303.4563]
- Available for $1 \to 2$ decays involving:
  - scalar, fermion, vector and tensor* particles
  - colour singlets, (anti)fundamental and adjoint reps of SU(3)



*Not for decays involving coloured tensors

Herwig++ 3.0

Main feature: automated LO and NLO cross sections
Also spin correlations in shower, QED radiation. No major changes for BSM

MATCHBOX framework

- Automated NLO calculations
- Matching to angular ordered/dipole showers via POWHEG and MC@NLO
- (Functionality for (N)LO merging)

Improved evaluation of shower and scale uncertainties.
Easy variation of:

- Renormalization scale, μ_R
- Factorization scale, μ_F
- Hard shower scale, μ_Q (p_T veto for shower emissions)

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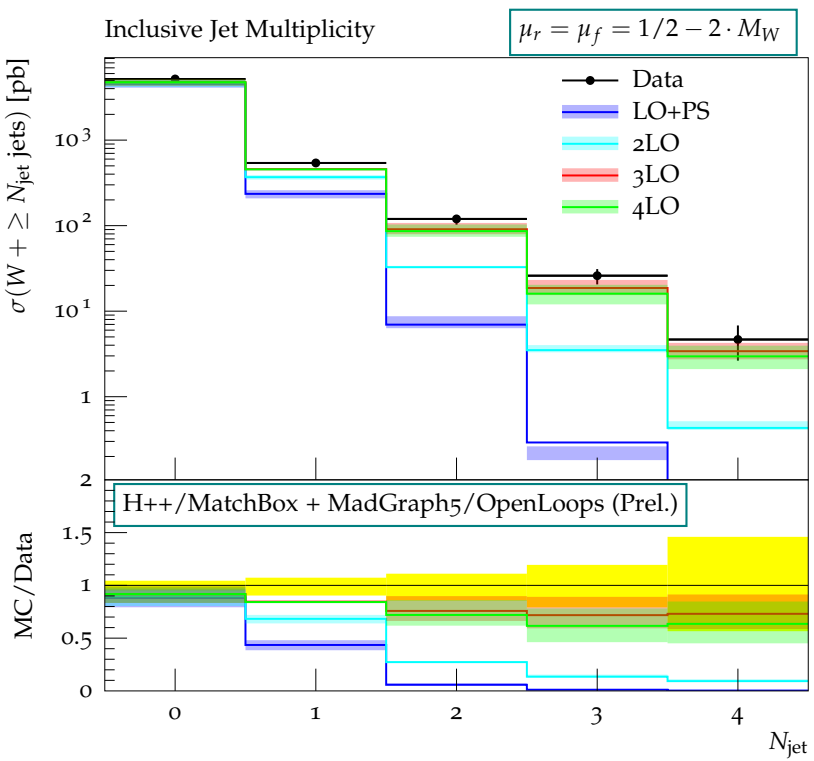
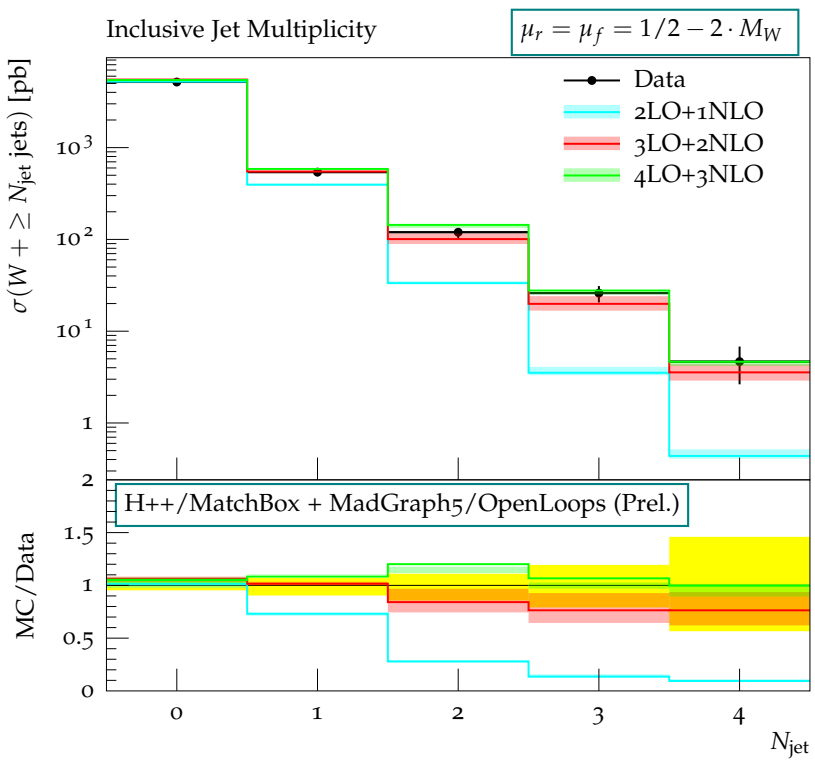
Matrix element merging in MATCHBOX [J. Bellm, S. Gieseke, S. Plätzer]

- Unitarized approach
- Smoothly integrated with no extra event files or external codes to run





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Matchbox Overview.

$$\sigma_{\text{NLO}} = \int_n \mathrm{d}\sigma_{\text{LO}} \begin{pmatrix} |\mathcal{M}_{n,0}\rangle \\ |\mathcal{M}_{n,0}|^2 \end{pmatrix} + \int_n \left[\mathrm{d}\sigma_{\text{V}} \begin{pmatrix} |\mathcal{M}_{n,0}\rangle, |\mathcal{M}_{n,1}\rangle \\ 2\text{Re}(\langle \mathcal{M}_{n,0} | \mathcal{M}_{n,1} \rangle) \end{pmatrix} + \int_1 \mathrm{d}\sigma_{\text{A}} \begin{pmatrix} |\mathcal{M}_{n,0}\rangle \\ |\mathcal{M}^{ij}_{n,0}|^2 \end{pmatrix} \right]$$
$$+ \int_{n+1} \left[\mathrm{d}\sigma_{\text{PS}} \begin{pmatrix} P(\tilde{q}), D(p_\perp) \\ R_{\text{ME}}(p_\perp) \end{pmatrix} - \mathrm{d}\sigma_{\text{A}} \begin{pmatrix} |\mathcal{M}_{n,0}\rangle \\ |\mathcal{M}^{ij}_{n,0}|^2 \end{pmatrix} \right]$$
$$+ \int_{n+1} \left[\mathrm{d}\sigma_{\text{R}} \begin{pmatrix} |\mathcal{M}_{n+1,0}\rangle \\ |\mathcal{M}_{n+1,0}|^2 \end{pmatrix} - \mathrm{d}\sigma_{\text{PS}} \begin{pmatrix} P(\tilde{q}), D(p_\perp) \\ R_{\text{ME}}(p_\perp) \end{pmatrix} \right]$$

Interfaces at amplitude level

- Color bases provided, including interface to `ColorFull`.
  [M. Sjödahl, S. Plätzer]
- Spinor helicity library and caching facilities.
- MadGraph5.
  [MadGraph & J. Bellm, S. Gieseke, S. Plätzer, AW]
- Some in-house calculations and parts of `HJets++`.
  [F. Campanario, T. Figy, S. Plätzer, M. Sjödahl]

Interfaces at squared amplitude level

- Dedicated interfaces.
  [HEJ & S. Plätzer]
  [nlojet++ & J. Kotanski, J. Katzy, S. Plätzer]
- BLHA2.
  [GoSam & J. Bellm, S. Gieseke, S. Plätzer, C. Reuschle]
  [NJet & S. Plätzer]
  [OpenLoops & J. Bellm, S. Gieseke]
  [VBFNLO & K. Arnold, S. Gieseke, S. Plätzer]

Matchbox infrastructure

based on [S. Plätzer & S. Gieseke – Eur.Phys.J. C72 (2012) 2187]

- Process generation and bookkeeping, integration.
- Automated Catani-Seymour dipole subtraction.
- Diagram-based mutli-channel phase space.

Shower plugins

matching details & uncertainties [in preparation]

- Dipole shower $D(p_\perp)$.
- Angular ordered shower $P(\tilde{q})$.
- ME correction $R_{\text{ME}}(p_\perp)$, including adaptive sampling.

Matrix-element corrections for BSM processes

Idea: use MATCHBOX framework and interfaces to add higher order corrections for BSM production processes

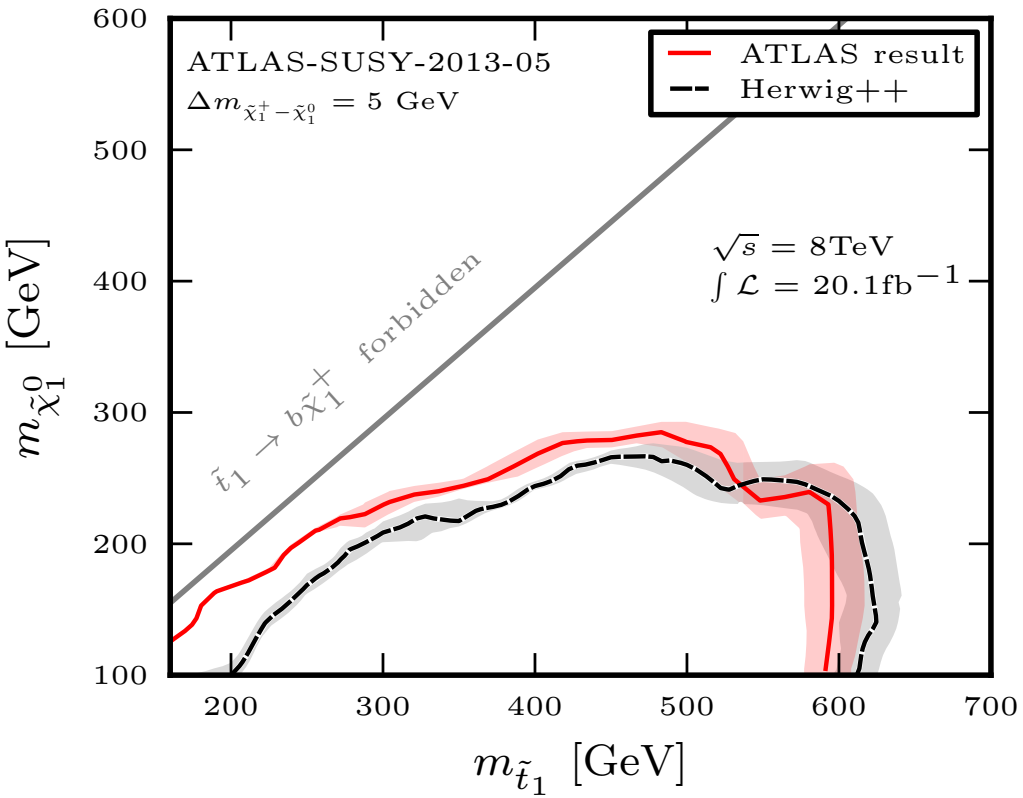
Generally limited by absence of virtual matrix elements
$\rightarrow$ POWHEG style matrix-element correction

- Correct hardest parton shower emission using NLO real-emission contribution
- But total cross section and inclusive observables still only at LO (not NLO)

Test case: $pp \rightarrow \tilde{q}\tilde{q}^*$ in MSSM using MATCHBOX and MADGRAPH 5 amplitudes

Top squark pair production: before

- ATLAS search for direct production of the top squark in events with missing E_T and two b-jets [arXiv:1308.2631]
- $\tilde{t}_1 \to b\tilde{\chi}_1^+ \to bf\bar{f}'\tilde{\chi}_1^0$ with $m_{\tilde{\chi}_1^+} - m_{\tilde{\chi}_1^0} = 5\,\mathrm{GeV}$
- Original signal simulated with MadGraph + PYTHIA 6 (with MLM merging)



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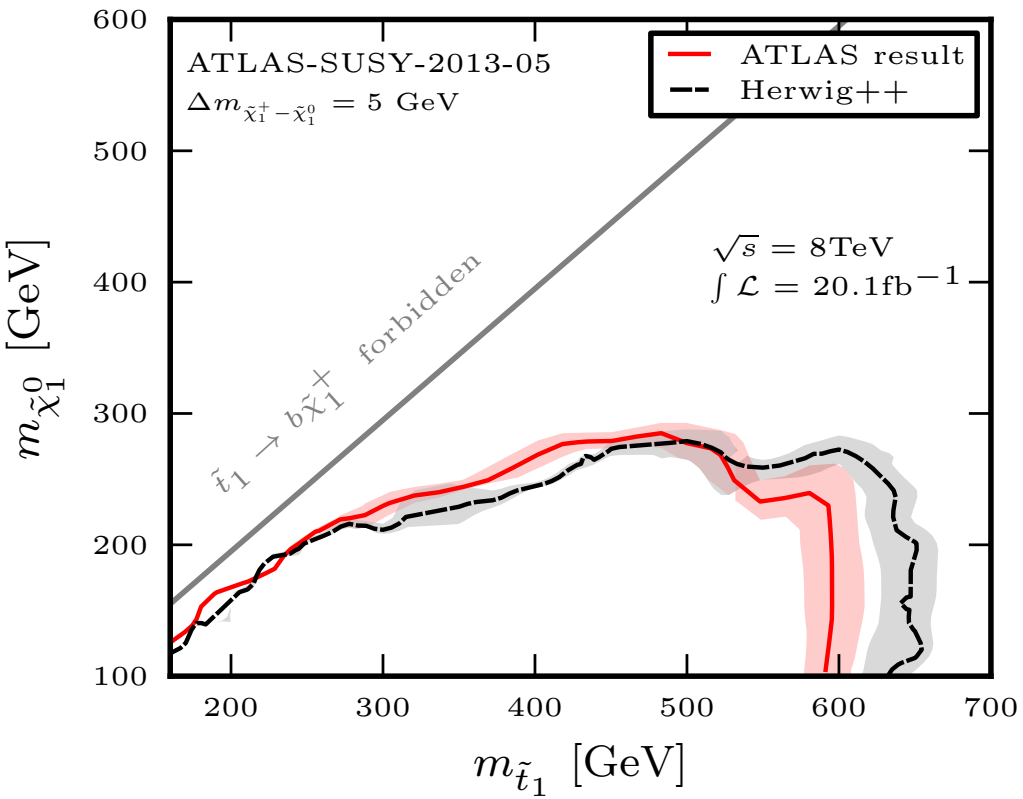
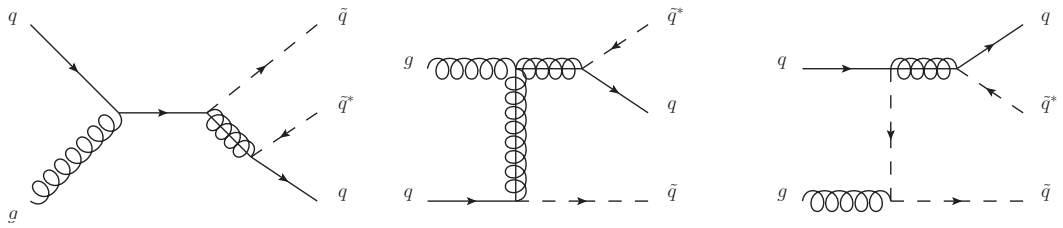
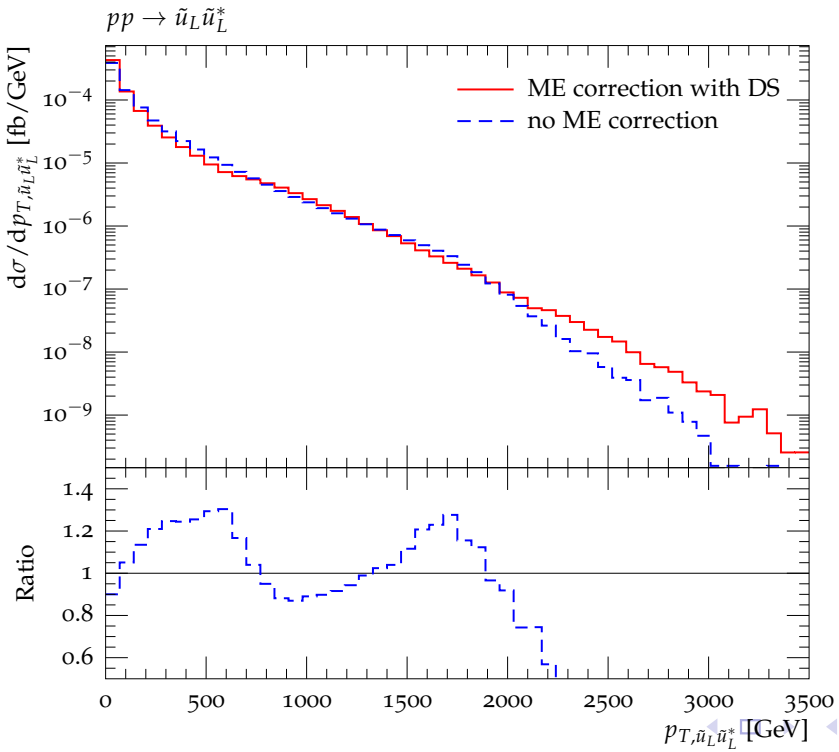


General squark pair production: $pp \to \tilde{q}\tilde{q}^*$ for $\tilde{q} \neq \tilde{t}$

New potentially divergent qg-initiated contributions if $m_{\tilde{g}} > m_{\tilde{q}}$



Subtract resonant contribution from real-emission correction
(treat instead as $qg \to \tilde{q}\tilde{g}$ with $\tilde{g} \to q\tilde{q}^*$)



Summary

- Herwig++ provides a flexible tool for BSM simulation
- Easy to add new models using UFO converter
- Automated NLO calculations for SM processes coming in Herwig++ 3.0
- Improvement to simulation of hard radiation in BSM processes coming soon

Thanks for your attention