BSM Physics in Herwig++

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Outline

Aim

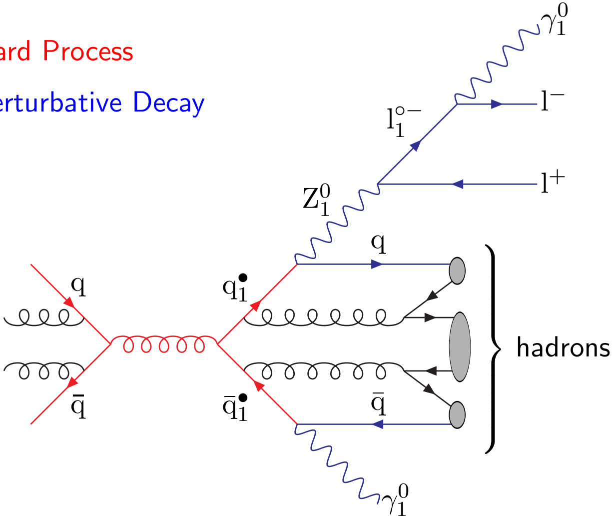
Avoid old approach of encoding new model processes by hand.

Implement a mechanism by which new physics models can be incorporated into Herwig++ with a minimal amount of work.

Do not compromise on the simulation of the physics, *i.e.* automatically include things like spin correlations throughout the simulation.

Monte Carlo BSM Event

1. Hard Process
2. Perturbative Decay



Model Content

To include a new model in Herwig++ several things are required:

- A set of Feynman rules for the new model;
- A list of all the new states in the model;
- Information on the calculation of the new particle spectrum.

M. Gigg and P. Richardson, Eur. Phys. J. C51 (2007) 989 [arXiv:hep-ph/0703199].

HELAS and Vertices

In general, vertices can have much more general Lorentz structures than the perturbative form, e.g. magnetic moment for FFV.

We take just the Lorentz structure for the perturbative part, which can be written down without the knowledge of the exact states that take part in the interaction.

For example, the perturbative form of the FFV vertex:

$$\mathrm{ic}\bar{\psi}\gamma^{\mu}\left(a_L P_L + a_R P_R\right)\psi\,\epsilon_{\mu}$$

The HELAS procedure then enables us to evaluate either; the vertex as a complex number, or an off-shell wavefunction for one of the particles.

This method is used extensively throughout Herwig++.

Hard Process

For a given process we need to be able to calculate $|\mathcal{M}|^2$.

We have implemented a library of $2 \to 2$ matrix elements that are based on external spins rather than specific processes.

The user specifies the external states when running the program and the diagrams that contribute to that process are calculated automatically.

In addition to calculating the amplitude each class is also responsible for setting up the colour structure of the hard process which is necessary for showering and hadronization.

On-Shell Decays

Any new physics model will contain heavy particles that require methods to decay them until they reach some stable point.

The release includes a library of classes to handle all $1 \to 2$ decays with spin correlations, again based on a specific Lorentz structures rather than implementing each by hand.

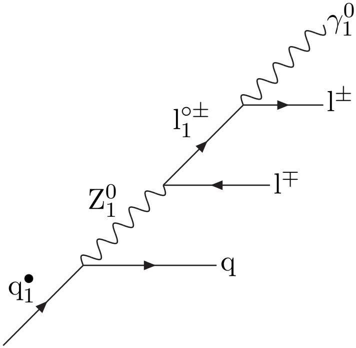
Currently impementing another library for the $1 \to 3$ decays.

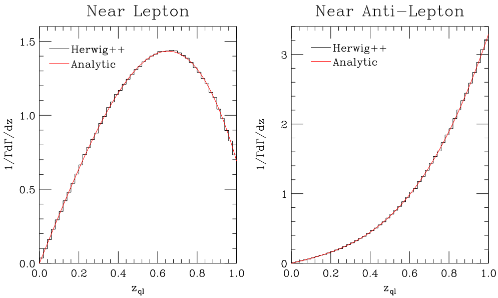
For SUSY the decay modes are read in, along with the spectrum information, from an SLHA file.

Other models where no such file is available have the possible decay modes calculated automatically and also require the spectrum to be calculated somehow.

Cascade Decays

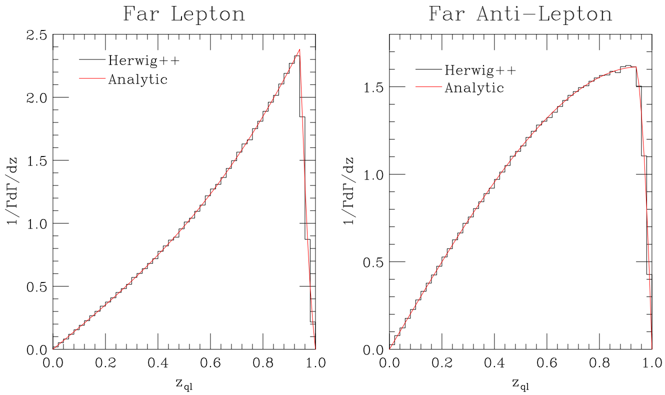
Plots for $R^{-1} = 500\,\mathrm{GeV}$ and $\Lambda R = 20$ in MUED.





z_{ql} is the rescaled mass variable m_{ql}/m_{max}.

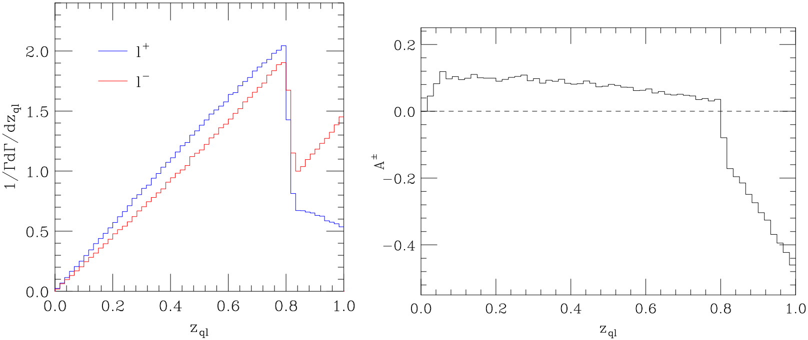
Cascade Decays



Analytic expressions taken from JHEP 0510 (2005) 069 [arXiv:hep-ph/0507170], J. M. Smillie and B. R. Webber

Cascade Decays

Cannot distinguish near and far lepton:

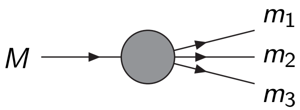


$$A^{\pm} = \frac{\frac{dP^{+}}{dz} - \frac{dP^{-}}{dz}}{\frac{dP^{+}}{dz} + \frac{dP^{-}}{dz}}$$

Three Body Decays

Using the same formalism as for the two body decays we are implementing a library of $1 \rightarrow 3$ classes based on spin structures.

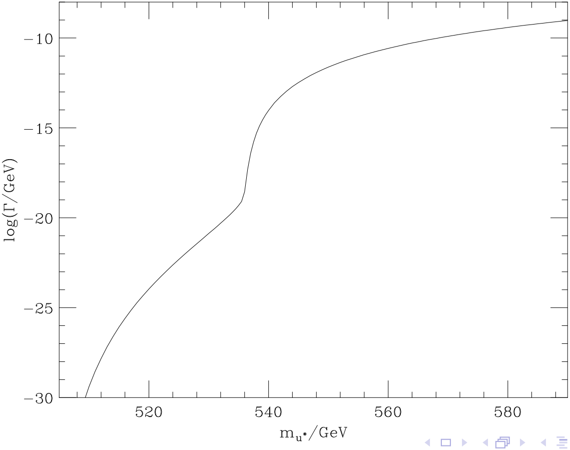
More complex as now we have channels to consider and 2 phase-space integrals to compute.



$$\mathrm{d}\Gamma = \frac{1}{(2\pi)^3}\frac{1}{32\mathrm{M}^3}\overline{\Sigma}|\mathcal{M}|^2\mathrm{dm}^2_{12}\mathrm{dm}^2_{23}$$

Three Body Example Decay: $u^\bullet \to u\, e_1^{\circ -}\, e^+$

Parameters $1/R = 500\,\mathrm{GeV}$ and $\Lambda R = 20$ give $M_{Z_1^0} = 535\,\mathrm{GeV}$ and $M_{e_1^\circ} = 504\,\mathrm{GeV}$



Off-Shell Effects

Until now all particles have been produced on-shell, but to have an accurate simulation off-shell effects must be taken into account.

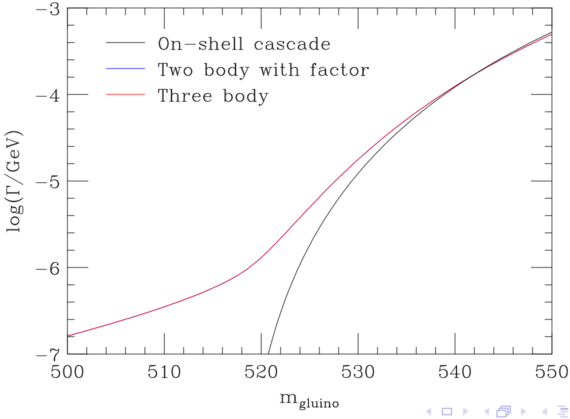
Include weight factor in generation of particle mass and in width calculation

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

This is relatively simple for the decay stages but there are subtleties when dealing production.

Off-Shell Effects in Decay

In decays where the off-shell particle is a scalar there should be exact agreement between the full three body result and the two body with the weight factor, *i.e.* $\tilde{g} \to \bar{b}\,\tilde{b}_1 \to \tilde{\chi}_2^0, b$ at SPS1a



Off-Shell Effects in Production

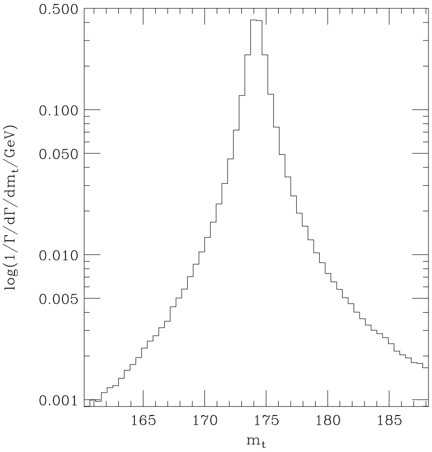
Naive inclusion of off-shell factor can lead to problems with gauge cancellations, for example consider $g\,g \to u_1^\bullet\,\bar{u}_1^\bullet$ or any process where the final-state has the same particle type.

In order to ensure gauge invariance the two outgoing particles, along with off-shell particles in scattering diagrams must have the same mass.

Some choice of rescaling of the outgoing momenta must be made before calculating the matrix element. We choose to use the average of the 2 outgoing masses and then rescale the momenta so as to preserve $\hat{s}$ and θ in the CM frame.

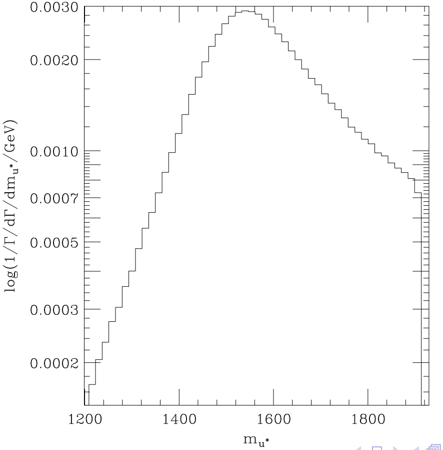
Lineshapes

As an example we first considered off-shell top quark production with $m_t = 174.2\,\mathrm{GeV}$, $\Gamma = 1.4\,\mathrm{GeV}$



Lineshapes

Also $u^\bullet$ production in UED with a heavy KK-quark spectrum via the process $u\,d \to u_1^\bullet\,d_1^\bullet$ with $m_{u_1^\bullet} = 1560\,\mathrm{GeV}$, $\Gamma = 312.759\,\mathrm{GeV}$



Summary and Outlook

- We have created a method to aid with the implementation of BSM physics in Herwig++. Descibed in full in [arXiv:hep-ph/0703199]
- The models available in subsequent releases will be Randall-Sundrum Model, MSSM, MUED, NMSSM, Little Higgs with and without T-Parity,
- The manual is now available [arXiv:0803.0883v1].