BSM Physics in Herwig++

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Outline

- Introduction
- Philosophy
- Current Status
- Three Body Decays and Off-Shell effects
- Adding new models
- Conclusions

Introduction

- Herwig++ is an ongoing project to provide a replacement for the FORTRAN HERWIG program.
- Based on the same physics philosophy but with improved physics simulation based on the theoretical developments of the last 10 years, not just a rewrite.
- There are many improvements to the simulation for both Standard Model and BSM physics.
- In this talk I will concentrate on BSM physics.
- Work in hep-ph/0703199 and arXiv:0805.3037 Gigg and Richardson

History

- FORTRAN HERWIG was highly developed for the simulation of SUSY:
  - 2→2 production matrix elements;
  - 1→2 and 1→3 decays including matrix elements and spin correlations;
  - option of R-parity violation, including both lepton and baryon number violating terms.
  - interface to TAUOLA for longitudinal correlations of taus.
- A lot of effort to produce detailed a simulation of one model. Adding additional models, e.g. UED, would have been as much work again.

Philosophy

- So for Herwig++ we wanted the following features:
  - retain the good features of FORTRAN HERWIG, e.g. the spin correlations;
  - make adding new models much easier;
  - simulate perturbative and non-perturbative decays in the same way so all correlations can be generated for taus;
  - generate QCD radiation from coloured BSM particles.

Philosophy

- The simulation of both Standard Model and Beyond the Standard Model hard processes and decays in Herwig++ is:
  - based on a reimplementation of the HELAS library in C++.;
  - all interactions are coded as vertex classes;
  - the Standard Model hard processes and decays are implemented using hard-coded matrix elements using these classes;
  - for BSM models the matrix elements for 2→2 scattering processes and 1→2 decays are automatically generated based on the spin structure of the process.

Vertex Classes

- The Feynman rules are coded as Vertex classes inheriting from one of the already implemented spin structures, e.g. for a new vector coupling need to supply, c ,g_L, g_R

$$\bar{\psi} c \gamma^{\mu} \left[g_L P_L + g_R P_R \right] \psi \varepsilon_{\mu}$$

- The interactions in new physics models can then be implemented by supplying the couplings in the model.

New Physics

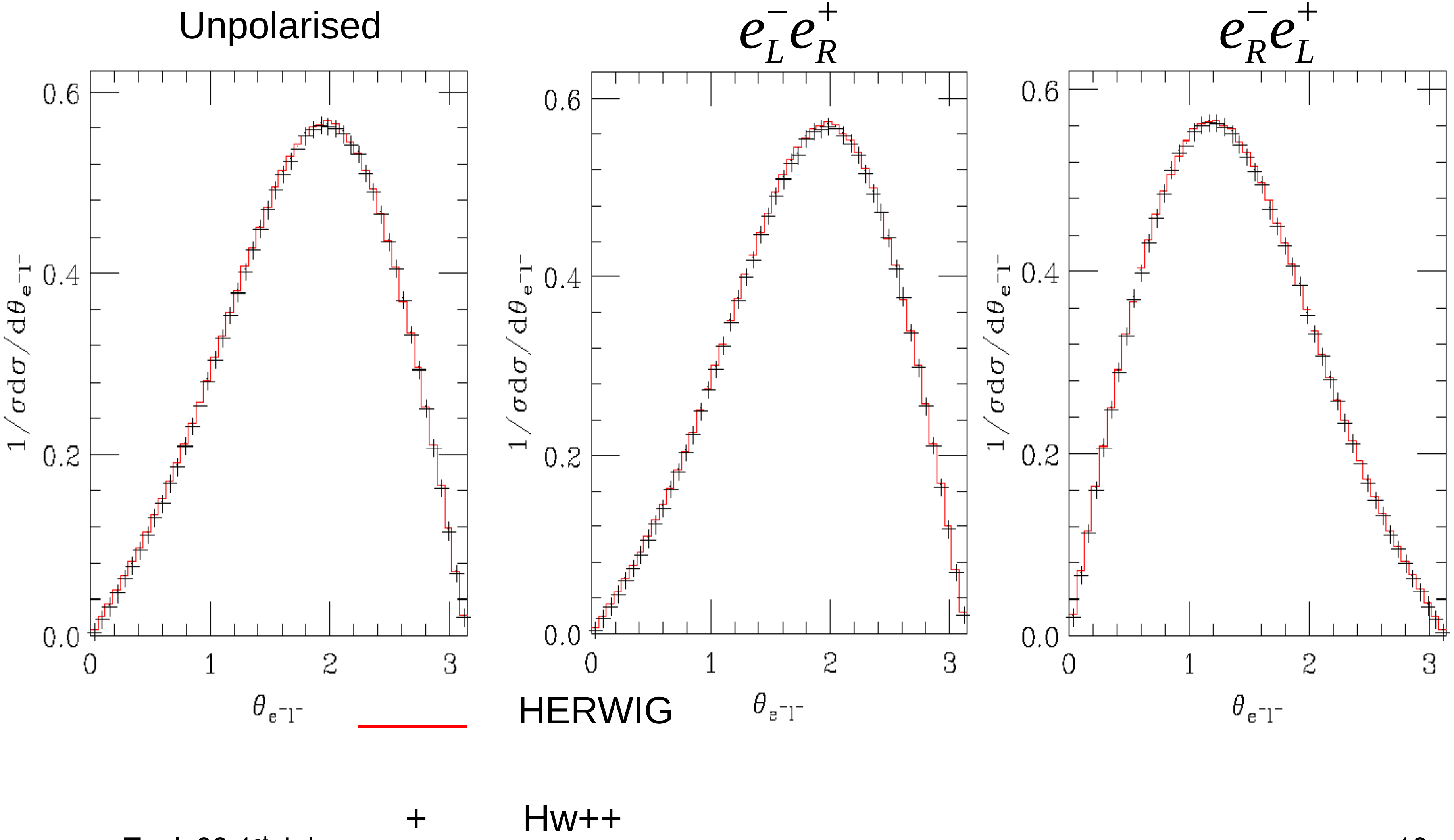
- Implementing a new model in Herwig++ is then simply a matter of:
  - implementing a new model class which inherits from the Herwig++ Standard Model class and stores or calculates any parameters needed in the model;
  - implementing the Vertex classes, specifying the interactions in the model;
  - specifying the particle content of the model.
- Still requires some coding for each model.

Current Status

- A second hadron-hadron version (2.1) of Herwig++ was released on 20 Nov 2007 with major improvements with respect to the previous version.
- Major changes:
  - multiple parton-parton scattering model of the underlying event, based on the FORTRAN JIMMY program;
  - new model of meson and tau decays;
  - inclusion of BSM physics including the MSSM, UED and RS models;
  - tuning of shower and hadronization to LEP, SLD and B-factory data.
- Various other minor improvements and a few more in the 2.2 release in April together with a full manual arXiv:0803.0883.

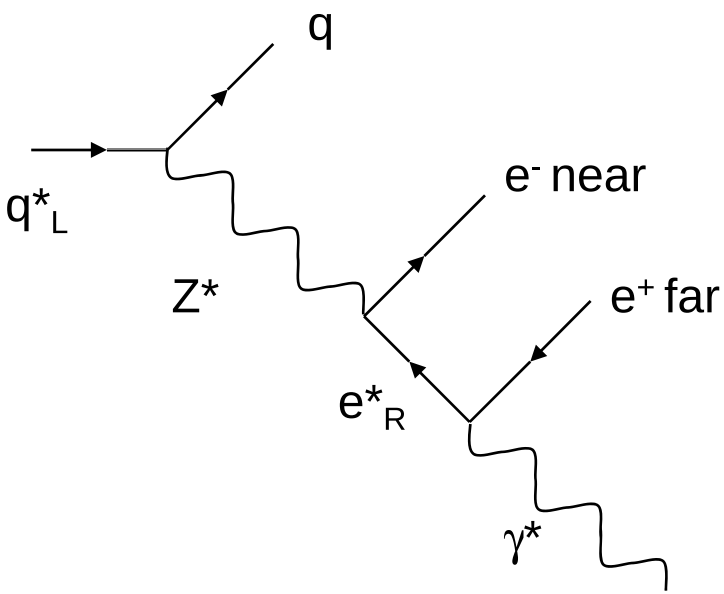
Correlations in e^+e^-

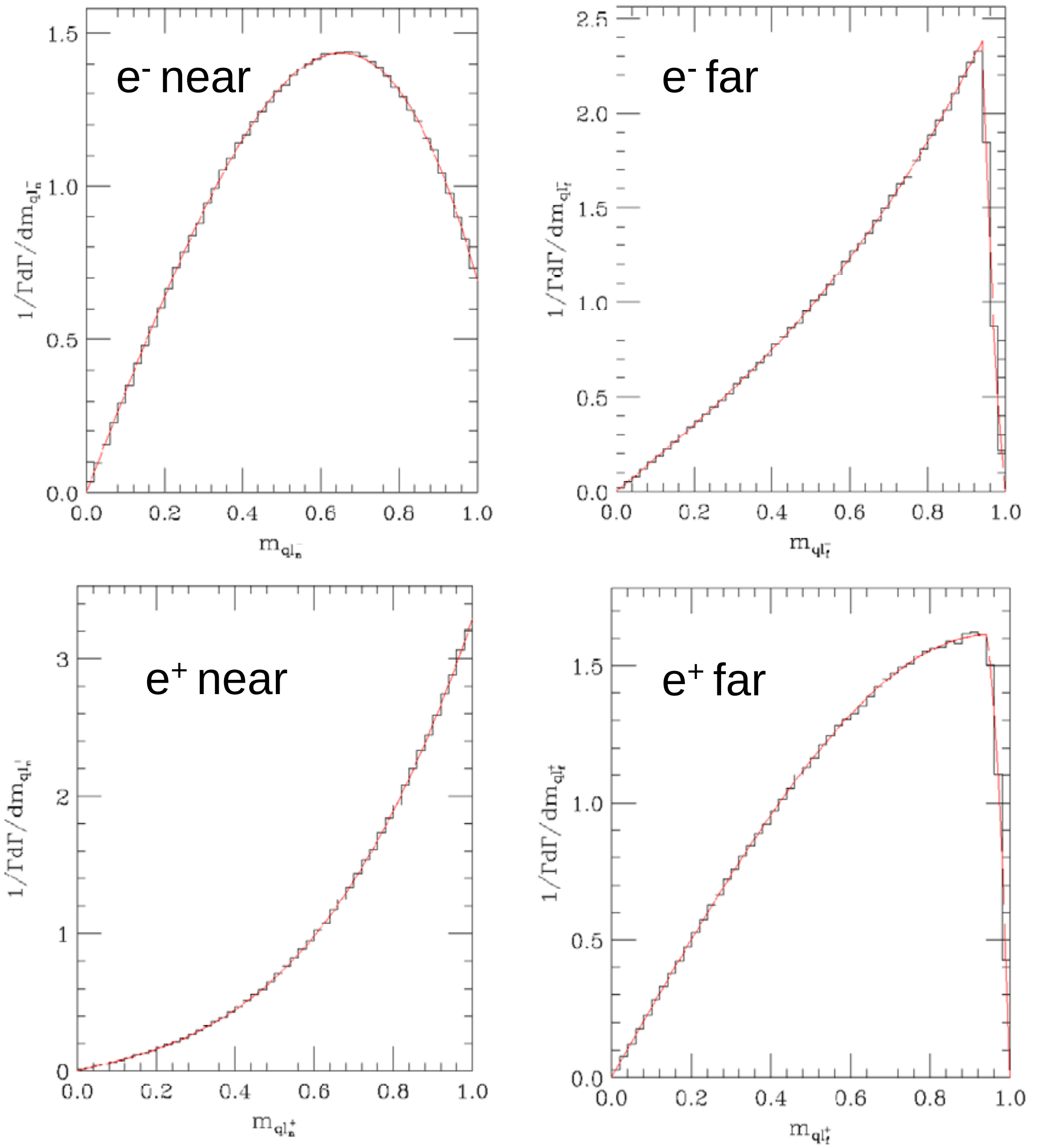
$$e^+e^- \to \chi_2^0\chi_1^0 \to \tilde{l}_R^+ l^- \chi_1^0$$



UED

Look at the decay

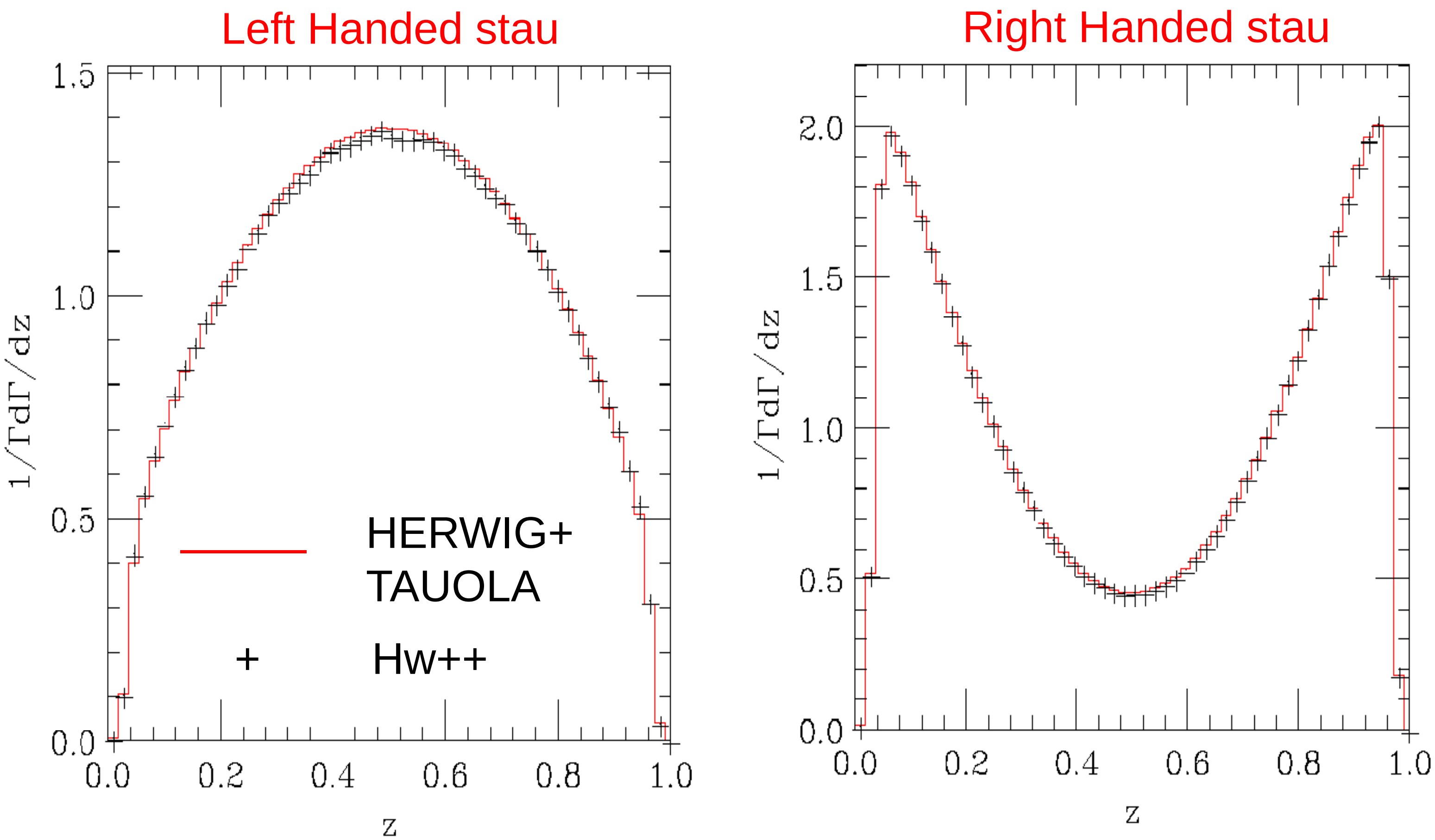




Herwig++ compared to hep-ph/0507170 Smillie and Webber

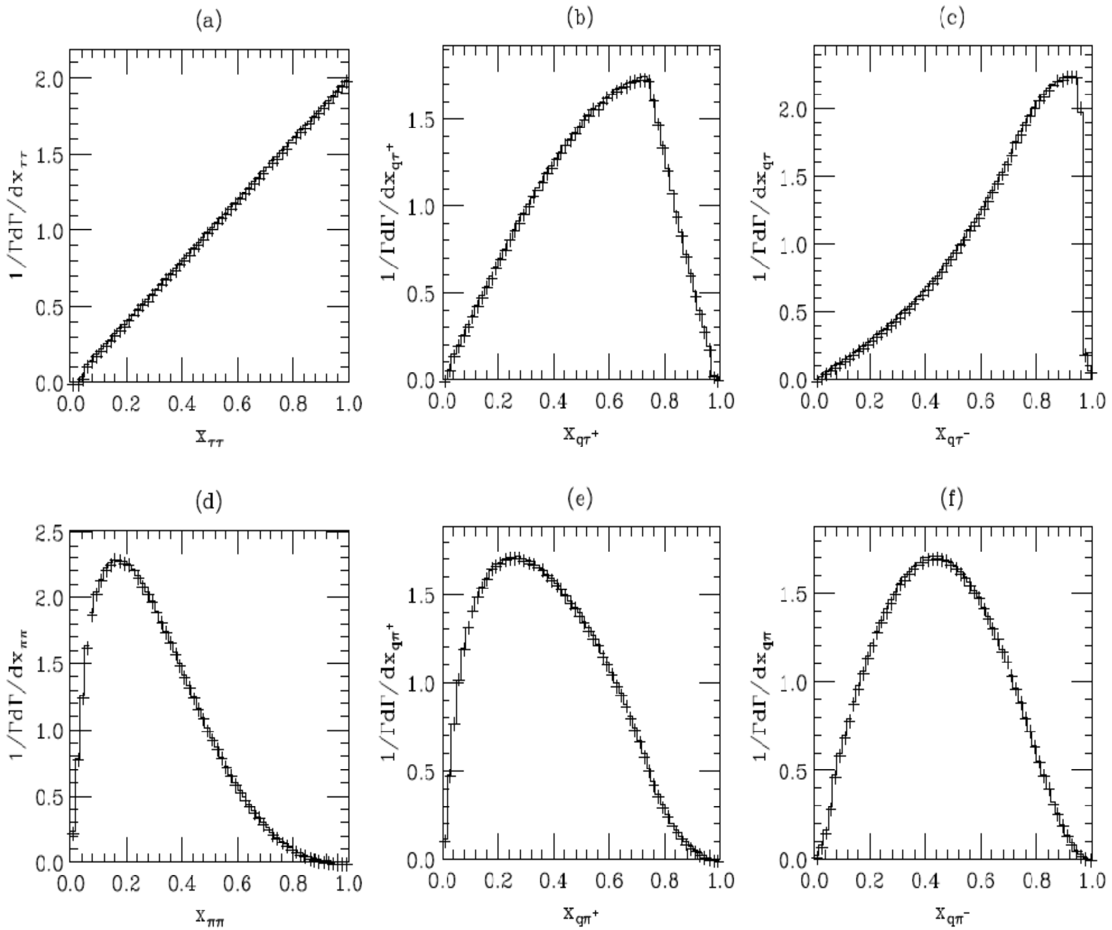
Correlations in Tau Decays

$$\tilde{\tau}^{\pm} \to \tilde{\chi}_1^0 \tau^{\pm} \to \tilde{\chi}_1^0 \rho^{\pm} \nu_\tau \to \tilde{\chi}_1^0 \pi^0 \pi^{\pm} \nu_\tau$$



Fraction of visible energy carried by the charged pion

Correlations in Tau Decays



$$\tilde{q}_\alpha \to q\chi_2^0 \to \tau_{near}^{\pm}\tilde{\tau}_1^{\mp} \to \tau_{far}^{\mp}\chi_1^0$$

- Based on hep-ph/0612237 Choi et al.

New Developments

- The main things missing from the current release are the:
  - simulation of three-body decays;
  - simulation of off-shell effects;
  - allowing different vertex Lorentz structures to be easily handled;
  - adding additional models, e.g NMSSM, Little Higgs with or without T-parity, other extended SUSY models.
- The three-body decays are handled in the same way as the 2 body decays.
- The matrix elements are automatically generated from the Feynman rules.

Finite Width Effects

- In the past finite width effects were handled in HERWIG using a variety of approaches:
  - W and Z bosons were produced using matrix elements including the decay products to get the correlations correct;
  - a sophisticated treatment of the Higgs lineshape was used.
  - the masses of the top and BSM particles were smeared using a Breit-Wigner distribution.
- In Herwig++ wanted to use a more sophisticated approach.

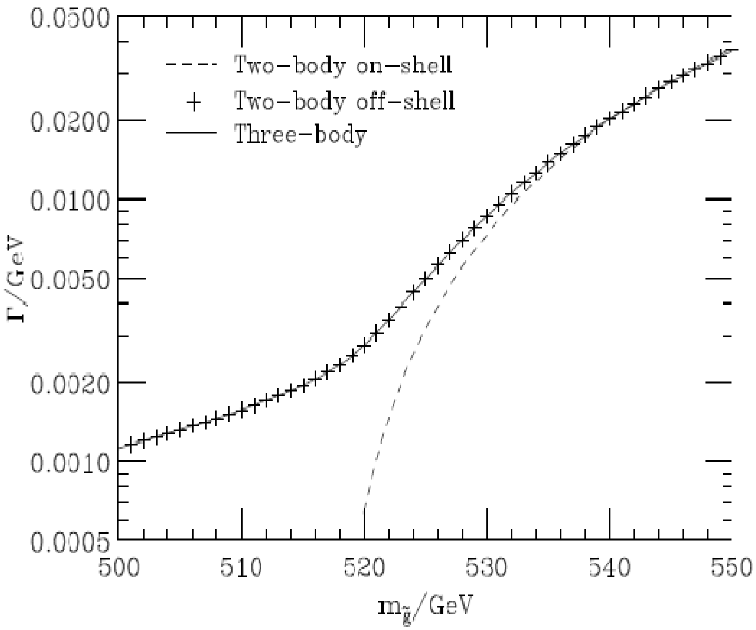
Finite Width Effects

- As with the rest of the simulation use the same machinery for both perturbative and hadronic decays.
- Include a weight factor

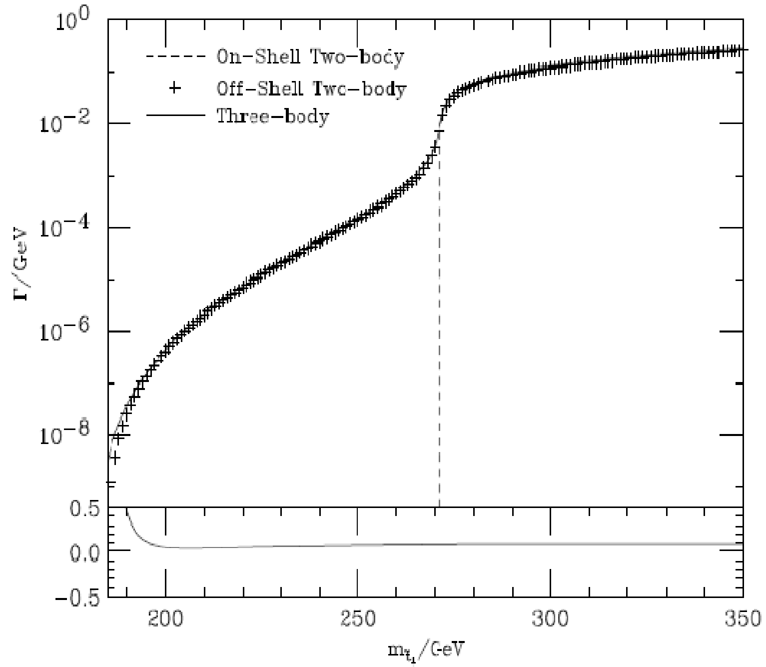
$$w = \tfrac{1}{\pi}\int dq^2 \frac{q\Gamma(q)}{(q^2 - M^2)^2 + q^2\Gamma^2(q)}$$

- For outgoing particles in hard production matrix elements and decays and generate the off-shell mass *q*.

Off-Shell effects in Decays

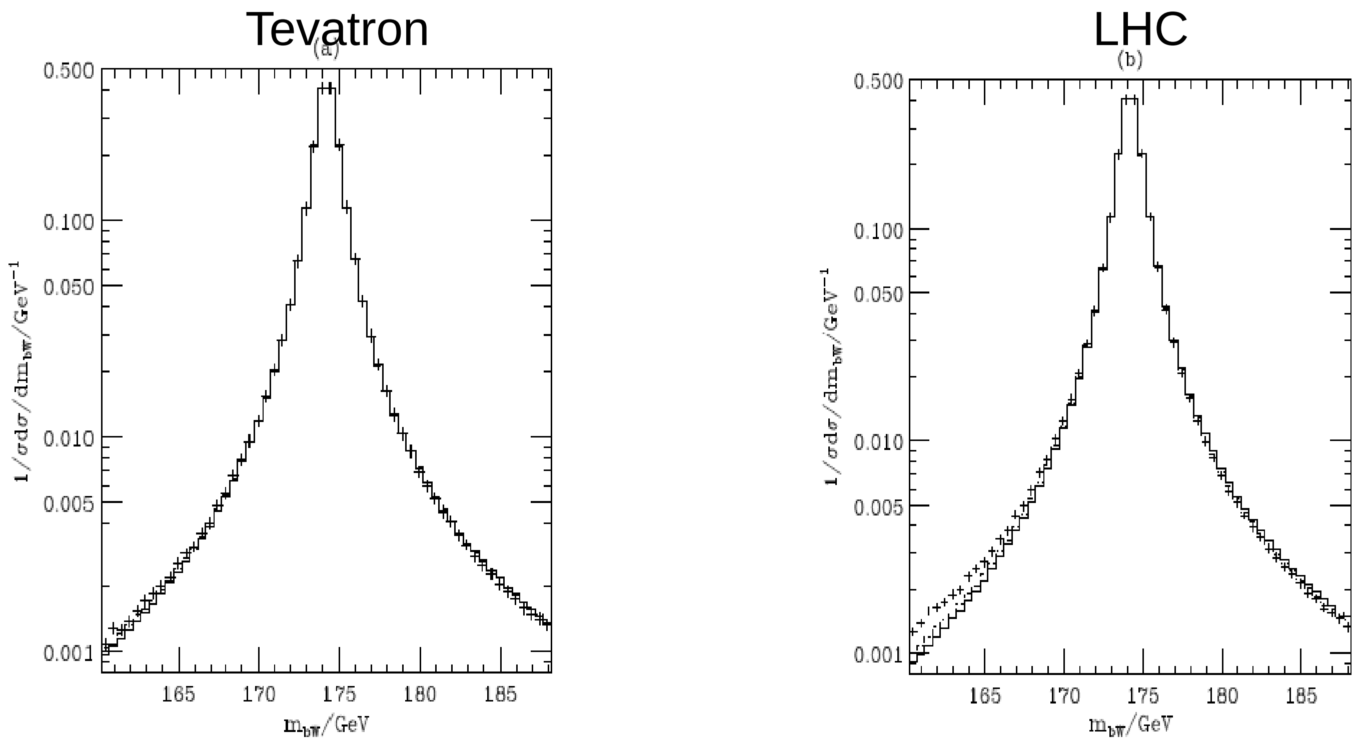


$$\tilde{g} \to \bar{b}\,\tilde{b}_1 \to \tilde{\chi}^0_2\, b$$



$$\tilde{t}_1 \to \tilde{\chi}^0_1\, t \to W^+\, b\, \tilde{\chi}^0_1.$$

Finite Width effects in Production



- Need to be careful with gauge invariance.
- Rescale mass used in the matrix element calculation to either the same value or the on-shell mass.

Different Spin Structures

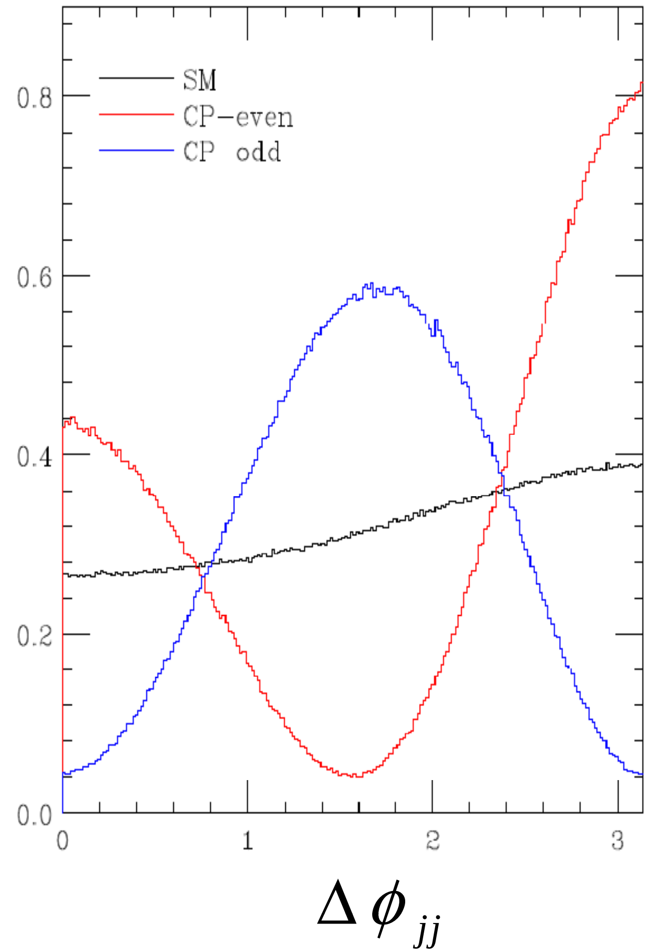
- With the exception of the code implementing the vertex the rest of the simulation doesn't care what the Lorentz structure of the vertex is, e.g. for a fermion-fermion-vector coupling

$$\bar{\psi} c \Gamma^{\mu} \psi \varepsilon_{\mu}$$

  only the code calculating Γ needs to know what it is.
- Introduce a new level of abstract classes to allow any Lorentz structure to be implemented.

Example: VBF Higgs Production

- To explore the CP structure of the Higgs can implement a new vertex class with the CP-even and CP-odd operators.
- Then from the input files replace the Standard Model HWW vertex and get the result using the Standard Model matrix elements.

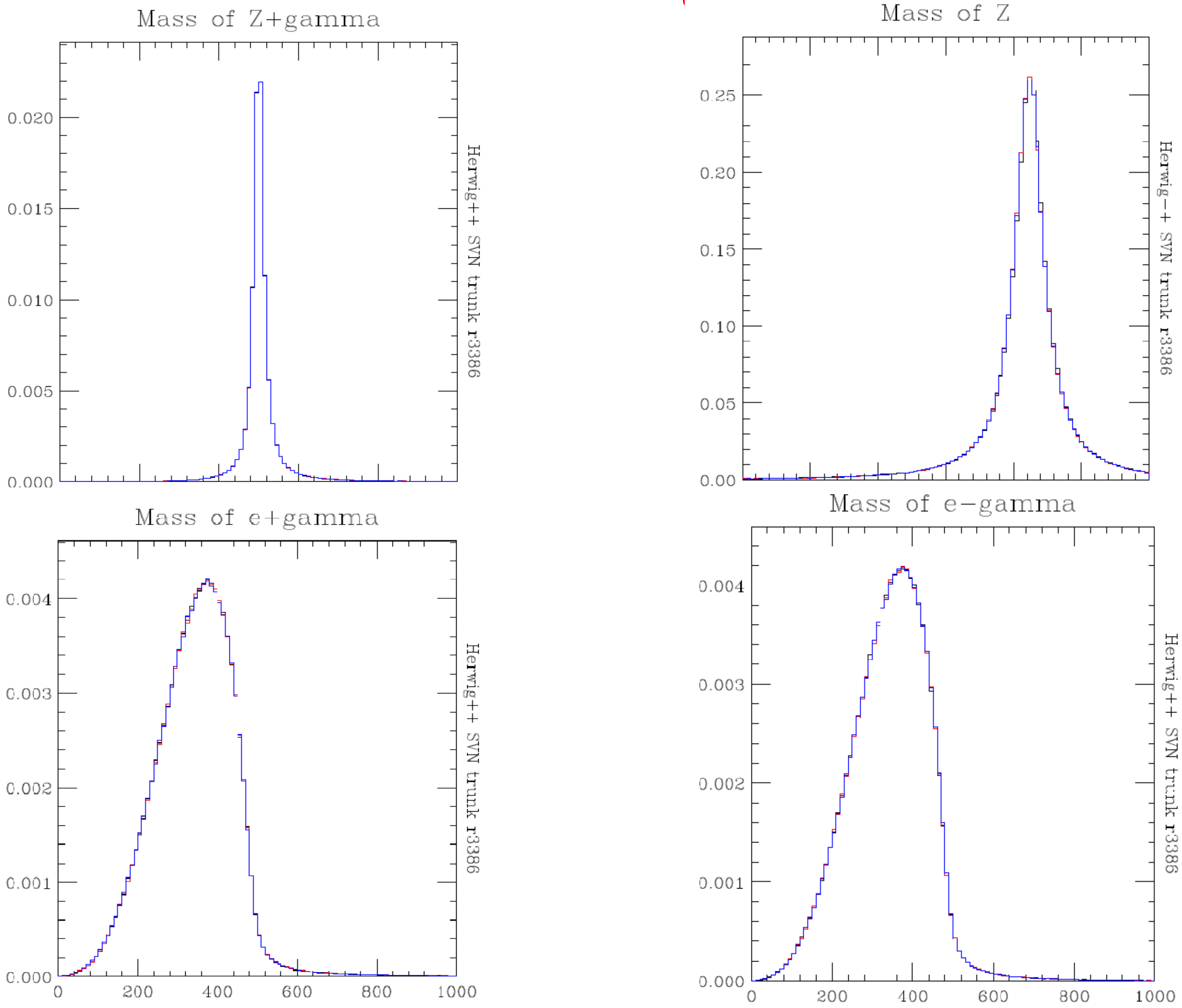


Based on hep-ph/0105325 Plehn et. al

Z' with Anomalous $\gamma ZZ'$ coupling

- Another example is the model of with a Z' coupling to both the SM fermions and γZ via an anomalous coupling hep-ph/0501154 Kozlov .
- The vertex for the Z' coupling to the Standard Model fermions can b essentially copied from the Z vertex.
- Need a new Lorentz structure for the anomalous vertex but then the generation of the hard matrix elements and decays proceeds using the general code.

Z' with Anomalous γZZ' coupling



Using Herwig++

- The source code is available from

  http://projects.hepforge.org/herwig/

  together with wiki and bug tracker.
- In order to improve user support in the first instance all requests for support to *herwig@projects.hepforge.org*.
- We will open a ticket for all issues and use this for all interactions to improve support and keep a record.

Using Herwig++

- Need to download and install ThePEG and Herwig++ as explained on

  http://projects.hepforge.org/herwig/versions.html

- Has been tested on a wide variety of Linux systems (32 and 64 bit) using gcc 3.4.6, 4.0.4, 4.1.2 and 4.2.2, 4.3.0 and Intel based Macs.
- We use autotools, configure and make for installation.
- Detailed instructions at

  http://projects.hepforge.org/herwig/trac/wiki/HerwigInstallation

- A number of examples for different colliders are provided.

Using Herwig++

- A number of examples are installed in the share directory.
- We have simplified the structure of the input files so that the majority of users should only need to edit one file.
- If you try the LHC example LHC.in
  - herwig-location/bin/Herwig++ read LHC.in
- Creates the event generator LHC.run
  - herwig-location/bin/Herwig++ run LHC.run –N#of-events
- Runs the event generator.

Using Herwig++

- The hard process can be changed by adding new matrix elements

```
# Drell-Yan Z/gamma
insert SimpleQCD:MatrixElements[0] MEqq2gZ2ff
# Drell-Yan W
# insert SimpleQCD:MatrixElements[0] MEqq2W2ff
# gamma-gamma
# insert SimpleQCD:MatrixElements[0] MEGammaGamma
# gamma+jet
# insert SimpleQCD:MatrixElements[0] MEGammaJet
# gg/qqbar -> Higgs
# insert SimpleQCD:MatrixElements[0] MEHiggs
# higgs+jet
# insert SimpleQCD:MatrixElements[0] MEHiggsJet
# QCD 2-2 scattering
# insert SimpleQCD:MatrixElements[0] MEQCD2to2
# top-antitop production
# insert SimpleQCD:MatrixElements[0] MEHeavyQuark
```

Using Herwig++

- Simple analysis of the events, producing output in topdraw format can be switched on

```
#######################################################
#  Useful analysis handlers for hadron-hadron physics
#######################################################
# analysis of W/Z events
# insert LHCGenerator:AnalysisHandlers 0 /Herwig/Analysis/DrellYan
# analysis of top-antitop events
# insert LHCGenerator:AnalysisHandlers 0 /Herwig/Analysis/TTbar
# analysis of gamma+jet events
# insert LHCGenerator:AnalysisHandlers 0 /Herwig/Analysis/GammaJet
# analysis of gamma-gamma events
# insert LHCGenerator:AnalysisHandlers 0 /Herwig/Analysis/GammaGamma
# analysis of higgs-jet events
# insert LHCGenerator:AnalysisHandlers 0 /Herwig/Analysis/HiggsJet
```

Using Herwig++

- Cuts on the particles produced in the hard process can be changed, e.g. p_T and η of photons

```
set PhotonKtCut:MinKT 20.0*GeV
set PhotonKtCut:MinEta -3.
set PhotonKtCut:MaxEta  3.
```

- Switch off parts of the event generation
- Hadron Decays

```
set /Herwig/EventHandlers/LHCHandler:DecayHandler NULL
```

- Multiple scattering

```
set /Herwig/Shower/ShowerHandler:MPI No
```

Using Herwig++

- A number of examples of BSM models, SUSY, RS and UED are included with the release and can be used in the same way.
- If you try the LHC MUED example LHC-MUED.in
  - herwig-location/bin/Herwig++ read LHC-MUED.in
- Creates the event generator LHC-MUED.run
  - herwig-location/bin/Herwig++ run LHC-MUED.run –N#of-events
- Generates events and provides the widths and branching ratios.

Plans for the Future

- At this point with the improvements I've described here the core of the BSM simulation is complete.
- Obviously more models can be added, and the mechanism for adding models made easier.
- Most of the development on Herwig++ at this point is concentrating on Standard Model physics.

Future Improvements

- We are continuing to work on a number of further improvements
  - CKKW matrix element matching;
  - The multi-scale shower;
  - MC@NLO;
  - The Nason approach to MC@NLO;
  - IVAN soft underlying event model;
  - Improved modelling of baryon decays;
  - Additional new physics models and better simulation of off-shell effects.

Summary

- Herwig++ is now fully ready for hadron collisions.
- It is a sophisticated tool for the simulation of BSM physics
- A comprehensive manual is now available.
- User support available from herwig@projects.hepforge.org
- The improvements I've described here will be released by the end of September.
- This release will contain numerous other improvements for the simulation of Standard Model physics.