Status of WHIZARD

Wolfgang Kilian

U Siegen

LC Forum, Bonn, April 2014

(Talk at AWLC14 will be given by T. Ohl)

WHIZARD in a Nutshell

WHIZARD is a universal event generator for elementary processes at colliders:

- e^+e^-: LEP and TESLA/NLC $\Rightarrow$ ILC, CLIC, ...
- pp: Tevatron $\Rightarrow$ LHC, ...

It contains

1. O'Mega: Automatic matrix elements for arbitrary elementary processes, supports SM and many BSM extensions
2. Phase-space parameterization module
3. VAMP: Generic adaptive integration and (unweighted) event generation
4. Intrinsic support or external interfaces for: Feynman rules, beam properties, cascade decays, shower, hadronization, analysis, event file formats, etc., etc.
5. Free-format steering language SINDARIN

Milestones

1.0 Project started around 1999: Studies for electroweak multi-particle processes at TESLA (W, Higgs, Z)

Event samples for LC studies at SLAC

1.9 Full SM w/ QCD, beam properties, SUSY/BSM, event formats

2.1 QCD shower+matching, FeynRules support, internal density-matrix formalism (cascade decays), language SINDARIN as user interface, OpenMP parallelization, ...
(production version)

2.2 Major refactoring of internals (same user interface), event sample reweighting, inclusive processes, improved LC beam description
(current status: final polishing, updating manual)

Plan Further improve ILC support; NLO + matching; improve user interface
$\Rightarrow$ adapt to specific needs of user groups

The WHIZARD Event Generator – Release 2.1

- Multi-Channel Monte-Carlo integration
- Efficient phase space and event generation (weighted & unweighted)
- Optimized tree-level matrix elements (O'Mega)
  - $e^+e^- \to t\bar{t}H \to b\bar{b}b\bar{b}jj\ell\nu$ (110,000 diagrams)
  - $e^+e^- \to ZHH \to ZWWWW \to bb + 8j$ (12,000,000 diagrams)
  - $pp \to \ell\ell + nj,\ n = 0, 1, 2, 3, 4, \ldots$ (2,100,000 diagrams with 4 jets + flavors)
  - $pp \to \tilde{\chi}_1^0\tilde{\chi}_1^0 bbbb$ (32,000 diagrams, 22 color flows, $\sim 10,000$ PS channels)
  - $pp \to VVjj \to jj\ell\ell\nu\nu$ incl. anomalous TGC/QGC
  - Test case $gg \to 9g$ (224,000,000 diagrams)

WHIZARD 2.1.1 release: 2012, Sept. 18

Old series: WHIZARD 1.97 (development stopped with 1.94)

WHIZARD team: F. Bach, B. Chokoufe, W. Kilian, T. Ohl, J. Reuter, M. Sekulla, C. Weiss, D. Wiesler

Web address: `http://projects.hepforge.org/whizard`

Standard Reference: WK/Ohl/Reuter, EPJC 71 (2011) 1742, arXiv:0708.4233

Hard matrix elements: particle types

Possible particle types

- Spin 0 particles
- Spin 1/2 fermions (Majorana and Dirac)
  Fermi statistics for both fermion-number conserving and violating cases
- Spin 1 particles
  - massive and massless
  - Unitarity and Feynman gauge
  - arbitrary R_ξ gauges
- Spin 3/2 particles (Majorana only, gravitinos)
- Spin 2 particles (massless and massive, gravitons)
- Dynamic particles vs. pure insertions
- Unphysical particles for Ward- and Slavnov-Taylor identities

WHIZARD – Overview over BSM Models

MODEL TYPE	with CKM matrix	trivial CKM
QED with e, μ, τ, γ	–	`QED`
QCD with d, u, s, c, b, t, g	–	`QCD`
Standard Model	`SM_CKM`	`SM`
SM with anomalous gauge couplings	`SM_ac_CKM`	`SM_ac`
SM with anomalous top couplings	`SMtop_CKM`	`SMtop`
SM with WW resonances and unitarization	—	`SSC`
MSSM	`MSSM_CKM`	`MSSM`
MSSM with gravitinos	—	`MSSM_Grav`
NMSSM	`NMSSM_CKM`	`NMSSM`
extended SUSY models	—	`PS/E/SSM`
Littlest Higgs	—	`Littlest`
Littlest Higgs with ungauged $U(1)$	—	`Littlest_Eta`
Littlest Higgs with T parity	—	`Littlest_Tpar`
Simplest Little Higgs (anomaly-free)	—	`Simplest`
Simplest Little Higgs (universal)	—	`Simplest_univ`
3-site model	—	`Threeshl`
UED	—	`UED`
SM with Z'	—	`Zprime`
SM with gravitino and photino	—	`GravTest`
Augmentable SM template	—	`Template`

QCD Effects

WHIZARD 2: Color is treated exactly, color-flow formalism

[old event samples: color flow was inferred from kinematics]

Color in final state: several options

1. Partonic event files with color correlation, to be handled by external shower/hadronization (PYTHIA 6, PYTHIA 8, HERWIG)
2. Internally linked PYTHIA 6 via Les Houches Interface (for color correlation) $\Rightarrow$ automatic generation of showered/hadronized event files
3. WHIZARD's own internal shower (analytic shower) and internal PYTHIA hadronization
4. WHIZARD's own internal shower (analytic shower) and external hadronization

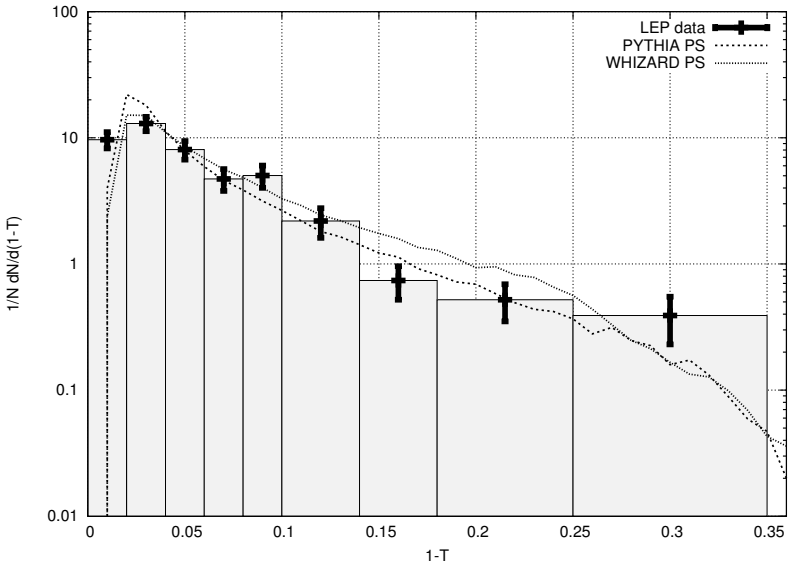
Extra radiation: avoid double-counting

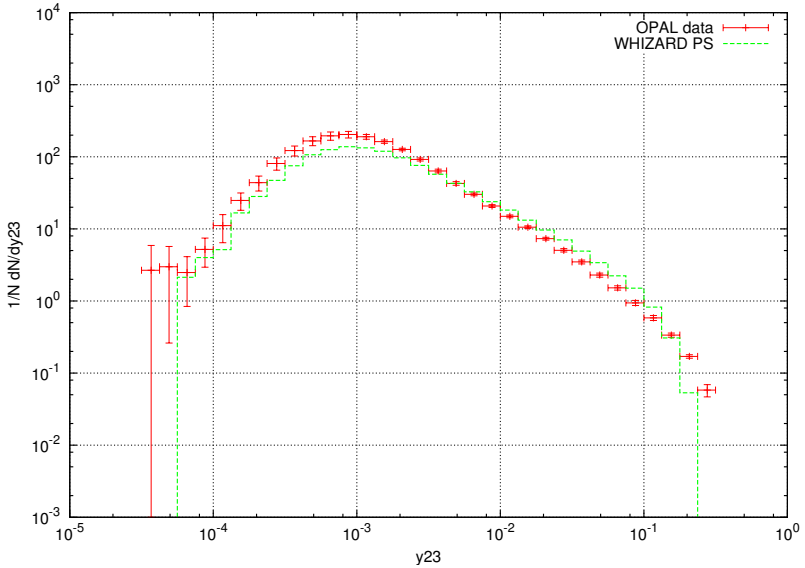
- Matrix element for extra radiation + MLM matching scheme

Analytic Parton Shower

Reuter/Schmidt/Wiesler, JHEP 2012

- Analytic Parton Shower:
  - no shower veto: shower history is exactly known
  - allows reweighting and maybe more reliable error estimate
- validated against PYTHIA shower (tuning: assistance welcome!)



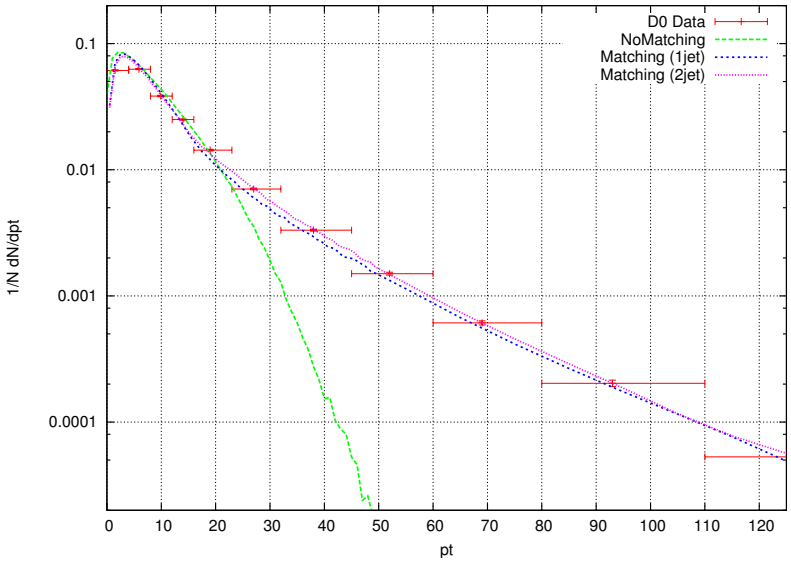


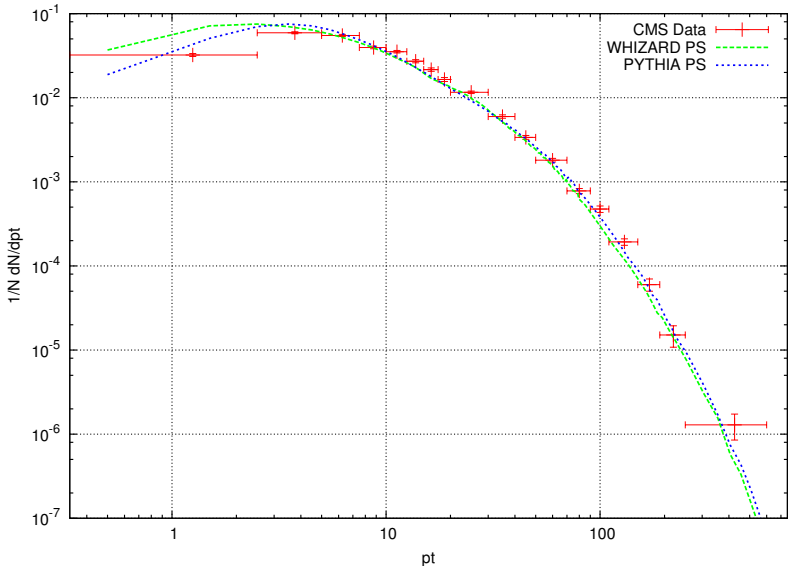
- matching with hard matrix elements

Analytic Parton Shower

Reuter/Schmidt/Wiesler, JHEP 2012

- Analytic Parton Shower:
  - no shower veto: shower history is exactly known
  - allows reweighting and maybe more reliable error estimate
- validated against PYTHIA shower (tuning: assistance welcome!)





- matching with hard matrix elements

More physics aspects/improvements in WHIZARD 2

- SINDARIN (Scripting INtegration, Data Analysis, Results display and INterfaces)
  - steering: process definition, parameters, models, beam structure, scans/loops, conditionals, I/O, file formats, ...
  - expressions: for cuts, scales, weights
  - analysis: observables, plots, histograms

```
cuts = any 5 degree < Theta < 175 degree
         [select if abs (Eta) < eta_cut [lepton]]
cuts = any E > 2 * mW [extract index 2
                         [sort by Pt [lepton]]]
```

- Decay cascades including full spin correlations
- `FeynRules` interface Christensen/Duhr/Fuks/Reuter/Speckner, EPJC 72 (2012) 1990
- Event-dependent scales in PDFs and running α_s
- Anomalous couplings, resonances and unitarity in vector-boson scattering

News 2013/14: Towards 2.2.X

- status: public beta stage (feature complete), final polishing
- WHIZARD core: insert an extra abstraction layer, consistently separate interface from implementation
  - Replaceable modules with well-defined interface: matrix-elements, beam structure, phase space, integration, decays, shower, ...
  - Much easier to contribute new parts to the code
  - Framework for testing ideas and algorithms
  - Technical changes hidden from the user
- Models for BSM interactions of electroweak vector bosons (w/ light Higgs)
- Automatically compute decay chains, depending on the model

```
?auto_decays = true
unstable Z ()
```

- Inclusive processes

```
process cpp = "e-", "e+" =>  "ch1+" + "ch2+",  "ch1-" + "ch2-"
```

- Read event files, reweight and reanalyze

Technical Features

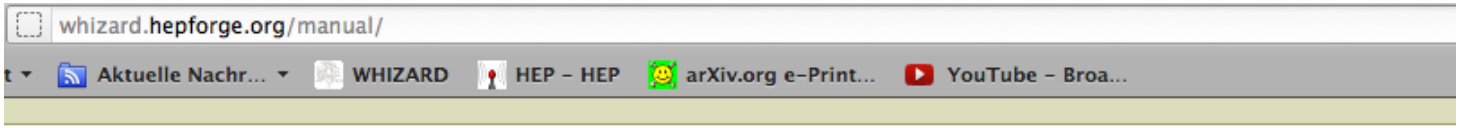
- WHIZARD 2: code basically rewritten, only Fortran 2003 (`gfortran 4.7`) and `O'Caml`
- Object-oriented implementation and clean modularization of code
- OpenMP parallelization
- Operation modes:
  - Dynamic linking (default mode) with on-the-fly generation of process code
  - Static linking (for batch clusters)
  - Library mode, callable from C/C++/Python/...
  - Interactive mode: WHIZARD works as a Shell – WHISH
- Standard conformance: uses `autotools`: `automake/autoconf/libtool`
- test suite
- Version control (`svn`) at HepForge: use of ticket system and bug tracker
- Continuous integration system (`jenkins`) linked with svn repository

WHIZARD 2 – Installation and Run

- Download WHIZARD from `http://www.hepforge.org/archive/whizard/whizard-2.1.1.tar.gz` and unpack it
- WHIZARD intended to be centrally installed on a system, e.g. in `/usr/local` (or locally on user account)
- Create build directory and `configure`
  External programs (LHAPDF, StdHEP, HepMC) might need flags
- `make`, `make install`
- Create SINDARIN steering file (in any working directory)
- Run `whizard` (in working directory)

```
O'Mega self tests:
make  check-TESTS
PASS: test_omega95
PASS: test_omega95_bispinors
PASS: test_qed_eemm
PASS: ects
PASS: ward
PASS: compare_split_function
PASS: compare_split_module
==================
All 7 tests passed
==================
WHIZARD self tests:
make  check-am
make  check-TESTS
PASS: empty.run
PASS: vars.run
PASS: md5.run
[..........]
XFAIL: errors.run
PASS: extpar.run
PASS: susyhit.run
PASS: libs.run
PASS: qedtest.run
PASS: helicity.run
PASS: smtest.run
PASS: defaultcuts.run
PASS: restrictions.run
PASS: decays.run
PASS: alphas.run
PASS: colors.run
PASS: cuts.run
PASS: lhapdf.run
PASS: ilc.run
PASS: mssmtest.run
PASS: models.run
PASS: stdhep.run
PASS: stdhep_up.run
====================================
All 53 tests behaved as expected (1 e
====================================
```

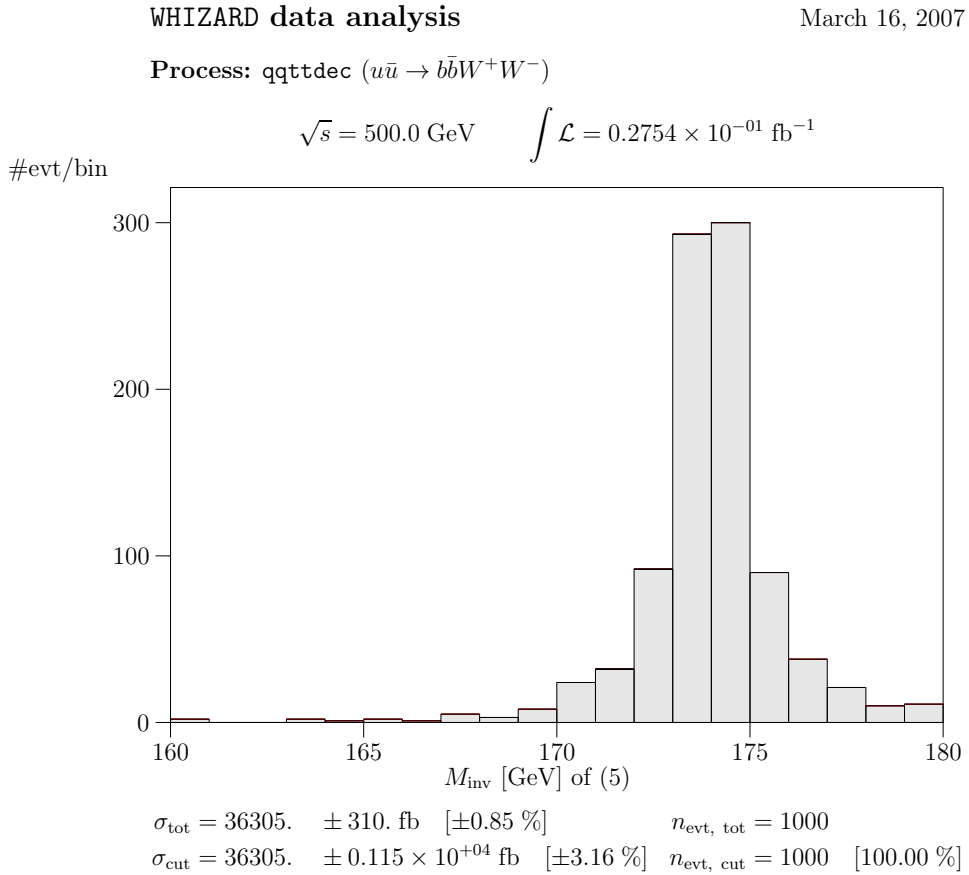
WHIZARD Manual



WHIZARD 2.0
A generic
Monte-Carlo integration and event generation package
for multi-particle processes
MANUAL [1]

Wolfgang Kilian,[2] Thorsten Ohl,[3] Jürgen Reuter,[4] Christian Speckner [5]

WHIZARD histograms



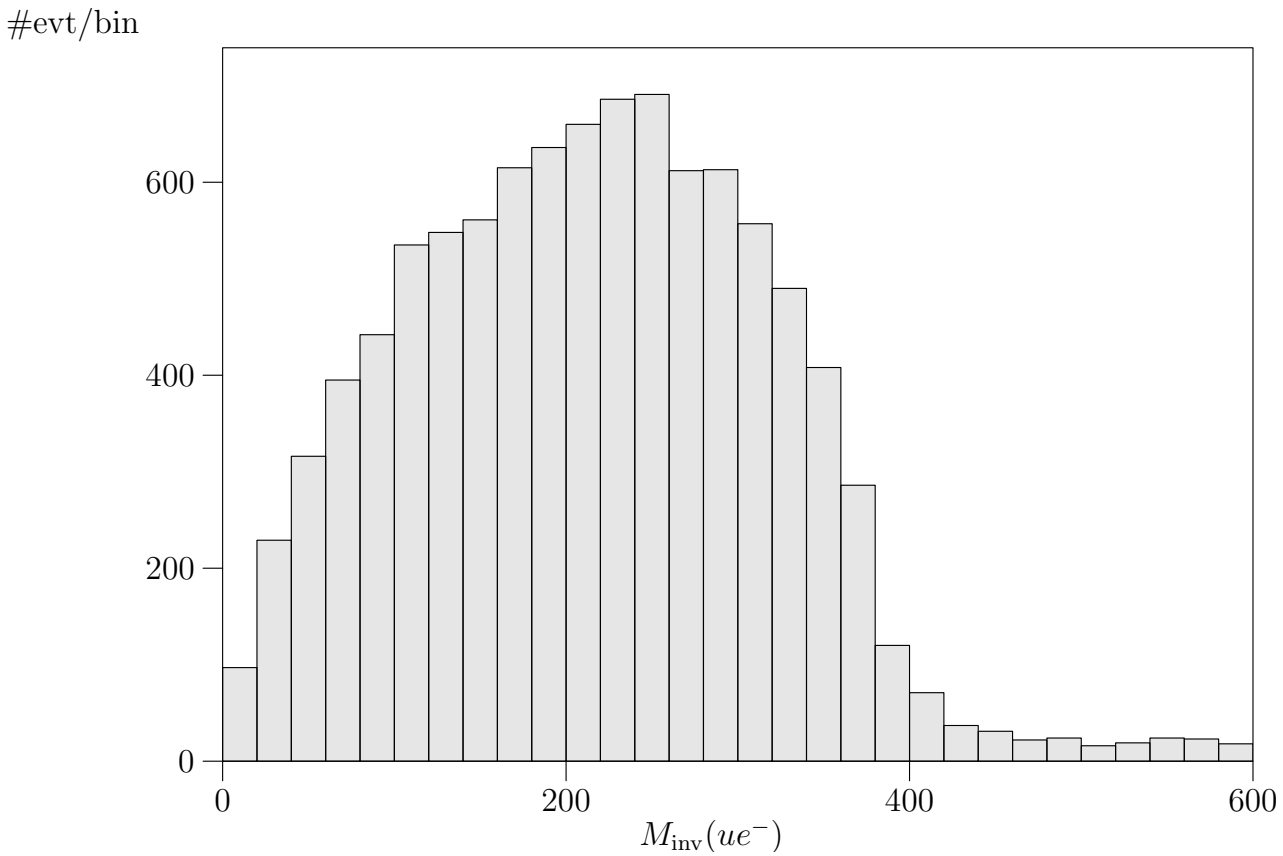
New completely general syntax in WHIZARD 2.x

```
$title = "Jet Energy in $pp\to \ell\bar\nu j$"
$x_label = "$E$/GeV"
histogram e_jet (0 GeV, 80 GeV, 2 GeV)
analysis = record pt_lepton (eval Pt [extract index 1 [sort by Pt [lepton]]]);
           record pt_jet (eval Pt [extract index 1 [sort by Pt [jet]]]);
           record e_lepton (eval E [extract index 1 [sort by Pt [lepton]]]);
           record e_jet (eval E [extract index 1 [sort by Pt [jet]]])
```

Example: LHC SUSY cascade decays

$$p + p \to \tilde{u} + \tilde{u}^* \to \bar{\tilde{u}}_1 + u + \tilde{e}^+_{12} + e^-$$

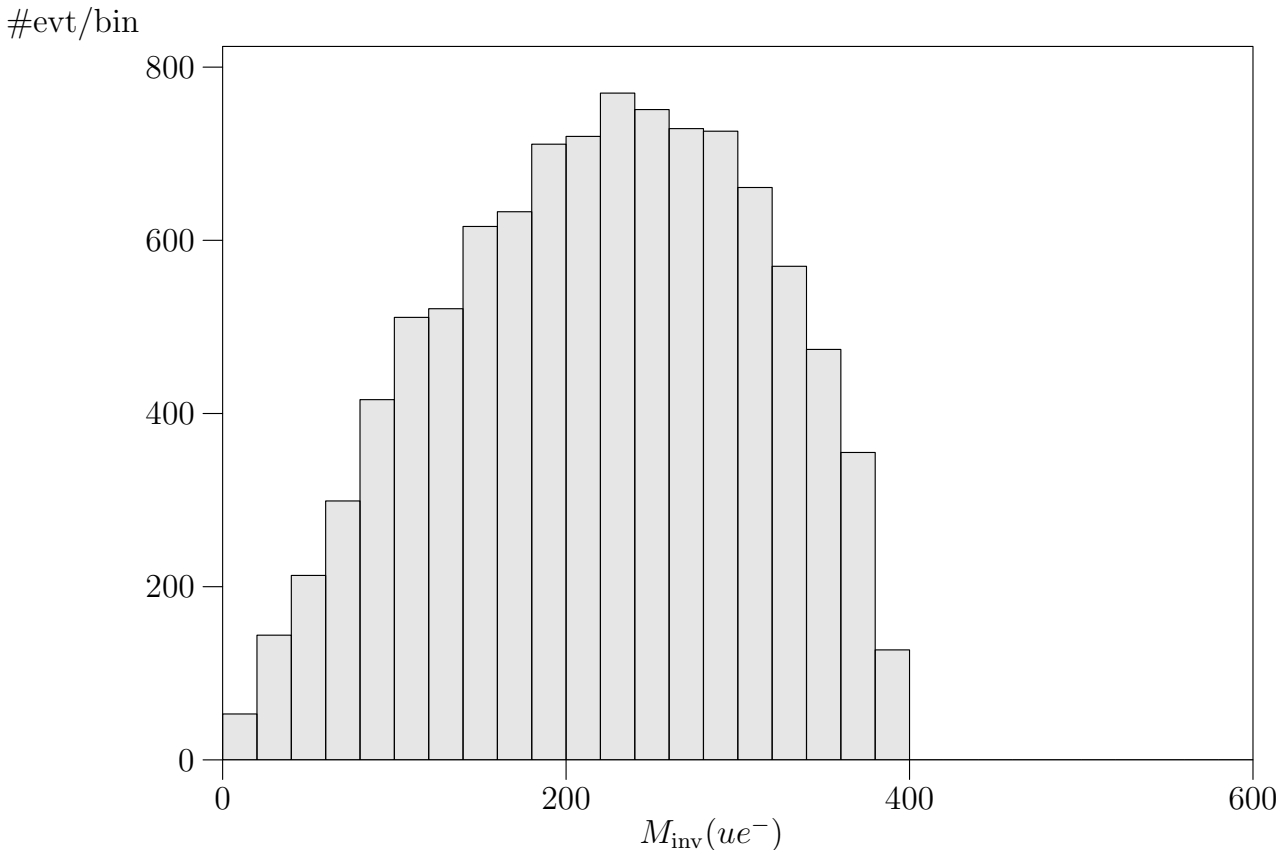
- **Full process:**



Example: LHC SUSY cascade decays

$$p + p \to \tilde{u} + \tilde{u}^* \to \bar{\tilde{u}}_1 + u + \tilde{e}^+_{12} + e^-$$

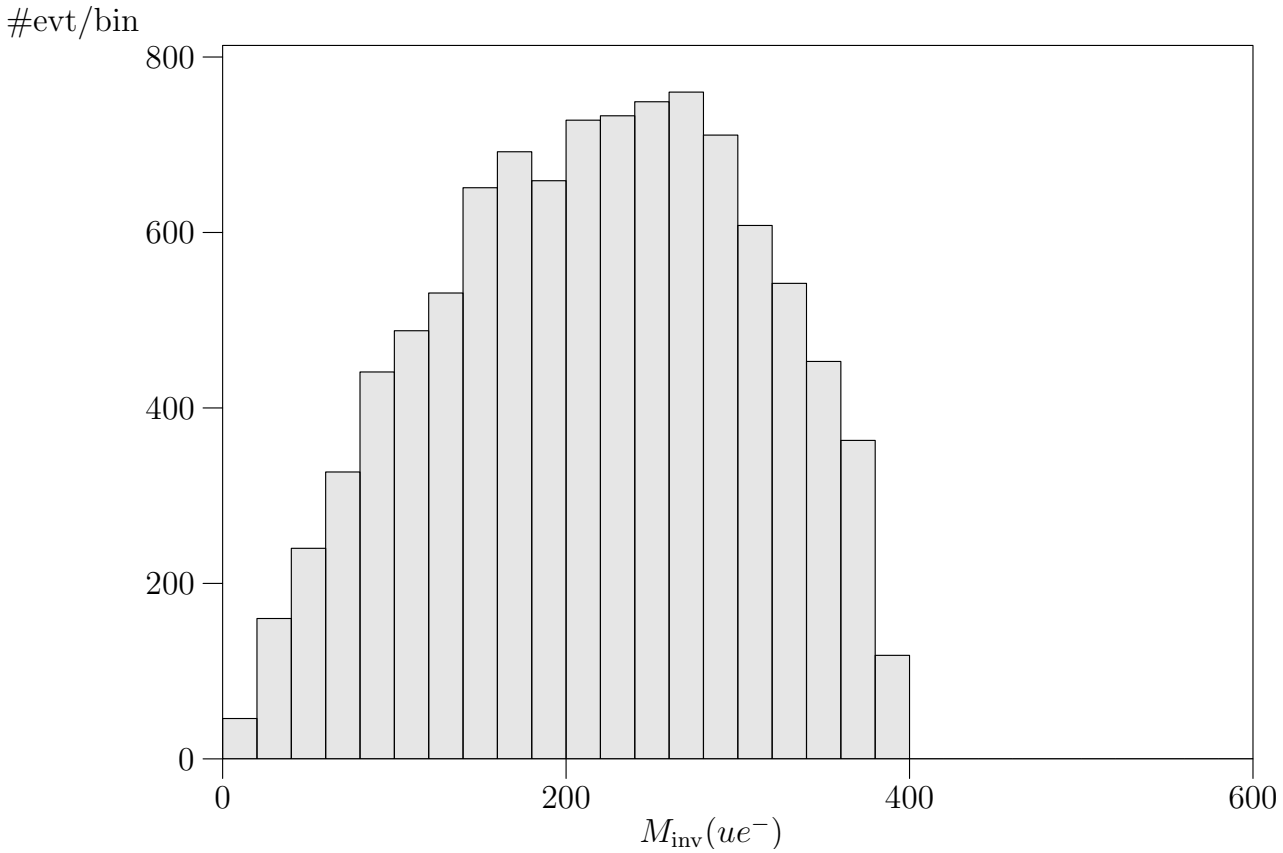
- **Factorized process w/ full spin correlations:**



Example: LHC SUSY cascade decays

$$p + p \to \tilde{u} + \tilde{u}^* \to \bar{\tilde{u}}_1 + u + \tilde{e}^+_{12} + e^-$$

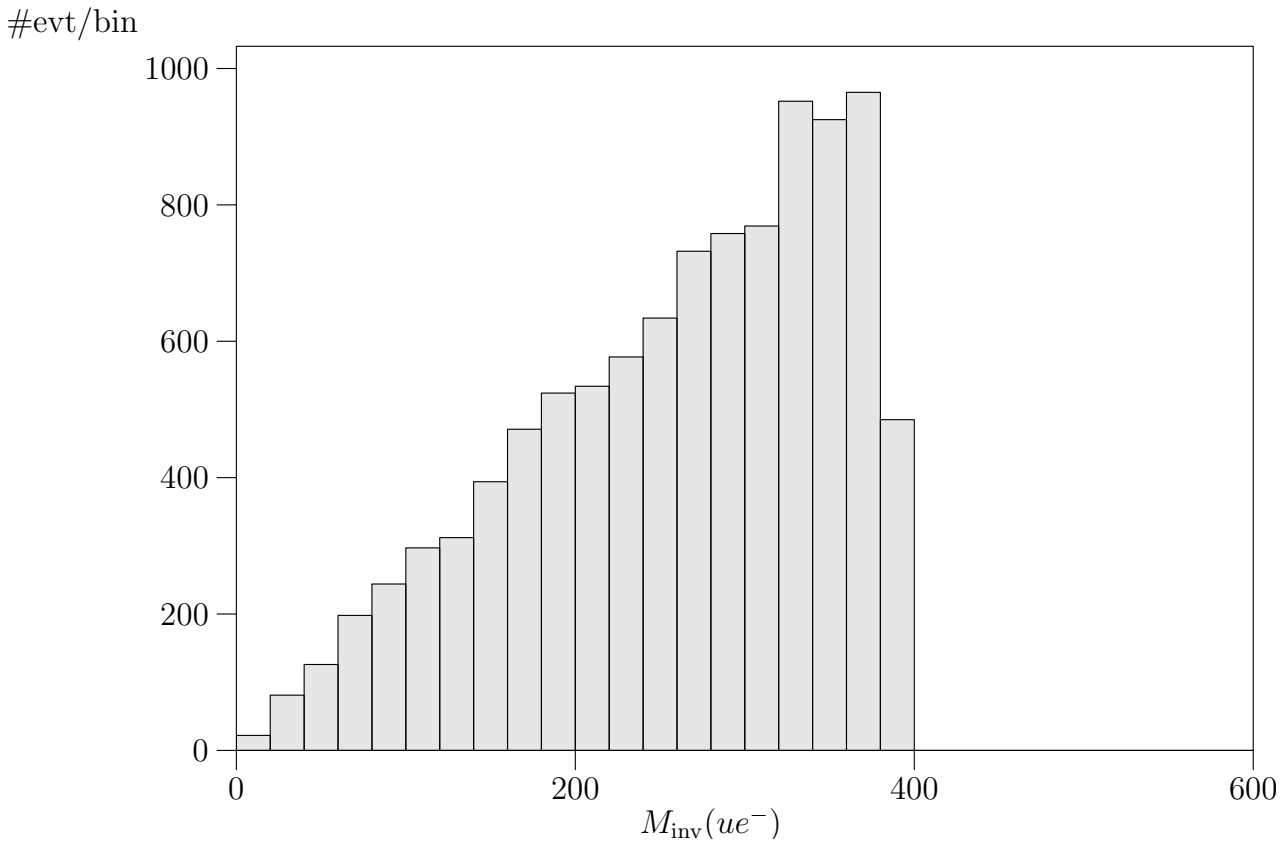
- **Factorized process w/ classical spin correlations:**



Example: LHC SUSY cascade decays

$$p + p \to \tilde{u} + \tilde{u}^* \to \bar{\tilde{u}}_1 + u + \tilde{e}^+_{12} + e^-$$

- **Factorized process w/ no spin correlations:**



Status of NLO development in WHIZARD

Proof-of-concept code in WHIZARD 2.1

by C. Speckner, support discontinued

New implementation under way for WHIZARD 2.2+

by C. Weiss

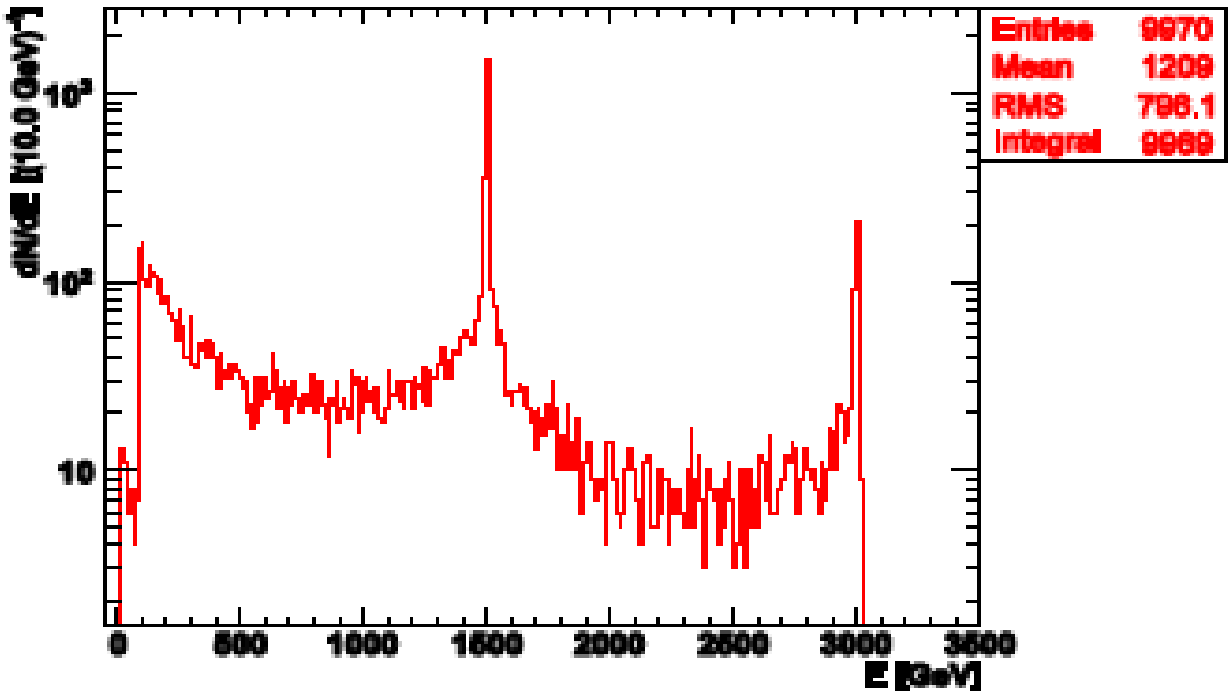
- Build upon the refactored WHIZARD core, exchangeable modules

Simulating Linear Colliders (2.1)

- Predefined parameter sets (CIRCE) (250/350/500/1000/2000/3000 GeV)
- ISR, beamstrahlung, strong fields (CLIC)
- Exhaustive support for these effects in WHIZARD (collaboration with LC groups)
- Example $e^+e^- \to b\bar{b}$:

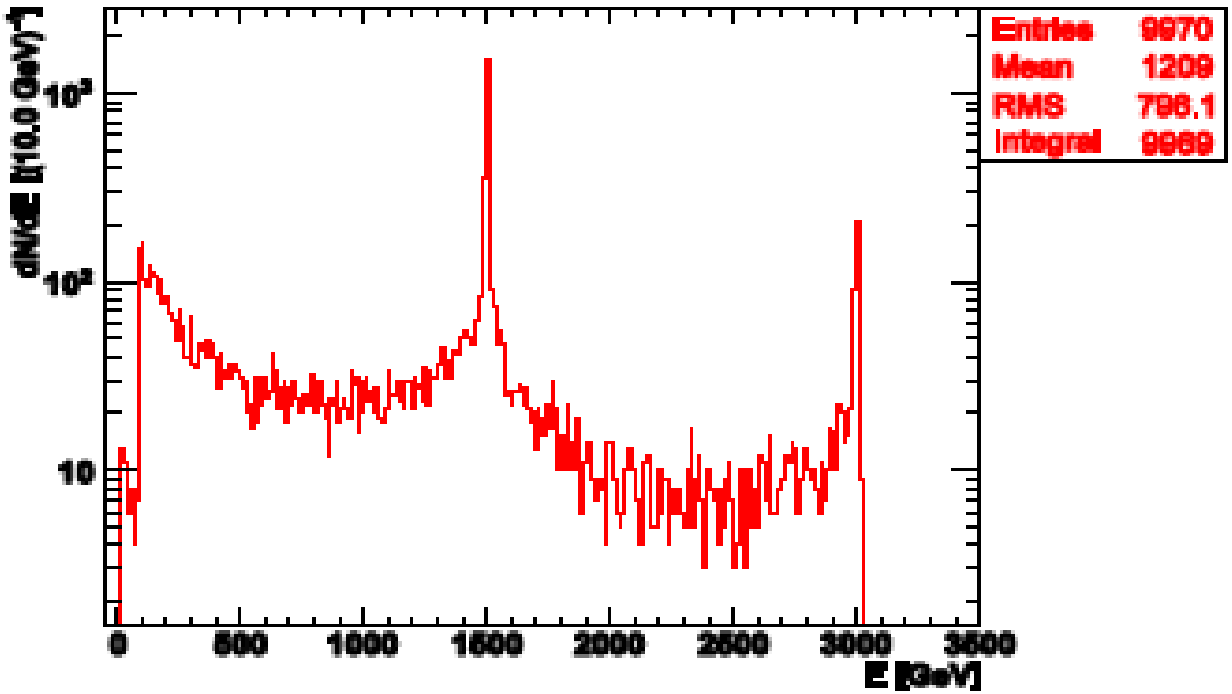
Simulating Linear Colliders (2.1)

- Predefined parameter sets (CIRCE) (250/350/500/1000/2000/3000 GeV)
- ISR, beamstrahlung, strong fields (CLIC)
- Exhaustive support for these effects in WHIZARD (collaboration with LC groups)
- Example $e^+e^- \to b\bar{b}$:



Simulating Linear Colliders (2.1)

- Predefined parameter sets (CIRCE) (250/350/500/1000/2000/3000 GeV)
- ISR, beamstrahlung, strong fields (CLIC)
- Exhaustive support for these effects in WHIZARD (collaboration with LC groups)
- Example $e^+e^- \to b\bar{b}$:



Luminosity spectrum picks up the Z resonance!

Simulating Linear Colliders (2.2)

Choose:

- ILC parameter set(s) (CIRCE1)

```
beams = "e-", "e+" => circe1 => isr
$circe1_acc = "ILC"
```

- Read from beam-event data file

```
beams = "e-", "e+" => beam_events => isr
$beam_events_file = "guineapig_output.dat"
```

- CIRCE2: parameterizes GuineaPig output and transforms into unweighted beam-event generator (cf. T. Barklow's LumiLinker code for WHIZARD1)

Specific mappings efficiently handle s-channel resonances and on-shell $2 \to 1$ production (ISR radiative return)

Users' input is required!

Simulating Linear Colliders (2.2)

More options for beams:

- Polarization (longitudinal, transversal, arbitrary)

```
beams = "e-", "e+"
beams_pol_density = @(-1), @(+1)
beams_pol_fraction = 80%, 40%
```

- Asymmetric beams

```
beams_momentum = 100 GeV, 900 GeV
```

- Crossing angle

```
beams_theta    = 0 degree, 10 degree
beams_phi      = 0 degree, 90 degree
```

- All parameters can be looped over (in Sindarin input)

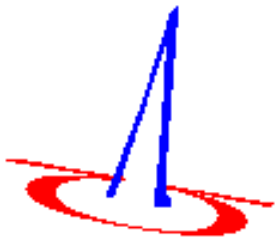
Polarization also accessible for final state (full correlations), just need a suitable event format . . .

ILC/CLIC: Projects

- Up-to-date parameter sets for ILC/CLIC beamstrahlung spectra
- Distribution of ISR photons with p_T (in collinear/infrared limit)
- LCIO as event format (F. Gaede)
- Jets, shower, matching: Bijan Chokoufe
- Unitary models for WW scattering at high energies: Marco Sekulla
- Top-quark threshold (resummed + corrected): Fabian Bach
- Automatic inclusion of NLO effects: C. Weiss

Summary and Outlook

- WHIZARD 2 for LC and LHC physics



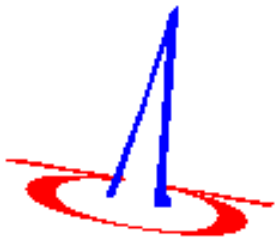
- Versatile, user-friendly tool
- Detailed implementation of ILC beam properties
- Steered via the HepForge page:
  `http://projects.hepforge.org/whizard`
- Expect continuous improvement

Thanks to all contributors (list is not exhaustive!)

T. Barklow, P. Bechtle, M. Berggren, M. Beyer, H. Boschmann, F. Braam, R. Chierici, K. Desch, T. Kleinschmidt, M. Mertens, N. Meyer, K. Mönig, M. Moretti, H. Reuter, T. Robens, K. Rolbiecki, S. Rosati, A. Rosca, S. Schmidt, J. Schumacher, M. Schumacher, S. Schwertfeger, C. Speckner, C. Schwinn, M. Trudewind

Summary and Outlook

- WHIZARD 2 for LC and LHC physics



- Versatile, user-friendly tool
- Detailed implementation of ILC beam properties
- Steered via the HepForge page:
  `http://projects.hepforge.org/whizard`
- Expect continuous improvement

Open for Suggestions (please contact us!)