Status of WHIZARD

Wolfgang Kilian

U Siegen

MC4BSM, DESY, 18. April 2013

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)

The WHIZARD team: F. Bach, [H. Boschmann], [F. Braam], W. Kilian, T. Ohl, J. Reuter, [S. Schmidt], [S. Schwertfeger], M. Sekulla, [C. Speckner], [M. Trudewind], D. Wiesler,

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

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

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WHIZARD 2.2.0 release: Spring 2013

Old series: WHIZARD 1.97 (development stopped with 1.94)

The WHIZARD team: F. Bach, [H. Boschmann], [F. Braam], W. Kilian, T. Ohl, J. Reuter, [S. Schmidt], [S. Schwertfeger], M. Sekulla, [C. Speckner], [M. Trudewind], D. Wiesler,

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Status 2011/12 – Technical Features

- WHIZARD 2: code basically rewritten, only `Fortran 2003` 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

News 2013: Work in Progress

- Several members of the WHIZARD team left physics in 2012, new members 2013
  - some features delayed, version 2.2.0 after MC4BSM (spring 2013)
  - Pre-release versions for ongoing studies
- 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
- Revised model for BSM interactions of electroweak vector bosons (w/ light Higgs)
- BSM: general Lorentz structures in matrix-element generator (O'Mega)
- Automatic generation of decays, depending on the model
- Improvements to the SINDARIN steering language

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.hepforge.org/manual/

Aktuelle Nachr... WHIZARD HEP – HEP arXiv.org e-Print... YouTube – Broa...

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]

Physics aspects/improvements in WHIZARD 2

- SINDARIN (Scripting INtegration, Data Analysis, Results display and INterfaces) allows for arbitrary expressions for cuts and scales etc. (examples later)

```
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]]]
```

- Process libraries: processes of different BSM models can be used in parallel
- Decay cascades including full spin correlations (cf. later)
- `FeynRules` interface — Christensen/Duhr/Fuks/Reuter/Speckner, EPJC 72 (2012) 1990
- MLM jet matching
- Event-dependent scales in PDFs and running α_s
- Parton Shower: p_T-ordered and analytic — WK/Reuter/Schmidt/Wiesler, JHEP 1204 (2012) 013

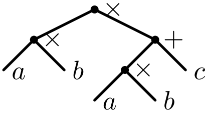
Structured Beams

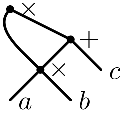
- **Hadron Colliders structured beams**
  - LHAPDF interface
  - CERN-/PDFLIB support no longer available
  - Most prominent PDFs directly included
  - ISR and FSR (two different own implementations, interface to PYTHIA)
  - Matching matrix elements/showers (MLM)
  - Underlying event/multiple interactions
- **Lepton Colliders structured beams**
  - ISR (implemented: Skrzypek/Jadach, Kuraev/Fadin, incl. p_T distributions)
  - arbitrarily polarized beams (density matrices)
  - Beamstrahlung (CIRCE module)
  - Photon collider spectra (CIRCE2 module)
  - external beam spectra can be read in (files/generating code)
  - FSR (e.g. YFS) not (yet) implemented (charged mesons/hadrons)
- **Hadronic events/hadronic decays**
  - through PYTHIA interface (or HERWIG or Sherpa)

O'Mega: Optimal matrix elements

Ohl/Reuter, 2001 Ω

- [.·.] Replace forest of tree diagrams by Directed Acyclical Graph (DAG) of the algebraic expression (including color).

$ab(ab + c) =$ 

$=$ 

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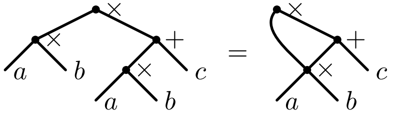
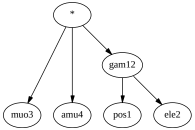


- simplest examples: $e^+e^- \to \mu^+\mu^-$, and



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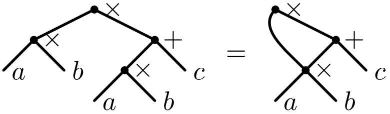
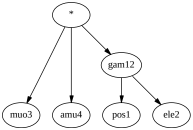
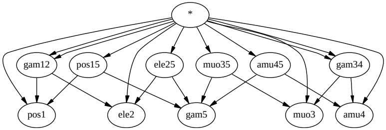


- simplest examples: $e^+e^- \to \mu^+\mu^-$, $e^+e^- \to \mu^+\mu^-\gamma$ and





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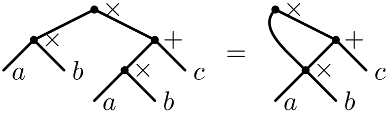
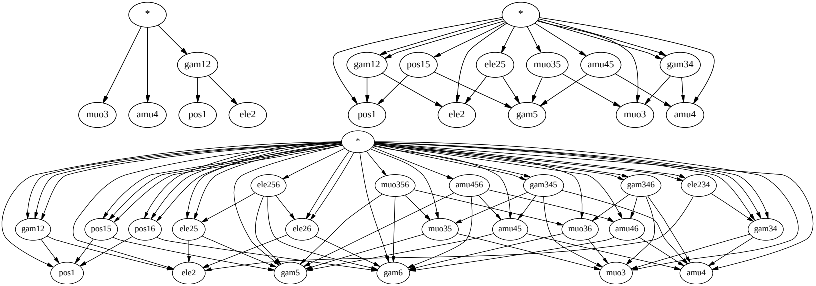


- simplest examples: $e^+e^- \to \mu^+\mu^-$, $e^+e^- \to \mu^+\mu^-\gamma$ and $e^+e^- \to \mu^+\mu^-\gamma\gamma$



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

Hard matrix elements: Lorentz structures

Hard-coded set of Lorentz structures

- Purely scalar couplings:
  $\phi^3, \quad \phi^4$
- Scalar couplings to vectors:
  $gV^\mu\phi_1 \mathrm{i}\overleftrightarrow{\partial_\mu}\phi_2, \quad \phi V^2, \quad \phi^2 V^2, \quad \frac{1}{2}\phi F_{1,\mu\nu}F_2^{\mu\nu}, \quad \frac{1}{2}\phi F_{1,\mu\nu}\tilde{F}_2^{\mu\nu}, \quad \phi(\mathrm{i}\partial_\mu V_1^\nu)(\mathrm{i}\partial_\nu V_2^\mu)$
- Pure vector couplings:
  $F_{\mu\nu}F^{\mu\nu}, \quad V_1^\mu((\mathrm{i}\partial_\nu V_2^\rho)\mathrm{i}\overleftrightarrow{\partial_\mu}(\mathrm{i}\partial_\rho V_3^\nu)), \quad gF_1^{\mu\nu}F_{2,\nu\rho}F_{3,}{}^\rho{}_\mu,$
  $g/2\cdot\epsilon^{\mu\nu\lambda\tau}F_{1,\mu\nu}F_{2,\tau\rho}F_{3,}{}^\rho{}_\lambda$
- Fermionic couplings to scalars:
  $g_S\bar\psi_1 S\psi_2, \quad g_P\bar\psi_1 P\gamma_5\psi_2, \quad \bar\psi_1\phi(g_S+g_P\gamma_5)\psi_2, \quad g_L\bar\psi_1\phi(1-\gamma_5)\psi_2,$
  $g_R\bar\psi_1\phi(1+\gamma_5)\psi_2, \quad g_L\bar\psi_1\phi(1-\gamma_5)\psi_2 + g_R\bar\psi_1\phi(1+\gamma_5)\psi_2$
- Fermionic couplings to vectors:
  $g_V\bar\psi_1 \not{V}\psi_2, \quad g_A\bar\psi_1\gamma_5\not{V}\psi_2, \quad \bar\psi_1\not{V}(g_V-g_A\gamma_5)\psi_2, \quad g_L\bar\psi_1\not{V}(1-\gamma_5)\psi_2,$
  $g_R\bar\psi_1\not{V}(1+\gamma_5)\psi_2, \quad g_L\bar\psi_1\not{V}(1-\gamma_5)\psi_2 + g_R\bar\psi_1\not{V}(1+\gamma_5)\psi_2$

- Fermionic couplings in SUSY Ward identities (not listed here)
- Fermionic couplings to tensors:
  $g_T T_{\mu\nu} \bar\psi_1 [\gamma^\mu, \gamma^\nu]_- \psi_2$
- Tensor couplings to vectors:
  $T^{\mu\nu}(V_{1,\mu} V_{2,\nu} + V_{1,\nu} V_{2,\mu})$, $T^{\alpha\beta}(V_1^\mu \mathrm{i}\overleftrightarrow{\partial}_\alpha \mathrm{i}\overleftrightarrow{\partial}_\beta V_{2,\mu}$,
  $T^{\alpha\beta}(V_1^\mu \mathrm{i}\overleftrightarrow{\partial}_\beta (\mathrm{i}\partial_\mu V_{2,\alpha}) + V_1^\mu \mathrm{i}\overleftrightarrow{\partial}_\alpha (\mathrm{i}\partial_\mu V_{2,\beta}))$, $T^{\alpha\beta}((\mathrm{i}\partial^\mu V_1^\nu)\mathrm{i}\overleftrightarrow{\partial}_\alpha \mathrm{i}\overleftrightarrow{\partial}_\beta (\mathrm{i}\partial_\nu V_{2,\mu}))$
- Gravitino couplings:
  $\bar\psi \gamma^\mu S \psi_\mu$, $\bar\psi \gamma^\mu \not{k}_S S \psi_\mu$, $\bar\psi \gamma^\mu \gamma^5 P \not{k}_P \psi_\mu$, $\bar\psi \gamma^5 \gamma^\mu [\not{k}_V, \not{V}] \psi_\mu$ etc.

  and many more to fill your advent calendar.....

- Completely general Lorentz structures:
  work in progress, to appear in version 2.2

Hard matrix elements: Color structures

Possible Color structures

- In principle all $SU(N)$ gauge theories supported, but specialize to $N = 3$
- Color flow formalism

  Stelzer/Willenbrock, 2003; WK/Ohl/Reuter/Speckner, 2011
- Fundamental representations: $\mathbf{3}, \overline{\mathbf{3}}$
- Adjoint representation: $\mathbf{8}$
- Covers all interactions e.g. in SUSY and extra dimensions
- in preparation: generalized color structures with representations $\mathbf{6}, \overline{\mathbf{6}}$, $\mathbf{10}, \overline{\mathbf{10}}$

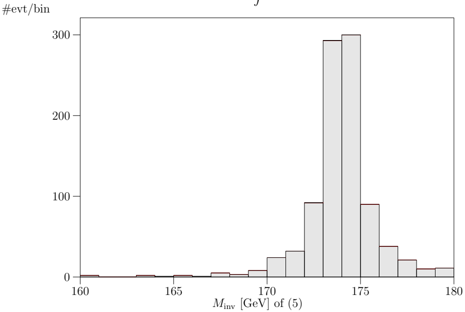
  as well as $\epsilon_{ijk}\phi_i\phi_j\phi_k$ couplings

WHIZARD histograms

WHIZARD data analysis March 16, 2007

Process: qqttdec ($u\bar{u} \to b\bar{b}W^+W^-$)

$\sqrt{s} = 500.0$ GeV $\int \mathcal{L} = 0.2754 \times 10^{-01}$ fb^{-1}



$\sigma_{\rm tot} = 36305. \pm 310.$ fb [± 0.85 %] $n_{\rm evt,\ tot} = 1000$

$\sigma_{\rm cut} = 36305. \pm 0.115 \times 10^{+04}$ fb [± 3.16 %] $n_{\rm evt,\ cut} = 1000$ [100.00 %]

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]]])
```

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 K matrix	—	SM_KM
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

new models easily: FeynRules interface Christensen/Duhr/Fuks/Reuter/Speckner, 1010.3251

Interface to SARAH in the SUSY Toolbox Staub, 0909.2863; Ohl/Porod/Speckner/Staub, 1109.5147

Comparison for the NMSSM

Braam, Fuks, Reuter, 0909.3059; 2012

Process	MG-FR	CH-FR	WO-ST	Comparison
tau+,tau->mu+,mu-	4.48997×10^{-3}	4.4892×10^{-3}	4.49068×10^{-3}	δ = 0.0330272 %
tau+,tau->tau+,tau-	7.52098×10^{2}	7.5179×10^{2}	7.59268×10^{2}	δ = 0.989717 %
tau+,tau->e+,e-	4.49207×10^{-3}	4.4892×10^{-3}	4.48806×10^{-3}	δ = 0.0893631 %
tau+,tau->ve,ve~	9.75351×10^{-4}	9.7635×10^{-4}	9.76355×10^{-4}	δ = 0.10288 %
tau+,tau->vm,vm~	9.7555×10^{-4}	9.7635×10^{-4}	9.76068×10^{-4}	δ = 0.0819325 %
tau+,tau->vt,vt~	5.35941×10^{1}	5.3592×10^{1}	5.36816×10^{1}	δ = 0.167014 %
tau+,tau->u,u~	7.12912×10^{-3}	7.1259×10^{-3}	7.12673×10^{-3}	δ = 0.0451506 %
tau+,tau->t,t~	7.11532×10^{-3}	7.1158×10^{-3}	7.10877×10^{-3}	δ = 0.0988431 %
tau+,tau->d,d~	3.61339×10^{-3}	3.6131×10^{-3}	3.61677×10^{-3}	δ = 0.101598 %
tau+,tau->b,b~	3.61069×10^{-3}	3.6139×10^{-3}	3.6143×10^{-3}	δ = 0.0997308 %
tau+,tau->W+,W-	1.90467×10^{-1}	1.9152×10^{-1}	1.91951×10^{-1}	δ = 0.776383 %
tau+,tau->Z,Z	1.02967×10^{-2}	1.0315×10^{-2}	1.03164×10^{-2}	δ = 0.191235 %
tau+,tau->Z,a	4.2117×10^{-2}	4.2129×10^{-2}	4.21696×10^{-2}	δ = 0.124826 %
tau+,tau->sl2-,sl2+	1.05047×10^{-3}	1.0504×10^{-3}	1.04972×10^{-3}	δ = 0.0713887 %
tau+,tau->sl5-,sl5+	1.17192×10^{-3}	1.172×10^{-3}	1.17143×10^{-3}	δ = 0.0487576 %
tau+,tau->sl4-,sl4+	1.17209×10^{-3}	1.1721×10^{-3}	1.17107×10^{-3}	δ = 0.0878297 %
tau+,tau->sl3-,sl3+	1.05015×10^{-3}	1.0503×10^{-3}	1.04997×10^{-3}	δ = 0.031815 %
tau+,tau->sl1-,sl1+	1.41851×10^{-2}	1.4178×10^{-2}	1.41878×10^{-2}	δ = 0.0689563 %
tau+,tau->sl6-,sl6+	1.39313×10^{-2}	1.3925×10^{-2}	1.39156×10^{-2}	δ = 0.112937 %
tau+,tau->sl6-,sl1+	1.5723×10^{-2}	1.5715×10^{-2}	1.56948×10^{-2}	δ = 0.179773 %
tau+,tau->sv3,sv3~	7.66119×10^{-2}	7.6632×10^{-2}	7.66407×10^{-2}	δ = 0.0376056 %
tau+,tau->sv2,sv2~	4.83808×10^{-4}	4.8377×10^{-4}	4.83538×10^{-4}	δ = 0.0557691 %
tau+,tau->sv1,sv1~	4.83818×10^{-4}	4.8377×10^{-4}	4.84209×10^{-4}	δ = 0.0906177 %
tau+,tau->su5,su5~	1.07924×10^{-3}	1.0791×10^{-3}	1.07879×10^{-3}	δ = 0.04155 %
tau+,tau->su2,su2~	1.63913×10^{-3}	1.6397×10^{-3}	1.63781×10^{-3}	δ = 0.115289 %
tau+,tau->su4,su4~	1.07887×10^{-3}	1.0791×10^{-3}	1.07862×10^{-3}	δ = 0.0441113 %
tau+,tau->su3,su3~	1.63962×10^{-3}	1.6397×10^{-3}	1.64002×10^{-3}	δ = 0.0249076 %
tau+,tau->su1,su1~	1.20597×10^{-3}	1.2063×10^{-3}	1.20707×10^{-3}	δ = 0.0912099 %
tau+,tau->su6,su6~	9.46274×10^{-4}	9.463×10^{-4}	9.46582×10^{-4}	δ = 0.0325208 %
tau+,tau->su1,su6~	2.78463×10^{-4}	2.7848×10^{-4}	2.78524×10^{-4}	δ = 0.0218196 %
tau+,tau->sd5,sd5~	1.1076×10^{-3}	1.1077×10^{-3}	1.10863×10^{-3}	δ = 0.0927793 %
tau+,tau->sd4,sd4~	1.10735×10^{-3}	1.1077×10^{-3}	1.10896×10^{-3}	δ = 0.144715 %
tau+,tau->sd6,sd6~	4.50337×10^{-4}	4.5034×10^{-4}	4.49875×10^{-4}	δ = 0.103213 %
tau+,tau->sd3,sd3~	2.69738×10^{-4}	2.697×10^{-4}	2.69575×10^{-4}	δ = 0.0603979 %
tau+,tau->sd1,sd1~	3.73641×10^{-4}	3.7367×10^{-4}	3.74042×10^{-4}	δ = 0.107316 %
tau+,tau->sd2,sd2~	2.69745×10^{-4}	2.697×10^{-4}	2.69754×10^{-4}	δ = 0.0199164 %
tau+,tau->sd1,sd6~	2.76715×10^{-4}	2.7676×10^{-4}	2.7705×10^{-4}	δ = 0.121224 %
tau+,tau->n1,n1	4.46003×10^{-3}	4.4579×10^{-3}	4.45895×10^{-3}	δ = 0.0478212 %
tau+,tau->n1,n2	6.30416×10^{-4}	6.3061×10^{-4}	6.3052×10^{-4}	δ = 0.0307715 %
tau+,tau->n1,n3	1.21883×10^{-3}	1.2189×10^{-3}	1.21746×10^{-3}	δ = 0.117815 %
tau+,tau->n1,n4	8.67964×10^{-5}	8.6752×10^{-5}	8.68336×10^{-5}	δ = 0.0939997 %
tau+,tau->n1,n5	3.89644×10^{-5}	3.8926×10^{-5}	3.89094×10^{-5}	δ = 0.141298 %
tau+,tau->n2,n2	9.62043×10^{-5}	9.6198×10^{-5}	9.63712×10^{-5}	δ = 0.179837 %
tau+,tau->n2,n3	9.2264×10^{-4}	9.2259×10^{-4}	9.21935×10^{-4}	δ = 0.076501 %
tau+,tau->n2,n4	6.51046×10^{-5}	6.4974×10^{-5}	6.49436×10^{-5}	δ = 0.247567 %
tau+,tau->n2,n5	3.71434×10^{-5}	3.7123×10^{-5}	3.70949×10^{-5}	δ = 0.1307 %
tau+,tau->n3,n3	3.11845×10^{-3}	3.1182×10^{-3}	3.11982×10^{-3}	δ = 0.052071 %
tau+,tau->n3,n4	1.82736×10^{-4}	1.8266×10^{-4}	1.82605×10^{-4}	δ = 0.0721419 %
tau+,tau->n3,n5	6.13979×10^{-5}	6.1358×10^{-5}	6.13801×10^{-5}	δ = 0.0649458 %
tau+,tau->n4,n4	1.58733×10^{-6}	1.5862×10^{-6}	1.58717×10^{-6}	δ = 0.0712317 %
tau+,tau->n4,n5	1.76086×10^{-3}	1.7621×10^{-3}	1.76277×10^{-3}	δ = 0.108888 %
tau+,tau->n5,n5	1.30224×10^{-6}	1.3027×10^{-6}	1.30388×10^{-6}	δ = 0.125935 %
tau+,tau->x1+,x1-	8.49209×10^{-3}	8.4901×10^{-3}	8.47272×10^{-3}	δ = 0.228377 %
tau+,tau->x2+,x2-	4.58133×10^{-3}	4.5956×10^{-3}	4.59502×10^{-3}	δ = 0.310892 %
tau+,tau->x1+,x2-	2.63941×10^{-4}	2.6422×10^{-4}	2.64165×10^{-4}	δ = 0.105543 %
tau+,tau->h01,h01	4.92753×10^{-9}	4.9314×10^{-9}	4.92995×10^{-9}	δ = 0.0784249 %
tau+,tau->h01,h02	2.16262×10^{-7}	2.1626×10^{-7}	2.16185×10^{-7}	δ = 0.035671 %
tau+,tau->h01,h03	7.80572×10^{-8}	7.805×10^{-8}	7.80465×10^{-8}	δ = 0.0137862 %
tau+,tau->h02,h02	5.11735×10^{-8}	5.1179×10^{-8}	5.12057×10^{-8}	δ = 0.0629171 %
tau+,tau->h02,h03	9.84532×10^{-7}	9.8445×10^{-7}	9.82302×10^{-7}	δ = 0.226698 %
tau+,tau->h03,h03	2.25701×10^{-8}	2.2581×10^{-8}	2.25684×10^{-8}	δ = 0.0559166 %
tau+,tau->A01,A01	2.38658×10^{-10}	2.3803×10^{-10}	2.39651×10^{-10}	δ = 0.678646 %
tau+,tau->A01,A02	1.07849×10^{-7}	1.0787×10^{-7}	1.07962×10^{-7}	δ = 0.105076 %
tau+,tau->A02,A02	1.48778×10^{-8}	1.4889×10^{-8}	1.48668×10^{-8}	δ = 0.149544 %
tau+,tau->Z,h01	4.85736×10^{-4}	4.8605×10^{-4}	4.89451×10^{-4}	δ = 0.762018 %
tau+,tau->Z,h02	1.04814×10^{-5}	1.0476×10^{-5}	1.04791×10^{-5}	δ = 0.0519548 %
tau+,tau->Z,h03	3.67139×10^{-5}	3.679×10^{-5}	3.67189×10^{-5}	δ = 0.207188 %
tau+,tau->Z,A01	9.0489×10^{-7}	9.0461×10^{-7}	9.03717×10^{-7}	δ = 0.12971 %
tau+,tau->Z,A02	3.63906×10^{-5}	3.6663×10^{-5}	3.66845×10^{-5}	δ = 0.804499 %
tau+,tau->A01,h01	4.79704×10^{-7}	4.7967×10^{-7}	4.79803×10^{-7}	δ = 0.0278007 %
tau+,tau->A01,h02	6.01345×10^{-8}	6.0131×10^{-8}	6.0137×10^{-8}	δ = 0.00999268 %
tau+,tau->A01,h03	2.81488×10^{-6}	2.8159×10^{-6}	2.82663×10^{-6}	δ = 0.416406 %
tau+,tau->A02,h01	1.08173×10^{-7}	1.0817×10^{-7}	1.08261×10^{-7}	δ = 0.0842393 %
tau+,tau->A02,h02	2.24843×10^{-6}	2.249×10^{-6}	2.24911×10^{-6}	δ = 0.030096 %
tau+,tau->A02,h03	2.93826×10^{-4}	2.9386×10^{-4}	2.93557×10^{-4}	δ = 0.103037 %
tau+,tau->H+,H-	7.32275×10^{-4}	7.3228×10^{-4}	7.3236×10^{-4}	δ = 0.0115347 %

Process	MG-FR	CH-FR	WO-ST	Comparison
W-,Z>b,t~	7.11557×10^{-1}	7.0989×10^{-1}	7.11436×10^{-1}	δ = 0.234537 %
W-,Z>Z,W-	3.01819×10^{2}	3.0264×10^{2}	3.0193×10^{2}	δ = 0.271739 %
W-,Z>a,W-	7.4661×10^{1}	7.4604×10^{1}	7.43748×10^{1}	δ = 0.384101 %
W-,Z>sl4-,sv1~	2.36706×10^{-3}	2.369×10^{-3}	2.37235×10^{-3}	δ = 0.223033 %
W-,Z>sl5-,sv2~	2.40865×10^{-3}	2.4109×10^{-3}	2.41163×10^{-3}	δ = 0.123994 %
W-,Z>sl1-,sv3~	1.16665×10^{-3}	1.1695×10^{-3}	1.17192×10^{-3}	δ = 0.45102 %
W-,Z>sl6-,sv3~	1.2085×10^{-3}	1.2067×10^{-3}	1.20652×10^{-3}	δ = 0.164307 %
W-,Z>sd5,su3~	3.51869×10^{-3}	3.5133×10^{-3}	3.51169×10^{-3}	δ = 0.199274 %
W-,Z>sd4,su2~	3.51372×10^{-3}	3.5133×10^{-3}	3.51307×10^{-3}	δ = 0.0186828 %
W-,Z>sd1,su1~	1.14587×10^{-2}	1.1447×10^{-2}	1.14423×10^{-2}	δ = 0.143534 %
W-,Z>sd6,su6~	2.3412×10^{-2}	2.3479×10^{-2}	2.34716×10^{-2}	δ = 0.285674 %
W-,Z>sd1,su6~	1.79614×10^{-2}	1.7953×10^{-2}	1.79362×10^{-2}	δ = 0.140162 %
W-,Z>sd6,su1~	1.27978×10^{-2}	1.2783×10^{-2}	1.27793×10^{-2}	δ = 0.144221 %
W-,Z>n1,x1-	5.58187×10^{-3}	5.5834×10^{-3}	5.5787×10^{-3}	δ = 0.0842243 %
W-,Z>n2,x1-	2.58653×10^{-2}	2.5885×10^{-2}	2.59104×10^{-2}	δ = 0.174 %
W-,Z>n3,x1-	1.87516×10^{-1}	1.8743×10^{-1}	1.87014×10^{-1}	δ = 0.267929 %
W-,Z>n4,x1-	5.29225×10^{-2}	5.2915×10^{-2}	5.28743×10^{-2}	δ = 0.091285 %
W-,Z>n5,x1-	8.68647×10^{-2}	8.6797×10^{-2}	8.68217×10^{-2}	δ = 0.0779207 %
W-,Z>n1,x2-	4.25162×10^{-3}	4.2539×10^{-3}	4.25377×10^{-3}	δ = 0.0535405 %
W-,Z>n2,x2-	1.86172×10^{-2}	1.8623×10^{-2}	1.86507×10^{-2}	δ = 0.179804 %
W-,Z>n3,x2-	5.08905×10^{-2}	5.0974×10^{-2}	5.10002×10^{-2}	δ = 0.215293 %
W-,Z>n4,x2-	3.87418×10^{-2}	3.8743×10^{-2}	3.87516×10^{-2}	δ = 0.0253781 %
W-,Z>n5,x2-	2.30577×10^{-2}	2.3033×10^{-2}	2.3038×10^{-2}	δ = 0.107112 %
W-,Z>h01,H-	3.06927×10^{-6}	3.069×10^{-6}	3.07074×10^{-6}	δ = 0.0566669 %
W-,Z>h02,H-	1.20593×10^{-4}	1.2061×10^{-4}	1.20462×10^{-4}	δ = 0.122403 %
W-,Z>h03,H-	2.1414×10^{-3}	2.1392×10^{-3}	2.13929×10^{-3}	δ = 0.102916 %
W-,Z>A01,H-	2.71579×10^{-4}	2.7161×10^{-4}	2.71278×10^{-4}	δ = 0.122268 %
W-,Z>A02,H-	1.28349×10^{-3}	1.2827×10^{-3}	1.28247×10^{-3}	δ = 0.0795463 %
W-,Z>W-,h01	7.94029×10^{1}	7.9468×10^{1}	7.93492×10^{1}	δ = 0.149577 %
W-,Z>W-,h02	1.70391	1.7037	1.7087	δ = 0.293178 %
W-,Z>W-,h03	3.98499×10^{-5}	3.9924×10^{-5}	4.00474×10^{-5}	δ = 0.494346 %
W-,Z>W-,A01	6.99895×10^{-8}	6.985×10^{-8}	7.00424×10^{-8}	δ = 0.275123 %
W-,Z>W-,A02	1.36107×10^{-5}	1.361×10^{-5}	1.36221×10^{-5}	δ = 0.0886822 %
W-,Z>Z,H-	1.40065×10^{-5}	1.4004×10^{-5}	1.39963×10^{-5}	δ = 0.0730172 %

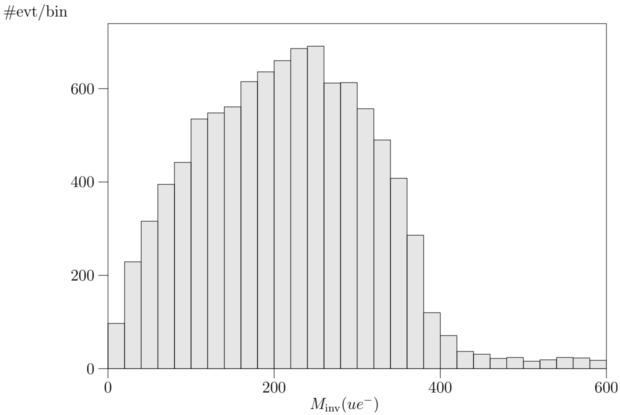
Example: LHC SUSY cascade decays, Input File

```
model = MSSM

process dec_su_q = su1 => u, neu2
process dec_neu_sl2  = neu2 => SE12, e1

process susybg = u,U => SU1, su1
process full = u, U => SU1, u, e1, SE12

compile

?slha_read_decays = true
read_slha("sps1ap_decays.slha")

integrate (dec_su_q, dec_neu_sl2) { iterations = 1:1000 }

sqrts = 14000
beams = p, p => lhapdf

integrate (susybg) { iterations = 5:10000, 2:10000 }
integrate (full)

n_events = 10000

$title = "Full process"
$description =
  "$p + p \to u+ \bar u \to \bar{\tilde u}_1 + u + \tilde e_{12}^+ + e^-$"
$xlabel = "$M_{\rm inv}(ue^-)$"
histogram inv_mass1_full (0,600,20)

simulate (full) {
  $sample = "casc_dec_full"
  analysis =
    record inv_mass1_full (eval M / 1 GeV [combine[u,e1]])
}

compile_analysis
$analysis_filename = "casc_dec"
write_analysis
```

Example: LHC SUSY cascade decays

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

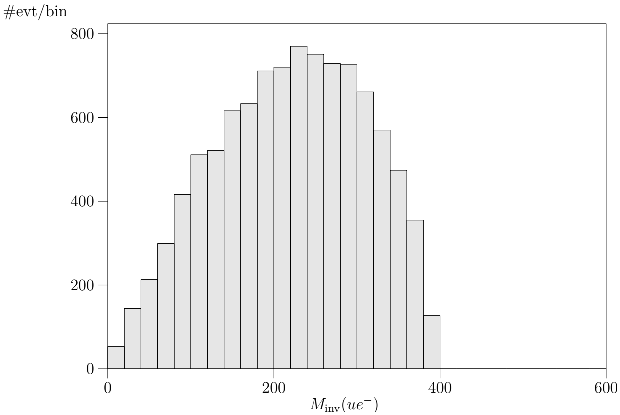
- **Full process:**



Example: LHC SUSY cascade decays

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

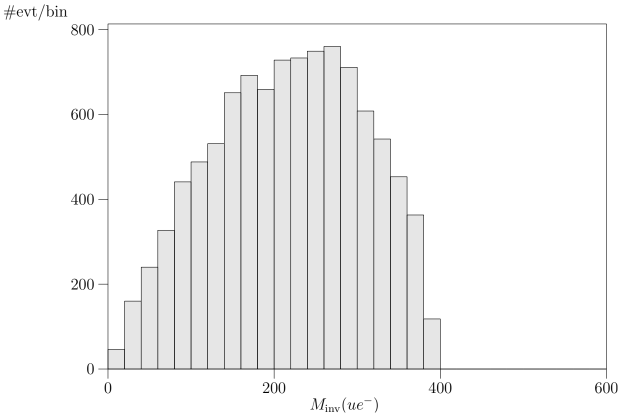
- **Factorized process w/ full spin correlations:**



Example: LHC SUSY cascade decays

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

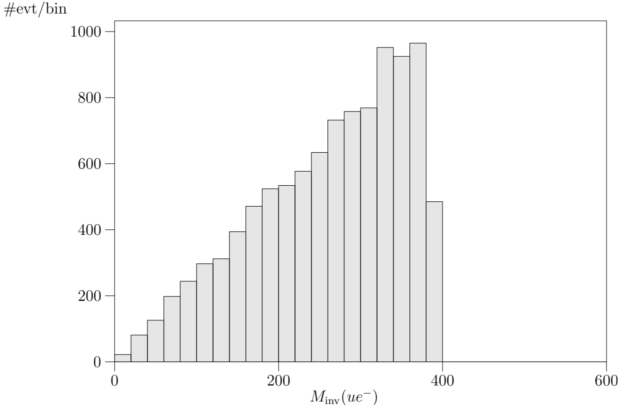
- **Factorized process w/ classical spin correlations:**



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:**



BSM,e.g. Resonances in VV scattering

Alboteanu/WK/Reuter, JHEP 0811 (2008) 010

Model-independent description for LHC, respect weak isospin ($\rho \approx 0$):

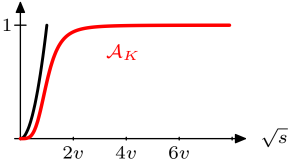
	$J = 0$	$J = 1$	$J = 2$
$I = 0$	σ^0 (Higgs ?)	ω^0 (γ'/Z' ?)	a^0 (Graviton ?)
$I = 1$	$\pi^\pm, \pi^0$ (2HDM ?)	$\rho^\pm, \rho^0$ (W'/Z' ?)	$t^\pm, t^0$
$I = 2$	$\phi^{\pm\pm}, \phi^\pm, \phi^0$ (Higgs triplet ?)	—	$f^{\pm\pm}, f^\pm, f^0$

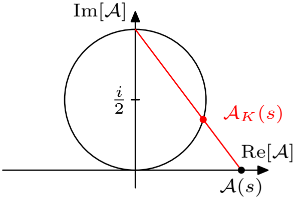
LHC access limited: 1. resonance correct, guarantee unitarity

K-Matrix unitarization

$$\mathcal{A}_K(s) = \mathcal{A}(s)/(1 - i\mathcal{A}(s))$$

- K-matrix ampl.: $|\mathcal{A}(s)|^2 \overset{s\to\infty}{\to} 1$
- Poles $\pm iv$: M_0, Γ large





- Unitarization in each spin-isospin eigen-channel
- breaks crossing invariance
- Explicit “time arrow” in WHIZARD

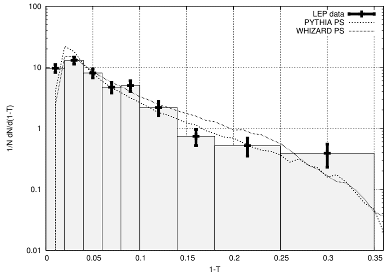
Revised Implementation and New Results

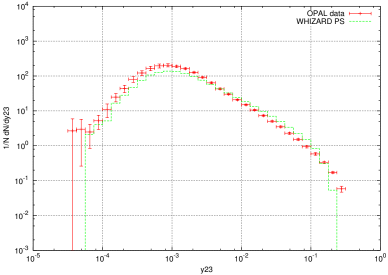
- Consistently implement anomalous couplings, resonances and unitarization in the presence of light Higgs
- Different power-counting
- Anomalous Higgs coupling
- Major impact on ongoing LHC (and ILC) studies
  - Model-independent approach is probably inapplicable
  - Unitarity is important
  - Are generic resonance models sufficient?

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
- new algorithm for initial state radiation





- matching with hard matrix elements, no ”power-shower”

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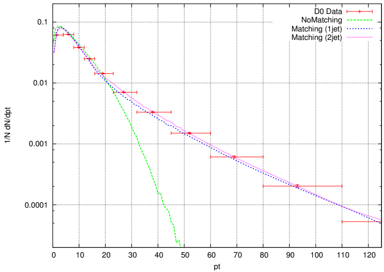

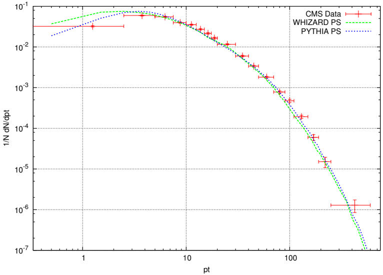

- matching with hard matrix elements, no ”power-shower”

Status of NLO development in WHIZARD

- BLHA interface: workflow — Speckner, 2012
  1. Process definition in SINDARIN $\Rightarrow$ WHIZARD writes contract file
  2. NLO generator generates code, WHIZARD reads contract
  3. NLO matrix element loaded as shared library

- First implementation: interfacing GoSAM and FeynArts

- Automatic generation of dipole subtraction terms — Reuter/Speckner, 2012
  - proof-of-concept code in WHIZARD 2.1
  - implementation in the context of the revised WHIZARD 2.2 core

First example: $u\bar{u} \to \mu^- \bar{\nu}_\mu e^+ \nu_e$

Input:

```
real mreg = 1 GeV

process test = u, ubar => "mu-", numubar, "e+", nue {
   $method = "dipole_integrated_qed"
   soft_mass_regulator = mreg
   collinear_mass_regulators = mreg, mreg, mreg, 0, mreg, 0
}

me = 0
mmu = 0
alpha_qed = 1.  / alpha_em_i

sqrts = 500 GeV

integrate (test) {iterations = 5:10000, 5:20000}
```

Result:

```
| Integrating process 'test':
|=============================================================================|
| It      Calls  Integral[fb]  Error[fb]   Err[%]    Acc  Eff[%]   Chi2 N[It] |
|=============================================================================|
  10     100000  1.9794090E+00  3.16E-03    0.16    0.50   12.33    0.12    5
|=============================================================================|
```

Simulating Linear Colliders

- High-Energy Linear Lepton Collider (250/350/500/1000/2000/3000 GeV)
- ISR, beamstrahlung, strong fields (CLIC)
- Exhaustive support for these effects in WHIZARD (close collaboration with all LC groups)
- Prime Example $e^+e^- \to b\bar{b}$:

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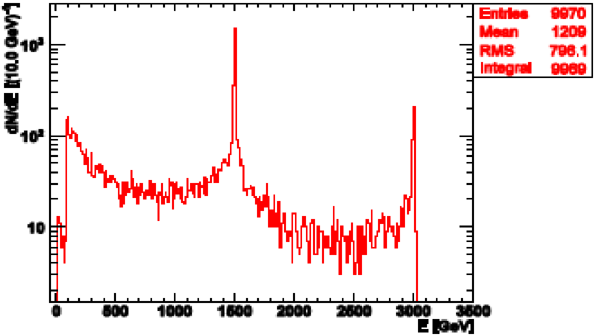

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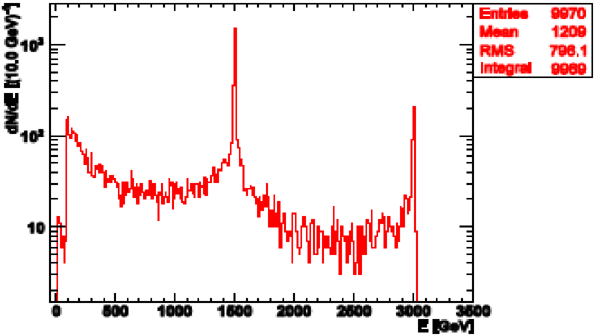

Luminosity spectrum picks up the Z resonance!

Summary and Outlook

- WHIZARD 2 for LHC and ILC physics

- Versatile, user-friendly tool
- Focus on BSM physics
- 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, 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, J. Schumacher, M. Schumacher, C. Schwinn

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as usual: **we're open to users wish list!**