

ECFA LC 2013 – WHIZARD Status Report

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ECFA LC workshop 2013, DESY Hamburg, May 28th, 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)
 - $e^+e^- \rightarrow t\bar{t}H \rightarrow b\bar{b}b\bar{b}jj\ell\nu$ (110,000 diagrams)
 - $e^+e^- \rightarrow ZHH \rightarrow ZWWWW \rightarrow bb + 8j$ (12,000,000 diagrams)
 - $pp \rightarrow \ell\ell + nj, n = 0, 1, 2, 3, 4, \dots$ (2,100,000 diagrams with 4 jets + flavors)
 - $pp \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0 b\bar{b}b\bar{b}$ (32,000 diagrams, 22 color flows, $\sim 10,000$ PS channels)
 - $pp \rightarrow VVjj \rightarrow jj\ell\ell\nu\nu$ incl. anomalous TGC/QGC
 - Test case $gg \rightarrow 9g$ (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], B. Choukoufé, **W. Kilian**, **T. Ohl**, **JRR**, [S. Schmidt], [S. Schwertfeger], M. Sekulla, [C. Speckner], M. Staub, [M. Trudewind], [D. Wiesler]

Web address: <http://projects.hepforge.org/whizard>

Standard Reference: [Kilian/Ohl/JRR, EPJC 71 \(2011\) 1742, arXiv:0708.4233](#)

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WHIZARD 2.2.0 release: Summer 2013

Old series: WHIZARD 1.97 (development stopped with 1.94)

The WHIZARD team: F. Bach, [H. Boschmann], [F. Braam], B. Choukoufé, **W. Kilian**, **T. Ohl**, **JRR**, [S. Schmidt], [S. Schwertfeger], M. Sekulla, [C. Speckner], M. Staub, [M. Trudewind], [D. Wiesler]

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Status 2011/12 – Technical Features

- WHIZARD 2: code basically rewritten, only `Fortran 2003` and `O'Cam1`
- 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

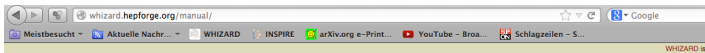
- Several members of the WHIZARD team left physics in 2012, new members 2013
 - ▶ some features delayed, version **2.2.0** after ECFA 2013 (summer 2013)
 - ▶ Pre-release versions for ongoing studies
- WHIZARD core: insert an extra abstraction layer, consistently separate interface from implementation
 - ▶ **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



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- Tracker
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WHIZARD 2.1 A generic Monte-Carlo integration and event generation package for multi-particle processes MANUAL

Wolfgang Kilian,[✉] Thorsten Ohl,[✉] Jürgen Reuter,[✉] Christian Speckner[✉]

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Physics aspects/improvements in WHIZARD 2

- **SINDARIN** (Scripting **I**ntegration, **D**ata **A**nalysis, **R**esults display and **I**nterfaces) 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]]]
```

- New syntax for decays and chains:

```
process higgsstr = e1, E1 => (Z => e2, E2), (H => b, bbar)
process wtf      = e1, E1 => (Z, h) + (Z, H) + (A, H)
```

- 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/JRR/Specckner, EPJC 72 \(2012\) 1990](#)

- **MLM jet matching**

- Event-dependent scales in PDFs and running α_s

- **Parton Shower: p_T -ordered and analytic**

[Kilian/JRR/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/JRR, 2001



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

$$ab(ab + c) = \begin{array}{c} \text{---} \times \text{---} \\ / \quad \backslash \\ \times \quad \times \\ / \quad \backslash \quad / \quad \backslash \\ a \quad b \quad a \quad b \quad c \end{array} = \begin{array}{c} \text{---} \times \text{---} \\ / \quad \backslash \\ \times \quad \times \\ / \quad \backslash \quad / \quad \backslash \\ a \quad b \quad a \quad b \quad c \end{array}$$

O'Mega: Optimal matrix elements

Ohl/JRR, 2001

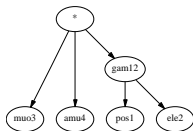


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- ▶ simplest examples: $e^+e^- \rightarrow \mu^+\mu^-$,

and



O'Mega: Optimal matrix elements

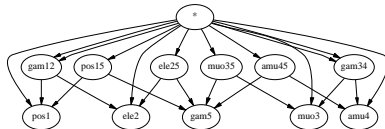
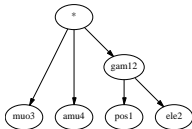
Ohl/JRR, 2001



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



O'Mega: Optimal matrix elements

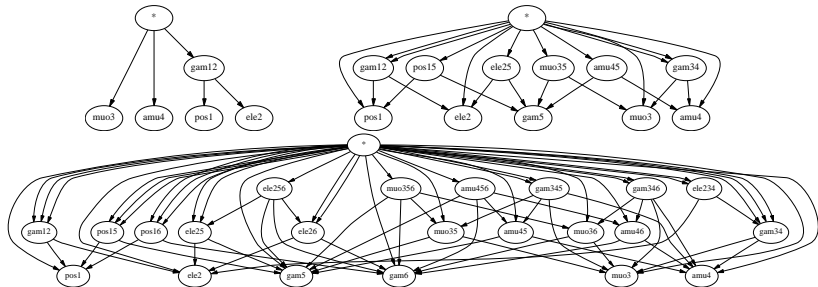
Ohl/JRR, 2001



- ▶ $[\cdot]$ Replace forest of tree diagrams by **Directed Acyclical Graph (DAG)** of the algebraic expression (including color).

$$ab(ab + c) = \begin{array}{c} \times \\ \diagup \quad \diagdown \\ a \quad b \quad \times \\ \diagdown \quad \diagup \\ a \quad b \end{array} + \begin{array}{c} \times \\ \diagdown \\ c \end{array} = \begin{array}{c} \times \\ \diagdown \quad \diagup \\ a \quad \times \\ \diagdown \quad \diagup \\ a \quad b \end{array} + \begin{array}{c} \times \\ \diagdown \\ c \end{array}$$

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



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:

$$\phi^3, \phi^4$$

- ▶ Scalar couplings to vectors:

$$gV^\mu\phi_1\overleftrightarrow{\partial}_\mu\phi_2, \quad \phi V^2, \quad \phi^2V^2, \quad \frac{1}{2}\phi F_{1,\mu\nu}F_2^{\mu\nu}, \quad \frac{1}{2}\phi F_{1,\mu\nu}\tilde{F}_2^{\mu\nu}, \quad \phi(i\partial_\mu V_1^\nu)(i\partial_\nu V_2^\mu)$$

- ▶ Pure vector couplings:

$$F_{\mu\nu}F^{\mu\nu}, \quad V_1^\mu((i\partial_\nu V_2^\rho)\overleftrightarrow{\partial}_\mu(i\partial_\rho V_3^\nu)), \quad gF_1^{\mu\nu}F_{2,\nu\rho}F_{3,\mu}^\rho, \\ g/2 \cdot \epsilon^{\mu\nu\lambda\tau}F_{1,\mu\nu}F_{2,\tau\rho}F_{3,\lambda}^\rho$$

- ▶ 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:

$$g_V\bar{\psi}_1 V\psi_2, \quad g_A\bar{\psi}_1\gamma_5 V\psi_2, \quad \bar{\psi}_1 V(g_V - g_A\gamma_5)\psi_2, \quad g_L\bar{\psi}_1 V(1 - \gamma_5)\psi_2, \\ g_R\bar{\psi}_1 V(1 + \gamma_5)\psi_2, \quad g_L\bar{\psi}_1 V(1 - \gamma_5)\psi_2 + g_R\bar{\psi}_1 V(1 + \gamma_5)\psi_2$$

- ▶ 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:

$$T^{\mu\nu} (V_{1,\mu} V_{2,\nu} + V_{1,\nu} V_{2,\mu}), \quad T^{\alpha\beta} (V_1^\mu i \overleftrightarrow{\partial}_\alpha i \overleftrightarrow{\partial}_\beta V_{2,\mu}, \\ T^{\alpha\beta} (V_1^\mu i \overleftrightarrow{\partial}_\beta (i \partial_\mu V_{2,\alpha}) + V_1^\mu i \overleftrightarrow{\partial}_\alpha (i \partial_\mu V_{2,\beta})), \quad T^{\alpha\beta} ((i \partial^\mu V_1^\nu) i \overleftrightarrow{\partial}_\alpha i \overleftrightarrow{\partial}_\beta (i \partial_\nu V_{2,\mu}))$$

- ▶ Gravitino couplings:

$$\bar{\psi} \gamma^\mu S \psi_\mu, \quad \bar{\psi} \gamma^\mu \not{k}_S S \psi_\mu, \quad \bar{\psi} \gamma^\mu \gamma^5 P \not{k}_P \psi_\mu, \quad \bar{\psi} \gamma^5 \gamma^\mu [\not{k}_V, V] \psi_\mu \text{ etc.}$$

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; Kilian/Ohl/JRR/Speckner, 2011
- ▶ Fundamental representations: $\mathbf{3}, \bar{\mathbf{3}}$
- ▶ Adjoint representation: $\mathbf{8}$
- ▶ Covers all interactions e.g. in SUSY and extra dimensions
- ▶ **in preparation:** generalized color structures with representations $\mathbf{6}, \bar{\mathbf{6}}, \mathbf{10}, \bar{\mathbf{10}}$
as well as $\epsilon_{ijk}\phi_i\phi_j\phi_k$ couplings **to appear in version 2.2**

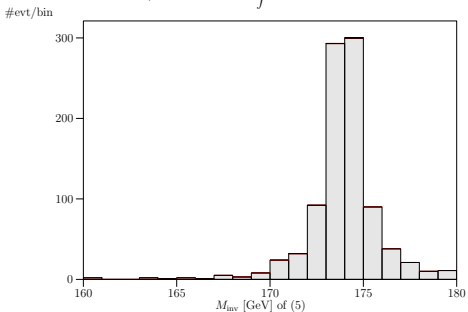
WHIZARD histograms

WHIZARD data analysis

March 16, 2007

Process: qttdec ($u\bar{u} \rightarrow b\bar{b}W^+W^-$)

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



$\sigma_{tot} = 36305. \pm 310. \text{ fb} \quad [\pm 0.85 \%]$ $n_{evt, tot} = 1000$
 $\sigma_{cut} = 36305. \pm 0.115 \times 10^{+04} \text{ fb} \quad [\pm 3.16 \%]$ $n_{evt, cut} = 1000 \quad [100.00 \%]$

New completely general syntax in WHIZARD 2.x

```
$title = "Jet Energy in $pp\to \ell\ell\bar{\nu}\nu j$"
$x_label = "$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/JRR/Specckner, 1010.3251](#)

Interface to SARAH in the SUSY Toolbox [Staub, 0909.2863; Ohl/Porod/Specckner/Staub, 1109.5147](#)

Comparison for the N²SM

Braam, Fuks, JRR, 0909.3059; 2012

Process	MG-FR	CH-FR	WO-ST	Comparison	MG-FR	CH-FR	WO-ST	Comparison	
CAU-CAU>SUu, SU-	1.48897 × 10 ⁻⁴	1.48892 × 10 ⁻⁴	1.48908 × 10 ⁻⁴	0.0339292	W-,Z>b,t-	7.11557 × 10 ⁻¹	7.0989 × 10 ⁻¹	7.11436 × 10 ⁻¹	$\delta = 0.234537\%$
CAU-CAU>SUu, CAU-	7.20298 × 10 ⁻⁴	7.5179 × 10 ⁻⁴	7.59246 × 10 ⁻⁴	0.089371	W-,Z>W-	3.01819 × 10 ²	3.0264 × 10 ²	3.0193 × 10 ²	$\delta = 0.271739\%$
CAU-CAU>SUe, e-	4.49207 × 10 ⁻⁴	4.4892 × 10 ⁻⁴	4.48806 × 10 ⁻⁴	0.0893631	W-,Z>u1-	7.4661 × 10 ⁻³	7.4604 × 10 ⁻³	7.43748 × 10 ⁻³	$\delta = 0.384101\%$
CAU-CAU>SUe, e+	9.75379 × 10 ⁻⁴	9.75379 × 10 ⁻⁴	9.75379 × 10 ⁻⁴	0.0893631	W-,Z>u1-,sv1-	2.36706 × 10 ⁻³	2.369 × 10 ⁻³	2.37235 × 10 ⁻³	$\delta = 0.223033\%$
CAU-CAU>SUv, V-	9.7555 × 10 ⁻⁴	9.7559 × 10 ⁻⁴	9.76016 × 10 ⁻⁴	0.0893235	W-,Z>u1-,sv2-	2.40865 × 10 ⁻³	2.4109 × 10 ⁻³	2.41163 × 10 ⁻³	$\delta = 0.123994\%$
CAU-CAU>SUv, V+	5.35941 × 10 ⁻⁴	5.35941 × 10 ⁻⁴	5.36164 × 10 ⁻⁴	0.167014	W-,Z>u1-,sv3-	1.16665 × 10 ⁻³	1.1695 × 10 ⁻³	1.17192 × 10 ⁻³	$\delta = 0.45102\%$
CAU-CAU>SUe, e-	7.12912 × 10 ⁻³	7.12912 × 10 ⁻³	7.12673 × 10 ⁻³	0.0988431	W-,Z>u1-,sv3-	1.2085 × 10 ⁻³	1.2067 × 10 ⁻³	1.20652 × 10 ⁻³	$\delta = 0.164307\%$
CAU-CAU>SUe, e+	7.1352 × 10 ⁻³	7.1358 × 10 ⁻³	7.13877 × 10 ⁻³	0.0988431	W-,Z>u1-,sv3-	3.51869 × 10 ⁻³	3.5133 × 10 ⁻³	3.51169 × 10 ⁻³	$\delta = 0.199274\%$
CAU-CAU>SUd, d-	3.61339 × 10 ⁻³	3.6133 × 10 ⁻³	3.61477 × 10 ⁻³	0.0497576	W-,Z>u1-,sv3-	3.51372 × 10 ⁻³	3.5133 × 10 ⁻³	3.51307 × 10 ⁻³	$\delta = 0.018628\%$
CAU-CAU>SUd, d+	3.10629 × 10 ⁻³	3.10629 × 10 ⁻³	3.10319 × 10 ⁻³	0.0497576	W-,Z>u1-,sv3-	1.4587 × 10 ⁻³	1.4447 × 10 ⁻³	1.44423 × 10 ⁻³	$\delta = 0.143534\%$
CAU-CAU>SUd, W-	3.90467 × 10 ⁻³	3.90467 × 10 ⁻³	3.90467 × 10 ⁻³	0.0497576	W-,Z>u1-,sv3-	2.3412 × 10 ⁻²	2.3479 × 10 ⁻²	2.34716 × 10 ⁻²	$\delta = 0.285674\%$
CAU-CAU>SUd, W+	3.02967 × 10 ⁻³	3.0313 × 10 ⁻³	3.03164 × 10 ⁻³	0.0497576	W-,Z>u1-,sv3-	1.79614 × 10 ⁻²	1.7953 × 10 ⁻²	1.79562 × 10 ⁻²	$\delta = 0.140162\%$
CAU-CAU>SUd, W-	8.21577 × 10 ⁻³	8.21577 × 10 ⁻³	8.21577 × 10 ⁻³	0.0497576	W-,Z>u1-,sv3-	1.27978 × 10 ⁻²	1.2783 × 10 ⁻²	1.27793 × 10 ⁻²	$\delta = 0.144221\%$
CAU-CAU>SUd, W+	3.90467 × 10 ⁻³	3.90467 × 10 ⁻³	3.90467 × 10 ⁻³	0.0497576	W-,Z>u1-,sv3-	5.58187 × 10 ⁻³	5.5834 × 10 ⁻³	5.5787 × 10 ⁻³	$\delta = 0.0842243\%$
CAU-CAU>SUd, W-	1.05047 × 10 ⁻³	1.0504 × 10 ⁻³	1.04972 × 10 ⁻³	0.0713687	W-,Z>u1-,sv3-	2.58653 × 10 ⁻²	2.5885 × 10 ⁻²	2.59104 × 10 ⁻²	$\delta = 0.174\%$
CAU-CAU>SUd, W+	1.17192 × 10 ⁻³	1.17192 × 10 ⁻³	1.17143 × 10 ⁻³	0.0497576	W-,Z>u1-,sv3-	8.78516 × 10 ⁻¹	8.743 × 10 ⁻¹	8.70416 × 10 ⁻¹	$\delta = 0.267929\%$
CAU-CAU>SUd, W+	1.17209 × 10 ⁻³	1.17209 × 10 ⁻³	1.17207 × 10 ⁻³	0.0912099	W-,Z>u1-,sv3-	5.29225 × 10 ⁻²	5.2915 × 10 ⁻²	5.28743 × 10 ⁻²	$\delta = 0.091285\%$
CAU-CAU>SUd, W+	3.90467 × 10 ⁻³	3.90467 × 10 ⁻³	3.90467 × 10 ⁻³	0.0497576	W-,Z>u1-,sv3-	8.68647 × 10 ⁻²	8.6797 × 10 ⁻²	8.68217 × 10 ⁻²	$\delta = 0.0779207\%$
CAU-CAU>SUd, W+	1.05047 × 10 ⁻³	1.0504 × 10 ⁻³	1.04972 × 10 ⁻³	0.0713687	W-,Z>u1-,sv3-	4.25162 × 10 ⁻²	4.2539 × 10 ⁻²	4.25377 × 10 ⁻²	$\delta = 0.0535405\%$
CAU-CAU>SUd, W+	1.17192 × 10 ⁻³	1.17192 × 10 ⁻³	1.17143 × 10 ⁻³	0.0497576	W-,Z>u1-,sv3-	1.86217 × 10 ⁻²	1.8623 × 10 ⁻²	1.86507 × 10 ⁻²	$\delta = 0.179804\%$
CAU-CAU>SUd, W+	1.17209 × 10 ⁻³	1.17209 × 10 ⁻³	1.17207 × 10 ⁻³	0.0912099	W-,Z>u1-,sv3-	5.08905 × 10 ⁻²	5.0974 × 10 ⁻²	5.10002 × 10 ⁻²	$\delta = 0.215293\%$
CAU-CAU>SUd, W+	3.90467 × 10 ⁻³	3.90467 × 10 ⁻³	3.90467 × 10 ⁻³	0.0497576	W-,Z>u1-,sv3-	3.87418 × 10 ⁻²	3.8743 × 10 ⁻²	3.87516 × 10 ⁻²	$\delta = 0.0253781\%$
CAU-CAU>SUd, W+	1.05047 × 10 ⁻³	1.0504 × 10 ⁻³	1.04972 × 10 ⁻³	0.0713687	W-,Z>u1-,sv3-	2.30577 × 10 ⁻²	2.3033 × 10 ⁻²	2.3038 × 10 ⁻²	$\delta = 0.107112\%$
CAU-CAU>SUd, W+	1.17192 × 10 ⁻³	1.17192 × 10 ⁻³	1.17143 × 10 ⁻³	0.0497576	W-,Z>u1-,sv3-	3.06927 × 10 ⁻⁶	3.069 × 10 ⁻⁶	3.07074 × 10 ⁻⁶	$\delta = 0.0566669\%$
CAU-CAU>SUd, W+	1.17209 × 10 ⁻³	1.17209 × 10 ⁻³	1.17207 × 10 ⁻³	0.0912099	W-,Z>u1-,sv3-	1.20593 × 10 ⁴	1.2061 × 10 ⁴	1.20462 × 10 ⁴	$\delta = 0.122403\%$
CAU-CAU>SUd, W+	3.90467 × 10 ⁻³	3.90467 × 10 ⁻³	3.90467 × 10 ⁻³	0.0497576	W-,Z>u1-,sv3-	2.1414 × 10 ⁻³	2.1392 × 10 ⁻³	2.13929 × 10 ⁻³	$\delta = 0.102916\%$
CAU-CAU>SUd, W+	1.05047 × 10 ⁻³	1.0504 × 10 ⁻³	1.04972 × 10 ⁻³	0.0713687	W-,Z>u1-,sv3-	2.71579 × 10 ⁻⁴	2.7161 × 10 ⁻⁴	2.71278 × 10 ⁻⁴	$\delta = 0.122268\%$
CAU-CAU>SUd, W+	1.17192 × 10 ⁻³	1.17192 × 10 ⁻³	1.17143 × 10 ⁻³	0.0497576	W-,Z>u1-,sv3-	1.28349 × 10 ⁻¹	1.2827 × 10 ⁻¹	1.28247 × 10 ⁻¹	$\delta = 0.0795463\%$
CAU-CAU>SUd, W+	1.17209 × 10 ⁻³	1.17209 × 10 ⁻³	1.17207 × 10 ⁻³	0.0912099	W-,Z>u1-,sv3-	7.94029 × 10 ⁻²	7.9468 × 10 ⁻²	7.93492 × 10 ⁻²	$\delta = 0.149577\%$
CAU-CAU>SUd, W+	3.90467 × 10 ⁻³	3.90467 × 10 ⁻³	3.90467 × 10 ⁻³	0.0497576	W-,Z>u1-,sv3-	1.70391	1.7037	1.7087	$\delta = 0.293178\%$
CAU-CAU>SUd, W+	1.05047 × 10 ⁻³	1.0504 × 10 ⁻³	1.04972 × 10 ⁻³	0.0713687	W-,Z>u1-,sv3-	3.98499 × 10 ⁻⁵	3.9924 × 10 ⁻⁵	4.00474 × 10 ⁻⁵	$\delta = 0.494346\%$
CAU-CAU>SUd, W+	1.17192 × 10 ⁻³	1.17192 × 10 ⁻³	1.17143 × 10 ⁻³	0.0497576	W-,Z>u1-,sv3-	6.98995 × 10 ⁻⁸	6.985 × 10 ⁻⁸	7.00424 × 10 ⁻⁸	$\delta = 0.275123\%$
CAU-CAU>SUd, W+	1.17209 × 10 ⁻³	1.17209 × 10 ⁻³	1.17207 × 10 ⁻³	0.0912099	W-,Z>u1-,sv3-	1.36107 × 10 ⁻⁵	1.361 × 10 ⁻⁵	1.36221 × 10 ⁻⁵	$\delta = 0.0886822\%$
CAU-CAU>SUd, W+	3.90467 × 10 ⁻³	3.90467 × 10 ⁻³	3.90467 × 10 ⁻³	0.0497576	W-,Z>u1-,sv3-	1.40065 × 10 ⁻⁵	1.4004 × 10 ⁻⁵	1.39963 × 10 ⁻⁵	$\delta = 0.0730172\%$

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("spslap_decays.slha")

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

sqrts = 14000
beams = p, p => lhpdf

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

n_events = 10000

$title = "Full process"
$description =
  "$p + p \to u + \bar{u} \to \bar{u} + 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]])
}

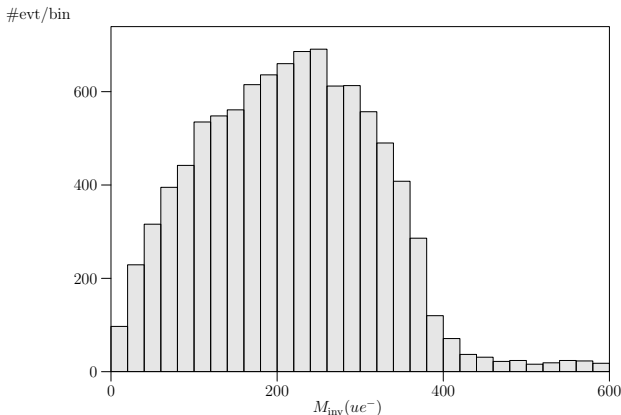
compile_analysis
$analysis_filename = "casc_dec"
write_analysis

```

Example: LHC SUSY cascade decays

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

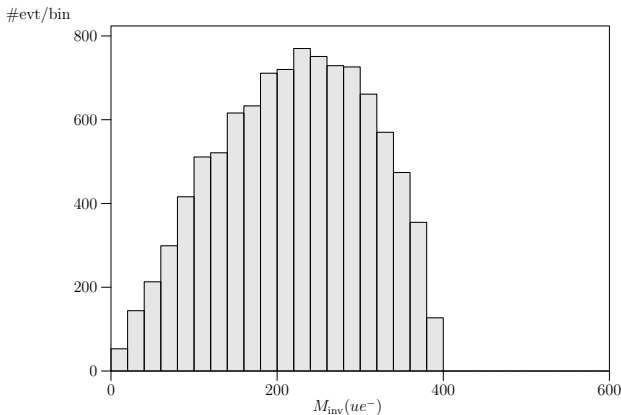
► Full process:



Example: LHC SUSY cascade decays

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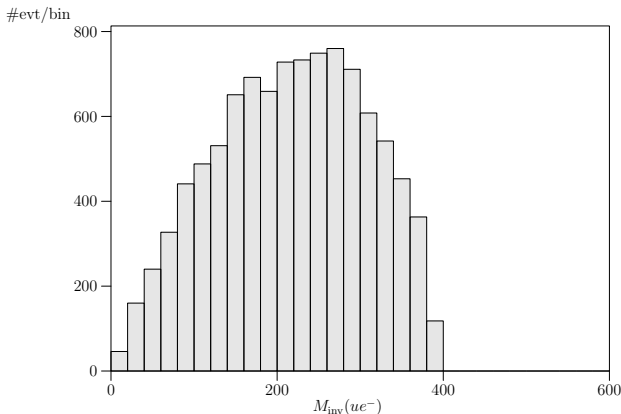
► **Factorized process w/ full spin correlations:**



Example: LHC SUSY cascade decays

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

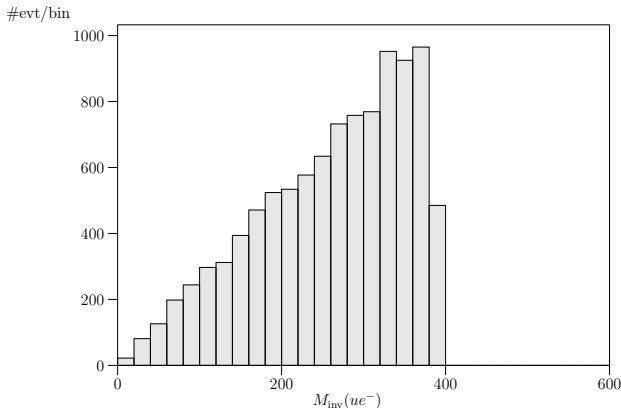
- **Factorized process w/ classical spin correlations:**



Example: LHC SUSY cascade decays

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

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



BSM, e.g. Resonances in VV scattering

Alboteanu/Kilian/JRR, JHEP 0811

(2008) 010

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

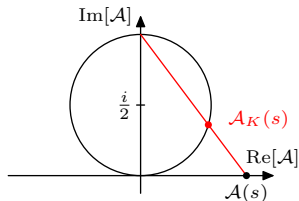
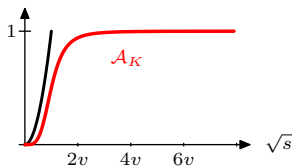
	$J = 0$	$J = 1$	$J = 2$
$I = 0$	σ^0 (Higgs ?)	ω^0 (γ'/Z' ?)	a^0 (Graviton ?)
$I = 1$	π^\pm, π^0 (2HDM ?)	ρ^\pm, ρ^0 (W'/Z' ?)	t^\pm, t^0
$I = 2$	$\phi^{\pm\pm}, \phi^\pm, \phi^0$ (Higgs triplet ?)	—	$f^{\pm\pm}, f^\pm, f^0$

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.: $|\mathcal{A}(s)|^2 \xrightarrow{s \rightarrow \infty} 1$
- ▶ Poles $\pm iv$: M_0, Γ large



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

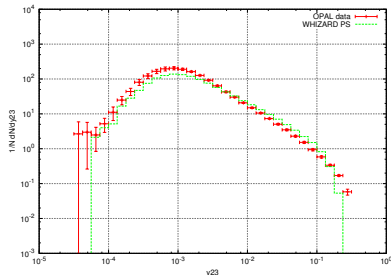
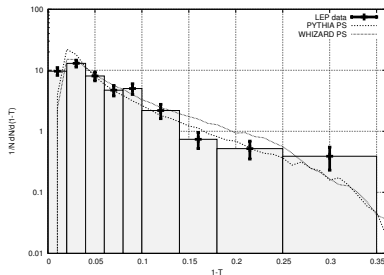
Revised Implementation and New Results

- 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

JRR/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

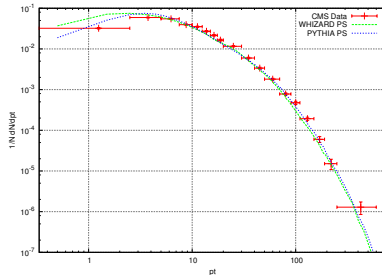
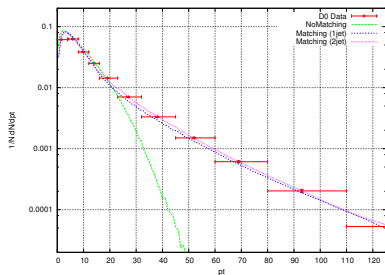


- ▶ matching with hard matrix elements, no "power-shower"

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JRR/Schmidt/Wiesler, JHEP 2012

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- ▶ new algorithm for initial state radiation



- ▶ 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** JRR/Speckner, 2013
 - proof-of-concept code in WHIZARD 2.1
 - implementation in the context of the revised WHIZARD 2.2 core

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

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

sqrt_s = 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    |
|=====|

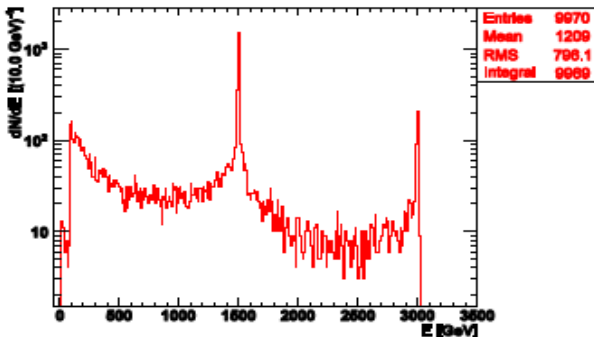
```

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 $e^+e^- \rightarrow b\bar{b}$:

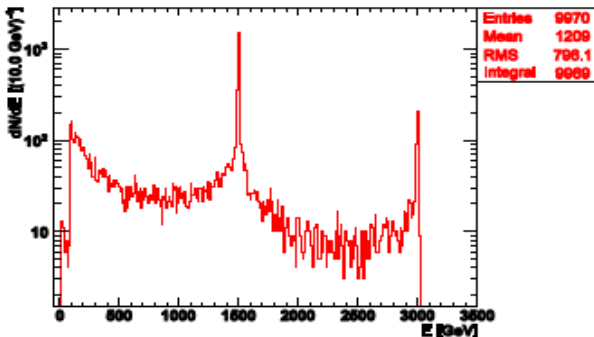
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Simulating Linear Colliders

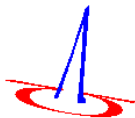
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Luminosity spectrum picks up the Z resonance!

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

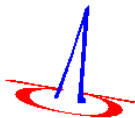
Thanks to all contributors (list is not exhaustive!)

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T. Røbns, 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!**