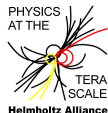


The Monte Carlo Event Generator WHIZARD

Jürgen R. Reuter

DESY Hamburg



Seminar, KEK, Tsukuba, Nov 18th, 2013

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 and selective decay chains

(public alpha version)

Plan Improve ILC support; NLO + matching; improve user interface
⇒ 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)
 - $e^+e^- \rightarrow t\bar{t}H \rightarrow b\bar{b}b\bar{b}j\ell\nu$ (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)
 - $pp \rightarrow \bar{\chi}_1^0\bar{\chi}_1^0 bbbb$ (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: Sep. 18, 2012

Old series: WHIZARD 1.97 (development stopped with 1.94)

The WHIZARD team: F. Bach, B. Chokouf , **W. Kilian**, **T. Ohl**, **JRR**, M. Sekulla, F. Staub, C. Weiss,



Web address: <http://projects.hepforge.org/whizard>
Standard Reference: [Kilian/Ohl/JRR, EPJC 71 \(2011\) 1742, arXiv:0708.4233](#)

The WHIZARD Event Generator – Release 2.2

- ▶ Multi-Channel Monte-Carlo integration
- ▶ Efficient phase space and event generation (weighted & unweighted)
- ▶ Optimized tree-level matrix elements (O'Mega)
 - $e^+e^- \rightarrow t\bar{t}H \rightarrow b\bar{b}b\bar{b}j\ell\nu$ (110,000 diagrams)
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WHIZARD 2.2.0_α-4 release: Nov. 13, 2013 (LCWS)



Old series: WHIZARD 1.97 (development stopped with 1.94)

The WHIZARD team: F. Bach, B. Chokouf , W. Kilian, T. Ohl, JRR, M. Sekulla, F. Staub, C. Weiss,

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WHIZARD 2.2.0 release: Feb. 5, 2014 (CLIC)

Old series: WHIZARD 1.97 (development stopped with 1.94)

The WHIZARD team: F. Bach, B. Chokouf , W. Kilian, T. Ohl, JRR, M. Sekulla, F. Staub, C. Weiss, + 2 bachelors



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

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

WHIZARD 2: Status 2010-13 – Technical Features

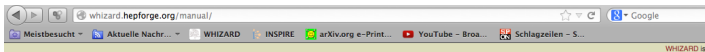
- WHIZARD 2: code basically rewritten, only `Fortran 2003` and `O'Caml`
- Clean modularization of code/(First) object-oriented implementation
- OpenMP parallelization
- Operation modes:
 - ▶ Dynamic linking (default mode) with on-the-fly generation of process code
 - ▶ Static linking (for batch clusters)
 - ▶ Library mode, callable from C/C++/Python/...
 - ▶ Interactive mode: WHIZARD works as a Shell – WHISH
- Standard conformance: uses `autotools: automake/autoconf/libtool`
- Large self 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)
- ▶ **Supported event formats:** HepMC, StdHEP, LHEF, LHA, div. ASCII formats

```
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: lhpdf.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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- News
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- Subversion
- Browser
- Tracker
- Internal

WHIZARD 2.1 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 Speckner⁵

- Contents
- Introduction
 - Disclaimer
 - Overview
 - About examples in this manual
- Installation
 - Package Structure
 - Prerequisites
 - Installation
 - Working With WHIZARD
- Getting Started
 - Hello World
 - A Simple Calculation
- SINDARIN: Overview
 - The command language for WHIZARD
 - SINDARIN scripts
 - Errors
 - Statements
 - Control Structures
 - Expressions
 - Variables

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]]]
```

- 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/Speckner, 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

▶ Lepton Colliders structured beams

- QED ISR (Skrzypek/Jadach, Kuraev/Fadin , incl. p_T distributions)
- arbitrarily polarized beams (density matrices)
- Beamstrahlung (CIRCE module) **more later**
- Photon collider spectra (CIRCE2 module)
- external beam spectra can be read in (files/generating code)
- QED FSR (e.g. YFS) not (yet) implemented (charged mesons/hadrons)

▶ Hadronic events/hadronic decays

- ▶ through PYTHIA interface [or HERWIG]

▶ Hadron Colliders structured beams

- LHAPDF interface
- Most prominent PDFs directly included
- QCD ISR and FSR (two different own implementations, interface to PYTHIA)
- Matching matrix elements/showers (MLM)
- Underlying event/multiple interactions

O'Mega: Optimal matrix elements

Oh/JRR, 2001



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

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

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: ϕ^3 , ϕ^4
- ▶ Scalar couplings to vectors: $g V^\mu \phi_1 i \overleftrightarrow{\partial}_\mu \phi_2$, ϕV^2 , $\phi^2 V^2$, $\frac{1}{2} \phi F_{1,\mu\nu} F_2^{\mu\nu}$, $\frac{1}{2} \phi F_{1,\mu\nu} \tilde{F}_2^{\mu\nu}$, $\phi (i \partial_\mu V_1^\nu) (i \partial_\nu V_2^\mu)$
- ▶ Pure vector couplings: $F_{\mu\nu} F^{\mu\nu}$, $V_1^\mu ((i \partial_\nu V_2^\rho) i \overleftrightarrow{\partial}_\mu (i \partial_\rho V_3^\nu))$, $g F_1^{\mu\nu} F_{2,\nu\rho} F_{3,\rho\mu}$
 $g/2 \cdot \epsilon^{\mu\nu\lambda\tau} F_{1,\mu\nu} F_{2,\tau\rho} F_{3,\rho\lambda}$
- ▶ Fermionic couplings to scalars:
 $g_S \bar{\psi}_1 S \psi_2$, $g_P \bar{\psi}_1 P \gamma_5 \psi_2$, $\bar{\psi}_1 \phi (g_S + g_P \gamma_5) \psi_2$, $g_L \bar{\psi}_1 \phi (1 - \gamma_5) \psi_2$, $g_R \bar{\psi}_1 \phi (1 + \gamma_5) \psi_2$,
 $g_L \bar{\psi}_1 \phi (1 - \gamma_5) \psi_2 + g_R \bar{\psi}_1 \phi (1 + \gamma_5) \psi_2$
- ▶ Fermionic couplings to vectors:
 $g_V \bar{\psi}_1 V \psi_2$, $g_A \bar{\psi}_1 \gamma_5 V \psi_2$, $\bar{\psi}_1 V (g_V - g_A \gamma_5) \psi_2$, $g_L \bar{\psi}_1 V (1 - \gamma_5) \psi_2$, $g_R \bar{\psi}_1 V (1 + \gamma_5) \psi_2$,
 $g_L \bar{\psi}_1 V (1 - \gamma_5) \psi_2 + g_R \bar{\psi}_1 V (1 + \gamma_5) \psi_2$
- ▶ Fermionic couplings to tensors: $g_T T_{\mu\nu} \bar{\psi}_1 [\gamma^\mu, \gamma^\nu]_- \psi_2$
- ▶ Tensor couplings to vectors:
 $T^{\mu\nu} (V_{1,\mu} V_{2,\nu} + V_{1,\nu} V_{2,\mu})$, $T^{\alpha\beta} (V_1^\mu i \overleftrightarrow{\partial}_\alpha i \overleftrightarrow{\partial}_\beta V_{2,\mu})$,
 $T^{\alpha\beta} (V_1^\mu i \overleftrightarrow{\partial}_\beta (i \partial_\mu V_{2,\alpha}) + V_1^\mu i \overleftrightarrow{\partial}_\alpha (i \partial_\mu V_{2,\beta}))$, $T^{\alpha\beta} ((i \partial^\mu V_1^\nu) i \overleftrightarrow{\partial}_\alpha i \overleftrightarrow{\partial}_\beta (i \partial_\nu V_{2,\mu}))$
- ▶ Gravitino couplings: $\bar{\psi} \gamma^\mu S \psi_\mu$, $\bar{\psi} \gamma^\mu \not{k}_S S \psi_\mu$, $\bar{\psi} \gamma^\mu \gamma^5 P \not{k}_P \psi_\mu$, $\bar{\psi} \gamma^5 \gamma^\mu [\not{k}_V, V] \psi_\mu$ etc.

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

Hard matrix elements: Color structures

Possible Color structures

- ▶ 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 reps. $\mathbf{6}, \bar{\mathbf{6}}, \mathbf{10}, \bar{\mathbf{10}}$
as well as $\epsilon_{ijk}\phi_i\phi_j\phi_k$ couplings **to appear in version 2.2.x**

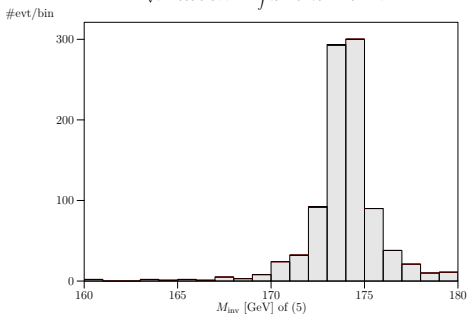
WHIZARD histograms

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 coupl.	SM_ac_CKM	SM_ac
SM with anomalous top coupl.	SMt_op_CKM	SMt_op
SM with K matrix	—	SM_KM
2HDM	2HDM_CKM	2HDM
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	—	Threshl
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/Speckner, 1010.3251](#)

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

Input files: Basic features

```
model = SM
```

```
process halloween = E1, e1 => t, tbar, H
```

```
compile
```

```
sqrts = 500
```

```
beams = E1, e1 => circel => isr
```

```
integrate (halloween) { iterations = 5:10000, 2:10000 }
```

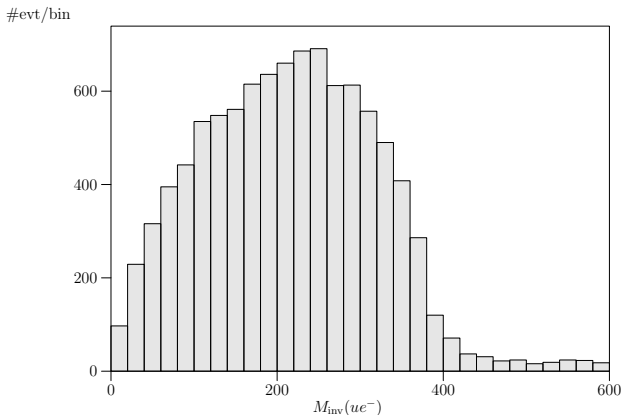
```
n_events = 10000
```

```
simulate (halloween) {  
}
```

Example: LHC SUSY cascade decays

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

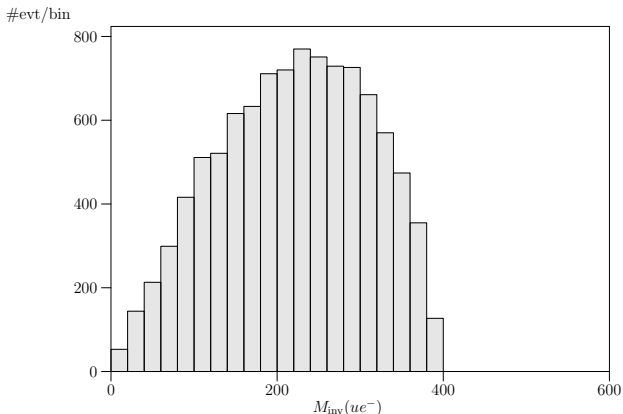
► Full process:



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

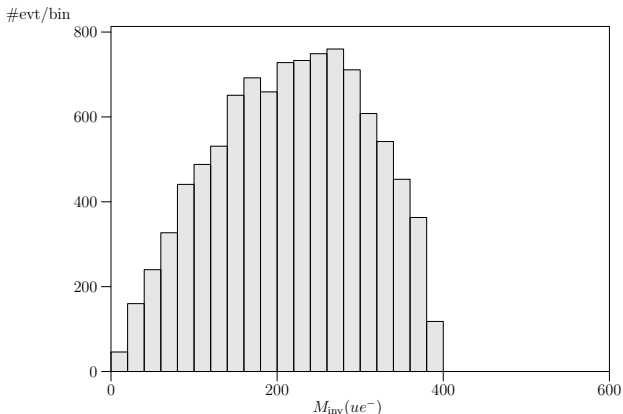
► **Factorized process w/ full spin correlations:**



Example: LHC SUSY cascade decays

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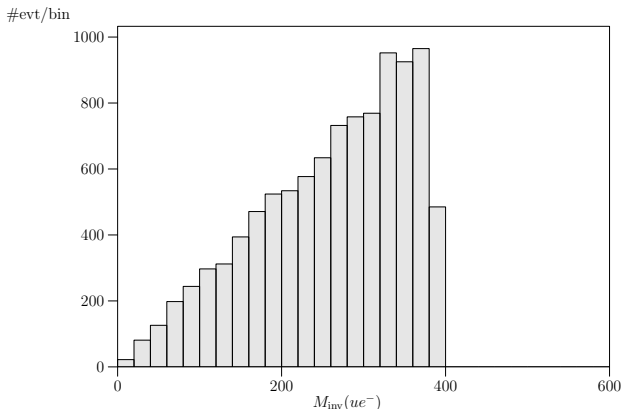
► **Factorized process w/ classical spin correlations:**



Example: LHC SUSY cascade decays

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

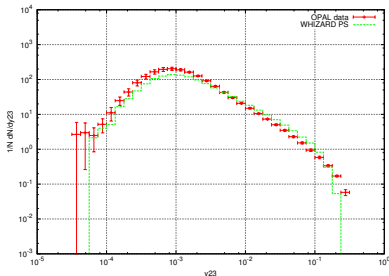
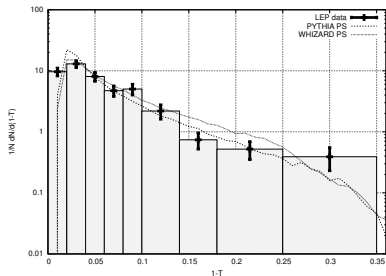
- **Factorized process w/ no spin correlations:**



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 QCD radiation

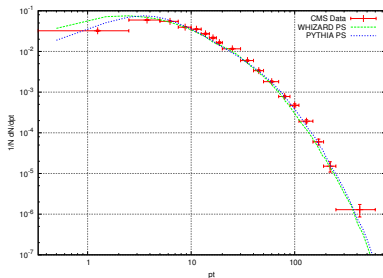
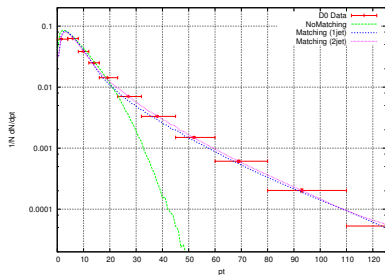


- ▶ matching with hard matrix elements, no "power-shower"

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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** Speckner, 2012; JRR/Weiss, 2014
 - proof-of-concept code in WHIZARD 2.1
 - implementation in the context of the revised WHIZARD 2.2 core

News 2013/early 2014: upcoming official release 2.2.x

- Lost of WHIZARD members 2012: some features delayed in 2013
(pre-)release version **2.2.0_α-4** available!

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- WHIZARD core: insert an extra abstraction layer, consistently separate interface from implementation **Complete object orientation**
 - ▶ **Replaceable modules** with well-defined interface: matrix-elements, beam structure, phase space, integration, decays, shower, ...
 - ▶ Much easier to contribute new parts to the code ⇒ **Industrialization**
 - ▶ **Technical changes hidden from the user**
 - ▶ Modern programming techniques: unit tests, pair programming etc.
 - ▶ **Much better self checks, regression testing and maintainability**

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- Automatic generation of **decays**, depending on the model

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- Revised model for BSM interactions of **electroweak vector bosons** (w/ light Higgs)
- Process containers: inclusive production samples (e.g. SUSY)
- Automatic generation of **decays**, depending on the model
- New syntax/features decays and chains:


```
process higgsstr = e1, E1 => (Z => e2, E2), (H => b, bbar)
process inclusive = e1, E1 => (Z, h) + (Z, H) + (A, H)
```
- Specification of QCD and electroweak order
- Improvements to the **SINDARIN** steering language

New (LC-related) features / Plans

- **LCIO support** (C++ interface) courtesy of F. Gaede
- **Lumi-linker** interface courtesy of T. Barklow
- Support for **ILC beam spectra within CIRCE1** courtesy of G. Wilson

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- BSM: **general Lorentz structures** in matrix-element generator (O'Mega)
- Parsing of UFO files
- **Complete Reweighting of Event Samples (incl. LHEF 2013)**
- Working on performance gain: multi-leg, parallelization, smaller expressions etc.
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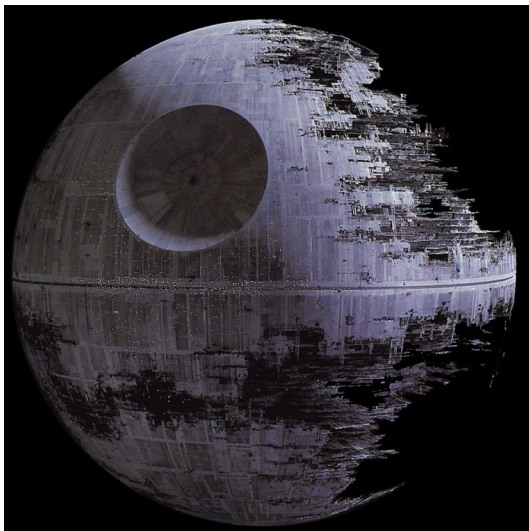
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- ▶ **Threshold resummation for $e^+e^- \rightarrow W^+W^-, t\bar{t}$ etc.** Bach/Hoang/Kilian/JRR/Prestel, ca. 2014

Status of refactoring:

Well, what shall I say ...

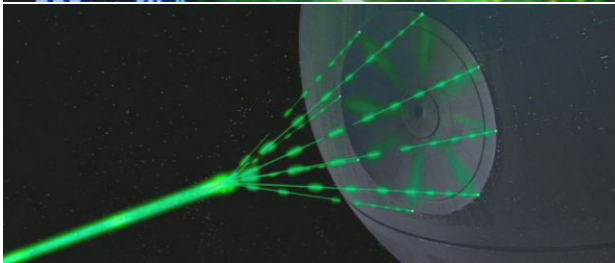
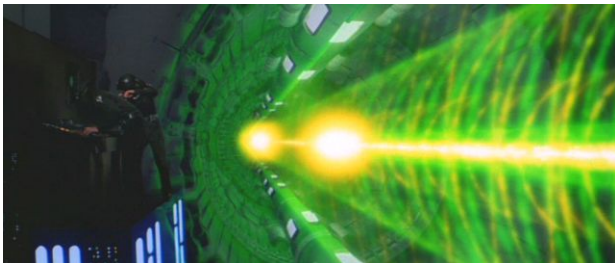
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Status of refactoring:

ok, LC features have pretty high priority



[German TV: science for the public]



Summary and Outlook

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- ▶ **Versatile, user-friendly tool for SM & BSM physics**
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- ▶ Covers the whole SM, and most possible paths beyond
- ▶ **Upgrade after a long technical overhaul**
- ▶ Expect continuous improvement



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Let us know of your needs!

`whizard@desy.de`

Interesting times ahead

ECFA LC2013
European Linear Collider Workshop
 27 – 31 May 2013
 DESY, Hamburg



Programme Committee
 Felix Heitsch (DESY/MPG/FAZ)
 Ingrid Fischer (DESY/FAZ, DESY, Hamburg)
 John Ross (CEA, Orsay)
 Michael Benedetti (DESY)
 Michael Goussard (EPFL, Lausanne, Switzerland)
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 European Particle Accelerator
 Facility for a Linear Collider

DESY **ALBERT-LUDEWIG-UNIVERSITÄT DUISBURG ESSEN** **UHH**

<http://lc2013.desy.de>

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Kent Nagano, Director General, 2015-



どうもありがとうございます