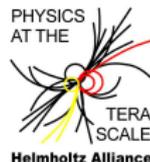


The Monte Carlo Event Generator WHIZARD

Jürgen R. Reuter

DESY Hamburg



CLIC workshop, CERN, Feb 4th, 2014

WHIZARD in a Nutshell

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

- ▶ e^+e^- : LEP and TESLA/NLC \Rightarrow **ILC**, **CLIC**, TLEP ...
- ▶ pp : Tevatron \Rightarrow LHC, HL/E-LHC, VLHC, XXX ...

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 beta version)

Plan Improve LC 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)
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WHIZARD 2.2.0_β release: Feb. 3, 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,

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WHIZARD 2.2.0 release: (Feb. 3 + ϵ), 2014

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 2010-14 – Technical Features

- WHIZARD 2: code basically rewritten, only `Fortran 2003` and `O'Cam1`
- 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-2.2.0_beta.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

```

WHIZARD self tests:
make check-am
make check-TESTS
PASS: expressions.run
PASS: beams.run
PASS: cputime.run
PASS: state_matrices.run
PASS: interactions.run
PASS: beam_structures.run
PASS: models.run
[.....]
PASS: pfs_forests.run
PASS: rng_base.run
PASS: selectors.run
PASS: pfs_wood.run
PASS: mci_vamp.run
PASS: particle_specifiers.run
PASS: prclib_stacks.run
PASS: slha_interface.run
PASS: subevt_expr.run
PASS: process_stacks.run
PASS: cascades.run
PASS: processes.run
PASS: decays.run
PASS: events.run
PASS: eig_base.run
PASS: rt_data.run
PASS: dispatch.run
PASS: process_configurations.run
PASS: event_weights_1.run
PASS: integrations.run
PASS: simulations.run
PASS: process_libraries.run
PASS: compilations.run
PASS: prclib_interfaces.run
PASS: commands.run
XFAIL: errors.run
PASS: helicity.run
PASS: prc_omega.run
PASS: qedtest_1.run
PASS: beam_setup_1.run
PASS: reweight_1.run
PASS: colors.run
PASS: lhef_1.run
PASS: alphas.run
PASS: smtest_1.run
PASS: hepmc.run
PASS: restrictions.run
PASS: pdf_builtin.run
PASS: stdhep_1.run
PASS: static_1.run

```

```
-----
Testsuite summary for WHIZARD 2.2.0_beta
-----
```

```

# TOTAL: 163
# PASS: 162
# SKIP: 0
# XFAIL: 1
# FAIL: 0
# XPASS: 0
# ERROR: 0
-----

```

WHIZARD Manual

Online only 2.1 Manual for now, 2.2 ships with distr.



- Home
- Downloads
- Wiki
- News
- ChangeLog
- Subversion
- Browser
- Tracker
- Internal

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[✉]

- Contents
- Introduction
 - Disclaimer
 - Overview
 - About examples in this manual
- Installation
 - Package Structure
 - Prerequisites
 - Installation
 - Working With WHIZARD
- Getting Started
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 - A Simple Calculation
- SINDARIN: Overview
 - The command language for WHIZARD
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 - Errors
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 - 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/Spekner, 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

O'Mega: Optimal matrix elements

Oh/JRR, 2001



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

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

O'Mega: Optimal matrix elements

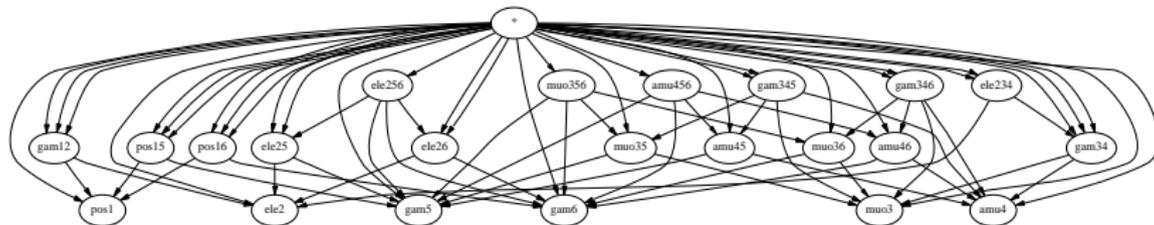
Ohl/JRR, 2001



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- ▶ LC example: $e^+e^- \rightarrow \mu^+\mu^-\gamma\gamma$



O'Mega: Optimal matrix elements

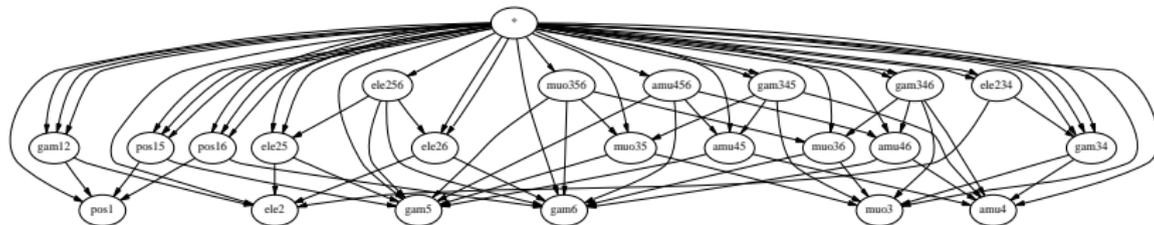
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- ▶ Specification of order of strong or EW coupling (2.2.x)

O'Mega: Optimal matrix elements

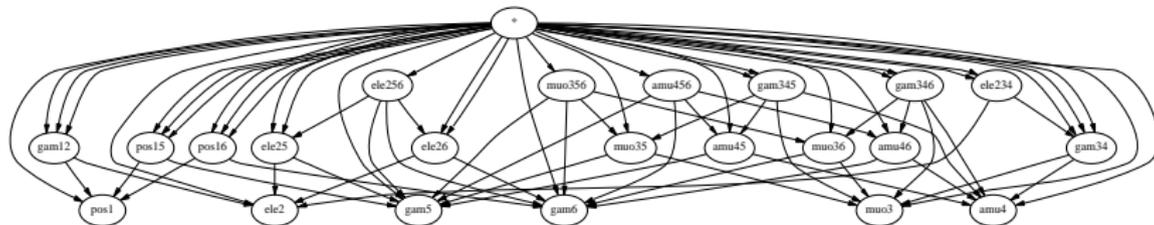
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- ▶ Unification of model setup: only one binary (2.3)

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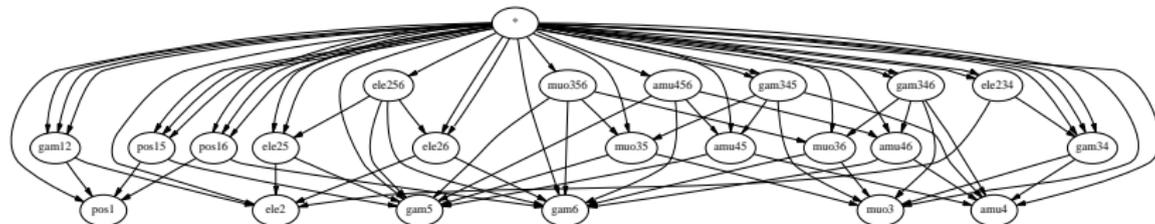
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- ▶ Specification of order of strong or EW coupling (2.2.x)
- ▶ Unification of model setup: only one binary (2.3)
- ▶ Teaser: new algorithm for generating loop diagrams (2.4 ?)

Beams and hard matrix elements

▶ **Hadron Colliders structured beams**

- LHAPDF interface (5.x for now), most prominent PDFs directly included
- QCD ISR and FSR (2 diff. own implementations, interface to PYTHIA)
- Matching matrix elements/showers (MLM)
- Underlying event/multiple interactions (proof of principle)

▶ **Hadronic events/hadronic decays + hadronic (QED) FSR**

- ▶ through PYTHIA 6 interface [or PYTHIA8/HERWIG in prep.]

▶ **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)

Hard matrix elements:

▶ **Particle spins:** $0, \frac{1}{2}, 1, \frac{3}{2}, 2$

▶ **Lorentz structures:** huge set of hard-coded structures

▶ Fully general Lorentz structures foreseen for 2.3.0

▶ **Color structures:** $\mathbf{3}, \bar{\mathbf{3}}, \mathbf{8}, [\mathbf{6}]$

▶ Color flow formalism

▶ General color structures $\mathbf{6}, \mathbf{10}, \epsilon_{ijk} \phi^i \phi^j \phi^k$

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.	SMtop_CKM	SMtop
SM with K matrix	—	SM_KM
SM ext. for VV scattering	—	VBS
SM with Z'	—	Zprime
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 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 helloworld = E1, e1 => t, tbar, H
```

```
compile
```

```
sqrts = 500
```

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

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

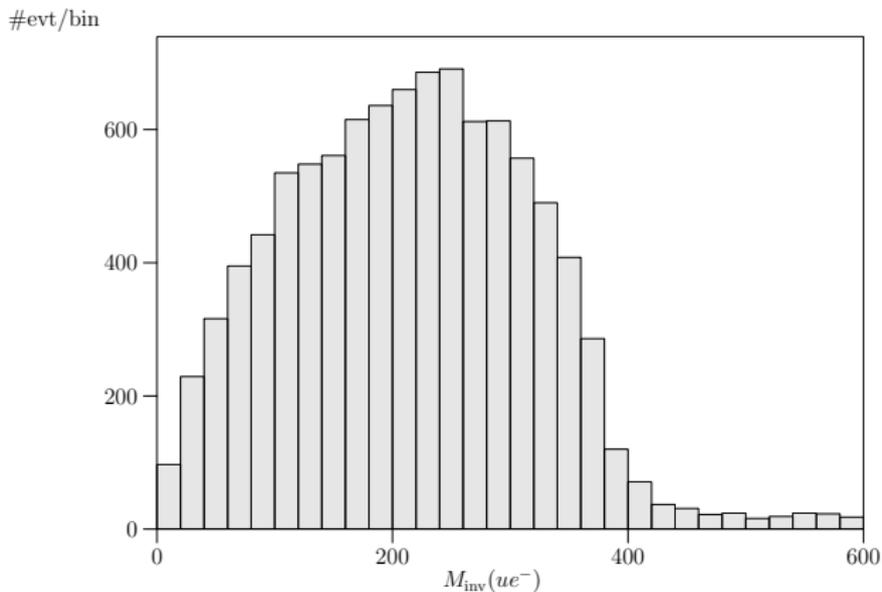
```
n_events = 10000
```

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

Example: LHC SUSY cascade decays

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

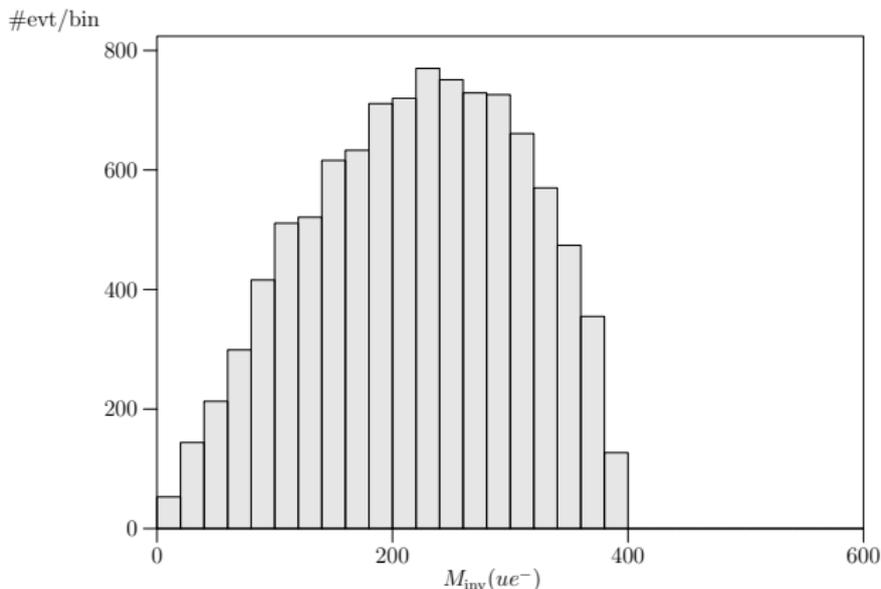
► Full process:



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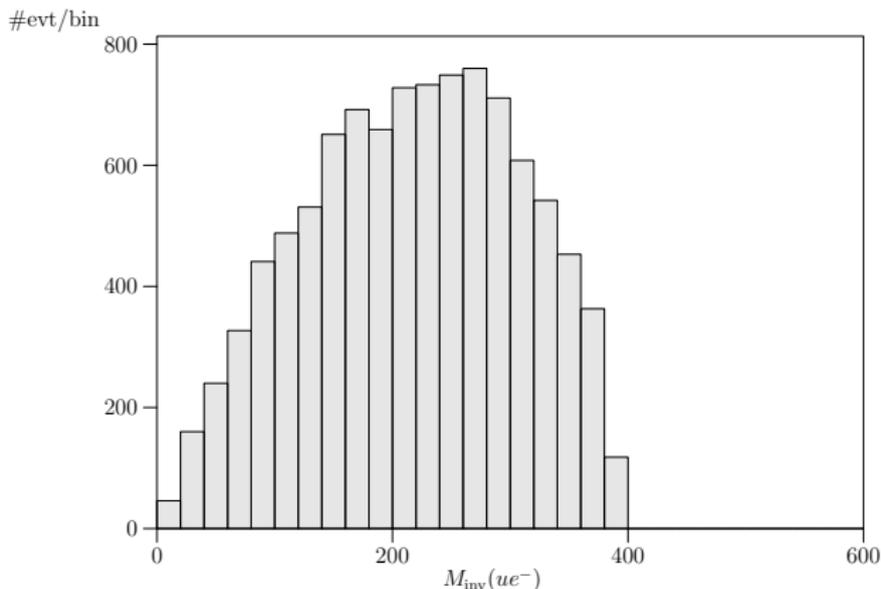
► **Factorized process w/ full spin correlations:**



Example: LHC SUSY cascade decays

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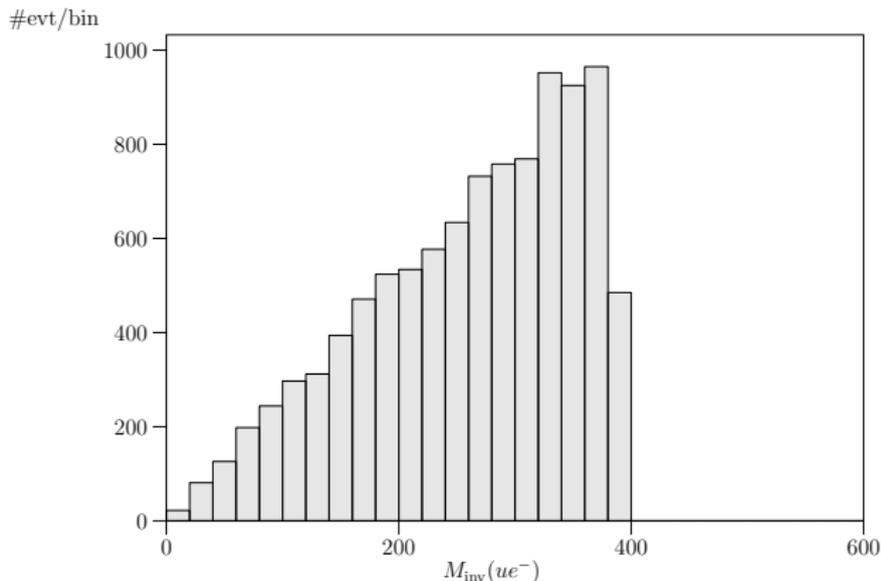
- **Factorized process w/ classical spin correlations:**



Example: LHC SUSY cascade decays

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

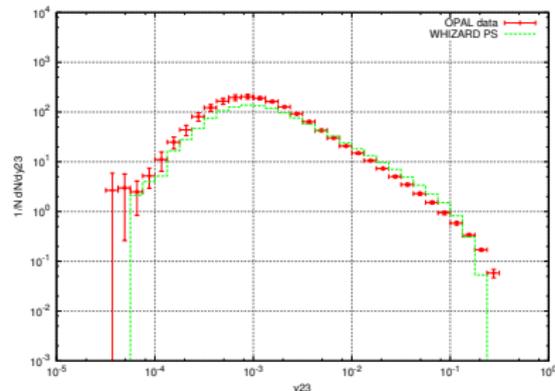
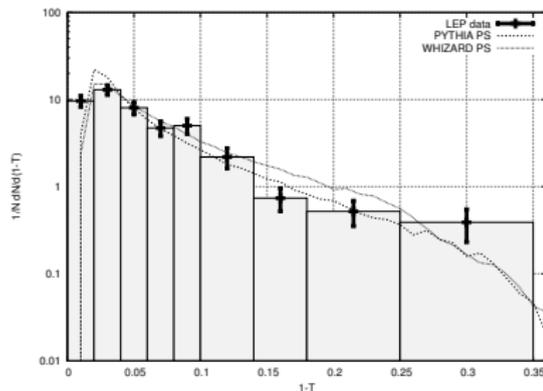
- **Factorized process w/ no spin correlations:**



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

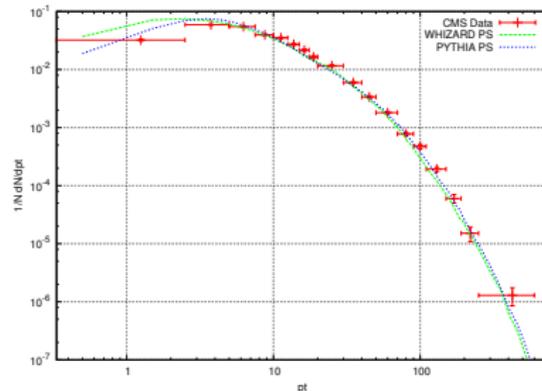
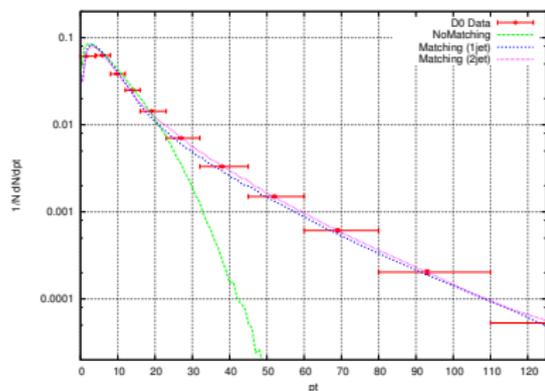


- ▶ matching with hard matrix elements, no "power-shower"

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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/FormCalc`

- ▶ **Automatic generation of 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
 - both dipole and FKS subtraction will be available
 - Provide PowHeg box formalism for NLO processes

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- β** available!

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 - ▶ **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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- Process containers: inclusive production samples (e.g. SUSY)
- Automatic generation of **decays**, depending on the model

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- Revised models 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.
MC over helicities, colors, PS, etc. etc. etc.

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2015

New (LC-related) features / Plans

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First plots for $t\bar{t}$ threshold for Paris workshop!

Questions to the User Community?

- ▶ **LCIO**: what are the needs for the format? spin info? color correlations?? Reweighting options?
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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
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 - WHIZARD 2.2.x-2.x.x on a regular basis !!!



Let us know of your needs!

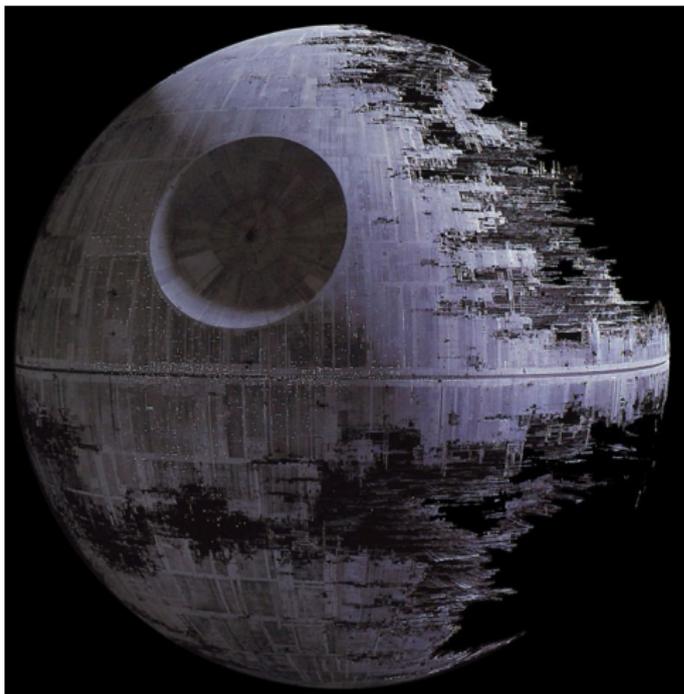
`whizard@desy.de`

Status of refactoring:

Status of LCWS 2013 ...

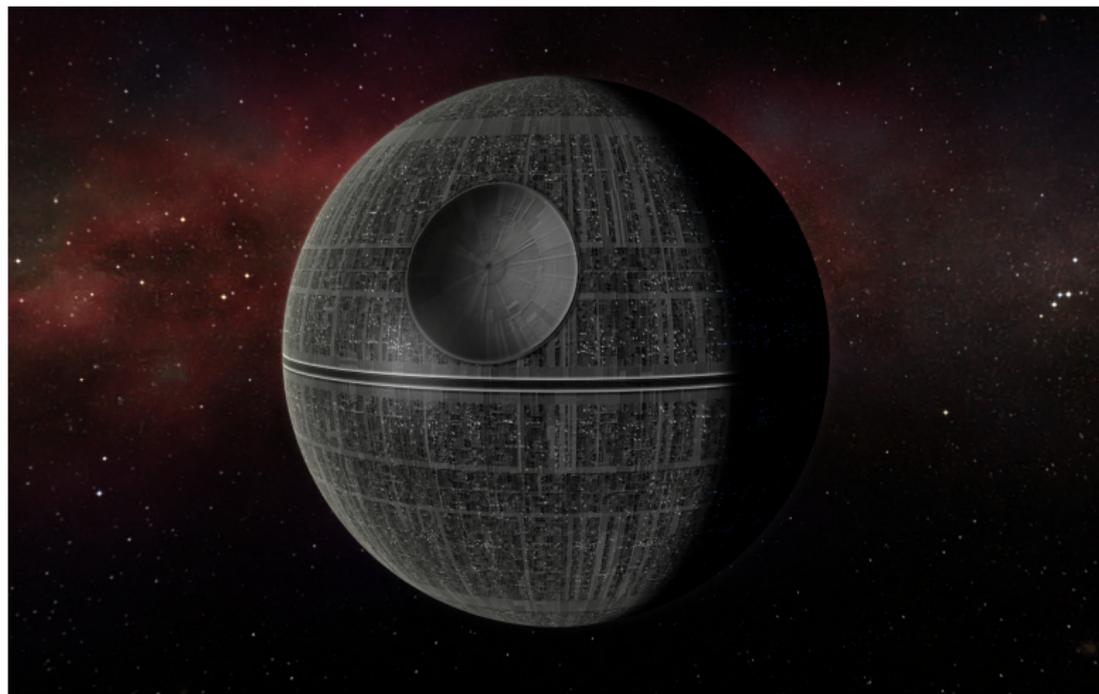
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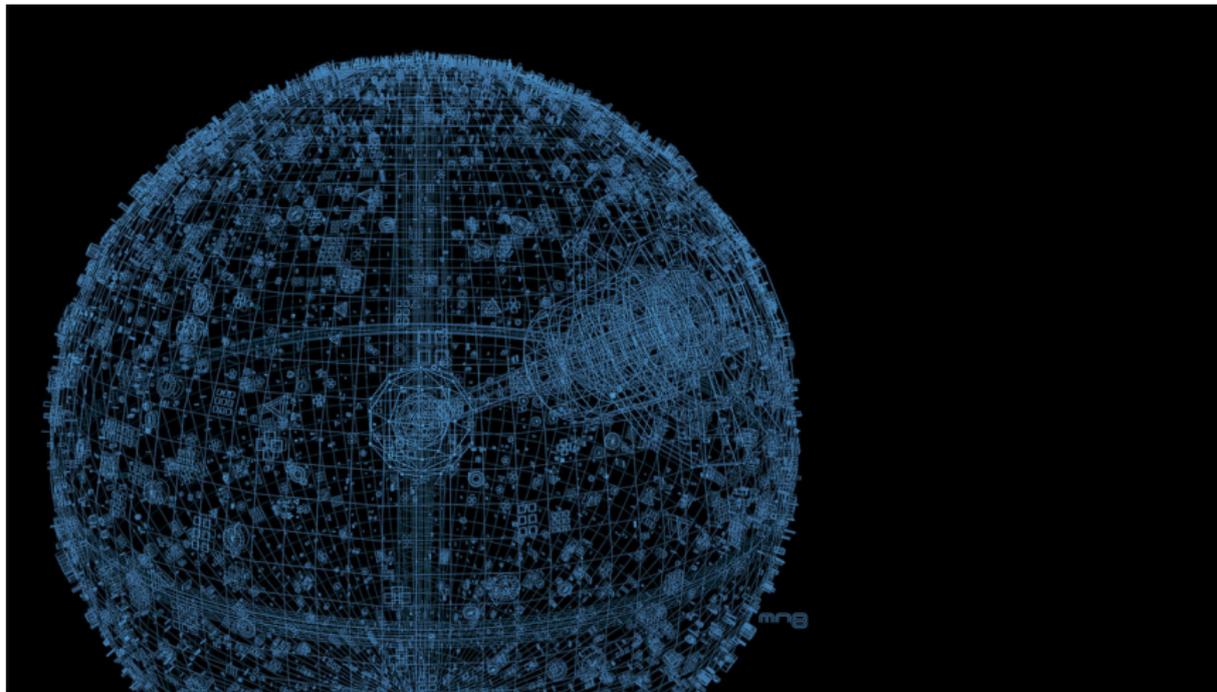
Status of refactoring:

CLIC 2014... we are almost there ...(it's β than nothing) ...

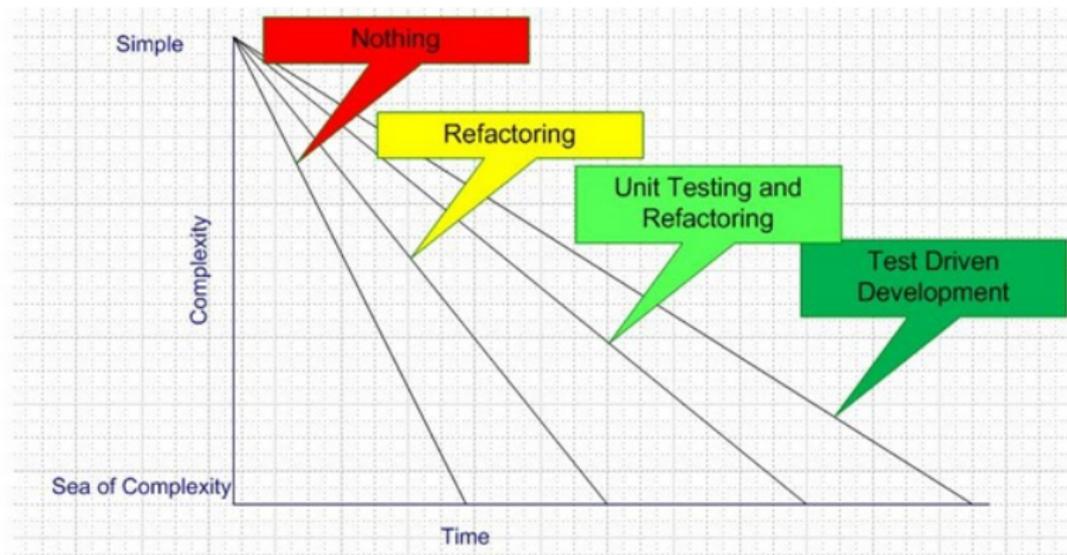


Status of refactoring:

... in a not too far future ... (a.k.a. March)

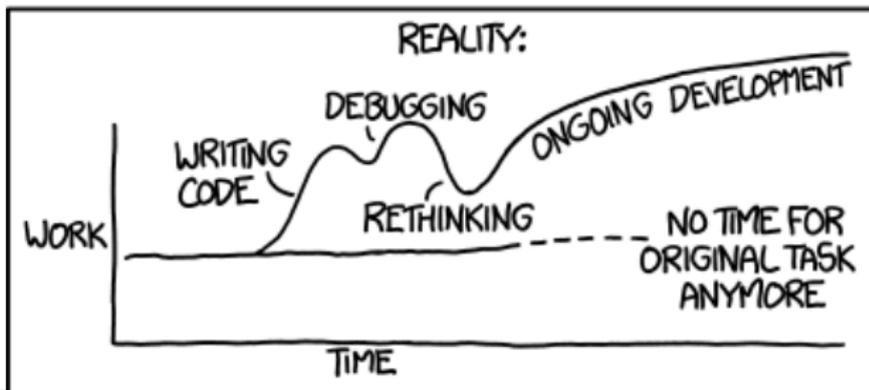
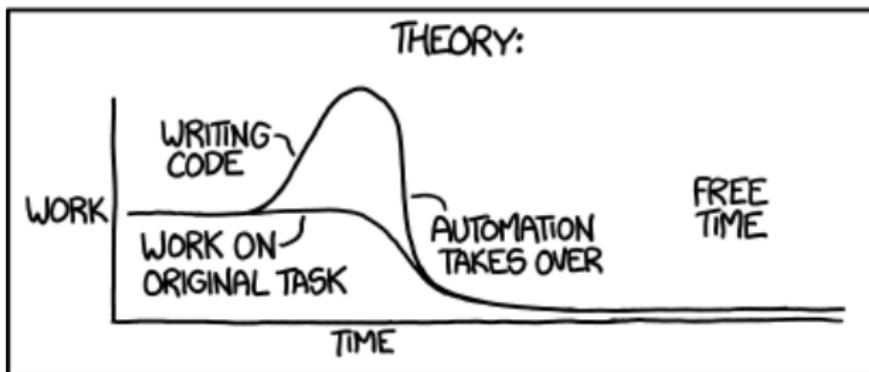


Theory predictions



Reality ... (?) ...

"I SPEND A LOT OF TIME ON THIS TASK.
I SHOULD WRITE A PROGRAM AUTOMATING IT!"



BACKUP SLIDES:

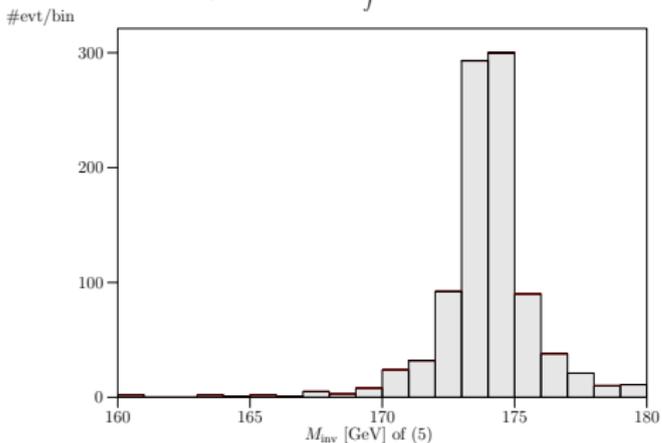
WHIZARD histograms

WHIZARD data analysis

March 16, 2007

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

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



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

New completely general syntax in WHIZARD 2.x

```
$title = "Jet Energy in $pp\to \ell\ell\bar{\nu}j$"
$x_label = "$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]]]);
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```