Modern Particle Physics Event Generation with WHIZARD

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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, HL/E-LHC, VLHC, FCC, 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. **CIRCE1/2**: Lepton/[photon] collider beam spectra
5. Intrinsic support or external interfaces for: Feynman rules, beam properties, cascade decays, shower, hadronization, analysis, event file formats, etc., etc.
6. 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, ...

2.2 Major refactoring of internals (same user interface), event sample reweighting, inclusive processes and selective decay chains (production version)

Plan Improve $e^+e^-$ support; NLO + matching; improve user interface ⇒ adapt to specific needs of user groups
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)
  - $e^+ e^- \rightarrow ZHH \rightarrow ZWWWW \rightarrow bb + 8j$ (12,000,000 diagrams)
  - $pp \rightarrow \ell\ell + nj, n = 0, 1, 2, 3, 4, \ldots$ (2,100,000 diagrams with 4 jets + flavors)
  - $pp \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 bbb$ (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 2.2.2 release: July 6, 2014**

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

**Web address:** [http://projects.hepforge.org/whizard](http://projects.hepforge.org/whizard)

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WHIZARD 2: Status 2010-14 – Technical Features

- Modern Fortran2003/2008 (gfortran 4.7.1 or newer) and O’Caml (for MEs)

- 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
  - Much better self checks, regression testing and maintainability

- 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-2.2.2.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, FastJet) 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 Manual

with distribution and online: http://whizard.hepforge.org/manual

WHIZARD 2.2
A generic Monte-Carlo integration and event generation package for multi-particle processes
MANUAL

Wolfgang Kittel, Thorsten Olt, Jürgen Reuter, with contributions from Fabian Bach, Sebastian Schmidt, Christian Speckner, Florian Staub
O’Mega: Optimal matrix elements

Ohl/JRR, 2001

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

\[ ab(ab + c) = \begin{array}{c} a \times b \times c \end{array} \]

Example:
\[ e^+ + e^- \rightarrow \mu^+ + \mu^- + \gamma \gamma \]
O’Mega: Optimal matrix elements

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\[ ab(ab + c) = \]

\[
\begin{align*}
  a & \times \\
  b & \times \\
  a & \times \\
  b & \times \\
  c & + \\
  a & \times \\
  b & + \\
  a & b
\end{align*}
\]

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![Diagram of DAG]

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- Unification of model setup: only one binary (2.3)
- Specification of order of strong or EW coupling (2.2.x/2.3)
- Teaser: new algorithm for generating loop diagrams (3.0 ?)
Beams and hard matrix elements

- **Hadron Colliders structured beams**
  - LHAPDF interface (also v6), most prominent PDFs directly included
  - QCD ISR and FSR (2 diff. own implementations, interface to PYTHIA)
  - Matching matrix elements/showers
  - Underlying event/multiple interactions (proof of principle)

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

- **Lepton Colliders structured beams**
  - QED ISR (Skrzypek/Jadach, Kuraev/Fadin, incl. $p_T$ distributions)
  - Arbitrarily polarized beams (density matrices)
  - Beam structure (CIRCE1/2 module) more later
  - [Photon collider spectra (CIRCE2 module)]

**Hard matrix elements:**

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

- **Lorentz structures:** hugh set of hard-coded structures
- Fully general Lorentz structures foreseen for 2.3.0
- **Color structures:** $3, 3, 8, [6]$
- **Color flow formalism**
- **General color structures** $6, 10$, $\epsilon_{ijk} \phi^i \phi^j \phi^k$

Stelzer/Willenbrock, 2003; Kilian/Ohl/JRR/Speckner, 2011
WHIZARD – Overview over BSM Models

| MODEL TYPE | with CKM matrix | trivial CKM |
|------------|----------------|-------------|
| QED with $e, \mu, \tau, \gamma$ | - | QED |
| QCD with $d, u, s, c, b, t, g$ | - | QCD |
| Standard Model | | |
| SM with anomalous gauge coupl. | SM_CKM | SM |
| SM with anomalous top coupl. | SM_ac_CKM | SM_ac |
| SM with anom. Higgs coupl. | SMtop_CKM | SMtop |
| SM ext. for VV scattering | - | SM_rx / NoH |
| SM with $Z'$ | - | SSC / AltH |
| 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/univ.) | - | Simplest_[univ] |
| 3-site model | - | Threeshl |
| UED | - | UED |
| SM with gravitino and photino | - | GravTest |
| Augmentable SM template | - | Template |

new models easily: FeynRules interface Christensen/Duhr/Fuks/JRR/Specsnek, 1010.3251
Interface to SARAH in the SUSY Toolbox Staub, 0909.2863; Ohl/Porod/Specsnek/Staubs, 1109.5147
SINDARIN Input files: Basic features

model = SM

process helloworld = E1, e1 => t, tbar, H

compile

sqrts = 500
beams = E1, e1 => circe1 => isr

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

n_events = 10000

simulate (helloworld)
SINDARIN Input files: Basic features

model = SM
alias lepton = e1:E1

process helloworld = E1, e1 => t, tbar, H
process t_dec = t => E1, n1, b
process tb_dec = tbar => e1, N1, bbar

compile

sqrts = 500
beams = E1, e1 => circe1 => isr

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]]

integrate (helloworld) { iterations = 5:10000, 2:10000 } 
unstable t (t_dec)
unstable tbar (tbar_dec)

n_events = 10000

simulate (helloworld)
Example: LHC SUSY cascade decays

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

▶ Full process:
Example: LHC SUSY cascade decays

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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

Kilian/JRR/Schmidt/Wiesler, JHEP 1204 013 (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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Difficulties of $e^+e^-$ beam simulation

- $E = 3000$ GeV (luminosity spectrum peak)
- $E = 1500$ GeV ($Z$ peak and lumi spectrum)
- $E = M_Z$ ($Z$ resonance)
- $E \approx 30$ GeV (due to $e^+e^- \rightarrow \gamma^* \rightarrow b\bar{b}$)

Simulation with WHIZARD (2.2.2)
Beam spectra now properly described in WHIZARD
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Correlated lepton beam spectra with Circe2

- Guinea-Pig++ event files too short for high lumi simulations
- Fixed width histogramming struggles with steep distributions
- Circe1 too restrictive, assumes
  - *factorized* beam spectra: $D_{p_1 p_2}(x_1, x_2) = D_{p_1}(x_1) D_{p_2}(x_2)$
  - power laws in continuum: $D(x) = d \cdot \delta(1 - x) + c \cdot x^\alpha (1 - x)^\beta$
- Circe2 algorithm:
  - Adapt 2D factorized variable width histogram (à la VEGAS) to steep part of distribution
  - smooth the correlated fluctuations with a moderate gaussian filter to suppress artifacts from limited Guinea-Pig++ statistics
  - smooth separately continuum/boundary bins (avoid artificial beam energy spread)

Smoothing $x_{e^+} = 1$ boundary bin with Gaussian filters of width 3 and 10 bins, resp. 5 bins reasonable compromise for histograms with 100 bins.
[bins are *not equidistant*, shrink with power law towards the $x_{e^-} = 1$ boundary on RHS!]
Workflow Guinea-Pig++/Circe2/WHIZARD

1. Run Guinea-Pig++ with

   do_lumi=7; num_lumi=100000000; num_lumi_eg=100000000; num_lumi_gg=100000000;

   to produce lumi.[eg][eg].out with \((E_1, E_2)\) pairs.

   [Large event numbers, as Guinea-Pig++ will produce only a small fraction!]

2. Run circe2_tool.opt with steering file

   { file="ilc500/beams.circe"  # to be loaded by WHIZARD
     { design="ILC" roots=500 bins=100 scale=250  # E in [0,1]
       { pid/1=electron pid/2=positron pol=0  # unpolarized e-/e+
         events="ilc500/lumi.ee.out" columns=2  # <= Guinea-Pig
         lumi = 1564.763360  # <= Guinea-Pig
         iterations = 10  # adapting bins
         smooth = 5 [0,1) [0,1)  # Gaussian filter 5 bins
         smooth = 5 [1] [0,1) smooth = 5 [0,1) [1] } } }

   to produce correlated beam description

3. Run WHIZARD with SINDARIN input:

   beams = e1, E1 => circe2
   $circe2_file = "ilc500.circe"
   $circe2_design = "ILC"
   ?circe_polarized = false
New features / Plans

- LCIO support (in prep.) courtesy of F. Gaede
- ILC TDR beam spectra within CIRCE1 ✓ courtesy of A. Hartin / J. List / G. Wilson
- also more than the official ILC TDR spectra (200 GeV and below)
- CLIC (correlated) spectra: a lot more difficult ✓
- Direct Guinea-Pig interface ✓ courtesy of D. Schulte/T. Barklow
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- **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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- Matched $e^+e^- \rightarrow$ jets at LO and NLO, POWHEG box formalism Chokoufé/JRR/Weiss, ca. 2015
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  ▶ Threshold resummation for $e^+e^- \rightarrow t\bar{t}$, $W^+W^-$ etc. Bach/Hoang/JRR/Stahlhofen/Teubner;
Top quark threshold in $e^+e^-$

- $e^+e^-$ top threshold scan offers best option for $m_t$
- now: analytic LL $ttV$ form factor implemented
- default parameters: $M^{1S} = 172$ GeV, $\Gamma_t = 1.5$ GeV, $\alpha_s(M^{1S}) = 0.1077$
- analytic LL unstable far off-shell: top mass cut $\Delta M_t \leq 30$ GeV
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![Graph showing $\sigma$ vs $\sqrt{s}$ with $\Delta M = 15$ GeV and $v = 0.1, 0.2, 0.4$](image)
Top quark threshold in $e^+e^-$

- Proper NLO/NLL matched implementation
- Own model: $\text{SM}_{tt\_\text{threshold}}$
- Parameters: $w_{\text{top}}, m_{1S}, v_{\text{soft}}, \text{match}$
Top quark threshold in $e^+e^-$

- Proper NLO/NLL matched implementation
- Own model: `SM_tt_threshold`
- Parameters: `wtop, mlS, vsoft, match`

![Graph showing top quark threshold and matching scale with notes on matched NLL/NLO, "true" NLO continuum, and "proper" NLL/NLO matching at intermediate energy.]
News 2014/early 2015: upcoming releases 2.3-2.4

- LHAPDF 6 support, FastJet interface ✓
- Revised models for BSM interactions of electroweak vector bosons (w/ light Higgs) ✓
- Process containers: inclusive production samples (e.g. SUSY) ✓
  
  \[
  \text{process inclusive = e}_1, \ E_1 \Rightarrow (Z, h) + (Z, H) + (A, H) \\
  \text{process vvv = e}_1, \ E_1 \Rightarrow (W^+, W^-, Z) + (W^+, W^-, Z) + (W^+, W^-, Z)
  \]
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- New syntax/features *decays* and chains (steering unstable particles):
  
  ```plaintext
  process higgsstr = e1, E1 => (Z => e2, E2), (H => b, bbar)
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- O’Mega Virtual Machine for faster and (much) smaller code (test phase)
- LL/LO → NLL/NLO matched $e^+e^-$ top threshold (test phase)
News 2014/early 2015: upcoming releases 2.3-2.4

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  ```

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- O’Mega Virtual Machine for faster and (much) smaller code  *(test phase)*

- LL/LO → NLL/NLO matched $e^+e^-$ top threshold  *(test phase)*

- Automatic QCD NLO corrections (massless)  *(test phase)*
Status of NLO development in WHIZARD

▶ BLHA interface: workflow

1. Process definition in SINDARIN ⇒ 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)

▶ Schedule / Plan

- Automatic generation of subtraction terms
- proof-of-concept code in WHIZARD 2.2
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- **Schedule / Plan**
  - Automatic generation of subtraction terms
  - proof-of-concept code in WHIZARD 2.2
  - first FKS then CS dipole subtraction will be available
  - Provide PowHeg box formalism for NLO processes
  - Special focus on $e^+e^-$ physics: top, Higgs, EW processes, BSM
Status of NLO development in WHIZARD

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- Provide PowHeg box formalism for NLO processes
- Special focus on $e^+e^-$ physics: top, Higgs, EW processes, BSM
- First tutorial example: $e^+e^- \rightarrow q\bar{q}$ and $e^+e^- \rightarrow Zq\bar{q}$
  @ FCC workshop/school, Beijing 08/2014
Status of NLO development in WHIZARD

▶ **BLHA interface**: workflow

1. Process definition in SINDARIN ⇒ 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*)

▶ **Schedule / Plan**

- **Automatic generation of subtraction terms**
  - Speckner, 2012; Kilian/JRR/Weiss, 2014
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- **Release**: WHIZARD 3.0
Questions to the User Community?

- **LCIO:** what are the needs for the format? spin info? color correlations?? Reweighting options?
- Interface to **beam setup**: details?
- **External code** for structure functions, analysis, cuts? What form?
- Other indispensable features for mass production missing?
- **Wish list** !?
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▶ Email requests via whizard@desy.de
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- Email requests via whizard@desy.de
- **WHIZARD** developer and user workshop: Würzburg 16.-18.3.2015
WHIZARD workshop 16.-18.3.2015

Würzburg baroque castle: “fake” Versailles from “Les trois mousquetaires” (2011)
Summary and Outlook

- WHIZARD 2 for LC/LHC/FCC physics
- Versatile, user-friendly tool for SM & BSM physics
- Highest-possible support for lepton beam structures
- Covers the whole SM, and most possible paths beyond
- Shooting out after a long technical overhaul
- Expect continuous improvement

• WHIZARD 2.2.2 available now
• WHIZARD 2.2.x-2.x.x on a regular basis !!!

Let us know of your needs!
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... enjoying being in Prague ...
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BACKUP SLIDES:
WHIZARD histograms

WHIZARD example plot

A WHIZARD 2.2 example. $e^+e^- \rightarrow t\bar{t}$ at a 500 GeV ILC

Data within bounds:
\[ \langle \text{Observable} \rangle = 172.95 \pm 0.063 \quad [n_{\text{entries}} = 939] \]

All data:
\[ \langle \text{Observable} \rangle = 174.7 \pm 0.42 \quad [n_{\text{entries}} = 1000] \]

New completely general syntax in WHIZARD 2.x

\$\text{title} = "\text{Jet Energy in } \sqrt{s} = 800 \text{ GeV} \}\$
\$\text{x\_label} = "E_{\text{T}}/\text{GeV}\$

\text{histogram e\_jet (0 GeV, 80 GeV, 2 GeV)}

\text{analysis = record pt\_lepton (eval Pt [extract index 1 [sort by Pt [lepton]]]);}
\text{ record pt\_jet (eval Pt [extract index 1 [sort by Pt [jet]]]);}
\text{ record e\_lepton (eval E [extract index 1 [sort by Pt [lepton]]]);}
\text{ record e\_jet (eval E [extract index 1 [sort by Pt [jet]]])}