The Monte-Carlo Event Generator WHIZARD

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Tsinghua University, September 2014
Monte Carlo programs for High-Energy Colliders

**LHC**, **ILC**, future projects:

The interesting processes contain 4, 6, or more final-state particles in the elementary hard scattering: electroweak, Higgs, new physics
Monte Carlo programs for High-Energy Colliders

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   Also requires proper handling of QCD (shower, hadronization)
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This is all covered by universal event generators: WHIZARD
WHIZARD in a Nutshell

WHIZARD for Colliders

- $pp$: Tevatron $\Rightarrow$ LHC, FCC, ... 
- $e^+e^-$: LEP and TESLA/NLC $\Rightarrow$ ILC, CEPC, CLIC, ...  
- $ep, \gamma\gamma, \ldots$

Key Parts of WHIZARD:

1. **O'Mega**: Automatic tree 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: 
   - Models and Feynman rules, beam properties, cascade decays, shower, hadronization, analysis, event file formats, etc., etc.  
5. Free-format steering language **SINDARIN**
2. Some History
Vector-Boson Scattering at high energies,

\[ e^-e^+ \rightarrow \nu\bar{\nu}W^+W^- \rightarrow \nu\bar{\nu} + 4f \]
Original Motivation for developing the WHIZARD program: Vector-Boson Scattering at high energies,

\[ e^+e^- \rightarrow \bar{\nu}\nu W^+W^- \rightarrow \nu\bar{\nu} + 4f \]
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Discovery of Vector-Boson Scattering
ATLAS collaboration, arXiv:1405.6241
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Milestones

1.0 1999: Generic MC generator for electroweak multi-particle processes at TESLA (W, Higgs, Z) [WK, LC-TOOL-2001-039]

1.97 Final v1: LHC physics, full Standard Model, detailed beam properties, new-physics models including MSSM, various event formats
  ⇒ Linear Collider event samples at SLAC
  ⇒ Base for most TESLA and ILC studies


2.2 Current production version:
  ▶ FeynRules support
  ▶ Internal density-matrix formalism ⇒ cascade decays
  ▶ QCD shower + matching
  ▶ OpenMP parallelization
  ▶ SINDARIN language for input and workflow
3. Amplitudes
Amplitudes

The amplitude generator for WHIZARD is called OMe
ga

[M. Moretti, T. Ohl, J. Reuter, hep-ph/0102195]

(integrated into WHIZARD since version 2).

Some Benchmarks:

- $e^+e^- \rightarrow t\bar{t}H \rightarrow b\bar{b}b\bar{b}jj\ell\nu$ (110,000 diagrams)
- $e^+e^- \rightarrow ZHH \rightarrow ZWWWW \rightarrow bb + 8j$ (12,000,000 diagrams)
- $pp \rightarrow \ell\ell + nj, n = 0, 1, 2, 3, 4, \ldots$ (2,100,000 diagrams with 4 jets + flavors)
- $pp \rightarrow \tilde{\chi}^0_1\tilde{\chi}^0_1 bbbb$ (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)

⇒ Complete tree-level amplitudes without approximations
[.] Replace forest of tree diagrams by Directed Acyclical Graph (DAG) of the algebraic expression (including color).
O’Mega: Optimal matrix elements

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O’Meta: Optimal matrix elements

- Replace forest of tree diagrams by
  Directed Acyclical Graph (DAG) of the algebraic expression (including color).
- 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 $R_\xi$ 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: restrictions

OMega does not use an expansion in terms of Feynman graphs. All possible Feynman graphs are implicitly included, but a selection of Feynman graphs is not possible.

```
process nnh = "e+", "e-" => nue, nuebar, H
```

Instead, one may restrict the intermediate states, if meaningful:

```
process nnh = "e+", "e-" => nue, nuebar, H { $restrictions = "3+4 ~ Z" }```

## WHIZARD – Overview over BSM Models

<table>
<thead>
<tr>
<th>MODEL TYPE</th>
<th>with CKM matrix</th>
<th>trivial CKM</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>QED with e, μ, τ, γ</strong></td>
<td>—</td>
<td>QED</td>
</tr>
<tr>
<td><strong>QCD with d, u, s, c, b, t, g</strong></td>
<td>—</td>
<td>QCD</td>
</tr>
<tr>
<td><strong>Standard Model</strong></td>
<td>SM_CKM</td>
<td>SM</td>
</tr>
<tr>
<td><strong>SM with anomalous gauge couplings</strong></td>
<td>SM_ac_CKM</td>
<td>SM_ac</td>
</tr>
<tr>
<td><strong>SM with anomalous top couplings</strong></td>
<td>SMtop_CKM</td>
<td>SMtop</td>
</tr>
<tr>
<td><strong>SM with WW resonances and unitarization</strong></td>
<td>—</td>
<td>SSC</td>
</tr>
<tr>
<td><strong>MSSM</strong></td>
<td>MSSM_CKM</td>
<td>MSSM</td>
</tr>
<tr>
<td><strong>MSSM with gravitinos</strong></td>
<td>—</td>
<td>MSSM_Grav</td>
</tr>
<tr>
<td><strong>NMSSM</strong></td>
<td>NMSSM_CKM</td>
<td>NMSSM</td>
</tr>
<tr>
<td><strong>extended SUSY models</strong></td>
<td>—</td>
<td>PS/E/SSM</td>
</tr>
<tr>
<td><strong>Littlest Higgs</strong></td>
<td>—</td>
<td>Littlest</td>
</tr>
<tr>
<td><strong>Littlest Higgs with ungauged U(1)</strong></td>
<td>—</td>
<td>Littlest_Eta</td>
</tr>
<tr>
<td><strong>Littlest Higgs with T' parity</strong></td>
<td>—</td>
<td>Littlest_Tpar</td>
</tr>
<tr>
<td><strong>Simplest Little Higgs (anomaly-free)</strong></td>
<td>—</td>
<td>Simplest</td>
</tr>
<tr>
<td><strong>Simplest Little Higgs (universal)</strong></td>
<td>—</td>
<td>Simplest_univ</td>
</tr>
<tr>
<td><strong>3-site model</strong></td>
<td>—</td>
<td>Threeshl</td>
</tr>
<tr>
<td><strong>UED</strong></td>
<td>—</td>
<td>UED</td>
</tr>
<tr>
<td><strong>SM with Z'</strong></td>
<td>—</td>
<td>Zprime</td>
</tr>
<tr>
<td><strong>SM with gravitino and photino</strong></td>
<td>—</td>
<td>GravTest</td>
</tr>
<tr>
<td><strong>Augmentable SM template</strong></td>
<td>—</td>
<td>Template</td>
</tr>
</tbody>
</table>

Automatic tools for adding a new model: **FeynRules** and **SARAH**.
4. Phase Space
Phase-space integration is the most difficult part of the algorithm, because:

- the integrand (amplitude squared) varies over orders of magnitude
- we integrate over \( \geq 10 \) dimensions
- the peak structure is not aligned to any dimension, because many pole structures interfere
- suitable mappings can only be found if the peak structures align
- the algorithm must yield a good accuracy (for the total cross section)

\[
\text{statistical error} = \frac{\Delta \sigma}{\sigma} = \frac{\text{accuracy}}{\sqrt{N}}
\]

and good rejection efficiency (for simulating unweighted events)

\[
\text{efficiency} = \frac{\text{average integrand}}{\text{maximum integrand}}
\]
Phase Space in WHIZARD

WHIZARD’s phase-space handling consists of three parts

1. Choice of parameterization of phase space (Wood):
   - Find the pole structures (channels) that dominate the matrix element

2. VEGAS discretization and adaptive grid improvement (VAMP)
   [T. Ohl, Comput. Phys. Commun. 120, 13 (1999)]
   - Each channel is assigned its own VEGAS grid

3. Combine all channels using the standard multi-channel formula, and iteratively adapt the weights of the channels.
Multichannel MC integration

Choose functions $g_i(q)$ and weights $w_i$:

$$
\int dq |A(q)|^2 = \int dq \frac{\sum_i w_i g_i(q)}{\sum_j w_j g_j(q)} |A(q)|^2
= \sum_i w_i \int dq \frac{g_i(q)}{g(q)} |A(q)|^2
$$

In WHIZARD, the $g_i$ are the Jacobians of the individual mappings,

$$
g_i(y^{(i)}) = \frac{1}{\left| \frac{dq}{dx^{(i)}} \right|} \times \prod_k \frac{1}{\left| \frac{dx_k^{(i)}}{dy_k^{(i)}} \right|}
$$

First factor: analytically known and numerically evaluated.
Second factor: given by bin widths of VAMP grids
The weights $w_i$ are iteratively adapted, simultaneously with the bin widths.
By choosing the combination of both methods, we get

⇒ dominant contributions with their singularities are regularized
⇒ the residual variation is tamed by VAMP grid adaptation. This can also lessen the impact of subdominant peaks.
⇒ Adapting both grids and weights simultaneously, we can achieve both an accurate Monte-Carlo integration

\[
\frac{\Delta \sigma}{\sigma} \approx \frac{0.1 \ldots 10}{\sqrt{N}}
\]

and a reasonable reweighting efficiency

\[\epsilon = \approx 0.1 \ldots 10 \%\]
5. Beams
Usage

Input in SINDARIN command language

**Hadron collider example**

```
sqrts = 14 TeV
$pdf\_builtin\_name = "CTEQ6L"
...
beams = p, p => pdf\_builtin
```

**Lepton collider example**

```
sqrts = 500 GeV
...
beams = "e+", "e-" => circe2 => isr
```
PDF (hadron colliders)

For PDF evaluation:

Standard package LHAPDF

must be linked to WHIZARD at compile time. Then, all LHAPDF structure functions that the user has downloaded, are available.

Alternative, for the impatient:

Built-in interface and data for a few commonly used structure functions (CTEQ6 etc.)

can be used anytime, no download necessary.
Beamstrahlung in WHIZARD

Classical interaction of the Coulomb fields of the two colliding beams, results in a statistical distribution of energy loss for the colliding particles.

   - Output of GuineaPig runs parameterized by smooth functions
   - Usable either as structure functions or as generator
   - In WHIZARD: analogous to PDF

   **Caveat:** Only fixed number of hard-coded parameter sets (ILC)

2. Circe2:
   - Output of GuineaPig/CAIN runs parameterized by histograms
   - Usable as generator
   - In WHIZARD: exchangable with Circe1

   **Caveat:** Requires histogram-data file for given parameter set

3. Beam-events file:
   - Output of GuineaPig/CAIN runs used directly
   - Usable as pseudo-generator
   - In WHIZARD: also analogous

   **Caveat:** Beam-event file has finite number of events
Initial-State Radiation

Photon radiation from incoming charged particles enhanced by powers of $\log \frac{s}{m^2}$

$$f(x) \approx \epsilon (1 - x)^{-1+\epsilon} \quad \text{with} \quad \epsilon = \frac{\alpha}{\pi} Q^2 \log \frac{s}{m^2}$$

⇒ important for electrons/positrons, less so for protons

WHIZARD implementation: result of all-order soft resummation and third-order explicit (parameterized) calculation

Simulation for $e^+e^-$ Colliders

- beamstrahlung + ISR
- Parameter sets in collaboration with ILC and CLIC groups
- Example $e^+e^- \rightarrow b\bar{b}$:
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Luminosity spectrum picks up the $Z$ resonance!
6. QCD
QCD Effects

Color in final state: several options

1. Partonic event files with color correlation, to be handled by external shower/hadronization (PYTHIA 6, PYTHIA 8, HERWIG)

2. Internally linked PYTHIA 6 via Les Houches Interface (for color correlation) \(\Rightarrow\) automatic generation of showered/hadronized event files

3. WHIZARD’s own internal shower (analytic shower) and internal PYTHIA hadronization

4. Internal shower with external hadronization

Extra radiation: avoid double-counting

- Matrix element for extra radiation + MLM matching scheme
Analytic Parton Shower

[WK, J. Reuter, S. Schmidt, D. Wiesler, JHEP 1204, 013 (2012)]

▶ Analytic Parton Shower:
  - no shower veto: shower history is exactly known
  - allows reweighting and maybe more reliable error estimate

▶ validated against PYTHIA shower (tuning: assistance welcome!)

▶ matching with hard matrix elements
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QCD NLO

A NLO module for WHIZARD is currently in development; first snapshot: tutorial at iSTEP/PKU

- Real radiation: automatically generated with OMEga matrix elements
- Virtual (loop) amplitude: external program (GoSam)
- IR/collinear subtraction: FKS scheme
- NLO-radiation combination: POWHEG algorithm

All algorithms are intended to be exchangeable, so multiple methods should eventually be implemented.
7. Features and Applications
More physics aspects/features of WHIZARD 2

- **SINDARIN**
  - *(Scripting INtegration, Data Analysis, Results display and INterfaces)*
    - steering: process definition, parameters, models, beam structure, scans/loops, conditionals, I/O, file formats, . . .
    - expressions: for cuts, scales, weights
    - analysis: observables, plots, histograms

- Decay cascades including full spin correlations
- Event-dependent scales in PDFs and running $\alpha_s$
- Event-file reanalysis (matrix-element reweighting)
- Anomalous couplings, resonances and *unitarity* in vector-boson scattering
WHIZARD histograms

WHIZARD data analysis

March 16, 2007

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

$\sqrt{s} = 500.0 \text{ GeV}$

$\int L = 0.2754 \times \text{10}^{-01} \text{ fb}^{-1}$

#evt/bin

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

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

Syntax in WHIZARD 2.x

$ttitle = "\text{Jet Energy in } pp\to \ell\ell\bar{\nu}j"$

$x_\text{label} = "$E$/\text{GeV}"

$\text{histogram e_jet (0 \text{ GeV, 80 GeV, 2 GeV)}$

$\text{analysis} = \text{record pt_lepton (eval Pt [extract index 1 [sort by Pt [lepton]]])}$

$\text{record pt_jet (eval Pt [extract index 1 [sort by Pt [jet]]])}$

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Example: LHC SUSY cascade decays

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

- Full process:

![Histogram](image)
Example: LHC SUSY cascade decays

\[ p + p \rightarrow \tilde{u} + \tilde{u}^* \rightarrow \bar{u}_1 + u + \tilde{e}^+_1 + e^- \]

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

![Graph showing the distribution of \( M_{\text{inv}(ue^-)} \) with bins ranging from 0 to 600 and event counts from 0 to 800.](image-url)
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

\[ p + p \rightarrow \tilde{u} + \tilde{u}^* \rightarrow \tilde{u}_1 + u + \tilde{e}_1^+ + e^- \]

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

![Graph showing the distribution of \( M_{\text{inv}}(ue^-) \)]
Extrapolation of Anomalous Vector-Boson Scattering

Process $pp \rightarrow W^+W^+jj$


naively calculated: violates unitarity limits
Extrapolation of Anomalous Vector-Boson Scattering

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Process \( pp \rightarrow W^+W^+jj \)

Resummation of Gluon Exchange at $t\bar{t}$ threshold

Process $e^+e^- \rightarrow b\bar{b}W^+W^-$ with WHIZARD

Shown: Leading-log and Next-to-leading-log resummed cross section

[not yet in public version]
8. Conclusions
WHIZARD Summary

Project Coordinators

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- Thorsten Ohl (University of Würzburg)
- Jürgen Reuter (DESY)

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http://whizard.hepforge.org
Future Directions

- **Significant improvements**: physics coverage, NLO, computing efficiency
- Close cooperation with ATLAS/CMS and ILC experimental groups

⇒ Direct involvement in WHIZARD as a tool for simulation, analysis, and establishing the Physics Case of future colliders

Second WHIZARD Forum
Castle of Würzburg, March 16–18, 2015
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  - Alternate algorithms and systematic comparison studies
  - Beam issues and precision calculations for CEPC
  - Phenomenology of multi-boson (electroweak) processes at high energies
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