SiD Meeting – Latest News from WHIZARD

Jürgen R. Reuter

DESY Hamburg

SiD Meeting, SLAC, Oct 15th, 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)
  - $e^+e^- \to t\bar{t}H \to b\bar{b}b\bar{b}jj\ell\nu$ (110,000 diagrams)
  - $e^+e^- \to ZHH \to ZWWWW \to bb + 8j$ (12,000,000 diagrams)
  - $pp \to \ell\ell + nj,\ n = 0, 1, 2, 3, 4, \ldots$ (2,100,000 diagrams with 4 jets + flavors)
  - $pp \to \tilde{\chi}_1^0\tilde{\chi}_1^0 bbbb$ (32,000 diagrams, 22 color flows, $\sim 10,000$ PS channels)
  - $pp \to VVjj \to jj\ell\ell\nu\nu$ incl. anomalous TGC/QGC
  - Test case $gg \to 9g$ (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, [H. Boschmann], [F. Braam], B. Chokoufé, W. Kilian, T. Ohl, JRR, [S. Schmidt], [S. Schwertfeger], M. Sekulla, [C. Speckner], F. Staub, [M. Trudewind], C. Weiss, [D. Wiesler]

Web address: `http://projects.hepforge.org/whizard`

Standard Reference: Kilian/Ohl/JRR, EPJC 71 (2011) 1742, arXive: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_α-3 release: Oct. 15th, 2013

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WHIZARD 2.2.0 release: Nov. 11, 2013 (LCWS)

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WHIZARD 2: Status 2011/12 – Technical Features

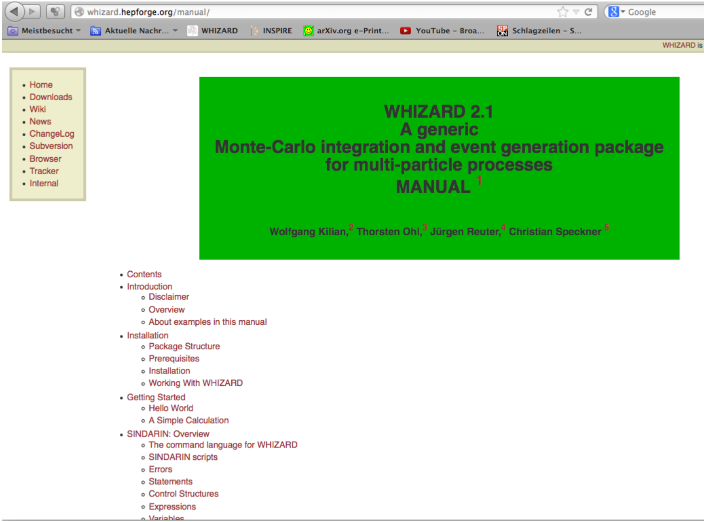
- WHIZARD 2: code basically rewritten, only `Fortran 2003` and `O'Caml`
- Clean modularization of code/(First) object-oriented implementation
- OpenMP parallelization
- Operation modes:
  - Dynamic linking (default mode) with on-the-fly generation of process code
  - Static linking (for batch clusters)
  - 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: 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



Physics aspects/improvements in WHIZARD 2

- SINDARIN (Scripting INtegration, Data Analysis, Results display and INterfaces) 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

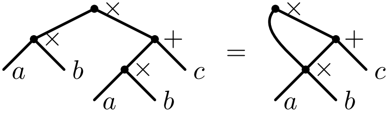
O'Mega: Optimal matrix elements

Ohl/JRR, 2001

Ω

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

$$ab(ab+c) =$$



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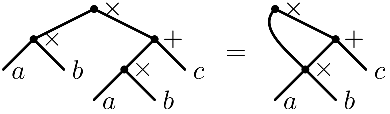
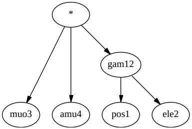
$ab(ab+c) =$ 

- simplest examples: $e^+e^- \to \mu^+\mu^-$, and



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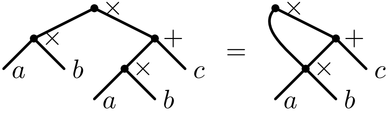
$ab(ab + c) =$ 

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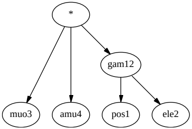

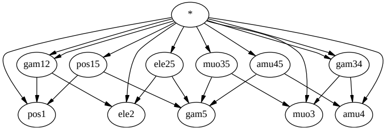

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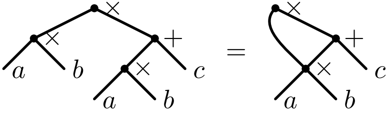
$ab(ab+c) =$ 

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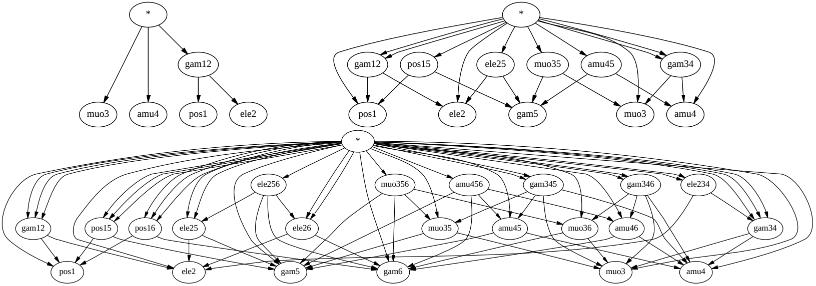


Hard matrix elements: particle types

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

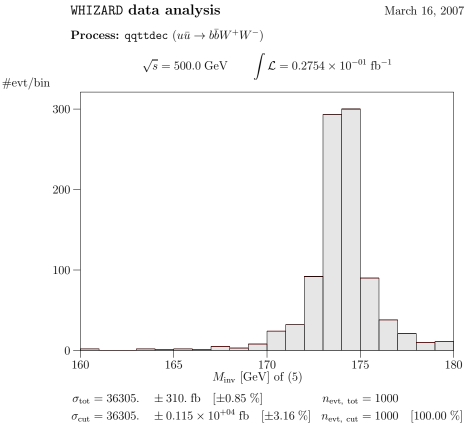
- **Hard-coded set of Lorentz structures**
  - Purely scalar couplings: $\phi^3, \quad \phi^4$
  - Scalar couplings to vectors: $g V^\mu \phi_1 \mathrm{i}\overleftrightarrow{\partial_\mu}\phi_2, \quad \phi V^2, \quad \phi^2 V^2, \quad \frac{1}{2}\phi F_{1,\mu\nu} F_2^{\mu\nu}, \quad \frac{1}{2}\phi F_{1,\mu\nu}\tilde{F}_2^{\mu\nu}, \quad \phi(\mathrm{i}\partial_\mu V_1^\nu)(\mathrm{i}\partial_\nu V_2^\mu)$
  - Pure vector couplings: $F_{\mu\nu}F^{\mu\nu}, \quad V_1^\mu((\mathrm{i}\partial_\nu V_2^\rho)\mathrm{i}\overleftrightarrow{\partial_\mu}(\mathrm{i}\partial_\rho V_3^\nu)), \quad g F_1^{\mu\nu} F_{2,\nu\rho} F_{3,}{}^{\rho}{}_{\mu},$
    $g/2 \cdot \epsilon^{\mu\nu\lambda\tau} F_{1,\mu\nu} F_{2,\tau\rho} F_{3,}{}^{\rho}{}_{\lambda}$
  - Fermionic couplings to scalars:
    $g_S \bar\psi_1 S \psi_2, \quad g_P \bar\psi_1 P\gamma_5\psi_2, \quad \bar\psi_1\phi(g_S + g_P\gamma_5)\psi_2, \quad g_L\bar\psi_1\phi(1-\gamma_5)\psi_2, \quad g_R\bar\psi_1\phi(1+\gamma_5)\psi_2,$
    $g_L\bar\psi_1\phi(1-\gamma_5)\psi_2 + g_R\bar\psi_1\phi(1+\gamma_5)\psi_2$
  - Fermionic couplings to vectors:
    $g_V\bar\psi_1 \not{V}\psi_2, \quad g_A\bar\psi_1\gamma_5\not{V}\psi_2, \quad \bar\psi_1\not{V}(g_V - g_A\gamma_5)\psi_2, \quad g_L\bar\psi_1\not{V}(1-\gamma_5)\psi_2, \quad g_R\bar\psi_1\not{V}(1+\gamma_5)\psi_2,$
    $g_L\bar\psi_1\not{V}(1-\gamma_5)\psi_2 + g_R\bar\psi_1\not{V}(1+\gamma_5)\psi_2$
  - Fermionic couplings to tensors: $g_T T_{\mu\nu}\bar\psi_1[\gamma^\mu,\gamma^\nu]_-\psi_2$
  - Tensor couplings to vectors:
    $T^{\mu\nu}(V_{1,\mu}V_{2,\nu} + V_{1,\nu}V_{2,\mu}), \quad T^{\alpha\beta}(V_1^\mu \mathrm{i}\overleftrightarrow{\partial}_\alpha \mathrm{i}\overleftrightarrow{\partial}_\beta V_{2,\mu},$
    $T^{\alpha\beta}(V_1^\mu \mathrm{i}\overleftrightarrow{\partial}_\beta(\mathrm{i}\partial_\mu V_{2,\alpha}) + V_1^\mu \mathrm{i}\overleftrightarrow{\partial}_\alpha(\mathrm{i}\partial_\mu V_{2,\beta})), \quad T^{\alpha\beta}((\mathrm{i}\partial^\mu V_1^\nu)\mathrm{i}\overleftrightarrow{\partial}_\alpha \mathrm{i}\overleftrightarrow{\partial}_\beta(\mathrm{i}\partial_\nu V_{2,\mu}))$
  - Gravitino couplings: $\bar\psi\gamma^\mu S\psi_\mu, \quad \bar\psi\gamma^\mu \not{k}_S S\psi_\mu, \quad \bar\psi\gamma^\mu\gamma^5 P\not{k}_P\psi_\mu, \quad \bar\psi\gamma^5\gamma^\mu[\not{k}_V, \not{V}]\psi_\mu$ 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: $\mathbf{3}, \overline{\mathbf{3}}$
- Adjoint representation: $\mathbf{8}$
- Covers all interactions e.g. in SUSY and extra dimensions
- in preparation: generalized color structures with reps. $\mathbf{6}, \overline{\mathbf{6}}, \mathbf{10}, \overline{\mathbf{10}}$ as well as $\epsilon_{ijk}\phi_i\phi_j\phi_k$ couplings to appear in version 2.2.x

WHIZARD histograms



New completely general syntax in WHIZARD 2.x

```
$title = "Jet Energy in $pp\to \ell\bar\nu j$"
$x_label = "$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]]]);
           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.	**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/Speckner, 1010.3251

Interface to SARAH in the SUSY Toolbox Staub, 0909.2863; Ohl/Porod/Speckner/Staub, 1109.5147

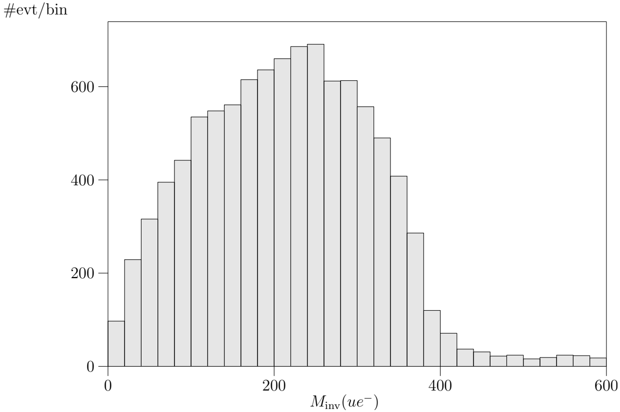
Input files: Basic features

```
model = SM

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

compile

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

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

n_events = 10000

simulate (halloween) {
}
```

Example: LHC SUSY cascade decays

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

- **Full process:**



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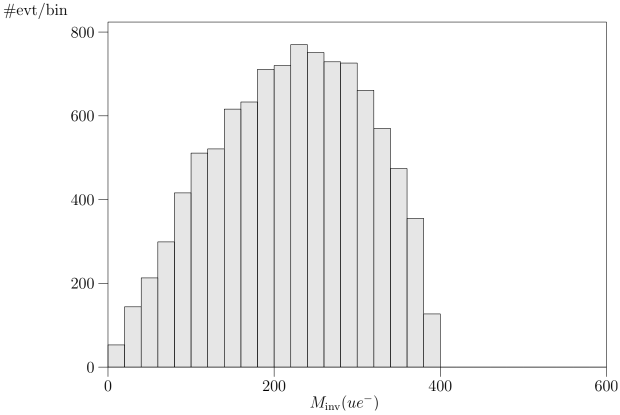
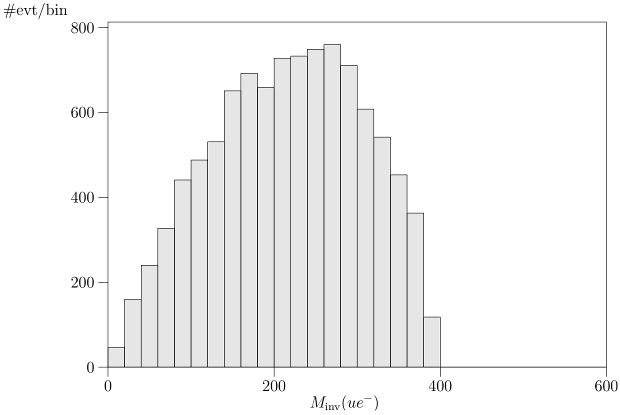
- **Factorized process w/ full spin correlations:**



Example: LHC SUSY cascade decays

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

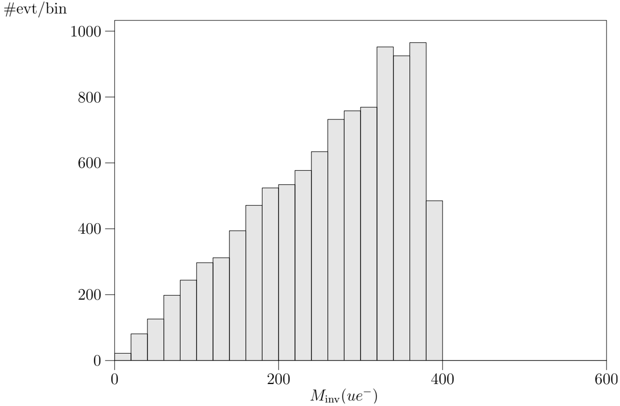
- **Factorized process w/ classical spin correlations:**



Example: LHC SUSY cascade decays

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

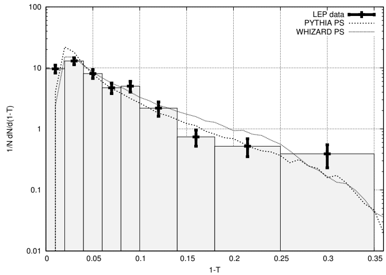
- **Factorized process w/ no spin correlations:**

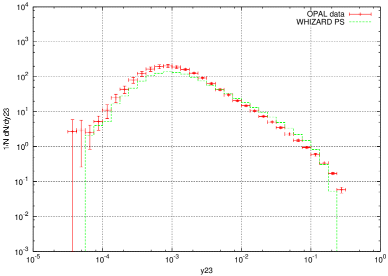


Analytic Parton Shower

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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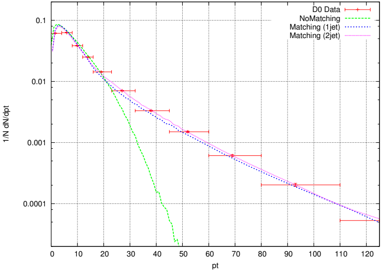

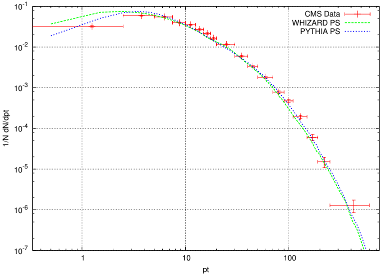

- matching with hard matrix elements, no ”power-shower”

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-3 available!

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  (pre-)release version 2.2.0_α-3 available!
- 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 $\Rightarrow$ 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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- 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
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▶ Threshold resummation for $e^+e^- \to W^+W^-$, $t\bar{t}$ etc. Bach/JRR/Prestel, ca. 2014

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Well, what shall I say ...

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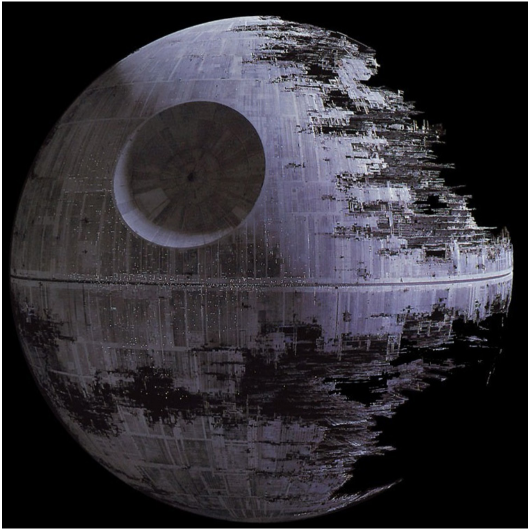
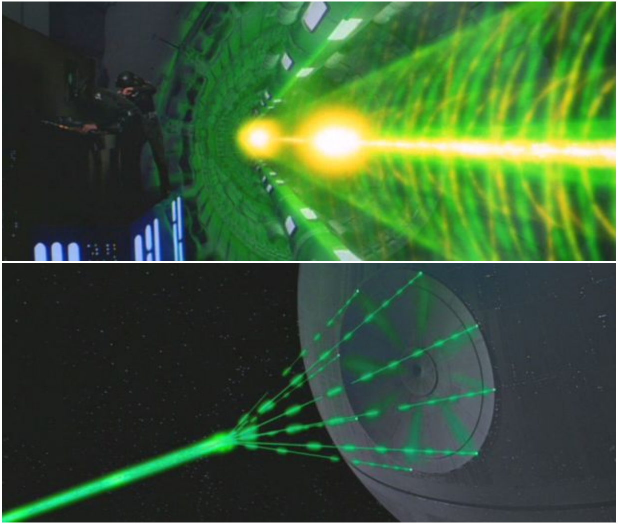
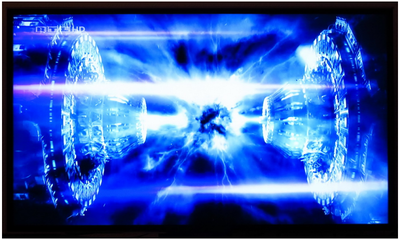


Status of refactoring:

ok, LC features have pretty high priority



[German TV: science for the public]



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Let us know of your needs!

whizard@desy.de

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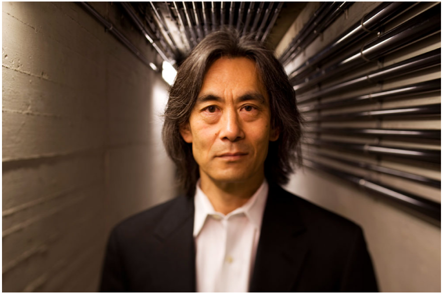

Kent Nagano, Director General, 2015-