The Monte Carlo Event Generator 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 ⇒ ILC, CLIC, FCC-ee/TLEP . . .
- pp: Tevatron ⇒ 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 $\Rightarrow$ 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)
  - $e^+e^- \to t\bar{t}H \to b\bar{b}b\bar{b}jj\ell\nu$ (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)
  - $pp \to \tilde{\chi}^0_1 \tilde{\chi}^0_1 bbbb$ (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 2.2.2 release: July 6, 2014

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

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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

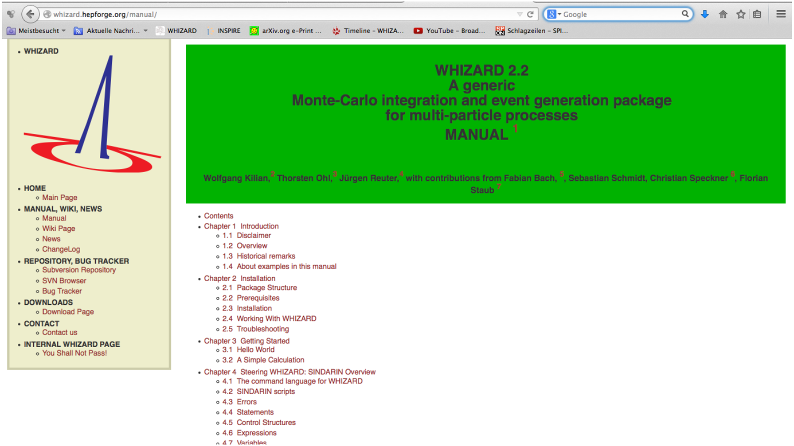
WHIZARD 2 – Installation and Run

- 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 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: phs_forests.run
PASS: rng_base.run
PASS: selectors.run
PASS: phs_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: eio_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: colors_hgg.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 2.2.2
============================================
# TOTAL: 241
# PASS:  236
# SKIP:  2
# XFAIL: 3
# FAIL:  0
# XPASS: 0
# ERROR: 0
============================================
```

WHIZARD Manual

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

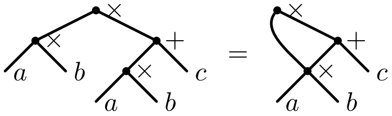


O'Mega: Optimal matrix elements

Ohl/JRR, 2001 Ω

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

$$ab(ab+c) =$$



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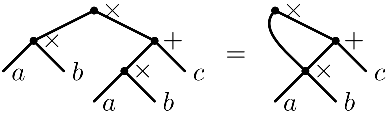
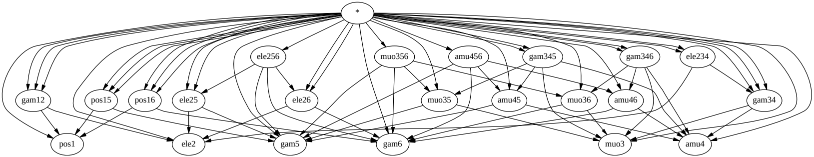


- Example: $e^+e^- \to \mu^+\mu^-\gamma\gamma$



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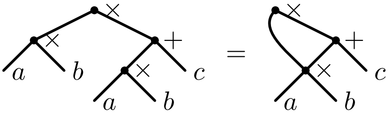

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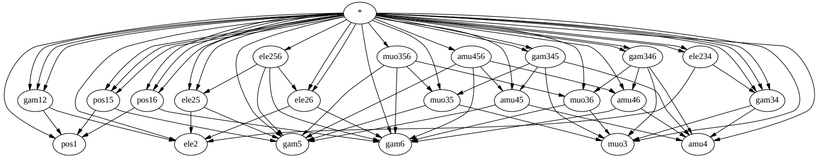

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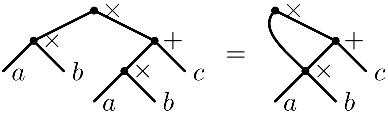

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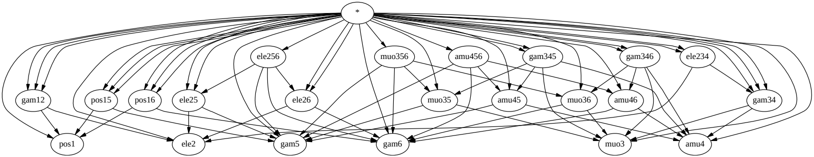

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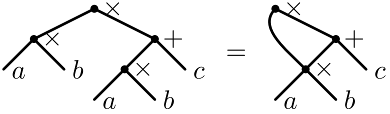

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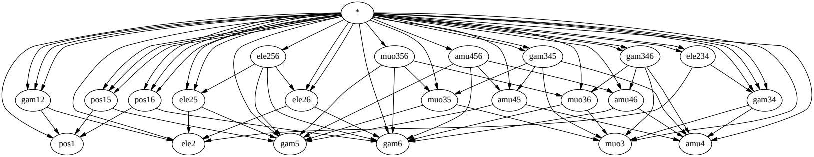


- Unification of model setup: only one binary (2.3)
- Specification of order of strong or EW coupling (2.2.x/2.3)
- Teaser: new algorithm for generating loop diagrams (3.0 ?)

Beams and hard matrix elements

- **Hadron Colliders structured beams**
  - LHAPDF interface, 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** (ext.)
- **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: $\mathbf{3}, \overline{\mathbf{3}}, \mathbf{8}, [\mathbf{6}]$
- Color flow formalism Stelzer/Willenbrock, 2003; Kilian/Ohl/JRR/Speckner, 2011
- 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 anom. Higgs coupl.	—	SM_rx / NoH
SM ext. for VV scattering	—	SSC / AltH
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/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/Speckner, 1010.3251

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

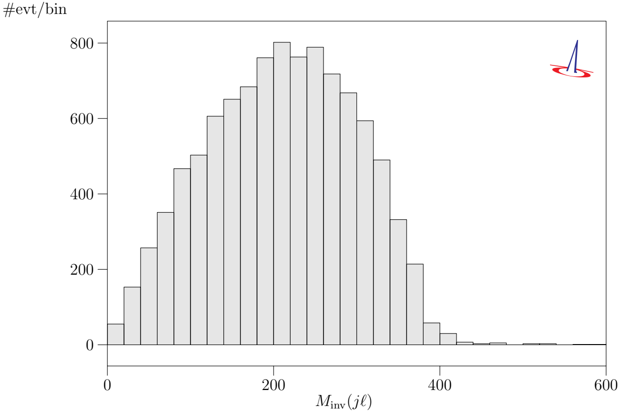
n_events = 10000

simulate (helloworld)
```

Example: LHC SUSY cascade decays

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

- **Full process:**



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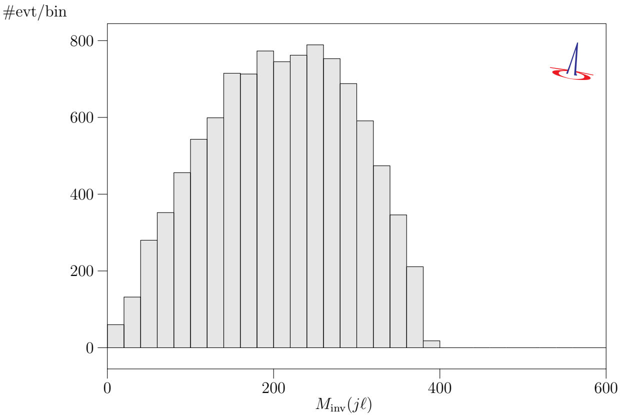
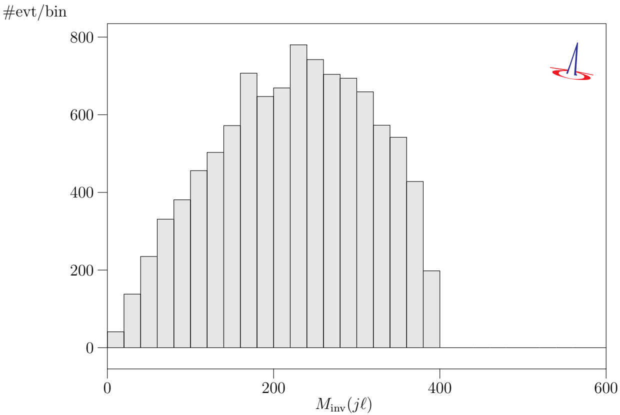
- **Factorized process w/ full spin correlations:**



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

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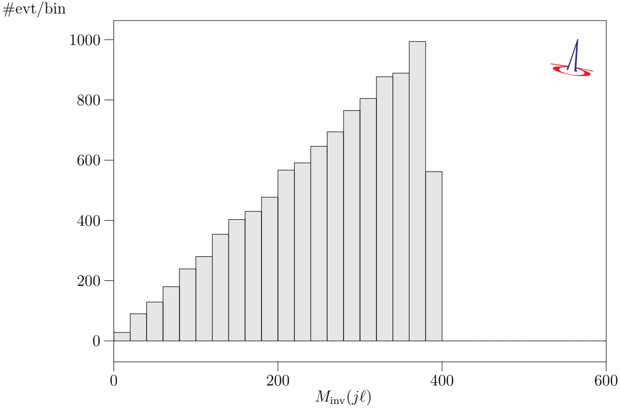
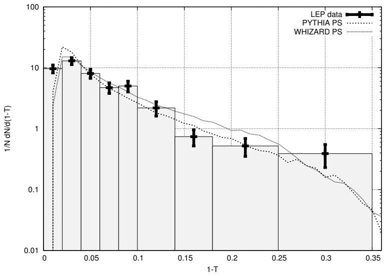
- **Factorized process w/ no spin correlations:**

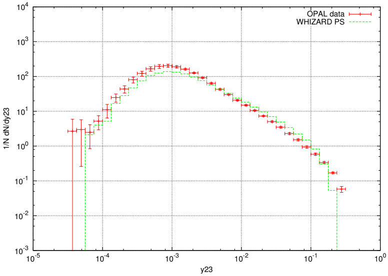


Analytic Parton Shower

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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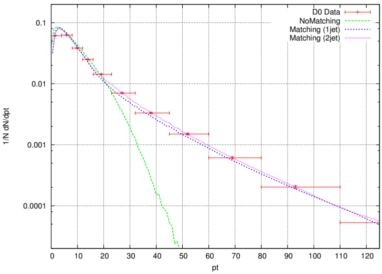

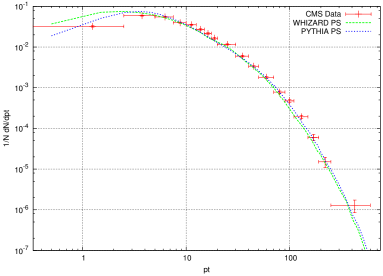

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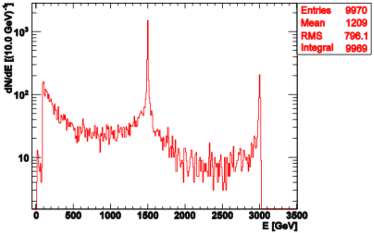
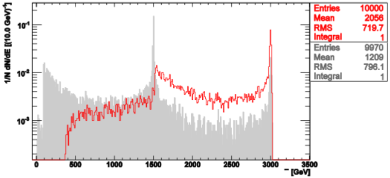
Difficulties of e^+e^- beam simulation





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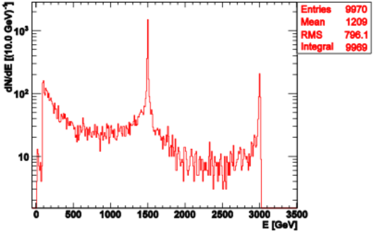

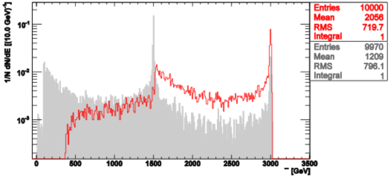

- $E = 3000$ GeV (luminosity spectrum peak)
- $E = 1500$ GeV (Z peak and lumi spectrum)
- $E = M_Z$ (Z resonance)
- $E \approx 30$ GeV (due to $e^+e^- \to \gamma^* \to b\bar{b}$)

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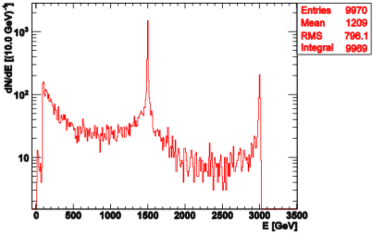

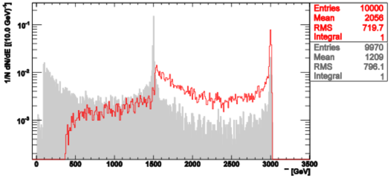

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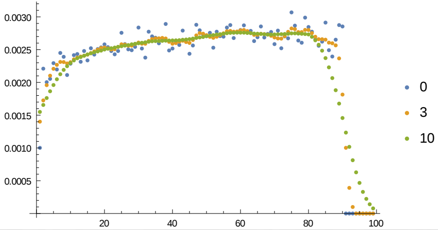
- Simulation with WHIZARD (2.2.2)
- Beam spectra now properly described in WHIZARD

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: $D_{p_1p_2}(x_1,x_2) = D_{p_1}(x_1)D_{p_2}(x_2)$
  - 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
   ```

- Replace ILC500 by FCC350 (corr. acc.dat file)

New (e^+e^-)-related) 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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- BSM: general Lorentz structures in matrix-element generator (O'Mega)

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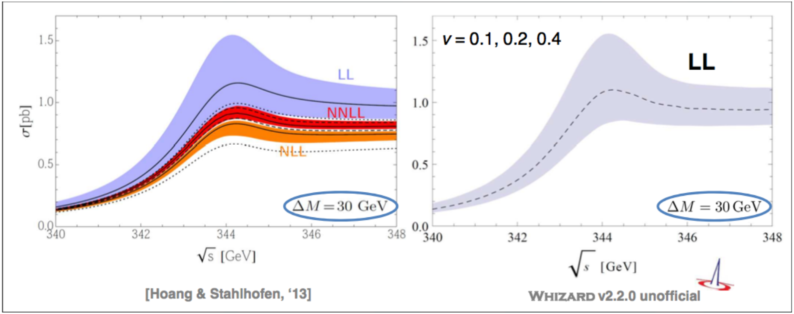
Top quark threshold in e^+e^-

- e^+e^- top threshold scan offers best option for m_t
- now: analytic LL ttV form factor implemented Bach/JRR/Stahlhofen
- 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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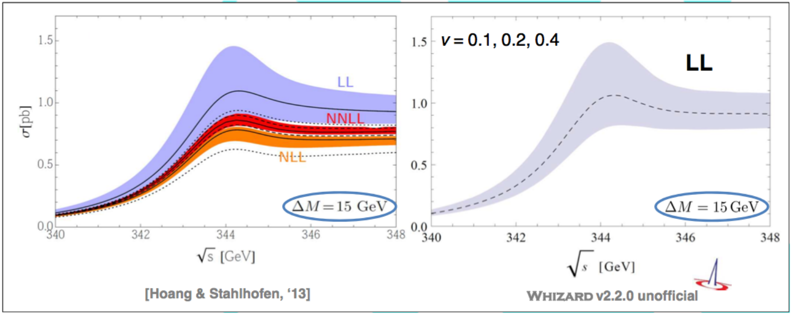

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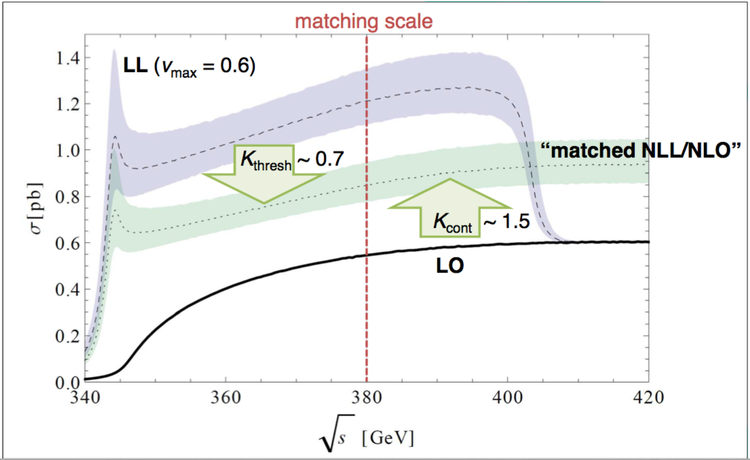

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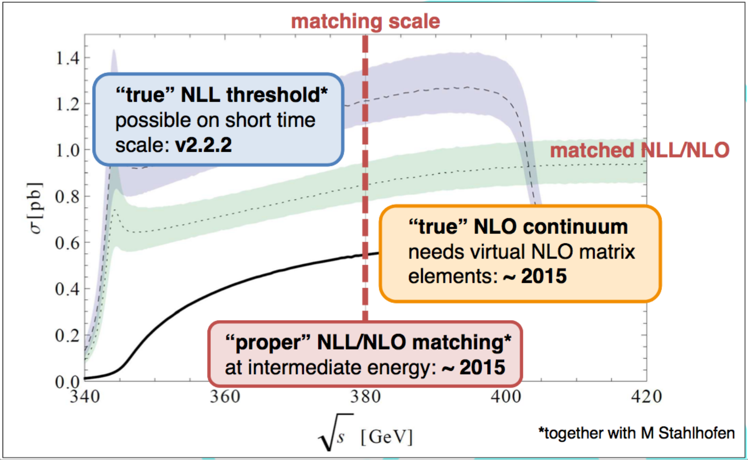

News 2014/early 2015: upcoming releases 2.3-2.4

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- Revised models for BSM interactions of electroweak vector bosons (w/ light Higgs) ✓
- Process containers: inclusive production samples (e.g. SUSY) ✓

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process inclusive = e1, E1 => (Z, h) + (Z, H) + (A, H)

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- Automatic QCD NLO corrections (massless) (test phase)

Status of NLO development in WHIZARD

- BLHA interface: workflow Speckner, 2012; JRR/Weiss, 2014
  1. Process definition in SINDARIN $\Rightarrow$ WHIZARD writes contract file
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Questions to the User Community?

- LCIO: what are the needs for the format? spin info? color correlations?? Reweighting options?
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WHIZARD workshop 16.-18.3.2015

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

Summary and Outlook

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- Versatile, user-friendly tool for SM & BSM physics
- Highest-possible support for lepton beam structures
- Covers the whole SM, and most possible paths beyond
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Let us know of your needs!

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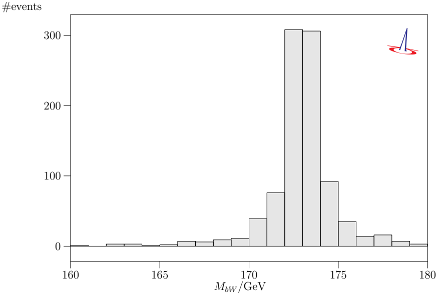
BACKUP SLIDES:

WHIZARD histograms

WHIZARD example plot

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



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

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

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]]]);
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