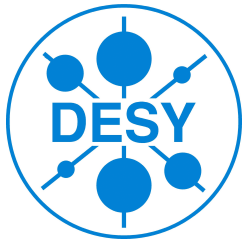
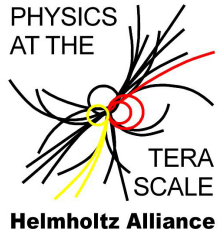
Modern Particle Physics Event Generation with WHIZARD

Jürgen R. Reuter

DESY Hamburg





ACAT, Prague, Sep. 1st, 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 ...
- 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
$\Rightarrow$ 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)
  - $pp \to \tilde{\chi}_1^0\tilde{\chi}_1^0 bbbb$ (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 2.2.2 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`

Standard Reference: Kilian/Ohl/JRR, EPJC **71** (2011) 1742, arXiv:0708.4233

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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

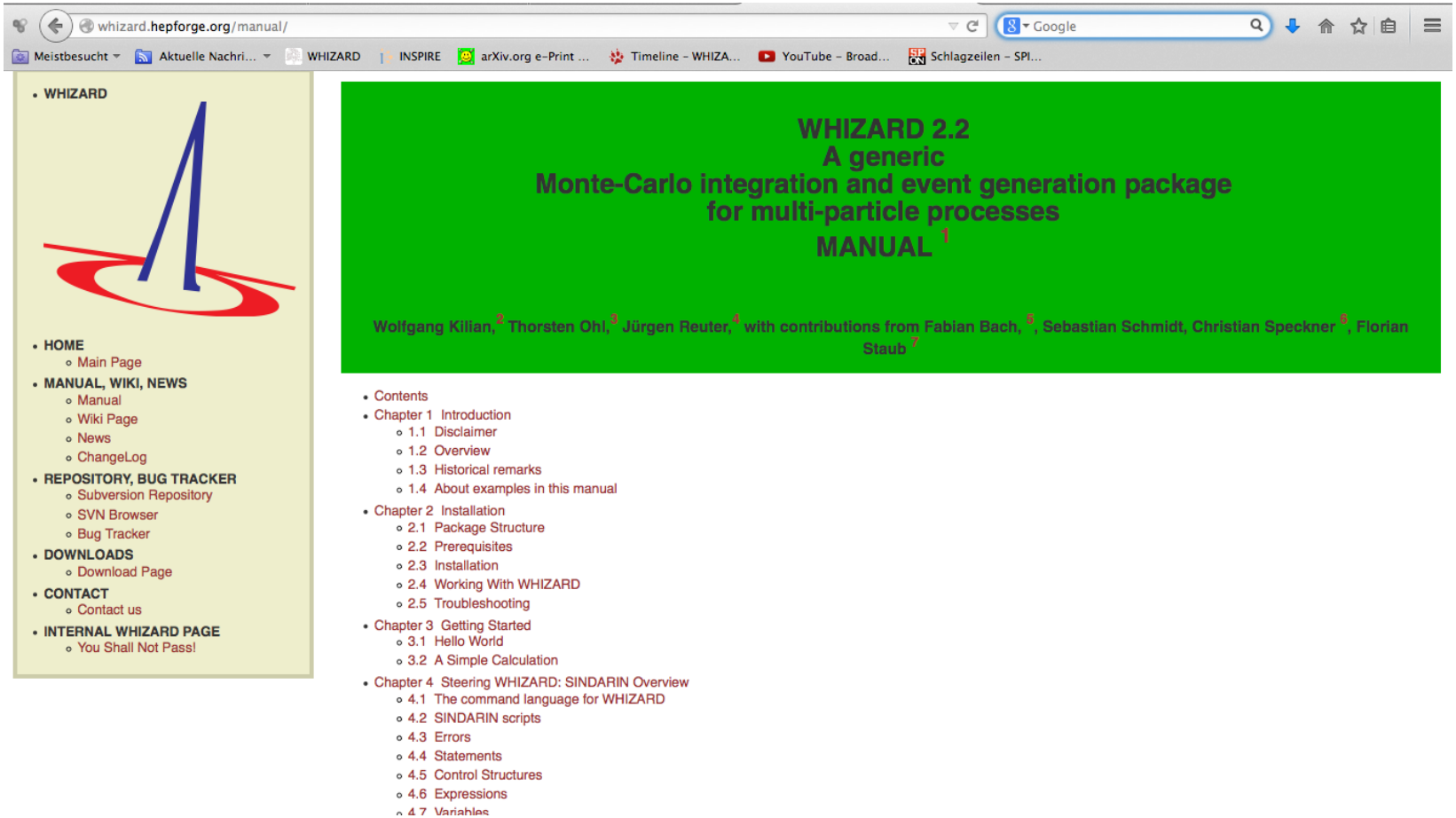
WHIZARD 2 – Installation and Run

- 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: 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
============================================
# 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`



whizard.hepforge.org/manual/

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  - You Shall Not Pass!

WHIZARD 2.2
A generic
Monte-Carlo integration and event generation package
for multi-particle processes
MANUAL [1]

Wolfgang Kilian,[2] Thorsten Ohl,[3] Jürgen Reuter,[4] with contributions from Fabian Bach, [5], Sebastian Schmidt, Christian Speckner [6], Florian Staub [7]

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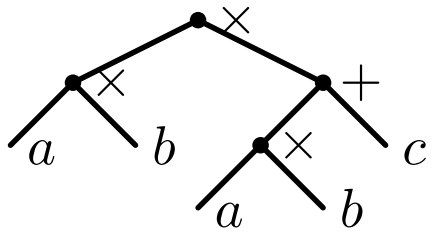
O'Mega: Optimal matrix elements

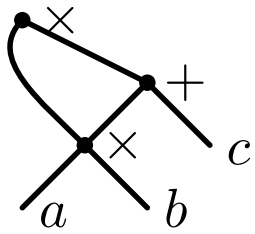
Ohl/JRR, 2001 Ω

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

$$ab(ab+c) =$$



$=$



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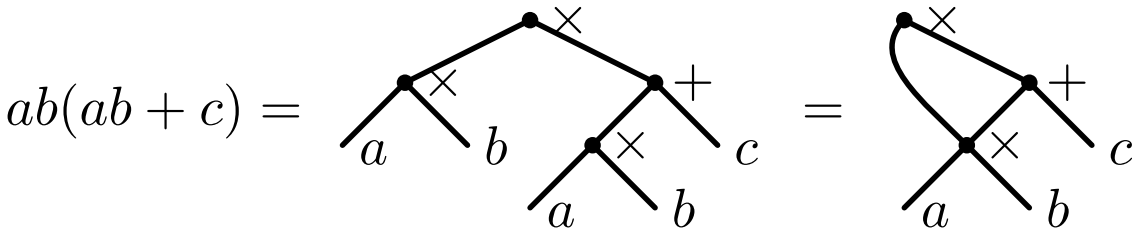
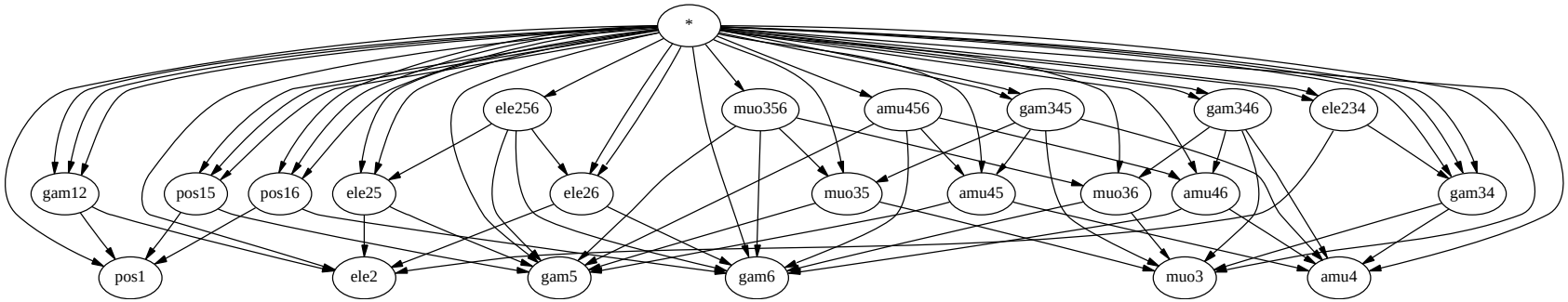


- Example: $e^+e^- \to \mu^+\mu^-\gamma\gamma$



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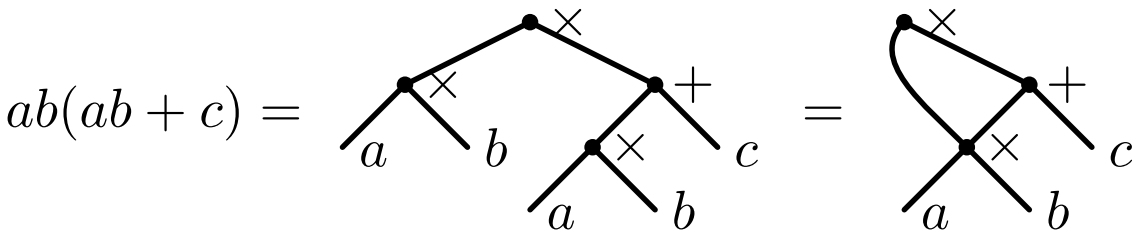

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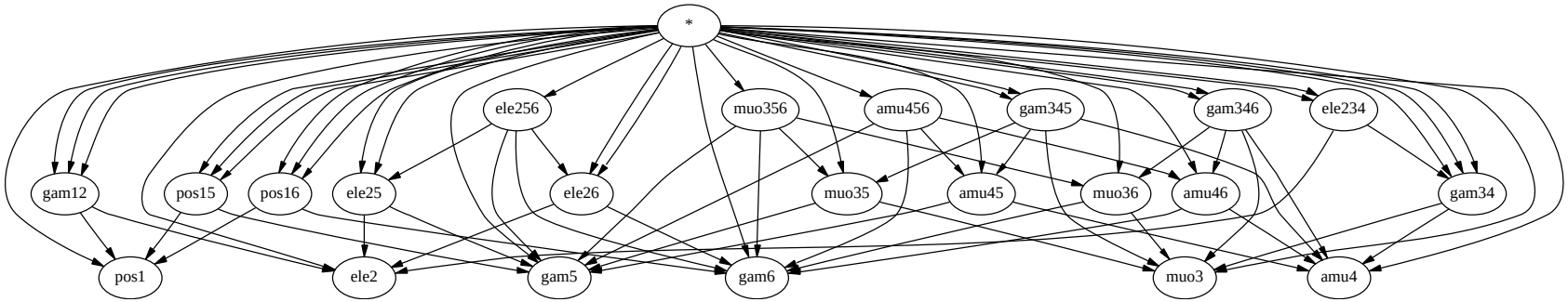

- Unification of model setup: only one binary (2.3)

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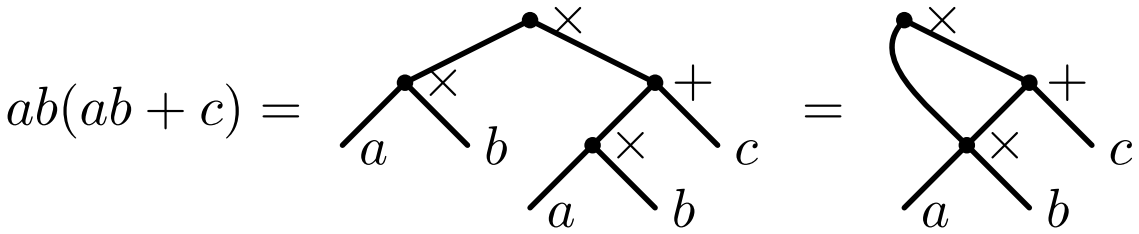

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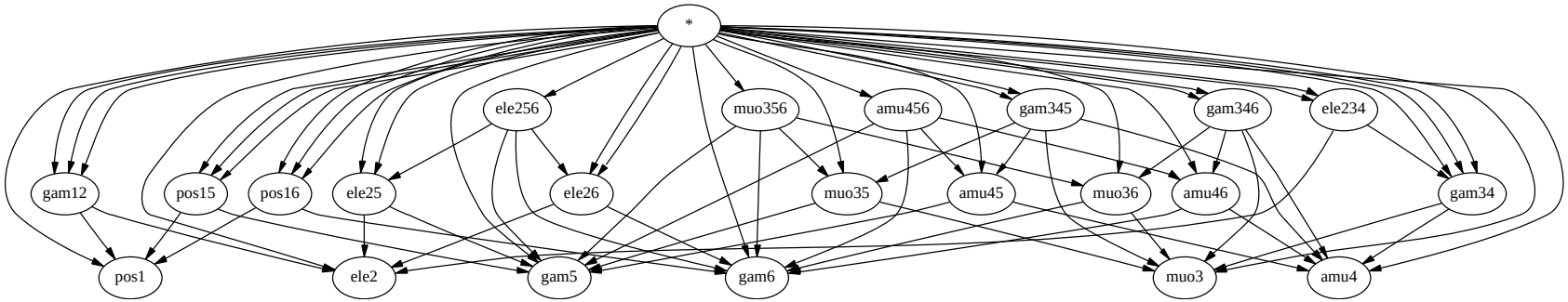

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- Specification of order of strong or EW coupling (2.2.x/2.3)

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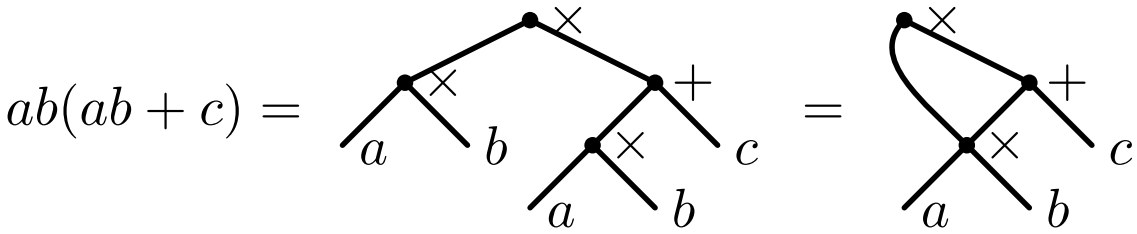

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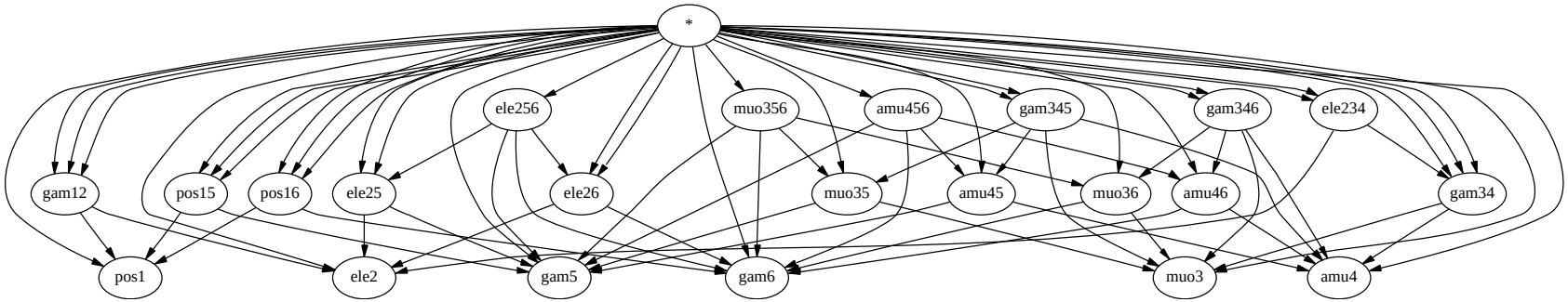


- Unification of model setup: only one binary (2.3)
- Specification of order of strong or EW coupling (2.2.x/2.3)
- Teaser: new algorithm for generating loop diagrams (3.0 ?)

Beams and hard matrix elements

- **Hadron Colliders structured beams**
  - LHAPDF interface (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** (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)
```

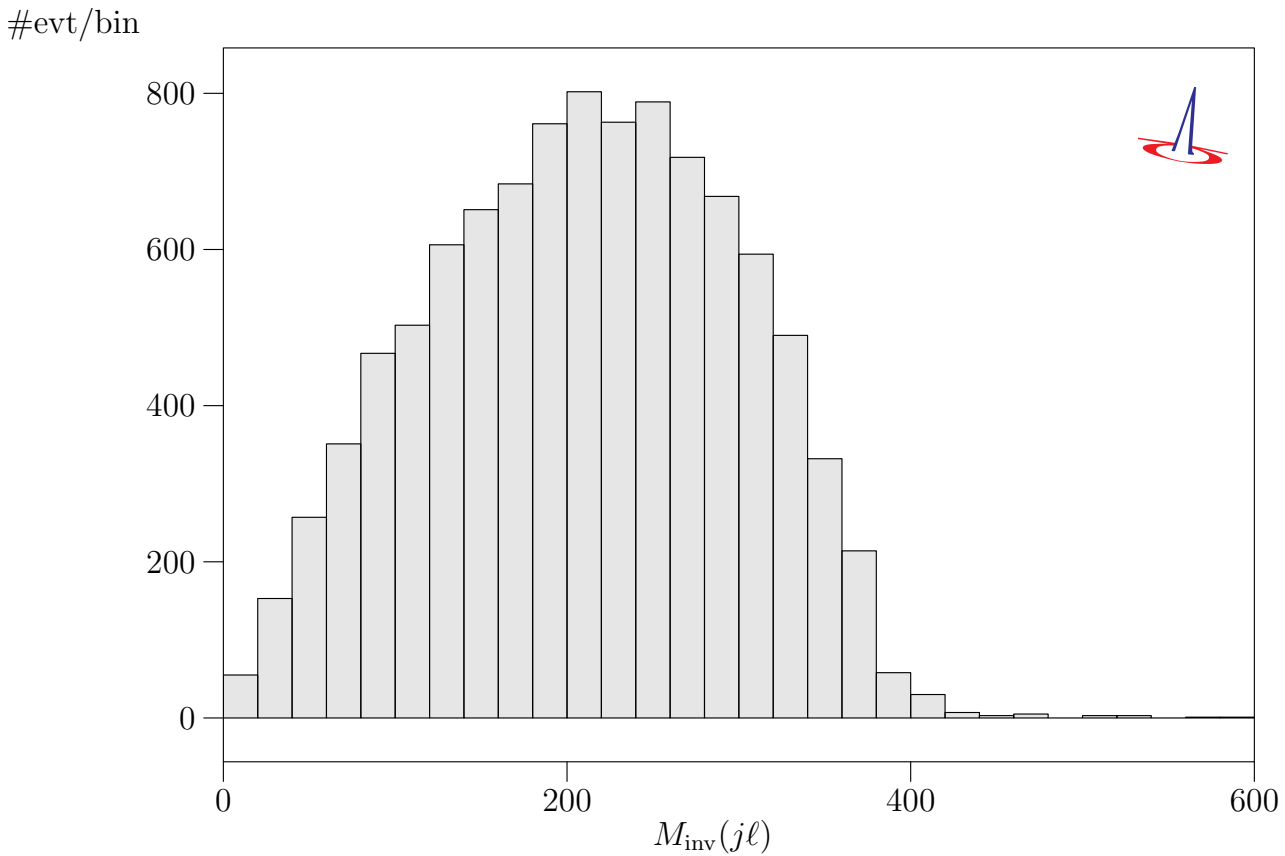
SINDARIN Input files: Basic features

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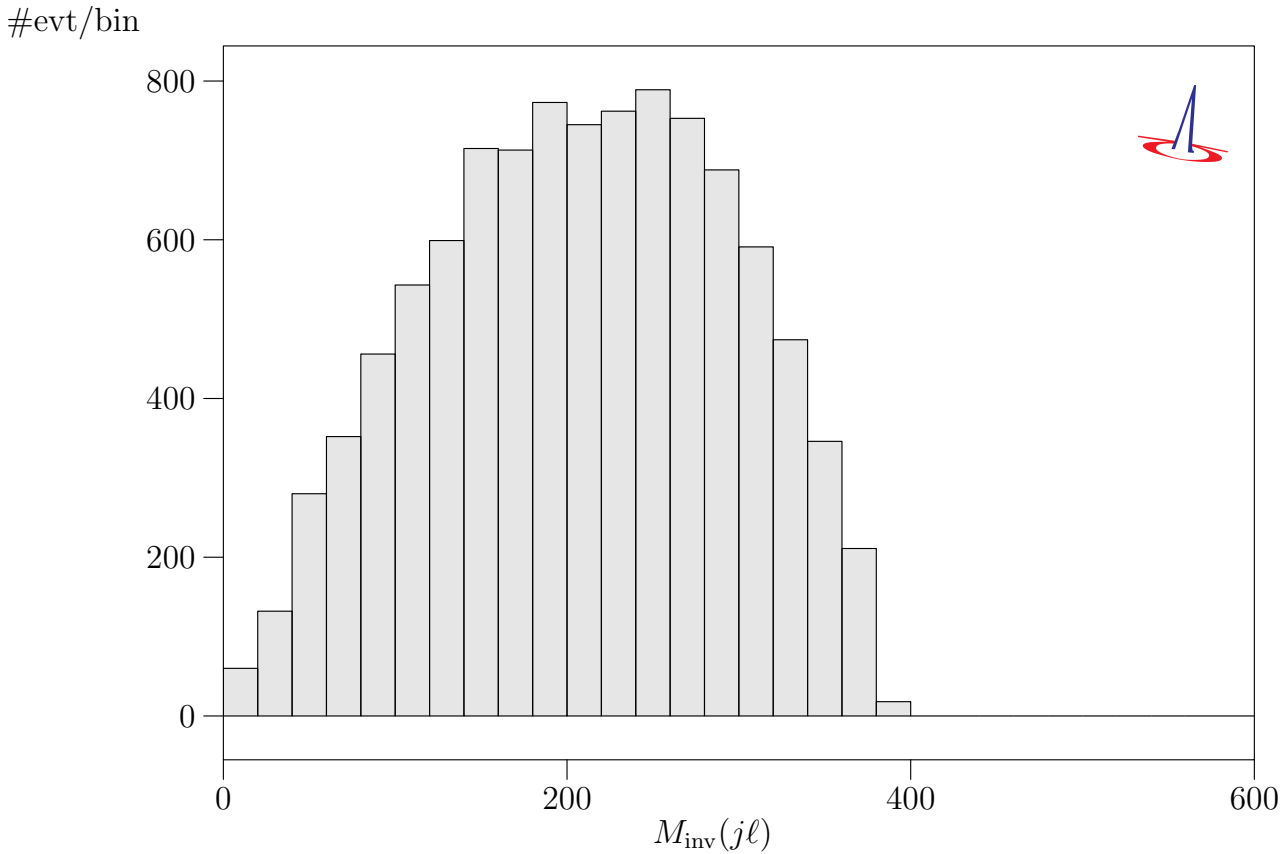
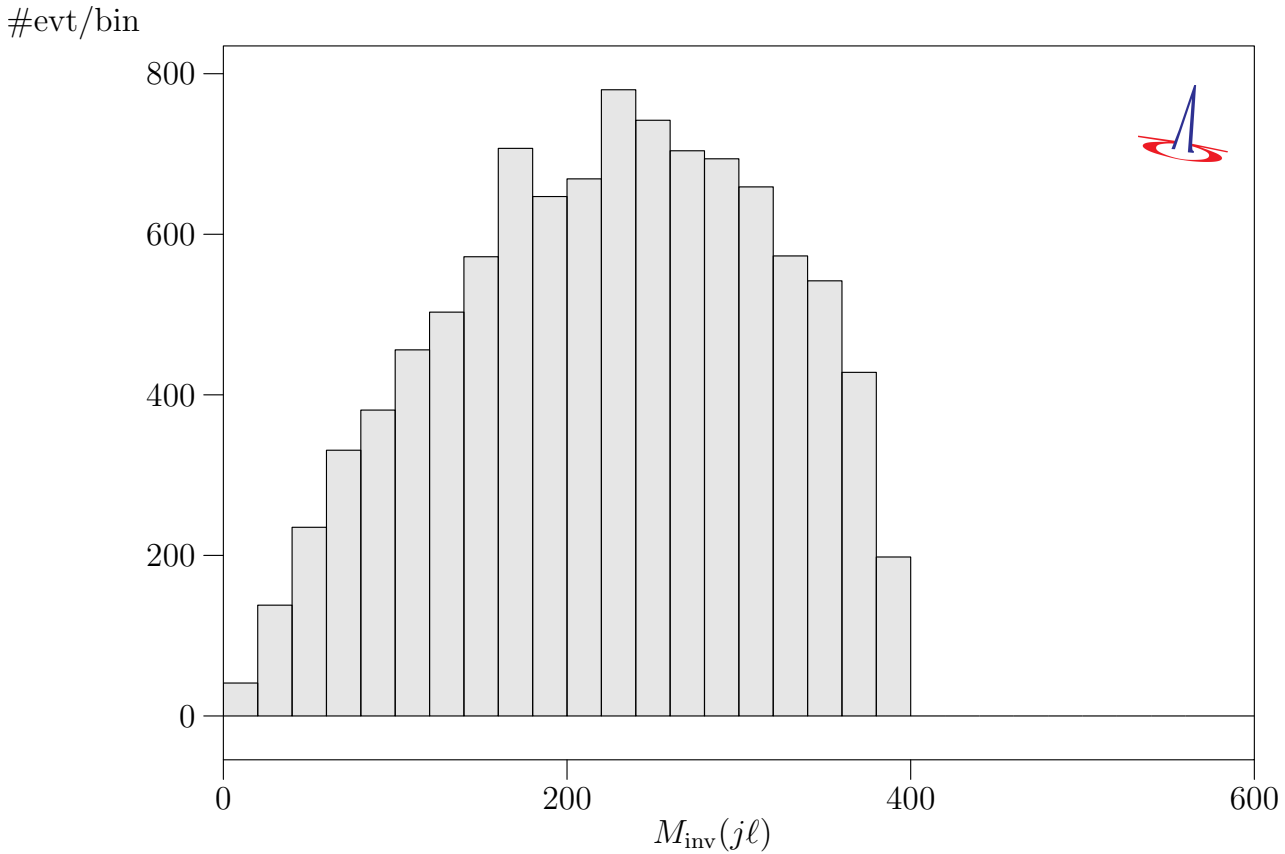
- **Factorized process w/ full spin correlations:**



Example: LHC SUSY cascade decays

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

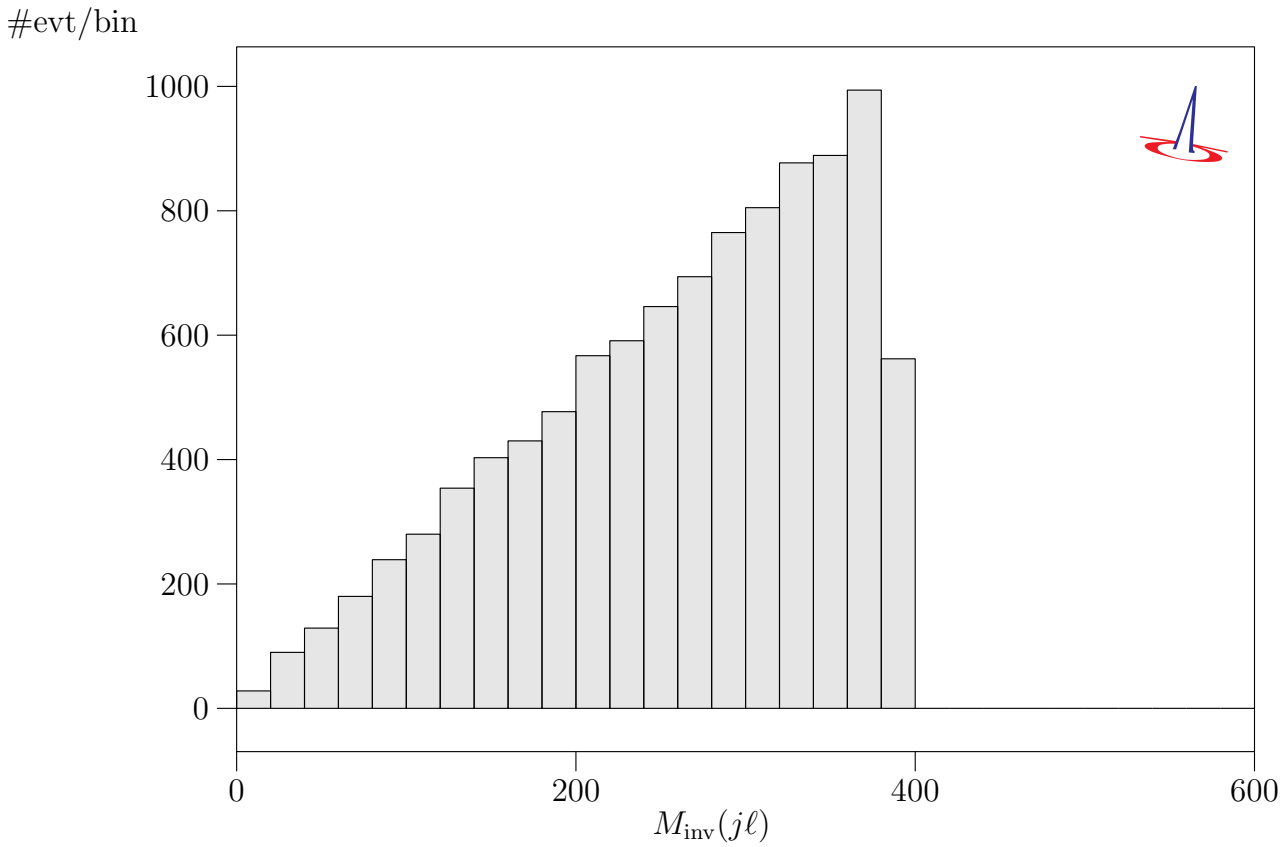
- **Factorized process w/ classical spin correlations:**



Example: LHC SUSY cascade decays

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

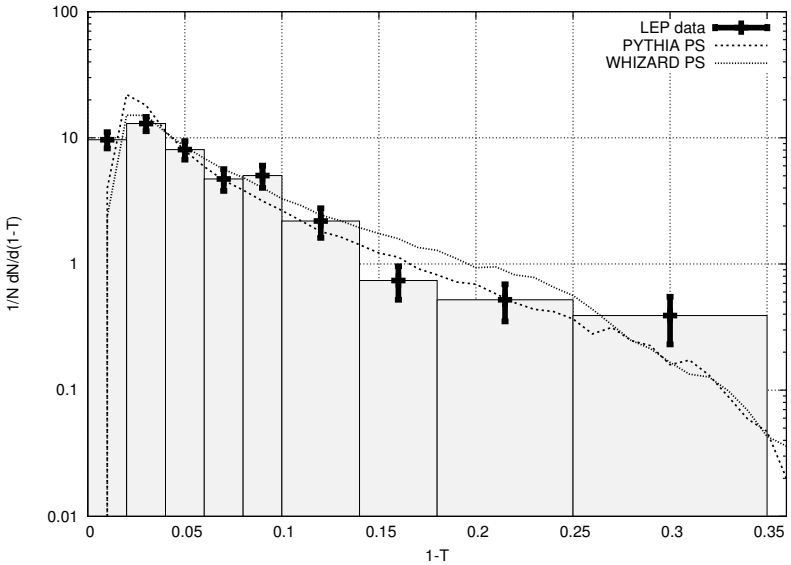
- **Factorized process w/ no spin correlations:**

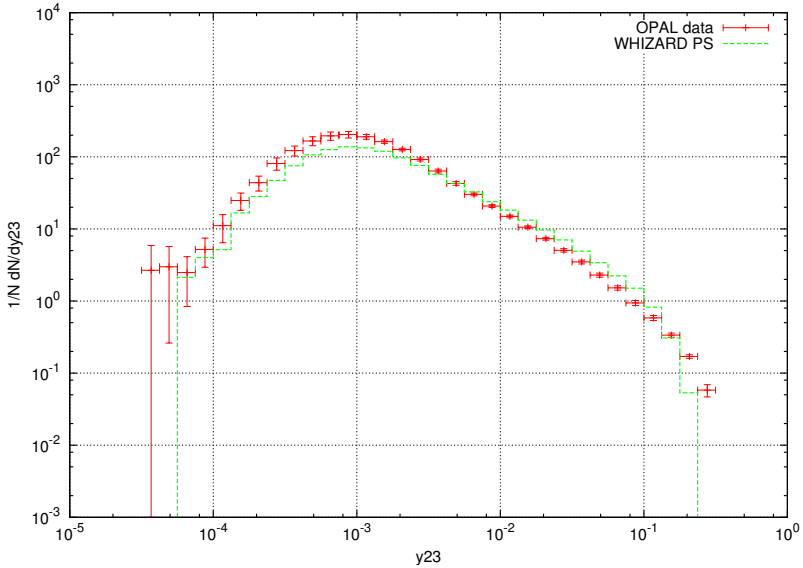


Analytic Parton Shower

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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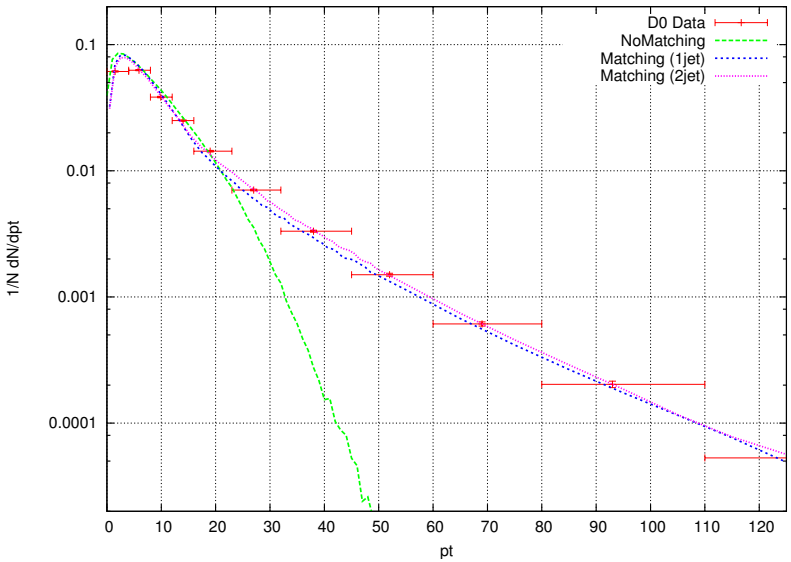
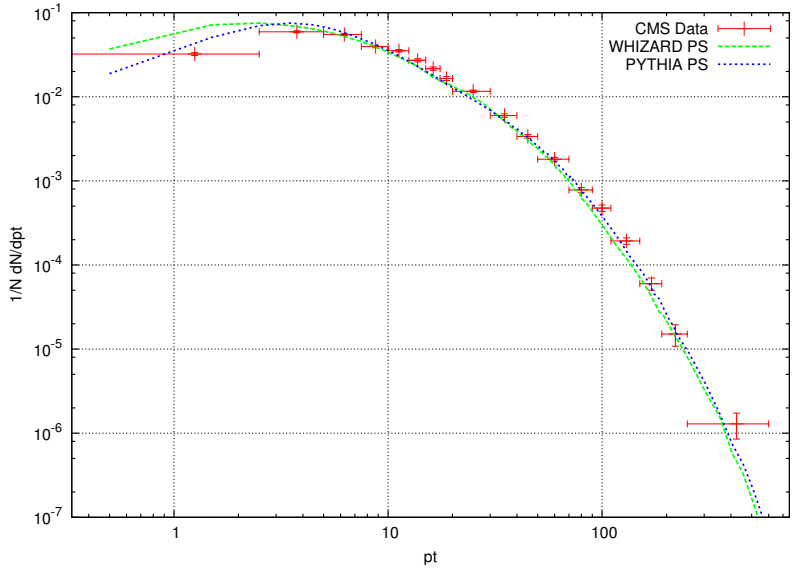
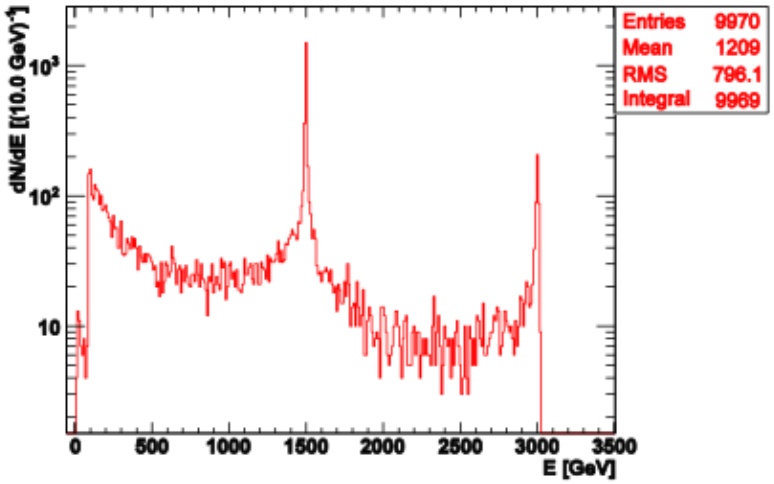
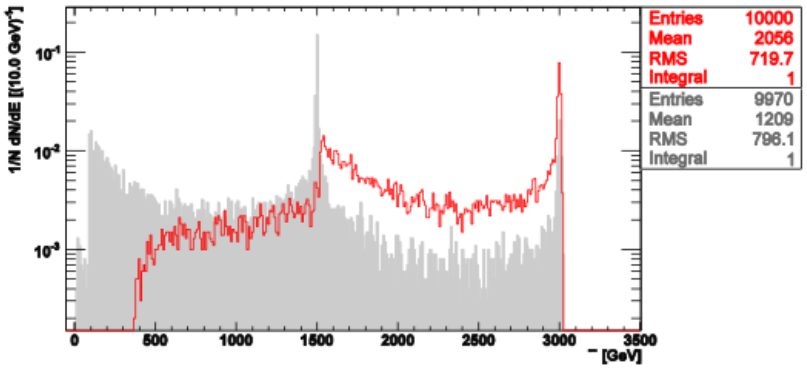




- matching with hard matrix elements, no ”power-shower”

Difficulties of e^+e^- beam simulation





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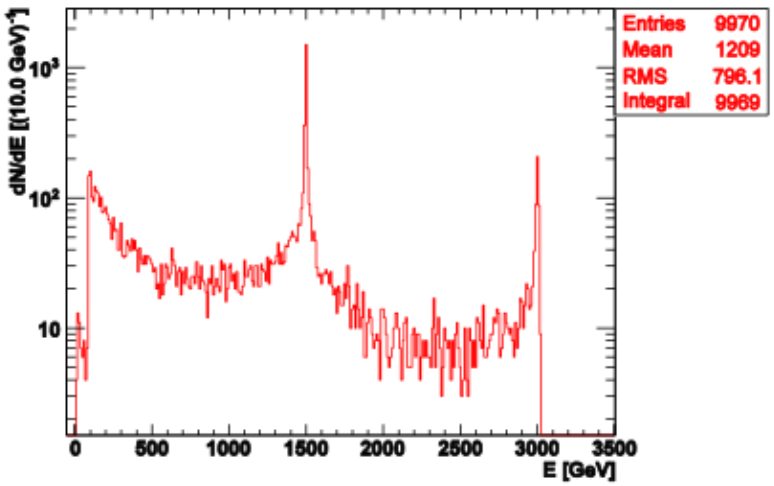
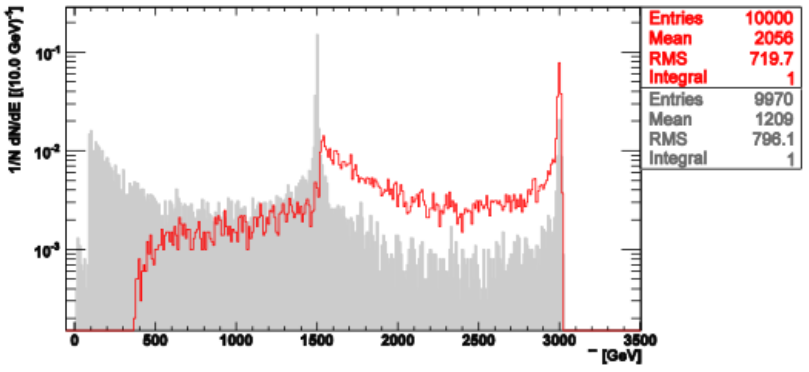
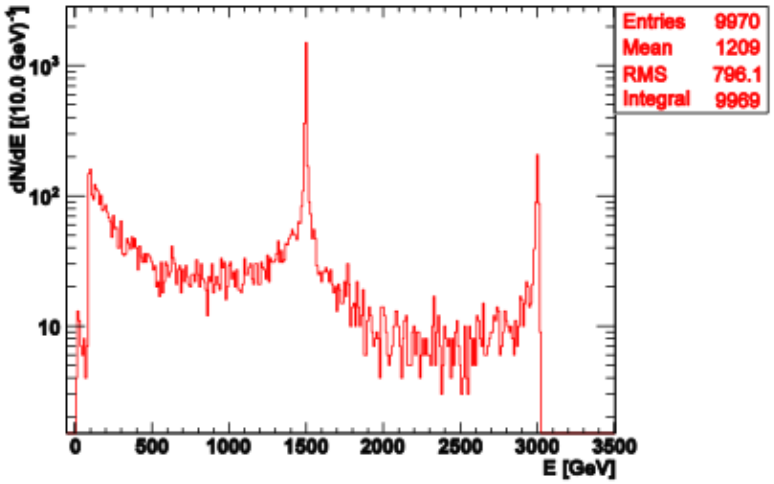
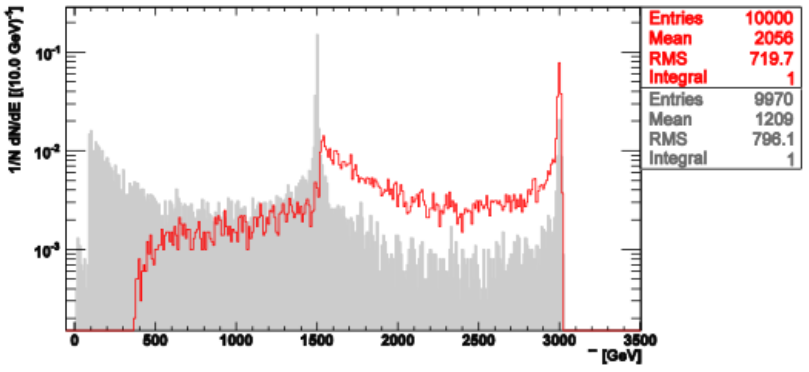




- $E = 3000$ GeV (luminosity spectrum peak)
- $E = 1500$ GeV (Z peak and lumi spectrum)
- $E = M_Z$ (Z resonance)
- $E \approx 30$ GeV (due to $e^+e^- \to \gamma^* \to b\bar{b}$)

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 $e^+e^- \to \gamma^* \to b\bar{b}$)

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

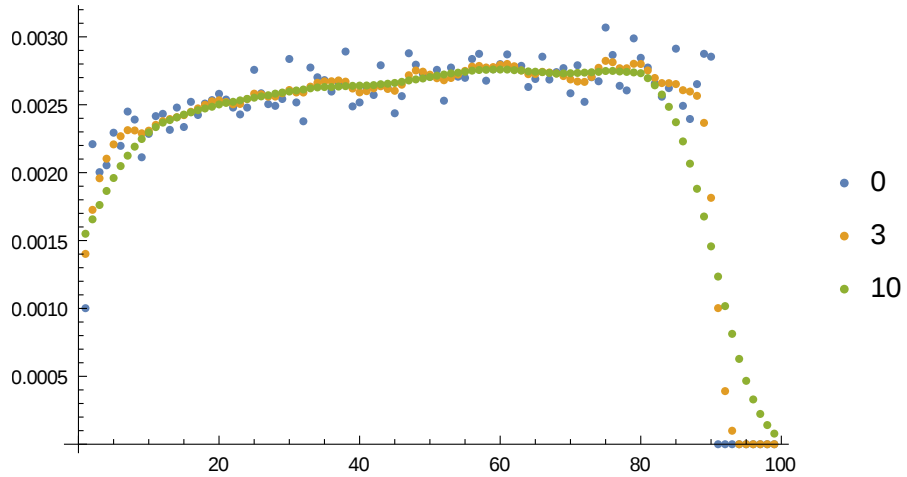
Correlated lepton beam spectra with `Circe2`

- `Guinea-Pig++` event files too short for high lumi simulations
- Fixed width histogramming struggles with steep distributions
- `Circe1` too restrictive, assumes
  - *factorized* beam spectra: $D_{p_1 p_2}(x_1, x_2) = D_{p_1}(x_1) D_{p_2}(x_2)$
  - 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 ✓
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  MC over helicities, colors, PS, etc. etc. etc.

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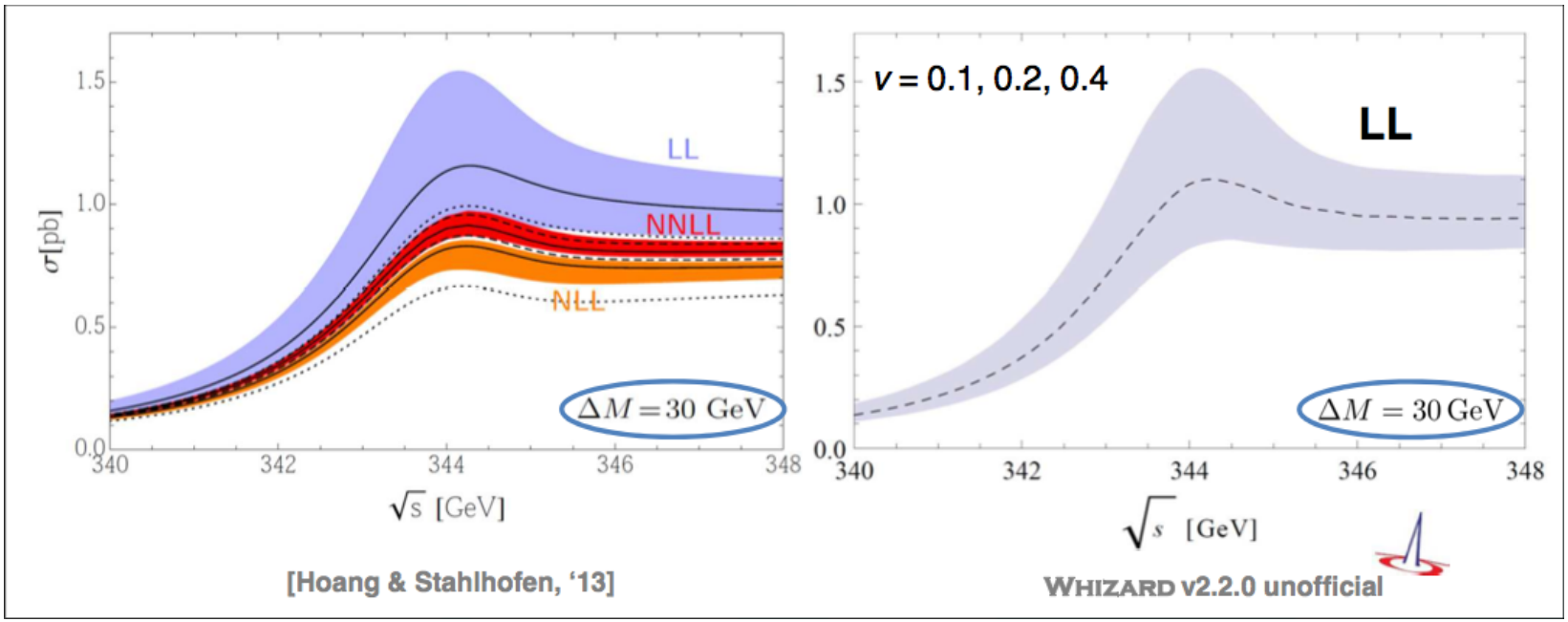
- ▶ Threshold resummation for $e^+e^- \to t\bar{t}, W^+W^-$ etc. Bach/Hoang/JRR/Stahlhofen/Teubner;
  Bach/JRR/Schwinn

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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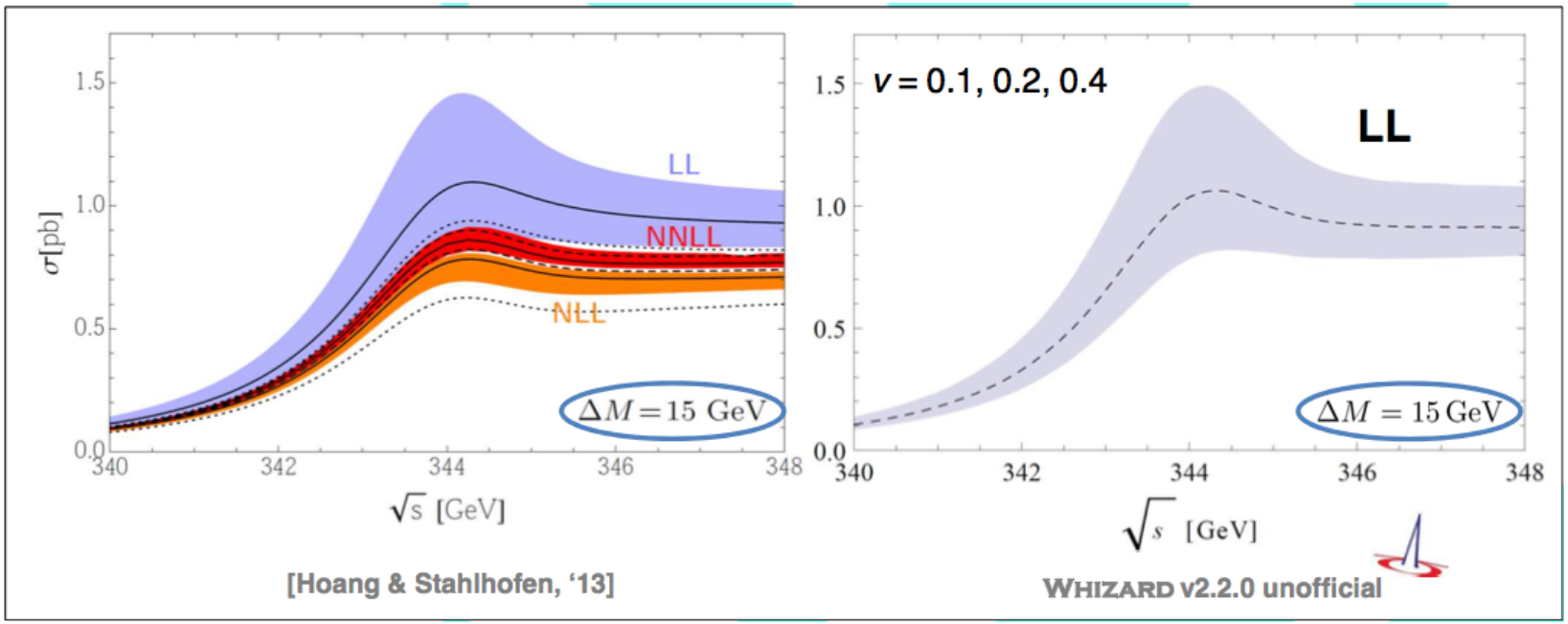

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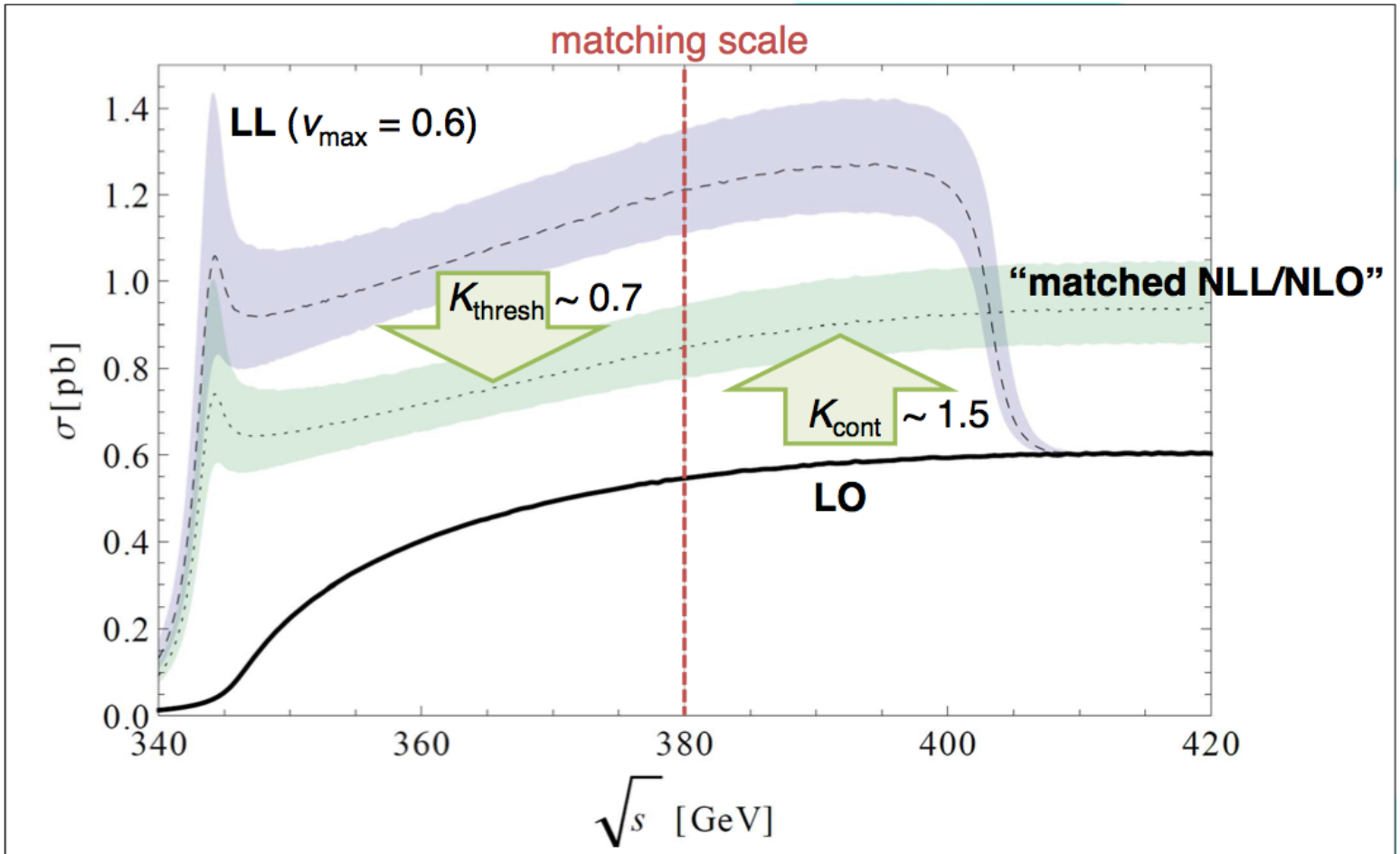

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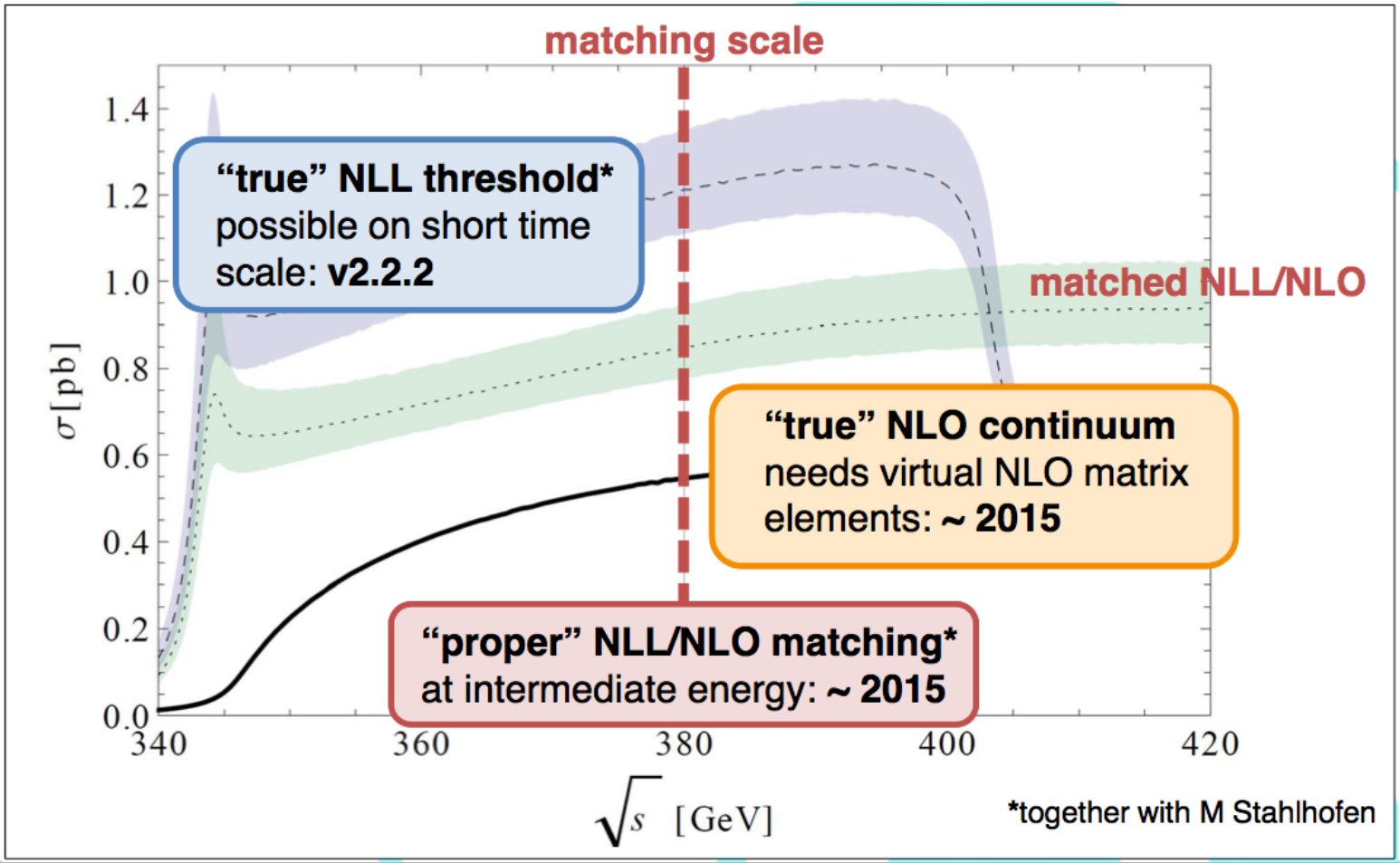

News 2014/early 2015: upcoming releases 2.3-2.4

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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)

process vvv = e1, E1 => (Wp,Wm,Z) + (Wp,Wm,Z) + (Wp,Wm,Z)
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- Automatic generation of decays, depending on the model ✓

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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
  2. NLO generator generates code, WHIZARD reads contract
  3. NLO matrix element loaded as shared library

- First implementation: interfacing `GoSAM` (and `FeynArts/FormCalc`)

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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?
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- `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

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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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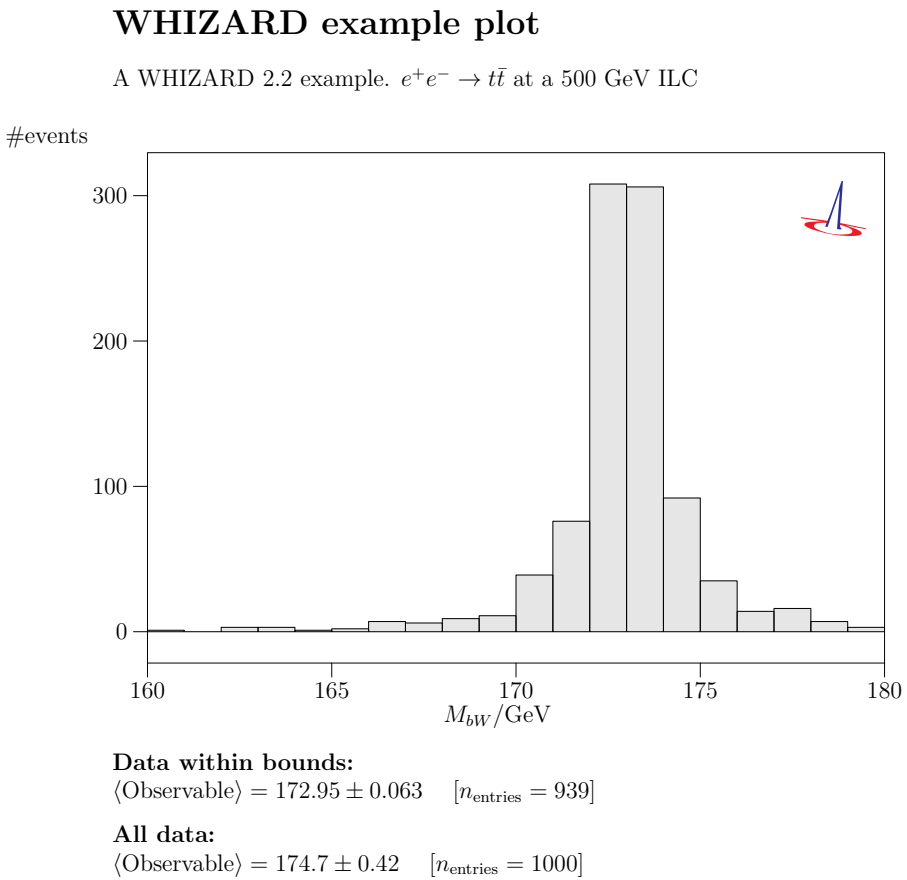
BACKUP SLIDES:

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]]]);
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```