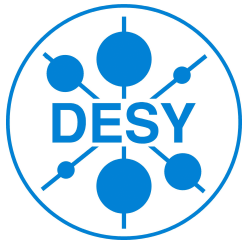
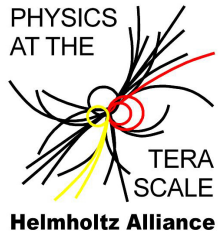
WHIZARD Event Generation for LCs
From Beam Spectra to Higher Orders

Jürgen R. Reuter

DESY Hamburg





LCWS 2014, Belgrade, October 8th, 2014

The WHIZARD has come to the 'White City'

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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, FCC-ee ...
- pp: Tevatron $\Rightarrow$ LHC, HL/E-LHC, VLHC, FCC, XXX ...

It contains

1. O'Mega: Optimized automatic matrix elements for arbitrary elementary processes, supports SM and many BSM extensions
2. Phase-space parameterization module (very efficient PS)
3. VAMP: Generic adaptive Monte Carlo 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

The WHIZARD Event Generator – Release 2.2

1.0 Project started around 1999: Studies for electroweak multi-particle processes at TESLA (W, Higgs, Z)

1.5 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), SINDARIN as user interface, OpenMP, ...

2.2 Major refactoring, event 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

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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, + 2 bachelors + DESY summer students

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

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

WHIZARD 2: Status 2010-14 – Technical Features

- `Fortran2003/2008` (`gfortran 4.7.1` or newer) and `OCaml` (for MEs)
- WHIZARD core: 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 outsource small(er) projects
  - 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

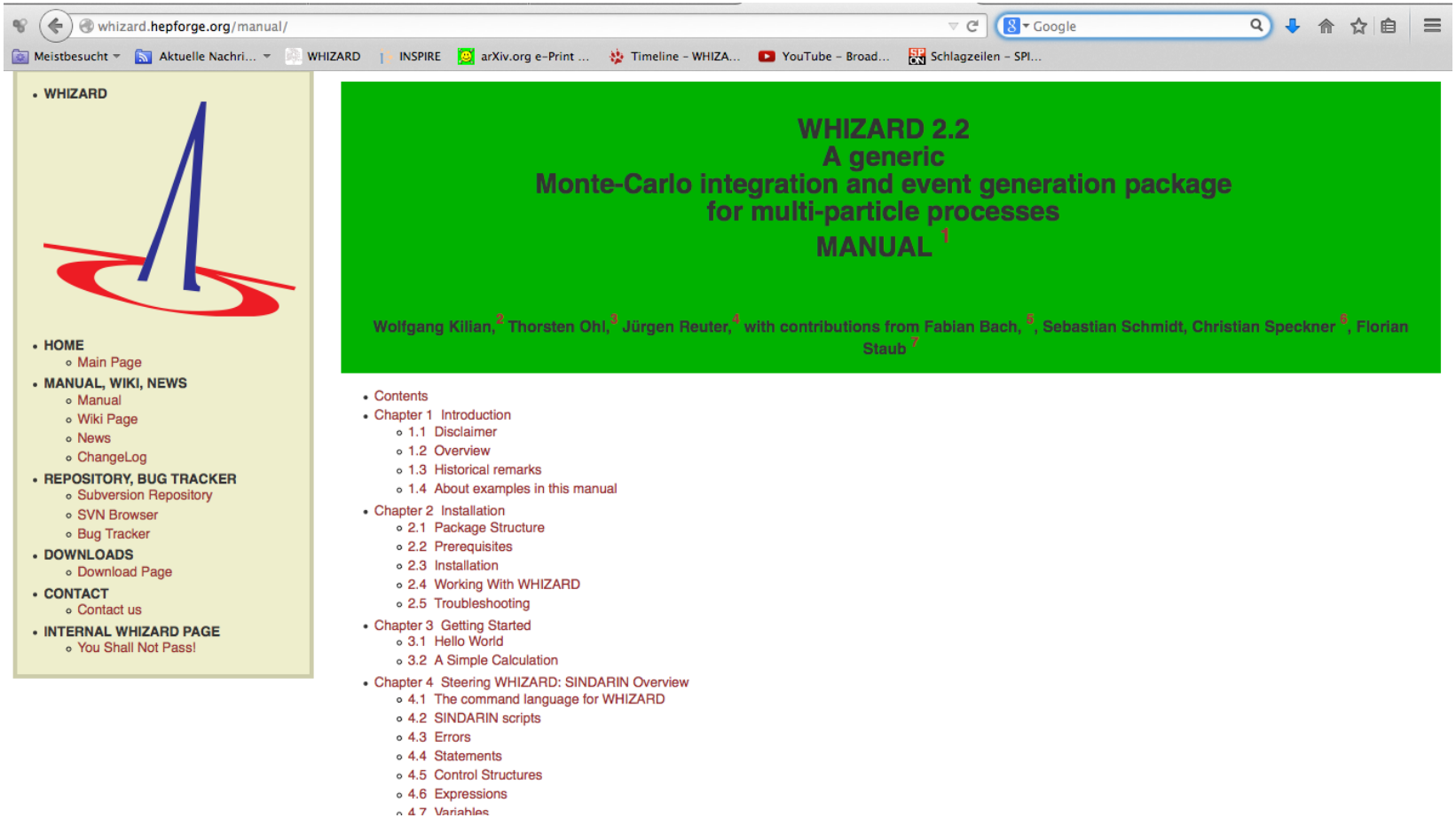
WHIZARD 2 – Installation and Run

- 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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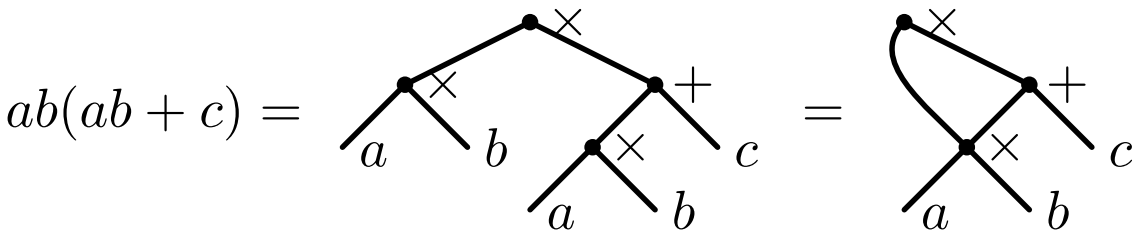
O'Mega: Optimal matrix elements

Ohl/JRR, 2001

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



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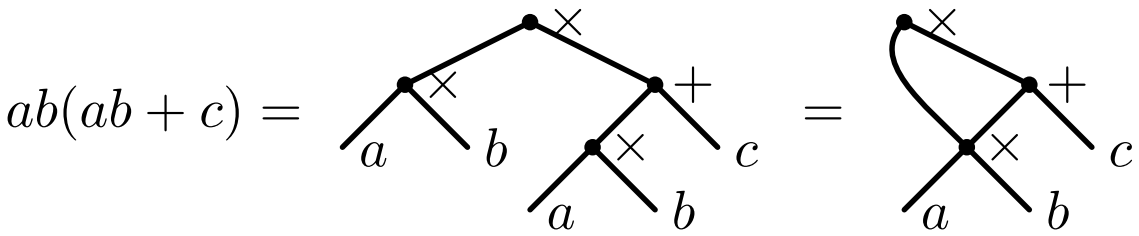
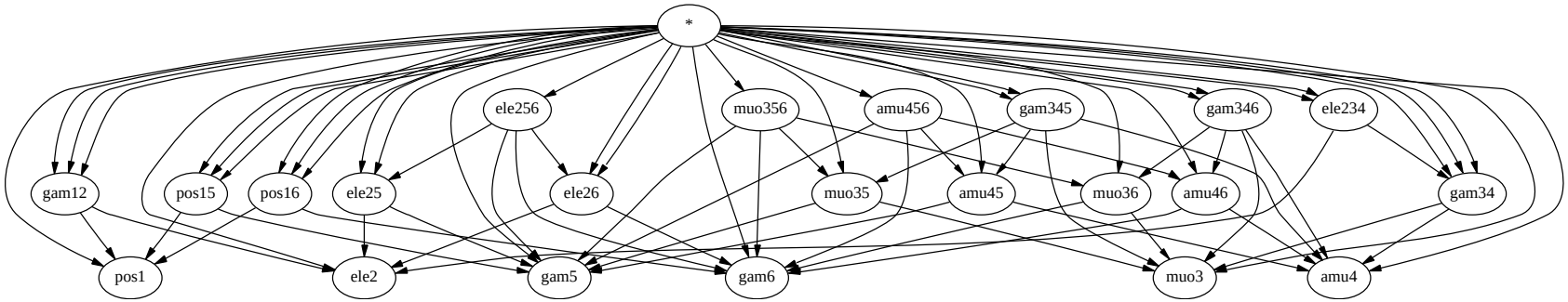


- Example: $e^+e^- \to \mu^+\mu^-\gamma\gamma$



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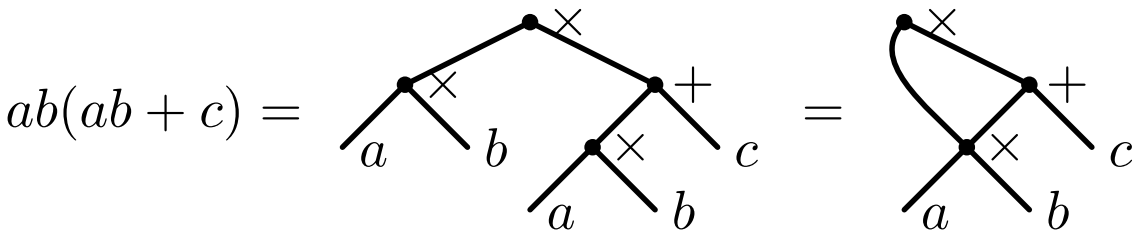

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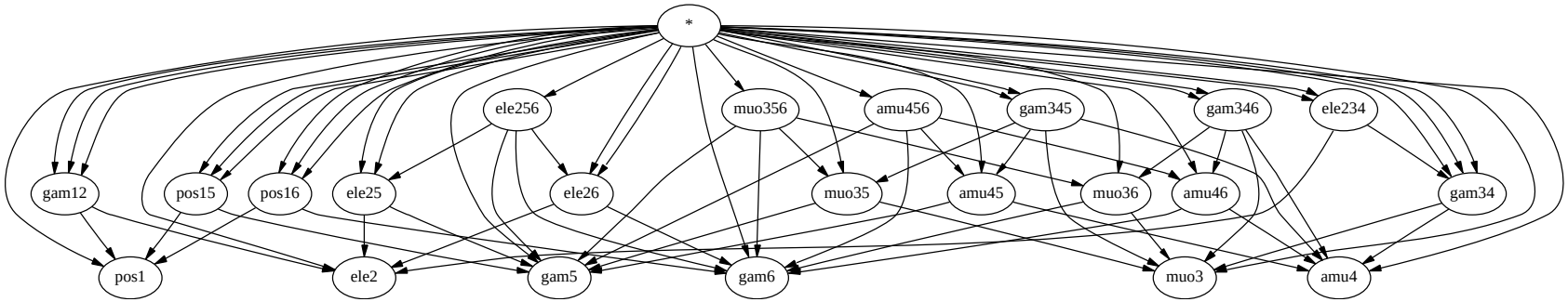

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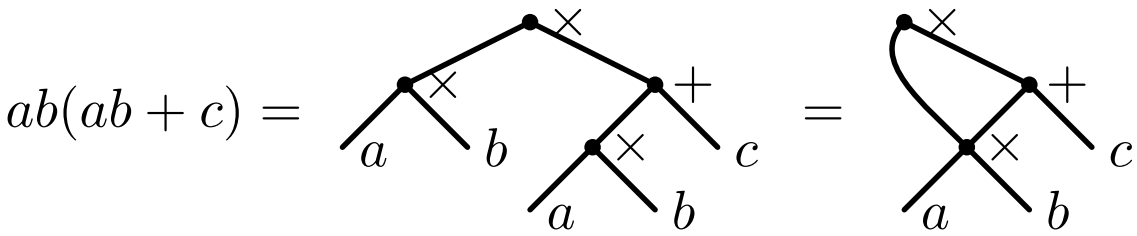

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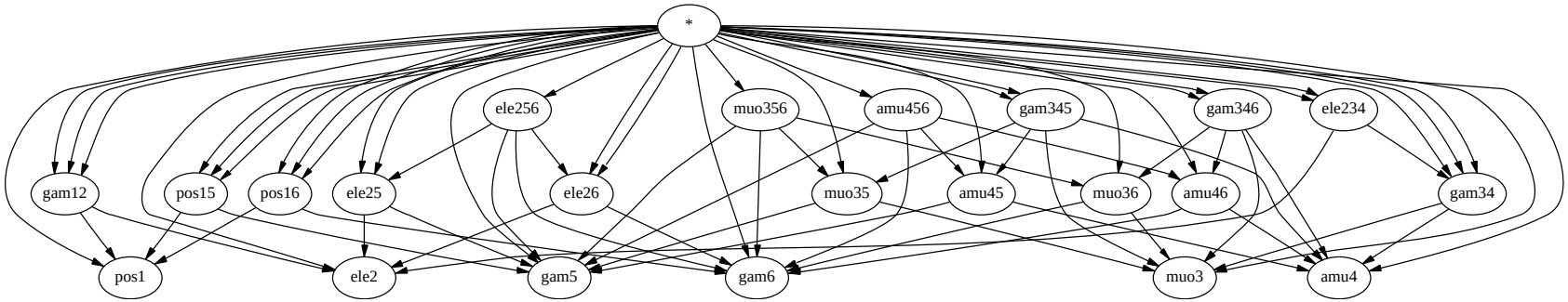

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- Specification of order of strong or EW coupling (2.3.x/2.4)

O'Mega: Optimal matrix elements

Ohl/JRR, 2001 Ω

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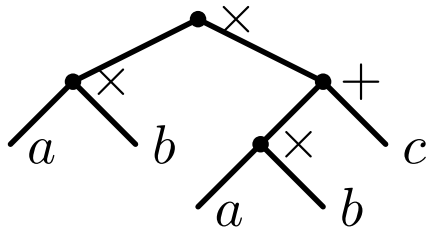
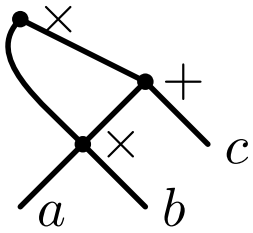
$$ab(ab+c) =$$



$=$



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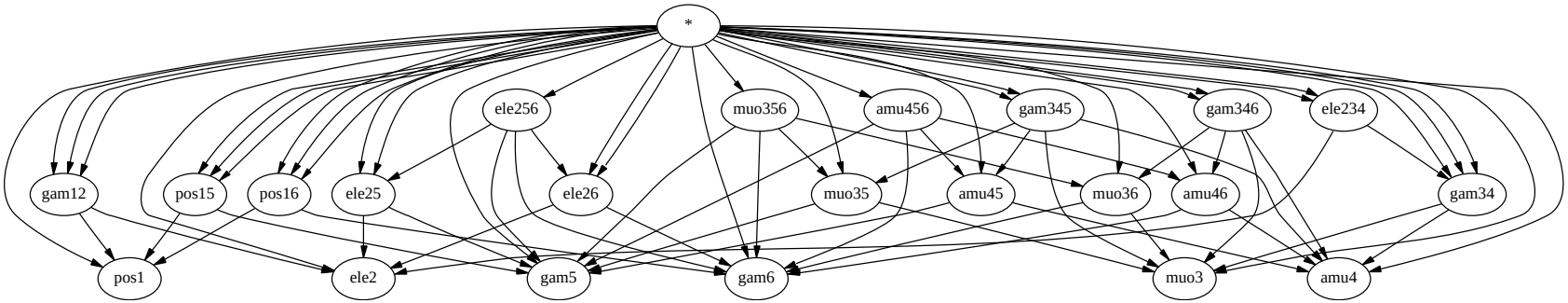

- Unification of model setup: only one binary (2.3.0)
- Specification of order of strong or EW coupling (2.3.x/2.4)
- Teaser: new algorithm for generating loop diagrams (3.0 ?)

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/merging matrix elements/showers
  - Underlying event/multiple interactions (proof of principle)
- **Hadronic events/hadronic decays + hadronic (QED) FSR** (ext.)
- **Lepton Colliders structured beams**
  - Beam structure (CIRCE1/2 module) **more later**
  - arbitrarily polarized beams (density matrices)
  - QED ISR (Skrzypek/Jadach, Kuraev/Fadin , incl. p_T distributions [caveat!])
  - [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 Physics 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 for e^+e^- top threshold	**—**	**`SM_tt_threshold`**
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

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JRR et al. 1408.6207
Talk LCWS14 EW session 7.10.

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SINDARIN Input files: Basic features

```
model = SM


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




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




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



n_events = 10000

simulate (helloworld)
```

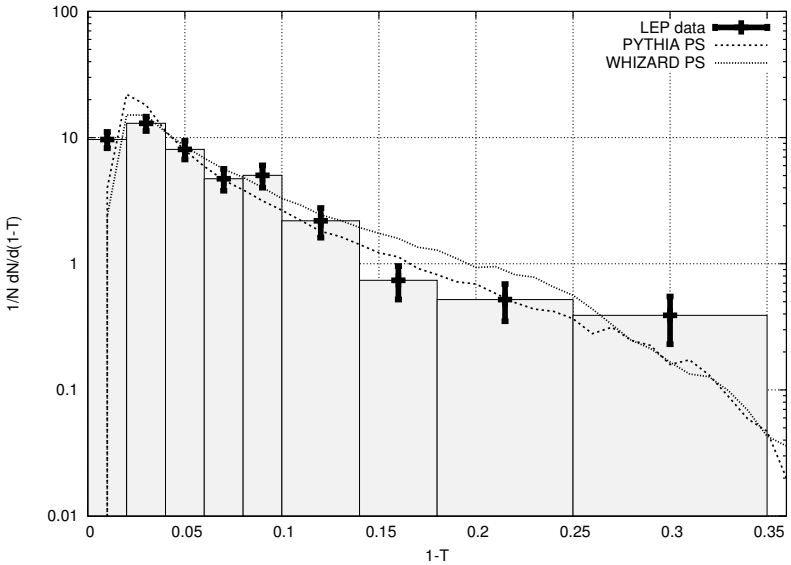
SINDARIN Input files: Basic features

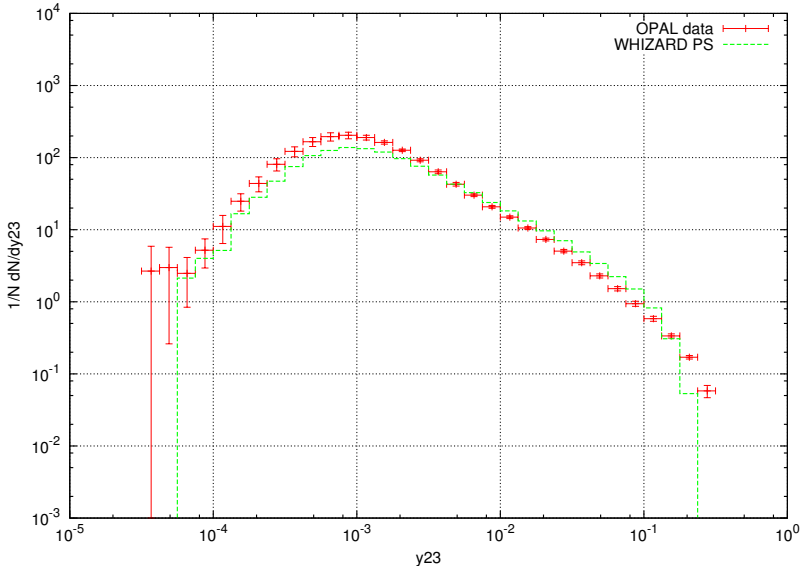
```
model = SM
alias lepton = e1:E1

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

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

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)
```

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





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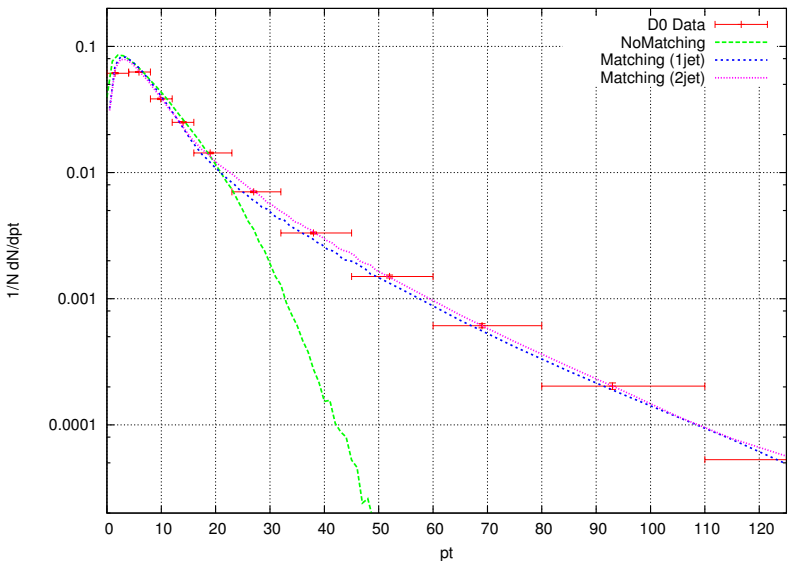
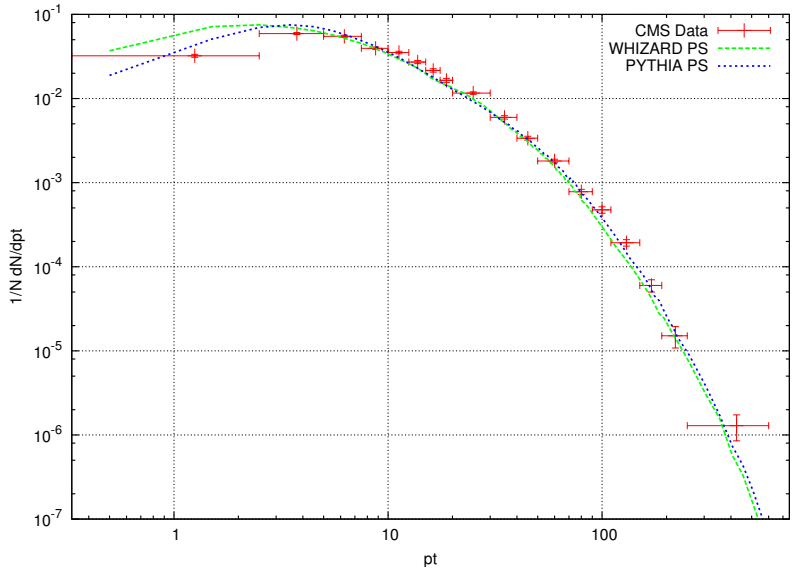
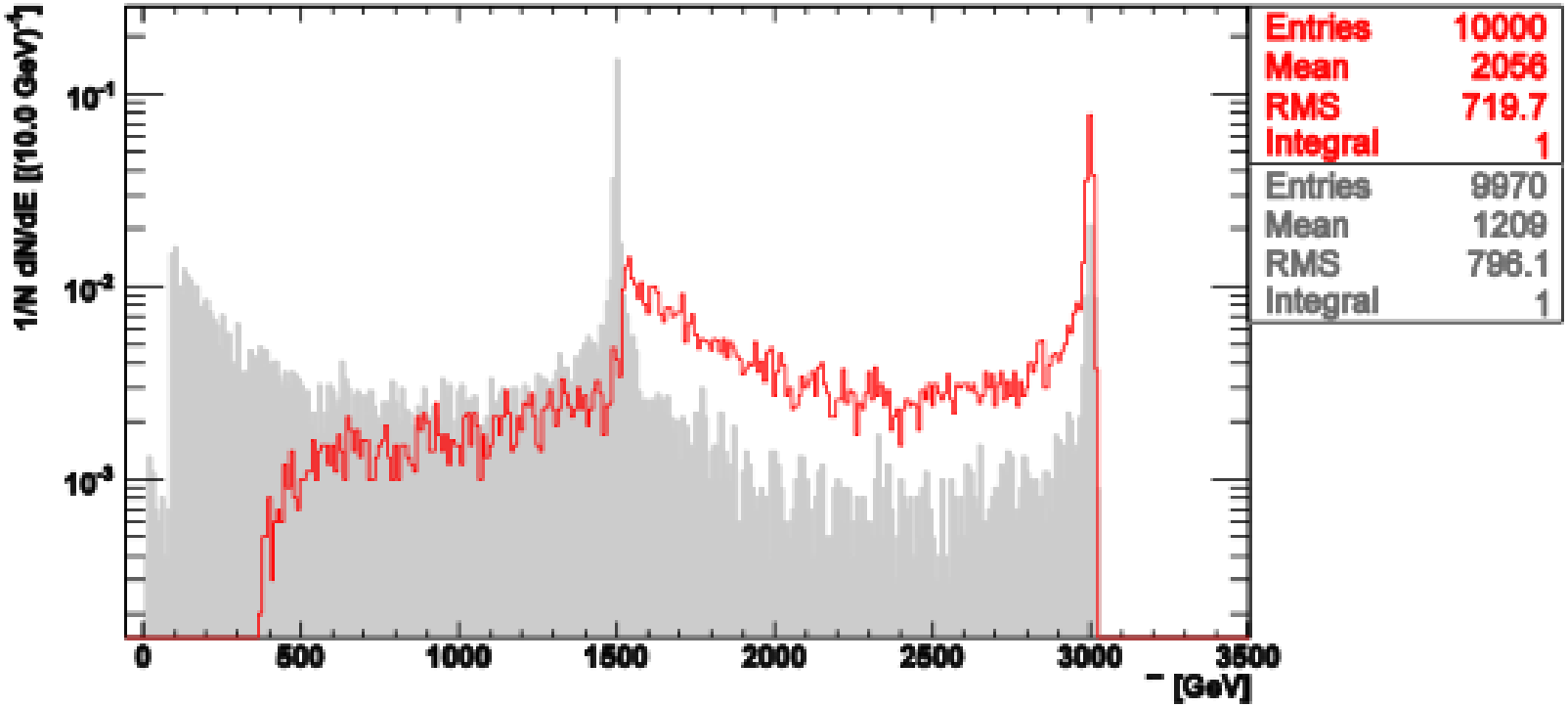




- matching with hard matrix elements, no ”power-shower”
- Merging with higher-order matrix elements Chokoufé/JRR

e^+e^- beam simulation in WHIZARD



- $E = 3000$ 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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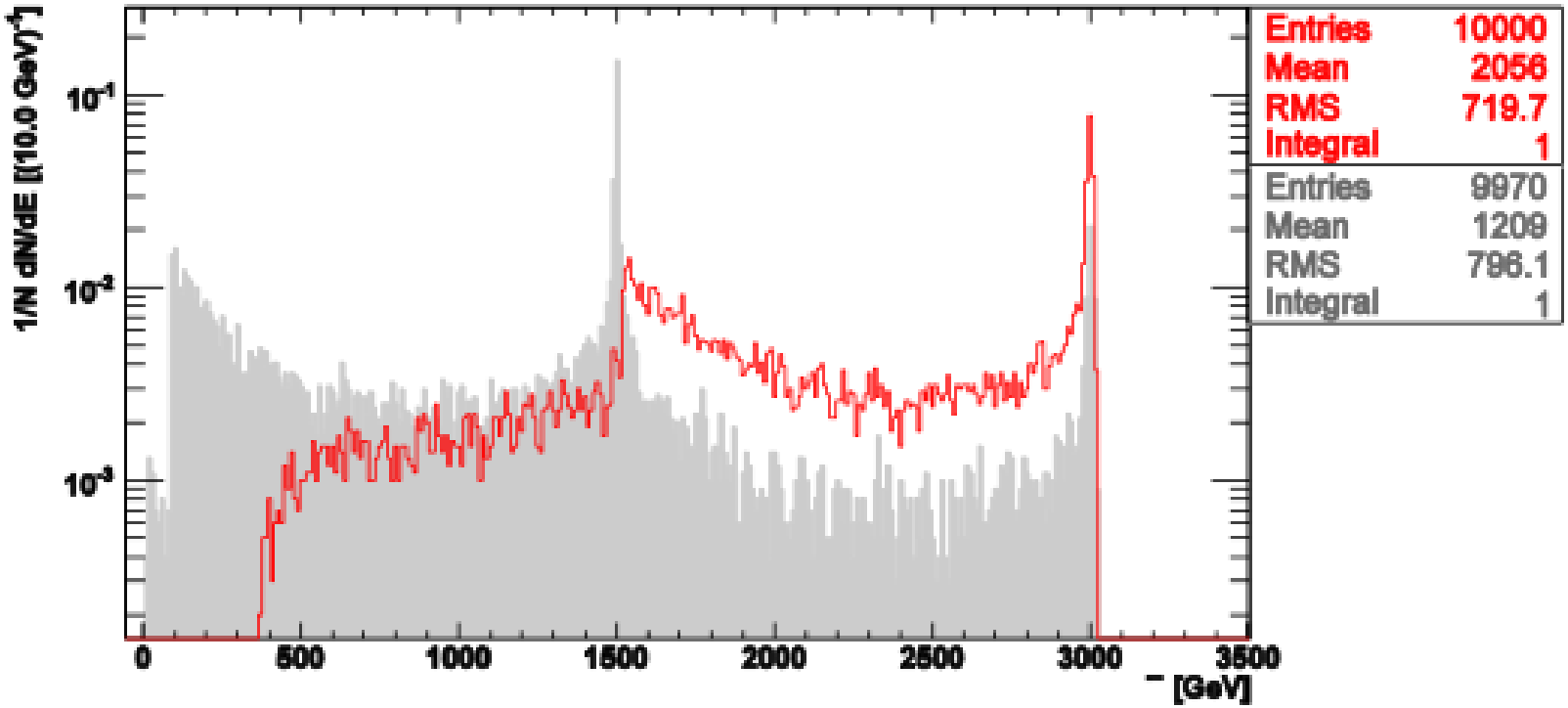

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Even correlated beam spectra supported now!

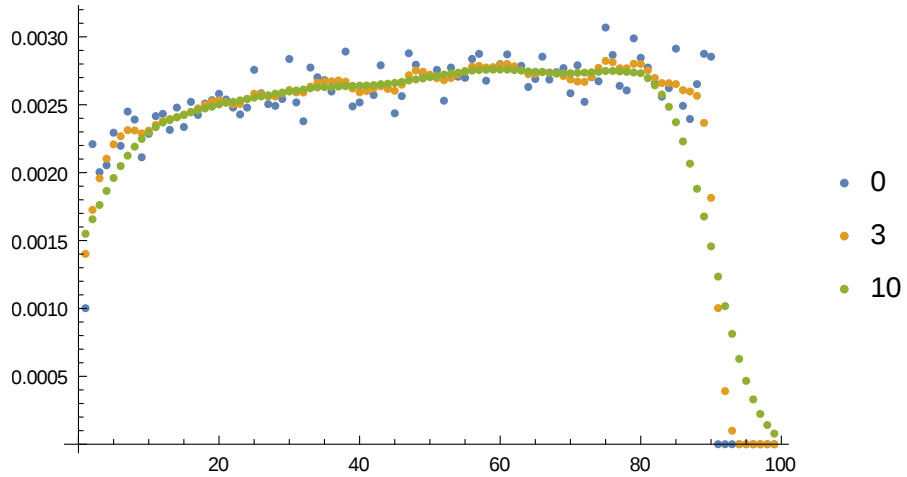
Correlated lepton beam spectra with `Circe2`

- `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

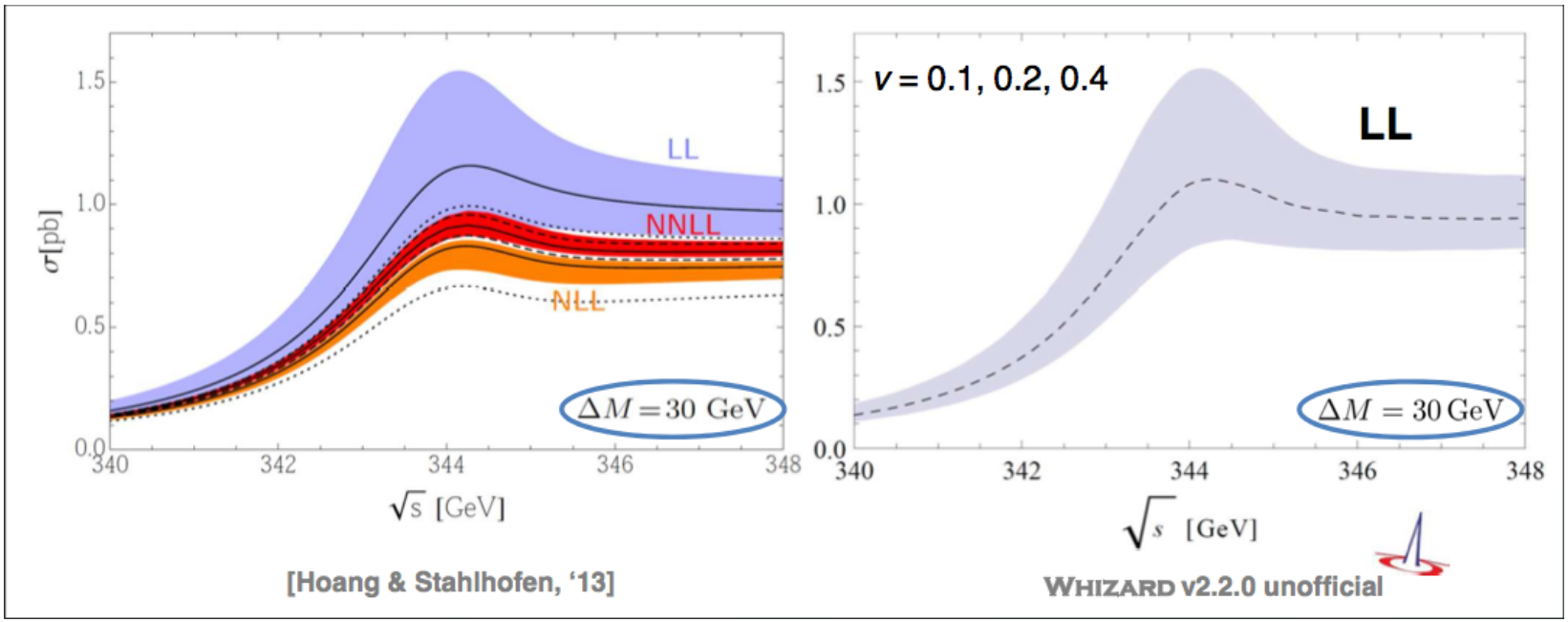
3. Run WHIZARD with SINDARIN input:

   ```
   beams = e1, E1 => circe2
   $circe2_file = "ilc500.circe"
   $circe2_design = "ILC"
   ?circe_polarized = false
   ```

- Soon also files for polarized beams within distribution

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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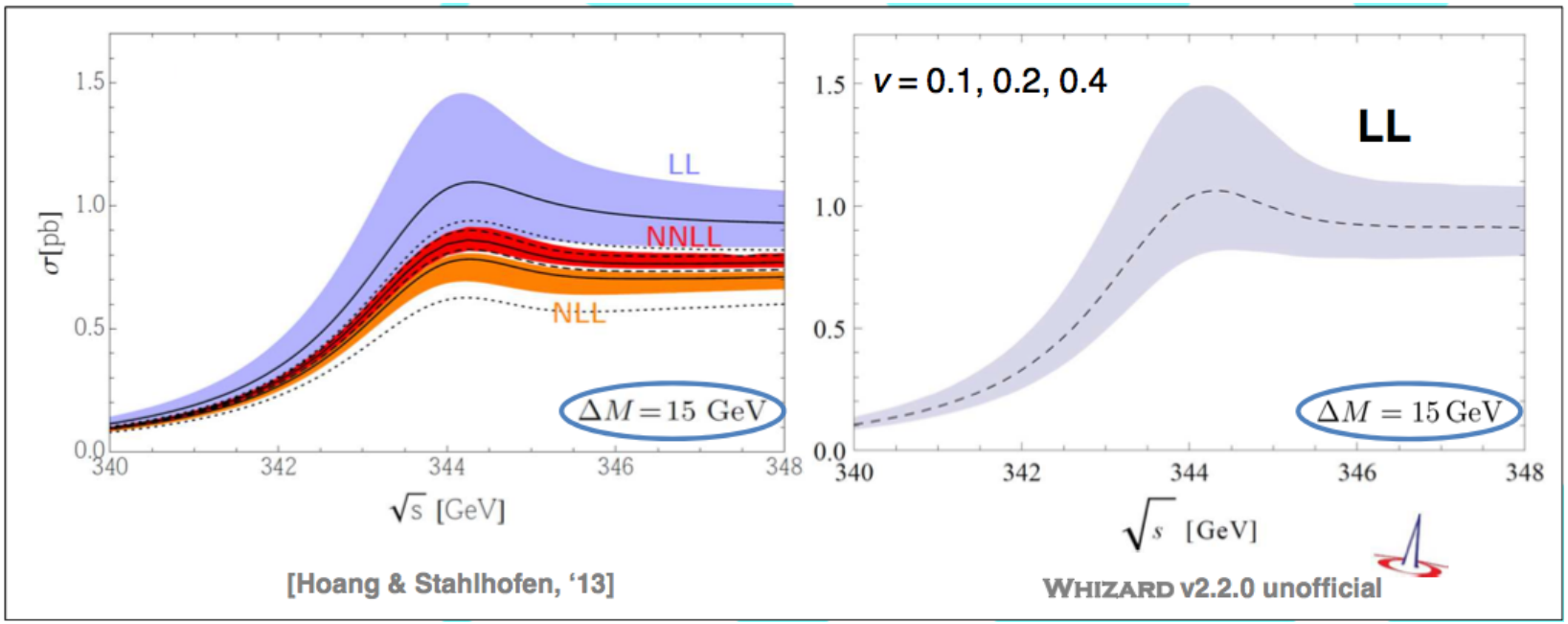

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- Proper NLO/NLL matched implementation — Bach/Hoang/JRR/Stahlhofen/Teubner
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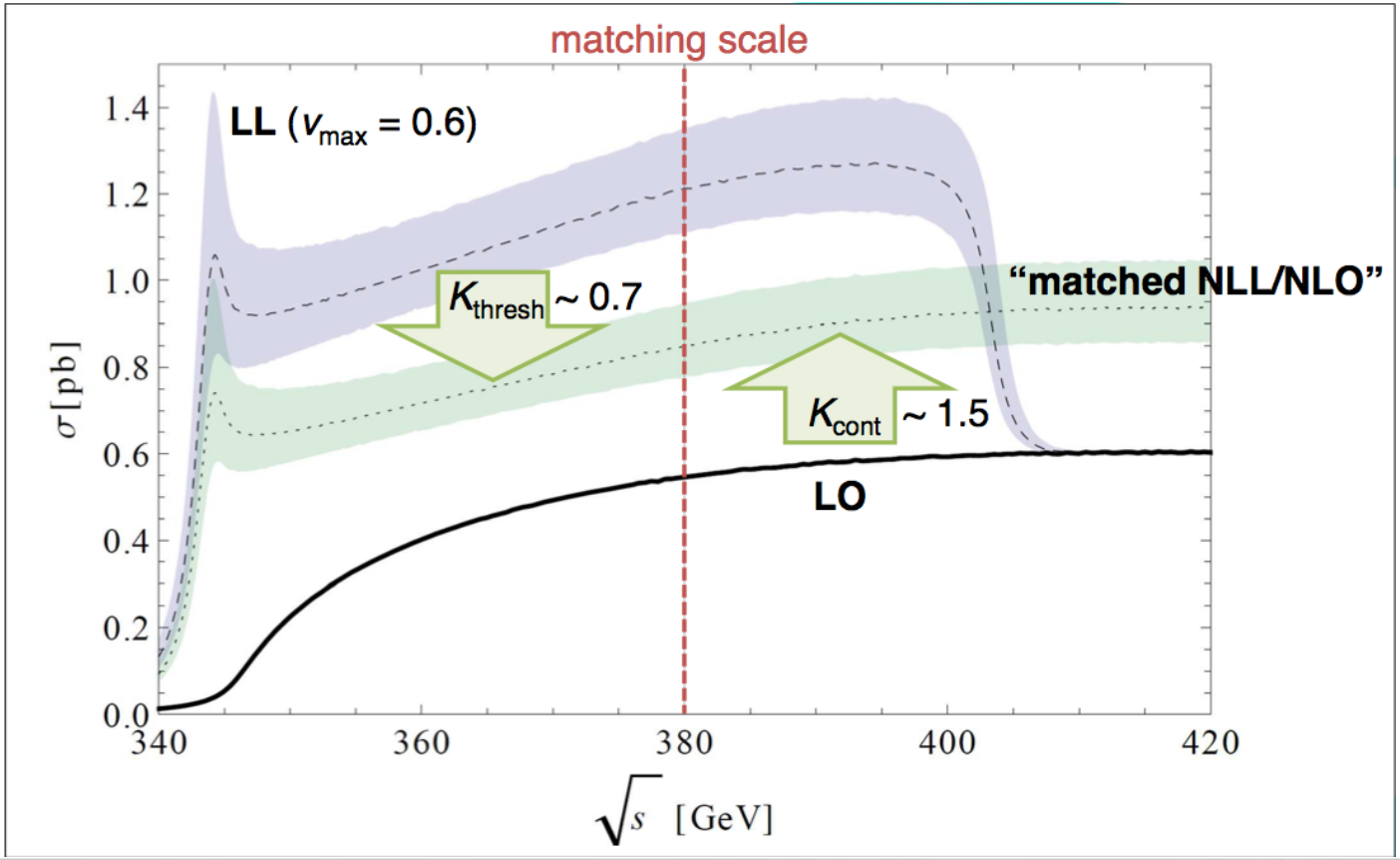
- Parameters: `wtop`, `m1S`, `vsoft`, `match`



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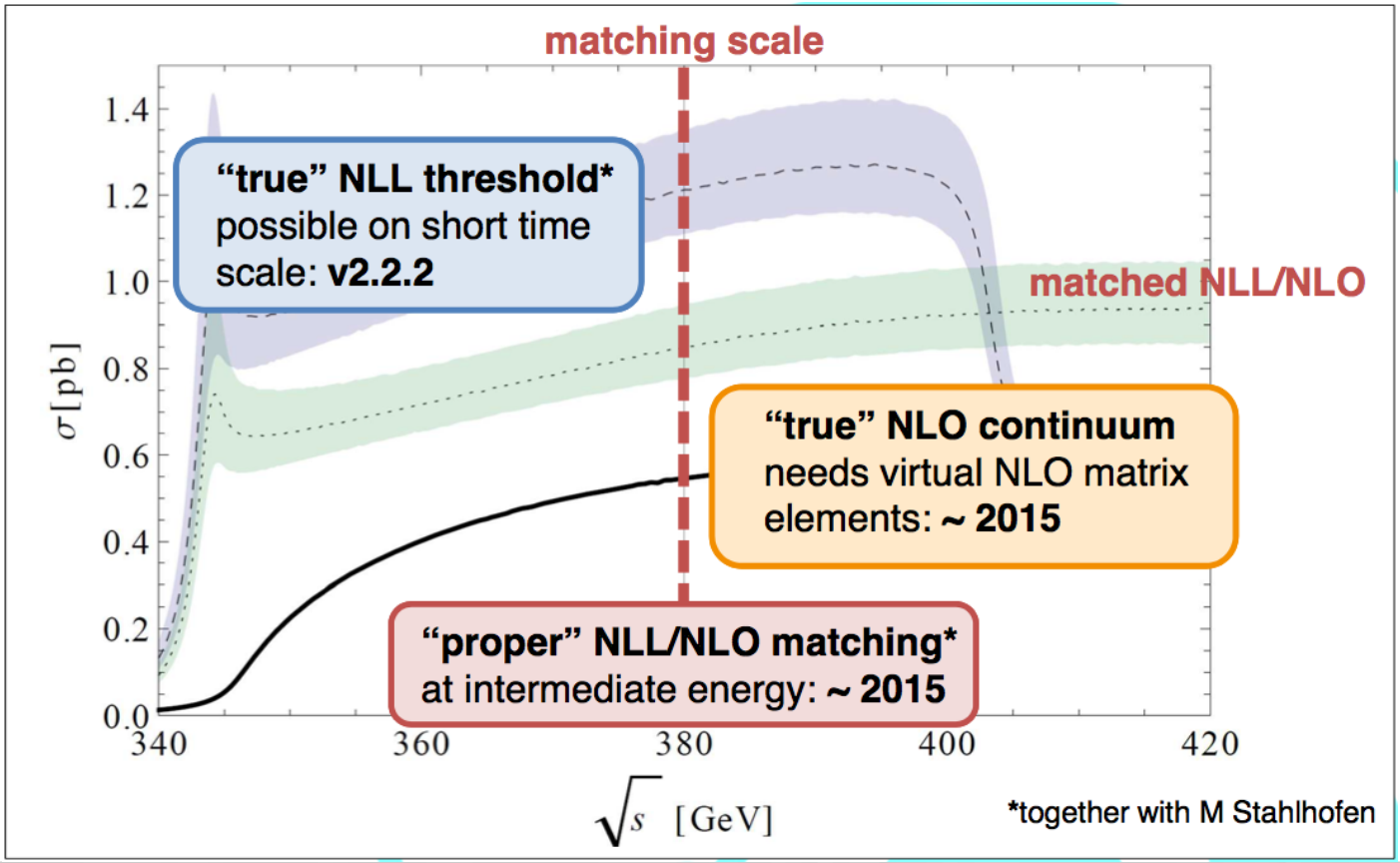

Status of NLO development in WHIZARD

- BLHA interface: workflow Speckner, 2012; JRR/Weiss, 2014
  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`)

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  - Release: `WHIZARD 3.0`

News 2014/early 2015: upcoming releases 2.3-2.4

- **New features in production version 2.2**
  - LHAPDF 6 support, FastJet interface ✓
  - ILC TDR beam spectra (`CIRCE1`), CLIC (correlated) spectra (`CIRCE2`) ✓
  - Direct Guinea-Pig interface ✓
  - Complete Reweighting of Event Samples (incl. LHEF 2013) ✓
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- **Features in preparation: 2.3 – 2.4**
  - BSM: general Lorentz structures in matrix-element generator (O'Mega)
  - LCIO support (in prep.)
  - O'Mega Virtual Machine for faster and (much) smaller code (test phase)
  - Performance: parallelization, flavor sums, MC over helicities/colors, PS, etc.
  - Matched $e^+e^- \to$ jets at LO and NLO, POWHEG box formalism JRR/Weiss, 2015
  - NLL/NLO matched e^+e^- top threshold (test phase) Bach/Hoang/JRR/Stahlhofen
  - New syntax/features decays and chains (steering unstable particles):

```
process higgsstr = e1, E1 => (Z => e2, E2), (H => b, bbar)
```

  - Improved matching/merging for jets/photons Chokoufé/JRR/Kilian/Weiss, ca. 2015
  - Specification of QCD and electroweak order
  - Automatic QCD NLO corrections (massless) (test phase)

Summary and Outlook

- WHIZARD 2 for LC & LHC physics and beyond
- Versatile, user-friendly & highly reliable tool
- Covers the whole SM, and most possible paths beyond (BSM)
- Highest-possible support for lepton collider physics
- Immense internal technical improvements
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Let us know of your needs!

whizard@desy.de

2nd International WHIZARD Forum 16.-18.3.2015

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- Higher orders and automation
- Parton shower, matching and merging
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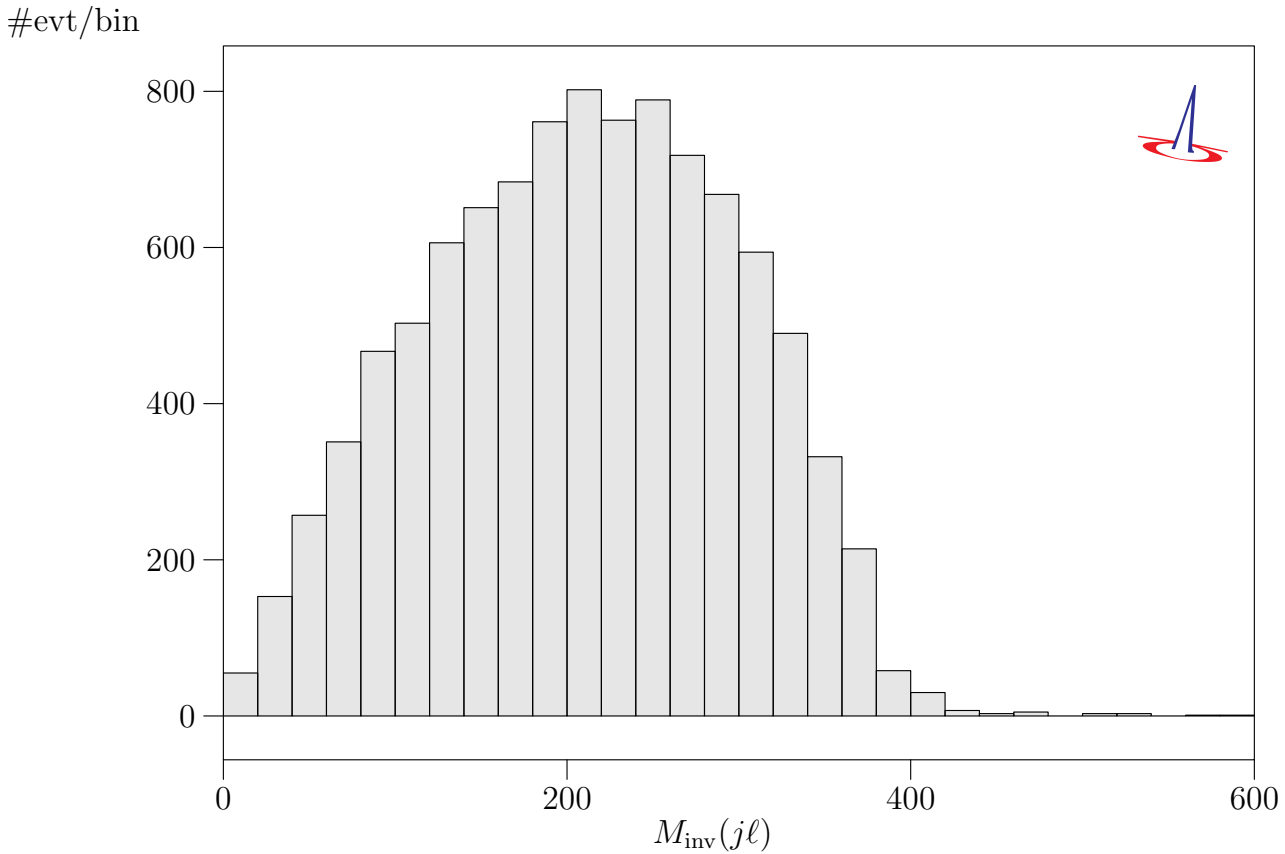
BACKUP SLIDES:

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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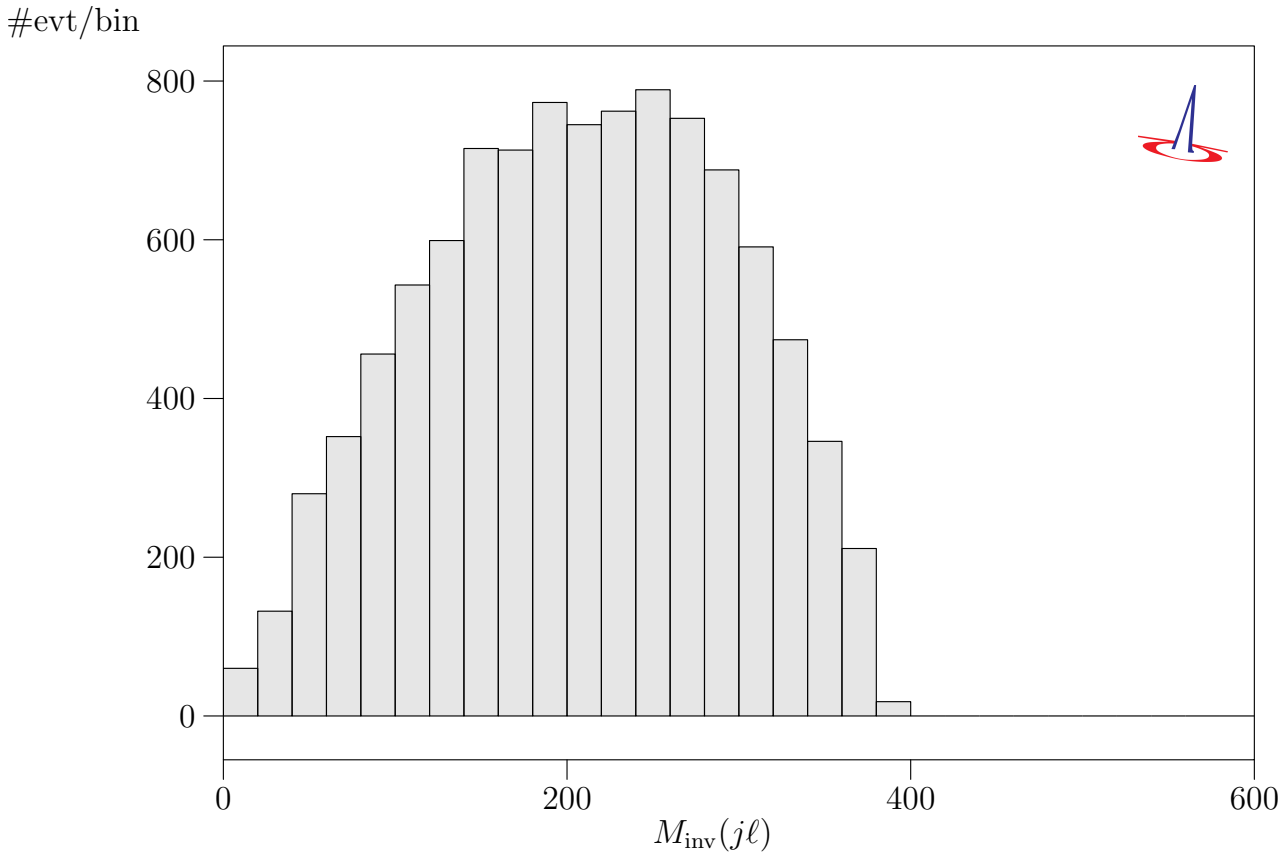

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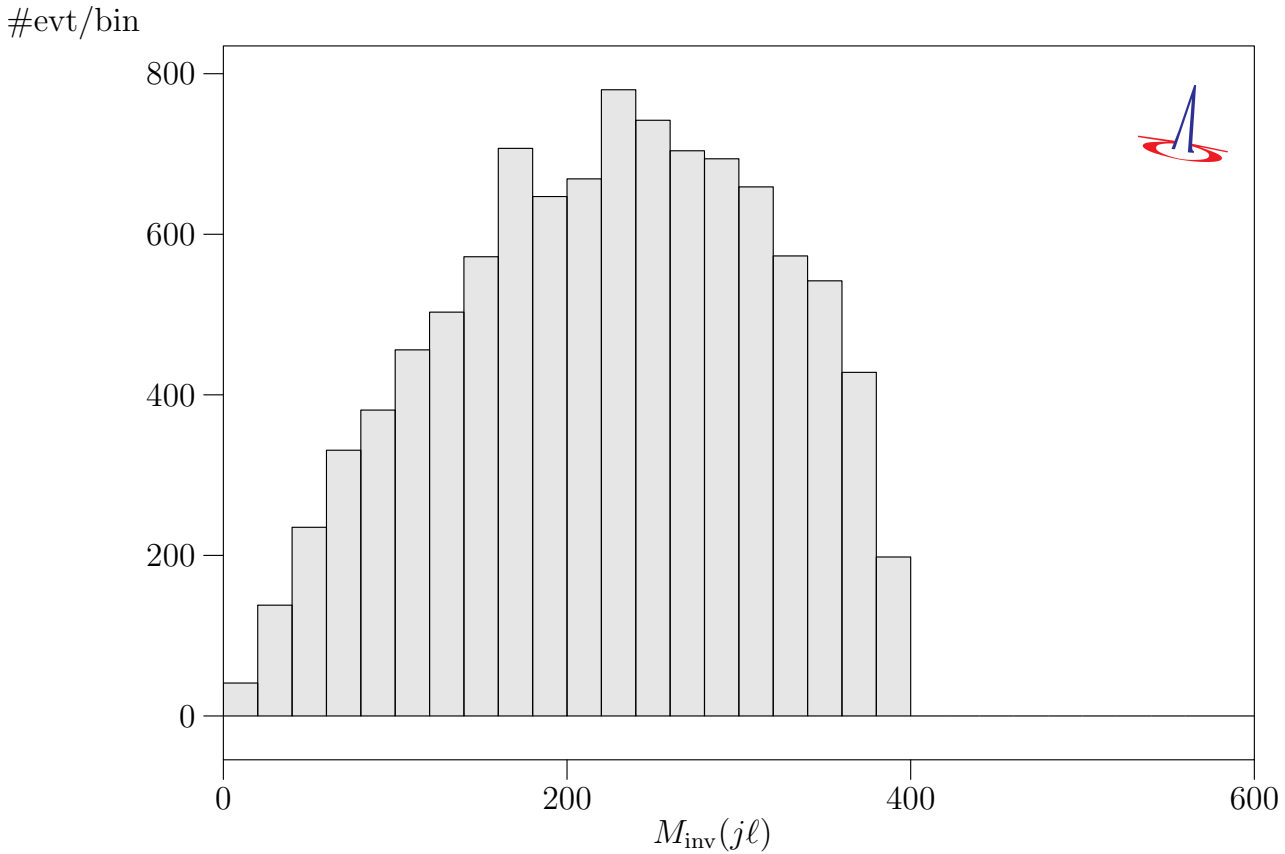

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