Status of the WHIZARD Generator

Workshop on the Circular Electron-Positron Collider,
EU Edition 2019
Oxford, UK, April 15 - 17, 2019

Jürgen R. Reuter, DESY
Status of the WHIZARD Generator

In Wizard’s Isle still lay forgot, enmeshed and tortured in that grot cold, evil, doorless, without light, and blank-eyed stared at endless night two comrades. Now alone they were. The others lived no more, but bare their broken bones would lie and tell how ten had served their master well.

J.R.R. Tolkien, Lay of Leithian, Canto 9
WHIZARD: Introduction / Technical Facts

WHIZARD v2.7.1 (27.03.2019)  http://whizard.hepforge.org  <whizard@desy.de>

WHIZARD Team:  Wolfgang Kilian, Thorsten Ohl, JRR
Simon Braß / Nils Kreher / Vincent Rothe / So Young Shim / Pascal Stienemeier

PUBLICATIONS


- Programming Languages:  Fortran2008 (gfortran ≥5.1.0), OCaml (≥3.12.0)
- Standard installation:  configure <FLAGS>, make, [make check], make install
- Installed centrally, production runs in specific workspaces
- Large self test suite, unit tests [module tests], regression testing
- Continous integration system (gitlab CI @ Siegen)

WHIZARD: Introduction / Technical Facts

- Universal event generator for lepton and hadron colliders (SM and BSM physics)
- Tree ME generator O’Mega optimized ME generator
- Generator/simulation tool for lepton collider beam spectra: CIRCE1/2

- Interfaces to external packages:
  FastJet, GoSam, GuineaPig(++, HepMC, HOPPET, LCIO, LHAPDF(5/6), LoopTools, OpenLoops, PYTHIA6 [internal], PYTHIA8, Recola, StdHep [internal], Tauola [internal]

- Scattering processes (2→10 etc.) and [auto-] decays, factorized processes
- Scripting language for the steering: SINDARIN
- Beam structure: polarization, asymmetric beams, crossing angle, structured beams, decays

```
beams = e1, E1
beams_pol_density = @(−1), @(+1)
beams_pol_fraction = 80%, 30%
```

```
beams = p, p => lhapdf
$lhapdf = "NNPDF3"
```

```
beams = e1, E1 => circe2 => isr => ewa
```
WHIZARD: Past and recent timeline (I)

- Original scope: electroweak (multi-fermion) studies at 1.6 TeV TESLA [≈ 1998–2000]
- Milestone: first-ever multi-leg implementation of MSSM v1.25 [2003]
- Color flow formalism [≈2005]
- Used for many TESLA studies and most ILC CDR and TDR, CLIC CDR and detector Lol studies (versions v1.24, v1.50, v1.95) [≈ 2002–2013]

**Major refactoring phase I:** LHC physics → v2.0.0 [≈ 2007–2010; 38 months]
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**Major refactoring phase I:** LHC physics \( \rightarrow \) v2.0.0 \( \approx 2007–2010; \) **38 months**

Validation inside ATLAS and CMS \( \approx 2011–2014 \)

**Refactoring phase II:** NLO automation / maintainability \( \rightarrow \) v2.2.0

\[ \approx 2012–2014; \) **18 months**

Strong interest of CEPC group for CEPC simulations \( \approx 2013 — \) now

04/2015, ALCW’15 Tokyo: LC generator group endorsed v2.2 for new mass productions

FCC-ee interest in simulations: [ca. spring 2016]

**Refactoring phase III:** first NLO implementation overhaul [2016; **3 months**]
WHIZARD: Past and recent timeline (II)

Final validation for $e^+e^-$ physics between v1.95 & v2  [until end of 2017, partially mid 2018]

Special thanks to:  [beam spectra, photon background, event formats, shower/hadronization, tau decays]

Mikael Berggren  Jean-Jacques Blaising  Moritz Habermehl  Mo Xin  Akiya Miyamoto  Tim Barklow  Philipp Roloff  Junping Tian
WHIZARD: Past and recent timeline (II)

Final validation for $e^+e^-$ physics between v1.95 & v2 [until end of 2017, partially mid 2018]

Special thanks to: [beam spectra, photon background, event formats, shower/hadronization, tau decays]

01/2018, CERN, LC generator meeting: only trivial minor, ready for mass production

Refactoring phase IV: core data structure overhaul: NLO [fall 2018; ca. 2-3 months]
[dust-layer buried students, total-code-no-man-wasteland alarm]

Preparation for WHIZARD 3.0.0α started: ... PARALLEL TO ....

Work on: [NLO QCD final validation; structure functions; NLO EW; shower and matching/merging]

(Technical) refactoring phase V: code modernization (submodules etc: gfortran 6.1+)
[fall / winter of 2019; when NAG debugging compiler support ready]

Mikael Berggren  Jean-Jacques Blaising  Moritz Habermehl  Mo Xin  Akiya Miyamoto  Tim Barklow  Philipp Roloff  Junping Tian
Examples for $e^+e^- \rightarrow thh$ @ 1 TeV in 8 jets

```
6  / 25

SLAC

Seiten / Home / Data Samples

Standard Model Data Samples

Angell von Timothy Behnke, zuletzt geändert am 03 12, 2019

<table>
<thead>
<tr>
<th>Lumi_linker number</th>
<th>Ecm(GeV)</th>
<th>General Description</th>
<th>Machine Configuration</th>
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<td>2</td>
<td>500</td>
<td>RDR (Jul 2006)</td>
<td>rdr</td>
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<tr>
<td>3</td>
<td>350</td>
<td>RDR (Aug 2005)</td>
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<tr>
<td>4</td>
<td>250</td>
<td>RDR (Aug 2005) but do_isr=T (ISR turned on by mistake)</td>
<td>rdr_isr_on</td>
</tr>
<tr>
<td>5</td>
<td>250</td>
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<td>rdr_beams_swapped</td>
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<td>TDR_ws</td>
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</tbody>
</table>
```

“SLAC DBD samples” and more: full SM!
High-energy e⁺e⁻ colliders need to achieve extreme luminosities

**Price for limited AC power:** high bunch charges and tiny bunch cross sections

Dense beams generate strong EM fields: deflect particles in other bunch (beamstrahlung)

\[ L \approx \frac{N}{4\pi \sigma_x \sigma_y} \frac{\eta P_{AC}}{E_{CM}} \]
High-energy e+e- colliders need to achieve extreme luminosities

Price for limited AC power: high bunch charges and tiny bunch cross sections

Dense beams generate strong EM fields: deflect particles in other bunch (beamstrahlung)
• Adapt GuineaPig beam spectra for WHIZARD v2
• For WHIZARD v1.95 simulations done by Lumilinker [T.Barklow]
• TESLA/SLC spectra were rather simple
• Fits with 6 or 7 parameters possible [CIRCE1]
• Beams not factorizable: $D_{B_1 B_2}(x_1, x_2) \neq D_{B_1}(x_1) \cdot D_{B_2}(x_2)$
• No simple power law: $D_{B_1 B_2}(x_1, x_2) \neq x_1^{\alpha_1} (1 - x_1)^{\beta_1} x_2^{\alpha_2} (1 - x_2)^{\beta_2}$
- Adapt GuineaPig beam spectra for WHIZARD v2
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Tesla, \( \sqrt{s} = 500 \text{GeV} \)

\[
\begin{align*}
\text{Dalena/Esbjerg/Schulte [LCWS 2011]} \\
\text{Tails @ CLIC much more complicated (wakefields)}
\end{align*}
\]
Lepton Collider Beam Simulation

- Adapt GuineaPig beam spectra for WHIZARD v2
- For WHIZARD v1.95 simulations done by Lumilinker [T. Barklow]
- TESLA/SLC spectra were rather simple
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- No simple power law:  
  \[ D_{B_1 B_2}(x_1, x_2) \neq x_1^{\alpha_1} (1 - x_1)^{\beta_1} x_2^{\alpha_2} (1 - x_2)^{\beta_2} \]

CIRCE2 algorithm (WHIZARD 2.2.5, 02/15)

- Adapt 2D factorized variable width histogram to steep part of distribution
- Smooth correlated fluctuations with moderate Gaussian filter [suppresses artifacts from limited GuineaPig statistics]
- Smooth continuum/boundary bins separately [avoid artificial beam energy spread]

Dalena/Esbjerg/Schulte [LCWS 2011]

Tails @ CLIC much more complicated (wakefields)
Iterations of Beam Spectrum

(171,306 GuineaPig events in 10,000 bins)
Iterations of Beam Spectrum

- \textbf{iterations} = 0 and \textbf{smooth} = 0, 3, 5:

- \textbf{iterations} = 2 and \textbf{smooth} = 0, 3, 5:

- \textbf{iterations} = 4 and \textbf{smooth} = 0, 3, 5:
Inclusive Lepton Collider ISR included

Soft exponentiation to all orders

\[ \epsilon = \frac{\alpha}{\pi} q^2 e \ln \left( \frac{s}{m^2} \right) \]

\[ f_0(x) = \epsilon \cdot (1 - x)^{-1+\epsilon} \]

Gribov/Lipatov, 1971

Hard-collinear photons up to 3rd QED order
Soft exponentiation to all orders
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Hard-collinear photons up to 3rd QED order
Kuraev/Fadin, 1983; Skrzypek/Jadach, 1991

\[ g_3(\epsilon) = 1 + \frac{3}{4} \epsilon + \frac{27 - 8\pi^2}{96} \epsilon^2 + \frac{27 - 24\pi^2 + 128\zeta(3)}{384} \epsilon^3 \]

\[ f_3(x) = g_3(\epsilon) f_0(x) - \frac{\epsilon}{2} (1 + x) \]
\[ - \frac{\epsilon^2}{8} \left( \frac{1 + 3x^2}{1 - x} \ln x + 4(1 + x) \ln(1 - x) + 5 + x \right) \]
\[ - \frac{\epsilon^3}{48} \left( (1 + x) \left[ 6 Li_2(x) + 12 \ln^2(1 - x) - 3\pi^2 \right] + 6(x + 5) \ln(1 - x) \right. \]
\[ + \frac{1}{1 - x} \left[ \frac{3}{2} (1 + 8x + 3x^2) \ln x + 12(1 + x^2) \ln(x \ln(1 - x)) \right. \]
\[ - \frac{1}{2} (1 + 7x^2) \ln^2 x + \frac{1}{4} (39 - 24x - 15x^2) \right] \]

\[ \zeta(3) = 1.20205690315959428539973816151 \ldots \]
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Hard-collinear photons up to 3rd QED order

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One explicit ISR photon / beam: ISR/EPA handler generates physical \( p_T \) distributions

Explicit matching needed: heuristic procedures LO \( \cdots \) \textit{tbd} for NLO!

Collinear structure functions: plans for implementations of YFS / different schemes
Phase Space Integration

- VAMP: adaptive multi-channel Monte Carlo integrator
- VAMP2: fully MPI-parallelized version, using RNG stream generator

WHIZARD algorithm: heuristics to classify phase-space topology, adaptive multi-channel mapping \(\implies\) resonant, t-channel, radiation, infrared, collinear, off-shell

Complicated processes: factorization into production and decay with the unstable option

Resonance-aware factorization for NLO processes and parton showers (e.g. \(e^+e^- \rightarrow jjjj\))
Event generation trivially parallelizable

**Major bottleneck:** adaptive phase space integration (generation of grids)

Parallelization of integration: OMP multi-threading for different helicities since long

**NEW (after v2.5.0/2.6.4/2.7.1):** MPI parallelization (using OpenMPI or MPICH)

Distributes workers over multiple cores, grid adaption needs non-trivial communication

Amdahl’s law: \[ S = \frac{1}{1-p+\frac{p}{N}} \]

Speedups of 10 to 30, saturation at \( O(100) \) tasks

Integration times go down from weeks to hours! [can do also parallel event generation]

Load balancer is being implemented [expected for v2.8.0]

\[ T = \frac{p}{N} \]

\[ p = 1.0 \]

\[ p = 0.9 \]

\[ e^+e^- \rightarrow \mu^+\mu^- \]

\[ e^+e^- \rightarrow \mu^+\mu^- \bar{\nu}_\mu \bar{\nu}_\mu \]

\[ jj \rightarrow W_j \]

\[ jj \rightarrow Wjj \]

\[ jj \rightarrow Wg \]

\[ jj \rightarrow Wgg \]
Ballestrero et al., 1803.07943

<table>
<thead>
<tr>
<th>Code</th>
<th>$\sigma$ [fb]</th>
</tr>
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<tbody>
<tr>
<td>BONSAY</td>
<td>1.43636 ± 0.00002</td>
</tr>
<tr>
<td>MG5_aMC</td>
<td>1.4304 ± 0.0007</td>
</tr>
<tr>
<td>MoCaNLO+Recola</td>
<td>1.43476 ± 0.00009</td>
</tr>
<tr>
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<td>WHIZARD</td>
<td>1.4381 ± 0.0002</td>
</tr>
</tbody>
</table>

$\sigma$ = $\alpha_s^6$, $\alpha_s^2\alpha_s^4$, $\alpha_s^3\alpha_s^3$

$\sigma$ (LO) = $2.292 \pm 0.002$, $\alpha_s^6$

$\sigma$ (LO+PS) = $1.477 \pm 0.001$, $\alpha_s^2\alpha_s^4$

$\sigma$ (MoCaNLO+Recola) = $0.223 \pm 0.003$, $\alpha_s^3\alpha_s^3$

$p_T,\ell > 20$ GeV $|y| < 2.5$ $\Delta R_{\ell\ell} > 0.3$

$p_T,\text{miss} > 40$ GeV

Anti-$k_T$ jets with $R = 0.4$:

$p_T,j > 30$ GeV $|y_j| < 4.5$ $\Delta R_{j\ell} > 0.3$

$m_{jj} > 500$ GeV $|\Delta y_{jj}| > 2.5$

Transverse momentum of the leading jet (LO+PS)

<table>
<thead>
<tr>
<th>Code</th>
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<tbody>
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<td>1.342 ± 0.003</td>
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<td>MG5_aMC+Herwig7</td>
<td>1.275 ± 0.003</td>
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<tr>
<td>MG5_aMC+Herwig7, $T_{\text{rec}}$</td>
<td>1.266 ± 0.003</td>
</tr>
<tr>
<td>PHANTOM</td>
<td>1.235 ± 0.001</td>
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<tr>
<td>PHANTOM+Pythia8</td>
<td>1.258 ± 0.001</td>
</tr>
<tr>
<td>VBFNLO+Herwig7-Dipole</td>
<td>1.3001 ± 0.0002</td>
</tr>
<tr>
<td>WHIZARD+Pythia8</td>
<td>1.229 ± 0.001</td>
</tr>
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</table>
LHC VBS: Comparison LO & LO+PS

Ballestrero et al., 1803.07943

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\[ \sigma \,[\text{fb}] \]

\( 2.292 ± 0.002 \) | \( 1.477 ± 0.001 \) | \( 0.223 ± 0.003 \)

\( p_{T,\ell} > 20 \text{ GeV} \) \( |y_{\ell}| < 2.5 \) \( \Delta R_{\ell\ell} > 0.3 \)

\( p_{T,\text{miss}} > 40 \text{ GeV} \)

Anti-\( k_T \) jets with \( R = 0.4 \):

\( p_{T,j} > 30 \text{ GeV} \) \( |y_j| < 4.5 \) \( \Delta R_{j\ell} > 0.3 \)

\( m_{jj} > 500 \text{ GeV} \) \( |\Delta y_{jj}| > 2.5 \)

Rapidity of the subleading jet (LO+PS)

- NLO (fixed order)
- MG5\_aMC+H7-Default
- MG5\_aMC+Py8
- PHANTOM+Py8
- VBFNLO +H7-Dipole
- WHIZARD+Py8
- WHIZARD+H7-Default
**LHC VBS: Comparison LO & LO+PS**

First official use of MPI-parallelized phase space & first published application of WHIZARD & HERWIG showering

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<td>1.4274 ± 0.0006</td>
</tr>
<tr>
<td>POWHEG</td>
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</tr>
<tr>
<td>VBFNLO</td>
<td></td>
</tr>
<tr>
<td>WHIZARD</td>
<td></td>
</tr>
</tbody>
</table>

$\frac{d}{d\Delta y_{jj}} \sigma$ [fb] [GeV]

<table>
<thead>
<tr>
<th>Ratio /MoCaNLO+Recola</th>
<th>500</th>
<th>1000</th>
<th>1500</th>
<th>2000</th>
<th>2500</th>
<th>3000</th>
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<tr>
<td>BONSAY</td>
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<tr>
<td>MG5_aMC</td>
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<tr>
<td>MoCaNLO+Recola</td>
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<td>1.0</td>
<td>1.0</td>
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**LO+PS**

- $p_{T,\ell} > 20$ GeV
- $|y_{\ell}| < 2.5$
- $\Delta R_{\ell\ell} > 0.3$
- $p_{T,\text{miss}} > 40$ GeV
- Anti-$k_T$ jets with $R = 0.4$

**LO**

- $p_{T,j} > 30$ GeV
- $|y_j| < 4.5$
- $m_{jj} > 500$ GeV
- $|y_{jj}| > 2.5$
Keep resonances in ME-PS merging

- **Problem:**  $	ext{e}^+\text{e}^- \rightarrow jjjj$ not dominated by highest $\alpha_s$ power, but by resonances $\text{e}^+\text{e}^- \rightarrow WW/ZZ \rightarrow (jj)(jj)$

- **Solution:** proper merging with resonant subprocesses by means of resonance histories

- **WHIZARD v2.6.0:** option to set resonance histories

```plaintext
?resonance_history = true
resonance_on_shell_limit = 4
resonance_on_shell_turnoff = 1
resonance_background_factor = 1e-10
```
Keep resonances in ME-PS merging

- **Problem:** \(e^+e^- \rightarrow jjjj\) not dominated by highest \(\alpha_s\) power, but by resonances \(e^+e^- \rightarrow WW/ZZ \rightarrow (jj)(jj)\)

- **Solution:** proper merging with resonant subprocesses by means of resonance histories

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```plaintext
#jets

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Keep resonances in ME-PS merging

- **Problem:** \( e^+e^- \rightarrow jjjj \) not dominated by highest \( \alpha_s \) power, but by resonances \( e^+e^- \rightarrow WW/ZZ \rightarrow (jj)(jj) \)
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Keep resonances in ME-PS merging

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- **Solution:** proper merging with resonant subprocesses by means of resonance histories

- **WHIZARD v2.6.0:** option to set resonance histories

\[
\begin{align*}
\text{resonance}_\text{history} &= \text{true} \\
\text{resonance}_\text{on}_\text{shell}_\text{limit} &= 4 \\
\text{resonance}_\text{on}_\text{shell}_\text{turnoff} &= 1 \\
\text{resonance}_\text{background}_\text{factor} &= 1e-10
\end{align*}
\]

- **LC Generator Group** first successful tests on \(e^+e^- \rightarrow 6j\); includes tests w/ resonant \(H \rightarrow bb\)
Scanning parameter space of BSM models (or SM templates)

**Major bottleneck:** MC samples have to be produced over and over again

**Feature:** rescanning of event files with different setup

**Assumption:** phase space is identical, sampling can be done in the same way

**NEW v2.7.0:** works also w/ differently concatenated structure functions (e.g. ISR + beamstr.)

**Open issues:** rescanning with resonance matching in showered events
**Event Formats**

**Event formats:** conventions for outputting details of the events

```plaintext
sample_format = hepmc
sample_format = lhef \{$lhef_version = "3.0"\}
sample_format = stdhep, stdhep_up, stdhep_ev4
sample_format = ascii, debug, mokka, lha
sample_format = lcio
simulate (<process>)
```

- **External format, ASCII:** HepMC [Dobbs/Hansen, 2001]
- **External format, binary:** LCIO [Gaede, 2003]
- **Internal formats, binary:** StdHEP [Lebrun, 1990]
- **Internal formats, ASCII:** LHA, LHEF [Alwall et al., 2006]
Event Formats

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- External format, binary: LCIO [Gaede, 2003]
- Internal formats, binary: StdHEP [Lebrun, 1990]
- Internal formats, ASCII: LHA, LHEF [Alwall et al., 2006]

LCIO Format (LC I/O, particle-flow motivated): (ASCII transcription from binary)

```plaintext
Event : 1 - run: 0 - timestamp [...]

date: [...]
detector : unknown
event parameters:
  parameter Event Number [int]: 1,
  parameter ProcessID [int]: 1,
  parameter Run ID [int]: 0,
  parameter beamPDG0 [int]: 11,
  parameter beamPDG1 [int]: -11,
  parameter Energy [float]: 500,
  parameter Pol0 [float]: 0,
  parameter Pol1 [float]: 0,
  parameter _weight [float]: 1,
  parameter alphaQCD [float]: 0.1178,
  parameter crossSection [float]: 338.482,
  parameter crossSectionError [float]: 7.2328,
  parameter scale [float]: 500,
  parameter BeamSpectrum [string]: ,
  parameter processName [string]: lcio_5_p,
  collection name : MCParticle

parameters:
---- print out of MCParticle collection -----
flag: 0x0
  simulator status bits: [sbvtcls] s: created in simulation b: backscatter v: vertex is not endpoint of parent t: decayed in tracker c: decayed in calorimeter l: has left detector s: stopped o: overlay
  energy [gen] | vertex x, y, z | mass | charge | spin | colorflow | [par] - [dau]
[hec000084] 11 | 0.00e+00, 0.00e+00, 2.50e+02 | 2.50e+02 | 3 | [ 0 ] | 0.0, 0.0, 0.0, 0.0 | 5.11e-04 | 1.00e+00 | 0, 0, 0, 0, 0 | (0, 0) | [] - [2.3]
[hec000085] 11 | 0.00e+00, 0.00e+00, -2.50e+02 | 2.50e+02 | 3 | [ 0 ] | 0.0, 0.0, 0.0, 0.0 | 5.11e-04 | 1.00e+00 | 0, 0, 0, 0, 0 | (0, 0) | [] - [2.3]
[hec000086] 11 | 1.42e+02, 1.99e+02, -5.22e+01 | 2.50e+02 | 3 | [ 0 ] | 0.0, 0.0, 0.0, 0.0 | 1.06e-01 | 1.00e+00 | 0, 0, 0, 0, 0 | (0, 0) | [0, 1] - [1]
[hec000087] 11 | -1.42e+02, -1.99e+02, 5.22e+01 | 2.50e+02 | 3 | [ 0 ] | 0.0, 0.0, 0.0, 0.0 | 1.06e-01 | 1.00e+00 | 0, 0, 0, 0, 0 | (0, 0) | [0, 1] - [1]
```
<table>
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- Automated models: **UFO interface**  
  [new WHIZARD/0’Mega model format]
Models from UFO Files in WHIZARD

model = SM (ufo)

UFO file is assumed to be in working directory OR

model = SM (ufo ("<my UFO path>"))

UFO file is in user-specified directory

```
WHIZARD 2.5.1

Reading model file '/Users/reuter/local/share/whizard/models/SM.mdl'
Preloaded model: SM
Process library 'default_lib': initialized
Preloaded library: default_lib
Reading model file '/Users/reuter/local/share/whizard/models/SM_hadrons.mdl'
Reading commands from file 'ufo_2.sin'
Model: Generating model 'SM' from UFO sources
Model: Searching for UFO sources in working directory
Model: Found UFO sources for model 'SM'
Model: Model file 'SM.ufo.mdl' generated
Reading model file 'SM.mdl'

Switching to model 'SM' (generated from UFO source)
```

All the setup works the same as for intrinsic models

Old FeynRules / SARAH interface will get deprecated

kept at the moment for user backwards compatibility
Modeling from UFO Files in WHIZARD

- **model = SM (ufo)**
- **model = SM (ufo ("<my UFO path>")**)

UFO file is assumed to be in the working directory OR

- UFO file is in the user-specified directory

Old FeynRules / SARAH interface will get deprecated kept at the moment for user backwards compatibility

- **WHIZARD 2.8.0** Release will contain full UFO support (Mid/end June 2019)
- New version will demand OCaml ≥4.02.3
NLO Automation in WHIZARD

Working NLO interfaces to:

- GoSam [N. Greiner, G. Heinrich, J. v. Soden-Fraunhofen et al.]
- OpenLoops [F. Cascioli, J. Lindert, P. Maierhöfer, S. Pozzorini]
- Recola [A. Denner, L. Hofer, J.-N. Lang, S. Uccirati]

NLO QCD (massless & massive) fully supported

- alpha_power = 2
- alphas_power = 0
- process eett = e1,E1 => j, j, j
  \{ nlo_calculation = “full” \}

- FKS subtraction [Frixione/Kunszt/Signer, hep-ph/9512328]
- Resonance-aware treatment [Ježo/Nason, 1509.09071]
- Virtual MEs external
- Real and virtual subtraction terms internal
- NLO decays available for the NLO processes
- Fixed order events for plotting (weighted)
- Automated POWHEG damping and matching
- NLO QCD: final validation  
- NLO EW started

Approaching WHIZARD 3.0.0α  (ca. end 2019)
## Validation of NLO QCD for ee/pp Collisions

<table>
<thead>
<tr>
<th>Process</th>
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</tr>
</thead>
<tbody>
<tr>
<td>(e^+e^- \to jj)</td>
<td>622.3(5)</td>
<td>639(1)</td>
<td>1.02684</td>
<td>622.73(4)</td>
<td>639.7(2)</td>
<td>1.02725</td>
</tr>
<tr>
<td>(e^+e^- \to jjj)</td>
<td>340.1(2)</td>
<td>317.3(8)</td>
<td>0.93297</td>
<td>342.4(5)</td>
<td>318.6(7)</td>
<td>0.9305</td>
</tr>
<tr>
<td>(e^+e^- \to jjjj)</td>
<td>104.7(1)</td>
<td>103.5(2)</td>
<td>0.98854</td>
<td>105.1(4)</td>
<td>104.4(6)</td>
<td>0.99335</td>
</tr>
<tr>
<td>(e^+e^- \to jjjjj)</td>
<td>22.11(6)</td>
<td>24.36(35)</td>
<td>1.10176</td>
<td>22.80(2)</td>
<td>24.72(59)</td>
<td>1.08421</td>
</tr>
<tr>
<td>(e^+e^- \to b\bar{b})</td>
<td>92.37(6)</td>
<td>94.89(1)</td>
<td>1.02728</td>
<td>92.32(1)</td>
<td>94.78(7)</td>
<td>1.02664</td>
</tr>
<tr>
<td>(e^+e^- \to t\bar{t})</td>
<td>116.5(2)</td>
<td>174.5(6)</td>
<td>1.04994</td>
<td>166.4(1)</td>
<td>175.1(1)</td>
<td>1.05228</td>
</tr>
<tr>
<td>(e^+e^- \to t\bar{t}j)</td>
<td>48.13(5)</td>
<td>53.43(1)</td>
<td>1.11012</td>
<td>48.3(2)</td>
<td>53.66(9)</td>
<td>1.11098</td>
</tr>
<tr>
<td>(e^+e^- \to t\bar{t}jj)</td>
<td>8.614(9)</td>
<td>10.49(3)</td>
<td>1.21777</td>
<td>8.612(8)</td>
<td>10.46(6)</td>
<td>1.21458</td>
</tr>
<tr>
<td>(e^+e^- \to t\bar{t}ttt)</td>
<td>6.45(1) \cdot 10^{-4}</td>
<td>12.21(5) \cdot 10^{-4}</td>
<td>1.89302</td>
<td>6.463(2) \cdot 10^{-4}</td>
<td>12.16(2) \cdot 10^{-4}</td>
<td>1.88147</td>
</tr>
<tr>
<td>(e^+e^- \to b\bar{b}b)</td>
<td>1.644(3) \cdot 10^{-1}</td>
<td>3.60(1) \cdot 10^{-1}</td>
<td>2.1897</td>
<td>1.64(2) \cdot 10^{-1}</td>
<td>3.67(4) \cdot 10^{-1}</td>
<td>2.2378</td>
</tr>
<tr>
<td>(e^+e^- \to t\bar{b}b)</td>
<td>1.819(3) \cdot 10^{-1}</td>
<td>2.92(1) \cdot 10^{-1}</td>
<td>1.6052</td>
<td>1.86(1) \cdot 10^{-1}</td>
<td>2.93(2) \cdot 10^{-1}</td>
<td>1.5752</td>
</tr>
<tr>
<td>(e^+e^- \to t\bar{t}h)</td>
<td>2.018(3)</td>
<td>1.91(6)</td>
<td>0.947</td>
<td>2.02(3)</td>
<td>1.913(3)</td>
<td>0.9461</td>
</tr>
<tr>
<td>(e^+e^- \to t\bar{t}\gamma)</td>
<td>12.7(2)</td>
<td>13.3(4)</td>
<td>1.04726</td>
<td>12.71(4)</td>
<td>13.78(4)</td>
<td>1.08418</td>
</tr>
<tr>
<td>(e^+e^- \to t\bar{t}Z)</td>
<td>4.642(6)</td>
<td>4.95(1)</td>
<td>1.06636</td>
<td>4.64(1)</td>
<td>4.94(1)</td>
<td>1.06467</td>
</tr>
<tr>
<td>(e^+e^- \to t\bar{t}HZ)</td>
<td>3.600(6) \cdot 10^{-2}</td>
<td>3.58(1) \cdot 10^{-2}</td>
<td>0.99445</td>
<td>3.59(1) \cdot 10^{-2}</td>
<td>3.58(2) \cdot 10^{-2}</td>
<td>0.9958</td>
</tr>
<tr>
<td>(e^+e^- \to t\bar{t}\gamma Z)</td>
<td>0.2212(3)</td>
<td>0.2364(6)</td>
<td>1.06873</td>
<td>0.220(1)</td>
<td>0.240(2)</td>
<td>1.09094</td>
</tr>
<tr>
<td>(e^+e^- \to t\bar{t}H)</td>
<td>9.75(1) \cdot 10^{-2}</td>
<td>9.42(3) \cdot 10^{-2}</td>
<td>0.96614</td>
<td>9.748(6) \cdot 10^{-2}</td>
<td>9.58(7) \cdot 10^{-2}</td>
<td>0.98277</td>
</tr>
<tr>
<td>(e^+e^- \to t\bar{t}\gamma)</td>
<td>0.383(5)</td>
<td>0.416(2)</td>
<td>1.08618</td>
<td>0.382(3)</td>
<td>0.420(3)</td>
<td>1.09952</td>
</tr>
<tr>
<td>(e^+e^- \to t\bar{t}ZZ)</td>
<td>3.788(4) \cdot 10^{-2}</td>
<td>4.00(1) \cdot 10^{-2}</td>
<td>1.05597</td>
<td>3.756(4) \cdot 10^{-2}</td>
<td>4.005(2) \cdot 10^{-2}</td>
<td>1.0663</td>
</tr>
<tr>
<td>(e^+e^- \to t\bar{t}HH)</td>
<td>1.358(1) \cdot 10^{-2}</td>
<td>1.206(3) \cdot 10^{-2}</td>
<td>0.888</td>
<td>1.367(1) \cdot 10^{-2}</td>
<td>1.218(1) \cdot 10^{-2}</td>
<td>0.8909</td>
</tr>
<tr>
<td>(e^+e^- \to t\bar{t}W^+W^-)</td>
<td>0.1372(3)</td>
<td>0.1540(6)</td>
<td>1.1225</td>
<td>0.1370(4)</td>
<td>0.1538(4)</td>
<td>1.1257</td>
</tr>
<tr>
<td>(e^+e^- \to t\bar{t}W^\pm j)</td>
<td>2.400(4) \cdot 10^{-4}</td>
<td>3.72(1) \cdot 10^{-4}</td>
<td>1.54999</td>
<td>2.41(1) \cdot 10^{-4}</td>
<td>3.74(2) \cdot 10^{-4}</td>
<td>1.55186</td>
</tr>
</tbody>
</table>

## Status of WHIZARD

**POWHEG**

<table>
<thead>
<tr>
<th>Process</th>
<th>(\sigma^{\text{LO}}[\text{nb}])</th>
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<th>(K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(pp \to e^+e^-)</td>
<td>0.9629(3)</td>
<td>1.0961(3)</td>
<td>1.13829</td>
<td>0.9637(1)</td>
<td>1.0962(2)</td>
<td>1.13742</td>
</tr>
<tr>
<td>(pp \to e^+\nu_e)</td>
<td>5.808(1)</td>
<td>6.657(1)</td>
<td>1.14616</td>
<td>5.808(1)</td>
<td>6.649(1)</td>
<td>1.1448</td>
</tr>
<tr>
<td>(pp \to e^+e^-j)</td>
<td>1.824(3)</td>
<td>2.21(2)</td>
<td>1.2116</td>
<td>1.823(2)</td>
<td>2.920(5)</td>
<td>1.6017</td>
</tr>
<tr>
<td>(pp \to jj)</td>
<td>397.3(1.5) \cdot 10^4</td>
<td>639.0(1.3) \cdot 10^4</td>
<td>1.60835</td>
<td>401.2(0.9) \cdot 10^4</td>
<td>3656(150) \cdot 10^4</td>
<td>9.11266</td>
</tr>
</tbody>
</table>

\[\text{CEPC Workshop 2019, Oxford, 16.04.19}\]
NLO QCD for semi-leptonic $e^+e^- \rightarrow WW$

Niedermeier/JRR/Rothe/Stienemeier, work in progress

$$e^+e^- \rightarrow \mu \nu jj$$

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<tr>
<th>$\sqrt{s}$ [GeV]</th>
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<tr>
<td>160</td>
<td>0.4446</td>
<td>$0.4711^{+0.36%}_{-0.62%}$</td>
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<tr>
<td>200</td>
<td>2.755</td>
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<td>$1.036^{+0.19%}_{-0.77%}$</td>
</tr>
<tr>
<td>250</td>
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<td>500</td>
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<td>1000</td>
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<td>$1.006^{+0.00%}_{-0.70%}$</td>
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$K$ factor mostly $\frac{\alpha_s}{\pi}$
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K factor mostly $\frac{\alpha_s}{\pi}$
Top Threshold/Continuum in WHIZARD

- Top threshold scan best-known method to measure top quark mass, \( \Delta M \sim 30-70 \text{ MeV} \)
- Continuum top production best-known method to measure top couplings
- WHIZARD provides special model for top threshold
- Matches threshold resummation with NLO QCD
- Allows for (almost) fully exclusive final states

Chokoufé/Hoang/Kilian/JRR/Stahlhofen/Teubner/Weiss, 1712.02220 [JHEP 1803(2018)184]

Allows to study top mass dependence of differential distributions at threshold
Interface between WHIZARD — PYTHIA8

- Intention: directly communicate between event records of WHIZARD and PYTHIA8
- No intermediate files: direct communication between event records
- Allows for using all the machinery for matching and merging from PYTHIA8
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```
$shower_method = "PYTHIA8"
$hadronization_method = "PYTHIA8"
```

Allows to use the PYTHIA8 toolbox for matching
Gridpack functionality in WHIZARD

- Workspace subdirectory for GRID communication: job ID
- Pack and unpack features: transfers whole directories, relies on `tar`

```
./whizard --job_id "42"  or  [actually for the integration grids!]
./whizard -J "42"
```

```
$grid_path = "<afs/.../...>"
```

```
=./whizard script1_tar.sin --pack my_workspace
```

script1_tar.sin contains

```
$compile_workspace = "my_workspace"
```

On the remote machine, you can run this with

```
./whizard script2_tar.sin --unpack my_workspace.tgz
```
Summary & Outlook

- **WHIZARD 2.7.1** event generator for collider physics (ee, pp, ep)
- High-multiplicity SM hard processes (2→10 etc.)
- Allows to simulate all possible BSM models
- Strong focus on $e^+e^-$ physics: beam spectra, $e^+e^-$ ISR, LCIO, polarizations
- **NLO QCD** (almost) done → WHIZARD 3.0.0α [EW validation started]
- **NEW:**
  - ✔ UFO models: [general Lorentz structures WHIZARD 2.8.0]
  - ✔ MPI parallel integration
  - ✔ Possibility to pre-set branching ratios for factorized processes
  - ✔ Resonance matching to parton shower
  - ✔ Fully integrated PYTHIA8 interface
  - ✔ Batch mode / gridpack functionality
  - ✔ Dedicated work on WW threshold (match NLO + NLL) w/ C. Schwinn
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We’re happy to accommodate specific demands of the CEPC community
Looking forward to CEPC

1) Qinhuaogou, Hesse province (Completed in 2014)
2) Hongling, Shanxi Province (Completed in 2017)
3) Shenzhen, Guangdong Province (Completed in 2016)
4) Baoxing (Xiin gni), Sichuan Province (Started in August 2017)
5) Mudong, Zhejiang Province (Started in March 2018)
6) Zhangjiajie, Hunan Province (Started in May 2019)
BACKUP
WHIZARD cannot only do scattering processes, but also decays

Example  Energy distribution electron in muon decay:

```plaintext
model = SM
process mudec = e2 => e1, N1, n2
integrate (mudec)

histogram e_e1 (0, 60 MeV, 1 MeV)
analysis = record e_e1 (eval E [e1])

n_events = 100000
simulate (mudec)
compile_analysis { $out_file = "test.dat" }
```

\[ dN/dE_e(\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu) \]
WHIZARD cannot only do scattering processes, but also decays.

### Example: Energy distribution electron in muon decay:

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analysis = record e_e1 (eval E [e1])

n_events = 100000
simulate (mudec)
compile_analysis { $out_file = "test.dat" }
```

### Automatic integration of particle decays

- `auto_decaysMultiplicity = 2`
- `auto_decaysRadiative = false`

```plaintext
unstable Wp () { auto_decays = true }
```

**Preset branching ratios possible:**

- `integral (br_hZA_redef) = 200 keV`

---

\[ dN/dE(e^{-}\rightarrow e^{-}\bar{\nu}_{e}\nu_{\mu}) \]
Spin Correlation and Polarization in Cascades

Cascade decay, factorize production and decay

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

simulate (fullproc)

simulate (casc)

?diagonal_decay = true

?isotropic_decay = true
Spin Correlation and Polarization in Cascades

Cascade decay, factorize production and decay

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

Possibility to select specific helicity in decays!

unstable “W+” { decay_helicity = 0 }
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"
     { design="ILC" roots=500 bins=100 scale=250
       { pid/1=electron pid/2=positron pol=0
         events="ilc500/lumi_ee.out" columns=2
         lumi = 1564.763360
         iterations = 10
         smooth = 5 [0,1) [0,1)
         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

---

3 simulation options

1. Unpolarized simulation with unpol. spectra
2. Pol. simulation: unpol. spectra + pol. beams
3. Polarized spectrum with helicity luminosities
Beam polarization, ILC-like setup

```
beams = e1, E1
beams_pol_density = @(-1), @(+1)
beams_pol_fraction = 80%, 30%
```

Polarized decays: longitudinal $Z$

```
process zee = Z => e1, E1
beams = Z
beams_pol_density = @(0)
```

Scan over polarizations

```
scan int h1 = (-1,1) {
  scan int h2 = (-1,1) {
    beams_pol_density = @(h1), @(h2)
    integrate (proc)
  }
}
```

Asymmetric beams

```
beams = e1, E1
beams_momentum = 100 GeV, 900 GeV
```

Beams with crossing angle

```
beams_momentum = 250 GeV, 250 GeV
beams_theta = 0, 10 degree
```

Beams with rotated crossing angle

```
beams_momentum = 250 GeV, 250 GeV
beams_theta = 0, 10 degree
beams_phi = 0, 45 degree
```

Structure functions (also concatenated)

```
beams = p, p => pdf_builtin
$pdf_builtin_set = "mmht2014lo"

beams = p, pbar => lhapdf

beams = e, p => none, pdf_builtin

beams = e1, E1 => circe1
$circe1_acc = "TESLA"
?circe1_generate = false
circe1_mapping_slope = 2

beams = e1, E1 => circe2 => isr => ewa

beams = e1, E1 => beam_events
$beam_events_file = "uniform_spread_2.5%.dat"
```
Beam polarization

beams_pol_density = @([<spin entries>]), @([<spin entries>])
beams_pol_fraction = <degree beam 1>, <degree beam 2>

Different density matrices

<table>
<thead>
<tr>
<th>Spin $j$</th>
<th>Particle type</th>
<th>possible $m$ values</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Scalar boson</td>
<td>0</td>
</tr>
<tr>
<td>1/2</td>
<td>Spinor</td>
<td>+1, -1</td>
</tr>
<tr>
<td>1</td>
<td>(Massive) Vector boson</td>
<td>+1, (0), -1</td>
</tr>
<tr>
<td>3/2</td>
<td>(Massive) Vectorspinor</td>
<td>+2, (+1), (-1), -2</td>
</tr>
<tr>
<td>2</td>
<td>(Massive) Tensor</td>
<td>+2, (+1), (0), (-1), -2</td>
</tr>
</tbody>
</table>

Beams polarization

beams_pol_density = @()
Unpolarized beams $\rho = \frac{1}{|m|} \mathbb{I}$

beams_pol_density = @(+j)
Circular polarization $\rho = \text{diag} \left( \frac{1 + f}{2}, 0, \ldots, 0, \frac{1 + f}{2} \right)$

beams_pol_density = @(0)
Longitudinal polarization (massive) $\rho = \text{diag} \left( \frac{1 - f}{|m|}, \ldots, \frac{1 - f}{|m|}, \frac{1 + f(|m| - 1)}{|m|}, \frac{1 - f}{|m|}, \ldots, \frac{1 - f}{|m|} \right)$

beams_pol_density = @(j, -j, j:-j:exp(-I*phi))
Transversal polarization (along an axis) $\rho = \begin{pmatrix} 1 & 0 & \cdots & \cdots & \frac{f}{2} e^{-i\phi} \\ 0 & 0 & \ddots & 0 \\ \vdots & \ddots & \ddots & \ddots & \ddots \\ 0 & \ddots & 0 & 0 & 0 \\ \frac{f}{2} e^{i\phi} & \ddots & \ddots & \ddots & \ddots \\ 0 & \ddots & 0 & 0 & 0 \\ f \sin \theta e^{i\phi} & \ddots & \ddots & \ddots & \ddots \\ 0 & \ddots & 0 & 0 & 0 \\ f \sin \theta e^{-i\phi} & \ddots & \ddots & \ddots & \ddots \end{pmatrix}$

Polarization along arbitrary axis ($\theta, \phi$) $\rho = \frac{1}{2} \begin{pmatrix} 1 - f \cos \theta & 0 & \cdots & \cdots & f \sin \theta e^{-i\phi} \\ 0 & 0 & \ddots & 0 & 0 \\ \vdots & \ddots & \ddots & \ddots & \ddots \\ 0 & \ddots & 0 & 0 & 0 \\ f \sin \theta e^{i\phi} & \ddots & \ddots & \ddots & \ddots \\ 0 & \ddots & 0 & 0 & 0 \\ f \sin \theta e^{i\phi} & \ddots & \ddots & \ddots & \ddots \end{pmatrix}$

beams_pol_density = @(j:j:1-cos(theta),
  j:-j:sin(theta)*exp(-I*phi), -j:-j:1+cos(theta))

Diagonal / arbitrary density matrices

beams_pol_density = @(j:j:1-cos(theta),
  j:-j:sin(theta)*exp(-I*phi), -j:-j:1+cos(theta))

beams_pol_density = @({m:m':x_m,m'})
Resonance mappings for NLO processes

- Amplitudes (except for pure QCD/QED) contain resonances ($Z, W, H, t$).
- In general: resonance masses not respected by modified kinematics of subtraction terms.
- Collinear (and soft) radiation can lead to mismatch between Born and subtraction terms.
- Algorithm to include resonance histories [Ježo/Nason, 1509.09071]
  - Avoids double logarithms in the resonances’ width.
  - Most important for narrow resonances ($H \rightarrow bb$).
  - Separate treatment of Born and real terms, soft mismatch [, collinear mismatch].
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\begin{itemize}
  \item $f_s=1$
  \item $f_s=2$
  \item $f_s=3$
  \item $f_s=4$
  \item $f_s=5$
  \item $f_s=6$
\end{itemize}
Resonance mappings for NLO processes

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WHIZARD complete automatic implementation: example \( e^+ e^- \rightarrow \mu \mu bb \) (ZZ, ZH histories)

<table>
<thead>
<tr>
<th>It</th>
<th>Calls</th>
<th>Integral[fb]</th>
<th>Error[fb]</th>
<th>Err[%]</th>
<th>Acc</th>
<th>Eff[%]</th>
<th>Ch12 N[It]</th>
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standard FKS

J.R. Reuter

Status of WHIZARD

CEPC Workshop 2019, Oxford, 16.04.19
Resonance mappings for NLO processes

Amplitudes (except for pure QCD/QED) contain resonances \((Z, W, H, t)\)

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Most important for narrow resonances \((H \rightarrow bb)\)

Separate treatment of Born and real terms, soft mismatch \([,\text{collinear mismatch}]\)

\[ \begin{align*}
\text{f}_r=1 & \quad u \quad \bar{d} \\
\text{f}_r=2 & \quad \bar{u} \
\end{align*} \]

\[ \begin{align*}
\text{f}_r=3 & \quad \bar{u} \quad Z \\
\text{f}_r=4 & \quad \bar{d} \
\end{align*} \]

\[ \begin{align*}
\text{f}_r=5 & \quad \bar{u} \quad Z \\
\text{f}_r=6 & \quad \bar{d} \
\end{align*} \]

WHIZARD complete automatic implementation: example \(e^+e^- \rightarrow \mu\mu bb\) \((ZZ, ZH\) histories\)

<table>
<thead>
<tr>
<th>It</th>
<th>Calls</th>
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standard FKS

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FKS with resonance mappings
Differential Results for off-shell $e^+e^- \rightarrow tt$

\[ m_t^2 = m_W^2 + \frac{2 \langle m_{tj}^2 \rangle}{1 - \langle \cos \theta_{tj} \rangle} \]
NLO QCD Results for off-shell $e^+e^- \to ttH$

\[ e^+e^- \to t\bar{t}H \text{ and } e^+e^- \to W^+W^-b\bar{b}H \]

CHOKOUFÉ/KILIAN/LINDE/LINDE/LINDEN/Pozzorini/JRR/WEISS, 1609.03390

<table>
<thead>
<tr>
<th>$\sqrt{s}$ [GeV]</th>
<th>$\sigma^{LO}$ [fb]</th>
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<tr>
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<td>0.42$^{+3.6%}_{-3.1%}$</td>
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<td>0.27</td>
<td>0.44$^{+2.6%}_{-2.4%}$</td>
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<td>1.32$^{+2.6%}_{-3.0%}$</td>
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<td>0.35$^{+1.4%}_{-1.6%}$</td>
<td>0.84</td>
<td>0.55</td>
<td>0.44$^{+2.9%}_{-4.3%}$</td>
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CEPC Workshop 2019, Oxford, 16.04.19

J.R.Reuter

Status of WHIZARD
NLO QCD Results for off-shell $e^+e^- \rightarrow ttH$

Chokoufé/Kilian/Lindert/Pozzorini/JRR/Weiss, 1609.03390

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Top threshold scan best-known method to measure top quark mass, $\Delta M \sim 30-70$ MeV

Continuum top production best-known method to measure top couplings

**Heavy quark production** at lepton colliders, qualitatively:
**Top Threshold/Continuum at lepton colliders**

- Top threshold scan best-known method to measure top quark mass, $\Delta M \sim 30$-70 MeV
- Continuum top production best-known method to measure top couplings

Heavy quark production at lepton colliders, qualitatively:

<table>
<thead>
<tr>
<th>error source</th>
<th>$\Delta m_t^{PS}$ [MeV]</th>
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<td>stat. error (200 fb$^{-1}$)</td>
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<td>theory (NNNLO scale variations, PS scheme)</td>
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<tr>
<td>parametric ($\alpha_s$, current WA)</td>
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<tr>
<td>non-resonant contributions (such as single top)</td>
<td>$&lt; 40$</td>
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<tr>
<td>residual background / selection efficiency</td>
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<td>beam energy uncertainty</td>
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<td>25 – 50</td>
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<td>total (stat. + syst.)</td>
<td>40 – 75</td>
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from 1702.05333
Top threshold scan best-known method to measure top quark mass, $\Delta M \sim 30$-70 MeV

Continuum top production best-known method to measure top couplings

Heavy quark production at lepton colliders, qualitatively:

Threshold region: top velocity $v \sim \alpha_s \ll 1$ non-relativistic EFT: $(v)\text{NRQCD}$ from 1702.05333

Continuum region: “standard” fixed-order QCD
Top threshold scan best-known method to measure top quark mass, $\Delta M \sim 30$-70 MeV

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Threshold region: top velocity $v \sim \alpha_s \ll 1$  
non-relativistic EFT: $(v)\text{NRQCD}$ from 1702.05333

Continuum region: “standard” fixed-order QCD
Top threshold: validation and matching

- Transition region between relativistic and resummation effects

\[ \sigma_{NLO+NLL} = \sigma_{NLO} + \left( F_{\text{NLL}} - F_{\text{NLL}}^{\text{exp}} \right) \]

\[ + \left( F_{\text{NLL}} - F_{\text{NLL}}^{\text{exp}} \right) \]

\[ + \left( F_{\text{NLL}} - F_{\text{NLL}}^{\text{exp}} \right) \]

\[ + \left( F_{\text{NLL}} - F_{\text{NLL}}^{\text{exp}} \right) \]

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\[ + \left( F_{\text{NLL}} - F_{\text{NLL}}^{\text{exp}} \right) \]

\[ + \left( F_{\text{NLL}} - F_{\text{NLL}}^{\text{exp}} \right) \]

Smoothstep matching function:

\[ f_s(v) = \begin{cases} 
1 & v < v_1 \\
1 - 3 \left( \frac{v-v_1}{v_2-v_1} \right)^2 & v_1 \leq v \leq v_2 \\
0 & v > v_2 
\end{cases} \]

Chokoufé/Hoang/Kilian/JRR/Stahlhofen/Teubner/Weiss, 1712.02220
Top threshold: validation and matching

NLO predictions for on- and off-shell $tt$ production

$\Delta m_t = 30$ GeV, expanded, evaluated with $\alpha_s$, only s-wave contributions

Bach/Chokouf/Hoang/Kilian/JRR/Stahlhufen/Teubner/Weiss, 1712.02220
Top threshold: validation and matching

NLO predictions for on- and off-shell $t\bar{t}$ production

$\Delta_{mt} = 30$ GeV, LL, only s-wave contributions

Bach/Chokoufè/Hoang/Kilian/JRR/Stahlhofen/Teubner/Weiss, 1712.02220
Top threshold: validation and matching

NLO predictions for on- and off-shell $t\bar{t}$ production

$\sqrt{s}$ [GeV]

$\Delta m_t = 30$ GeV, NLL, only s-wave contributions

$\Delta m_t = 30$ GeV, LL, only s-wave contributions

Whizard signal
Analytic
Whizard factorized
Matching threshold NLL to continuum NLO

**Total uncertainty:** $h$-$f$ variation band and matching [switch-off function]

**Symmetrization of error bands:**

$$
\sigma_{\text{max}} = \max \left[ \max_{i \in \text{HF}} \sigma_i, \sigma_0 + (\sigma_0 - \min_{i \in \text{HF}} \sigma_i) \right]
$$

$$
\sigma_{\text{min}} = \min \left[ \min_{i \in \text{HF}} \sigma_i, \sigma_0 - (\max_{i \in \text{HF}} \sigma_i - \sigma_0) \right]
$$
Threshold matching with QED ISR

_matched, no switch-off_

Matched inclusive $W^+bW^-\bar{b}$ cross section, with QED ISR

Scale vars

<table>
<thead>
<tr>
<th>h = 1, f = 1</th>
<th>h = 1/2, f = 2</th>
<th>h = 1/2, f = 1</th>
<th>h = 2, f = 1</th>
<th>h = 2, f = 1/2</th>
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<td>matched, combined, symmetrized</td>
<td>envelope</td>
<td>envelope symmetrized</td>
<td>NLO</td>
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Matched threshold differential distributions

\begin{align*}
\text{For } e^+e^- \rightarrow W^+bW^-\bar{b}, \ N_{\text{jets}} \geq 2, \ \sqrt{s} = 344\text{GeV} \\
\text{For } e^+e^- \rightarrow \mu^+\nu_{\mu}\bar{\nu}_{\bar{\mu}}b\bar{b}H, \ N_{\text{jets}} \geq 2, \ \sqrt{s} = 800\text{GeV}
\end{align*}
NLO QCD Results for off-shell $e^+e^- \rightarrow tt$

Chokoufé/Kilian/Lindert/Pozzorini/JRR/Weiss, 1609.03390
NLO QCD Results for off-shell $e^+e^- \rightarrow t\bar{t}$

$e^+e^- \rightarrow t\bar{t}$ and $e^+e^- \rightarrow W^+W^-b\bar{b}$

**K-factor**

<table>
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<tr>
<th>$\sqrt{s}$ [GeV]</th>
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<th>$\sigma^{\text{NLO}}$ [fb]</th>
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<th>$\sigma^{\text{NLO}}$ [fb]</th>
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</tbody>
</table>

Table: NLO QCD Results for off-shell $e^+e^- \rightarrow t\bar{t}$ and $e^+e^- \rightarrow W^+W^-b\bar{b}$

Chokoufè/Kilian/Lindert/Pozzorini/JR/Weiss, 1609.03390
NLO QCD Results for off-shell $e^+e^- \rightarrow tt$

Chokoufé/Kilian/Lindert/Pozzorini/JRR/Weiss, 1609.03390