The Event Generator

WHIZARD

Jürgen R. Reuter, DESY
in memoriam: Maria Callas

Μαρία Καλογεροπούλου ★ 2.12.1923 — † 16.9.1977

La Traviata  Lucia di Lammermoor  Medea
in memoriam: Maria Callas

Μαρία Καλογεροπούλου  ★  2.12.1923 — † 16.9.1977

Greek National Opera Presents

Maria Callas

Opera Gala
WHIZARD: Some (technical) facts

WHIZARD v2.6.0 (08.09.2017)  http://whizard.hepforge.org

<whizard@desy.de>

Ancient acronym:  W, Higgs, Z, and Respective Decays

WHIZARD Team:  Wolfgang Kilian, Thorsten Ohl, JRR
Simon Braß/Vincent Rothe/Christian Schwinn/Marco Sekulla/So Young Shim/Florian Staub/Pascal Stienemeier/
Zhijie Zhao + 2 Master

PUBLICATIONS

WHIZARD: Introduction / Technical Facts

- Universal event generator for lepton and hadron colliders
- Tree ME generator 0’Mega optimized ME generator (recursive via Directed Acyclical Graphs)
- Generator/simulation tool for lepton collider beam spectra: CIRCE1/2
- Parton showering internal: analytic + $k_T$-ordered, hadronization: external
- Interfaces to external packages for Feynman rules, hadronization, tau decays, event formats, analysis, jet clustering etc.: FastJet, GoSam, GuineaPig(++)
  HepMC, HOPPET, LCIO, LHAPDF(4/5/6), LoopTools, OpenLoops, PYTHIA6 [internal], [PYTHIA8], Recola, StdHep [internal], Tauola [internal]
- Event formats: LHE, StdHEP, HepMC, LCIO + several ASCII
- Programming Languages: Fortran2003/2008 (gfortran $\geq 4.8.4$), OCaml ($\geq 3.12.0$)
- Standard installation: configure <FLAGS>, make, [make check], make install
- Large self test suite, unit tests [module tests], regression testing
- Continuous integration system (gitlab CI @ Siegen)
WHIZARD: Past and recent timeline

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 LoI studies (versions v1.24, v1.50, v1.95) [≈ 2002–2013]

Major refactoring phase I: LHC physics ➝ v2.0.0 [≈ 2007–2010]

Validation inside ATLAS and CMS [≈2011–2014]

2nd refactoring phase II: NLO automation / maintainability ➝ v2.2.0 [≈ 2012–2014]

Strong interest of CEPC/FCC-ee study group(s) for simulations [≈ 2013/14 — now]

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

Final validation for LC [ee] physics between v1.95 and v2 [finalized until November]

Special thanks to:

[beam spectra, photon background, event formats, shower/hadronization, tau decays]
WHIZARD: Manual

A generic Monte-Carlo integration and event generation package for multi-particle processes

MANUAL

Wolfgang Kilian, Thorsten Ohl, Jürgen Reuter, with contributions from Fabian Bach, Simon Braat, Rajan Chokouma Keje, Christian Fipper, Vincent Rothe, Sebastian Schmidt, Marco Sasu, Christian Speckner, So Young Shim, Florian Staub, Christian Weber

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WHIZARD Manual @ HepForge

still disturbingly incomplete: nevertheless 300 pages

also documented source code: ≈ 6,000 pages
$e^+e^- \rightarrow \tilde{\mu}^+\tilde{\mu}^-$

3 TeV

Courtesy to Philipp Roloff
e^+ e^- Beam spectra

- High-energy e^+e^- colliders need to achieve extreme luminosities
- Price for limited AC power: high bunch charges and tiny 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 cross sections

Dense beams generate strong EM fields: deflect particles in other bunch (beamstrahlung)
Another demand: 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: $D_{B_1B_2}(x_1, x_2) \neq D_{B_1}(x_1) \cdot D_{B_2}(x_2)$
No simple power law: $D_{B_1B_2}(x_1, x_2) \neq x_1^{\alpha_1}(1 - x_1)^{\beta_1} x_2^{\alpha_2}(1 - x_2)^{\beta_2}$
Lepton Collider Beam Simulation

- Another demand: adapt GuineaPig beam spectra for WHIZARD v2
- For WHIZARD v1.95 simulations done by Lumilinker [T. Barklow]
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Tails @ CLIC much more complicated (wakefields)

Dalena/Esbjerg/Schulte [LCWS 2011]
Another demand: adapt GuineaPig beam spectra for WHIZARD v2
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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]

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

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

- **iterations** = 0 and **smooth** = 0, 3, 5:

- **iterations** = 2 and **smooth** = 0, 3, 5:

- **iterations** = 4 and **smooth** = 0, 3, 5:
Inclusive Lepton Collider ISR included

Soft exponentiation to all orders

\[ \epsilon = \frac{\alpha}{\pi} q_e^2 \ln \left( \frac{s}{m^2} \right) \]  
Gribov/Lipatov, 1971

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

Hard-collinear photons up to 3rd QED order
Inclusive Lepton Collider ISR included

Soft exponentiation to all orders
\[ \epsilon = \frac{\alpha}{\pi} q^2 e \ln \left( \frac{s}{m^2} \right) \quad \text{Gribov/Lipatov, 1971} \]
\[ f_0(x) = \epsilon \cdot (1 - x)^{-1+\epsilon} \]

Hard-collinear photons up to 3rd QED order
Kuraev/Fadin, 1983; Skrzypek/Jadach, 1991
\[ g_3(\epsilon) = 1 + \frac{3}{4} \epsilon + \frac{27 - 8\pi^2}{96} \epsilon^2 + \frac{27 - 24\pi^2 + 128\zeta(3)}{384} \epsilon^3 \]
\[ f_3(x) = g_3(\epsilon) f_0(x) - \frac{\epsilon}{2} (1 + x) \]
\[ - \frac{\epsilon^2}{8} \left( \frac{1+3x^2}{1-x} \ln x + 4(1+x) \ln(1-x) + 5 + x \right) \]
\[ - \frac{\epsilon^3}{48} \left( (1+x) \left[ 6 \operatorname{Li}_2(x) + 12 \ln^2(1-x) - 3\pi^2 \right] + 6(x+5) \ln(1-x) \right) \]
\[ + \frac{1}{1-x} \left[ \frac{3}{2} (1+8x+3x^2) \ln x + 12(1+x^2) \ln x \ln(1-x) \right. \]
\[ \left. - \frac{1}{2} (1+7x^2) \ln^2 x + \frac{1}{4} (39 - 24x - 15x^2) \right] \]
\[ \zeta(3) = 1.20205690315959428539973816151 \ldots \]
Inclusive Lepton Collider ISR included

Soft exponentiation to all orders
\[ \epsilon = \frac{\alpha}{\pi} q^2 e \ln \left( \frac{s}{m^2} \right) \] \quad \text{Gribov/Lipatov, 1971}

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

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

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

\[ f_3(x) = g_3(\epsilon) f_0(x) - \frac{\epsilon}{2} (1 + x) \]

\[ - \frac{\epsilon^2}{8} \left( \frac{1}{1 - x} \ln x + 4(1 + x) \ln(1 - x) + 5 + x \right) \]

\[ - \frac{\epsilon^3}{48} \left( (1 + x) \left[ 6 \ln^2(1 - x) - 3\pi^2 \right] + 6(x + 5) \ln(1 - x) \right) \]

\[ + \frac{1}{1 - x} \left[ \frac{3}{2} (1 + 8x + 3x^2) \ln x + 12(1 + x^2) \ln x \ln(1 - x) \right] \]

\[ - \frac{1}{2} (1 + 7x^2) \ln^2 x + \frac{1}{4} (39 - 24x - 15x^2) \]

\[ \zeta(3) = 1.20205690315959428539973816151 \ldots \]

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

[from J.-J. Blaising]
Beamstrahlung / ISR for high-energy searches

\[ \frac{d\sigma}{dM_{\text{miss}}} \text{ [fb/GeV]} \]

\[ e^+e^- \rightarrow b\bar{b}\tilde{\chi}_1^0\tilde{\chi}_1^0 \]

Hagiwara/Kilian/Krauss/Ohl/Plehn/Rainwater/JRR/Schumann [CATPISS collaboration], hep-ph/0512260
Beamstrahlung / ISR for high-energy searches

\[ \frac{d\sigma}{dM_{\text{miss}}} \ [\text{fb/GeV}] \]

\[ e^+e^- \rightarrow b\bar{b}\tilde{\chi}_1^0\tilde{\chi}_1^0 \]

w. ISR + beamstr.

Hagiwara/Kilian/Krauss/Ohl/Plehn/Rainwater/JRR/Schumann [CATPISS collaboration], hep-ph/0512260
General structure of SINDARIN input

model = NMSSM

alias ll = "e-":"e+":"mu+":"mu-
alias parton = u:U:d:D:s:S:g
alias jet = parton
alias stop = st1:st2:ST1:ST2

process susyprod = parton, parton =>
    stop,stop + gg,gg + gg,stop

sqrts = 13000 GeV
beams = p, p => lhapdf

integrate (susyprod)
    { iterations = 15:500000, 5:1000000 }
n_events = 10000

sample_format = lhef, stdhep, hepmc
sample = "susydata"
simulate (susyprod)

Standard cut expression:
cuts = all Pt > 100 GeV [lepton]

Cuts on tensor products:
cuts = all Dist > 2 [e1:E1, e2:E2]

Selection cuts:
cuts = any PDG == 13 [lepton]
cuts = any M > 100 GeV [combine if cos(Theta) > 0.5
    [lepton,neutrino]

Sorting and selecting:
cuts = any E > 2*mW [extract index 2
    [sort by -Pt [lepton]]

Clustering: [FastJet: Cacciari/Salam/Soyez]
jet_algorithm = antikt_algorithm
jet_r = 0.7
?keep_flavors_when_clustering = true

Subevents and jet counts:
cuts = let subevt @clustered_jets = cluster [jet] in
cuts = let subevt @pt_selected =
    select if Pt > 30 GeV [@clustered_jets] in
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" }
```

\[
\frac{dN}{dE_e}(\mu^- \rightarrow e^- \bar{\nu}_e \nu_{\mu})
\]
Decay processes / auto decays

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” }
```

Automatic integration of particle decays

```plaintext
auto_decays_multiplicity = 2
?auto_decays_radiative = false
unstable Wp () { ?auto_decays = true }
```

![Energy distribution electron in muon decay](image)

\[
dN/dE_{e}(\mu^{-} \rightarrow e^{-}\bar{\nu}_{e}\nu_{\mu})
\]
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

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

- simulate (fullproc)
- simulate (casc)
- \(?\text{diagonal\_decay} = \text{true}\)
- \(?\text{isotropic\_decay} = \text{true}\)

Possibility to select specific helicity in decays!

unstable “W+” { decay_helicity = 0 }
Beam structure: beam polarization

Beam polarization

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

Different density matrices

Unpolarized beams
beams_pol_density = @()

Circular polarization
beams_pol_density = @(±j)
beams_pol_fraction = f

Longitudinal polarization (massive)
beams_pol_density = @(θ)
beams_pol_fraction = f

Transversal polarization (along an axis)
beams_pol_density = @(j, -j, j:-j:exp(-I*phi))
beams_pol_fraction = f

Polarization along arbitrary axis (θ,Φ)
beams_pol_density = @(j:j:1-cos(theta), j:-j:sin(theta)*exp(-I*phi), -j:-j:1+cos(theta))
beams_pol_fraction = f

Diagonal / arbitrary density matrices
beams_pol_density = @({m:m'::x_{m,m'}})

Table: Different particle types

<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, 1, -1</td>
</tr>
<tr>
<td>1/2</td>
<td>(Massive) Vector boson</td>
<td>+1, (0), -1</td>
</tr>
<tr>
<td>1</td>
<td>(Massive) Vectorspinor</td>
<td>+2, (+1), (-1), -2</td>
</tr>
<tr>
<td>3/2</td>
<td>(Massive) Tensor</td>
<td>+2, (+1), (0), (-1), -2</td>
</tr>
</tbody>
</table>
Beam structure: special beams

Beam polarization, ILC-like setup

\[
\text{beams} = \text{e1, E1} \\
\text{beams\_pol\_density} = @(\text{-1}), @(\text{+1}) \\
\text{beams\_pol\_fraction} = 80\%, 30\%
\]

Polarized decays: longitudinal $Z$

\[
\text{process zee} = Z \rightarrow \text{e1, E1} \\
\text{beams} = Z \\
\text{beams\_pol\_density} = @(0)
\]

Scan over polarizations

\[
\text{scan int h1} = (-1,1) \{
\text{scan int h2} = (-1,1) \{
\text{beams\_pol\_density} = @(h1), @(h2) \\
\text{integrate (proc)}
\}
\}
\]

Asymmetric beams

\[
\text{beams} = \text{e1, E1} \\
\text{beams\_momentum} = 100 \text{ GeV, 900 GeV}
\]

Beams with crossing angle

\[
\text{beams\_momentum} = 250 \text{ GeV, 250 GeV} \\
\text{beams\_theta} = 0, 10 \text{ degree}
\]

Beams with rotated crossing angle

\[
\text{beams\_momentum} = 250 \text{ GeV, 250 GeV} \\
\text{beams\_theta} = 0, 10 \text{ degree} \\
\text{beams\_phi} = 0, 45 \text{ degree}
\]

Structure functions (also concatenated)

\[
\text{beams} = \text{p, p} \rightarrow \text{pdf\_builtin} \\
\$\text{pdf\_builtin\_set} = \text{“mmht2014lo”}
\]

\[
\text{beams} = \text{p, pbar} \rightarrow \text{lhapdf}
\]

\[
\text{beams} = \text{e, p} \rightarrow \text{none, pdf\_builtin}
\]

\[
\text{beams} = \text{e1, E1} \rightarrow \text{circe1} \\
\$\text{circe1\_acc} = \text{“TESLA”} \\
\text{?circe1\_generate} = \text{false} \\
\text{circe1\_mapping\_slope} = 2
\]

\[
\text{beams} = \text{e1, E1} \rightarrow \text{beam\_events} \\
\$\text{beam\_events\_file} = \text{“uniform\_spread\_2.5\%\_dat”}
\]

\[
\text{beams} = \text{e1, E1} \rightarrow \text{circe2} \rightarrow \text{isr} \rightarrow \text{ewa}
\]
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 $\Rightarrow$ 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. $e^+e^- \rightarrow j jj$)

Integration display $\Rightarrow$ vis_history = true
MPI Parallelization

- Event generation trivially parallelizable
- **Major bottleneck:** phase space integration (generation of grids)
- Parallelization of integration: OMP multi-threading for different helicities since long
- NEW (after v2.5.0): MPI parallelisation (using OpenMPI)
- 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!
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

- **WHIZARD v2.6.0:** option to set resonance histories
  ```
  ?resonance_history = true
  resonance_on_shell_limit = 4
  ```
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
- **WHIZARD v2.6.0:** option to set resonance histories

```plaintext
?resonance_history = true
resonance_on_shell_limit = 4
```

![Graph showing the impact of resonances on the number of jets and K-factor](image)
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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```
?resonance_history = true
resonance_on_shell_limit = 4
```

- **NEW**
### BSM Models in WHIZARD

<table>
<thead>
<tr>
<th>MODEL TYPE</th>
<th>with CKM matrix</th>
<th>trivial CKM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yukawa test model</td>
<td>---</td>
<td>Test</td>
</tr>
<tr>
<td>QED with $e, \mu, \tau, \gamma$</td>
<td>---</td>
<td>QED</td>
</tr>
<tr>
<td>QCD with $d, u, s, c, b, t, g$</td>
<td>---</td>
<td>QCD</td>
</tr>
<tr>
<td>Standard Model</td>
<td>SM_CKM</td>
<td>SM</td>
</tr>
<tr>
<td>SM with anomalous gauge couplings</td>
<td>SM_ac_CKM</td>
<td>SM_Higgs</td>
</tr>
<tr>
<td>SM with $H_{gg}, H_{\gamma \gamma}, H_{\mu \mu}$</td>
<td>---</td>
<td>SM_dim6</td>
</tr>
<tr>
<td>SM with bosonic dim-6 operators</td>
<td>---</td>
<td>SM_top</td>
</tr>
<tr>
<td>SM with charge 4/3 top</td>
<td>---</td>
<td>SM_top_anom</td>
</tr>
<tr>
<td>SM with anomalous top couplings</td>
<td>---</td>
<td>SM_rx/NoH_rx/SM_ul</td>
</tr>
<tr>
<td>SM with anomalous Higgs couplings</td>
<td>---</td>
<td>SSC/AltH/SSC_2/SSC_AltT</td>
</tr>
<tr>
<td>SM extensions for $VV$ scattering</td>
<td>---</td>
<td>Zprime</td>
</tr>
<tr>
<td>SM with $Z'$</td>
<td>2HDM_CKM</td>
<td>2HDM</td>
</tr>
<tr>
<td>Two-Higgs Doublet Model</td>
<td>2HDM_CKM</td>
<td>2HDM</td>
</tr>
<tr>
<td>MSSM</td>
<td>MSSM_CKM</td>
<td>MSSM</td>
</tr>
<tr>
<td>MSSM with gravitinos</td>
<td>---</td>
<td>MSSM_Grav</td>
</tr>
<tr>
<td>NMSSM</td>
<td>NMSSM_CKM</td>
<td>NMSSM</td>
</tr>
<tr>
<td>extended SUSY models</td>
<td>---</td>
<td>PSSSM</td>
</tr>
<tr>
<td>Littlest Higgs</td>
<td>---</td>
<td>Littlest</td>
</tr>
<tr>
<td>Littlest Higgs with ungauged $U(1)$</td>
<td>---</td>
<td>Littlest_Eta</td>
</tr>
<tr>
<td>Littlest Higgs with $T$ parity</td>
<td>---</td>
<td>Littlest_Tpar</td>
</tr>
<tr>
<td>Simplest Little Higgs (anomaly-free)</td>
<td>---</td>
<td>Simplest</td>
</tr>
<tr>
<td>Simplest Little Higgs (universal)</td>
<td>---</td>
<td>Simplest_univ</td>
</tr>
<tr>
<td>SM with graviton</td>
<td>---</td>
<td>Xdim</td>
</tr>
<tr>
<td>UED</td>
<td>---</td>
<td>UED</td>
</tr>
<tr>
<td>“SQED” with gravitino</td>
<td>---</td>
<td>GravTest</td>
</tr>
<tr>
<td>Augmentable SM template</td>
<td>---</td>
<td>Template</td>
</tr>
</tbody>
</table>

- Automated models: interface to SARAH/BSM Toolbox  
  Staub, 0909.2863; Ohl/Porod/Staub/Speckner, 1109.5147
- Automated models: interface to FeynRules  
  Christensen/Duhr; Christensen/Duhr/Fuks/JRR/Speckner, 1010.3251
<table>
<thead>
<tr>
<th>MODEL TYPE</th>
<th>with CKM matrix</th>
<th>trivial CKM</th>
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<tr>
<td>Yukawa test model</td>
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<tr>
<td>QED with $e, \mu, \tau, \gamma$</td>
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<td>QED</td>
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<tr>
<td>QCD with $d, u, s, c, b, t, g$</td>
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<td>Standard Model</td>
<td>SM_CKM</td>
<td>SM</td>
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<tr>
<td>SM with anomalous gauge couplings</td>
<td>SM_ac_CKM</td>
<td>SM_ac</td>
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<tr>
<td>SM with $Hgg, H\gamma\gamma, H\mu\mu$</td>
<td>---</td>
<td>SM_Higgs</td>
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<td>SM with bosonic dim-6 operators</td>
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<tr>
<td>SM with charge 4/3 top</td>
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<tr>
<td>SM with anomalous top couplings</td>
<td>---</td>
<td>SM_top_anom</td>
</tr>
<tr>
<td>SM with anomalous Higgs couplings</td>
<td>SM_rx/NoH_rx/SM_ul</td>
<td></td>
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<tr>
<td>SM extensions for $VV$ scattering</td>
<td>---</td>
<td>SSC/AltH/SSC_2/SSC_AltT</td>
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<tr>
<td>SM with $Z'$</td>
<td>---</td>
<td>Zprime</td>
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<td>MSSM with gravitinos</td>
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<td>PSSSSM</td>
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<td>Littlest Higgs</td>
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<td>Littlest</td>
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<tr>
<td>Littlest Higgs with ungauged $U(1)$</td>
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<td>Littlest_Eta</td>
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<td>Littlest Higgs with $T$ parity</td>
<td>---</td>
<td>Littlest_Tpar</td>
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<tr>
<td>Simplest Little Higgs (anomaly-free)</td>
<td>---</td>
<td>Simplest</td>
</tr>
<tr>
<td>Simplest Little Higgs (universal)</td>
<td>---</td>
<td>Simplest_univ</td>
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<tr>
<td>SM with graviton</td>
<td>---</td>
<td>Xdim</td>
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<tr>
<td>UED</td>
<td>---</td>
<td>UED</td>
</tr>
<tr>
<td>“SQED” with gravitino</td>
<td>---</td>
<td>GravTest</td>
</tr>
<tr>
<td>Augmentable SM template</td>
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</tr>
</tbody>
</table>

- Automated models: interface to SARAH/BSM Toolbox  
  Staub, 0909.2863; Ohl/Porod/Staub/Specchner, 1109.5147
- Automated models: interface to FeynRules  
  Christensen/Duhr; Christensen/Duhr/Fuks/JRR/Specchner, 1010.3251
- Automated models: UFO interface  
  [new WHIZARD/0’Mega model format]  
  NEW in v2.5.0
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.ufo.mdl'

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

All the setup works the same as for intrinsic models

Old FeynRules / SARAH interface might get deprecated

kept at the moment for user backwards compatibility

All SM-like models/scalar extensions already supported
Higher-dim. operators, general Lorentz/color structures is work in progress (scheduled end of 2017)
New Physics in Vector Boson Scattering: LHC

- Vector Boson Scattering (VBS) major measurement of LHC runs II/III  
  Gianotti, 01/2014
- Light Higgs suppression makes VBS prime candidate for BSM searches
- Model-independent EFT descriptions not so useful: either weakly-coupled resonances in reach or strongly-coupled sectors  
  Alboteanu/Kilian/JRR, 0806.4145; Kilian/Ohl/JRR/Sekulla, 1408.6207
- Parameterize new physics by dim 6/dim 8 operators, calculate unitarity limits
- **Dimension-8 operators for longitudinal/mixed/transverse modes**  
  Fleper/Kilian/JRR/Sekulla, 2017
- T-matrix unitarization implemented in **WHIZARD** (both for operators and resonances)

\[
\mathcal{L}_{S,0} = F_{S,0} \text{Tr}[(D_\mu H)\dagger(D_\nu H)] \text{Tr}[(D_\mu H)\dagger(D_\nu H)] \\
\mathcal{L}_{S,1} = F_{S,1} \text{Tr}[(D_\mu H)\dagger(D_\nu H)] \text{Tr}[(D_\nu H)\dagger(D_\mu H)] \\
\mathcal{L}_{M,0} = -g^2 F_{M,0} \text{Tr}[(D_\mu H)\dagger(D_\mu H)] \text{Tr}[W_{\nu\rho}W^{\nu\rho}] \\
\mathcal{L}_{M,1} = -g^2 F_{M,1} \text{Tr}[(D_\mu H)\dagger(D_\rho H)] \text{Tr}[W_{\nu\rho}W^{\nu\mu}] \\
\mathcal{L}_{T,0} = g^4 F_{T,0} \text{Tr}[W_{\mu\nu}W^{\mu\nu}] \text{Tr}[W_{\alpha\beta}W^{\alpha\beta}] \\
\mathcal{L}_{T,1} = g^4 F_{T,1} \text{Tr}[W_{\alpha\nu}W^{\mu\beta}] \text{Tr}[W_{\mu\beta}W^{\alpha\nu}] \\
\mathcal{L}_{T,2} = g^4 F_{T,2} \text{Tr}[W_{\alpha\mu}W^{\mu\beta}] \text{Tr}[W_{\beta\nu}W^{\nu\alpha}] \\
\]

**T-matrix unitarization**
New Physics in VBS: LHC & Lepton Colliders


Unitarity limits for
\( pp \rightarrow VVV \)

Kilian/JRR/Sekulla

Fleper/Kilian/JRR/Sekulla: to appear soon

WIP:
VBS SM: Comparison VBScan COST network

A. Karlberg/M. Pellen/M. Rauch/JRR/V. Rothe/C. Schwan/P. Stienemeier/M. Zaro

$\mathcal{O}(\alpha^6)$ Integrated Cross Sections for $pp \rightarrow e^+\nu_e \mu^+\nu_\mu jj + X$

<table>
<thead>
<tr>
<th>Code</th>
<th>LO $\sigma$ [fb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>BONSAY</td>
<td>1.5524 ± 0.0002</td>
</tr>
<tr>
<td>MG5_AMC</td>
<td>1.547 ± 0.001</td>
</tr>
<tr>
<td>POWHEG</td>
<td>1.5573 ± 0.0003</td>
</tr>
<tr>
<td>Recola+MoCanLO</td>
<td>1.5503 ± 0.0003</td>
</tr>
<tr>
<td>VBFNLO</td>
<td>1.5538 ± 0.0002</td>
</tr>
<tr>
<td>WHIZARD</td>
<td>1.5539 ± 0.0004</td>
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</tbody>
</table>

NLO comparison still under way

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<td>A. Karlberg</td>
<td>POWHEG</td>
<td>t/u</td>
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<td>Yes</td>
<td>No</td>
<td>No</td>
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<tr>
<td>M. Pellen</td>
<td>Recola+MoCanLO</td>
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<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>M. Rauch</td>
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<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>C. Schwan</td>
<td>BONSAY</td>
<td>t/u</td>
<td>No</td>
<td>V+I PA</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>M. Zaro</td>
<td>MG5_AMC</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>V. Rothe</td>
<td>WHIZARD</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
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</tbody>
</table>

Code | LO $\sigma$ [fb] | NLO $\sigma$ [fb] |
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>BONSAY</td>
<td>1.5524 ± 0.0002</td>
<td>1.3469 ± 0.0008</td>
</tr>
<tr>
<td>MG5_AMC</td>
<td>1.547 ± 0.001</td>
<td>1.318 ± 0.003</td>
</tr>
<tr>
<td>POWHEG</td>
<td>1.5573 ± 0.0003</td>
<td>1.334 ± 0.003</td>
</tr>
<tr>
<td>Recola+MoCanLO</td>
<td>1.5503 ± 0.0003</td>
<td>1.317 ± 0.004</td>
</tr>
<tr>
<td>VBFNLO</td>
<td>1.5538 ± 0.0002</td>
<td>1.3531 ± 0.0003</td>
</tr>
<tr>
<td>WHIZARD</td>
<td>1.5539 ± 0.0004</td>
<td></td>
</tr>
</tbody>
</table>
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 emitters) fully supported

\[
\begin{align*}
\alpha_{\text{power}} &= 2 \\
\alpha_s^{\text{power}} &= 0
\end{align*}
\]

process \( e^+e^- \rightarrow t\bar{t} \)

\[
\{ \text{nlo\_calculation} = \text{“full”} \}
\]

- FKS subtraction [Frixione/Kunszt/Signer, 1509.09071]
- 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, either LHEF or HepMC)
- Automated POWHEG damping and matching
NLO Automation in WHIZARD

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- Recola [A. Denner, L. Hofer, J.-N. Lang, S. Uccirati]

NLO QCD (massless & massive emitters) fully supported

```
alpha_power = 2
alphas_power = 0
process eett = e1,E1 => t, tbar
  { nlo_calculation = "full" }
```

- FKS subtraction [Frixione/Kunszt/Signer,
- 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, either LHEF or HepMC)
- Automated POWHEG damping and matching
Examples and Validation

List of validated NLO QCD processes

- $e^+e^- \rightarrow jj$
- $e^+e^- \rightarrow jjj$
- $e^+e^- \rightarrow \ell^+\ell^- jj$
- $e^+e^- \rightarrow \ell^+\nu\ell jj$
- $e^+e^- \rightarrow tt$
- $e^+e^- \rightarrow tt\bar{t}t$
- $e^+e^- \rightarrow \ell\bar{t}W^+ jj$
- $e^+e^- \rightarrow tW^- b$
- $e^+e^- \rightarrow W^+W^- bb, \ \ell^+\ell^-\nu\ell\nu\ell b\bar{b}$
- $e^+e^- \rightarrow b\ell\ell+\ell^-$
- $e^+e^- \rightarrow ttH$
- $e^+e^- \rightarrow W^+W^- \bar{b}bH, \ \ell^+\ell^-\nu\ell\nu\ell b\bar{b}H$
- $pp \rightarrow \ell^+\ell^-$
- $pp \rightarrow \ell\nu$
- $pp \rightarrow ZZ$

- Simplest hadron collider processes validated:
  \[ pp \rightarrow (Z \rightarrow ll) + X, \ pp \rightarrow (W \rightarrow l\nu) + X, \ pp \rightarrow ZZ + X \]

- QCD NLO infrastructure in pp close to complete
- After complete NLO QCD validation: WHIZARD v3.0.0
- Status of EW corrections: all parts technically completed, validation phase started [Rothe et al.]

NEW
# Validation of NLO QCD for Lepton Collisions

<table>
<thead>
<tr>
<th>Final state</th>
<th>$\sigma^{\text{LO}}[\text{fb}]$</th>
<th>MG5_AMC $\sigma^{\text{NLO}}[\text{fb}]$</th>
<th>$K$</th>
<th>$\sigma^{\text{LO}}[\text{fb}]$</th>
<th>WHIZARD $\sigma^{\text{NLO}}[\text{fb}]$</th>
<th>$K$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$jj$</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>1.0272</td>
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<tr>
<td>$bb$</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>1.0266</td>
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<tr>
<td>$tt$</td>
<td>166.2(2)</td>
<td>174.5(6)</td>
<td>1.04994</td>
<td>166.4(1)</td>
<td>175.1(1)</td>
<td>1.0522</td>
</tr>
<tr>
<td>$tttt$</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>
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<td>$bbbb$</td>
<td>$1.644(3) \cdot 10^{-1}$</td>
<td>$3.60(1) \cdot 10^{-1}$</td>
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<td>$1.64(2) \cdot 10^{-1}$</td>
<td>$3.67(4) \cdot 10^{-1}$</td>
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<td>$ttbb$</td>
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<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>
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<tr>
<td>$ttj$</td>
<td>$48.13(5)$</td>
<td>$53.43(1)$</td>
<td>1.11012</td>
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<td>$53.66(9)$</td>
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<tr>
<td>$ttH$</td>
<td>$2.018(3)$</td>
<td>$1.911(6)$</td>
<td>0.947</td>
<td>$2.022(3)$</td>
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<td>$tt\gamma$</td>
<td>$12.7(2)$</td>
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<tr>
<td>$ttHZ$</td>
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<td>$3.58(1) \cdot 10^{-2}$</td>
<td>0.99445</td>
<td>$3.596(1) \cdot 10^{-2}$</td>
<td>$3.58(2) \cdot 10^{-2}$</td>
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<tr>
<td>$tt\gamma Z$</td>
<td>$0.2212(3)$</td>
<td>$0.2364(6)$</td>
<td>1.06873</td>
<td>$0.22(1)$</td>
<td>$0.24(2)$</td>
<td>1.0909</td>
</tr>
<tr>
<td>$tt\gamma H$</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>
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</tr>
<tr>
<td>$tt\gamma \gamma$</td>
<td>$0.383(5)$</td>
<td>$0.416(2)$</td>
<td>1.08618</td>
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<td>$4.00(1) \cdot 10^{-2}$</td>
<td>1.05597</td>
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<td>$4.005(2) \cdot 10^{-2}$</td>
<td>1.0663</td>
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<tr>
<td>$ttHH$</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>
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<tr>
<td>$ttW^+W^-$</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>1.1225</td>
</tr>
<tr>
<td>$ttW^\pm jj$</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>1.5518</td>
</tr>
</tbody>
</table>

| $jjj$       | $340.1(2)$                      | $316(2)$                        | 0.92914 | $342.4(5)$                      | $319(1)$                                   | 0.9316 |
| $jjjj$      | $104.7(1)$                      | $109.0(6)$                      | 1.04106 | $105.1(4)$                      | $118(1)$                                   | 1.1227 |
| $ttttj$     | $2.719(5) \cdot 10^{-5}$       | $5.34(3) \cdot 10^{-5}$        | 1.96394 | $2.722(1) \cdot 10^{-5}$       | $4.471(5) \cdot 10^{-5}$                  | 1.6425 |
| $ttHj$      | $0.2533(3)$                     | $0.2658(9)$                     | 1.04935 | $0.254(1)$                      | $0.307(1)$                                 | 1.2087 |
| $tt\gamma j$ | $2.355(2)$                    | $2.62(1)$                       | 1.11253 | $2.47(1)$                       | $3.14(2)$                                  | 1.2712 |
| $ttZj$      | $0.6059(6)$                     | $0.694(3)$                      | 1.14548 | $0.610(4)$                      | $0.666(5)$                                 | 1.0918 |
NLO QCD Results for off-shell $e^+e^- \rightarrow tt$

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

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

![Graph showing NLO QCD Results for off-shell $e^+e^- \rightarrow t\bar{t}H$ and $e^+e^- \rightarrow W^+W^-b\bar{b}H$.](image)

<table>
<thead>
<tr>
<th>$\sqrt{s}$ [GeV]</th>
<th>$\sigma_{LO}[fb]$</th>
<th>$\sigma_{NLO}[fb]$</th>
<th>K-factor</th>
<th>$\sigma_{LO}[fb]$</th>
<th>$\sigma_{NLO}[fb]$</th>
<th>K-factor</th>
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</thead>
<tbody>
<tr>
<td>500</td>
<td>0.26</td>
<td>0.42$^{+3.6%}_{-3.1%}$</td>
<td>1.60</td>
<td>0.27</td>
<td>0.44$^{+3.6%}_{-2.4%}$</td>
<td>1.63</td>
</tr>
<tr>
<td>800</td>
<td>2.36</td>
<td>2.34$^{+0.1%}_{-0.1%}$</td>
<td>0.99</td>
<td>2.50</td>
<td>2.40$^{+2.1%}_{-1.9%}$</td>
<td>0.96</td>
</tr>
<tr>
<td>1000</td>
<td>2.02</td>
<td>1.91$^{+0.5%}_{-0.5%}$</td>
<td>0.95</td>
<td>2.21</td>
<td>2.00$^{+2.5%}_{-2.5%}$</td>
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</tr>
<tr>
<td>1400</td>
<td>1.33</td>
<td>1.21$^{+0.9%}_{-1.0%}$</td>
<td>0.90</td>
<td>1.53</td>
<td>1.39$^{+2.6%}_{-3.0%}$</td>
<td>0.86</td>
</tr>
<tr>
<td>3000</td>
<td>0.41</td>
<td>0.35$^{+1.8%}_{-1.8%}$</td>
<td>0.84</td>
<td>0.55</td>
<td>0.44$^{+4.3%}_{-3.3%}$</td>
<td>0.79</td>
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</table>

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

The event generator **WHIZARD**

Tools 2017, Corfu, 13.09.17
Differential Results for off-shell $ttH$

\[ E_h = \frac{1}{2\sqrt{s}} \left[ s + M_h^2 - (k_1 + k_2)^2 \right] \]

Determinant of top Yukawa coupling ($ttH$)

<table>
<thead>
<tr>
<th>$ttH$</th>
<th>$W^+W^-bbH$</th>
</tr>
</thead>
<tbody>
<tr>
<td>LO</td>
<td>$0.514 \pm 0.0002$</td>
</tr>
<tr>
<td>NLO</td>
<td>$0.485 \pm 0.0002$</td>
</tr>
</tbody>
</table>

cf. Talk by Alexander Mitov
Differential Results for off-shell $ttH$

\[ E_h = \frac{1}{2\sqrt{s}} \left[ s + M_h^2 - (k_1 + k_2)^2 \right] \]

Polarized Results ($tt$)

- ILC will always run polarized
- Polarized 1-loop amplitudes beyond BLHA

Determination of top Yukawa coupling ($ttH$)

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

cf. Talk by Alexander Mitov
Top Threshold at lepton colliders

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

Heavy quark production at lepton colliders, qualitatively:

Threshold region: top velocity $v \sim \alpha_s \ll 1$
Implement resummed threshold effects as effective vertex [form factor] in WHIZARD

\[ G^{v,a}(0, p_t, E + i\Gamma_t, \nu) \] from TOPPIK code [Jezabek/Teubner], included in WHIZARD

- Default parameters:
  \[ M^{1S} = 172 \text{ GeV}, \quad \Gamma_t = 1.54 \text{ GeV}, \]
  \[ \alpha_s(M_Z) = 0.118 \]
  \[ M^{1S} = M_t^{\text{pole}} (1 - \Delta^{LL/NLL}_{\text{Coul.}}) \]

Important effects: beamstrahlung; ISR; LO EW terms

Exclusive observables accessible

Theory uncertainties from scale variations: hard and soft scale

\[ \mu_h = h \cdot m_t \quad \mu_s = f \cdot m_t \nu \]
Top Threshold in WHIZARD

- Implement resummed threshold effects as effective vertex [form factor] in WHIZARD
- \( G^{v,a}(0, p_t, E + i\Gamma_t, \nu) \) from TOPPIK code [Jezabek/Teubner], included in WHIZARD

<table>
<thead>
<tr>
<th>error source</th>
<th>( \Delta m_{1S}^{PS} ) [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>stat. error (200 fb(^{-1}))</td>
<td>13</td>
</tr>
<tr>
<td>theory (NNNLO scale variations, PS scheme)</td>
<td>40</td>
</tr>
<tr>
<td>parametric (( \alpha_s ), current WA)</td>
<td>35</td>
</tr>
<tr>
<td>non-resonant contributions (such as single top)</td>
<td>&lt; 40</td>
</tr>
<tr>
<td>residual background / selection efficiency</td>
<td>10 – 20</td>
</tr>
<tr>
<td>luminosity spectrum uncertainty</td>
<td>&lt; 10</td>
</tr>
<tr>
<td>beam energy uncertainty</td>
<td>&lt; 17</td>
</tr>
<tr>
<td>combined theory &amp; parametric</td>
<td>30 – 50</td>
</tr>
<tr>
<td>combined experimental &amp; backgrounds</td>
<td>25 - 50</td>
</tr>
<tr>
<td>total (stat. + syst.)</td>
<td>40 – 75</td>
</tr>
</tbody>
</table>

- Default parameters:
  \[ M^{1S} = 172 \text{ GeV}, \quad \Gamma_t = 1.54 \text{ GeV}, \quad \alpha_s(M_Z) = 0.118 \]
  \[ M^{1S} = M_t^{pole} (1 - \Delta^{LL/NLL}_{(Coul.)}) \]
  from 1702.05333

Important effects: beamstrahlung; ISR; LO EW terms

Exclusive observables accessible

Theory uncertainties from scale variations: hard and soft scale
\[ \mu_h = h \cdot m_t \quad \mu_s = f \cdot m_t \nu \]
Top threshold: validation and matching

- Transition region between relativistic and resummation effects

\[
\sigma_{\text{NLO+NLL}} = \sigma_{\text{NLO}} + \left( \tilde{F}_{\text{NLO}} - \tilde{F}_{\text{NLO}}^{\text{exp}} \right) + \tilde{F}_{\text{NLO}} + \left\{ \tilde{F}_{\text{NLO}} \left( \begin{array}{c}
1 + \frac{1}{2}
\end{array} \right) + \tilde{F}_{\text{NLO}} \left( \begin{array}{c}
2
\end{array} \right) \right\}
\]

Smoothstep matching function:

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

Chokoufè/Hoang/Kilian/JRR/StahlhufenTeubner/Weiss,

to appear very soon

\[
\sigma_{\text{matched}} = \sigma_{\text{FO}} [\alpha_H] + \sigma_{\text{NRQCD}}^{\text{full}} [f_s \alpha_H, f_s \alpha_S, f_s \alpha_{US}] - \sigma_{\text{NRQCD}}^{\text{expanded}} [f_s \alpha_H, f_s \alpha_H],
\]
Top threshold: validation and matching

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

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

Bach/Chokoufé/Hoang/Kilian/JRR/Stahlhofen/Teubner/Weiss, *to appear very soon*
Top threshold: validation and matching

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

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

Bach/Chokoufé/Hoang/Kilian/JRR/Stahlhofen/Teubner/Weiss, to appear very soon
Top threshold: validation and matching

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

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

Bach/Chokoufé/Hoang/Kilian/JRR/Stahlhofen/Teubner/Weiss, to appear very soon
Matching threshold NLL to continuum NLO

Total uncertainty: matching and $h$-$f$ variation band

Bach/Chokoufé/Hoang/Kilian/JRR/Stahlhofen/Teubner/Weiss, to appear very soon
Matched threshold differential distributions

$e^+e^- \rightarrow W^+bW^-\bar{b}, N_{jets} \geq 2, \sqrt{s} = 344\text{GeV}$

$e^+e^- \rightarrow \mu^+\nu_\mu\bar{\nu}_\mu b\bar{b}H, N_{jets} \geq 2, \sqrt{s} = 800\text{GeV}$

$e^+e^- \rightarrow W^+bW^-\bar{b}, N_{jets} \geq 2, \sqrt{s} = 344\text{GeV}$
Conclusions & Outlook

- **WHIZARD 2.6** event generator for collider physics (ee, pp, ep)
- Allows to simulate all possible BSM models
- High-multiplicity SM processes (2→10 etc.)
- $e^+e^-$ physics: beam spectra, $e^+e^-$ ISR, LCIO, polarizations
- **NLO automation**: reals and subtraction terms (FKS) [+ virtuals externally],
- **NLO QCD** (almost) done $\rightarrow$ **WHIZARD 3.0** [EW in validation]
- Automated POWHEG matching
- **Top threshold in $e^+e^-$**: NLL NRQCD threshold / NLO continuum matching
- **NEW**: UFO models, MPI parallel integration, Resonance matching to shower
BACKUP
More SINDARIN references

int i = 3

real a = 2.78
real foo = -7.8%
real coeff = 20.1 TeV^(-2)

complex ca = 2 + I

string $str = “foo”

logical ?ok = false

printf “abc”
printf “%i” (12345)

if i == 1 then
    printf “one = %1” (i)
elsif i == 2 then
    printf “two”
endif

alias lepton = e1,e2,e3

scan mW = (75 GeV,
    (80 GeV => 82 GeV +/- 0.5 GeV),
    (83 GeV => 90 GeV *// 5)) {
    <scan body>
}

real eta_cut = 5

Space-like cuts (incoming particles):
cuts = all M2 < -(50 GeV)^2
    [combine [incoming lepton, lepton]]

Combine two cuts:
cuts = all Pt > 100 GeV [lepton]
    and all M > 10 GeV [lepton, lepton]

Collecting particles:
cuts = E <= 200 GeV [collect [neutrino]]

Cut window on a selection:

real eta_cut = 5
cuts = any 5 degree < Theta < 175 degree
    [select of abs(Eta) < eta_cut [lepton]]

MLM matching:
mlm_ptmin = 5 GeV; mlm_etamax = 2.5
mlm_Rmin = 1
mlm_nmaxMEjets = 1

integer variables
real variables
complex variables
string variables
logical variables
printing
conditionals
aliases
scanning
**WHIZARD Parton Shower**

- Two independent implementations: kT-ordered QCD and Analytic QCD shower
- Analytic shower: no shower veto ⇒ exact shower history known, allows reweighting

Kilian/JRR/Schmidt/Wiesler, JHEP **1204** 013 (2012)

- Technical overhaul of the shower / merging part
- Plans: implement GKS matching, QED shower (also interleaved, infrastructure ready)
Tuning of the WHIZARD Parton Shower

- First tunes of both kT-ordered QCD and Analytic QCD shower
- Di- and Multijet data from LEP as given in RIVET analysis
- Usage of the PROFESSOR tool for determining the best fit

Chokoufe/Englert/JReu, 2015
Buckley et al., 2009
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]
Resonance mappings for NLO processes

- Amplitudes (except for pure QCD/QED) contain resonances \((Z, W, H, t)\)
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Algorithm to include resonance histories \cite{Jezo/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 \([, \text{collinear mismatch}]\)

\[
\begin{align*}
&f_1 = 1 & f_2 = 2 & f_3 = 3 \\
\text{root} & W & W & W \\
\bar{u} & d & d & d \\
& \bar{u} & \bar{u} & \bar{u}
\end{align*}
\]
Resonance mappings for NLO processes

- Amplitudes (except for pure QCD/QED) contain resonances ($Z, W, H, t$)
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Algorithm to include resonance histories

- Avoids double logarithms in the resonances’ width
- Most important for narrow resonances ($H \rightarrow bb$)
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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>
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</tbody>
</table>

standard FKS
Resonance mappings for NLO processes

- Amplitudes (except for pure QCD/QED) contain resonances \((Z, W, H, t)\)
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\[
\begin{align*}
\text{WHIZARD} \quad & \text{complete automatic implementation: example} \quad e^+ e^- \rightarrow \mu \mu bb \quad (ZZ, ZH \text{ histories})
\end{align*}
\]

<table>
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</table>

standard FKS  \hspace{2cm} \text{FKS with resonance mappings}
Lepton colliders: \( tt \) and \( ttH \) (on- & off-shell)

- Cross checks for \( 2 \to 2 \) and \( 2 \to 4 \) processes with Sherpa and Munich
- Using massive \( b \) quarks: no cuts necessary for \( e^+e^- \to W^+W^-bb \)
- Full process \( e^+e^- \to \mu^+\nu_\mu\nu_e bb \) exhibits Coulomb singularity:
- \( ttH \) production: 8\% contamination from Higgsstrahlung
- Contribution from quartic SM vertices
Lepton colliders: \( tt \) and \( ttH \) (on- & off-shell)

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- Using massive \( b \) quarks: no cuts necessary for \( e^+e^- \to W^+W^-bb \)
- Full process \( e^+e^- \to \mu^+\nu_\mu\bar{\nu}_e\bar{b}b \) exhibits Coulomb singularity:
- \( ttH \) production: 8% contamination from Higgsstrahlung
- Contribution from quartic SM vertices

**INPUT PARAMETERS:**

\[
\begin{align*}
    m_Z &= 91.1876 \text{ GeV}, & m_W &= 80.385 \text{ GeV} \\
    m_b &= 4.2 \text{ GeV}, & m_t &= 173.2 \text{ GeV}. \\
    \Gamma^\text{LO}_{t\to Wb} &= 1.4986 \text{ GeV}, & \Gamma^\text{LO}_{t\to Wb} &= 1.3681 \text{ GeV}, \\
    \Gamma^\text{NLO}_{t\to Wb} &= 1.4757 \text{ GeV}, & \Gamma^\text{NLO}_{t\to Wb} &= 1.3475 \text{ GeV}. \\
    m_H &= 125 \text{ GeV} & \Gamma_H &= 0.000431 \text{ GeV} \\
    \mu_i^2 &= M_i^2 - i \Gamma_i M_i \quad \text{for } i = W, Z, t, H & s^2_w &= 1 - c^2_w = 1 - \frac{\mu_W^2}{\mu_Z^2}
\end{align*}
\]
Lepton colliders: $t \bar{t}$ and $t t H$ (on- & off-shell)

Cross checks for $2 \rightarrow 2$ and $2 \rightarrow 4$ processes with Sherpa and Munich

Using massive $b$ quarks: no cuts necessary for $e^+e^- \rightarrow W^+W^-bb$

Full process $e^+e^- \rightarrow \mu^+\nu_{\mu}\bar{\nu}_e\bar{b}b$ exhibits Coulomb singularity:

$t t H$ production: 8% contamination from Higgsstrahlung

Contribution from quartic SM vertices

**INPUT PARAMETERS:**

- $m_Z = 91.1876$ GeV,
- $m_W = 80.385$ GeV,
- $m_b = 4.2$ GeV,
- $m_t = 173.2$ GeV.
- $\Gamma_{t \rightarrow Wb}^{LO} = 1.4986$ GeV,
- $\Gamma_{t \rightarrow Wb}^{NLO} = 1.3681$ GeV,
- $\Gamma_{t \rightarrow fb}^{LO} = 1.4757$ GeV,
- $\Gamma_{t \rightarrow fb}^{NLO} = 1.3475$ GeV.
- $m_H = 125$ GeV,
- $\Gamma_H = 0.000431$ GeV.
- $\Gamma_Z^{LO} = 2.4409$ GeV,
- $\Gamma_Z^{NLO} = 2.5060$ GeV,
- $\Gamma_W^{LO} = 2.0454$ GeV,
- $\Gamma_W^{NLO} = 2.0978$ GeV.

**Typical pentagons/hexagons:**

**Complex mass scheme:**

$$\mu_i^2 = M_i^2 - i \Gamma_i M_i$$

for $i = W, Z, t, H$

$$s_w^2 = 1 - c_w^2 = 1 - \frac{\mu_W^2}{\mu_Z^2}$$

**Typical pentagons/hexagons:**
Differential Results for off-shell $e^+e^- \rightarrow tt$

$$e^+e^- \rightarrow \mu^+\nu_\mu e^-\bar{\nu}_e b\bar{b}, \ N_{\text{jets}} \geq 2, \ \sqrt{s} = 800\,\text{GeV}$$

$$m_t^2 = m_W^2 + \frac{2\langle m_{\ell_j}\rangle}{1 - \langle \cos \theta_{\ell_j}\rangle}$$
### Top-Forward Backward Asymmetry

The asymmetry $A_{FB}$ is defined as:

$$A_{FB} = \frac{\sigma(\cos \theta_t > 0) - \sigma(\cos \theta_t < 0)}{\sigma(\cos \theta_t > 0) + \sigma(\cos \theta_t < 0)}.$$ 

Gluon emission is symmetric in $\theta \Rightarrow$ NLO QCD corrections small.

**$A_{FB}$ of the top quark**

<table>
<thead>
<tr>
<th>Process</th>
<th>$A_{FB}^{LO}$</th>
<th>$A_{FB}^{NLO}$</th>
<th>$A_{FB}^{NLO}/A_{FB}^{LO}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^+e^- \rightarrow t\bar{t}$</td>
<td>-0.535</td>
<td>-0.539</td>
<td>1.013</td>
</tr>
<tr>
<td>$W^+W^-b\bar{b}$</td>
<td>-0.428</td>
<td>-0.426</td>
<td>0.995</td>
</tr>
<tr>
<td>$\mu^+e^-\nu_\mu\bar{\nu}_e b\bar{b}$</td>
<td>-0.415</td>
<td>-0.409</td>
<td>0.986</td>
</tr>
<tr>
<td>$\mu^+e^-\nu_\mu\bar{\nu}_e b\bar{b}$, without neutrinos</td>
<td>-0.402</td>
<td>-0.387</td>
<td>0.964</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Process</th>
<th>$\bar{A}_{FB}^{LO}$</th>
<th>$\bar{A}_{FB}^{NLO}$</th>
<th>$\bar{A}<em>{FB}^{NLO}/A</em>{FB}^{LO}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t\bar{t}$</td>
<td>0.535</td>
<td>0.539</td>
<td>1.013</td>
</tr>
<tr>
<td>$W^+W^-b\bar{b}$</td>
<td>0.428</td>
<td>0.426</td>
<td>0.995</td>
</tr>
<tr>
<td>$\mu^+e^-\nu_\mu\bar{\nu}_e b\bar{b}$</td>
<td>0.415</td>
<td>0.409</td>
<td>0.986</td>
</tr>
<tr>
<td>$\mu^+e^-\nu_\mu\bar{\nu}_e b\bar{b}$, without neutrinos</td>
<td>0.377</td>
<td>0.350</td>
<td>0.928</td>
</tr>
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Resonances: Simplified models

- Resonances might be in direct reach of LHC
- EFT framework EW-restored regime: $SU(2)_L \times SU(2)_R$, $SU(2)_L \times U(1)_Y$ gauged
- Include EFT operators in addition (more resonances, continuum contribution)
- Apply $T$-matrix unitarization beyond resonance (“UV-incomplete” model)

Spins 0, 2 considered, Spin 1 has different physics (mixing with $W/Z$)
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<td>$\phi^-^-, \phi^-^-, \phi^+_t, \phi^+_t, \phi^++_t$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\phi^0_v, \phi^+_v, \phi^+_v$</td>
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<td>$\phi_0^1_s$</td>
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<tr>
<td>tensor</td>
<td>$f^0$</td>
<td>$X^-^-, X^-^-, X^+_t, X^+_t, X^++_t$</td>
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**Tensor resonances**
- Symmetric tensor $f_{\mu\nu}$
- On-shell: $10 \rightarrow 5$ components
- Tracelessness: $f_{\mu}^{\mu} = 0$
- Transversality: $\partial_{\mu} f^{\mu\nu} = 0$

- Fierz-Pauli conditions not valid off-shell
- Fierz-Pauli propagator has bad high-energy behavior
- Stückelberg formalism to make off-shell behavior explicit

In the MC: compensator fields $\Rightarrow$
- no propagators with momentum factors

\[ f_{\mu\nu} \quad \text{on-shell} \quad f^{\mu\nu} \]
\[ \phi : \partial_\mu \partial_\nu f^{\mu\nu} \]
\[ A^{\mu} : \partial_\nu f^{\mu\nu} \]
\[ \sigma : f^{\mu\mu} \]

Gauge fixing: $\sigma = -\phi$
WW production in $e^+e^- — CC10$ process

model = SM

process cc10 = e1, E1 => e2, N2, u, D

sqrts = 209 GeV

integrate (cc10)
  { iterations = 15:500000, 5:1000000 }

# For better statistics: 100 times LEP
luminosity = 10 / fb

histogram m_jets (70 GeV, 90 GeV, 0.5 GeV)

histogram e_muon (0 GeV, 209 GeV, 4)

analysis = record m_jets (eval M [u, D]);
           record e_muon (eval E [e2])

simulate (cc10)

compile_analysis ( "out_file" = cc10.dat)
LEP Higgs Search

model = SM
alias n = n1:n2:n3
alias N = N1:N2:N3
alias q = u:d:s:c
alias Q = U:D:S:C

# Higgsstrahlung's process
process zh = e1, E1 => Z, h

# Missing energy channel
process nnbb = e1, E1 => n, N, b, B

# 4-jet channels
process qqbb = e1, E1 => q, Q, b, B
process bbbb = e1, E1 => b, B, b, B
process eebb = e1, E1 => e1, E1, b, B
process qttt = e1, E1 => q, Q, e3, E3
process bttt = e1, E1 => b, B, e3, E3

sqrts = 209 GeV

# would-be Higgs mass at LEP
mH = 115 GeV
wh = 3.228 MeV
mb = 2.9 GeV
me = 0 ms = 0 mc = 0
cuts = all M >= 10 GeV [q, Q]

luminosity = 10 / fb

integrate (nnbb,qqbb,eebb,qttt,bttt)
  { iterations = 12:20000, 1:30000 }

analysis = record m_invisible (eval M [n, N]);
          record m_bb (eval M [b, B])

histogram m_invisible (70 GeV, 130 GeV, 0.5 GeV)
histogram m_bb (70 GeV, 130 GeV, 0.5 GeV)
histogram m_jj (70 GeV, 130 GeV, 0.5 GeV)
simulate (nnbb)
simulate (qqbb) { analysis = record m_jj (eval M / 1 GeV
[combine [q,Q]]) }
Z-lineshape at SLC/LEP I

model = SM
alias lep = e1:E1:e2:E2
alias prt = lep:A

process bornproc = e1, E1 => e2, E2
process rc = e1, E1 => e2, E2, A

cuts = all E >= 100 MeV [prt]
    and all abs (cos(Theta)) <= 0.99 [prt]
    and all M2 >= (1 GeV)^2 [prt, prt]

integrate (enj) { iterations = 5:20000:"gw", 3:10000 }

plot lineshape_born { x_min=88 GeV x_max= 95 GeV }
plot lineshape_rc { x_min=88 GeV x_max= 95 GeV }

scan sqrts = ((88.0 GeV => 90.0 GeV /+ 0.5 GeV),
    (90.1 GeV => 91.9 GeV /+ 0.1 GeV),
    (92.0 GeV => 95.0 GeV /+ 0.5 GeV)) {
    beams = e1, E1
    integrate (bornproc) { iterations = 2:1000:"gw", 1:2000 }
    record lineshape_born (sqrts, integral (bornproc) / 1000)
    integrate (rc) { iterations = 5:3000:"gw", 2:5000 }
    record lineshape_rc (sqrts, integral (rc) / 1000)
}

compile_analysis { $out_file = “Z-lineshape.dat” }
model = model

alias parton = u:U:d:D:g
alias jet = parton
alias lepton = e1:e2
alias neutrino = n1:N1:n2:N2

process enj = parton, parton => lepton, neutrino, jet

sqrts = 14 TeV
beams = p, p => pdf_builtin
$pdf_builtin_set = "cteq6l"

me = 0  mmu = 0  ms = 0  mc = 0

cuts = all Pt >= 10 GeV [jet, lepton]
integrate (enj) { iterations = 5:20000:"gw", 3:10000 }

n_events = 20000

histogram pt_lepton (0 GeV, 80 GeV, 2 GeV)
histogram pt_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]]])

checkpoint = 1000

simulate (enj)

compile_analysis { $out_file = "W-endpoint.dat" }