Whizard for FCC-ee and other $e^+e^-/\mu^+\mu^-$ colliders

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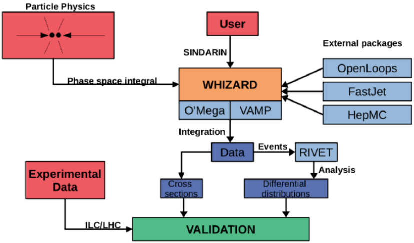
Whizard Overview

- 1999 Whizard 1 — 2007 Whizard 2
  - Hard-interaction physics at high-energy colliders (LHE, ILC, CLIC, CECP, HALHF, . . .)
  - Tree-level matrix element code generated (O'Mega)
  - Universal multi-channel integrator VAMP
  - Cross sections, distributions, event streams (HepMC, LCIO, StdHepi, LHE)
  - Full polarization support
  - Beam spectra ISR, PDF (LHAPDF. . .)
  - Shower and hadronization (PYTHIA6, PYTHIA8. . .)
  - SM and BSM models
- 2021 — now Whizard 3 (current version 3.1.4)
  - Parallel computing MPI and OpenMP
  - Full UFO-1 support (UFO-2 support but NLO with UFO is incomplete)
  - NLO Matrix elements at NLO (OpenLoops, Recola, Gosam)

[hep-ph/9607454, hep-ph/9806432, hep-ph/0102195, 0708.4241, 1112.1039, 1206.3700, 1411.3834, 1510.02739, 1609.03390, 1811.09711, 2108.05362, 2208.09438, 2304.09883]

Whizard Overview




```
# We choose our favourite model
model = SM

# Define incomming particle beam
beams = e1, E1

# Set sqrts
sqrts = 200 GeV

# Define some particle containers for the cuts
alias lep = e1:E1:e2:E2
alias prt = lep:A

# These are the two processes we want to compare
process bornproc = e1, E1 => e2, E2
process realcorr = e1, E1 => e2, E2, gamma

# Compile model and process information
compile

# This is a cut on the phase space
cuts = all E >= 100 MeV [prt]
   and all abs (cos(Theta)) <= 0.99 [prt]
   and all M2 >= (1 GeV)^2 [prt, prt]

# Integrate
integrate (bornproc){ iterations = 1:2000:"gw", 2:2000}
integrate (realcorr){ iterations = 5:3000:"gw", 2:5000}
```

Whizard Development Team

The WHIZARD 3 Team

- **U Siegen:** Wolfgang Kilian, Pia Bredt, Nils Kreher, Tobias Striegl
- **DESY:** Jürgen Reuter, Maximilian Löschner, Krzysztof Mękała
  (S. Brass, B. Chokoufe, V. Rothe, P. Stienemeier, C. Weiss)
- **U Würzburg:** Thorsten Ohl
- **U Warsaw:** Filip Żarnecki
- **KIT**: Marius Höfer

Official Webpage

To download Whizard and the offical manual, or for tutorials visit our Webpage: `https://whizard.hepforge.org/`

- **HOME**
  - Main Page
- **MANUAL, WIKI, NEWS**
  - Manual (HTML)
  - Manual (PDF)
  - Wiki Page
  - CLIC page on WHIZARD
  - News
  - Tutorials
  - Delphes Fast Simulation
  - WHIZARD talks
  - ChangeLog
- **REPOSITORY, LAUNCHPAD, BUG TRACKER**
  - Launchpad Support Page
  - Subversion Repository
  - Public Git Repository
  - Support Questions
  - Bug Tracker
- **DOWNLOADS**
  - Download Page
  - LC beam spectra
  - FeynRules and SARAH models
  - Patches/Unofficial versions
- **SUBPACKAGES/INTERFACES**
  - O'Mega Matrix Element Generator
  - VAMP Monte Carlo Integrator
  - CIRCE1/2 Beam Spectra Generator
  - WHIZARD/FeynRules interface (deprecated)
- **CONTACT**
  - Launchpad Support Page
  - Contact us

The Generator of Monte Carlo Event Generators for Tevatron, LHC, ILC, CLIC, CEPC, FCC-ee, FCC-hh, SppC, the muon collider and other High Energy Physics Experiments

What is WHIZARD?

WHIZARD is a program system designed for the efficient calculation of multi-particle scattering cross sections and simulated event samples.

WHIZARD can evaluate NLO QCD corrections in the SM for arbitary lepton and hadron colliders. Tree-level matrix elements are generated automatically for arbitrary partonic processes by using the Optimized Matrix Element Generator O'Mega. Matrix elements obtained by alternative methods (e.g., including loop corrections) may be interfaced as well. The program is able to calculate numerically stable signal and background cross sections and generate unweighted event samples with reasonable efficiency for processes with up to eight final-state particles; more particles are possible. For more particles, there is the option to generate processes as decay cascades including complete spin correlations. Different options for QCD parton showers are available.

Polarization is treated exactly for both the initial and final states. Final-state quark or lepton flavors can be summed over automatically where needed. For hadron collider physics, an interface to the standard LHAPDF is provided. For Linear Collider physics, beamstrahlung (CIRCE) and ISR spectra are included for electrons and photons. The events can be written to file in standard formats, including ASCII, StdHEP, the Les Houches event format (LHEF), HepMC, or LCIO. These event files can then be hadronized.

WHIZARD supports the Standard Model and a huge number of BSM models. Model extensions or completely different models can be added. WHIZARD fully supports external models from UFO files. There are also legacy interfaces to FeynRules and SARAH.

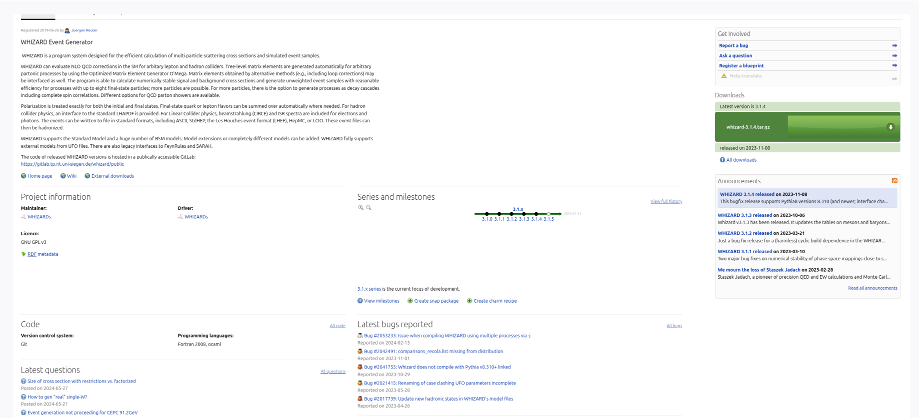
CURRENT RELEASE

- **The official version is 3.1.4 (released: November 8th, 2023).**

  The distribution tarball of the sources can be found here (3.1.4, link).
- Nightly build tarballs can be downloaded: (link).
- Before installing WHIZARD, you should check the note on compilers and the page on possible build problems in the WHIZARD Wiki.
- **The manual for WHIZARD 3** is not yet completed. We regularly update the version from the distributions (last update: 2023-11-08). The manual is available as PDF (link) and HTML (link). You can find a few physics examples in the WHIZARD Wiki. The documented WHIZARD source code can be found here (link). There is also a manual for GAMELAN, the graphics package based on MetaPost for WHIZARD's internal analyses.
- You may also want to inspect the latest **news** and the **list of changes**.
- **Support** is provided through our **launchpad site** (link), where questions will be answered (link).

User Support and Bug Reports

Launchpad: `https://launchpad.net/whizard`
Email: `whizard@desy.de`

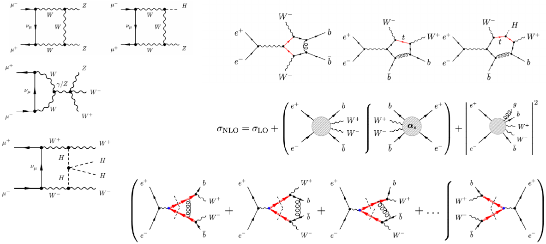


News on the Whizard Development

NLO Calculations

$$\sigma_{\text{NLO}} = \int d\Phi_n \mathcal{B} + \int \underbrace{d\Phi_{n+1}\left[\mathcal{R}(\Phi_{n+1}) - d\sigma_S(\Phi_{n+1})\right]}_{\text{finite by construction}} + \underbrace{\int d\Phi_n \mathcal{V} + \int d\Phi_n d\sigma_{S,\text{int}}}_{\text{IR poles cancelled analyt.}}$$

- NLO SM automation for lepton-/hadron colliders completed [Chokoufé, Weiss 2017, Rothe 2021, Stienemeier, Bredt 2022]
- Resonance-aware FKS subtraction, NLO matrix elements from OpenLoops, Recola or GoSam. [cf. Jeo/Nason, arXiv:1509.09071; Chokoufé, 2017]
- Setup for automatic differential fixed-order results (histogrammed distributions) Photon isolation, photon recombination, light-, b-, c-jet selection; loop-induced processes
- Process independent matching for NLO real emission from hard ME and parton shower with POWHEG method (hardest emission first [Frixione/Nason et al.]).



Some Example NLO results

ee @ 1 TeV, NLO QCD

Process	WHIZARD+OpenLoops $\sigma_{\rm LO}$ [fb]	$\sigma_{\rm NLO}$ [fb]
$e^+e^- \to jj$	622.737(8)	639.39(5)
$e^+e^- \to jjj$	340.6(5)	317.8(5)
$e^+e^- \to jjjj$	105.0(3)	104.2(4)
$e^+e^- \to jjjjj$	22.33(5)	24.57(7)
$e^+e^- \to jjjjjj$	3.583(17)	4.46(4)
$e^+e^- \to t\bar{t}$	166.37(12)	174.55(20)
$e^+e^- \to t\bar{t}j$	48.12(5)	53.41(7)
$e^+e^- \to t\bar{t}jj$	8.592(19)	10.526(21)
$e^+e^- \to t\bar{t}jjj$	1.035(4)	1.405(5)
$e^+e^- \to t\bar{t}t\bar{t}$	$0.6388(8) \cdot 10^{-3}$	$1.1922(11) \cdot 10^{-3}$
$e^+e^- \to t\bar{t}t\bar{t}j$	$2.673(7) \cdot 10^{-5}$	$5.251(11) \cdot 10^{-5}$
$e^+e^- \to t\bar{t}H$	2.020(3)	1.912(3)
$e^+e^- \to t\bar{t}Hj$	$2.536(4) \cdot 10^{-1}$	$2.657(4) \cdot 10^{-1}$
$e^+e^- \to t\bar{t}Hjj$	$2.646(8) \cdot 10^{-2}$	$3.123(9) \cdot 10^{-2}$
$e^+e^- \to t\bar{t}Z$	4.638(3)	4.937(3)
$e^+e^- \to t\bar{t}Zj$	$6.027(9) \cdot 10^{-1}$	$6.921(11) \cdot 10^{-1}$
$e^+e^- \to t\bar{t}Zjj$	$6.436(21) \cdot 10^{-2}$	$8.241(29) \cdot 10^{-2}$
$e^+e^- \to t\bar{t}W^\pm jj$	$2.387(8) \cdot 10^{-4}$	$3.716(10) \cdot 10^{-4}$
$e^+e^- \to t\bar{t}HZ$	$3.623(19) \cdot 10^{-2}$	$3.584(19) \cdot 10^{-2}$
$e^+e^- \to t\bar{t}ZZ$	$3.788(6) \cdot 10^{-2}$	$4.032(7) \cdot 10^{-2}$
$e^+e^- \to t\bar{t}HH$	$1.3650(15) \cdot 10^{-2}$	$1.2168(16) \cdot 10^{-2}$
$e^+e^- \to t\bar{t}W^+W^-$	$1.3672(21) \cdot 10^{-1}$	$1.5385(22) \cdot 10^{-1}$

pp @ 13 TeV, NLO QCD

Process Vector boson (pair) plus jets	WHIZARD $\sigma_{\rm LO}$[fb]	$\sigma_{\rm NLO}$[fb]	K
$pp \to W^\pm$ *	$1.3749(8) \cdot 10^8$	$1.7696(10) \cdot 10^8$	1.29
$pp \to W^\pm j$ *	$2.046(3) \cdot 10^7$	$2.854(5) \cdot 10^7$	1.39
$pp \to W^\pm jj$	$6.856(12) \cdot 10^6$	$7.814(27) \cdot 10^6$	1.14
$pp \to W^\pm jjj$ †	$1.840(5) \cdot 10^6$	$1.978(7) \cdot 10^6$	1.07
$pp \to Z$	$4.2541(3) \cdot 10^7$	$5.4086(16) \cdot 10^7$	1.27
$pp \to Zj$	$7.215(4) \cdot 10^6$	$9.733(10) \cdot 10^6$	1.35
$pp \to Zjj$	$2.364(5) \cdot 10^6$	$2.676(7) \cdot 10^6$	1.13
$pp \to Zjjj$	$6.381(23) \cdot 10^5$	$6.85(3) \cdot 10^5$	1.07
$pp \to W^+W^-(4f)$	$7.352(10) \cdot 10^4$	$10.268(11) \cdot 10^4$	1.40
$pp \to W^+W^-j(4f)$	$2.853(7) \cdot 10^4$	$3.733(7) \cdot 10^4$	1.31
$pp \to W^+W^-jj(4f)$ *	$1.150(5) \cdot 10^4$	$1.372(6) \cdot 10^4$	1.19
$pp \to W^+W^+jj$ *	$1.506(5) \cdot 10^2$	$2.235(7) \cdot 10^2$	1.48
$pp \to W^-W^-jj$	$6.772(24) \cdot 10^1$	$9.982(28) \cdot 10^1$	1.47
$pp \to ZW^\pm$	$2.780(5) \cdot 10^4$	$4.488(4) \cdot 10^4$	1.61
$pp \to ZW^\pm j$	$1.609(4) \cdot 10^4$	$2.0940(28) \cdot 10^4$	1.30
$pp \to ZW^\pm jj$	$8.06(3) \cdot 10^3$	$9.02(4) \cdot 10^3$	1.12
$pp \to ZZ$ *	$1.0969(10) \cdot 10^4$	$1.4183(11) \cdot 10^4$	1.29
$pp \to ZZj$	$3.667(9) \cdot 10^3$	$4.807(8) \cdot 10^3$	1.31
$pp \to ZZjj$ *	$1.356(6) \cdot 10^3$	$1.684(8) \cdot 10^3$	1.24

pp @ 13 TeV, NLO QCD/EW mixed

$pp \to t\bar{t}W^+$	$\alpha_s^n\alpha^m$	$\sigma^{\rm tot}$ [fb] MUNICH$_{\rm (CS)}$	WHIZARD	$\sigma^{\rm sig}$ / dev MUNICH$_{\rm (CS)}$-WHIZARD
LO$_{21}$	$\alpha_s^2\alpha$	$2.411403(1) \cdot 10^2$	$2.4114(1) \cdot 10^2$	0.72 / 0.003%
LO$_{12}$	$\alpha_s\alpha^2$	0.000	0.000	0.00 / 0.000%
LO$_{03}$	α^3	$2.31909(1) \cdot 10^0$	$2.3193(1) \cdot 10^0$	1.76 / 0.009%
δNLO$_{31}$	$\alpha_s^3\alpha$	$1.18993(2) \cdot 10^2$	$1.1905(5) \cdot 10^2$	1.06 / 0.048%
δNLO$_{22}$	$\alpha_s^2\alpha^2$	$-1.09511(9) \cdot 10^1$	$-1.0947(3) \cdot 10^1$	1.13 / 0.035%
δNLO$_{13}$	$\alpha_s\alpha^3$	$2.93251(3) \cdot 10^1$	$2.9334(8) \cdot 10^1$	1.14 / 0.030%
δNLO$_{04}$	α^4	$5.759(3) \cdot 10^{-2}$	$5.756(4) \cdot 10^{-2}$	0.58 / 0.049%

μμ @ 3 TeV, NLO EW

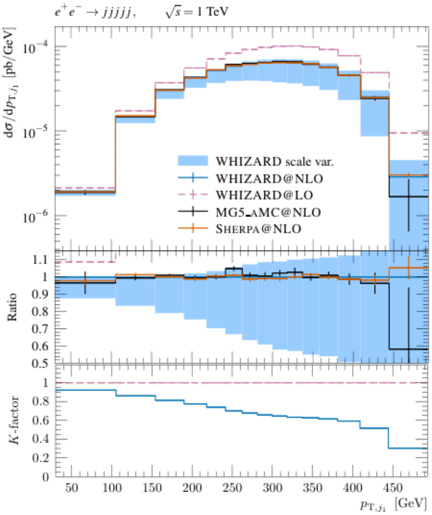
$\mu^+\mu^- \to X, \sqrt{s} =$	$\sigma^{\rm incl}_{\rm LO}$ [fb]	$\sigma^{\rm incl}_{\rm NLO}$ [fb]	$\delta_{\rm EW}$ [%]
W^+W^-	$4.6591(2) \cdot 10^2$	$4.847(7) \cdot 10^2$	+4.0(2)
ZZ	$2.5988(1) \cdot 10^1$	$2.656(2) \cdot 10^1$	+2.19(6)
HZ	$1.3719(1) \cdot 10^0$	$1.3512(5) \cdot 10^0$	−1.51(4)
HH	$1.60216(7) \cdot 10^{-7}$	$5.66(1) \cdot 10^{-7}$ *	
W^+W^-Z	$3.330(2) \cdot 10^1$	$2.568(8) \cdot 10^1$	−22.9(2)
W^+W^-H	$1.1253(5) \cdot 10^0$	$0.895(2) \cdot 10^0$	−20.5(2)
ZZZ	$3.598(2) \cdot 10^{-1}$	$2.68(1) \cdot 10^{-1}$	−25.5(3)
HZZ	$8.199(4) \cdot 10^{-2}$	$6.60(3) \cdot 10^{-2}$	−19.6(3)
HHZ	$3.277(1) \cdot 10^{-2}$	$2.451(5) \cdot 10^{-2}$	−25.2(1)
HHH	$2.9699(6) \cdot 10^{-8}$	$0.86(7) \cdot 10^{-8}$ *	
$W^+W^-W^+W^-$	$1.484(1) \cdot 10^0$	$0.993(6) \cdot 10^0$	−33.1(4)
W^+W^-ZZ	$1.209(1) \cdot 10^0$	$0.699(7) \cdot 10^0$	−42.2(6)
W^+W^-HZ	$8.754(8) \cdot 10^{-2}$	$6.05(4) \cdot 10^{-2}$	−30.9(5)
W^+W^-HH	$1.058(1) \cdot 10^{-2}$	$0.655(5) \cdot 10^{-2}$	−38.1(4)
$ZZZZ$	$3.114(2) \cdot 10^{-3}$	$1.799(7) \cdot 10^{-3}$	−42.2(2)
$HZZZ$	$2.693(2) \cdot 10^{-3}$	$1.766(6) \cdot 10^{-3}$	−34.4(2)
$HHZZ$	$9.828(7) \cdot 10^{-4}$	$6.24(2) \cdot 10^{-4}$	−36.5(2)
$HHHZ$	$1.568(1) \cdot 10^{-4}$	$1.165(4) \cdot 10^{-4}$	−25.7(2)

ee @ .25 TeV, NLO EW, pol.av. + pol.

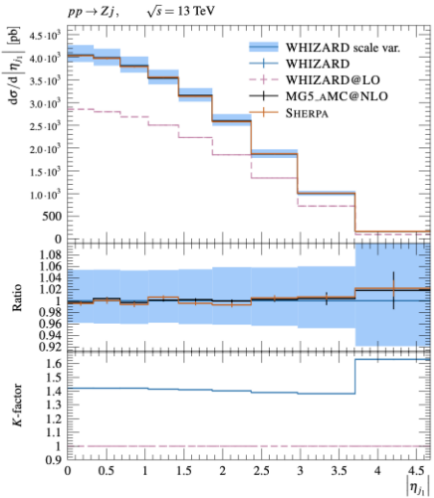
$\sqrt{s}$ [GeV]	MCSANCee[37] $\sigma^{\rm tot}_{\rm LO}$ [fb]	$\sigma^{\rm tot}_{\rm NLO}$ [fb]	WHIZARD+RECOLA $\sigma^{\rm tot}_{\rm LO}$ [fb]	$\sigma^{\rm tot}_{\rm NLO}$ [fb]	$\delta_{\rm EW}$ [%]	$\sigma^{\rm sig}$ (LO/NLO)
250	225.59(1)	206.77(1)	225.60(1)	207.0(1)	−8.25	0.4/2.1
500	53.74(1)	62.42(1)	53.74(3)	62.41(2)	+16.14	0.2/0.3
1000	12.05(1)	14.56(1)	12.0549(6)	14.57(1)	+20.84	0.5/0.5

Some Example NLO results

ee @ 1 TeV, NLO QCD



pp @ 13 TeV, NLO QCD

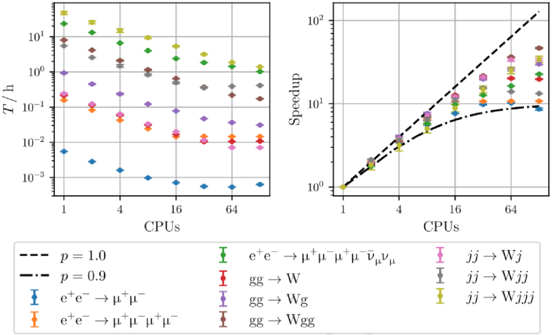


UFO Interface for BSM calculations

- Full UFO-1 [1108.2040] support since WHIZARD-2.8.3
- Fermion-number violating interactions since whizard-3.0.0
- Arbitrary Lorentz structures are supported.
- 5-, 6-, 7-, 8-,... point vertices (optimization for code generation pending)
- Customized propators for Spin-0, $^1/_2$, 1, $^3/_2$ and 2 particles.
- Lots of bug reports and constructive feedback from many different users.
- Partial support for NLO matrix elements from UFO models

Parallelisation

- ☑ Parallelize Helicities with OpenMP (Mulit Thread)
- ☑ MPI (For parallel computing archtectures, like HPC cluster)
  - Grid adaption, event generation
  - Speedup 20 to 50, saturation at about 100
  - Uses load balancer since verison 3.0.0
- ☐ Whizard on GPU



Currently Under Development

Electron PDFs

- Starting point: Known analytical solutions for Electron-PDFs in $\overline{MS}$-scheme. [1911.12040]
- Goal: Implement and stabilize them for numerical calculations in Whizard.

☑ Rewriting of analytic expressions in redundant variables x and $\bar{x} = 1 - x$ and guarantee Numerically stable for for $x \to 1$.

☑ Numerically stable and quadruple precision safe logs and polylogs

☑ Solve integrals for which only numerical solutions existed

☑ NLL ePDF form allows exponential mappings

☐ Reduce useage of explicit quadruple precision (critical points only)

☐ Final cleaning in Whizard

☐ Validate

$$
\begin{aligned}
\hat{J}^{\mathrm{NLL}}_{S,2,\mathrm{an}} = {} & \frac{1}{108 b_0 z \big(z^2-1\big)} \times \Big(608 b_0 N_F^2 z^5 + 192 b_0 L_0 N_F^2 z^5 - 432 b_0 N_F z^5 + 96 b_0 N_F \pi^2 z^5 - 960 b_0^2 N_F \pi z^5 + \\
& 1152 b_1 N_F \pi z^5 + 1152 b_0^2 L_0 N_F \pi z^5 + 144 b_0 N_F^2 z^4 + 144 b_0 L_0 N_F^2 z^4 - 486 b_0 z^4 - 405 b_0 L_0 z^4 - 3852 b_0 N_F z^4 + \\
& 1656 b_0 L_0 N_F z^4 + 360 b_0^2 \pi^3 z^4 + 432 b_0^3 \pi^2 z^4 + 324 b_0 \pi^2 z^4 - 432 b_0 b_1 \pi^2 z^4 - 432 b_0^3 L_0 \pi^2 z^4 + 216 b_0 L_0 \pi^2 z^4 + \\
& 120 b_0 N_F \pi^2 z^4 + 432 b_1 \pi z^4 + 432 b_0^2 L_0 \pi z^4 - 3984 b_0^2 N_F \pi z^4 + 864 b_1 N_F \pi z^4 + 864 b_0^2 L_0 N_F \pi z^4 - 1328 b_0 N_F^2 z^3 - \\
& 336 b_0 L_0 N_F^2 z^3 + 1350 b_0 z^3 - 1539 b_0 L_0 z^3 + 4092 b_0 N_F z^3 - 1656 b_0 L_0 N_F z^3 - 360 b_0^2 \pi^3 z^3 - 432 b_0^3 \pi^2 z^3 - \\
& 504 b_0 \pi^2 z^3 + 432 b_0 b_1 \pi^2 z^3 + 432 b_0^3 L_0 \pi^2 z^3 - 216 b_0 L_0 \pi^2 z^3 - 216 b_0 N_F \pi^2 z^3 - 1080 b_0^2 \pi z^3 + 1296 b_1 \pi z^3 + \\
& 1296 b_0^2 L_0 \pi z^3 + 3504 b_0^2 N_F \pi z^3 - 2016 b_1 N_F \pi z^3 - 2016 b_0^2 L_0 N_F \pi z^3 - 176 b_0 N_F^2 z^2 - 336 b_0 L_0 N_F^2 z^2 + \\
& 486 b_0 z^2 + 405 b_0 L_0 z^2 + 5004 b_0 N_F z^2 - 1656 b_0 L_0 N_F z^2 - 648 b_0^2 \pi^3 z^2 - 432 b_0^3 \pi^2 z^2 + 108 b_0 \pi^2 z^2 + \\
& 432 b_0 b_1 \pi^2 z^2 + 432 b_0^3 L_0 \pi^2 z^2 - 216 b_0 L_0 \pi^2 z^2 - 216 b_0 N_F \pi^2 z^2 - 432 b_1 \pi z^2 - 432 b_0^2 L_0 \pi z^2 + 6672 b_0^2 N_F \pi z^2 - \\
& 2016 b_1 N_F \pi z^2 - 2016 b_0^2 L_0 N_F \pi z^2 + 720 b_0 N_F^2 z + 144 b_0 L_0 N_F^2 z - 1350 b_0 z + 1539 b_0 L_0 z - 3660 b_0 N_F z + \\
& 1656 b_0 L_0 N_F z + 864 b_0 (z-1) \Big((\log(z+1) - \log(1-z)) z^2 + \log(1-z) - \log(z+1) - 5 \log(2) \Big) \mathrm{Li}_2\Big(\frac{1-z}{2}\Big) z - \\
& 4z \Big(\log(z) z^3 + \log(1-z) z - \log(1-z) + \log(z) + (z(z+6)-5) \log(z+1) \Big) \Big) \mathrm{Li}_2(-z) + 8z \Big((z-1) \Big(- \\
& 4z^2 + 2z - 6 \log(1-z) + 6 b_0 \pi + 3 \Big) - 2 \Big(z^3 + 5z - 4 \Big) \log(z+1) \Big) \mathrm{Li}_2\Big(\frac{1}{z+1}\Big) + 4 \Big(z^2 - 1 \Big) (z(5z-8) + \\
& 10(z-1) z \log(z+1) - 6) \mathrm{Li}_2\Big(\frac{z}{z+1}\Big) + 8z \Big(z^2 - 1 \Big) (3z + 4 N_F (z+1) + 8) \mathrm{Li}_3(1-z) - 8z (6 N_F + z) \Big(z^2 - \\
& 1 \Big) \mathrm{Li}_3\Big(\frac{z-1}{z}\Big) + 8z(z+1)(z(7z-16)+7) \mathrm{Li}_3(-z) + 4z(8z N_F + 20 N_F + 3z + 9) \Big(z^2 - 1 \Big) \mathrm{Li}_3(z) + 16z(z + \\
& 1)(z(3z-4)+3) \mathrm{Li}_3\Big(\frac{1}{z+1}\Big) - z(16 N_F (z-1)(z+1)(2z+5) + z(z(21z+67)+99) - 107) \zeta(3) \Big) \Big) - \\
& 216 b_0 (z-1)(z+1)(z(9z+7)+3) \log^2(2) + 96 b_0 N_F \pi^2 - 2688 b_0^2 N_F \pi + 1152 b_1 N_F \pi + 1152 b_0^2 L_0 N_F \pi \Big)
\end{aligned}
$$

Electroweak PDFs

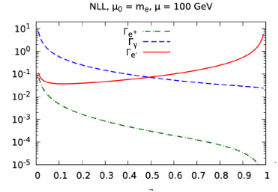
- Collinear factorization not only in QED, but in full SM [Han/Ma/Xie, 2007.14300, 2103.09844]
- Improvement of EWA (Effective W-approximation) Fully inclusive in forwardbeam direction.
- Fast interpolation (CTEQ-like/LHAPDF-like) as grids available. [2303.16964]
- $\gamma\gamma$ part (quasi-) identical to collinear QED lepton PDFs.

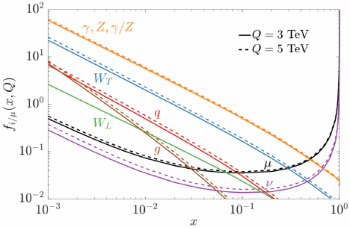
☑ Infrastructure in Whizard [Mękała/Reuter]

☐ Validation against existing EWA implementation [Dahlén]

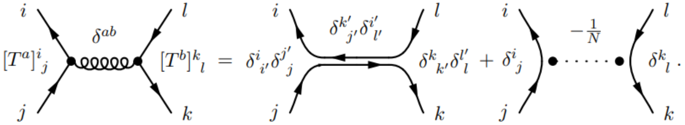
☐ Necessitates a special incarnation of SM implementation for MEs

☐ EW fragmentation functions for event selection





Exotic Colors in Whizard



- Very important for dim_6, dim_8, ... operators in SMEFT (e.g. Dark Sector,Dark Matter models).
- Epsilon structures (e.g. RPV SUSY), sextets, decuplets etc. Comes with automated Clebsch-Gordan decomposition.

☑ Recent work allows to generate completely arbitrary $SU(N)$ [T. Ohl, JHEP 06 (2024) 203] .

☐ Implementation of birdtrack algorithm: allows for generic Lie groups based on color-flow implementation in Whizard.

☐ Matrix element generator fully capable of completely general color exotics.

☐ Support to handle this on the event generation.

Conclusions and Outlook

- Whizard is a viable tool for physics studies and analyses at HEP experiments: LHC, Belle II, ILC, CLIC, FCC, CEPC, MuCol, ...
- Any SM (NLO) and BSM processes can be handled, limited mainly by external programs and CPU time
- OpenMP and MPI parallelisation available
- Specific support for e^+e^- to be improved to full SM NLO (and SMEFT, ...)

Currently under development and planned:

- General color structures
- Whizard on GPU
- NLL ePDFs
- EWPDFs
- QED Shower, YFS

BACKUP

Technical Remarks

Language: `Fortran` (2018, object-oriented/modular) with `O'Caml`

Development: `gitlab` with automated test suite and CI

Installation: `configure && make && make install`

Numerics: Support for extended and quadruple precision (if needed)

Running: Options

1. Stand-alone with input script: `whizard` ⟨*input*⟩`.sin` (optional workspace transfer for cluster operation)
2. As a library, callable from: `Fortran`, `C`, `C++`, `Python`

BSM: Predefined (many models) and UFO (everything else)

Script: SINDARIN (input, parameters, cuts, workflow, result aggregation, output control, . . .)

Parallel: OpenMP (multi-core), MPI (HPC cluster)

The WHIZARD 3 Team

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- **KIT**: Marius Höfer

Links

- WHIZARD Portal: `https://whizard.hepforge.org/`
- User Support: `https://launchpad.net/whizard`
- Git: `https://gitlab.tp.nt.uni-siegen.de/whizard/public`
- Email: `whizard@desy.de`

Hadron collisions at NLO EW

- QED FKS subtraction terms:

$$d\sigma_{S,\text{coll}} \sim \alpha \underbrace{\hat{P}^{\mu\nu}_{E\to(i,j),\text{QED}}\mathcal{B}^{(E)}_{\mu\nu}}_{\text{pol. AP kernel}\,\times\,\text{spin-corr.}} \qquad d\sigma_{S,\text{soft}} \sim \alpha \sum_{k,l=1}^{n} \underbrace{\frac{\bar{k}_k \cdot \bar{k}_l}{(\bar{k}_k \cdot \hat{k}_j)(\bar{k}_l \cdot \hat{k}_j)}\mathcal{B}_{kl}}_{\text{eikonal}\,\times\,\text{charge-corr.}}$$

- EW schemes & photons entering at Born level (e. g. $pp \to W^+W^-$)

$Q^2_\gamma \to 0$	$Q^2_\gamma \sim$ EW scale
on-shell photons no γ splittings	*off-shell* photons $\gamma^* \to f\bar{f}$
$\alpha(0)$	$\alpha\vert_{G_\mu}$, $\alpha(M_Z)$
$\left[\frac{\delta\alpha(0)}{\alpha(0)} + \delta Z_{AA}\right]_{\text{light}} = 0$	$\left[\frac{\delta\alpha(M_Z)}{\alpha(M_Z)} + \delta Z_{AA}\right]_{\text{light}} + \delta Z_{\gamma,\text{PDF}}$ $\to$ finite overall photon factor $\neq 0$

with photon virtuality Q^2_γ

Hadron collisions at NLO EW

IR-safety conditions:

- photon recombination with charged leptons – 'dressed' leptons
- jet clustering including photon – 'democratic' jets

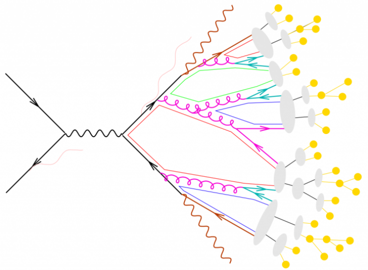
Pure electroweak pp processes with off-shell vector bosons

LHC setup (Run II): $\sqrt{s} = 13$ TeV $\mu_R = \mu_F = \frac{1}{2}\sum_i \sqrt{p_{T,i}^2 + m_i^2}$ EW scheme: G_μ CMS

PDF set: `LUXqed_plus_PDF4LHC15_nnlo_100` cuts from ref. [1804.10017]

process $pp \to$	α^m	`MG5_aMC@NLO` [1804.10017] $\sigma^{\text{tot}}_{\text{NLO}}$ [pb]	`WHIZARD+OpenLoops` $\sigma^{\text{tot}}_{\text{NLO}}$ [pb]	δ [%]	$\sigma^{\text{sig}}_{\text{NLO}}$
$e^+\nu_e$	α^2	$5.2005(8)\cdot 10^3$	$5.1994(4)\cdot 10^3$	-0.73	1.24
e^+e^-	α^2	$7.498(1)\cdot 10^2$	$7.498(1)\cdot 10^2$	-0.50	0.004
$e^+\nu_e\mu^-\bar\nu_\mu$	α^4	$5.2794(9)\cdot 10^{-1}$	$5.2816(9)\cdot 10^{-1}$	$+3.69$	1.69
$e^+e^-\mu^+\mu^-$	α^4	$1.2083(3)\cdot 10^{-2}$	$1.2078(3)\cdot 10^{-2}$	-5.25	1.26
$He^+\nu_e$	α^3	$6.4740(17)\cdot 10^{-2}$	$6.4763(6)\cdot 10^{-2}$	-4.04	1.24
He^+e^-	α^3	$1.3699(2)\cdot 10^{-2}$	$1.3699(1)\cdot 10^{-2}$	-5.86	0.32
Hjj	α^3	$2.7058(4)\cdot 10^0$	$2.7056(6)\cdot 10^0$	-4.23	0.27
tj	α^2	$1.0540(1)\cdot 10^2$	$1.0538(1)\cdot 10^2$	-0.72	0.74

Final-state effects



- Jets: integrated `FastJet` interface
- Polarized decays (e.g., W, Z, H, t) as alternative to full matrix elements
- Tau decays via TAOLA
- Resonance selection for shower initialization
- Parton shower + hadronization: PYTHIA6 (integrated)
- Parton shower + hadronization: Pythia 8 (interface or via event file)
- Event file formats: ILC-like (legacy, LCIO/Key4HEP) and LHC-like (legacy, LHE, HepMC)

Polarization in Whizard

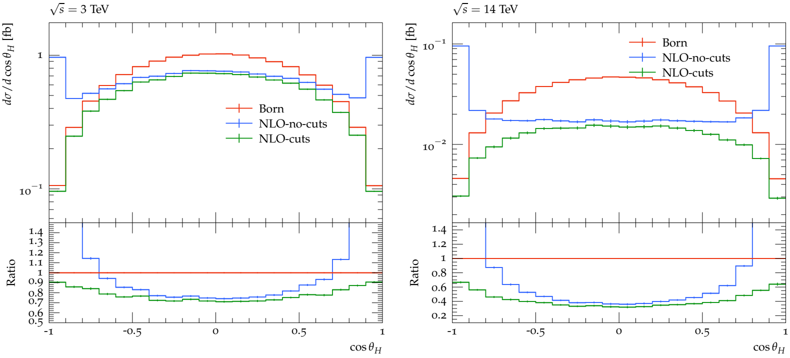
- Lazy method for simulation: merge distinct event samples with 100% $\pm$left/right polarization
- "Classical" polarization: project on helicities and postprocess particles with definite helicity
- "Quantum" method: polarization via initial-state and final-state density matrices, allows for arbitrary polarization fraction, spin rotation, polarized decays, etc. $\Rightarrow$ supported in Whizard since v1
- Polarization of outgoing particles: depend on event-file formats

$\Rightarrow$ NLO: polarization support relies on spin-correlated squared matrix element output

Multi-boson processes at a muon collider at NLO EW

[PB, W. Kilian, J. Reuter, P. Stienemeier, 2208.09438]

Fixed order differential distributions: $d\sigma(\mu^+\mu^- \to HZ)/d\cos\theta_H$



LHC: on-shell heavy bosons at NLO EW

Cross-validation of WHIZARD and MUNICH/MATRIX orig. ref. [Kallweit *et. al.*: 1412.5157]

process $pp \to$	MUNICH (CS) +OpenLoops $\sigma^{\text{tot}}_{\text{NLO}}$ [fb]	WHIZARD +OpenLoops $\sigma^{\text{tot}}_{\text{NLO}}$ [fb]	δ [%]	dev [%]	$\sigma^{\text{sig}}_{\text{NLO}}$
ZZ	$1.05729(1) \cdot 10^4$	$1.05729(11) \cdot 10^4$	-4.20	0.0001	0.01
W^+Z	$1.71505(2) \cdot 10^4$	$1.71507(2) \cdot 10^4$	-0.15	0.001	0.88
W^-Z	$1.08576(1) \cdot 10^4$	$1.08574(1) \cdot 10^4$	$+0.07$	0.001	0.90
W^+W^-	$7.93106(7) \cdot 10^4$	$7.93087(21) \cdot 10^4$	$+4.55$	0.002	0.89
ZH	$6.18523(6) \cdot 10^2$	$6.18533(6) \cdot 10^2$	-5.29	0.002	1.17
W^+H	$7.18070(7) \cdot 10^2$	$7.18072(9) \cdot 10^2$	-2.31	0.0003	0.18
W^-H	$4.59289(4) \cdot 10^2$	$4.59299(5) \cdot 10^2$	-2.15	0.002	1.62
ZZZ	$9.7429(2) \cdot 10^0$	$9.7417(11) \cdot 10^0$	-9.47	0.012	1.01
W^+W^-Z	$1.08288(2) \cdot 10^2$	$1.08293(10) \cdot 10^2$	$+7.67$	0.004	0.45
W^+ZZ	$2.0188(4) \cdot 10^1$	$2.0188(23) \cdot 10^1$	$+1.58$	0.0001	0.01
W^-ZZ	$1.09844(2) \cdot 10^1$	$1.09838(12) \cdot 10^1$	$+3.09$	0.006	0.51
$W^+W^-W^+$	$8.7979(2) \cdot 10^1$	$8.7991(15) \cdot 10^1$	$+6.18$	0.014	0.79
$W^+W^-W^-$	$4.9447(1) \cdot 10^1$	$4.9441(2) \cdot 10^1$	$+7.13$	0.013	2.52
ZZH	$1.91607(2) \cdot 10^0$	$1.91614(18) \cdot 10^0$	-8.78	0.004	0.39
W^+ZH	$2.48068(2) \cdot 10^0$	$2.48095(28) \cdot 10^0$	$+1.64$	0.011	0.96
W^-ZH	$1.34001(1) \cdot 10^0$	$1.34016(15) \cdot 10^0$	$+2.51$	0.011	1.02
W^+W^-H	$9.7012(2) \cdot 10^0$	$9.700(2) \cdot 10^0$	$+9.83$	0.014	0.75
ZHH	$2.39350(2) \cdot 10^{-1}$	$2.39337(32) \cdot 10^{-1}$	-11.06	0.005	0.41
W^+HH	$2.44794(2) \cdot 10^{-1}$	$2.44776(24) \cdot 10^{-1}$	-12.04	0.007	0.74
W^-HH	$1.33525(1) \cdot 10^{-1}$	$1.33471(19) \cdot 10^{-1}$	-11.53	0.041	2.80

LHC setup (Run II) $\quad \delta \equiv \frac{\sigma^{\text{tot}}_{\text{NLO}} - \sigma^{\text{tot}}_{\text{LO}}}{\sigma^{\text{tot}}_{\text{LO}}} \quad \text{dev} \equiv \frac{|\sigma^{\text{tot}}_{\text{WHIZARD}} - \sigma^{\text{tot}}_{\text{MUNICH}}|}{\sigma^{\text{tot}}_{\text{WHIZARD}}} \quad \sigma^{\text{sig}} \equiv \frac{|\sigma^{\text{tot}}_{\text{WHIZARD}} - \sigma^{\text{tot}}_{\text{MUNICH}}|}{\sqrt{\Delta^2_{\text{err,WHIZARD}} + \Delta^2_{\text{err,MUNICH}}}}$

Multi-boson processes at a muon collider at NLO EW

[PB, W. Kilian, J. Reuter, P. Stienemeier, 2208.09438] WHIZARD+RECOLA, G_μ scheme, $m_\mu = 0.1056\ldots$ GeV

$\mu^+\mu^- \to X, \sqrt{s} = 3$ TeV	$\sigma^{\text{incl}}_{\text{LO}}$ [fb]	δ_{EW} [%]	δ_{ISR} [%]
W^+W^-	$4.6591(2) \cdot 10^2$	$+4.0(2)$	$+13.82(4)$
ZZ	$2.5988(1) \cdot 10^1$	$+2.19(6)$	$+15.71(4)$
HZ	$1.3719(1) \cdot 10^0$	$-1.51(4)$	$+30.24(3)$
W^+W^-Z	$3.330(2) \cdot 10^1$	$-22.9(2)$	$+2.90(9)$
W^+W^-H	$1.1253(5) \cdot 10^0$	$-20.5(2)$	$+7.10(8)$
ZZZ	$3.598(2) \cdot 10^{-1}$	$-25.5(3)$	$+5.24(8)$
HZZ	$8.199(4) \cdot 10^{-2}$	$-19.6(3)$	$+8.39(8)$
HHZ	$3.277(1) \cdot 10^{-2}$	$-25.2(1)$	$+7.58(7)$
$W^+W^-W^+W^-$	$1.484(1) \cdot 10^0$	$-33.1(4)$	$-1.3(1)$
W^+W^-ZZ	$1.209(1) \cdot 10^0$	$-42.2(6)$	$-1.8(1)$
W^+W^-HZ	$8.754(8) \cdot 10^{-2}$	$-30.9(5)$	$-0.1(1)$
W^+W^-HH	$1.058(1) \cdot 10^{-2}$	$-38.1(4)$	$+1.7(1)$
$ZZZZ$	$3.114(2) \cdot 10^{-3}$	$-42.2(2)$	$+0.8(1)$
$HZZZ$	$2.693(2) \cdot 10^{-3}$	$-34.4(2)$	$+1.4(1)$
$HHZZ$	$9.828(7) \cdot 10^{-4}$	$-36.5(2)$	$+2.2(1)$
$HHHZ$	$1.568(1) \cdot 10^{-4}$	$-25.7(2)$	$+5.7(1)$

with $\delta_{\text{EW}} = \sigma^{\text{incl}}_{\text{NLO}}/\sigma^{\text{incl}}_{\text{LO}} - 1$ and $\delta_{\text{ISR}} = \sigma^{\text{incl}}_{\text{LO,LL-ISR}}/\sigma^{\text{incl}}_{\text{LO}} - 1$

NLO: FKS subtraction for soft/collinear cancellation

EW + QCD @ LO (`O'Mega`)

[hep-ph/0102195]

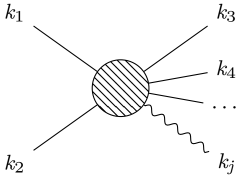
- automated perturbative helicity-amplitude calculation for multi-leg processes with interfering resonances
- color-flow formalism (phantom 9th gluon) [JHEP 10 (2012) 022]

EW + QCD @ NLO

- Virtual matrix elements: One-Loop Provider (GoSam, Recola, OpenLoops)
- Real-radiation matrix elements: O'Mega or OpenLoops
- IR and collinear cancellation against massless radiation is (slightly) non-local in phase space ⇒Subtraction algorithm

[Catani-Seymour or Frixione-Kunszt-Signer]

$$\sigma_{\text{NLO}} = \int d\Phi_n \mathcal{B} + \int \underbrace{d\Phi_{n+1} \left[\mathcal{R}(\Phi_{n+1}) - d\sigma_S(\Phi_{n+1})\right]}_{\text{finite by construction}} + \underbrace{\int d\Phi_n \mathcal{V} + \int d\Phi_n \, d\sigma_{S,\text{int}}}_{\text{IR poles cancelled analyt.}}$$



1. 'j' radiated with several different emitters ⇒ Subtract singularities related to QED splittings systematically
2. Divide phase space into disjoint regions with **at most one** soft and/or collinear singularity.

⇒ kinematical weight factors related to pairs (i, j)