Notes on the Whizard MC Generator

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Meinerzhagen, Feb 15, 2024

The Whizard MC generator

1999 WHIZARD 1 + **2007** Whizard 2

- Hard-interaction physics at high-energy colliders
- Tree-level ME code (O'Mega)
- Universal multi-channel integrator (VAMP)
- Cross sections, distributions, event streams
- Full polarization / spin correlation support
- PDF/ISR/beamstrahlung, shower/hadronization (PYTHIA)
- SM and BSM models
- Scripting language included (SINDARIN)

2021 Whizard 3

- MPI/OpenMP, UFO, NLO (full SM)

Whizard @ CPPS

Functionality?

- Comparable to Madgraph/Powheg/Sherpa + interfaces
- Focus on EW interactions, resonant signals, full off-shell effects
- NLO QCD+SM support finished 2021 (**Pia Bredt**/DESY+SI)

Whizard @ CPPS

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LHC physics?

- Fully functional
- E.g.: off-shell top physics description w/ NLO and spin correlations
  [e^+e^- also: threshold resummation (NRQCD)]

Whizard @ CPPS

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LHC support?

- Whizard integrated in all e^+e^- studies, IDT generator steering group
- LHC contacts limited by our own resources (time, personpower)
- CPPS: collaboration options?

(Reference + backup slides)

Matrix Elements for Hard Processes (LO)

`O'Mega:`

automated perturbative helicity-amplitude calculation for multi-leg processes with interfering resonances [hep-ph/0102195]

- avoid redundant common subexpressions altogether: no Feynman-graph expansion $\Rightarrow$ factorial growth of # terms reduced to power law
- color-flow formalism (phantom 9th gluon) [JHEP 10 (2012) 022]

Matrix Elements for Hard Processes (NLO)

EW + QCD at NLO

- Virtual matrix elements: One-Loop Provider (GoSam, Recola, OpenLoops, etc.)

  One-loop amplitudes = NLO in any gauge/Yukawa/Higgs coupling, UV-renormalized

- Real-radiation matrix elements: O'Mega or also OLP

IR and collinear cancellation against massless radiation is (slightly) non-local in phase space

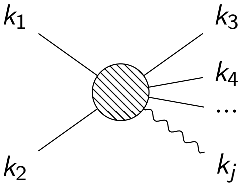
$\Rightarrow$ Subtraction algorithm (e.g. Catani-Seymour or Frixione-Kunszt-Signer)

FKS subtraction for soft/collinear cancellation

$$\sigma_{\text{NLO}} = \underbrace{\int d\Phi_n \mathcal{B}}_{\text{Born}} + \underbrace{\int d\Phi_{n+1} \mathcal{R}}_{\text{div. real}} + \underbrace{\int d\Phi_n \mathcal{V}}_{\text{div. virtual}} = \text{finite}$$

For observables **exclusive** in kinematic properties:

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



- 'j' radiated with several different emitters ⇒ Subtract singularities related to QED splittings systematically
- Divide phase space into disjoint regions with **at most one** soft and/or collinear singularity.
- ⇒ kinematical weight factors related to pairs (i, j)

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

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`$_{\text{(CS)}}$ `+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) $\delta \equiv \frac{\sigma^{\text{tot}}_{\text{NLO}} - \sigma^{\text{tot}}_{\text{LO}}}{\sigma^{\text{tot}}_{\text{LO}}}$ $\text{dev} \equiv \frac{|\sigma^{\text{tot}}_{\texttt{WHIZARD}} - \sigma^{\text{tot}}_{\texttt{MUNICH}}|}{\sigma^{\text{tot}}_{\texttt{WHIZARD}}}$ $\sigma^{\text{sig}} \equiv \frac{|\sigma^{\text{tot}}_{\texttt{WHIZARD}} - \sigma^{\text{tot}}_{\texttt{MUNICH}}|}{\sqrt{\Delta^2_{\text{err},\texttt{WHIZARD}} + \Delta^2_{\text{err},\texttt{MUNICH}}}}$

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] $\sigma_{\text{NLO}}^{\text{tot}}$ [pb]	`WHIZARD+OpenLoops` $\sigma_{\text{NLO}}^{\text{tot}}$ [pb]	δ [%]	$\sigma_{\text{NLO}}^{\text{sig}}$
$e^+\nu_e$	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

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

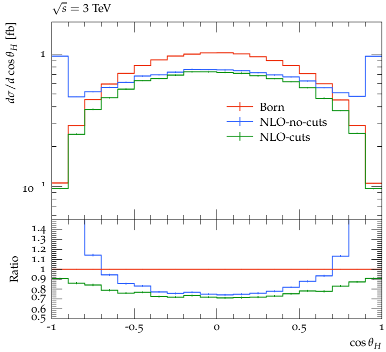
$\mu^+\mu^- \to X, \sqrt{s} = 3$ TeV	$\sigma^{\text{incl}}_{\text{LO}}$ [fb]	δ_{EW} [%]	δ_{ISR} [%]
W^+W^-	$4.6591(2) \cdot 10^2$	$+4.0(2)$	$+13.82(4)$
ZZ	$2.5988(1) \cdot 10^1$	$+2.19(6)$	$+15.71(4)$
HZ	$1.3719(1) \cdot 10^0$	$-1.51(4)$	$+30.24(3)$
W^+W^-Z	$3.330(2) \cdot 10^1$	$-22.9(2)$	$+2.90(9)$
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	$1.058(1) \cdot 10^{-2}$	$-38.1(4)$	$+1.7(1)$
$ZZZZ$	$3.114(2) \cdot 10^{-3}$	$-42.2(2)$	$+0.8(1)$
$HZZZ$	$2.693(2) \cdot 10^{-3}$	$-34.4(2)$	$+1.4(1)$
$HHZZ$	$9.828(7) \cdot 10^{-4}$	$-36.5(2)$	$+2.2(1)$
$HHHZ$	$1.568(1) \cdot 10^{-4}$	$-25.7(2)$	$+5.7(1)$

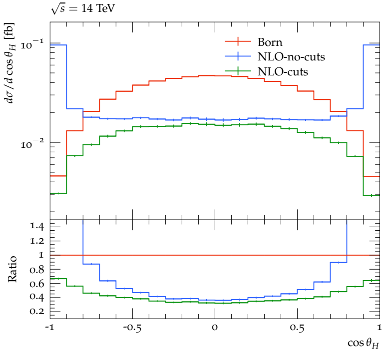
with $\delta_{\text{EW}} = \sigma^{\text{incl}}_{\text{NLO}}/\sigma^{\text{incl}}_{\text{LO}} - 1$ and $\delta_{\text{ISR}} = \sigma^{\text{incl}}_{\text{LO,LL-ISR}}/\sigma^{\text{incl}}_{\text{LO}} - 1$

Multi-boson processes at a muon collider at NLO EW

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

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





Conclusions and Outlook

- Whizard is a viable tool (I hope) 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
- Specific support for e^+e^- and muon colliders

Current projects: computing efficiency (ML), NLO applications, photons at e^+e^-, future colliders
(+ core cleanup)

The WHIZARD 3 Team

U Siegen: WK, Pia Bredt, Nils Kreher, Tobias Striegl

DESY: Jürgen Reuter, Krzysztof Mękała
(S. Brass, B. Chokoufe, V. Rothe, P. Stienemeier, C. Weiss)

U Würzburg: Thorsten Ohl

Links

- Reference: WK/Ohl/Reuter, EPJ C71 (2011) 1742
- WHIZARD Portal: `https://whizard.hepforge.org/`
- Launchpad Page: `https://launchpad.net/whizard`
- gitlab repo:
`https://gitlab.tp.nt.uni-siegen.de/whizard/public`

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

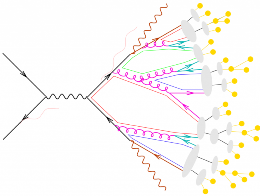
1. Stand-alone with input script: `whizard` ⟨*input*⟩`.sin` (optional workspace transfer for cluster operation)
2. As a library, callable from: `Fortran`, `C`, `C++`, `Python`

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

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

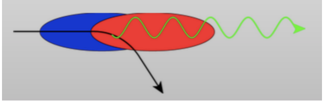
Parallel: OpenMP (multi-core), MPI (HPC cluster)

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)

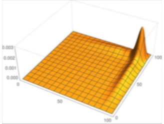
Beam Properties (e^+e^-)



Beamstrahlung

- Detailed simulation of machine and interaction region (GuineaPig)
  $\Rightarrow$ to be repeated for each parameter set
- Circular colliders: beamstrahlung $\Rightarrow$ beam-energy spread
- Fit to beam-simulation data
  - parameterized spectra (Circe1)
  - beam-event generator (Circe2)

  https://whizard.hepforge.org/circe.html



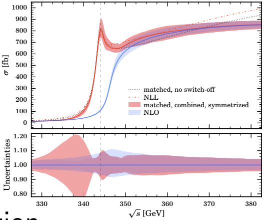
- Beamstrahlung interfaced with MCGenerator
  - Whizard: integrated in e^+e^- physics simulation framework
  - Others: Circe2 available as plug-in module

Polarization in Whizard

- Lazy method for simulation: merge distinct event samples with 100% ±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.
  ⇒ supported in Whizard since v1
- Polarization of outgoing particles: depend on event-file formats

⇒ NLO: polarization support relies on spin-correlated squared matrix element output

Specific Processes



$e^+e^- \to t\bar{t}$ (and $t\bar{t}H$)

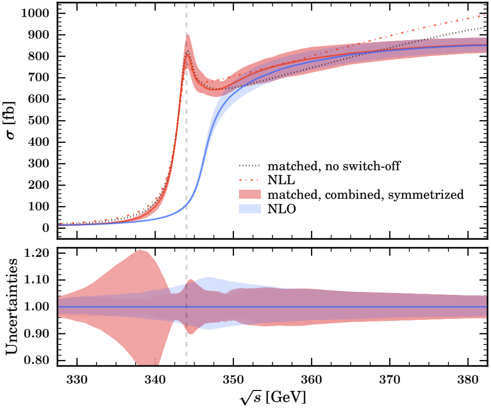
- tt on-shell multi-loop / threshold resummation
- off-shell NLO MC + threshold resummation: Whizard

Soft Background

- $\gamma\gamma \to$ hadrons
  $\Rightarrow$ SLAC code based on Chen, Barklow, Peskin, PRD49 (1994)

(From Whizard talk 2017 (CEPC Conference Beijing))

Top Threshold, Precisely



Chokoufé, WK, Lindner, Pozzorini, Reuter, Weiss, JHEP 12 (2016) 075

Bach, Chokoufé, Hoang, WK, Reuter, Stahlhofen, Teubner, Weiss, in prep.

Top Threshold, Precisely

Achievements:

- Most precise universal description of the $t\bar{t}$ threshold
- Combines NLO QCD (overall) with NLO-NRQCD (threshold region), Coulomb resummation (potential) and NLL-NRQCD threshold improvement (RG)
- Applies to the real final states, e.g.

$$e^+e^- \to b\bar{b}\mu^-\bar{\nu}_\mu e^+\nu_e$$

$\Rightarrow$ Testbed for the precise description and exclusive event generation for any thresholds in e^+e^-, e.g., W^+W^-, ZZ, ...

Event Handlers

WHIZARD uses the twofold-adapted phase space to generate unweighted event samples. Further processing:

1. Particle decays (cascades):
   - using WHIZARD's own decay processes (explicit or automatic)
   - full control over polarization transfer (uncorrelated, classical, quantum correlation)
2. Photon radiation: exclusive photons from inclusive ISR
3. Resonance histories: control shower behavior
4. Shower, Hadronization: optionally call PYTHIA (internally)
5. POWHEG algorithm for matching NLO events
6. Event output: file formats StdHEP, LHEF, HepMC, LCIO, ASCII

Photon Handler

Inclusive ISR description (LL soft, 3rd order collinear) accounts for precise cross section and energy dependence

New Photon Handler in WHIZARD 2.6

Take generated events

- Collinear photons (both beams) are given transverse momentum according to scale-less logarithmic distribution (w/ cutoffs)
- Both beams handled: exact energy-momentum conservation
- Common scheme for ISR (e^+e^- process) and EPA ($\gamma\gamma$ process)

$\Rightarrow$ extend to multiple photons matched with NLO SM

Resonances and Parton Shower

Current standard for simulation with WHIZARD 2

PYTHIA 6 parton shower (internal). Ongoing validation by LC generator group.

Important LC processes: $(WW, ZZ, ZH \to)4f$, $(WWZ, ZZZ, WWH, \ldots \to)6f$, etc.: contain resonances

PYTHIA 6 modes:

1. Default: local interaction, shower starts at process energy scale, invariant masses reshuffled
2. Resonance: nonlocal interaction, shower starts at resonance mass, invariant masses fixed

Interplay of resonant/nonresonant background?

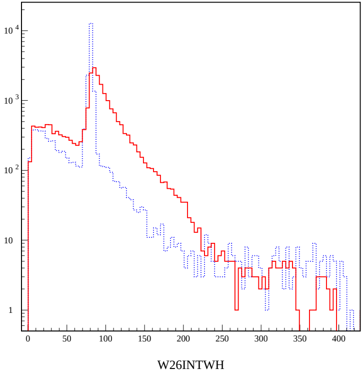
New solution for WHIZARD 2 (WIP)

Generate event sample as usual, no change to cross section (LO).

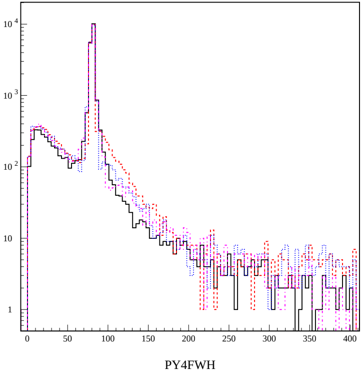
1. Determine possible resonance histories for each single event
2. For all applicable histories, compute factorized matrix elements *in addition to* complete matrix element
3. Use relative ME values to determine probabilities for histories, including background (remainder)
4. Select one of the applicable histories to modify the event record

Resonance / Background in Event History

Resonance by color / no resonance



Resonance by ME, varied cutoff



Plots by M. Berggren (WIP)

This is to be applied to matched NLO event generation in the presence of multiple resonances.

Plots, observables

```
histogram ptplot (0 GeV, 100 GeV, 5 GeV)

simulate (twojets) {
  n_events = 10000
  analysis =
    record ptplot (eval Pt [q])
}
compile_analysis
```