

# NLO Physics Simulation with Whizard

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with slides from Pia Bredt

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# The Whizard MC generator

1999 WHIZARD 1 + 2007 Whizard 2

- ▶ Hard-interaction physics at high-energy colliders (LHC, ILC, ...)
- ▶ Tree-level ME code generated&linked on-the-fly by O'Mega
- ▶ Universal multi-channel integrator VAMP
- ▶ Cross sections, distributions, event streams (HepMC, LCIO, ...)
- ▶ Full polarization support
- ▶ Beam spectra/ISR/PDF, shower/hadronization (PYTHIA), etc.
- ▶ SM and BSM models

## Applications:

ILC/CLIC samples for physics studies

Signal and background processes for LHC analyses

Future collider studies (muon collider, photon collider, etc.)

2021 Whizard 3 (this talk)

- ▶ MPI/OpenMP, UFO, improvements/updates, NLO (full SM)

# 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

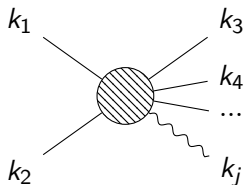
⇒ **Subtraction algorithm** (e.g. Catani-Seymour or Frixione-Kunszt-Signer)

# 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:

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



'j' radiated with several different emitters  $\Rightarrow$  Subtract singularities related to QED splittings systematically

Divide phase space into disjoint regions with **at most one** soft and/or collinear singularity.

$\Rightarrow$  kinematical weight factors related to pairs  $(i, j)$

# Hadron collisions at NLO EW

- ▶ QED FKS subtraction terms:

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

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

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

with photon virtuality  $Q_\gamma^2$

# LHC: on-shell heavy bosons at NLO EW

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

process $pp \rightarrow$	MUNICH(CS) $\sigma_{\text{NLO}}^{\text{tot}}$ [fb] +OpenLoops	WHIZARD $\sigma_{\text{NLO}}^{\text{tot}}$ [fb] +OpenLoops	$\delta$ [%]	dev [%]	$\sigma_{\text{NLO}}^{\text{sig}}$
$ZZ$	$1.05729(1) \cdot 10^4$	$1.05729(11) \cdot 10^4$	-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)

$$\delta \equiv \frac{\sigma_{\text{NLO}}^{\text{tot}} - \sigma_{\text{LO}}^{\text{tot}}}{\sigma_{\text{LO}}^{\text{tot}}}$$

$$\text{dev} \equiv \frac{|\sigma_{\text{WHIZARD}}^{\text{tot}} - \sigma_{\text{MUNICH}}^{\text{tot}}|}{\sigma_{\text{WHIZARD}}^{\text{tot}}}$$

$$\sigma^{\text{sig}} \equiv \frac{|\sigma_{\text{WHIZARD}}^{\text{tot}} - \sigma_{\text{MUNICH}}^{\text{tot}}|}{\sqrt{\Delta_{\text{err,WHIZARD}}^2 + \Delta_{\text{err,MUNICH}}^2}}$$

# 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:  $G_\mu$  CMS  
PDF set: LUXqed\_plus\_PDF4LHC15\_nnlo\_100 cuts from ref. [1804.10017]

process $pp \rightarrow$	$\alpha^m$	MG5_aMC@NLO[1804.10017] $\sigma_{\text{NLO}}^{\text{tot}}$ [pb]	WHIZARD+OpenLoops $\sigma_{\text{NLO}}^{\text{tot}}$ [pb]	$\delta$ [%]	$\sigma_{\text{NLO}}^{\text{sig}}$
$e^+ \nu_e$	$\alpha^2$	$5.2005(8) \cdot 10^3$	$5.1994(4) \cdot 10^3$	-0.73	1.24
$e^+ e^-$	$\alpha^2$	$7.498(1) \cdot 10^2$	$7.498(1) \cdot 10^2$	-0.50	0.004
$e^+ \nu_e \mu^- \bar{\nu}_\mu$	$\alpha^4$	$5.2794(9) \cdot 10^{-1}$	$5.2816(9) \cdot 10^{-1}$	+3.69	1.69
$e^+ e^- \mu^+ \mu^-$	$\alpha^4$	$1.2083(3) \cdot 10^{-2}$	$1.2078(3) \cdot 10^{-2}$	-5.25	1.26
$He^+ \nu_e$	$\alpha^3$	$6.4740(17) \cdot 10^{-2}$	$6.4763(6) \cdot 10^{-2}$	-4.04	1.24
$He^+ e^-$	$\alpha^3$	$1.3699(2) \cdot 10^{-2}$	$1.3699(1) \cdot 10^{-2}$	-5.86	0.32
$Hjj$	$\alpha^3$	$2.7058(4) \cdot 10^0$	$2.7056(6) \cdot 10^0$	-4.23	0.27
$tj$	$\alpha^2$	$1.0540(1) \cdot 10^2$	$1.0538(1) \cdot 10^2$	-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,  $G_\mu$  scheme,  $m_\mu = 0.1056\dots$  GeV

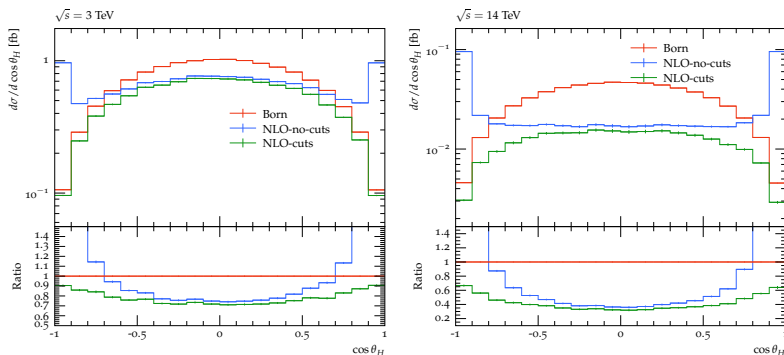
$\mu^+\mu^- \rightarrow X, \sqrt{s} = 3$ TeV	$\sigma_{\text{LO}}^{\text{incl}}$ [fb]	$\delta_{\text{EW}}$ [%]	$\delta_{\text{ISR}}$ [%]
$W^+W^-$	$4.6591(2) \cdot 10^2$	+4.0(2)	+13.82(4)
$ZZ$	$2.5988(1) \cdot 10^1$	+2.19(6)	+15.71(4)
$HZ$	$1.3719(1) \cdot 10^0$	-1.51(4)	+30.24(3)
$W^+W^-Z$	$3.330(2) \cdot 10^1$	-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  $\delta_{\text{EW}} = \sigma_{\text{NLO}}^{\text{incl}}/\sigma_{\text{LO}}^{\text{incl}} - 1$  and  $\delta_{\text{ISR}} = \sigma_{\text{LO,LL-ISR}}^{\text{incl}}/\sigma_{\text{LO}}^{\text{incl}} - 1$

# Multi-boson processes at a muon collider at NLO EW

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

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



# 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'Cam1

**Development:** gitlab with automated test suite and CI

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

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

**Running:** Options

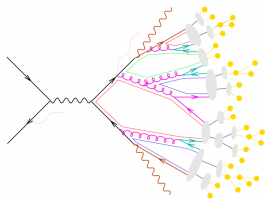
1. Stand-alone with input script: `whizard <input>.sin`  
(optional workspace transfer for cluster operation)
2. As a library, callable from: Fortran, C, C++, Python

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

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

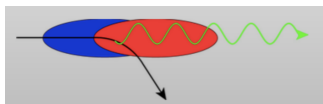
**Parallel:** OpenMP (multi-core), MPI (HPC cluster)

## 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 ( $e^+e^-$ )

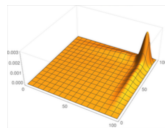


## Beamstrahlung

- ▶ Detailed **simulation of machine** and interaction region (GuineaPig)  
⇒ to be repeated for each parameter set
- ▶ Circular colliders: beamstrahlung ⇒ **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



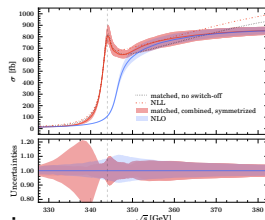
# Polarization in Whizard

- ▶ Lazy method for simulation: merge distinct event samples with 100%  $\pm$ 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.  
⇒ 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

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

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



## Soft Background

- ▶  $\gamma\gamma \rightarrow \text{hadrons}$   
⇒ SLAC code based on Chen, Barklow, Peskin, PRD49 (1994)