

# Physics of Heavy Electroweak Particles and the Whizard Project

Wolfgang Kilian

CPPS, University of Siegen

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# The Phenomenology of Heavy Electroweak Particles

⇒  $W^\pm$ ,  $Z$ , Higgs, top

- ▶ **Collider** (LEP, LHC) pheno:  
appear as short-lived resonances, decay: jets + leptons + neutrinos
- ▶ **Model** (SM):  
appear as fundamental degrees of freedom, electroweak symmetry and electroweak symmetry breaking

# The Phenomenology of Heavy Electroweak Particles

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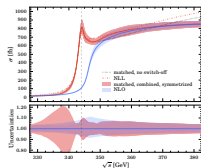
- ▶ **Collider** (LEP, LHC) pheno:  
appear as short-lived resonances, decay: jets + leptons + neutrinos
- ▶ **Model** (SM):  
appear as fundamental degrees of freedom, electroweak symmetry and electroweak symmetry breaking
  
- ▶ **Production so far predominantly near threshold**
  - ▶ Low resolution, low multiplicity, large impact of QCD
  - ▶ **Calculation needs:** NLO-QCD off-shell events, QCD matching and shower, threshold enhancement, higher-order corrections
  
- ▶ **Detailed studies (self interactions, SM dynamics) require future colliders** with higher effective luminosity and energy
  - ▶ **Calculation needs:** NLO-SM off-shell, high multiplicity, EW matching and shower

# Projects Overview

Working group: Siegen (Kilian) with DESY (Reuter) and Würzburg (Ohl)

## 1. Physics Studies and Calculations

- ▶ Vector-boson scattering
- ▶  $t\bar{t}$  threshold off-shell
- ▶ Multi-boson production at lepton colliders
- ▶ Muon collider (EW symmetry restoration)



## 2. Software Framework and Computational Tool: Whizard

- ▶ Automatic LO cross sections and off-shell events for colliders
- ▶ NLO-QCD and NLO-SM via ME providers (OpenLoops, Recola, GoSAM) with FKS subtraction, PowHEG matching + Pythia
- ▶ Specific modules for  $e^+e^-$  colliders (beam structure, polarization)  
⇒  $e^+e^-$  studies since 2000 based on Whizard event samples



# NLO calculation + simulation within the SM (2HDM)

(Slides: J. Reuter for the Whizard Team, ACAT 2025, Hamburg)

- NLO SM automation for lepton-/hadron colliders completed 2022 [Chokouf ; Weiss 2017; Rothe 2021; Stienemeier; Bredt 2022](#) [arXiv: 2208.09438](#)
- FKS subtraction automated, NLO matrix elements from OpenLoops2/RecoLa1+2/GoSam2+3/...
- also: resonance-aware FKS subtraction [cf. Jezo/Nason, arXiv:1509.09071; Chokouf , 2017](#)

ee @ 1 TeV, NLO QCD

pp @ 13 TeV, NLO QCD/EW mixed

   @ 3 TeV, NLO EW

Process	WHIZARD+OpenLoops	
	$\sigma_{LO}$ [fb]	$\sigma_{NLO}$ [fb]
$e^+e^- \rightarrow jj$	622.737(8)	639.39(5)
$e^+e^- \rightarrow jjj$	340.6(5)	317.8(5)
$e^+e^- \rightarrow jjjj$	105.0(3)	104.2(4)
$e^+e^- \rightarrow jjjjj$	22.33(5)	24.57(7)
$e^+e^- \rightarrow jjjjjj$	3.583(17)	4.46(4)

$pp \rightarrow t\bar{t}W^+$	$\alpha_s^2 \alpha^m$	$\sigma^{tot}$ [fb]		$\mu^+\mu^- \rightarrow X, \sqrt{s} =$	$\sigma_{LO}^{int}$ [fb]	$\sigma_{NLO}^{int}$ [fb]	$\delta_{EW}$ [%]
		MUNICH <sub>(CS)</sub>	WHIZARD				
LO <sub>21</sub>	$\alpha_s^2 \alpha^m$	$2.411403(1) \cdot 10^2$	$2.4114(1) \cdot 10^2$	$W^+W^-$	$4.6591(2) \cdot 10^2$	$4.847(7) \cdot 10^2$	+4.0(2)
LO <sub>12</sub>	$\alpha_s \alpha^2$	0.000	0.000	ZZ	$2.5988(1) \cdot 10^1$	$2.656(2) \cdot 10^1$	+2.19(6)
LO <sub>03</sub>	$\alpha^3$	$2.31909(1) \cdot 10^0$	$2.3193(1) \cdot 10^0$	HZ	$1.3719(1) \cdot 10^0$	$1.3512(5) \cdot 10^0$	-1.51(4)
$\delta NLO_{31}$	$\alpha_s^3 \alpha$	$1.18993(2) \cdot 10^2$	$1.1905(5) \cdot 10^2$	HH	$1.60216(7) \cdot 10^{-7}$	$5.66(1) \cdot 10^{-7}$	*
$\delta NLO_{22}$	$\alpha_s^2 \alpha^2$	$-1.09511(9) \cdot 10^1$	$-1.0947(3) \cdot 10^1$	$W^+W^-Z$	$3.330(2) \cdot 10^1$	$2.568(8) \cdot 10^1$	-22.9(2)
$\delta NLO_{13}$	$\alpha_s \alpha^3$	$2.93251(3) \cdot 10^1$	$2.9334(8) \cdot 10^1$	$W^+W^-H$	$1.1253(5) \cdot 10^0$	$0.895(2) \cdot 10^0$	-20.5(2)
$\delta NLO_{04}$	$\alpha^4$	$5.759(3) \cdot 10^{-2}$	$5.756(4) \cdot 10^{-2}$	ZZZ	$3.598(2) \cdot 10^{-1}$	$2.68(1) \cdot 10^{-1}$	-25.5(3)
				HHZ	$8.199(4) \cdot 10^{-2}$	$6.60(3) \cdot 10^{-2}$	-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)
				$W^+W^-HZ$	$8.75(4) \cdot 10^{-2}$	$6.05(4) \cdot 10^{-2}$	-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)
				HHZZ	$2.693(2) \cdot 10^{-3}$	$1.766(6) \cdot 10^{-3}$	-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)

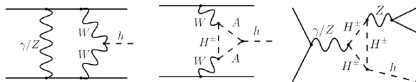
ee @ .25 TeV, NLO EW, pol.av. + pol.

$\sqrt{s}$ [GeV]	MCSANee[37]		WHIZARD+RECOLA		$\delta_{EW}$ [%]	$\sigma^{th}$ (LO/NLO)
	$\sigma_{LO}^{int}$ [fb]	$\sigma_{NLO}^{int}$ [fb]	$\sigma_{LO}^{int}$ [fb]	$\sigma_{NLO}^{int}$ [fb]		
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

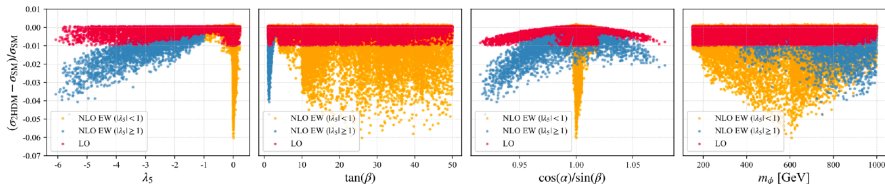
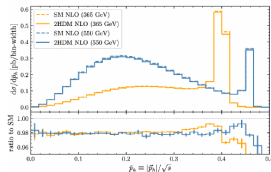
# NLO Calculation Beyond the SM (2HDM)

- NLO EW calculation for discrimination of SM vs. e.g. 2HDM:

- 160,000 data points for NLO EW:  $e^+e^- \rightarrow H_{125}\nu\bar{\nu}$

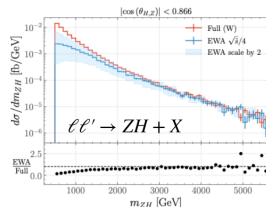
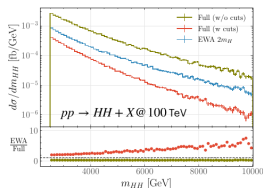
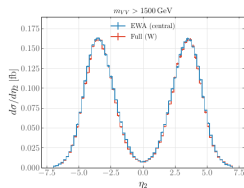


Bredt/Banno/Höfer/Iguero/Kilian/Ma/JRR/Zhang,  
arXiv:2509.XXXXX

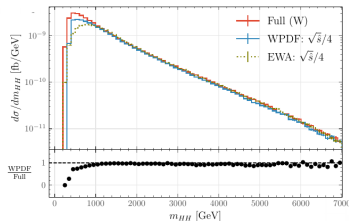


# SM at High Energy: Electroweak PDFs

- Collinear factorization not in QED, but in full SM [Han/Ma/Xie, 2007.14300, 2103.09844](#)
- Kinematic approximation: EVA (“Equivalent V approximation”)
- Implemented and validated in Whizard
- Application to MuC/FCC-hh [\[Dahlén/Löschner/Mękała/JRR/Stylianou, 2507.19285\]](#)

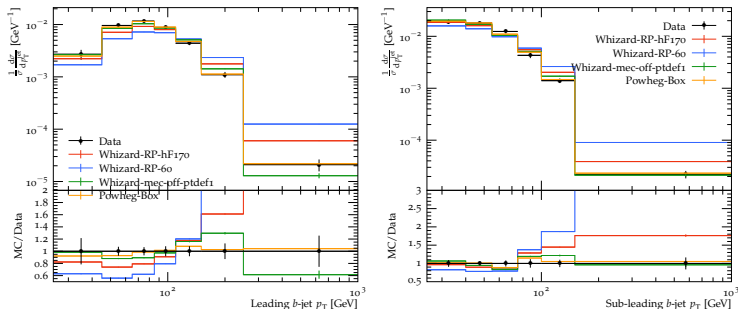


- Full EW/SM splitting picture; DGLAP evolution: 59 partons (all helicities)
- Fast interpolation (CTEQ-like/LHAPDF-like) grids available
- Implemented and validated in Whizard [\[Han/Kilian/Ma/Mękała/JRR/Xie, w.i.p.\]](#)



# WIP: Heavy Particles Near Threshold (LHC)

Validation:  $t\bar{t}$  NLO off-shell with matching (Pia Brecht)



Perspective:  $t\bar{t}X$  ( $X = Z, H, \dots$ ), threshold enhancement

Further: VBS and  $VVV$  production,  $H + X$ , spin correlations

# WIP: Efficiency of (NLO) Calculation: MPI

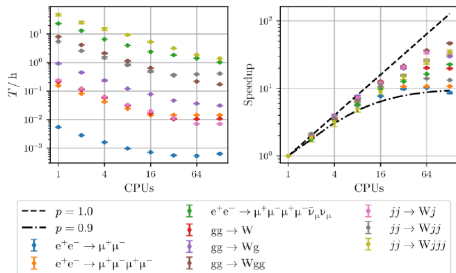
- Parallelization of integration: OMP multi-threading for different helicities
- MPI parallelization (using OpenMPI or MPICH)
- Distributes workers over multiple cores, grid adaption needs non-trivial communication
- Speedups of 20 to 50, saturation at O(100) tasks [can do also parallel event generation]
- Load balancer / non-blocking communication [v3.0.0]

Braß, 2021

- Extensive tests: 250 GeV  $e^+e^-$  complete SM full sim.
- Several NLO QCD + EW projects, e.g.  $pp \rightarrow \ell\ell\nu\nu jj, HHjj$
- PS integration goes down from several weeks to hours
- Load balancer only marginal improvements

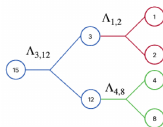
Speckner, 2011; Chokoufe, 2014

Braß/Kilian/JRR, arXiv:1811.09711



# WIP: Efficiency of (NLO) Calculation: GPU Offloading

- 0' Mega creates CUDA (C++) kernels, each kernel evaluates a fixed helicity
- Phase-space generator re-implemented in CUDA and linked to Fortran
- Data transfer CPU <-> GPU kept at minimum. Many arrays only allocated on GPU
- Reduce branchings in GPU kernel (keeps parallel threads under control)
- Recursive PS construction necessitates calculation of all boosts beforehand



## Benchmarking of LO integration on CPU vs. GPU

Process	$\sigma^{CPU} [fb]$	$\sigma^{GPU} [fb]$	$t^{CPU} [s]$	$t^{GPU} [s]$
$e^+e^- \rightarrow 3j$	$500.75 \pm 0.46$	$500.74 \pm 0.46$	125	32
$e^+e^- \rightarrow 4j$	$783.61 \pm 0.88$	$784.16 \pm 0.87$	2497	318
$e^+e^- \rightarrow 5j(5:50000, 2 \text{ local batches})$	$65.35 \pm 2.6$	$65.55 \pm 2.67$	3457	613
$e^+e^- \rightarrow b\bar{b}\nu_e e^+ \bar{\nu}_e e^-$	$1.653 \pm 0.004$	$1.651 \pm 0.004$	2679	1451
$pp \rightarrow e^+e^-$	$331.6 \pm 0.3$	$331.8 \pm 0.3$	36	17
$pp \rightarrow jj$	$30.4429 \cdot 10^6 \pm 2.75 \cdot 10^4$	$30.4409 \cdot 10^6 \pm 3.75 \cdot 10^4$	1011	311
$p\bar{p} \rightarrow jjj$	$83456 \pm 227$	$82654 \pm 215$	10643	3007

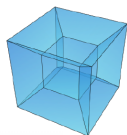
C. Weiss, 2025;

Host: Intel i7 (10 cores), 32 GB RAM  
GPU: NVidia RTX 3600, 12 GB RAM

# WIP: Efficiency of (NLO) Calculation: ML Framework

VAMP = Whizard's built-in ML algorithm for phase space

1. Invertible, parameterized mappings with adaptive optimization (⇒ normalizing-flow ansatz)
2. Multi-channel decomposition with adaptive optimization for weights (⇒ attention / transformer ansatz)
3. Initial setup not from random noise ⇒ use ME singularity structure and phase-space topology

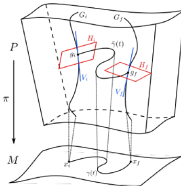


$$U = (0, 1)^{\otimes n}$$

$g(U)$

physics-inspired invertible diff. mappings from unit hypercube to cut-constrained phase space manifold

$g^{-1}(\phi)$

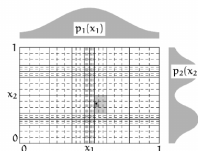


Latent space (Integrator variables)

$$\int_{s_0}^{s_1} f(s) ds = \sum_i \alpha_i \int_{s_0}^{s_1} \frac{f(s)}{g(s)} g_i(s) ds$$

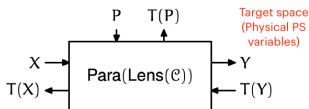
channel weights

channel mappings



## Parameterized lenses in category theory

Channel weights / other parameters



Crutwell, Gavranović et al., 1910.07065; 2103.01931; 2203.12478; 2403.13001; 2404.00408

# Outlook

## Looking forward to collaboration within CmF!

- ▶ LHC validation and future analyses with NLO/off-shell events
- ▶ Studies for future colliders
- ▶ Computational methods and algorithms
- ▶ ...