The Whizard Monte Carlo and Top-Quark Physics

Wolfgang Kilian and Pia Bredt

with Jürgen Reuter (DESY)

CPPS, University of Siegen

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The Top Quark (2026)

- The top quark interacts with all forces (strong, electro-weak, Higgs [and gravity]) with “natural” strength
- Top quark is a narrow resonance; decay and hadronization compete with each other
- Top quark can be produced only at hadron colliders (LHC)
  - large samples
  - near threshold
  - complex radiation + background

- Simulation: describe interplay and interconnection of production, decay, background, virtual, radiation, hadronization, and experimental constraints in detail and with precision

The Whizard MC generator

1999 WHIZARD 1 + 2007 Whizard 2

- Multi-particle processes, complete partonic amplitudes
  account for all signal and background
- Phase-space integration, interfaced shower/hadronization, events
- Large SM event sample data bases for future collider studies
- LHC: $pp \to 6$ partons $\to$ hadrons:
  $t\bar{t}$ tree-level off-shell

2021 Whizard 3 (this talk): NLO

- NLO virtuals with help of OpenLoops/Recola/GoSaM matrix elements
- Resonance-aware subtraction, NLO matching, shower, event samples

- **LHC:** $pp \to 6(+1)$ partons $\to$ hadrons:
  $t\bar{t}$ NLO(QCD) off-shell simulation

Calculation and simulation I

Matrix elements

1. Tree level: **O'Mega** = full off-shell final state, all SM particles, direct recursive amplitude evaluation instead of Feynman-graph expansion
2. NLO: e.g. **OpenLoops** = QCD 1-loop + real radiation for complete off-shell process
3. Reassign IR radiation / divergences: identify and add/subtract IR/singular regions = **FKS**
4. Resonances: evaluate radiation in moving top-quark (resonance) frame where applicable

Calculation and simulation II

Cross section and distributions for multi-parton processes

1. Phase-space parameterization along singularity patterns of matrix element = **multi-channel**
2. ML integration algorithm: iterative simultaneous training of binned invertible mappings ("network", "flow") with multi-channel weight functions ("attention"): **VAMP**
3. Parallel evaluation on multi-CPU system: **MPI**
4. Trained parameter set ("model") ready for event generation

Calculation and simulation III

Realistic event samples

1. First radiation (NLO) compatible with shower: **PowHeg**
2. Resonant subamplitudes, e.g. single-top: assign shower history statistically according to auxiliary factorized matrix elements
3. Shower and hadronization: **Pythia**
4. Simulated event samples ready for data analysis

Top pairs at the LHC (ATLAS data)

Process:

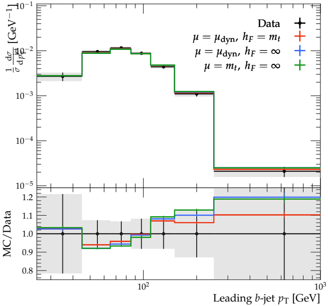
$$pp \to b\bar{b} + \ell^+\ell^- + 2\nu \text{ (+jets)} \quad \text{LHC 13 TeV}$$

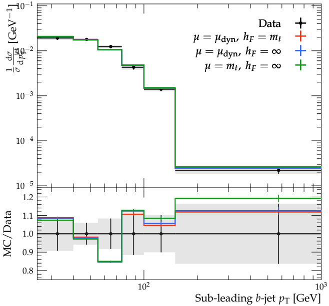
Analyses considered here:

- Eur. Phys. J. C77 (2017) 220:
  $t\bar{t}$ + jets
- Phys. Rev. Lett. 121, 152002 (2018):
  top-pair and single-top interference
- JHEP 01 (2025) 068:
  top-pair + b jets

Top pairs at the LHC (ATLAS data) vs. Whizard

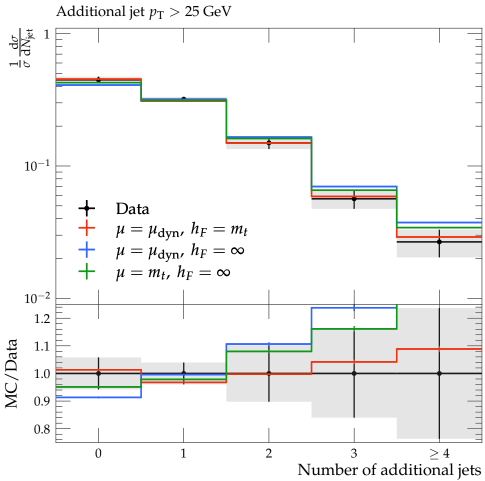
Top-quark remnants: look for hardest b jets





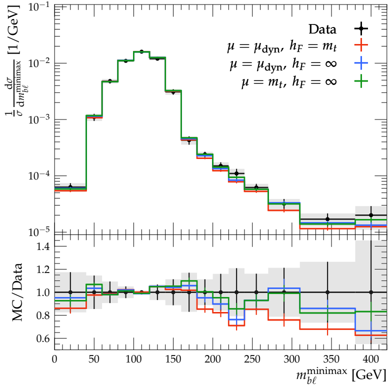
Top pairs at the LHC (ATLAS data) vs. Whizard

Matching and shower: look at additional jets



Top pairs at the LHC (ATLAS data) vs. Whizard

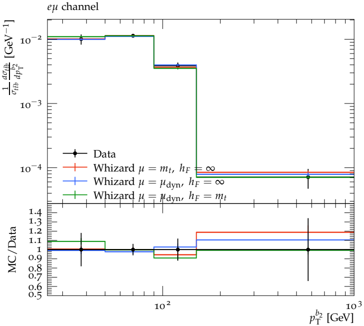
Combinatorics and off-shell: identify the most likely top-quark system

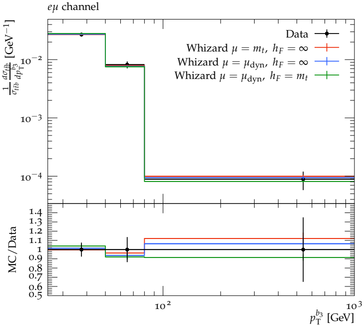


$$m_{b\ell}^{\rm minimax} \equiv \min\{\max(m_{b_1\ell_1}, m_{b_2\ell_2}), \max(m_{b_1\ell_2}, m_{b_2\ell_1})\}$$

Top pairs at the LHC (ATLAS data) vs. Whizard

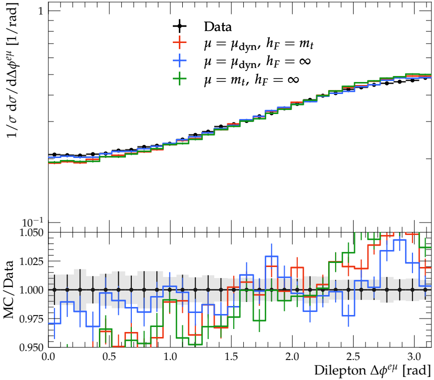
Extra *b*s





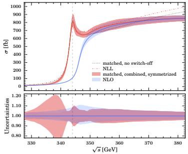
Top pairs at the LHC (ATLAS data) vs. Whizard

Spin correlations: lepton angles



Status and Outlook

- Whizard NLO off-shell calculation and simulation describe public ATLAS top data without significant deviations
- Accuracy is comparable to bb4l (used in the ATLAS analyses)
- Framework is validated and automated



$\Rightarrow$ Threshold enhancement (analogous to $e^+e^- \to t\bar{t}$)

$\Rightarrow$ Studies of spin correlations

$\Rightarrow$ Shower effects (eg PYTHIA vs HERWIG)

$\Rightarrow$ More complex processes (improving virtual ME availability)

$\Rightarrow$ NLO EW, NNLO $\Rightarrow$ HL-LHC analyses

The WHIZARD 3 Team

U Siegen: WK, Pia Bredt, Nils Kreher, Krzysztof Mękała

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

U Warsaw: A. Filip Żarnecki

U Würzburg: Thorsten Ohl

Links

- Reference: WK/Ohl/Reuter, EPJ C71 (2011) 1742
- Whizard Launchpad Portal: `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` $\langle \mathit{input} \rangle$`.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, ...)

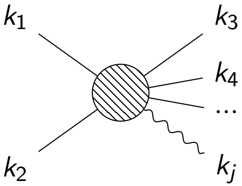
Parallel: OpenMP (multi-core), MPI (HPC cluster)

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:

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

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

$Q_\gamma^2 \to 0$	$Q_\gamma^2 \sim$ 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_γ^2

LHC: on-shell heavy bosons at NLO EW

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

process $pp \to$	MUNICH$_{(CS)}$ +OpenLoops σ^{tot}_{NLO} [fb]	WHIZARD +OpenLoops σ^{tot}_{NLO} [fb]	δ [%]	dev [%]	σ^{sig}_{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) $\delta \equiv \frac{\sigma^{tot}_{NLO} - \sigma^{tot}_{LO}}{\sigma^{tot}_{LO}}$ dev $\equiv \frac{|\sigma^{tot}_{WHIZARD} - \sigma^{tot}_{MUNICH}|}{\sigma^{tot}_{WHIZARD}}$ $\sigma^{sig} \equiv \frac{|\sigma^{tot}_{WHIZARD} - \sigma^{tot}_{MUNICH}|}{\sqrt{\Delta^2_{err,WHIZARD} + \Delta^2_{err,MUNICH}}}$

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] $\sigma^{\text{tot}}_{\text{NLO}}$ [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

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

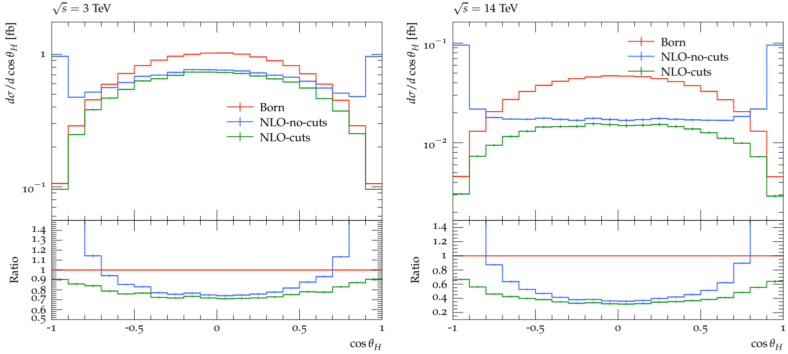
$\mu^+\mu^- \to X, \sqrt{s} = 3$ TeV	$\sigma_{\text{LO}}^{\text{incl}}$ [fb]	δ_{EW} [%]	δ_{ISR} [%]
W^+W^-	$4.6591(2) \cdot 10^2$	$+4.0(2)$	$+13.82(4)$
ZZ	$2.5988(1) \cdot 10^1$	$+2.19(6)$	$+15.71(4)$
HZ	$1.3719(1) \cdot 10^0$	$-1.51(4)$	$+30.24(3)$
W^+W^-Z	$3.330(2) \cdot 10^1$	$-22.9(2)$	$+2.90(9)$
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 $\delta_{\text{EW}} = \sigma_{\text{NLO}}^{\text{incl}}/\sigma_{\text{LO}}^{\text{incl}} - 1$ and $\delta_{\text{ISR}} = \sigma_{\text{LO,LL-ISR}}^{\text{incl}}/\sigma_{\text{LO}}^{\text{incl}} - 1$

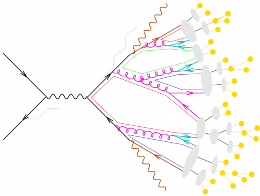
Multi-boson processes at a muon collider at NLO EW

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

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



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)