9 Precision Monte Carlo simulations with WHIZARD

Contribution* by: S. Braß, W. Kilian, T. Ohl, J. Reuter, V. Rothe, P. Stienemeier
Corresponding author: J. Reuter [juergen.reuter@desy.de]

The precision physics programmes of the FCC-ee demand for a precise simulation of all Standard Model (SM) processes and possible beyond-the-SM (BSM) signals in a state-of-the-art way by means of Monte Carlo (MC) techniques. As a standard tool for e^+e^- simulations, the multipurpose event generator WHIZARD [1,2] has been used: this generator was originally developed for the TESLA project, and was later used, e.g., for the ILC Technical Design Report [3,4]. The WHIZARD package has a modular structure, which serves a modern unit-test driven software development and guarantees a high level of maintainability and extendability. WHIZARD comes with its own fully general tree-level matrix element generator for the hard process, O'Mega [5]. It generates amplitudes in a recursive way, based on the graph-theoretical concepts of directed acyclical graphs, thereby avoiding all redundancies. The matrix elements are generated either as compilable modern Fortran code or as byte-code instructions interpreted by a virtual machine [6]. For QCD, WHIZARD uses the colour flow formalism [7]. Matrix elements support all kinds of particles and interactions up to spin-2. A large number of BSM models are hardcoded, particularly the minimal supersymmetric Standard Model (MSSM) and next-to-MSSM (NMSSM) [8, 9]. General BSM models can be loaded from a Lagrangian level tool, using the interface to FeynRules [10]; from version 2.8.0 of WHIZARD on (early summer 2019) a fully fledged interface to the general UFO format is available. One of the biggest assets of WHIZARD is its general phase space parametrization, which uses a heuristic based on the dominating subprocesses, which allows integration and simulation of processes with up to ten fermions in the final state. The integration is based on an adaptive multichannel algorithm, called VAMP [11]. Recently, this multichannel adaptive integration has been enhanced to a parallelized version using the MPI3 protocol, showing speed-ups of up to 100 [12], while a first physics study using this MPI parallelized integration and event generation has been published [13].

WHIZARD allows all the necessary ingredients for a high-precision e^+e^- event simulation to be described: the CIRCE1/CIRCE2 modules [14] simulate the spectrum of beamstrahlung (including beam energy spectra) that comes from classical electromagnetic radiation, owing to extreme space charge densities of highly collimated bunches for high-luminosity running. This takes care of a precise description of the peaks of the luminosity spectra and a smooth mapping of the tail that does not lead to artificial spikes and kinks in differential distributions. For the beam set-up, WHIZARD furthermore allows polarised beams to be correctly described, with arbitrary polarisation settings and fractions, asymmetric beams, and crossing angles. QED initial-state radiation (ISR) is convoluted in a collinear approximation according to a resummation of soft photons to all orders and hard-collinear photons up to third order [15]. While this will give a correct normalization of the cross-section to the given QED order, one explicit ISR photon per beam will be inserted into the event record. A special handler generates transverse momentum according to a physical p_{T} distribution and boosts the complete events

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accordingly. This treatment is also available for the photon beam components, according to the Weizsäcker–Williams spectrum (equivalent photon approximation, EPA).

The MC generator WHIZARD offers a vast functionality, which cannot be given full justice here, e.g., automatic generation of decays, factorised processes, including full spin correlations (which can also be switched off for case studies), specification of the helicity of decaying resonances, preset branching ratios, etc. WHIZARD supports all used HEP event formats, such as StdHEP, LHE, HepMC, LCIO, and various ASCII formats. It allows easy reweighting of event samples. WHIZARD has its own two QCD parton shower algorithms, a k_T-ordered shower and an analytic parton shower [16], and ships with the final version of PYTHIA6 [17] for showering and hadronization. The event records are directly interfaced and exchanged, and the framework has been validated with the full LEP dataset by the Linear Collider Generator Group in a set-up similar to the FCC-ee. Recently, we added a corresponding interface for an externally linked PYTHIA8 [18], which, again, allows direct communication between the event records of WHIZARD and PYTHIA. This offers the ability to use all the machinery for QCD jet matching and merging from PYTHIA inside WHIZARD. WHIZARD also directly interfaces Fastjet [19] for jet clustering. One important feature of WHIZARD is the proper resonance matching of hadronically decaying resonances, e.g., in the process $e^+e^- \to jjjj$. This is predominantly WW production ($\sim$80%), followed by ZZ production ($\lesssim$20%) and the QCD four-jet continuum. When simulating full quantum theoretical amplitudes for four-jet production, the parton shower does not know intermediate resonances because of the full coherence of the process, and hence does not preserve the resonance mass of the hadronic Ws. WHIZARD allows one to automatically determine underlying resonance histories, evaluates their approximate rates, and inserts resonance histories for final-state jets according to these rates. Figure C.9.1 shows, for the process $e + e^- \to jjjj$, the photon energy distribution after hadronization and hadronic decays. The central line in the inset (red) shows the full process, which disagrees with LEP data, while the blue line shows the factorised process $e^+e^- \to W^+W^- \to (jj)(jj)$ (where the shower program knows the resonance history) and the resonance-matched processes (green and orange). These correctly reproduce the data using full matrix elements, thereby allowing different handles on how far to take Breit–Wigner tails of resonances into account. This type of matching has now been validated for six-jet processes, including $H \to b\bar{b}$.

Finally, we comment on the NLO QCD capabilities of WHIZARD: WHIZARD has completed its final validation phase for lepton collider QCD NLO corrections, and version 3.0.0 will be released (approximately at the end of 2019) when proton collider processes are also completely validated. For NLO QCD corrections, WHIZARD uses the Frixione–Kunszt–Signer subtraction (FKS) formalism [20], where real and integrated subtraction terms are automatically generated for all processes. WHIZARD also implements the resonance-aware variant [21]. Virtual multileg one-loop matrix elements are included from one-loop providers, such as GoSam [22], OpenLoops [23, 24], and RECOLA [25, 26]. First proof-of-principle NLO calculations have been made for electroweak corrections [27, 28] in lepton collisions, while NLO QCD has been implemented for LHC processes first [29, 30]. The automated FKS subtraction has been tested and reported in a study of off-shell $t\bar{t}$ and $t\bar{t}H$ processes in lepton collisions [31]. The complete validation of the automated NLO QCD set-up will be available after the version 3.0.0 release of WHIZARD (S. Braß *et al.*, in preparation). WHIZARD allows fixed-order NLO events for differential distributions to be generated at NLO QCD using weighted events, as well as automatically POWHEG-matched and damped events [32, 33]. Decays at NLO QCD are treated in the same set-up as scattering processes.

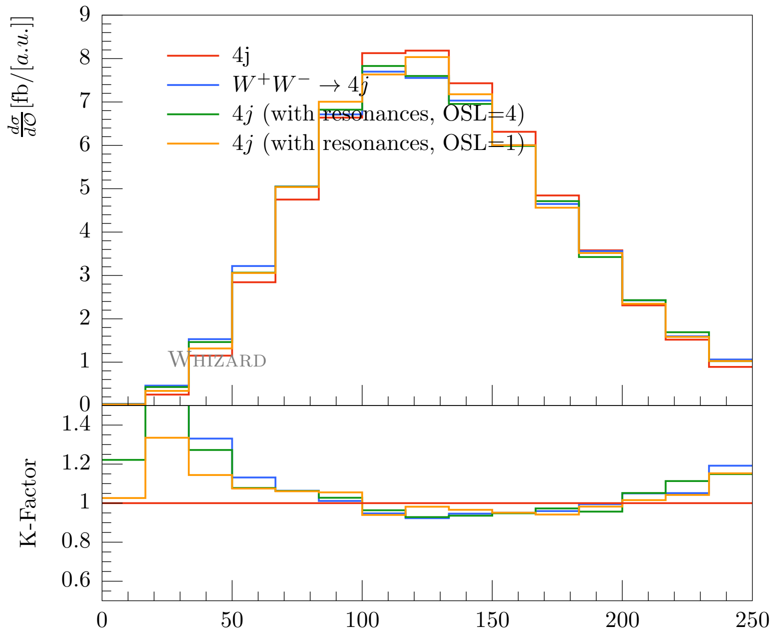

Fig. C.9.1: Energy distribution of photons in $e^+e^- \to jjjj$ after parton shower and hadronization. Full amplitudes without resonance histories (red), factorised process $e^+e^- \to W^+W^- \to (jj)(jj)$ (blue), and full process with resonance histories and different Breit–Wigner settings (green and orange, respectively).

The scan of the top threshold is a crucial component of the FCC-ee physics programme. To determine systematic uncertainties from, e.g., event selection, WHIZARD allows simulation at the completely exclusive final-state $e^+e^- \to W^+bW^-\bar{b}$, matching the continuum NLO QCD calculation to the NRQCD threshold NLL resummation [34]. This simulation is available via a specific top threshold model inside WHIZARD.

References

[1] W. Kilian *et al.*, *Eur. Phys. J.* **C71** (2011) 1742. arXiv:0708.4233, doi:10.1140/epjc/s10052-011-1742-y

[2] http://whizard.hepforge.org, last accessed 24 January 2020.

[3] H. Baer *et al.*, The international linear collider technical design report, vol. 2: physics (2013), arXiv:1306.6352

[4] H. Abramowicz *et al.*, The international linear collider technical design report, vol. 4: detectors, arXiv:1306.6329

[5] M. Moretti *et al.*, O'Mega: an optimising matrix element generator, 2001, arXiv:hep-ph/0102195

[6] B. Chokoufe Nejad *et al.*, *Comput. Phys. Commun.* **196** (2015) 58. arXiv:1411.3834, doi:10.1016/j.cpc.2015.05.015

[7] W. Kilian *et al.*, *JHEP* **10** (2012) 022. arXiv:1206.3700, doi:10.1007/JHEP10(2012)022

[8] T. Ohl and J. Reuter, *Eur. Phys. J.* **C30** (2003) 525. arXiv:hep-th/0212224, doi:10.1140/epjc/s2003-01301-7

[9] K. Hagiwara *et al.*, *Phys. Rev.* **D73** (2006) 055005. arXiv:hep-ph/0512260, doi:10.1103/PhysRevD.73.055005

[10] N.D. Christensen *et al.*, *Eur. Phys. J.* **C72** (2012) 1990. arXiv:1010.3251, doi:10.1140/epjc/s10052-012-1990-5

[11] T. Ohl, *Comput. Phys. Commun.* **120** (1999) 13. arXiv:hep-ph/9806432, doi:10.1016/S0010-4655(99)00209-X

[12] S. Brass *et al.*, *Eur. Phys. J.* **C79** (2019) 344. arXiv:1811.09711, doi:10.1140/epjc/s10052-019-6840-2

[13] A. Ballestrero *et al.*, *Eur. Phys. J.* **C78** (2018) 671. arXiv:1803.07943, doi:10.1140/epjc/s10052-018-6136-y

[14] T. Ohl, *Comput. Phys. Commun.* **101** (1997) 269. arXiv:hep-ph/9607454, doi:10.1016/S0010-4655(96)00167-1

[15] M. Skrzypek and S. Jadach, *Z. Phys.* **C49** (1991) 577. doi:10.1007/BF01483573

[16] W. Kilian *et al.*, *JHEP* **04** (2012) 013. arXiv:1112.1039, doi:10.1007/JHEP04(2012)013

[17] T. Sjöstrand *et al.*, *JHEP* **05** (2006) 026. arXiv:hep-ph/0603175, doi:10.1088/1126-6708/2006/05/026

[18] T. Sjöstrand *et al.*, *Comput. Phys. Commun.* **178** (2008) 852. arXiv:0710.3820, doi:10.1016/j.cpc.2008.01.036

[19] M. Cacciari *et al.*, *Eur. Phys. J.* **C72** (2012) 1896. arXiv:1111.6097, doi:10.1140/epjc/s10052-012-1896-2

[20] S. Frixione *et al.*, *Nucl. Phys.* **B467** (1996) 399. arXiv:hep-ph/9512328, doi:10.1016/0550-3213(96)00110-1

[21] T. Jezo and P. Nason, *JHEP* **12** (2015) 065. arXiv:1509.09071, doi:10.1007/JHEP12(2015)065

[22] G. Cullen *et al.*, *Eur. Phys. J.* **C74** (2014) 3001. arXiv:1404.7096, doi:10.1140/epjc/s10052-014-3001-5

[23] F. Cascioli *et al.*, *Phys. Rev. Lett.* **108** (2012) 111601. arXiv:1111.5206, doi:10.1103/PhysRevLett.108.111601

[24] F. Buccioni *et al.*, *Eur. Phys. J.* **C78** (2018) 70. arXiv:1710.11452, doi:10.1140/epjc/s10052-018-5562-1

[25] S. Actis *et al.*, *Comput. Phys. Commun.* **214** (2017) 140. arXiv:1605.01090, doi:10.1016/j.cpc.2017.01.004

[26] A. Denner *et al.*, *Comput. Phys. Commun.* **224** (2018) 346. arXiv:1711.07388, doi:10.1016/j.cpc.2017.11.013

[27] W. Kilian *et al.*, *Eur. Phys. J.* **C48** (2006) 389. arXiv:hep-ph/0607127, doi:10.1140/epjc/s10052-006-0048-y

[28] T. Robens *et al.*, *Acta Phys. Pol.* **B39** (2008) 1705. arXiv:0803.4161

[29] T. Binoth *et al.*, *Phys. Lett.* **B685** (2010) 293. arXiv:0910.4379, doi:10.1016/j.physletb.2010.02.010

[30] N. Greiner *et al.*, *Phys. Rev. Lett.* **107** (2011) 102002. arXiv:1105.3624, doi:10.1103/PhysRevLett.107.102002

[31] B. Chokoufe Nejad *et al.*, *JHEP* **12** (2016) 075. arXiv:1609.03390, doi:10.1007/JHEP12(2016)075

[32] B. Chokoufe Nejad *et al.*, *PoS* **EPS-HEP2015** (2015) 317. arXiv:1510.02739, doi:10.22323/1.234.0317

[33] J. Reuter *et al.*, *J. Phys. Conf. Ser.* **762** (2016) 012059. arXiv:1602.06270, doi:10.1088/1742-6596/762/1/012059

[34] F. Bach *et al.*, *JHEP* **03** (2018) 184. arXiv:1712.02220, doi:10.1007/JHEP03(2018)184