

## 9 Precision Monte Carlo simulations with WHIZARD

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The precision physics programs of FCC-ee demands 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 multi-purpose event generator WHIZARD [1, 2] has been used: this generator has been originally developed for the TESLA project, and later on been 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 (DAGs), thereby avoiding all redundancies. The matrix elements are generated either as compilable modern Fortran code or as bytecode instructions interpreted by a virtual machine [6]. For QCD, WHIZARD uses the color-flow formalism [7]. Matrix elements support all kinds of particles and interactions up to spin-2. A large number of BSM models is hard-coded, particularly the MSSM and NMSSM [8, 9]. General BSM models can be loaded from a Lagrangian level tool, using the interface to FeynRules [10]; from the version 2.8.0 of WHIZARD on (early summer 2019) a full-fledged interface to the general UFO format will be available. One of the biggest assets of WHIZARD is its general phase-space parameterization which uses a heuristic based on the dominating sub-processes, which allows to integrate and simulate processes with up to 10 fermions in the final state. The integration is based on an adaptive multi-channel algorithm, called VAMP [11]. Recently, this multi-channel adaptive integration has been enhanced to a parallelized version using the MPI3 protocol showing speedups of up to 100 [12], while a first physics study using this MPI parallelized integration and event generation has been published in [13].

WHIZARD allows to describe all the necessary ingredients for a high-precision  $e^+e^-$  event simulation: the CIRCE1/CIRCE2 modules [14] simulate the spectrum of beamstrahlung (including beam energy spectra) that comes from the classical electromagnetic radiation due 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 setup, WHIZARD furthermore allows to correctly describe polarized beams with arbitrary polarization 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 accordingly. This treatment is available also 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, factorized processes including full spin correlations (which can also be switched off for case studies), specification of the helicity of decaying res-

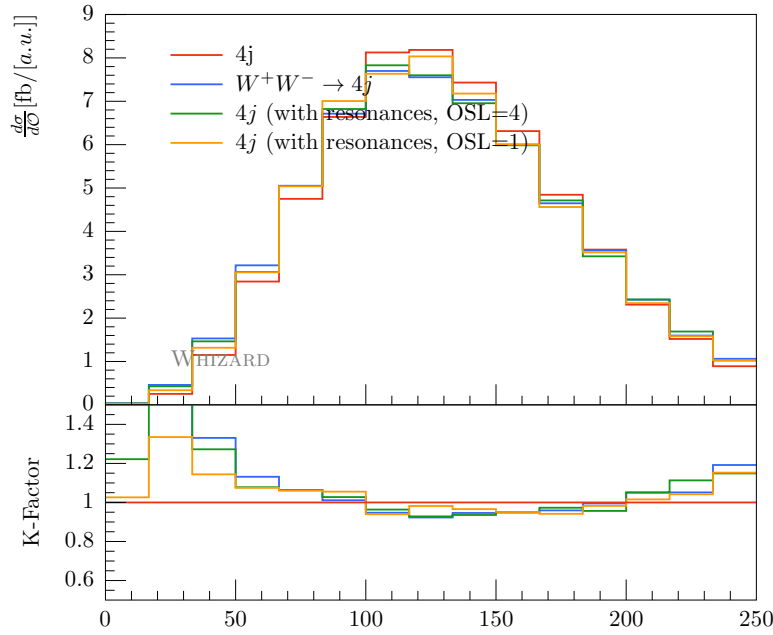


Fig. C.7: Energy distribution of photons in  $e^+e^- \rightarrow jjjj$  after parton shower and hadronization. Full amplitudes without resonance histories (red), factorized process  $e^+e^- \rightarrow W^+W^- \rightarrow (jj)(jj)$  (blue), and full process with resonance histories and different Breit-Wigner settings (green and orange, respectively).

onances, preset branching ratios, etc. WHIZARD supports all used HEP event formats, like 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 data set by the Linear Collider Generator Group in a setup similar to the FCC-ee. Recently, we added a corresponding interface for an externally linked PYTHIA8 [18] which uses again direct communication between the event records of WHIZARD and PYTHIA. This offers 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  $e^+e^- \rightarrow jjjj$ . 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  $W$ s. WHIZARD allows to automatically determine underlying resonance histories, evaluates their approximate rates and inserts according to these rates resonance histories for final-state jets. Fig. C.7 shows for the process  $e^+e^- \rightarrow jjjj$  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 factorized process  $e^+e^- \rightarrow W^+W^- \rightarrow (jj)(jj)$  (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 into account

Breit-Wigner tails of resonances. This kind of matching has now been validated for six-jet processes including  $H \rightarrow b\bar{b}$ .

Finally, we comment on the NLO QCD capabilities of WHIZARD: WHIZARD has completed its final validation phase for lepton collider QCD NLO corrections, and v3.0.0 will be released (approximately 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 automatically for all processes real and integrated subtraction terms are generated. WHIZARD also implements the resonance-aware variant [21]. Virtual multi-leg one-loop matrix elements are included from one-loop providers like GoSam [22], OpenLoops [23,24], and RECOLA [25,26]. First proof-of-principle NLO calculations have been done for electroweak corrections [27,28] in lepton collisions, while NLO QCD have been implemented for LHC processes first [29,30]. The automatized FKS subtraction has been tested and published in the study of off-shell  $t\bar{t}$  and  $t\bar{t}H$  processes in lepton collisions in [31]. The complete validation of the automatized NLO QCD setup will be available after the v3.0.0 release of WHIZARD [32]. WHIZARD allows to generate fixed-order NLO events for differential distributions at NLO QCD using weighted events, but also to automatically do POWHEG-matched and -damped events [33,34]. Decays at NLO QCD are treated in the same set-up as scattering processes.

The scan of the top threshold is a crucial component of the FCC-ee physics program. In order to determine systematic uncertainties from e.g. the event selection, WHIZARD allows to simulate at the completely exclusive final-state  $e^+e^- \rightarrow W^+bW^-\bar{b}$  matching the continuum NLO QCD calculation to the NRQCD threshold NLL resummation [35]. This simulation is available via a specific top-threshold model inside WHIZARD.

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