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# Simulating hard photon production with WHIZARD

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One of the important goals of the proposed future $e^+e^-$ collider experiments is the search for the dark matter particles using different experimental approaches. The most general search approach is based on the mono-photon signature, which is expected when production of the invisible final state is accompanied by a hard photon from initial state radiation. Analysis of the energy and angular distributions of those photons can shed light on the nature of a dark matter particle and its interactions. Therefore, it is crucial to simulate the signal and background samples in the uniform framework, to avoid possible systematic biases. The WHIZARD program is a flexible tool, which is widely used by $e^+e^-$ collaborations for simulation of many different "new physics" scenarios.
We propose the procedure of merging the hard photon emission from matrix element with the soft photon emission parametrised as the lepton ISR structure function implemented in WHIZARD. It allows us to reliably simulate the mono-photon events, including the two main Standard Model background processes: radiative neutrino pair production and radiative Bhabha scattering. We demonstrate that cross sections and kinematic distributions of mono-photon in neutrino pair-production events agree with corresponding predictions of the LEP-tuned $\mathcal{KK}$ MC generator.
We also propose a new approach to calculating limits on dark matter production at $e^+e^-$ colliders based on the analysis of the two-dimensional distributions of the reconstructed mono-photon events.

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## 1. Motivation

The search for dark matter (DM) particles is one of the main research goals of many running and planned experiments. Many different theoretical models have been proposed to describe the nature of DM and they result also in many different discovery scenarios. Collider experiments, assuming DM particles can be produced at high energy collisions, have to rely on indirect signatures, as direct observation of DM particle in the detector is not possible. Experimental searches are based on the processes in which the DM particle production is associated (due to production mechanism or in the decay chain of more massive objects) with the production of particular final state objects like jets, massive gauge bosons or high energy photons.

The mono-photon signature is considered to be the most general way to look for DM particle production in future $e^+e^-$ colliders. It is usually assumed that DM particles, denoted $\mathcal{X}$ in the following, can be pair produced in the $e^+e^-$ collisions via exchange of a new mediator particle, which couples to both Standard Model (SM) particles and DM states: $e^+e^- \to \mathcal{X}\mathcal{X}$. However, if this is the case, the produced final state is invisible in the detector. The simplest way to detect this process is via the observation of additional hard photon radiation from initial state leptons, as shown in Fig. 1. By studying the distribution of photons emitted in the process $e^+e^- \to \mathcal{X}\mathcal{X}\gamma$ we should be able to constrain the DM particle production cross section.

For proper estimation of the experimental sensitivity, precise modelling of all background processes is required. Main SM background contributions are expected to come from the radiative neutrino pair production process $e^+e^- \to \nu\bar{\nu}\gamma$, which can not be distinguished from the signal process on the detector level, and the radiative Bhabha scattering $e^+e^- \to e^+e^-\gamma$, which contributes to the mono-photon background when both electrons escape undetected along the beam pipe [1].

The ultimate goal of the present study is to introduce an experimental-like approach to the DM searches, which would set limits on DM cross sections as functions of mediator masses and widths. For proper estimate of the expected sensitivity of future $e^+e^-$ colliders a realistic description of the discussed background processes is a must. Such a simulation procedure, allowing for handling the signal and background events, has been developed in [2] and is briefly described in the next section. Taking into account the expected acceptance of the experiments, 2-dimensional distributions of mono-photon events can be obtained from the discussed procedure and used to calculate upper limits on the dark matter production cross sections, as alluded to in the last section.

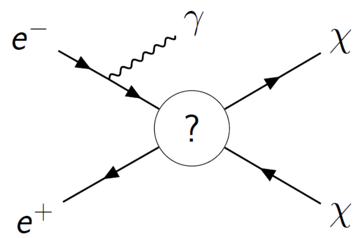


**Figure 1:** Diagram describing DM particle pair production process with additional ISR photon radiation.

## 2. Simulating mono-photon events with WHIZARD

One of the key elements of the mono-photon analyses is the proper simulation of the initial/final state radiated photons (ISR/FSR). The standard procedure to take ISR effects into account when generating events with WHIZARD [3, 4] is to use the built-in lepton ISR structure function which includes all orders of soft and soft-collinear photons as well as up to the third order in high-energy collinear photons. However, this approach allows only for a proper modelling of the kinematics of the hard scattering, but is not suitable when we expect photons to be detected in the experiment. The ISR photons generated by WHIZARD should not be considered as ordinary final state particles. Their energy and transverse momenta correspond to the sum over all photons radiated in the event from a given lepton line. For proper description of the photon measurement, the hard non-collinear photon emission should be included in the generation of the considered background process on the matrix element level. Generator-level cuts can be applied, corresponding to the detector acceptance, on the final state photon(s), which should also allow to remove divergences in the cross section calculations. To avoid double-counting, a dedicated merging procedure is then used to remove events with photons from ISR structure function emitted in the same kinematic region.

In the presented procedure [2] we use the following variables, calculated separately for each emitted photon, to describe kinematics of the emission:

$$q_- = \sqrt{4E_0 E_\gamma} \cdot \sin\frac{\theta_\gamma}{2} \,,$$
$$q_+ = \sqrt{4E_0 E_\gamma} \cdot \cos\frac{\theta_\gamma}{2} \,,$$

where $E_0$ is the nominal $e^+$ and $e^-$ beam energy, while $E_\gamma$ and $\theta_\gamma$ are the energy and scattering angle of the emitted photon in question. For the single photon emission they would correspond to the virtuality of the electron or positron after (real) photon emission. Variables $q_-$ and $q_+$ are independent and the pair of values ($q_-$,$q_+$) gives the information on both the energy and scattering angle of a given photon. Only photons with large values of virtualities $q_-$ and $q_+$ can be measured in the detector. More details about ($q_-$,$q_+$) plane, its correspondence to detector acceptance and consequent cuts can be found in [2].

ISR is also taken into account in the cross section integration and generating events, always resulting in two additional photons in the WHIZARD event record. The transverse momenta of ISR photons are taken into account on the event simulation level. At the same time, to avoid double counting, we reject the events with any of the ISR photons passing the ME photon selection cuts. After the ISR photon selection procedure, the phase space for photon radiation is unambiguously divided into ME emission and ISR regions. As mentioned above, photons generated by WHIZARD from the ISR structure function should not be considered as single physical particles, but correspond to the sum over all photons radiated in the event from a given lepton line. Therefore, the proposed merging procedure is only approximate.

Additional photon selection on the generator level is required for efficient simulation of mono-photon events. We assume the final signal selection will require photon to be reconstructed in the angular range $7^\circ < \theta^\gamma < 173^\circ$ and with the transverse momentum $p_T^\gamma > p_T^{min} = 5$ GeV. These requirements will be referred to as 'hard photon selection' in the following and ME photons passing

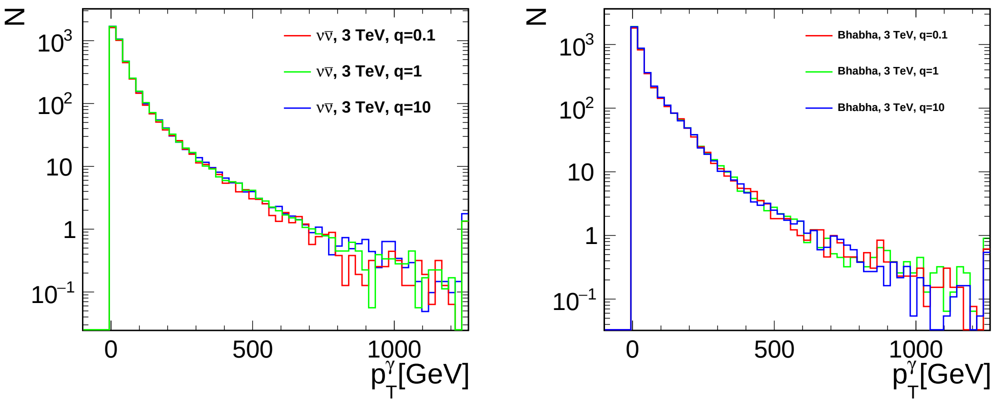


**Figure 2:** Distribution of the hard photon transverse momenta for radiative neutrino pair production (left) and radiative Bhabha scattering (right) at 3 TeV, for different values of the merging parameter $q_{min}$. Figures taken from [2].

this selection will be described as 'hard'. For multi-photon events, at least one ME photon needs to pass the hard photon selection.

Impact of the choice of the ISR-ME merging scale $q_{min}$ on the cross sections calculations for both background processes, for different photon mutliplicities and collision energies has been discused in details in [2]. In figure 2, example distributions of the photon transverse momenta, for radiative neutrino pair production and radiative Bhabha scattering at 3 TeV are shown, for different values of merging parameter $q_{min}$. It demonstrates that the photon transverse momentum distribution, after hard photon selection, is not sensitive to the choice of the $q_{min}$ parameter. This is one of arguments that the proposed ISR-ME merging procedure, despite being only approximate, works very well.

When the Bhabha process is to be considered as the background source in the mono-photon analysis, we should not set any constraints on the final state leptons (electron or positron) on the generator level. As they do not need to be observed in the detector, no requirement can be imposed on the minimum momentum transfer or minimum lepton scattering angle. This is the main problem in generation of Bhabha events, as the cross section for this process diverges for low scattering angles due to the Coulomb singularity. However, most of the divergencies are removed when we require a hard photon in the final state, as described above.

Cross section variation with $q_{min}$ can also be attributed to the contribution from the final state radiation (FSR) and the ISR-FSR interference, which are taken into account in ME approach, but not in the ISR parametrisation. When increasing the $q_{min}$ cut, the phase space for photons generated with ISR parametrisation is increased while it is reduced for ME generation. This effect should be further reduced when additional selection cuts (in particular electron veto) are applied in the analysis.

### 2.1 Comparison with the $\mathcal{KK}$ MC generator

The merging procedure described above has been compared with the $\mathcal{KK}$ MC [5, 6] generator for the neutrino background. Single photon differential distributions in the $\mathcal{KK}$ MC have a full NLO

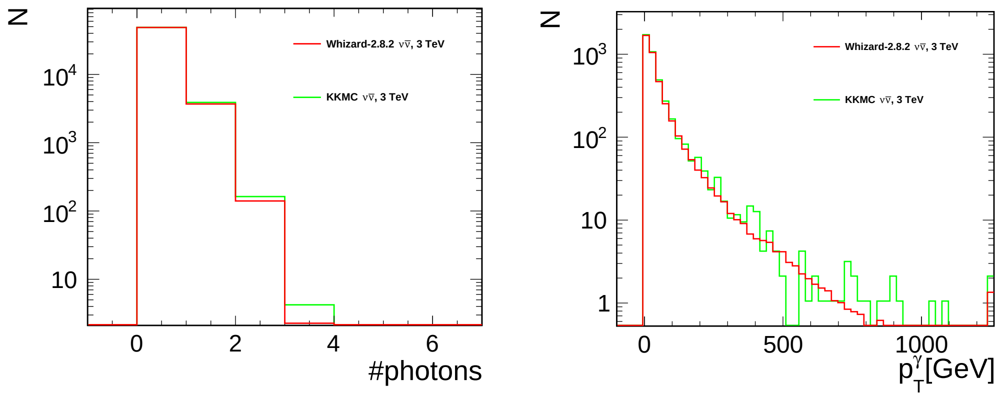


**Figure 3:** Distributions of the number of reconstructed photons (left) and the photon transverse momentum (right) in the neutrino pair production events generated by WHIZARD (red) and the $\mathcal{KK}$MC (green). for collision energy of 3 TeV, with 'hard photon' selection imposed. Figures taken from [2].

accuracy. WHIZARD on the other hand includes all order resummation of soft and soft-collinear, and hard-collinear emissions up to 3rd order in the ISR. The proposed procedure supplements WHIZARD's default precision with exact hard matrix elements up to order $\mathcal{O}(\text{Born}+\alpha^{3/2})$. Therefore we expect that observables with at least 2 hard non-collinear photons for processes without FSR should have a similar accuracy as in the $\mathcal{KK}$MC while single photon ones will differ by missing genuine 1-loop QED corrections. To allow for direct comparison of the two approaches, electroweak corrections not available in WHIZARD are also disabled in the $\mathcal{KK}$MC (these corrections contribute to 2-3% of the total cross section). After hard photon selection cuts are applied, corresponding to the expected detector acceptance, the multiplicity distributions obtained with WHIZARD and the $\mathcal{KK}$MC are in good agreement, see Fig. 2. Very good agreement is also observed for the photon transverse momentum distribution.

## 3. Prospects on DM searches

Mono-photon events can be described by just two variables: photon energy and its polar angle or rapidity. Shown in Fig. 4 are the rapidity vs energy distributions for mono-photon events at 3 TeV CLIC, expected for SM background processes and one of the considered signal scenarios. Expected signal distribution is very different from that for the SM background. These 2-D distributions, also measured for different beam polarisations, can be used as an input for building measurement model in RooFit [7] and calculating the expected 95% C.L. cross section limits for radiative DM pair-production. The study is ongoing and the plan is to present the expected limits on the light DM production cross section as a function of the mediator mass and width. We expect that limits on the production cross section calculated as a function of the mediator mass and width should be independent on the coupling values assumed in the model.

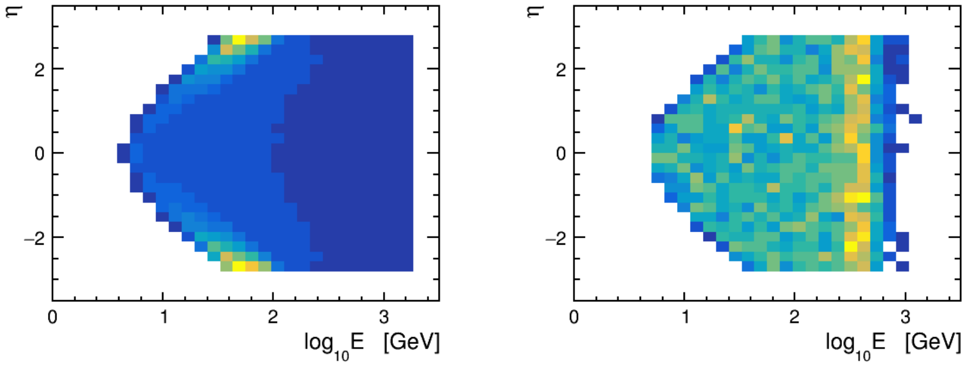


**Figure 4:** Pseudorapidity vs energy distributions for mono-photon events at 3 TeV CLIC, expected for SM background processes (left) and the signal of radiative DM pair-production, for DM mass of 50 GeV, mediator mass of 2.5 TeV and mediator width of 200 GeV (right).

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