Monte Carlo Event Generator updates, for τ pair events at Belle II energies

Sw. Banerjee[1], D. Biswas[1], T. Przedzinski[2] and Z. Was[3°]

1 University of Louisville, Louisville, Kentucky, 40292, USA
2 Institute of Physics, Jagellonian University, 30-348 Krakow, Lojasiewicza 11, Poland
3 Institute of Nuclear Physics, Polish Academy of Sciences, PL-31342 Krakow

Abstract

The Monte Carlo for lepton pair production and τ decays consist of `KKMC` for lepton pair production, `tauola` for τ lepton decays and `photos` for radiative corrections in decays. An effort for adaptation of the system for precision data to be collected at `Belle II` experiment lead to extension of phase space generation modules both in `photos` and `tauola` to enable decays and/or radiative corrections of additional light lepton pairs. The phase-space and matrix element parts of the programs are separated, that is why extension to processes where lepton pair is produced through narrow resonances, like dark photon, was straight forward. In the present version of `tauola`, the list of τ decay channels is enriched with multitude of exotic ones, useful for searches of new physics. The hadronic currents parametrization of main decay channels is prepared for basic simulation in the experiment. The basis for future work on precise fits of hadronic currents including Machine Learning is retained, but development of necessary software solutions is left for the forthcoming years. Presented programs versions are available in stand-alone format from GitLab or through the `basf2` system of Belle II software. Official distribution web pages, documenting programs tests, are retained but not necessarily up to date.

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Contents

° Speaker

1 Introduction

The `tauola` package [1–4] for simulation of τ-lepton decays and `photos` [5–7] for simulation of QED radiative corrections in decays, are computing projects with a rather long history. Written and maintained by well-defined principal authors, they nonetheless migrated into a wide range of applications where they became essential ingredients of complicated simulation chains. In the following, we shall concentrate on the version of the programs which are prepared for installation in `basf2` software of the Belle II experiment. The following programs are installed in the system: (i) KKMC for the τ lepton production process $e^- e^+ \rightarrow \tau^- \tau^+ n\gamma$ (ii) `tauola` for τ lepton decays, (iii) `photos` for bremsstrahlung in decays of particles and resonances, (iv) `photospp`, the C++ version of `photos`, which at present is used only for supplementing events with lepton pairs, produced through virtual careers of the electroweak interaction in the Standard Model or through New Physics processes.

Our presentation is organized as follows: Section 2 is devoted to technical changes prepared in Ref. [8] for `tauola` and earlier in Ref. [9] for `photos`. These extensions of phase space generators, enable not only full implementation of bremsstrahlung-like processes where virtual photon decay into a pair of leptons, but also the possibilities of emitting dark photon or dark scalars, now introduced into `tauola` and `photospp`. In Section 3 we concentrate on `photos` Monte Carlo for radiative corrections in decays. The new version of the program features emissions of light lepton pairs, which may originate from virtual photon or from dark photons or scalars. Numerical tests of dark scalar implementation into KKMC [10] $e^- e^+ \rightarrow \tau^- \tau^+ n\gamma$ event samples are presented. Section 4 is devoted to the discussion of initialization for `tauola` hadronic currents and new decay channels as prepared for `basf2` of Belle II. This point was already announced in [11] and presented in [12], that is why, we will address only those points which may be important for the future users. Section 5 summarizes this proceeding.

2 Technical aspects: phase space presamplers

From a technical point of view, the most important update was the introduction of phase space presamplers for lepton pairs originating from virtual photon or narrow exotic resonances, either vector or scalar in nature. Both `tauola` and `photos` rely on exact phase space parametrization. In principle, results of simulations also depend on parameterization of matrix elements and/or form factors used, but if presamplers of phase-space are not appropriate, efficiency of generation is poor and in extreme cases the distributions may be unreliable. Usually, the weight monitoring functionalities point to the difficulties. In fact, the necessity of changes can be identified from inspection of matrix elements to be installed. Details for the case of lepton pairs can be found in Ref. [8] and are not repeated here. What is important, is that phase space parametrization in both `tauola` and `photospp` now have presamplers for virtual photon or narrow resonances decaying to lepton pairs.

Once matrix element installed and distributions generated, it is necessary to perform tests. Semi-analytical, or analytical results for pair emissions are rare, but nonetheless were reported in Ref. [8] and [11]. These numerical results are mostly about final state rates and rely on eikonal approximations for matrix elements. Pair emission can also be generated with other generators. That was used for test already long time ago. Automated comparison package MC-TESTER [13] was used to construct histograms and compare results from KORALW [14] with those from photos in tandem with KKMC. Such tests are very helpful. We have used them in study of CP sensitive observables in $H \to \tau\tau$ channel [15], where events simulated with tauola universal interface [16] are compared with those including parity effects introduced with the tauspinner algorithm [17]. For $\tau\tau$ *jet jet* such test and comparisons with MadGraph [18] are reported in [19]. Now events simulated with photos were compared with events simulated with MadGraph for the $e^-e^+ \to \tau^-\tau^+X$ ($X \to l\bar{l}$) process, where X is an exotic particle motivated by new physics models, and can be vector Z' [20, 21] or dark scalar [22]. The spin state of τ flips when X is scalar, which needs to be taken into account in proper simulation of $\tau - \tau$ spin correlations. For these developments, distributions prepared with MC-TESTER were obtained, and used in the development of tauola and photospp.

3 PHOTOS **Monte Carlo for bremsstrahlung and lepton pair emission**

Numerical tests for pair emission algorithm are published [23], and following updates to the program presented in [9]. This update opened up new possibilities, in particular, generation of lepton pairs in the process $e^-e^+ \to \tau^-\tau^+n\gamma$ with τ decays and implementation into final state of an exotic particle X motivated by new physics. There are two reasons, why matrix elements of refs [20–22] could not be used directly. First is to preserve modularity of photos Monte Carlo design. The second is because the matrix element form must enable its interpolation for use when additional bremsstrahlung photons are present. That is why a factorized form, with the emission factor similar to the eikonal one, was necessary to be devised and checked for the process shown in Fig. 1.

In QED, the eikonal factor is the difference between the amplitude of some scattering process and the one when additional soft photon is present. If there are many photons in final states and all are at small energies, products of such factors, are added. In the soft photon limit, each such factor depends only on momenta of outgoing and incoming charged particles and on the momentum of the photon. The resulting formula is quite simple $\sum_{\text{charged particles}} Q_i \frac{2p_i^\mu}{2p_i \cdot k}$ and well known. What is important is that it can be expressed with four momenta and can be
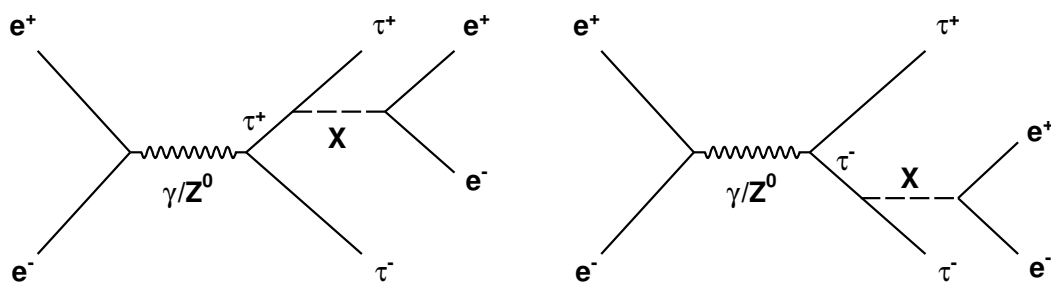
Figure 1: Feynman diagrams for $e^-e^+ \to \tau^-\tau^+X(\to e^-e^+)$, used for preparation of photospp emission kernel.

used all over the phase space. One should not forget it is the zeroth level approximation, and thus, corrections obtained from matrix element calculations are necessary. This is an essential element of exclusive exponentiation for photon generation in KKMC [10] or photos. Hard photon configuration corrections in general depend on momenta of all photons in a particular event.

The QED matrix elements for configurations with additional lepton pairs has a similar form if lepton pair virtuality and energies are small. In this case, the emission factor is process independent, and has a form which can be used all over the phase space. In photospp variant of eq. (1) from [24] is used.

For configurations where lepton pairs from decay of exotic scalars or vector particles are present, approximate matrix elements were derived, following educated guesses. The approximations were then validated with MadGraph simulation [18] samples. The best of several variants was chosen. This opened up the gateway for simultaneous inclusion of large QED effects, e.g. ISR as implemented in KKMC. ISR effects were incorporated in MadGraph simulation using the recipe from [25].

In fact, not only test with MadGraph simulation [18] samples were necessary. Several iterations of photos matrix elements were performed to achieve better a simulation tool. Validations and choices were performed with the help of MC–TESTER Shape Difference Parameter. Final validation of photos was the check on the distributions of the recoil mass of the τ-pair system for the process $e^-e^+ \to \tau^-\tau^+\phi_{\text{Dark Scalar}}$, where the $\phi_{\text{Dark Scalar}}$ decays into a pair of oppositely charged electrons or muons, as shown in Figs. 2 and 3.

The photospp version of photos is implemented in C, its external parts, the interfaces are implemented in C++. In general, it features both photon and lepton pair emissions in decays of resonances or particles. In particular the emitted lepton pairs can be due to QED interactions or due to dark photon or dark scalars.

The photospp generation can be combined with KKMC+tauola+photos.f one. For the sake of rapid developments, photospp was not used for photon emissions. This enables more flexibility and some testing could be spared. The photospp is used for construction of final states of the type $Z/\gamma^* \to \tau\tau X(scalar/pseudoscalar/vector/\gamma^*)$ with usual τ decays and with full $\tau\tau$ spin correlations and with $X \to ee(\mu\mu)$ decays too.

Let us indicate some technical foundations in the following. The partial width of the decay of a resonance or particle to an intermediate state of n final state particles, is given by the following formula:

$$d\Gamma = \frac{1}{2M}|\bar{M}_n|^2 dLips_n = \frac{1}{2M}|\bar{M}_n|^2 J_n \prod_{j=1}^{k_n} dx_j, \tag{1}$$

where M denotes the mass of the decaying object, $\bar{M}_n$ denotes the decay matrix element and $dLips_n$ denotes the Lorentz invariant phase space integration element. The $dLips_n$ can be expressed, after change of variables, as a product of integration elements dx_j, of the x_j real integration variables in the [0,1] range. Finally J_n denotes Jacobian of the variable change. This formula is used in photos. Formally speaking, it is used twice, first for the n-body decay of the input particle, where the x_j vector is recovered from the event to be modified by photos. Then the set of $\{x_j\}$ is supplemented with additional x'_j to complement the set of coordinates necessary to parametrize n+1 or n+2 body phase space. These are finally used for construction of event where particles are added. That is the general idea, which explains why the algorithm can perform without approximations for phase space, and why the full phase space coverage can be guaranteed. Explanations of complications due to matrix element with collinear/soft or narrow resonance approximations are now omitted. We address the reader to Refs. [9, 26] for further details.
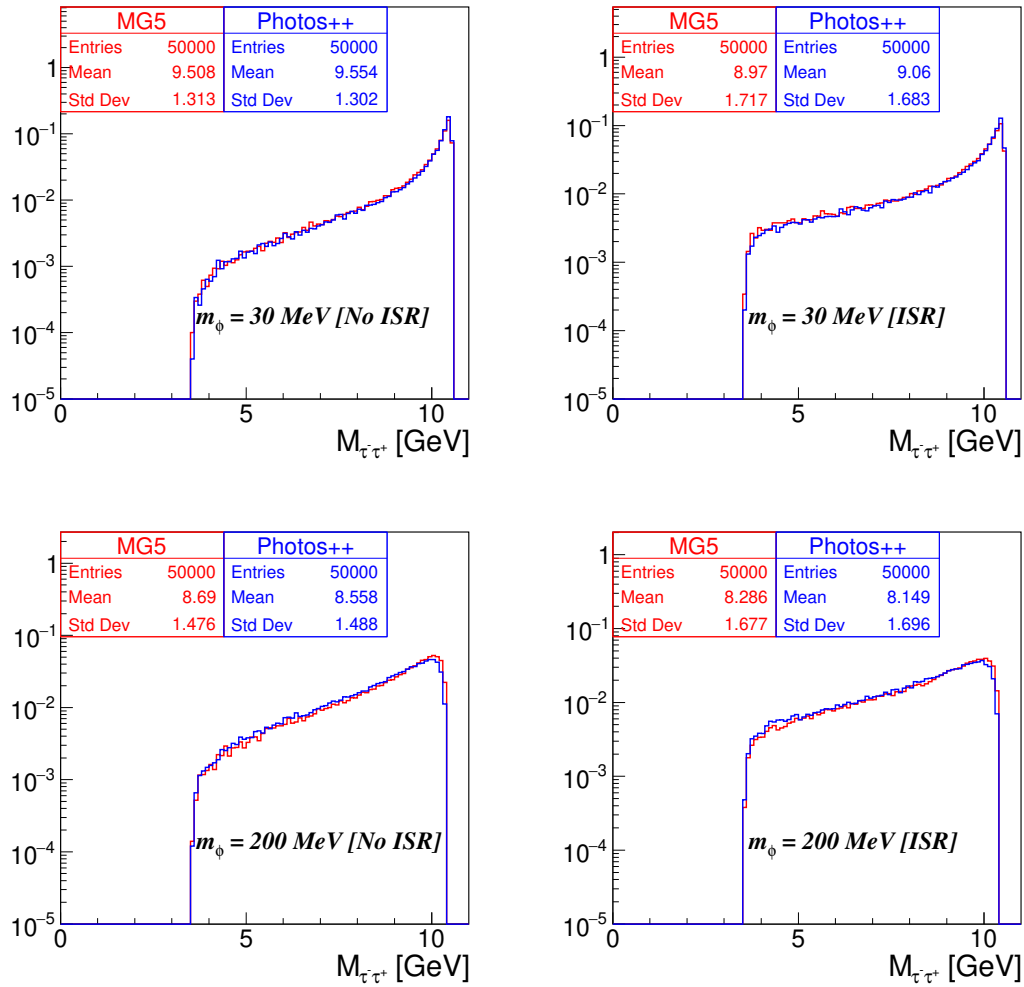
Figure 2: $e^-e^+ \rightarrow \tau^-\tau^+\phi_{\text{Dark Scalar}}(\rightarrow e^-e^+)$.

4 Status of `tauola` Monte Carlo initializations

We do not aim at repeating, this what was already documented in Ref. [23] and in references therein, but we concentrate on recent changes, introduced for Belle II applications.

For simulations in the Belle II software, many channels were prepared to establish defaults:

1. Total number of decay channels: 278

2. 2 body neutrinoless non SM decays: 58

3. 3 body neutrinoless non SM decays: 46

4. Number of generic SM decay channels: 92, initialized with PDG Branching Fractions [27]. For matrix elements, choices from older versions of parametrization were taken, except:

    (a) for high precision data obtained for $\tau^- \rightarrow \pi^-\pi^0\nu_\tau$ decays [28] by the Belle collaboration, and for $\tau^- \rightarrow \pi^-\pi^+\pi^-\nu_\tau$ decays by the BaBar collaboration using the Resonance Chiral Lagrangian initialization [29].
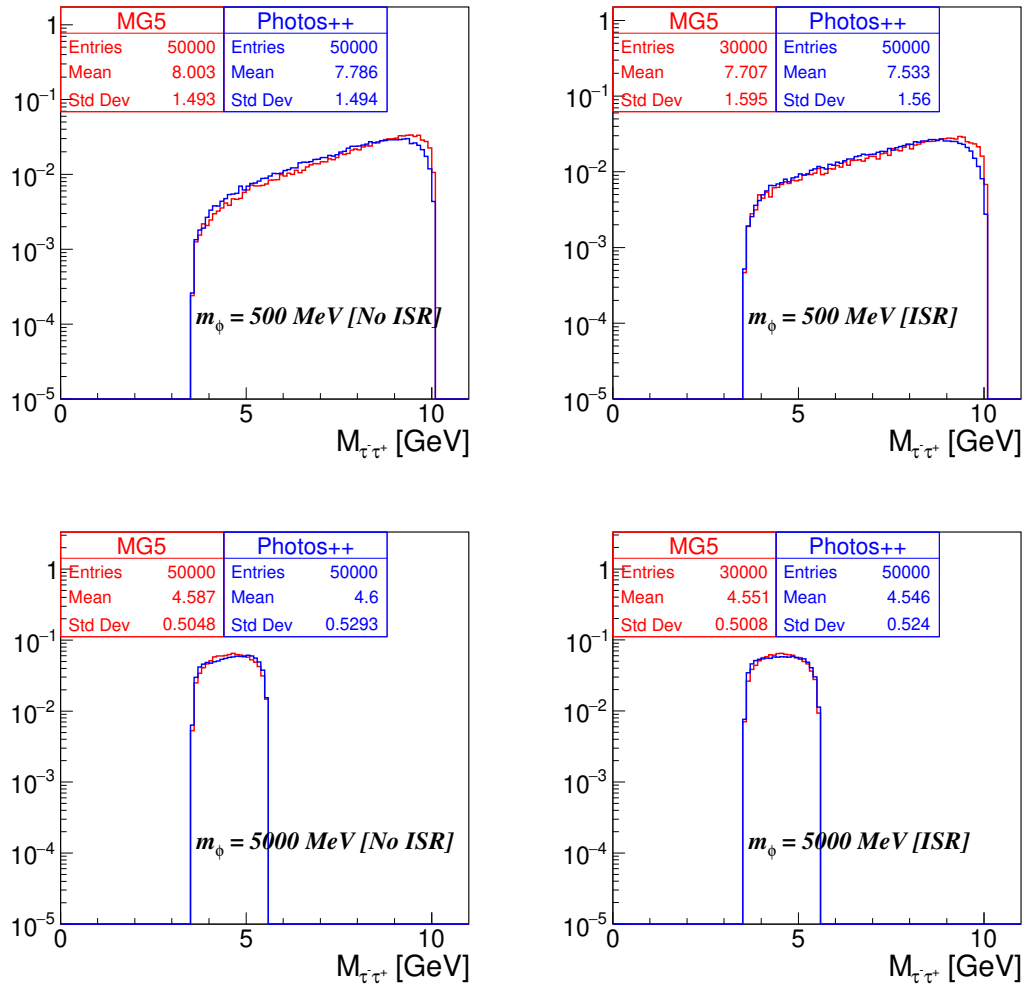
Figure 3: $e^-e^+ \to \tau^-\tau^+ \phi_{\text{Dark Scalar}}(\to \mu^-\mu^+)$.

(b) Theoretical uncertainty of models is worse than quality of data. That is why, new, or alternative decay modes can be installed by the user with the help of specially prepared for that routines but must be validated by experimental data. User can choose decay product flavors, their masses, as well as matrix element or hadronic current and tune it to data in the future. Note that temporarily this option inactive, pending necessary arrangements for basf2 library.

5. New decay modes with SM photons or Dark photons decaying to lepton pair with mass $\in [50, 1500]$ MeV with matrix elements cross-validated with MadGraph [18] for

- $\tau^- \to \nu_\tau \bar{\nu}_\ell \ell^- \ell^+ \ell^-$ decays. A typical Feynman diagram for such a process is shown in Fig. 4.
- $\tau^- \to \nu_\tau \pi^- \ell^+ \ell^-$ decays.
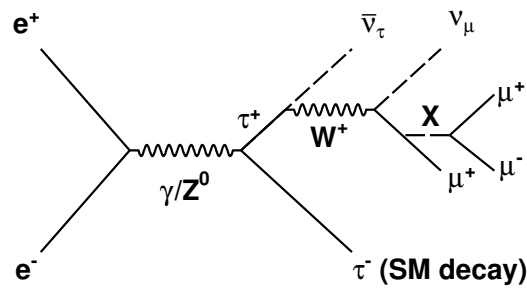
Figure 4: Feynman diagram for $e^-e^+ \rightarrow \tau^- (SM\ decay)\ \tau^+(\rightarrow \bar{\nu}_\tau \nu_\mu \mu^+ X(\rightarrow \mu^- \mu^+))$ process with X emitted in τ^+ decay, used in `tauola`.

5 Summary

Final states of τ lepton pairs with bremmstrahlung photons and dark scalar/photon (decaying to the lepton pair) were introduced for study of e^-e^+ collisions. The τ pair production and decay were introduced with `KKMC` and `tauola`, dark scalar/photon with `photospp`. Efforts on τ lepton decays have been focused on channels, their matrix element and presamplers initializations. An extended list of τ decay channels is now available in the `basf2` software for the Belle II collaboration, in particular New Physics neutrinoless ones.

Introductory steps for language change in `tauola` are completed. Parts aimed for migration into C are localized. Parts more convenient for migration into C++ are separated as well. Evolution is prepared to follow the same development path as was chosen for `photos`; its C++ version is already installed. Also, C++ version, focused on FCC applications of `KKMC` exist.

Not much progress has been made for re-arrangements for fits of multidimensional signatures and ML solutions, but it is kept in mind, even if temporarily deactivated.

The speaker of this talk (Z.W.) hopes to provide help with future developments of `tauola`, perhaps including reweighting techniques with `TauSpinner` weights, originally deployed for the study of spin-parity of the Higgs Boson, but this time applicable to the physics of τ decays.

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