The $\tau$ lepton Monte Carlo Event Generation – imprinting New Physics models with exotic scalar or vector states into simulation samples

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Abstract

The Monte Carlo for lepton pair production and $\tau$ decays consist of KKMC for lepton pair production, tauola for $\tau$ lepton decays and photos for radiative corrections in decays.

An effort for adaptation of the system for precision data being collected at the Belle II experiment included simulation of additional light lepton pairs. Extension to processes where lepton pair is produced through narrow resonances, like dark photon or dark scalar ($\phi$) resonances, was straightforward.

Modified programs versions are available in stand-alone format from gitlab repository or through the basf2 system of Belle II software. It was explained recently during the International Workshop on Tau Lepton Physics September, 2021, Bloomington IN. Now we concentrate on simulations for $\phi$ resonance, a hypothetical object which could be responsible for anomalous moment $g-2$ in $Z-\tau-\tau$ interactions through virtual contributions.

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1 Introduction

The tauola package [1, 2, 3, 4] for simulation of $\tau$-lepton decays and photos [5, 6, 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 use 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 $\tau$ lepton production process $e^-e^+ \rightarrow \tau^-\tau^+\gamma\gamma$ (ii) tauola for $\tau$ 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.

Technical changes are not addressed, they can be found in Ref. [8]. Recent extensions of phase space generators, enable not only full implementation of bremsstrahlung-like processes where virtual photon decay into pair of leptons, but also the possibilities of emitting dark photon or dark scalars, now introduced into tauola and photospp, and instrumental for the present talk.

Example numerical results of dark scalar implementation into KKMC [9] $e^-e^+ \rightarrow \tau^-\tau^+\gamma\gamma$ event samples are presented. From technical point of view, first the introduction of phase space presamplers for lepton pairs originating from virtual photon or narrow exotic resonances, either vector or scalar in nature was necessary. Both tauola and photos rely on exact phase space parametrisations. Of course results of simulations also depend on parametrization of matrix elements, but if presamplers of phase-space are not appropriate, efficiency of generation is poor and in extreme cases the distributions may be unreliable.

Pair emission can be also generated with other generators. That was used for test already long time ago. Automated comparison package MC-TESTER [10] was used to construct histograms and compare results from KORALW [11] with those from photos in tandem with KKMC. Such tests are very helpful. Now events simulated with photos were compared with events simulated with MadGraph for the $e^-e^+ \rightarrow \tau^-\tau^+X \ (X \rightarrow ll)$ process, where X is an exotic particle motivated by new physics models, and can be dark photon or dark scalar [12]. The spin state of $\tau$ 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.

Numerical tests for Standard Model pair emission algorithm are published [13], and following updates on the program presented in [14]. This update opened up new possibilities, in particular, generation of lepton pairs in the process $e^-e^+ \rightarrow \tau^-\tau^+\gamma\gamma$ with $\tau$ decays and implementation into final state of an exotic particle X motivated by new physics. There are two reasons, why matrix elements of refs [15, 16, 12] could not be used directly. First is to preserve modularity of photos Monte Carlo design. 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.

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 [17] 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 [18].

In fact, not only test with MadGraph simulation [17] samples were necessary, but also several iteration 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 $\tau$-pair system for the process $e^-e^+ \rightarrow \tau^-\tau^+\phi_{\text{Dark Scalar}}$, where the $\phi_{\text{Dark Scalar}}$ decays into a pair of oppositely
Figure 1: Feynman diagrams for $e^- e^+ \rightarrow \tau^- \tau^+ X (\rightarrow e^- e^+)$, used for preparation of photospp emission kernel.

charged electrons or muons, as shown in Figs. 2 and 3.

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 [17] was introduced into tauola. In particular $\tau^- \rightarrow \nu_\tau \ell^- \ell^+ \ell^-$ decays. A typical Feynman diagram for such process is shown in Fig. 4.

Example numerical results are given in Fig. 2 and 3 results of our simulation is compared with the one of MadGraph.

2 Summary

Final states of $\tau$ lepton pairs with bremsstrahlung photons and dark scalar/photon (decaying to the lepton pair) were introduced for study of $e^- e^+$ collisions. The $\tau$ pair production and decay were in-
Motivation of the talk was to present solutions that may be of some use to the broader community than just the Belle II users of KKMC. In principle solution is straightforward to extend to any New Physics states which decay to a pair of $\tau$ leptons. However alternative solution based on similar modifications to the KORALW generator may be more appropriate. This is because contributions from terms proportional to $\tau$ mass play a more important role than initial state bremsstrahlung in such cases.

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