Precision simulations with TAUOLA and PHOTOS

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The status of the Monte Carlo programs for the simulation of τ-lepton production and decay in high-energy accelerator experiments is reviewed. No significant changes in the organization of the programs were introduced since previous TAU conference, that is why we will concentrate on some physical topics: (i) For TAUOLA Monte Carlo generator of τ-lepton decays, simulation of five scalar final states based on the hadronic current became available for the first time. As an example, simple, but realistic current for final states: \(2\pi^-\pi^+\pi^0\nu_\tau\), \(\pi^-4\pi^0\nu_\tau\) and \(3\pi^-2\pi^+\nu_\tau\) is presented. The current is installed into TAUOLA. (ii) For the PHOTOS Monte Carlo, which generates radiative corrections in arbitrary decays, new results on next to leading order corrections became available for some decay modes. The complete corrections were installed for leptonic Z and B decays into a pair of scalars. (iii) During conference discussions, the importance of checking the uncertainty of the overall normalization for KORALB and KKMC simulations was underlined. Necessary steps to check the uncertainty and to adjust the programs to Belle and BaBar conditions are also listed.

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1. Introduction

The TAUOLA package [1,2,3,8] for the simulation of τ-lepton decays and PHOTOS [4,5] for the simulation of radiative corrections in decays, are computing projects with a rather long history. Written and maintained by well-defined authors, they nonetheless migrated into a wide range of applications where they became ingredients of complicated simulation chains. As a consequence, a large number of different versions are presently in use. From the algorithmic point of view, they often differ only in a few small details, but incorporate many specific results from distinct τ-lepton measurements. Such versions were mainly maintained (and will remain so) by the experiments taking precision data on τ leptons. On the other hand, many new applications were developed recently, often requiring a program interface to other packages (e.g. generating events for LHC, LC, Belle or BaBar physics processes). The programs organization, prepared for the convenience of users, was presented during previous τ conference, in year 2004 [6] and we will not repeat it here.

This time, let us concentrate on more physics oriented results. Progress in the simulation of τ decays into final states of five scalars was achieved recently. This work has some consequences for the general form how the Monte Carlo programs for decay chains have to be organized. We will devote section 2 to discussion of that subject. In section 3 we will present some new results for the simulation of radiative corrections in decays with PHOTOS Monte Carlo. Here papers [9,10], where Next to Leading Order effects were introduced into generation for the first time, will be presented. Even though those results do not affect simulation of τ decays in the direct way, nonetheless open the way for future precision statements on radiative effects in τ decays. That is why they should find their place in τ conference proceedings.
During my talk and in discussions later, I found significant interest in domain of overall normalization of $\tau$-lepton pair production cross sections as calculated by KORALB [12,11] and KKMC [17] generators. These programs were written for higher energies. For the use at Belle, BaBar energies some effort necessary to adjust photon vacuum polarization need to be completed. Section 3 is devoted to that purpose. List of necessary benchmarks is given and necessary steps are explained.

Because of the limited space of the contribution, and sizable amount of other physically interesting results, some of them will be excluded from conference proceedings. In particular, this time we will skip completely the applications related to testing results, some of them will be excluded from conference proceedings. The five-pion amplitude is thus based on a simple model, which, however, can be considered as a first realistic example. As usual, hadronic current is easy to replace by the more sophisticated one, once it is required. Also, multitude of additional decay channels of five scalars (pions or K-ons) are pre-installed. Appropriate flavours and hadronic currents have to be provided by the user.

From that perspective, and in general from the point of view of any future Monte Carlo program, it is of some interest to show some of the numerical results. We will concentrate mainly on effects of the different types of interferences.

In the numerical results, collected in Table 1 the following two currents are used. Current A: $\pi^- \rightarrow a_1^- \nu \rightarrow \rho^- (\rightarrow \pi^- \pi^0) \omega (\rightarrow \pi^-\pi^+\pi^0) \nu$, Current B: $\tau^- \rightarrow a_1^- \nu \rightarrow a_1^- (\rightarrow 2\pi^-\pi^+ f_0 (\rightarrow 2\pi^0) \nu$, and $\tau^- \rightarrow a_1^- \nu \rightarrow a_1^- (\rightarrow \pi^- 2\pi^0) f_0 (\rightarrow \pi^+\pi^-) \nu$ are introduced with simple assumptions about the couplings and propagators of the various resonances. Similar amplitudes (without the $\rho\omega$ contributions) are adopted for the $\pi^- 4\pi^0$ and $3\pi^- 2\pi^+$ modes.

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## Table 1: Test results of the generator for realistic choices of parameters; see the text of the paper [7] for details. Two currents A and B are used in different combinations. The s. (or no s.) comment, denotes that for the particular channel symmetrization over identical pions was (was not) included. With the • we denote the result difficult to interpret, because of $m_{\pi^0} \neq m_{\pi^\pm}$ see the text.

| Final state | Current | $\Gamma_X/\Gamma_\tau \times 10^3$ (TAUOLA) | $\Gamma_X/\Gamma_\tau \times 10^3$ (exp.) |
|-------------|---------|------------------------------------------|------------------------------------------|
| 1           | $2\pi^- \pi^+ 2\pi^0$ | A no s. | 24.04 | – |
| 2           | $2\pi^- \pi^- 2\pi^0$ | B no s. | • 9.28 | – |
| 3           | $2\pi^- \pi^+ 2\pi^0$ | A s. | 25.30 | $25 \pm 3$ |
| 4           | $2\pi^- \pi^+ 2\pi^0$ | B s. | 6.05 | $6.2 \pm 2$ |
| 5           | $2\pi^- \pi^- 2\pi^0$ | A+B s. | 31.35 | $31 \pm 2$ |
| 6           | $\pi^- 4\pi^0$ | B s. | 9.37 | $5.5_{-2.2}^{+3.4}$ |
| 7           | $3\pi^- 2\pi^+$ | B s. | 11.03 | $4.6 \pm 0.3$ |
the other hand, modest agreement of TAUOLA with the data (lines 6 and 7), provide test of the predictive power of our model.

Rather unpredictable nature of interference effects is of importance in construction of Monte Carlo programs, if they are supposed to be used in comparisons with the precision data on decays. The constructive/destructive interferences originate from the corrections of order $\Gamma/Q$ for intermediate resonances, which appear in the cascade decays. If widths of the resonances saturating currents would be sufficiently small then of course interferences would be negligibly small. At the same time the intermediate states would be well formed and necessities to use different parametrizations for example of $\rho$ resonance, depending on how it was formed and how it will decay, would not be necessary.

Unfortunately, in practice, it is not the case, and we have to bear this constraint unpleasant for program construction in mind.

3. PHOTOS and NLO effects in $B$ and $Z$ decays

There were significant changes introduced into PHOTOS Monte Carlo project over the last two years. The complexity of the subject matches neither size nor the purpose of the present talk. Recently collected results [11] only indirectly affect predictions of simulation for $\tau$ physics. However as for the first time explicit form of the approximate matrix elements actually used was written, new possibilities opened. In particular, for the two-body decay modes into fermions ($Z \to \mu^+\mu^-$) or scalars (eg. $B \to K^+\pi^-$) exact NLO order matrix elements were implemented into PHOTOS kernel. In cases when the correction kernels were switched on and simulations were restricted to the first order, the differences with results of reference Monte Carlo programs were below statistical errors of $10^8$ event samples. Also technical tests of PHOTOS performed at that or even better statistical level confirmed the correctness of program design; even though significant changes in crude distributions were introduced, the results did not change at all.

To visualize the results let us present the example plots for ($Z \to \mu^+\mu^-$) and $B \to K^+\pi^-$ cases. In case of ($Z \to \mu^+\mu^-$) we could perform comparisons for multi-photon version of the generation, because our reference program KKMC has such possibility as well. The histogram with the worst agreement of all possible invariant masses which could be constructed from four momenta of: $\mu^+, \mu^-$ and eventually up to two hardest photons (their energies had to be above 1 GeV) is shown in Fig 1 where the invariant mass of $\gamma\gamma$ pair is plotted. Even in this case, the green and red (gray) lines for PHOTOS and KKMC nearly overlap (the logarithmic left side scale has to be used for that lines). To visualize the differences, we show on the plot the ratio of the two histograms which is depicted with the black line and follows linear right scale. The differences in the ratio are rather small for the masses of $\gamma\gamma$ pair up to about 50 GeV. For larger masses which contribute about $10^{-3}$ to the sample of two-photon configurations the difference gradually grow to about 15% close to the phase space limit. Note that fraction of events with at least two photons each of which with energies above 1 GeV is 1.26 % from KKMC and 1.29 % from PHOTOS.

In case of the $B$ meson decays the agreement between PHOTOS and reference calculation, even without the use of correcting weight was excellent, that is better than for the presented above result for $Z$ decay. That is why we skip numerical result and address the reader to conference transparencies or to ref. [9].

4. Normalization issues for Monte Carlo programs for $\tau$-lepton pair production at Belle/BaBar energies

In discussions it became obvious that some comments on the overall normalization of KORALB and KKMC predictions for $\tau$-lepton pair production at Belle and BaBar energies is of importance for the present day users.

One has to bear in mind that KORALB was published [12][11] more than twenty years ago. The program was supposed to feature orthodox first order QED corrections and complete mass and spin effects. Such formula turned out to be very useful, and program remains in broad use until
now. On the other hand, some of its inputs are rather outdated and do not match the present day requirements, even for technical tests. To be precise, I have in mind the function $\text{PIRET}(S)$, which features the real part of hadronic vacuum polarization of photon as measured by the data collected until early 80’s. Obviously this function need to be replaced by the more modern one. A possible choice can be the function $\text{REPI}$ of ref. [13] because it has similar functionality as $\text{PIRET}$ of KORALB.

Unfortunately the improvements on FORTRAN function $\text{PIRET}(S)$ describing hadronic vacuum polarization of photon, do not solve all normalization problems of KORALB. It is well known since long, that the genuine one loop corrections are not enough, and the solutions are available. The two major improvements which appeared as a consequence of phenomenology improvements during the LEP era was introduction of higher order QED corrections into Monte Carlo simulations and better way to combine loop corrections with the rest of the field theory calculations. It was found to be safe to sum contributions of loop corrections into photon (and $Z$) propagators. Then, terms of all, but incomplete, orders of perturbation expansion are taken into account. That is why significant effort was needed to justify the approach [13]. At lower energies things are of course simpler, as there is no need to worry about $Z$-lineshape. The KKMC Monte Carlo [17] could thus be a complete solution to B-factory needs and ready to use. This program features higher order QED matrix elements with the help of exclusive exponentiation, and explicit matrix element up to the second order. Unfortunately electroweak library (which include vacuum polarization, the only function interesting for low energy applications) was never adopted to requirements of processes below 13 GeV center-of-mass energies.

To provide reasonably good results, this library needs thus to be overruled (analogously to the function $\text{PIRET}(S)$ of KORALB) by a more suitable one [13]. After small tests the function $\text{REPI}$ of ref. [13] should be suitable (overall normalization constants and other details of conventions need to be checked).

Once this is completed, and if two-loop photon vacuum polarization can be neglected, KORALB and KKMC can form a base for tests and studies of systematic errors for cross section normalizations at low energies. The necessary strategy should be similar to the one for the Bhabha scattering see eg. [18] for description.

For that purpose the following calculations of the total cross section should be performed:

1. KORALB radiative corrections switched off.

2. KKMC, both electroweak corrections and initial state QED bremsstrahlung switched off (final state bremsstrahlung need to be kept on, otherwise spin amplitudes necessary for

\begin{footnote}{In KKMC similar improvements require to overwrite in routine $\text{DZfaceMakeGSW}$ (file $dizet/Dzface.f$) calculation of GSW(6) with the one using function $\text{PIRET}(SS)$ or $\text{REPI}(SS)$. The $\text{PIRET}(SS)$ must be supplemented with the leptonic contribution to vacuum polarization as well. It was checked by S. Banerjee that pretabulation (in contrast of low energy numerical values of KKMC vacuum polarization) is not a problem. To this end he simply increased density of pretabulation points.}

\end{footnote}
calculation of \( \tau \) spin correlations are not calculated and program stops).

3. Radiative corrections switched on in \texttt{KORALB}.

4. Radiative corrections switched on in \texttt{KORALB}. Vacuum polarization switched off with the help of internal key \texttt{IFVAC=0}.

5. \texttt{KKMC}: electroweak corrections on, initial state QED bremsstrahlung switched off.

6. \texttt{KKMC}: electroweak corrections switched off but initial state QED bremsstrahlung switched on.

7. \texttt{KKMC}: both electroweak corrections and initial state QED bremsstrahlung switched on.

The results, we will call them respectively \( \sigma_1 \ldots \sigma_7 \), can be calculated for \( \tau \)- or \( \mu \)-pair production. Also experimental cuts can be applied in the calculation of these cross section. Let us list now some of the possible checks. Of course all calculations being compared must be performed with the same assumptions on experimental cuts and final state flavours.

- \( \sigma_2 \) should be larger by a factor of \( 1 + \frac{3}{4} \alpha \) than \( \sigma_1 \) for all center of mass energies in case no experimental cuts are applied.
- \( \sigma_6 \): the following relation should hold: \( \sigma_3 - \sigma_4 = \sigma_1 2(1 - \sqrt{\frac{s}{s}}) \).
- \( \sigma_7 \): the relation \( \sigma_3 = \sigma_4 \) is not expected to hold precisely. It can hint on numerical importance of convoluting QED bremsstrahlung and vacuum polarization with respect to naive factorization.

If comparisons are repeated with experimental cuts applied, some extra care must be taken, because of cut off dependence of final state bremsstrahlung effects. On the other hand, numerically significant and theoretically ambiguous contributions from events with very low final state lepton pair invariant masses, are removed.

Unfortunately the above points must remain in sketchy form. Full clarification, as LEP experience showed, require significant amount of work.

5. Summary and future possibilities

The status of the computer programs for the decay of \( \tau \) leptons and associated projects was reviewed. The high-precision version of \texttt{PHOTOS} for radiative corrections was presented. In particular, the option to run the program with multiple-photon radiation was mentioned. New results for leptonic decays of \( Z \) and \( B \) meson decays into pair of scalars, were presented. For these channels complete next-to-leading order effects can now be simulated. However, for the most of the applications these effects are not necessary, leaving standard modular version of \texttt{PHOTOS} sufficient. The important result of the above work, is that the path to include electromagnetic form-factors of the particles participating in decay is now open for the future fits to the data. These form-factor effects may be significantly larger and physically more justified, than complete next-to-leading order effects of scalar QED in \( B \) meson decays recently installed.

The presentation of the \texttt{TAUOLA} general-purpose interface was omitted because of lack of time. Examples for its use in the case of the Higgs boson parity measurement at a future Linear Collider \cite{192021} and for Higgs searches at the LHC \cite{22} can be found in the literature. Recently, a similar application was developed for the case of studies in hypothetical effects of CP-parity breaking in the \( B_0-\bar{B}_0 \) system at Belle and BaBar \cite{23}.

Distinct versions of the \texttt{TAUOLA} library for \( \tau \) lepton decay, and of \texttt{PHOTOS} for radiative corrections in decays, are now in use. The principles how to use the distribution package, are presented in refs. \cite{50}.

In the talk we have reviewed the results for the novel decay modes of \texttt{TAUOLA} into five scalars. These modes feature now the hadronic current.

\footnote{In case of \texttt{KORALB} vacuum polarization increase the cross section by \( (2\pi \epsilon_{\gamma,\gamma}(s)) \) times Born cross section. In case of \texttt{KKMC} the vacuum polarization factor \( (1-\epsilon_{\gamma,\gamma}(s))^2 \) appears for all events. In case when initial state bremsstrahlung is switched on, the effective transfer \( s' \) depends on the amount of energy carried out by the initial state radiation convolution with initial state radiation spectrum is formed.}
The simple but realistic current \cite{7} is available for decay modes $2\pi^- \pi^+ 2\pi^0\nu_\tau$, $\pi^- 4\pi^0\nu_\tau$ and $3\pi^- 2\pi^+ \nu_\tau$. Numerical study of the new decay modes helped to formulate comments on the importance of $\Gamma/M$ terms for the intermediate resonances. It is argued that the constructive or destructive interferences appear and that their existence must be taken into account by builders of the future Monte Carlo programs for decays (not necessarily $\tau$ decays).

Finally, presentation of adjustments for \textsc{Koralb} and \textsc{Kkmc} programs in treatment of photonic vacuum polarization was given. It was explained, that without such changes the programs can not be used for discussion of the normalization uncertainty for the $\tau$-lepton pair production cross section at Belle/BaBar energies.

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