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# ON THEORETICAL AND EXPERIMENTAL CONTEXT FOR HIGGS BOSON OBSERVATION AT THE LHC*

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Last year a new particle with the mas of $\sim$ 125 GeV and decaying into $ZZ$, $WW$ and $\gamma\gamma$ pairs was discovered at the LHC. The evidence of the decays to fermions is still to be established. The measurement of its basic properties such as spin, parity, branching ratios are important for validation that the discovered particle is indeed the Standard Model Higgs.

Such observables require not only experimental effort to understand detector performance. Precision evaluation of known physics dynamic for the processes to be measured and their backgrounds is to be completed as well. In the present paper, we will adress a part of this technical subject using as an example some of the activities performed in our theory group in Kraków. As a consequence, we will limit ourselves to simulation tools for the Higgs boson observables involving $\tau$ decays and to effect of QED bremsstrahlung in decays of $W$ and $Z$ bosons important for the background estimations. Discussion of observables for precision measurement of the $W$ boson mass important together with the top-quark and Higgs boson mass for consistency test of the Standard Model, represents complementary subject covered in this presentation.

More specifically, status and applications of $\tau$ lepton decay Monte Carlo generator TAUOLA with its interfaces enabling study of heavy boson spin, will be revieved. Generator PHOTOS for bremsstrahlung in decays will be presented together with its major applications.

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## 1. Introduction

The main purpose of LHC experiments is to search for new elementary particles and interactions. The Higgs-like particle observability papers [1, 2] document a fundamental achievement for this goal. Possible implications of this fact should not be underestimated. One should keep it mind that in the past, relative simple observed phenomena, like change of specific heat of some material at a given temperature [3] required massive research over a century before it was fully understood, within microscopic theory, as the second order phase transition. On the way, completely new world of quantum mechanics was opened and became foundation of the new picture for elementary physics [4].

That is an example which illustrates why, even though expected new particle is discovered, confirmation that it is indeed the Standar Model Higgs require further measurements of its spin, parity and decay branching ratios. Only then, we can become convinced that the new particle is indeed the missing keystone of the Standard Model foundation.

The spin of this newly observed state has recently been discussed [5] in the context of its couplings to a pair of vector bosons. However, from an experimental point of view, the spin property should be investigated channel-by-channel, and other alternative hypotheses should be investigated and excluded. At the HCP'12 conference, the ATLAS [6] and the CMS [7] collaborations reported observed significances of 1.1 $\sigma$ and 1.5 $\sigma$ respectively, for the $H \to \tau^+\tau^-$ decay channel. Their corresponding expected significances are 1.7 $\sigma$ and 2.5 $\sigma$, which when added in quadrature are already at the 3 $\sigma$ level. We still may expect an evidence from RunI LHC data for the $\tau$ channel.

Searches for $H \to \tau^+\tau^-$ decay are challenging because the $\tau$ neutrino's escape detection. Experimental signatures are categorized over multiple channels in terms of observable final state decay products. Data from the multi-channel inputs must be compared with simulation of large samples of Monte Carlo (MC) events, which includes detector resolution and acceptance effects, as well contributions from background events in the selected sample.

The study of $\tau$ polarization can provide additional leverage for this search. The TauSpinner algorithm [8] provides a mechanism to evaluate the polarization effects of $\tau$ spin. The algorithm based on the re-weighting technique, implemented there, can be applied to the existing sample of simulated MC events, thereby reducing the need for computationally intensive simulation of independent samples, and has successfully been applied for measurements of $\tau$ polarization in $W^\pm \to \tau^\pm \nu$ [9] and $Z \to \tau^+\tau^-$ [10] decays.

Another important class of the LHC measurements aims on high-precision consistency tests of the Standard Model. In this respect, a precise measurement of the $W$ mass plays a particularly important role [11]. Combined results of the top quark, Higgs and $W$ mass measurements, provide powerful constraint on the Standard Model dynamics [12]. To reduce systematic errors, improvements in the measurement techniques, particularly for the $W$ mass, are desirable. It is generally believed that higher precision can be achieved thanks to the use, whenever possible, of leptonic degrees of freedom rather than hadronic ones. In this way, the precision better by even an order of magnitude can be expected. At present, the best measurements of $W$ mass have been performed in $p\bar{p}$ collisions at Tevatron [13–15]. In the CDF Collaboration the impressive precision of 19 MeV on the $W$ mass was achieved [13, 14]. At present, the largest contribution from theory to the systematic error originates from parton distribution functions (PDFs) and initial-state hadronic interactions in general.

An approach [16–18] based on measuring the $\phi^*_\eta$ angle, instead of the $Z$ boson transverse momentum ($p_{\mathrm{T}}^Z$) directly, may offer a significant improvement

$$\phi^*_\eta \equiv \tan\frac{\phi_{\mathrm{acop}}}{2}\,\sin\theta^*_\eta\,, \tag{1}$$

where $\phi_{\mathrm{acop}} \equiv \pi - \Delta\phi$, $\Delta\phi$ is the azimuthal opening angle between the two leptons, and the angle $\theta^*_\eta$ is a measure of the scattering angle of the leptons with respect to the proton beam direction in the rest frame of the dilepton system. The angle $\theta^*_\eta$ is defined [17] by $\cos\theta^*_\eta \equiv \tanh[(\eta^- - \eta^+)/2]$, where $\eta^-$ and $\eta^+$ are the pseudorapidities of the negatively and positively charged lepton, respectively.

The observable $\phi^*_\eta$ is expected to be less sensitive to experimental resolution and it can probe largely the same physics as $p_{\mathrm{T}}^Z$ for small $p_{\mathrm{T}}^Z$ or $\phi^*_\eta$. The theoretical calculations for the $\phi^*_\eta$ are documented in Refs. [20, 21]. The first experimental measurement of the $\phi^*_\eta$ by the DØCollaboration [22] demonstrated that the order of magnitude improvements in experimental precision could be achieved with the $\phi^*_\eta$ technique. The $\phi^*_\eta$ was then employed by the ATLAS and LHCb experiments in recent publications [19, 23]. The first measurement of the normalized $\phi^*_\eta$ distribution at $\sqrt{s} = 7$ TeV $pp$ collisions performed by the ATLAS experiment, is very likely one of the most precise measurement at the LHC, to date, with the total uncertainty at the level of 0.5–0.8%.

In that experimental publication, the systematic error of 0.3% to $\phi^*_\eta$ due to implementation of QED final state radiation (FSR) in the Monte Carlo generators used, was estimated in proportion of differences observed between PHOTOS [24–26] and Sherpa [27] predictions. If one understands the pattern of these differences better, one can hopefully reduce systematic errors even further.

Let us now review some of the tools used in these data analyzes and in estimation of the systematic errors. For more details on the systematic error estimations for those tools, let us point to the recent efforts documented in Refs. [28, 29].

Our presentation is organized as follows: Section 2 is devoted to general introduction to the TAUOLA and PHOTOS projects. Section 3 is devoted to the discussion of optional weights in TAUOLA and their use for fits to experimental data. In Section 4 we concentrate on PHOTOS Monte Carlo for radiative corrections in decays. Section 5 is devoted to new interfaces of TAUOLA and PHOTOS based on HepMC and written in C++. Work on interface to genuine weak corrections, transverse spin effects and new tests and implementation of bremsstrahlung kernels will be presented as well. Section 6, Summary, closes this presentation.

## 2. Monte Carlo programs and algorithms

The TAUOLA package [30–33] for simulation of $\tau$-lepton decays and PHOTOS [24, 26, 34] for simulation of QED radiative corrections in decays are computing projects with a rather long history. Written and maintained by well-defined (main) authors, they nonetheless migrated into a variety of applications where they became ingredients of complicated simulation chains. As a consequence, a large number of different versions are presently in use. These modifications, especially in the case of TAUOLA, are valuable from the physics point of view, even though they are often not ported back to the distributed versions of the program. From the algorithmic point of view, versions may differ only in details, but they incorporate many physics results from distinct $\tau$-lepton measurements or phenomenological projects. Such specific versions were mainly maintained (and will remain so) by the experiments taking precision data on $\tau$ leptons. Interesting from the physics point of view changes are still developed in FORTRAN. That is why, for convenience of such partners, part of the TAUOLA should still remain in FORTRAN for a few forthcoming years.

Many new applications were developed in C++, often requiring an additional program interface to other packages (*e.g.*, for generating events for LHC, LC, Belle or BaBar physics processes). For the manipulation of matrix element, techniques of re-weighting events were further developed. This required attention on numerical stability issues.

The program structure did not change significantly since $\tau$ conference [35] of 2010. Let us concentrate then on physics extentions and novel applications, also with respect to status documented in [36]. Here, we will only mention the work on new hadronic currents based on the Resonance Chiral approach. This topic was covered in talks of the $\tau$-lepton conference [37–39]. Important results are already obtained, but sufficiently good agreement with the experimental data is not yet achieved. New currents are not so far integrated into main distribution tar-balls for FORTRAN and C++ applications. Analyses of high precision, high-statistics data from Belle and BaBar are expected to profit from these solutions. Other aspects of the project such as interfaces for applications based on HepMC [40] event record or new tests and weighting algorithms for spin effects in production processes should be mentioned as well. In this context, numerical stability of solutions used in re-weighting events stored in datafiles is of importance.

### *2.1.* PHOTOS

Already in the era of data analysis of LEP experiments simulation of bremsstrahlung in decays of resonances and particles required specialized tools. In parallel to programs oriented towards highest possible overall precision for the whole processes in $e^+e^-$ collisions such as kkmc [41] or Koralz [42], programs dealing with decays only, gradually became of a broad use. The PHOTOS Monte Carlo was one of such applications [34, 43]. Naturally, comparisons with these high precision generators became parts of test-beds for PHOTOS package.

The principle of PHOTOS algorithm is to replace, on the basis of well defined rules, the decay vertex embedded in the event record such as HEPEVT [44] or HepMC [40] with the new one, where additional photons are added. Such solution, initially not aimed for high precision simulations, turned out to be very effective and precise as well. Phase space parameterization was carefully documented in [51]. Gradually for selected decays [25, 50–52], also exact matrix elements were implemented and could be activated in place of universal kernels[1]. Originally [34], only single photon radiation was possible and approximations in the universal kernel were present even in the soft photon region. With time, multiphoton radiation was introduced [24] and then installation of exact first order matrix elements in $W$ and $Z$ decays became available with C++ implementation of PHOTOS [49]. The algorithm of PHOTOS is constructed in such a way, that the same function, but with different input kinematical variables, is used if the single photon emission or full multiphoton emission is requested. Such an arrangement enables tests in a rigorous first order emission environment. For multiphoton emission, the same kernel is used iteratively, thanks to the factorization properties. Technical checks are thus spared. Optimal solution for the iteration was chosen and verified with alternative calculations [45, 46] based on the second order matrix element. It was later extended to the multiphoton case for $Z$ decays in Ref. [25]. Numerical tests of that paper, for distributions of generic kinematical observables pointed to the theoretical precision for the simulation of photon bremsstrahlung of the 0.1% level.

[1] Prior to introduction of the C++ interface matrix element kernels were available for our test only. They require more detailed information from the event record which was available from PHOTOS interface in FORTRAN.

## 3. Approach of Resonance Chiral Lagrangians and TAUOLA Monte Carlo

In Refs. [37–39] of the conference, Resonance Chiral Lagrangian approach was used for calculations of new hadronic currents to be installed in TAUOLA. That is why, we do not need to repeat its description here. In Ref. [47] implementation of those currents is documented in a great detail.

Physics of $\tau$ lepton decays requires sophisticated strategies for the confrontation of phenomenological models with experimental data. On the one hand, high-statistics experimental samples are collected, and the obtained precision is high, on the other hand, there is a significant cross-contamination between distinct $\tau$ decay channels. Starting from a certain precision level all channels need to be analyzed simultaneously. Change of parameterization for one channel contributing to the background to another one may be important for the fit of its currents. This situation leads to a complex configuration where a multitude of parameters (and models) needs to be simultaneously confronted with a multitude of observables. One has to keep in mind that the models used to obtain distributions in the fits may require refinements or even substantial rebuilds as a consequence of comparison with the data. The topic was covered in detail in the $\tau$ section of Ref. [48]. At present, our comparison with the data still does not require such refined methods.

We enable calculation of alternative weights for each generated event (separately for decay of $\tau^+$ and/or $\tau^-$); the ratios of the matrix element squared obtained with new currents, and the one actually used in generation. Then, the vector of such weights can be prepared and used in new current parameter fits. We have checked that such a solution not only can be easily installed into TAUOLA as a stand-alone generator, but it can also be incorporated into the simulation frameworks of Belle and BaBar collaborations. The weights can be calculated after the simulation of detector response is completed. Only then choice of parameters for the hadronic currents has to be performed and the fits completed. This idea was also behind the TauSpinner project for LHC applications, described in Section 5.

## 4. PHOTOS Monte Carlo for bremsstrahlung and its systematic uncertainties

Thanks to exponentiation properties and factorization, the bulk of the final state QED bremsstrahlung can be described in a universal way. However, the kinematic configurations caused by QED bremsstrahlung are affecting in an important way signal/background separation. It may affect selection criteria and background contaminations in quite complex and unexpected ways. In many applications, not only in $\tau$ decays, such bremsstrahlung corrections are generated with the help of the PHOTOS Monte Carlo. That is why it is of importance to review the precision of this program as documented in Refs. [24, 26, 34]. For the C++ applications, the version of the program is available now. It is documented in Ref. [49].

In C++ applications, the complete first-order matrix elements for the two-body decays of the $Z$-boson [25] and $W$-boson [50] decays into a lepton pair are now available. Kernels with complete matrix elements, for the decays of scalar $B$ mesons into a pair of scalars [51], are available for the C++ users as well. For $K \to l\nu\pi$ and for $\gamma^* \to \pi^+\pi^-$ decays [50, 52] matrix element based kernels are still available for tests only. Properly oriented reference frames are needed in those cases. It will be rather easy to integrate those NLO kernels into the main version of the program, because of better control on the decay particle rest frame than in the FORTRAN interface.

In all of these cases, the universal kernel of PHOTOS is replaced with the one matching an exact first-order matrix element. In this way, terms necessary for the NLO/NLL precision level are implemented[2]. A discussion relevant for control of program systematic uncertainty in $\tau \to \pi\nu$ decay can be found in Ref. [54].

The algorithm covers the full multiphoton phase-space and becomes exact in the soft limit. This is rather unusual for NLL compatible algorithms. One should not forget that PHOTOS generates weight-one events, and does not exploit any phase space ordering. There is a full phase space overlap between the one where a hard matrix element is used and the one for iterated photon emission. All interference effects (between consecutive emissions and emissions from distinct charged lines) are implemented with the help of internal weights.

The results of all tests of PHOTOS with a NLO kernels confirm sub-permille precision level. This is very encouraging, and points to the possible extension of the approach outside of QED (scalar QED). In particular, to the domain of QCD or to QED when phenomenological form factors for interactions of photons need to be used. For that work to be completed, spin amplitudes need to be studied. Let us point to Ref. [55] as an example of such work.

New tests of PHOTOS are available from Ref. [56]. In those tests, in particular, results from the second-order matrix element calculations embedded in KKMC [41] Monte Carlo are used in the case of $Z$ decay. Results for comparisons in the case of $W$ decays, with electroweak calculations of Refs. [57, 58], are shown there.

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[2] Note that here the LL (NLL) denotes collinear logarithms (or in the case of differential predictions terms integrating into such logarithms). The logarithms of soft singularities are taken into account to all orders. This is resulting from mechanisms of exclusive exponentiation [53] of QED. The algorithm used in PHOTOS Monte Carlo is compatible with exclusive exponentiation. Note that our LL/NLL precision level would even read as respectively NLL/NNNLL level in some naming conventions of QCD.

## 5. TAUOLA universal interface and PHOTOS interface in C++

In the development of packages such as TAUOLA or PHOTOS, questions of tests and appropriate relations to users' applications are essential for their usefulness. In fact, user applications may be much larger in size and human efforts than the programs discussed here. Good example of such 'user applications' are complete environments to simulate physics process and control detector response at the same time. Distributions of final state particles are not always of direct interest. Often properties of intermediate states, such as a spin state of $\tau$-lepton, coupling constants or masses of intermediate heavy particles are of prime interest. As a consequence, it is useful that such intermediate state properties are under direct control of the experimental user and can be manipulated to understand detector responses. Our programs worked well with FORTRAN applications where HEPEVT event record is used. For the C++ HepMC [40] case, interfaces were rewritten, both for TAUOLA [59] and for PHOTOS [49]. The interfaces and, as a consequence, the programs themselves were enriched; for PHOTOS new matrix element kernels are available; for TAUOLA interface, a complete (not longitudinal only) spin correlations are available for $Z/\gamma^*$ decay. Electroweak corrections taken from Refs. [57, 58] are also used. For the scheme of programs communications, see Fig. 1. In this spirit, an algorithm of TauSpinner [8] to study detector sensitivity to spin effects in $Z, W$ and $H$ decays, was developed. Recently, TauSpinner was enriched [60] with the option to study effects of New Physics, such as effects of spin-2 states in $\tau^+\tau^-$ pairs produced at the LHC. Modular organization opens ways for further efficient algorithms to understand detector systematics, but at the same time responsibility to

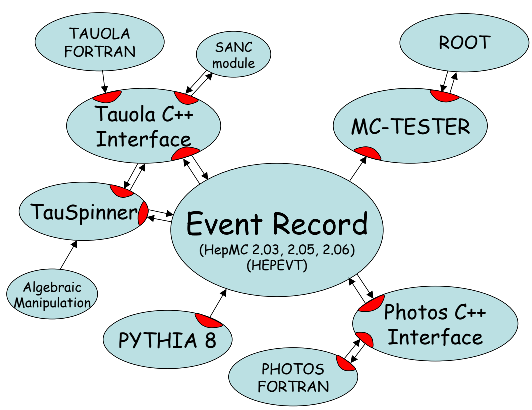


Fig. 1. Scheme of the Monte Carlo simulation system with communication based on event record. Each segment feature contribution from different people, may be coded in distinct programinng language and/or be developped with the help of algebraic manipulation systems.

control software precision must be shared by the user. Automated tests of MC-Tester were prepared [61] to help in this process. New functionalities were also introduced into the testing package [62]. In particular, it works now with the HepMC event record, the standard of C++ programs, spectrum of available tests is enriched and events stored on datafiles are easier to test.

The program is available through the LHC Computing Grid (LCG) Project. See GENSER webpage, Ref. [63], for details. This is also the case for TAUOLA C++ and for PHOTOS C++ codes. The FORTRAN predecessors are available in this framework as well.

## 6. Summary and future possibilities

We have started with presentation of motivation and some technical challenges behind discovery of a new particle at LHC, expected to be the Higgs boson — the keystone of the Standard Model foundation, and of measurements of its main properties. Instead of entering into this broad spectrum of subjects, we have concentrated on some specific tools and techniques which were used in this complex effort. As an example, for TauSpinner use, measurement of the Higgs spin and spin of $W$ transmitted into decays of $\tau$s was mentioned. Also generator for QED radiative corrections PHOTOS was presented. It is used in experiments for evaluation of theoretical systematic error in the measurement of $W$ mass; directly, for the reconstruction of the final state leptons and for the $\phi^*_\eta$ angle.

Later, recent development for these packages themselves was reviewed. Versions of the hadronic currents, available for the TAUOLA library until now, are all based on old models and experimental data of 90s. The implementation of new currents, based on the Resonance Chiral Lagrangian approach, is now under preparation and tests from the technical side. Methods for efficient confrontation with the experimental data are prepared as well. Once comparison with Belle and BaBar data is successfully completed, new parameterizations will be straightforward for use in a spectrum of applications in FORTRAN or C++ environments.

The status of associated projects: TAUOLA universal interface and MC-TESTER was reviewed. Also the high-precision version of PHOTOS for radiative corrections in decays was presented. All these programs are available now for C++ applications thanks to the HepMC interfaces.

New results for PHOTOS were discussed. For the leptonic $Z$ and $W$ decays, the complete effects of next-to-leading collinear logarithms can now be simulated in C++ applications. However, in most cases these effects are not important, leaving the standard version sufficient. Thanks to this work the path for fits to the data of electromagnetic form factors is opened [52], *e.g.* in the case of $K_{l3}$ decays.

The presentation of the TAUOLA general-purpose interface in C++ was given. It is more refined than the FORTRAN predecessor. Electroweak corrections can be used in calculation of complete spin correlations in $Z/\gamma^*$ mediated processes. An algorithm for study of detector responses to spin effects in $Z$, $W$ and $H$ decays was shown.

These projects rely on effort of several people over many years working on rather diverse topics. Nonetheless, by comparison, they represent rather minor contribution to the common challenge behind the LHC community. This example, hopefully could hint to the scale and complexity of the overall LHC effort, possibly one of the largest projects in the history of the whole science and not only the high energy physics alone.

Presented results, which were found to be useful in LHC applications, illustrate the status of the projects performed in collaboration with Swagato Banerjee, Zofia Czyczula, Nadia Davidson, Jan Kalinowski, Wojciech Kotlarski Tomasz Przedziński, Olga Shekhovtsova, Elżbieta Richter-Wąs, Pablo Roig, Jakub Zaremba, Qingjun Xu and others. The work is supported in part by the Polish National Centre of Science Grants No. DEC-2011/03/B/ST2/00220 and DEC-2011/03/B/ST2/00107,

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