# The Monte Carlo Program KKMC, for the Lepton or Quark Pair Production at LEP/SLC Energies – updates of electroweak calculations

A. Arbuzov<sup>a</sup>, S. Jadach<sup>b</sup>, Z. Wąs<sup>b</sup>, B.F.L. Ward<sup>c</sup> and S.A. Yost,<sup>d</sup>

<sup>a</sup>Joint Institute for Nuclear Research, Joliot-Curie str. 6, 141980, Dubna, Russia <sup>b</sup>Institute of Nuclear Physics, Polish Academy of Sciences, ul. Radzikowskiego 152, 31-342 Kraków, Poland

<sup>c</sup>Department of Physics, Baylor University, Waco, TX 76798-7316, USA <sup>d</sup> The Citadel. Charleston. SC. USA

#### ABSTRACT

Since the KKMC program was published for the first time over 20 years ago, it has gained popularity and was exploited in a broad spectrum of applications. The core part of the program itself did not change much. In contrast, some of the libraries have evolved substantially.

The aim of this publication is to archive four versions, alternative to the one published 20 years ago versions of the electroweak libraries (or just parameter initialization versions), which were instrumental for the precision Standard Model calculation from the end of LEP era till now and for the sake of the future applications/comparisons for the future electron-positron colliders, in particular for the FCC-ee related studies. These electroweak libraries are useful for the hadron collider applications as well, for instance for KKMC-hh or TauSpinner projects.

To be submitted to Computer Physics Communications

### IFJPAN-IV-2020-05, BU-HEPP-20-01 May 2020

<sup>&</sup>lt;sup>†</sup> This work is partly supported by the Polish National Science Center grant 2016/23/B/ST2/03927, under decisions DEC-2017/27/B/ST2/01391 and the CERN FCC Design Study Programme.

## UPDATE SUMMARY

Title of the program: KKMC .

Reference to original program: Comput. Phys. Commun. **130** (2000) 260 Authors of original program: S. Jadach, B.F.L. Ward and Z. Wąs Operating system: LINUX Programming language used: FORTRAN 77 High-speed storage required: < 1 MB No. of bits in a word: 32, 64 Peripherals used: Line printer Keywords: Radiative corrections, heavy lepton  $\tau$ , Monte Carlo simulation, quantum electrodynamics, spin polarization, electroweak theory, anomalous couplings.

Nature of the physical problem: Spin polarization of the  $\tau$  in the process  $e^+e^- \rightarrow \tau^+\tau^-(n\gamma)$ ,  $\tau^{\pm} \rightarrow X^{\pm}$  is used as an important data point for precise tests of the standard electroweak theory. The effects due to QED bremsstrahlung and apparatus efficiency have to be subtracted from the data. The program applies, as well, to the muon and neutrino pair production processes. It can simulate also the electron positron annihilation into u, d, s, c, b quark pairs. An important segment of the calculations rely on electroweak loop effects provided by the appropriate program library.

Method of solution: The Monte Carlo simulation of the combined  $\tau$  production and decay process is used to calculate the spin effects and effects of radiative corrections, including hard bremsstrahlung, simultaneously. Any experimental cut and apparatus efficiency may easily be introduced by rejecting some of the generated events. Electroweak effects are provided with an external library with the help of disk stored lookup tables.

Restrictions on the complexity of the problem: The high precision of the program is assured in the region near the Z resonance. For other energy ranges it varies. At low energies predictions from electroweak libraries need to be replaced with an appropriate dedicated code.

We document variants of electroweak libraries introduced over the years since KKMC was published [1] leaving other changes to further publications. The distribution package provided now corresponds to KKMC version 4.16 and its physics content is documented in Ref. [2]. Details other than the electroweak details of this version are not addressed, they do not differ much from those of Ref. [1].

S. Jadach, B.F.L. Ward and Z. Was, Comput. Phys. Commun. **130** (2000), 260-325
 S. Jadach, B.F.L. Ward and Z. Was, Phys. Rev. D **63** (2001), 113009

The KKMC Monte Carlo [1] is designed to simulate two fermion production process in the electron-positron colliders,  $e^+e^- \rightarrow 2f n\gamma$ ,  $(f = \mu, \tau, u, d, c, s, b, \nu, f \neq e)$ . It is armed with the most advanced QED matrix element based on the coherent exclusive exponentiation (CEEX) of the initial and final state bremsstrahlung, valid up to the highest FCC-ee energies [2,3].

The detailed description of how to use the KKMC Monte Carlo program can be found in Ref. [1], The physics content of the version 4.16 which we will use in the present paper as a reference is explained in Ref. [3]. For further details see references therein and KKMC webpage [4], where up to date envelopment versions of KKMC can also be found. For novel applications and for further references see e.g. Ref. [5].

The differences of the new KKMC program versions, with respect to the published ones, are not big – the structure of the program and user interface have not changed. In particular the methodology of interfacing electroweak corrections calculation to the core KKMC code still follows the prescription given in Ref. [1].

Now, when the FCC effort takes momentum, it is a good time to archive the KKMC program, its cross-checks and documentation, for the future references. The important first step in this direction is the proper archiving of the variants of electroweak libraries used in KKMC program over the past two decades and at present. Let us keep in mind that the recently developed offspring program KKMC-hh [6] for Z production in hadron collider applications also uses the same electroweak (EW) libraries. In addition, TauSpinner of ref. [7] exploits EW results obtained from the EW libraries update presented here. The present paper may be treated as an appendix to [1] rather than as an independent publication.

Already nowadays, work on experimental tests of Standard Model in ATLAS turned out to pose some challenges for proper adjustment of electroweak software and to conventions of LEP 1 and LEP 2 times [8]. This experience contributes also to our motivation. This may be even more important in the future, when expertise of people involved in LEP efforts will be less available than now.

In the following, a minimal information on the content of the upgrade will be provided.

#### **Electroweak libraries**

The electroweak library DIZET version 6.21 [9,10] was installed in the KKMC from the very beginning in versions of Refs. [1,3]. Since then the KKMC code includes WW and ZZ boxes and other non-QED corrections such as top loop/vertex corrections important for precision predictions. The basics of the original DIZET interface did not require modifications and is the same until the present days<sup>1</sup>.

Luckily, the pretabulation procedure (interface) of the electroweak form factors, that is in the form of the lookup tables in the disk files, used in KKMC offers an easy way for the upgrades with the newer versions of the DIZET library. In the KKMC program these lookup tables can be also optionally produced in flight, instead of being stored in text disk files. However, for the sake of archivization, the version with lookup tables on the disk is included in the present distribution because it demonstrates manifestly how well

<sup>&</sup>lt;sup>1</sup>Note however that the interface of the DIZET library to the function calculating the contribution of low energy  $e^+e^- \rightarrow hadrons$  data varies between version 6.21 and later versions.

the EW library is independent from the rest of the MC code and also has some practical advantages – the electroweak initialization can be more easily adjusted locally for each electroweak library variant.

Using the pretabulating algorithm for the DIZET version 6.21 of Ref. [1] the presented distribution package includes KKMC version 4.16d compatible with Ref. [1] and several versions of the DIZET library:

- 1. Version 6.21 with updated input parameters, directory dizet-6.21. A thorough verification of the implementation DIZET 6.21 into KKMC was performed in Ref. [11].
- 2. Version 6.42 [12] used at the time when final LEP data was analyzed, directory dizet-6.42-cpc. This code was published with the version of hadronic contribution to virtual photon vacuum polarization [13], obsolete already at that publication time. However, its importance is that it is the last published version of the code and could be useful to reproduce some old published benchmarks [1,11].
- 3. Version 6.42 with the updated vacuum polarization of Ref. [14], directory dizet-6.42.
- 4. Version 6.45 of Ref. [15], directory dizet-6.45.

It should be stressed that each variant of the DIZET library includes a specific variant for the dizet-xxx/input.data file, which redefines a few default input parameters defined in the .KK2f\_defaults file<sup>2</sup>. Version specific parameters in the .KK2f\_defaults of KKMC are for version 6.21, but constants like masses the of Z boson, Higgs boson and top quark, masses of other fermions and the QCD coupling constant are already updated to the present PDG values<sup>3</sup>.

At the lower energies, e.g. those of Belle-II it is required that the EW calculations are replaced by the fine tuned prediction for the photon vacuum polarization. Related issues are covered in the work of Ref. [16], being the most up to date version of the public archivization. It is not integrated into presented upgrade, as this is mainly targeting the needs of future high energy projects, while Belle-II is an on-going project.

Note that the SANC project [17,18] is now the vigorous continuation of the DIZET and ZFITTER project.

### How to install and run

The main directory (Dizet\_Upgrades\_in\_KKMC4.16) in the distribution tarball includes the KKMC-v.4.16e directory and next to it the directories dizet-6.21, dizet-6.42, dizet-6.42-cpc and dizet-6.45.

The KKMC program version 4.16 does not differ much from the version 4.13 published in Ref. [1]. Version 4.13 is the one that was used during the LEP workshop 1999/2000, see Ref. [11]. It corresponds also closely to documentation of the physics content of KKMC in Ref. [3] and to Ref. [3].

 $<sup>^{2}</sup>$ In case of the use of predefined EW lookup tables, these redefinitions have to be repeated one more time in the user input file of KKMC used for the Monte Carlo generation run.

<sup>&</sup>lt;sup>3</sup>The original version is kept for the record as .KK2f\_defaults-2000.

The KKMC-v.4.16e directory does not include subdirectory dizet. It is now placed outside and renamed as dizet-6.21. It is the original EW library DIZET version 6.21 published in Refs. [9,10] and present in the code of Ref. [1]. (For input parameter initialization see below). The other three newer versions of DIZET, dizet-6.42, dizet-6.42-cpc and dizet-6.45. are also placed not directly inside the KKMC-v.4.16e directory but outside, next to it.

The source codes of all four DIZET directories do not require any new documentation, because the description given in [1] for interfacing the EW correction into the matrix element of KKMC and of the methodology of the use of the lookup tables of the EW formfactors in KKMC remains valid for all the above new EW directories.

The appropriate interface subprograms creating EW lookup tables are executed inside each of the above listed directories of the choice. The interface subprograms TabMain.f and DZface.f are compiled and executed independently of the main KKMC program. The only connection with the main KKMC source code is that they read physics input parameters and other configuration parameters from the default input data of KKMC encoded in the file .KK2f\_defaults. The header file BornV.h which defines the range and density of the lookup tables must be identical in the interface programs creating tables in a given DIZET directory and in the bornv subdirectory of the KKMC-v.4.16e directory, otherwise KKMC will stop and print a message.

Switching form one EW library to another is described below. For a given EW library one should create EW tables locally by means of executing the make table.all command in the directory of the relevant EW library.

Let us explain carefully the structure of the input parameters. First of all, TabMain.f reads default data and parameters from the KKMC-v.4.16e/.KK2f\_defaults file of the KKMC. The values of the physics constants like masses of particles are updated in this file to present PDG values. In case the user would like to check backward compatibility with old benchmarks we also keep the original version as .KK2f\_defaults-2000. Next TabMain.f reads the local dizet-x.yy/input.all file and input data in this file overwrites the default values taken from .KK2f\_defaults. The main purpose of dizet-x.yy/input.all is to adjust steering parameters specific for a given version of DIZET and following the preferences of the user. Tables on the disk are created with the input data from global .KK2f\_defaults and local input.all take preference.

Once EW look-up tables are created, then a simple benchmark run of KKMC in the KKMC-v.4.16e/ffbench/ can be executed following instructions in

the KKMC-v.4.16e/ffbench/HowToStart file. Note that in the Monte Carlo run using lookup tables KKMC will read one more time the .KK2f\_defaults file and possibly some user input data in the work directory of the MC run. It is the user's responsibility to take care that the above user input data of the MC run are compatible, or even identical, with input data used during the creation of the lookup EW tables<sup>4</sup>.

In order to facilitate switching quickly from one EW library to another, we have automatized it adding extra functionality to KKMC-v.4.16e/ffbench/Makefile. For example staying in the ffbench directory while executing the command make link-dizet-6.45

 $<sup>^4</sup>$  KKMC will try to detect mismatch of the input data in pretabulation and in the MC run, but this is not a completely foolproof procedure.

creates convenient *soft links* to ../dizet-6.45 directory and executing next make EWtables will create new EW lookup tables. Similar commands like make link-dizet-6.21 are available. In the above scenario switching from one to another EW library is fast and easy. Summarizing, after unpacking Dizet\_Upgrades\_for\_KKMC4.16.tgz, the interested user may execute the following set of commands in order to check the integrity of the provided source code:

cd	KKMC-v.4.16e/ffbench/	
make	link-dizet-6.45	creating soft links
make	makflag	updating compiler flags everywhere
make	EWtables	creating EW lookup tables
make	demo-start	running short MC run

In case of switching to another library, for example with make link-dizet-6.21, one should do make Clean and repeat the above sequence of commands one more time.

Finally, there is also an available option in KKMC, of the *in flight initialization* of the EW lookup tables, placing them directly in the fortran common blocks, without storing them in the disk files<sup>5</sup>. In this case input data and parameters in input.all are ignored, hence the user may not worry about possible mismatch between input used during table creation phase and their use in the MC generation run (or some other application using them). All input parameters are taken from .KK2f\_defaults and are corrected/updated by the user input of the actual MC run, which obviously must fit the type of the EW library actually being used. This option is more convenient for the KKMC user who is using all the time just one EW library. The in flight creation of EW tables takes only a few seconds of CPU time.

## Acknowledgments

We acknowledge work of E. Richter-Was which was important for the completion of the present work. We would like to thank all authors of libraries used in the program for their cooperation and support, especially the authors of DIZET. This work is partly supported by the Polish National Science Center grant 2016/23/B/ST2/03927, under decisions DEC-2017/27/B/ST2/01391 and the CERN FCC Design Study Programme. A. Arbuzov is grateful for support to the RFBR grant 20-02-00441.

# References

- [1] S. Jadach, B. F. L. Ward, Z. Was, The Precision Monte Carlo event generator KK for two fermion final states in  $e^+e^-$  collisions, Comput. Phys. Commun. 130 (2000) 260-325 (2000). arXiv:hep-ph/9912214, doi:10.1016/S0010-4655(00)00048-5.
- [2] S. Jadach, B. F. L. Ward, Z. Was, Coherent exclusive exponentiation CEEX: The Case of the resonant e<sup>+</sup>e<sup>-</sup> collision, Phys. Lett. B449 (1999) 97–108 (1999). arXiv: hep-ph/9905453, doi:10.1016/S0370-2693(99)00038-6.

<sup>&</sup>lt;sup>5</sup>The in flight creation of EW tables (without 'make EWtable') for the use in KKMC can be activated very easily, by means of uncommenting  $EXT_LIBRARYd$  in the ffbench/Makefile.

- [3] S. Jadach, B. F. L. Ward, Z. Was, Coherent exclusive exponentiation for precision Monte Carlo calculations, Phys. Rev. D63 (2001) 113009 (2001). arXiv:hep-ph/ 0006359, doi:10.1103/PhysRevD.63.113009.
- [4] S. Jadach, KKMC webpage, http://jadach.web.cern.ch/jadach/.
- [5] B. F. L. Ward, S. Jadach, Z. Was, S. Yost, A Precision Event Generator for EW Radiative Corrections in Hadron Scattering: *KK*-hh, PoS ICHEP2018 (2019) 189 (2019). arXiv:1811.09509, doi:10.22323/1.340.0189.
- [6] S. Jadach, B. F. L. Ward, Z. Was, S. Yost, KK MC-hh: Resumed exact O(α<sup>2</sup>L) EW corrections in a hadronic MC event generator, Phys. Rev. D 94 (7) (2016) 074006 (2016). arXiv:1608.01260, doi:10.1103/PhysRevD.94.074006.
- [7] E. Richter-Was, Z. Was, Documentation of *TauSpinner* approach for electroweak corrections in LHC  $Z \rightarrow \ell \ell$  observables, Eur. Phys. J. C 79 (6) (2019) 480 (2019). arXiv:1808.08616, doi:10.1140/epjc/s10052-019-6987-x.
- [8] Measurement of the effective leptonic weak mixing angle using electron and muon pairs from Z-boson decay in the ATLAS experiment at  $\sqrt{s} = 8$  TeV, Tech. Rep. ATLAS-CONF-2018-037, CERN, Geneva (Jul 2018). URL https://cds.cern.ch/record/2630340
- [9] D. Y. Bardin, M. S. Bilenky, T. Riemann, M. Sachwitz, H. Vogt, P. C. Christova, DIZET: A program package for the calculation of electroweak one loop corrections for the process e<sup>+</sup>e<sup>-</sup> → f<sup>+</sup>f<sup>-</sup> around the Z<sup>0</sup> peak, Comput. Phys. Commun. 59 (1990) 303–312 (1990). doi:10.1016/0010-4655(90)90179-5.
- [10] D. Yu. Bardin, P. Christova, M. Jack, L. Kalinovskaya, A. Olchevski, S. Riemann, T. Riemann, ZFITTER v.6.21: A Semianalytical program for fermion pair production in e<sup>+</sup>e<sup>-</sup> annihilation, Comput. Phys. Commun. 133 (2001) 229–395 (2001). arXiv: hep-ph/9908433, doi:10.1016/S0010-4655(00)00152-1.
- M. Kobel, et al., Two-Fermion Production in Electron-Positron Collisions, in: Proceedings, Monte Carlo Workshop: Report of the working groups on precision calculation for LEP-2 physics: CERN, Geneva, Switzerland, March 12-13, June 25-26, October 12-13 Oct 1999, 2000 (2000). arXiv:hep-ph/0007180, doi:10.5170/CERN-2000-009.269.
  URL http://weblib.cern.ch/abstract?CERN-2000-09-D
- [12] A. Arbuzov, M. Awramik, M. Czakon, A. Freitas, M. Grunewald, K. Monig, S. Riemann, T. Riemann, ZFITTER: A Semi-analytical program for fermion pair production in e+ e- annihilation, from version 6.21 to version 6.42, Comput. Phys. Commun. 174 (2006) 728-758 (2006). arXiv:hep-ph/0507146, doi:10.1016/j.cpc.2005.12. 009.

- [13] S. Eidelman, F. Jegerlehner, Hadronic contributions to g-2 of the leptons and to the effective fine structure constant alpha (M(z)\*\*2), Z. Phys. C 67 (1995) 585-602 (1995). arXiv:hep-ph/9502298, doi:10.1007/BF01553984.
- [14] F. Jegerlehner, Variations on Photon Vacuum Polarization, EPJ Web Conf. 218 (2019) 01003 (2019). arXiv:1711.06089, doi:10.1051/epjconf/201921801003.
- [15] Version 6.45 of DIZET [10], to be documented in the CERN Yellow Report on fitting  $\sin^2 \theta_W^{eff}$  at LHC, 2020.
- [16] S. Banerjee, B. Pietrzyk, J. Roney, Z. Was, Tau and muon pair production crosssections in electron-positron annihilations at  $s^{1/2} = 10.58$  GeV, Phys. Rev. D 77 (2008) 054012 (2008). arXiv:0706.3235, doi:10.1103/PhysRevD.77.054012.
- [17] A. Andonov, A. Arbuzov, D. Bardin, S. Bondarenko, P. Christova, L. Kalinovskaya, G. Nanava, W. von Schlippe, SANCscope v.1.00, Comput. Phys. Commun. 174 (2006) 481–517, [Erratum: Comput.Phys.Commun. 177, 623–624 (2007)] (2006).
  arXiv:hep-ph/0411186, doi:10.1016/j.cpc.2005.12.006.
- [18] SANC Project, "Support of Analytical an Numeric Calculations for Experiments at Colliders", http://sanc.jinr.ru, 2020.