

PHOTOS Interface in C++

Technical and Physics Documentation

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Abstract

For five years now, PHOTOS Monte Carlo for bremsstrahlung in the decay of particles and resonances has been available with an interface to the C++ HepMC event record. The main purpose of the present paper is to document the technical aspects of the PHOTOS Monte Carlo installation and present version use. A multitude of test results and examples are distributed together with the program code.

The PHOTOS C++ physics precision is better than its FORTRAN predecessor and more convenient steering options are also available. An algorithm for the event record interface necessary for process dependent photon emission kernel is implemented. It is used in Z and W decays for kernels of complete first order matrix elements of the decays. Additional emission of final state lepton pairs is also available.

Physics assumptions used in the program and properties of the solution are reviewed. In particular, it is explained how the second order matrix elements were used in design and validation of the program iteration procedure. Also, it is explained that the phase space parameterization used in the program is exact.

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1 Introduction

For a long time, PHOTOS Monte Carlo [1, 2] has been used for the generation of bremsstrahlung in the decay of particles and resonances. Over the years the program has acquired popularity and it evolved into a high precision tool [3]. Since 2005, when multi-photon radiation was introduced [4] into the program (version 2.15), there were no further public upgrades of the program until 2010. The efforts were concentrated on documentation and new tests; phase space treatment was shown to be exact [5] and for several processes [3, 5, 6] an exact matrix element was studied with the help of optional weights. Benchmark distributions, including comparisons with other simulation programs, were collected on the MC-TESTER [7] (special program devoted to tests) web page [8]².

Such high precision applications require good control of the event record content on which PHOTOS operates. On one side it requests skills and experience of the user and on the other it provides the flexibility necessary for the study of effects like, for example, systematic errors for measurements of anomalous couplings or W cross section. Methods of correlated samples can be applied³.

Until 2010 the HEPEVT [11] event record was used as the structure for communication between physics Monte Carlo programs and detector/reconstruction packages. Experimental physicists used HEPEVT for their own applications as well. Later, to gain flexibility, FORTRAN was replaced by C++ and instead of HEPEVT, the C++ event structure HepMC [12] was used. Nothing prevented moving PHOTOS to a C++ environment, allowing the use of event records such as HepMC, and to rewrite the whole of PHOTOS to C++. In fact implementation of the algorithm in that language is clearer and easier to maintain. Because of its design the PHOTOS algorithm benefits from the object oriented features of C++. It is our third program, after MC-TESTER [7] and the TAUOLA interface [13], already previously ported to HepMC and C++. This completes the main step of migration of these three programs to the new style.

Such migration is convenient for the users too; they can now work with homogeneous C++ software. From the physics point of view, transformation of PHOTOS from FORTRAN to C++ brings some benefits as well. The channel dependent, complete first order matrix elements of PHOTOS, in FORTRAN, are available only in special kinematical configurations. With the help of the new event record interface they become available for general use. For that purpose, better access to the information necessary to orient the spin state of decaying particles is now provided.

Our paper is organized as follows. Section 2 is devoted to a description of the physics information which must be available in the event record for the algorithm to function. Later, particular requirements for the information stored in HepMC are given. Section 3 describes the program structure. In Section 4 methods prepared for extensions to improve the physics precision of the generator are explained. Section 5 presents the program tests and benchmarks. A summary, section 6, closes the paper. There are three appendices A, B and C attached to the paper. Respectively, they describe the interface to the old part of the code, which has been rewritten from FORTRAN to C, provide a user guide and explain the program configuration methods and parameters.

This document concentrates on features of PHOTOS version 3.60, for other versions, consult

²An up-to-date version of the PHOTOS code described in this paper is available from the web page of our project [9].

³To exploit such methods in the high precision regime, good control of matrix element properties is necessary. As was shown in [10], complications for such methods arise at the second order matrix element only, thus at the precision level of $(\frac{\alpha_{QED}}{\pi})^2 \simeq 10^{-5}$.

README files and `changelog.txt` of the `documentation/doxygen` directory.

2 Requirements of the PHOTOS Interface

The algorithm of PHOTOS Monte Carlo can be divided into two parts. The first, internal part, operates on elementary decays. Thanks to carefully studied properties of the Quantum Electrodynamics (QED) and scalar QED, the algorithm (with certain probability) replaces the kinematical configuration of the Born level decay with a new one, where a bremsstrahlung photon, photons or lepton pairs are added and other particle momenta are modified. This part of the program is sophisticated from the physics point of view [3, 5], but from the point of view of data structures the algorithm is simple. That is why the gain from re-writing this part of the program to C is rather limited. Nonetheless, there were no obstacles for such a transformation to be performed and it is completed now. In fact it was already done previously [14], but the resulting program was developed too early and did not attract users because of a lack of a C++ event record format standard at that time.

The typical result of high energy process simulation are events of complex structure. They include, for example, initial state parton showers, hard scattering parts, hadronization and finally chains of cascade decays of resonances. A structure similar to a tree is created, but properties of such data structures are sometimes violated. For its action, PHOTOS needs to scan an event record (tree) and localize decays (branches in the tree) where it is supposed to act. The decaying particle (mother) and its primary decay products (daughters) have to be passed into the internal event structure of PHOTOS. For calculation of matrix element kernels, mothers of the decaying particle are needed as well. Finally for each daughter a list of all its subsequent decay products has to be formed. Kinematical modifications need to be performed on all descendants of the modified daughter.

In the new C++ version of the event record part of the algorithm, additional functionality is added. The first mother of the decaying particle will be localized and passed together with the elementary branching⁴ to the internal part of the program. Prior to activation of the algorithm for photon(s) (and/or lepton pairs) generation and kinematic construction, the whole decay branching (supplemented with its mother(s)) will be boosted into the decaying particle's rest frame and the first mother will be oriented along the z axis. In many cases, the spin state of the decaying particle can be calculated from kinematics of its production process. Later it is passed on, to the code which calculates the matrix element for the branching.

The part of the code responsible for photon(s) (lepton pair) generation and kinematic construction has been also rewritten from FORTRAN to C. It has been extended over the last five years and features the options presented above.

Before an actual description of the program, let us list the tasks the event record interface must be able to perform:

1. a method to read particles stored in the event tree.
2. a method to add or modify particles of the event tree.
3. a method to search for elementary decays over the entire tree of the event.

⁴We will use branching to refer to decay of particle or resonance (usually, but not always, represented by a decay vertex) which PHOTOS can process.

4. a method to form lists of all subsequent decay products originating from each elementary decay product.
5. a method to localize the first mother of the decaying particle.
6. a method to localize the second mother for the special case of a $t\bar{t}$ pair.

2.1 Requirements specific to event records

The C++ version of the PHOTOS interface implements all functionality of its predecessor, PHOTOS version 2.15 [4] coded in FORTRAN. The program has the process-dependent correcting weights of refs [3, 6] installed. PHOTOS can be attached to any Monte-Carlo program, provided that its output is available through an event record for which an interface has been provided. The default distribution of PHOTOS contains an interface for the HepMC [12] event record, as well as an interface for an old FORTRAN event record, HEPEVT⁵.

It seems that HepMC will remain a generally accepted standard for the near future. However, already now several different options for how HepMC is used are widespread. The possibility of the flexible adaptation of our event record interface to different options has been considered in the design, drawing experience from MC-TESTER [7, 15].

2.2 Object Oriented Event Records – The Case of HepMC

In adapting the PHOTOS interface to the C++ event record format the difference between the HEPEVT event record, with its variant still used by the core of the PHOTOS code (as a struct type), and the HepMC event record has to be taken into account. In the first case a FORTRAN `common` block containing a list of particles with their properties and with integer variables denoting pointers to their origins and descendants is used. The HepMC event structure is built from vertices, each of them having pointers to their origins and descendants. Links between vertices represent particles (or fields). Fortunately, in both FORTRAN and C++ cases, the event is structured as a tree⁶; the necessary algorithms are analogous, but nonetheless different. The HepMC structure based on vertices is more convenient for the PHOTOS interface.

In HepMC, an event is represented by a `GenEvent` object, which contains information such as event id, units used for dimensional quantities in the event and the list of produced particles. The particles themselves are grouped into `GenVertex` objects allowing access to mother and daughter particles of a single decay. Vertices provide an easy way to point to the whole branch in a decay tree that needs to be accessed, modified or deleted if needed. The information of a particle itself is stored in a `GenParticle` object containing the particle id, status and momentum as well as information needed to locate its position in the decay tree. This approach allows traversing the event record structure in several different ways.

The HepMC event record format is evolving with time, making it necessary to adapt the code to new versions. The HepMC versions 2.06, 2.05 and 2.03 were used in the final tests of our distribution⁷.

Evolution of the HepMC format itself is not a crucial problem. In contrast, conventions on

⁵This standard is less commonly used, thus the interface to it is less tested.

⁶At least in principle, because in practice its properties may be rather like a graph without universally defined properties. This makes our task challenging.

⁷The interface has also been tested and is fully compatible with the alpha4 version of HepMC 3.0

how physics information is filled into **HepMC** represent the main source of technical and also physics challenges for our interface. This is quite similar to the previous **HEPEVT - FORTRAN** case. Let us discuss this point in more detail now.

2.2.1 Event Record Structure Scenarios

While many Monte-Carlo generators (e.g. **PYTHIA 8.1** [16], **HERWIG++** [17]), **SHERPA** [18] can store events in **HepMC** format, the representations of these events are not subject to strict standards, and can therefore vary between Monte-Carlo generators or even physics processes. Some examples of these variations include the conventions of status codes, the way documentary information on the event is added, the direction of pointers at a vertex and the conservation (or lack of conservation) of energy-momentum at a vertex. Below is a list of properties for basic scenario we have observed in Monte-Carlo generators used for testing the code.

This list will serve as a declaration for the conventions of **HepMC** filling, which the interface should interpret correctly.

- **4-momentum conservation** is assumed for all vertices in the event record where **PHOTOS** is expected to act.
- **Status codes:** only information on whether a given particle is decaying (status 2) or stable (status 1) is used.
- **Pointers at a vertex** are assumed to be bi-directional. That is, the record structure may be traversed from mother to daughter and from daughter to mother along the same path.

Extensions/Exceptions to these specifications are handled in some cases. We will call them options for conventions of event record filling.

- Vertices like $\tau^\pm \rightarrow \tau^\pm$ and $\tau^\mp \rightarrow \tau^\mp \gamma$ where the decaying particle flavor is among its decay products will prevent **PHOTOS** being invoked.
- If there is 4-momentum non-conservation⁸ in the vertex, **PHOTOS** will not be invoked too. A special kinematic correcting method to remove smaller inconsistencies resulting e.g. from rounding errors is available, but it must be used carefully to avoid action on vertices where four-momentum is not conserved because of physics reasons.
- As in the **FORTRAN** cases, we expect that new types of conventions for filling the event record will appear, because of physics motivated requirements. Unfortunately, the resulting options do not always guarantee an algebraically closed structure. Host program-specific patches may need to be defined for **PHOTOS**. Debugging can then be time consuming, and will need to be repeated for every new case.
- In the case of low-mass particles that are vulnerable to numerical fluctuation (such as muons and electrons), the correct information about a particle's mass is expected. Since in such cases the mass calculated from a 4-vector can often be incorrect (including negative values). An appropriate method of **PHOTOS** must be used to correct that information (see C.6).

⁸For details see Appendix C.6.

In the future, an important special case of event record's filling, with information extracted from experimentally observed events (e.g. $Z \rightarrow \mu^+\mu^-$ modified later to $Z \rightarrow \tau^+\tau^-$) should be allowed. Obviously, a new type (or types) of **HepMC** filling will then appear. The possibility of reverse operation of **PHOTOS**, actually to remove photons from the decay vertex may be then envisaged.

Our aim was to be as flexible as possible. We provide user with options to adapt to event record to be used with **Photos** (see Appendix C.6). However, we have not blocked user from using **Photos** on events where **Photos** may be able to act correctly (such as cases described in this section), because user may willingly apply **Photos** to such cases, for example to test functionality that we have not thought of. In such cases, user is advised to take into account warnings produced by **Photos** but otherwise may proceed unhindered.

A good example for event record divergence from the standard, is the evolution of **PYTHIA**. While in version 8.108 the status codes for our example processes took the values 0, 1 or 2 only (in the part of the record important for **PHOTOS**), other values were already present in version 8.135. As a consequence the status code for otherwise nicely decaying particles was not always 2 anymore. We have introduced a change in the file `PhotosEvent.cxx` to adjust. After the change the program should work for all previous cases as before, changes like this one are usually difficult to validate and complicated tests are necessary. One could investigate if instead of changes to the **PHOTOS** algorithm a different choice of input for **PYTHIA** would not be a more appropriate solution, but in this case we choose to adapt our algorithm⁹.

One of the key concepts of the design of **Photos** C++ interface, described in Section 3, is that it allows user to adapt to variety of different Event Records and Event Record standards in coding physics information. We have provided the interface to the most universal **HepMC** structure that does not take into account how event information has been filled. There are too many variations of **HepMC** event filling scenarios for us to include within the project. Instead, this basic interface can be easily extended to adapt to the different variations on how **HepMC** event is handled.

2.3 Interface to the Event Record struct of HEPEVT type

It was rather simple to rewrite **PHOTOS** to C++ completely. To profit from numerical tests, the core of **PHOTOS** was rewritten to essentially plain C. Common blocks were replaced with structs, old names of methods and functions were preserved. The C++ part of the code searches the whole event for suitable **HepMC** vertices for the generation of bremsstrahlung. Once such a vertex is found it is copied to an internal event record struct which is called `hep` (in older versions it was `FORTTRAN PH_HEPEVT` common block); it uses `HEPEVT` as a specification for struct type definition. The C code of **PHOTOS** is then executed. The data structure passed in this way is rather simple. Only a single vertex consisting of the decaying particle along with its mothers and daughters is passed. Information on mothers is necessary for the calculation of process dependent, matrix element based, kernels.

A description of the interface to the internal, essentially plain C, parts of the code is given in Appendix A.

⁹At present, our programs, **TAUOLA** and **PHOTOS**, supplement the event record with new particle entries carrying bar codes with values starting from 10001. That is the choice resulting from our use of **HepMC** methods and defaults.

3 Design

3.1 Classes and Responsibilities

The choice of splitting the source code into three main modules allows the separation of the C code of the numerical algorithm from the abstract C++ interface and the concrete implementation of the interface created for the appropriate event record.



Figure 1: PHOTOS C++ interface class relation diagram

- **photos-C**

This part of the code includes numerical algorithms of PHOTOS. In particular, the code for generating photons as well as electron-positron and muon pairs. The **HEPEVT_struct** class located here is responsible for writing the decay branch to be processed into the internal event record struct **hep** as well as for writing the output of the processing back to the event record. For further details see Appendix A.

- **PHOTOS C++ Interface**

This is an abstract interface to the event record. The class **PhotosEvent** contains information regarding the whole event structure, while **PhotosParticle** stores all information regarding a single particle. All particles used by the interface are located in the event in the form of a list of **PhotosParticle** objects. The last class located here,

PhotosBranch, contains information regarding elementary branching to be processed by PHOTOS. In particular, it contains the algorithm which selects single branching for processing and filters out branchings that will not be processed.

- **Event Record Interface**

This contains the event record implementation classes. All classes stored here represent the implementation of specific event record interfaces and are responsible for reading, traversing and writing to the event record structure. Only the **PhotosEvent** and **PhotosParticle** classes must be implemented. The **HepMC** event record interface is implemented through **PhotosHepMCEvent** and **PhotosHepMCParticle**. These classes are similar to the analogous **TAUOLA** [13] event record classes. An example of a minimalistic interface to an event record has been provided through the classes **PhotosHEPEVTEvent** and **PhotosHEPEVTParticle**¹⁰. For example, a separate set of classes deriving from **PhotosParticle** and **PhotosEvent** can be written for **HepMC** events generated by **PYTHIA**, treating particle status codes differently than before, and a separate set for **HepMC** events taken from other MC generators. The choice between these two implementations can be introduced by the user's code.

3.2 Directory Structure

- **src/eventRecordInterfaces/** - source code for classes which interface with event records. Currently, the **HepMC** interface and an interface to the **FORTRAN** event record **HEPEVT** are located here.

Classes:

- **PhotosHepMCEvent** - interface to **HepMC::GenEvent** objects.
- **PhotosHepMCParticle** - interface to **HepMC::GenParticle** objects.
- **PhotosHEPEVTEvent** - interface to the event structure of the **HEPEVT** format, used in the interface to the **HEPEVT** common block of **FORTRAN** example only.
- **PhotosHEPEVTParticle** - interface to a single particle from the **HEPEVT** event record, used in the interface to the **HEPEVT** common block of **FORTRAN** example only.

- **src/photosCInterfaces/** - source code for the abstract event record interface.

Classes:

- **Photos** - controls the configuration and initialization of **PHOTOS**.
- **PhotosEvent** - abstract base class for event information.
- **PhotosParticle** - abstract base class for particles in the event.
- **PhotosBranch** - contains one **PhotosParticle** and pointers to its mothers and daughters. The main algorithms of the abstract interface, such as invoking **PHOTOS** processing or filtering out branchings that will not be processed, is defined here.

- **src/utilities/** - source code for utilities.

Files/classes:

- **Log** - general purpose logging class that allows filtering out output messages of the **PHOTOS C++ Interface** and tracks statistics for each run.

¹⁰This interface is the only way of implementing NLO corrections in programs using the **HEPEVT** event record. Let us note that for this part of the code only minimal set of tests was completed, and its use should be restricted, until further tests.

- **PhotosRandom** - random number generator from Ref. [19, 20] taken from PHOTOS FORTRAN and rewritten to C++.
- **PhotosDebugRandom** - static class derived from **PhotosRandom** that provides several tools to store and restore the state of the PHOTOS random number generator.
- **PhotosUtilities.cxx** - support functions (e.g. boosting, rotations, etc.)
- **src/photos-C/** - core PHOTOS code. Since version 3.54, PHOTOS has been fully rewritten to C++ and located in its own namespace **Photospp**¹¹. For algorithmic backward compatibility¹² the code structure as in FORTRAN version is kept. The appropriate descriptions remain valid; in publications as well as in the code, now in C++.

Files:

- **photos-C.cxx** - core functionality of PHOTOS. Structures of this code contain internal variables such as weights, angles, four momenta, etc. The **Photos** class uses some of these structures to set several initialization options.
- **HEPEVT_struct.cxx** - static class translating information about particles passed through the abstract event record interface to a HEPEVT-like structure used by the core PHOTOS code.
- **forW-MEc.cxx** - routines to calculate the matrix element in W decays. Note distinct programming style from the rest of code in the **photos-C** directory.
- **forZ-MEc.cxx** - routines to calculate the matrix element in Z decays. Note distinct programming style from the rest of code in the **photos-C** directory.
- **pairs.cxx** - code for electron-positron and muon pairs emission.
- **examples/** - examples of different PHOTOS C++ Interface uses.
 - **photos_hepevt_example** - stand alone example with a simple $e^+e^- \rightarrow \tau^+\tau^-$ event written in HEPEVT format and then processed by PHOTOS.
 - **photos_standalone_example** - the most basic example which loads pre-generated events stored in a file in HepMC format which are then processed by PHOTOS.
 - **single_photos_gun_example** - an example of using the **processOne** method to process only selected vertices within the event record.
 - **photos_pythia_example** - an example of $e^+e^- \rightarrow Z \rightarrow \mu^+\mu^-$ events generated by PYTHIA 8 and processed by PHOTOS. The analysis is done using MC-TESTER, initialization for emission of lepton pairs is demonstrated.
 - **photosLCG_pythia_example** - similar to previous case, prepared to demonstrate LCG scripts.
 - **tauola_photos_pythia_example** - an example of TAUOLA linked with PYTHIA 8. The decay chain is processed by PHOTOS and then analyzed with MC-TESTER.
 - **testing/photos_tauola_test** - test program, may be useful as an example for the user's own work, but rather not as an introductory example. See README files of the directory.
 - **testing/photos_test** - test program, may be useful as an example for user own work, but rather not as an introductory example. See README files of the directory. An example of pair emission use is given.
 - **testing/further_subdirectories** directories with numerical benchmark results, see Subsection 5.1.

¹¹This means that no part of the code is shared with old PHOTOS FORTRAN and both versions can be loaded simultaneously without the risk of one version overwriting the options of the other.

¹²The resulting modules are however not interchangeable and the program will not function if the PHOTOS FORTRAN library is loaded instead of the code encapsulated in the **src/photos-C/** directory.

- **include/** - directory for the header files.
- **lib/** - directory for the compiled libraries.
- **documentation/** - contains doxygen documentation and this latex file.

3.3 Algorithm Outline

An overview of the algorithm for the **PHOTOS C++ Interface** is given below. For clarity, the example assumes that the processed event is stored in the **HepMC** event record structure.

The first step is creation of a **PhotosHepMCEvent** object from a **HepMC::GenEvent** event record. After that, the **process()** method should be executed by the user's code¹³, invoking the following process:

1. The **HepMC** event record is traversed and a list of all decaying particles is created.
2. Each particle is checked and if the resulting branching is a self-decay¹⁴ it is skipped.
3. For each remaining particle a branch, including the particle's mothers and daughters is created. Special cases consisting of mothers and daughters but without intermediate particle to be decayed are also added to the list of branches.
4. Branchings are filtered out again, this time with the user's choice of processes to be skipped by **PHOTOS**.
5. Each branching is processed by **PHOTOS** separately:
 - (a) The branch is written to a **hep** struct.
 - (b) The **PHOTOS** photon and pair adding algorithm is invoked.
 - (c) The resulting branching is taken back from **hep** and introduced to the event record.
 - (d) Any changes made by **PHOTOS** to the already existing particles invokes kinematical changes to their whole decay trees.
 - (e) Finally, the created particles are added to the event record.

The underlying **HepMC::GenEvent** is hence modified with the insertion of new particles. Alternatively, as in our example, **PHOTOS/examples/photos_hepevt_example.f**, the interface **HEPEVT** in **FORTRAN** is used and then the content of **HEPEVT** is modified.

4 Extensibility

The first purpose of the **C++** interface to the **C** **PHOTOS** algorithm is to make available all the functionality of its **FORTRAN** predecessor for **C++** data structures. Some new methods for

¹³Instead of creating a **PhotosHepMCEvent** and processing the whole event, a user may want to execute **Photos::processParticle(...)** or **Photos::processBranch(...)** on the single branching or branch where **PHOTOS** is expected to perform its tasks. For details see Appendix C.3.

¹⁴A history entry in the event record, like $Z \rightarrow Z$ or $\tau \rightarrow \tau$.

improved initialization are introduced. The new program functionality has been prepared to enable extensions, such as emission kernels based on matrix elements or emission of pairs. Let us briefly discuss some of these points.

4.1 PHOTOS Extensions

So far we have presented an algorithm, as it was already implemented in FORTRAN. Further extensions were introduced:

- We have prepared the structure (branching including particle's mothers) for the implementation of channel dependent matrix elements. This was integrated into the C++ version of PHOTOS.
- Methods devised to check the content of the event record are described in Appendix C.5. They need to be used whenever PHOTOS processes events from a new generator e.g. upgraded versions of PYTHIA, which may fill the event record in an unexpected way. Experience gained from many years of developing and maintaining the algorithm have shown that this is the most demanding task; the necessity to adapt to varying physics and technical inputs of the event record pose a multitude of problems. The nature of these difficulties cannot be predicted in advance.
- For the sake of debugging we have introduced new control methods and ones which activate internal printouts of the C part of the code. The routine PHLUPA [2] can be activated to verify how an event is constructed/modified, and to investigate energy momentum (non-) conservation or other inconsistencies. This is quite convenient, for example, for tracing problems in the information passed to PHOTOS.
- Numerical stability is another consideration; it cannot be separated from physics constraints. The condition $E^2 - p^2 = m^2$ may be broken because of rounding errors. However, due to intermediate particles with substantial widths, the on-mass-shell condition may not be applicable. PHOTOS may be adapted to such varying conditions, but it requires good interaction with users. The protection which removes inconsistencies in the event record may be a source of unexpected difficulties in other cases.

4.2 Event Record Interface

In the times of FORTRAN, the PHOTOS interface used an internal event structure which was based on HEPEVT, adding to it (understood as a data type) an extra variable defining the status of particles with respect to QED Bremsstrahlung. We still use event objects based on HEPEVT but they are declared as C structs and used internally in the PHOTOS algorithm.

In some cases, like $\tau \rightarrow l\nu_l\nu_\tau$, bremsstrahlung was already generated earlier by other generator, and PHOTOS should not be active on such decays. At present, a set of initialization methods is prepared as described in Appendix C.1. This superseeds the role of QED emission flags of FORTRAN times.

There is definite room for improvement. For example if the vertex $q\bar{q} \rightarrow l^\pm l^\mp g$ is encountered (note the presence of g in the final state), the interface could ‘on the fly’ add an intermediate Z into the record and enable PHOTOS on the temporarily constructed decay branching, $Z \rightarrow l^\pm l^\mp$. We can process $q\bar{q} \rightarrow l\bar{l}$ without an intermediate Z though.

Internally, in the C part of PHOTOS, the data structs of C based on HEPEVT: `pho` and `hep` are used, but they store only a single elementary decay. This solution prevented the need to redo many of the FORTRAN era benchmarks.

5 Testing

Some of the most important parts of the PHOTOS project are its physics oriented tests. Several domains of physics tests should be mentioned. Users interested in precision simulations of Z or W decays will find the papers [6, 3, 4] most interesting. There, careful comparison with the first order matrix element and confirmation of the agreement was shown. For Z decays, comparisons with a Monte Carlo program based on exclusive exponentiation with up to the second order matrix element is possible and was performed on some benchmark distributions. Inclusion of a correcting weight for complete first order matrix elements was found to be numerically less important than the absence of the second order matrix element in the YFS exponentiation scheme used by the reference programs. In these comparisons the Monte Carlo programs from LEP [21, 22] were used as the reference. In numerical tests MC-TESTER [7] was used. The advantage of the method is that C++ and FORTRAN program results can be easily compared¹⁵.

For inclusive calculations, FSR radiative corrections are at the one permille level. For semi-inclusive cross sections, such as the total rates of Z decay for events where the hardest photon energy (or two hardest photon energies) exceed 1 GeV in the Z rest frame, differences between results from PHOTOS, with the matrix element correcting weight turned off, and and YFS based generators of the first or second order were also at the 0.2 % level. On the other hand, if two hard photons were requested and invariant masses constructed from leptons and hard photons were monitored, the level of differences exceeded 30 %. However, even in this region of phase space, PHOTOS, without the correcting weight, performs better¹⁶ than programs based on exponentiation and the first order matrix element only.

This conclusion needs to be investigated if realistic experimental cuts are applied. Fortunately the necessary programs are available for Z decay. In the case of W decay, second order Monte Carlo generators supplemented with exponentiation are not available at this moment.

For users interested in the simulation of background for Higgs searches at the LHC and for any other applications where two hard photon configurations are important, studies based on the comparison with a double photon matrix element are of interest. For PHOTOS Monte Carlo such tests were initiated in refs. [2, 23, 24]. Finally, users interested in low energy processes where the underlying physics model for photon emission cannot be controlled by theory sufficiently well (scalar QED may be considered only as the starting point), will profit from [5, 6]. In all cases it is important that the program generation cover the full phase-space and that there are no approximations in phase-space. As in the FORTRAN version, the code features approximation in the kernel. In some cases the process dependent complete first order kernel is available. At present such an option is prepared (see Section 2.3) for W and Z decays. It is also available for the decays of scalars into two scalars. Then, exact means exact with respect to scalar QED only.

¹⁵We thank Andy Buckley for checking numerically that our conclusions on the first order exact YFS exponentiation results extend to the programs presently used at the LHC such as SHERPA and HERWIG++.

¹⁶In the phase space region where only one hard photon is tagged this conclusion seems to depend on the variant of exponentiation in use, [21] or [22].

The main purpose of the present paper is program documentation. This is why we also need to cover the program tests that guarantee its proper installation. The physics tests discussed above do not guarantee that the program will perform well on a particular platform and installation. Tests and debugging of the installation are necessary too. If the content of the event record is non-standard or rounding errors are large, the performance of PHOTOS will deteriorate.

The first check after installation of PHOTOS is whether some energy momentum non-conservation appears. Such offending events should be studied before PHOTOS and after PHOTOS is run to modify them. If it is impossible to understand why inconsistencies for energy momentum non-conservation were created by PHOTOS, the authors should be contacted. Sometimes monitoring how an event is constructed inside the internal C part of the code may be useful. For that purpose a monitoring option¹⁷ is available from the C++ part of the code. In practice only rather advanced users will profit from the printouts. However, it may be sent to the authors and help to quickly identify the cause of the problems.

The next step in benchmarking relies on comparisons with reference distributions. At present, we store these tests using ROOT [25] and our MC-TESTER program [7].

5.1 MC-TESTER Benchmark Files

Over years of development of the TAUOLA and PHOTOS programs a certain level of the automation of tests was achieved. It was found that monitoring all the invariant mass distributions which can be constructed out of a given decay represent a quite restrictive but easy to implement test. Finding the relative fraction of events for each distinct final state complemented that test and is implemented now in the public version of MC-TESTER. We have applied this method for PHOTOS too. In this case, some soft final state particles have to be ignored because we are bound to work with samples which otherwise would exhibit properties of unphysical infrared regulators (see Section 6.1 of ref [7] for more details). For the most popular decays the benchmarks are collected on our project web page [8]. In our distribution, we have collected numerical results in the directory `examples/testing` and its sub-directories: `Htautau`, `pairs`, `ScalNLO`, `ttbar`, `Wenu`, `Wmunu`, `WmunuNLO`, `Zee`, `Zmumu`, `ZmumuNLO` and `Ztautau`. Each of them includes an appropriate initialization file for the particular run of PYTHIA. Numerical results from long runs of MC-TESTER based tests are stored for reference¹⁸. At present, our choice of tests is oriented toward the LHC user and radiative corrections in decay of W 's, Z 's and Higgs particles. Most users at low energy experiments use the FORTRAN version of the code, which is why our tests and examples for the C++ version are not geared toward low energy applications yet.

5.2 Results

In principle, for the algorithm performing photon(s) construction, the C++ interface of PHOTOS introduces nothing new with respect to the version of PHOTOS available in FORTRAN. That is why the tests which are collected in [8] are not recalled here, they were only reproduced and found to be consistent with the ones for old PHOTOS FORTRAN. However the algorithm for combining a modified branching, including the added photon(s), to the rest of the event tree was rewritten. Examples of spin dependent observables are of more interest because they

¹⁷See Appendix C.5 for the command `Log::LogPhlupa(int from, int to)`

¹⁸Details on the initialization for the runs are given in `README-benchfiles`.

test this new part of the code. The π energy spectrum in the decaying Z boson rest-frame is the first example. The π^\pm originates from a $\tau^\pm \rightarrow \pi^\pm \nu$ decay and, as was already shown a long time ago [26], its energy spectrum is modified by bremsstrahlung both in τ and Z decays. The net bremsstrahlung effect is similar to the one of e.g. Z polarization. In Fig. 2 this result is reproduced.

Let us now turn to tests using observables which are sensitive to transverse spin effects. For this purpose we study the decay chain: $H \rightarrow \tau^+ \tau^-$, $\tau^\pm \rightarrow \rho^\pm \nu_\tau$, $\rho^\pm \rightarrow \pi^\pm \pi^0$, where PHOTOS may act on any of the branchings listed above. An inappropriate action of the C++ part of PHOTOS could result in faulty kinematics, manifesting itself in a failure of energy-momentum conservation or faulty spin correlation sensitive distributions. However, as we can see from Fig. 3, the distributions (as they should be) remain nearly identical to the ones given in [13, 27]. The emission of soft and/or collinear photons to the τ^+ or τ^- does not change the effects of spin correlations. The kinematical effects of hard, non collinear photons are responsible for dips in the acoplanarity distributions at 0, π and 2π .

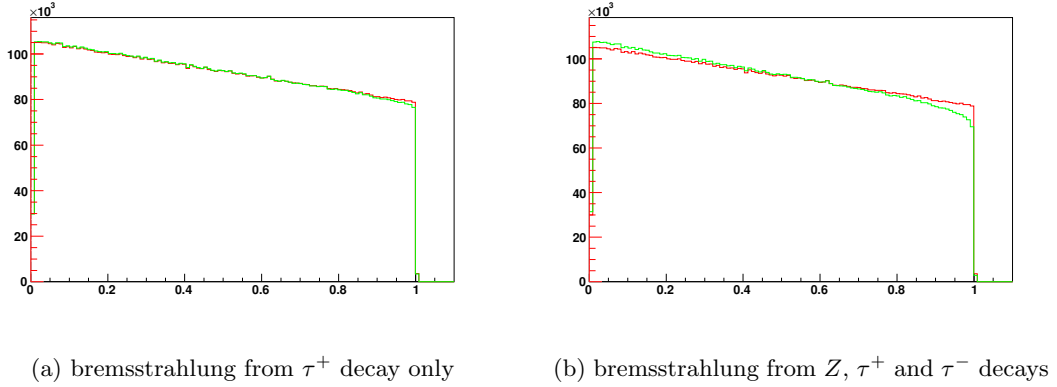


Figure 2: Bremsstrahlung effects for longitudinal spin observables for the cascade decay: $Z \rightarrow \tau^+ \tau^-$, $\tau^\pm \rightarrow \pi^\pm \nu$. The π^+ energy spectrum in the Z rest-frame is shown. The red line is for bremsstrahlung switched off and green (light grey) when its effect is included. In the left plot, bremsstrahlung is in τ^+ decay only. In the right plot, bremsstrahlung from Z and τ^\pm decays is taken into account. These plots have been prepared using a custom `UserTreeAnalysis` of MC-TESTER. They can be recreated with the test located in the `examples/testing/Ztautau` directory, see `examples/testing/README-plots` for technical details. Results are consistent with Fig. 5 of Ref. [28].

In Ref. [31] a discussion of the systematic errors for the measurement of the Z cross section at the LHC is presented. One of the technical tests of our software is to obtain Fig. 1b of that paper. In our Fig. 4 we have reproduced that plot using PYTHIA 8.1 and PHOTOS. Qualitatively, the effect of FSR QED bremsstrahlung is quite similar in the two cases.

In Fig. 4 we present a plot of the bare electron pair (which means electrons are not combined with the collinear photons that accompany them) from Z decay with and without PHOTOS. It is similar to the plots shown for Horace or Winhac; see Refs. [32, 33] and related studies. One should bear in mind that this is again a technical test with little direct application to physics. As explained in the figure caption, the LHC production process was used.

We have also checked that PHOTOS works for $t\bar{t}$ events and the simulations explained in [24] can be repeated. For this purpose we have produced $t\bar{t}$ pairs in pp collisions at 14 TeV center-of-mass energy. We have produced rates for events with zero, one or at least two photons of energy above 0.001 of the $t\bar{t}$ pair mass (energies are calculated in the hard scattering frame). Results are given in the following table which is constructed from $gg \rightarrow t\bar{t}$ events only:



Figure 3: Bremsstrahlung effects for transverse spin observable: The distribution of the acoplanarity angle of oriented planes spanned respectively on the $\pi^+\rho^+$ and $\pi^-\rho^-$ momenta is shown. The distribution is defined in the rest frame of the $\rho^+\rho^-$ pair for the scalar Higgs decay chain $H \rightarrow \tau^+\tau^-$, $\tau^\pm \rightarrow \rho^\pm \nu_\tau$, $\rho^\pm \rightarrow \pi^\pm \pi^0$. PHOTOS is used to generate bremsstrahlung. The red curve indicates the distribution when bremsstrahlung effects are ignored and for the green curve (light grey) only events with bremsstrahlung photons of energy larger than 1 GeV in the H rest frame are taken. For the definition of selections C and D see. [29, 30]. These plots have been created using a custom `UserTreeAnalysis` of MC-TESTER. They can be recreated by the test located in the `examples/testing/Htautau` directory, see `examples/testing/README-plots` for technical details.

Final state	Branching Ratio (%) \pm Statistical Errors (%)
$\tilde{t}\tilde{t}$	99.0601 ± 0.0315
$\tilde{t}\tilde{t}\gamma$	0.9340 ± 0.0031
$\tilde{t}\tilde{t}\gamma\gamma$	0.0060 ± 0.0002

10 million events were generated and a slightly modified version of MC-TESTER’s `LC-analysis` from Ref. [15] was used for calculation of the event rates¹⁹. ROOT files for differential distributions are collected in the directory `examples/testing/ttbar`.

5.3 Tests Relevant for Physics Precision

Let us now turn to an example of the test for the two photon final state configuration. We compare (i) KKMC [22] with exponentiation and second order matrix element (`CEEX2`), (ii) KKMC with exponentiation and first order matrix element (`CEEX1`) and finally (iii) the results of PHOTOS with exponentiation activated. As one can see from the table, the rates coincide for the three cases up to two permille for the event configurations where zero, one or at least two photons of energy above 1 GeV accompany the $\mu^+\mu^-$ pair.

Agreement at this level is not seen in the differential distributions, see Fig. 5. For example the spectrum of the two photon mass is quite different between the first and second order exponentiation result. This is of potential interest for background simulations for $H \rightarrow \gamma\gamma$. In contrast, the difference between the results from PHOTOS and `CEEX2` are much smaller. PHOTOS exploits the first order matrix element in a better way than exponentiation. As a

¹⁹We do not supplement the list of final state particles with the second mother, in contrast to the choice used in `LC-analysis` from Ref. [15].



Figure 4: Distribution of the bare e^+e^- invariant mass. The green curve (light grey) represents results when final state bremsstrahlung is generated (with the help of PHOTOS Monte Carlo). For the red curve FSR bremsstrahlung is absent. The simulation of pp collisions at 14 TeV center-of-mass energy is performed using PYTHIA 8.1. The Z/γ mediated hard process is used. This plot has been created using a custom `UserTreeAnalysis` of MC-TESTER. It can be recreated with the test located in the `examples/testing/Zee` directory, see `examples/testing/README-plots` for technical details.

consequence it reproduces terms resulting in second order leading logarithms. This observation is important not only for the particular case of Z decay but for the general case of double bremsstrahlung in any decay as well.

The numerical results collected here provide part of the program benchmarks. They are of limited but nonetheless of some physics interest as well. PHOTOS provides only one step in the simulation chain: bremsstrahlung in decays of particles or resonances. One can ask the question of whether such a specialized unit is of interest and whether it is not better to provide the complete chain for “truth physics simulation” as a single simulation package. Obviously, this will depend on particular needs. Final state QED corrections can be separated from the remaining genuine electroweak corrections and in particular the initial state QED bremsstrahlung from quarks. One should bear in mind, that final state bremsstrahlung needs to be disentangled from detector acceptance dependencies and is usually not of interest in

Decay channel	Branching Ratio \pm Statistical Errors (100M event samples)		
	KKMC CEEEX2 (%)	KKMC CEEEX1 (%)	PHOTOS exp. (%)
$Z^0 \rightarrow \mu^+\mu^-$	83.9190 ± 0.0092	83.7841 ± 0.0092	83.8470 ± 0.0092
$Z^0 \rightarrow \gamma\mu^+\mu^-$	14.8152 ± 0.0038	14.8792 ± 0.0039	14.8589 ± 0.0039
$Z^0 \rightarrow \gamma\gamma\mu^+\mu^-$	1.2658 ± 0.0011	1.3367 ± 0.0012	1.2940 ± 0.0011



Figure 5: The spectrum of the $\gamma\gamma$ invariant mass, for the bremsstrahlung photons in $Z \rightarrow \mu^+\mu^-$ decays. Events with two hard photons, both of energy above 1 GeV in the Z rest frame are taken. Comparisons are shown for CEE2 and CEE1 (left plot), and CEE2 and PHOTOS (right plot). The prediction from PHOTOS is clearly superior for the simulation of Higgs boson backgrounds. In the case of solutions based on YFS exponentiation, the second order matrix element must be taken into account. Fig. 5(b) was obtained from our example, `examples/testing/Zmumu`, after adaptation of the center-of-mass energy (91.17 GeV) and test energy threshold (1 GeV). Samples of 100 million events were used. See `examples/testing/README-plots` for technical details. Reference ROOT files for KKMC CEE samples are, however, created outside of the PHOTOS distribution package.

itself. This must be done e.g. to measure the properties of weak bosons.

One should bear in mind that even for QED FSR alone, the discussion of the physics precision of the simulation result requires further checks. In the case of Z decays, Refs. [3, 4] may not be enough. With increasing precision, the estimation of uncertainty becomes dependent on the particular choice of details for the experimental cuts. Comparisons of different calculations become important too. A good example of such work in the context of other measurements can be found in Refs. [34, 35]; for the simulation of FSR QED corrections. The Monte Carlo programs collected for PHOTOS generator tests are probably enough. A discussion of QED initial final state interference may follow the strategy presented in [36]. There, the question of experimental cuts must be included as well. Once these steps are finished, discussion of complete electroweak corrections in the context of realistic observables should be simplified.

Genuine weak corrections have to be taken into account separately. Such solutions may be possible, if together with the **PHOTOS Interface**, weak corrections are provided, for example, using the **TAUOLA Interface**. A discussion of the complete electroweak corrections, as shown in Fig. 1a of [31], is not the purpose of our document. Let us point out however that electroweak non-QED corrections can be, in principle, installed into the **PYTHIA 8.1 + PHOTOS** simulation using the e.g. **TAUOLA** interface [13]. But for such a solution to be precise, further work is needed [37].

Sizeable initial state QED corrections are usually embodied in units simulating parton showers. This may need some experimental analysis as well. Experimental data from LEP1 were revisited by the DELPHI collaboration [38]. Tension between data and the theoretical description was mentioned. This may mean that the description of initial state QED bremsstrahlung at the LHC will need to be re-investigated using LHC data as well. That is also why it might be useful to keep initial state QED, final state QED and their interference corrections in separate modules.

6 Summary and outlook

We have presented a new version of PHOTOS Monte Carlo. The part of PHOTOS which operates on event records is now rewritten into C++ and an interface to the HepMC event record is prepared. Interface to the HEPEVT event record of FORTRAN is provided as well. The physics performance of the program is the same, or better, than that of the FORTRAN/HEPEVT version and better steering options are introduced. When an elementary decay is to be modified by PHOTOS, it is first transformed to its rest frame. The z -axis is orientated along the decaying particle's mother's direction, as seen in this rest frame. Such modification is necessary to calculate process dependent kernels featuring the complete first order matrix element. The appropriate kernels explained in Refs. [3, 5, 6] are installed into the version, now fully in C, of the internal algorithms of PHOTOS. The necessary information is extracted from the event record and used. No more parts of the algorithm are left in FORTRAN. The remaining FORTRAN part of the code is for the optional interface to HEPEVT.

Finally let us point to ref. [39]. Thanks to this work, for LHC applications in Z and W decays, the PHOTOS Monte Carlo systematic error was established at 0.3%, even 0.2% for the case when matrix element corrections were activated. The estimation is valid for complete final state radiative corrections, not for photonic bremsstrahlung alone, even in the case when lepton pair emission is not taken into account.

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A Appendix: Interface to internal C part of PHOTOS

This appendix is addressed to developers of the interface, and special users interested in advanced options of PHOTOS. The **COMMON** blocks of **FORTRAN** discussed below were used in the program up to version 3.53. Starting from version 3.54 some of these **COMMON** blocks were preserved, as the struct objects of C. The following ones may be of particular interest for the user: **PHOCOP**, **PHOKEY**, **PHOSTA**. Names of variables and structs are not modified with respect to **FORTRAN**, the C++ definition style is however adopted: small letters are used for structs and their variable names.

The event record common block, **HEPEVT**, is preserved but for use only in the **FORTRAN** examples. The interface is available through the classes `PhotosHEPEVTEvent.h` and `PhotosHEPEVTParticle.h`. Let us recall once again, that internally in the C++ PHOTOS code, the **HEPEVT**-like data type is used in structs declaration.

A.1 Common Blocks migrated to struct objects of C

In the following let us list the original common blocks of **FORTRAN** PHOTOS which are in fact now replaced with struct objects of C. To simplify and to preserve continuity of the mathematical formulae shapes, in many places we use aliases to the struct elements which differ only in that they are written in capital letters instead of small ones. Note that relevant parameters listed only here, can be set through the appropriate accessors see Appendix C.6 for more explanations.

PHOCOP coupling constant and related parameters.

ALPHA *double* coupling constant α_{QED} .

XPHCUT *double* minimal energy (in units of half of the decaying particle's mass) for photons to be explicitly generated.

PHOKEY keys and parameters controlling the algorithm options.

FSEC *double* internal variable for algorithm options, the default is $FSEC=1.0$.

FINT *double* maximum interference weight.

EXPEPS *double* technical parameter which blocks the crude level high photon multiplicity from configurations less probable than **EXPEPS**. The default is 10^{-4} .

INTERF *bool* switch for interference, in the matrix element weight.

ISEC *bool* switch for double bremsstrahlung generation.

ITRE *bool* switch for bremsstrahlung generation up to a multiplicity of 4.

IEXP *bool* switch for exponentiation mode.

IFTOP *bool* switch for photon emission in top pair production in quark (gluon) pair annihilation.

IFW *bool* switch for leading effects of the matrix element in leptonic W decays.

PHOSTA Status information.

STATUS[10] *int* Status codes for the last 10 errors/warnings that occurred.

PHPICO π value definition.

PI *double* π .

TWOPI *double* $2 * \pi$.

A.2 Routines

In the following let us list routines which are called from the interface.

PHODMP prints out the content of struct **hep**.

Return type: *void*

Parameters: none

PHOTOS_MAKE_C like **PHOTOS_MAKE** from the **FORTTRAN** part of the interface, but now in C.

Return type: *void*

Parameters:

1. *int id* ID of the particle from which **PHOTOS** starts processing. In the C++ case the importance of this parameter is limited as only one branch, reduced to the decay (process) under consideration, is in the **hep** struct at a time.

PHCORK initializes kinematic corrections.

Return type: *void*

Parameters:

1. *int modcor* type of correction. See Ref. [4] for details.

IPHQRK enables/blocks (2/1) emission from quarks.

Return type: *int*

Parameters: *int*

IPHEKL enables/blocks (2/1) emission in: $\pi^0 \rightarrow \gamma e^+ e^-$.

Return type: *int*

Parameters: *int*

B Appendix: User Guide

B.1 Installation

Photos C++ Interface is distributed in the form of an archive containing source files and examples. Currently only the Linux and Mac OS²⁰ operating systems are supported: other systems may be supported in the future if sufficient interest is found.

²⁰For this case LCG configuration scripts explained in Appendix B.2 have to be used.

The main interface library uses **HepMC** [12] (version 2.03 or later) and requires that either its location has been provided or compilation without **HepMC** has been chosen as an option during the configuration step. The later is only sufficient to compile the interface and to run the **HEPEVT** example.

In order to run further examples located in the `/examples` directory, **HepMC** is required. To run all of the available examples, it is required to install:

- **ROOT** [40] version 5.18 or later
- **PYTHIA** 8.2 [16] or later²¹.
- **MC-TESTER** [15, 7] version 1.24 or later. Do not forget to type `make libHepMCEvent` after compilation of **MC-TESTER** is done.
- **TAUOLA** [13] version 1.0.5 or later. **TAUOLA** must be compiled with **HepMC**.

In order to compile the **PHOTOS C++** Interface:

- Execute `./configure` with the additional command line options:
 - `--with-hepmc=<path>` provides the path to the **HepMC** installation directory. One can also set the `HEPMCLOCATION` variable instead of using this directive. To compile the interface without **HepMC** use `--without-hepmc`
 - `--prefix=<path>` specifies the installation path. The `include` and `lib` directories will be copied there if `make install` is executed later. If none has been provided, the default directory for installation is `/usr/local`.
- Execute `make`
- Optionally, execute `make install` to copy files to the directory provided during configuration.

The **PHOTOS C++** interface will be compiled and the `/lib` and `/include` directories will contain the appropriate libraries and include files.

In order to compile the examples, compile the **PHOTOS C++** interface, enter the `/examples` directory and:

- Execute `./configure` to determine which examples can be compiled. Optional paths, required to compile additional examples and tests, can be provided as command line options (note that all of them are required for tests located in `examples/testing` directory):
 - `--with-pythia8=<path>` provides the path to the **Pythia8** installation directory. One can set the `PYTHIALOCATION` variable instead of using this directive.
 - `--with-mc-tester=<path>` provides the path to the **MC-TESTER** installation directory (the `libHepMCEvent` must be compiled as well, see Ref. [7] for more details). One can set the `MCTESTERLOCATION` variable instead of using this directive. This option implies that **ROOT** has already been installed (since it is required by **MC-TESTER**).

²¹Examples can be adapted to use `pythia8.1`. The necessary changes are explained in `examples/README-PYTHIA-VERSIONS`. In fact, many of our numerical results stored in a code tar ball were obtained with older versions of **PYTHIA**.

The `ROOT` directory `bin` should be listed in the variable `PATH` and the `ROOT` libraries in `LD_LIBRARY_PATH`.

`--with-tauola=<path>` provides the path to the `TAUOLA` installation directory. One can set the `TAUOLALOCATION` variable instead of using this directive.

- Execute `make`

The `/examples` directory will contain the executable files for all examples that can be compiled and linked. Their availability depends on the optional paths listed above. If neither `HepMC`, `Pythia8`, `Tauola` nor `MC-TESTER` are accessible, only the `HEPEVT` example will be provided.

B.2 LCG configuration scripts; available from version 3.1

For our project still another configuration/automake system was prepared for use in LCG/Genser projects²² [41, 42]. This subsection documents solution prepared specifically for the CERN software of the LCG library and may be of no interest for other users.

To activate this set of autotool based [43] installation scripts, enter the `platform` directory and execute the `use-LCG-config.sh` script. Then, the installation procedure and the names of the configuration script parameters will differ from the ones described in our paper. Instruction given in the `./INSTALL` readme file, created by the `use-LCG-config.sh` script, should be followed. One can also execute `./configure --help`, which will list all options available for the configuration script.

Brief information on these scripts can be found in `README` in the main directory as well.

B.3 Elementary Tests

The most basic test which should be performed, for our custom examples but also for a user's own generation chain, is verification that the interface is installed correctly, photons are indeed added by the program and that energy momentum conservation is preserved²³.

A set of example programs located in directory `PHOTOS/examples` has been provided, along with an example output of these programs. `PHOTOS/README-examples` file has been provided as well, with a set of instructions that can be followed to compile all of the examples. These examples can be used to test the most basic functionality of `Photos` interface.

²²We have used the expertise and advice of Dmitri Konstantinov and Oleg Zenin in organization of configuration scripts for our whole distribution tar-ball as well. Thanks to this choice, we hope, our solution will be compatible with ones in general use.

²³We have performed such tests for `HepMC` events obtained from `PYTHIA 8.1`, `PYTHIA 8.135`, `PYTHIA 8.165`, `PYTHIA 8.185` and `PYTHIA 8.201` using all configurations mentioned in this paper, all config files in `examples` directory and subdirectories of `examples/testing`. Further options for initializations (parton shower hadronization or QED bremsstrahlung on/off etc.) were also studied for different `PYTHIA 8.1` versions. This was a necessary step in our program development.

However, we do not document studies of `Pythia` physics initialization for all of its versions. That is why, distributions monitoring production processes obtained from distributed initialization for `PYTHIA 8.201`, may differ from the reference ones. See e.g. `User Histograms`, plots `mother-PT` `mother-eta`, in `examples/testing/ScalNLO` or `examples/testing/WmunuNLO`.

In principle, these tests have to be performed for any new hard process and after any new installation. This is to ensure that information is passed from the event record to the interface correctly and that physics information is filled into the `HepMC` event in the expected manner. Misinterpretation of the event record content may result in faulty `PHOTOS` operation.

B.4 Executing Examples

Once elementary tests are completed one can turn to the more advanced ones. The purpose is not only to validate the installation but to demonstrate the interface use.

The examples can be run by executing the appropriate `.exe` file in the `/examples` directory. In order to run some more specific tests for the following processes: $H \rightarrow \tau^+\tau^-$, $e^+e^- \rightarrow t\bar{t}$, $W \rightarrow e\nu_e$, $W \rightarrow \mu\nu_\mu$, $Z \rightarrow e^+e^-$, $Z \rightarrow \mu\mu$ or $Z \rightarrow \tau^+\tau^-$, $K_0^S \rightarrow \pi\pi$, the main programs residing in the subdirectories of `/examples/testing` should be executed. Note that all paths listed as optional in Appendix B.1 are required for these tests to work. In all cases the following actions have to be performed:

- Compile the `PHOTOS C++ Interface`.
- Check that the appropriate system variables are set. Execution of the script `/configure.paths.sh` can usually perform this task; the configuration step announces this script.
- Enter the `/examples/testing` directory. Execute `make`. Modify `test.inc` if needed.
- Enter the sub-directory for the particular process of interest and execute `make`.

The appropriate `.root` files as well as `.pdf` files generated by `MC-TESTER` will be created inside the chosen directory. One can execute 'make clobber' to clean the directory. One can also execute 'make run' inside the `/examples/testing` directory to run all available tests one after another. Changes in source code can be partly validated in this way. Most of the tests are run using the executable `examples/testing/photos.test.exe`. The $K_0^S \rightarrow \pi\pi$, $H \rightarrow \tau^+\tau^-$ and $Z \rightarrow \tau^+\tau^-$ examples require `examples/testing/photos_tauola.test.exe` to be run. After generation, `MC-TESTER` booklets will be produced, comparisons to the benchmark files will be shown. A set of benchmark `MC-TESTER` root files have been included with the interface distribution. They are located in the subdirectories of `examples/testing/`. Note that for the $W \rightarrow e\nu_e$, $W \rightarrow \mu\nu_\mu$ and $Z \rightarrow \mu\mu$ examples, differences higher than statistical error will show. This is because photon symmetrization was used in the benchmark files generated with `KKMC`, and not in the ones generated with `PHOTOS`. In the case of `KKMC` the generated photons are strictly ordered in energy. In the case of `PHOTOS` they are not. Nonetheless, on average, the second photon has a smaller energy than the one written as the first in the event record.

The comparison booklets can be useful to start new work or simply to validate new versions or new installations of the `PHOTOS` interface.

In Appendix C, possible modifications to the example's settings are discussed. This may be interesting as an initial step for user's physics studies. The numerical results of some of these tests are collected in Section 5.2 and can be thus reproduced by the user.

B.5 How to Run PHOTOS with Other Generators

If a user is building a large simulation system she or he may want to avoid integration with our full configuration infrastructure and only load the libraries. For that purpose our stand-alone example `examples/photos_standalone_example.exe` is a good starting point.

In order to link the libraries to the user's project, both the static libraries and shared objects are constructed. To use the PHOTOS interface in an external project, additional compilation directives are required. For the static libraries:

- add `-I<PhotosLocation>/include` at the compilation step,
- add `<PhotosLocation>/lib/libPhotospp.a` as well as one or both of the libraries: `<PhotosLocation>/lib/libPhotosppHepMC.a` and `<PhotosLocation>/lib/libPhotosppHEPEVT.a` to the linking step of your project.

For the shared objects:

- add `-I<PhotosLocation>/include` at the compilation step,
- add `-L<PhotosLocation>/lib` along with `-lPhotospp` as well as one or both of the libraries: `-lPhotosppHepMC` and `-lPhotosppHEPEVT` to the linking step.
- PHOTOS libraries must be provided for the executable; e.g. with the help of `LD_LIBRARY_PATH`.

`<PhotosLocation>` denotes the path to the PHOTOS installation directory. In most cases it should be enough to include within a user's program `Photos.h` and `PhotosHepMCEvent.h` (or any other header file for the class implementing abstract class `PhotosEvent`) With that, the `Photos` class can be used for configuration and `PhotosHepMCEvent` for event processing.

B.5.1 Running PHOTOS C++ Interface in a FORTRAN environment

For backward-compatibility with HEPEVT event records, an interface has been prepared allowing the PHOTOS C++ Interface to be invoked from the FORTRAN project. An example, `photos_hepevt_example.f`, has been prepared to demonstrate how PHOTOS can be initialized and executed from FORTRAN code. Since PHOTOS works in a C++ environment, `photos_hepevt_example_interface.cxx` must be introduced to invoke PHOTOS.

Since version 3.54, PHOTOS is fully in C++ and initialization can no longer be performed from FORTRAN code through the use of common blocks. In particular, information from the field QEDRAD localized in FORTRAN times common block PHOQED – the extension of HEPEVT is ignored. The `Photospp` initialization methods can be used easily instead.

Note that in the case of HEPEVT, the PHOTOS algorithm has to modify the pointers (stored as integer variables) between mothers and daughters for all particles stored downstream of the added photons or lepton pairs. This part of the code was not replicated in full detail. Also, most of our tests were performed only on cases where the modified decay was the last one in the event record, thus shifting consecutive entries was not necessary. We do not foresee the use of the program and its development for circumstances distinct from these.

C Appendix: User Configuration

C.1 Suppress Bremsstrahlung

In general, PHOTOS will attempt to generate bremsstrahlung for every branching point in the event record. This is of course not always appropriate. Already inside the internal `C` part of PHOTOS, bremsstrahlung is normally prevented for vertices involving gluons or quarks (with the exception of top quarks).

This alone is insufficient. By default we suppress bremsstrahlung generation for vertices like $l^\pm \rightarrow l^\pm \gamma$ because a “self-decay” is unphysical. We cannot request that all incoming and/or outgoing lines are on mass shell, because it is not the case in cascade decays featuring intermediate states of sizeable width. If a parton shower features a vertex with $l^\pm \rightarrow l^\pm \gamma$ with the virtuality of the incoming l^\pm matching the invariant mass of the outgoing pair then the action of PHOTOS at this vertex will introduce an error. This is prevented by forbidding bremsstrahlung generation at vertices where one of the decay products has a flavor which matches the flavor of an incoming particle.

Some exceptions to the default behavior may be necessary. For example in cascade decays, the vertex $\rho \rightarrow \rho \pi$ may require the PHOTOS algorithm to be activated.

Methods to re-enable these previously prevented cases or to prevent generation in special branches have been introduced and are presented below.

- `Photos::suppressBremForDecay(daughterCount, motherID, d1ID, d2ID, ...)`
The basic method of channel suppression. The number of daughters, PDGID of the mother and the list of PDGIDs of daughters must be provided. There is no upper limit to the number of daughters. If a decay with the matching pattern is found, PHOTOS will skip the decay. The decay will be skipped if it contains additional photons or other particles, as long as all of the particles from the pattern are present in the list of daughters.
- `Photos::suppressBremForDecay(0, motherID)`
When only the PDGID of the mother is provided, (the *daughterCount* is 0) PHOTOS will skip all decay channels of this particle.
- `Photos::suppressBremForBranch(daughterCount, motherID, d1ID, d2ID, ...)`
`Photos::suppressBremForBranch(0, motherID)`
The usage of this function is similar to the two cases of the previous function. The difference is that PHOTOS will skip not only the corresponding channel, but also all consecutive decays of its daughters, making PHOTOS skip the entire branch of decays instead of just one.
- `Photos::suppressAll()` All branchings will be suppressed except those that are forced using the methods described in the next section.
- **Example:**
`Photos::suppressBremForDecay(3, 15, 16, 11, -12);`
`Photos::suppressBremForDecay(2, -15, -16, 211);`
`Photos::suppressBremForDecay(0, 111);`

If the decays $\tau^- \rightarrow \nu_\tau e^- \bar{\nu}_e$ or $\tau^+ \rightarrow \bar{\nu}_\tau \pi^+$ are found, they will be skipped by PHOTOS²⁴. In addition, all decays of π^0 will also be skipped. Note, that the minimum number of parameters that must be provided is two - the number of daughters (which should be zero if suppression for all decay channels of the particle is chosen) and the mother PDGID.

`Photos::suppressBremForBranch(2, 15, 16, -213);`

When the decay $\tau^- \rightarrow \nu_\tau \rho^-$ is found, it will be skipped by PHOTOS along with the decays of ρ^- (in principle also ν_τ) and all their daughters. In the end, the whole decay tree starting with $\tau^- \rightarrow \nu_\tau \rho^-$ will be skipped.

In future, an option to suppress a combination of consecutive branches may be introduced. For example if bremsstrahlung in leptonic τ decays is generated by programs prior to PHOTOS, and the decay is stored in HepMC as the cascade $\tau^\pm \rightarrow W^\pm \nu$, $W^\pm \rightarrow l^\pm \nu$, PHOTOS must be prevented from acting on both vertices, but only in cases when they are present one after another. One can also think of another PHOTOS extension. If a vertex $q\bar{q} \rightarrow l^\pm l^\mp$ is found, then it should not be ignored that intermediate state can be then attributed, $q\bar{q} \rightarrow Z/\gamma^* \rightarrow l^\pm l^\mp$, and used for matrix element calculation.

C.2 Force PHOTOS Processing

Forcing PHOTOS to process a branch can be used in combination with the suppression of all branches i.e. to allow selection of only a particular processes for bremsstrahlung generation.

Forced processing using the methods below has higher priority than the suppression described in the previous section, therefore even if both forcing and suppressing of the same branch or decay is done (regardless of order), the processing will not be suppressed.

- `Photos::forceBremForDecay(daughterCount, motherID, d1ID, d2ID, ...)`
`Photos::forceBremForDecay(0, motherID)`
 The usage of this function is similar to `Photos::suppressBremForDecay(...)` described in the previous section. If a decay with the matching pattern is found, PHOTOS will be forced to process the corresponding decay, even if it was suppressed by any of the methods mentioned in the previous section.
- `Photos::forceBremForBranch(daughterCount, motherID, d1ID, d2ID, ...)`
`Photos::forceBremForBranch(0, motherID)`
 The usage is similar to the above functions. The difference is that PHOTOS will force not only the corresponding channel, but also all consecutive decays of its daughters, making PHOTOS process the entire branch of decays instead of just one. This method can activate part of the later branch previously prevented.
- **Example:**
`Photos::suppressAll();`
`Photos::forceBremForDecay(4, 15, 16, -211, -211, 211);`
`Photos::forceBremForDecay(2, -15, -16, 211);`
`Photos::forceBremForBranch(0, 111);`

²⁴Note that the first line of this example states that any decays of τ^- that contain ν_τ , e^- and $\bar{\nu}_e$ will be skipped regardless of how many other particles are in the decay. So, for example, $\tau^- \rightarrow \nu_\tau e^- \bar{\nu}_e \gamma$ will be skipped as well. It is important to realize that excluding $\tau^- \rightarrow \nu_\tau \pi^-$ leads to exclusion of $\tau^- \rightarrow \nu_\tau \pi^- \pi^0$ as well. If it is not required it must be allowed separately.

Since suppression of all processes is used, only the listed decays will be processed, these are $\tau^- \rightarrow \nu_\tau \pi^- \pi^- \pi^+$, $\tau^+ \rightarrow \bar{\nu}_\tau \pi^+$ and all instances of the decay of π^0 and its descendants.

C.3 Use of the processParticle and processBranch Methods

In Section 3.3 the algorithm for processing a whole event record is explained and is provided through the `process()` method. To process a single branch in the event record, in a way independent of the entire event, a separate method is provided.

- `Photos::processParticle(PhotosParticle *p)`
The main method for processing a single particle decay vertex. A pointer to a particle must be provided. Pointers to mothers and daughters of this particle should be accessible through this particle or its event record. From this particle a branch containing its mothers and daughters will be created and processed by PHOTOS.
- `Photos::processBranch(PhotosParticle *p)`
Usage is similar to the above function. When a pointer to a particle is provided, PHOTOS will process the whole decay branch starting from the particle provided.

An example, `single_photos_gun_example.c`, is provided in the directory `/examples` showing how this functionality can be used to process the decay of selected particles. $Z^0 \rightarrow \tau^+ \tau^-$ decays are generated and the event record is traversed searching for the first τ^- particle in the event record. Instead of processing the whole event, only the decay of a τ^- is processed by PHOTOS.

C.4 Lepton pair emission and event record momentum unit

For the purpose of pair emission, introduced for the first time with Photos version 3.57, the information about the momentum unit (either GEV or MEV) used by the event has to be provided. For other Photos applications this information is not needed.

In case of the HepMC event record, this information is automatically obtained from the event. For HEPEVT events, GEV is assumed. For all other interfaces, the unit is undefined and has to be set in the event record interface by calling

```
Photos::setMomentumUnit(MomentumUnits unit);  
(e.g. Photos::setMomentumUnit(Photos::MEV); ).
```

See constructors for the `PhotosHepMCEvent` or `PhotosHEPEVEEvent` class for further examples.

To select available emission from PHOTOS use:

- `Photos::setPairEmission(bool flag);`
Turn on or off emission of pairs (electrons or muons). Default is off.
- `Photos::setPhotonEmission(bool flag);`
Turn on or off emission of photons. Default is on.

Tests and implementation of final state radiation pair emission, presently follow formulae 1 and 11 from Ref. [44]. The agreement, when pair emission phase space was restricted to the

soft region, was at the 2-5 % level of the pair effect (which itself is at the 0.1 % level of the cross section). The phase space is parametrized without any mass or other approximations. This feature was checked separately with special runs (matrix element removed) of 100 Mevt samples.

The matrix element used for pair emission in decays is easy to improve. Dependence of four-momenta of final state particles is coded explicitly. Further work [45] will be devoted to this task.

C.5 Logging and Debugging

This section describes the basic functionality of the logging and debugging tool. For details on its content we address the reader to comments in the `/src/utilities/Log.h` header file.

Let us present however a general scheme of the tool's functionality. The PHOTOS interface allows control over the amount of message data displayed during program execution and provides a basic tool for memory leak tracking. The following initialization functions can be used in a user's main program. The `Log.h` header has to be then included.

- `Log::LogPhlupa(int from, int to)`
Turns logging of debug messages from the C part of the program on and off. Parameters of this routine specify the range of debug codes for the `phlupa` routine.
- `Log::Summary()` - Displays a summary of all messages from C++ part of the code.
- `Log::SummaryAtExit()` - Displays the summary at the end of a program run.
- `Log::LogInfo(bool flag)`
`Log::LogWarning(bool flag)`
`Log::LogError(bool flag)`
`Log::LogDebug(int s, int e)`
`Log::LogAll(bool flag)`
Turns the logging of *info*, *warning*, *error* and *debug* messages on or off depending on the flag value being true or false respectively. In the case of *debug* messages - the range of message codes to be displayed must be provided. By default, only *debug* messages (from 0 to 65535) are turned off. If the range is negative ($s > e$) *debug* messages won't be displayed. The last method turns displaying all of the above messages on and off.

With `Log::LogDebug(s,e)` messages of s to e range, will be printed at execution time, in particular:

- `Debug(0)` - seed used by the random number generator
- `Debug(1)` - which type of branching was found in `HepMC` (regular or a case without an intermediate particle, for details see `PhotosBranch.cxx`)
- `Debug(700)` - execution of the branching filter has started
- `Debug(701)` - branching is forced
- `Debug(702)` - branching is suppressed
- `Debug(703)` - branching is processed (i.e. passed to the filter)

- Debug(900) - started check of Matrix Element (ME) calculation for the channel
- Debug(901) - ME channel value obtained
- Debug(902) - final ME channel value after checking all flags
- Debug(2) - execution of the branching filter was completed
- Debug(1000) - the number of particles sent to and retrieved from internal PHOTOS event record.

The option `Log::SetWarningLimit(int limit)` results in only the first ‘limit’ warnings being displayed. The default for `limit` is 100. If `limit=0` is set, then there are no limits on the number of warnings to be displayed.

The memory leak tracking function allows checking of whether all memory allocated within `PHOTOS Interface` is properly released. However, using the debug option significantly increases the amount of time needed for each run. Its use is therefore recommended for debugging purposes only. In order to use this option modify `make.inc` in the main directory by adding the line:

```
DEBUG = -D" _LOG_DEBUG_MODE_"
```

Recompile the interface. Now, whenever the program is executed a table will be printed at the end of the run, listing all the pointers that were not freed, along with the memory they consumed. If the interface works correctly without any memory leaks, one should get an empty table.

It is possible to utilize this tool within a user’s program; however there are a few limitations. The debugging macro from “Log.h” can create compilation errors if one compiles it along with software which has its own memory management system (e.g. ROOT). To make the macro work within a user’s program, ensure that `Log.h` is the last header file included in the main program. It is enough to compile the program with the `-D" _LOG_DEBUG_MODE_"` directive added, or `#define _LOG_DEBUG_MODE_` placed within the program before inclusion of the `Log.h` file²⁵.

C.6 Other User Configuration Methods

The following auxiliary methods are prepared. They are useful for initialization or are introduced for backward compatibility.

- `Photos::setRandomGenerator(double (*gen)())` *installed in PHOTOS 3.52*
Replace random number generator used by `Photos`. The user provided generator must return a `double` between 0 and 1. `Photos::setRandomGenerator(NULL)` will reset the program back to the default generator, which is a copy of RANMAR [19, 20].
- `Photos::setSeed(int iseed1, int iseed2)`
Set the seed values for our copy of the random number generator RANMAR [19, 20].
- `Photos::maxWtInterference(double interference)`
Set the maximum interference weight. The default, 2, is adopted to decays where at

²⁵Note that `Log.h` does not need to be included within the user’s program for the memory leak tracking tool to be used only for the `PHOTOS` interface.

most two charged decay products are present²⁶ and no matrix element based kernel is used²⁷.

- `Photos::setInfraredCutOff(double cut_off)`
Set the minimal energy (in units of decaying particle mass) for photons to be explicitly generated.
- `Photos::setAlphaQED(double alpha)`
Set the coupling constant, alpha QED.
- `Photos::setInterference(bool interference)`
A switch for interference, matrix element weight.
- `Photos::setDoubleBrem(bool doub)`
Set double bremsstrahlung generation.
- `Photos::setQuatroBrem(bool quatroBrem)`
Set bremsstrahlung generation up to a multiplicity of 4.
- `Photos::setExponentiation(bool expo)`
Set the exponentiation mode.
- `Photos::setCorrectionWtForW(bool corr)`
A switch for leading effects of the matrix element (in leptonic W decays)
- `Photos::setMeCorrectionWtForScalar(bool corr)`
A switch for complete effects of the matrix element (in scalar to two scalar decays) *installed in PHOTOS 3.3.*
- `Photos::setMeCorrectionWtForW(bool corr)`
A switch for complete effects of the matrix element (in leptonic decays of W 's produced from annihilation of light fermions) *installed in PHOTOS 3.2*
- `Photos::setMeCorrectionWtForZ(bool corr)`
A switch for complete effects of the matrix element (in leptonic Z decays) *installed in PHOTOS 3.1*
- `Photos::setTopProcessRadiation(bool top)`
Set photon emission in top pair production in quark (gluon) pair annihilation and in top decay.
- `Photos::initializeKinematicCorrections(int flag)`
Initialize kinematic corrections necessary to avoid consequences of rounding errors.
- `Photos::forceMassFrom4Vector(bool flag)`
By default, for all particles used by PHOTOS, mass is re-calculated and $\sqrt{E^2 - p^2}$ is used. If `flag=false`, the particle mass stored in the event record is used. The choice may be important for the control of numerical stability in the case of very light stable particles, but may be incorrect for decay products themselves of non-negligible width.
- `Photos::forceMass(int pdgid, double mass)` *installed in PHOTOS 3.4*
For particles of PDGID (or -PDGID) to be processed by PHOTOS, the mass value attributed by the user will be used instead of the one calculated from the 4-vector. Note

²⁶For the decays like $J/\psi \rightarrow 5\pi^+5\pi^-$ a higher value, at least equal to the number of charged decay products, should be set. The algorithm performance will slow down linearly with the maximum interference weight but all simulation results will remain unchanged.

²⁷Also in this case a higher than default 2 should be used.

that if both `forceMass` and `forceMassFromEventRecord` is used for the same PDGID, the last executed function will take effect. Up to version 3.51, the option is active if `forceMassFrom4Vector = true` (default). From version 3.52, the option works regardless of the setting of `forceMassFrom4Vector`.

- `Photos::forceMassFromEventRecord(int pdgid)` *installed in PHOTOS 3.4*
For particles of PDGID (or -PDGID) to be processed by PHOTOS, the mass value taken from the event record will be used instead of the one calculated from the 4-vector. Note that if both `forceMass` and `forceMassFromEventRecord` is used for the same PDGID, the last executed function will take effect. Up to version 3.51, the option is active if `forceMassFrom4Vector = true` (default). From version 3.52, the option works regardless of the setting of `forceMassFrom4Vector`.
- `Photos::createHistoryEntries(bool flag, int status)` *installed in PHOTOS 3.4*
If set to `true`, and if the event record format allows, Photos will store history entries consisting of particles before processing²⁸. History entries will have status codes equal to `status`. The value of `status` will also be added to the list of status codes ignored by Photos (see `Photos::ignoreParticlesOfStatus`). An example is provided in `photos_pythia_example.cxx`.
- `Photos::ignoreParticlesOfStatus(int status)` Decay products with the status code `status` will be ignored when checking momentum conservation and will not be passed to the algorithm for generating bremsstrahlung.
- `Photos::deIgnoreParticlesOfStatus(int status)` Removes `status` from the list of status codes created with `Photos::ignoreParticlesOfStatus`.
- `bool Photos::isStatusCodeIgnored(int status)` Returns `true` if `status` is on the list of ignored status codes.
- `Photos::setMomentumConservationThreshold(double momentum_conservation_threshold)`
Threshold relative to the difference of the sum of the 4-momenta of incoming and outgoing particles. The default value is 0.1. If larger energy-momentum non-conservation is found then photon generation is skipped in the vertex²⁹.
- `Photos::iniInfo()`
The printout performed with `Photos::initialize()` will exhibit outdated information once the methods listed above are applied. The reinitialized data can be printed using the `Photos::iniInfo()` method. The same format as `Photos::initialize()` will be used.

C.7 Creating Advanced Plots and Custom Analysis

In Section 5.2, we have presented results of a non-standard analysis performed by MC-TESTER. Figure 4 has been obtained using a custom `UserTreeAnalysis` located in the `ZeeAnalysis.C` file residing in the `examples/testing/Zee` directory. This file serves as an example of how custom analysis can be performed and how new plots can be added to the project with the help of MC-TESTER.

²⁸In case of HepMC, it creates copies of all particles on the list of outgoing particles in vertices where the photon was added and will be added at the end of the list.

²⁹In the past, momentum conservation was checked using the standard method of HepMC. That effectively meant that *only* momentum, but not energy was checked. This turned out to be insufficient in some rare cases.

The basic MC-TESTER analysis contains methods used by pre-set examples in the subdirectories of `examples/testing` to focus on at most one or two sufficiently hard photons from all the photons generated by PHOTOS. Its description and usage have already been documented in [7]. The content of `ZeeAnalysis.C` is identical to the default `UserTreeAnalysis` of MC-TESTER with the only addition being a method to create the previously mentioned plot.

In order to create the $t\bar{t}$ example, an additional routine had to be added to `photos_test.c`. Since MC-TESTER is not designed to analyze processes involving multiple incoming particles, we have used a method similar to that previously used in the FORTRAN examples, `LC_Analysis`, mentioned in [15], Section 6.1. This routine, `fixForMctester`, transforms the $XY \rightarrow t\bar{t}$ process to the $100 \rightarrow t\bar{t}$ process, where the momentum of the special particle 100 is $X + Y$. With this modification, MC-TESTER can be set up to analyze the particle 100 in order to get a desirable result.

For more details regarding the plots created for this documentation, see `README-plots` located in the `examples/testing/` directory.