

# SFGen v1.04

A Monte Carlo for photon-initiated production in the  
structure function approach

## Users guide

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# 1 Overview

The `SFGen` MC provides a publicly available tool for lepton pair production and lepton–lepton scattering within the SF approach, including initial–state  $\gamma$ ,  $Z$  and mixed  $Z/\gamma + q$  contributions. Arbitrary distributions and unweighted events can be generated, and errors due to the experimental uncertainty on the structure function (the equivalent of PDF uncertainties in the photon PDF framework) can be calculated on–the–fly. The LO collinear photon–initiated predictions can also be calculated for comparison, for arbitrary factorization and renormalization scales. The code makes use of structure function grids in the LHAPDF [1] format, as calculated using APFEL [2], as presented in [3,4]. These structure function grids are provided with the MC, and are calculated with MSHT20qed nnlo PDFs [5] in the high  $Q^2$  region.

# 2 Installation

To run `SFGen` you will need to download `SF_MSHT20qed_nnlo` from the website at <http://projects.hepforge.org/sfgen> and place this in the relevant directory for your LHAPDF 6 installation, after extracting the tarball.

The MC code is also available here. To extract it, simply execute `tar -xzvf SFGen1.04.tar.gz` and the `SFGen1.04` directory will be created. This consists of:

- `bin`: the executable `SFGen` and the input card `input.DAT`.
- `doc`: the source for this document.
- `obj`: the object files produced by the compiler.
- `src`: the Fortran source files in various subdirectories.
- `lib`: static and shared libraries produced by compiler.

To compile, simply run

```
> make
```

which will create the `SFGen` executable in the `bin` directory as well as the object files in the `obj` directory.

### 3 Running with LHAPDF

By default the program makes use of the LHAPDF library, however there may be some issues with correctly linking to this, depending on the particular system used. If in the first instance of executing `SFGen` the following error then appears:

```
error while loading shared libraries: libLHAPDF.so.0: cannot open
shared object file: No such file or directory
```

please add the following lines to the shell (bash) login script:

```
export LHAPDFSYS=/yourpath/LHAPDF-X.Y.Z
export PATH=${PATH}:${LHAPDFSYS}/bin
LD_LIBRARY_PATH=${LD_LIBRARY_PATH}:${LHAPDFSYS}/lib
```

### 4 Input parameters and runtime options

After compilation, the main MC code may be run with

```
> ./SFGen < input.DAT
```

The adjustable parameters in the input file are described below in order:

- `rts`: collider energy,  $\sqrt{s}$ , in GeV.
- `proc`: process number, to specify the produced state. These are defined in Section 7.
- `outtag`: label for file output `[outtag].dat`, created in `bin/outputs` directory, and event record `evrec[outtag].dat`, created in `bin/evrecs` directory. Contains input parameter and cross section information, as well as histograms (see Section 5).
- `diff`: Set to `tot` to include both elastic and inelastic photon emission, i.e. relevant for standard inclusive production. Alternatively, can be used for purely elastic (`e1`), single proton dissociation (`sd`) or double dissociation (`dd`). For single dissociation the default includes the dissociation of either protons, but for the purposes of bookkeeping in the

event record it is also possible to only generate events were proton A (`sda`) or B (`sdb`) dissociates, with the sum of these two giving the total SD cross section.

- `SFerror`: if `.true.` then calculate error on cross section due to experimental uncertainty on structure functions. Performed on-the-fly, but will result in slower generation. Also calculates PDF uncertainty if `coll` is `.true..`
- `mixed`: if `.true.` then include mixed  $\gamma + q$  diagrams (and  $Z + q$  if `Zinit` set to `.true.`). Note  $s$ -channel  $\gamma/Z \rightarrow l^+l^-$  included in this case. This option can only be included for lepton pair production (`proc` = 1 – 3).
- `Zinit`: if `.true.` then include  $Z$  bosons in the initial state.
- `subt`: if `.true.` then calculate subtraction for corresponding mixed  $\gamma + q$  contribution. Note only the subtraction is evaluated, and this must then be subtracted from the cross section calculated with `mixed` = `.true.`, if appropriate.
- `lep1`: lepton 1 for lepton–lepton scattering. Can be set to  $e^+$ ,  $\mu^+$ ,  $\tau^+$ ,  $e^-$ ,  $\mu^-$ , or  $\tau^-$ .
- `lep2`: lepton 2 for lepton–lepton scattering. Can be set as above.
- `kmu`: factorization/renormalization scale set to  $\mu_0$  multiplied by `kmu` for collinear, subtraction and mixed contributions.
- `coll`: if `.true.` then calculate photon–initiated lepton pair production in the collinear LO approach.
- `PDFname`, `PDFmember`: name of PDF set, in the appropriate format for LHAPDF version 6, and set number. For collinear running and calculation of subtraction term only.
- `ncall`, `itms`: number of iterations and calls in VEGAS preconditioning run. It is recommended to set the number of calls in units of 1000, and to increase the number when applying cuts.
- `ncall1`, `inccall`, `itend`: number of calls in VEGAS main run, and increase per iteration, as well as maximum number of iterations before

run will automatically terminate. The run is automatically adjusted so that the number of calls passing cuts is approximately equal to `ncall1`.

- `prec`: the required % accuracy by the user; the main run will terminate once this level of accuracy has been reached.
- `iseed`: random number seed, must be a positive integer.
- `genunw`, `nev`, `erec`: set `genunw` to `.true.` to generate unweighted events, and specify required number of events with `nev`. Only event record format `erec = lhe`, i.e. Les Houches currently supported.
- `ymin`, `ymin`, `mmin`, `mmax`: general cuts on the dilepton rapidity and invariant mass.
- `gencuts`: flag to determine if further cuts will be placed.

## 5 Output, histograms and cuts

The input parameters for a run, the output cross section, and the generated histograms are stored in the `output[outtag].dat` file in the `bin/outputs` directory.

By default, the system rapidity and invariant mass (where appropriate) distributions are output, however the user may define their own histograms in `src/user/histo.f`. In addition, further user-defined cuts may be placed in `src/user/cuts.f`. In both cases the particle momenta are stored in the array `q(i,j)`, where  $i = 1, 2, 3$  corresponds to the  $x, y, z$  components of the 3-momentum and  $i = 4$  the energy component, while  $j$  specifies the particle number. The incoming (outgoing) protons correspond to  $j = 1, 2$  (3,4) and the central system to  $j = 5$ , while the remaining final-state particles are defined for each process in Section 7

## 6 Interfacing to Pythia

The unweighted event output can be passed to external MCs for showering and hadronization. This has only been tested for Pythia, where some care is needed in choosing the runtime options. The user should in particular produce individual runs for `diff` set to `e1`, `sda`, `sdb`, `dd`. These correspond

to the cases of purely elastic scattering, single dissociation and double dissociation. The sum of these cross sections will be equal to that of running with `diff` set to `tot`.

Then, the following flags should be set:

```
PartonLevel:MPI = off for all cases other than double dissociation, where
it should be = on
PartonLevel:Remnants = off
Check:event = off
BeamRemnants:primordialKT = off
LesHouches:matchInOut = off
PartonLevel:FSR = on
SpaceShower:dipoleRecoil = on
SpaceShower:pTmaxMatch = 2
SpaceShower:QEDshowerByQ = off
SpaceShower:pTdampMatch=1
BeamRemnants:unresolvedHadron = 1 for single dissociation (sdb), = 2 for
single dissociation (sda).
```

Note however that if rapidity vetoes are placed in the final state the survival factor is not included. For lepton pair production the user should then instead use the `SuperChic MC`, see [6] and references therein.

If no vetoes are imposed a complete implementation of MPI effects is not currently modelled here (or indeed anywhere for the PI case), but nor will it be by simply turning MPI on universally; this will greatly overestimate the contribution from MPI for elastic and inelastic production. As discussed in [6] the probability for MPI to occur in these cases is rather close to unity, while the MPI probability in double dissociation is significantly higher. The above settings therefore provide a first approximation to the more complete result, by assuming no MPI in the elastic and single dissociative cases, and default Pythia MPI generation in double dissociative production.

## 7 Notes on processes

In this section further details are given about the generated processes.

## 7.1 Processes 1–3 : lepton pair production

The production of a lepton pair,  $l^+l^-$ , with  $l = e, \mu, \tau$  for the processes 1,2,3, respectively. For cuts, the momenta of the  $l^+l^-$  are given by  $\mathbf{p}(\mathbf{a})$ ,  $\mathbf{p}(\mathbf{b})$ , and labels  $j = 6, 7$ , respectively.

## 7.2 Process 4 : lepton–lepton scattering

The production of a dilepton system via the lepton–lepton scattering process. The central lepton 1 and 2 momenta are given by  $\mathbf{p}(\mathbf{a})$  and  $\mathbf{p}(\mathbf{b})$ , and labels  $j = 6,7$  respectively. Note for the opposite sign, same flavour case the dominant  $\gamma\gamma \rightarrow l^+l^-$  process is not included. To achieve a reliable cross section prediction, a `prec` value of at least 1 % should be requested.

# 8 References

The physics of the structure function approach is described in [3,4]. Please reference both papers if you use the MC for a publication.

# 9 Version Information

Here we provide details of the changes made in the releases from version 1.01 onwards:

- Version 1.01: Bug in lepton–lepton scattering cross sections fixed. This lead to all cases with non-identical leptons being a factor of 2 too low.
- Version 1.02: Bug in electron pair production fixed. Electron mass was previously set to that of the  $\tau$ .
- Version 1.03: Latest `SF_MSHT20qed_nnlo` structure function input applied, calculated using the `MSHT20qed` set [5]. Minor bug in  $Z$ -initiated lepton pair production fixed. Very small impact on cross section.
- Version 1.04. Bug fixed in LHE event record, so that beam energy correct.

## References

- [1] A. Buckley *et al.*, Eur. Phys. J. C **75**, 132 (2015), 1412.7420.
- [2] V. Bertone, S. Carrazza, and J. Rojo, Comput. Phys. Commun. **185**, 1647 (2014), 1310.1394.
- [3] L. A. Harland-Lang, JHEP **03**, 128 (2020), 1910.10178.
- [4] L. A. Harland-Lang, Phys. Rev. D **104**, 073002 (2021), 2101.04127.
- [5] T. Cridge, L. A. Harland-Lang, A. D. Martin, and R. S. Thorne, (2021), 2111.05357.
- [6] L. A. Harland-Lang, M. Tasevsky, V. A. Khoze, and M. G. Ryskin, Eur. Phys. J. C **80**, 925 (2020), 2007.12704.