SuperChic v2.04

A Monte Carlo for Central Exclusive Production

Users guide

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Contents

1 Overview

SuperChic 2 is a Fortran based Monte Carlo event generator for central exclusive production at parton level, for a range of Standard Model final states. User–defined histograms may be output, as well as unweighted events in HEPEVT and Les Houches formats. By default the program makes use of the LHAPDF library, but otherwise the code is completely stand–alone. Relevant references are listed in Section 8.

2 Installation

A compressed tar file containing all of the relevant code can be downloaded at http://projects.hepforge.org/superchic/superchic2. To extract it, simply execute `tar -xzvf superchicv2.0.tar.gz` and the `superchicv2.0` directory will be created. This consists of:

- `bin`: the executables `superchic` and `init` and the input card `input.DAT`.
- `bin/PDFsets`: the directory where the `LHAPDF` grid files must be placed.
- `doc`: the source for this document.
- `obj`: the object files produced by the compiler.
- `src`: the Fortran source files in various subdirectories.

To compile simply run

```
> make
```

which will create the `superchic` and `init` executables in the `bin` directory as well as the object files in the `obj` directory. It is also possible to compile these executables separately with

```
> make superchic
```

and

```
> make init
```

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 this is the case, please set `LHOPT=2` in the makefile and attempt to recompile. If in the first instance of executing `init` (or `superchic`) 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 `superchic` and `init` executables can then be run in the `bin` directory, using the `input.DAT` file to adjust the input parameters by

```
> ./init < input.DAT
```

This creates the `hg[intag]`, `screening[intag]` and `sudakov[intag].dat` input files in the `bin/inputs` directory, which are used by the main `superchic` executable, where `[intag]` is specified in the input file (see below). This must be run in the first instance, and if any of the first five parameters in the input file, corresponding to the model of soft survival, the c.m.s. energy $\sqrt{s}$, the PDF set/member and the input `[intag]`, are changed. After this the main MC code may be run with

```
> ./superchic < input.DAT
```

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

- `rts`: collider energy, $\sqrt{s}$, in GeV.

- `isurv`: Model of soft survival, as defined in [1]: must be an integer from 1 to 4.

- `intag`: defines the label for the input files created by executing `init` and read in when executing `superchic`.

- `PDFname`, `PDFmember`: name of PDF set, in the appropriate format for `LHAPDF` version 5 or 6, and set number. The corresponding grid file must be present in the `bin/PDFsets` directory. Alternatively, the code is set up for use with the MMHT14 standalone PDF set [2], if the appropriate grid file is present in the `bin/PDFsets` directory. In this case the `PDFINPUT` flag in the makefile must be set to `USER` instead of the default `LHAPDF`. Other standalone PDF sets may be implemented, at the user's own risk, by suitable editing of the `src/PDFs/PDFuser.f` and `src/PDFs/alphasuser.f` files.

- `proc`: process number, to specify the produced state. These are defined in Section 6.

- `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).

- `sfaci`: set to `.false.` to turn off soft survival effects. If `.true.` then runtime is longer.

- `ncall`, `itms`: number of iterations and calls in `VEGAS` preconditioning run. Soft survival effects are turned off to decrease the runtime. 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.
- `s2int`: determines precision of pomeron loop momentum integration performed to calculated screened amplitude. While comfortably set to high enough (sub % level) precision for most uses, if the average survival factor is close to unity (as in the case of two–photon initiated processes), and/or restrictive cuts are placed, in particular on the outgoing proton momenta, it is recommended that the user increases the parameter in increments of 4, and confirms that the output is stable within the required precision. If not, it should set at a sufficiently high value that this stability is reached: this will result in a longer runtime.
- `genunw`, `nev`, `erec`: set `genunw` to `.true.` to generate unweighted events, and specify required number of events with `nev`, and event record format (`lhe` and `hepevt` for Les Houches and HEPEVT, respectively) with `erec`.
- `readwt`, `wtmax`: set `readwt` to `.true.` to read in maximum weight `wtmax` input by the user. This should be given by the output 'maximum weight' in `output[outtag].dat` of a run with `genunw=.true.`, with all other physics inputs left unchanged. Setting `readwt` to `.true.` bypasses the maximum weight evaluation stage in the run. This allows for a shorter runtime, and is useful when setting multiple runs with `genunw=.true.` (i.e. each with a different `iseed`, in order to produce multiple event records in parallel).
- `ymin`, `ymax`, `mmin`, `mmax`: general cuts on the central system rapidity and invariant mass. Note that QCD–induced processes must have `mmin` $>$ 2 GeV.
- `gencuts`: flag to determine if further cuts will be placed.
- `spincorr` : flag to determine if spin correlations are included in the particle decays. The processes for which these may be included are described in Section 7.
- `fwidth` : flag to determine if a finite width is included for χ_c production.

- `ptamin`, `etamin`, `etaamax` (...): cuts on two, three and four body final states: see Section 7 for momentum assignments.

- `rjet`, `jalg`: jet algorithm parameters: jet radius R and algorithm (`antikt` or `kt` used for 3–jet events.

- `m2b`, `pdgid1`, `pdgid2`: $\chi_{c,b}$ two–body decay parameters: set mass and PDG numbers for decays, see Section 7.

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/ouputs` 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 particle are defined for each process in Table 1.

6 Summary of processes

The generated process are summarised in Table 1.

Table 1: Generated processes, with momenta numbering specified by $p(j)$, as stored in array $q(i, j)$.

QCD–induced (Durham model)	
Number	Final–State
1	$H(5) \to b(6) + \bar{b}(6)$
2	$\gamma(6) + \gamma(7)$
3	$g(6) + g(7)$

Table 1: (continued)

4	$q(6)\ +\ \overline{q}(7)$
5	$c(6)\ +\ \overline{c}(7)$
6	$b(6)\ +\ \overline{b}(7)$
7	$g(6)\ +\ g(7)\ +\ g(8)$
8	$q(6)\ +\ \overline{q}(7)\ +\ g(8)$
9	$\pi^+(6)\ +\ \pi^-(7)$
10	$\pi^0(6)\ +\ \pi^0(7)$
11	$K^+(6)\ +\ K^-(7)$
12	$K_0(6)\ +\ K_0(7)$
13	$\rho_0(6)\ +\ \rho_0(7)$
14	$\eta(6)\ +\ \eta(7)$
15	$\eta(6)\ +\ \eta'(7)$
16	$\eta'(6)\ +\ \eta'(7)$
17	$\phi(6)\ +\ \phi(7)$
18	$J/\psi(6)(\rightarrow \mu^+(8) + \mu^-(9))\ +\ J/\psi(7)(\rightarrow \mu^+(10) + \mu^-(11))$
19	$J/\psi(6)(\rightarrow \mu^+(8) + \mu^-(9))\ +\ \psi_{2S}(7)(\rightarrow \mu^+(10) + \mu^-(11))$
20	$\psi_{2S}(6)(\rightarrow \mu^+(8) + \mu^-(9))\ +\ \psi_{2S}(7)(\rightarrow \mu^+(10) + \mu^-(11))$
21	$\chi_{c0}(5) \rightarrow \gamma(6)\ +\ J/\psi(7)(\rightarrow \mu^+(8) + \mu^-(9))$
22	$\chi_{c1}(5) \rightarrow \gamma(6)\ +\ J/\psi(7)(\rightarrow \mu^+(8) + \mu^-(9))$
23	$\chi_{c2}(5) \rightarrow \gamma(6)\ +\ J/\psi(7)(\rightarrow \mu^+(8) + \mu^-(9))$
24	$\chi_{c0}(5) \rightarrow S(6)\ +\ S(7)$
25	$\chi_{c1}(5) \rightarrow S(6)\ +\ S(7)$
26	$\chi_{c2}(5) \rightarrow S(6)\ +\ S(7)$
27	$\chi_{c1}(5) \rightarrow f(6)\ +\ \overline{f}(7)$
28	$\chi_{c2}(5) \rightarrow f(6)\ +\ \overline{f}(7)$
29	$\chi_{c0}(5) \rightarrow \pi^+(6) + \pi^-(7) + \pi^+(8) + \pi^-(9)$
30	$\chi_{c1}(5) \rightarrow \pi^+(6) + \pi^-(7) + \pi^+(8) + \pi^-(9)$
31	$\chi_{c2}(5) \rightarrow \pi^+(6) + \pi^-(7) + \pi^+(8) + \pi^-(9)$
32	$\chi_{c0}(5) \rightarrow \pi^+(6) + \pi^-(7) + K^+(8) + K^-(9)$
33	$\chi_{c1}(5) \rightarrow \pi^+(6) + \pi^-(7) + K^+(8) + K^-(9)$
34	$\chi_{c2}(5) \rightarrow \pi^+(6) + \pi^-(7) + K^+(8) + K^-(9)$
35	$\chi_{c0}(5) \rightarrow 3(\pi^+(6,8,10)\ +\ \pi^-(7,9,11))$
36	$\chi_{c1}(5) \rightarrow 3(\pi^+(6,8,10)\ +\ \pi^-(7,9,11))$
37	$\chi_{c2}(5) \rightarrow 3(\pi^+(6,8,10)\ +\ \pi^-(7,9,11))$
38	$\eta_c(5)$
39	$\chi_{b0}(5) \rightarrow \gamma(6)\ +\ \Upsilon_{1S}(7)(\rightarrow \mu^+(8) + \mu^-(9))$

Table 1: (continued)

40	$\chi_{b1}(5) \to \gamma(6) + \Upsilon_{1S}(7)(\to \mu^+(8) + \mu^-(9))$
41	$\chi_{b2}(5) \to \gamma(6) + \Upsilon_{1S}(7)(\to \mu^+(8) + \mu^-(9))$
42	$\chi_{b0}(5) \to S(6) + S(7)$
43	$\chi_{b1}(5) \to S(6) + S(7)$
44	$\chi_{b2}(5) \to S(6) + S(7)$
45	$\chi_{b1}(5) \to f(6) + \overline{f}(7)$
46	$\chi_{b2}(5) \to f(6) + \overline{f}(7)$
47	$\eta_b(5)$
Photoproduction	
48	$\rho_0(5) \to \pi^+(6)\pi^-(7)$
49	$\phi(5) \to K^+(6)K^-(7)$
50	$J/\psi(5) \to \mu^+(6)\mu^-(7)$
51	$\Upsilon_{1S}(5) \to \mu^+(6)\mu^-(7)$
52	$\psi_{2S}(5) \to \mu^+(6)\mu^-(7)$
53	$\psi_{2S}(5) \to J/\psi(6)(\to \mu^+(9) + \mu^-(10)) + \pi^+(7) + \pi^-(8)$
Two–photon collisions	
pp	
54	$W^+(\to \nu_\mu(8) + \mu^+(9)) + W^-(\to \overline{\nu}_\mu(10) + \mu^-(11))$
55	$W^+(\to \nu_e(8) + e^+(9)) + W^-(\to \overline{\nu}_e(10) + e^-(11))$
56	$e^+(6) + e^-(7)$
57	$\mu^+(6) + \mu^-(7)$
58	$\tau^+(6) + \tau^-(7)$
59	$\gamma(6) + \gamma(7)$
60	$H(5) \to b(6) + \overline{b}(6)$
e^+e^-	
61	$W^+(\to \nu_\mu(8) + \mu^+(9)) + W^-(\to \overline{\nu}_\mu(10) + \mu^-(11))$
62	$W^+(\to \nu_e(8) + e^+(9)) + W^-(\to \overline{\nu}_e(10) + e^-(11))$
63	$e^+(6) + e^-(7)$
64	$\mu^+(6) + \mu^-(7)$
65	$\tau^+(6) + \tau^-(7)$
66	$\gamma(6) + \gamma(7)$
67	$H(5) \to b(6) + \overline{b}(6)$

7 Notes on processes

In this section further details are given about the generated processes listed in Section 6. We note that the runtime is typically much shorter for photoproduction and two–photon induced processes, due to the simpler underlying theoretical calculation.

7.1 Process 1 : SM $H \to b\bar{b}$ production

The production of a SM Higgs boson of mass $m_H = 126$ GeV, decaying to $b\bar{b}$, with mass $m_b = 4.75$ GeV, with branching ratio $\mathrm{Br}(H \to b\bar{b}) = 56.1\%$. Two body cuts may be placed using the input file with b and $\bar{b}$ momenta given by `p(a)` and `p(b)`, respectively.

7.2 Process 2 : $\gamma\gamma$ production

The production of photon pairs via the $gg \to \gamma\gamma$ quark–loop induced process. Two body cuts may be placed using the input file on the final–state photons of momenta `p(a)` and `p(b)`. Amplitudes in the $\hat{s}, \hat{t}, \hat{u} \gg m_f^2$ limit are used, where m_f is the mass of the fermion in the loop.

7.3 Process 3–6 : dijet production

The production of gg, massless $q\bar{q}$ and $c\bar{c}$, $b\bar{b}$ dijets, with masses $m_c = 1.40$ GeV, $m_b = 4.75$ GeV, is given by processes 3, 4 and 5, respectively. Two body cuts may be placed using the input file with $q(b)$ and $\bar{q}(\bar{b})$ momenta given by `p(a)` and `p(b)`, respectively.

7.4 Processes 7–8 : trijet production

The production of ggg and $q\bar{q}g$ trijets, with massless quarks, is given by processes 7 and 8, respectively. Three body cuts may be placed using the input file with the q, $\bar{q}$ and g having momenta given by `p(a)`, `p(b)` and `p(c)`, respectively.

7.5 Processes 9–17 : light meson pair production

The production of light meson pairs, following the formalism described in [3, 4], where further details and definitions can be found. Two body cuts may be placed using the input file with the momenta of positive and negatively charged mesons, and the η and η' meson (for the case of $\eta\eta'$ production), given by `p(a)` and `p(b)`, respectively.

7.5.1 Processes 9–10 : $\pi\pi$ production

Charged $\pi^+\pi^-$ and neutral $\pi^0\pi^0$ production are given by processes 9 and 10, respectively. The 'Chernyak–Zhitnisky' (CZ) wave function [5] is taken for the pion with $f_\pi = 93$ MeV, i.e. with $a_2^1(\mu_0^2) = 2/3$ and the rest zero.

7.5.2 Processes 11–12 : KK production

Charged K^+K^- and neutral K_0K_0 production are given by processes 11 and 12, respectively. The CZ wave function is taken, with $f_K = f_\pi = 93$ MeV set in order to approximately account for corrections due to the strange quark mass and deviations from the wave function choice.

7.5.3 Process 13: $\rho_0\rho_0$ production

The CZ wave function is again taken, with $f_\rho = 141$ MeV.

7.5.4 Processes 14–16 : $\eta(')\eta(')$ production

$\eta\eta$, $\eta\eta'$ and $\eta'\eta'$ production are given by processes 14, 15 and 16, respectively. A general two–angle mixing scheme is taken for the η and η' decay constants, with the values given in [4]. The CZ wave function is taken for the flavour–singlet and octet $q\overline{q}$ components, and the gluonic component $a_2^G(\mu_0^2)$ is set to zero by default (although a non–zero contribution will enter at higher scales due to the wave function evolution). A non–zero starting value may be taken by adjust the variable `a2g` in the appropriate part of `scr/main/process.f`.

7.5.5 Process 17 : $\phi\phi$ production

The ϕ wave function and decay constant is given as described in Appendix B of [6].

7.6 Processes 18–20 : J/ψ and $\psi(2S)$ pair production

$J/\psi J/\psi$, $J/\psi\psi(2S)$ and $\psi(2S)\psi(2S)$ production, via the $\mu^+\mu-$ decay channel, are given by processes 18, 19 and 20, respectively; see [6] for theory discussion. The branching ratios are given by $\text{Br}(J/\psi \to \mu^+\mu^-) = 5.961\%$ and $\text{Br}(\psi(2S) \to \mu^+\mu^-) = 0.79\%$. Spin correlations in these decays may be included with the `spincorr` flag. Four body cuts on the final–state muons may be placed using the input file, with the momenta $\mu^+(8)$, $\mu^-(9)$, $\mu^+(10)$ and $\mu^-(11)$, as defined in Table 1 given by `p(a)`, `p(b)`, `p(c)` and `p(d)`, respectively.

7.7 Processes 21–23 : $\chi_{cJ} \to J/\psi\gamma \to \mu^+\mu^-\gamma$ production

χ_{c0}, χ_{c1} and χ_{c2} production are given by processes 21, 22 and 23, respectively. The $\chi_{cJ} \to J/\psi\gamma$ branching ratios are given by 1.27%, 33.9% and 19.2%, respectively, and $\text{Br}(J/\psi \to \mu^+\mu^-) = 5.961\%$. Spin correlations in these decays may be included with the `spincorr` flag. Three body cuts may be placed using the input file, with the γ, μ^+ and μ^- momenta given by `p(a)`, `p(b)` and `p(c)`, respectively.

7.8 Processes 24–28 : χ_{cJ} two–body decays

Two–body decays of the χ_{cJ} into arbitrary states are included, where the mass and PDG numbers may be specified in the input file. χ_{c1} and χ_{c2} decays into a pair of scalar states S are given by processes 25 and 26, respectively, while χ_{c1} and χ_{c2} decays into a pair of fermion states f are given by processes 27 and 28, respectively. Spin correlations in these decays may be included with the `spincorr` flag. The χ_{c0} decay (for which scalar and fermion final–states are treated in the same way) is given by process 23. Two body cuts may be placed using the input file, with the S^+ (f) and S^- ($\overline{f}$) momenta given by `p(a)` and `p(b)`, respectively.

7.9 Processes 29–31 : $\chi_c \to 2(\pi^+\pi^-)$ production

χ_{c0}, χ_{c1} and χ_{c2} production are given by processes 29, 30 and 31, via the four body decay to two $\pi^+\pi^-$ pairs, with branching ratios 2.24%, 0.76% and 1.07%, respectively. All decays performed simply according to phase space. Four body cuts on the final–state pions may be placed using the input file, with the momenta $\pi^+(6)$, $\pi^-(7)$, $\pi^+(8)$ and $\pi^-(9)$, as defined in Table 1 given by `p(a)`, `p(b)`, `p(c)` and `p(d)`, respectively.

7.10 Processes 32–34 : $\chi_c \to \pi^+\pi^-K^+K^-$ production

χ_{c0}, χ_{c1} and χ_{c2} production are given by processes 32, 33 and 34, via the four body decay to $\pi^+\pi^-K^+K^-$, with branching ratios 1.75%, 0.45% and 0.89%, respectively. All decays performed simply according to phase space. Four body cuts on the final–state pions/kaons may be placed using the input file, with the momenta $\pi^+(6)$, $\pi^-(7)$, $K^+(8)$ and $K^-(9)$, as defined in Table 1 given by `p(a)`, `p(b)`, `p(c)` and `p(d)`, respectively.

7.11 Processes 35–37 : $\chi_c \to 3(\pi^+\pi^-)$ production

χ_{c0}, χ_{c1} and χ_{c2} production are given by processes 32, 33 and 34, via the six body decay to $3(\pi^+\pi^-)$, with branching ratios 1.20%, 0.58% and 0.86%, respectively. All decays performed simply according to phase space. Six body cuts on the final–state pions may be placed using the input file, with the momenta $\pi^+(6)$, $\pi^-(7)$, $\pi^+(8)$, $\pi^-(9)$, $\pi^+(10)$ and $\pi^-(11)$ as defined in Table 1 given by `p(a)`, `p(b)`, `p(c)`, `p(d)`, `p(e)` and `p(f)` respectively.

7.12 Process 38 : η_c production

Currently included without any further decay. The $\eta_c \to gg$ width is taken as 32.2 MeV.

7.13 Processes 39–41 : $\chi_{bJ} \to \Upsilon\gamma \to \mu^+\mu^-\gamma$ production

χ_{b0}, χ_{b1} and χ_{b2} production are given by processes 30, 31 and 32, respectively. The $\chi_{bJ} \to \Upsilon\gamma$ branching ratios are given by 1.76%, 33.9% and 19.1%, respectively, and the $\mathrm{Br}(\Upsilon \to \mu^+\mu^-)$ is given by 2.48%. Spin correlations in these decays may be included with the `spincorr` flag. Three body cuts may be placed using the input file, with the γ, μ^+ and μ^- momenta given by `p(a)`, `p(b)` and `p(c)`, respectively.

7.14 Processes 42–46 : χ_{bJ} two–body decays

Two–body decays of the χ_{bJ} into arbitrary states are included, where the mass and PDG numbers may be specified in the input file. χ_{b1} and χ_{b2} decays into a pair of scalar states S are given by processes 34 and 35, respectively, while χ_{b1} and χ_{b2} decays into a pair of fermion states f are given by processes 36 and 37, respectively. Spin correlations in these decays may be included with the `spincorr` flag. The χ_{b0} decay (for which scalar and fermion final–states are treated in the same way) is given by process 32. Two body cuts may be placed using the input file, with the S^+ (f) and S^- ($\overline{f}$) momenta given by `p(a)` and `p(b)`, respectively.

7.15 Process 47: η_b production

Currently included without further decay. The $\eta_b \to gg$ width is taken as 10.8 MeV.

7.16 Processes 48–60: general comment

The equivalent photon flux for these processes is calculated as described in [7], however from version 2.04 onwards the more precise 'double–dipole' parameterisation of the proton electric and magnetic form factors given in [8] is taken.

7.17 Process 48: $\rho_0(770) \to \pi^+\pi^-$ photoproduction

Included with a simple power–law fit to the $\gamma p \to \rho p$ cross section, with the parameters given in [7]. The ρ resonance decay is treated with a simple modification of the Breit–Wigner distribution given in [9]. The $\pi^+\pi^-$ decay is performed according to phase space only and the branching ratio is assumed to be $\mathrm{Br}(\rho \to \pi^+\pi^-) = 100\%$. Two body cuts may be placed using the input file, with the π^+ and π^- momenta given by `p(a)` and `p(b)`, respectively.

7.18 Process 49: $\phi(1020) \to K^+K^-$ photoproduction

Included with a simple power–law fit to the $\gamma p \to \phi p$ cross section, with the parameters given in [7]. The K^+K^- decay is performed according to phase space only with branching ratio $\mathrm{Br}(\phi \to K^+K^-) = 48.9\%$. Two body cuts may be placed using the input file, with the K^+ and K^- momenta given by `p(a)` and `p(b)`, respectively.

7.19 Process 50: $J/\psi \to \mu^+\mu^-$ photoproduction

Included with a simple power–law fit to the $\gamma p \to J/\psi p$ cross section, with the parameters given in [7]. Spin correlations for the $J/\psi \to \mu^+\mu^-$ decay may be included with the `spincorr` flag. The branching ratio is given by $\mathrm{Br}(J/\psi \to \mu^+\mu^-) = 5.961\%$. Two body cuts may be placed using the input file, with the μ^+ and μ^- momenta given by `p(a)` and `p(b)`, respectively.

7.20 Process 51: $\Upsilon(1S) \to \mu^+\mu^-$ photoproduction

Included with a simple power–law fit to the $\gamma p \to \Upsilon p$ cross section, with the parameters given in [7]. Spin correlations for the $\Upsilon \to \mu^+\mu^-$ decay may be included with the `spincorr` flag. The branching ratio is given by $\mathrm{Br}(J/\psi \to \mu^+\mu^-) = 2.48\%$. Two body cuts may be placed using the input file, with the μ^+ and μ^- momenta given by `p(a)` and `p(b)`, respectively.

7.21 Processes 52: $\psi(2S) \to \mu^+\mu^-$ photoproduction

Included with a simple power–law fit to the $\gamma p \to \psi(2S)p$ cross section, assumed to have the same energy scaling parameter δ as in the case of J/ψ production, but with $\sigma(\psi(2S))/\sigma(J/\psi) = 16.6\%$, prior to branching. Spin correlations for the $\psi(2S) \to \mu^+\mu^-$ decay may be included with the `spincorr` flag. The branching ratio is given by $\mathrm{Br}(\psi(2S) \to \mu^+\mu^-) = 0.79\%$. Two body cuts may be placed using the input file, with the μ^+ and μ^- momenta given by `p(a)` and `p(b)`, respectively.

7.22 Processes 53: $\psi(2S) \to J/\psi(\to \mu^+\mu^-)\pi^+\pi^-$ photoproduction

Included as described above. Decay performed according to phase space, and with $\mathrm{Br}(\psi(2S) = J/\psi\pi^+\pi^-) = 34.45\%$ and $\mathrm{Br}(J/\psi \to \mu^+\mu^-) = 5.961\%$. Four body cuts on the final–state muons may be placed using the input file, with the momenta $\pi^+(7)$, $\pi^-(8)$, $\mu^+(9)$ and $\mu^-(10)$, as defined in Table 1 given by `p(a)`, `p(b)`, `p(c)` and `p(d)`, respectively.

7.23 Processes 54–55: W^+W^- production (pp)

Two–photon induced W boson pair production. Process 54 and 55 correspond to the muon and electron decay channels respectively, with $\text{Br}(W \to \nu\mu) = 10.63\%$ and $\text{Br}(W \to \nu e) = 10.71\%$. Spin correlations may be included with the `spincorr` flag. Cuts on the final–state muons may be placed using the input file, with the momenta $\mu^+(9)$, $\mu^-(11)$, as defined in Table 1, given by `p(a)`, `p(b)`, and similarly for the election decay channel.

7.24 Processes 56–59: l^+l^- production (pp)

Two–photon induced lepton pair production. Processes 56 to 59 correspond to e^+e^-, $\mu^+\mu^-$ and $\tau^+\tau^-$ production (in the latter case without further decay). Two body cuts may be placed using the input file, with the l^+ and l^- momenta given by `p(a)` and `p(b)`, respectively.

7.25 Process 59 : $\gamma\gamma$ production (pp)

The production of photon pairs via the $\gamma\gamma \to \gamma\gamma$ quark–loop induced process. Two body cuts may be placed using the input file on the final–state photons of momenta `p(a)` and `p(b)`. Amplitudes in the $\hat{s}, \hat{t}, \hat{u} \gg m_f^2$ limit are used, where m_f is the mass of the fermion in the loop.

7.26 Process 60 : SM $H \to b\bar{b}$ production (photon–initiated)

The two–photon initiated production of a SM Higgs boson of mass $m_H = 126$ GeV, decaying to $b\bar{b}$, with mass $m_b = 4.75$ GeV, with branching ratio $\text{Br}(H \to b\bar{b}) = 56.1\%$. Two body cuts may be placed using the input file with b and $\bar{b}$ momenta given by `p(a)` and `p(b)`, respectively.

7.27 Processes 61–67: e^+e^- initial state

Two–photon processes as above, but with initial–state e^+e^-.

8 References

Physics details and selected results for jet and $\chi_{c,b}$ production as well photoproduction and two–photon induced processes from `SuperChic 2` may be found in [7], while a summary of the Durham model can be found in e.g. [10–12]. Further references for other specific processes are listed below:

- SM Higgs boson: [13].
- $\gamma\gamma$: [14, 15].
- heavy $\chi_{c,b}$, $\eta_{c,b}$, quarkonia: [14, 16, 17].
- Light meson pairs: [3, 4, 18].
- J/ψ and $\psi(2S)$ pair production: [6].

References

[1] V. A. Khoze, A. D. Martin, and M. G. Ryskin, Eur.Phys.J. **C73**, 2503 (2013), 1306.2149.

[2] L. A. Harland-Lang, A. D. Martin, P. Motylinski, and R. S. Thorne, (2014), 1412.3989.

[3] L. A. Harland-Lang, V. A. Khoze, M. G. Ryskin, and W. J. Stirling, Eur.Phys.J. **C71**, 1714 (2011), 1105.1626.

[4] L. A. Harland-Lang, V. A. Khoze, M. G. Ryskin, and W. J. Stirling, Eur.Phys.J. **C73**, 2429 (2013), 1302.2004.

[5] V. L. Chernyak and A. R. Zhitnitsky, Nucl.Phys. **B201**, 492 (1982).

[6] L. A. Harland-Lang, V. A. Khoze, and M. G. Ryskin, J.Phys. **G42**, 055001 (2015), 1409.4785.

[7] L. A. Harland-Lang, V. A. Khoze, and M. G. Ryskin, (2015), 1508.02718.

[8] A1, J. C. Bernauer *et al.*, Phys. Rev. **C90**, 015206 (2014), 1307.6227.

[9] S. Leupold, W. Peters, and U. Mosel, Nucl. Phys. **A628**, 311 (1998), nucl-th/9708016.

[10] L. Harland-Lang, V. Khoze, and M. Ryskin, Int.J.Mod.Phys. **A29**, 1446004 (2014).

[11] L. A. Harland-Lang, V. A. Khoze, M. G. Ryskin, and W. J. Stirling, (2014), 1405.0018.

[12] L. A. Harland-Lang, V. A. Khoze, and M. G. Ryskin, Int.J.Mod.Phys. **A30**, 1542013 (2015).

[13] L. A. Harland-Lang, V. A. Khoze, M. G. Ryskin, and W. J. Stirling, (2013), 1301.2552.

[14] L. A. Harland-Lang, V. A. Khoze, M. G. Ryskin, and W. J. Stirling, Eur.Phys.J. **C69**, 179 (2010), 1005.0695.

[15] L. A. Harland-Lang, V. A. Khoze, M. G. Ryskin, and W. J. Stirling, (2012), 1204.4803.

[16] L. A. Harland-Lang, V. A. Khoze, M. G. Ryskin, and W. J. Stirling, Eur.Phys.J. **C65**, 433 (2010), 0909.4748.

[17] L. A. Harland-Lang, V. A. Khoze, M. G. Ryskin, and W. J. Stirling, Eur.Phys.J. **C71**, 1545 (2011), 1011.0680.

[18] L. A. Harland-Lang, V. A. Khoze, M. G. Ryskin, and W. J. Stirling, Phys.Lett. **B725**, 316 (2013), 1304.4262.