HRes version 2.3

This is a note about the `HRes` program, which combines the calculation of the cross section for Standard Model (SM) Higgs boson production in hadron collisions up to NNLO in QCD perturbation theory with the NNLL resummation of the logarithmically enhanced contributions at small transverse momenta. The calculation retains the full kinematics of the Higgs boson and of its decay products, allowing the user to apply arbitrary cuts on the final state, and to plot the corresponding distributions in the form of bin histograms. As an alternative, it is possible to write the momenta of the generated particles and the corresponding weight in an event file and analyse it by `root`. The present version of the program includes the exact dependence on the masses of the top and bottom quarks. The decay modes included are $H \to \gamma\gamma$, $H \to WW \to l\nu l\nu$ and $H \to ZZ \to 4$ leptons. When referring to this program, please quote Refs. [1, 2].

1 Introduction

The `HRes` program computes the cross section for SM Higgs boson production in hadron collisions performing the resummation of the large logarithmic contributions which appear when the Higgs boson transverse-momentum is much smaller than its mass ($p_T \ll m_H$). The method followed to perform the resummation is presented in Ref. [3].

The calculation includes the Higgs boson decay, retaining the full kinematics of the Higgs boson and of its decay products. The resummed result is consistently matched to the fixed order calculation valid at high p_T ($p_T \sim m_H$) as implemented in the numerical code `HNNLO` [4].

The program implements the exact top and bottom mass dependence up to NLL+NLO [2]. Beyond NLL+NLO, only the top quark contribution is considered, which is included up to NNLL+NNLO (see Ref. [2] for more details).

The decay modes included are $H \to \gamma\gamma$, $H \to WW \to l\nu l\nu$ and $H \to ZZ \to 4$ leptons. In the latter case the user can choose between $H \to ZZ \to \mu^+\mu^-e^+e^-$ and $H \to ZZ \to e^+e^-e^+e^-$, which includes the appropriate interference contribution.

The program treats the Higgs boson in the narrow width approximation. In the decay modes $H \to WW \to l\nu l\nu$ and $H \to ZZ \to 4$ leptons, the finite width of the W and Z bosons is instead taken into account.

The program can be downloaded from `http://theory.fi.infn.it/grazzini`. To extract it, simply use

```
tar -xzvf HRes20.tar.gz
```

and the `HRes` directory will be created. The structure of the directory is

- `bin`: The directory containing the executable `HRes` and the input and output files.
- `doc`: The directory containing this note.
- `obj`: The directory containing the object files.
- `src`: The directory containing the source of the code.

2 Implementation of cuts

Before compiling the program, the user can choose the cuts to be applied on the final states. This is done through the `cuts` subroutine. The default version of the subroutine `cuts` contains some selection cuts that are used in the search for the Higgs boson at the LHC. In the default version, the lines of the code implementing the various cuts are all commented, in order to activate the various cuts the user must uncomment the corresponding lines in `cuts.f`.

Since the resummation procedure is necessarily inclusive over the QCD radiation recoiling against the Higgs boson, cuts on jets or isolation cuts on final state leptons (photons) can *not* be implemented.

The `cuts.f` file can be found in the `/src/User` directory and the `setup.f` source file can be found in the `/src/Need` directory.

3 Compilation

The program is self-contained and it has been successfully tested on Linux and Mac-OS X environments. It supports different Fortran compilers, and allows the user to choose between built in (native) Parton Distribution Functions (PDFs) or PDFs supplied through the LHAPDF interface [5]. To compile the code, edit the `makefile` to choose compilation options and PDF implementation (by commenting and uncommenting the corresponding lines) and insert the correct path to the LHAPDF libraries in case the LHAPDF interface is used. Then descend in the `HRes` directory and simply type

- `make`

To run the program simply go in the `bin` directory and type:

- `./HRes < infile`

4 The input file

This is a typical example of input file:

```
8d3 !  Collider CME: sroot
1 1 !  Collision type:  ih1 ih2
125d0 !  Higgs mass:  hmass
62.5d0 !  Resumm.  scale:  Q1
4.75d0 !  Resumm.  scale:  Q2
1d0 1d0 !  Ren.  and Fact.  scales factors:  smuR, smuF
.false.  !  Dynamic scale
2 !  perturbative order
1 !  Higgs decay:  higgsdec
'tota' !  part
20 2000000 !  itmx1, ncall1
40 4000000 !  itmx2, ncall2
123456 !  random number seed:  rseed
92 0 !  for native-pdf only:  iset, nset
172.5d0 !  top-quark mass
4.75d0 !  bottom-quark mass
```

```
2 !  approxim parameter
'MSTW2008nnlo68cl.LHgrid' 0 !  for LHAPDF only:  'name', 'mem'
'hres_mh125_dec1_ord2' !  output file name:  runstring
.false.  'full_mh125_dec1_ord2' !  write all, file name
```

- `sroot`: Double precision variable for CM energy (GeV), in the range (1d3∼14d3).
- `ih1,ih2`: Integers identifying the beam (proton=1, antiproton=-1).
- `hmass`: Higgs boson mass (GeV). This is a double precision variable that sets the mass of the SM Higgs boson, in the range (100d0∼400d0).
- Q_1: Resummation scale (GeV). This is a double precision variable that can be different from the other scales, but always of the order $m_H/2$.
- Q_2: Second resummation scale (GeV). This is a double precision variable which controls the bottom quark contribution, and should be taken of the order of the bottom-quark mass m_b.
- `smur, smuf`: Renormalization and factorization scale factors. Double precision variables, they can be be different from each other but always of order of one.
- `dynamicscale`: When this logical variable is set to `false` the central value for renormalization and factorization scales is m_H. When `dynamicscale` it is set to `true` the central scale used in the resummed calculation is still m_H, whereas in the fixed order calculation the central scale is the transverse mass $\sqrt{m_H^2 + p_T^2}$. Scale variations can be studied by varying the `smur` and `smuf` parameters.
- `order`: Integer setting the order of the calculation: NLL+NLO (1), NNLL+NNLO (2).
- `higgsdec`: Decay mode of the Higgs: $H \to \gamma\gamma$ (1), $H \to WW \to l\nu l\nu$ (2), $H \to ZZ \to e^+e^-\mu^+\mu^-$ (31), $H \to ZZ \to e^+e^-e^+e^-$ (32).
- `part`: String identifying the part of the calculation to be performed: `virt` for resummed contribution, `real` for finite contribution, `tota` for the complete calculation.
- `itmx1, ncall1`: Number of iterations and calls to Vegas for setting the grid, respectively of the order (15∼20) and (500000∼10000000).
- `itmx2, ncall2`: Number of iterations and calls to Vegas for the main run, respectively of the order (20∼50) and (1000000∼20000000).
- `rseed`: Random number seed (integer).
- `iset, nset`: Only in case of native PDFs (in case LHAPDF is used they are dummy). Integers identifying the PDF set chosen and the eigenvector for computing PDF errors (for MSTW2008 only). A list of available PDFs is given below.
- `mtop`: Top-quark mass (GeV).
- `mbot`: Bottom-quark mass (GeV).

- `approxim`: This parameters allows the user to select the approximation to be used in the calculation: large-m_t limit (0); exact top mass dependence (1); exact top and bottom mass dependence (2).
- `name, mem`: Only in case of LHAPDFs (in case of native PDFs they are dummy). The specific PDFset name and individual PDF member it has to be initialized.
- `runstring`: String for grid and output files (max 25 characters).
- `fulloutput,namefull`: fulloutput is a logic variable (true= write, false= do not write) that decides if you want to write all the events in an output whose name is in the string 'namefull' (max 25 characters). This file can be analysed by `root` [6]. WARNING: the output file size could be from 1GB to ∼300GB, depending on the decay mode and the required statistic.

5 Output

At the end of the run, the program returns the cross section and its error. The program also writes an output file in the topdrawer [7] format containing the required histograms with an estimate of the corresponding statistical errors. During the run, the user can control the intermediate results. The plots are defined in the `plotter.f` subroutine. The user can easily modify this subroutine according to his/her needs.

6 Native Parton distributions

In order to run the `HRes` program, a parton distribution set has to be chosen. We point out that the value of $\alpha_S(m_Z)$ is not adjustable; it is hard-wired with the value of $\alpha_S(m_Z)$ in the parton distributions. Moreover, the choice of the parton distributions also specifies the number of loops that should be used in the running of α_S. A list of available parton distributions is given in Table 1. When MSTW2008 partons are used, the `nset` variable selects one of the possible 40 grids used to compute the uncertainties at 90% CL. The default choice is `nset=0`, corresponding to the central set. The variable `nset` is dummy when other sets are used.

7 Root interface

In this code you can write all the generated events on a ASCII file.

This is an example header of such file:

```
( pp -> H -> gamma(p3)+gamma(p4)
( Number of virtual and real plots:
   40   40
( n  wt            p3_0              p3_1              p3_2              p3_3              p4_0
  1  1.558323E-06  6.532088310E+01  4.209289260E+01  1.300803003E+01  4.822652089E+01  6.060344880E+01...
  1  1.558323E-06  6.656363442E+01  3.453466345E+01 -1.812075729E+01  5.394175194E+01  5.936069749E+01...
  1  1.558323E-06  6.126076995E+01  5.644590094E+01  1.563159533E+01  1.795537325E+01  6.466356195E+01...
  1  1.558323E-06  5.614183013E+01  4.188560821E+01  1.487483673E+01 -3.429635763E+01  6.978250177E+01...
  1  1.558323E-06  6.500432259E+01  4.594121258E+01 -5.624015185E+00  4.564359095E+01  6.092000931E+01...
...
```

The lines starting with "`(`" are comments. The third line is the number of `Vegas` iterations, respectively for the "virt" and "real" parts.

Each event is written on a line. The first column represent the Vegas iteration (positive integer for "virt" and negative for "real" iteration). The second column is the weight of the event: the events have different (positive or negative) weights. Only the weighted sum has physical meaning. The remaining columns are the final state particle 4-momenta: `pi_j`, where `i` is the particle label and `j` is the Lorentz index (0=energy, 1,2,3=spatial momenta).

Two elementary examples of the `root` script* to read and use such output are in the files (in the directory `bin`) `gamgam.C` for the diphoton decay and `WW.C` for the decay into two W bosons. Note that the user can apply experimental cuts in the `HRes` run, or alternatively generate the events without applying cuts and then select the events in the `root` script.

To run such script, just type on the terminal

- `root -l -q gamgam.C`

and provide the input file name `<name>`. The file containing the histograms, `<name>.root`, will be created. The computational time is about 1∼2 minutes every 1GB (it depends also on the I/O speed of the HDD).

An example of building histograms with statistical error estimation (as the topdrawer plots) is reported in the file `gamgam_error.C`. The main idea is to create a different histogram for every `Vegas` iteration and then by combining all the histograms estimate the central value and the standard deviation for each bin. To run this script the syntax is the same as for the others.

8 From version 2.0 to version 2.1

The only modification implemented in the version 2.1 of the code is that the possibility of running with a dynamic scale is provided. When the logical variable `dynamicscale` is set to `true` the central value of the renormalization and factorization scales in the fixed order calculation is the transverse mass of the Higgs boson, $\sqrt{m_H^2 + p_T^2}$. This option can be useful if the user is interested in the high-p_T tail of the spectrum.

9 From version 2.1 to version 2.2

In the version 2.2 a bug affecting the $H \to ZZ$ channels has been fixed.

10 From version 2.2 to version 2.3

In the version 2.3 a bug affecting the runs with `dynamicscale=.false.` has been fixed.

References

[1] D. de Florian, G. Ferrera, M. Grazzini and D. Tommasini, JHEP **1206** (2012) 132 [arXiv:1203.6321 [hep-ph]].

[2] M. Grazzini and H. Sargsyan, JHEP **1309** (2013) 129 [arXiv:1306.4581 [hep-ph]].

*We thank Massimo Calamai for his help with the ROOT package.

[3] S. Catani, D. de Florian and M. Grazzini, Nucl. Phys. B **596** (2001) 299 [hep-ph/0008184]; G. Bozzi, S. Catani, D. de Florian and M. Grazzini, Nucl. Phys. B **737** (2006) 73 [hep-ph/0508068]; G. Bozzi, S. Catani, D. de Florian and M. Grazzini, Nucl. Phys. B **791** (2008) 1 [arXiv:0705.3887 [hep-ph]]; D. de Florian, G. Ferrera, M. Grazzini and D. Tommasini, JHEP **1111** (2011) 064 [arXiv:1109.2109 [hep-ph]].

[4] S. Catani and M. Grazzini, Phys. Rev. Lett. **98** (2007) 222002 [hep-ph/0703012]; M. Grazzini, JHEP **0802** (2008) 043 [arXiv:0801.3232 [hep-ph]].

[5] http://lhapdf.hepforge.org/

[6] http://root.cern.ch/drupal/

[7] http://gnxas.unicam.it/XASLABwww/pag_gnxas/gnxas_rel_soft.html
http://kicp.uchicago.edu/~galtsev/topdrawer/

`iset`	Pdf set	$\alpha_S(m_Z)$
1	CTEQ4 LO	0.132
2	CTEQ4 Standard NLO	0.116
11	MRST98 NLO central gluon	0.1175
12	MRST98 NLO higher gluon	0.1175
13	MRST98 NLO lower gluon	0.1175
14	MRST98 NLO lower α_S	0.1125
15	MRST98 NLO higher α_S	0.1225
16	MRST98 LO	0.125
21	CTEQ5M NLO Standard Msbar	0.118
22	CTEQ5D NLO DIS	0.118
23	CTEQ5L LO	0.127
24	CTEQ5HJ NLO Large-x gluon enhanced	0.118
25	CTEQ5HQ NLO Heavy Quark	0.118
28	CTEQ5M1 NLO Improved	0.118
29	CTEQ5HQ1 NLO Improved	0.118
30	MRST99 NLO	0.1175
31	MRST99 higher gluon	0.1175
32	MRST99 lower gluon	0.1175
33	MRST99 lower α_S	0.1125
34	MRST99 higher α_S	0.1225
41	MRST2001 NLO central gluon	0.119
42	MRST2001 NLO lower α_S	0.117
43	MRST2001 NLO higher α_S	0.121
44	MRST2001 NLO better fit to jet data	0.121
45	MRST2001 NNLO	0.1155
46	MRST2001 NNLO fast evolution	0.1155
47	MRST2001 NNLO slow evolution	0.1155
48	MRST2001 NNLO better fit to jet data	0.1180
51	CTEQ6L LO	0.118
52	CTEQ6L1 LO	0.130
53	CTEQ6M NLO	0.118
49	MRST2002 LO	0.130
61	MRST2002 NLO	0.1197
62	MRST2002 NNLO	0.1154
71	MRST2004 NLO	0.1205
72	MRST2004 NNLO	0.1167
90	MSTW2008 LO	0.13939
91	MSTW2008 NLO	0.12018
92	MSTW2008 NNLO	0.11707

Table 1: Available PDF sets and their corresponding `iset` and values of $\alpha_S(m_Z)$.