HqT version 2.0

This is a note about the HqT program, which implements the formalism of Refs. [1, 2] to compute the transverse momentum (q_T) spectrum of the SM Higgs boson in hadron collisions. The rapidity of the Higgs boson is integrated over the entire kinematical range. When referring to the program, please quote Ref. [2, 3].

1 Overview

The program performs the resummation of the large logarithmic contributions appearing at transverse momenta q_T much smaller than the mass m_H of the Higgs boson. The method to perform the resummation is presented in Refs. [1, 2]. The resummed result is consistently matched to the fixed order calculation valid at high q_T ($q_T \sim m_H$), for which we implemented the analytic results of Ref. [4]. The program can be used at NLL+LO and NNLL+NLO accuracy. At NLL+LO the resummed part is evaluated at NLL, and the fixed order part is evaluated at LO (Higgs+1 parton). At NNLL+NLO the resummed part is evaluated at NNLL and the fixed order is evaluated at NLO (Higgs+1 or 2 partons). At NLL+LO the normalization is fixed to the total NLO cross section. At NNLL+NLO the normalization is the total NNLO cross section.

2 Compilation

The program can be downloaded from `http://theory.fi.infn.it/grazzini`

- To extract it type:
  `tar -xzvf HqT2.0.tgz`
- To compile it simply use
  `make`
- To run it type:
  `hqt < infile`

3 Use with the LHAPDF interface

The program can be compiled to be used with the LHAPDF interface [5], by setting the variable `PDFROUTINES = LHAPDF` in the makefile, and the variable LIB to the path of the LHAPDF library.

If at the first run the following error appears:

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

the following lines to the shell (bash) login script should be added:

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

When the program is launched, it will look for the LHAPDF grids in the `/usr/local/share/lhapdf/PDFsets` directory. The user can set the environmental variable `LHAPATH` to specify a different directory.

4 The input file

This is a typical example of input file:

```
'HqTspectrum.out' ! output file name
1 ! pp(1) or ppbar (-1) collisions
7d3 ! centre of mass energy
165d0 ! Higgs mass
82.5d0 ! resummation scale (Q)
165d0 165d0 ! renormalization and factorization scales
2 ! order of calculation: NLL+LO (1) NNLL+NLO (2)
92 0 ! for native-pdf only: pdf, errors (for MSTW2008 only)
3 ! for native-pdf only: nloop (for LHAPDF given by the pdfset)
'MSTW2008nnlo68cl.LHgrid' 0 ! for LHAPDF only: 'name' and 'mem'
0d0 ! g: NP spearing
0 ! normalization (0) mtop->infinity (1) full mt,mb dependence
1d0 21d0 2d0 ! qtmin qtmax qtbin
```

- `runstring`: String for output file
- `icoll`: Integer variable defining collider type: pp(1) or $p\bar{p}$ (-1) collisions
- `sroot`: Center of mass energy (GeV)
- `aMH`: Higgs boson mass (GeV). This is a double precision variable that sets the mass of the SM Higgs boson;
- `Q`: Resummation scale (GeV). It can be different from m_H: we suggest $Q = m_H/2$ as central value.
- `mur`, `muf`: Renormalization and factorization scales (GeV). They can be different from each other but always of order m_H.

- `ord`: Integer variable fixing the order of the calculation:
  1=NLL+LO and 2=NNLL+NLO;

- `ipdf,nset`: Integer variables for pdf choice and errors (dummy if LHAPDF are used).

- `nloop`: Integer variable for the number of loops to which $\alpha_{\rm S}$ should be evaluated (dummy if LHAPDF is used).

- `name,mem`: LHAPDF name (string) and member (integer): dummy if native PDFs are used.

- `g`: Double precision variable for non perturbative smearing. The smearing is applied as an additional factor $\exp\{-gb^2\}$ in the program. The choice `g=0` means that no smearing is applied to the perturbative result.

- `inorm`: Integer variable setting the normalization. Choosing `inorm=0` the program computes the cross section strictly in the $M_t \to \infty$ limit. Choosing `inorm=1` the Born cross section is evaluated exactly, as a function of the masses M_t and M_b of top and bottom quarks. We use $M_t = 175$ GeV and $M_b = 4.75$ GeV.

- `qtmin, qtmax, qtbin`: Double precision variables setting minimum, maximum and step (GeV) in loop over the transverse momenta of the Higgs boson.

5 Output

At the beginning, the code will perform a fit of the chosen parton distribution at the given factorization scale and obtain the necessary Mellin moments. Then the program computes the cross section for the given values of q_T. The results are written in a file whose name is specified by the user in the input file. An example of output corresponding to a calculation at NNLL+NLO accuracy is shown below. The transverse momentum, the purely resummed result, asymptotic and fixed order results are displayed in the first four columns, respectively. The last two columns display the final matched and switched result, respectively. The matched result is the NNLL+NLO (or NLL+LO) result. The switched result is defined as follows. It coincides with the matched result in the low q_T region up to the value of q_T at which the resummation contribution vanishes. From there on the switched result coincides with the fixed-order NLO (or LO) result.

The results are given in pb/GeV. Running on a Intel Xeon Machine with 2.8 Ghz it takes about 35 minutes to obtain this output. The same calculation at NLL+LO accuracy takes instead about 3 minutes.

```
( This is second order matching
( CM energy= 7.000TeV, collider:  1
( HqT2.0 runs with native PDFs routines,
( pdf= 92, nset= 0, nloop= 3
( alphaS( 165.00 GeV) = 0.107536
( Mh= 165.00GeV, complex plane
( Q= 82.50GeV
( mur= 165.00GeV, muf= 165.00GeV
( g= 0.00, norm= 0
( qt res asym fixor matched switched
1.0000000E+00 3.3115212E-02 -5.5647479E+00 -5.5749164E+00 2.2946766E-02 2.2946766E-02
3.0000000E+00 9.0602595E-02 2.9939817E-01 3.0323381E-01 9.4438230E-02 9.4438230E-02
5.0000000E+00 1.2928448E-01 4.5875995E-01 4.6640151E-01 1.3692604E-01 1.3692604E-01
7.0000000E+00 1.5005313E-01 3.9486126E-01 4.0518335E-01 1.6037521E-01 1.6037521E-01
9.0000000E+00 1.5792730E-01 3.2384936E-01 3.3600008E-01 1.7007802E-01 1.7007802E-01
1.1000000E+01 1.5760530E-01 2.6601235E-01 2.7958710E-01 1.7118005E-01 1.7118005E-01
1.3000000E+01 1.5244277E-01 2.2076311E-01 2.3547497E-01 1.6715463E-01 1.6715463E-01
1.5000000E+01 1.4462261E-01 1.8527475E-01 2.0087809E-01 1.6022595E-01 1.6022595E-01
1.7000000E+01 1.3550921E-01 1.5710162E-01 1.7340368E-01 1.5181126E-01 1.5181126E-01
1.9000000E+01 1.2593581E-01 1.3442424E-01 1.5125520E-01 1.4276677E-01 1.4276677E-01
2.1000000E+01 1.1640015E-01 1.1592710E-01 1.3314082E-01 1.3361387E-01 1.3361387E-01
```

6 PDFs

The HqT program can be compiled with its own Parton Distribution Functions (PDF) interface (set `PDFROUTINES = NATIVE` in the makefile) or with the LHAPDF interface (set `PDFROUTINES = LHAPDF` in the makefile). A list of available PDFs for the native PDF interface is given below.

```
C Ipdf distribution

c 0 CTEQ4M NLO (MS)
c 2 CTEQ4L LO
```

```
c 3 grv-98 NLO (MS)
c 4 MRST ft08a-98 NLO
c 5 MRST ft09a-98 NLO
c 6 MRST ft11a-98 NLO
c 7 MRST ft24a-98 NLO
c 8 MRST ft23a-98 NLO
c 9 MRST lo05a-98 LO
c 10 MRST lo09a-98 LO
c 11 MRST lo10a-98 LO
c 12 MRST lo01a-98 LO
c 13 MRST lo07a-98 LO
C 14 CTEQ5M Standard MSbar scheme
C 15 CTEQ5D Standard DIS scheme
C 16 CTEQ5L Leading Order
C 17 CTEQ5HJ Large-x gluon enhanced
C 18 CTEQ5HQ Heavy Quark
C 19 CTEQ5F3 Nf=3 FixedFlavorNumber
C 20 CTEQ5F4 Nf=4 FixedFlavorNumber
C 21 CTEQ5M1 Improved CTEQ5M
C 22 CTEQ5HQ1 Improved CTEQ5HQ
c 24 HMRS b
c 25 MRS S0
C 30 MRST 99 default (MS)

C MRST2000 set:

C 31 VNV000 new NLO (g-up)
C 32 VNV001 NNLO average
C 33 VNV002 NNLO AA C 34 VNV003 NNLO BB
C 35 VNV004 NNLO AB
C 36 VNV005 NNLO BA
C 37 VNV006 LO

C MRST2001 NLO set:

C 41 alf119 central gluon
C 42 alf117 lower alphas
C 43 alf121 higher alphas
C 44 j121 better fit to jet data

C MRST2001 NNLO set:

C 45 vnvalf1155 'average' evolution
C 46 vnvalf1155a 'fast' evolution
C 47 vnvalf1155b 'slow' evolution
C 48 vnvalf1180j better fit to jet data
```

```
C MRST2002 LO set:

C 49 lo2002

C CTEQ6:

C 50 cteq6l
C 51 cteq6m

C MRST2002 updated set:

c 61 mrst2002 NLO
c 62 mrst2002 NNLO

C MRST2004 set:
c 71 mrst2004 NLO
c 72 mrst2004 NNLO

C MSTW2008 set

c 90 LO
c 91 NLO
c 92 NNLO
```

7 From version 1.2 to 2.0

The present version of the code contains various improvements [3]. The main difference with version 1.2 is that the program now includes the exact $\mathcal{O}(\alpha_S^2)$ hard-collinear coefficients computed in Ref. [6], and the value of the resummation coefficient $A^{(3)}$ derived in Ref. [7] (the previous version of the code used a reasonable approximation of the NNLO hard-collinear coefficients and the coefficient $A^{(3)}$ was taken from threshold resummation [8]). The quantitative effect of these improvements is relatively small.

Another improvement in version 2.0 is the full implementation of the resummation scale dependence. In version 1.2 the resummation scale was fixed to $Q = m_H$. The resummation scale can now be varied around its central value (that we suggest to take as $Q = m_H/2$) to study uncertainties from yet uncalculated higher-order logarithmic contributions.

In this version of the program we provide a *matched* and a *switched* result. The matched result is the standard NNLL+NLO (or NLL+LO) result. This result should be considered reliable up to values of q_T of the order of the mass of the Higgs boson. For larger values of q_T the fixed-order result should be used. The switched result offers the user a simple automatic way to pass from the former to the latter: it coincides with the matched result in the region of low and intermediate q_T. At the value of q_T in which the effect of resummation vanishes, the switched result becomes the standard fixed order result.

Finally, two technical improvements have been implemented: the code is now compatible with different fortran compilers and it has an interface with LHAPDF [5].

References

[1] S. Catani, D. de Florian and M. Grazzini, Nucl. Phys. B **596** (2001) 299.

[2] G. Bozzi, S. Catani, D. de Florian and M. Grazzini, Nucl. Phys. B **737** (2006) 73.

[3] D. de Florian, G. Ferrera, M. Grazzini, D. Tommasini, JHEP **11** (2011) 064.

[4] C. J. Glosser and C. R. Schmidt, JHEP **0212** (2002) 016.

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

[6] S. Catani and M. Grazzini, arXiv:1106.4652 [hep-ph].

[7] T. Becher and M. Neubert, Eur. Phys. J. C **71** (2011) 1665.

[8] S. Moch, J. A. M. Vermaseren and A. Vogt, Nucl. Phys. B **688** (2004) 101.