HATHOR

HAdronic Top and Heavy quarks crOss section calculatoR.

— Release Notes —

See [1] for the original program description and [2] for the extension to single top-quark production.

Required libraries: The code uses the FF library [3] to calculate scalar one-loop integrals and the dilogarithm. Random numbers for the Monte Carlo integration are generated using the Ranlux library written by Martin Lüscher [4]. Monte Carlo integration is done using an adapted version of Vegas [5, 6]. For convenience Ranlux and the FF library are included in the package. Please cite the aforementioned libraries if you publish anything based on this code.

Installation: From version 2.0 on, the installation procedure has been changed. In particular we have separated source and object files. To install version 2.0 untar the package and change the directory to the subdirectory `lib` in the Hathor directory. Hathor requires the LHAPDF library to access the parton distribution functions. The location, where the LHAPDF library can be found on your system, can be specified through the environment variable `LHAPDF` or by editing the makefile in the library directory. The recommended way is to use the environment variable. To build the Hathor library simply type `make` in the subdirectory `lib`. This should build the FF library and the Hathor library in the subdirectory lib. Runing make in the Hathor directory should build some sample applications. Running the script `CreateJavaGui.csh` in the `gui` subdirectory should build a graphical user interface to the library. Note that this requires that the Java include file jini.h can be found in the standard location looked up by the compiler. For the graphical user interface we recommend to use the Oracle Java version.

Hathor Version 2.1

Release date: July 2014

—Enhancements—

Weak corrections to top-quark pair production

This Hathor version includes the weak corrections for top-quark pair production. In particular, corrections for the differential cross sections are provided. For the $q\bar{q}$ channel the full set of weak corrections is included. For the gluon fusion process all dominant corrections are included. Tiny corrections due to box contributions and real corrections are neglected. In Ref. [7] it has been shown that these contributions are small. This work is based on Refs. [7–9]. Please cite the corresponding articles if you use the Hathor implementation of the weak corrections in your scientific work.

Usage: To calculate the weak corrections to the differential cross section using the default parameters use for example:

```
#include "Hathor.h"
Lhapdf pdf("MSTW2008nnlo90cl");
Hathor weak(pdf);
double mt = 173.;
double gg, qqbarup, qqbardown;
gg = weak.dsigmaWeakgg(mt,s,z);
weak.dsigmaWeakqq(mt,s,z,qqbarup,qqbardown);
```

The member functions

```
double dsigmaWeakgg(double mt, double s,double z)
```

and

```
void dsigmaWeakqq(double mt, double s, double z,
                  double & up, double & down)
```

take as input the partonic center of mass energy squared and the cosine of the scattering angle z. The value returned is the partonic differential cross section $d\sigma/dz$ in pb. Note that the PDF provided in the constructor is not used when partonic cross sections are calculated. In the evaluation of the partonic cross sections we set the coupling constant $\alpha_s(\mu)$ of the strong interaction to one. The partonic cross sections for $\alpha_s \neq 1$ are obtained by multiplying the results with α_s^2. (The partonic results for the weak corrections do not depend on the factorization/renormalization scale.)

Note that the vertex corrections in the s-channel are different for incoming up- and down quarks. For convenience we have also included the leading-order QCD differential cross sections for $q\bar{q} \to t\bar{t}$ and $gg \to t\bar{t}$. They are calculated using the member functions

```
double dsigmagg(double mt, double s, double z)
```

and

```
double dsigmaqq(double mt, double s, double z)
```

The mass of the b-quark, Z-Boson, W-boson or Higgs boson can be changed using the member function

```
setmass(PARTONS parton, double mass);
```

with parton set to Hathor::BQUARK, Hathor::ZBOSON, Hathor::WBOSON, Hathor::HIGGSBOSON. As default parameters we use

$$
\begin{aligned}
m_b &= 4.82 \text{ GeV}/c^2, \\
m_Z &= 91.1876 \text{ GeV}/c^2, \\
m_W &= 80.385 \text{ GeV}/c^2, \\
m_h &= 126. \text{ GeV}/c^2.
\end{aligned}
$$

Note that these masses are only used in the evaluation of the weak corrections. The QED coupling constant can be changed using the member function

`setAlpha(double newval)`

As default value we use

$$\alpha = \frac{1}{126.3} \tag{1}$$

The sine squared of the weak mixing angle ϑ_W is set using the member function

`setSwq(double value)`

As default value we use the on-shell value

$$\sin^2(\vartheta_W) = 1 - \frac{m_W^2}{m_Z^2} \tag{2}$$

with the masses set to the values as shown before. Whenever the masses are updated ϑ_W is recalculated and set to the on-shell value. If a different value should be used an additional call to `setSwq` is required afterwards. The value used for $(\hbar c)^2$ can be changed with

`setHc2(double newval)`

As default we use

$$(\hbar c)^2 = 0.389379323 \times 10^9 \text{ GeV}^2 \text{ pb}.$$

For the coupling of the top-quark to the Higgs boson the SM value

$$-i\frac{m_t}{v}\lambda_t \quad (\lambda_t = 1) \tag{3}$$

is used. Using the method

`setLambdat(double value)`

the value for λ_t can be set to a non-SM value. Note that most Hathor methods used for the evaluation of the NNLO QCD corrections to top-quark pair production don't affect the evaluation of the weak corrections!

—Defects Addressed—

Single top-quark production: In the Wt channel an inconsistency in the evaluation of the parton flux has been fixed. The bug produced wrong results for the anti top-quark production in the Wt channel. In particular top-quark and anti top-quark cross sections at the Tevatron were slightly different.

Hathor Version 2.0

Release date: June 2014

—Enhancements—

Extension to single top-quark production:

With version 2.0 [2] we extend Hathor to single top-quark production. Based on the MCFM program [10–13] and a private implementation of the t- and s-channel for single top-quark production (based on [14]), the corresponding cross sections in next-to-leading order QCD have been made available in the new Hathor version. The inclusive cross sections for the t-channel, s-channel and Wt production are accessible via three new classes

- `HathorSgTopT`

- `HathorSgTopS`

- `HathorSgTopWt`

— offering basically the same functionality as the original Hathor class used for top-quark pair production. In particular

```
...
double res,err;
double mur=mt,muf=mt;
Lhapdf pdf(pdfname);
HathorSgTopT XS(pdf);
XS.setColliderType(Hathor::PP);
XS.setSqrtShad(8000.);
XS.setParticle(SgTop::TOPQUARK);
XS.setScheme(Hathor::LO | Hathor::NLO);
XS.getXsection(mt, mur, muf);
XS.getResult(0, val, err);
...
```

calculates the cross section for single top-quark production in pp collisions with $\sqrt{s} = 8$ TeV at NLO accuracy.

Since single production of top-quarks and anti–top-quarks is in general different, the method `setParticle` can be used to specify whether the cross section for top-quarks (`SgTop::TOPQUARK`), anti–top-quarks (`SgTop::ANTITOPQUARK`) or both added together (`SgTop::BOTH`) should be calculated. Per default the cross section for top-quark production is calculated.

In addition to the QCD coupling constant α_s single–top-quark production depends also on the weak mixing angle squared $\sin^2(\theta_W)$ and the QED coupling constant α_e. As default Hathor uses

$$\sin^2(\theta_W) = 0.2228972, \text{ and } \alpha_e = 1./132.2332298.$$

which correspond to the G-scheme, using as input $m_W = 80.385$ GeV, $m_Z = 91.1876$ GeV and $G_F = 1.1663787 \times 10^{-5}$ Gev^{-2}. Through the methods `setAlpha` and `setSwq` the values can be changed by the user. The W-boson mass can not be changed, since it is hard wired in the cross section grids which are used for interpolation of the partonic cross sections.

The CKM matrix can be read and changed using the methods `void getCkmMatrix(double ckm[3][3])` and `void setCkmMatrix(const double ckm[3][3])` To change for example V_{tb} to 0.95 the following code can be used:

```
double Vtb = 0.95
Lhapdf pdf(pdfname);
HathorSgTopT XS(pdf);
double ckm[3][3];
XS.getCkmMatrix(ckm);
ckm[2][2]=Vtb;
XS.setCkmMatrix(ckm);
```

The Hathor library does not check the unitarity of the provided matrix. It is the responsibility of the user to provide a meaningful input. Per default the CKM matrix is set to the PDG12 [15] values.

For more details on the implementation and the usage of the Hathor extension to single top-quark production we refer to [2]. Please cite the references [2, 10–14] together with the aforementioned libraries [3–6], if you use the results of this code in your publication

LHAPD6 support:

Version 2.0 of the Hathor library supports now version 6 of the LHAPDF library.

—Defects Addressed—

Hathor Version 1.5

Release date: April 2013

—Enhancements—

For the gg channel the exact results as presented in [16] have been included. As default the exact results are used for all channels. The various approximations are still accessible through the options `NNLOAPPROX` and `NOHIGHENERGY`.

—Defects Addressed—

In some cirumstances the program crashed for specific compiler versions in combination with specific PDF sets (i.e. `HERAPDF15NLO_EIG`, `CT10as`).[1] The problem has been fixed. No false results were produced since the program crashed before producing anything.

Hathor Version 1.4

Release date: March 2013

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[1] We thank our colleagues from Wuppertal and Thomas Kintscher for pointing this out.

—Enhancements—

To allow future extensions parts of the code were reorganized. This should however not effect any user code.

Exact results for additional channels

In version 1.4 we have included the exact results for additional parton channels $(qg, qq, qq'q\bar{q}'$, $q \neq q')$ as presented in refs. [17, 18]. Where available, the exact results are used as default. For convenience and comparison with earlier versions the NNLO approximate results for the aforementioned channels can be activated using the option NNLOAPPROX. For the gg channel the NNLO approximate results combined with the high energy approximation in the $(A + B)/2$ scheme is used as in version 1.3.

Select individual channels

We have introduced additional options to switch of the parton flux for specific channels. In particular we define:

`Hathor::NOQG`	no contribution from qg and $\bar{q}g$
`Hathor::NOGG`	no contribution from gg
`Hathor::NOQQB`	no contribution from $q\bar{q}$
`Hathor::NOQQ`	no contribution from qq
`Hathor::NOQQP`	no contribution from qq' $(q \neq q')$
`Hathor::NOQQPB`	no contribution from $q\bar{q}'$ $(q \neq q')$

Note that the last 3 channels appear only at next-to-next-to-leading order. Furthermore the factorization and renormalization scale invariance requires in general to include all possible channels. To include only the contribution from gluon fusion the following command would be used:

```
scheme |= Hathor::NOQG | Hathor::NOQQB | Hathor::NOQQ |
          Hathor::NOQQP | Hathor::NOQQPB;
```

Support of the LHAPDF pdf file format `.LHpdf`

The interface to LHAPDF supports now the format `.LHpdf`. If the pdfname is specified without extension, the `.LHgrid` format is used as default. If the extension `.LHgrid` or `.LHpdf` is appended to the pdfname the respective file format will be used.

—Defects Addressed—

Inconsistent function call

In versions before 1.4 the function call `getResult` is inconsistent.[2] Before 1.4 the last argument in `getResult` is defined as optional argument which can however not be combined

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[2]We thank Thomas Kintscher for pointing this out.

with the call-by-reference mechanism. The value `chi2a` is thus not properly set in versions before 1.4. For backward compatibility we have introduced now two functions:

```
getResult(int pdfset, double &integral, double &err, double & chi2a);
getResult(int pdfset, double &integral, double &err);
```

Since the returned value `chi2a` gives only a rough feedback on the quality of the Monte Carlo integration physics results should not be affected.

Hathor Version 1.3

Release date: June 2012

—Enhancements—

High energy behavior

In Ref. [19] the high energy limit of the cross section is investigated in NNLO accuracy. The dominant behavior can be predicted through BFKL dynamics. The subleading terms were estimated from a Padé approximation. In Ref. [19] it is shown that this information can be used to further constrain the $NNLO_{approx}$ predictions obtained from soft gluon resummation. In Hathor version 1.3 the high energy approximation is set as default with the (A+B)/2 prescription as described in Ref. [19]. The A-, B- or (A+B)/2-schemes as described in Ref. [19] can be selected using the member function `setHighEnergyScheme(ABSCHEMES scheme)` with `HATHOR::ASCHEME`, `HATHOR::BSCHEME`, or `HATHOR::ABSCHEME` as argument. The high energy approximation can be switched off with the option `NOHIGHENERGY`. A detailed example reproducing the central values from Tabs. 1–3 of Ref. [19] is given in `demo-hathor-1.3.cxx`.

Exact NNLO results for qq channel

In Ref. [20] first results for the NNLO corrections for the $q\bar{q} \to t\bar{t}$ channel are presented. The results are given in terms of a fit function. We have implemented the corresponding formulae (i.e. eqs. (3)–(8) of [20]) in the current Hathor version.

1. Per default Hathor uses the option `NNLO` with the exact results for the $q\bar{q}$ channel while for the remaining contributions $NNLO_{approx}$ is used together with the high energy approximation of [19] in the (A+B)/2 scheme.

2. To activate the approximate results (as available in previous version 1.2) use the option `NNLOAPPROX` together with the option `NOHIGHENERGY`.

If the exact NNLO results for $q\bar{q}$ channel is used Ref. [20] must be cited.

—Defects Addressed—

Inconsistent handling of error PDFs in rare circumstances

In previous Hathor versions a minor inconsistency was introduced when error PDF sets were used with different values for α_s for each error PDF (i.e. ABKM or ABM set). The problem occured only when the option `PDF_SCAN` was used for the specific PDF sets. We note that most PDF sets use a common α_s value for all error PDFs so that the results are not affected by the inconsistency. In the case of ABKM and ABM the difference of the different α_s values is very small so that the total error introduced is at the per cent level or even smaller.

Hathor Version 1.2

Release date: September 2011

—Enhancements—

Runtime

Minor change in phase space mapping and PDF evaluation to improve speed.

—Defects Addressed—

PDF error evaluation

Fix concerning the evaluation of PDF uncertainties:
Since `LHAPDF` does not provide a method to figure out whether asymmetric or symmetric errors are used within the error PDFs it was up to now up to the user to select one or the other by adding the option `PDF_SYM_ERR` (Hathor default is asymmetric error). However even with the option `PDF_SYM_ERR` set the additional factor $1/\sqrt{N}$ required for NNPDF was not properly taken into account (thanks to U. Husemann for pointing this out).
In version 1.2 we have taken now the following approach:

- New option `NNPDF` is introduced to select the NNPDF error evaluation. This option also forces `PDF_SYM_ERR` to be set.

- If the strings "NNPDF" or "abkm" are found in the PDF name the option `PDF_SYM_ERR` is used and in case of NNPDF the additional factor $1/\sqrt{N}$ is introduced.

- New functions to register an own function provided by the user to evaluate the PDF uncertainty:

  ```
  void clearErrorFun();
  void setErrorFun(void (*fun)(int n, double res[],double & up,
                              double & down))
  ```

n is the number of PDF sets, `double res[]` the result of the integration for each set (`res[0]` is the central value), `up` and `down` are the up and down errors as evaluated by the user in `fun`.

Example:

```
void symerr(int n,double res[], double & up, double & down){
  for(int i=1; i <= n; i++){
    up += pow(res[i]-res[0],2);
  }
  up = sqrt(up);
  down = up;
}
...
Lhapdf lhapdf(pdfname);
Hathor XS(lhapdf);
XS.setErrorFun(symerr);
```

To remove the function use: `XS.clearErrorFun();`

Hathor Version 1.1

Release date: March 2011

—Enhancements—

—Defects Addressed—

PDFs error evaluation

Using NNPDF created a segmentation fault when using `PDF_SCAN`. Problem fixed, PDF sets with up to 1020 error PDFs are now possible.

Hathor Version 1.0

Release date: July 2010
First public version.

References

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[16] M. Czakon, P. Fiedler and A. Mitov, *"The total top quark pair production cross-section at hadron colliders through $O(\alpha_S^4)$"*, `arxiv:1303.6254`.

[17] M. Czakon and A. Mitov, *"NNLO corrections to top pair production at hadron colliders: the quark-gluon reaction"*, JHEP 1301, 080 (2013), `arxiv:1210.6832`.

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