HEPLike: an open source framework for experimental likelihood evaluation

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Abstract

We present a computer framework to store and evaluate likelihoods coming from High Energy Physics experiments. Due to its flexibility it can be interfaced with existing fitting codes and allows to uniform the interpretation of the experimental results among users. The code is provided with large open database, which contains the experimental measurements. The code is of use for users who perform phenomenological studies, global fits or experimental averages.

Keywords: experimental high energy physics, likelihoods

PROGRAM SUMMARY/NEW VERSION PROGRAM SUMMARY

Program Title: HEPLike
Licensing provisions (please choose one): GPLv3
Programming language: C++

Supplementary material:
Journal reference of previous version: FIRST VERSION OF PROGRAM

Nature of problem (approx. 50-250 words): Provide a uniform way of store, share and evaluate experimental likelihoods in a proper statistical manner. The code can be easily interfaced with existing global fitting codes. In addition a large database with the measurements is published. The program targets users who perform in their scientific work: phenomenological studies, global fits or measurements

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averages. The HEPLike has been created for FlavBit project[1], which was used to perform several analysis[2,3] and here we present an updated version, which can be used in standalone mode.

Solution method(approx. 50-250 words): C++ code that evaluates the statistical properties of the measurements without user intervention. The large open database is provided as well. The measurements are stored in YAML files allowing for easy readability and extensions.

References

[1] arXiv: 1705.07933
[2] arXiv: 1705.07935
[3] arXiv: 1705.07917
1. Introduction

In the High Energy Physics (HEP) the experimental measurements are performed by several collaborations, which measure various different observables. The experimental results are presented in various ways; some being as simple as a measurement with an Gaussian error, some more complicated as multiple correlated measurements with asymmetric errors or in some places even a full likelihood function is being published. To make things more complicated in some cases multiple representations of the same measurement are being published. All of this makes it hard to directly use and compare various different results. It also leaves a room for misinterpreting the results by theorists, which use these inputs to their studies. It happens that the asymmetric errors are being symmetrized, instead of using the full likelihood only central value with approximated asymmetric error is being used.

The High Energy Physics Likelihoods (HEPLike) is a computer program that allows to store and share the likelihoods of various measured quantities. The published code can be useful for users performing phenomenological studies using experimental results, global fitting collaborations or experimental averages. Thanks to its structure it is easy to be interface with existing codes. It simplifies the work of people as instead of looking up the appropriate measurement and coding up their own likelihood they can download the database of measurements and choose the one they need. Furthermore, it shifts the burden of constructing the proper likelihood functions back to the experimentalists, which performed the measurement at the first place and are clearly the most appropriate people to handle this task.

The computer code described in this paper is written in C++, making it useful for majority of fitting programs available on the market [1, 2, 3, 4, 5]. The library can be used in both the $\chi^2$ and likelihood fits. Moreover, it contains a statistical module with useful functions that can be used in the statistical analysis. Besides the computer code a database with the likelihoods is being published. The measurements are stored in the YAML files making them easy to read by both the machine and human. This database can be easily extended by adding new YAML files if new measurement becomes available. With the software we provide useful utilities, which allows to perform searches inside the database, create BiBtex containing publications, which have been in the fit, etc.

The paper is organized as follows: in Sec. 2 construction of the likelihood functions is presented. Sec. 3 explains the detailed code implementations and
data storage, while Sec. 4 describes how to install and use HEPLike software.

2. Likelihood constructions

In this section we will present how likelihoods in HEPLike are stored and constructed. Each measurement is stored in separate YAML file. There are several ways collaborations published their results depending on the measurements itself:

- Upper limits,
- Single measurement with symmetric uncertainty,
- Single measurement with asymmetric uncertainty,
- Multiple measurements with symmetric uncertainty,
- Multiple measurements with asymmetric uncertainty,
- One dimensional likelihood function,
- n-dimensional likelihood function.

In addition, there is growing interest from the community that the experimental collaborations instead of only the results of the analysis publish also the dataset that has been used to obtain the result. For this future occasion we have also implement a way that this data can be directly used in the fits.

Each of these cases has a different module of HEPLike that is designed to evaluate the likelihood functions. In this section we will present the statistical treatment of the above cases and the modules that are responsible for their evaluation. Each of the YAML files is required to have the following information (here for example we use the $R_{K^*}$ measurement [7]):

BibCite: Aaij:2017vbb
BibEntry: '@article{Aaij:2017vbb,
    author = "Aaij, R. and others",
    title = "Test of lepton universality with $B^0 \rightarrow K^{*0} \ell^+ \ell^-\$ decays",
    collaboration = "LHCb",
    journal = "JHEP",
}
The above informations are used to store the information relevant for the bookkeeping. For instance the entries BibCite and BibEntry correspond to the information that are used to generate a BiBtex citation file with the measurements that have been used in the studies. The DOI corresponds to the digital object identifier of the publication. The Decay defines the process that has been studied. It can also be replaced by the Process entry. The Name is a unique name of this measurement type. If the measurement gets updated with more data or by other collaboration the Name entry in the new YAML file should be the same as in the old one. Source entry corresponds to the source of the measurement. This can be either a HEPData or the collaboration itself. The SubmissionYear (PublicationYear) refers to the year of appearance (publication) of the result. The Arxiv codes the Arxiv number,
while the **Collaborations** stores the information which experimental collaboration has performed the measurement. Finally, the **Kinematics** stores additional information about the kinematic region that has been measured. The **HLAuthor** and **HLEmail** encode the information about the **YAML** file author and his email in case user needs further information about the encoded measurement. Last but not least the entry **HLType** contains the information about which **HEPLike** object should be used to read the file.

Reading of this content in the **YAML** is implemented in the **HLData** class. All other classes that construct the likelihood functions inherit from this class its capabilities. Please note that if the information is missing in the **YAML** file the program will omit reading this entry. The only exception is the **FileName**, which is mandatory. If a user wants to be notified by the program that some informations are missing the **HL_debug_yaml** variable has to be set to **true** (default value is **false**).

### 2.1. Upper limits

In case where the measurement did not observe a significant access of signal candidates the collaborations usually report an upper limit on the measured quantity. Commonly 90% or 95% upper limits are quoted. Experiments use various statistical approaches to compute this limits. It can be the **CLs** method [8], Feldman–Cousins [9] or some variation of Bayesian methods [10]. Publication of only an upper limits does not provide enough information to use the result in global fits. However, nowadays experiments besides the aforementioned upper limits publish a full p-value scans. Examples of such scans are shown in Fig. 1. The plots are usually available in digital format, which allows the information to be extracted and used in computer program.

In **HEPLike** a class **HLLimit** is responsible for handling this type of measurements. It reads the **YAML** file that contains the standard information about the measurement (see Sec. 2 for details). The additional information of the observed **CLs**/p-value is stored in the **YAML** file in the following way:

```
Cls:
  - [0.0, 1.0]
  - [1.0e-10, 0.977091694706]
```

Please note that the besides this information the previous information from Sec. 2 should be included.
Figure 1: Example of p-value scans for the $B^0 \to \tau^- \tau^+$ [11] (left) and $D \to e \mu$ [8] (right). Please note that the CL$_s$ value can be interpreted as p-value as explained in [12]. The black line corresponds to the observed CL$_s$/p-value.

- $[2.0 \cdot 10^{-10}, 0.954375824297]$
- $[3.0 \cdot 10^{-10}, 0.93200355343]$
- $[4.0 \cdot 10^{-10}, 0.910630700546]$
- $[5.0 \cdot 10^{-10}, 0.889382721809]$

The CL$_s$ can be replaced in the YAML file by p-value as they correspond to the same information. The first number in each array is the value of tested hypothesis (for example branching fraction), while the second is the corresponding CL$_s$/p-value. These values are then interpreted using a $\chi^2$ distribution with one degree of freedom:

$$pdf(x) = \frac{1}{2^{1/2} \Gamma(1/2)} x^{1/2-1} e^{-x/2},$$

which had the cumulative distribution function defined as:

$$cdf(x) = \frac{1}{\Gamma(1/2)} \gamma(1/2, x/2).$$

In the above equations the $\Gamma(x)$ and $\gamma(k, x)$ correspond to Gamma and incomplete gamma functions. By revering the $cdf(x)$ one can obtain the $\chi^2$ value:

$$\chi^2 = cdf^{-1}(1 - p),$$

where $p$ corresponds to the p-value of a given x hypothesis. This $\chi^2$ can be
then translated to the log-likelihood via Wilks theorem [13]:

$$- \log(\mathcal{L}) = \frac{1}{2} \chi^2,$$

(4)

where the $\mathcal{L}$ is the likelihood. The user can choose if he wants to obtain the $\chi^2$, likelihood or a log-likelihood value of a given hypothesis.

### 2.2. Single measurement with symmetric uncertainties

The simplest case of a published experimental result is a single value with a symmetric uncertainty. This is for example a typical result of an PDG of HFLAV average [14, 15]. The measurement is coded in the YAML file as:

```
Observables:
- [ "Br_A2BCZ", 0.1, 0.05, 0.01 ]
```

The first argument in the array "Br_A2BCZ" corresponds to the observable name. Then the first number corresponds to the measured central value. The 2nd and the 3rd number are the statistical and systematic uncertainties. In case where only one uncertainty is available the 3rd number should be omitted and it will be automatically set to 0 in the software. We have decided to keep the plural Observables to be more uniform in case where more observables are measured.

The module responsible for reading this YAML file is called HL_Gaussian, it calculates the $\chi^2$ for an $x$ hypothesis:

$$\chi^2 = \frac{(x_{obs} - x)^2}{\sigma_{stat}^2 + \sigma_{syst}^2},$$

(5)

where the $x_{obs}$ correspond to the measured central value in the YAML file and the $\sigma_{stat}$ and $\sigma_{syst}$ are the statistical and systematic uncertainties respectively. This can be the again translated to the likelihood and log-likelihood value using Eq. 4.

### 2.3. Single measurement with asymmetric uncertainties

A simple extension of the Gaussian uncertainty is when an asymmetric uncertainty is reported. This type of measurements although less frequent appear in the literature. The publication in this case reports the central value and two uncertainties: $\sigma_+$ and $\sigma_-$, which correspond to the right (for values larger than the measured central value) and left (for values smaller than the measured central value) uncertainty. In HEPlike we have created a HL_BifurGaussian class, which reads the following entry in the YAML file:
Observables:
- [ "Br_A2BCZ", 0.1, 0.05, -0.06, 0.01, -0.02 ]

The first argument is again the name of the observable and the second one is its central value. The third and fourth arguments correspond to the statistical $\sigma_+$ and $\sigma_-$ uncertainties, while the fifth and sixth to the systematical $\sigma_+$ and $\sigma_-$ uncertainties. It is important to keep the minus sign before the left side uncertainties. The code will indicate the error in case of missing sign. In some cases the systematical uncertainty is reported to be symmetric. In such case the last number can be omitted in the YAML entry.

In the literature there exist number of ways to interpret asymmetric uncertainties [16]. We have chosen the most commonly used one which is the so-called bifurcated Gaussian:

$$\chi^2 = \begin{cases} 
\frac{(x_{\text{obs}}-x)^2}{\sigma_+^2}, & \text{if } x \geq x_{\text{obs}} \\
\frac{(x_{\text{obs}}-x)^2}{\sigma_-^2}, & \text{if } x < x_{\text{obs}},
\end{cases}$$

(6)

where the $\sigma_{\pm}^2$ is the sum of squared statistical and systematic uncertainties for right/left case. Once $\chi^2$ is calculated it can be translated to the log-likelihood using Eq. 4.

2.4. Multiple measurements with symmetric uncertainties

Nowadays the most common are simultaneous measurements of various quantities, which are correlated between each other. For instance cross section measurements in different kinematic bins, or measurements of angular coefficients in heavy mesons decays. In HEPlike the class responsible for handling these cases is called HL_nDimGaussian. It reads the following information from the YAML file:

Observables:
- [ "BR1", 0.1, 0.02 ]
- [ "BR2", 0.2, 0.01, 0.01 ]
- [ "BR3", 0.4, 0.04 ]

Correlation:
- [ "BR1", "BR2", "BR3" ]
- [ 1. , 0.2 , 0 ]
- [ 0.2 , 1. , 0. ]
- [ 0 , 0. , 1. ]
The information in the “Observables” entry is exactly the same as in the HL_Gaussian class. Please note that similarly to the previous class the systematic uncertainty is not mandatory and in case if it is not provided the code will treat it as 0. The next entry in the YAML file is the “Correlation”, which encodes the correlation matrix. The first "row" is the names of the variables it is important to keep the same order of variables as in the “Observables” entry. The HL_nDimGaussian evaluates the $\chi^2$ in the following way:

$$\chi^2 = V^T \text{Cov}^{-1} V,$$

(7)

where $V$ is a column matrix, which is the difference between the measured and the tested i-th observable value. The Cov is a square matrix, constructed from the correlation matrix (Corr): $\text{Cov}_{i,j} = \text{Corr}_{i,j}\sigma_i\sigma_j$.

Often a user does not want to use the full set of measured quantities but just their subset. In this case a function `Restrict(vector<string>)` can be used. By passing in a form of vector the list of observables to be used, the program will create new smaller covariance matrix, which will be used to evaluate the $\chi^2$. In a similar manner the $\chi^2$ can be translated to the likelihood and log-likelihood value by Eq. 4.

2.5. Multiple measurements with asymmetric uncertainties

More complicated case is when multiple correlated measurements are reported with asymmetric uncertainties. The case is similar to the one discussed in Sec. 2.3 and same statistic comments apply in this case. The YAML file encoding such a measurement will contain the following entries:

Observables:
- [ "BR1", 0.1, +0.02, -0.01, 0.02]
- [ "BR2", 0.2, +0.01, -0.05, +0.03, -0.02]
- [ "BR3", 0.3, +0.04, -0.03, 0.05]

Correlation:
- [ "BR1", "BR2", "BR3"]
- [ 1. , 0.1 , 0.2 ]
- [ 0.1 , 1. , 0.1 ]
- [ 0.2 , 0.1 , 1. ]

The meaning of the “Observables” entry is the same as in the previous class (cf. Sec. 2.3) and the “Correlation” encodes the same information as
in the HL
DimGaussian class (cf.. Sec. 2.4). The rules about the minus sign and symmetric systematic uncertainty are the same as in case of the HL_BifurGaussian (cf. Sec. 2.3). The difference arises when one evaluates the $\chi^2$, namely the cov matrix is constructed depending if $\sigma_+$ and $\sigma_-$ uncertainty is relevant:

$$
\text{Cov}_{i,j} = \begin{cases} 
\text{Corr}_{i,j} \sigma_i \sigma_j^*, & \text{if } x^i \geq x^i_{\text{obs}} \text{ and } x^j \geq x^j_{\text{obs}} \\
\text{Corr}_{i,j} \sigma_i^* \sigma_j, & \text{if } x^i \geq x^i_{\text{obs}} \text{ and } x^j < x^j_{\text{obs}} \\
\text{Corr}_{i,j} \sigma_i^* \sigma_j^*, & \text{if } x^i < x^i_{\text{obs}} \text{ and } x^j \geq x^j_{\text{obs}} \\
\text{Corr}_{i,j} \sigma_i \sigma_j^*, & \text{if } x^i < x^i_{\text{obs}} \text{ and } x^j < x^j_{\text{obs}} 
\end{cases}
$$ (8)

The obtained Cov matrix is then used to calculate the $\chi^2$ using Eq. 7. The rest follows the same procedure as described in Sec. 2.4.

### 2.6. One dimensional likelihood function

The best way a result can be published is by providing the (log-)likelihood function. This type of results are more and more common in the literature. The most easy is the one-dimensional likelihood scans as can be presented in form of a figure, which examples are shown in Fig. 2.

![Figure 2](image)

**Figure 2:** Examples of published one-dimensional likelihoods in the Lepton Universality Violation of the $B \rightarrow K^* \ell \ell$ [7] (left) and $B \rightarrow K \ell \ell$ [17] (right).

The biggest advantage of publishing the results in this form is its completeness. The (log-)likelihood curve contains all the information about all the non-Gaussian effects and incorporates the systematic uncertainties. The technical problem is how to publish such information. Usually plots are published in the pdf or png formats which makes them hard to be used. Since experiments are mostly using ROOT [18] framework the plots are saved also in
the C format, which contains the points in the form of arrays. This of course makes the points accessible however it is not easy to automate retrieving this data from the C file. The best solution is provided by the HEPData portal [19]. It allows to download the data in a user preferred format. In HEPLike we have chosen to use the ROOT format by default, in which the data points are saved in the form of a TGraph object, which is also the way experimentalists like to store this information. In the YAML file we specify the path of the ROOT in the following way:

```plaintext
ROOTData: data/HEPData-ins1599846-v1-Table_1.root
TGraphPath: "Table 1/Table1D_y1"
```

The ROOTData encodes the location of the ROOT file, while the TGraphPath encodes the location of the TGraph object in that ROOT file. In HEPLike the class HL_ProfLikelihood is responsible for reading and encoding this likelihood. The value of the log-likelihood can be then translated again into the $\chi^2$ with Eq. 4.

### 2.7. n-dimensional likelihood function

The natural extension of one dimensional likelihood is an n-dim likelihood, where $n \geq 2$. Currently experimental collaborations publish only 2-dim likelihood functions (cf. Fig. 3).

![Figure 3: Examples of published two-dimensional likelihoods. The $\mathcal{B}(B_s^0 \to \mu\mu)$ vs $\mathcal{B}(B_d^0 \to \mu\mu)$ likelihood [20] (left) and $\sigma(t\bar{t}Z)$ vs $\sigma(t\bar{t}W)$ likelihood [21] (right).](image-url)
The natural way of encoding such information is a histogram: \( \text{TH2D} \) or \( \text{TH3D} \) and we have chosen this way to store this information. The corresponding entry in the \text{YAML} \) file looks as following:

\begin{verbatim}
ROOTData: data/LHCb/RD/Bs2mumu_5fb/histB2mumu.root
TH2Path: "h_2DScan"
\end{verbatim}

Similar to the one dimensional likelihood (Sec. 2.6) the \text{ROOTData} \) encodes the location of the \text{ROOT} \) file, while the \text{TH2Path}(\text{TH3Path}) encodes the location of the \text{TH2D}(\text{TH3D}) object. In the long run the community will have to address the question how to publish higher dimensional likelihoods and this module (\text{HL_nDimLikelihood}) will have to be extended for such use cases.

### 2.8. Fits to experimental data

It is possible that in the future experimental collaborations besides the results will make the datasets public. The procedure and the form in which the data should be published is not decided and there is an ongoing debate if the published data should correspond to the raw detector data, the final selected points used in the analysis or something between? Clearly publishing a raw data is problematic, as people outside the collaboration do not have the necessary knowledge about the calibration and efficiency correction procedures or data taking conditions. The most useful way to publish the dataset is to allow the experimentalists to perform all the selection, all the necessary efficiency corrections and publish the final dataset that has been used for analysis. This would allow the theory community to use the dataset directly in their fits without knowing the technicalities about the experimental data analysis. For this case in \text{HEPLike} \) we have implemented such a class \text{HL_ExpPoints}.

The data are stored in the \text{TTree} \) structure located in the \text{ROOT} \) file. The \text{YAML} \) file encodes this information in form:

\begin{verbatim}
ROOTData: data/toy/data.root
TTreePath: t
Observables:
  - [ x ]
  - [ y ]
  - [ z ]
Weight: w
\end{verbatim}
where the ROOTData points to the ROOT file and the TTreePath stores the information of the TTree location inside the ROOT file. It is assumed that the experiments will provide all the corrections in form of event-by-event weights. The name of the weight inside the TTree is encoded in the Weight entry. In general the data points are elements of $\mathbb{R}^n$ vector space, which coordinates are stored in the Observables entry.

The only thing that user needs to provide to the HL_ExprPoints object is a pointer to the function to be fitted. The function should have a form: double (*fun)(vector<double> par , vector<double> point), where the par vector encodes the parameters that want to be fitted and the point corresponds to a data point. The HL_ExprPoints will then evaluate the likelihood:

$$L(\omega) = f(x|\omega)w(x)$$

for the whole dataset. In the above the x corresponds to the n-dimensional point, $\omega$ denotes the parameters that want to be fitted par, and $f$ denotes the fitting function (fun). The HEPLike does not provide a minimalizer or a scanner tool as it is not purpose of this type of software. It has to be interfaced with proper scanner tool for example [1]. Again the user can decide if he/she prefers to perform a $\chi^2$ or log-likelihood fit.

The biggest advantage of such format is the compatibility with the experimental analysis. Experimentalist can in principle publish as well the function that they have used to fit this data and therefore a theorists reproduce the experimental result and start where the experimentalists finished.

3. Code implementation

In this section we will discuss the implementation of the code used to create likelihoods discussed in Sec. 2. The code is build in several classes:

- **HL_Data**: base class from which other classes inherit their base functionality.
- **HL_Limit**: class that handles the upper limit measurements.
- **HL_Gaussian**: class that handles measurements with Gaussian uncertainty.
- **HL_BifurGaussian**: class that handles measurements with asymmetric uncertainty.
• **HL_nDimGaussian**: class that handles measurements with n-dimensional Gaussian uncertainties.

• **HL_nDimBifurGaussian**: class that handles measurements with n-dimensional asymmetric uncertainties.

• **HL_ProfLikelihood**: class that handles measurements with one-dimensional likelihood function.

• **HL_nDimLikelihood**: class that handles measurements with 2(3)-dimensional likelihood function.

• **HL_ExpPoints**: class that allows to perform the fits to experimental datasets.

In Tab. 1 we present the functionality of these classes. In addition we present the hierarchy of the structure of the class inheritance in Fig. 4.

Table 1: Functions available in the HEPLike software.

| Function               | Description                                                                 |
|------------------------|-----------------------------------------------------------------------------|
| HL_Data()              | Constructor of the HL_Data class.                                            |
| HL_Data(string)        | Constructor of the HL_Data class. The argument that is taken by constructor is the path for the YAML file encoding the measurement. |
| HL_Limit()             | Constructor of the HL_Limit class.                                           |
| HL_Limit(string)       | Constructor of the HL_Limit class. The argument that is taken by constructor is the path for the YAML file encoding the measurement. |
| HL_Gaussian()          | Constructor of the HL_Gaussian class.                                        |
| HL_Gaussian(string)    | Constructor of the HL_Gaussian class. The argument that is taken by constructor is the path for the YAML file encoding the measurement. |
| HL_BifurGaussian()     | Constructor of the HL_BifurGaussian class.                                   |
| Function                          | Description                                                                 |
|----------------------------------|-----------------------------------------------------------------------------|
| HL_BifurGaussian(string)          | Constructor of the HL_Gaussian class. The argument that is taken by constructor is the path for the YAML file encoding the measurement. |
| HL_nDimGaussian()                | Constructor of the HL_nDimGaussian class.                                   |
| HL_nDimGaussian(string )         | Constructor of the HL_nDimGaussian class. The argument that is taken by constructor is the path for the YAML file encoding the measurement. |
| HL_nDimBifurGaussian()           | Constructor of the HL_nDimBifurGaussian class.                              |
| HL_nDimBifurGaussian(string)     | Constructor of the HL_nDimBifurGaussian class. The argument that is taken by constructor is the path for the YAML file encoding the measurement. |
| HL_ProfLikelihood()              | Constructor of the HL_ProfLikelihood class.                                 |
| HL_ProfLikelihood(string)        | Constructor of the HL_ProfLikelihood class. The argument that is taken by constructor is the path for the YAML file encoding the measurement. |
| HL_nDimLikelihood()              | Constructor of the HL_nDimLikelihood class.                                 |
| HL_ProfLikelihood(string)        | Constructor of the HL_nDimLikelihood class. The argument that is taken by constructor is the path for the YAML file encoding the measurement. |
| HL_ExpPoints()                   | Constructor of the HL_ExpPoints class.                                     |
| HL_ExpPoints(string)             | Constructor of the HL_ExpPoints class. The argument that is taken by constructor is the path for the YAML file encoding the measurement. |
| read_standard()                  | Function that reads the general information about the measurement from the YAML file. |
| Function                      | Description                                                                                                                                                                                                 |
|-------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| `set_debug_yaml(bool)`        | Function that enables debugging the YAML file. By default the debugging is switched off and can be switched on by passing a `true` bool argument to this function. Debugging will print a message that for a given information in the YAML file is missing. |
| `Read()`                      | Function reading the YAML file. The function                                                                                                                                                                 |
| `GetChi2(double)`             | Function that returns the $\chi^2$ value for a given point (passed to the function as double). Function is available for all classes besides HL_Data.                                                            |
| `GetLogLikelihood(double)`    | Function that returns the log-likelihood value for a given point (passed to the function as double). Function is available for all classes besides HL_Data.                                                            |
| `GetLikelihood(double)`       | Function that returns the likelihood value for a given point (passed to the function as double). Function is available for all classes besides HL_Data.                                                            |
| `GetCLs(double)`              | Function that returns CLs or p-value for a given point (passed to the function as double). The function is a member of the HL_Limit class.                                                                     |
| `Restrict(vector<string>)`    | Function that restricts number of observables from the YAML file. Function is a member of the HL_nDimGaussian, HL_nDimBifurGaussian and HL_nDimLikelihood classes.                                          |
| `InitData()`                  | Function of HL_ExpPoints class that reads to the memory the data from the TTree object.                                                                                                                     |
| `Profile()`                   | Function of HL_nDimLikelihood class that creates the profile log-likelihood projections.                                                                                                                     |
| `SetFun()`                    | Function of HL_ExpPoints class, that sets the pointer to the function to be fitted.                                                                                                                      |
4. Installation and usage

In this chapter we will present the requirements and installation for the HEPLike package. The software is distributed via the github site: https://github.com/mchrzasz/HEPLike

In order to compile HEPLike the following packages (and the minimal version) needs to be installed:

- git
- cmake, 2.8
- yaml-cpp, 1.58.0
- gsl, 2.1
- Boost, 1.58.0
- ROOT, 6.08

The compilation is done in the following way:

```
1 cd <installation dir>
2 git clone https://github.com/mchrzasz/HEPLike.git
3 cd HEPLike
4 mkdir build
5 cd build
```
In the above the `make` can be replaced with `make -jN`, where N is the number of threads that user wants to be used for compilation. Please note that in case of non standard installation of some packages one might have to provide `cmake` with a proper path to the library. After successful compilation a `libHEPLike.a` and `libHEPLike.so` libraries will be created in the `build` directory.

The `HEPLike` is provided with seven examples:

- **Br_example.cc**: example program showing the usage of the `HL_Gaussian` class.
- **BrBifurGaussian_example.cc**: example program showing the usage of the `HL_BifurGaussian` class.
- **Data_Fit_example.cc**: example program showing the usage of the `HL_ExpPoints` class.
- **Limit_example.cc**: example program showing the usage of the `HL_Limit` class.
- **Ndim_BifurGaussian_example.cc**: example program showing the usage of the `HL_nDimBifurGaussian` class.
- **Ndim_Gaussian.cc**: example program showing the usage of the `HL_nDimGaussian` class.
- **Ndim_Likelihood_example.cc**: example program showing the usage of the `HL_nDimLikelihood` class.
- **ProfLikelihood_example.cc**: example program showing the usage of the `HL_ProfLikelihood` class.

To compile them a proper variable has to be set during the `cmake` stage:

```bash
cd build
make
```

After the compilation in the build directory will contain executables from the following examples. The HEPLike package comes also with test procedures for each of the classes. To perform the tests user has to perform the command:

c test

or an equivalent:

make test

If the HEPLike was successfully installed the output will look as following:

Test project /storage/github/HEPLike/build
Start 1: HL_Test_YAML
1/7 Test #1: HL_Test_YAML ......................... Passed 0.01 sec
Start 2: HL_Limit
2/7 Test #2: HL_Limit ......................... Passed 0.27 sec
Start 3: HL_Br_example
3/7 Test #3: HL_Br_example ......................... Passed 0.02 sec
Start 4: HL_BrBifurGaussian_example
4/7 Test #4: HL_BrBifurGaussian_example ...... Passed 0.01 sec
Start 5: HL_Ndim_Gaussian
5/7 Test #5: HL_Ndim_Gaussian ......................... Passed 0.01 sec
Start 6: HL_ProfLikelihood_example
6/7 Test #6: HL_ProfLikelihood_example ...... Passed 0.25 sec
Start 7: HL_Ndim_BifurGaussian_example
7/7 Test #7: HL_Ndim_BifurGaussian_example .... Passed 0.01 sec

100% tests passed, 0 tests failed out of 7

Total Test time (real) = 0.57 sec
4.1. Available measurement

The YAML files that contain the stored measurements are located in a second independent repository. The reason for this separation is that the YAML files are expected to be updated more frequently then the code itself. It is expected that users and experiments will contribute to this repository. By implementing such model it is ensured that the repository will contain the most up to date measurements.

The repository can be found at: https://github.com/mchrzasz/HEPLikeData

The repository should be downloaded or cloned:

```
1 cd <some new dir>
git clone https://github.com/mchrzasz/HEPLikeData.git
```

Since the repository contains only YAML files there is no need for any compilation. The repository contains a directory data, where all the YAML files are kept. It should be linked by a symbolic link to the HEPlike package. Inside the data the measurements are grouped by experiments (ex. LHCb, ATLAS, CMS, etc.). Inside the experiment directory the measurements are grouped according to type of measurement in the collaborations, for example: RD, Semileptonic, Charmless, Exotica, etc. The names of the YAML files should be named accordingly to publication report number. For example: CERN-EP-2018-331.yaml. If a single publication produced more independent measurements, user might code them in the independent files and give further information at the end of the file, for example: CERN-PH-EP-2015-314_q2.01.0.98.yaml.

Currently we are publishing the measurements that have been used by us in other projects [22, 23, 24]. The list of YAML files with the context is presented in Tab. 2.

| File               | Description                                                                 |
|--------------------|-----------------------------------------------------------------------------|
| CERN-EP-2017-100.yaml | YAML file encoding the measurement of branching fraction of the $B^0_d \rightarrow \mu \mu$ and $B^0_s \rightarrow \mu \mu$ decays [20]. |
| File                                  | Description                                                                                                                                                                                                 |
|--------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| PH-EP-2015-314_q2.0.1_0.98.yaml      | YAML files encoding the measurements of the angular coefficients of $B^0_d \to K^* \mu \mu$ decay in different $q^2$ regions [25].                                                                                 |
| PH-EP-2015-314_q2.11.0_12.5.yaml     |                                                                                                                                                                                                            |
| PH-EP-2015-314_q2.1.1_2.5.yaml       |                                                                                                                                                                                                            |
| PH-EP-2015-314_q2.15.0_19.yaml       |                                                                                                                                                                                                            |
| PH-EP-2015-314_q2.2.5_4.0.yaml       |                                                                                                                                                                                                            |
| PH-EP-2015-314_q2.4.0_6.0.yaml       |                                                                                                                                                                                                            |
| PH-EP-2015-314_q2.6.0_8.0.yaml       |                                                                                                                                                                                                            |
| CERN-EP-2016-141_q2.0.1_0.98.yaml    | YAML files encoding the measurements of the branching fraction of the $B^0_d \to K^* \mu \mu$ decay in different $q^2$ regions [26].                                                                       |
| CERN-EP-2016-141_q2.11.0_12.5.yaml   |                                                                                                                                                                                                            |
| CERN-EP-2016-141_q2.1.1_2.5.yaml     |                                                                                                                                                                                                            |
| CERN-EP-2016-141_q2.15.0_19.yaml     |                                                                                                                                                                                                            |
| CERN-EP-2016-141_q2.2.5_4.0.yaml     |                                                                                                                                                                                                            |
| CERN-EP-2016-141_q2.4.0_6.0.yaml     |                                                                                                                                                                                                            |
| CERN-EP-2016-141_q2.6.0_8.0.yaml     |                                                                                                                                                                                                            |
| CERN-EP-2016-215_q2.0.1_0.98.yaml    | YAML files encoding the measurements of the branching fraction of the $B^0_d \to K \pi \mu \mu$ decay in different $q^2$ regions [27].                                                                 |
| CERN-EP-2016-215_q2.11.0_12.5.yaml   |                                                                                                                                                                                                            |
| CERN-EP-2016-215_q2.1.1_2.5.yaml     |                                                                                                                                                                                                            |
| CERN-EP-2016-215_q2.2.5_4.0.yaml     |                                                                                                                                                                                                            |
| CERN-EP-2016-215_q2.4.0_6.0.yaml     |                                                                                                                                                                                                            |
| CERN-EP-2016-215_q2.6.0_8.0.yaml     |                                                                                                                                                                                                            |
| CERN-PH-EP-2015-145_0.1_2.yaml       | YAML files encoding the measurements of the branching fraction of the $B^0_s \to \phi \mu \mu$ decay in different $q^2$ regions [27].                                                                  |
| CERN-PH-EP-2015-145_11_12.5.yaml     |                                                                                                                                                                                                            |
| CERN-PH-EP-2015-145_15.19.yaml       |                                                                                                                                                                                                            |
| CERN-PH-EP-2015-145_1.6.yaml         |                                                                                                                                                                                                            |
| CERN-PH-EP-2015-145_2.5.yaml         |                                                                                                                                                                                                            |
| CERN-PH-EP-2015-145_5.8.yaml         |                                                                                                                                                                                                            |
| CERN-EP-2019-043.yaml                | YAML file encoding the measurement of the $R_K$ [28].                                                                                                                                                    |
| CERN-EP-2017-100_q2.0.045_1.1.yaml   | YAML file encoding the measurement of the $R_{K^*}$ [7].                                                                                                                                                |
| CERN-EP-2017-100_q2.1.1_6.yaml       | YAML file encoding the HFLAV average of the $b \to s \gamma$ [15].                                                                                                                                       |
| b2sgamma.yaml                        | YAML file encoding the HFLAV average of the $R(D)$ and $R(D^*)$ [15].                                                                                                                                     |
| RD_RDstar.yaml                       | YAML file encoding the HFLAV average of the $R(D)$ and $R(D^*)$ [15].                                                                                                                                       |
Table 2 – Continued from previous page

| File                  | Description                                                                 |
|-----------------------|-----------------------------------------------------------------------------|
| HFLAV_2016_157.yaml   | YML files encoding the upper limits of τ Lepton Flavour Violation decays [27]. |
| HFLAV_2016_160.yaml   |                                                                             |
| HFLAV_2016_161.yaml   |                                                                             |
| HFLAV_2016_162.yaml   |                                                                             |
| HFLAV_2016_164.yaml   |                                                                             |
| HFLAV_2016_165.yaml   |                                                                             |
| HFLAV_2016_166.yaml   |                                                                             |
| HFLAV_2016_167.yaml   |                                                                             |
| HFLAV_2016_168.yaml   |                                                                             |
| HFLAV_2016_169.yaml   |                                                                             |
| HFLAV_2016_170.yaml   |                                                                             |
| HFLAV_2016_171.yaml   |                                                                             |
| HFLAV_2016_176.yaml   |                                                                             |
| HFLAV_2016_177.yaml   |                                                                             |
| HFLAV_2016_178.yaml   |                                                                             |
| HFLAV_2016_179.yaml   |                                                                             |
| HFLAV_2016_180.yaml   |                                                                             |
| HFLAV_2016_181.yaml   |                                                                             |
| HFLAV_2016_182.yaml   |                                                                             |
| HFLAV_2016_183.yaml   |                                                                             |
| HFLAV_2016_211.yaml   |                                                                             |
| HFLAV_2016_212.yaml   |                                                                             |

As already mentioned the measurements are constantly growing and there is expected that the community will contribute to develop this repository. When a new YAML file is wrote before merging it with the repository it should be checked if it contains all the necessary information. It can be checked with the Test_YAML.cc program. It can be used in the following way:

```
cd HEPLike
./build/Test_YAML <PATH_TO_YAML>
```

If an entry is missing the user will be notified by a printout. The HEPLikeData repository contains also a template YAML (data/template.yaml) file which can be used to create new measurements YAML files.

As already mentioned we provide useful utilities for the encoded measurements. The first is the ability to create BiBtex file for the measurements.
that have been used. The user should store the **BiBtex** items or **YAML** file names:

Aaij:2017vbb
b2mumu.yaml

To prepare the **BiBtex** file user should run the `make_citations.py` script located in the `utils` directory:

```
cd utils
python make_citations.py list.txt
```

after this command a new file `references.bib`, will be created, which will contain the full **BiBtex** entries. This can be directly used in preparing the publication.

Another useful feature of **HEPLike** is the ability to search the measurement database for relevant measurements. The script allowing for that utility is also located in the `utils`. Currently the database can be searched for using the year of publication, Arxiv number, author of the **YAML** file or the unique name of the measurements. The syntax for running a search is the following:

```
python lookup.py --Arxiv 1705.05802
```

To see all available search options in the following script user can run it with help option: `python lookup.py -h`.

### 5. Summary

We have presented a computer program **HEPLike** that enables to construct and evaluate experimental likelihoods. The software is designed to handle the interpretation of wide range of published results. It also allows to perform direct fits to data once it is provided by the experimental collaborations.

The program can be easily interfaced with other computer programs and is aimed to help users, who perform fits to experimental results in their scientific work. It is especially useful for large fitting collaborations, which till now had to implement the experimental measurements on their own. The measurement themselves are stored in **YAML** files in separate repository. This allows for easy extensions of the database without the need of compilation. Furthermore, users and experimental collaborations can share their encoded measurements with the community.
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