HEPfit

A Code for the Combination of Indirect and Direct Constraints on High Energy Physics Models

Jorge de Blas

Istituto Nazionale di Fisica Nucleare
Sezione di Roma

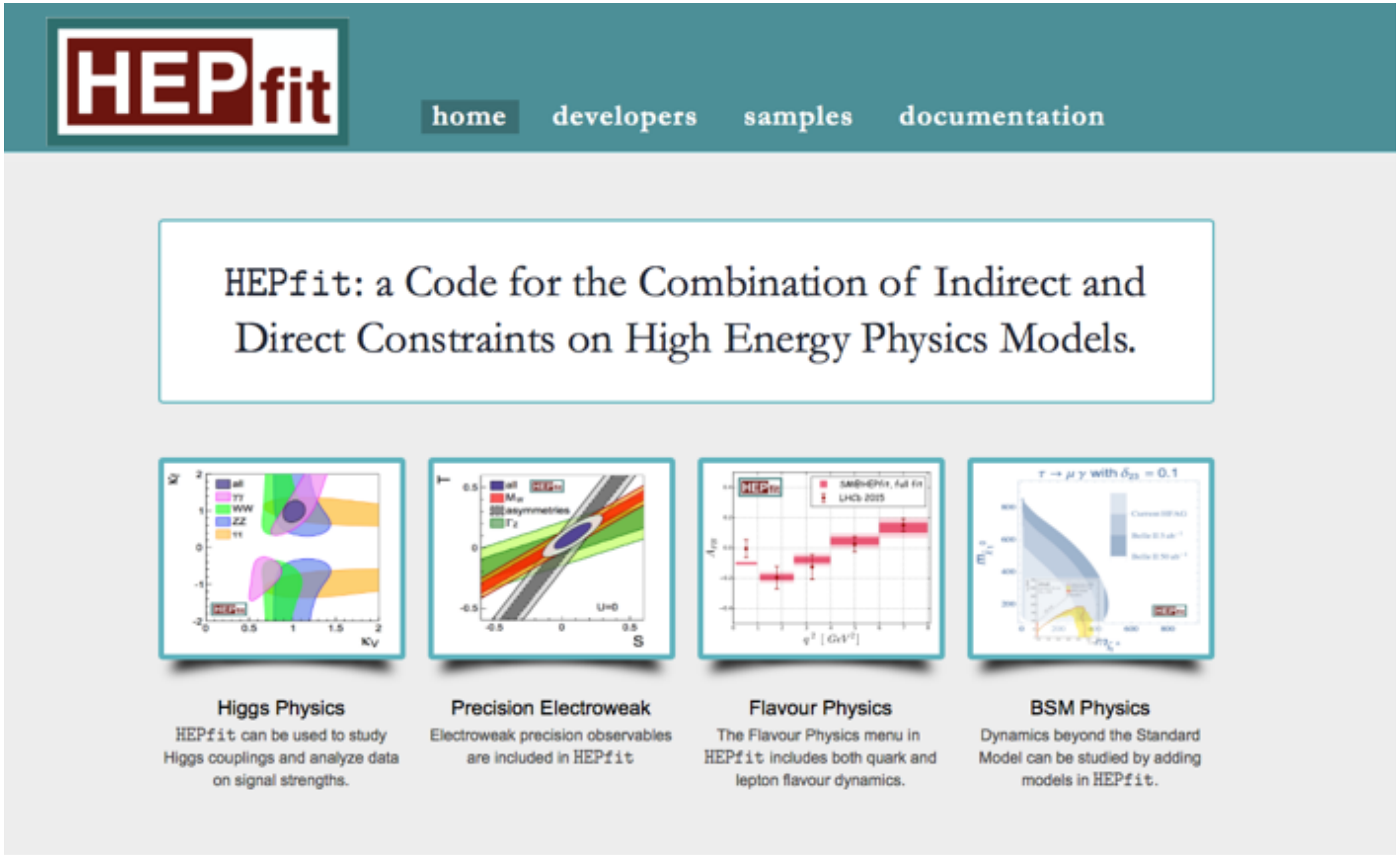
On behalf of the HEPfit collaboration

European Research Council
Established by the European Commission
Supporting top researchers from anywhere in the world

INFN Istituto Nazionale di Fisica Nucleare

SUSY 2016
Melbourne, July 4, 2016

- General **H**igh **E**nergy **P**hysics **fit**ting tool to combine indirect and direct searches of new physics (available under GPL on github)
  https://github.com/silvest/HEPfit
- Webpage: http://hepfit.roma1.infn.it



The HEPfit code: Developers

Jorge de Blas

Debtosh Chowdhury

Marco Ciuchini

Otto Eberhardt

Marco Fedele

Enrico Franco

Ayan Paul

Luca Silvestrini

Giovanni Grilli di Cortona

Mauro Valli

Satoshi Mishima

Norimi Yokozaki

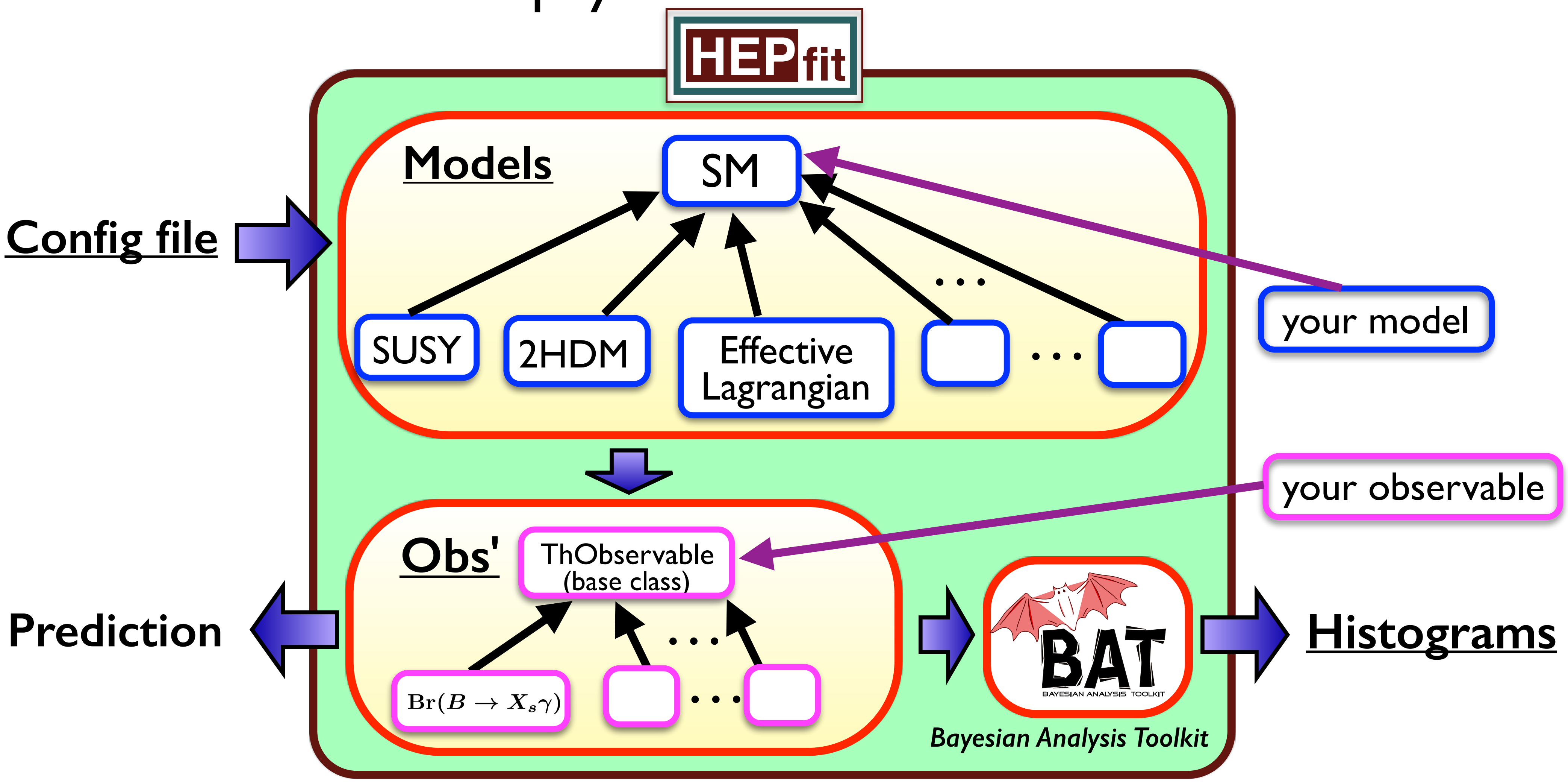
Maurizio Pierini

Laura Reina

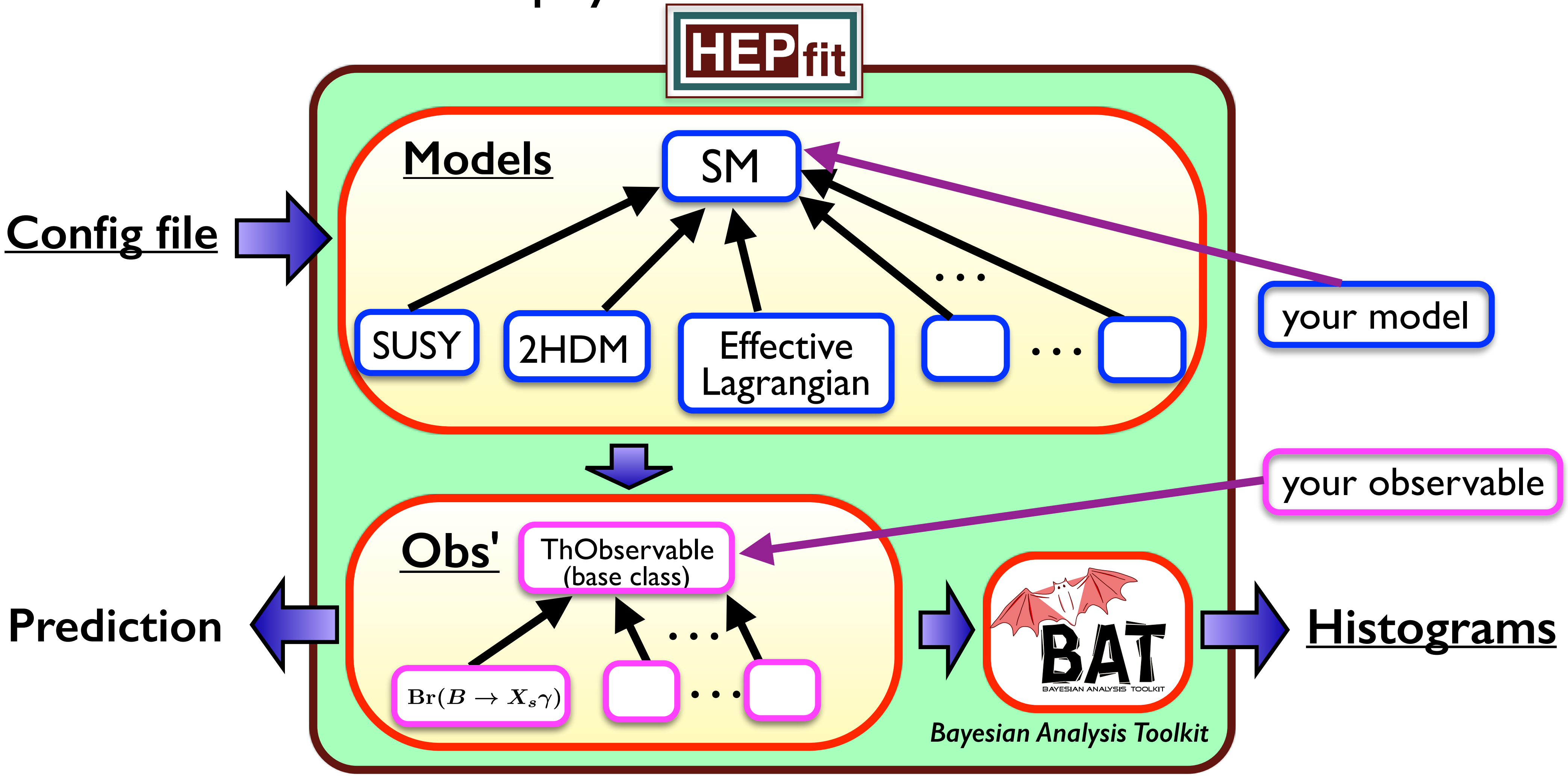
Fu-Sheng Yu

THE HEPfit CODE

- General **H**igh **E**nergy **P**hysics **fit**ting tool to combine indirect and direct searches of new physics

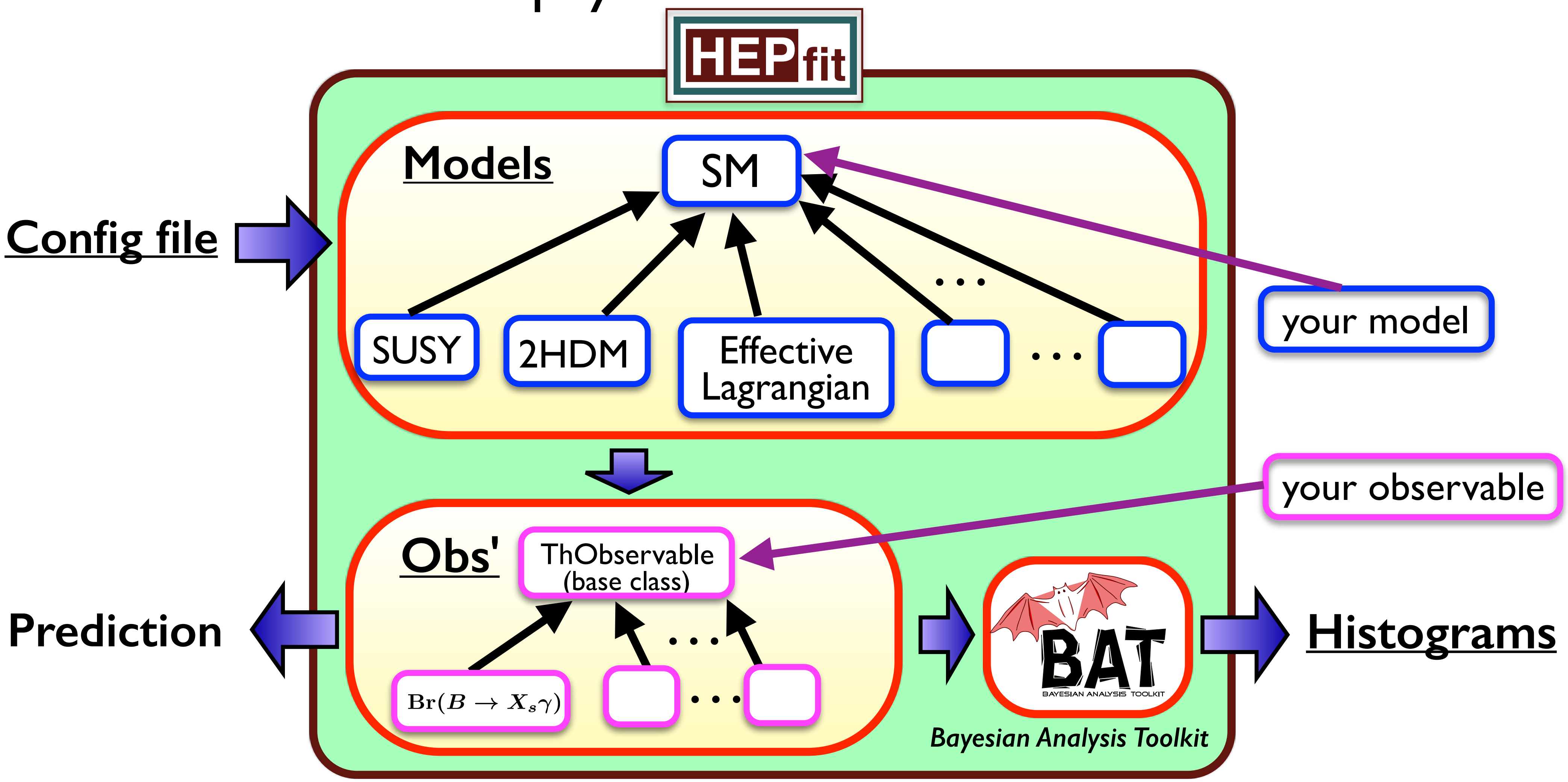


- General **H**igh **E**nergy **P**hysics **fit**ting tool to combine indirect and direct searches of new physics



- Flexible open-source C++ code

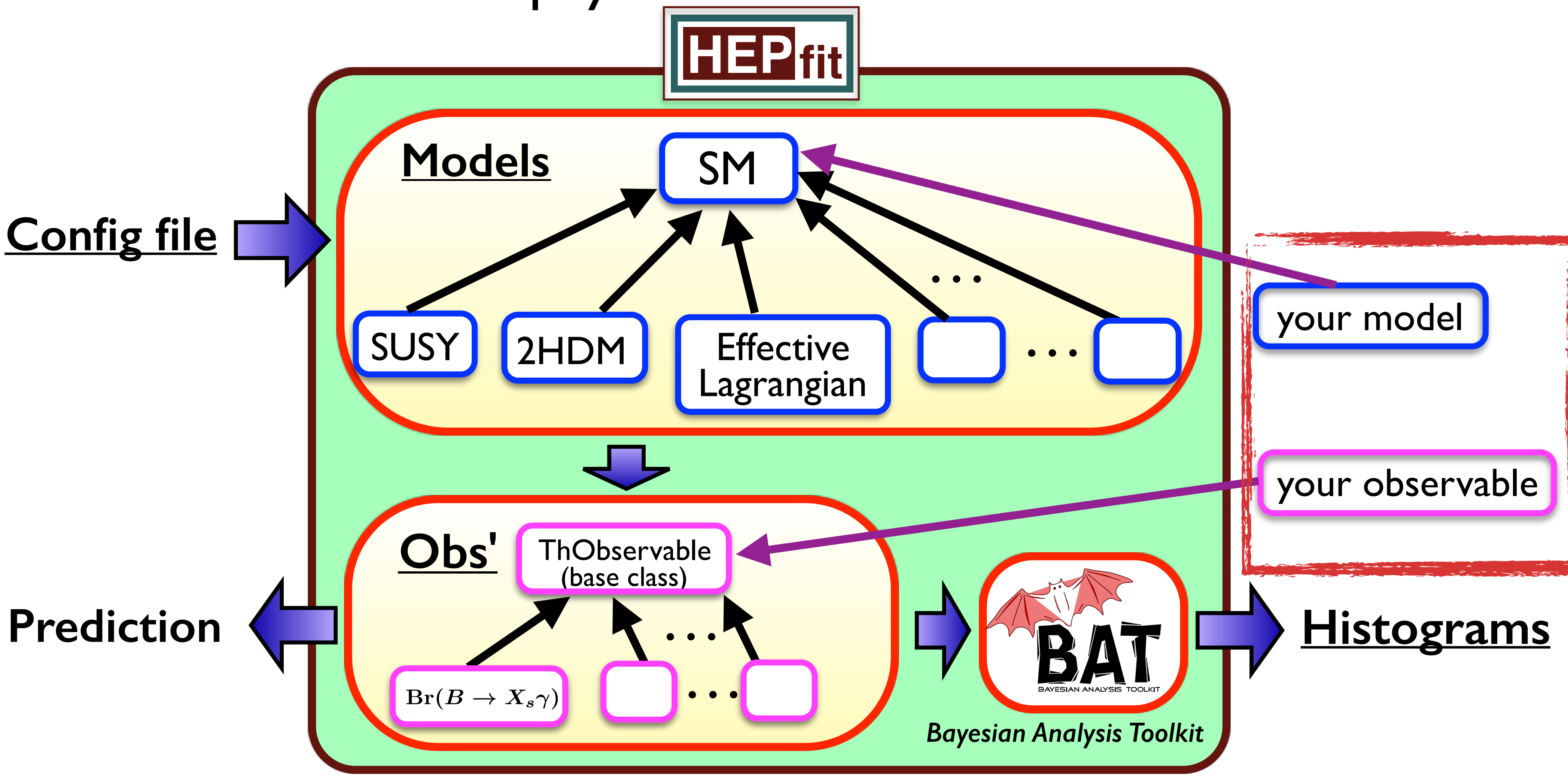
- General **H**igh **E**nergy **P**hysics **fit**ting tool to combine indirect and direct searches of new physics



- Flexible open-source C++ code
- Stand-alone and library modes to compute observables in the SM & beyond

THE HEPfit CODE

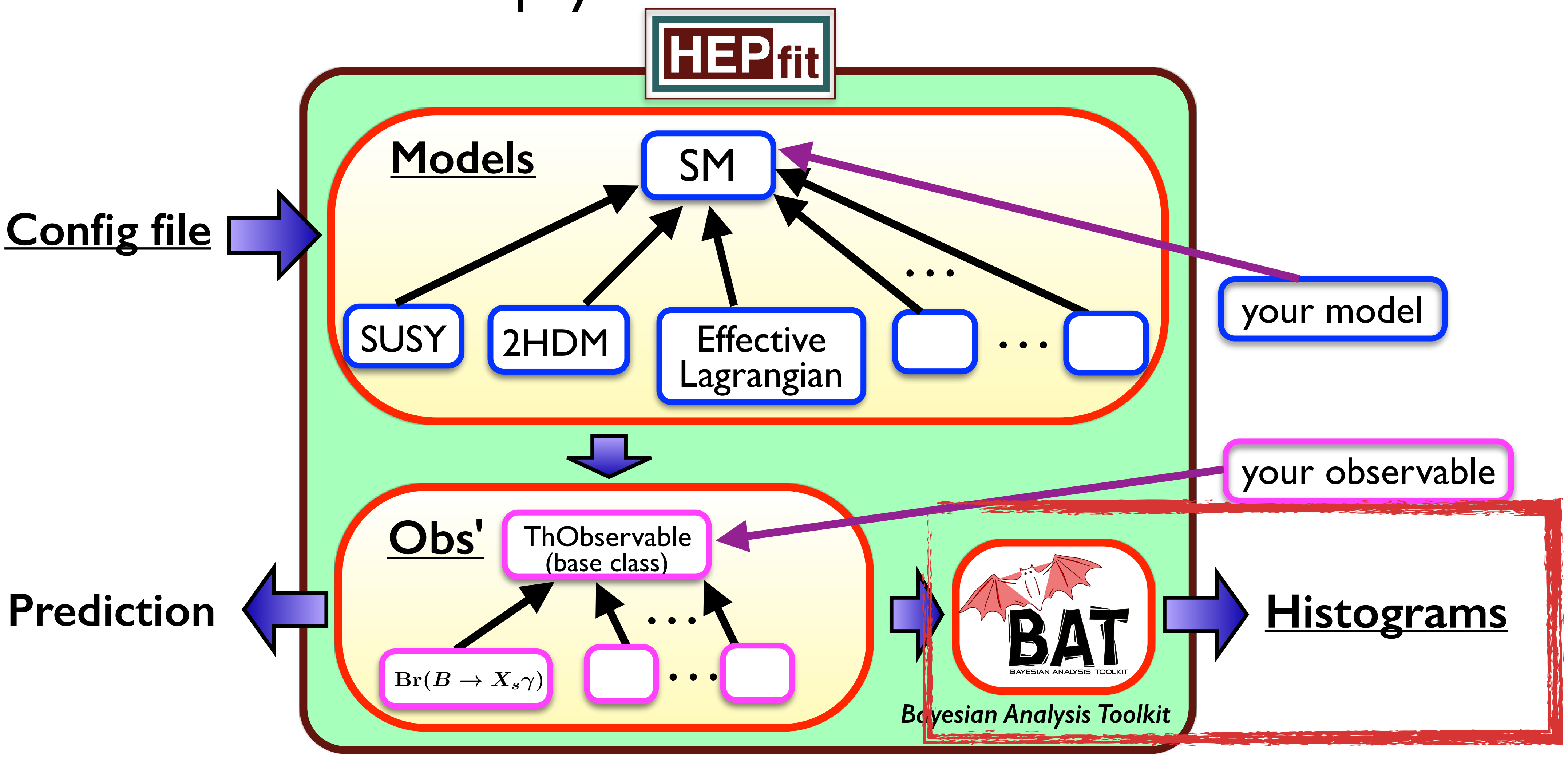
- General **H**igh **E**nergy **P**hysics **fit**ting tool to combine indirect and direct searches of new physics



- Flexible open-source C++ code
- Stand-alone and library modes to compute observables in the SM & beyond
- Add new models and/or observables as external modules

THE HEPfit CODE

- General **H**igh **E**nergy **P**hysics **fit**ting tool to combine indirect and direct searches of new physics



- Flexible open-source C++ code
- Stand-alone and library modes to compute observables in the SM & beyond
- Add new models and/or observables as external modules
- Optional Bayesian Statistical Analysis framework (supports MPI parallelization)

Dependencies

- ROOT (https://root.cern.ch)
  - Plotting. Stores all histograms generated at run time (*.pdf & *.root)
  - Compatible with ROOT v5 and v6
- BOOST C++ Libraries (http://www.boost.org)
  - Used for efficient and safe memory handling
- GSL (https://www.gnu.org/software/gsl/)
  - GNU Scientific Libraries are used for efficient matrix operations and integrals

(Working developer version (available through git) requires NetBeans IDE)

Optional Dependencies

- BAT (https://www.mppmu.mpg.de/bat/)
  - Bayesian Analysis Tool based Markov Chain Monte Carlo routines
  - Required if using our MCMC engine
  - Compatible with BAT v0.9 and v1 (Dev. version)
- OpenMPI (https://www.open-mpi.org) /MPICH (https://www.mpich.org)
  - Necessary only for parallel runs
  - Tested for large scale @ $O(10^3)$ cores in batch submission systems
- Installation:

```
tar zxvf HEPfit-x.x.tar.gz
cd HEPfit-x.x
cmake . -DLOCAL_INSTALL_ALL=ON -DMPIBAT=ON
make
make install
```

Input

- Model, Parameter values & Observables via configuration files

Types of Likelihoods/priors

- Gaussian & Flat likelihoods built in the code
- It can read any likelihood from ROOT histograms
- Work in progress: custom likelihoods

Correlations

- Correlated observables
- Correlated parameters
- 2D likelihoods can be read from ROOT 2D histograms for 2 correlated observables

Input: Config file for Model & Observables

```
StandardModel
# Model parameters:
ModelParameter  mtop        173.2       0.9         0.
ModelParameter  mHl         125.6       0.3         0.
...
CorrelatedGaussianParameters   V1_lattice 2
ModelParameter  a_0V    0.496    0.067    0.
ModelParameter  a_1V   -2.03     0.92     0.
1.00    0.86
0.86    1.00

<All the model parameters have to be listed here>

# Observables:
Observable  Mw        Mw        M_{W}       80.3290 80.4064 MCMC weight 80.385 0.015 0.
Observable  GammaW    GammaW    #Gamma_{W} 2.08569 2.09249 MCMC weight 2.085  0.042 0.
#
# Correlated observables:
CorrelatedGaussianObservables Zpole2 7
Observable  Alepton   Alepton   A_{l}       0.143568 0.151850 MCMC weight 0.1513  0.0021  0.
Observable  Rbottom   Rbottom   R_{b}       0.215602 0.215958 MCMC weight 0.21629 0.00066 0.
Observable  Rcharm    Rcharm    R_{c}       0.172143 0.172334 MCMC weight 0.1721  0.0030  0.
Observable  AFBbottom AFBbottom A_{FB}^{b} 0.100604 0.106484 MCMC weight 0.0992  0.0016  0.
Observable  AFBcharm  AFBcharm  A_{FB}^{c} 0.071750 0.076305 MCMC weight 0.0707  0.0035  0.
Observable  Abottom   Abottom   A_{b}       0.934320 0.935007 MCMC weight 0.923   0.020   0.
Observable  Acharm    Acharm    A_{c}       0.666374 0.670015 MCMC weight 0.670   0.027   0.
1.00    0.00    0.00    0.00    0.00    0.09    0.05
0.00    1.00   -0.18   -0.10    0.07   -0.08    0.04
0.00   -0.18    1.00    0.04   -0.06    0.04   -0.06
0.00   -0.10    0.04    1.00    0.15    0.06    0.01
0.00    0.07   -0.06    0.15    1.00   -0.02    0.04
0.09   -0.08    0.04    0.06   -0.02    1.00    0.11
0.05    0.04   -0.06    0.01    0.04    0.11    1.00
#
# Output correlations:
Observable2D  MwvsGammaW Mw M_{W} 80.3290 80.4064 noMCMC noweight GammaW #Gamma_{W} 2.08569 2.09249
...
Observable2D Bd_Bsbar_mumu noMCMC noweight
Observable   BR_Bdmumu      BR(B_{d}#rightarrow#mu#mu)    1. -1.  1.05e-10   0.   0.
Observable   BRbar_Bsmumu   BR(B_{s}#rightarrow#mu#mu)    1. -1.  3.65e-9    0.   0.
...
Observable2D S5_P5 noMCMC noweight
BinnedObservable   S_5      S_5    1. -1.  0.   0.   0.   4.   6.
BinnedObservable   P_5      P_5    1. -1.  0.   0.   0.   4.   6.
#
# Including other configuration files
IncludeFile Flavour.conf
```

Input: Config file for Model & Observables

```
StandardModel
# Model parameters:
ModelParameter  mtop         173.2        0.9          0.
ModelParameter  mHl          125.6        0.3          0.
...
CorrelatedGaussianParameters   V1_lattice 2
ModelParameter  a_0V     0.496    0.067    0.
ModelParameter  a_1V    -2.03     0.92     0.
1.00      0.86
0.86      1.00

<All the model parameters have to be listed here>

# Observables:
Observable  Mw        Mw        M_{W}      80.3290 80.4064 MCMC weight 80.385 0.015 0.
Observable  GammaW    GammaW    #Gamma_{W} 2.08569 2.09249 MCMC weight 2.085  0.042 0.
#
# Correlated observables:
CorrelatedGaussianObservables Zpole2 7
Observable  Alepton   Alepton   A_{l}       0.143568 0.151850 MCMC weight 0.1513  0.0021  0.
Observable  Rbottom   Rbottom   R_{b}       0.215602 0.215958 MCMC weight 0.21629 0.00066 0.
Observable  Rcharm    Rcharm    R_{c}       0.172143 0.172334 MCMC weight 0.1721  0.0030  0.
Observable  AFBbottom AFBbottom A_{FB}^{b}  0.100604 0.106484 MCMC weight 0.0992  0.0016  0.
Observable  AFBcharm  AFBcharm  A_{FB}^{c}  0.071750 0.076305 MCMC weight 0.0707  0.0035  0.
Observable  Abottom   Abottom   A_{b}       0.934320 0.935007 MCMC weight 0.923   0.020   0.
Observable  Acharm    Acharm    A_{c}       0.666374 0.670015 MCMC weight 0.670   0.027   0.
1.00    0.00    0.00    0.00    0.00    0.09    0.05
0.00    1.00   -0.18   -0.10    0.07   -0.08    0.04
0.00   -0.18    1.00    0.04   -0.06    0.04   -0.06
0.00   -0.10    0.04    1.00    0.15    0.06    0.01
0.00    0.07   -0.06    0.15    1.00   -0.02    0.04
0.09   -0.08    0.04    0.06   -0.02    1.00    0.11
0.05    0.04   -0.06    0.01    0.04    0.11    1.00
#
# Output correlations:
Observable2D  MwvsGammaW Mw M_{W} 80.3290 80.4064 noMCMC noweight GammaW #Gamma_{W} 2.08569 2.09249
...
Observable2D Bd_Bsbar_mumu noMCMC noweight
Observable    BR_Bdmumu      BR(B_{d}#rightarrow#mu#mu)    1. -1.  1.05e-10   0.   0.
Observable    BRbar_Bsmumu   BR(B_{s}#rightarrow#mu#mu)    1. -1.  3.65e-9    0.   0.
...
Observable2D S5_P5 noMCMC noweight
BinnedObservable   S_5      S_5    1. -1.  0.   0.   0.   4.   6.
BinnedObservable   P_5      P_5    1. -1.  0.   0.   0.   4.   6.
#
# Including other configuration files
IncludeFile Flavour.conf
```

Model name

Uncorrelated parameters:
Initial values, priors

Correlated parameters

Input: Config file for Model & Observables

```
StandardModel
# Model parameters:
ModelParameter  mtop        173.2       0.9         0.
ModelParameter  mH1         125.6       0.3         0.
...
CorrelatedGaussianParameters   V1_lattice 2
ModelParameter  a_0V     0.496    0.067    0.
ModelParameter  a_1V    -2.03     0.92     0.
1.00      0.86
0.86      1.00

<All the model parameters have to be listed here>

# Observables:
Observable  Mw        Mw        M_{W}       80.3290 80.4064 MCMC weight 80.385 0.015 0.
Observable  GammaW    GammaW    #Gamma_{W} 2.08569 2.09249 MCMC weight 2.085  0.042 0.
#
# Correlated observables:
CorrelatedGaussianObservables Zpole2 7
Observable  Alepton   Alepton   A_{l}       0.143568 0.151850 MCMC weight 0.1513  0.0021  0.
Observable  Rbottom   Rbottom   R_{b}       0.215602 0.215958 MCMC weight 0.21629 0.00066 0.
Observable  Rcharm    Rcharm    R_{c}       0.172143 0.172334 MCMC weight 0.1721  0.0030  0.
Observable  AFBbottom AFBbottom A_{FB}^{b} 0.100604 0.106484 MCMC weight 0.0992  0.0016  0.
Observable  AFBcharm  AFBcharm  A_{FB}^{c} 0.071750 0.076305 MCMC weight 0.0707  0.0035  0.
Observable  Abottom   Abottom   A_{b}       0.934320 0.935007 MCMC weight 0.923   0.020   0.
Observable  Acharm    Acharm    A_{c}       0.666374 0.670015 MCMC weight 0.670   0.027   0.
1.00     0.00     0.00     0.00     0.00     0.09     0.05
0.00     1.00    -0.18    -0.10     0.07    -0.08     0.04
0.00    -0.18     1.00     0.04    -0.06     0.04    -0.06
0.00    -0.10     0.04     1.00     0.15     0.06     0.01
0.00     0.07    -0.06     0.15     1.00    -0.02     0.04
0.09    -0.08     0.04     0.06    -0.02     1.00     0.11
0.05     0.04    -0.06     0.01     0.04     0.11     1.00
#
# Output correlations:
Observable2D  MwvsGammaW Mw M_{W} 80.3290 80.4064 noMCMC noweight GammaW #Gamma_{W} 2.08569 2.09249
...
Observable2D Bd_Bsbar_mumu noMCMC noweight
Observable    BR_Bdmumu       BR(B_{d}#rightarrow#mu#mu)    1. -1.  1.05e-10   0.   0.
Observable    BRbar_Bsmumu    BR(B_{s}#rightarrow#mu#mu)    1. -1.  3.65e-9    0.   0.
...
Observable2D S5_P5 noMCMC noweight
BinnedObservable   S_5      S_5     1. -1.  0.   0.   0.   4.   6.
BinnedObservable   P_5      P_5     1. -1.  0.   0.   0.   4.   6.
#
# Including other configuration files
IncludeFile Flavour.conf
```

Uncorrelated observables

Correlated Observables

2D obs, Binned Obs, …

Input: Config file for Model & Observables

```
StandardModel
# Model parameters:
ModelParameter  mtop        173.2       0.9         0.
ModelParameter  mHl         125.6       0.3         0.
...
CorrelatedGaussianParameters   V1_lattice 2
ModelParameter  a_0V     0.496    0.067    0.
ModelParameter  a_1V    -2.03     0.92     0.
1.00     0.86
0.86     1.00

<All the model parameters have to be listed here>

# Observables:
Observable  Mw         Mw         M_{W}       80.3290 80.4064 MCMC weight 80.385 0.015 0.
Observable  GammaW     GammaW     #Gamma_{W} 2.08569 2.09249 MCMC weight 2.085  0.042 0.
#
# Correlated observables:
CorrelatedGaussianObservables Zpole2 7
Observable  Alepton    Alepton    A_{l}       0.143568 0.151850 MCMC weight 0.1513  0.0021  0.
Observable  Rbottom    Rbottom    R_{b}       0.215602 0.215958 MCMC weight 0.21629 0.00066 0.
Observable  Rcharm     Rcharm     R_{c}       0.172143 0.172334 MCMC weight 0.1721  0.0030  0.
Observable  AFBbottom AFBbottom A_{FB}^{b} 0.100604 0.106484 MCMC weight 0.0992  0.0016  0.
Observable  AFBcharm  AFBcharm  A_{FB}^{c} 0.071750 0.076305 MCMC weight 0.0707  0.0035  0.
Observable  Abottom    Abottom    A_{b}       0.934320 0.935007 MCMC weight 0.923   0.020   0.
Observable  Acharm     Acharm     A_{c}       0.666374 0.670015 MCMC weight 0.670   0.027   0.
1.00   0.00   0.00   0.00   0.00   0.09   0.05
0.00   1.00  -0.18  -0.10   0.07  -0.08   0.04
0.00  -0.18   1.00   0.04  -0.06   0.04  -0.06
0.00  -0.10   0.04   1.00   0.15   0.06   0.01
0.00   0.07  -0.06   0.15   1.00  -0.02   0.04
0.09  -0.08   0.04   0.06  -0.02   1.00   0.11
0.05   0.04  -0.06   0.01   0.04   0.11   1.00
#
# Output correlations:
Observable2D  MwvsGammaW Mw M_{W} 80.3290 80.4064 noMCMC noweight GammaW #Gamma_{W} 2.08569 2.09249
...
Observable2D Bd_Bsbar_mumu noMCMC noweight
Observable   BR_Bdmumu      BR(B_{d}#rightarrow#mu#mu)    1. -1.  1.05e-10   0.   0.
Observable   BRbar_Bsmumu   BR(B_{s}#rightarrow#mu#mu)    1. -1.  3.65e-9    0.   0.
...
Observable2D S5_P5 noMCMC noweight
BinnedObservable   S_5      S_5     1. -1.  0.   0.   0.   4.   6.
BinnedObservable   P_5      P_5     1. -1.  0.   0.   0.   4.   6.
#
# Including other configuration files
IncludeFile Flavour.conf
```

Include additional config files

Input: Using our MCMC engine

- Example: MonteCarlo config file

```
NChains                     10    (Default: 5)
PrerunMaxIter               50000 (Default: 1000000)
Iterations                  10000 (Default: 100000)
#Seed                        1
PrintAllMarginalized        true  (Default: false)
PrintCorrelationMatrix      true  (Default: false)
PrintKnowledgeUpdatePlots   false (Default: false)
PrintParameterPlot          false (Default: false)
OrderParameters             true  (Default: true)
```

- Other options:

```
FindModeWithMinuit        (Default: false)
MinimumEfficiency         (Default: 0.15, set to 0. - 1.)
WriteChain                (Default: false)
CalculateNormalization    (Default: false)
WritePreRunData           (Mandatory: name of file)
ReadPreRunData            (Read existing prerun data file)
```

Input: Using our MCMC engine

- Example: MonteCarlo config file

```
NChains                    10    (Default: 5)
PrerunMaxIter              50000 (Default: 1000000)
Iterations                 10000 (Default: 100000)
#Seed                       1
PrintAllMarginalized       true  (Default: false)
PrintCorrelationMatrix     true  (Default: false)
PrintKnowledgeUpdatePlots  false (Default: false)
PrintParameterPlot         false (Default: false)
OrderParameters            true  (Default: true)
```

MCMC settings

- Other options:

```
FindModeWithMinuit        (Default: false)
MinimumEfficiency         (Default: 0.15, set to 0. - 1.)
WriteChain                (Default: false)
CalculateNormalization    (Default: false)
WritePreRunData           (Mandatory: name of file)
ReadPreRunData            (Read existing prerun data file)
```

Output

- Statistics.txt:

Statistical results for observables and model parameters

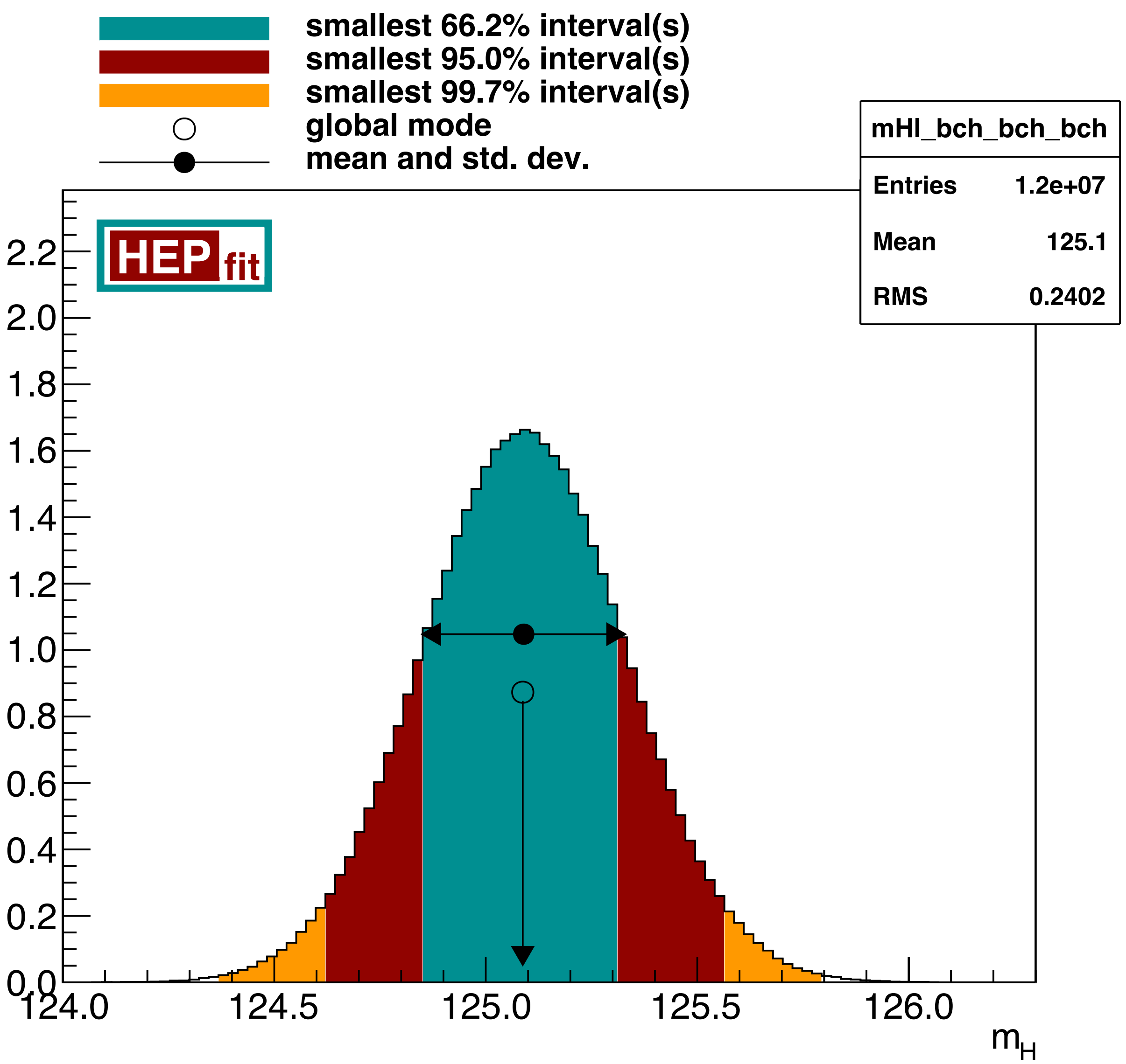
```
                                    ...
   (21) Observable "Kfm_AR":
      Mean +- sqrt(V):                1.01 +- 0.11
      (Marginalized) mode:            1
      Smallest interval(s) containing at least 66% and local mode(s):
       (0.91, 1.12) (local mode at 1 with rel. height 1; rel. area 1)

      Smallest interval(s) containing at least 95% and local mode(s):
       (0.79, 1.22) (local mode at 1 with rel. height 1; rel. area 1)

      Smallest interval(s) containing at least 1e+02% and local mode(s):
       (0.7, 1.33) (local mode at 1 with rel. height 1; rel. area 1)

LogLikelihood mean value: -27
LogLikelihood variance: 1.5

                                    ...

Value of the Parameters and Observables at the global mode:

KW: 1.0001
KZ: 1.0812
Kf: 1.0018
                                    ...
```

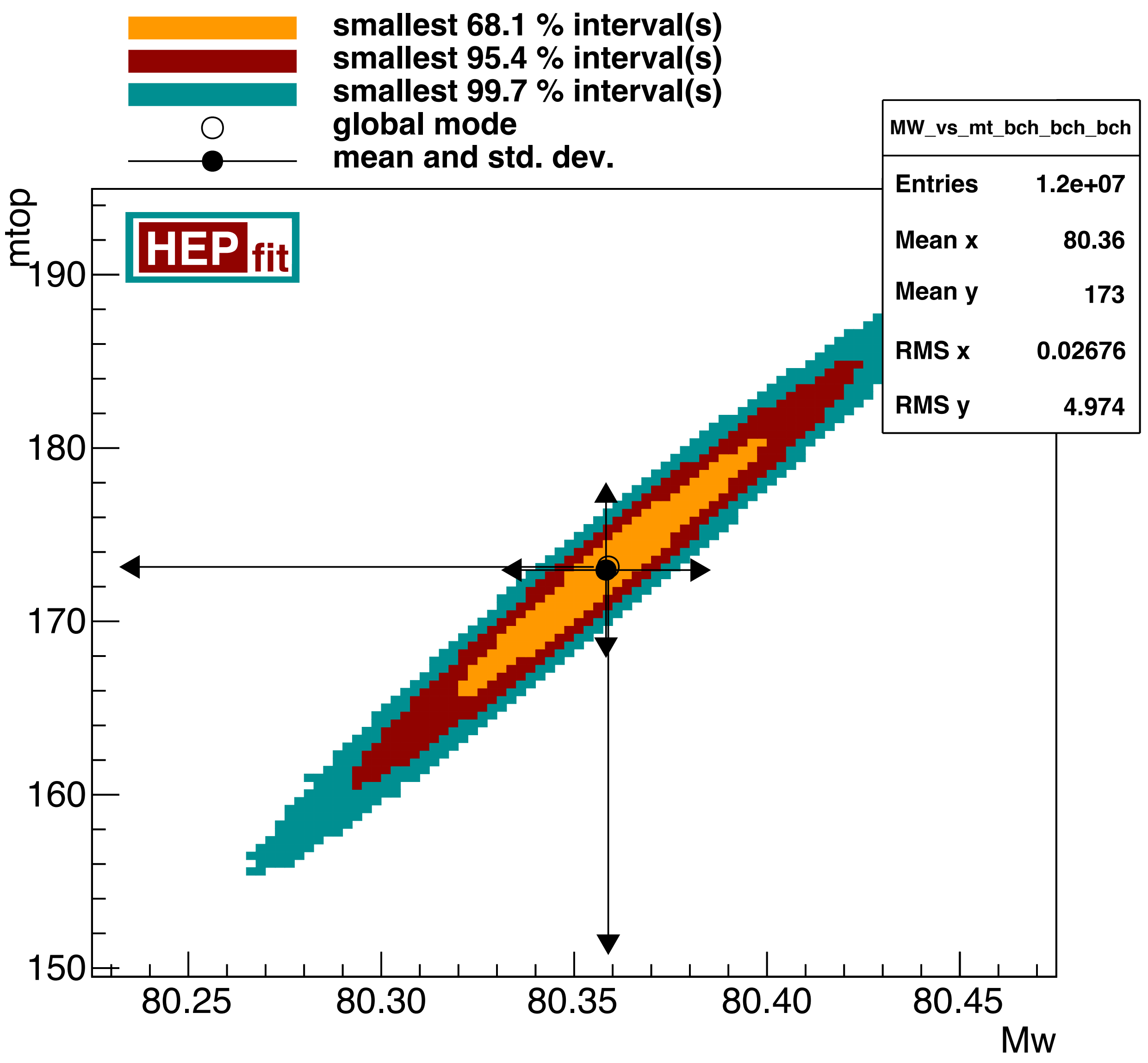
- Log.txt: Check for convergence, problems, etc…

```
Detail  :      * Efficiency status: Efficiencies not within predefined range after 1500 iterations. Efficiency of
Detail  :          chain 0 is below 15 % (15 %). Scale decreased to 0.5594
Detail  :          chain 1 is below 15 % (14 %). Scale decreased to 0.5594
Detail  :          chain 3 is below 15 % (13 %). Scale decreased to 0.8392
Detail  :          chain 4 is below 15 % (14 %). Scale decreased to 0.5594
Detail  :          chain 5 is below 15 % (13 %). Scale decreased to 0.5594
Detail  :          chain 7 is below 15 % (13 %). Scale decreased to 0.5594
Detail  :          chain 8 is below 15 % (13 %). Scale decreased to 0.5594
Detail  :          chain 9 is below 15 % (12 %). Scale decreased to 0.5594
Summary :   --> Set of 12 Markov chains converged within 2000 iterations, and all scales are adjusted.
Summary :   --> 3 updates to multivariate proposal function's covariances were made.
Detail  :   --> Scale factors and efficiencies (measured in last 500 iterations):
Detail  :         - Chain : Scale factor    Efficiency
                                    ...
```

Output

- Plots:

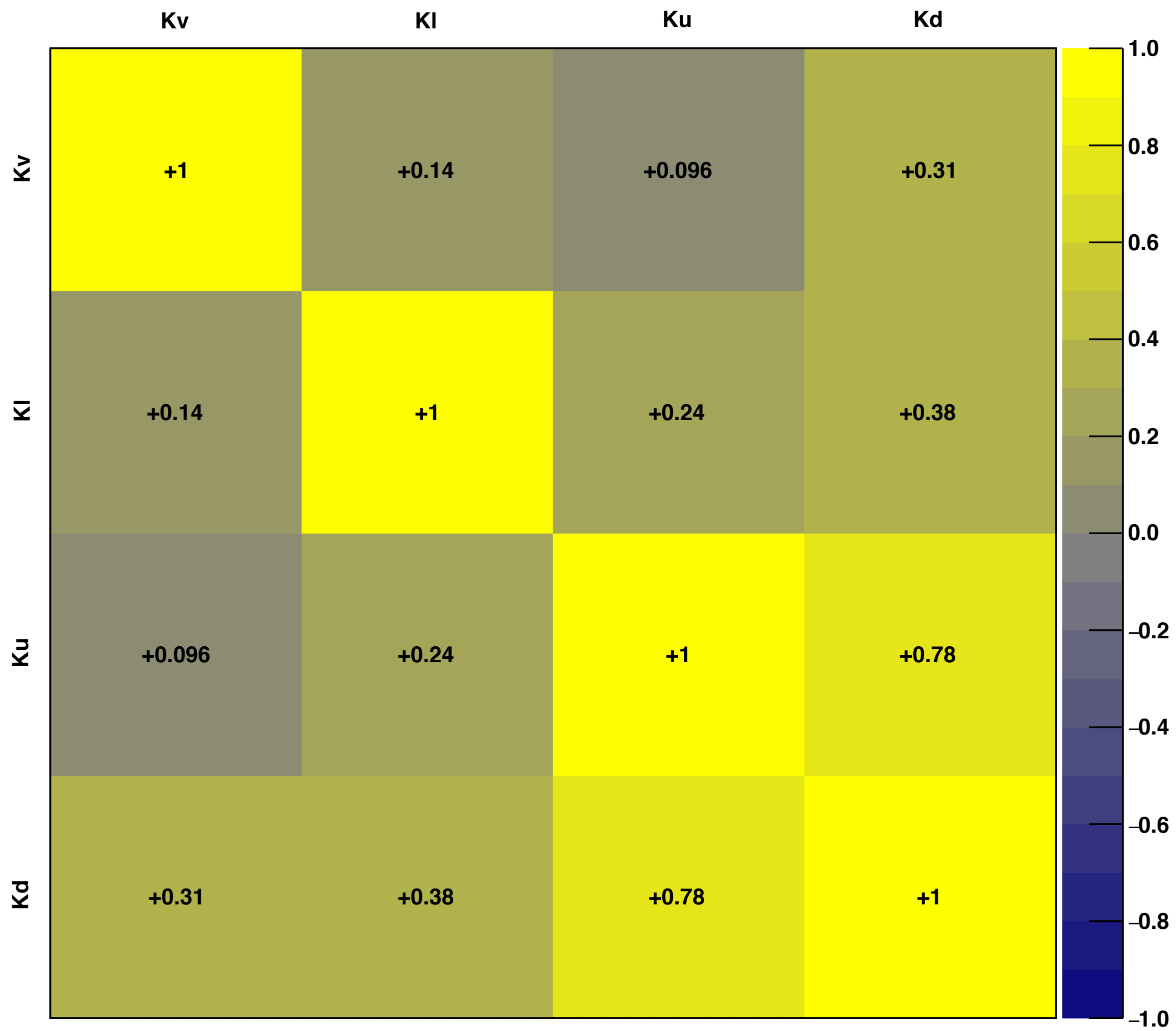


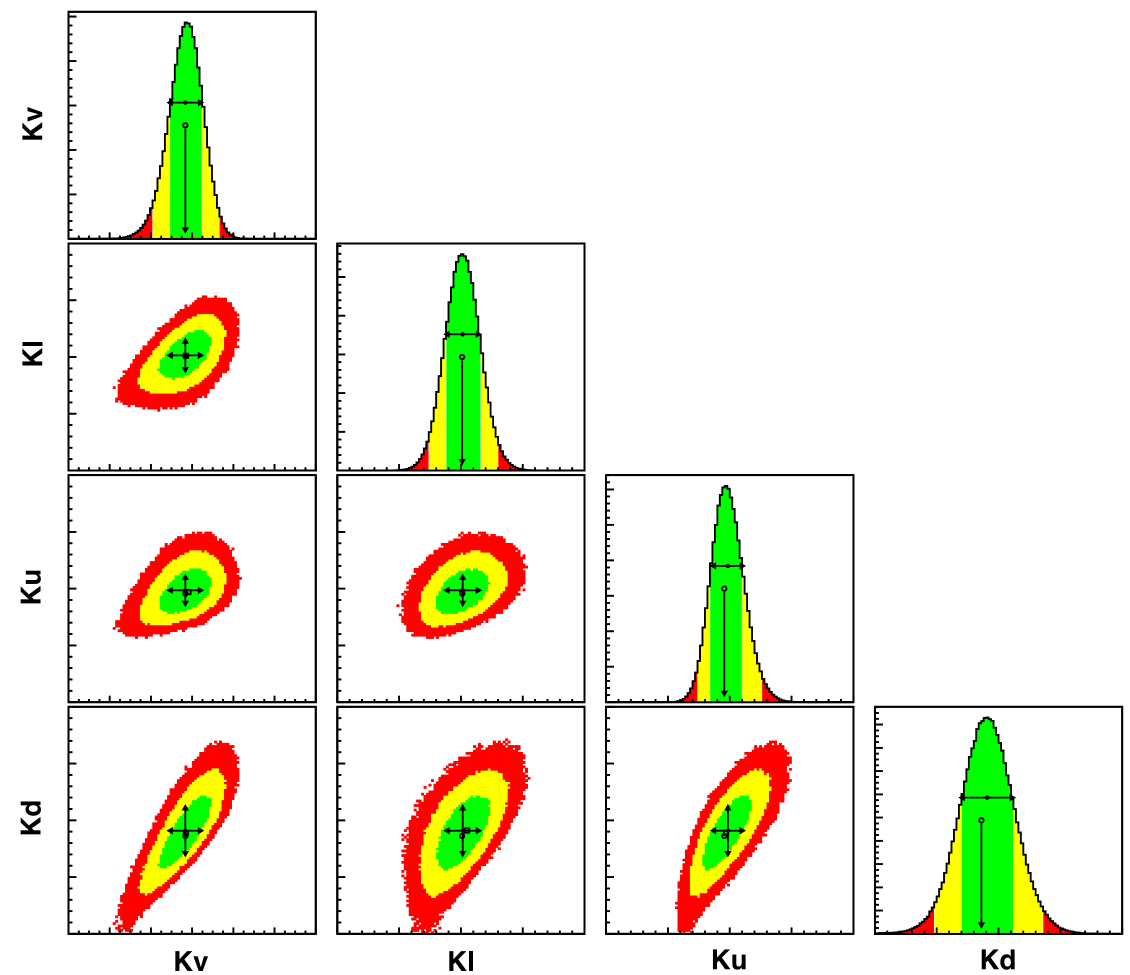


1D and 2D marginalized distributions

Output

- Plots:





Correlation plots

Want more?… use the whole output included in a ROOT file (MCout.root)

Run time / Speed

- Observable computation rate of O(KHz) or better for most implemented observables
- Run times for single thread (core) single chain analysis:
  - Test run (Stats. O(10K)) $\Longrightarrow$ Minutes
  - Results analysis (Stats. O(100K)) $\Longrightarrow$ Hours
  - Publication-level analysis (Stats. O($\gtrsim$1M)) $\Longrightarrow$ Days
- Use the built-in MPI implementation to reduce running time (O(N) for N threads (cores) used)
- Example: Unitarity triangle fit possible in a laptop in ~1h using 8 cores

Models and Observables

Already in the code:

Models

- Standard Model
- Oblique pars: S,T,U
- ε_i parameters
- Modified *Zbb* couplings
- Modified Higgs coup: κ_V, κ_f
- SMEFT dim 6
- General THDM

⇐Tested

- SUSY
- LR models

⇐WiP

Observables

- EWPO
- Higgs signal strengths
- Flavor: ΔF=2, UT, B decays
- LFV

⇐Tested

- LEP 2 cross sections

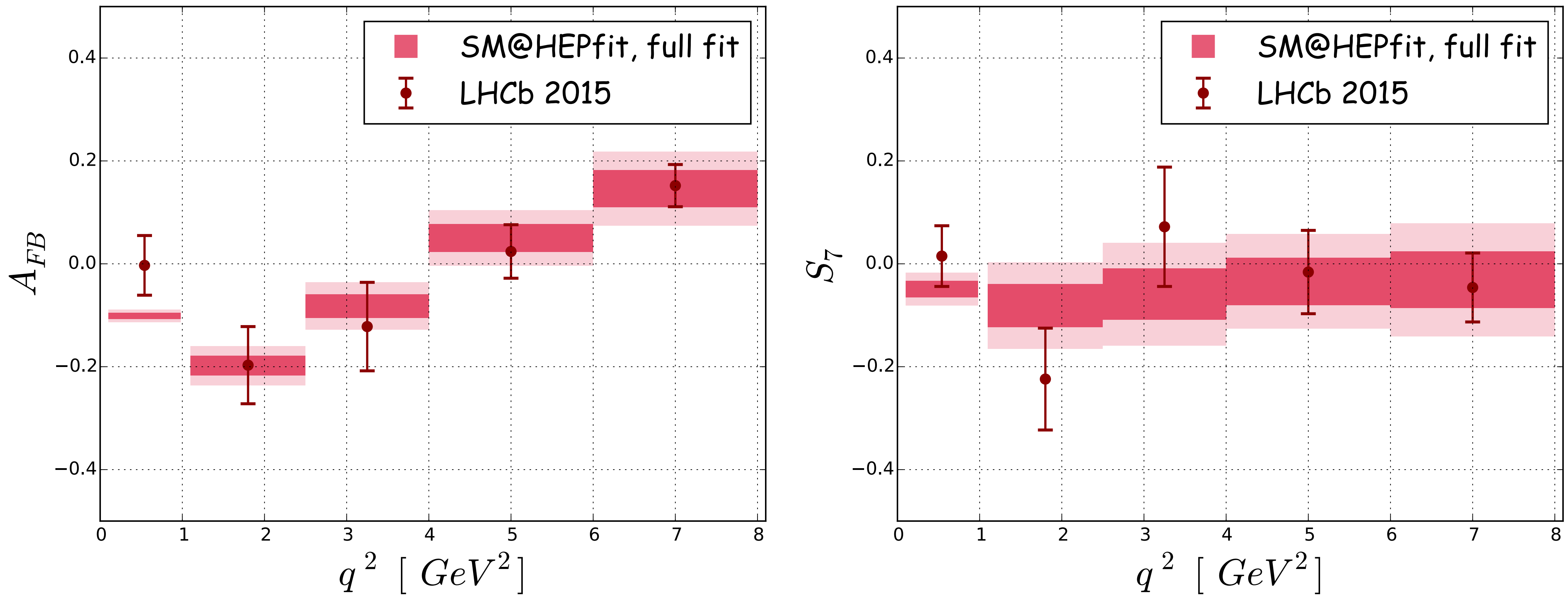
⇐WiP

Models and Observables

Observable	SM	THDM	SUSY	Dim-6
Flavour:				
$\mathcal{B}(B_s \to \mu^+\mu^-)$	✓	✓	×	×
$\mathcal{B}(\bar{B} \to X_s\gamma)$	✓	✓	×	×
$\mathcal{B}(\tau \to \mu\gamma, 3\mu)$	–	–	✓	×
(...)				
Higgs:				
μ's	✓	✓	×	✓
Direct searches	–	✓	×	–
Electroweak precision observables:				
	✓	✓	×	✓
(...)				

- Standard Model:
  - Flavor observables: Rare decays, non-leptonic decays, … Most of them at the highest available precision
  - Example: $B \to K^* \ell\ell$

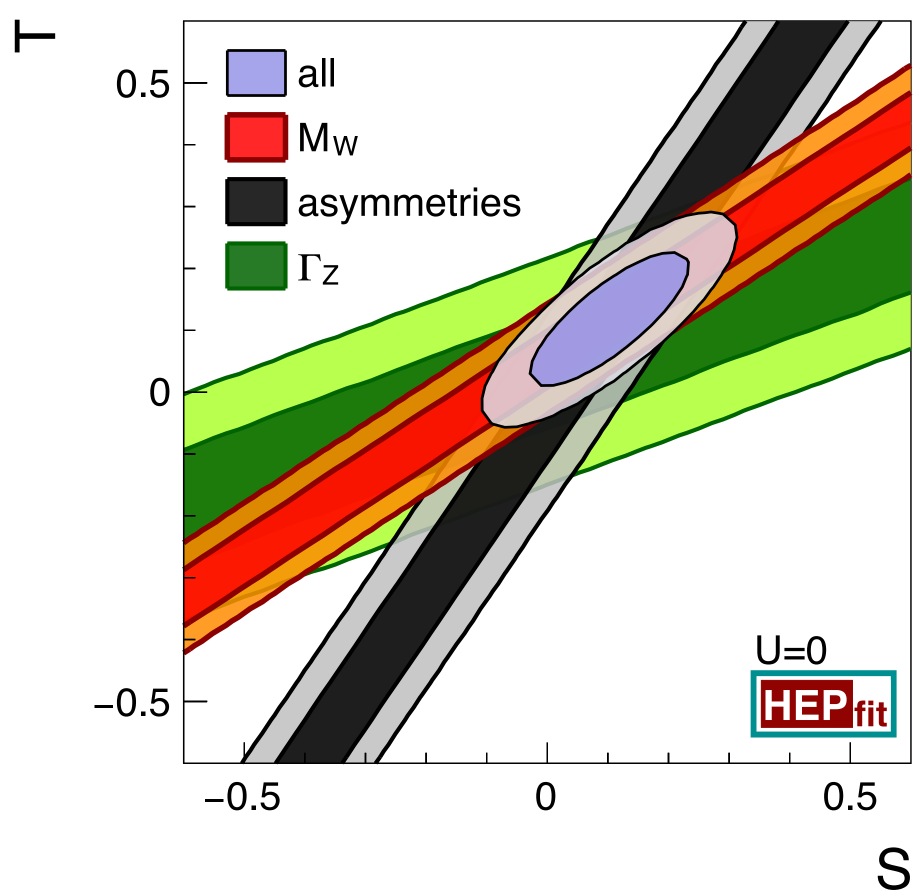
M. Ciuchini et al. , arXiv: 1512.07157 [hep-ph]

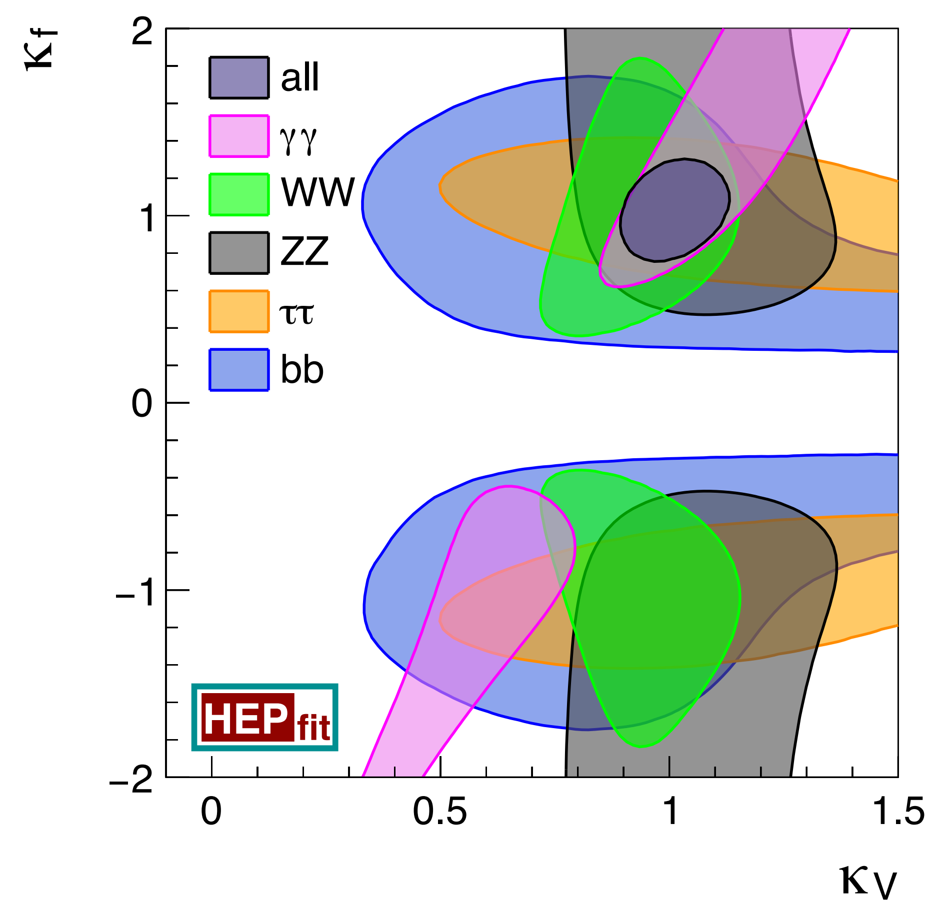


HEPfit Results

- Standard Model and Beyond (oblique parameters, dim 6 SMEFT,…):
  - Electroweak Precision Observables
  - Higgs signal strengths

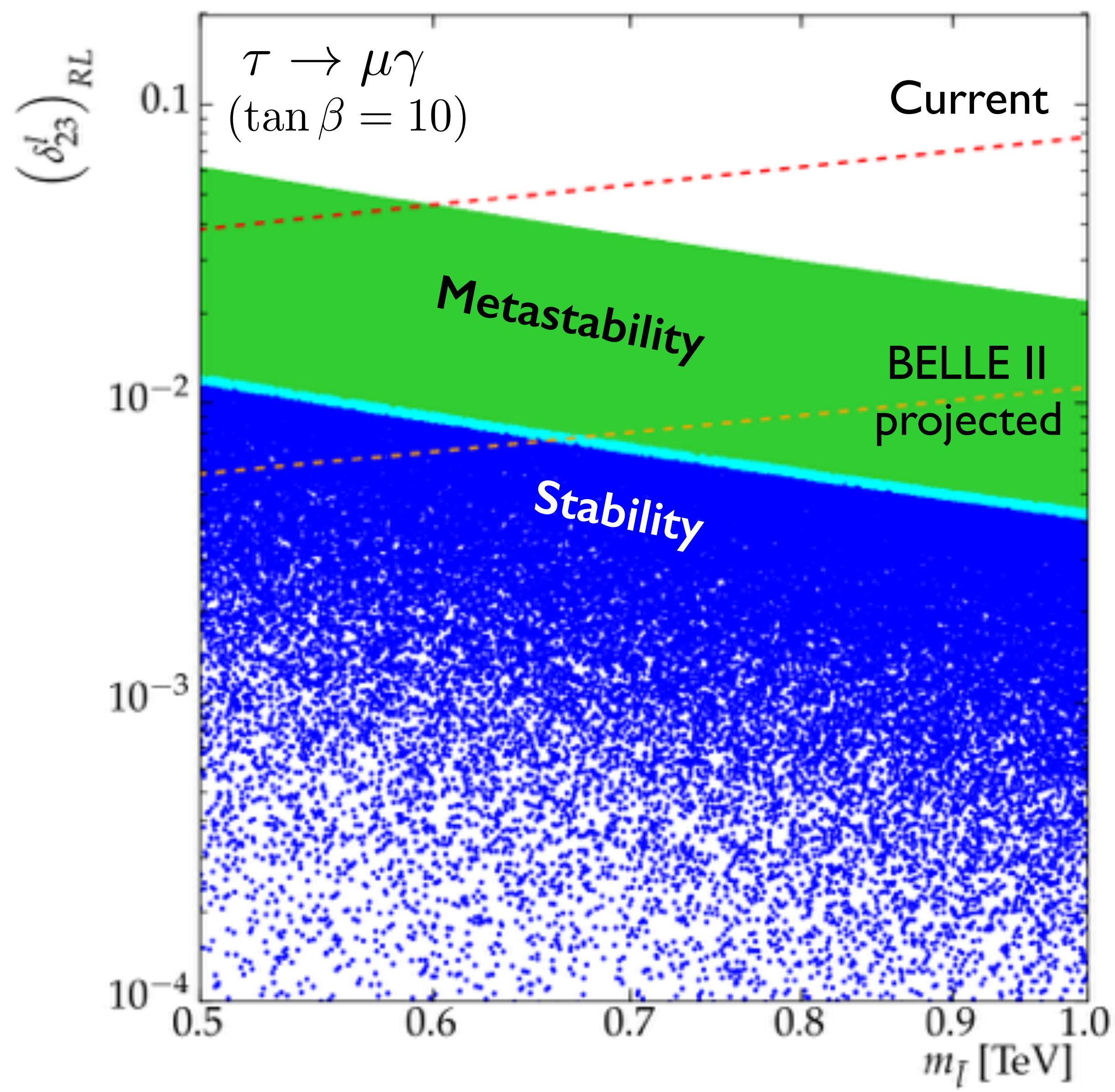
J. de Blas et al. , arXiv: 1607.XXXX [hep-ph]
J. de Blas et al. , In preparation





See my next talk at 16:50 today

- MSSM:
  - Generic flavour structure implemented
  - Lepton Flavor violation:
    $\ell_i \to \ell_j \gamma$, $\ell_i \to 3\ell_j$,
    $\mu \to e$ conv., $(g_\mu - 2)$
  - Stability constraints
  - WiP: metastability and RGE

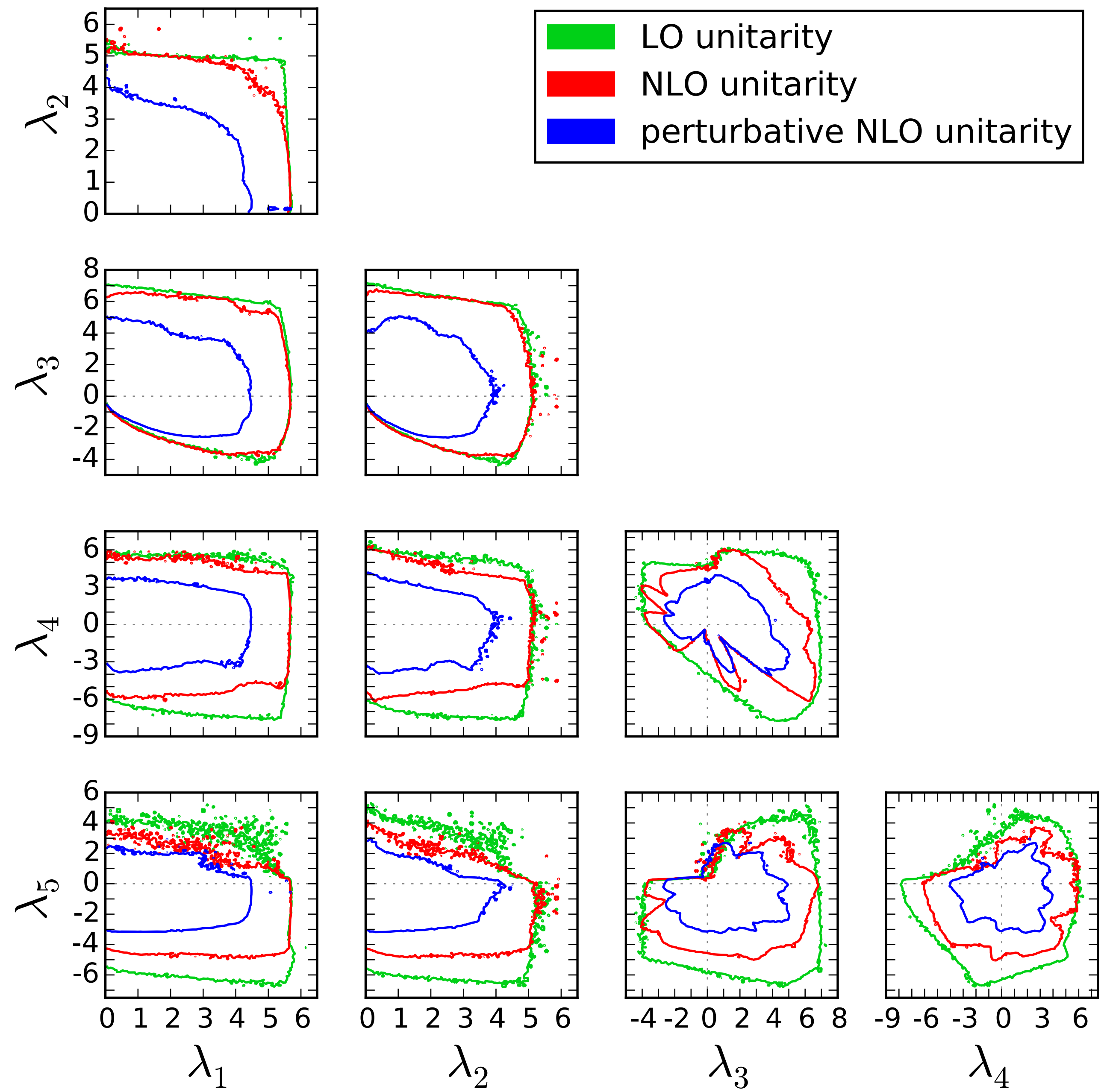


$$\delta^{RL}_{23} \equiv \frac{A^l_{23}\langle H^0_d\rangle}{m^2_{\tilde{l}}}$$

$$m_{\tilde{l}} \equiv \sqrt{m^2_R m^2_L}$$

See D. Chowdhury talk today at 16:30 (SUSY models session)

- THDM (with softly broken Z_2):
  - Stability constraints
  - NLO Unitarity constraints
  - NLO RGE
  - EWPO via STU parameters
  - Higgs signal strengths
  - Heavy Higgs direct searches
  - Flavor: $b \to s\gamma$ (NNLO)
    Δm_{B_s} (LO)
    $B \to \tau\nu$ (LO)
    $B_s \to \mu\mu$ (LO)



See D. Chowdhury talk on thursday 17:50 (Higgs physics session)

Summary

- HEPfit is a computational framework designed having in mind both theorist and experimentalist
- Currently focused mostly on indirect tests of New Physics using EWPD, Higgs observables, Flavor, …
- …working on the combination of direct and indirect searches
- Flexibility:
  - Modular structure allows users to modify or add new models & observables
  - Different kinds of statistical analyses (Bayesian MCMC built in via BAT)
- For more details & documentation please check:

http://hepfit.roma1.infn.it https://github.com/silvest/HEPfit