`SpaceMath` version 1.0 a `Mathematica` package for beyond the standard model parameter space searches

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We present a pedagogical `Mathematica` package, so-called `SpaceMath`, for Beyond the Standard Model parameter space searches. This software is directed mainly for the training of human resources related to elementary particle physics phenomenology, however, it is sophisticated enough to be used in researches. In this first version, `SpaceMath v1.0` works with Higgs Boson Data whose results are the most up-to-date experimental measurements made at the Large Hadron Collider. In addition, we also include the expected results at future colliders, namely, High Luminosity LHC and High Energy LHC. `SpaceMath v1.0` is able to find allowed regions for free parameters of extension models using the Higgs Boson Data within a friendly interface and an intuitive environment in which the user enters the couplings symbolically, sets parameters and execute `Mathematica` in the traditional way. As result, both tables as plots with values and areas agree with experimental data are generated. We present examples using `SpaceMath v1.0` to analyze the free *Two-Higgs Doublet Model* and the *Simplest Little Higgs Model* parameter spaces, step by step, in order to start new users in a fast and efficient way. Finally, to validate `SpaceMath v1.0`, widely known results are reproduced.

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1. Introduction

Our current knowledge of elementary particles and their interactions is based on solid theoretical foundations that are embodied in the Standard Model (SM). This theory provides a description of the weak, strong and electromagnetic interactions, satisfactorily explaining the experimental results, except for isolated exceptions. However, despite these achievements, there are phenomena that do not help us understand, for example: the problem of hierarchy, the origin of dark matter, the problem of flavor, etc. The fact that the SM cannot provide an answer to these phenomena suggests physics beyond the SM. In the last decades, several extensions of the SM have been presented to try to solve them, however this results in the emergence of free parameters that are not predicted by theory.

The search for physics Beyond the Standard Model (BSM) is necessarily a multidisciplinary effort, since the evidence for new physics could appear in physical observables that have been proposed both theoretically and experimentally. One strategy is to produce new hypothetical particles in colliders (for example, LHC and future stages of it), searching in decays and/or in high precision measurements. In this context, the reports by different collaborations have given exclusions on specific regions of the parameter space that, however, have been valuable so far. On the other hand, there have been many supposed signatures of new physics, often only to be refuted by the lack of correlated signals in other experiments. Properly and fully weighing the sum of data relevant to a theory and making rigorous statistical statements about which models are allowed and which are not, has become a challenging task for both theory and experiment.

Secondly, with the discovery of the Higgs boson [1, 2] is established that the Higgs mechanism explains the electroweak symmetry breaking and it generate the mass of all particles of the SM, omitting the neutrino masses. The SM is the most successful theory that explains many experimental results. However, it is well known that, despite its great success, the SM cannot help us to understand several issues, it encourages the study of SM extensions [3–18], with the aim of solving some issue unexplained. The price to pay is the emergence of free parameters whose values are not predicted by the theory. From a phenomenological point of view, one frequently encounters these free parameters which should be constrained in some way, but at same time, motivated and allowed by experimental measurements or by theoretical restrictions. With the `SpaceMath` package, it is possible to do it. Free model parameter spaces can be constrained automatically within a friendly interface and an intuitive environment, where the user defines the couplings and executing the `SpaceMath` commands generates plots and tables showing the areas and numerical values according to experimental data, respectively, for the free BSM parameters. Similar packages to `SpaceMath` are shown in Table and can be consulted in the Refs. [19–25].

TABLE I. Similar packages to SpaceMath.

Software	Features	Library Dependencies	Memory requirements (RAM)	Required user level	Execution mode
GAMBIT 2.1	• Large database of models, SUSY and others • Extensive library of observables • Tools for simple interfacing with external codes • Massively parallel, both OpenMP and MPI • Easy to add new models, observables, likelihoods, and scanners	• g++/gfortran 5.1 or greater • Cmake 2.8.12 or greater • Python 2.7 or greater • Python modules and Git • Boost 1.48 or greater • GSL 2.1 or greater • Eigen 3.1.0 or greater • LAPACK • pkg-config	• Require more than 20 GB • Release mode is only intended for performance-critical applications, such as when running on supercomputer architectures. • It is not advised for laptops.	Advanced user	Terminal
HEPfit 1.0	HEPfit is a flexible open-source tool which, given the Standard Model or any of its extensions, allows to • fit the model parameters to a given set of experimental observables; • obtain predictions for observables.	• CMake • GSL • ROOT v5 or greater • BOOST • MPI (optional) • BAT v1.0	Minimum 4 Gb.	Intermediate user	Terminal
Gfitter 2.2	• Gfitter consists of abstract object-oriented code in C++ using ROOT functionality. • Tools for the handling of the data, the fitting, and statistical analyses are provided by a core package, where theoretical errors, correlations, and inter-parameter dependencies are consistently dealt with.	• GCC 4.7 or 5.3 • ROOT 6.06/01	Minimum 4 Gb.	Intermediate user	Terminal
ScannerS 2.0	• ScannerS performs parameter scans and checks parameter points in theories BSM with extended scalar sectors. • Incorporates theoretical and experimental constraints from many different sources in order to judge whether a parameter point is allowed or excluded at approximately 95 % CL.	• gcc-7 or newer • CMake 3.11 • Eigen3 • GSL	• It requires at least 8 Gb or more depending on the number of points to be calculated.	Intermediate user	Terminal
EasyScan_HEP 0.1.0	EasyScan_HEP is a tool for connecting programs to scan parameter space of high energy physics models using various sampling algorithms. • It allows one to set parameters for scan algorithm. • Connect different programs that calculate physical quantities. • Apply constraints in one user-readable configuration file.	• Python3 with dependencies on numpy, scipy and ConfigParser libraries. • Optionally:matplotlib, pandas and pymultinest libraries.	4 Gb.	Intermediate user	Terminal
CheckMATE	CheckMATE is a program that allows models of new physics to be easily tested against the recent LHC data.	• Python 2.7 • ROOT • Delphes • Optional Packages: Pythia 8, MadGraph5_aMC@NLO and HepMC.	At least 4 Gb.	Intermediate user	Terminal
HDECAY	HDECAY is a program that determines: • The partial decay widths and branching ratios of the Higgs bosons within the Standard Model with three and four generations of fermions. • It addresses all decay channels including the dominant higher-order effects such as radiative corrections and multi-body channels.	• Fortran	Minimum 4 Gb.	Intermediate user	Terminal

However, SpaceMath has the feature that it only requires the installation of Mathematica Wolfram (available in many universities and research institutes) and a basic level user to be used, since at this stage of SpaceMath development its purpose is pedagogical. Unlike other programs that require prior knowledge of programming languages (see Table), the SpaceMath package has a fast learning curve and a practical approach which makes it a better option for quick results.

In this first version of SpaceMath, LHC Higgs boson data (HBD) and expected results at HL-LHC, HE-LHC are included:

1. Higgs boson data
   (a) Signal strength modifiers $\mathcal{R}_X$ 1.1.1.
   (b) Higgs boson coupling modifiers κ_i 1.1.2.

1.1. LHC Higgs boson data

1.1.1. *Signal strength modifiers $\mathcal{R}_X$*

For a production process $\sigma(pp \to H_i)$ and a decay $H_i \to X$, the signal strength is defined as follows:

$$\mathcal{R}_X = \frac{\sigma(pp \to h) \cdot \mathcal{BR}(h \to X)}{\sigma(pp \to h^{\text{SM}}) \cdot \mathcal{BR}(h^{\text{SM}} \to X)}, \tag{1}$$

where $\sigma(pp \to H_i)$ is the production cross section of H_i, with $H_i = h,\ h^{\text{SM}}$; here h is the SM-like Higgs boson coming from an extension of the SM and h^{SM} is the SM Higgs boson; $\mathcal{BR}(H_i \to X)$ is the branching ratio of the decay $H_i \to X$, with $X = b\bar{b},\ \tau^-\tau^+,\ \mu^-\mu^+,\ WW^*,\ ZZ^*,\ \gamma\gamma$. In SpaceMath v1.0, we only consider the Higgs boson production cross section via the gluon fusion mechanism and we use the narrow width approximation:

$$\mathcal{R}_X \approx \frac{\Gamma(h \to gg) \cdot \mathcal{BR}(h \to X)}{\Gamma(h^{\text{SM}} \to gg) \cdot \mathcal{BR}(h^{\text{SM}} \to X)}. \tag{2}$$

1.1.2. *Higgs boson coupling modifiers κ_i*

The coupling modifiers κ_i are introduced to quantify the deviations of the SM-like Higgs boson to other particles. The coupling modifiers κ_i for a production cross section or a decay mode, are defined as follows:

$$\kappa_{pp}^2 = \frac{\sigma(pp \to h)}{\sigma(pp \to h^{\text{SM}})} \text{ or } \kappa_X^2 = \frac{\Gamma(h \to X)}{\Gamma(h^{\text{SM}} \to X)}. \tag{3}$$

We consider tree-level Higgs boson couplings to different particles, i.e., g_{hZZ^*}, g_{hWW^*}, $g_{h\tau^-\tau^+}$, $g_{h\mu^-\mu^+}$, $g_{hb\bar{b}}$, as well as effective coupling modifiers g_{hgg} and $g_{h\gamma\gamma}$ which describe gluon fusion production ggh and the $h \to \gamma\gamma$ decay, respectively.

The organization of our work is as follows. In Sec. 2 we present, in a concise way, how `SpaceMath v1.0` can be installed. Section 3 is devoted to show as `SpaceMath v1.0` works, giving a detailed example. Section 4 is focused on the validation of `SpaceMath v1.0` by reproducing several results shown in the literature. Finally, conclusion and perspectives are presented in Sec. 5.

2. Installation

Stable version of `SpaceMath v1.0` package that contains all the features tested can be downloaded and installed as following:

2.1. Automatic Installation

Run the following instructions in a Notebook of `Mathematica`

```
Import["https://raw.githubusercontent.com/spacemathapp/spacemath/stable/SpaceMath/Install.m"]
InstallSpaceMath[]
```

Note that an error may appear due to the quotation marks (””); this can be resolved by deleting and then explicitly writing both quotation marks. We take the installation method implemented in FeynCalc [26].

2.2. Manual installation

1. Download `SpaceMath v1.0` from `https://github.com/spacemathapp/spacemath/archive/refs/heads/stable.zip`

2. Unzip the zip file and copy the `SpaceMath` directory from `$SpaceMath-stable/SpaceMath/` to the Applications directory inside `$UserBaseDirectory.`

To delete Spacemath package automatically, the user only has to execute the following instruction:

```
DeleteSpaceMath[]
```

3. First steps

In order to introduce new users quickly and concisely, we display a collection of the basic `SpaceMath v1.0` commands for the `Signal Strenghts` with their application to the Two-Higgs-Doublet Model Type-III (THDM-III). There are common arguments in all `SpaceMath v1.0` commands; for this reason, let us first list them in Table II. While in Tables III-VI, we display the main commands to generate plots and tables with allowed regions by the most up-to-date experimental results.

3.1. Constraint on free model parameter space of the THDM-III by using `SpaceMath v1.0`

We now turn to constrain the free model parameter space of the THDM-III focusing on the Yukawa interactions. As previously we mentioned, in `SpaceMath` v1.0 only the Higgs boson data are enabled. Then, we use signal strengths to find allowed regions which are in accordance with the most up-to-date experimental reports. We give, step by step, instructions on how `SpaceMath` v1.0 works. For enthusiastic users go to the Sec. 3.1.

We first present an overview of the THDM-III focusing only on the details relevant of the Yukawa Lagrangian. For a detailed account of this model and the study of its phenomenology we refer the readers to Refs. [28–39].

The most general $SU(2)_L \times U(1)_Y$ invariant scalar potential is given by [40, 41]:

$$V(\Phi_1,\Phi_2) = \mu_1^2(\Phi_1^\dagger\Phi_1) + \mu_2^2(\Phi_2^\dagger\Phi_2) - \Big(\mu_{12}^2(\Phi_1^\dagger\Phi_2) + H.c.\Big) + \frac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \frac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2)$$
$$+ \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \left(\frac{1}{2}\lambda_5(\Phi_1^\dagger\Phi_2)^2 + \Big(\lambda_6(\Phi_1^\dagger\Phi_1) + \lambda_7(\Phi_2^\dagger\Phi_2)\Big)(\Phi_1^\dagger\Phi_2) + H.c.\right), \quad (4)$$

TABLE II. Description of `SpaceMath v1.0` command arguments.

Argument	Description
ghtt	Coupling of the Higgs boson to a top quark pair.
ghbb	Coupling of the Higgs boson to a bottom quark pair.
ghtautau	Coupling of the Higgs boson to a τ lepton pair.
ghVV	Coupling of the Higgs boson to a $V = W, Z$ gauge boson pair.
gCH	Coupling of the Higgs boson to a charged scalar boson pair.
x, y, xfor, yfor	Parameters to be constrained.
xmin, xmax	Interval from xmin to xmax for parameter x: xmin$\leq$ x$\leq$ xmax.
ymin, ymax	Interval from ymin to ymax for parameter y: ymin$\leq$ y$\leq$ ymax.
xformin, xformax	Interval from xformin to xformax for parameter xfor: xformin$\leq$ xfor$\leq$ xformax.
yformin, yformax	Interval from yformin to yformax for parameter yfor: yformin$\leq$ yfor$\leq$ yformax.
xforstep	Steps from xformin to xformax .
yforstep	Steps from yformin to yformax .
xlabel (ylabel)	Label for x axis (y axis).
PP	Sample points to use for plotting functions. We suggest to consider values until PP =100 and for PP >100 High-Performance Computing is recommend, or you can use our server, see Appx. A for details.
NN	Number of random values to generate.
[[i]]	Stands for confidence level i=1 (2), indicates 1σ (2σ).
mCH	Charged scalar mass.
xi, i=1, 2, 3, 4.	Random values parameters to be generated.

TABLE III. Commands to generate $\mathcal{R}_X$ graphs when there are dependence on one or up to four free parameters. A description of all arguments is shown in Table II.

Commands to generate $\mathcal{R}_X$ graphs.
RVone[ghtt_,ghbb_,ghVV_,x_,xmin_,xmax_,xlabel_][[i]]
This command graphs $\mathcal{R}_V$ ($V = W, Z$) as a function of x.
RGAMone[ghtt_,ghbb_,ghWW_,gCH_,mCH_,x_,xmin_,xmax_,xlabel_][[i]]
This command graphs $\mathcal{R}_\gamma$ as a function of x.
RTAUone[ghtt_, ghbb_, ghtautau_, x_, xmin_, xmax_, xlabel_][[i]]
This command graphs $\mathcal{R}_\tau$ as a function of x.
RBOTone[ghtt_, ghbb_, x_, xmin_, xmax_, xlabel_][[i]]
This command graphs $\mathcal{R}_b$ as a function of x.
RV[ghtt_, ghbb_, ghVV_, x_, y_, xmin_, xmax_, ymin_, ymax_, xlabel_, ylabel_, xfor_, yfor_, xformin_, xformax_, xforstep_, yformin_, yformax_, yforstep_, PP_][[i]]
This command graphs $\mathcal{R}_V$ ($V = W, Z$) as a function of the parameters to be constrained: x, y, xfor, yfor.
RGam[ghtt_, ghbb_, ghWW_, gCH_, mCH_, x_, y_, xmin_, xmax_, ymin_, ymax_, xlabel_, ylabel_, xfor_, yfor_, xformin_, xformax_, xforstep_, yformin_, yformax_, yforstep_, PP_][[i]]
This command graphs $\mathcal{R}_\gamma$ as a function of the parameters to be constrained: x, y, xfor, yfor.
Rtau[ghtt_, ghbb_, ghtautau_, x_, y_, xmin_, xmax_, ymin_, ymax_, xlabel_, ylabel_, xfor_, yfor_, xformin_, xformax_, xforstep_, yformin_, yformax_, yforstep_, PP_] [[i]]
This command graphs $\mathcal{R}_\tau$ as a function of the parameters to be constrained: x, y, xfor, yfor.
Rb[ghtt_, ghbb_, x_, y_, xmin_, xmax_, ymin_, ymax_, xlabel_, ylabel_, xfor_, yfor_, xformin_, xformax_, xforstep_, yformin_, yformax_, yforstep_, PP_][[i]]
This command graphs $\mathcal{R}_b$ as a function of the parameters to be constrained: x, y, xfor, yfor.

TABLE IV. Commands for generate both plots as tables for $\mathcal{R}_X$ when there are dependence on one or up to four free parameters. A description of all arguments is shown in Table II.

Commands to generate random values for $\mathcal{R}_X$.
RVRandom[ghtt_,ghbb_,ghVV_,x1_,x1min_,x1max_, x2_,x2min_,x2max_,x3_,x3min_,x3max_,x4_,x4min_,x4max_,NN_]
This command generates random values that satisfy the experimental constraint on $\mathcal{R}_V$.
PlotRVRandom[ci_,cj_,xlabel_,ylabel_][[i]]
This command graphs the plane ci-cj once RVRandom was executed.
RgamRandom[ghtt_,ghbb_,ghWW_,gCH_,mCH_,x1_,x1min_,x1max_, x2_,x2min_,x2max_,x3_,x3min_,x3max_,x4_,x4min_,x4max_,NN_]
This command generates random values that satisfy the experimental constraint on $\mathcal{R}_\gamma$.
PlotRgamRandom[ci_,cj_,xlabel_,ylabel_][[i]]
This command graphs the plane ci-cj once RgamRandom was executed.
RtauRandom[ghtt_,ghbb_,ghtautau_,x1_,x1min_,x1max_, x2_,x2min_,x2max_,x3_,x3min_,x3max_,x4_,x4min_,x4max_,NN_]
This command generates random values that satisfy the experimental constraint on $\mathcal{R}_\tau$.
PlotRtauRandom[ci_,cj_,xlabel_,ylabel_][[i]]
This command graphs the plane ci-cj once RtauRandom was executed.
RbRandom[ghtt_,ghbb_,x1_,x1min_,x1max_, x2_,x2min_,x2max_,x3_,x3min_,x3max_,x4_,x4min_,x4max_,NN_]
This command generates random values that satisfy the experimental constraint on $\mathcal{R}_b$.
PlotRbRandom[ci_,cj_,xlabel_,ylabel_][[i]]
This command graphs the plane ci-cj once RbRandom was executed.

TABLE V. Commands to generate tables in arrays: $\{a,b\}$ and $\{a,b,c\}$.

Commands for generate tables of $\mathcal{R}_X$'s.
TableRVone[ghtt_,ghbb_,ghVV_,x_,xmin_,xmax_,xstep_]
This command generates a table with two columns: RVone-x. The output file will be saved as TableRVone_1sigma.txt and TableRVone_2sigma.txt in $UserDocumentsDirectory. Here $V=W$, Z.
TableRGAMone[ghtt_,ghbb_,ghWW_,gCH_,mCH_,x_,xmin_,xmax_,xstep_]
This command generates a table with two columns: RGAMone-x. The output file will be saved as TableRGAMone_1sigma.txt and TableRGAMone_2sigma.txt in $UserDocumentsDirectory.
TableRTAUone[ghtt_,ghbb_, ghtautau_,x_,xmin_,xmax_,xstep_]
This command generates a table with two columns: RTAUone-x. The output file will be saved as TableRTAUone_1sigma.txt and TableRTAUone_2sigma.txt in $UserDocumentsDirectory.
TableRBOTone[ghtt_,ghbb_,x_,xmin_,xmax_,xstep_]
This command generates a table with two columns: RBOTone-x. The output file will be saved as TableRBOTone_1sigma.txt and TableRBOTone_2sigma.txt in $UserDocumentsDirectory.

TableRV[ghtt_, ghbb_, ghVV_, x_, xmin_, xmax_, xstep_, y_, ymin_, ymax_, ystep_]
This command generates a table with three entries arranged as {RV, x, y}, The output file will be saved as TableRV_1sigma.txt and TableRV_2sigma.txt in $UserDocumentsDirectory.

TableRGam[ghtt_, ghbb_, ghWW_, gCH_, mCH_, x_, xmin_, xmax_, xstep_, y_, ymin_, ymax_, ystep_]
This command generates a table with three entries arranged as {RGam, x, y}, The output file will be saved as TableRgam_1sigma.txt and TableRgam_2sigma.txt in $UserDocumentsDirectory.

TableRb[ghtt_, ghbb_, x_, xmin_, xmax_, xstep_, y_, ymin_, ymax_, ystep_]
This command generates a table with three entries arranged as {RV, x, y}, The output file will be saved as TableRb_1sigma.txt and TableRb_2sigma.txt in $UserDocumentsDirectory.

TableRtau[ghtt_, ghbb_, ghtautau_, x_, xmin_, xmax_, xstep_, y_, ymin_, ymax_, ystep_]
This command generates a table with three entries arranged as {Rtau, x, y}, The output file will be saved as TableRtau_1sigma.txt and TableRtau_2sigma.txt in c.

TABLE VI. Commands to generate $\mathcal{R}_X$ graphs when there are dependence on one or up to four free parameters.

Commands to generate $\mathcal{R}_X$ graphs.
RXALL[ghtt_, ghbb_, ghZZ_, ghWW_, ghtautau_, gCH_, mCH_, x_, y_, xmin_, xmax_, ymin_, ymax_, xlabel_, ylabel_, xfor_, yfor_, xformin_,xformax_,xforstep_,yformin_,yformax_,yforstep_,PP_][[i]]
This command graphs all signal strengths in a same plot as a function of x, y, xfor, yfor.
RXintersection[ghtt_, ghbb_, ghZZ_, ghWW_, ghtautau_, gCH_, mCH_, x_, y_, xmin_, xmax_, ymin_, ymax_, xlabel_, ylabel_, xfor_, yfor_, xformin_,xformax_,xforstep_,yformin_,yformax_,yforstep_,PP_][[i]]
This command graphs the intersection of all signal strengths, if any.

where $\mu_{1,2}$, $\lambda_{1,2,3,4}$ are real parameters while μ_{12}, $\lambda_{5,6,7}$ can be complex in general. The doublets are written as $\Phi_a^T = (\phi_a^+, \phi_a^0)$ for $a = 1, 2$. After the Spontaneous Symmetry Breaking (SSB) the two Higgs doublets acquire non-zero expectation values. The Vacuum Expectation Values (VEV) are selected as

$$\langle\Phi_a\rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \upsilon_a \end{pmatrix}, \qquad a = 1,\, 2; \tag{5}$$

where υ_1 and υ_2 satisfy $\upsilon_1^2 + \upsilon_2^2 = \upsilon^2$ for $\upsilon = 246$ GeV.

In the most general case both doublets can participate in the interactions with the fermion fields. The Yukawa Lagrangian is written as

$$\mathcal{L}_Y = Y_1^u \bar{Q}_L^{'} \tilde{\Phi}_1 u_R^{'} + Y_2^u \bar{Q}_L^{'} \tilde{\Phi}_2 u_R^{'} + Y_1^d \bar{Q}_L^{'} \Phi_1 d_R^{'} + Y_2^d \bar{Q}_L^{'} \Phi_2 d_R^{'} + Y_1^\ell \bar{L}_L^{'} \Phi_1 \ell_R^{'} + Y_2^\ell \bar{L}_L^{'} \Phi_2 \ell_R^{'} + H.c., \tag{6}$$

Because we are interested in neutral interactions we only present the neutral part of the Yukawa Lagrangian of Eq. (6) which reads: [31]

$$\mathcal{L}_Y^N = Y_1^u \bar{Q}_L^0 \tilde{\Phi}_1 u_R^0 + Y_2^u \bar{Q}_L^0 \tilde{\Phi}_2 u_R^0 + Y_1^d \bar{Q}_L^0 \Phi_1 d_R^0 + Y_2^d \bar{Q}_L^0 \Phi_2 d_R^0 + Y_1^\ell \bar{L}_L^0 \Phi_1 \ell_R^0 + Y_2^\ell \bar{L}_L^0 \Phi_2 \ell_R^0 + h.c. \tag{7}$$

with

$$Q_L^0 = \begin{pmatrix} u_L \\ d_L \end{pmatrix}, \qquad L^0 = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix},$$
$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \phi_1^0 \end{pmatrix}, \qquad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \phi_2^0 \end{pmatrix}, \qquad \tilde{\Phi}_j = i\sigma_2 \Phi_j^*. \tag{8}$$

Here Φ_i $(i = 1,\ 2)$ denotes the Higgs doublets and Y_i^f stand for 3×3 Yukawa matrices. After SSB and algebraic manipulations, the Yukawa Lagrangian in term of physical states is given as follows:

$$\begin{aligned}\mathcal{L}_Y =& \frac{g}{2}\left(\frac{m_d}{m_W}\right)\bar{d}_i\left[\frac{\cos\alpha}{\cos\beta}\delta_{ij} + \frac{\sqrt{2}\sin(\alpha-\beta)}{g\cos\beta}\left(\frac{m_W}{m_d}\right)\left(\tilde{Y}_2^d\right)_{ij}\right]d_jH \\ &+ \frac{g}{2}\left(\frac{m_d}{m_W}\right)\bar{d}_i\left[-\frac{\sin\alpha}{\cos\beta}\delta_{ij} + \frac{\sqrt{2}\cos(\alpha-\beta)}{g\cos\beta}\left(\frac{m_W}{m_d}\right)\left(\tilde{Y}_2^d\right)_{ij}\right]d_jh \\ &+ i\frac{g}{2}\left(\frac{m_d}{m_W}\right)\bar{d}_i\left[-\tan\beta\delta_{ij} + \frac{\sqrt{2}}{g\cos\beta}\left(\frac{m_W}{m_d}\right)\left(\tilde{Y}_2^d\right)_{ij}\right]\gamma^5 d_jA \\ &+ \frac{g}{2}\left(\frac{m_u}{m_W}\right)\bar{u}_i\left[\frac{\sin\alpha}{\sin\beta}\delta_{ij} - \frac{\sqrt{2}\sin(\alpha-\beta)}{g\sin\beta}\left(\frac{m_W}{m_u}\right)\left(\tilde{Y}_2^u\right)_{ij}\right]u_jH \\ &+ \frac{g}{2}\left(\frac{m_u}{m_W}\right)\bar{u}_i\left[\frac{\cos\alpha}{\sin\beta}\delta_{ij} - \frac{\sqrt{2}\cos(\alpha-\beta)}{g\sin\beta}\left(\frac{m_W}{m_u}\right)\left(\tilde{Y}_2^u\right)_{ij}\right]u_jh \\ &+ i\frac{g}{2}\left(\frac{m_u}{m_W}\right)\bar{u}_i\left[-\cot\beta\delta_{ij} + \frac{\sqrt{2}}{g\sin\beta}\left(\frac{m_W}{m_u}\right)\left(\tilde{Y}_2^u\right)_{ij}\right]\gamma^5 u_jA,\end{aligned} \tag{9}$$

where i and j stand for the fermion flavors, with $i \neq j$, in general. As far as the lepton interactions, it is similar to type-down quarks part with the exchange $d \to \ell$ and $m_d \to m_\ell$. The physical particles $h,\ H,\ A$ were obtained through a rotation depending on mixing angles α and β as follows:

$$\begin{pmatrix} H \\ h \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix}\begin{pmatrix} Re\Phi_1 \\ Re\Phi_2 \end{pmatrix}, \tag{10}$$

$$\begin{pmatrix} G \\ A \end{pmatrix} = \begin{pmatrix} \cos\beta & \sin\beta \\ -\sin\beta & \cos\beta \end{pmatrix}\begin{pmatrix} Im\Phi_1 \\ Im\Phi_2 \end{pmatrix}, \tag{11}$$

$$\begin{pmatrix} G^\pm \\ H^\pm \end{pmatrix} = \begin{pmatrix} \cos\beta & \sin\beta \\ -\sin\beta & \cos\beta \end{pmatrix}\begin{pmatrix} \Phi_1^\pm \\ \Phi_2^\pm \end{pmatrix}, \tag{12}$$

with the angle β given by:

$$\tan\beta = \frac{v_2}{v_1}. \tag{13}$$

THDM-III in `SpaceMath v1.0`

We will show how `SpaceMath v1.0` works for the particular case of $\mathcal{R}_\tau$ (`Rtau` in the `SpaceMath v1.0` nomenclature).

1. Open a `Mathematica` notebook,
2. Load `SpaceMath v1.0` through `<<SpaceMath‘`,
3. Define couplings as a function of the free model parameters. For the THDM-III case they are given in Table VII.

   We define `a`=α, `Cab`=$\cos(\alpha-\beta)$, `sab`=$\sin(\alpha-\beta)$, `tb`=$\tan\beta$, $\left(\tilde{Y}_2^F\right)_{ij} = \sqrt{m_i m_j}A_{ij}/v$ and $\sin\beta = \tan\beta\cos(\tan^{-1}(\tan\beta))$. The terms `mf (f= fermions), mV (V=Z, W), g` and `vev` are the fermion masses, gauge boson masses, $SU(2)$ coupling constant and the vacuum expectation value, respectively. These quantities are loaded once `SpaceMath v1.0` is executed. The file containing such information is `data.m`. From time to time the `data.m` file is updated according to new information from the state of art, so that the user has available this new information simply to run the following instruction:

```
UpdateSpaceMathData[]
```

TABLE VII. Left: THDM-III `ghXX` couplings. Right: Intries for `SpaceMath` v1.0.

Coupling from Yukawa Lagrangian in eq. (9)	Input to SpaceMath v1.0
ghtt $= \frac{g}{2}\frac{m_t}{m_W}\left[\frac{\cos\alpha}{\sin\beta}\delta_{ij} - \frac{\sqrt{2}\cos(\alpha-\beta)}{g\sin\beta}\left(\frac{m_W}{m_t}\right)\left(\tilde{Y}_2^U\right)_{tt}\right]$	`ghtt[a_,Att_,Cab_,tb_]:=(g/2)(mt/mW) ((Cos[a]/tb*Cos[ArcTan[tb]])- (Sqrt[2]*Cab/(g*tb*Cos[ArcTan[tb]])*(mW/mt)*(mt/vev*Att)))`
ghbb $= \frac{g}{2}\frac{m_b}{m_W}\left[-\frac{\sin\alpha}{\cos\beta}\delta_{ij} - \frac{\sqrt{2}\cos(\alpha-\beta)}{g\cos\beta}\left(\frac{m_W}{m_b}\right)\left(\tilde{Y}_2^D\right)_{bb}\right]$	`ghbb[a_,Abb_,Cab_,tb_]:=(g/2)(mb/mW) ((-Sin[a]*tb/Sin[ArcTan[tb]])+ (Sqrt[2]*(Cab*tb)/(g*Sin[ArcTan[tb]])*(mW/mb)*(mb/vev*Abb)))`
gh$\tau\tau$ $= \frac{g}{2}\frac{m_\tau}{m_W}\left[-\frac{\sin\alpha}{\cos\beta}\delta_{ij} - \frac{\sqrt{2}\cos(\alpha-\beta)}{g\cos\beta}\left(\frac{m_W}{m_\tau}\right)\left(\tilde{Y}_2^\ell\right)_{\tau\tau}\right]$	`ghtautau[a_,Atata_,Cab_,tb_]:=(g/2)(mtau/mW) ((-Sin[a]*tb/Sin[ArcTan[tb]])+ (Sqrt[2]*(Cab*tb)/(g*Sin[ArcTan[tb]])*(mW/mtau)*(mtau/vev*Atata)))`

4. To generate a graph of the signal strenght $\mathcal{R}_\tau$ when it depends on more than one parameter you must execute the command `Rtau[...]` which is described in Table III, namely:

```
Rtau[ghtt[ArcCos[cab] + ArcTan[tb], Att, cab, tb],
     ghbb[ArcCos[cab] + ArcTan[tb], Abb, cab, tb],
     ghtautau[ArcCos[cab] + ArcTan[tb], 1, cab, tb],
     cab, tb, -1, 1, 1, 15, "cos(α − β)" , "tan β",
     Att, Abb, 0.9, 1, 0.05, 0.9, 1, 0.05, 100][[2]].       (14)
```

In Eq. (14) we have:

- `ghtt=ghtt[ArcCos[cab] + ArcTan[tb], Att, cab, tb]`,
- `ghbb=ghbb[ArcCos[cab] + ArcTan[tb], Abb, cab, tb]`,
- `ghtautau=ghtautau[ArcCos[cab] + ArcTan[tb], 1, cab, tb]`,
- `x=cab, y=tb, xmin=-1, xmax=1, ymin=1, ymax=15`,
- `xlabel=`$\cos(\alpha-\beta)$`, ylabel=`$\tan\beta$`, xfor=Att, yfor=Abb`,
- `xformin=0.9, xformax=1, xforstep=0.05, yforstep=0.05`,
- `PP=100, [[i]]=[[2]](`2σ` of C.L.)`

Once the instruction in Eq. (14) was executed, it can take several minutes depending on the resources of your computer equipment. If the message `$Aborted` appears, don't worry, be patient. On an upgraded computer, it will take a few seconds

Alternatively, `SpaceMath v1.0` also is able to generate random values as shown in Table IV. The command to do it is the following:

```
RtauRandom[ghtt_, ghbb_,ghtautau_, x1_, x1min_, x1max_,x2_, x2min_, x2max_, x3_, x3min_, x3max_, x4_, x4min_, x4max_, NN_]
```

This command generates `NN` random values and export it to `$UserDocumentsDirectory`. To graph the generated random values use the following command:

```
PlotRtauRandom[ci_, cj_, xlabel_, ylabel_]
```

Here, `ci, cj` represent the `i-th` and `j-th` columns to graph in the plane `ci-cj`.

Figure 1 shows the graphs generated by `SpaceMath v1.0` using both `Rtau` and `RtauRandom`.

We observe that both methods yield the same results, as it should be. In this way, the user can choose the path that suits him best. `SpaceMath v1.0` also generates graphs displaying each of the individual observables; Figure 2 shows the graph generated by `SpaceMath v1.0`.

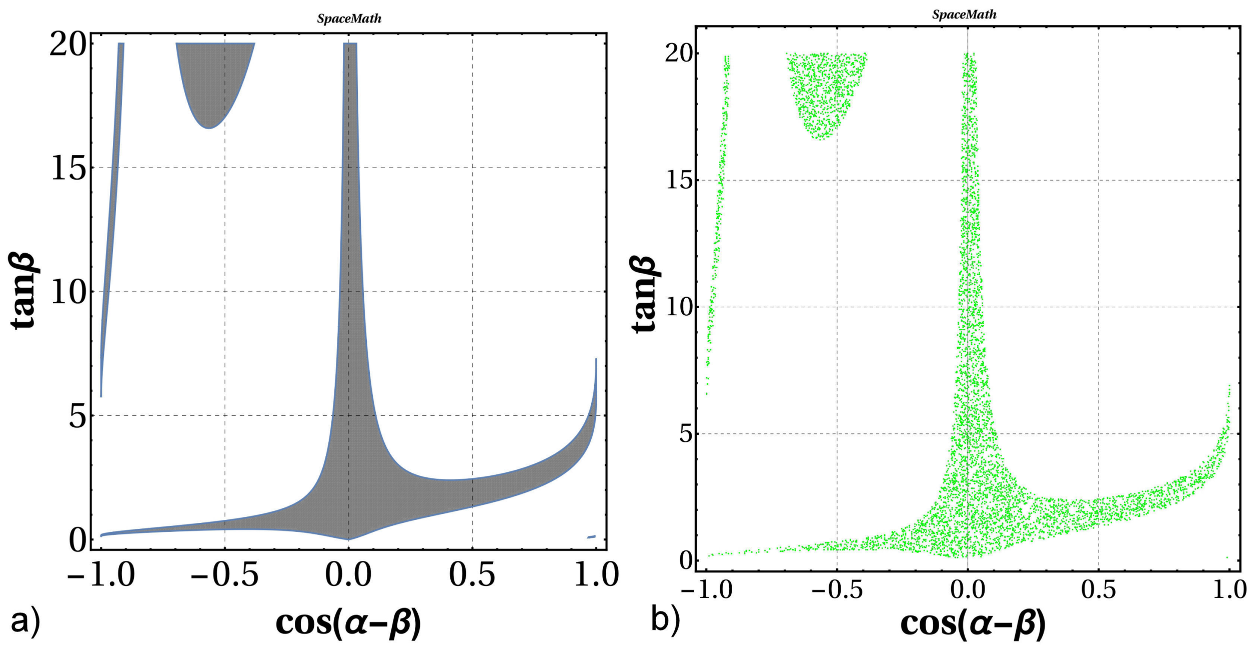

FIGURE 1. a) Plots generated by `SpaceMath v1.0` in which the method `RegionPlot` is shown in b) and the method `Random Values` is displayed.

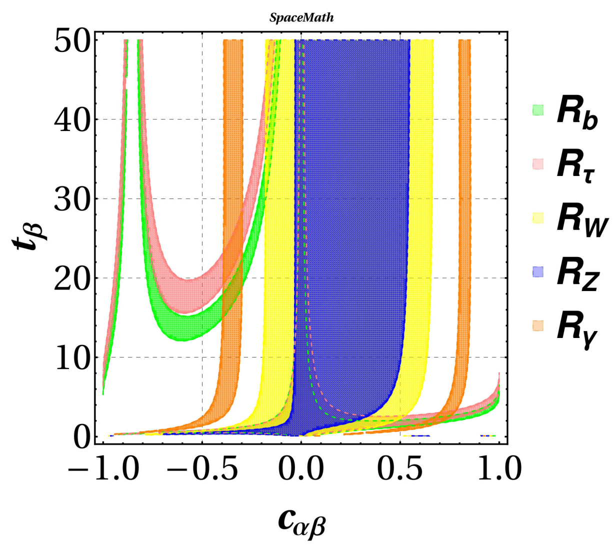

FIGURE 2. Plot generated by `SpaceMath v1.0` displaying each of the individual observables.

The command to graph Fig. 2 is the following:

```
RXALL[ghtt[ArcCos[Cab] + ArcTan[tb], Att, Cab, tb],
      ghbb[ArcCos[Cab] + ArcTan[tb], Abb, Cab, tb],
      ghZZ[Sqrt[1 - Cab^2]], ghWW[Sqrt[1 - Cab^2]]
      ghtautau[ArcCos[Cab] + ArcTan[tb], 1, Cab, tb],
      0, mCH, Cab, tb, -1, 1, 0.1, 50,"cos(α − β)",
"tan β", Att, Abb, 0.9, 1, 0.1, 0.9, 1, 0.1, 80][[2]]
```
(15)

TABLE VIII. First column: THDM-I, -II couplings, second column: coupling defined in `SpaceMath` `(v(V)=, z(Z), w(W))` and third column: `SpaceMath` code.

Coupling	Input to SpaceMath	Command κ_i
$g_{hbb}^{THDM-I} = \frac{g m_b}{2 m_W}\left(\frac{\cos\alpha}{\sin\beta}\right)$	`ghbb[Sa_,Tb_,Cb_]:=g*mb*Sqrt[1-Sa^2]/(2*mW*Tb*Cb)`	`kb[ghbb[Sa,Tb,Cos[ArcTan[Tb]]]]`
$g_{hbb}^{THDM-II} = \frac{g m_b}{2 m_W}\left(\frac{-\sin\alpha}{\cos\beta}\right)$	`ghbb[Sa_,Tb_,Sb_]:=-g*mb*Sa*Tb/(2*mW*Sb)`	`kb[ghbb[Sa,Tb,Sin[ArcTan[Tb]]]]`
$g_{hVV}^{THDM-I,-II} = g_V m_V \sin(\beta-\alpha)$	`ghVV[Tb_,Cb_,Sb_,Sa_]:=((Tb*Cb*Sqrt[1-Sa^2])-(Sb/Tb*Sa))*(gv*mV)`	`kV[ghVV[Tb, Cos[ArcTan[Tb]], Sin[ArcTan[Tb]], Sa]]`

On the other hand, as far as the κ_i's are concerned, the procedure is the same as with $\mathcal{R}_X$. As an additional example, we use the κ_i parameterization, also enabled in `SpaceMath v1.0`, to constrain parameters of the *Simplest Little Higgs Model* (SLHM). We encourage the reader to consult the Refs. [42, 43] to become familiar with the theoretical framework. Figure 3 shows the region allowed by κ_{gluon} in the $\tan\beta - f$ plane, where $\tan\beta$ and f(GeV) are free SLHM parameters.

For both κ_i and $\mathcal{R}_X$, we make available to the users the directory `LHC_HiggsBosonData` with examples which they can take as a guide for their own analyzes. This directory can be found in:

`$SpaceMath/Examples/LHC_HiggsBosonData` or click on the button `"Examples"` once `SpaceMath v1.0` was loaded.

4. Validation

In order to validate `SpaceMath` v1.0, we apply the coupling modifiers κ_i defined in Eq. (3) to the Two-Higgs Doublet Model of Type I and II (THDM-I, II). In Ref. [44] are reported κ_b and κ_V in the context of these models. To reproduce these results via `SpaceMath` v1.0 the only thing we need is to know the model couplings, which are given in Table IX. The commands to evaluate κ_b and κ_V are displayed in Table VIII.

Notice that `Sa`$\equiv$`sin`α, `Tb`$\equiv\tan\beta$, `Cb`$\equiv\cos\beta$, `Sb`$\equiv\sin\beta$ are free parameters of THDM-I, -II and $V = Z, W$; users can name them as they like; besides $\tan\beta = \sin\beta/\cos\beta$, $\sin(\beta-\alpha) = \sin\beta\cos\alpha - \cos\beta\sin\alpha$ has been used. The commands `kb` and `kV` can be directly evaluated by introducing values for `Sa, Tb, Cb`, or since `SpaceMath` is hosted in `Mathematica`, we can use its commands to graph. For this example we use:

- `ContourPlot[kb[ghbb[Sa,Tb,Cos[ArcTan[Tb]]]]^2,{Sa,-1,1},{Tb,0,20}]`,
- `ContourPlot[kV[ghVV[Tb,Cos[ArcTan[Tb]],Sin[ArcTan[Tb]],Sa]]^2,{Sa,-1,1},{Tb,0,20}]`,

which generate the graphs displayed in Figs. 4-6. The codes that generate these graphs can be found in the `"Examples"` directory, whose path is: `$SpaceMath/Examples/Validation_RX/SPACEMATH_RX-Validation-THDM.nb` or click on the link `"Examples"` once `SpaceMath` was loaded.

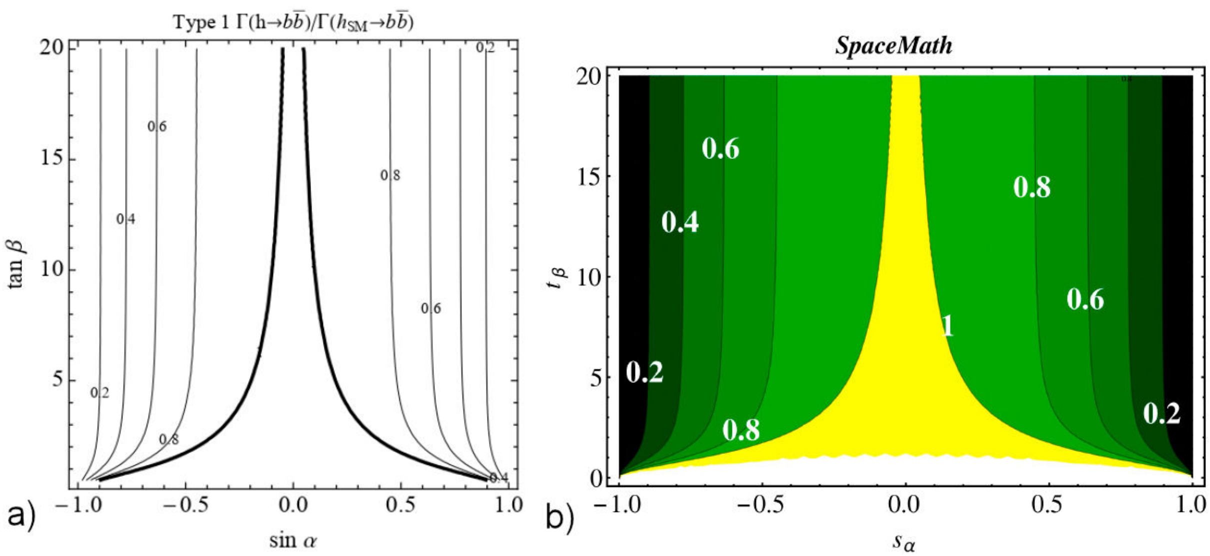

FIGURE 4. Contours of $\Gamma(h \to b\bar{b})/\Gamma(h_{SM} \to b\bar{b})$ for the SM-like Higgs boson as a function of $\sin\alpha$ and $\tan\beta$ in Type 1 THDM. Left: figure taken from [44] and Right: figure generated by `SpaceMath v1.0`.

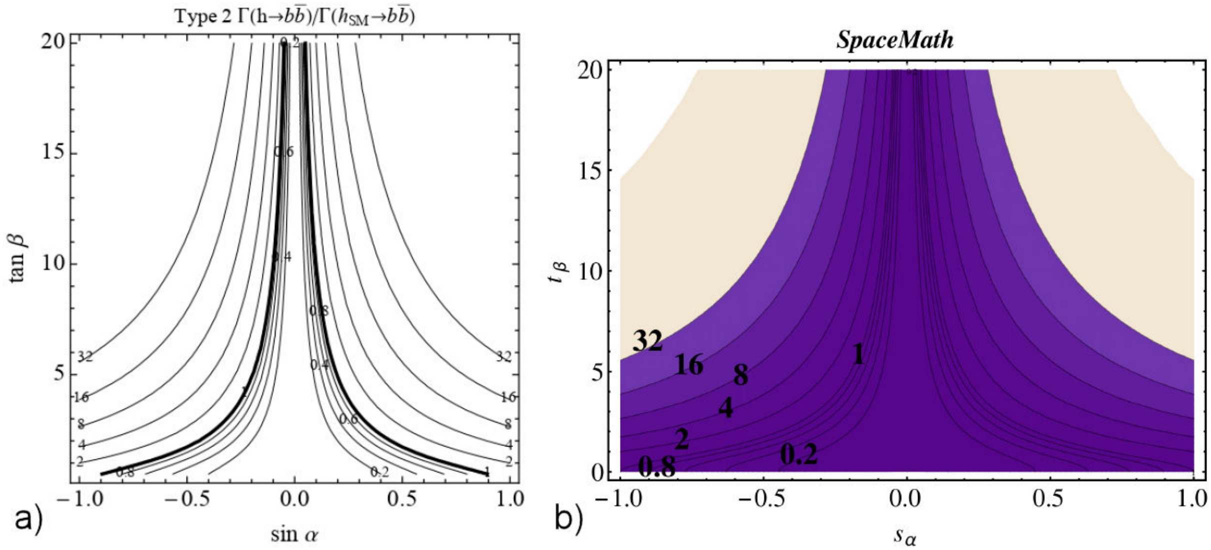

FIGURE 5. Contours of $\Gamma(h \to b\bar{b})/\Gamma(h_{SM} \to b\bar{b})$ for the SM-like Higgs boson as a function of $\sin\alpha$ and $\tan\beta$ in Type 2 THDM. Left: figure taken from [44] and Right: figure generated by `SpaceMath v1.0`.

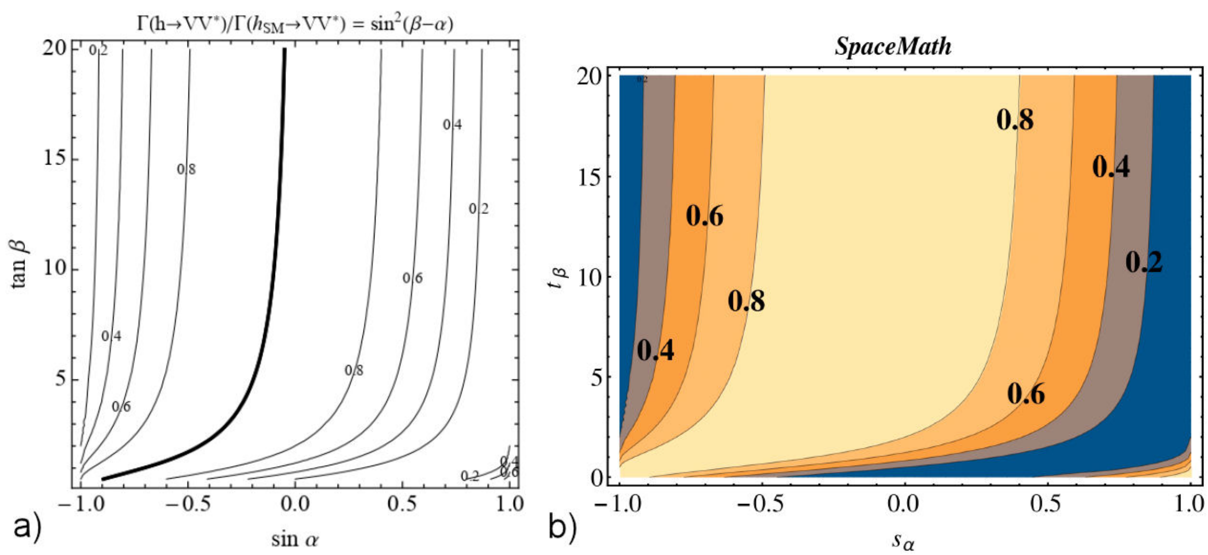

FIGURE 6. Contours of $\Gamma(h \to VV^\star)/\Gamma(h_{SM}VV^\star)$ for the SM-like Higgs boson as a function of $\sin\alpha$ and $\tan\beta$ in any of the THDMs. Left: figure taken from [44] and Right: figure generated by `SpaceMath v1.0`.

In addition, we also show in Fig. 7 the THDM-I, -II, Lepton Specific and Flipped parameter spaces in the $\cos(\beta-\alpha)-\tan\beta$ plane. Again, couplings are shown in Table IX. We compare our results with the ones reported by authors of Ref. [45]. In these graphs we perform a χ^2 test define as follows:

$$\chi^2 = \sum_{i=1}^{n}\left(\frac{O_i - E_i}{\sigma_i}\right)^2, \tag{16}$$

where O_i and E_i are the observed and expected values, respectively, and σ_i indicates uncertainty. The command for plot these figures is:

```
•Chi2Rx95[ghtt[-ArcCos[Cab] + ArcTan[tb], tb],ghbb[-ArcCos[Cab] + ArcTan[tb], tb],
ghtautau[-ArcCos[Cab] + ArcTan[tb], tb], ghZZ[Sqrt[1 - Cab^2]],ghWW[Sqrt[1 - Cab^2]], 0, 2000, Cab, tb]
•Chi2Rx68[ghtt[-ArcCos[Cab] + ArcTan[tb], tb],ghbb[-ArcCos[Cab] + ArcTan[tb], tb],
ghtautau[-ArcCos[Cab] + ArcTan[tb], tb],ghZZ[Sqrt[1 - Cab^2]],ghWW[Sqrt[1 - Cab^2]], 0, 2000, Cab, tb]
```

Complete instructions can be found at:
`$SpaceMath/Examples/Validation_RX/SPACEMATH_RX-Validation-THDM-Chi2Rx.nb`.

TABLE IX. THMD's hff and hVV couplings.

Coupling	THDM-I	THDM-II	THDM-Lepton Specific	THDM-Flipped
hVV	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$
hu_iu_i	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
hd_id_i	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
$h\ell_i\ell_i$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$

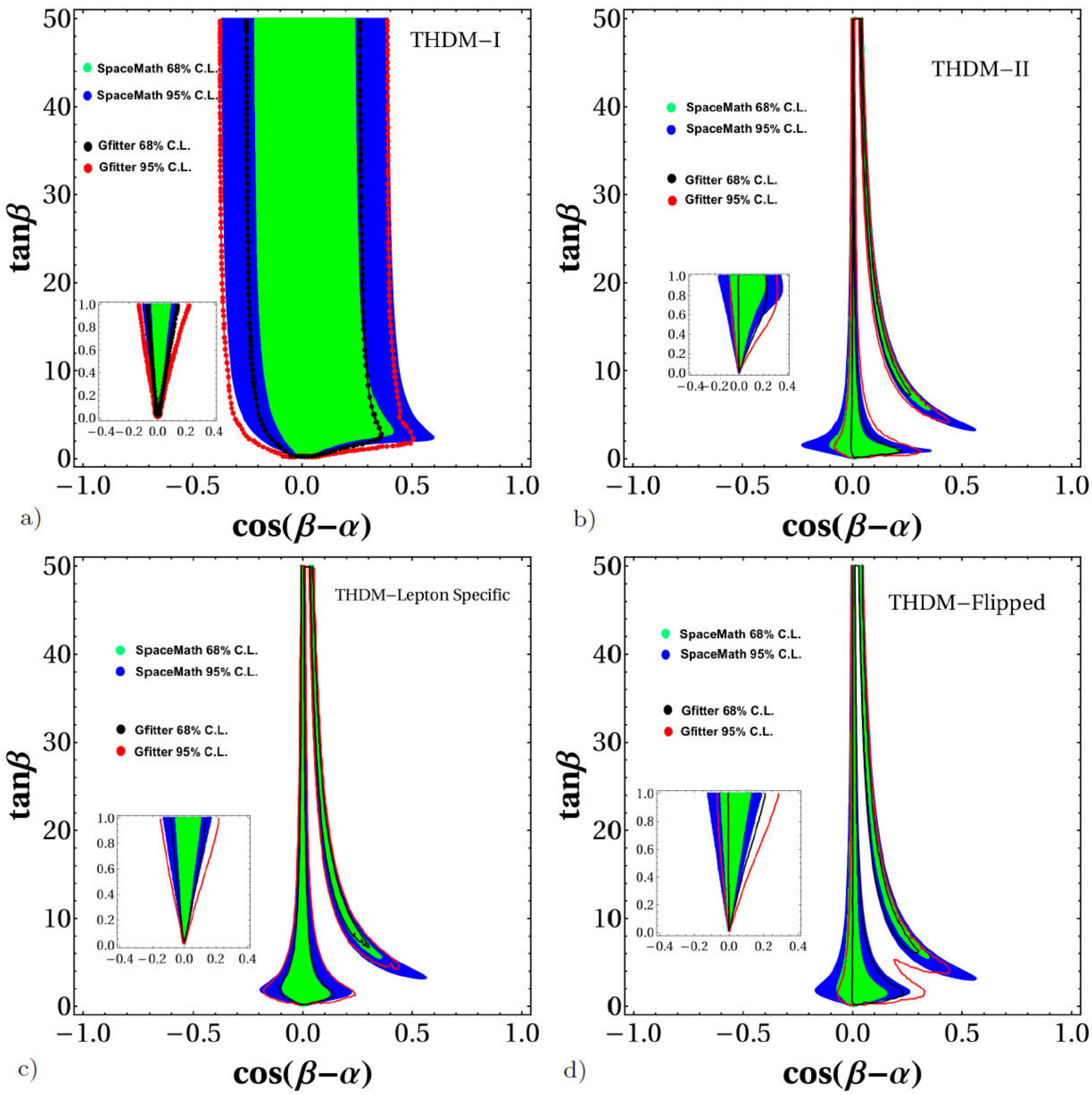

FIGURE 7. Plane $\cos(\beta-\alpha)-\tan\beta$ for different versions of THDM's: a) Type I, b) Type II, c) Lepton Specific, d) Flipped. The plots were generated in `SpaceMath v1.0`.

We can observe slight differences between the graphs generated via `SpaceMath v1.0` and those of the `Gfitter` group, this is due to two sources: 1) The experimental data that `SpaceMath` considers are the most recent and 2) the `Gfitter` team includes all production modes of the Higgs boson. Here, it is worth mentioning that even though `SpaceMath v1.0` only has gluon fusion production implemented, our results are highly similar, this may be because it is the dominant channel for the production of the higgs boson.

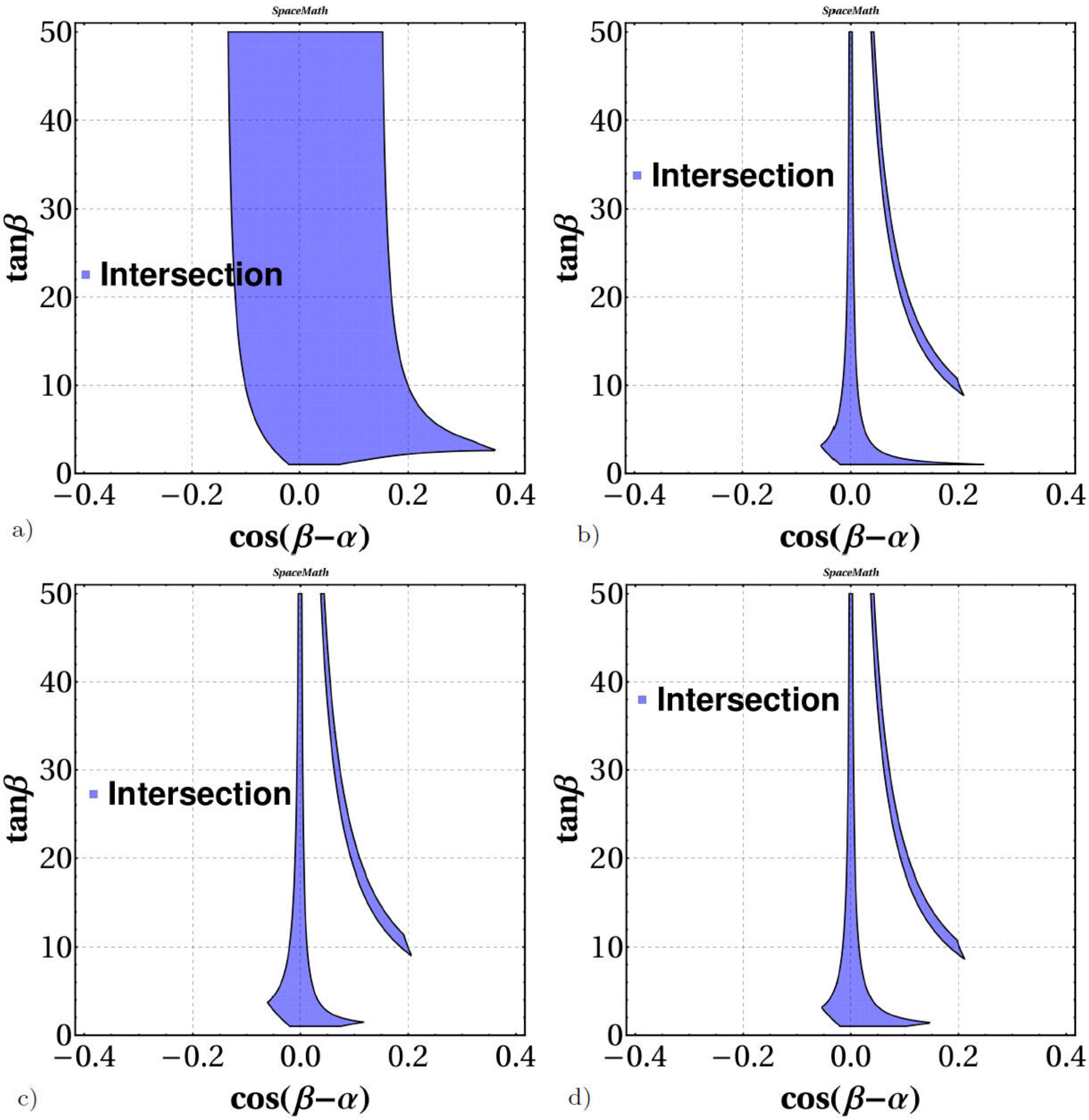

FIGURE 8. Intersection of all channels in the $\cos(\beta-\alpha)-\tan\beta$ plane for different versions of THDM's: a) Type I, b) Type II, c) Lepton Specific, d) Flipped. The plots were generated in `SpaceMath v1.0`.

Besides the χ^2 test, `SpaceMath v1.0` also generates the region consistent with all individual observables; Figure 8 shows the graph generated by `SpaceMath v1.0`.

Finally, we shown in Table X a comparison between our numerical evaluations and those made via `HDecay` package [23], which the branching ratios of the Higgs boson decaying to pair of particles ($b\bar{b}$, $s\bar{s}$, $c\bar{c}$, $t\bar{t}$, $\tau^+\tau^-$, $\mu^+\mu^-$, gg, $\gamma\gamma$, $Z\gamma$, W^+W^-, ZZ) in the theoretical framework of the THDM-I are shown. Again, the Feynman rules needed for evaluations are shown in Table IX, where it can be seen that only two parameters are introduced. We take the same inputs for these free THDM-I parameters as in Ref. [23], namely,

- $\tan\beta$= 1.29775,
- α=-0.684653,

and we also consider a Higgs boson mass of m_h=125.09 GeV.

TABLE X. Comparison of numerical evaluations computed by `SpaceMath v1.0` and `HDecay`. The theoretical framework used is the THDM-I, whose Feynman rules are shown in Table IX. Results in brackets are those generated via `SpaceMath V1.0`.

$\mathcal{BR}(h \to b\bar{b})$ 0.6080 (*0.6080*)	$\mathcal{BR}(h \to \tau\tau)$ 0.6542 (*0.6542*)$\times10^{-1}$	$\mathcal{BR}(h \to \mu\mu)$ 0.2316 (*0.2316*)$\times10^{-3}$	$\mathcal{BR}(h \to s\bar{s})$ 0.2294 (*0.2294*)$\times10^{-3}$	$\mathcal{BR}(h \to c\bar{c})$ 0.2653(*0.2653*)$\times10^{-1}$	$\mathcal{BR}(h \to t\bar{t})$ 0 (*0*)
$\mathcal{BR}(h \to gg)$ 0.7041 (*0.7041*)$\times10^{-1}$	$\mathcal{BR}(h \to \gamma\gamma)$ 0.2126 (*0.2126*)$\times10^{-2}$	$\mathcal{BR}(h \to Z\gamma)$ 0.1458 (*0.1458*)$\times10^{-2}$	$\mathcal{BR}(h \to WW)$ 0.2005 (*0.2005*)	$\mathcal{BR}(h \to ZZ)$ 0.2507 (*0.2507*)$\times10^{-1}$	
$\mathcal{BR}(h \to AA)$ 0 (*0*)	$\mathcal{BR}(h \to AZ)$ 0 (*0*)	$\mathcal{BR}(h \to W\pm h\mp)$ 0 (*0*)	$\mathcal{BR}(h \to h+h-)$ 0 (*0*)	$\Gamma_h^{\rm tot}$ 0.4248 (*0.4248*)$\times10^{-2}$ GeV	

In Table X, the quantities in brackets are the results generated via `SpaceMath`. We observe that our results are identical to those `HDecay`, which is to be expected since we actually reproduced the relevant expressions of the decay widths of the Higgs boson reported in Ref. [46].

5. Conclusion and perspectives

A version of a new `Mathematica` package, so-called `SpaceMath v1.0`, was presented. In this stage, `SpaceMath v1.0` has a pedagogical purpose for the training of human resources involved in the phenomenology of particle physics. We show how `SpaceMath v1.0` works, being able to find allowed regions by experimental data in a friendly and intuitive way, focusing on detailed examples applied to *Two-Higgs Doublet Models* and the *Simplest Little Higgs Model*. In order to offer a reliable program to users, we compare our results with consolidated software, finding slightly different results due to the inputs used by their developers, which shows that `SpaceMath v1.0` can be used for both teaching and frontier research. As mentioned in the main text, the observables enabled in `SpaceMath v1.0` are Higgs boson data reported by the LHC, as well as measurements expected at the HL-LHC and HE-LHC, which would allow greater constrain on the free model parameters, as shown in Fig. 3.

In the near future, new versions will have additional observables enabled, such as: Lepton Flavor Violating processes, oblique parameters, unitarity, perturbativity and meson physics. The forthcoming version also will have an alternative platform for `python` users, enriching the applicability of `SpaceMath`. Finally, `SpaceMath v1.0` offers an alternative to carry out research in the area of particle physics and bring this new tool closer to the scientific community for both researchers and students.

Appendix

A. Remote connection

Requirements to remote connection:

- `Mathematica` version: 11.0.++
- PowerShell (windows).

Steps to connect to server "$Negrito$".

1. Open a terminal and type `$ ssh spacemathuser @148.228.14.13 -Y`.
2. Enter password: `spacemath`
3. Type `mathematicaX`, where `X` represents the `Mathematica` version.
4. Enjoy `SpaceMath v1.0` package.

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