PROCEEDINGS OF SCIENCE

Global fits beyond the standard Beyond-the-Standard-Model models

Anders Kvellestad*, on behalf of the GAMBIT Community
Department of Physics, University of Oslo,
N-0316 Oslo, Norway
E-mail: anders.kvellestad@fys.uio.no

Given the plethora of competing Beyond-the-Standard-Model (BSM) theories, we need to make the best possible use of all current and upcoming experimental results to help guide the search for BSM physics. In this conference paper I discuss how BSM global fits are key in this effort, and what the main challenges of such analyses are. I give brief introductions to the model-independent GAMBIT framework for BSM global fits and the recently released GAMBIT Universal Model Machine (GUM), which uses Lagrangian-level tools to automatically set up a GAMBIT global fit starting from a BSM Lagrangian.

Computational Tools for High Energy Physics and Cosmology (CompTools2021)
22-26 November 2021
Institut de Physique des 2 Infinis (IP2I), Lyon, France

https://pos.sissa.it/

PoS(CompTools2021)033

1. Introduction

A key task for Beyond-the-Standard-Model (BSM) phenomenology research is to help realise the full scientific potential of hard-won experimental results. This is achieved by reinterpreting available experimental results in terms of a wide range of viable and promising BSM theories, and within each theory fully explore the tensions and complementarities between the different experiments, from searches and measurements at colliders, to astrophysical and cosmological observations. The importance of such reinterpretation work, and various challenges associated with it, have been recognised and discussed in several recent community papers [1–3].

Experimental collaborations usually interpret their results in terms of simplified BSM scenarios, and without necessarily considering all complementary results from other experiments. Thus, it is particularly important that the broader BSM community investigates how the *full* set of available results impact the space of non-simplified BSM theories with many free parameters and rich phenomenological structures. A *BSM global fit* is a statistically rigorous approach to this problem. In this conference paper I highlight some key technical challenges of BSM global fits, and I discuss how the GAMBIT software framework [4], with its recent extension GUM [5], now make it much easier to subject a new BSM theory to a global fit analysis.

2. Global fits

A BSM global fit is a parameter estimation analysis where all the free parameters of the BSM theory are simultaneously fitted using all relevant experimental constraints. Such an analysis can be carried out within either a frequentist or a Bayesian statistical framework, and it can also provide the basis for a *global* assessment of the BSM theory, either in the form of a frequentist goodness-of-fit evaluation (see *e.g.* [6, 7]) or a Bayesian model comparison (see *e.g.* [8]).

Independent of the statistical framework, the starting point for a BSM global fit is a *joint likelihood function*,

$$L(\boldsymbol{\theta}) = L_{\text{collider}}(\boldsymbol{\theta}) L_{\text{DM}}(\boldsymbol{\theta}) L_{\text{flavour}}(\boldsymbol{\theta}) \ldots, \tag{1}$$

where $\boldsymbol{\theta}$ denotes the set of BSM parameters and any relevant nuisance parameters. The likelihood function is constructed from the joint probability density that describes the theory predictions for the complete set of relevant experimental observables $O_i(\boldsymbol{\theta})$. It is by basing the analysis on a properly formulated joint likelihood function that we ensure that all complementarities between different experimental results are fully exploited in a statistically sound manner. This likelihood function is then explored across the typically many-dimensional parameter space using some adaptive parameter sampling algorithm, *e.g.* nested sampling or differential evolution. See Refs. [9–11] for discussions and illustrations of the importance of using suitable sampling algorithms, rather than naive "random sampling" of parameter points, such as simply sampling from a uniform probability distribution over the many-dimensional parameter space.

There are three main challenges associated with large-scale BSM global fits:

- The need for sampling algorithms able to explore complicated likelihood functions across many-dimensional parameter spaces in sufficient detail.[1]

[1] In general, Bayesian and frequentist analyses require different sampling algorithms [9].

PoS(CompTools2021)033

- The need for fast yet sufficiently precise theory predictions for the relevant observables $O_i(\boldsymbol{\theta})$. This is particularly challenging for predictions for *e.g.* LHC searches and measurements, for which computationally expensive Monte Carlo event simulations are required to fully utilise the experimental results, see *e.g.* Refs. [12, 13].

- The need for sufficiently detailed likelihoods, or better, full statistical models, to describe the relevant experiments [1, 2]. A lack of sufficient public information will severely reduce phenomenologists' ability to properly reinterpret an experimental result, and thus directly limit the scientific impact of the experiment.

These challenges connect to a number of more specific software requirements for global fits software to be suitable for large-scale fits using high-performance computing clusters. Among other things, these requirements include

- a model-independent core framework, to avoid having to reinvent the wheel for every new BSM model to be studied;

- parallelisation, both at the level of the scanning algorithm and the physics computations;

- memory-based interfaces to existing physics codes used to evaluate theory predictions and/or likelihoods; and

- strictly non-terminating exception handling, including within all external codes interfaced to the global fits code. This is to avoid *e.g.* an order 10,000-CPU scan being killed by one of the external physics tools terminating when it encounters a parameter point that gives an invalid computation.

3. GAMBIT

The Global And Modular Beyond-the-Standard-Model Inference Tool (GAMBIT) is an open-source software framework for BSM global fits, developed by the GAMBIT Community.[2] The aim of the GAMBIT Community is two-fold: to provide the HEP community with a model-independent global fits tool that can tackle such challenges as outlined in the previous section, and to use this tool to carry out comprehensive global fits of promising BSM theories.

Here I give only a brief outline of how GAMBIT is designed, focusing on code modularity and model-independence. For a detailed discussion of the GAMBIT framework, see Refs. [4, 14]. A sketch of GAMBIT's modular structure is given in Fig. 1. All scanning algorithms are implemented as plug-ins for the ScannerBit module [9], while all physics-specific computations are organised in a series of physics modules: ColliderBit [15], CosmoBit [16], DarkBit [17], DecayBit [18], FlavBit [19], NeutrinoBit [20], PrecisionBit [18] and SpecBit [18].[3] These physics modules can both contain native physics computations and make use of external physics codes (referred to as *backends*) connected to GAMBIT as plug-ins. The latest version of GAMBIT (2.1) ships with interfaces to the physics backends and scanners listed in Fig. 1 [9, 21–76].

[2]See `https://gambit.hepforge.org` and `https://github.com/GambitBSM/gambit_2.1`

[3]Not shown in Fig. 1 is the ObjectivesBit module, which contains a collection of objective functions for testing scanning algorithms.

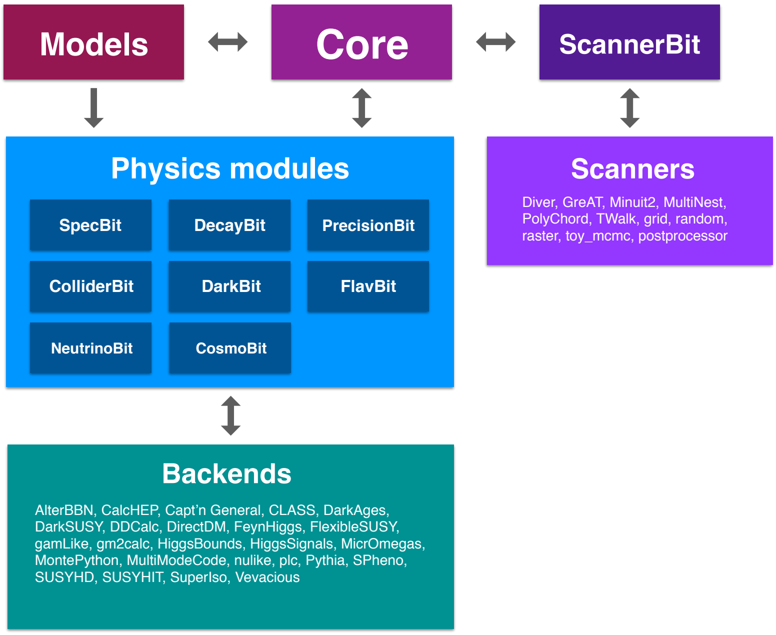

Figure 1: A sketch of the GAMBIT code structure. See the text for further details.

The basic unit in the GAMBIT system is the *module function*. This is any function within one of the physics modules that has been registered to provide a single *capability* to the rest of the GAMBIT system. Any other module function can then register this capability as one of its *dependencies*, *i.e.* a required input. This capability-dependency system ensures that the exact function call chain does not have to be hardcoded, but can be automatically adapted and optimised to the requirements for each run. Based on the user-specified configuration file, GAMBIT at runtime solves a directed, acyclic graph of module function dependencies to determine the correct order of function calls for the given run. This system also helps ensure that the core GAMBIT framework stays model-independent. Each module function can declare whether it can be used only for specific BSM models or for any model. A typical example of the latter would be a module function that evaluates a likelihood contribution $L(O(\boldsymbol{\theta}))$, after some other module function has taken care of the model-specific computation of the observable $O(\boldsymbol{\theta})$.

That GAMBIT indeed can fulfill its purpose as a model-independent framework for global fits is demonstrated by the broad range of theories that have so far been studied with GAMBIT. The most recent examples include a large-scale exploration of WIMP dark matter scenarios [77], a study of the general two-Higgs-doublet model in light of flavour physics anomalies and the muon $g-2$ [78], and a global fit that constrains the lightest neutrino mass through a combination of cosmological and terrestrial experimental results [79].

4. GUM: the GAMBIT Universal Model Machine

Truly comprehensive investigations of the BSM implications of experimental results would be practically infeasible if software for computing theory predictions had to be written from scratch for every new BSM theory to be studied. However, recent years have a seen the development of an ecosystem of tools that, when used together, can autogenerate code for a wide range of BSM

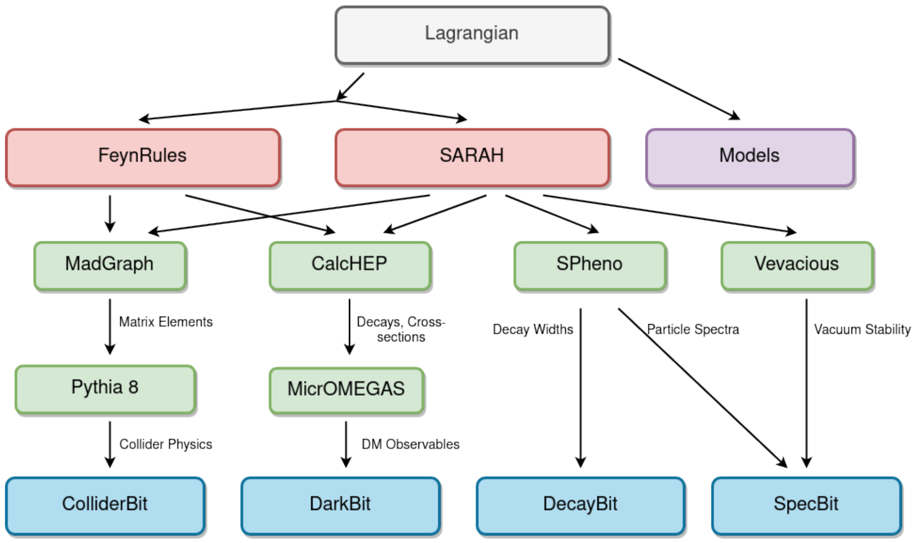

Figure 2: A diagram of the code-generation pathways implemented in the current version of GUM. Diagram made by C. Chang. See the text for further details.

physics computations starting from only a Lagrangian-level theory definition, see *e.g.* Refs. [5, 80] for an overview.

The steps required to implement a new model in GAMBIT and connect GAMBIT to model-specific physics backends are detailed in Ref. [4]. Yet, to do this "by hand" does require a significant amount of work and some understanding of the GAMBIT code design. Thus, to truly enable large-scale BSM global fits of any given BSM theory, the ecosystem of Lagrangian-level tools should be connected to GAMBIT in an automated manner. This was recently achieved with the release of the GAMBIT Universal Model Machine (GUM) [5]. GUM starts from a user-defined BSM Lagrangian, uses FeynRules [81–85], SARAH [86–90], MadGraph [91–93], and CalcHEP [23, 24] to generate code for the GAMBIT modules ColliderBit, DarkBit SpecBit and DecayBit and to generate interfaces to model-specific versions of SPheno [63, 64], micrOMEGAs [47–53], Pythia 8 [62, 94], and Vevacious [73]. GUM thus effectively works as a pre-GAMBIT step: starting from a BSM Lagrangian, it prepares a version of GAMBIT that is ready to perform a global fit of the given theory, without the user having to write GAMBIT code directly. Figure 2 shows a diagram of the various code pathways incorporated in the current version of GUM.

A fully worked example of how to use GUM is given in Ref. [5]. Moving forward, the next steps will be to extend the GUM system to include code generation for more observables and likelihoods. In particular, we will enable autogeneration of code for the FlavBit module in GAMBIT, by making use of FlavorKit [95] and/or MARTY [96]. We will also extend GUM with interfaces to other public tools, including FlexibleSUSY [41] and MadDM [97].

Acknowledgements

All the work presented here result from long-term collaborative projects within the GAMBIT Community and I thank all my fellow GAMBIT colleagues. I also thank the organisers of the TOOLS 2021 conference for the opportunity to present this work. I acknowledge PRACE for awarding GAMBIT access to the supercomputing clusters Marconi at CINECA and Joliot-Curie at CEA. The GAMBIT projects presented here have also been supported by computing resources from the Australian National Computational Infrastructure (NCI), and from UNINETT Sigma2, the National Infrastructure for High Performance Computing and Data Storage in Norway, under project nn9284k.

References

[1] HEP Software Foundation: J. Albrecht *et. al.*, *A Roadmap for HEP Software and Computing R&D for the 2020s*, *Comput. Softw. Big Sci.* **3** (2019) 7, [arXiv:1712.06982].

[2] LHC Reinterpretation Forum: W. Abdallah *et. al.*, *Reinterpretation of LHC Results for New Physics: Status and Recommendations after Run 2*, *SciPost Phys.* **9** (2020) 022, [arXiv:2003.07868].

[3] K. Cranmer *et. al.*, *Publishing statistical models: Getting the most out of particle physics experiments*, *SciPost Phys.* **12** (2022) 037, [arXiv:2109.04981].

[4] GAMBIT: P. Athron *et. al.*, *GAMBIT: The Global and Modular Beyond-the-Standard-Model Inference Tool*, *Eur. Phys. J.* **C77** (2017) 784, [arXiv:1705.07908].

[5] S. Bloor, T. E. Gonzalo, *et. al.*, *The GAMBIT Universal Model Machine: from Lagrangians to likelihoods*, *Eur. Phys. J. C* **81** (2021) 1103, [arXiv:2107.00030].

[6] P. Bechtle *et. al.*, *Killing the cMSSM softly*, *Eur. Phys. J. C* **76** (2016) 96, [arXiv:1508.05951].

[7] P. Athron *et. al.*, *Global fits of axion-like particles to XENON1T and astrophysical data*, *JHEP* **05** (2021) 159, [arXiv:2007.05517].

[8] GAMBIT: P. Athron *et. al.*, *Global analyses of Higgs portal singlet dark matter models using GAMBIT*, *Eur. Phys. J. C* **79** (2019) 38, [arXiv:1808.10465].

[9] GAMBIT: G. D. Martinez, J. McKay, *et. al.*, *Comparison of statistical sampling methods with ScannerBit, the GAMBIT scanning module*, *Eur. Phys. J. C* **77** (2017) 761, [arXiv:1705.07959].

[10] GAMBIT, MasterCode, Fittino, HEPfit, BayesFits: S. S. AbdusSalam *et. al.*, *Simple and statistically sound strategies for analysing physical theories*, arXiv:2012.09874.

[11] DarkMachines High Dimensional Sampling Group: C. Balázs *et. al.*, *A comparison of optimisation algorithms for high-dimensional particle and astrophysics applications*, arXiv:2101.04525.

[12] GAMBIT: P. Athron *et. al.*, *Combined collider constraints on neutralinos and charginos*, *Eur. Phys. J. C* **79** (2019) 395, [arXiv:1809.02097].

[13] J. M. Butterworth, D. Grellscheid, M. Krämer, B. Sarrazin, and D. Yallup, *Constraining new physics with collider measurements of Standard Model signatures*, *JHEP* **03** (2017) 078, [arXiv:1606.05296].

PoS(CompTools2021)033

[14] A. Kvellestad, P. Scott, and M. White, *GAMBIT and its Application in the Search for Physics Beyond the Standard Model*, *Progress in Particle and Nuclear Physics* **113** (2020) [arXiv:1912.04079].

[15] GAMBIT: C. Balázs *et. al.*, *ColliderBit: a GAMBIT module for the calculation of high-energy collider observables and likelihoods*, *Eur. Phys. J.* **C77** (2017) 795, [arXiv:1705.07919].

[16] GAMBIT Cosmology Workgroup: J. J. Renk *et. al.*, *CosmoBit: A GAMBIT module for computing cosmological observables and likelihoods*, *JCAP* **02** (2021) 022, [arXiv:2009.03286].

[17] GAMBIT Dark Matter Workgroup: T. Bringmann *et. al.*, *DarkBit: A GAMBIT module for computing dark matter observables and likelihoods*, *Eur. Phys. J. C* **77** (2017) 831, [arXiv:1705.07920].

[18] GAMBIT Models Workgroup: P. Athron *et. al.*, *SpecBit, DecayBit and PrecisionBit: GAMBIT modules for computing mass spectra, particle decay rates and precision observables*, *Eur. Phys. J. C* **78** (2018) 22, [arXiv:1705.07936].

[19] GAMBIT Flavour Workgroup: F. U. Bernlochner *et. al.*, *FlavBit: A GAMBIT module for computing flavour observables and likelihoods*, *Eur. Phys. J. C* **77** (2017) 786, [arXiv:1705.07933].

[20] M. Chrzaszcz, M. Drewes, *et. al.*, *A frequentist analysis of three right-handed neutrinos with GAMBIT*, *Eur. Phys. J. C* **80** (2020) 569, [arXiv:1908.02302].

[21] A. Arbey, *AlterBBN: A program for calculating the BBN abundances of the elements in alternative cosmologies*, *Comput. Phys. Commun.* **183** (2012) 1822–1831, [arXiv:1106.1363].

[22] A. Arbey, J. Auffinger, K. P. Hickerson, and E. S. Jenssen, *AlterBBN v2: A public code for calculating Big-Bang nucleosynthesis constraints in alternative cosmologies*, *Comput. Phys. Commun.* **248** (2020) 106982, [arXiv:1806.11095].

[23] A. Pukhov, *CalcHEP 2.3: MSSM, structure functions, event generation, batchs, and generation of matrix elements for other packages*, hep-ph/0412191.

[24] A. Belyaev, N. D. Christensen, and A. Pukhov, *CalcHEP 3.4 for collider physics within and beyond the Standard Model*, *Comput. Phys. Commun.* **184** (2013) 1729–1769, [arXiv:1207.6082].

[25] GAMBIT: P. Athron *et. al.*, *Global analyses of Higgs portal singlet dark matter models using GAMBIT*, *Eur. Phys. J. C* **79** (2019) 38, [arXiv:1808.10465].

[26] N. A. Kozar, A. Caddell, L. Fraser-Leach, P. Scott, and A. C. Vincent, *Capt'n General: A generalized stellar dark matter capture and heat transport code*, in *Tools for High Energy Physics and Cosmology* (2021) [arXiv:2105.06810].

PoS(CompTools2021)033

[27] D. Blas, J. Lesgourgues, and T. Tram, *The Cosmic Linear Anisotropy Solving System (CLASS) II: Approximation schemes*, *JCAP* **07** (2011) 034, [arXiv:1104.2933].

[28] P. Stöcker, M. Krämer, J. Lesgourgues, and V. Poulin, *Exotic energy injection with ExoCLASS: Application to the Higgs portal model and evaporating black holes*, *JCAP* **03** (2018) 018, [arXiv:1801.01871].

[29] P. Gondolo, J. Edsjo, *et. al.*, *DarkSUSY: Computing supersymmetric dark matter properties numerically*, *JCAP* **07** (2004) 008, [astro-ph/0406204].

[30] T. Bringmann, J. Edsjö, P. Gondolo, P. Ullio, and L. Bergström, *DarkSUSY 6 : An Advanced Tool to Compute Dark Matter Properties Numerically*, *JCAP* **07** (2018) 033, [arXiv:1802.03399].

[31] GAMBIT Dark Matter Workgroup: T. Bringmann *et. al.*, *DarkBit: A GAMBIT module for computing dark matter observables and likelihoods*, *Eur. Phys. J. C* **77** (2017) 831, [arXiv:1705.07920].

[32] F. Bishara, J. Brod, B. Grinstein, and J. Zupan, *DirectDM: a tool for dark matter direct detection*, arXiv:1708.02678.

[33] J. Brod, A. Gootjes-Dreesbach, M. Tammaro, and J. Zupan, *Effective Field Theory for Dark Matter Direct Detection up to Dimension Seven*, *JHEP* **10** (2018) 065, [arXiv:1710.10218].

[34] H. Bahl, S. Heinemeyer, W. Hollik, and G. Weiglein, *Reconciling EFT and hybrid calculations of the light MSSM Higgs-boson mass*, *Eur. Phys. J. C* **78** (2018) 57, [arXiv:1706.00346].

[35] H. Bahl and W. Hollik, *Precise prediction for the light MSSM Higgs boson mass combining effective field theory and fixed-order calculations*, *Eur. Phys. J. C* **76** (2016) 499, [arXiv:1608.01880].

[36] T. Hahn, S. Heinemeyer, W. Hollik, H. Rzehak, and G. Weiglein, *High-Precision Predictions for the Light CP -Even Higgs Boson Mass of the Minimal Supersymmetric Standard Model*, *Phys. Rev. Lett.* **112** (2014) 141801, [arXiv:1312.4937].

[37] M. Frank, T. Hahn, *et. al.*, *The Higgs Boson Masses and Mixings of the Complex MSSM in the Feynman-Diagrammatic Approach*, *JHEP* **02** (2007) 047, [hep-ph/0611326].

[38] G. Degrassi, S. Heinemeyer, W. Hollik, P. Slavich, and G. Weiglein, *Towards high precision predictions for the MSSM Higgs sector*, *Eur. Phys. J. C* **28** (2003) 133–143, [hep-ph/0212020].

[39] S. Heinemeyer, W. Hollik, and G. Weiglein, *The Masses of the neutral CP - even Higgs bosons in the MSSM: Accurate analysis at the two loop level*, *Eur. Phys. J. C* **9** (1999) 343–366, [hep-ph/9812472].

[40] S. Heinemeyer, W. Hollik, and G. Weiglein, *FeynHiggs: A Program for the calculation of the masses of the neutral CP even Higgs bosons in the MSSM*, Comput. Phys. Commun. **124** (2000) 76–89, [hep-ph/9812320].

[41] P. Athron, M. Bach, *et. al.*, *FlexibleSUSY 2.0: Extensions to investigate the phenomenology of SUSY and non-SUSY models*, Comput. Phys. Commun. **230** (2018) 145–217, [arXiv:1710.03760].

[42] P. Athron, M. Bach, *et. al.*, *GM2Calc: Precise MSSM prediction for $(g-2)$ of the muon*, Eur. Phys. J. C **76** (2016) 62, [arXiv:1510.08071].

[43] P. Bechtle, O. Brein, S. Heinemeyer, G. Weiglein, and K. E. Williams, *HiggsBounds: Confronting Arbitrary Higgs Sectors with Exclusion Bounds from LEP and the Tevatron*, Comput. Phys. Commun. **181** (2010) 138–167, [arXiv:0811.4169].

[44] P. Bechtle, O. Brein, S. Heinemeyer, G. Weiglein, and K. E. Williams, *HiggsBounds 2.0.0: Confronting Neutral and Charged Higgs Sector Predictions with Exclusion Bounds from LEP and the Tevatron*, Comput. Phys. Commun. **182** (2011) 2605–2631, [arXiv:1102.1898].

[45] P. Bechtle, O. Brein, *et. al.*, HiggsBounds – 4*: Improved Tests of Extended Higgs Sectors against Exclusion Bounds from LEP, the Tevatron and the LHC*, Eur. Phys. J. C **74** (2014) 2693, [arXiv:1311.0055].

[46] P. Bechtle, S. Heinemeyer, O. Stål, T. Stefaniak, and G. Weiglein, *HiggsSignals: Confronting arbitrary Higgs sectors with measurements at the Tevatron and the LHC*, Eur. Phys. J. C **74** (2014) 2711, [arXiv:1305.1933].

[47] G. Belanger, F. Boudjema, A. Pukhov, and A. Semenov, *MicrOMEGAs: A Program for calculating the relic density in the MSSM*, Comput. Phys. Commun. **149** (2002) 103–120, [hep-ph/0112278].

[48] G. Belanger, F. Boudjema, A. Pukhov, and A. Semenov, *micrOMEGAs: Version 1.3*, Comput. Phys. Commun. **174** (2006) 577–604, [hep-ph/0405253].

[49] G. Belanger, F. Boudjema, A. Pukhov, and A. Semenov, *MicrOMEGAs 2.0: A Program to calculate the relic density of dark matter in a generic model*, Comput. Phys. Commun. **176** (2007) 367–382, [hep-ph/0607059].

[50] G. Belanger, F. Boudjema, A. Pukhov, and A. Semenov, *Dark matter direct detection rate in a generic model with micrOMEGAs 2.2*, Comput. Phys. Commun. **180** (2009) 747–767, [arXiv:0803.2360].

[51] G. Belanger, F. Boudjema, *et. al.*, *Indirect search for dark matter with micrOMEGAs2.4*, Comput. Phys. Commun. **182** (2011) 842–856, [arXiv:1004.1092].

[52] G. Belanger, F. Boudjema, A. Pukhov, and A. Semenov, *micrOMEGAs_3: A program for calculating dark matter observables*, Comput. Phys. Commun. **185** (2014) 960–985, [arXiv:1305.0237].

PoS(CompTools2021)033

[53] G. Bélanger, F. Boudjema, A. Pukhov, and A. Semenov, *micrOMEGAs4.1: two dark matter candidates*, *Comput. Phys. Commun.* **192** (2015) 322–329, [arXiv:1407.6129].

[54] B. Audren, J. Lesgourgues, K. Benabed, and S. Prunet, *Conservative Constraints on Early Cosmology: an illustration of the Monte Python cosmological parameter inference code*, *JCAP* **02** (2013) 001, [arXiv:1210.7183].

[55] T. Brinckmann and J. Lesgourgues, *MontePython 3: boosted MCMC sampler and other features*, *Phys. Dark Univ.* **24** (2019) 100260, [arXiv:1804.07261].

[56] M. J. Mortonson, H. V. Peiris, and R. Easther, *Bayesian Analysis of Inflation: Parameter Estimation for Single Field Models*, *Phys. Rev. D* **83** (2011) 043505, [arXiv:1007.4205].

[57] L. C. Price, J. Frazer, J. Xu, H. V. Peiris, and R. Easther, *MultiModeCode: An efficient numerical solver for multifield inflation*, *JCAP* **03** (2015) 005, [arXiv:1410.0685].

[58] IceCube: P. Scott *et. al.*, *Use of event-level neutrino telescope data in global fits for theories of new physics*, *JCAP* **11** (2012) 057, [arXiv:1207.0810].

[59] IceCube: M. G. Aartsen *et. al.*, *Improved limits on dark matter annihilation in the Sun with the 79-string IceCube detector and implications for supersymmetry*, *JCAP* **04** (2016) 022, [arXiv:1601.00653].

[60] Planck: N. Aghanim *et. al.*, *Planck 2015 results. XI. CMB power spectra, likelihoods, and robustness of parameters*, *Astron. Astrophys.* **594** (2016) A11, [arXiv:1507.02704].

[61] Planck: N. Aghanim *et. al.*, *Planck 2018 results. V. CMB power spectra and likelihoods*, *Astron. Astrophys.* **641** (2020) A5, [arXiv:1907.12875].

[62] T. Sjöstrand, S. Ask, *et. al.*, *An introduction to PYTHIA 8.2*, *Comput. Phys. Commun.* **191** (2015) 159–177, [arXiv:1410.3012].

[63] W. Porod, *SPheno, a program for calculating supersymmetric spectra, SUSY particle decays and SUSY particle production at e+ e- colliders*, *Comput. Phys. Commun.* **153** (2003) 275–315, [hep-ph/0301101].

[64] W. Porod and F. Staub, *SPheno 3.1: Extensions including flavour, CP-phases and models beyond the MSSM*, *Comput. Phys. Commun.* **183** (2012) 2458–2469, [arXiv:1104.1573].

[65] F. Mahmoudi, *SuperIso: A Program for calculating the isospin asymmetry of B —> K* gamma in the MSSM*, *Comput. Phys. Commun.* **178** (2008) 745–754, [arXiv:0710.2067].

[66] F. Mahmoudi, *SuperIso v2.3: A Program for calculating flavor physics observables in Supersymmetry*, *Comput. Phys. Commun.* **180** (2009) 1579–1613, [arXiv:0808.3144].

[67] F. Mahmoudi, *SuperIso v3.0, flavor physics observables calculations: Extension to NMSSM*, *Comput. Phys. Commun.* **180** (2009) 1718–1719.

[68] J. Pardo Vega and G. Villadoro, *SusyHD: Higgs mass Determination in Supersymmetry*, *JHEP* **07** (2015) 159, [arXiv:1504.05200].

[69] A. Djouadi, M. M. Muhlleitner, and M. Spira, *Decays of supersymmetric particles: The Program SUSY-HIT (SUspect-SdecaY-Hdecay-InTerface)*, *Acta Phys. Polon. B* **38** (2007) 635–644, [hep-ph/0609292].

[70] M. Muhlleitner, A. Djouadi, and Y. Mambrini, *SDECAY: A Fortran code for the decays of the supersymmetric particles in the MSSM*, *Comput. Phys. Commun.* **168** (2005) 46–70, [hep-ph/0311167].

[71] A. Djouadi, J.-L. Kneur, and G. Moultaka, *SuSpect: A Fortran code for the supersymmetric and Higgs particle spectrum in the MSSM*, *Comput. Phys. Commun.* **176** (2007) 426–455, [hep-ph/0211331].

[72] A. Djouadi, J. Kalinowski, and M. Spira, *HDECAY: A Program for Higgs boson decays in the standard model and its supersymmetric extension*, *Comput. Phys. Commun.* **108** (1998) 56–74, [hep-ph/9704448].

[73] J. E. Camargo-Molina, B. O'Leary, W. Porod, and F. Staub, **Vevacious***: A Tool For Finding The Global Minima Of One-Loop Effective Potentials With Many Scalars*, *Eur. Phys. J. C* **73** (2013) 2588, [arXiv:1307.1477].

[74] F. James and M. Roos, *Minuit: A System for Function Minimization and Analysis of the Parameter Errors and Correlations*, *Comput. Phys. Commun.* **10** (1975) 343–367.

[75] F. Feroz and M. Hobson, *Multimodal nested sampling: an efficient and robust alternative to MCMC methods for astronomical data analysis*, *Mon.Not.Roy.Astron.Soc.* **384** (2008) 449, [arXiv:0704.3704].

[76] W. J. Handley, M. P. Hobson, and A. N. Lasenby, *POLYCHORD: next-generation nested sampling*, *MNRAS* **453** (2015) 4384–4398, [arXiv:1506.00171].

[77] GAMBIT: P. Athron *et. al.*, *Thermal WIMPs and the scale of new physics: global fits of Dirac dark matter effective field theories*, *Eur. Phys. J. C* **81** (2021) 992, [arXiv:2106.02056].

[78] P. Athron, C. Balazs, *et. al.*, *Likelihood analysis of the flavour anomalies and $g-2$ in the general two Higgs doublet model*, *JHEP* **01** (2022) 037, [arXiv:2111.10464].

[79] GAMBIT Cosmology Workgroup: P. Stöcker *et. al.*, *Strengthening the bound on the mass of the lightest neutrino with terrestrial and cosmological experiments*, *Phys. Rev. D* **103** (2021) 123508, [arXiv:2009.03287].

[80] T. E. Gonzalo, *BSM Developments and Tools*, *PoS* **LHCP2021** (2021) 297, [arXiv:2110.05924].

[81] A. Alloul, N. D. Christensen, C. Degrande, C. Duhr, and B. Fuks, *FeynRules 2.0 – A complete toolbox for tree-level phenomenology*, *Comput. Phys. Commun.* **185** (2014) 2250–2300, [arXiv:1310.1921].

PoS(CompTools2021)033

[82] N. D. Christensen and C. Duhr, *FeynRules - Feynman rules made easy*, *Comput. Phys. Commun.* **180** (2009) 1614–1641, [arXiv:0806.4194].

[83] N. D. Christensen, C. Duhr, B. Fuks, J. Reuter, and C. Speckner, *Introducing an interface between WHIZARD and FeynRules*, *Eur. Phys. J. C* **72** (2012) 1990, [arXiv:1010.3251].

[84] N. D. Christensen, P. de Aquino, *et. al.*, *A Comprehensive approach to new physics simulations*, *Eur. Phys. J. C* **71** (2011) 1541, [arXiv:0906.2474].

[85] C. Degrande, C. Duhr, *et. al.*, *UFO - The Universal FeynRules Output*, *Comput. Phys. Commun.* **183** (2012) 1201–1214, [arXiv:1108.2040].

[86] F. Staub, *SARAH 4 : A tool for (not only SUSY) model builders*, *Comput. Phys. Commun.* **185** (2014) 1773–1790, [arXiv:1309.7223].

[87] F. Staub, *SARAH 3.2: Dirac Gauginos, UFO output, and more*, *Comput. Phys. Commun.* **184** (2013) 1792–1809, [arXiv:1207.0906].

[88] F. Staub, *SARAH*, arXiv:0806.0538.

[89] F. Staub, *Automatic Calculation of supersymmetric Renormalization Group Equations and Self Energies*, *Comput. Phys. Commun.* **182** (2011) 808–833, [arXiv:1002.0840].

[90] F. Staub, *Exploring new models in all detail with SARAH*, *Adv. High Energy Phys.* **2015** (2015) 840780, [arXiv:1503.04200].

[91] J. Alwall, M. Herquet, F. Maltoni, O. Mattelaer, and T. Stelzer, *MadGraph 5 : Going Beyond*, *JHEP* **06** (2011) 128, [arXiv:1106.0522].

[92] J. Alwall, R. Frederix, *et. al.*, *The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations*, *JHEP* **07** (2014) 079, [arXiv:1405.0301].

[93] S. Frixione, B. Fuks, *et. al.*, *Automated simulations beyond the Standard Model: supersymmetry*, *JHEP* **12** (2019) 008, [arXiv:1907.04898].

[94] T. Sjostrand, S. Mrenna, and P. Z. Skands, *PYTHIA 6.4 Physics and Manual*, *JHEP* **05** (2006) 026, [hep-ph/0603175].

[95] W. Porod, F. Staub, and A. Vicente, *A Flavor Kit for BSM models*, *Eur. Phys. J. C* **74** (2014) 2992, [arXiv:1405.1434].

[96] G. Uhlrich, F. Mahmoudi, and A. Arbey, *MARTY - Modern ARtificial Theoretical phYsicist A C++ framework automating symbolic calculations Beyond the Standard Model*, *Comput. Phys. Commun.* **264** (2021) 107928, [arXiv:2011.02478].

[97] F. Ambrogi, C. Arina, *et. al.*, *MadDM v.3.0: a Comprehensive Tool for Dark Matter Studies*, *Phys. Dark Univ.* **24** (2019) 100249, [arXiv:1804.00044].