Global fits and Bayesian inference in beyond-Standard Model physics

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ISNET-9 — May 23, 2023

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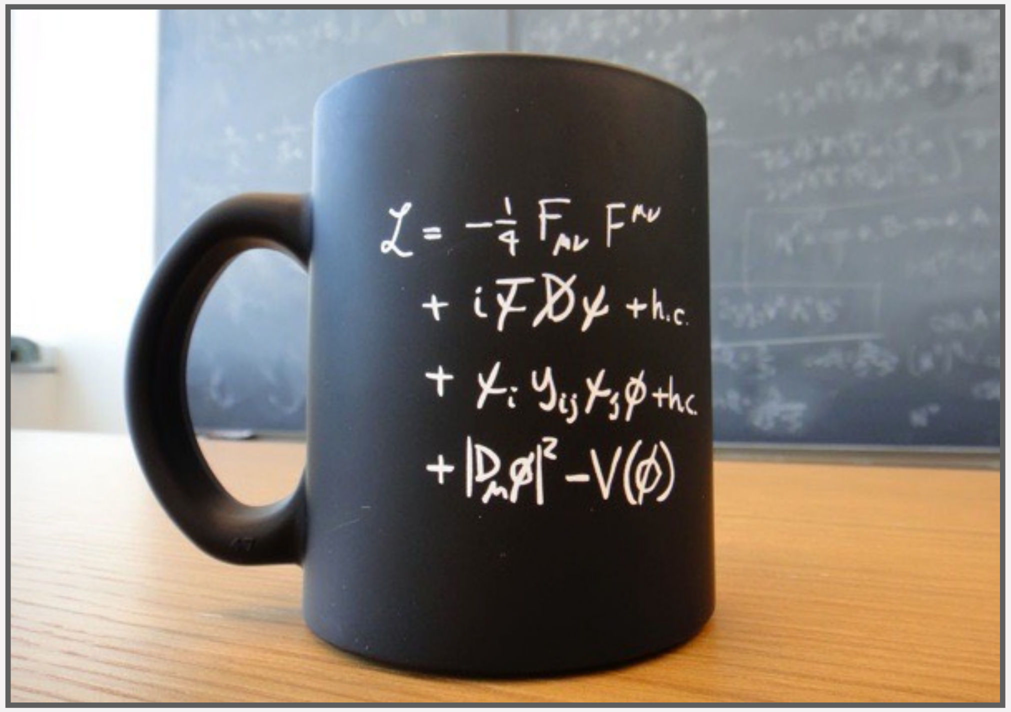
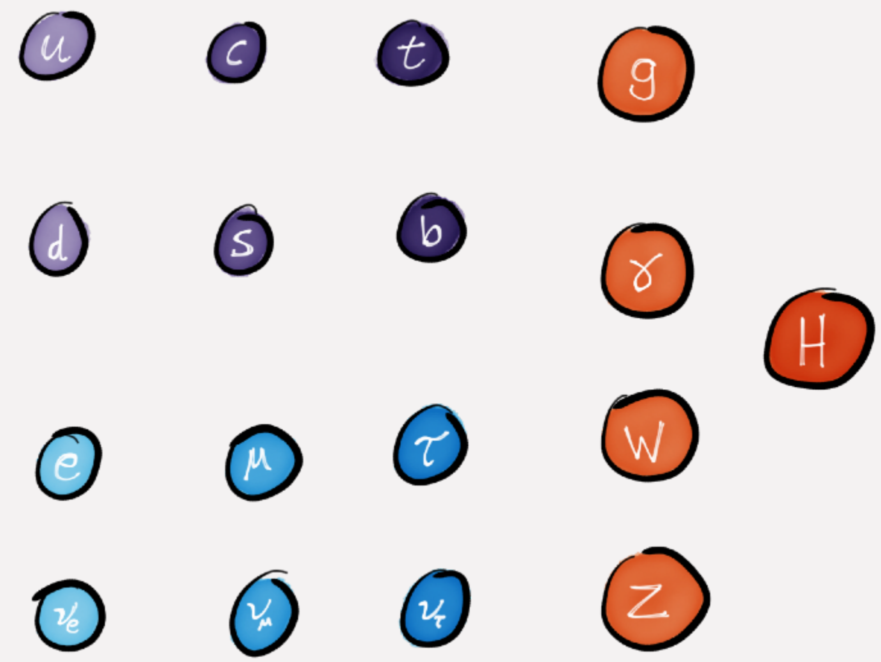
The Standard Model is incomplete!





- Why is the Higgs particle so light?
- Why are the neutrinos so *extremely* light?
- What is dark matter? And dark energy?
- Why do the matter particles come in three «generations»?
- How did we end up with slightly more matter than antimatter?
- …

Need beyond-Standard Model (BSM) physics to explain this

Understanding the full implications of [experimental] searches requires the interpretation of the experimental results in the context of many more theoretical models than are currently explored at the time of publication.

HEP Software Foundation [arxiv:1712.06982]

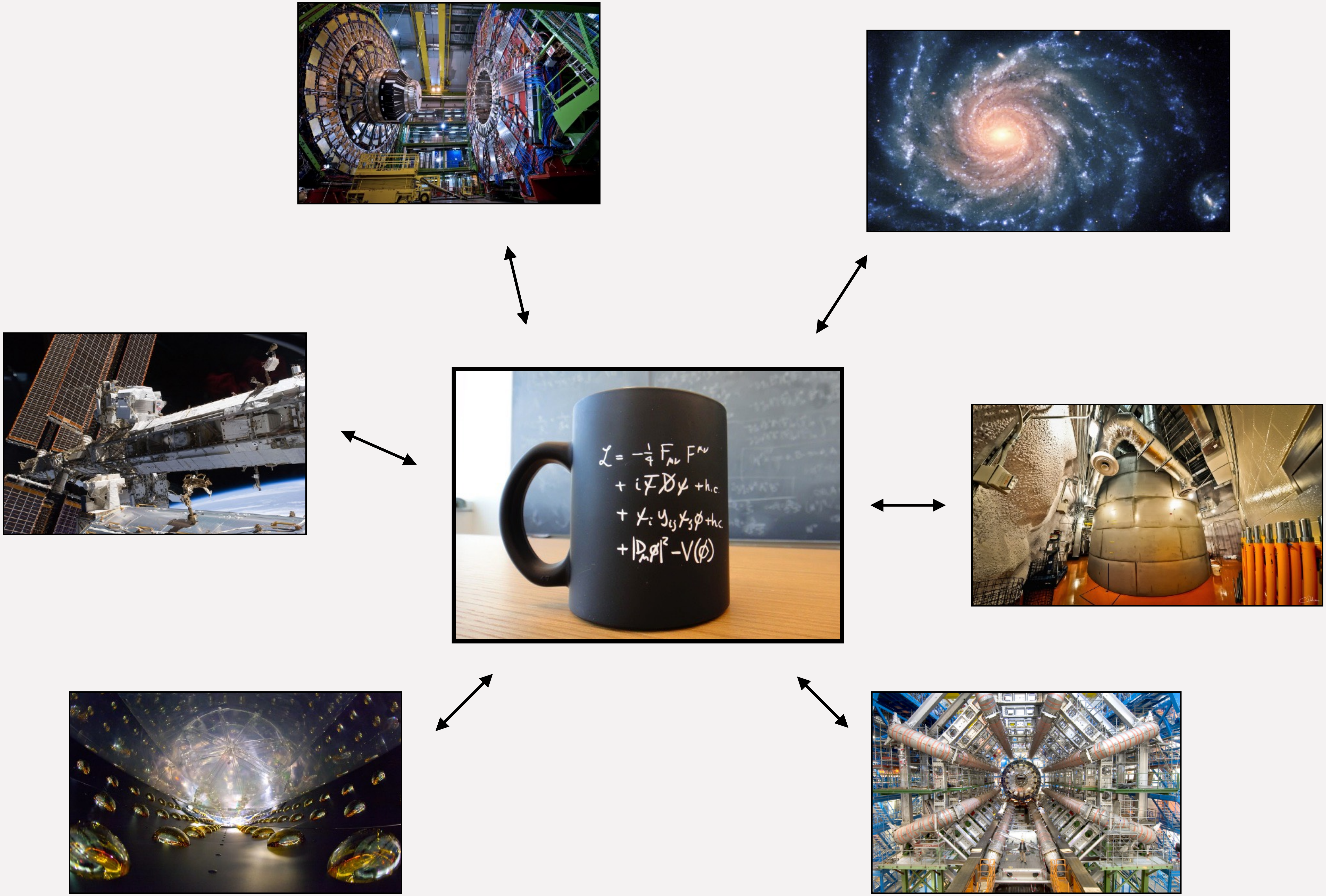
See also:

- *Publishing statistical models: Getting the most out of particle physics experiments* **[arxiv:2109.04981]**
- *Reinterpretation of LHC Results for New Physics: Status and Recommendations after Run 2* **[arxiv:2003.07868]**
- *Simple and statistically sound strategies for analysing physical theories* **[arxiv:2012.09874]**

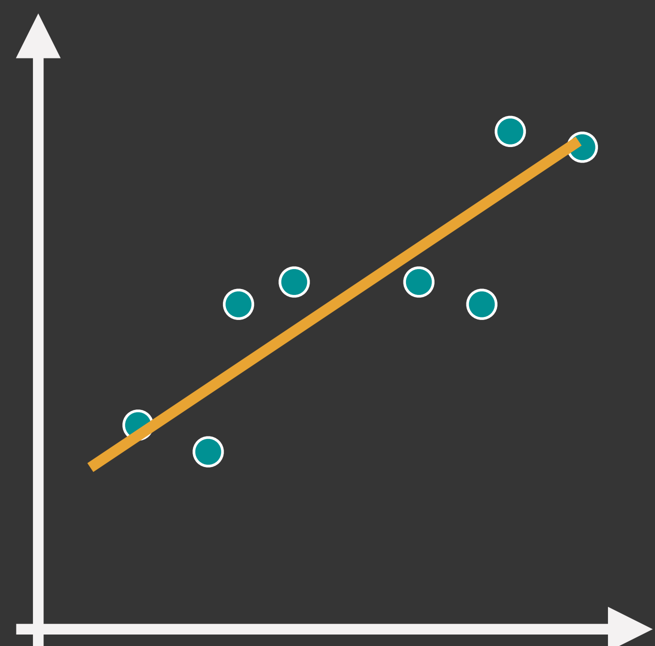
Outline

1. Global fits
2. GAMBIT
3. Applications of Bayesian inference
4. Summary

1. Global fits

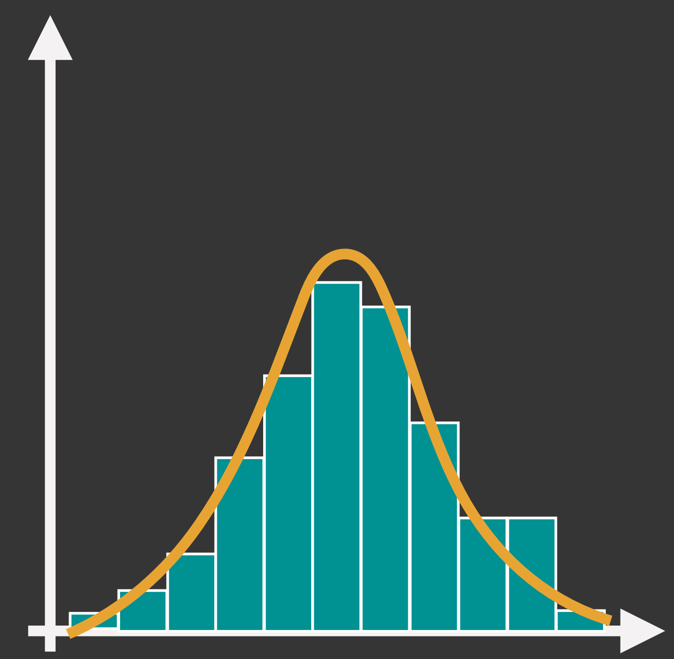

$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$
$+ i \bar{\psi} \not{D} \psi + h.c.$
$+ \psi_i y_{ij} \psi_j \phi + h.c.$
$+ |D_\mu \phi|^2 - V(\phi)$

Statistical fits

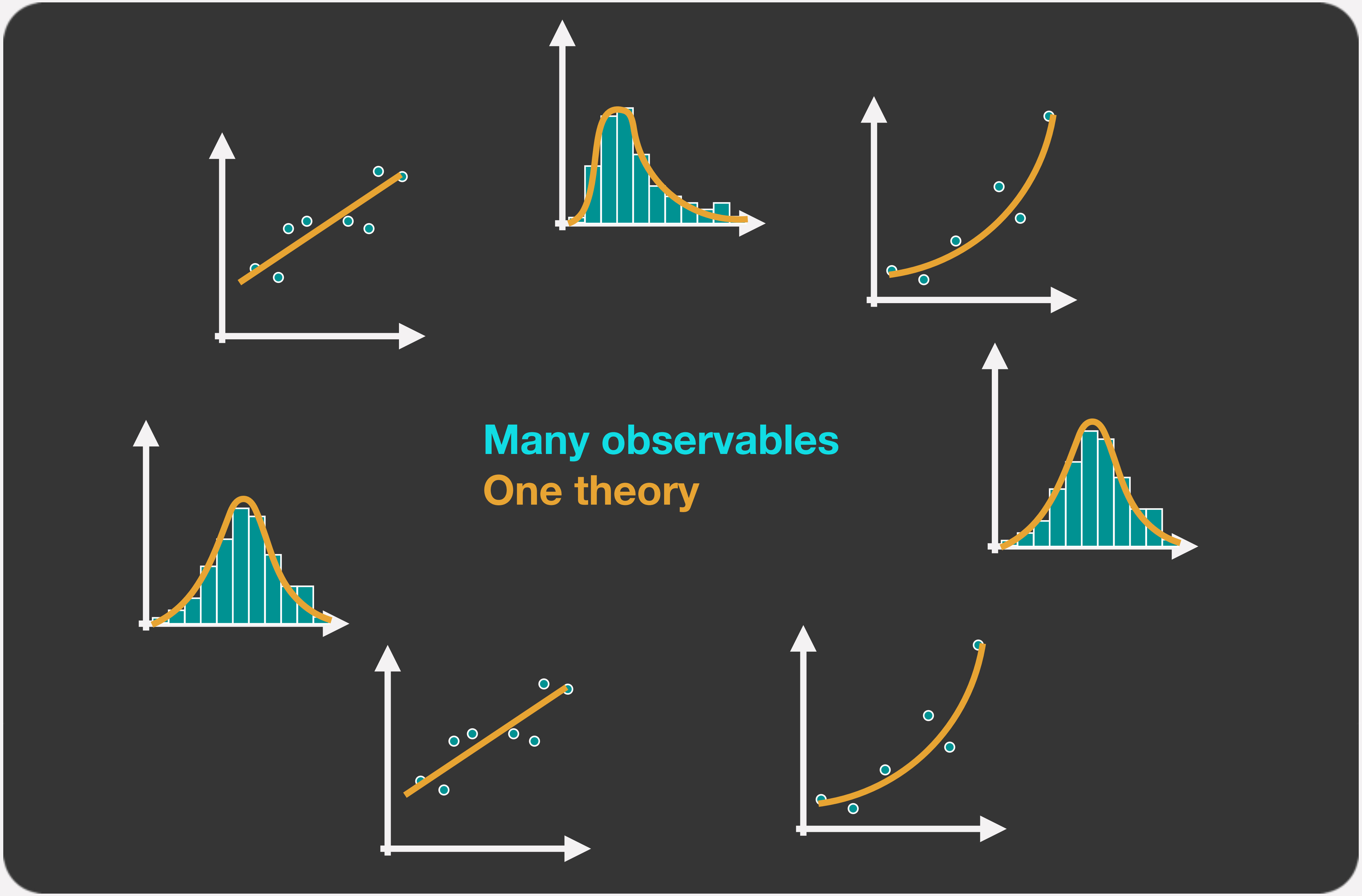


Some observable
Some model

Some other observable
Some other model



Global fits



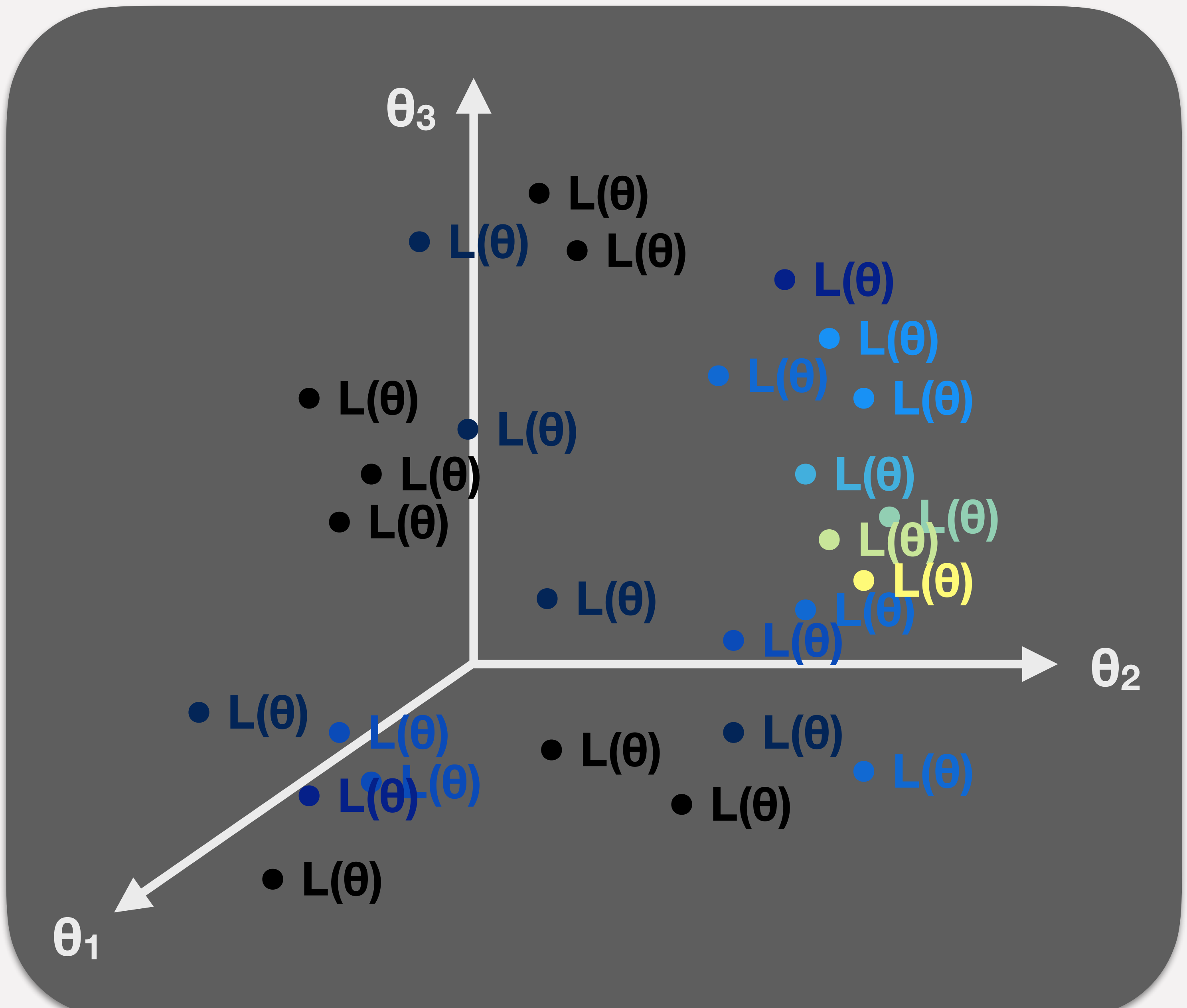
The basic steps of a BSM global fit

- Choose your **BSM theory and parameterisation**
- Construct the **joint likelihood function** including observables from collider physics, dark matter, flavor physics, +++

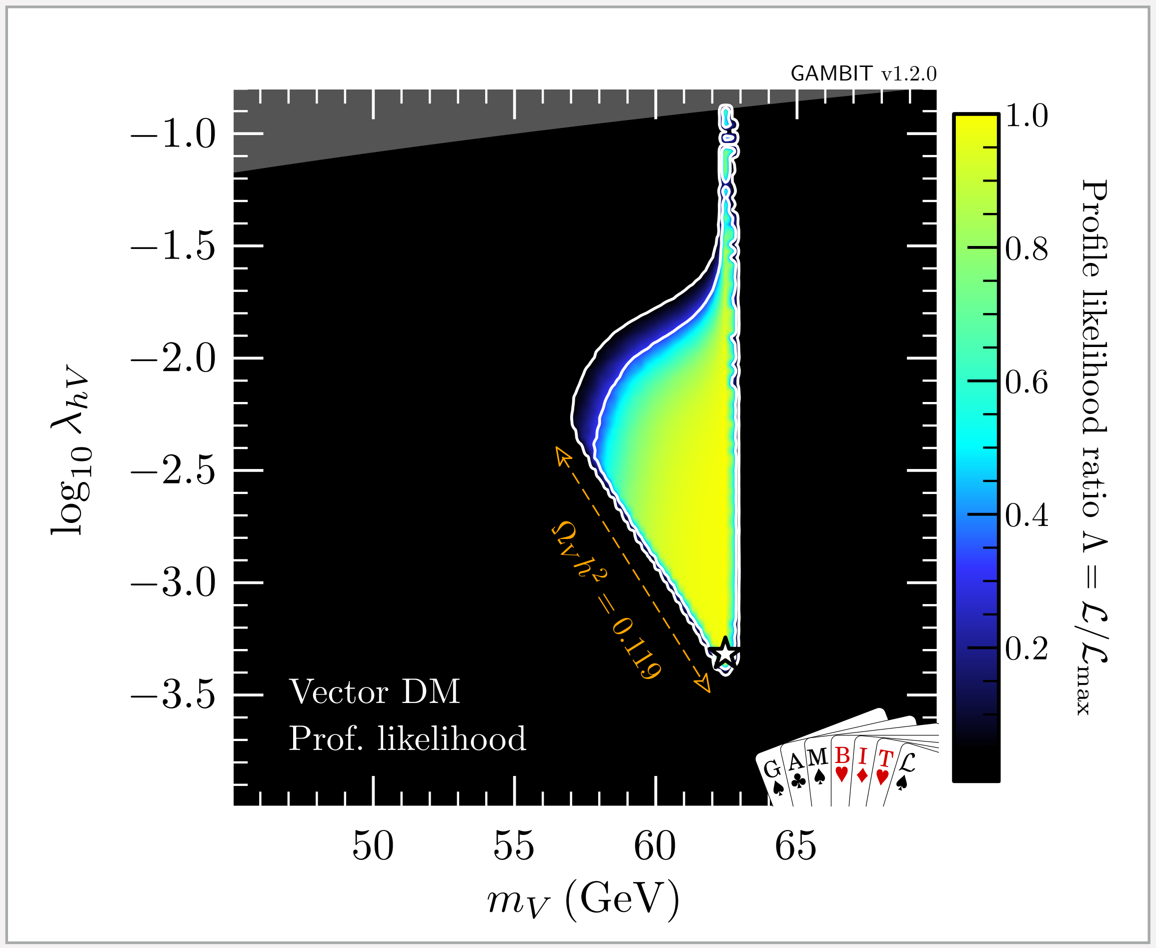
$$\mathcal{L} = \mathcal{L}_{\mathrm{collider}} \mathcal{L}_{\mathrm{DM}} \mathcal{L}_{\mathrm{flavor}} \mathcal{L}_{\mathrm{EWPO}} \cdots$$

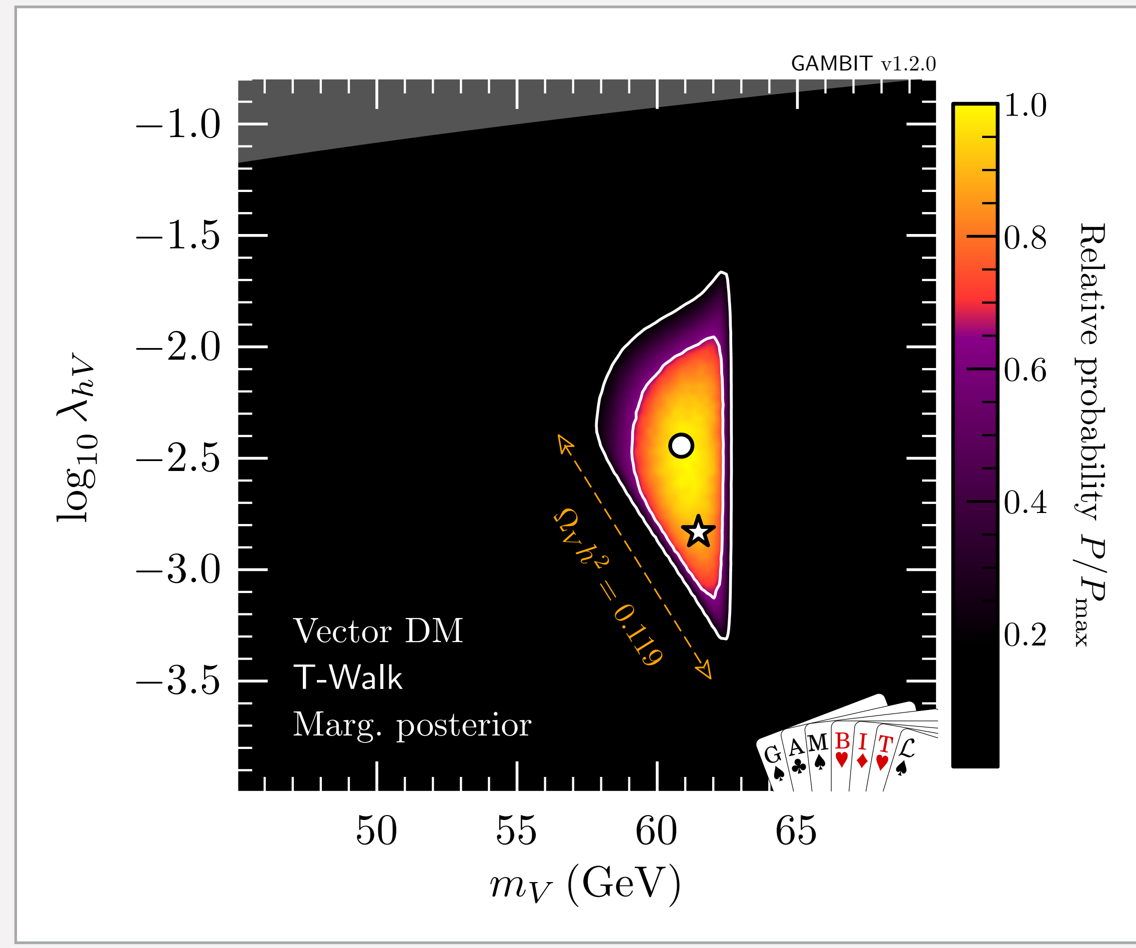
- Use **sophisticated scanning techniques** to explore the likelihood function across the parameter space of the theory
- From likelihood samples, carry out frequentist or Bayesian inference (parameter estimation, model comparison, …)

- **Explore the model parameter space** (θ_1, θ_2, θ_3, …)
- At every point θ: **calculate predictions(θ) → evaluate joint likelihood L(θ)**



Typical result:
Parameter estimation, presented as **profile likelihood** and/or **posterior density** plots

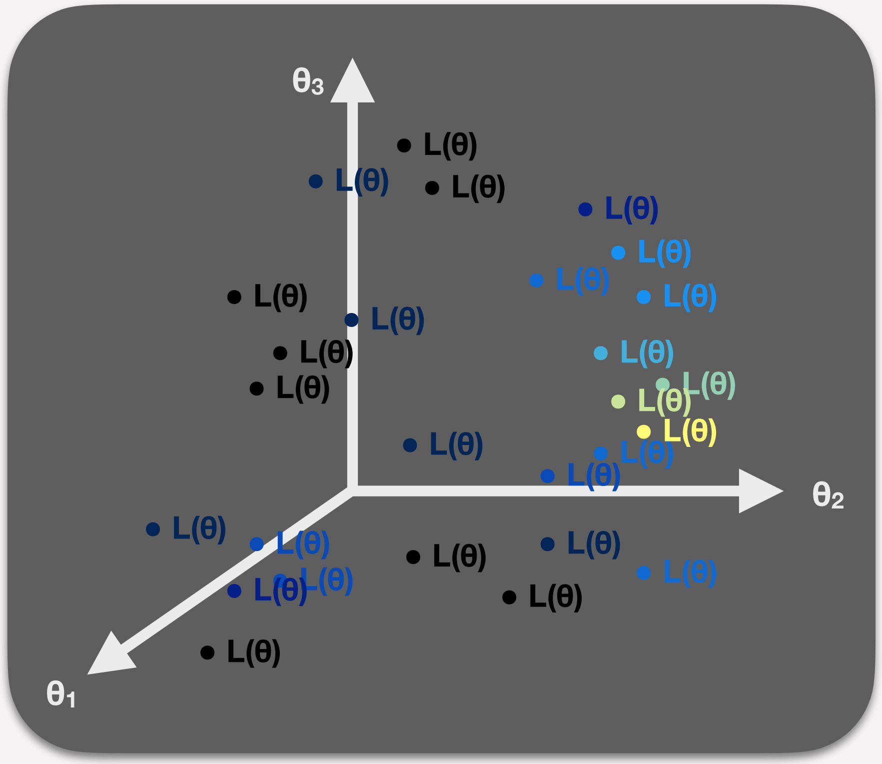




[arxiv:1808.10465]

Computational challenges:

- Need **smart exploration** of parameter space
- Need **fast theory calculations**
- Need **fast simulations of experiments** (e.g. LHC)
- Need **sufficiently detailed likelihoods** or **full statistical models**



JHEP

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Search for electroweak production of charginos and neutralinos in multilepton final states in proton-proton collisions at $\sqrt{s} = 13$ TeV

The CMS collaboration

E-mail: cms-publication-committee-chair@cern.ch

ABSTRACT: Results are presented from a search for the direct electroweak production of charginos and neutralinos in signatures with either two or more leptons (electrons or muons) of the same electric charge, or with three or more leptons, which can include up to two hadronically decaying tau leptons. The results are based on a sample of proton-proton collision data collected at $\sqrt{s} = 13$ TeV, recorded with the CMS detector at the LHC, corresponding to an integrated luminosity of 35.9 fb^{-1}. The observed event yields are consistent with the expectations based on the standard model. The results are interpreted in simplified models of supersymmetry describing various scenarios for the production and decay of charginos and neutralinos. Depending on the model parameters chosen, mass values between 180 GeV and 1150 GeV are excluded at 95% CL. These results significantly extend the parameter space probed for these particles in searches at the LHC. In addition, results are presented in a form suitable for alternative theoretical interpretations.

KEYWORDS: Hadron-Hadron scattering (experiments), Supersymmetry

ARXIV EPRINT: 1709.05406

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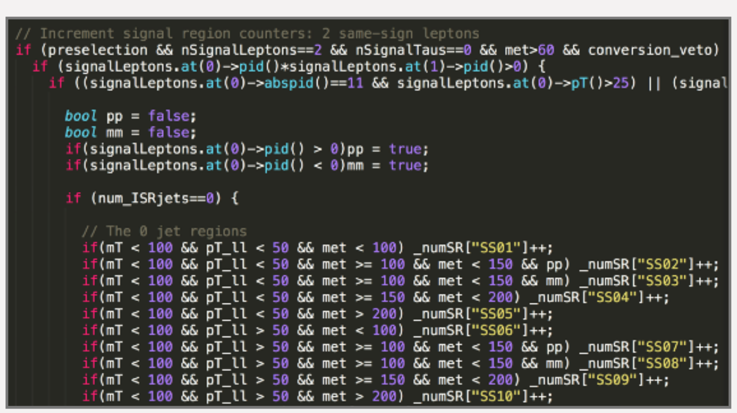
https://doi.org/10.1007/JHEP03(2018)166

JHEP03(2018)166



```
// Increment signal region counters: 2 same-sign leptons
if (preselection && nSignalLeptons==2 && nSignalTaus==0 && met>60 && conversion_veto)
  if (signalLeptons.at(0)->pid()*signalLeptons.at(1)->pid()>0) {
    if ((signalLeptons.at(0)->abspid()==11 && signalLeptons.at(0)->pT()>25) || (signal

      bool pp = false;
      bool mm = false;
      if(signalLeptons.at(0)->pid() > 0)pp = true;
      if(signalLeptons.at(0)->pid() < 0)mm = true;

      if (num_ISRjets==0) {

        // The 0 jet regions
        if(mT < 100 && pT_ll < 50 && met < 100) _numSR["SS01"]++;
        if(mT < 100 && pT_ll < 50 && met >= 100 && met < 150 && pp) _numSR["SS02"]++;
        if(mT < 100 && pT_ll < 50 && met >= 100 && met < 150 && mm) _numSR["SS03"]++;
        if(mT < 100 && pT_ll < 50 && met >= 150 && met < 200) _numSR["SS04"]++;
        if(mT < 100 && pT_ll < 50 && met > 200) _numSR["SS05"]++;
        if(mT < 100 && pT_ll > 50 && met < 100) _numSR["SS06"]++;
        if(mT < 100 && pT_ll > 50 && met >= 100 && met < 150 && pp) _numSR["SS07"]++;
        if(mT < 100 && pT_ll > 50 && met >= 100 && met < 150 && mm) _numSR["SS08"]++;
        if(mT < 100 && pT_ll > 50 && met >= 150 && met < 200) _numSR["SS09"]++;
        if(mT < 100 && pT_ll > 50 && met > 200) _numSR["SS10"]++;
```

Some code infrastructure challenges:

- Need **different parameter scanning algorithms**
- Need **model-agnostic core framework**
- Need to interface ***many*** **external physics codes**
- Need **massive parallelisation**…
- …which implies a need for **diskless interfacing**
- …which implies a need to **stop external codes from calling STOP and kill your 10,000-CPU scan**… :)

2. GAMBIT

GAMBIT: The Global And Modular BSM Inference Tool

gambit.hepforge.org github.com/GambitBSM EPJC 77 (2017) 784 arXiv:1705.07908

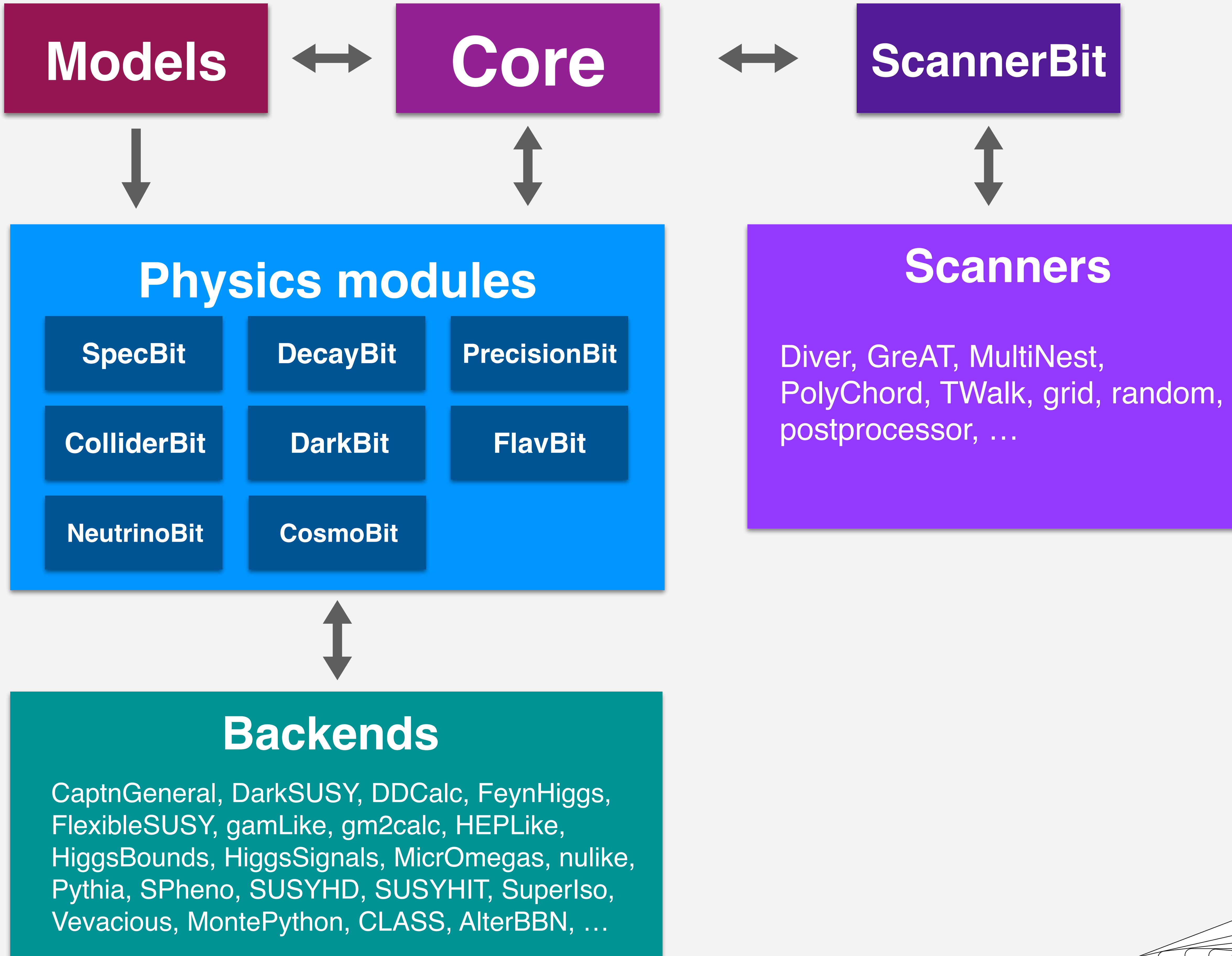
- Extensive model database, beyond SUSY
- Fast definition of new datasets, theories
- Extensive observable/data libraries
- Plug&play scanning/physics/likelihood packages
- Various statistical options (frequentist /Bayesian)
- Fast LHC likelihood calculator
- Massively parallel
- Fully open-source

Members of: ATLAS, Belle-II, CLiC, CMS, CTA, Fermi-LAT, DARWIN, IceCube, LHCb, SHiP, XENON

Authors of: BubbleProfiler, Capt'n General, Contur, DarkAges, DarkSUSY, DDCalc, DirectDM, Diver, EasyScanHEP, ExoCLASS, FlexibleSUSY, gamLike, GM2Calc, HEPLike, IsaTools, MARTY, nuLike, PhaseTracer, PolyChord, Rivet, SOFTSUSY, Superlso, SUSY-AI, xsec, Vevacious, WIMPSim

Recent collaborators: P Athron, C Balázs, A Beniwal, S Bloor, T Bringmann, A Buckley, J-E Camargo-Molina, C Chang, M Chrzaszcz, J Conrad, J Cornell, M Danninger, J Edsjö, T Emken, A Fowlie, T Gonzalo, W Handley, J Harz, S Hoof, F Kahlhoefer, A Kvellestad, P Jackson, D Jacob, C Lin, N Mahmoudi, G Martinez, MT Prim, A Raklev, C Rogan, R Ruiz, P Scott, N Serra, P Stöcker , W. Su, A Vincent, C Weniger, M White, Y Zhang, ++

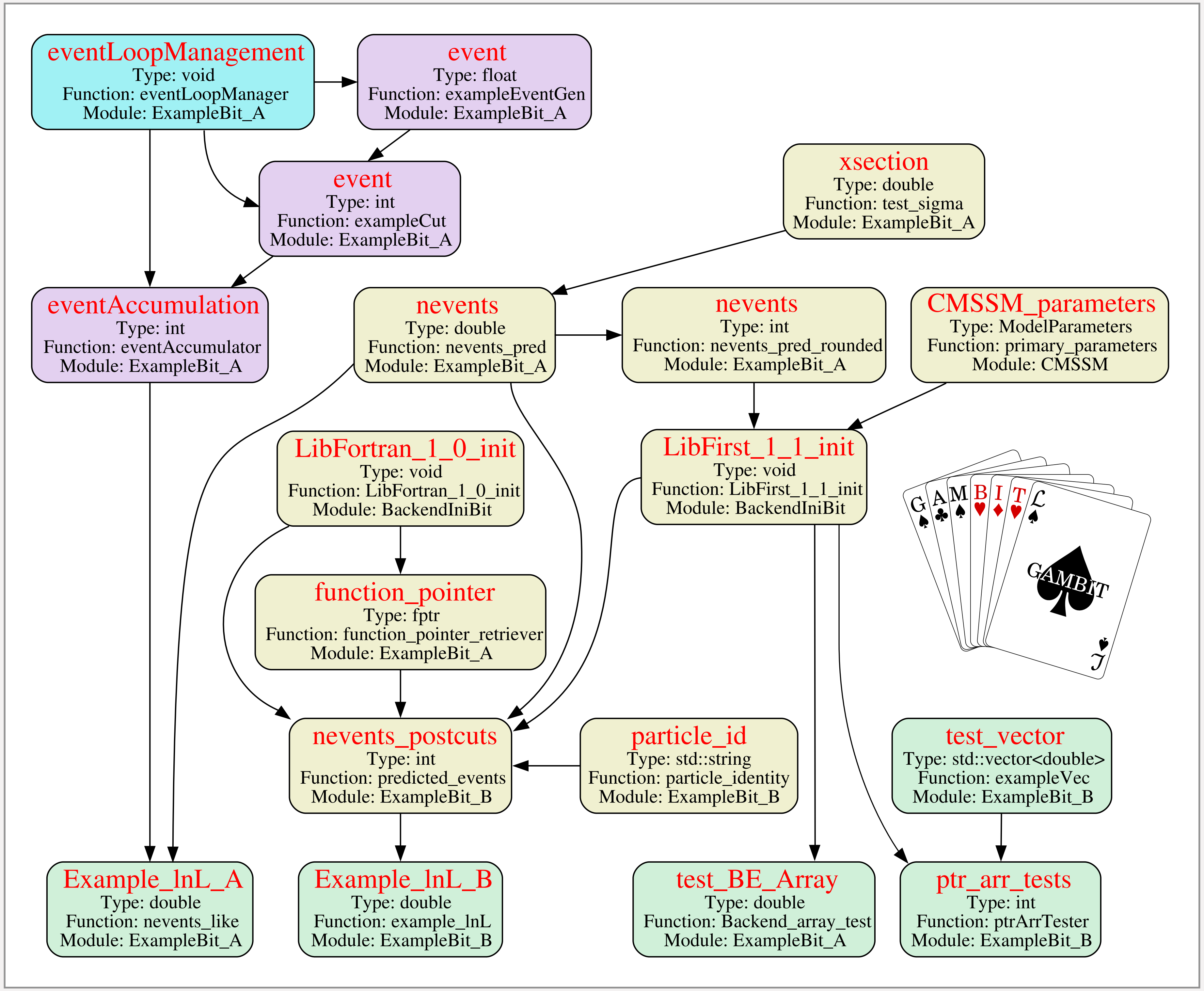
70+ participants in many experiments and numerous major theory codes


Models
Core
ScannerBit
Physics modules
SpecBit
DecayBit
PrecisionBit
ColliderBit
DarkBit
FlavBit
NeutrinoBit
CosmoBit
Scanners
Diver, GreAT, MultiNest, PolyChord, TWalk, grid, random, postprocessor, …
Backends
CaptnGeneral, DarkSUSY, DDCalc, FeynHiggs, FlexibleSUSY, gamLike, gm2calc, HEPLike, HiggsBounds, HiggsSignals, MicrOmegas, nulike, Pythia, SPheno, SUSYHD, SUSYHIT, SuperIso, Vevacious, MontePython, CLASS, AlterBBN, …

Some technical features

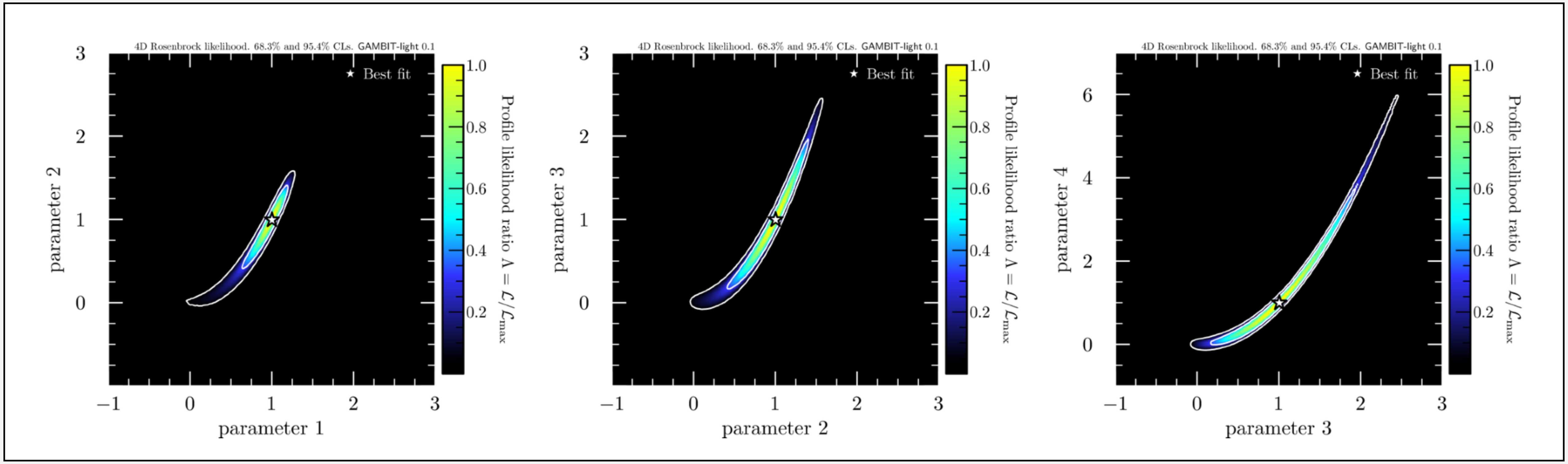
- **Two-level parallelisation**:
  - **MPI** for parameter sampling algorithm
  - **OpenMP** for per-point physics computations
- Collection of **sampling algorithms as plug-ins**
- Backend system for using **C**, **C++**, **Fortran**, **Python** and **Mathematica** codes as **runtime plug-ins** for physics computations
- Run configuration through **YAML** input file
- **Dynamic dependency resolution**: order of computations not hard-coded
- GAMBIT Universal Model machine (GUM): **code auto-generation** for new physics models

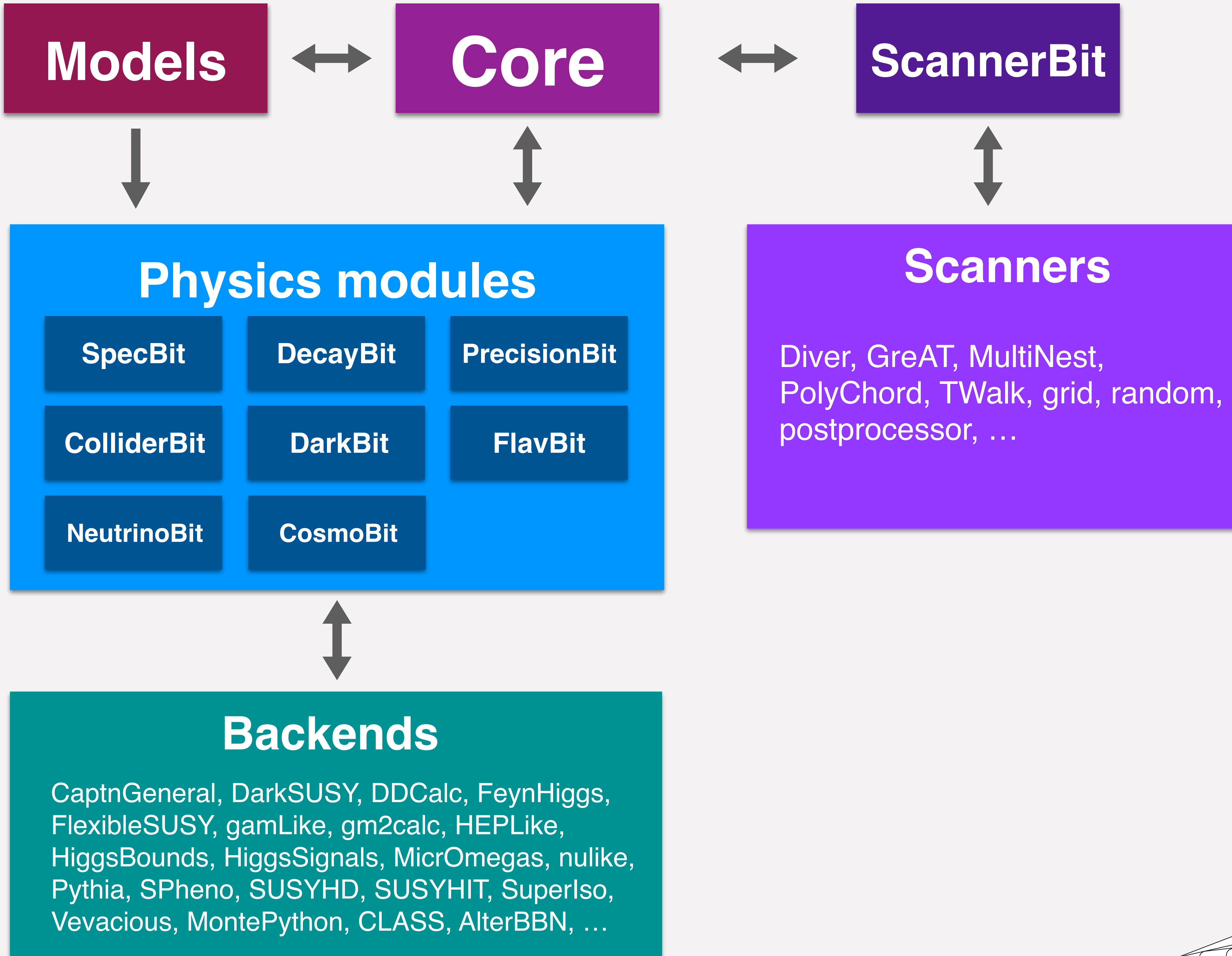
Dependency resolution



GAMBIT-light

- **GAMBIT** can be used **beyond particle physics**
- At its core: A general tool for **computationally heavy optimisation and parameter estimation** tasks
- Coming soon: **GAMBIT-light**
  A lightweight GAMBIT without the particle physics




Models
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CosmoBit
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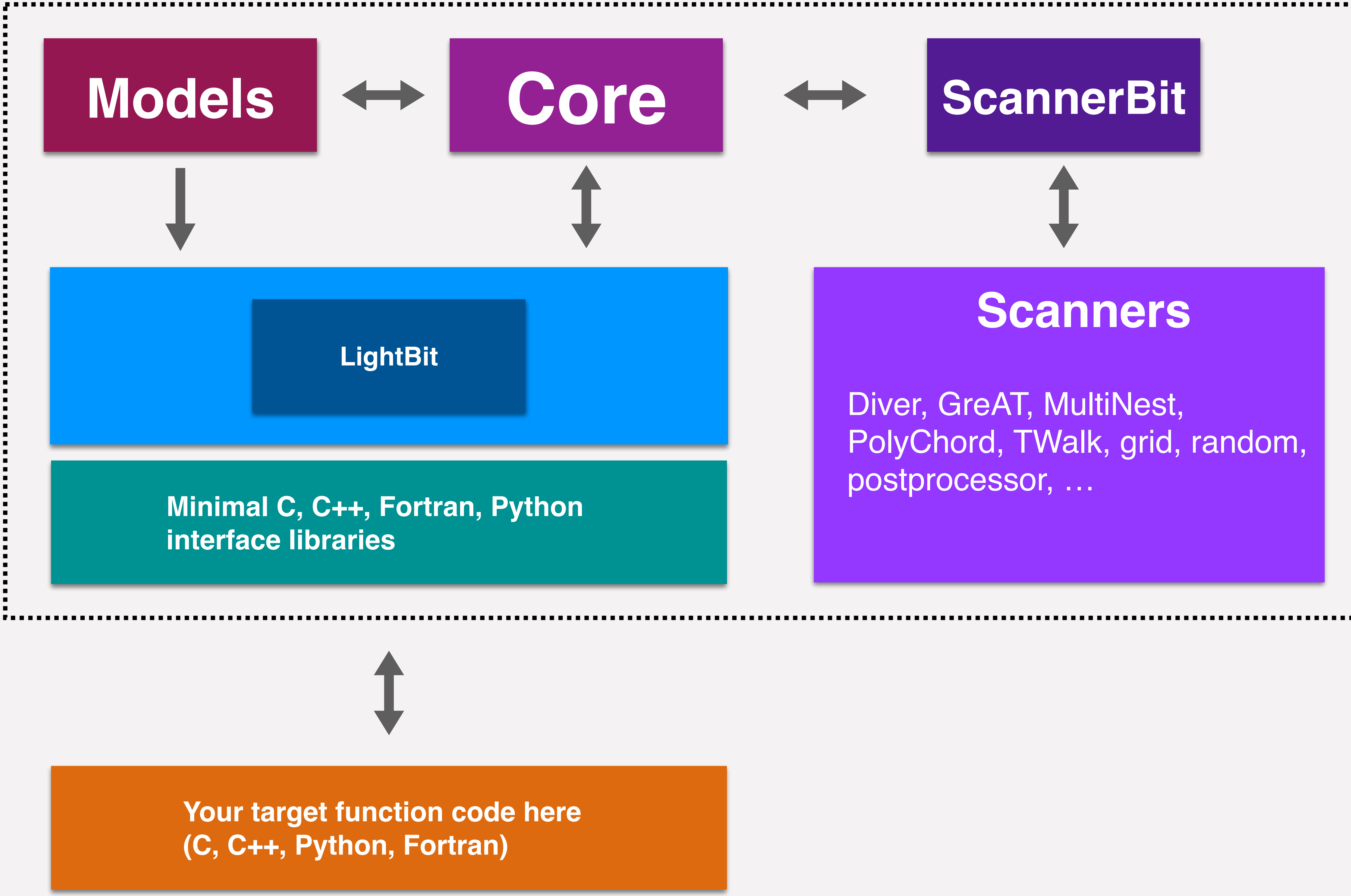
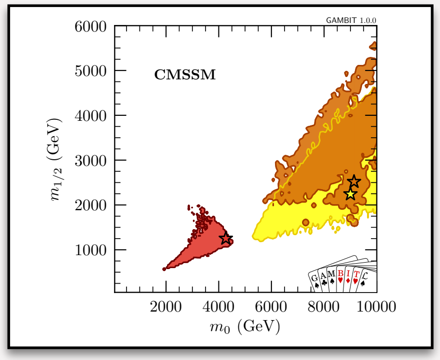
Diver, GreAT, MultiNest, PolyChord, TWalk, grid, random, postprocessor, …
Backends
CaptnGeneral, DarkSUSY, DDCalc, FeynHiggs, FlexibleSUSY, gamLike, gm2calc, HEPLike, HiggsBounds, HiggsSignals, MicrOmegas, nulike, Pythia, SPheno, SUSYHD, SUSYHIT, SuperIso, Vevacious, MontePython, CLASS, AlterBBN, …


Models
Core
ScannerBit
LightBit
Minimal C, C++, Fortran, Python interface libraries
Scanners
Diver, GreAT, MultiNest, PolyChord, TWalk, grid, random, postprocessor, …
Your target function code here (C, C++, Python, Fortran)

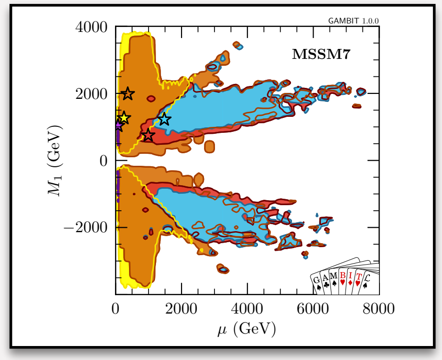
```yaml
UserModel:

  p1:
    name: param_name_1
    prior_type: flat
    range: [0.0, 1.0]

  p2:
    name: param_name_2
    prior_type: log
    range: [1.0e-2, 1.0e2]

  p3:
    name: param_name_3
    fixed_value: 3.0

  p4:
    name: param_name_4
    fixed_value: 4.0


UserLogLikes:

  my_library_A:
    lang: c
    user_lib: Backends/light_interface/libuser_c.so
    init_fun: init_user_loglike
    input:
      - param_name_1
      - param_name_2
      - param_name_3
    output:
      - my_library_A_output_1
      - my_library_A_output_2
      - my_library_A_output_3

  my_library_B:
    lang: fortran
    user_lib: Backends/light_interface/libuser_fortran.so
    init_fun: init_user_loglike
    input:
      - param_name_1
      - param_name_2
    output:
      - my_library_B_output_1

  my_library_C:
    lang: python
    user_lib: Backends/light_interface/libuser.py
    init_fun: init_user_loglike
    input:
      - param_name_1
      - param_name_2
      - param_name_4
    output:
      - my_library_C_output_1
      - my_library_C_output_2
```

```yaml
Printer:

  printer: hdf5
  options:
    output_file: "results.hdf5"
    group: "/data"
    buffer_length: 1000
    delete_file_on_restart: true


Scanner:

  use_scanner: polychord

  scanners:

    de:
      plugin: diver
      NP: 200
      convthresh: 1e-4
      verbosity: 1
      lambdajDE: false

    multinest:
      plugin: multinest
      nlive: 2000
      tol: 0.01

    twalk:
      plugin: twalk
      sqrtR: 1.001

    polychord:
      plugin: polychord
      tol: 0.01

    minuit2:
      plugin: minuit2
      tolerance: 0.0001
      precision: 0.0001
      max_loglike_calls: 100000
      max_iterations: 100000
      algorithm: combined


KeyValues:

  default_output_path: "runs/gambit_light_test"

  debug: false

  print_scanID: true

  rng:
    generator: ranlux48
    seed: -1

  likelihood:
    model_invalid_for_lnlike_below: -5e5
    print_invalid_points: false
```

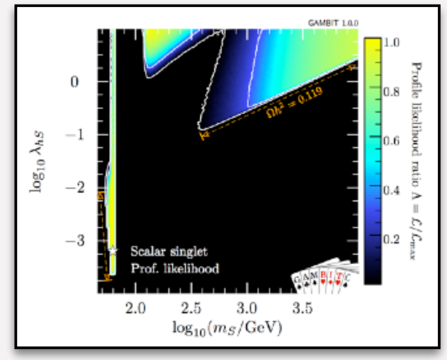
3. Applications of Bayesian inference



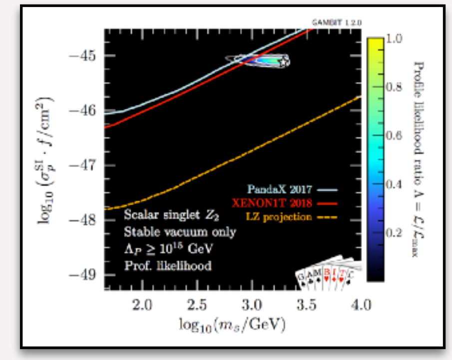
GUT-scale SUSY: 1705.07935



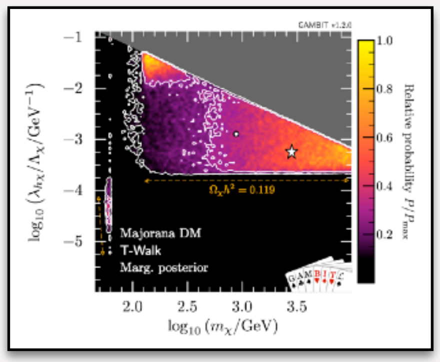
MSSM7: 1705.07917



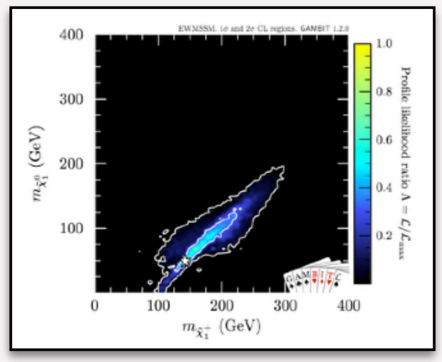
Scalar Higgs portal DM: 1705.07931



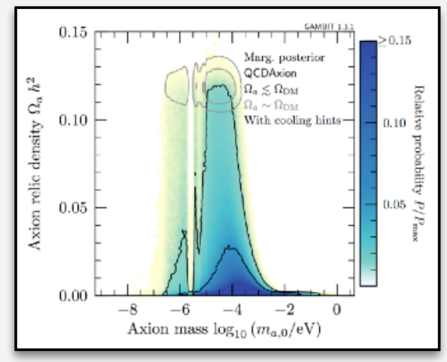
Scalar Higgs portal DM w/ vac. stability: 1806.11281



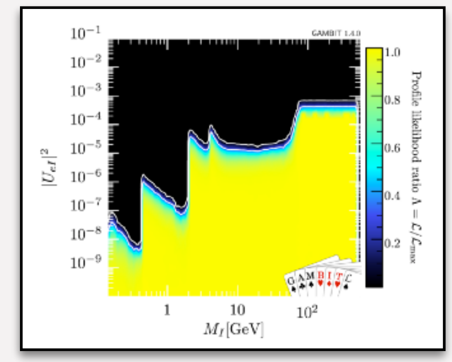
Vector and fermion Higgs portal DM: 1808.10465



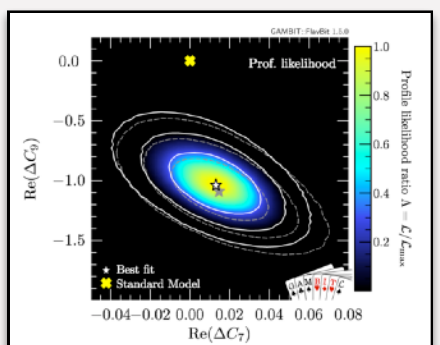
EW-MSSM: 1809.02097



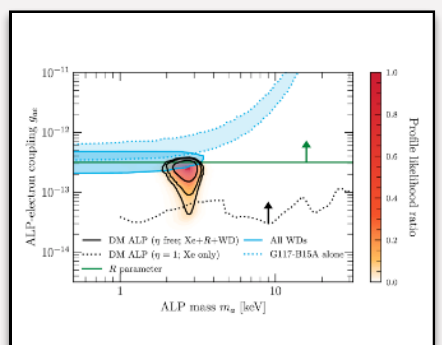
Axion-like particles: 1810.07192



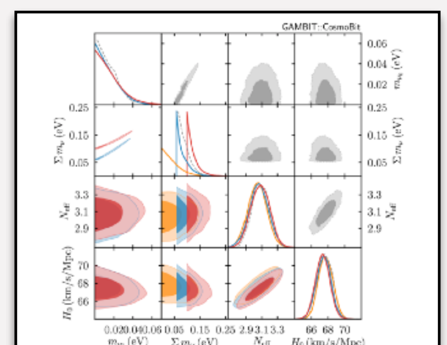
Right-handed neutrinos: 1908.02302



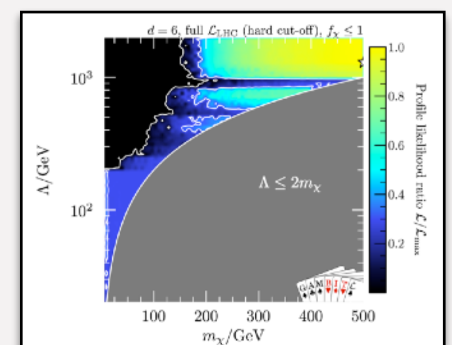
Flavour EFT: 2006.03489



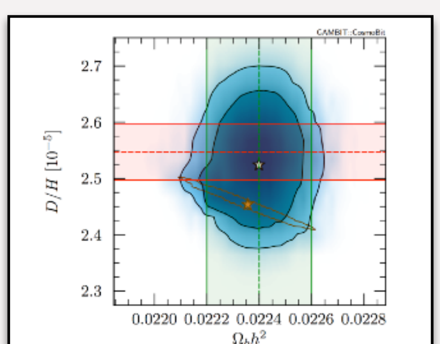
More axion-like particles: 2007.05517



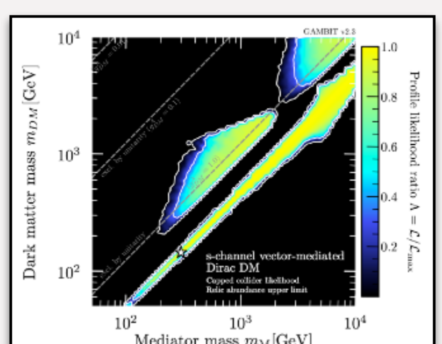
Neutrinos and cosmo: 2009.03287



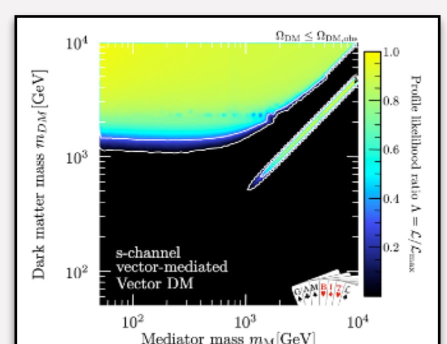
Dark matter EFTs: 2106.02056



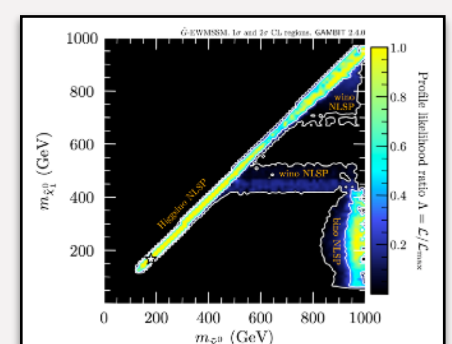
Cosmo ALPs: 2205.13549



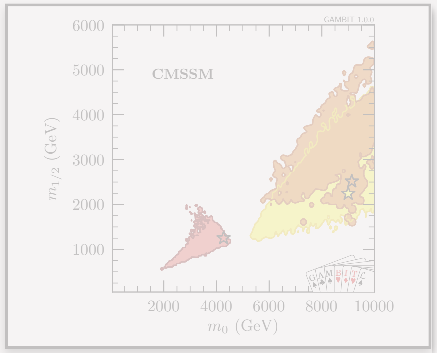
Simplified DM, scalar/fermion: 2209.13266

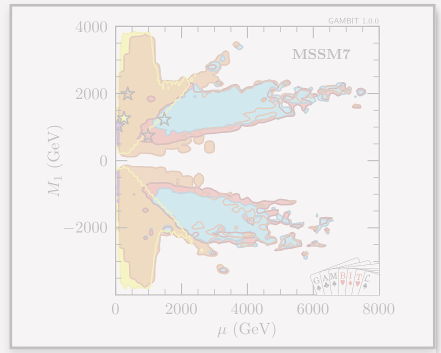


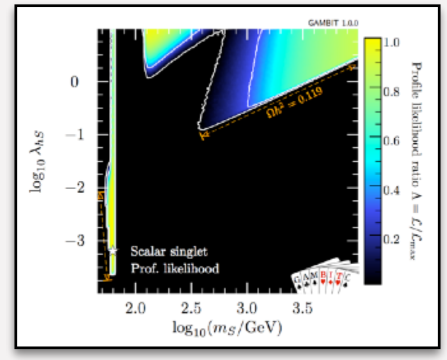
Simplified DM, vector: 2303.08351

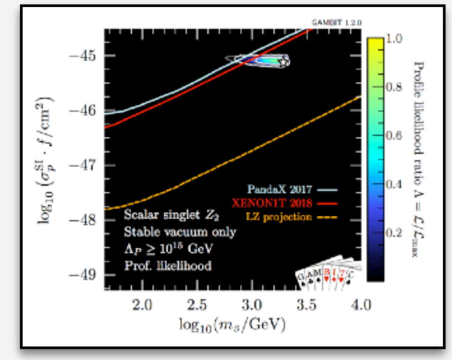


EW-MSSM w/ light gravitino: 2303.09082


GUT-scale SUSY: 1705.07935


MSSM7: 1705.07917


Scalar Higgs portal DM: 1705.07931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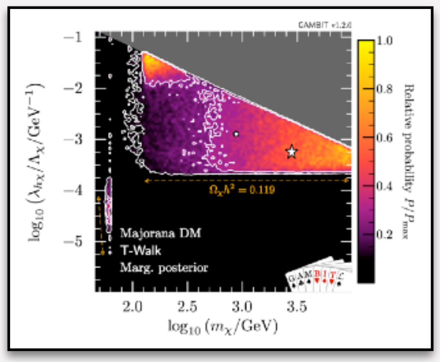
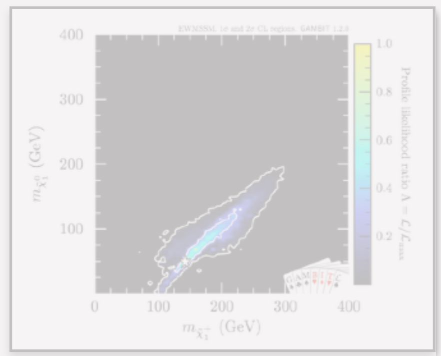
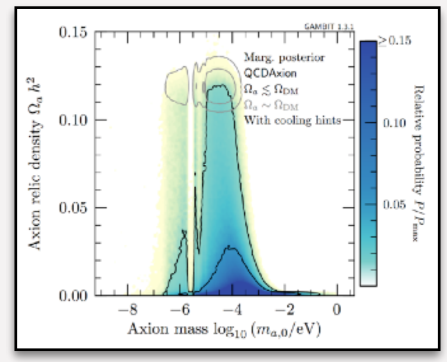
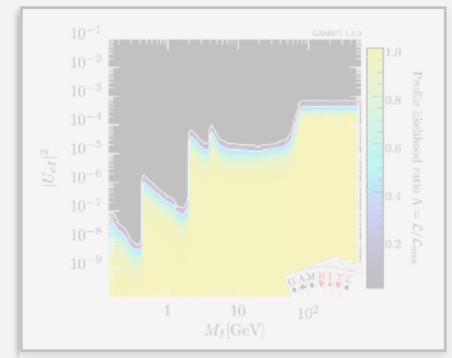
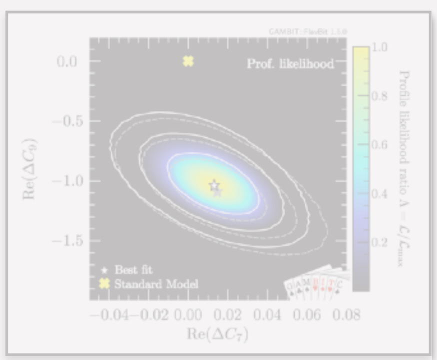
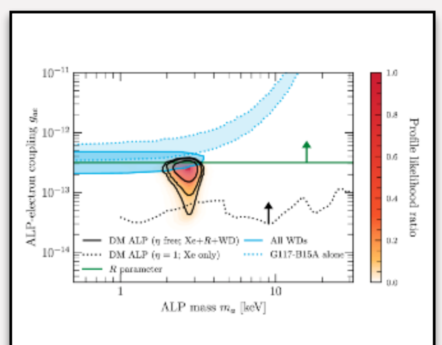

Vector and fermion Higgs portal DM: 1808.10465

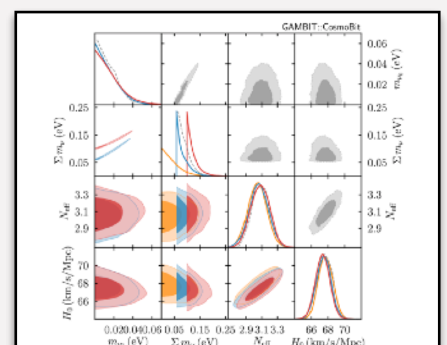

EW-MSSM: 1809.02097

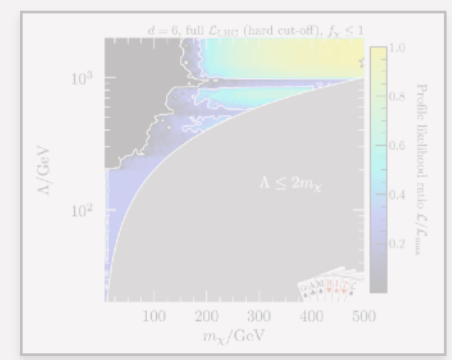

Axion-like particles: 1810.07192

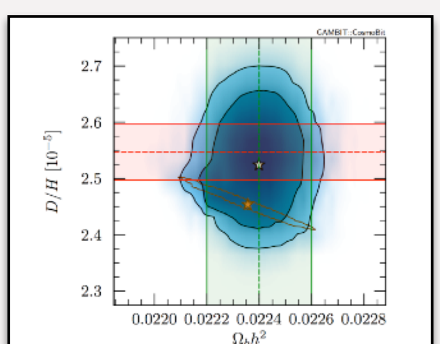

Right-handed neutrinos: 1908.02302

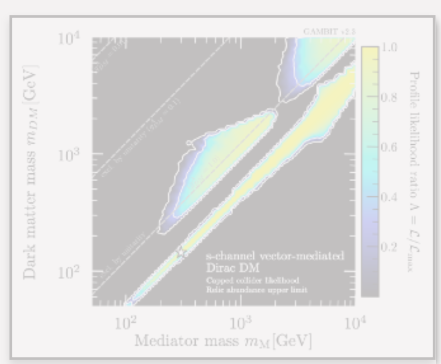

Flavour EFT: 2006.03489

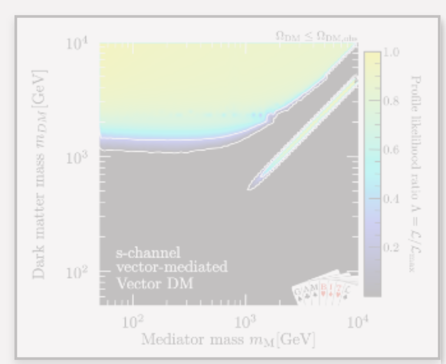

More axion-like particles: 2007.05517

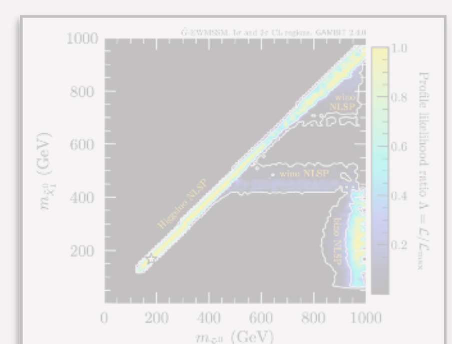

Neutrinos and cosmo: 2009.03287


Dark matter EFTs: 2106.02056


Cosmo ALPs: 2205.13549


Simplified DM, scalar/fermion: 2209.13266

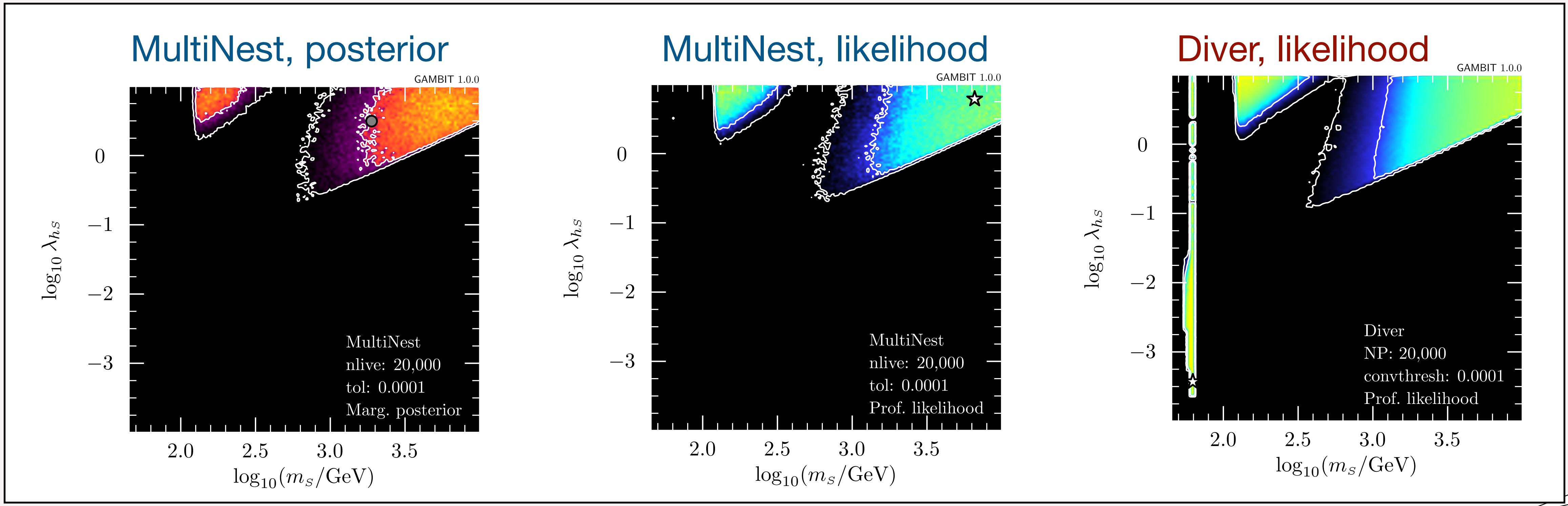

Simplified DM, vector: 2303.08351


EW-MSSM w/ light gravitino: 2303.09082

General strategy

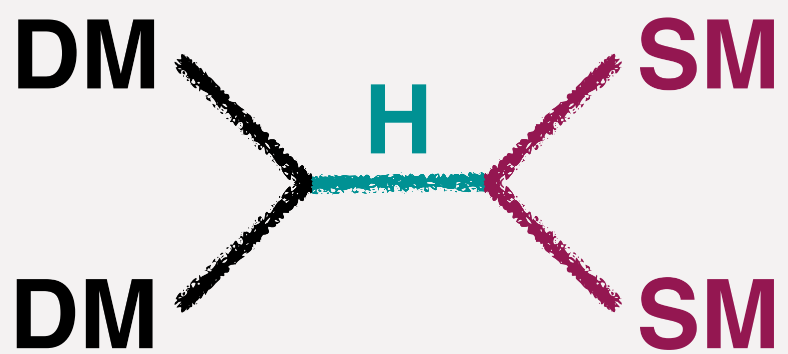
- Collecting **posterior samples:**
  - **T-Walk** (ensemble MCMC) or **PolyChord/MultiNest** (nested sampling)
- Computing **Bayesian evidences:**
  - **PolyChord** or **MultiNest**
- Sampling to map out **profile likelihood function:**
  - **Diver** (differential evolution)
  - And add all samples from the Bayesian scans

[arXiv:1705.07959]



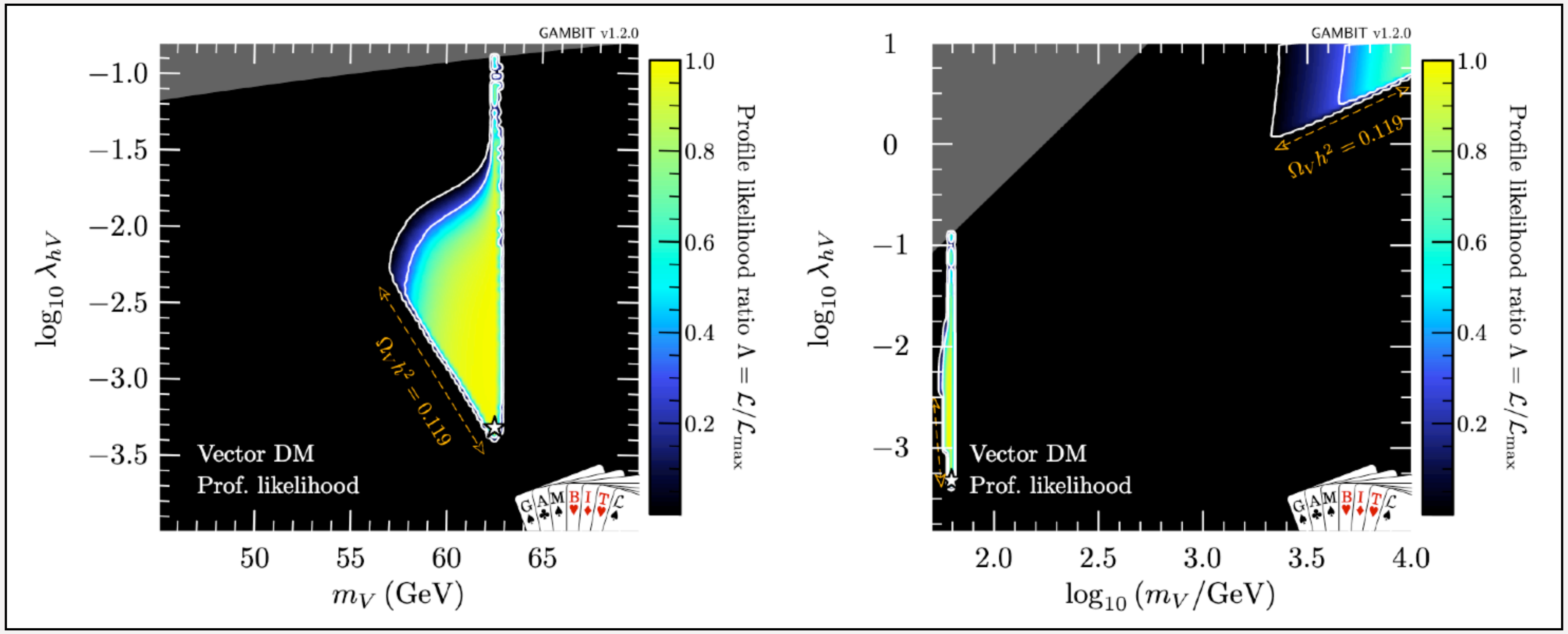
Example: «Higgs portal» dark matter

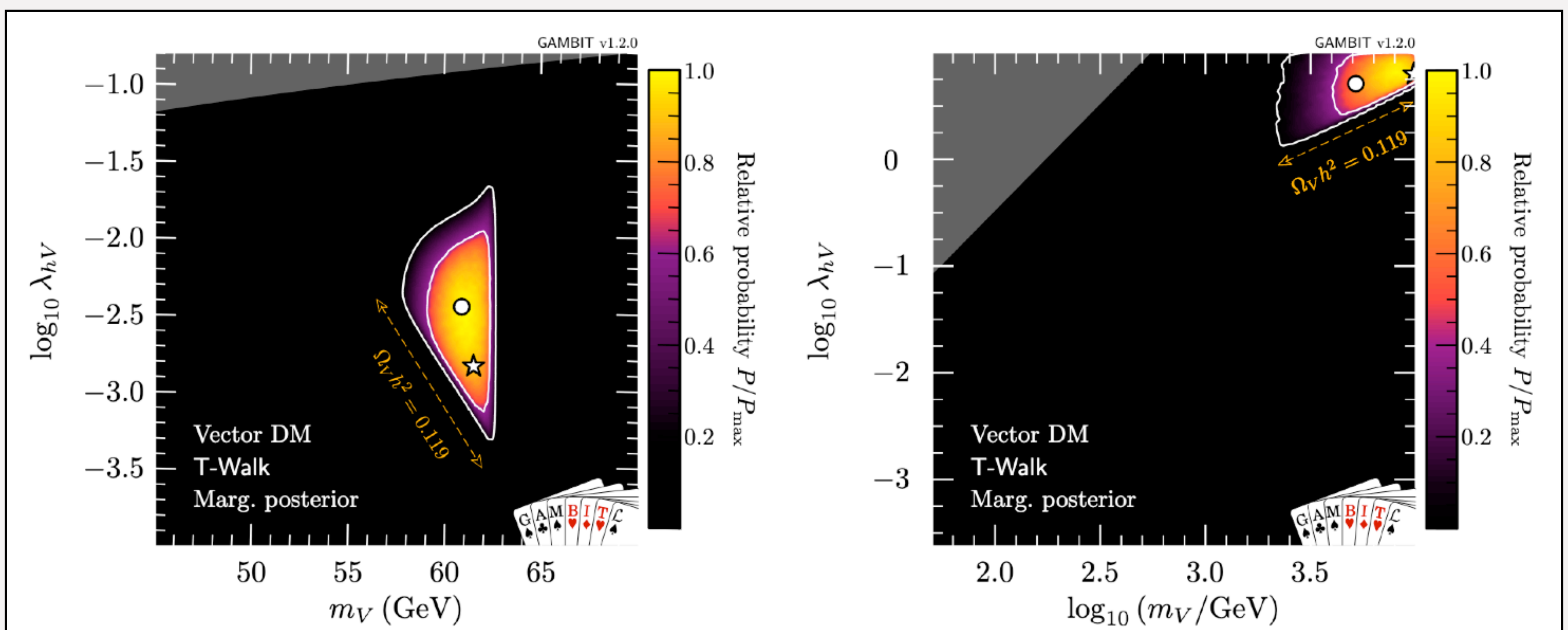
[arxiv:1808.10465]



- Study of three models where the dark matter (DM) field only interacts with the Standard Model fields through interactions with the Higgs field
- 1) Vector DM 2) Dirac fermion DM 3) Majorana fermion DM
- Parameter space
  - DM mass
  - 1—2 parameters for the DM-Higgs interaction
  - 7 nuisance parameters
- Likelihoods for DM density, Higgs «invisible decay width», and many experimental searches for DM signals (indirect and direct)
- Intended here as an example — the results are now somewhat outdated

- Both **profile likelihoods** and **posteriors**
- Helps disentangle **«low likelihood»** vs **«high likelihood but fine-tuned»**





- Both **profile likelihoods** and **posteriors**
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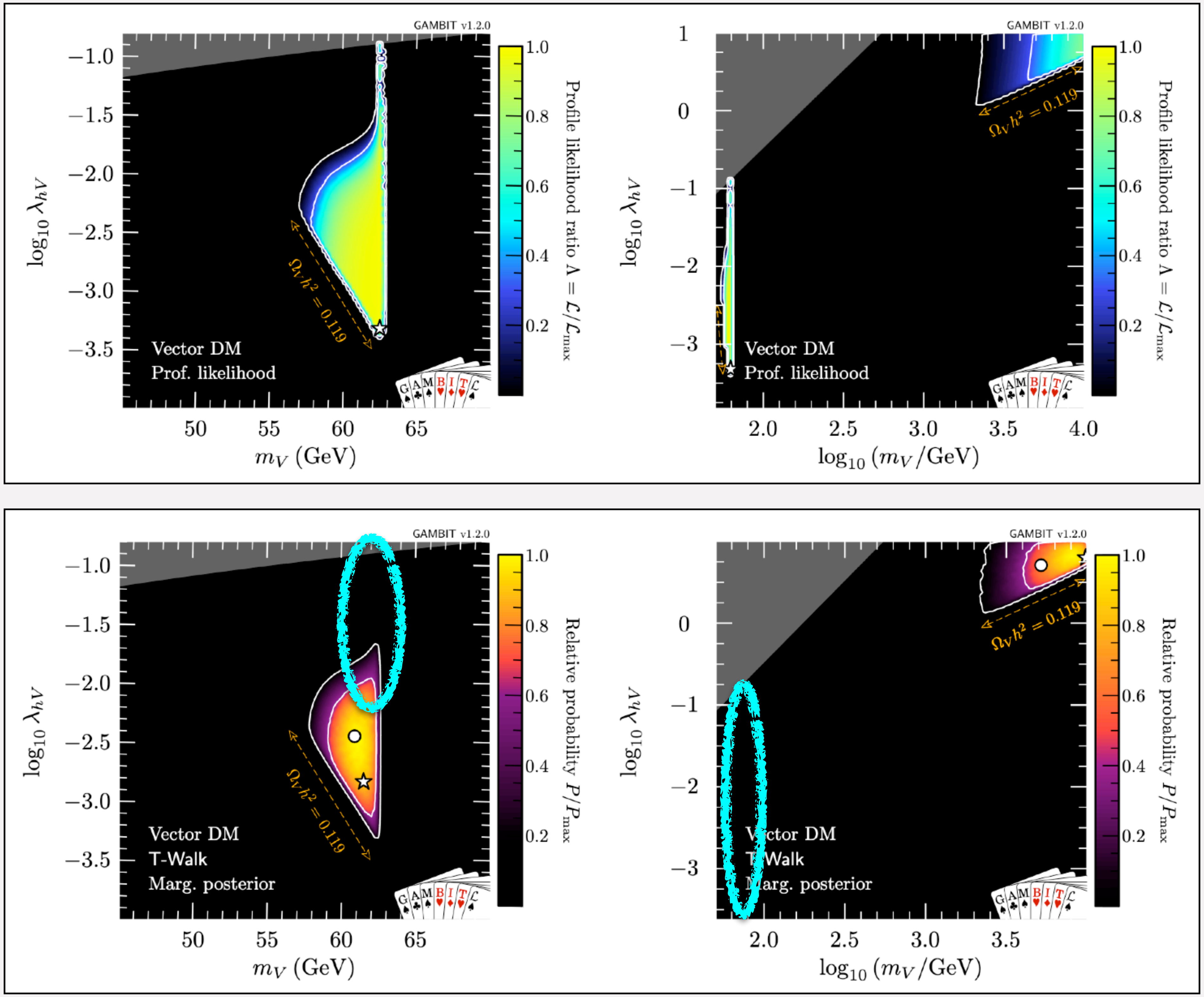


Bayesian model comparisons

Model	Comparison model and priors			Odds
$\xi = 0$	m_χ: log	$\lambda_{h\chi}/\Lambda_\chi$: log	ξ: flat	70:1
$g_{\mathrm{p}}/\Lambda_{\mathrm{p}} = 0$	m_χ: log	$g_{\mathrm{s}}/\Lambda_{\mathrm{s}}$: log	$g_{\mathrm{p}}/\Lambda_{\mathrm{p}}$: log	140:1

Table 8: Odds ratios for CP violation for the singlet Majorana fermion Higgs portal model. Here the odds ratios are those against a pure CP-even Higgs portal coupling, as compared to two different parametrisations (and thus priors) of the model in which the CP nature of the Higgs portal can vary freely.

Within the fermion DM models:

Strong evidence for model that allows a CP-violating H-DM interaction, i.e. a more complicated model

(Nested models)

No particular preference in comparisons between the different classes of DM models

(Non-nested models)

Model	Parameters and priors			Odds
S	m_S: log	λ_{hS}: log		1:1
V_μ	m_V: log	λ_{hV}: log		6:1
χ	m_χ: log	$\lambda_{h\chi}/\Lambda_\chi$: log	ξ: flat	1:1
ψ	m_ψ: log	$\lambda_{h\psi}/\Lambda_\psi$: log	ξ: flat	1:1

Table 9: Odds ratios against each singlet Higgs portal DM model with $\mathbb{Z}_2$ symmetry, relative to the scalar model.

More examples of Bayesian applications in BSM phenomenology

(by no means an exhaustive list)

- Fast **theory emulators,** fast **marginalised likelihoods**, …
  - Fast AMS-02 antiproton likelihoods: [arxiv:2303.07362]
  - Fast higher-order LHC cross-section predictions: [arxiv:2006.16273]
- Bayesian takes on **fine-tuning questions in BSM physics** [arxiv:1204.4940], [arxiv:1709.07895] (and many more…)
- Bayesian **uncertainties for missing higher-order terms** in QFT calculations: [arxiv:2006.16293]
- Creative applications of (originally) Bayesian methods
  - Nested sampling for **estimating small p-values** [arxiv:2105.13923]
  - Nested sampling for **event generation** [arxiv:2205.02030]
- + many applications of Bayesian parameter estimation and model comparison…

Summary

Summary

- How can we **learn the most physics from our experimental results?**
  Test all the results against all interesting theories!

- **GAMBIT** is an open-source tool for **large-scale global fits** of new theories in particle physics

- A **modular** and **model-independent** core software framework
  → GAMBIT has been used to investigate a wide range of new theories

- Bayesian approaches widely used in BSM physics:
  parameter estimation, **model comparison**, **emulation**, **theory uncertainties**

- **Different questions, different answers:** Useful to perform both Bayesian and frequentist analyses (if computationally feasible)

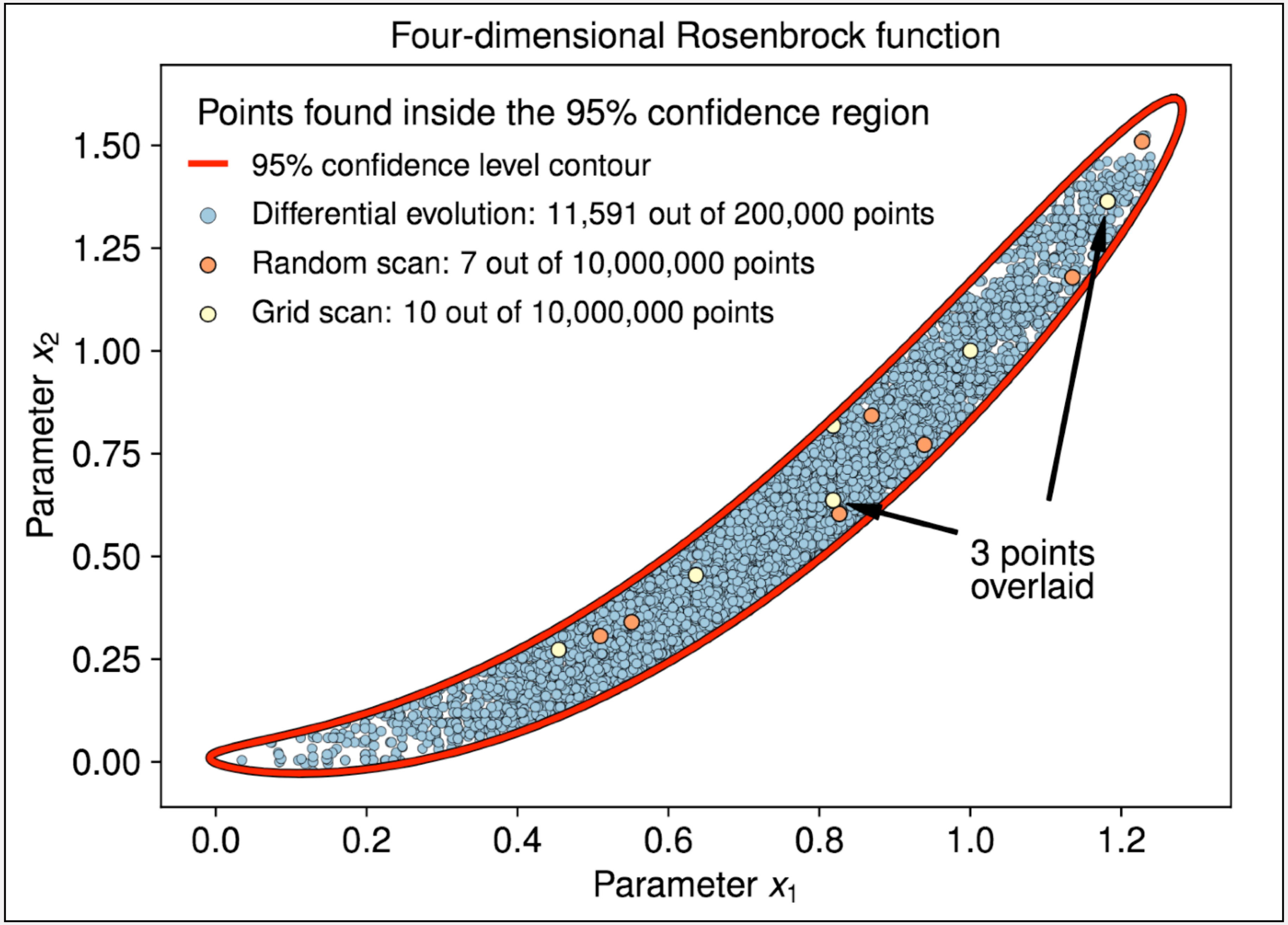
- Coming soon: **GAMBIT-light**

- gambit.hepforge.org and github.com/GambitBSM/gambit_2.4

- GAMBIT results are publicly available: zenodo.org/communities/gambit-official

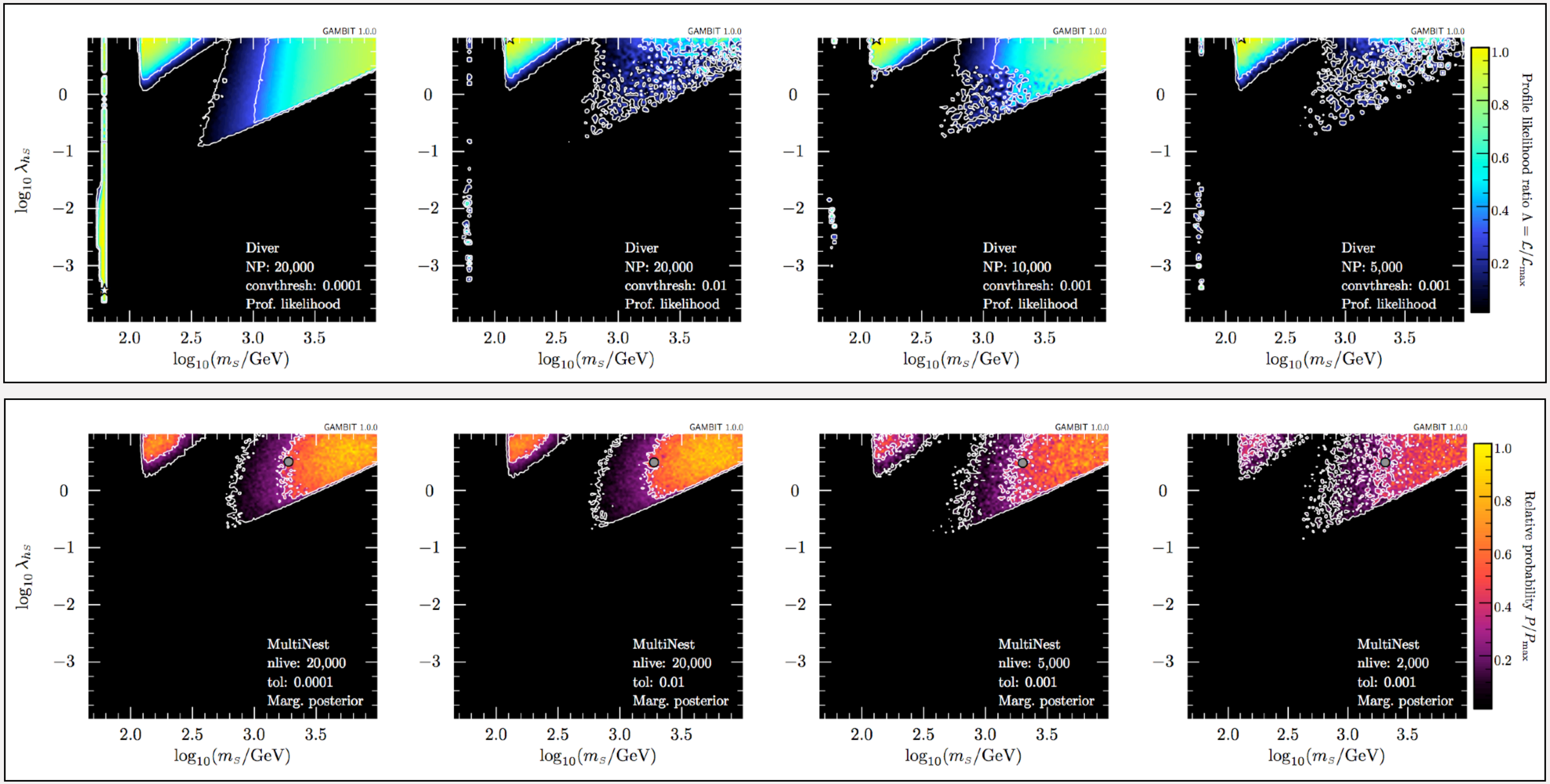
Bonus tracks

Parameter space exploration



[arxiv:2012.09874]

Parameter space exploration



[arxiv:1705.07959]

Dependency resolution

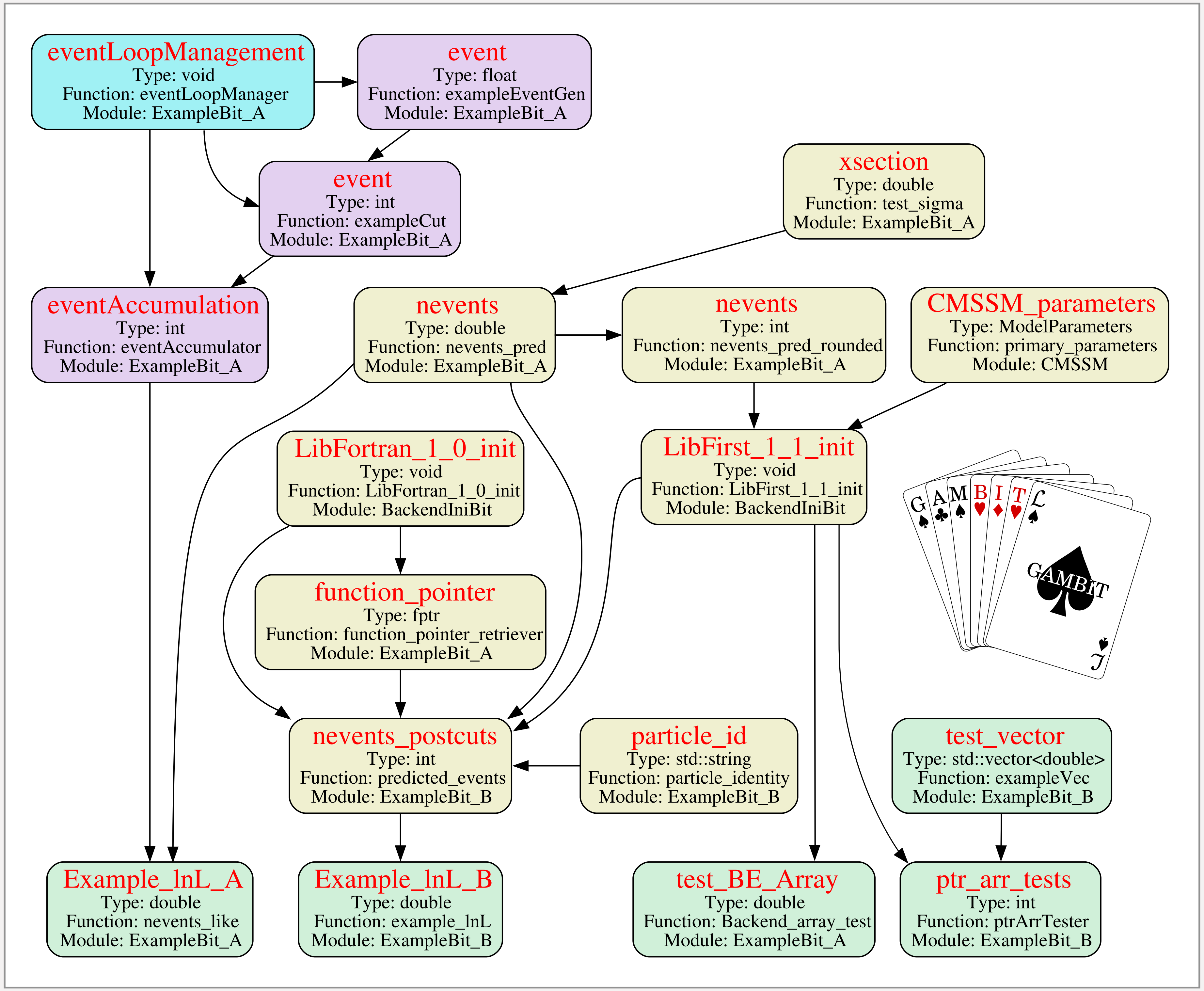
- Basic building blocks: **module functions**
- A physics module: **a collection of module functions** related to the same physics topic
- Each module function has a single **capability** (what it calculates)
- A module function can have **dependencies** on the results of other module functions
- A module function can declare which **models** it can work with
- GAMBIT determines which module functions should be run in which order for a given scan (**dependency resolution**)

```
void function_name(double &result)
{
  ...
  result = ... // something useful
}
```

```
// Observable: BR(B -> tau nu)
#define CAPABILITY Btaunu
START_CAPABILITY
  #define FUNCTION SI_Btaunu
  START_FUNCTION(double)
  DEPENDENCY(SuperIso_modelinfo, parameters)
  BACKEND_REQ(Btaunu, (libsuperiso), double, (const parameters*))
  BACKEND_OPTION( (SuperIso, 3.6), (libsuperiso) )
  #undef FUNCTION
#undef CAPABILITY
```

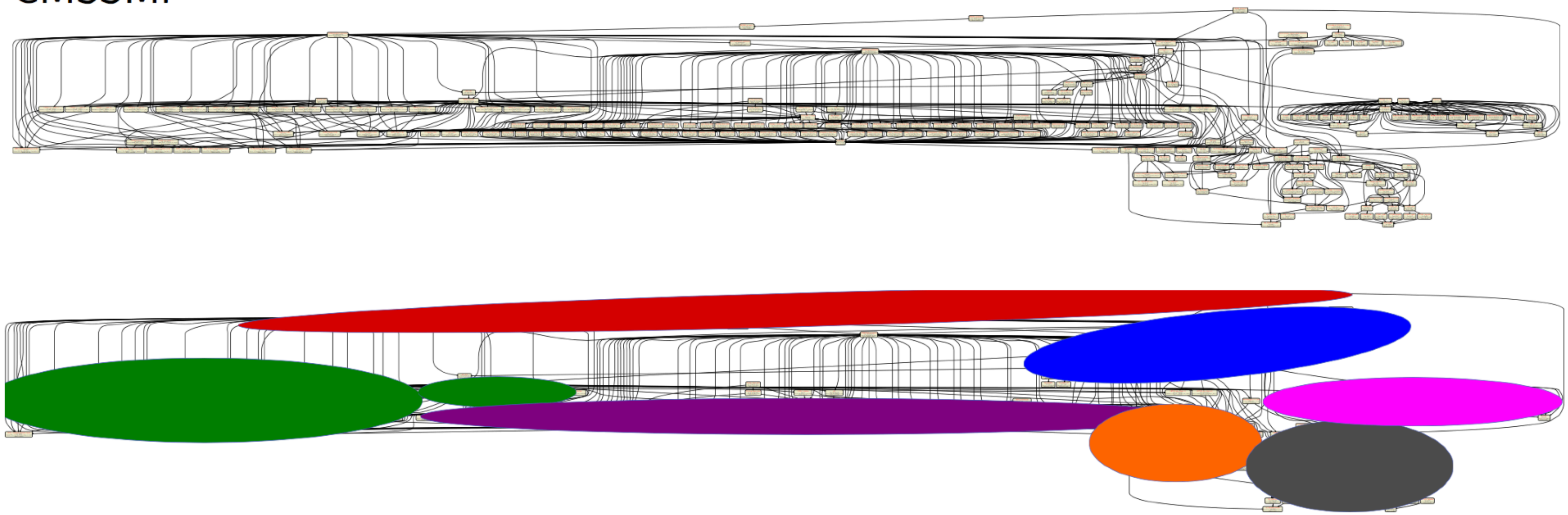
```
/// Br B->tau nu_tau decays
void SI_Btaunu(double &result)
{
  using namespace Pipes::SI_Btaunu;

  parameters const& param = *Dep::SuperIso_modelinfo;
  result = BEreq::Btaunu(&param);
}
```


Dependency resolution



Dependency resolution

CMSSM:



Red: Model parameter translations
Blue: Precision calculations
Green: LEP rates+likelihoods
Purple: Decays
Orange: LHC observables and likelihoods
Grey: DM direct, indirect and relic density
Pink: Flavour physics