Putting it all together: what we can learn from BSM global fits

Anders Kvellestad, University of Oslo
On behalf of the GAMBIT Collaboration

LNF, September 19, 2024

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Outline

1. BSM global fits
2. What we can learn (example: LHC global fits)
3. Why it’s difficult
4. GAMBIT

1. BSM global fits

How can we extract the most physics from our data?

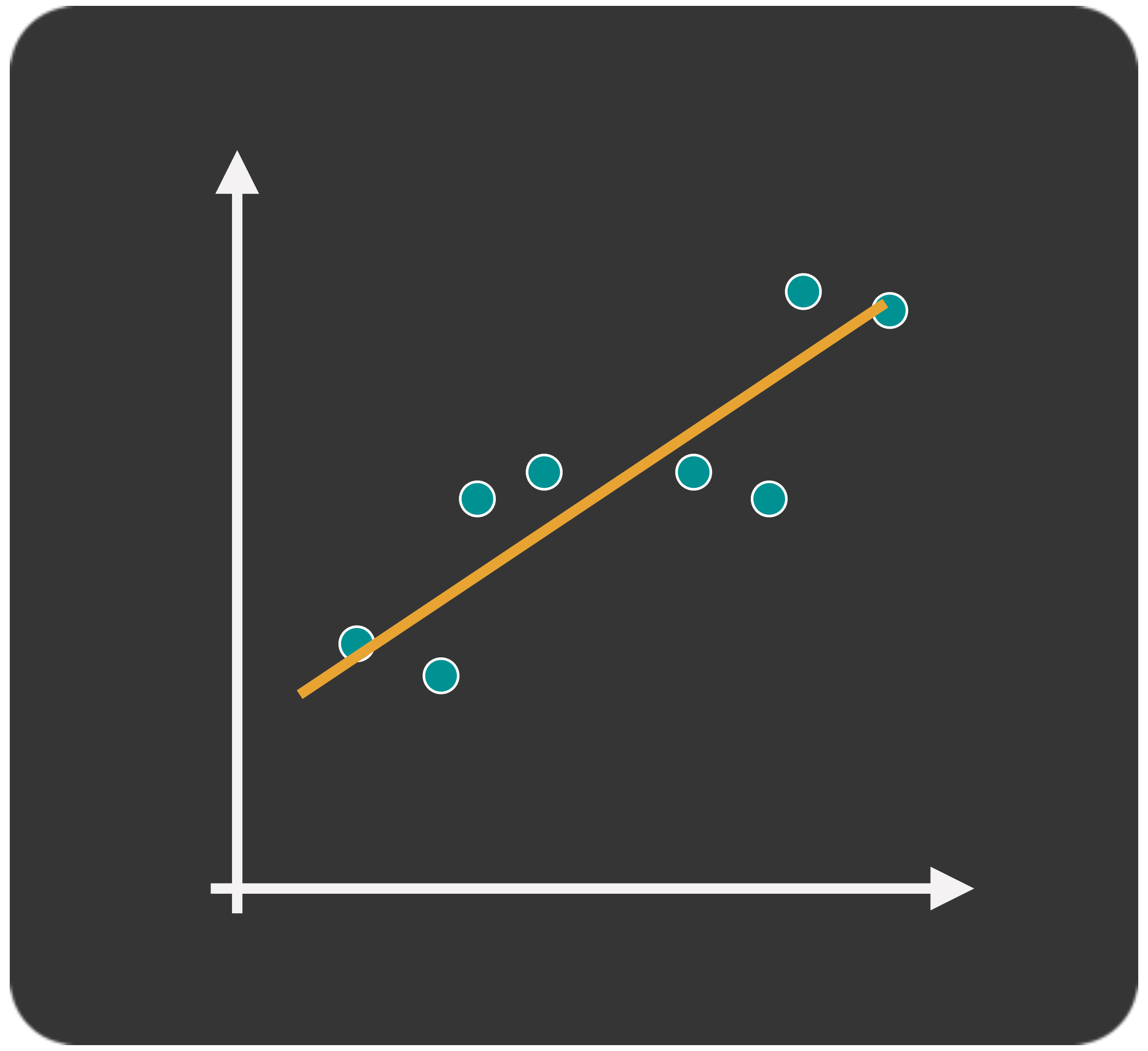
Easy! Construct a physics model, test it against data, repeat as needed…

- But what is **a model**?
- And **how** to test it against data?

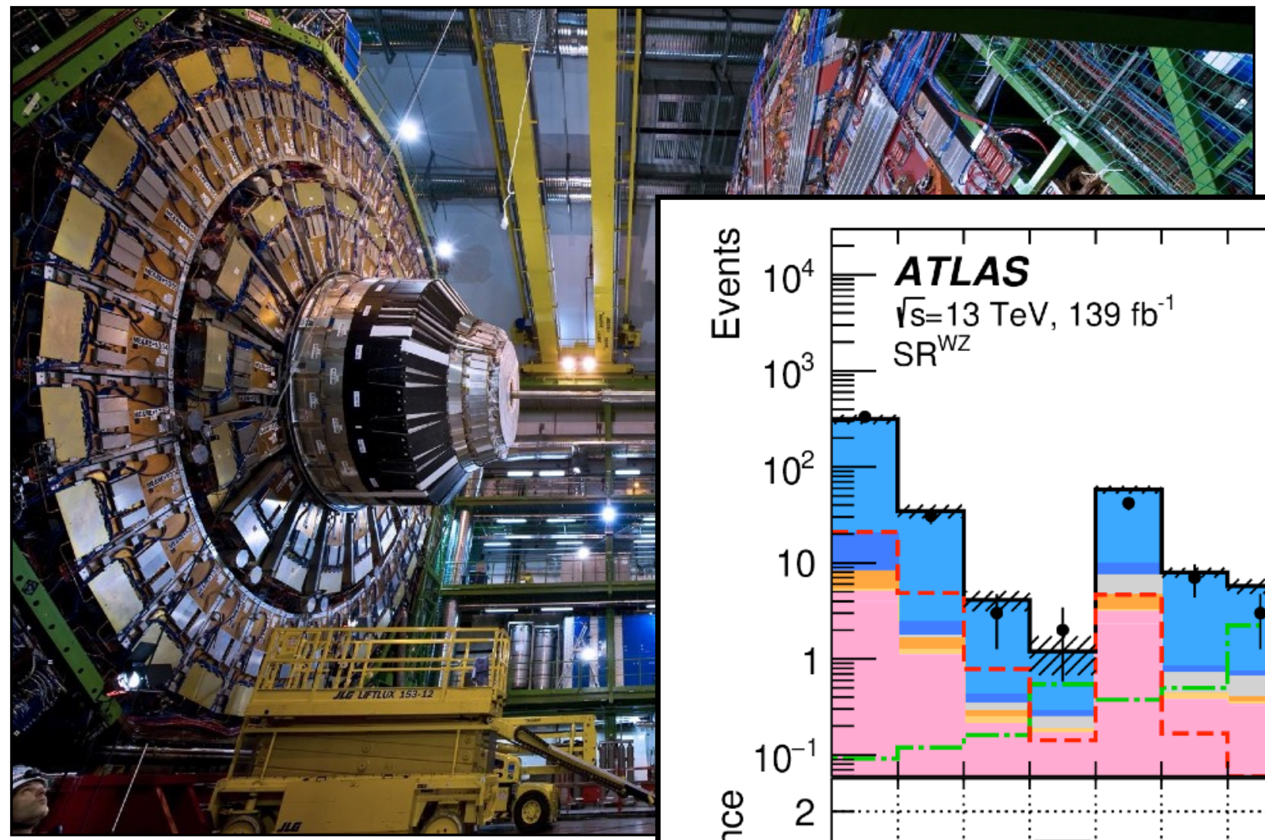
But what is a model?

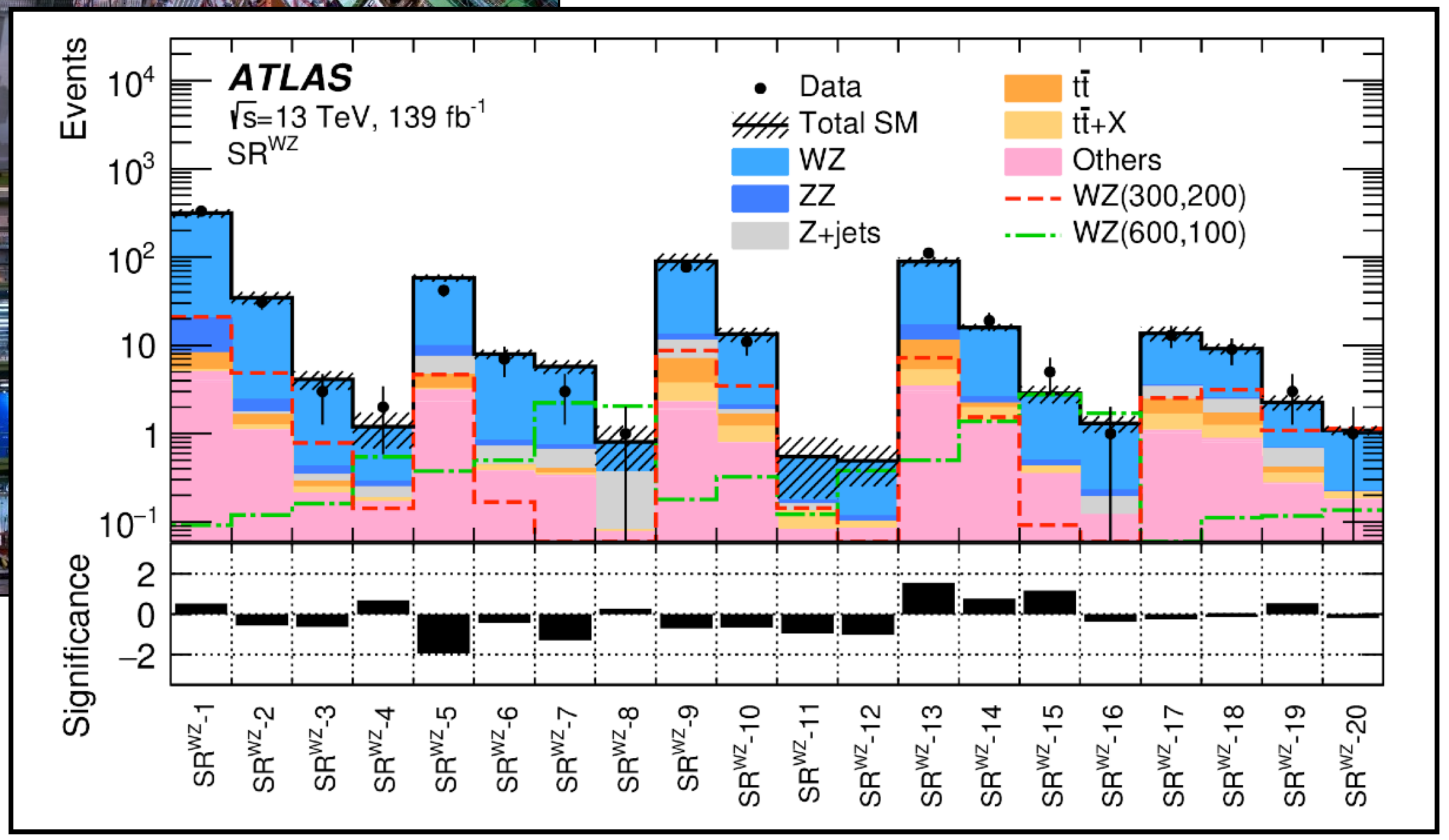
A joint probability distribution for the data

$$f(x) = ax + b + \epsilon, \quad \epsilon \sim N(0, \sigma)$$



$$p(y_1, y_2, \ldots | x_1, x_2, \ldots, a, b, \sigma) = N(f(x_1; a, b), \sigma)\, N(f(x_2; a, b), \sigma)\ \ldots$$





$$p(n_1, n_2, \ldots | \boldsymbol{\theta}) = \mathrm{Pois}(\lambda_1(\boldsymbol{\theta}))\,\mathrm{Pois}(\lambda_2(\boldsymbol{\theta}))\ \ldots$$

$$\mathrm{Pois}(\lambda(\boldsymbol{\theta})) = \frac{\lambda(\boldsymbol{\theta})^n e^{-\lambda(\boldsymbol{\theta})}}{n!}$$

$$\lambda(\boldsymbol{\theta}) \rightarrow$$

- Differential cross-sections, decay rates, …
- Simulate events
- Simulate detector effects
- Mimic the experiment's data selection procedure
- …

$$\boldsymbol{\theta} \rightarrow$$

- Lagrangian parameters
- Experiment parameters
- Expected background rates
- …

How to compare your model against data?

The **likelihood** is key

$$p(\boldsymbol{D}_{\mathrm{obs}}|\boldsymbol{\theta}) \equiv L(\boldsymbol{\theta})$$

Bayesian

$$p(\boldsymbol{\theta}|\boldsymbol{D}_{\mathrm{obs}}) = \frac{p(\boldsymbol{D}_{\mathrm{obs}}|\boldsymbol{\theta})\, p(\boldsymbol{\theta})}{p(\boldsymbol{D}_{\mathrm{obs}})}$$

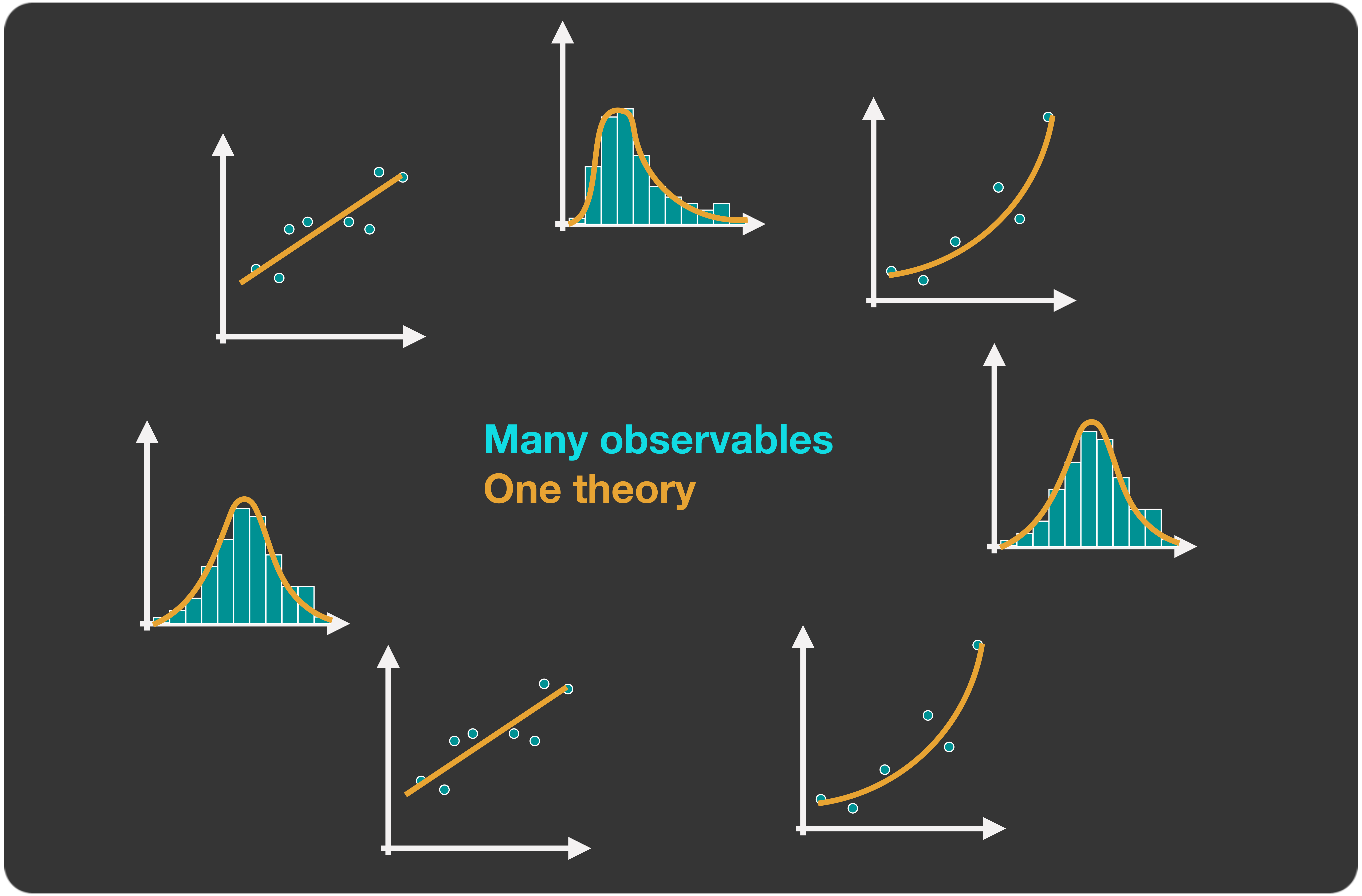
$$p(\boldsymbol{\theta}|\boldsymbol{D}_{\mathrm{obs}}) = \frac{L(\boldsymbol{\theta})\, \pi(\boldsymbol{\theta})}{Z}$$

frequentist

$$p(\boldsymbol{D}_{\mathrm{obs}}|\boldsymbol{\theta})$$

+ assumptions/simulations of hypothetical data

Global fits



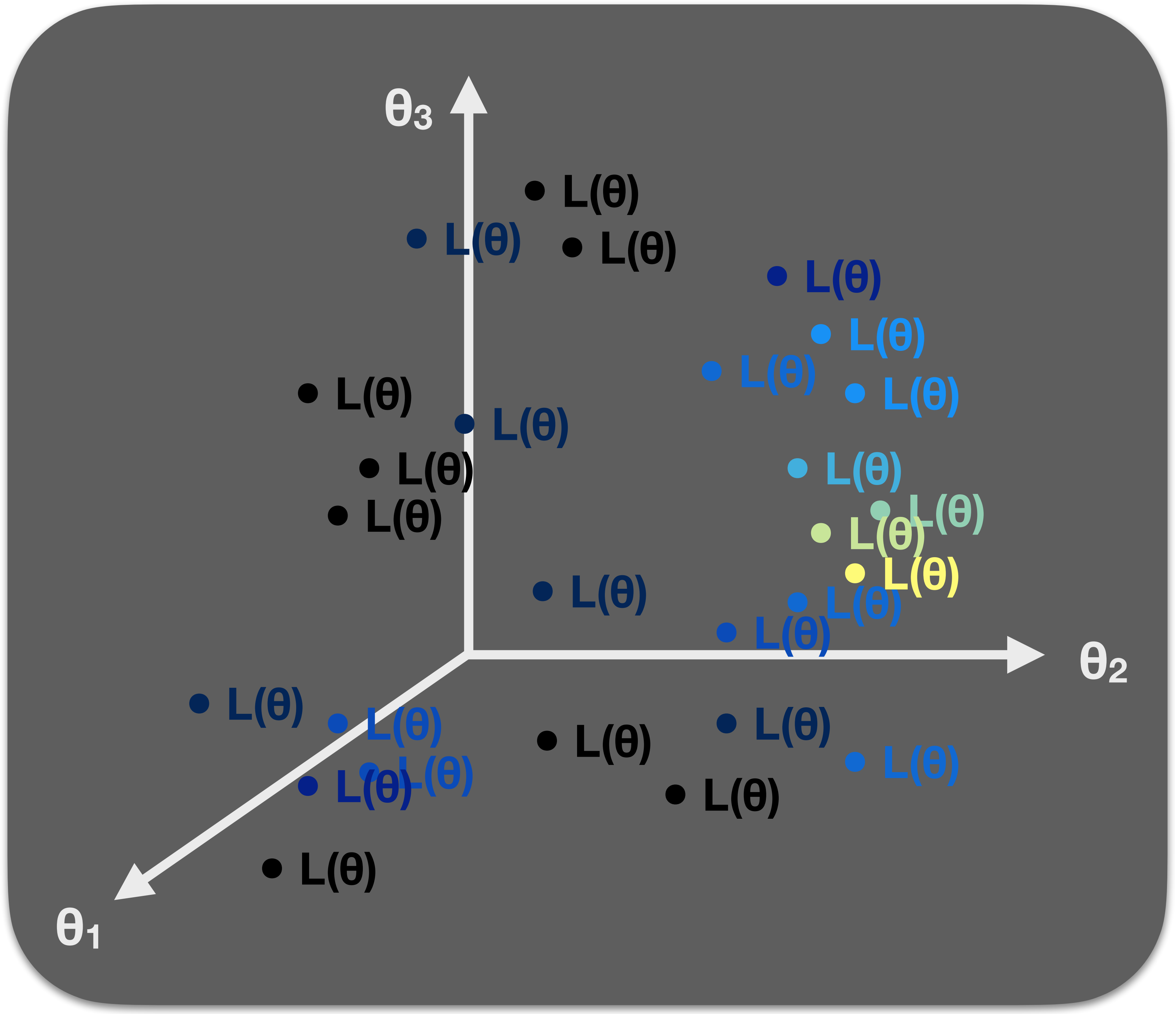
The basic steps of a BSM global fit

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

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

- 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: **compute all predictions(θ) → evaluate likelihood L(θ)**



- Region of highest L(θ):
  the model's highest predicted joint probability for the observed data
  (but not necessarily a *good* fit to the data, or the most *probable* θ…)

2. What we can learn

Example: LHC global fits

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]**

The many interpretations of «reinterpretation»

- **Analysis preservation and reuse internally in an experiment**
  - High accuracy (full access to analysis details, full detector simulation, …)
  - High computational cost per model point
- **Simulation-based reinterpretation by outside groups**
  - Medium accuracy
  - Medium-to-high computational cost per model point
- **Simulation-less reinterpretation by outside groups**
  - Medium accuracy
  - Often reduced exclusion sensitivity for a given model point
  - Low computational cost per model point
- **Wildly optimistic / very incomplete reinterpretations**
  - E.g. just checking model points from some many-parameter theory against a couple of 2D exclusion contours

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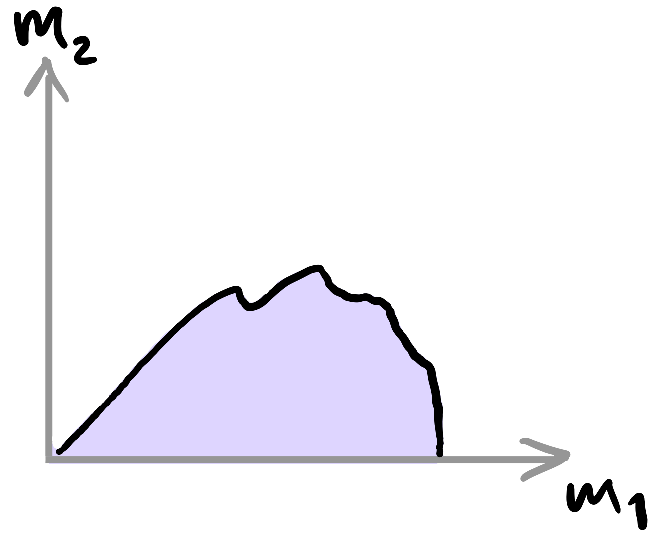
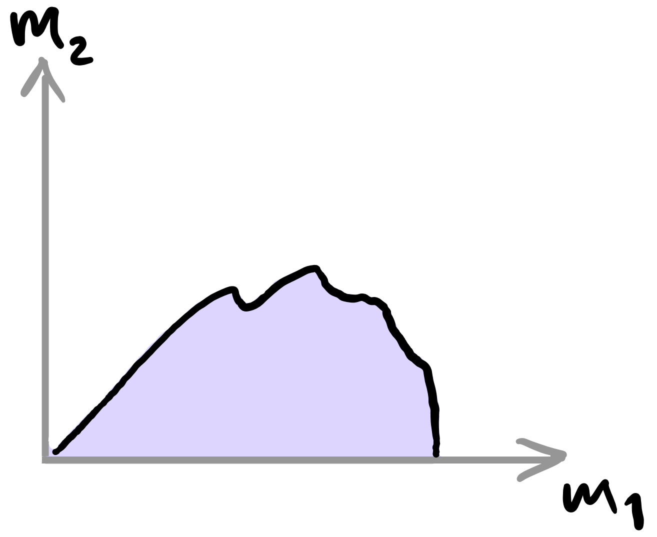
All the hard-won event counts with background estimates from the LHC experiments hold **a lot** of information about BSM theory space.

What we have learned at time of publication

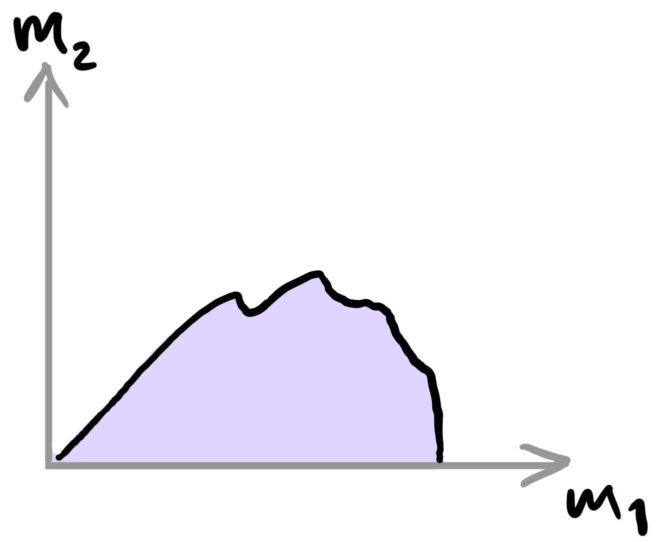
What we have learned long after publication

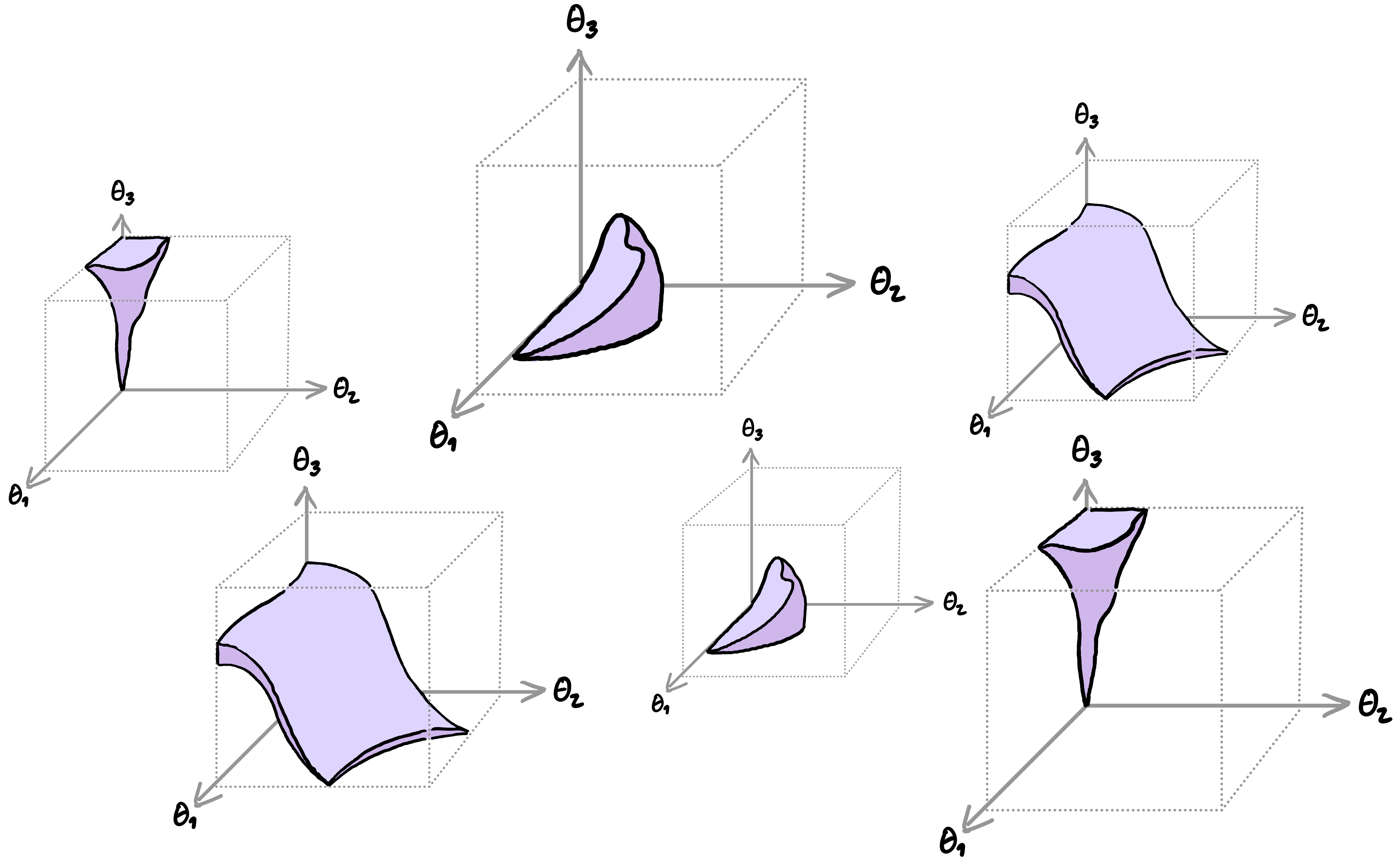
Impossible to reinterpret



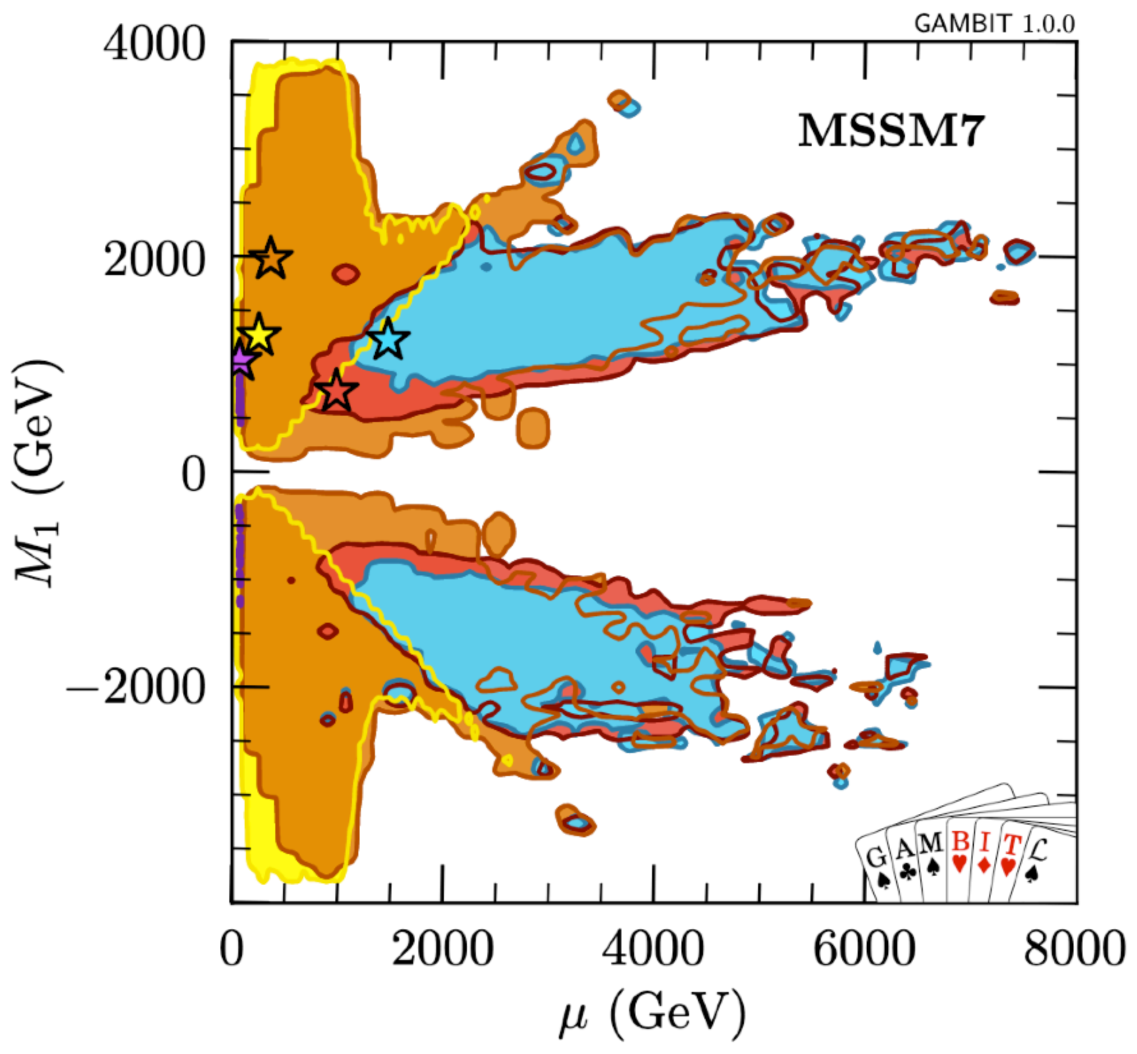


Possible to reinterpret

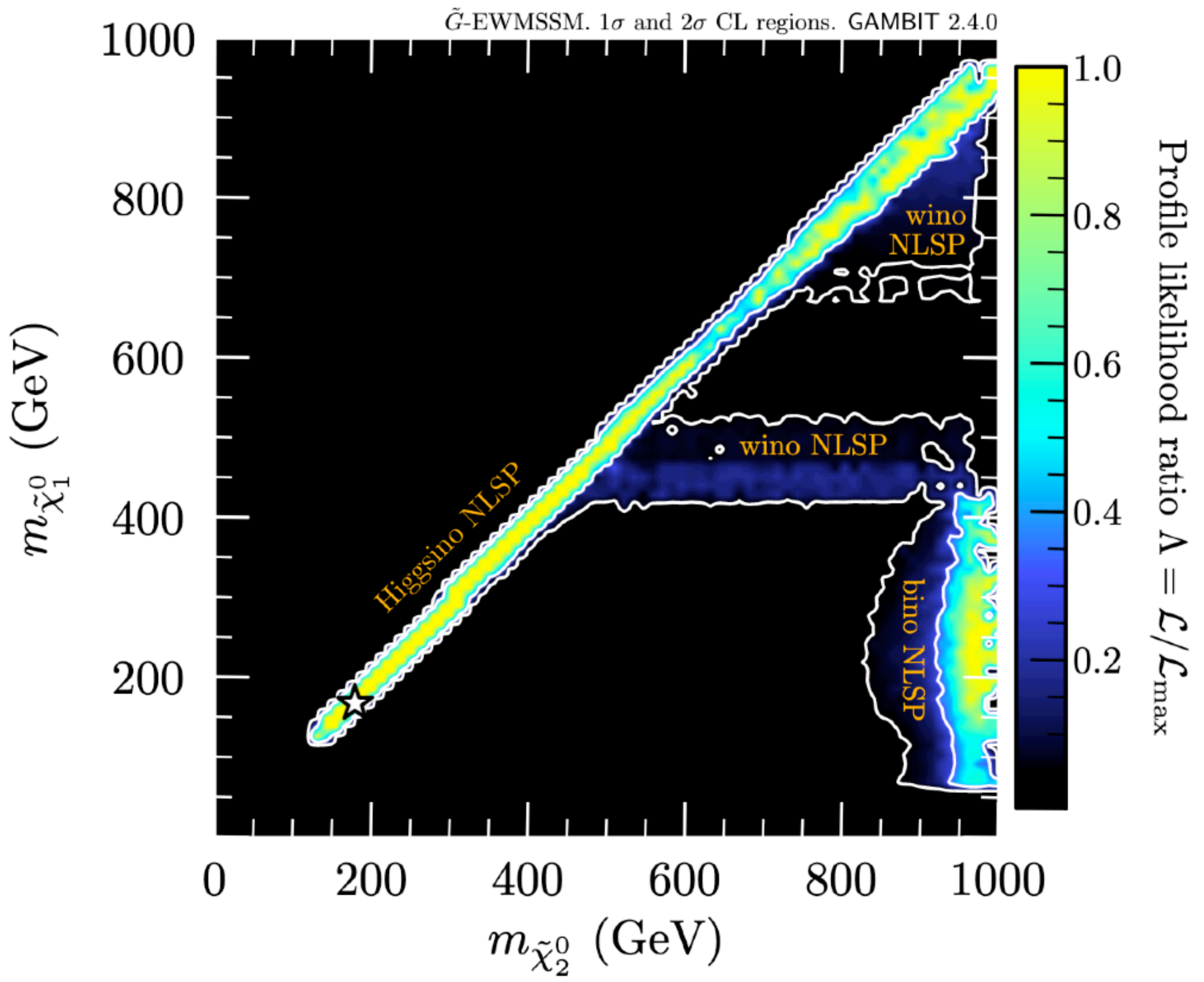




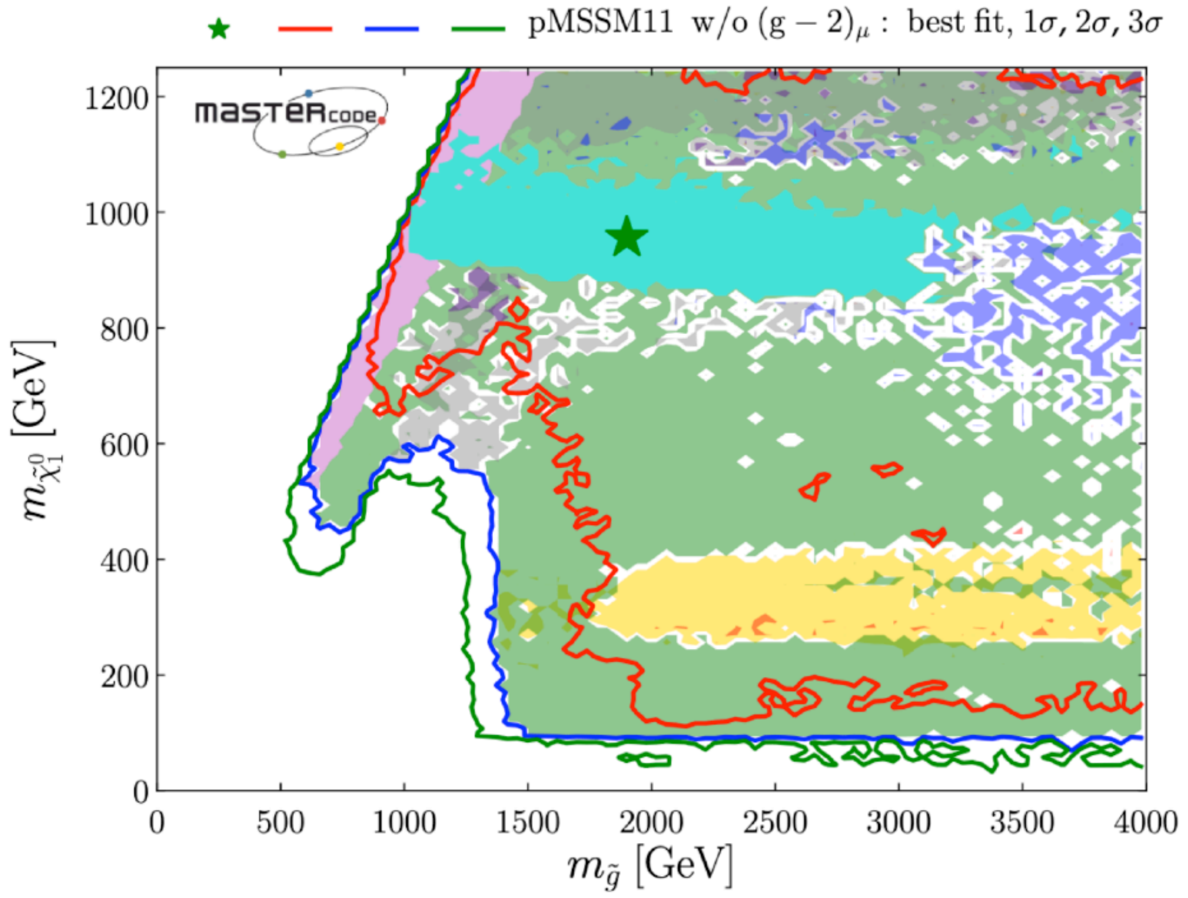
Learning more #1:
We can probe much more of BSM theory space



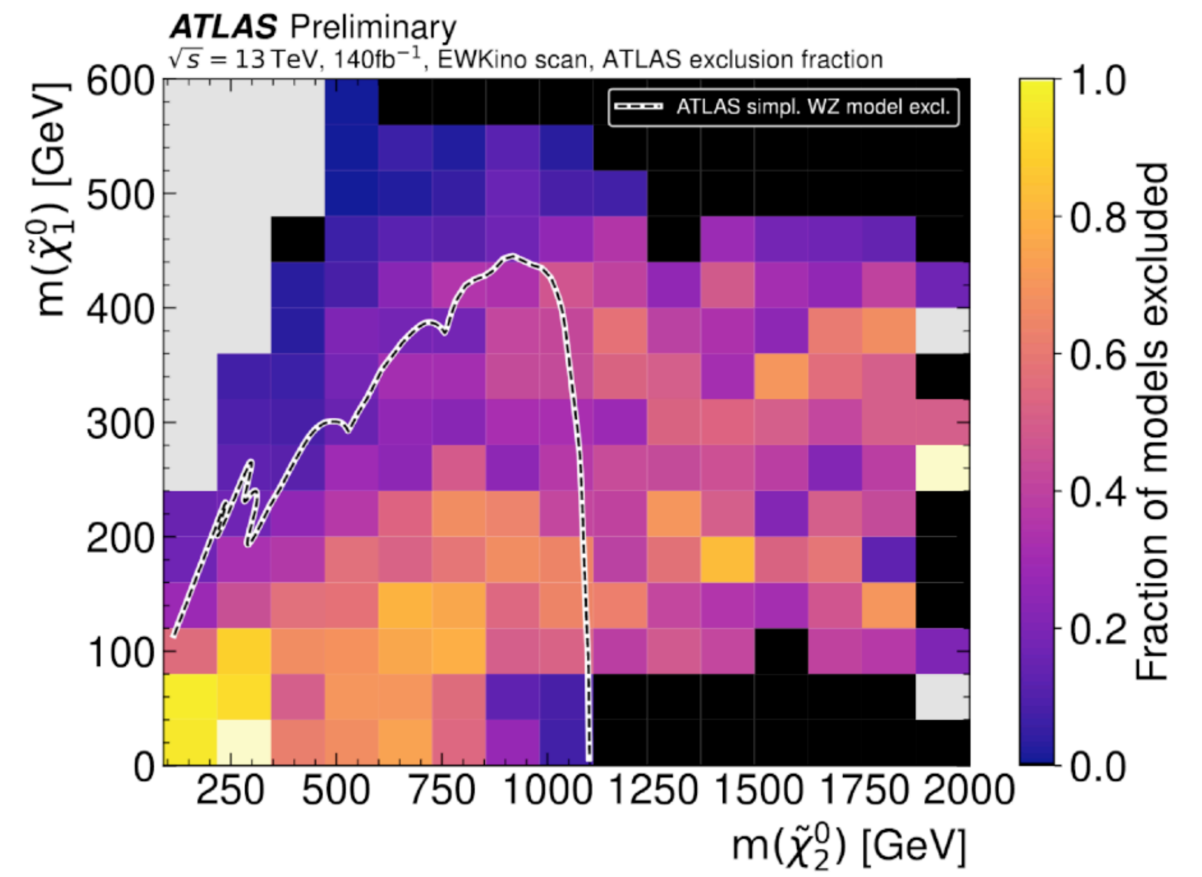
[1705.07917]



[2303.09082]



[1710.11091]



[2402.01392]

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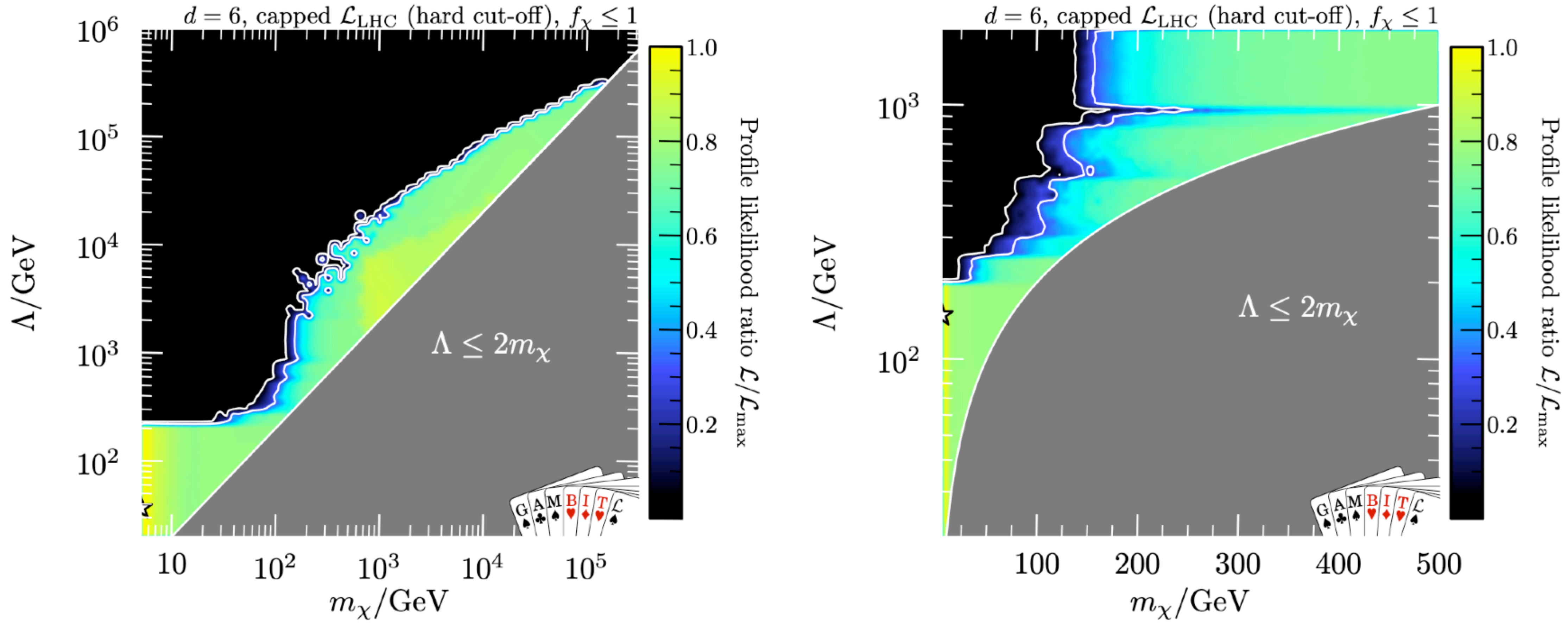
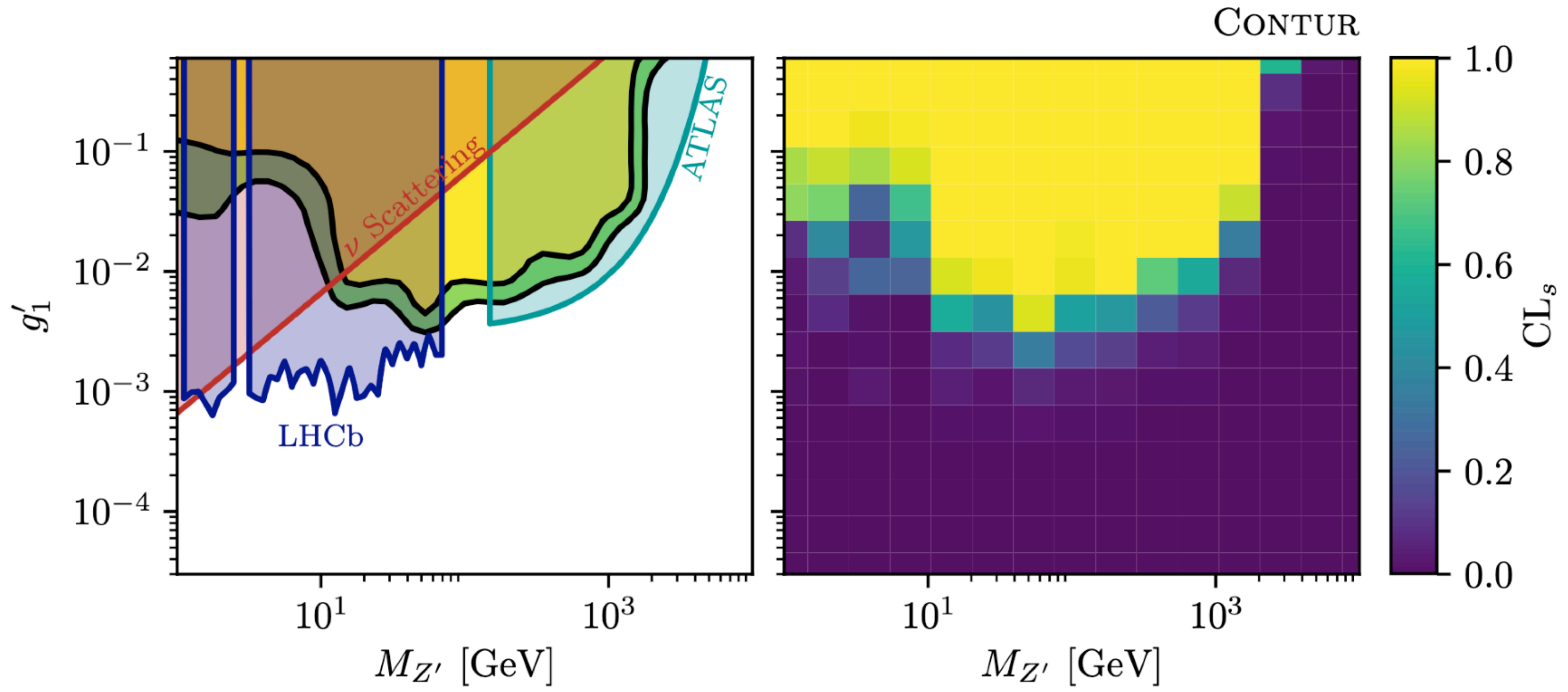
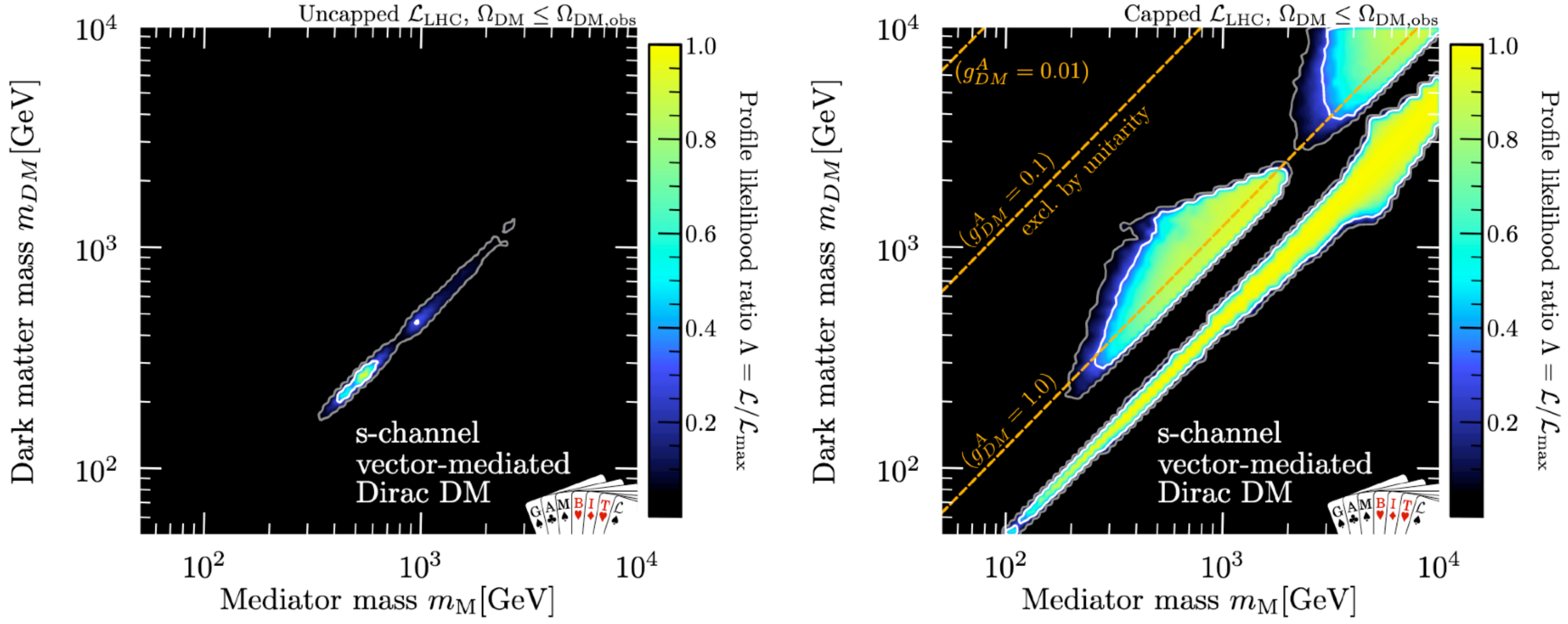


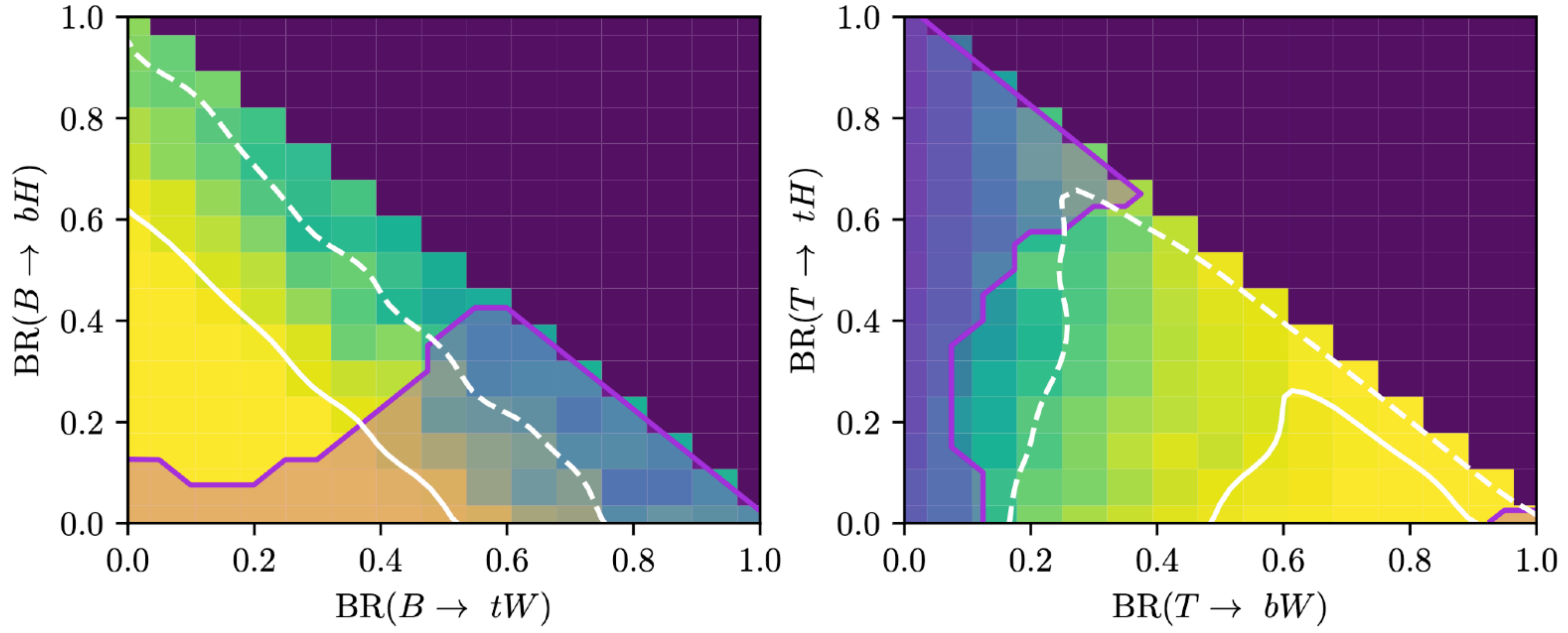
DM EFTs [2106.02056]



B-L gauge model [1811.11452]

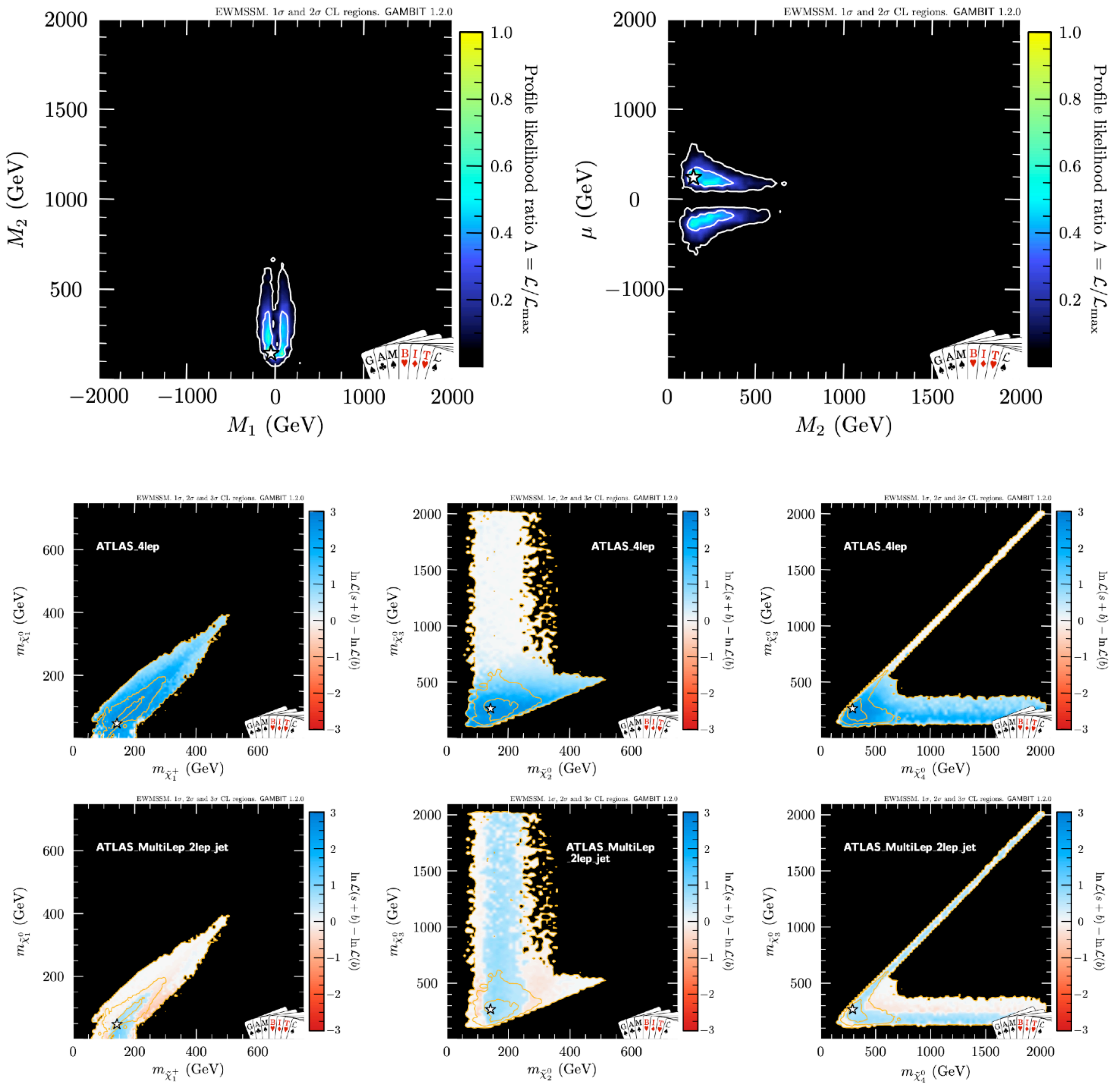


DM w/ vector mediator [2209.13266]

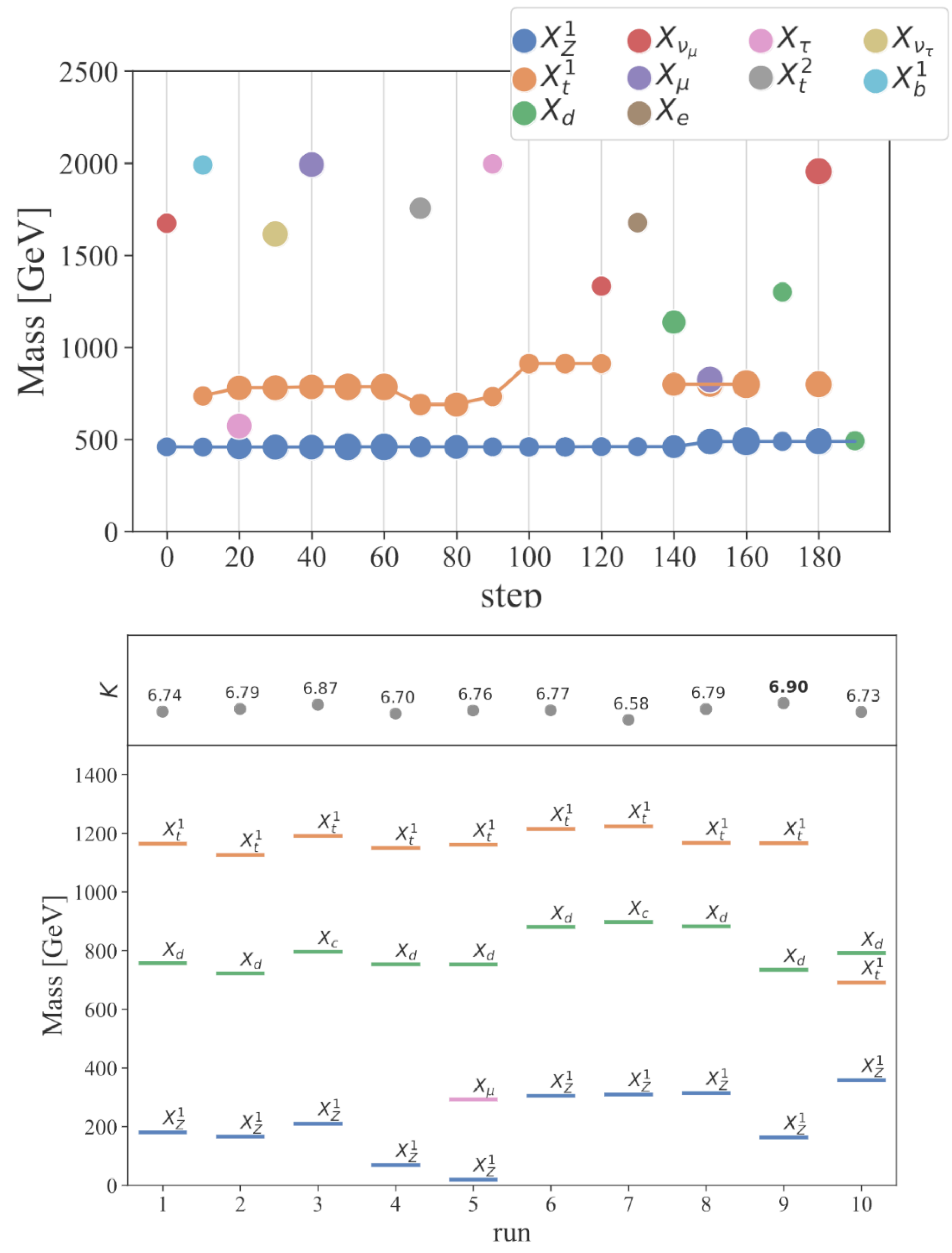


Vector-like quarks [2006.07172]

Learning more #2:
We can identify best-fit scenarios

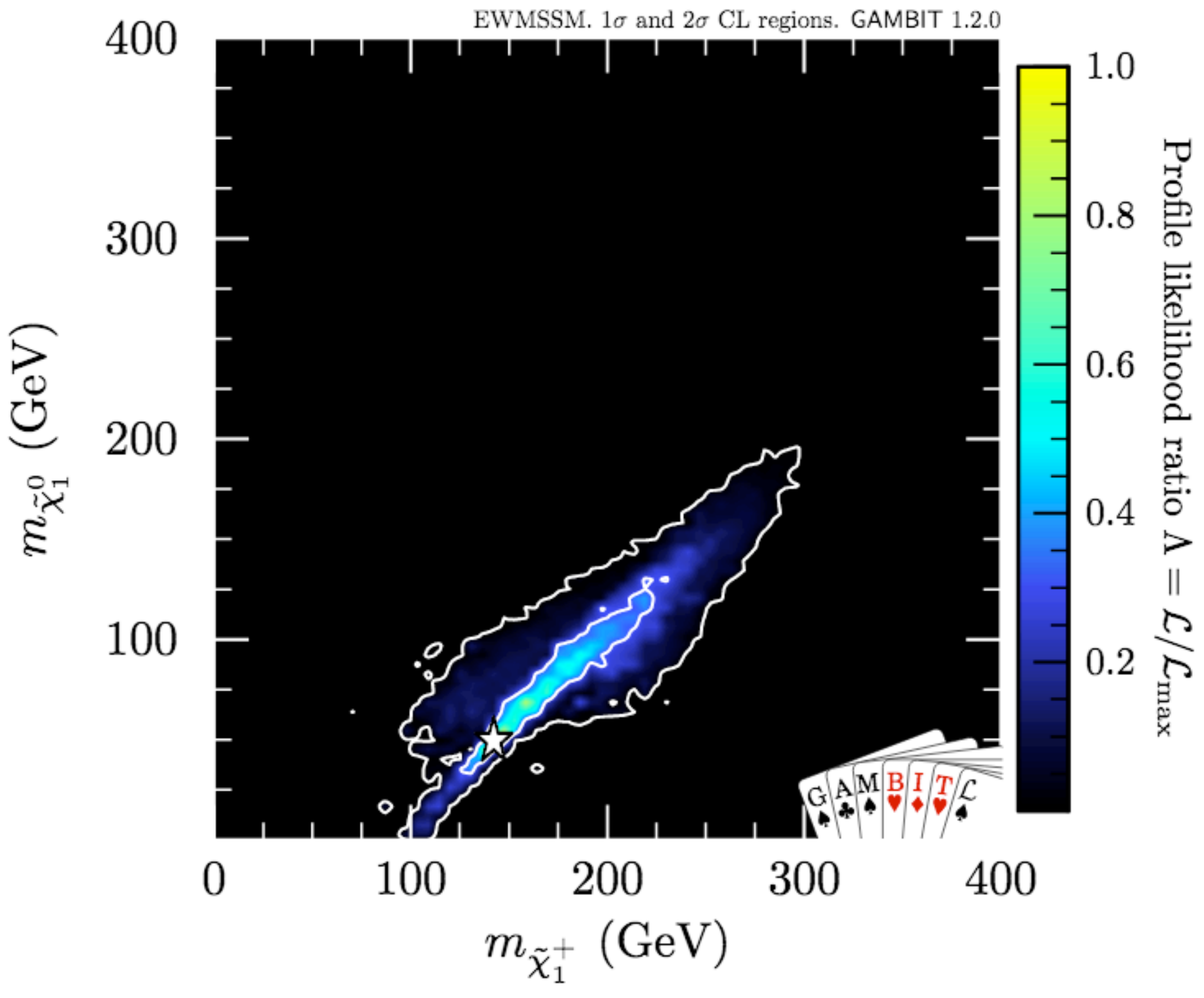


Explore MSSM EWino sector [1809.02097]

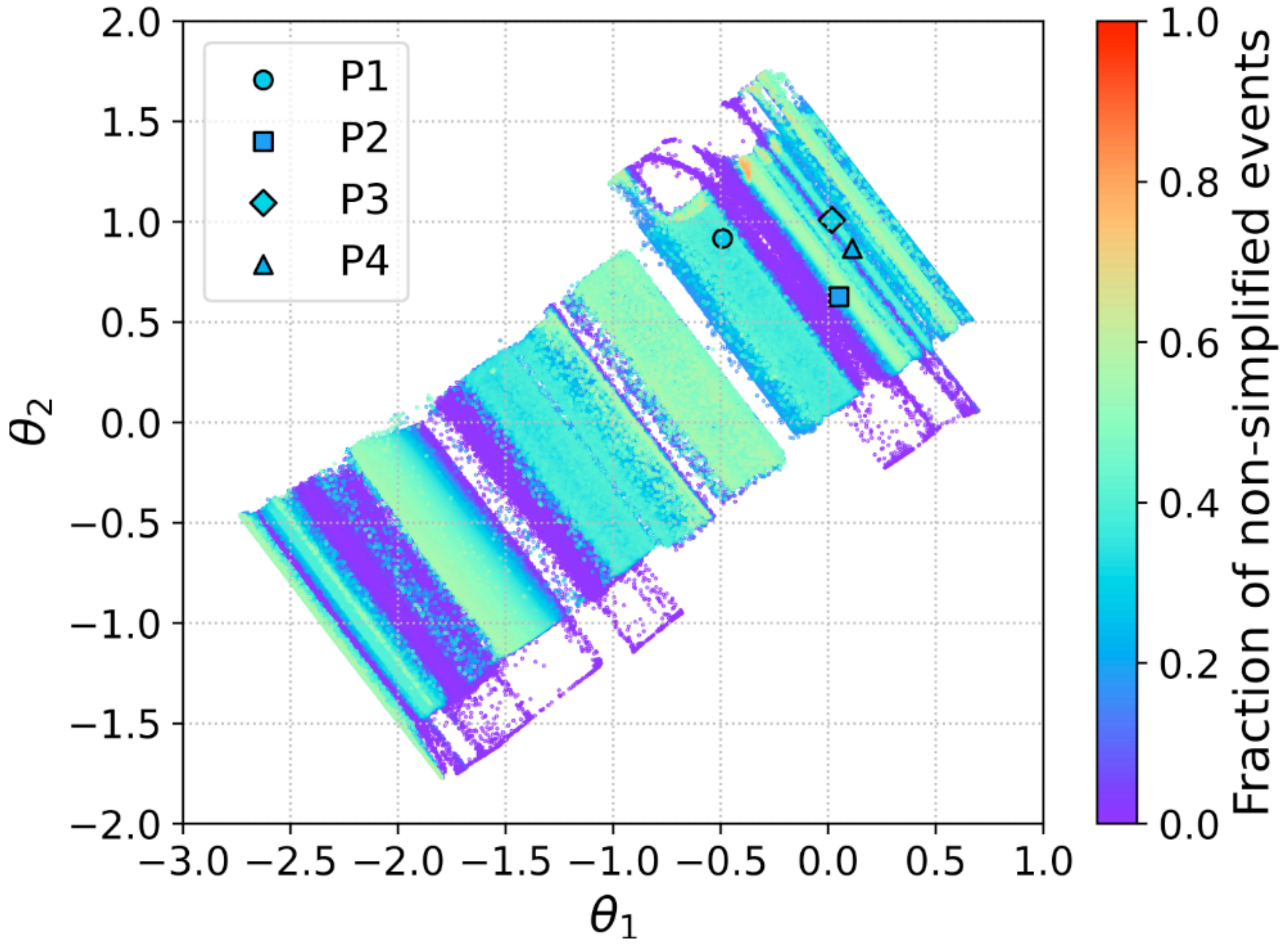


Explore space of simplified models [2012.12246]

Learning more #3:
We can learn how to plug «holes» in theory space



[1809.02097]



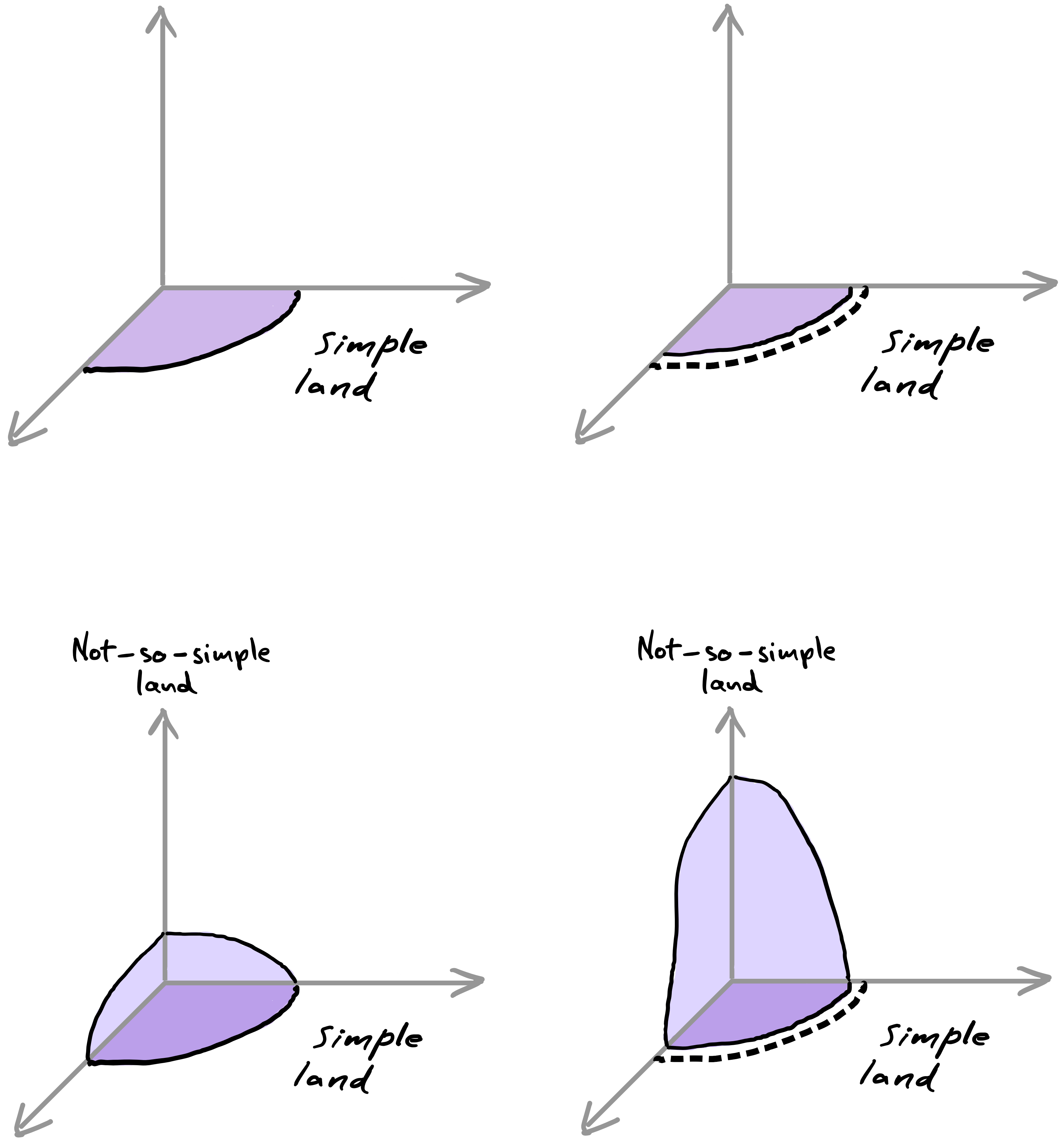
[2305.01835]

- Studied benchmark points that survived 36 fb^{-1} searches. Example:
  - 3 Higgsinos ~200 GeV, Δm ~ 40 GeV
  - 2 winos ~ 300 GeV
- Compare to wino/bino simplified model with Δm ~ 100 GeV
  - Main signature is similar: on-shell W + Z + MET
  - But gives **less clean final states**, due to not-necessarily-soft products from decays between higgsinos
- Replace «simplified model cut» $\mathbf{n_{jets} = 0}$ with a «less simplified» cut $\mathbf{H_T < X}$?

Learning more #3:

W

When optimising searches on simplified models, at what point do we start losing rather than gaining sensitivity to volumes of «similar» theory space?



400
300
200
100
$m_{\tilde{\chi}_1^0}$ (GeV)

fb^{-1}

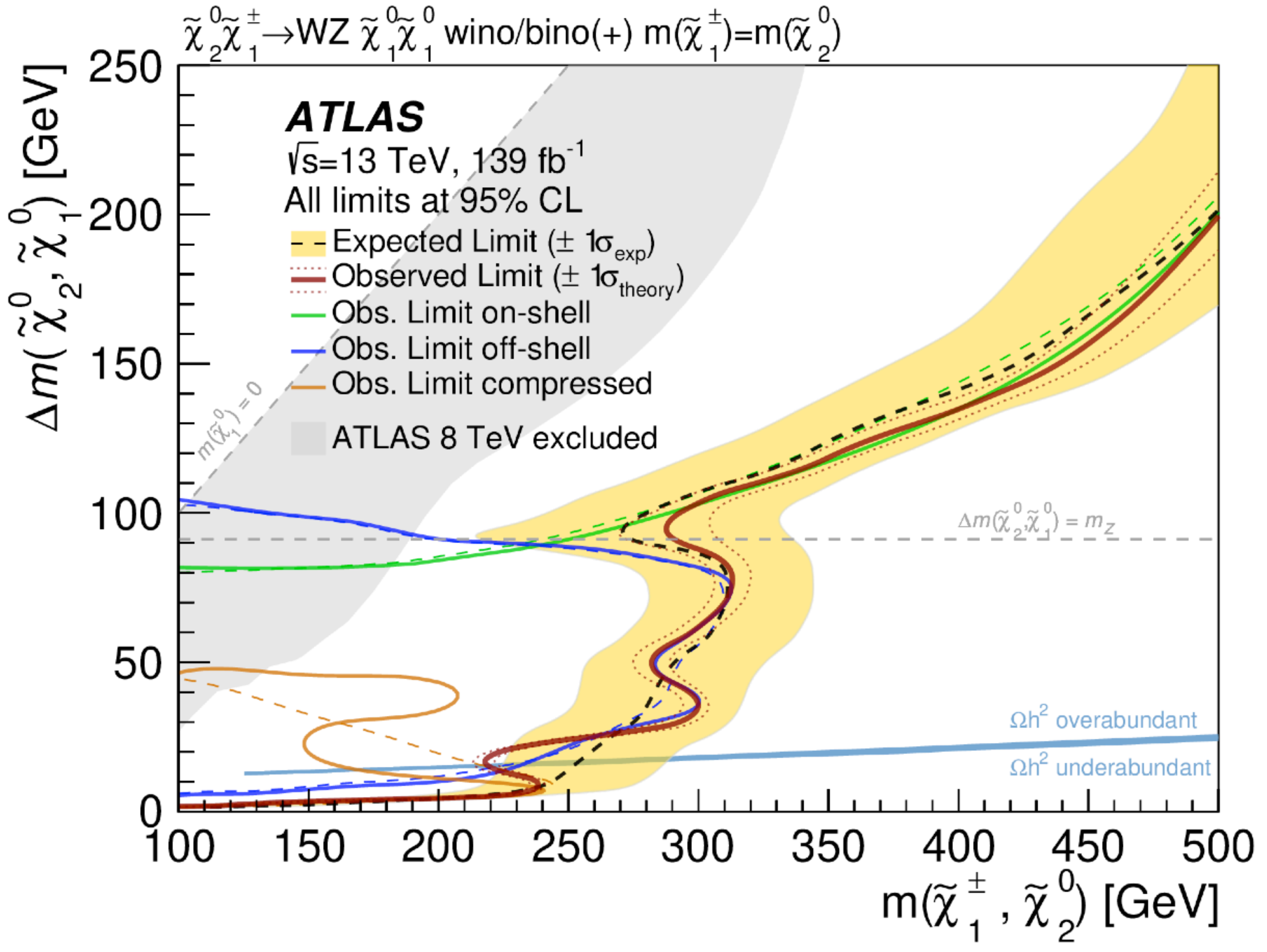
Δm

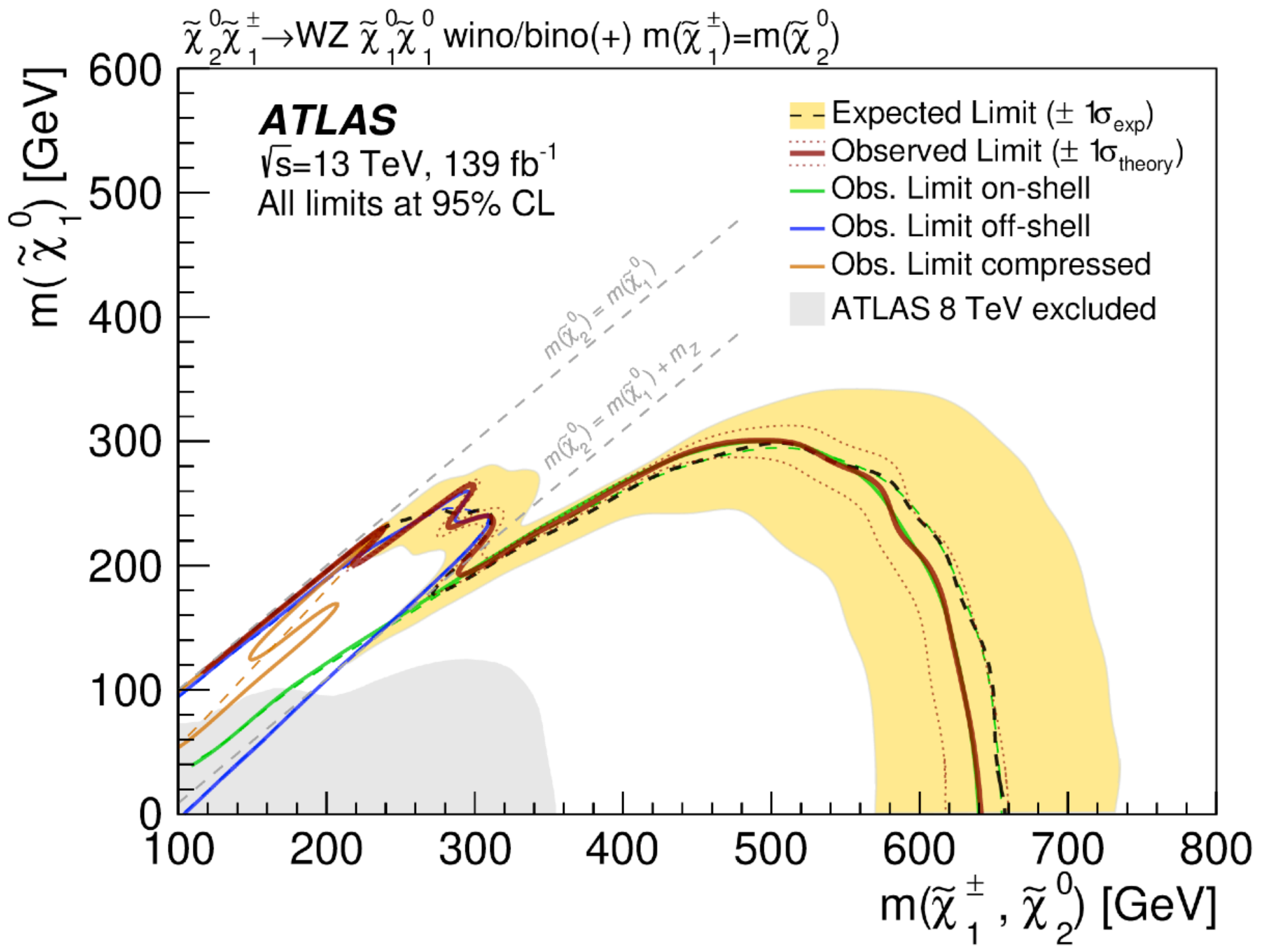
to

cays

with a «less simplified» cut **H_T < X** ?

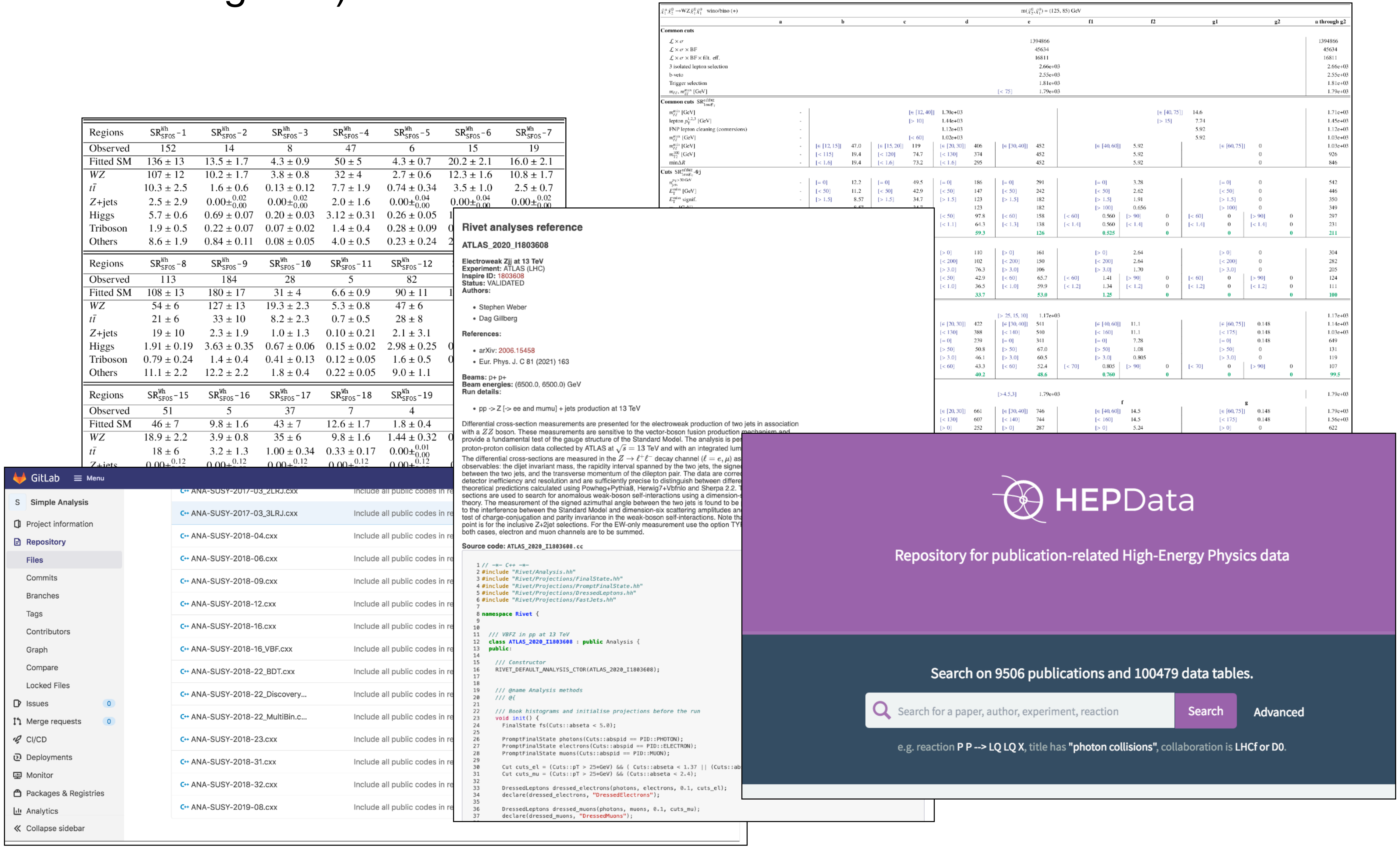
In short:
Results like these are very interesting and useful…





[ATLAS, 2106.01676]

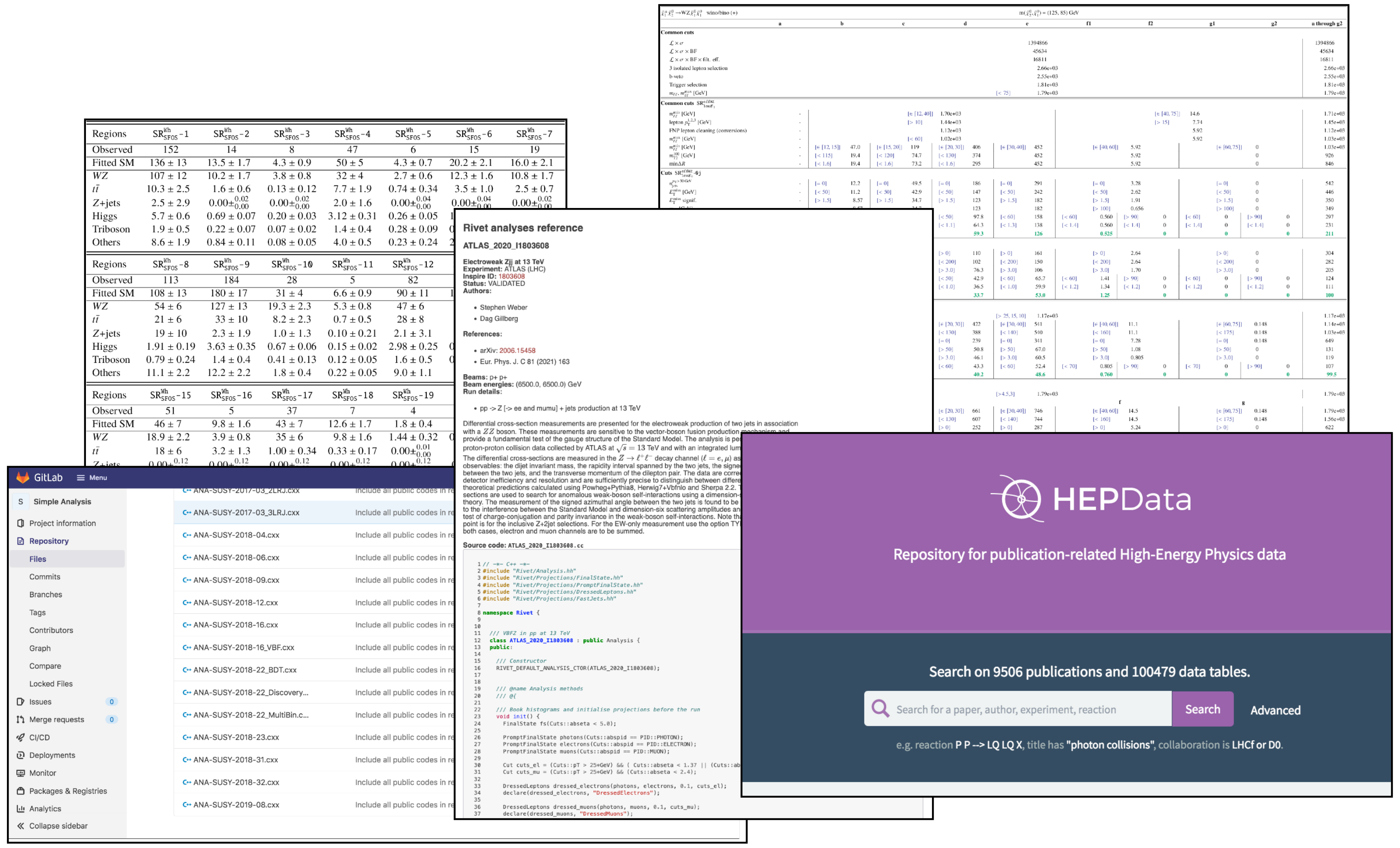
...but **this** is the real gold! :)



As a community we can **learn far more physics** from an experimental result that is **reinterpretable** compared to one that is not.

3. Why it’s difficult

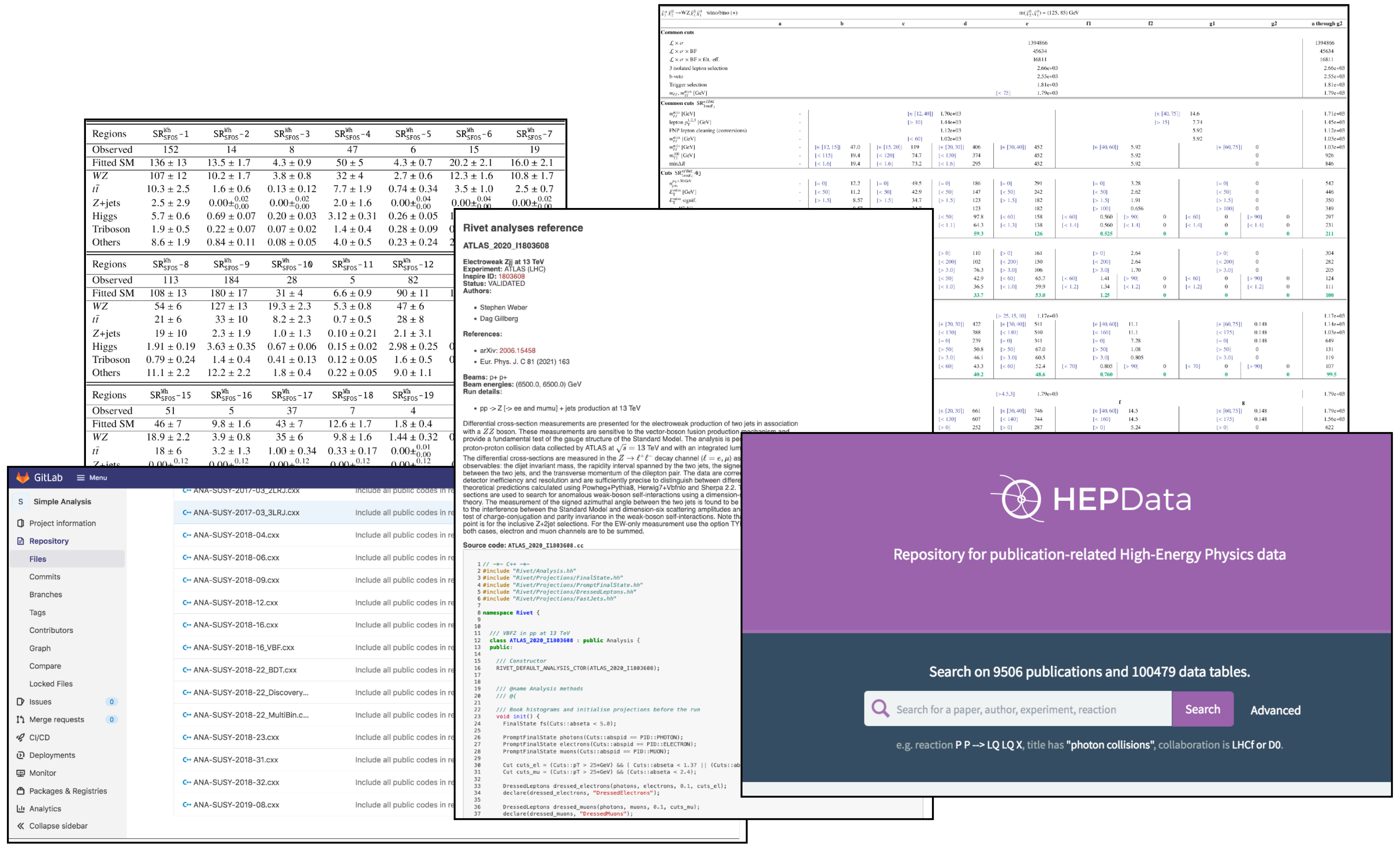
Is enough information public?



vs

Digitise a graph in Figure 73 c) in Appendix B of some PhD thesis from 10 years ago…

Is enough information public?



vs

Digitise a graph in Figure 73 c) in Appendix B of some PhD thesis from 10 years ago…

And can the information be used?

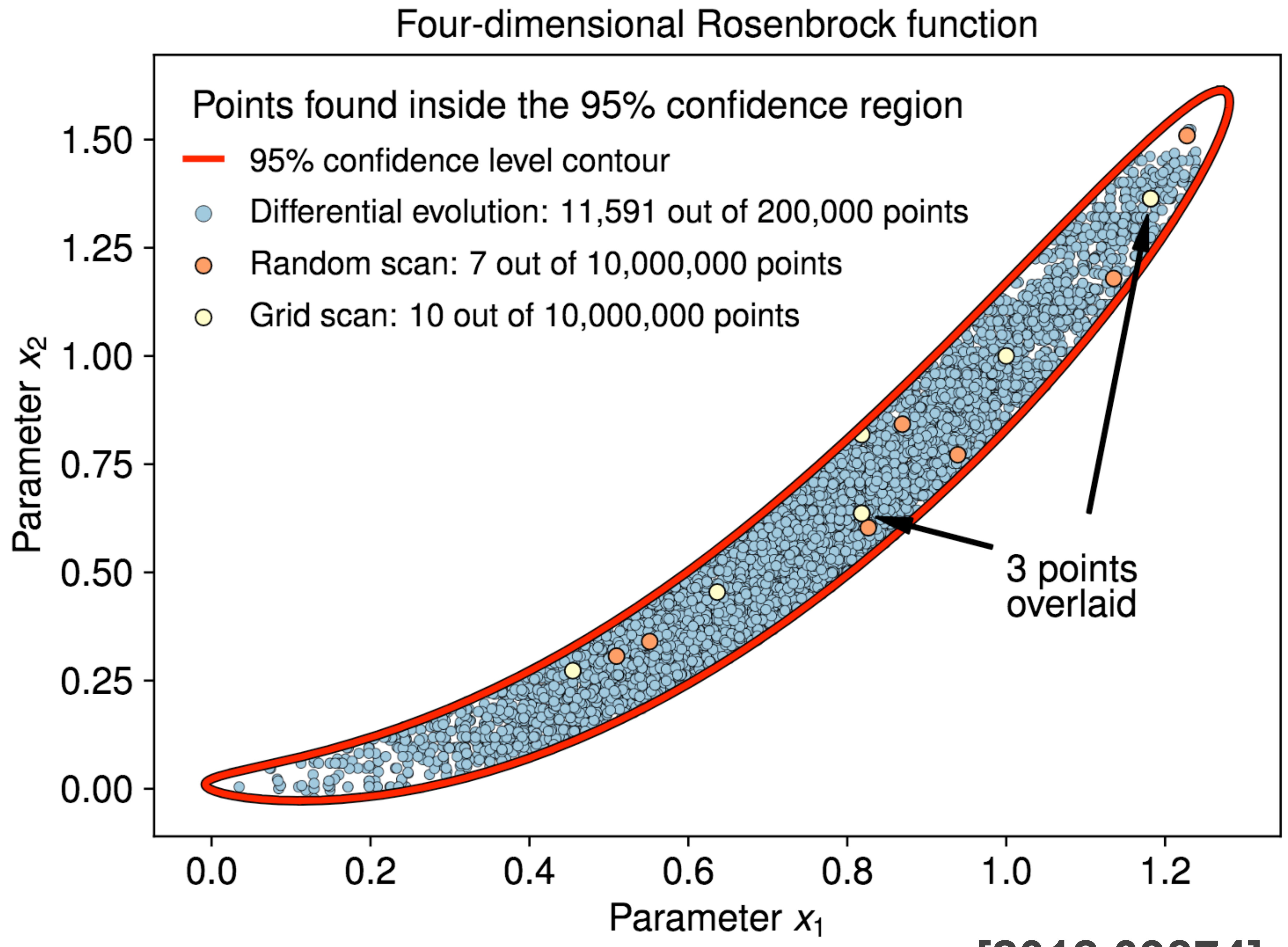
Les Houches guide to reusable ML models in LHC analyses

Jack Y. Araz[1], Andy Buckley[2], Gregor Kasieczka[3], Jan Kieseler[4], Sabine Kraml[5], Anders Kvellestad[6], Andre Lessa[7], Tomasz Procter[2], Are Raklev[6], Humberto Reyes-Gonzalez[8,9,10], Krzysztof Rolbiecki[11], Sezen Sekmen[12], Gokhan Unel[13]

[2312.14575]

Will the scan take forever?

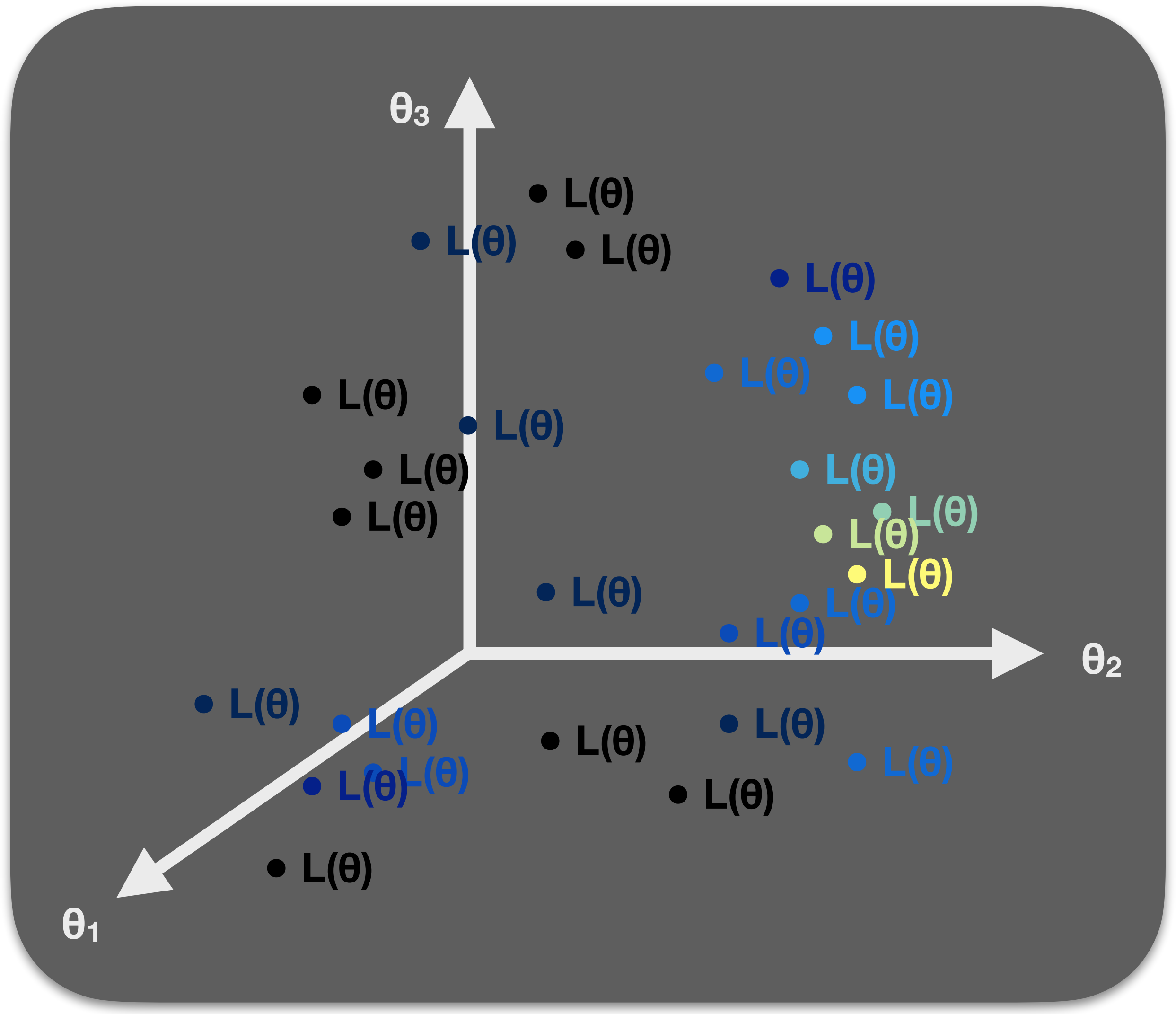
- First, BSM parameter spaces are **high-dimensional**
    - …and theorists have limited CPU resources
- Second, in **global fits** we seek statistically rigorous conclusions about **regions of BSM parameter spaces**
    - Need properly **converged** explorations of the **likelihood function / posterior distribution**
    - Must use **adaptive sampling algorithms**, that focus on higher-likelihood regions
    - So the problem is **not trivially parallelisable** (we can't just sample first, simulate later)

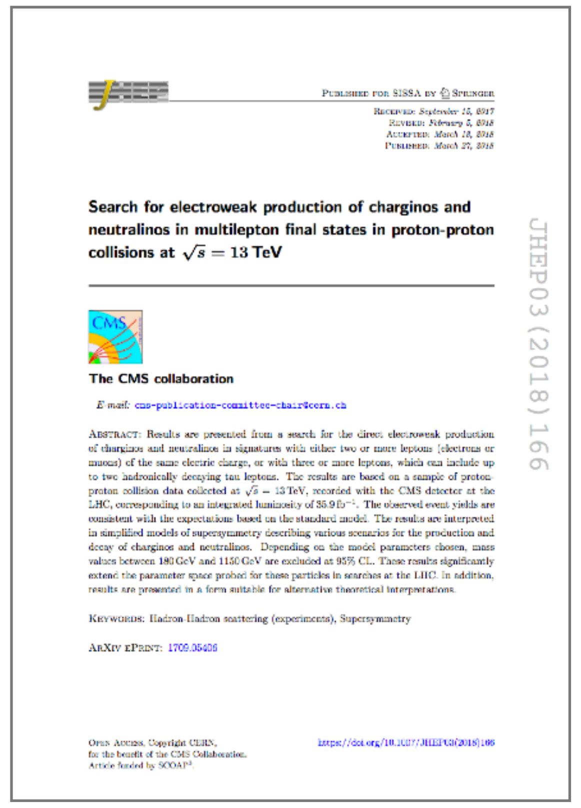


[2012.09874]

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**





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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

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:

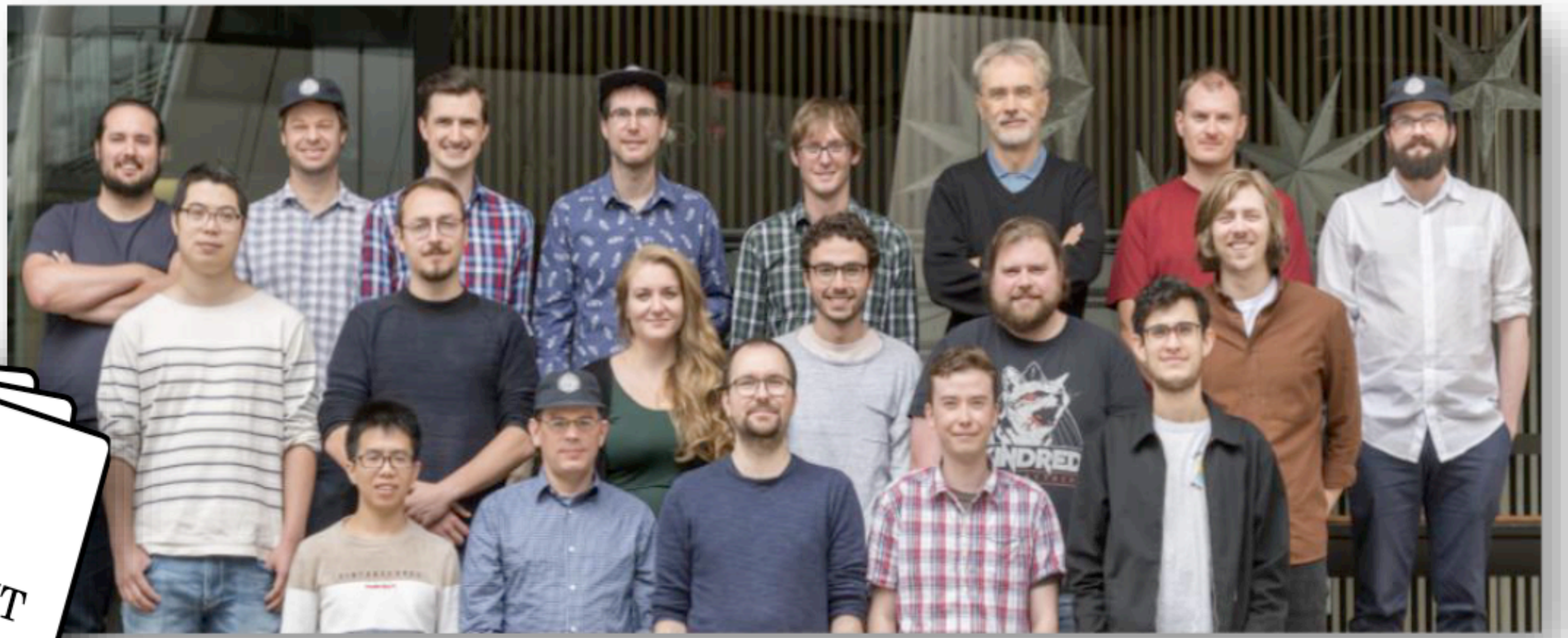
- Need **different parameter scanning algorithms**
- Need **model-agnostic core framework**
- Need to interface ***many*** **external physics codes**
- Need **massive parallelisation**…
- …which implies a need for **diskless interfacing**
- …which implies a need to **stop external codes from calling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

4. 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: V Ananyev, P Athron, N Avis-Kozar, C Balázs, A Beniwal, S Bloor, LL Braseth, T Bringmann, A Buckley, J Butterworth, 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, M Lecroq, P Jackson, D Jacob, C Lin, FN Mahmoudi, G Martinez, H Pacey, MT Prim, T Procter, F Rajec, A Raklev, JJ Renk, R Ruiz, A Scaffidi, P Scott, N Serra, P Stöcker, W. Su, J Van den Abeele, A Vincent, C Weniger, A Woodcock, M White, Y Zhang ++

80+ participants in many experiments and numerous major theory codes

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gambit.hepforge.org   github.com/GambitBSM   E… 1705.07908

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Models ↔ **Core** ↔ **ScannerBit**

Physics modules

- SpecBit
- DecayBit
- PrecisionBit
- ColliderBit
- DarkBit
- FlavBit
- NeutrinoBit
- CosmoBit

Scanners

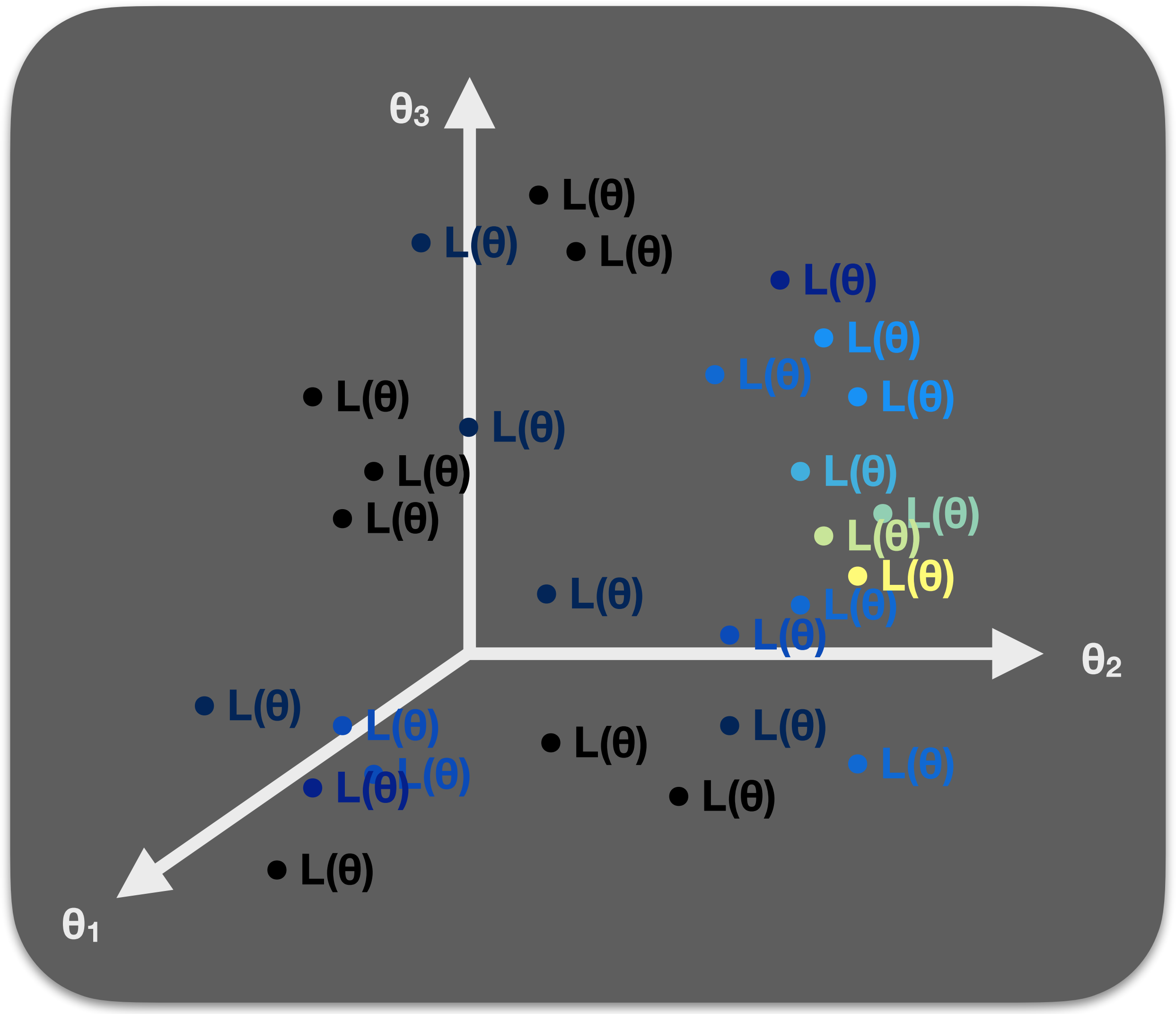
Diver, PolyChord, MultiNest, TWalk, Minuit, jswarm, emcee, ultranest, scipy.optimize, …

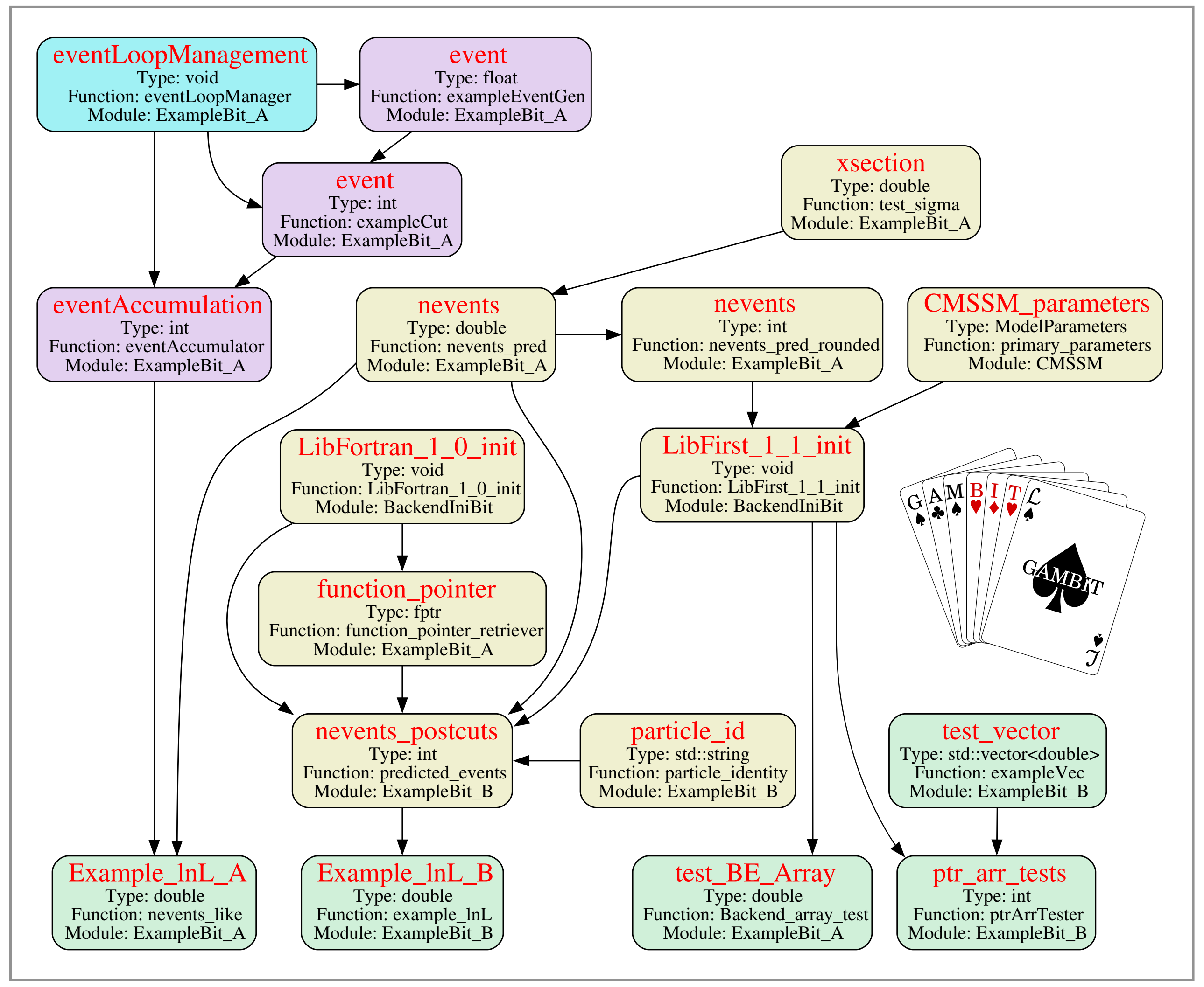
Backends

CaptnGeneral, DarkSUSY, DDCalc, FeynHiggs, FlexibleSUSY, gamLike, gm2calc, HEPLike, HiggsBounds, HiggsSignals, MicrOmegas, nulike, Pythia, SPheno, SUSYHD, SUSYHIT, SuperIso, Vevacious, MontePython, CLASS, AlterBBN, …

Technical features

- Collection of **state-of-the-art sampling algorithms** as **plug-ins** (*e.g.* evolutionary algorithms, nested sampling, …)
- **Model-agnostic** core framework
- Run configuration through **YAML** input file
- Many **highly detailed experiment likelihoods**





- **Fast parallel Monte Carlo simulations** of experiments (e.g. LHC)
- **Dynamic dependency resolution**: order of computations not hard-coded, decided at run time

Technical features

- **Two-level parallelisation**:
  - **MPI** for parameter sampling algorithm
  - **OpenMP** for per-point model computations
- **Diskless interface** to external (physics) codes. **C**, **C++**, **Fortran**, **Python** and **Mathematica** codes as **runtime plug-ins**
- **Printer system** to store results in different formats, with buffering and resume ability for aborted scans
- **Logging system** for information and debugging
- **GAMBIT Universal Model** machine (GUM): **code auto-generation** for new physics models

[2107.00030]

Dependency resolution

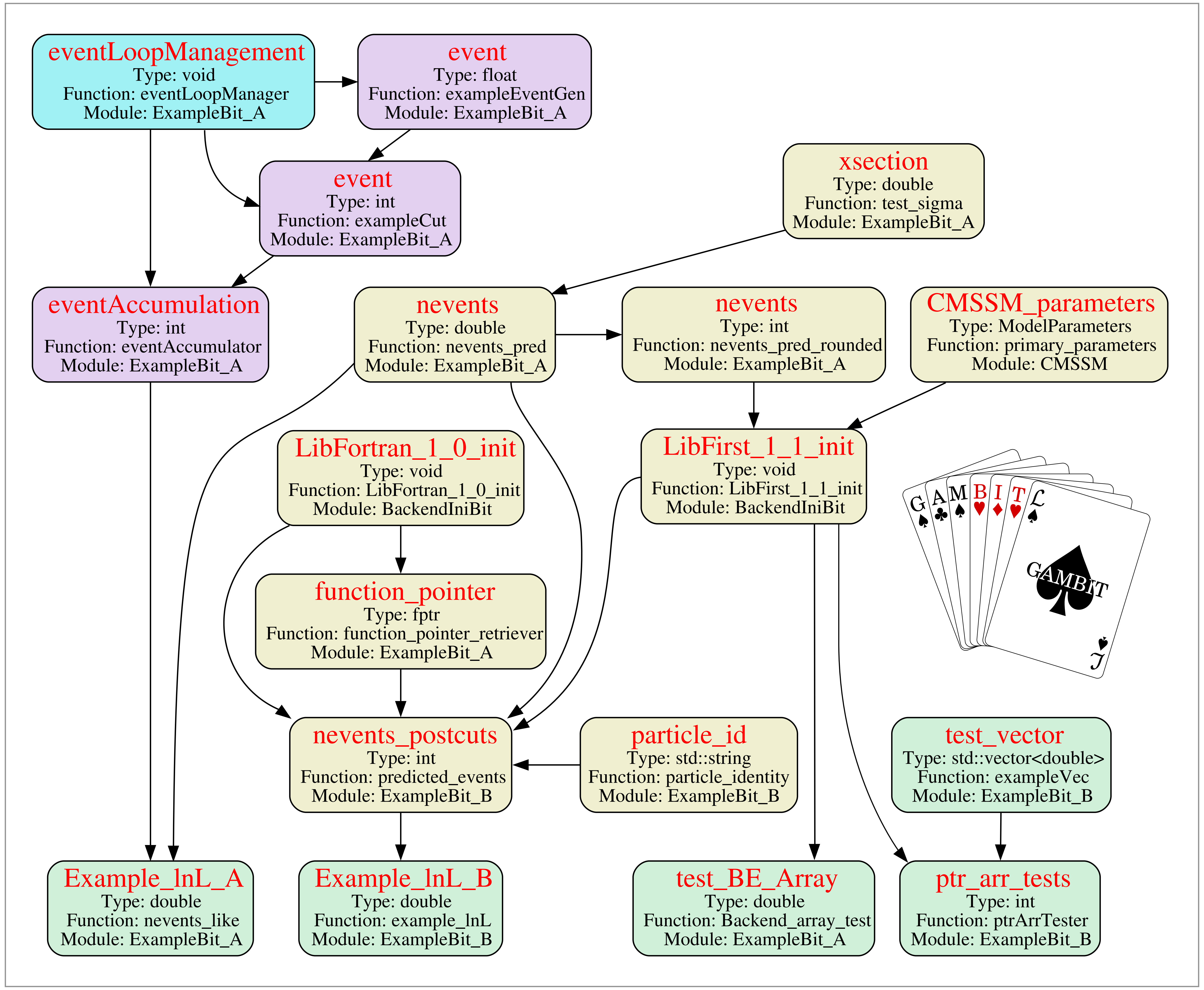
- Basic building blocks: **module functions**
- A physics module: **a collection of module functions** related to the same physics topic
- Each module function has a single **capability** (what it calculates)
- A module function can have **dependencies** on the results of other module functions
- A module 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
```

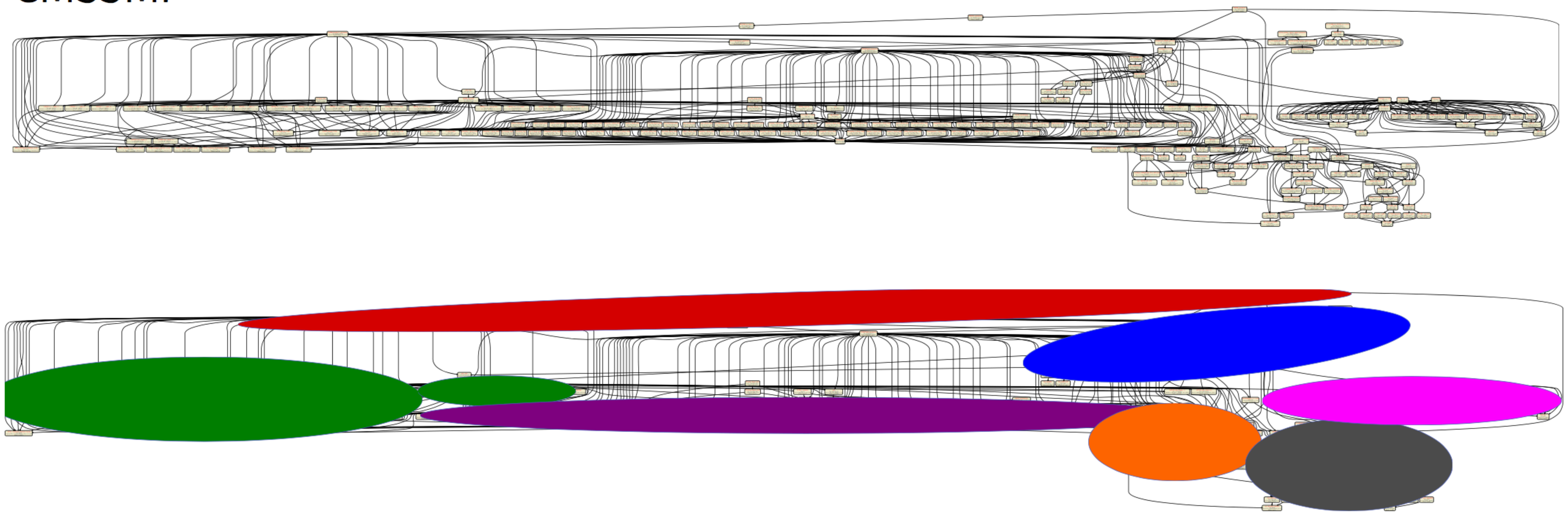
```
/// Br B->tau nu_tau decays
void SI_Btaunu(double &result)
{
  using namespace Pipes::SI_Btaunu;

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

Dependency resolution

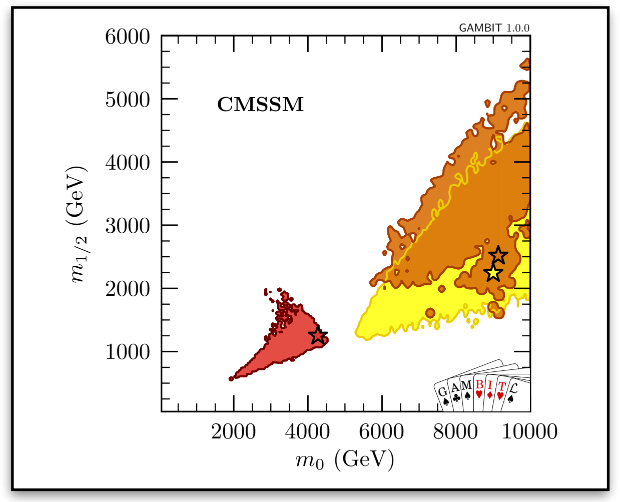


Dependency resolution

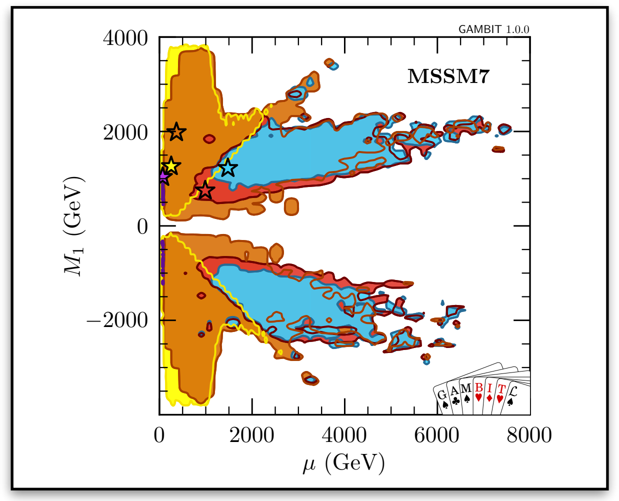
CMSSM:



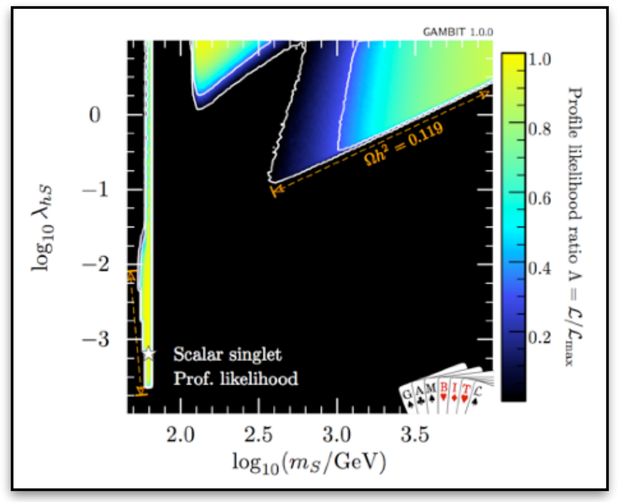
Red: Model parameter translations
Blue: Precision calculations
Green: LEP rates+likelihoods
Purple: Decays
Orange: LHC observables and likelihoods
Grey: DM direct, indirect and relic density
Pink: Flavour physics



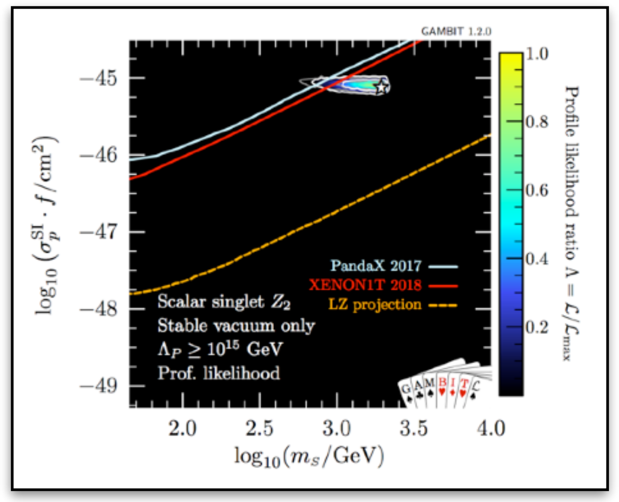
GUT-scale SUSY: 1705.07935



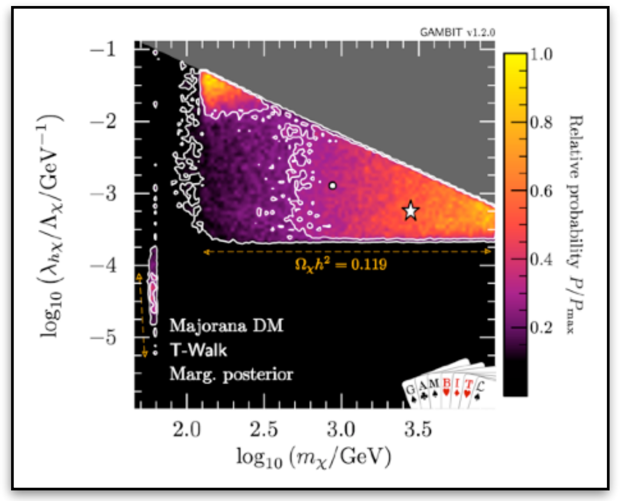
MSSM7: 1705.07917



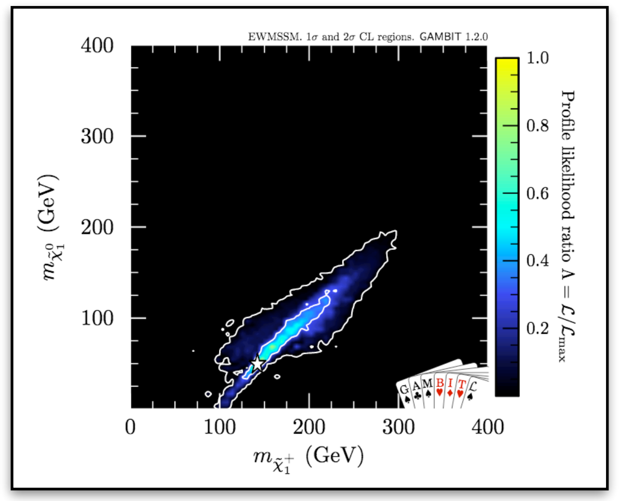
Scalar Higgs portal DM: 1705.07931



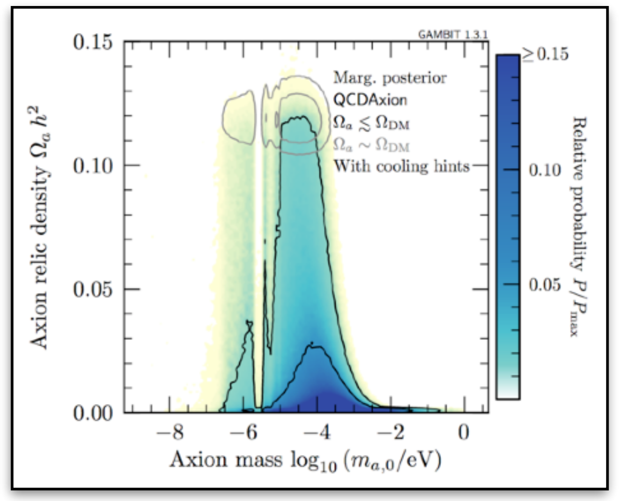
Scalar Higgs portal DM w/ vac. stability: 1806.11281



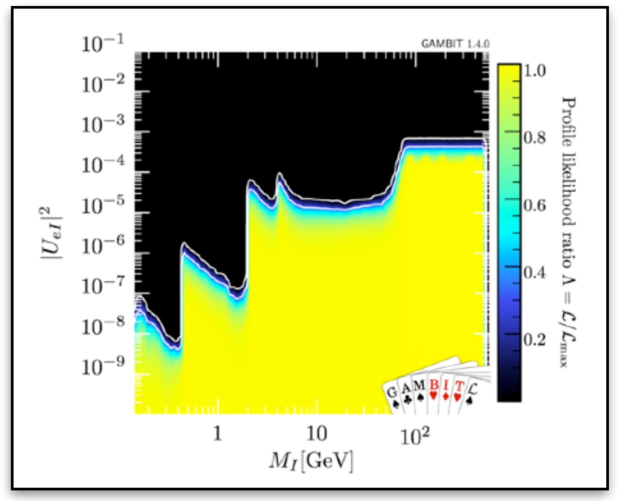
Vector and fermion Higgs portal DM: 1808.10465



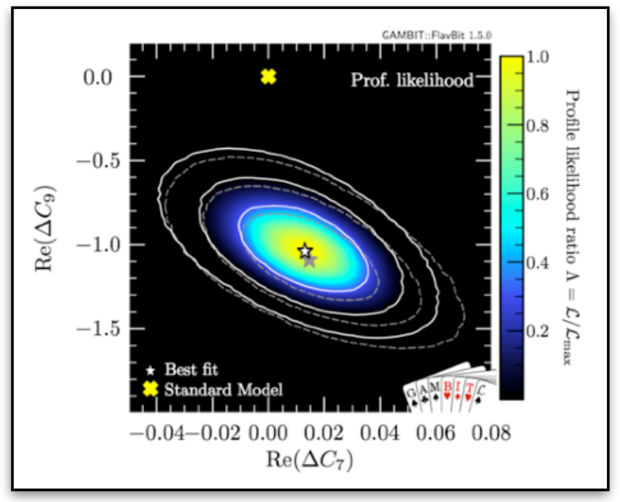
EW-MSSM: 1809.02097



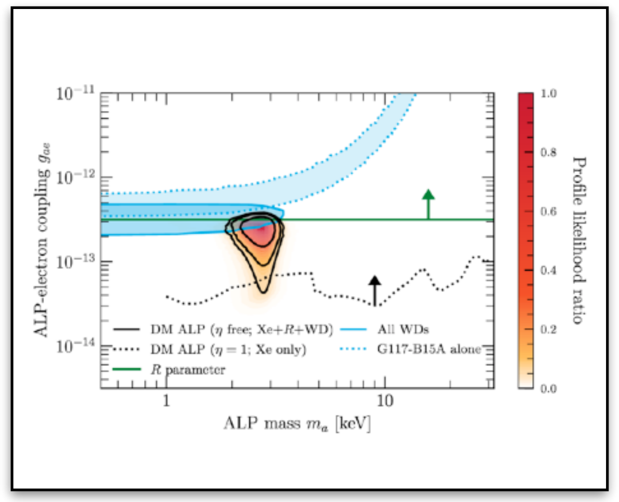
Axion-like particles: 1810.07192



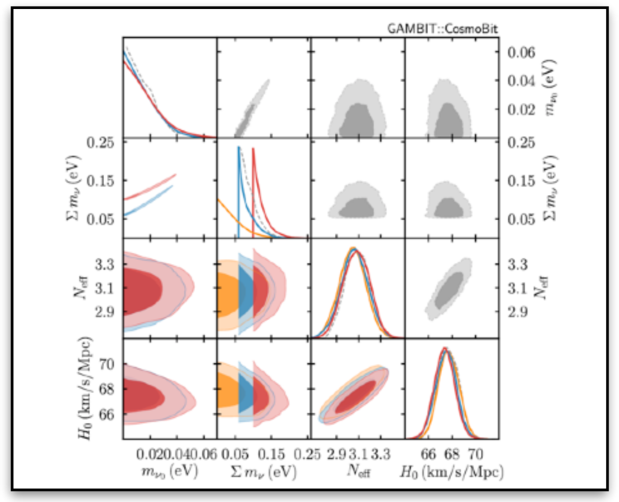
Right-handed neutrinos: 1908.02302



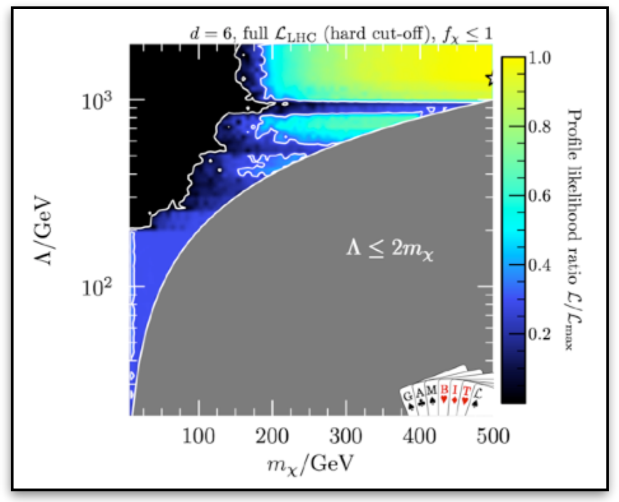
Flavour EFT: 2006.03489



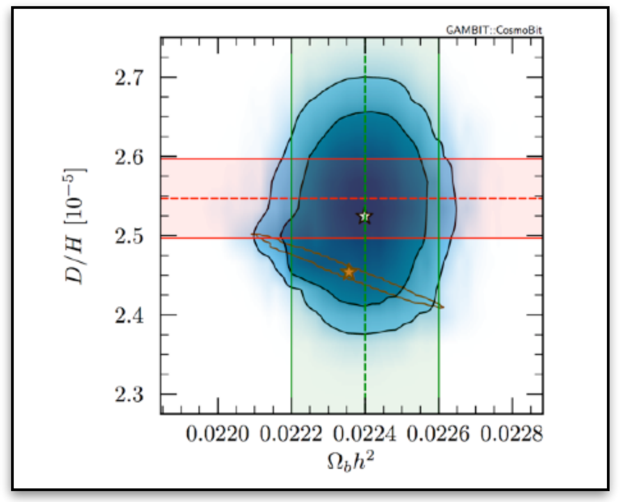
More axion-like particles: 2007.05517



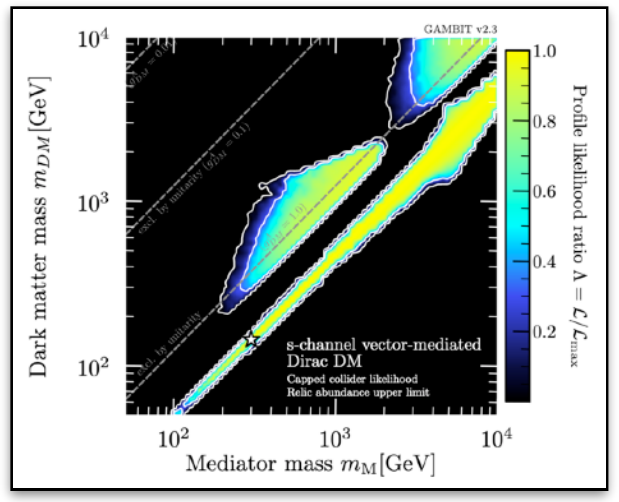
Neutrinos and cosmo: 2009.03287



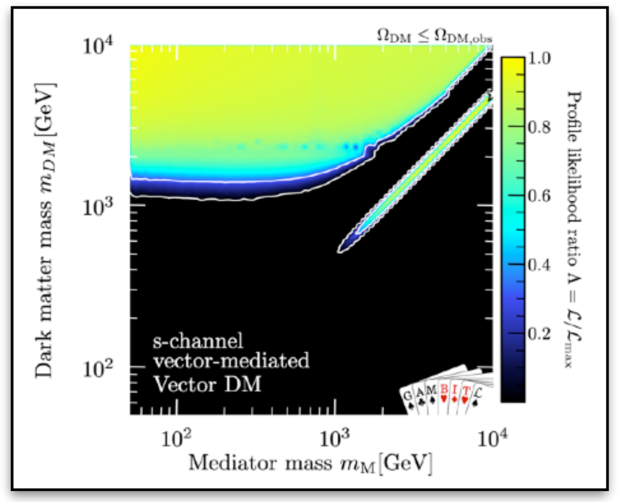
Dark matter EFTs: 2106.02056



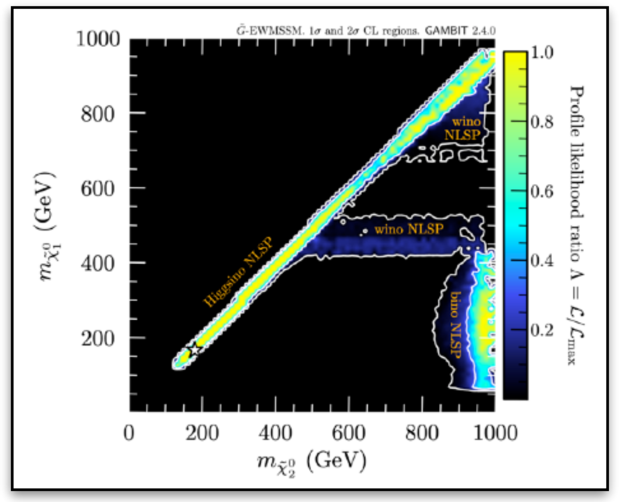
Cosmo ALPs: 2205.13549



Simplified DM, scalar/fermion: 2209.13266



Simplified DM, vector: 2303.08351



EW-MSSM w/ light gravitino: 2303.09082

Plus new results on sub-GeV DM! [2405.17548]

GUT-scale SUSY: 1705.07935

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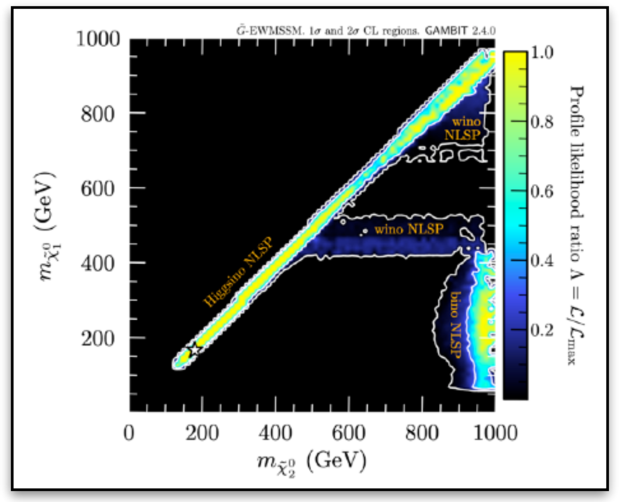


EW-MSSM w/ light gravitino: 2303.09082

Plus new results on sub-GeV DM! [2405.17548]

Simulation-based EWino fits with GAMBIT

Question:

What are the 13 TeV collider constraints on the chargino/neutralino sector of the MSSM?

(MSSM ≠ simplified model)

Method:

— Scan 4D EWino parameter space w/ adaptive sampler

— *At every point:* Run MC simulations of 13 TeV searches

— Calculate joint likelihood function for all searches

— Produce profile likelihood plots

Main challenges:

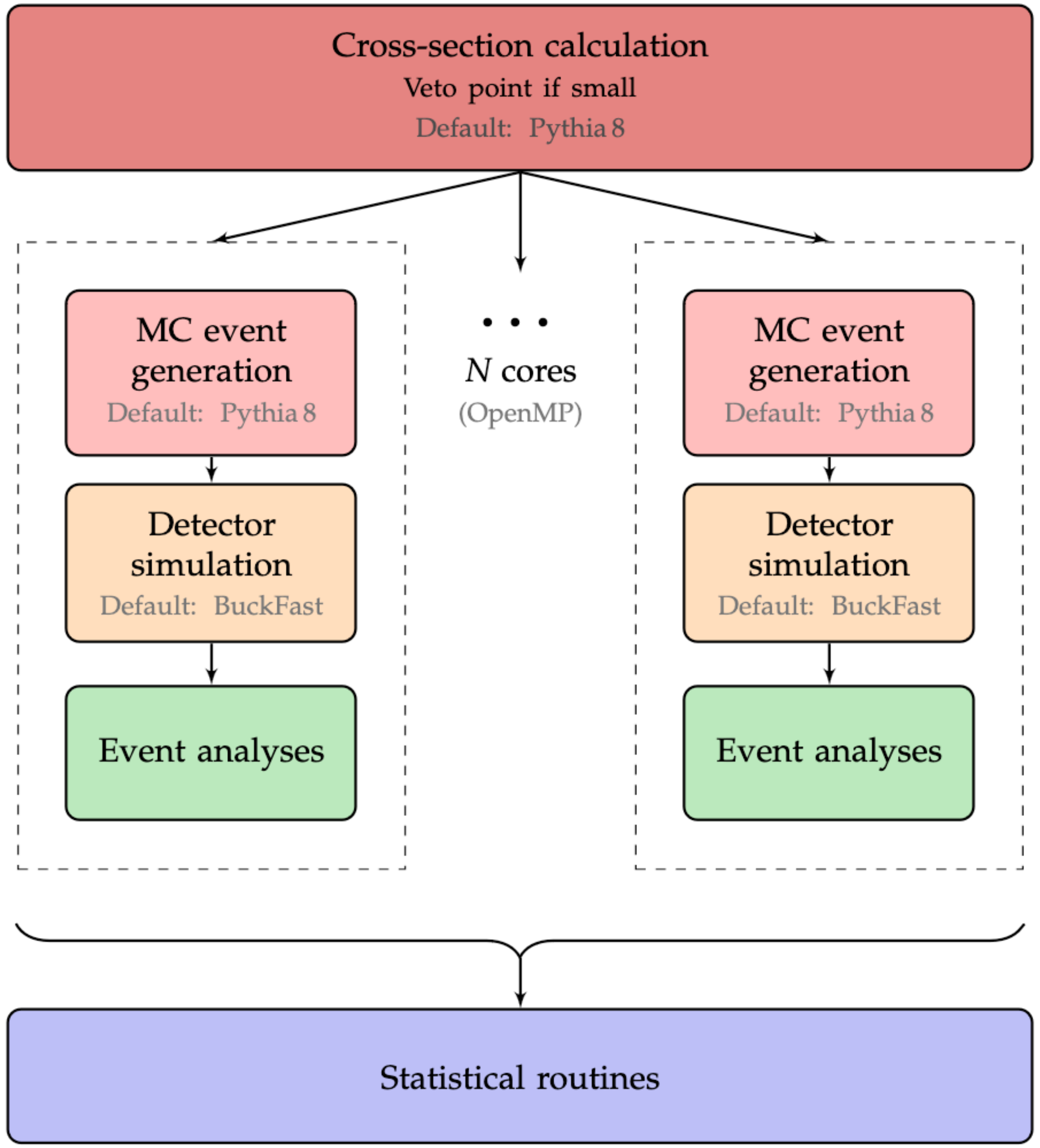
— Computational cost

— Reproduce ATLAS/CMS searches w/ sufficient accuracy

ColliderBit

- For **each parameter point** in a scan:
  - Run **Pythia simulations** of all relevant SUSY processes
  - Pass events through **fast detector simulation** (four-vector smearing + efficiencies)
  - Pass events through **our implementations of ATLAS and CMS searches**
    - → signal predictions for all SRs
  - Compute **a combined likelihood** for the parameter point
    - We combine as many analyses and SRs as we reasonably can, given available info

  - Plus an analogous pipeline for measurements, using **Rivet + Contur**



Two models: EWMSSM and G-EWMSSM

EWMSSM

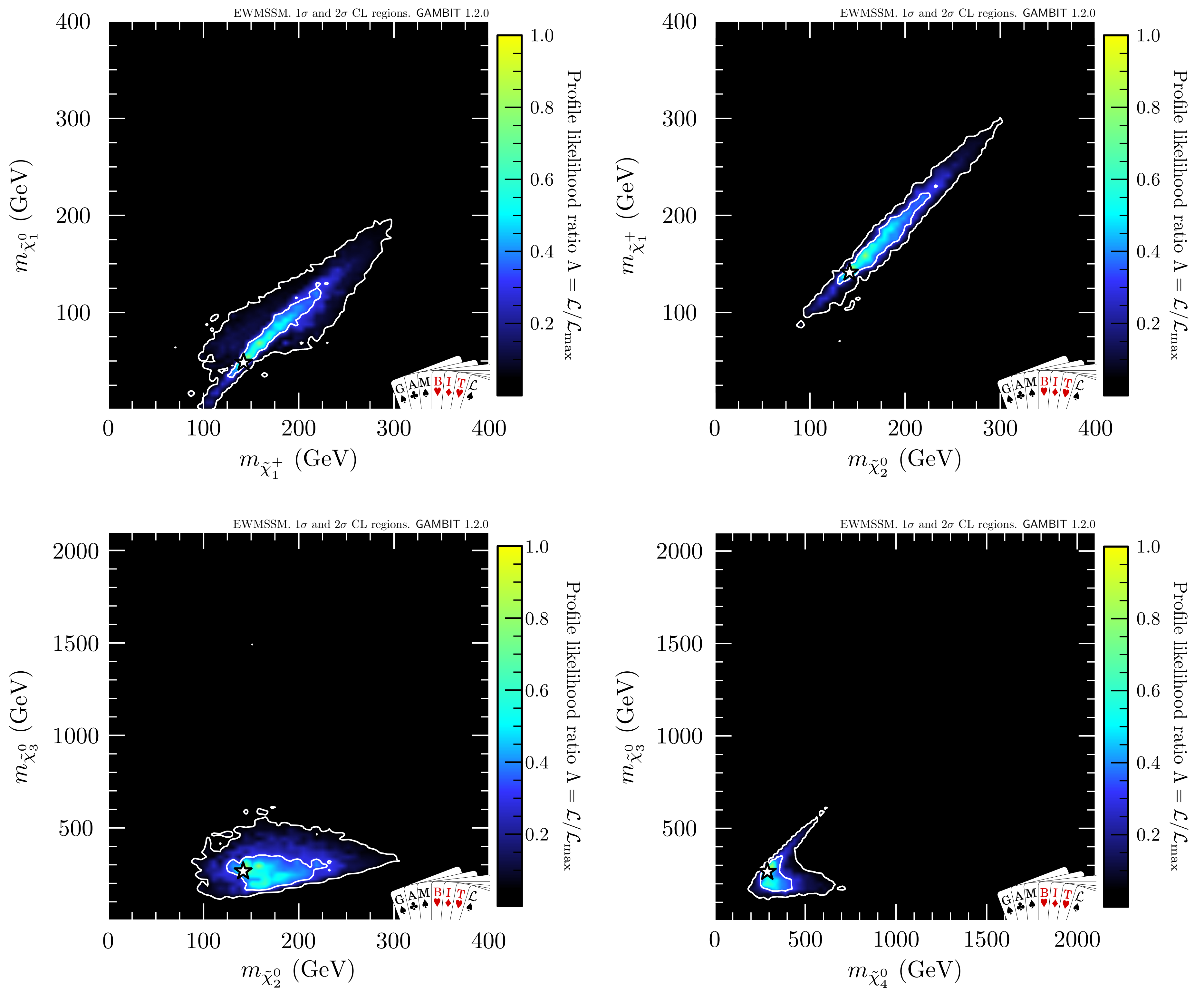
- **MSSM** w/ neutralinos and charginos within LHC reach
- **6 SUSY particles below 1.5 TeV**: 4 neutralinos, 2 charginos
- **4D theory parameter space**: M1, M2, mu, tan beta

G-EWMSSM

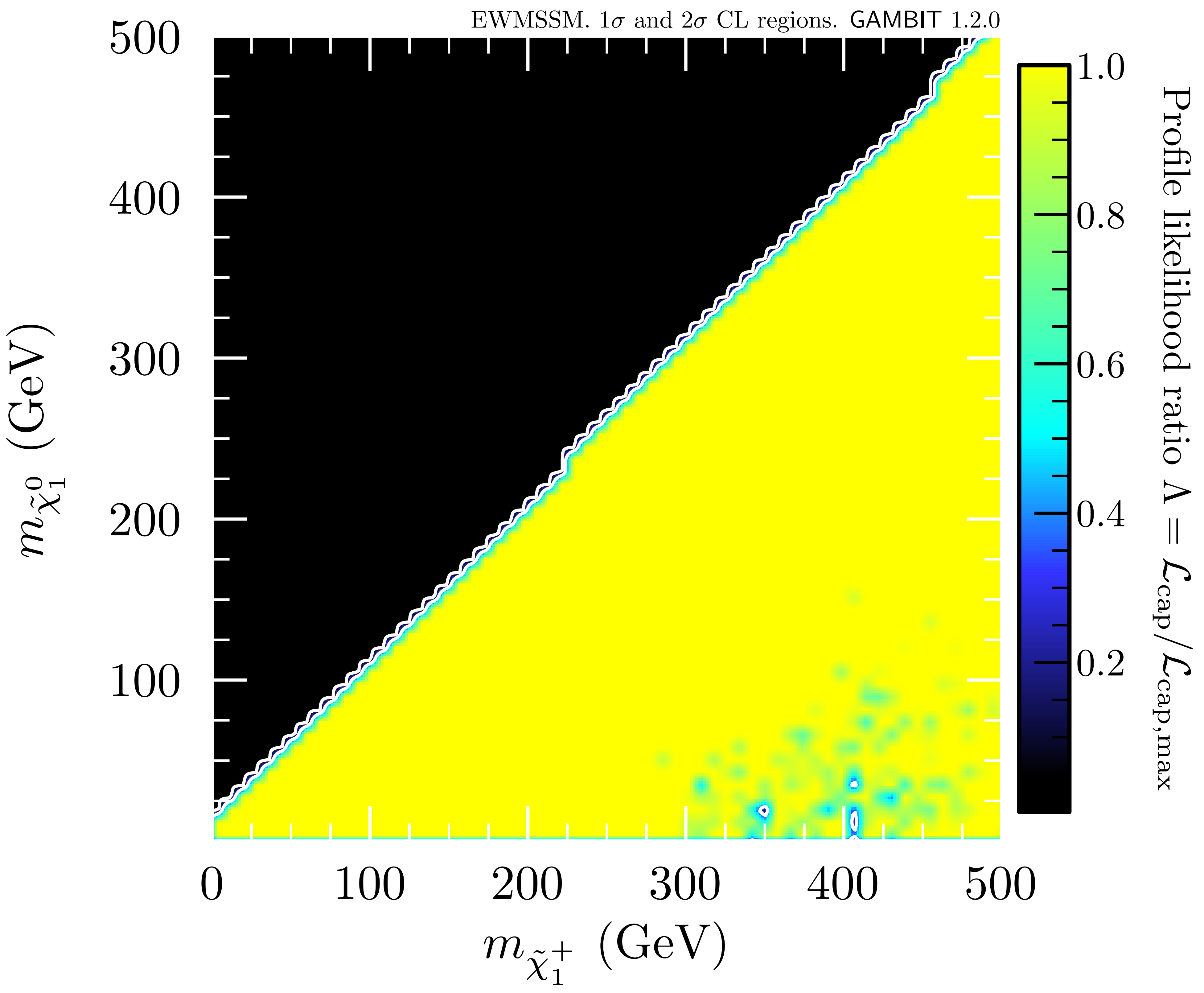
- **EWMSSM + near-massless gravitino** (1eV gravitino, for prompt decays)
- **7 SUSY particles below 1.5 TeV**: 4 neutralinos, 2 charginos, 1 gravitino
- Same 4D parameter space, quite different collider pheno

Back in 2019: EWMSSM

[1809.02097]
- 12 ATLAS/CMS searches
- LEP cross-section limits



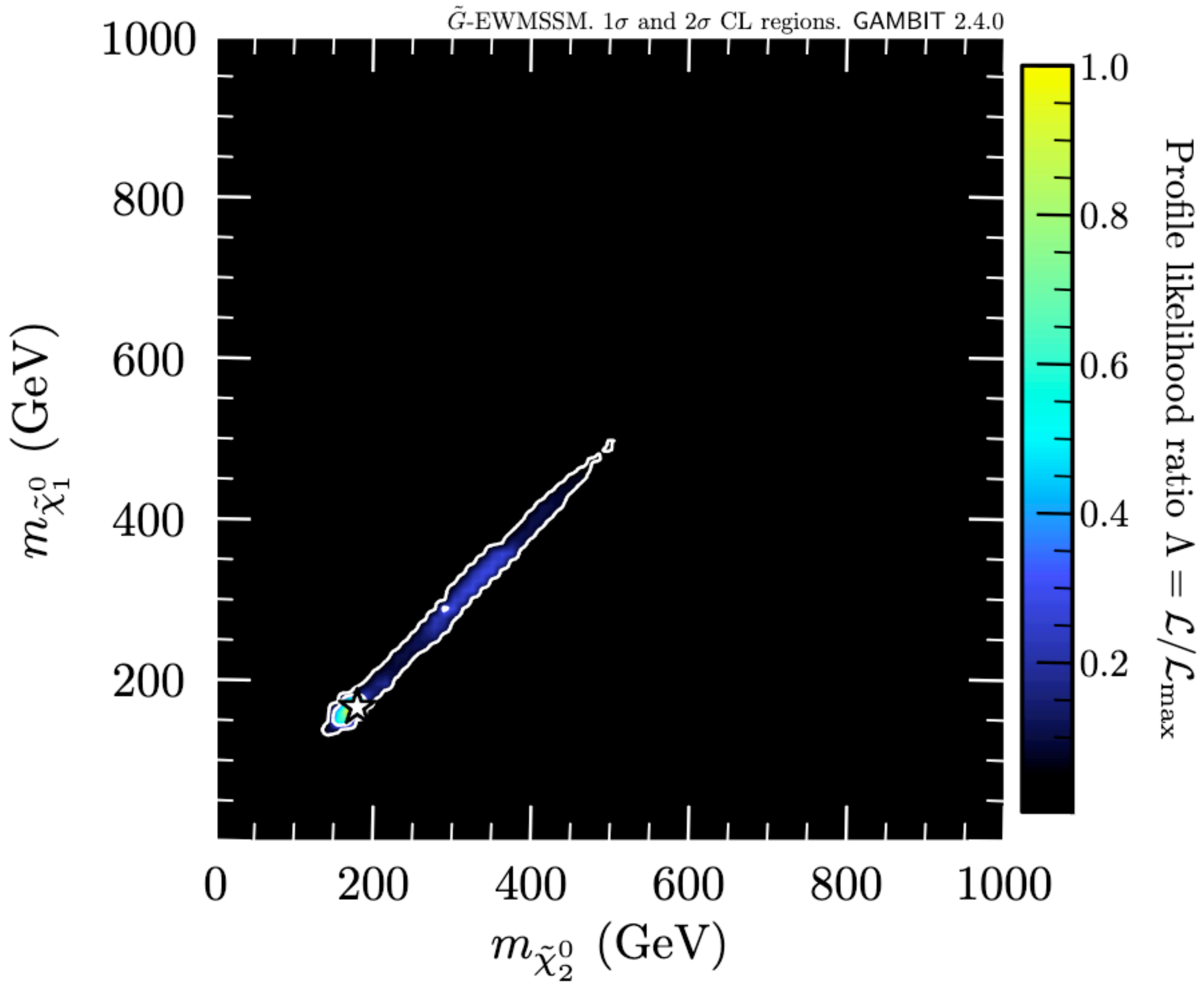
Identified a possible explanation for a pattern of (at the time interesting) excesses across multiple ATLAS searches



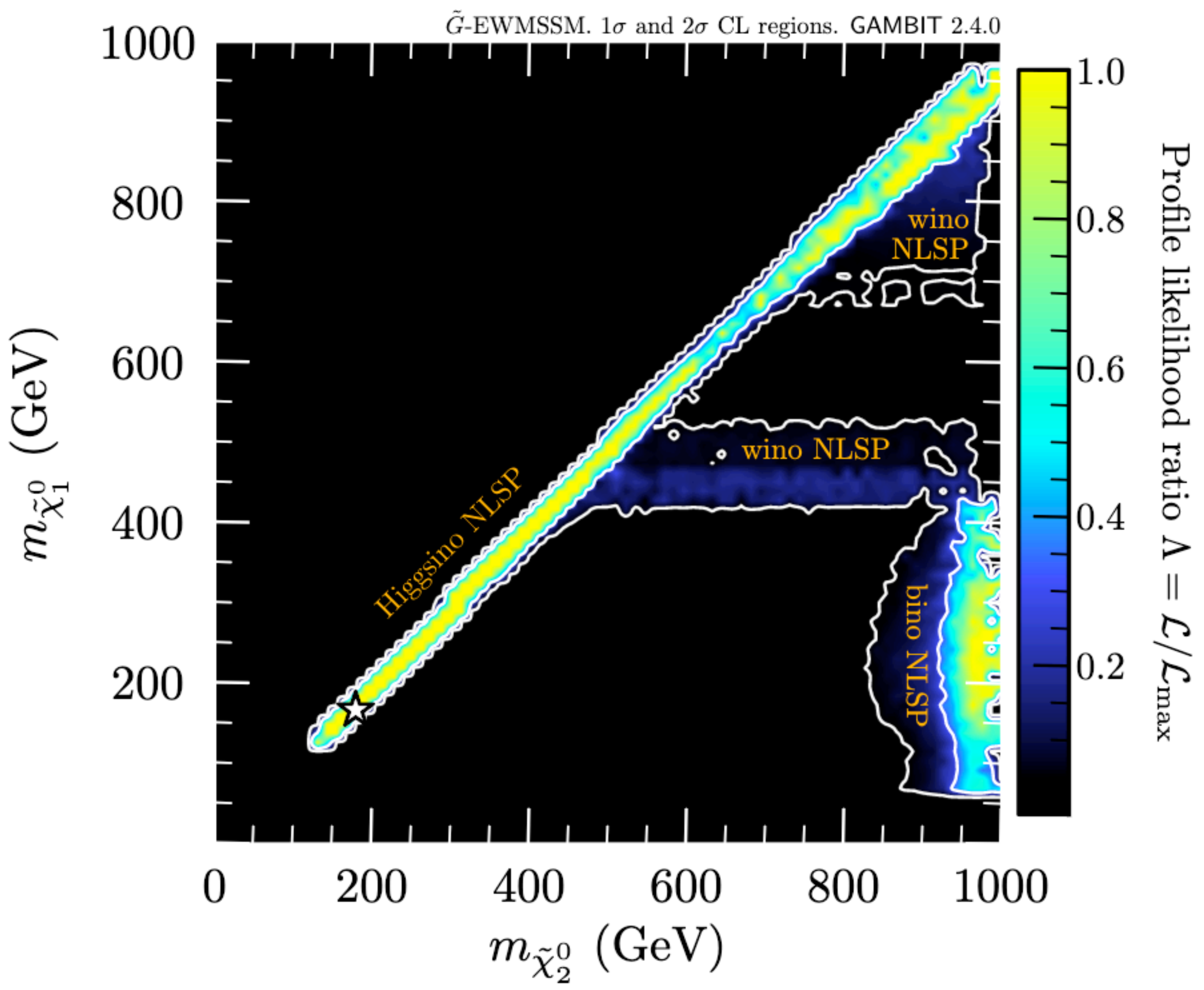
Comparing to SM rather than to the best-fit point: Found that no point in the chargino-neutralino mass plane was conclusively ruled out at that time

2023: G-EWMSSM

[2303.09082]
- 27 ATLAS/CMS searches
- Many «SM measurements»
- LEP cross-section limits



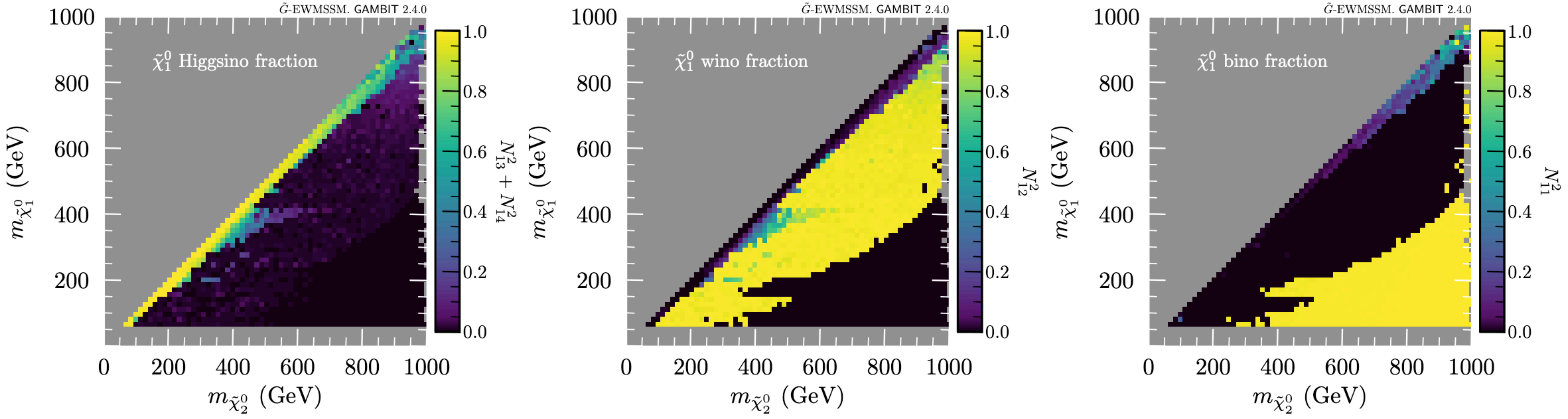
Scenario with light higgsinos → Z/H + gravitino could partly fit small excesses in searches for leptons + MET and b-jets + MET



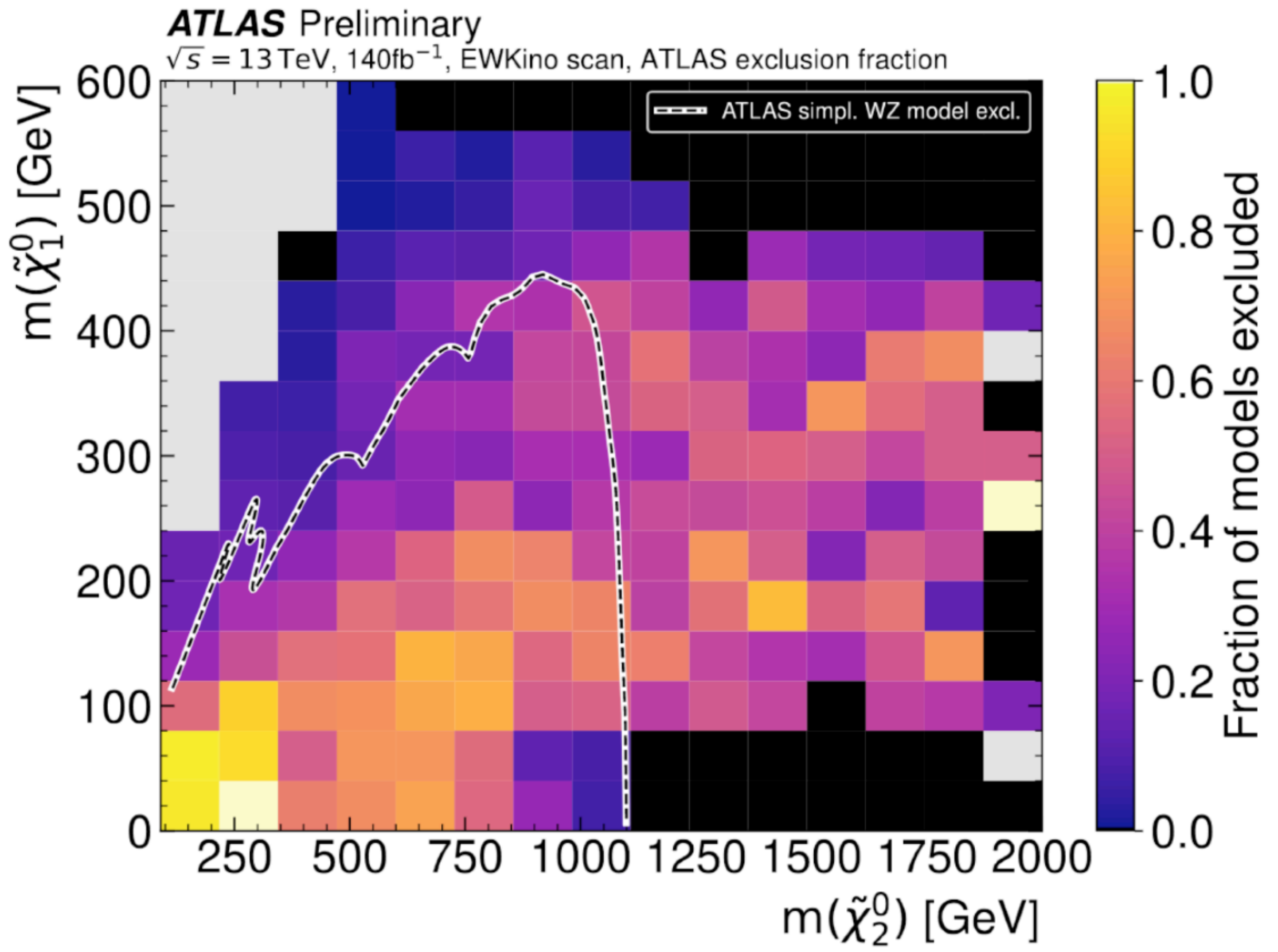
Comparing to SM rather than to the best-fit point:
Strong constraints, but several scenarios survive

2023: G-EWMSSM

[2303.09082]
- 27 ATLAS/CMS searches
- Many «SM measurements»
- LEP cross-section limits

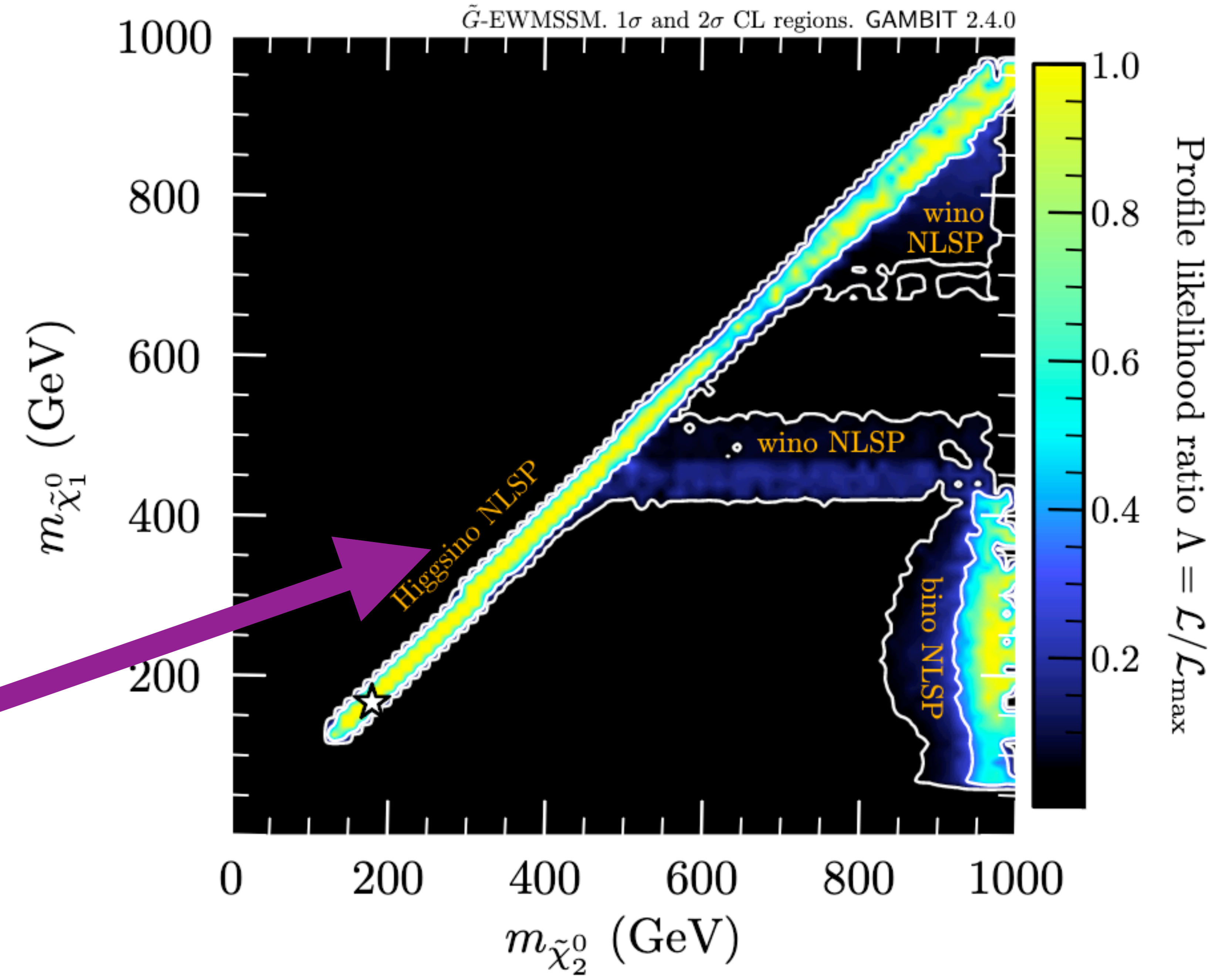


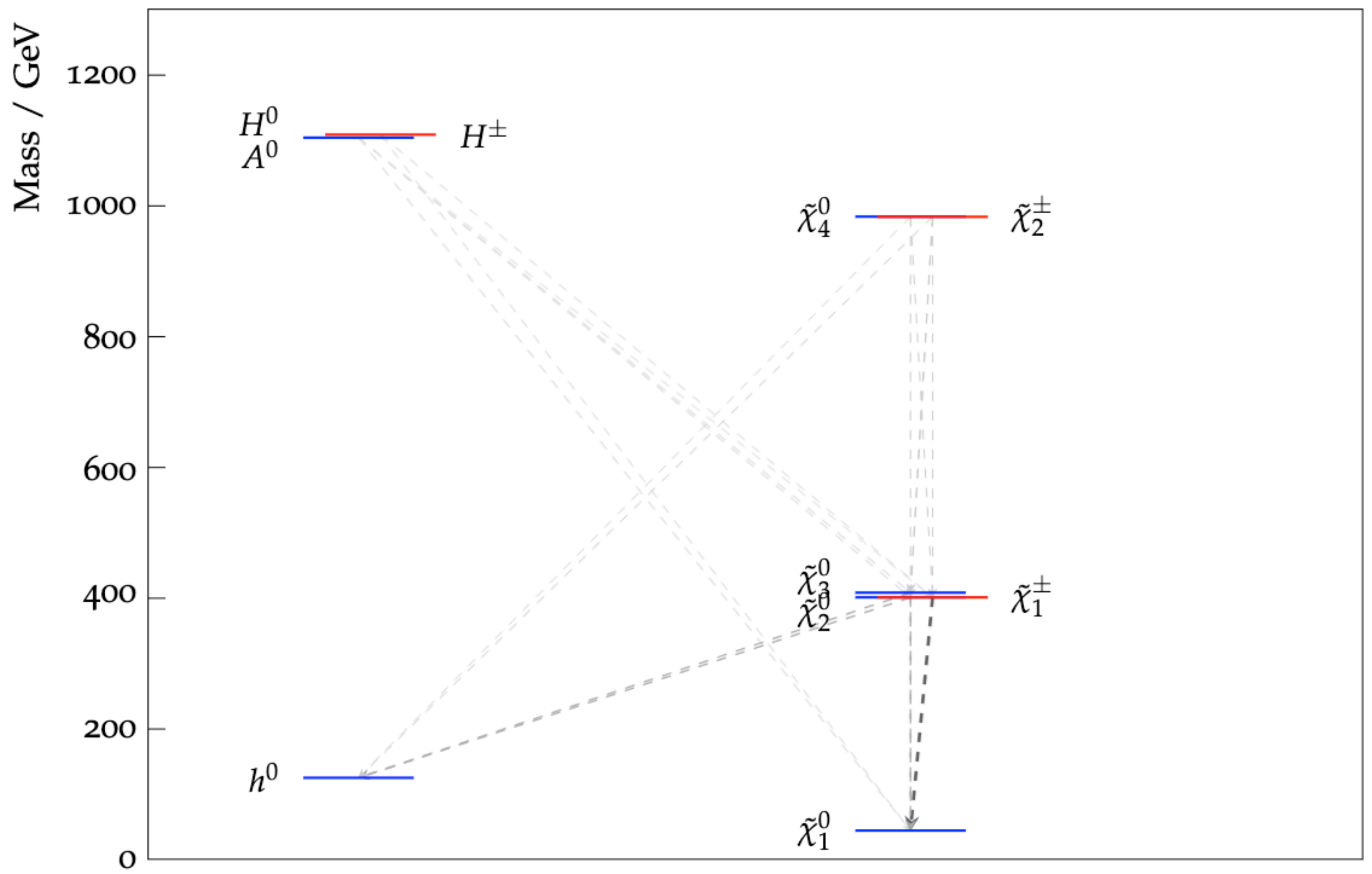
Profile likelihoods can be complicated:
Neighbouring points in e.g. a mass plane can belong to very different theoretical scenarios

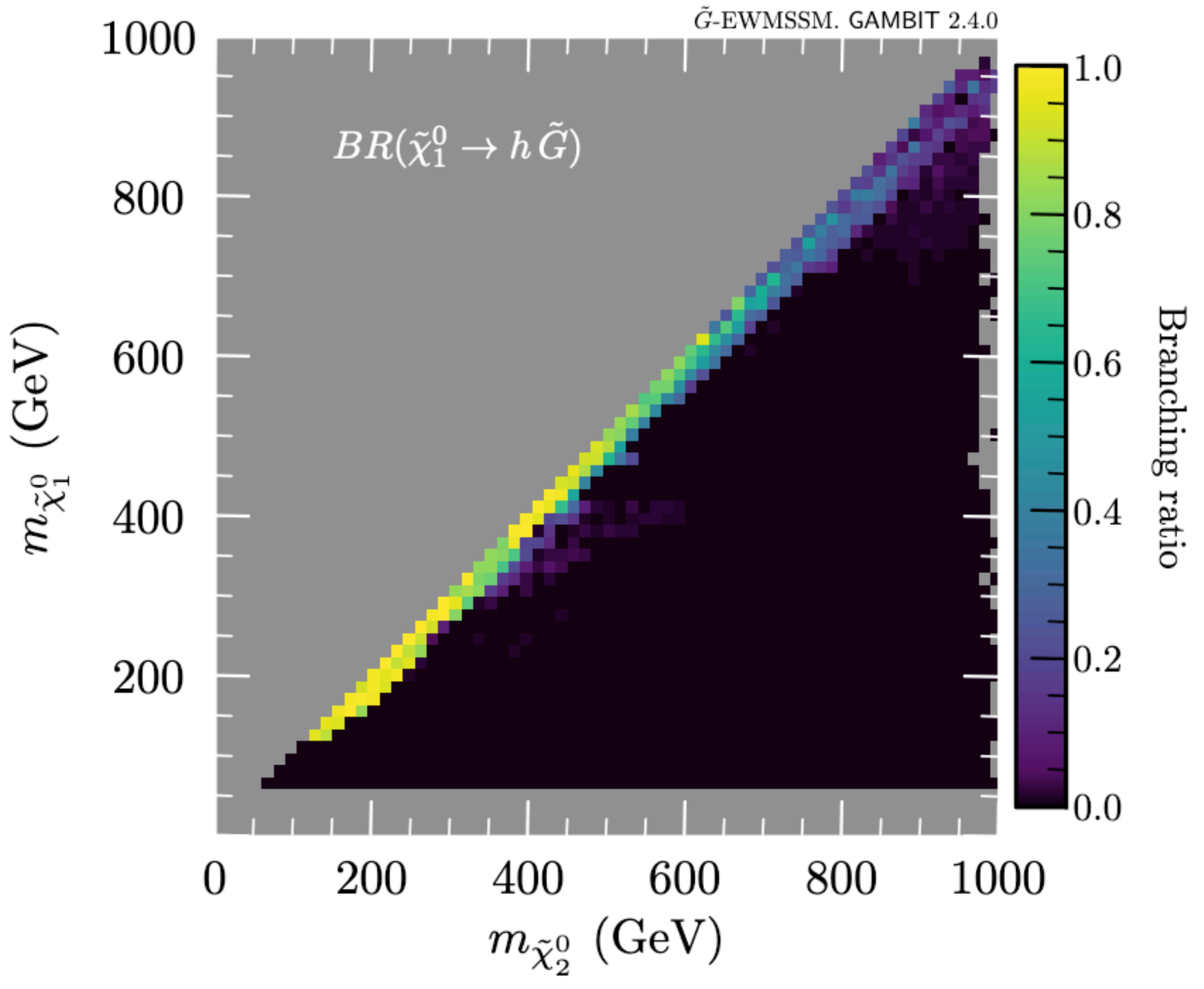


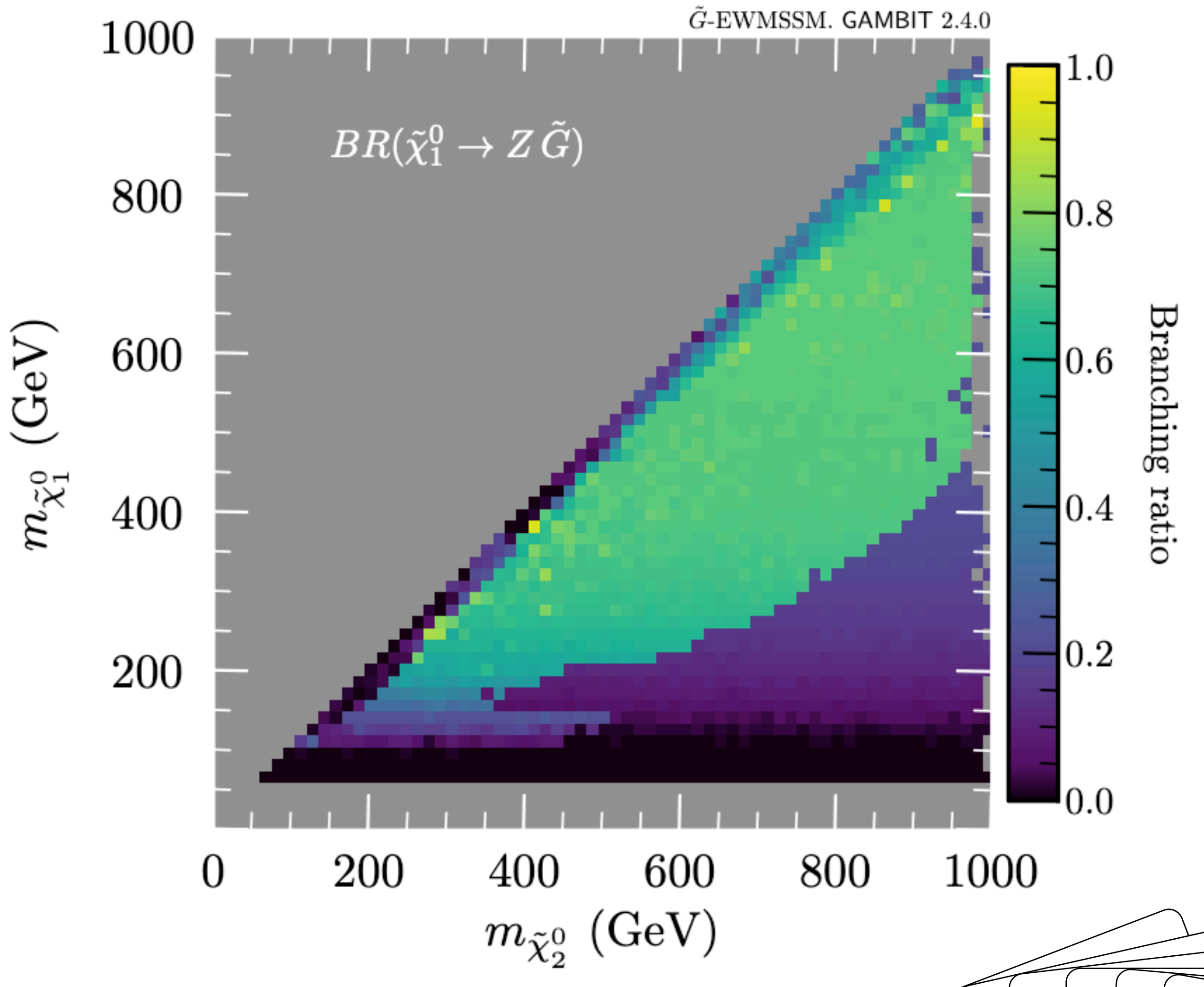
[2402.01392]

Quite similar scenarios





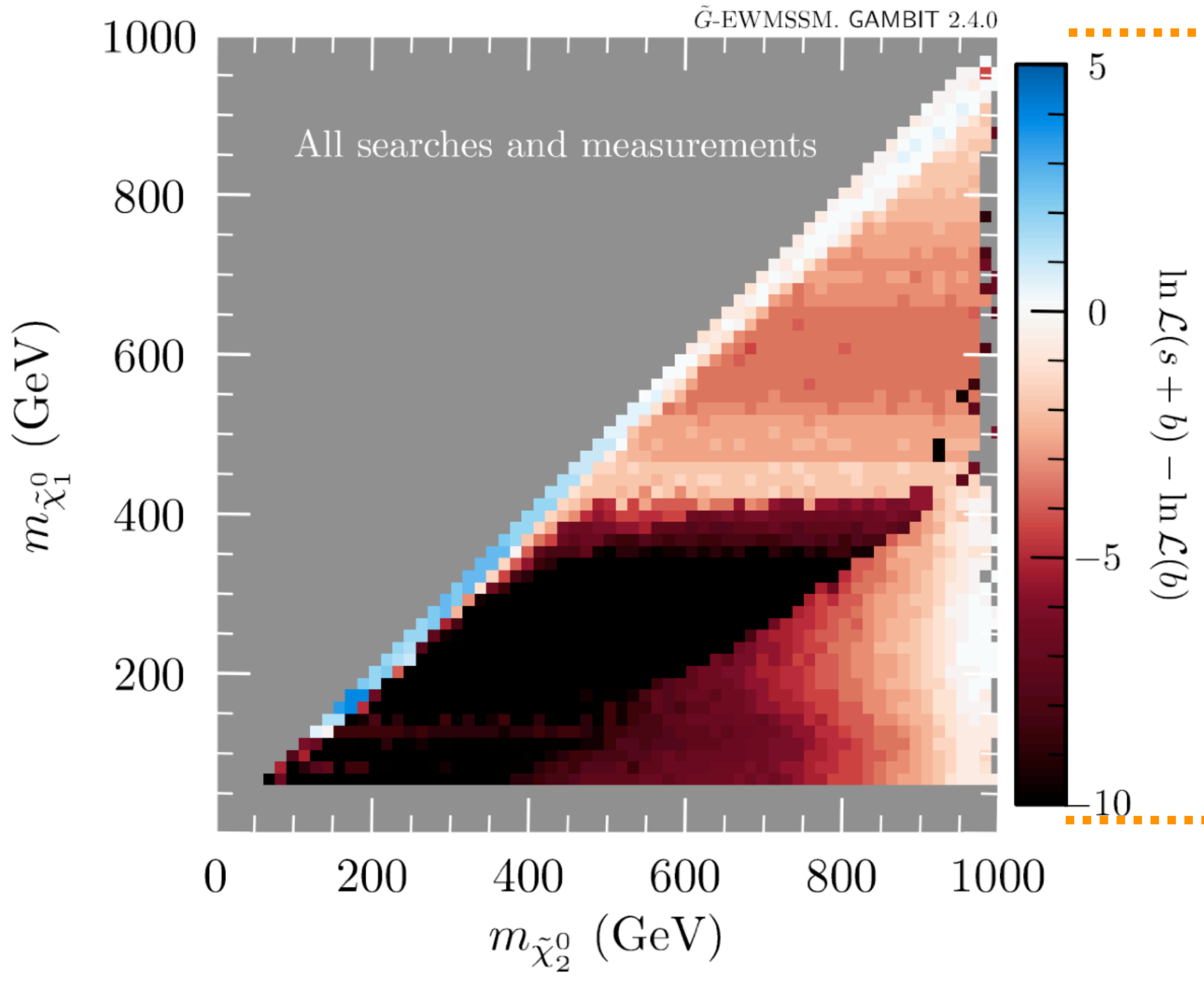




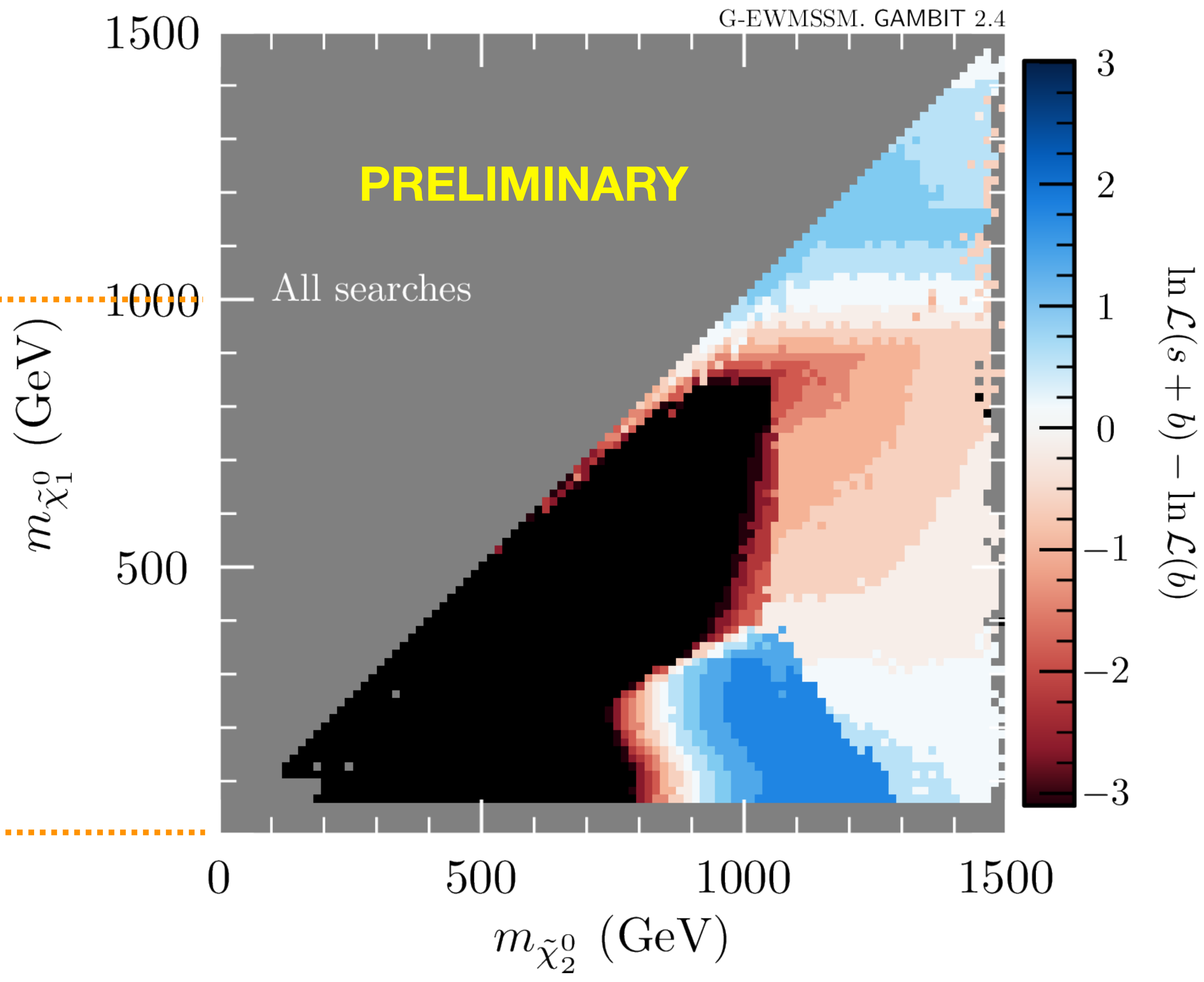
Ongoing work: **EWMSSM and G-EWMSSM after Run 2**

G-EWMSSM: Preliminary

Compared to 2023 G-EWMSSM study:



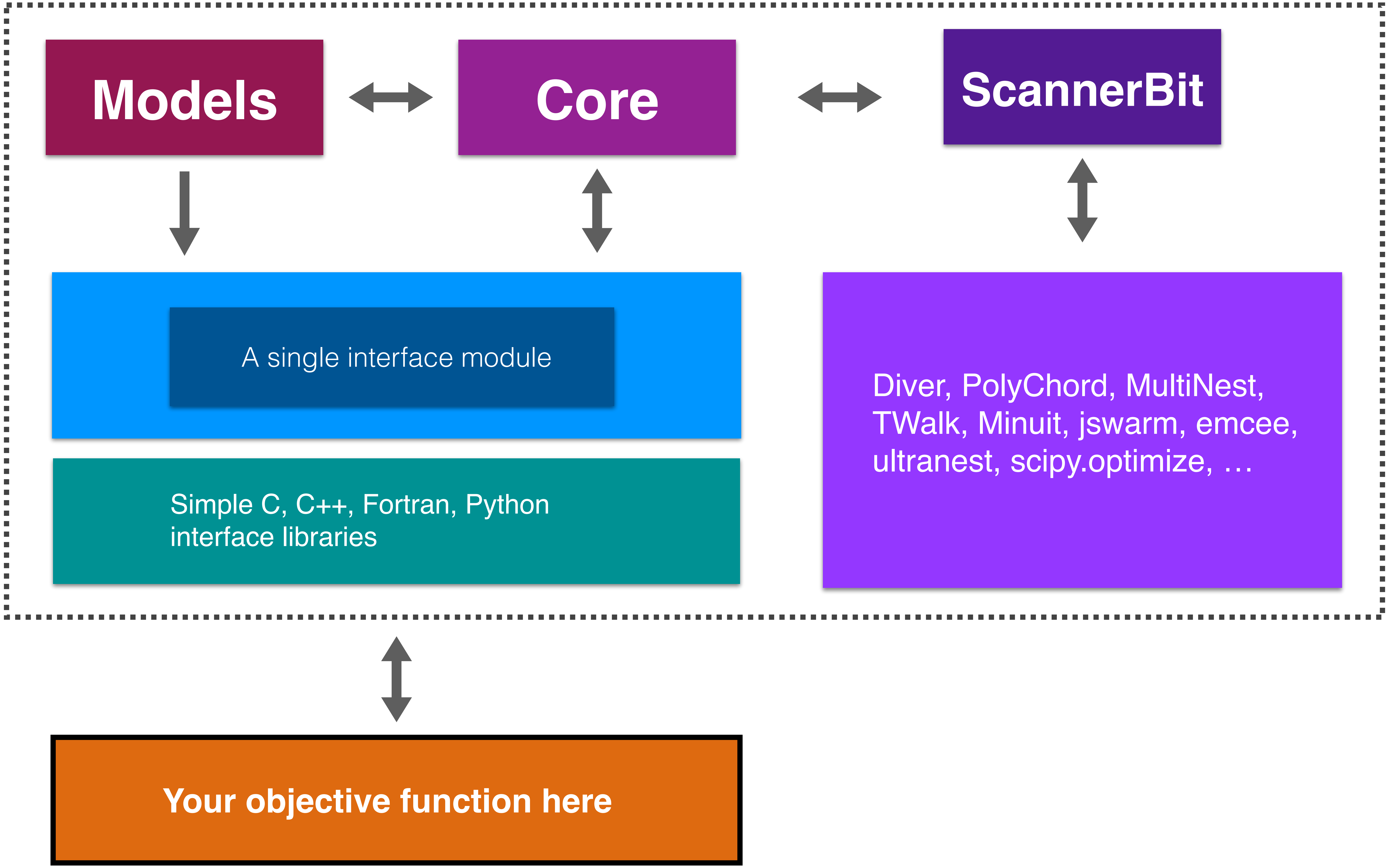
[2303.09082]



Summary

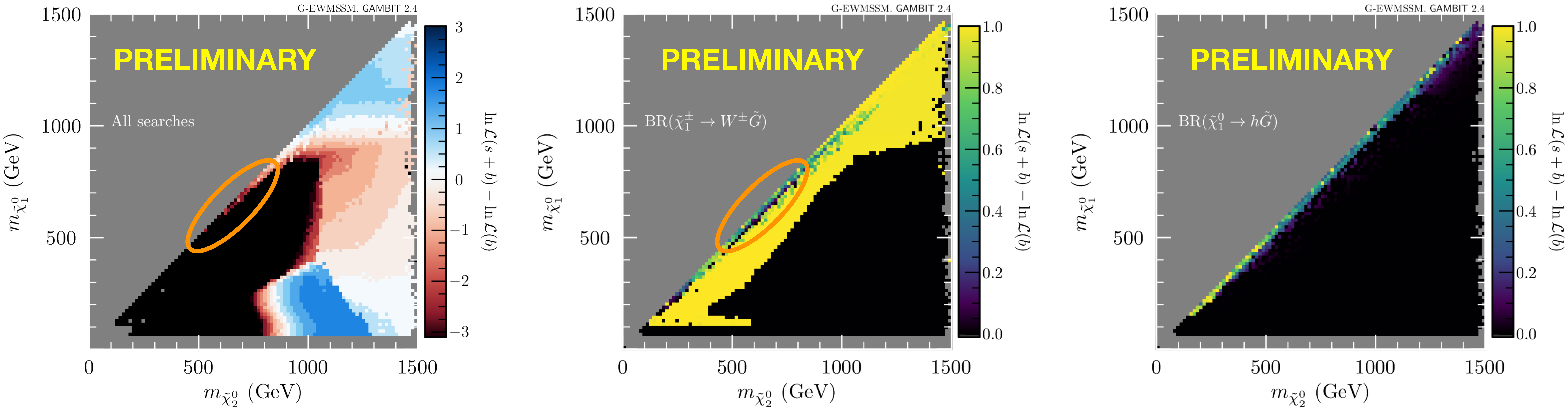
- How can we **maximise the scientific impact of experimental results?**
  - Reinterpret experimental results in terms of many (realistic) theories
  - Combine constraints from many experiments in a statistically sound way
  - → **Do global fits!**
- **GAMBIT** is an open-source tool for **large-scale BSM global fits**
- **Most recent GAMBIT results:**
  - *Here:* LHC impact on SUSY w/ light gravitino [2303.09082]
  - Sub-GeV dark matter [2405.17548]
- **More results in the pipeline**
  - Neutrinos, DM, SUSY after LHC Run 2, THDMs, …
- Got a neat idea for a global fit study? Got a new, shiny code for computing some theory prediction or likelihood? **Do get in touch :)**
- **gambitbsm.org**

Soon public: **GAMBIT-light**



G-EWMSSM: Preliminary

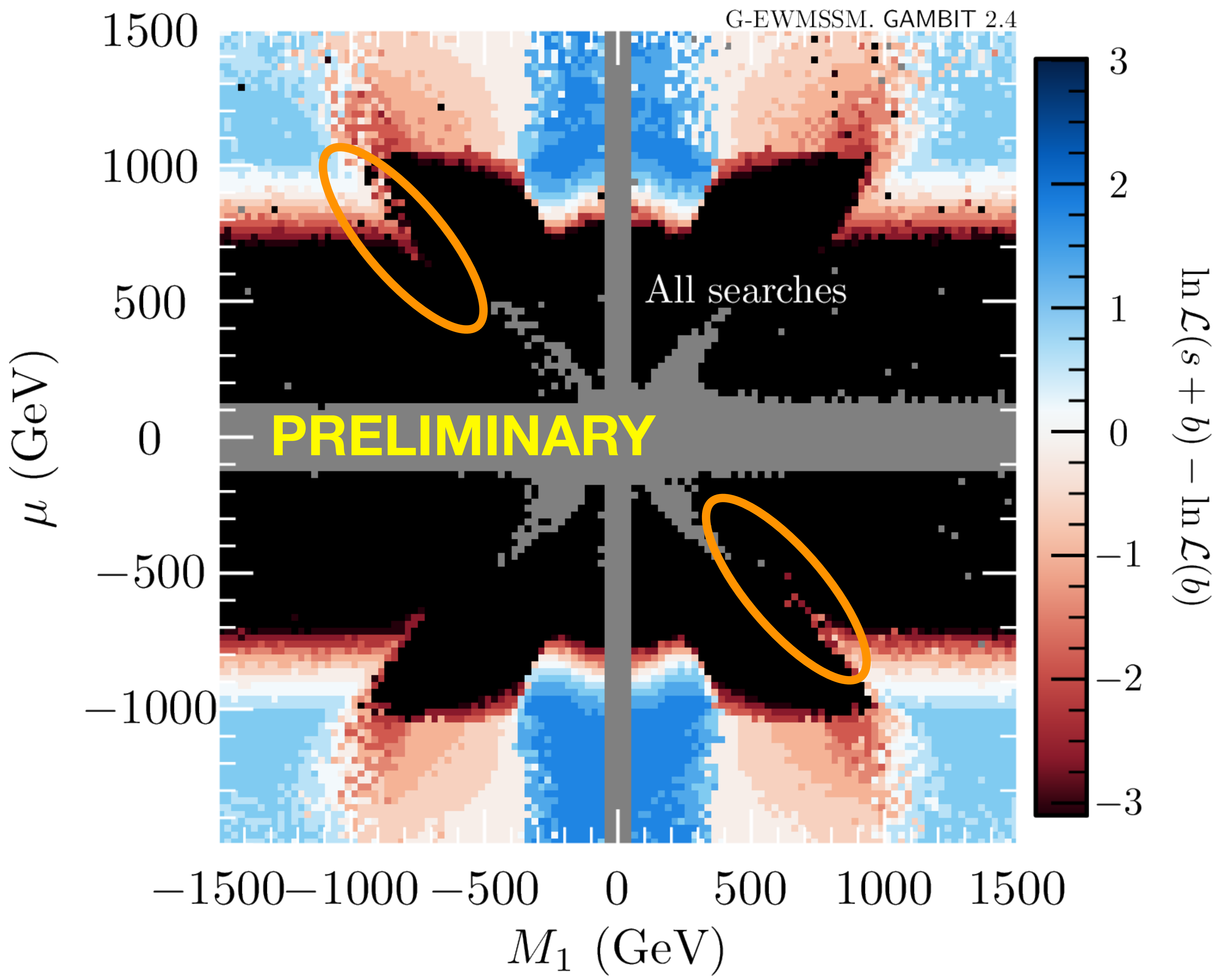
- 34 ATLAS/CMS searches
- LEP cross-section limits
- TODO: SM measurements

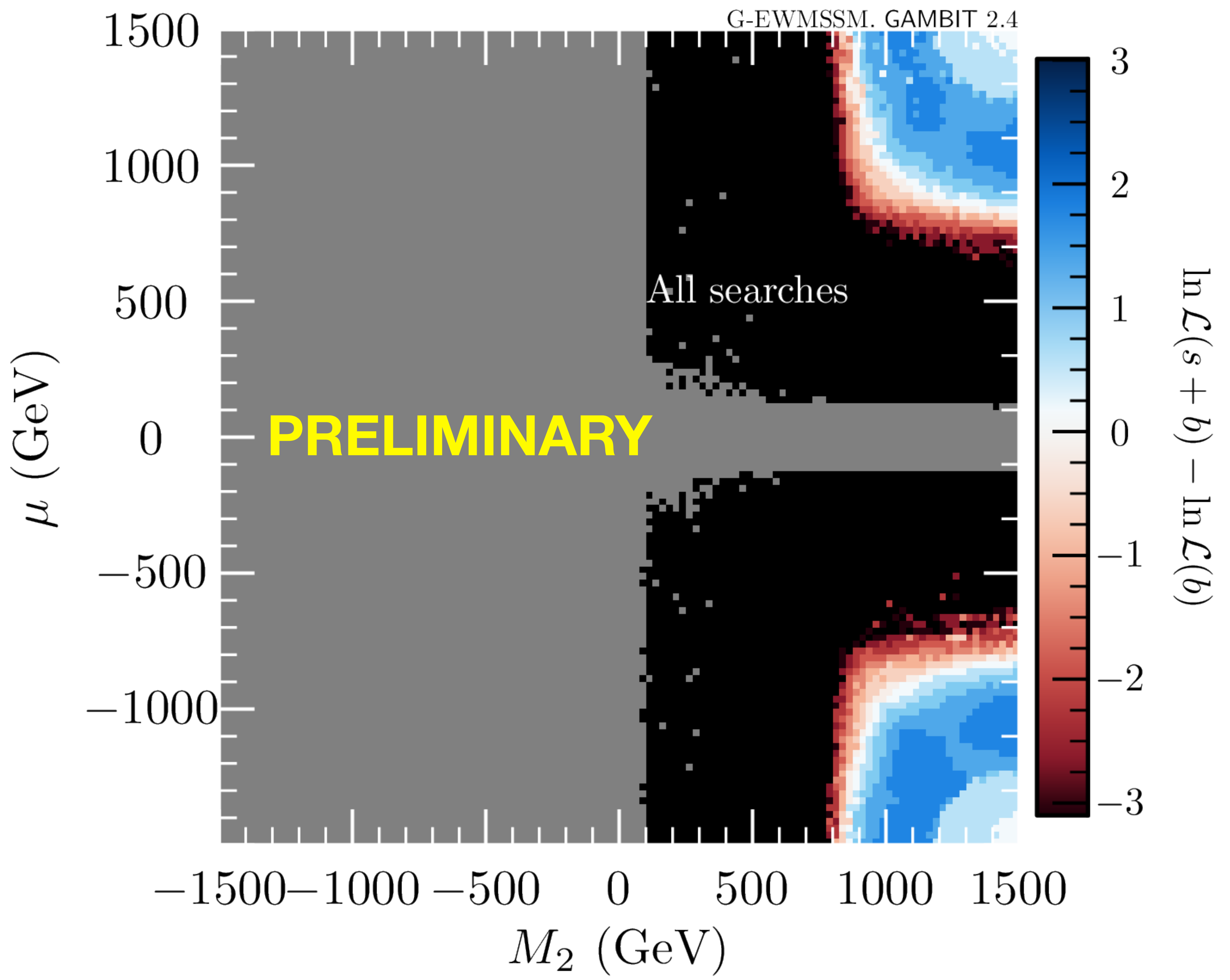


Lowest-mass non-excluded higgsino scenarios violate the common simplified model assumption that N2/C1 always decay to N1 + soft stuff

G-EWMSSM: Preliminary

- 34 ATLAS/CMS searches
- LEP cross-section limits
- TODO: SM measurements





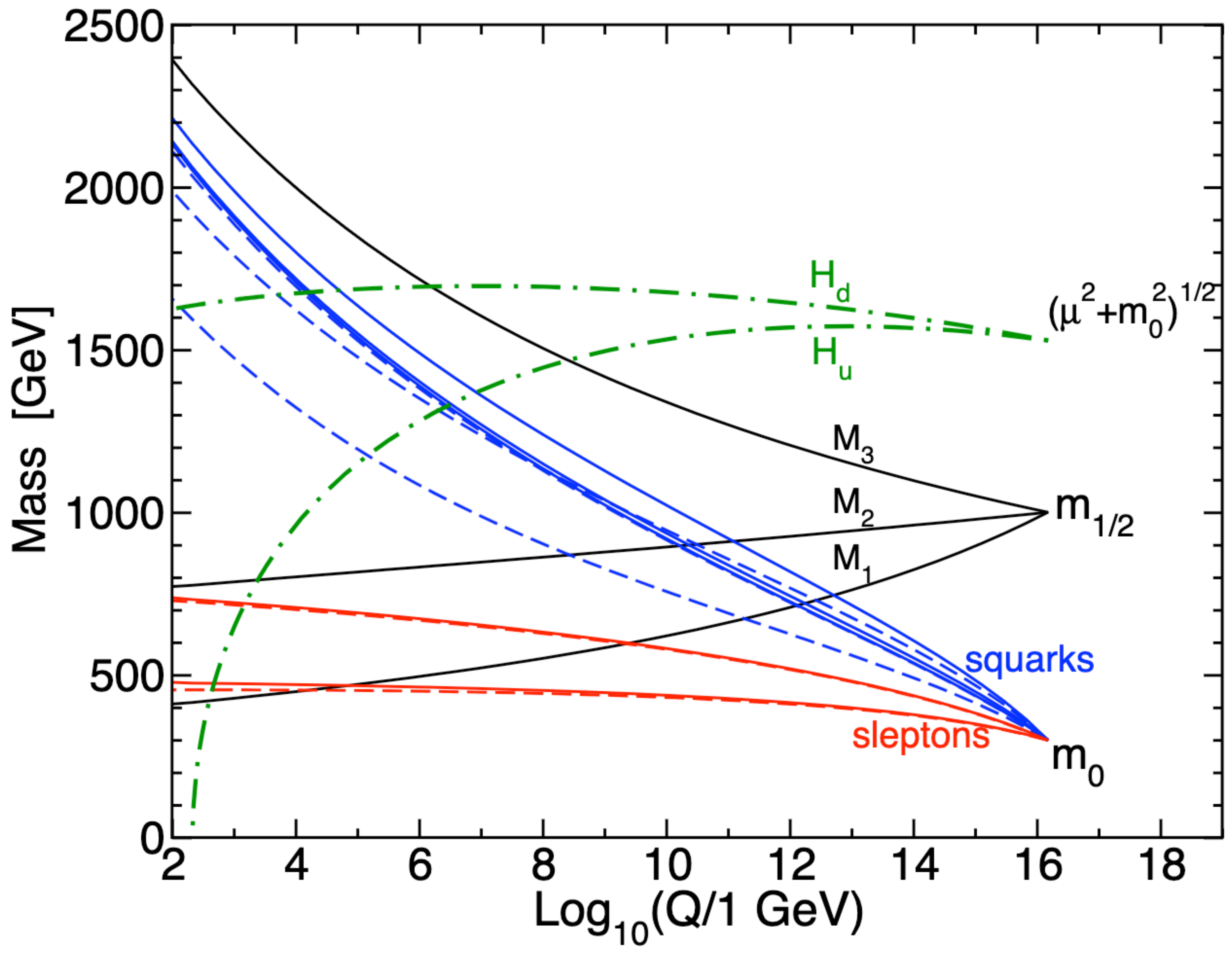
…and these scenarios are higgino-bino mixture scenarios (M1 ~ mu)

Reminder:
Theory space is a strange, implausible place

- «Everyone» would assign **negligible prior belief** to **almost all points** in the **low-scale MSSM parameter space**
- MSSM expresses our ignorance of SUSY breaking
- Any «elegant»/«economic»/«reasonable» high-scale model maps to some tiny subspace of the low-scale MSSM
- And any simplified model plane maps to some strange hypersurface through low-scale MSSM

- A «large» exclusion in simplified model space:
    - **Maybe large**, **maybe small** impact on MSSM

- A «large» exclusion in low-scale MSSM
    - **Maybe decisive**, **maybe negligible** impact on the space of plausible high-scale models



[hep-ph/9709356]

Parameter space

M_1 M_2 μ $\tan\beta$

Neutralinos

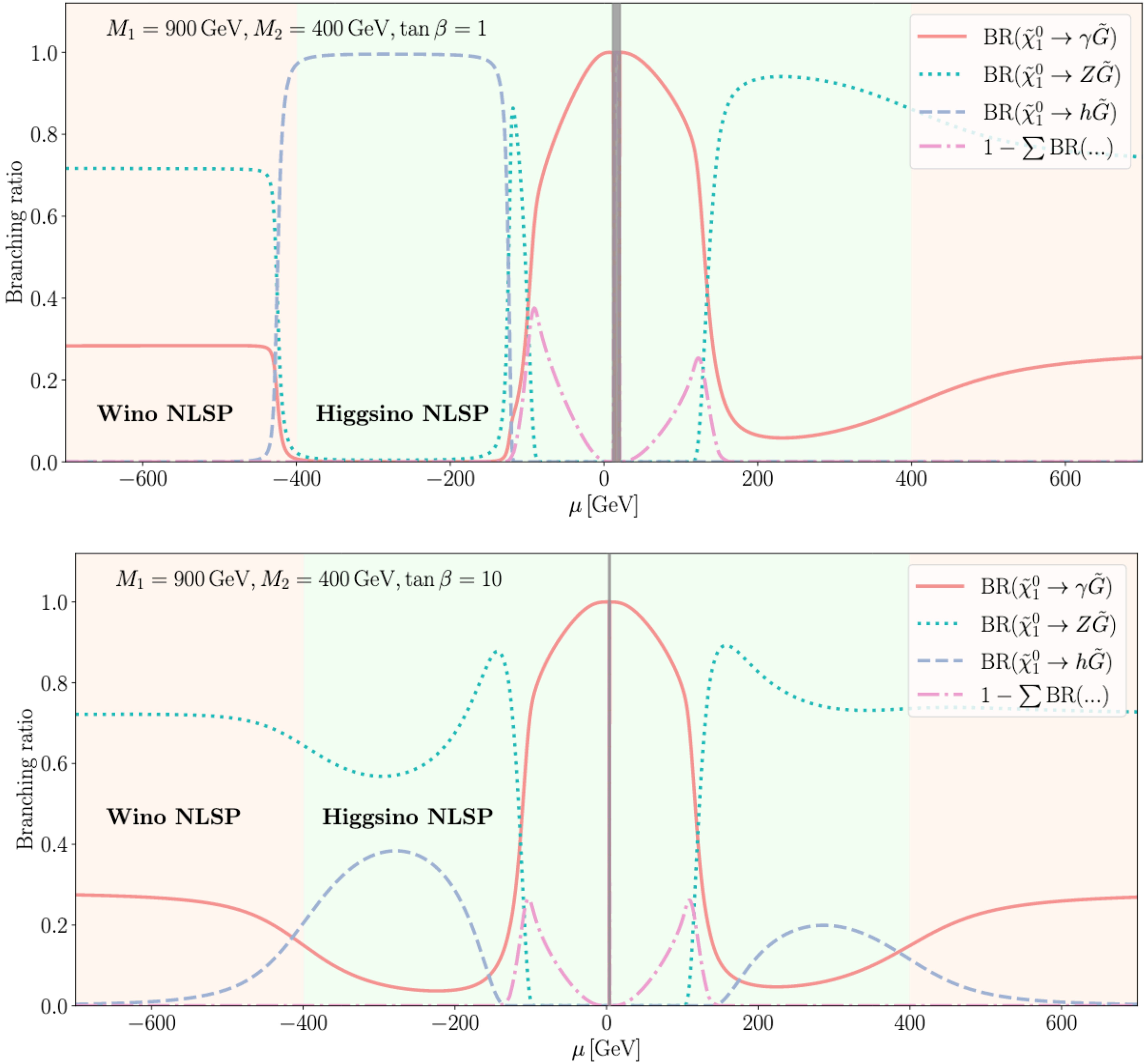
$$\psi^0 = (\tilde{B}, \tilde{W}^0, \tilde{H}_d^0, \tilde{H}_u^0)$$

$$M_N = \begin{pmatrix} M_1 & 0 & -\frac{1}{2}g'vc_\beta & \frac{1}{2}g'vs_\beta \\ 0 & M_2 & \frac{1}{2}gvc_\beta & -\frac{1}{2}gvs_\beta \\ -\frac{1}{2}g'vc_\beta & \frac{1}{2}gvc_\beta & 0 & -\mu \\ \frac{1}{2}g'vs_\beta & -\frac{1}{2}gvs_\beta & -\mu & 0 \end{pmatrix}$$

Charginos

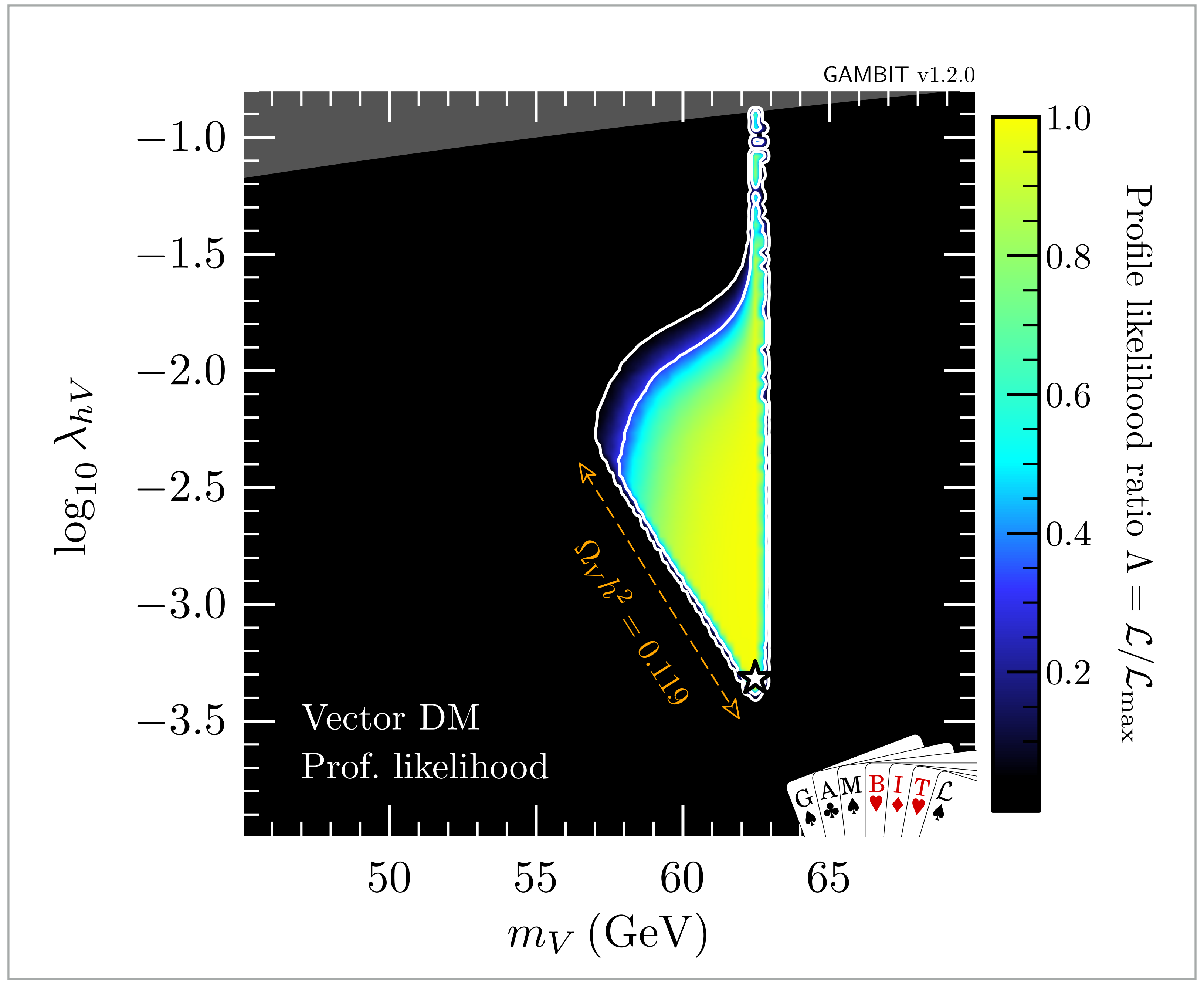
$$\psi^\pm = (\tilde{W}^+, \tilde{H}_u^+, \tilde{W}^-, \tilde{H}_d^-)$$

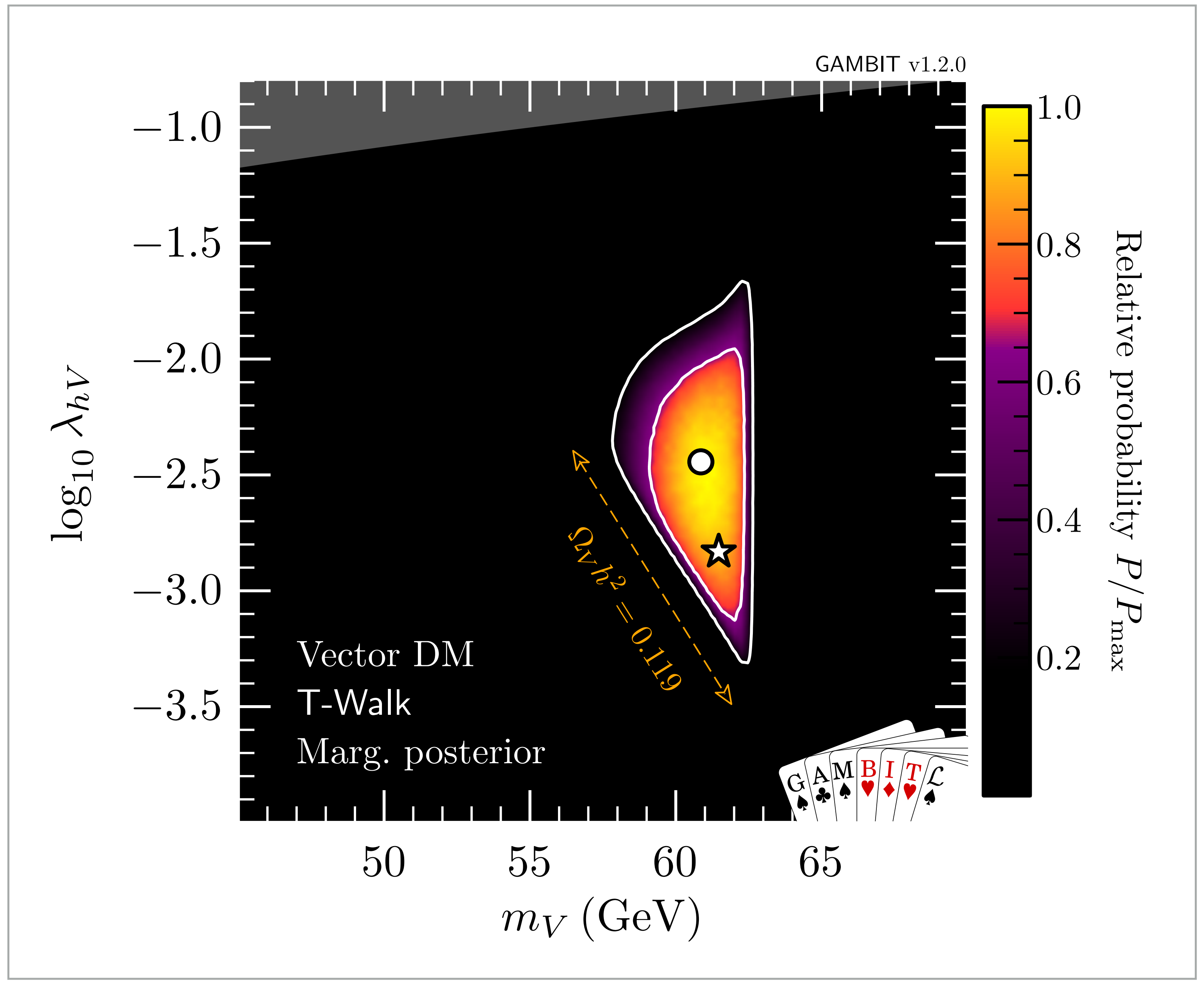
$$M_C = \begin{pmatrix} 0 & X^T \\ X & 0 \end{pmatrix}, \quad \text{where} \quad X = \begin{pmatrix} M_2 & \frac{gvs_\beta}{\sqrt{2}} \\ \frac{gvc_\beta}{\sqrt{2}} & \mu \end{pmatrix}.$$



$M_1 = 900\,\mathrm{GeV}, M_2 = 400\,\mathrm{GeV}, \tan\beta = 1$
$\mathrm{BR}(\tilde{\chi}_1^0 \to \gamma\tilde{G})$
$\mathrm{BR}(\tilde{\chi}_1^0 \to Z\tilde{G})$
$\mathrm{BR}(\tilde{\chi}_1^0 \to h\tilde{G})$
$1 - \sum \mathrm{BR}(...)$
Wino NLSP
Higgsino NLSP
Branching ratio
$\mu\,[\mathrm{GeV}]$
$M_1 = 900\,\mathrm{GeV}, M_2 = 400\,\mathrm{GeV}, \tan\beta = 10$
$\mathrm{BR}(\tilde{\chi}_1^0 \to \gamma\tilde{G})$
$\mathrm{BR}(\tilde{\chi}_1^0 \to Z\tilde{G})$
$\mathrm{BR}(\tilde{\chi}_1^0 \to h\tilde{G})$
$1 - \sum \mathrm{BR}(...)$
Wino NLSP
Higgsino NLSP
Branching ratio
$\mu\,[\mathrm{GeV}]$

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





[arxiv:1808.10465]

B

Interpretation: For every point in the mass plane, there is *at least one point* in the MSSM parameter space that fits the data as well as (or better than) the SM expectation.

This does not tell us anything about *the size* of the viable parameter space…