Combined collider constraints on SUSY with a light gravitino

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on behalf of the GAMBIT Collaboration

Spåtind 2023, 7 January, 2023

UNIVERSITETET
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Outline

1. How to get the most physics out of our data

2. LHC impact on SUSY with a light gravitino

1. How to get the most physics out of our data

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:

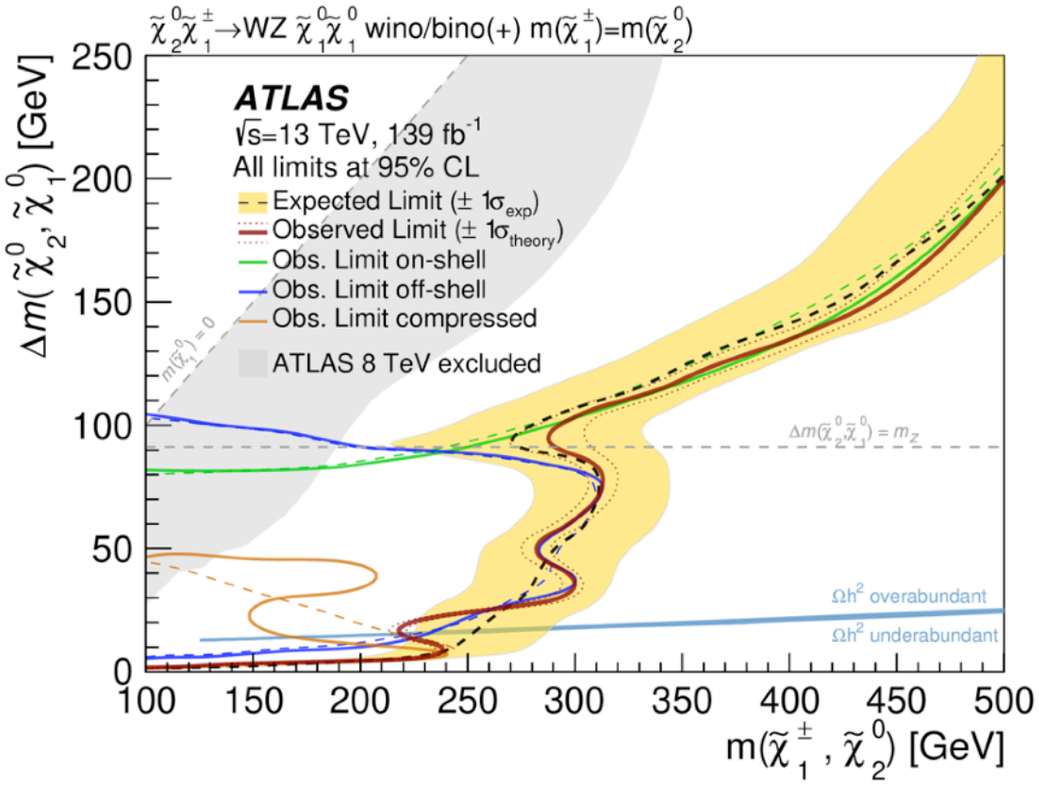
- *Publishing statistical models: Getting the most out of particle physics experiments*
  [arxiv:2109.04981]

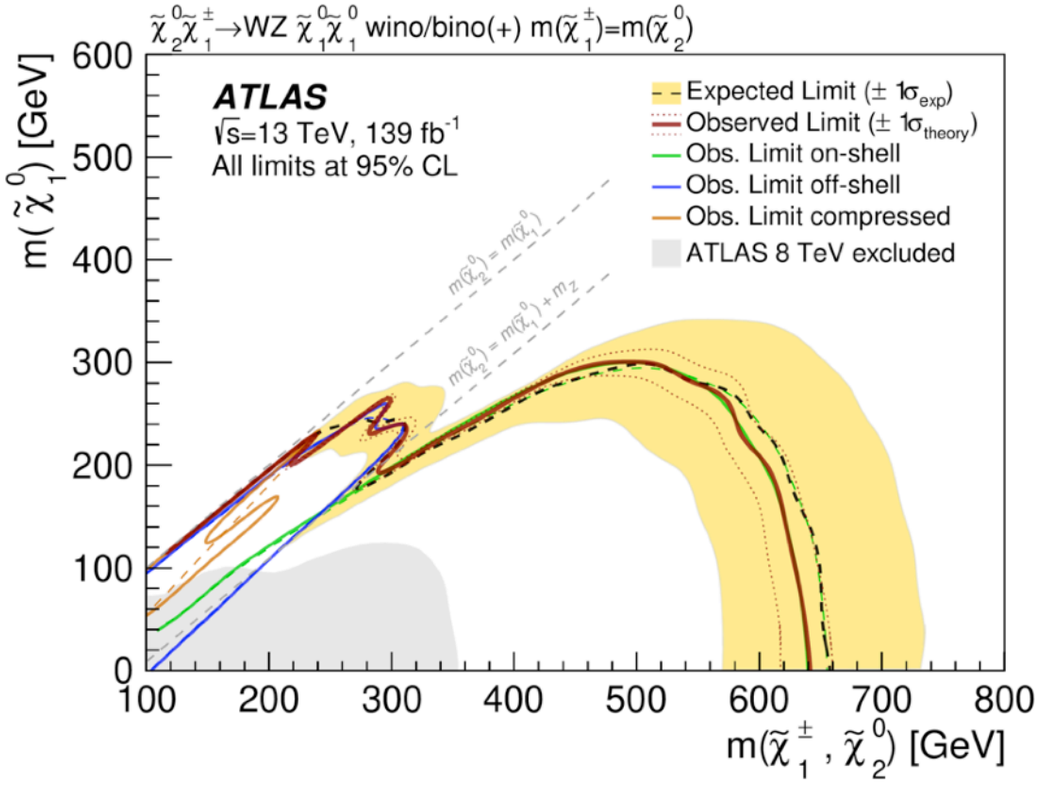
- *Reinterpretation of LHC Results for New Physics: Status and Recommendations after Run 2*
  [arxiv:2003.07868]

- *Simple and statistically sound strategies for analysing physical theories*
  [arxiv:2012.09874]

We need your help!

These are very nice…





[ATLAS, 2106.01676]

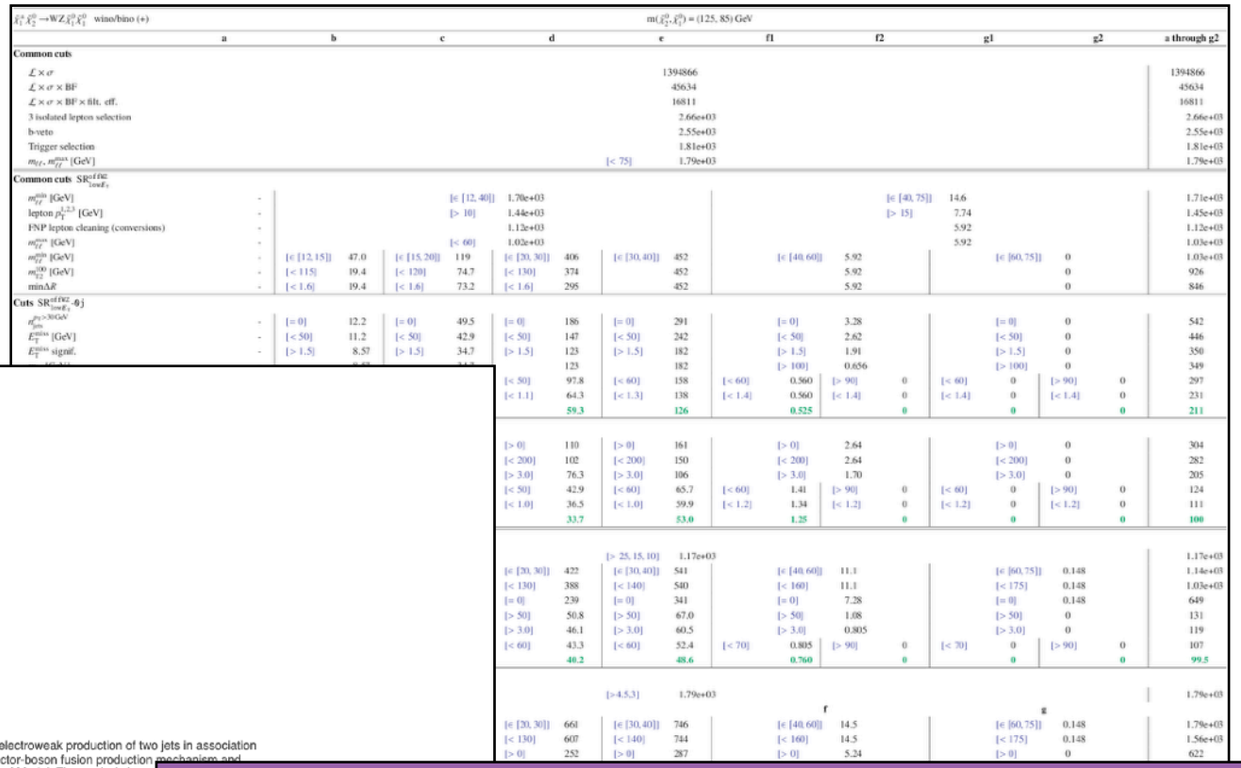
We need your help!

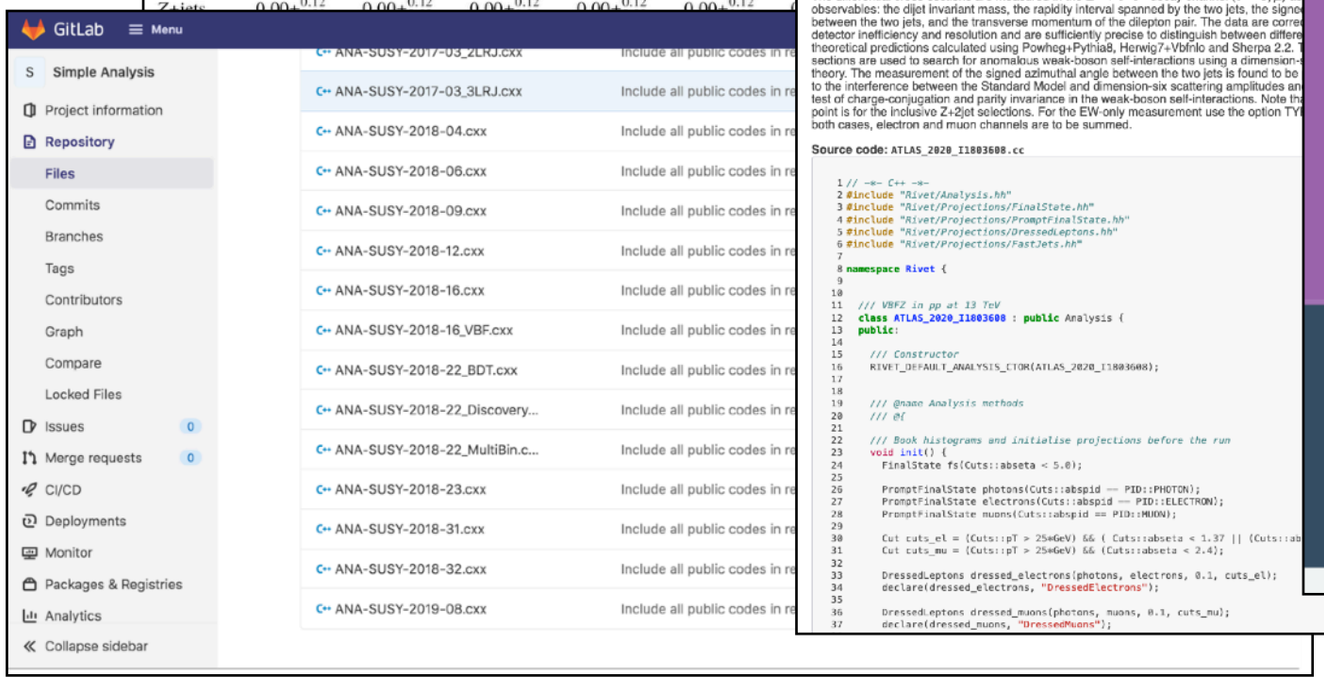
…but **this** is the real gold!

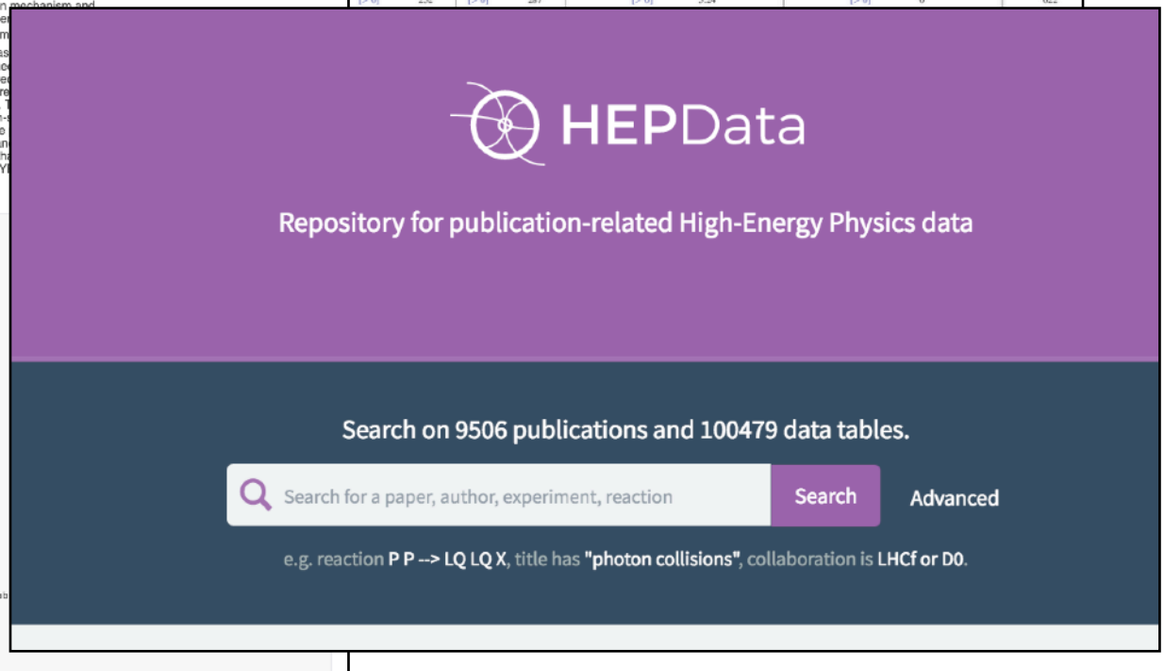
Regions	SR^{Wh}_{SFOS}-1	SR^{Wh}_{SFOS}-2	SR^{Wh}_{SFOS}-3	SR^{Wh}_{SFOS}-4	SR^{Wh}_{SFOS}-5	SR^{Wh}_{SFOS}-6	SR^{Wh}_{SFOS}-7
Observed	152	14	8	47	6	15	19
Fitted SM	136 ± 13	13.5 ± 1.7	4.3 ± 0.9	50 ± 5	4.3 ± 0.7	20.2 ± 2.1	16.0 ± 2.1
WZ	107 ± 12	10.2 ± 1.7	3.8 ± 0.8	32 ± 4	2.7 ± 0.6	12.3 ± 1.6	10.8 ± 1.7
$t\bar{t}$	10.3 ± 2.5	1.6 ± 0.6	0.13 ± 0.12	7.7 ± 1.9	0.74 ± 0.34	3.5 ± 1.0	2.5 ± 0.7
Z+jets	2.5 ± 2.9	$0.00^{+0.02}_{-0.00}$	$0.00^{+0.02}_{-0.00}$	2.0 ± 1.6	$0.00^{+0.04}_{-0.00}$	$0.00^{+0.04}_{-0.00}$	$0.00^{+0.02}_{-0.00}$
Higgs	5.7 ± 0.6	0.69 ± 0.07	0.20 ± 0.03	3.12 ± 0.31	0.26 ± 0.05	1	
Triboson	1.9 ± 0.5	0.22 ± 0.07	0.07 ± 0.02	1.4 ± 0.4	0.28 ± 0.09	0	
Others	8.6 ± 1.9	0.84 ± 0.11	0.08 ± 0.05	4.0 ± 0.5	0.23 ± 0.24	2	

Regions	SR^{Wh}_{SFOS}-8	SR^{Wh}_{SFOS}-9	SR^{Wh}_{SFOS}-10	SR^{Wh}_{SFOS}-11	SR^{Wh}_{SFOS}-12	
Observed	113	184	28	5	82	
Fitted SM	108 ± 13	180 ± 17	31 ± 4	6.6 ± 0.9	90 ± 11	1
WZ	54 ± 6	127 ± 13	19.3 ± 2.3	5.3 ± 0.8	47 ± 6	
$t\bar{t}$	21 ± 6	33 ± 10	8.2 ± 2.3	0.7 ± 0.5	28 ± 8	
Z+jets	19 ± 10	2.3 ± 1.9	1.0 ± 1.3	0.10 ± 0.21	2.1 ± 3.1	
Higgs	1.91 ± 0.19	3.63 ± 0.35	0.67 ± 0.06	0.15 ± 0.02	2.98 ± 0.25	0
Triboson	0.79 ± 0.24	1.4 ± 0.4	0.41 ± 0.13	0.12 ± 0.05	1.6 ± 0.5	0
Others	11.1 ± 2.2	12.2 ± 2.2	1.8 ± 0.4	0.22 ± 0.05	9.0 ± 1.1	

Regions	SR^{Wh}_{SFOS}-15	SR^{Wh}_{SFOS}-16	SR^{Wh}_{SFOS}-17	SR^{Wh}_{SFOS}-18	SR^{Wh}_{SFOS}-19
Observed	51	5	37	7	4
Fitted SM	46 ± 7	9.8 ± 1.6	43 ± 7	12.6 ± 1.7	1.8 ± 0.4
WZ	18.9 ± 2.2	3.9 ± 0.8	35 ± 6	9.8 ± 1.6	1.44 ± 0.32
$t\bar{t}$	18 ± 6	3.2 ± 1.3	1.00 ± 0.34	0.33 ± 0.17	$0.00^{+0.01}_{-0.00}$
Z+jets	$0.00^{+0.12}_{-}$	$0.00^{+0.12}_{-}$	$0.00^{+0.12}_{-}$	$0.00^{+0.12}_{-}$	$0.00^{+0.12}_{-}$







We need your help!

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

2. LHC impact on SUSY with a light gravitino

Collider constraints on electroweakinos in the presence of a light gravitino

The GAMBIT Collaboration: Viktor Ananyev[1], Csaba Balázs[2], Ankit Beniwal[3], Lasse Lorentz Braseth[1], Andy Buckley[4], Jonathan Butterworth[5], Christopher Chang[6], Matthias Danninger[7], Andrew Fowlie[8], Tomás E. Gonzalo[9], Anders Kvellestad[1], Farvah Mahmoudi[10,11], Gregory D. Martinez[12], Markus T. Prim[13], Tomasz Procter[4], Are Raklev[1], Pat Scott[14], Patrick Stöcker[15], Jeriek Van den Abeele[1], Martin White[16], Yang Zhang[17,18]

GAMBIT: The Global And Modular BSM Inference Tool

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

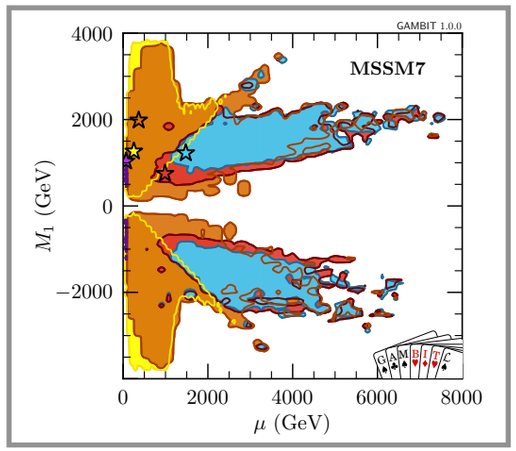
- Extensive model database, beyond SUSY
- Fast definition of new datasets, theories
- Extensive observable/data libraries
- Plug&play scanning/physics/likelihood packages
- Various statistical options (frequentist /Bayesian)
- Fast LHC likelihood calculator
- Massively parallel
- Fully open-source

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

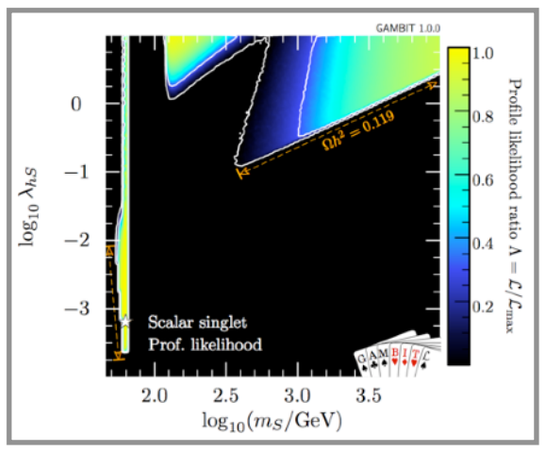
Authors of: BubbleProfiler, Capt'n General, Contur, DarkAges, DarkSUSY, DDCalc, DirectDM, Diver, EasyScanHEP, ExoCLASS, FlexibleSUSY, gamLike, GM2Calc, HEPLike, IsaTools, MARTY, nuLike, PhaseTracer, PolyChord, Rivet, SOFTSUSY, Superlso, SUSY-AI, xsec, Vevacious, WIMPSim

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, ++

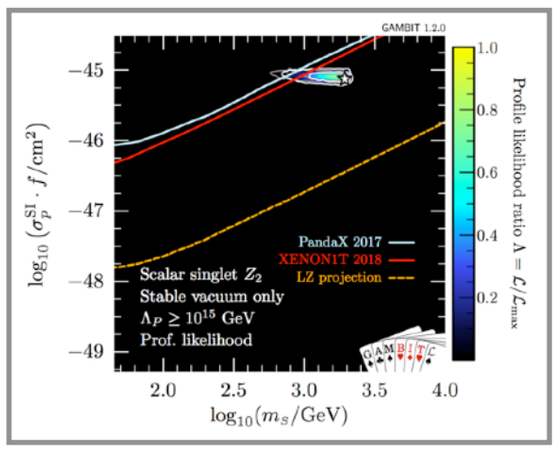
70+ participants in many experiments and numerous major theory codes



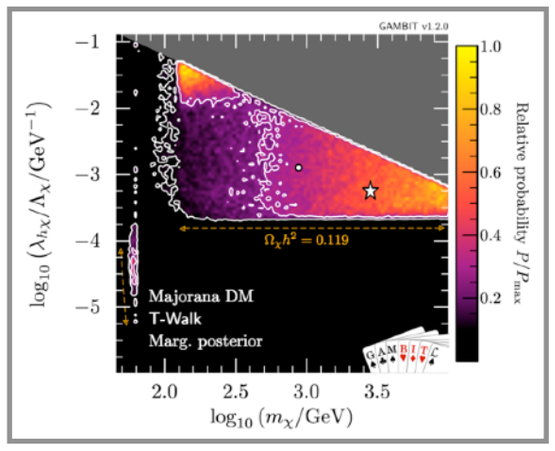
MSSM7: 1705.07917
GUT-scale SUSY: 1705.07935



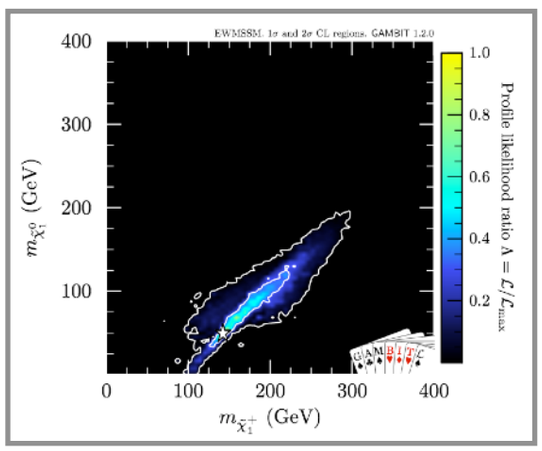
Scalar Higgs portal DM: 1705.07931



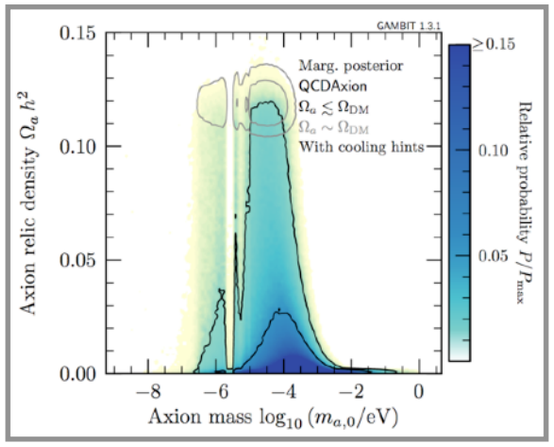
Scalar Higgs portal DM w/ vac. stability: 1806.11281



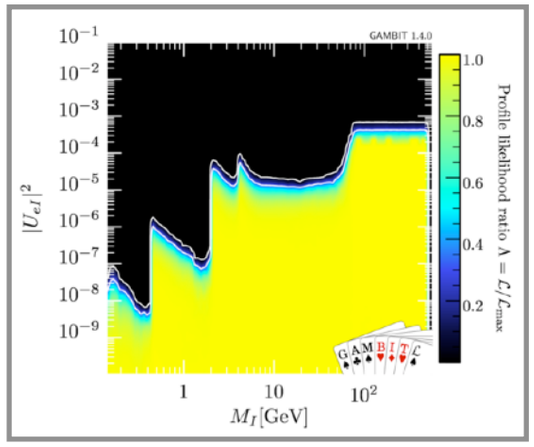
Vector and fermion Higgs portal DM: 1808.10465



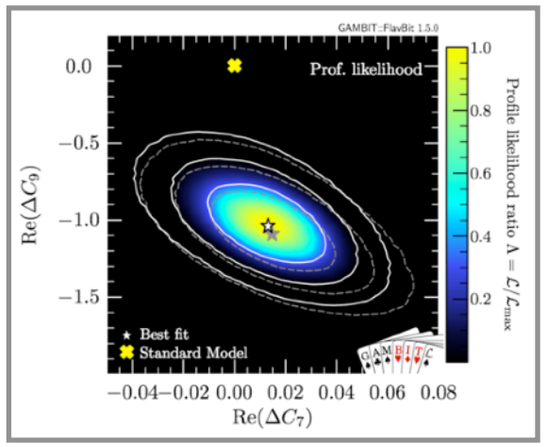
EWMSSM: 1809.02097



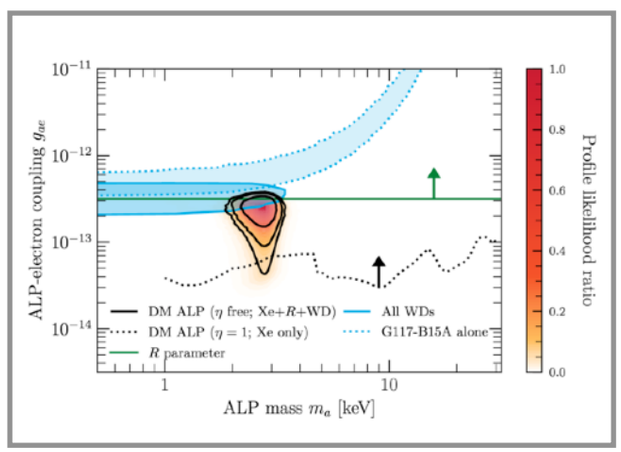
Axion-like particles: 1810.07192



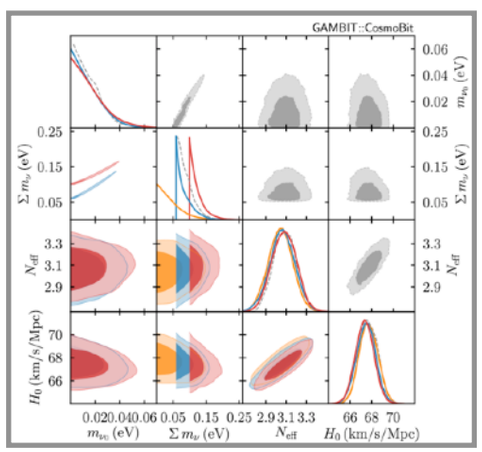
Right-handed neutrinos: 1908.02302



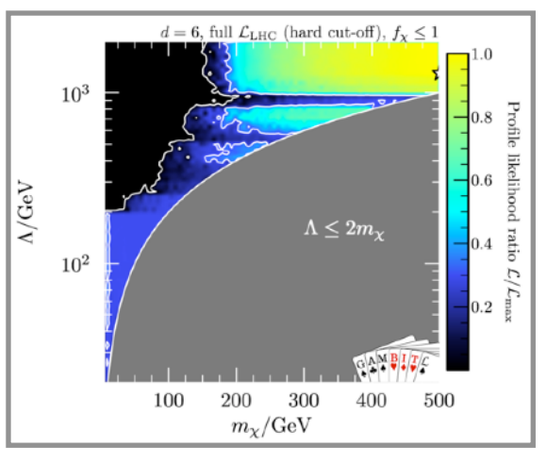
Flavour EFT: 2006.03489



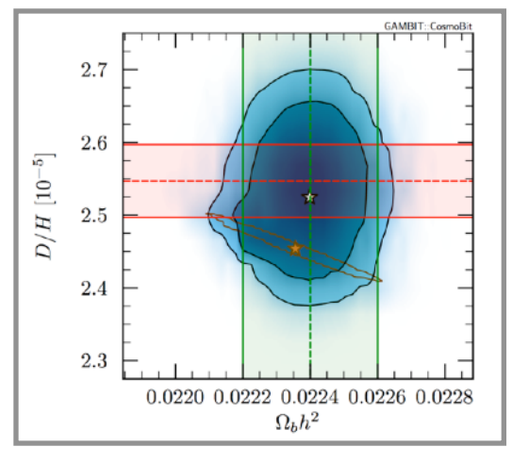
More axion-like particles: 2006.03489



Neutrinos and cosmo: 2009.03287

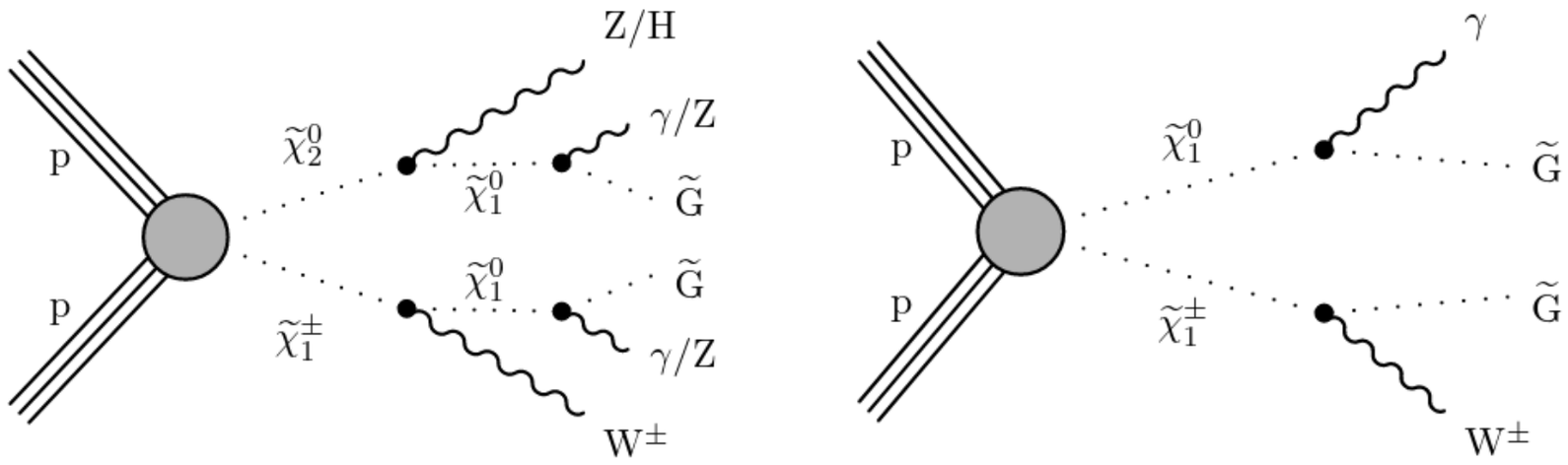


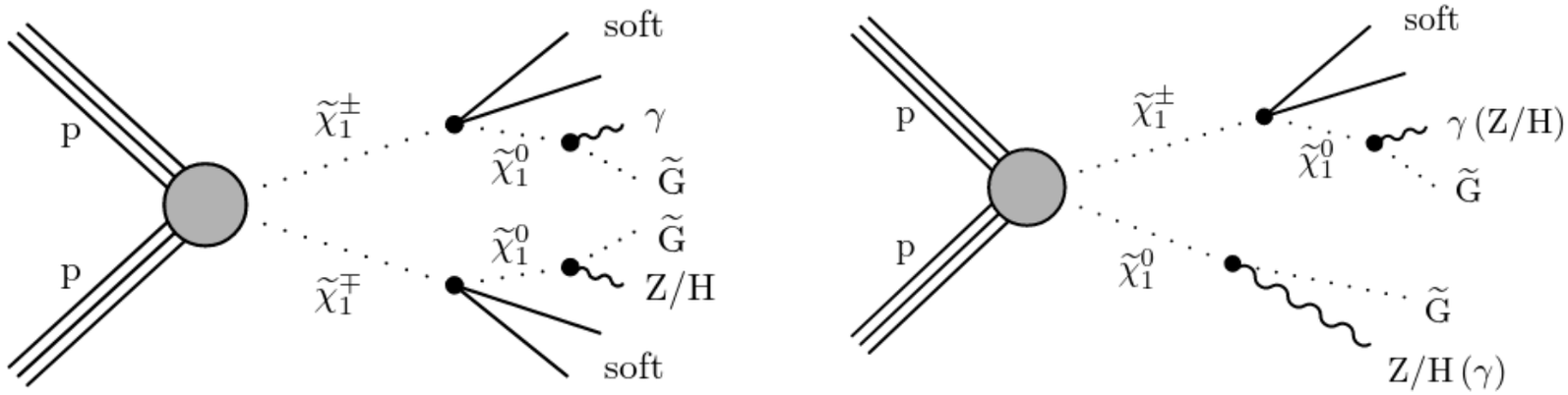
Dark matter EFTs: 2106.02056



Cosmo ALPs: 2205.13549

SUSY w/ light gravitino at the LHC





Typical ATLAS/CMS simplified model:

- Production of lightest neutralinos/charginos
- 1-2 fixed branching ratios
- Near massless gravitino as LSP

Our model: all MSSM EWinos + gravitino

- **Model**: MSSM w/ neutralinos, charginos and gravitino within LHC reach
- **7 SUSY particles below 1 TeV**: 4 neutralinos, 2 charginos, light gravitino
- **4D theory parameter space**: M1, M2, mu, tan beta
- **Why a gravitino?**
  - necessary consequence of supergravity
  - gauge-mediated symmetry breaking (GMSB): gravitino likely the LSP
- Distinct collider pheno: **the lightest neutralino/chargino will decay**
- Gravitino mass fixed to 1 eV → **prompt decay** of lightest neutralino/chargino

Parameter space

M_1 M_2 μ $\tan\beta$

Neutralinos

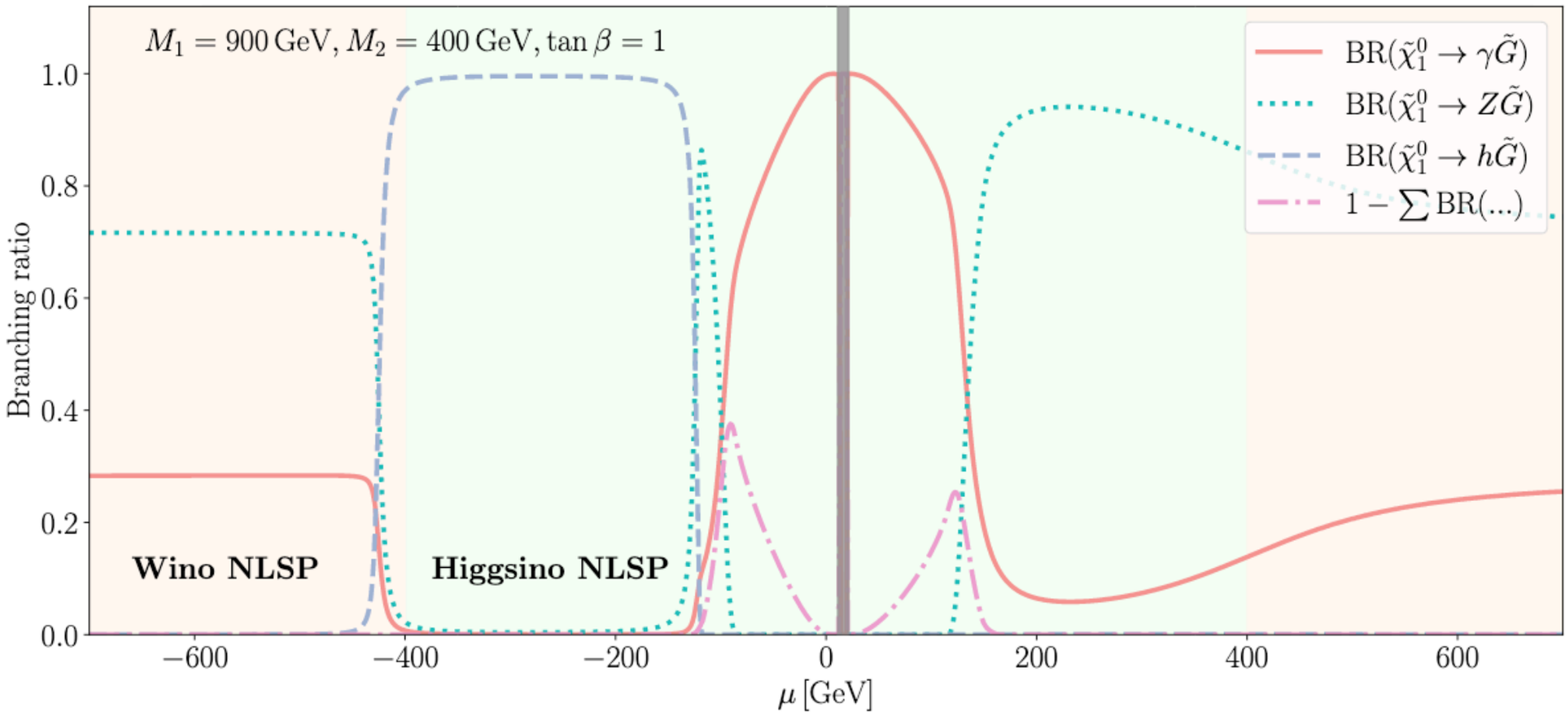
$$\psi^0 = (\tilde{B}, \tilde{W}^0, \tilde{H}_d^0, \tilde{H}_u^0)$$

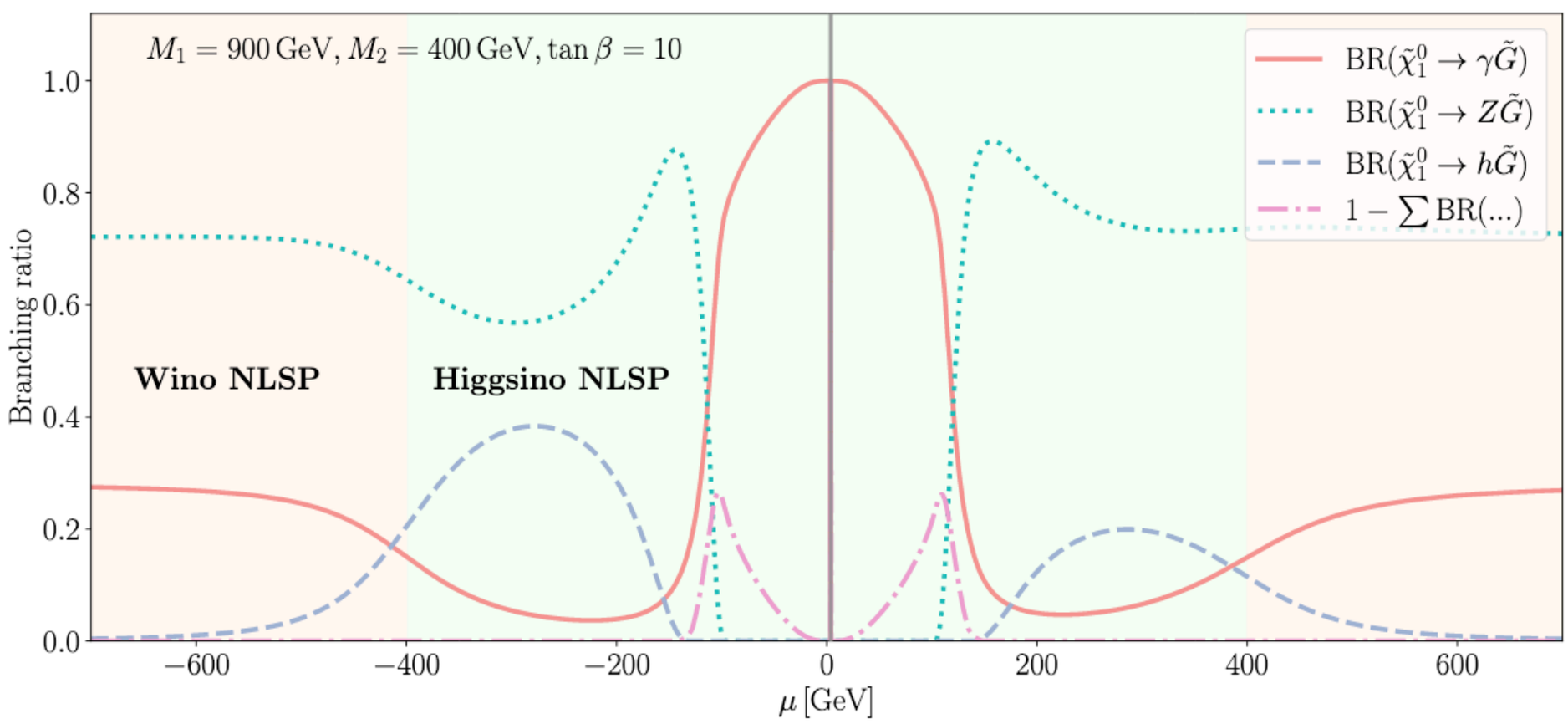
$$M_N = \begin{pmatrix} M_1 & 0 & -\frac{1}{2}g'vc_\beta & \frac{1}{2}g'vs_\beta \\ 0 & M_2 & \frac{1}{2}gvc_\beta & -\frac{1}{2}gvs_\beta \\ -\frac{1}{2}g'vc_\beta & \frac{1}{2}gvc_\beta & 0 & -\mu \\ \frac{1}{2}g'vs_\beta & -\frac{1}{2}gvs_\beta & -\mu & 0 \end{pmatrix}$$

Charginos

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

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


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

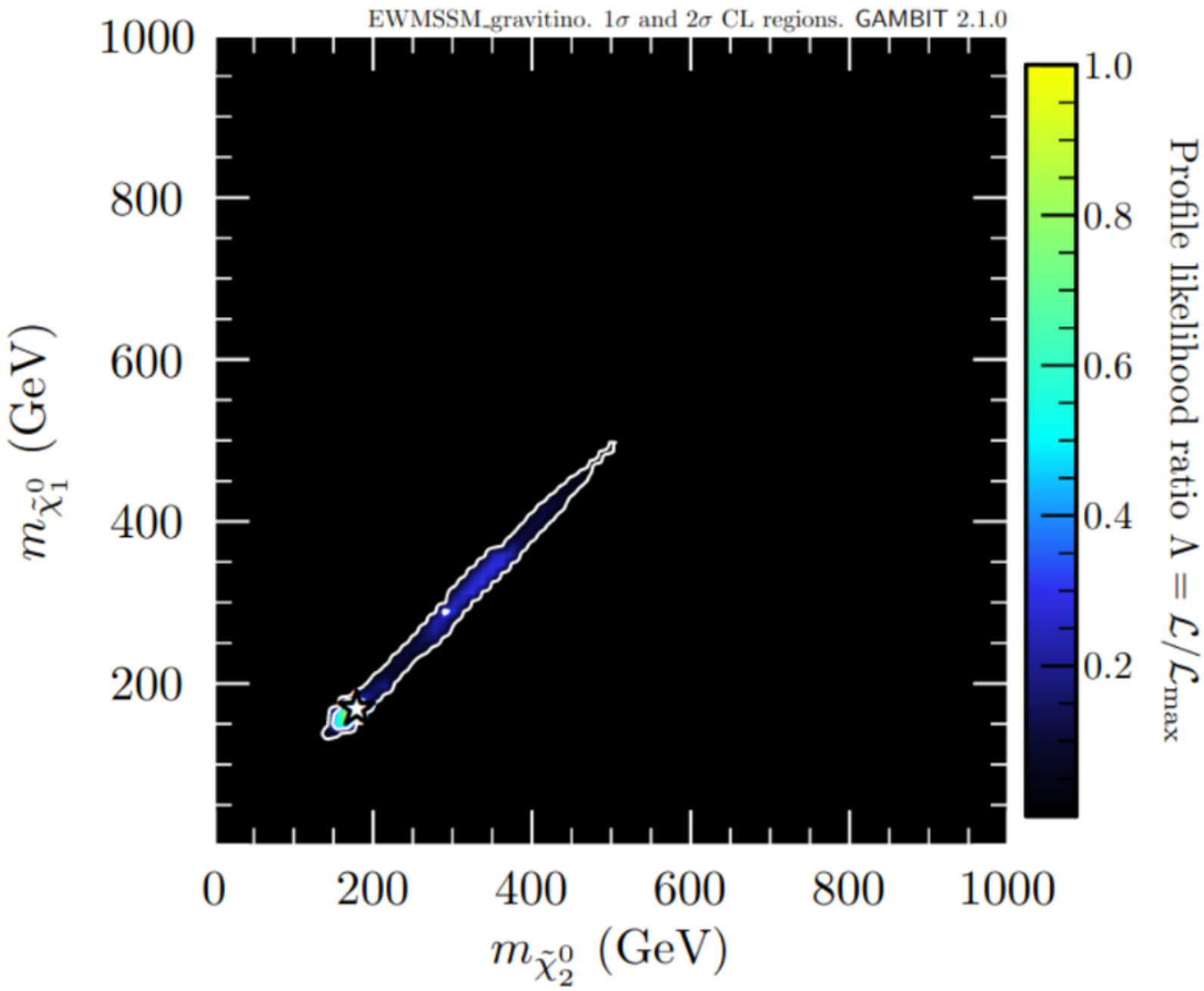

$M_1 = 900\,\text{GeV}, M_2 = 400\,\text{GeV}, \tan\beta = 10$
$\text{BR}(\tilde{\chi}_1^0 \to \gamma\tilde{G})$
$\text{BR}(\tilde{\chi}_1^0 \to Z\tilde{G})$
$\text{BR}(\tilde{\chi}_1^0 \to h\tilde{G})$
$1 - \sum \text{BR}(...)$
Wino NLSP
Higgsino NLSP
Branching ratio
μ [GeV]

Analysis

- Series of parameter scans w/ GAMBIT
- Scanner: **Diver** (differential evolution)
- Per point: **simulate 16M SUSY events** (Pythia, via ColliderBit)
- CPU cost: tens of millions of CPU hours…
- **Likelihoods**:
  - **ATLAS & CMS searches** (in ColliderBit)
  - **ATLAS & CMS «SM measurements»** (Contur+Rivet, via ColliderBit)
  - apply relevant LEP cross-section limits (in ColliderBit)

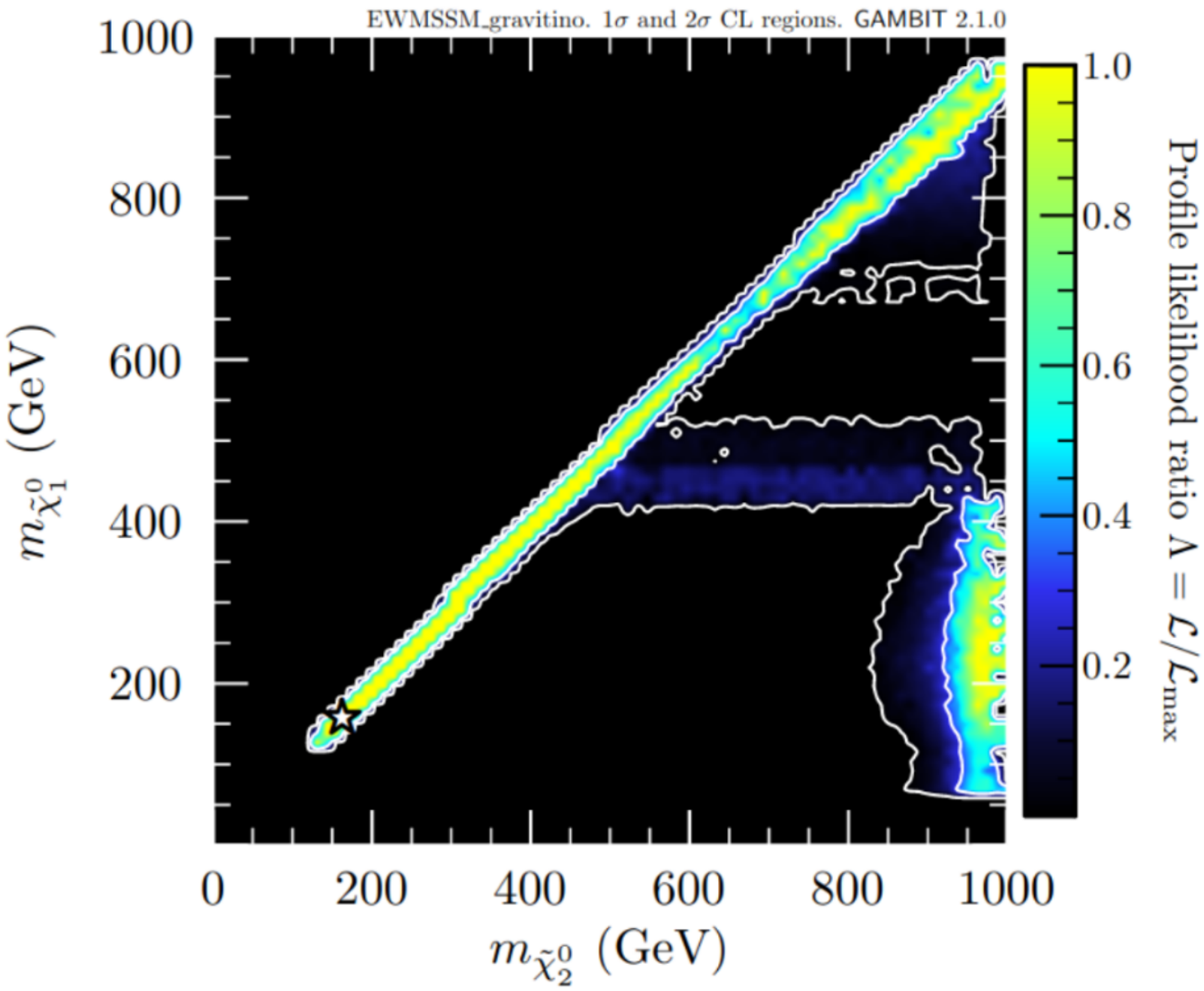
Preliminary results

Profile likelihood ratio



Preliminary results

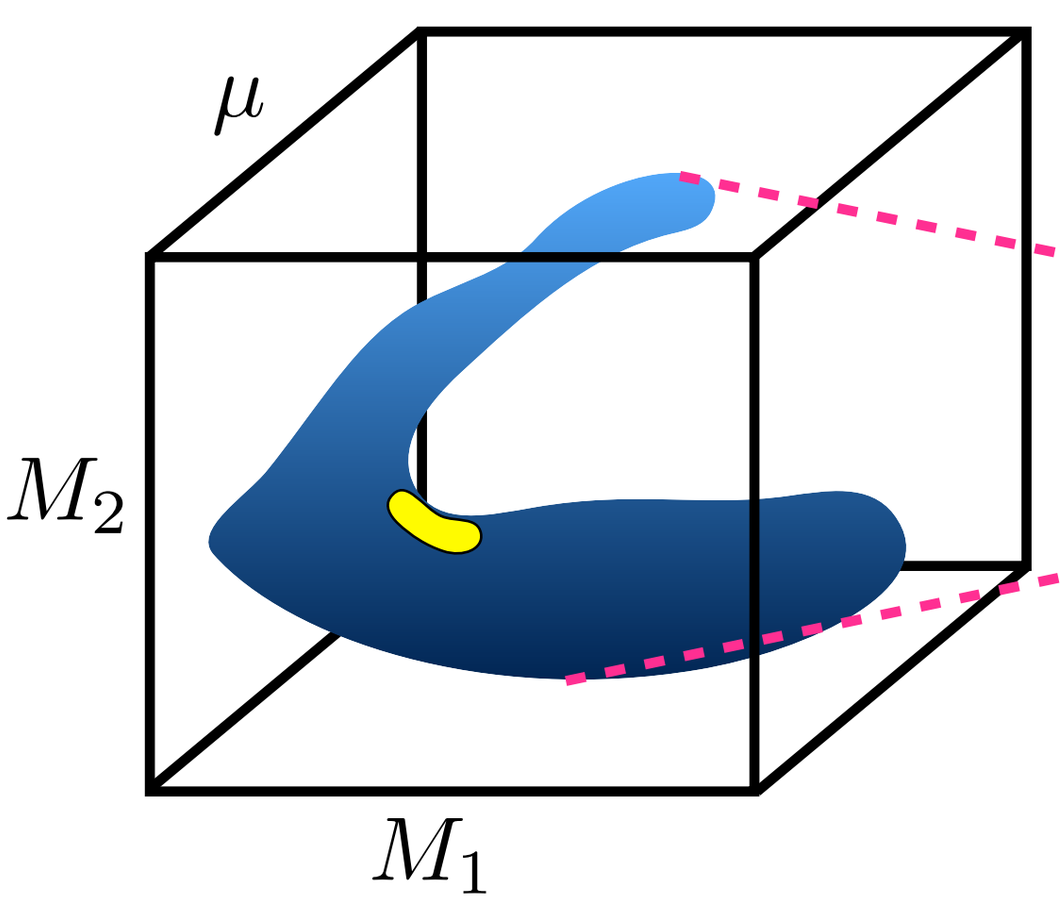
Profile likelihood ratio, likelihood capped at SM expectation (s=0)

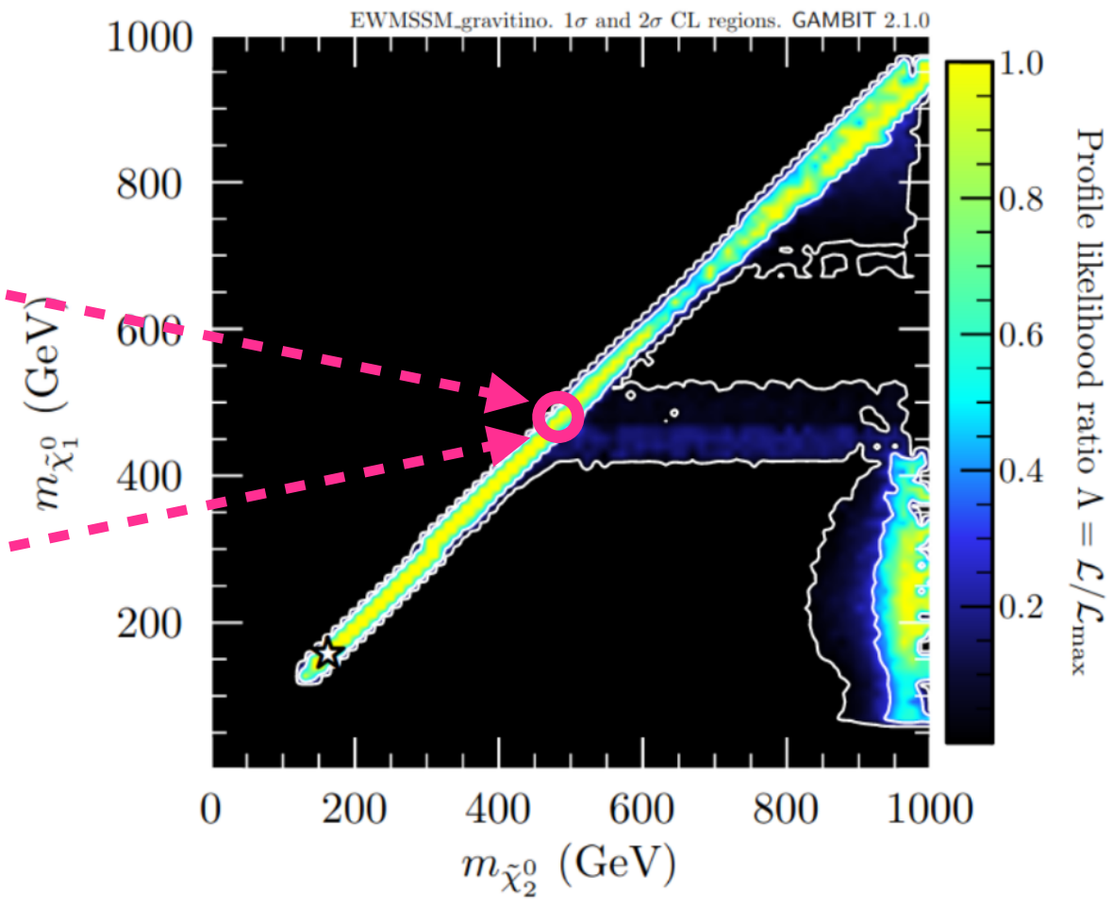


Preliminary results

Interpretation: A yellow point means that there is *at least one point* in the G-EWMSSM parameter space that fits the data as well as (or better than) the SM expectation.

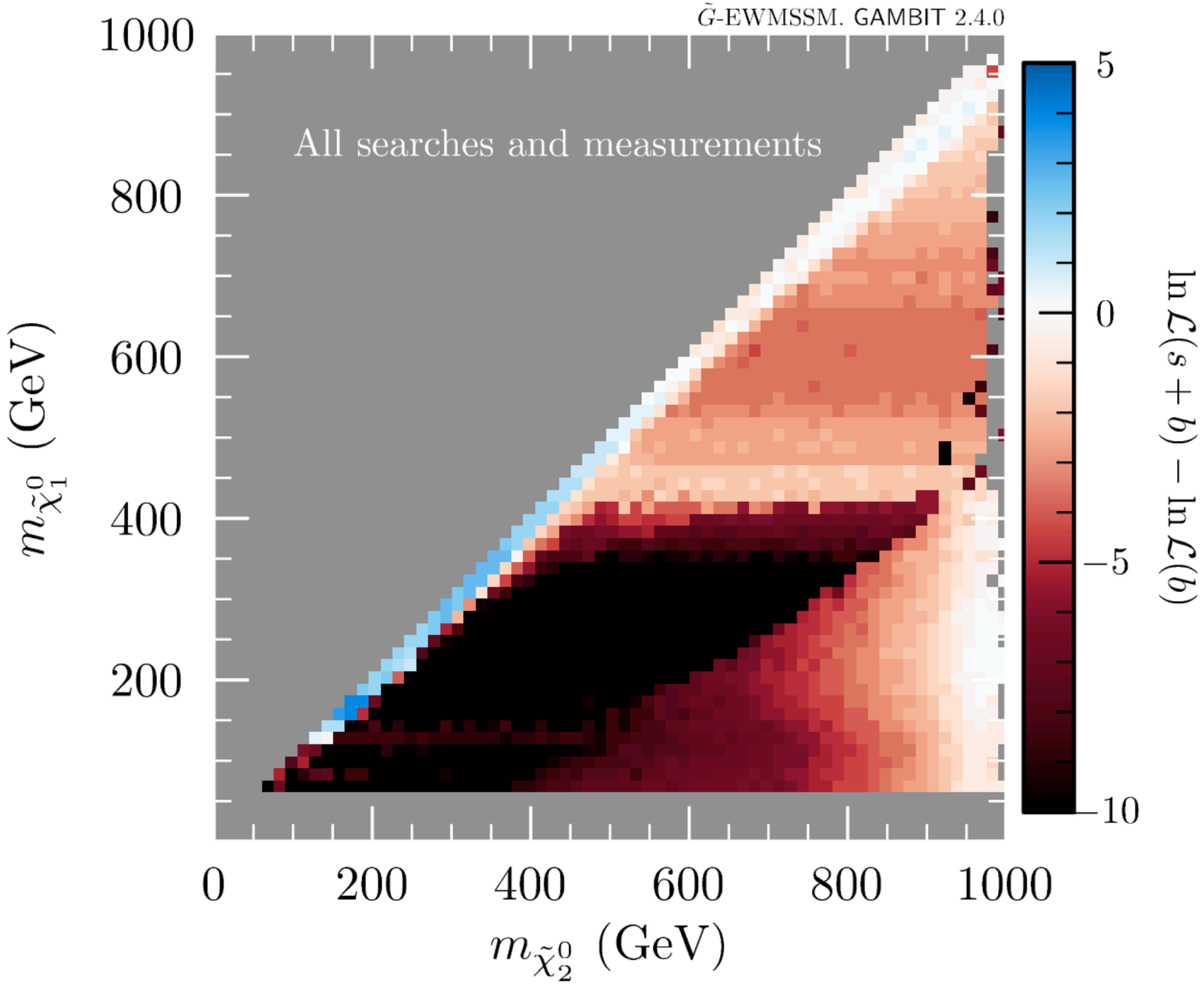
This does not tell us anything about *the size* of the viable parameter space…





Preliminary results

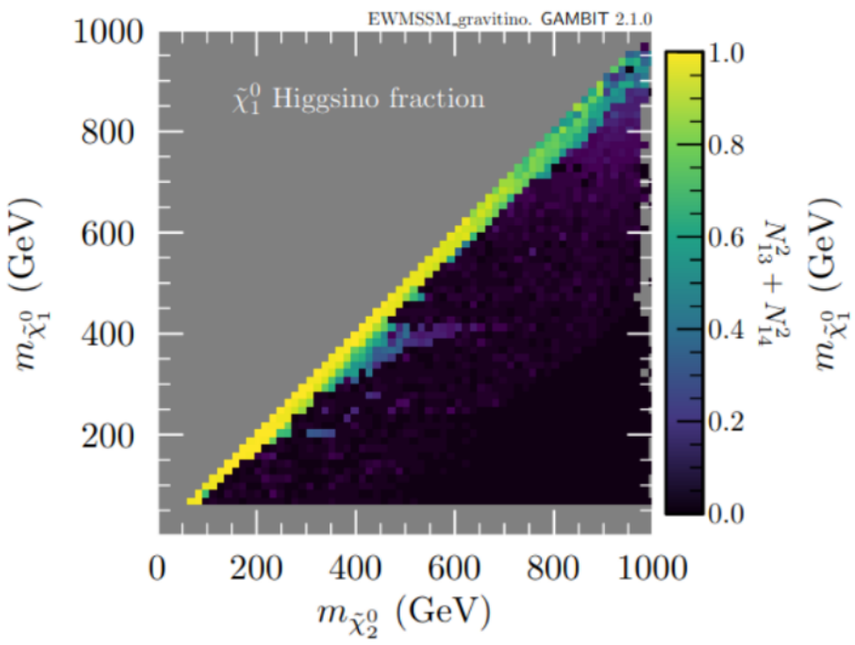
ln L(s+b) - ln L(b)



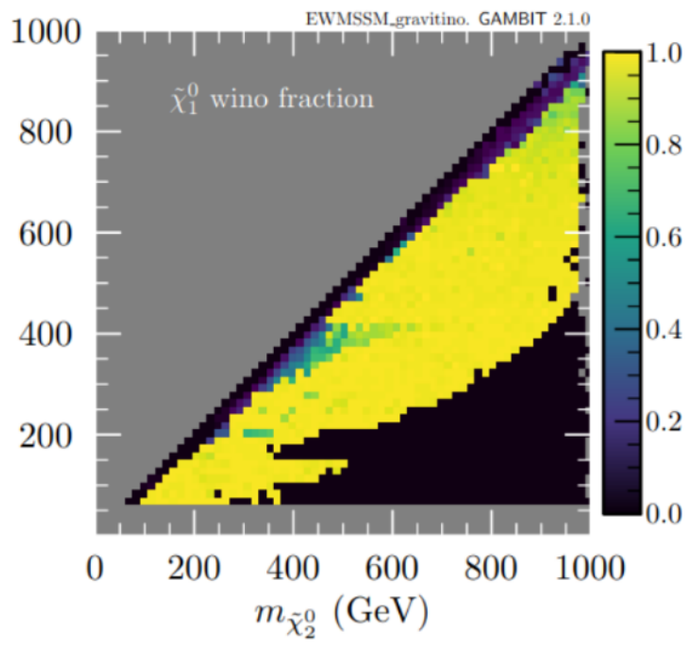
Preliminary results

Profiling picks out **different theory scenarios** in **different regions of the mass plane**

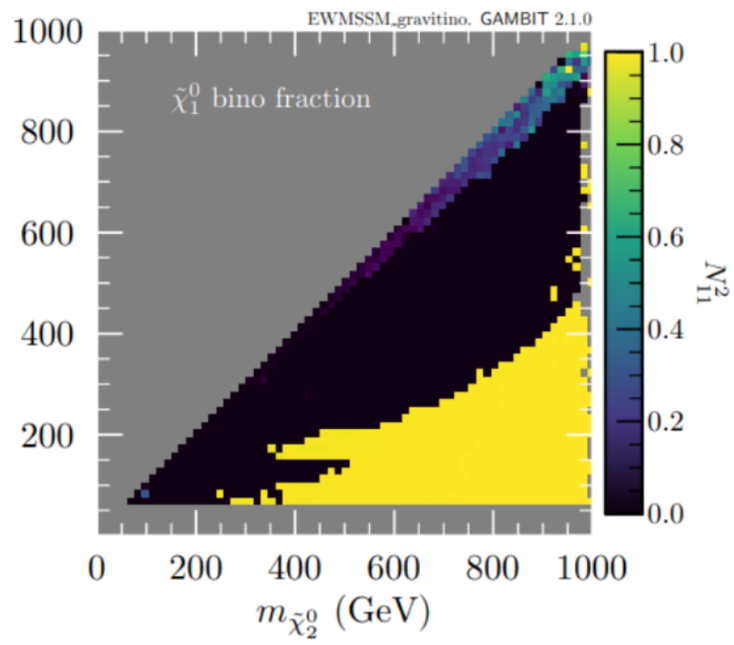
$\tilde{\chi}_0^1$ Higgsino fraction



$\tilde{\chi}_0^1$ wino fraction

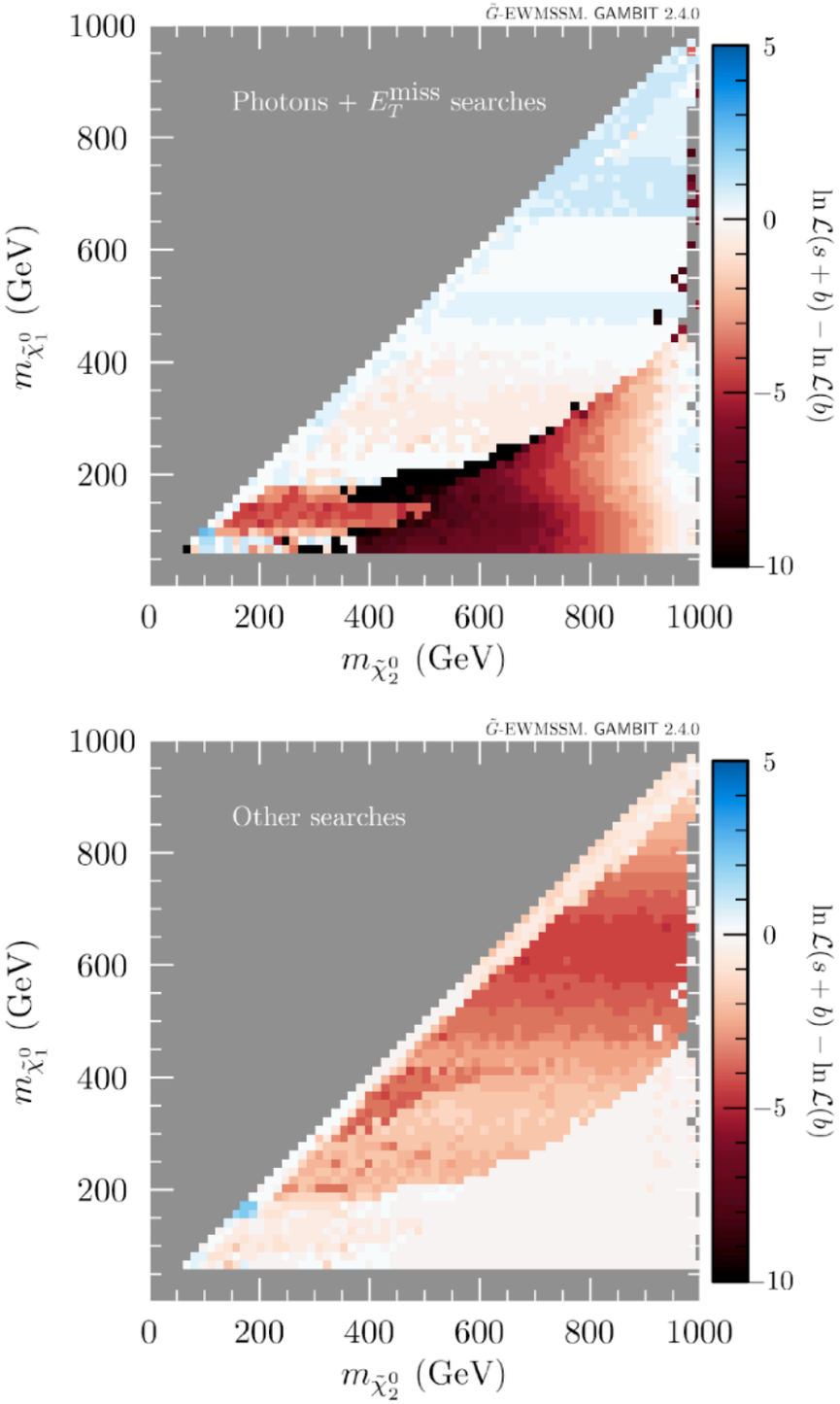


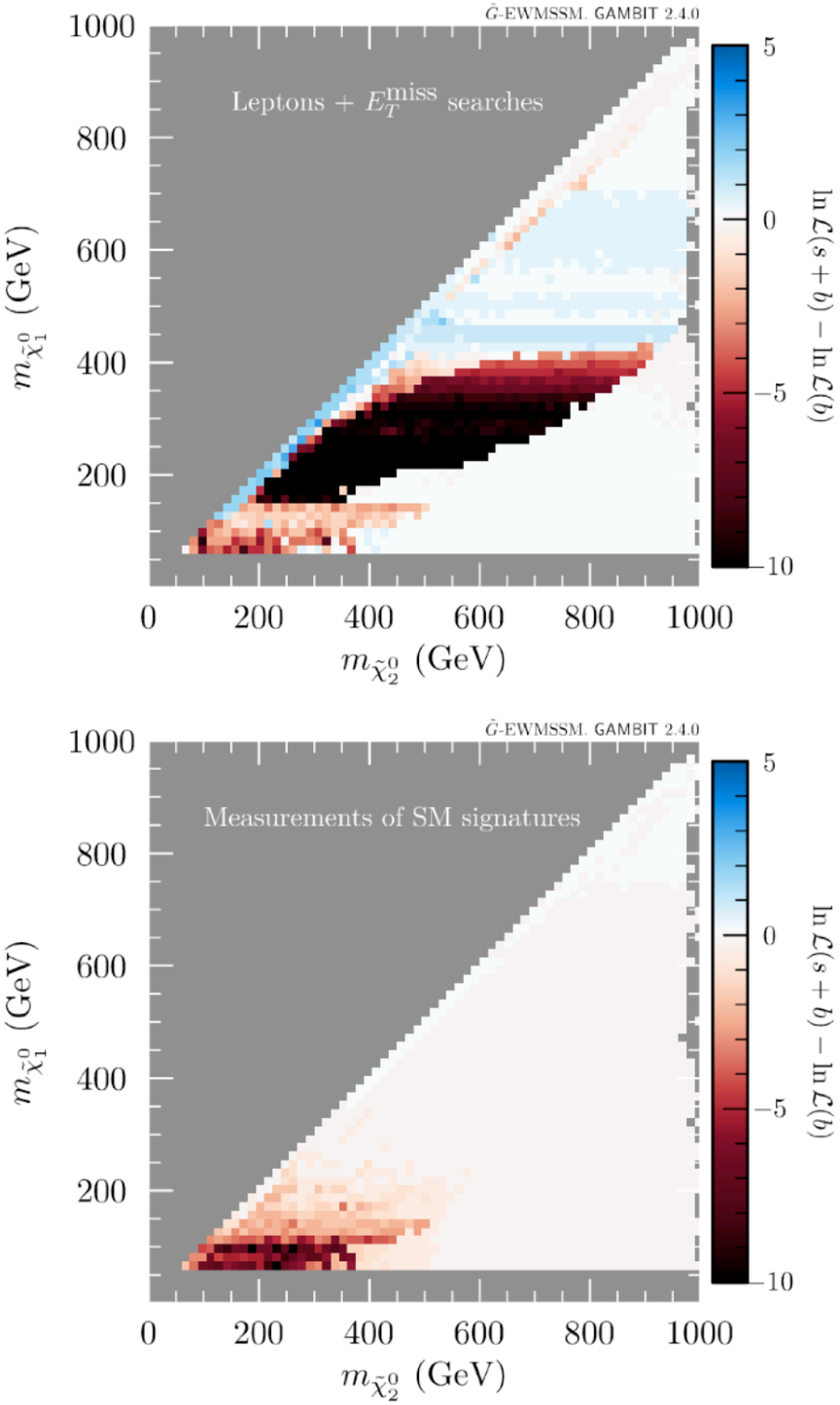
$\tilde{\chi}_0^1$ bino fraction



Preliminary results

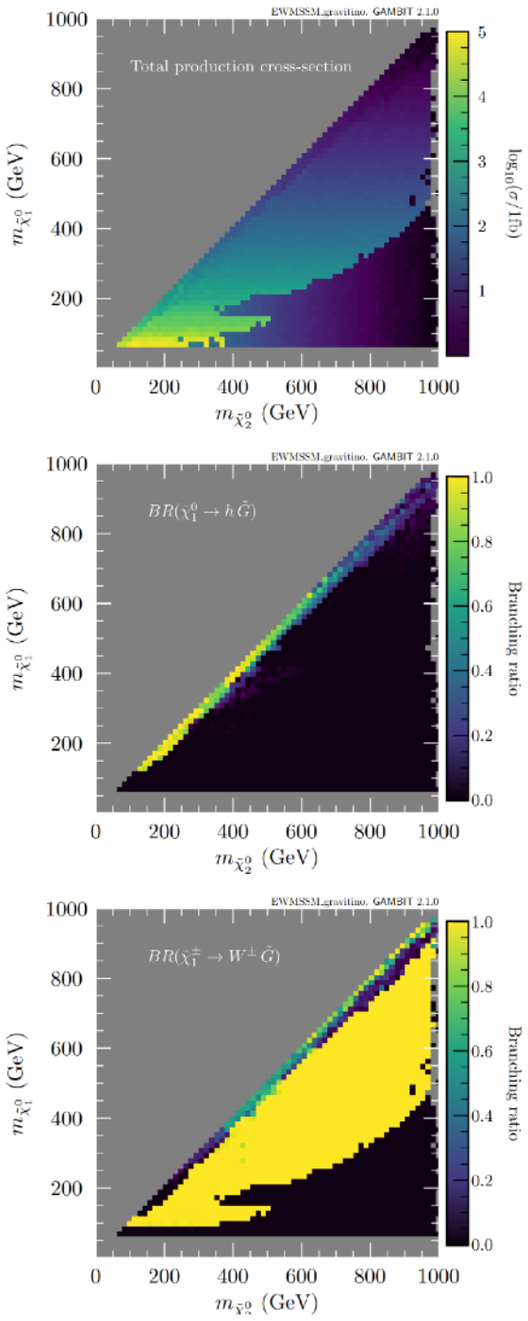
Impact of different classes of searches/measurements

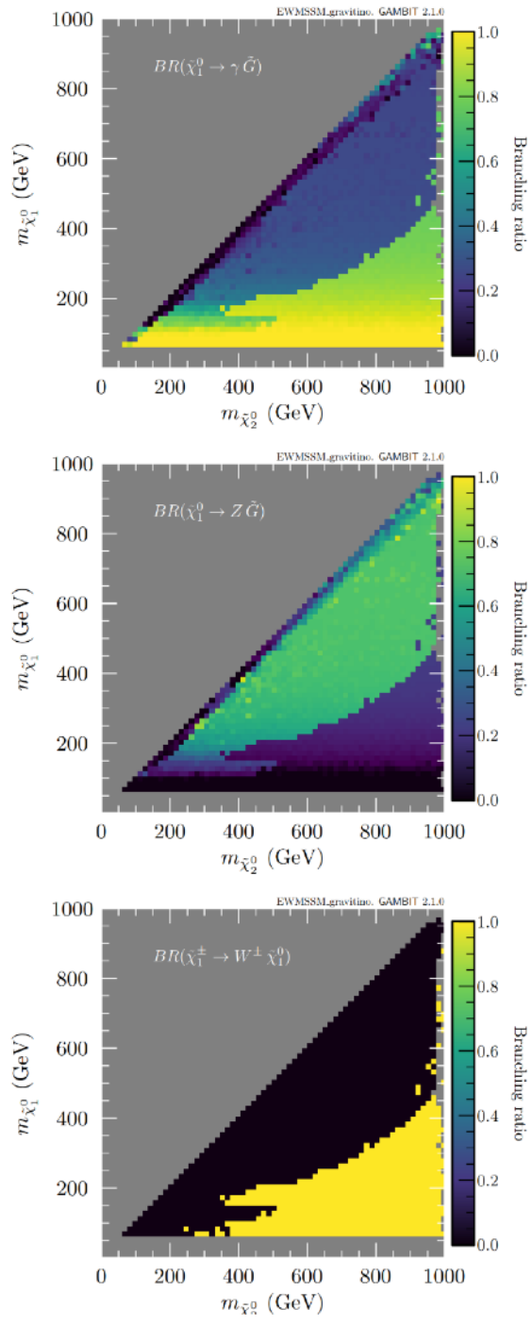


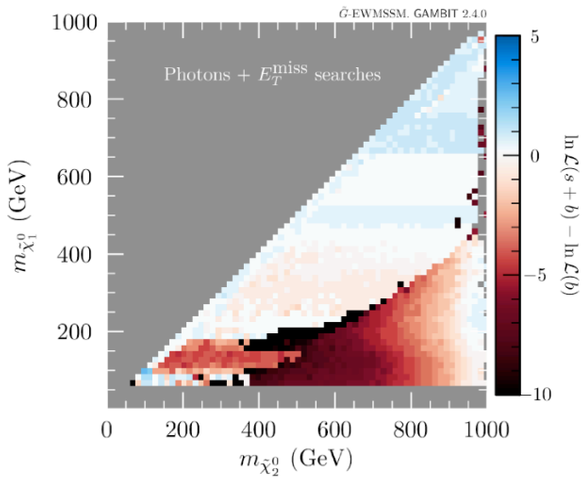


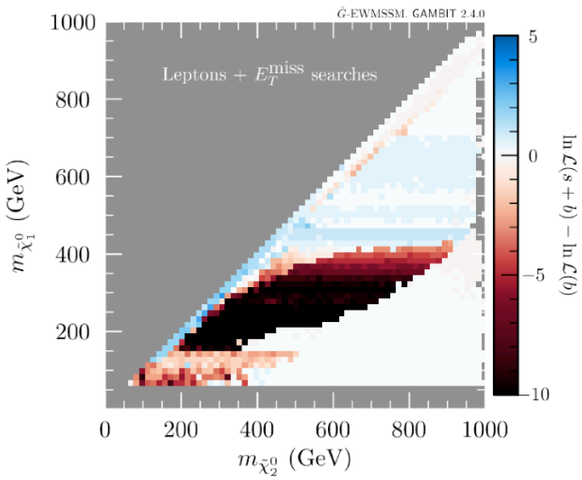
Preliminary results

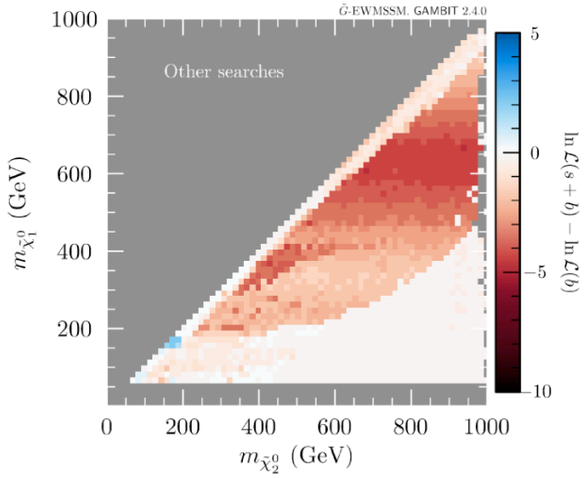
Structure of results explained by **collection of experimental results** + **profiling** + **pattern of BRs** + **total production cross-section**

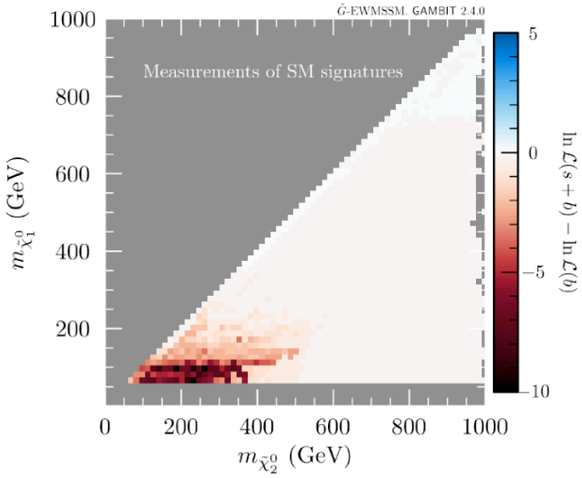






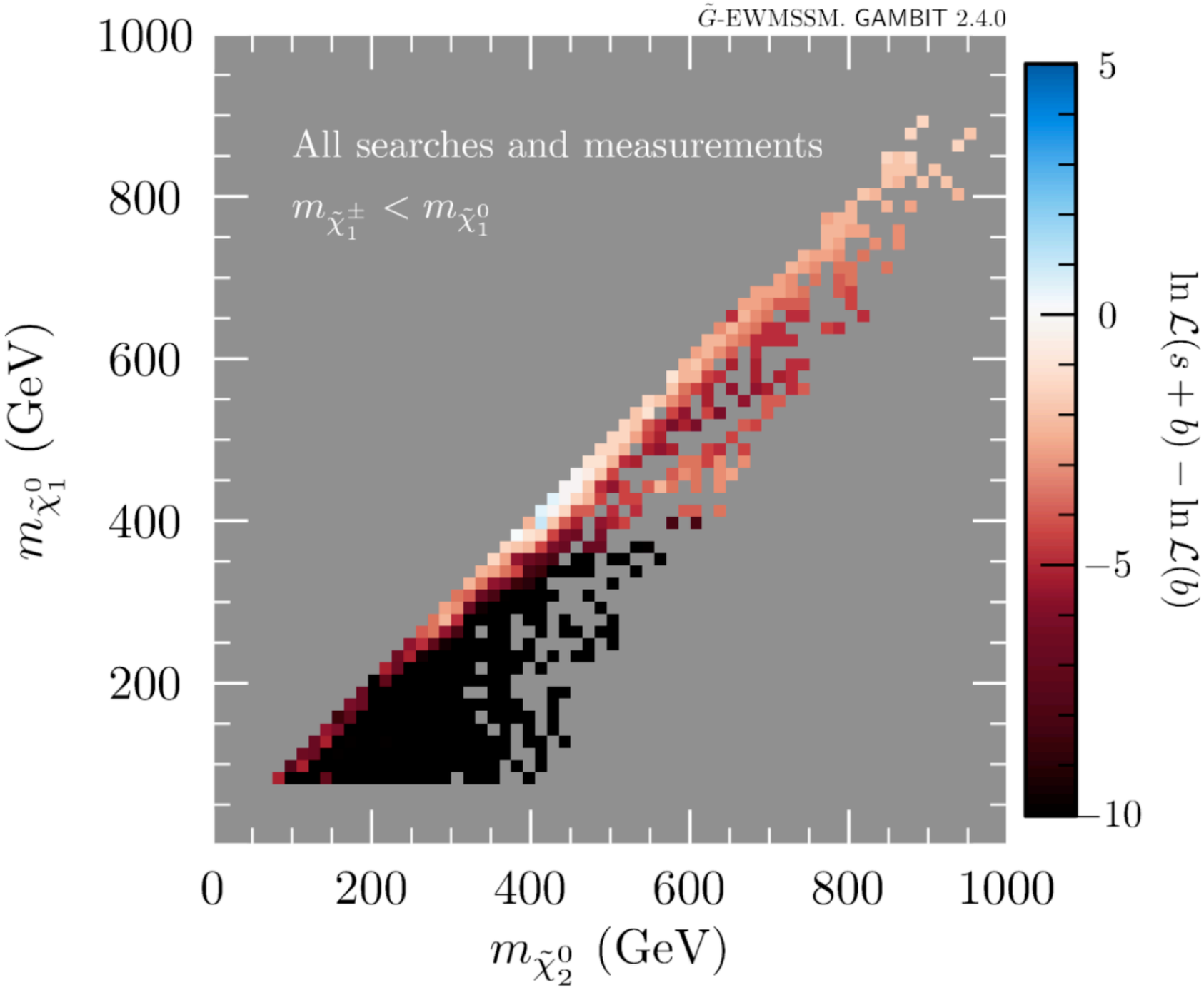






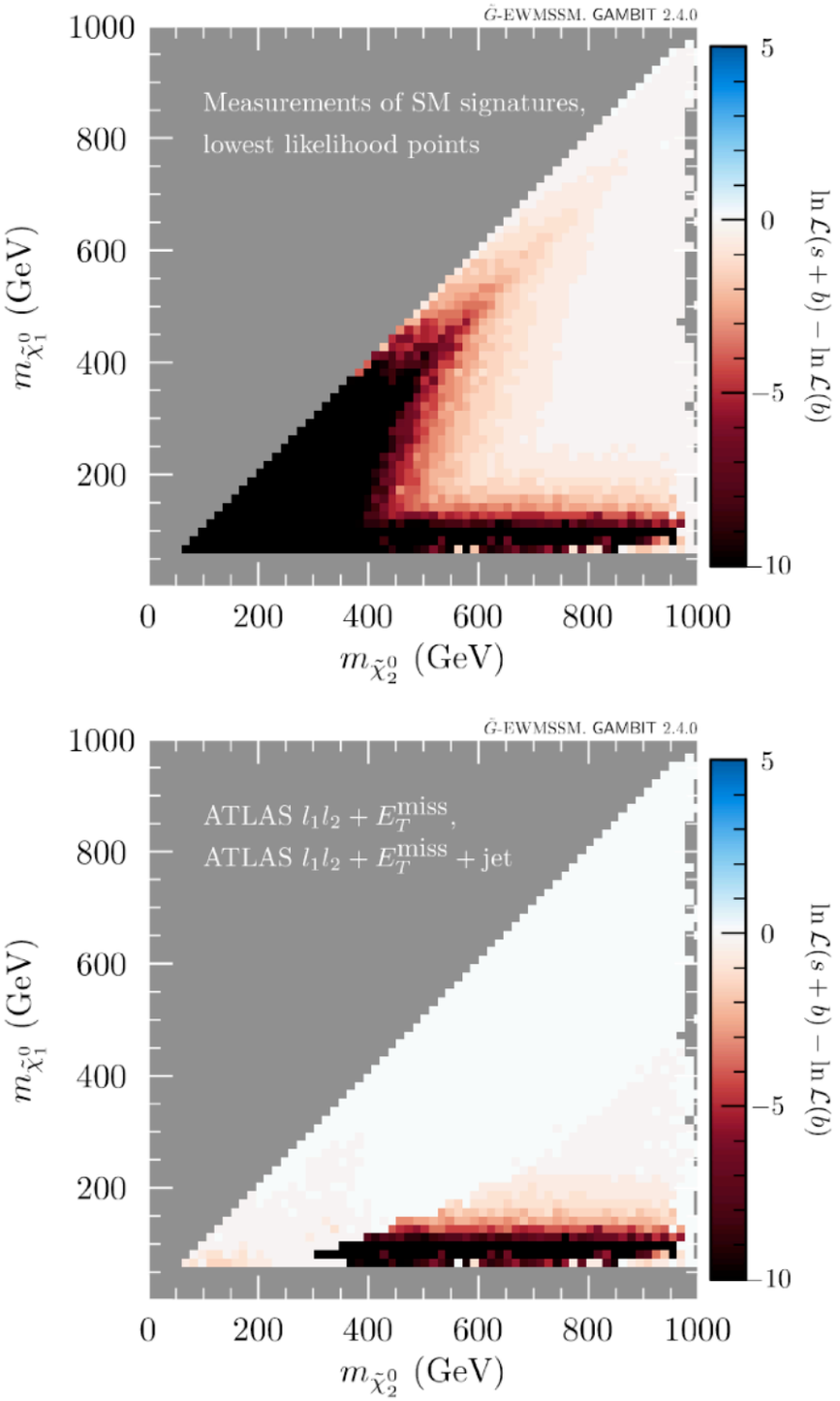
Preliminary results

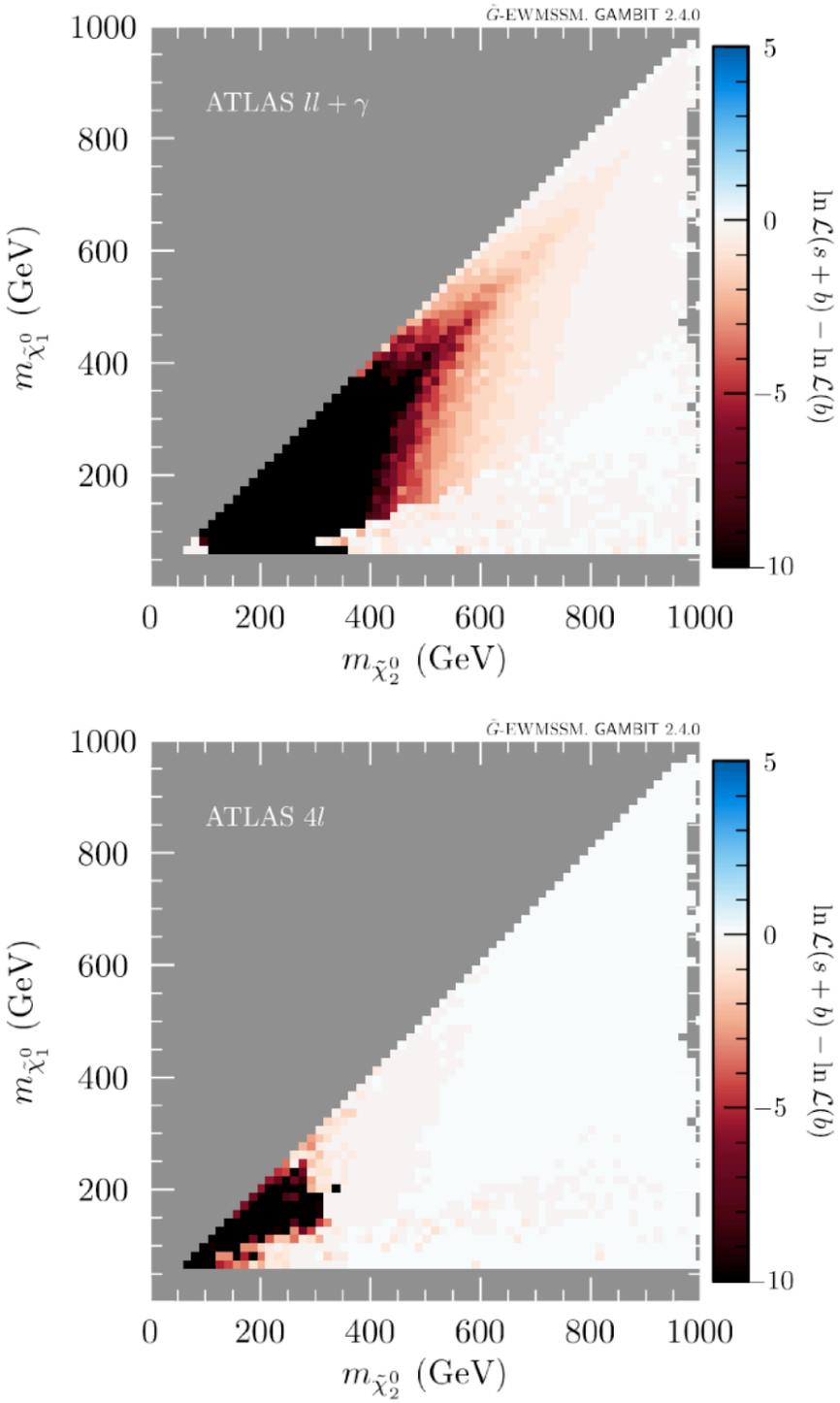
Can have a chargino lighter than the lightest neutralino



Preliminary results

Points most constrained by the «SM measurements» alone





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

- **New GAMBIT study:** LHC impact on SUSY w/ light gravitino
  - Largest proper global fit with full collider event simulations
  - First time we include LHC «SM measurements» w/ full event simulations
  - Weak preference for Higgsinos ~ 200 GeV
    (small excesses in MET+leptons/jets searches)
  - Difficult to exclude: lightest EWinos as mostly, but not pure, Higgsinos
  - Demonstrates importance of recasting LHC results in non-simplified models
  - Results will be publicly available: zenodo.org/communities/gambit-official

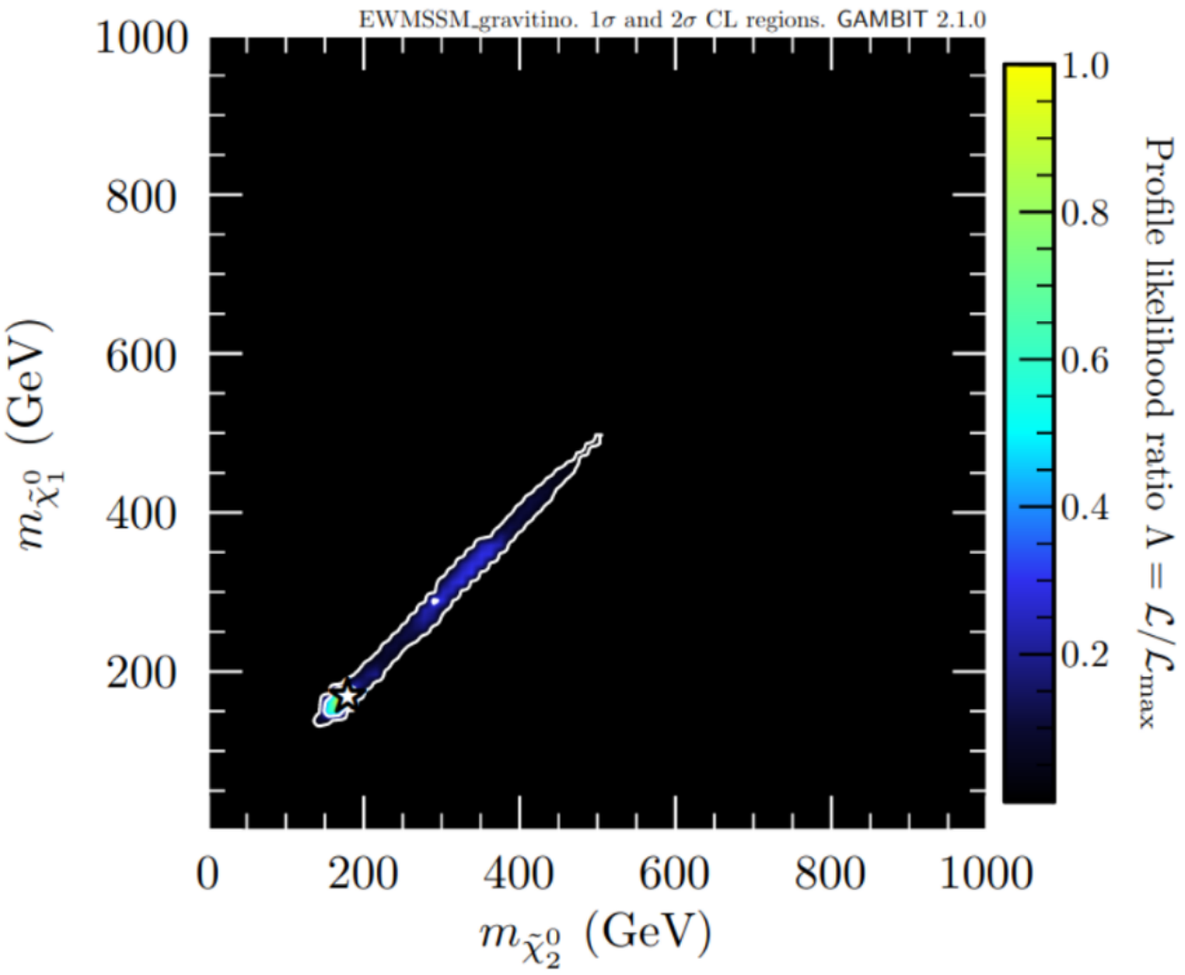
Bonus tracks

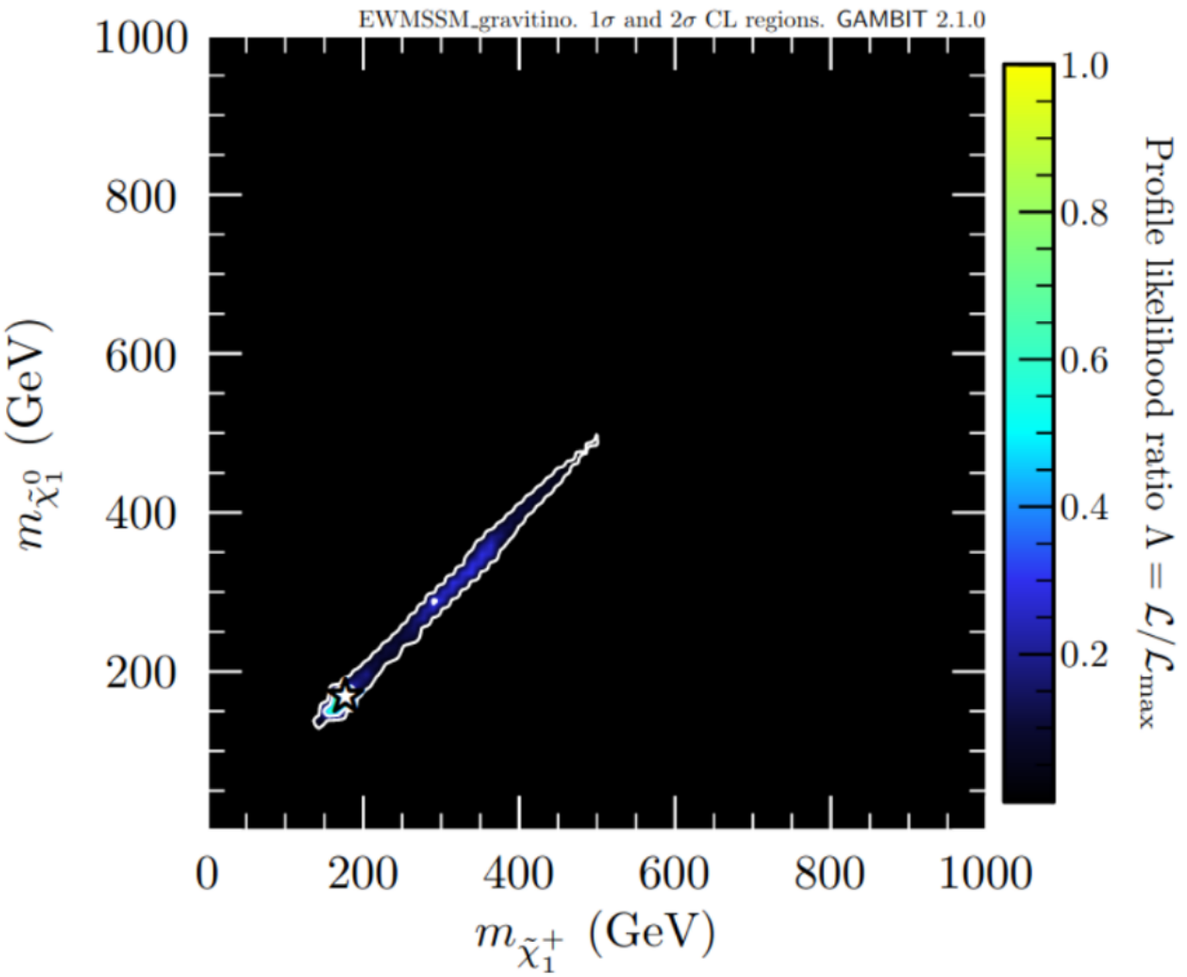
LHC searches:

Search label	Luminosity	Source
ATLAS_2BoostedBosons	$139\,\mathrm{fb}^{-1}$	ATLAS hadronic chargino/neutralino search [102]
ATLAS_0lep	$139\,\mathrm{fb}^{-1}$	ATLAS 0-lepton search [94]
ATLAS_0lep_stop	$36\,\mathrm{fb}^{-1}$	ATLAS 0-lepton stop search [103]
ATLAS_1lep_stop	$36\,\mathrm{fb}^{-1}$	ATLAS 1-lepton stop search [104]
ATLAS_2lep_stop	$139\,\mathrm{fb}^{-1}$	ATLAS 2-lepton stop search [105]
ATLAS_2OSlep_Z	$139\,\mathrm{fb}^{-1}$	ATLAS stop search with Z/H final states [107]
ATLAS_2OSlep_chargino	$139\,\mathrm{fb}^{-1}$	ATLAS 2-lepton chargino search [95]
ATLAS_2b	$36\,\mathrm{fb}^{-1}$	ATLAS 2-b-jet stop/sbottom search [108]
ATLAS_3b	$24\,\mathrm{fb}^{-1}$	ATLAS 3-b-jet Higgsino search [109]
ATLAS_3lep	$139\,\mathrm{fb}^{-1}$	ATLAS 3-lepton chargino/neutralino search [96]
ATLAS_4lep	$139\,\mathrm{fb}^{-1}$	ATLAS 4-lepton search [97]
ATLAS_MultiLep_strong	$139\,\mathrm{fb}^{-1}$	ATLAS leptons + jets search [98]
ATLAS_PhotonGGM_1photon	$139\,\mathrm{fb}^{-1}$	ATLAS 1-photon GGM search [110]
ATLAS_PhotonGGM_2photon	$36\,\mathrm{fb}^{-1}$	ATLAS 2-photon GGM search [111]
ATLAS_Z_photon	$80\,\mathrm{fb}^{-1}$	ATLAS Z + photon search [112]
CMS_0lep	$137\,\mathrm{fb}^{-1}$	CMS 0-lepton search [113]
CMS_1lep_bb	$36\,\mathrm{fb}^{-1}$	CMS 1-lepton + b-jets chargino/neutralino search [115]
CMS_1lep_stop	$36\,\mathrm{fb}^{-1}$	CMS 1-lepton stop search [116]
CMS_2lep_stop	$36\,\mathrm{fb}^{-1}$	CMS 2-lepton stop search [117]
CMS_2lep_soft	$36\,\mathrm{fb}^{-1}$	CMS 2 soft lepton search [118]
CMS_2OSlep	$137\,\mathrm{fb}^{-1}$	CMS 2-lepton search [119]
CMS_2OSlep_chargino_stop	$36\,\mathrm{fb}^{-1}$	CMS 2-lepton chargino/stop search [120]
CMS_2SSlep_stop	$137\,\mathrm{fb}^{-1}$	CMS 2 same-sign lepton stop search [121]
CMS_MultiLep	$137\,\mathrm{fb}^{-1}$	CMS multilepton chargino/neutralino search [100]
CMS_photon	$36\,\mathrm{fb}^{-1}$	CMS 1-photon GMSB search [122]
CMS_2photon	$36\,\mathrm{fb}^{-1}$	CMS 2-photon GMSB search [123]
CMS_1photon_1lepton	$36\,\mathrm{fb}^{-1}$	CMS 1-photon + 1-lepton GMSB search [124]

Preliminary results

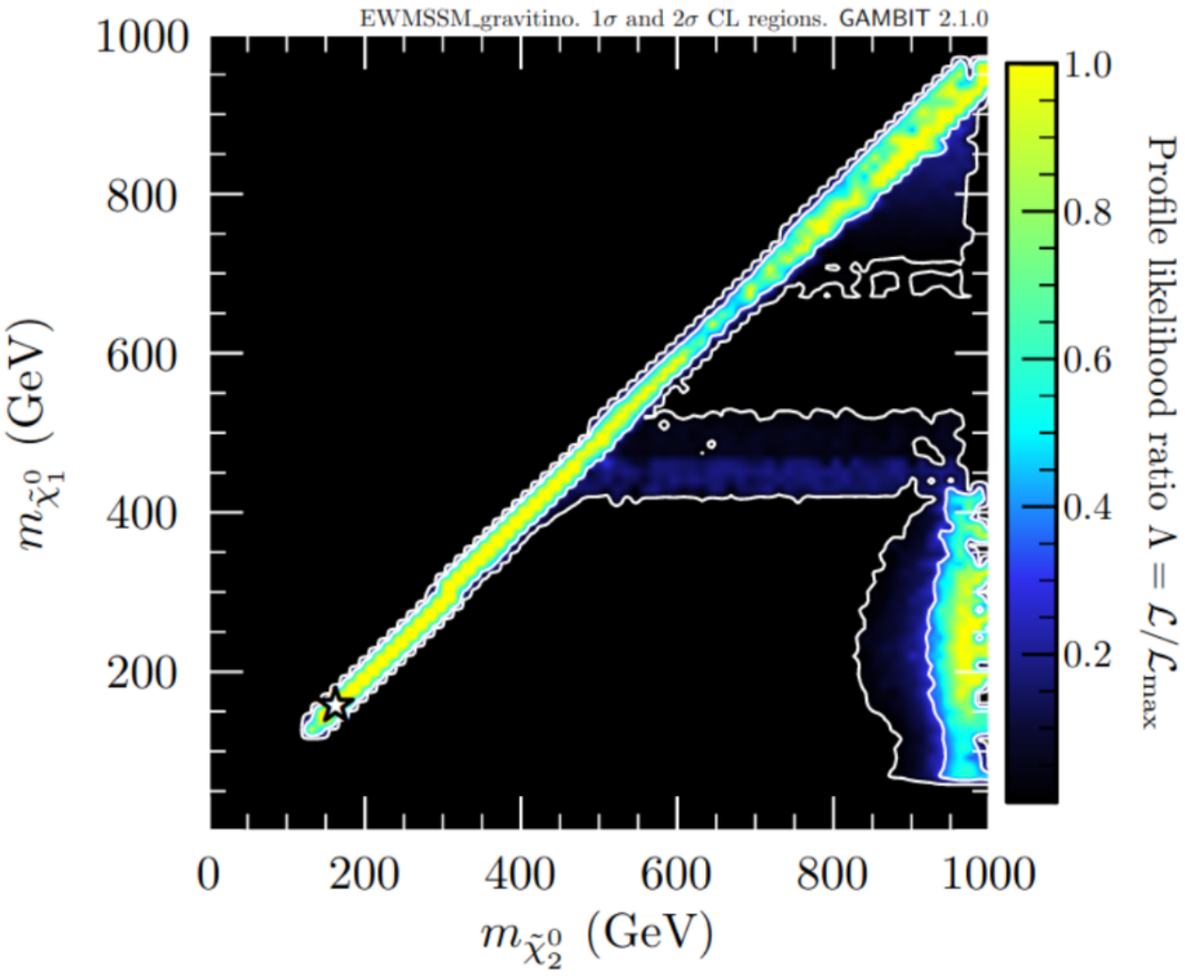
Profile likelihood ratio

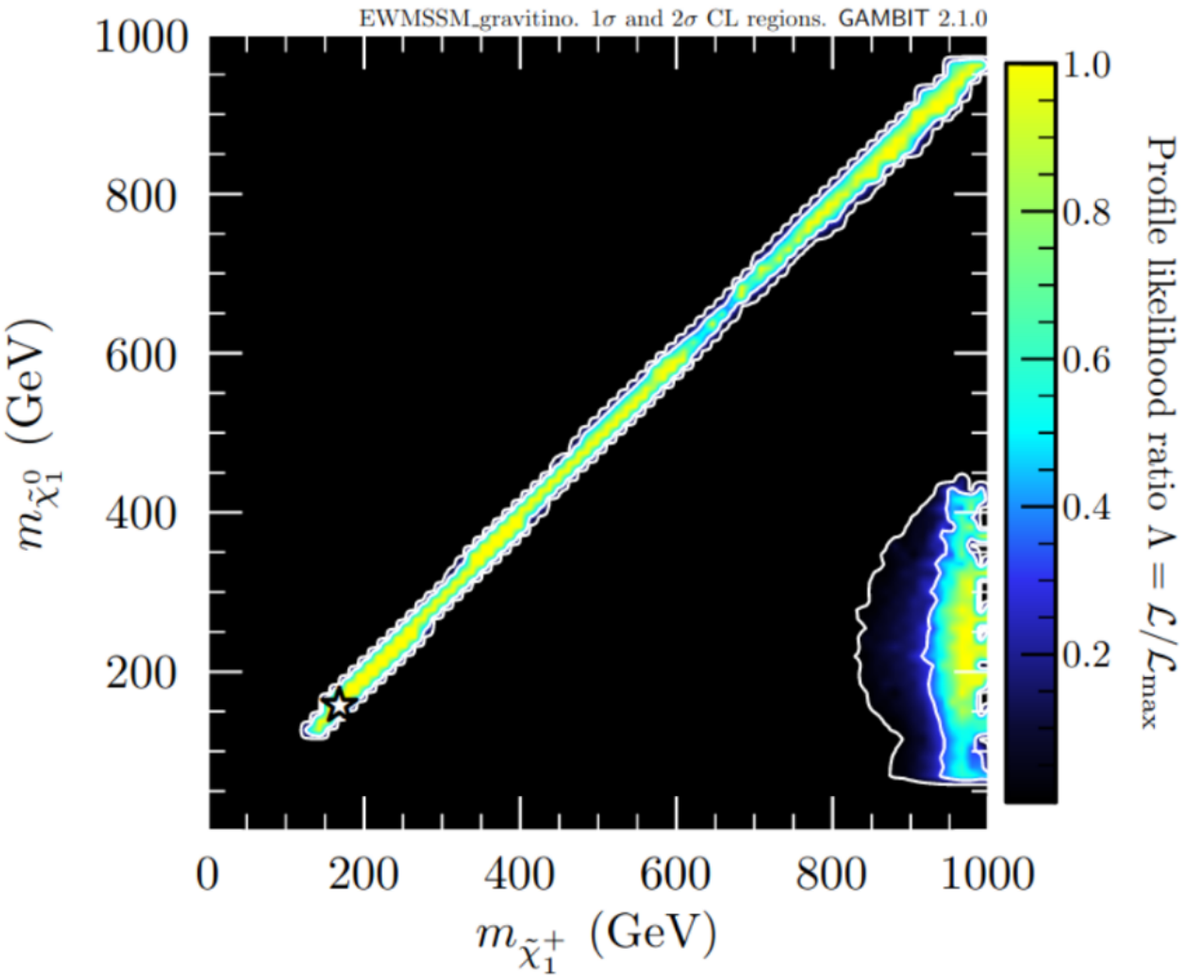




Preliminary results

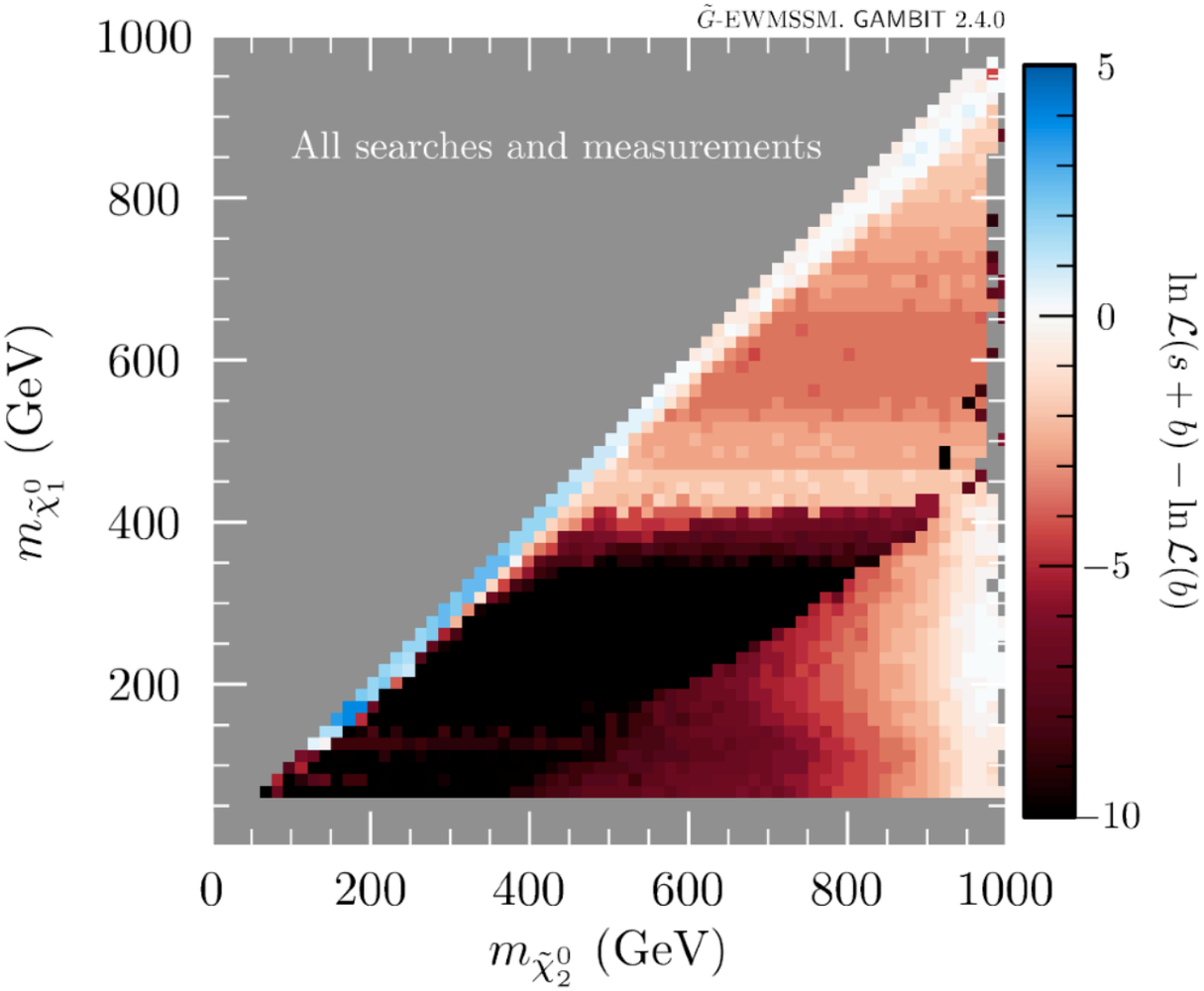
Profile likelihood ratio, likelihood capped at SM expectation (s=0)

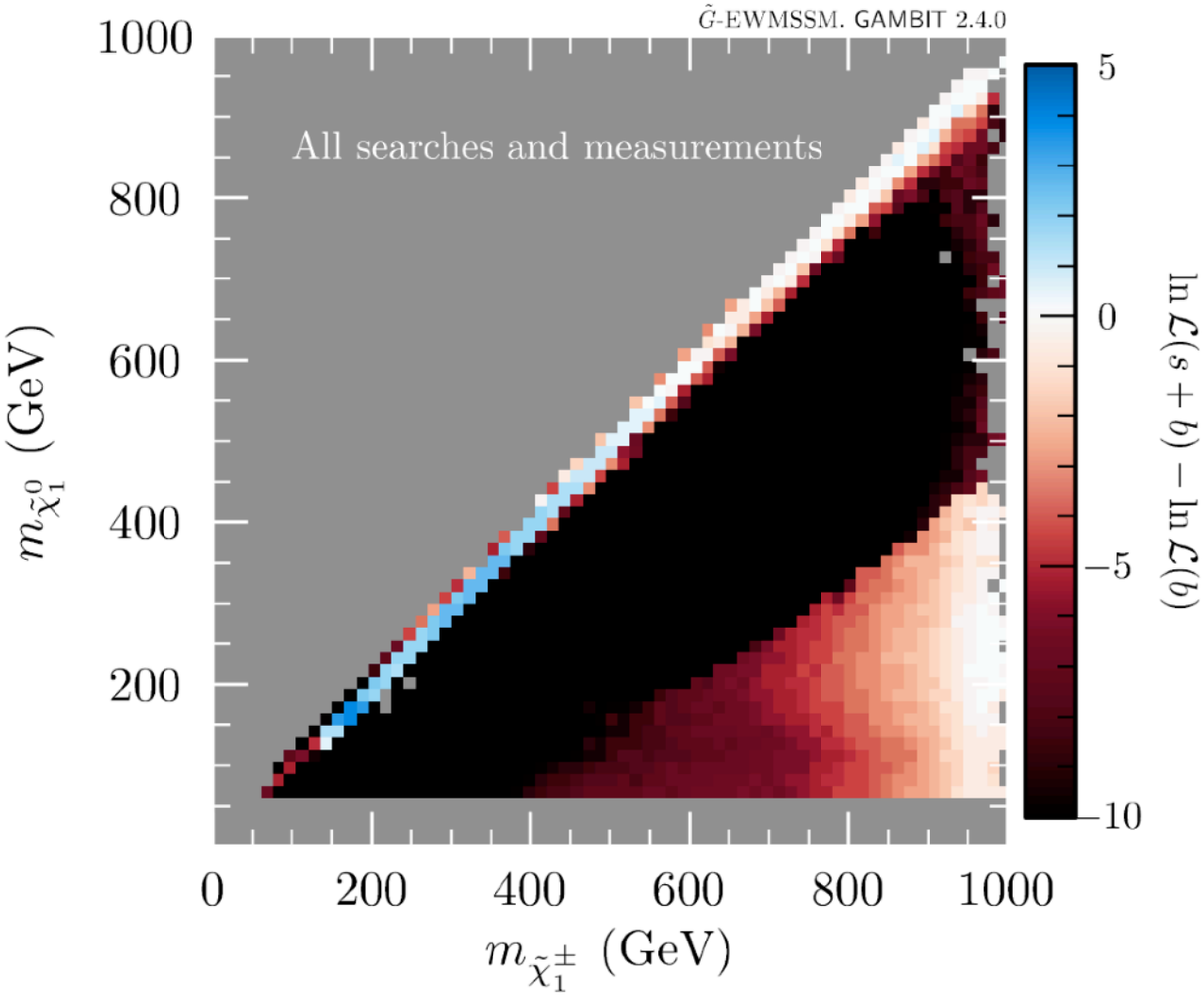




Preliminary results

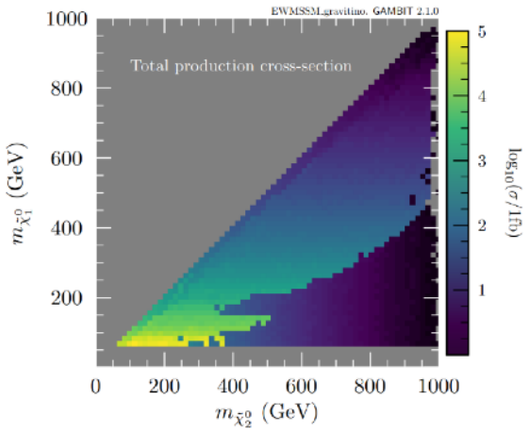
ln L(s+b) - ln L(b)

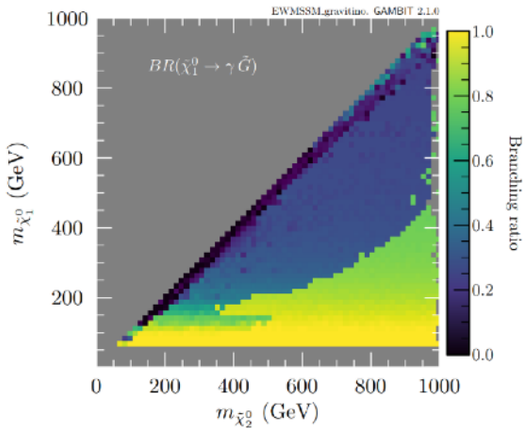


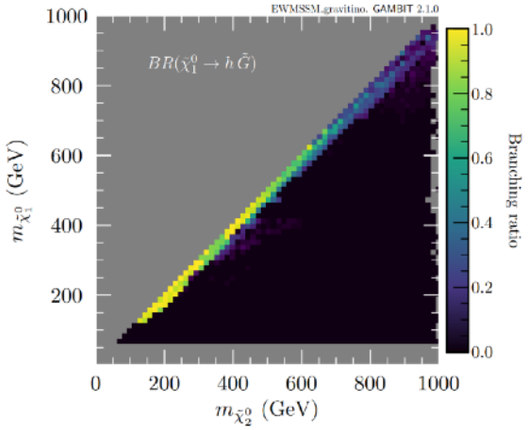


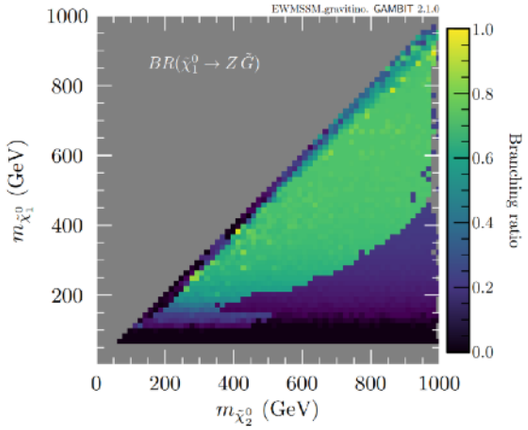
Preliminary results

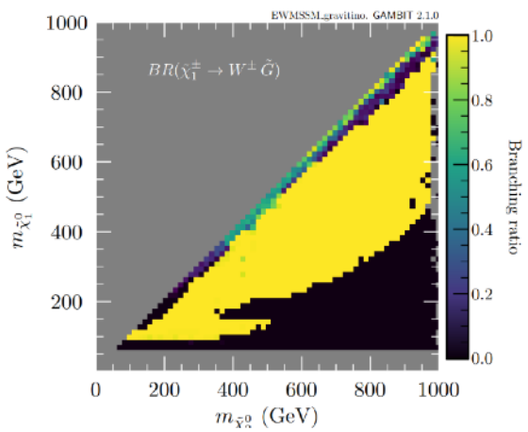
Structure of results explained by **collection of experimental results** + **profiling** + **pattern of BRs** + **total production cross-section**

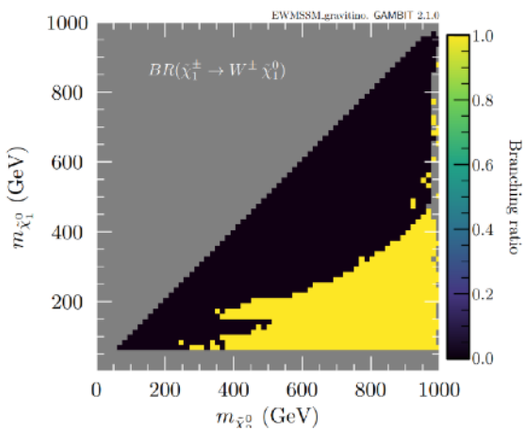


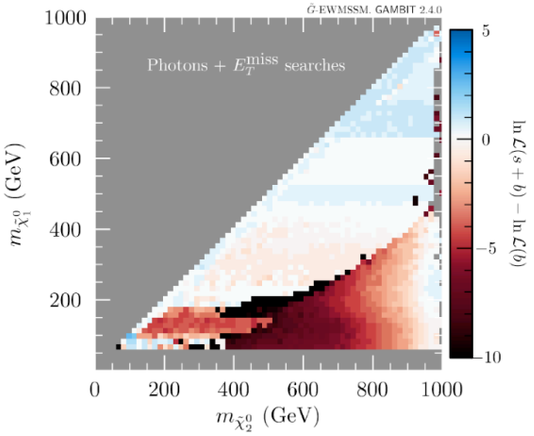


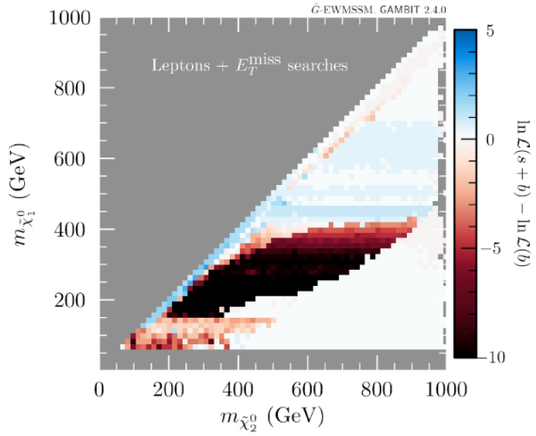


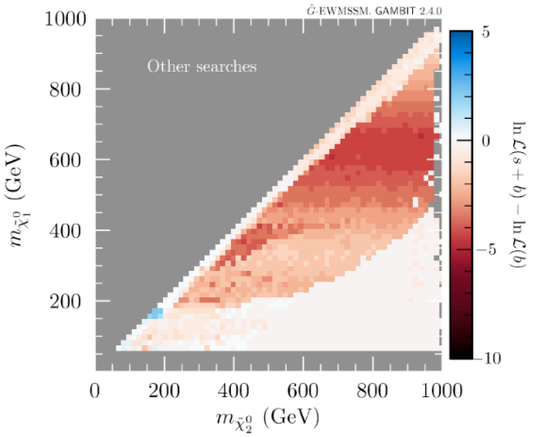


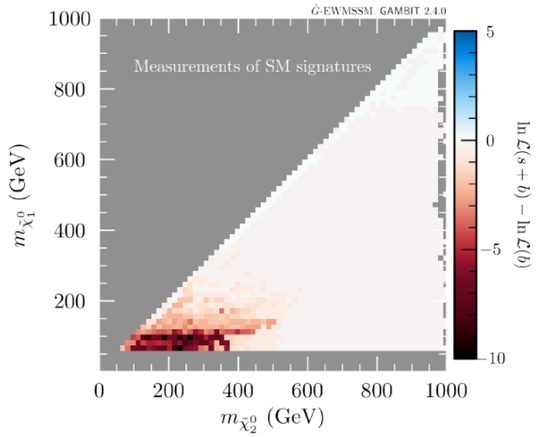






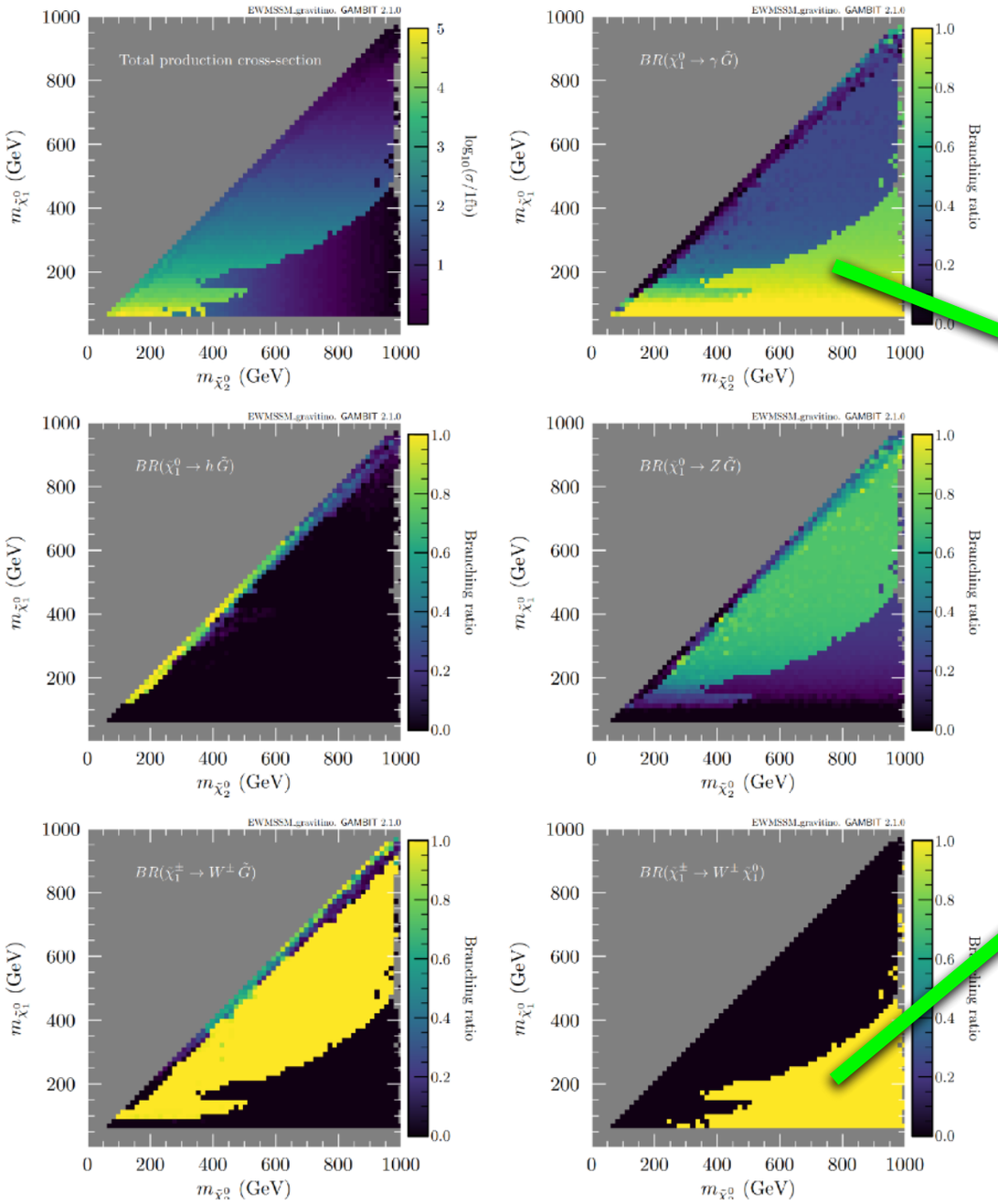


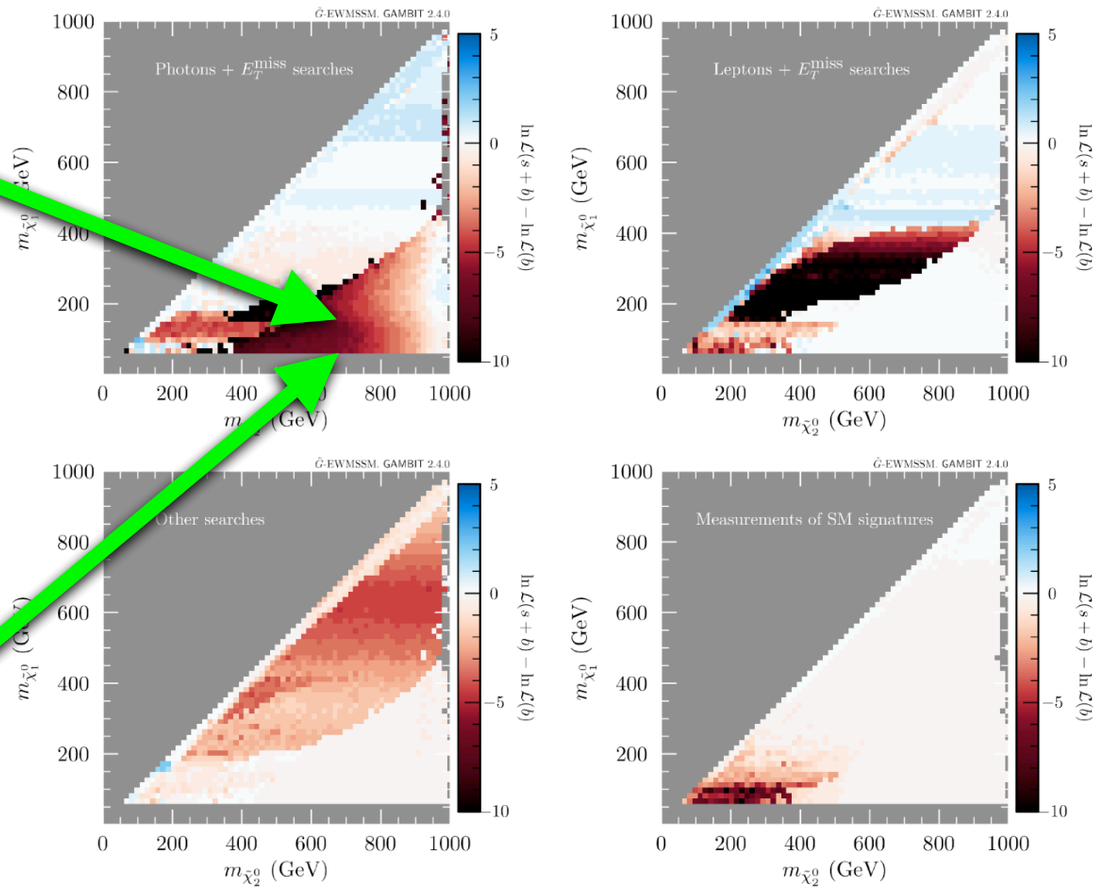




Preliminary results

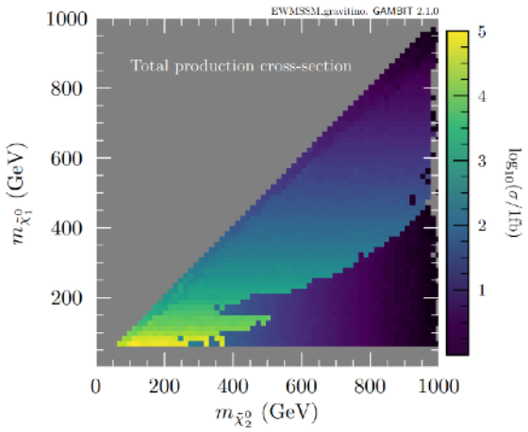
Structure of results explained by **collection of experimental results** + **profiling** + **pattern of BRs** + **total production cross-section**

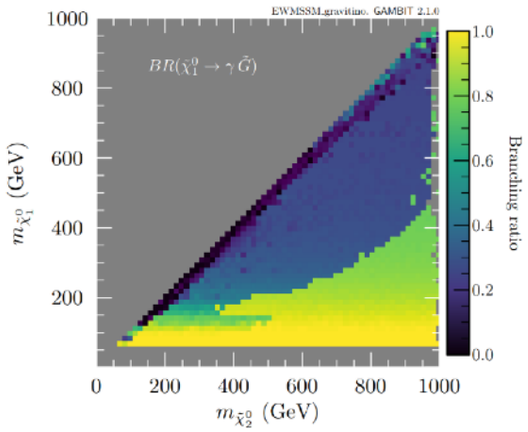


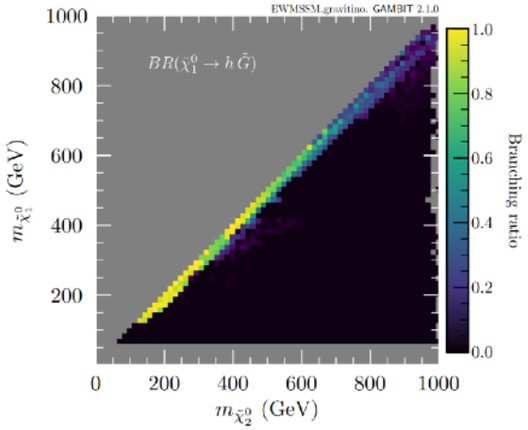


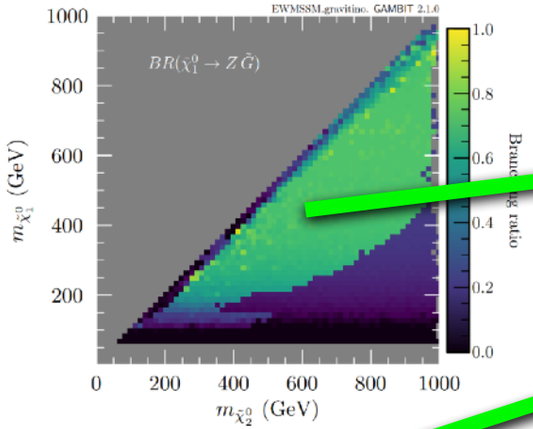
Preliminary results

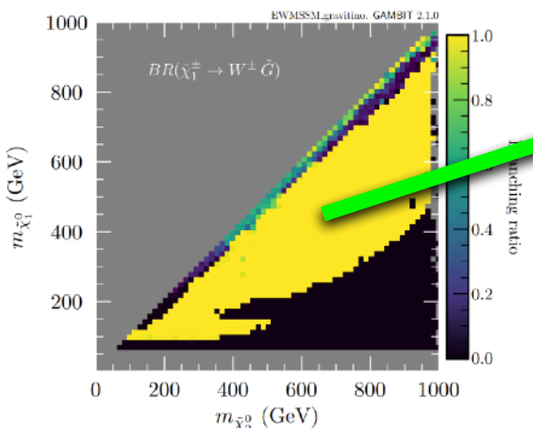
Structure of results explained by **collection of experimental results** + **profiling** + **pattern of BRs** + **total production cross-section**

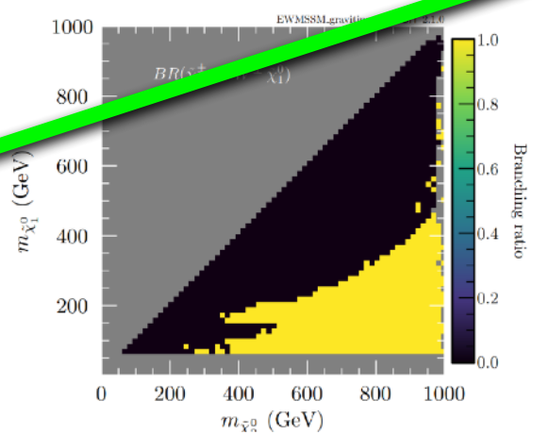


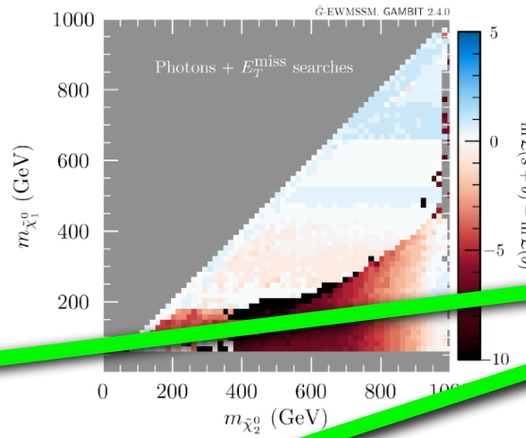


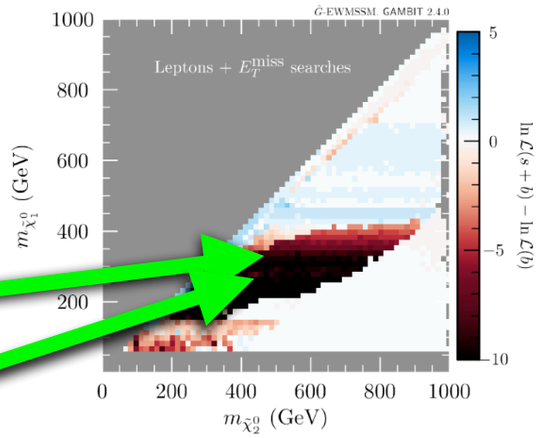


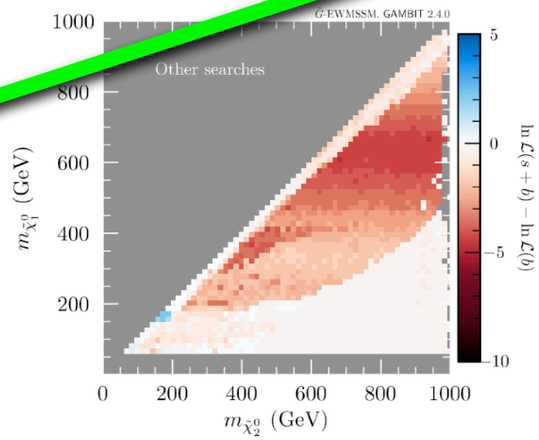


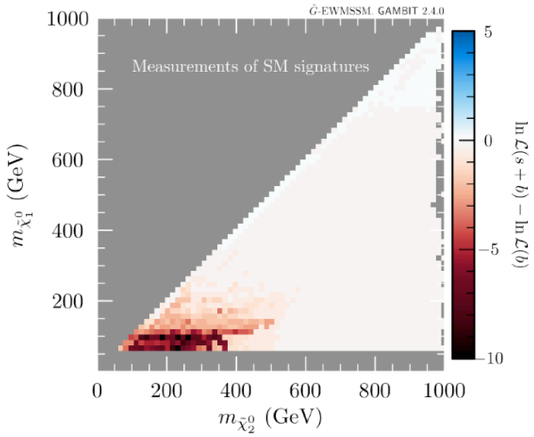






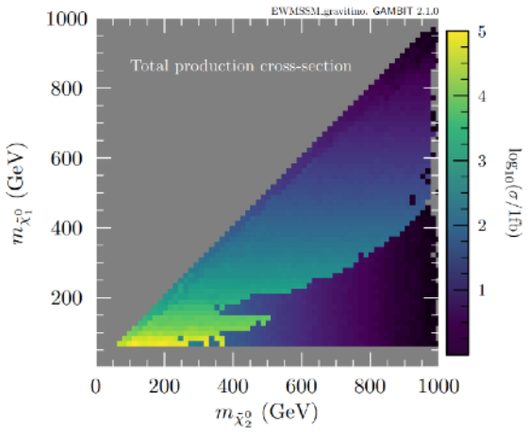


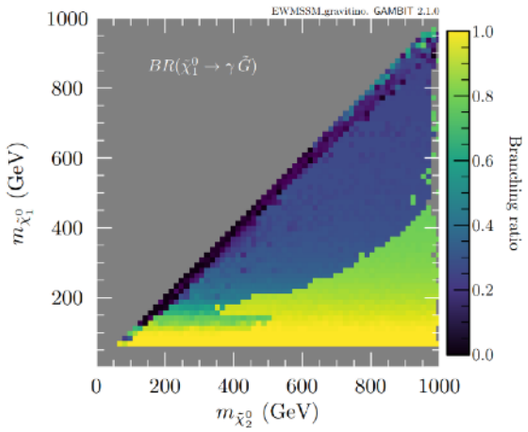


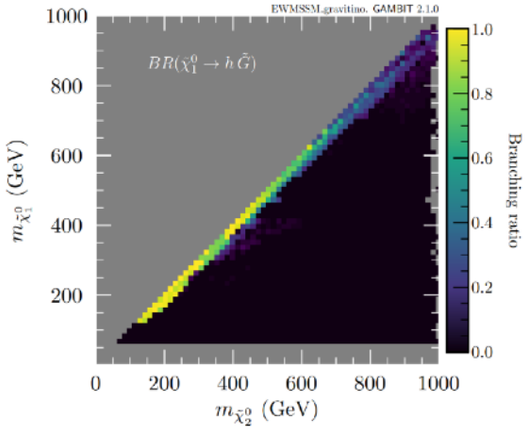


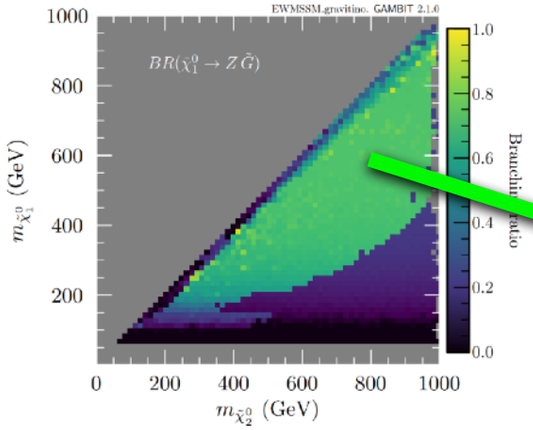
Preliminary results

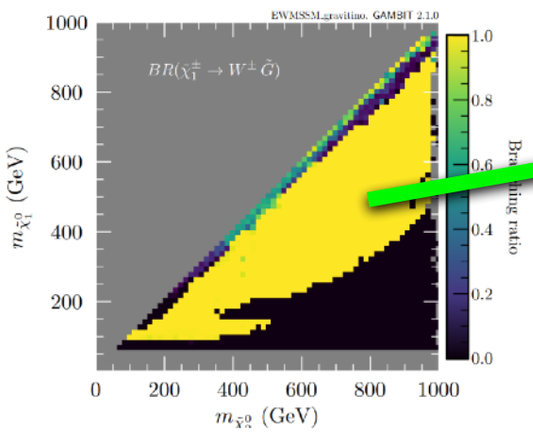
Structure of results explained by **collection of experimental results** + **profiling** + **pattern of BRs** + **total production cross-section**

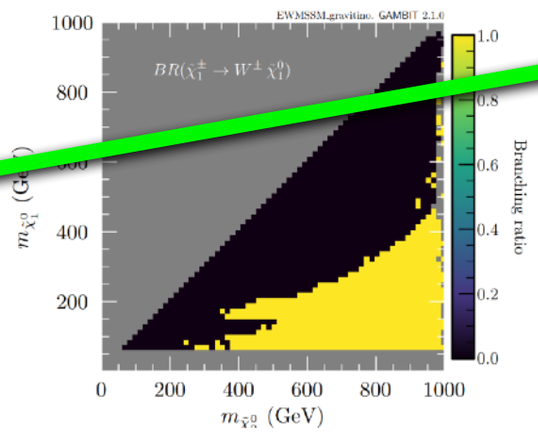


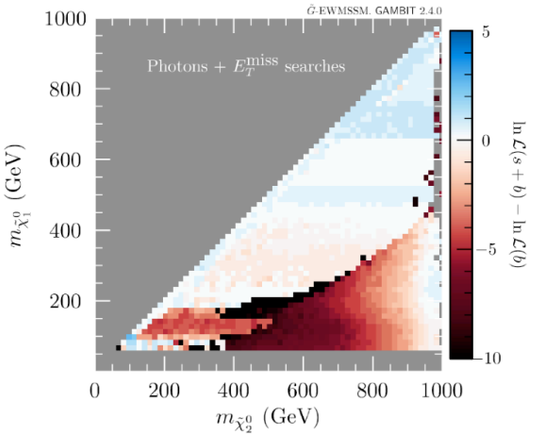


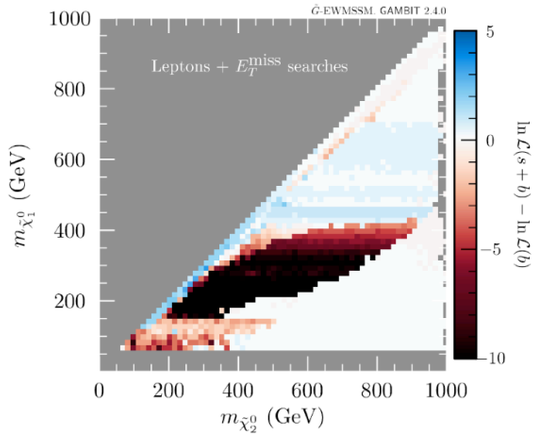


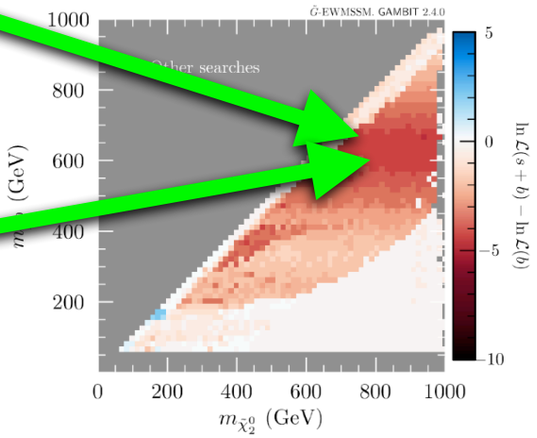


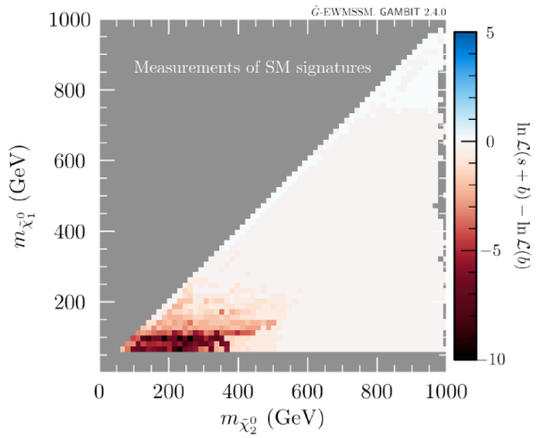




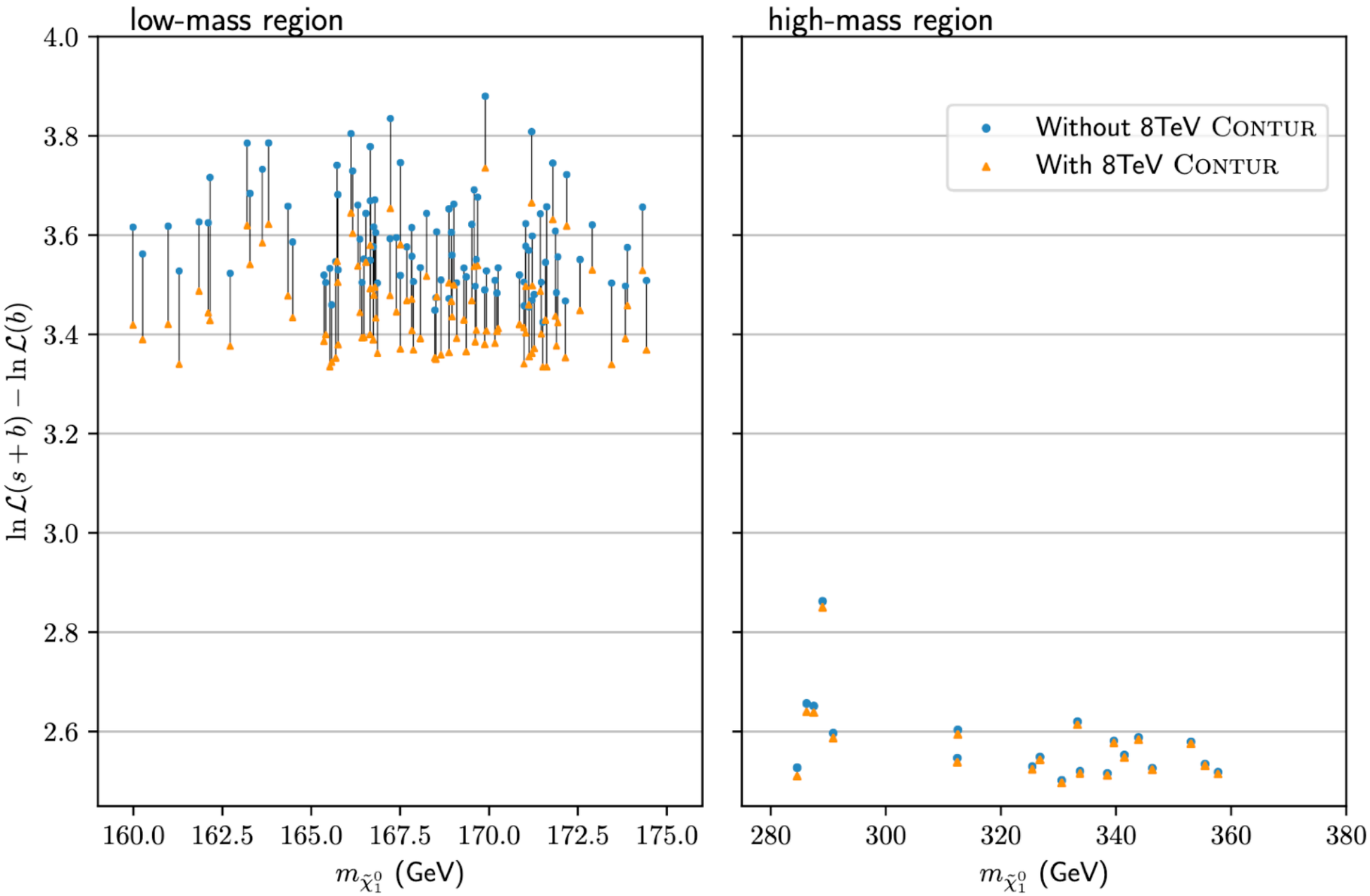


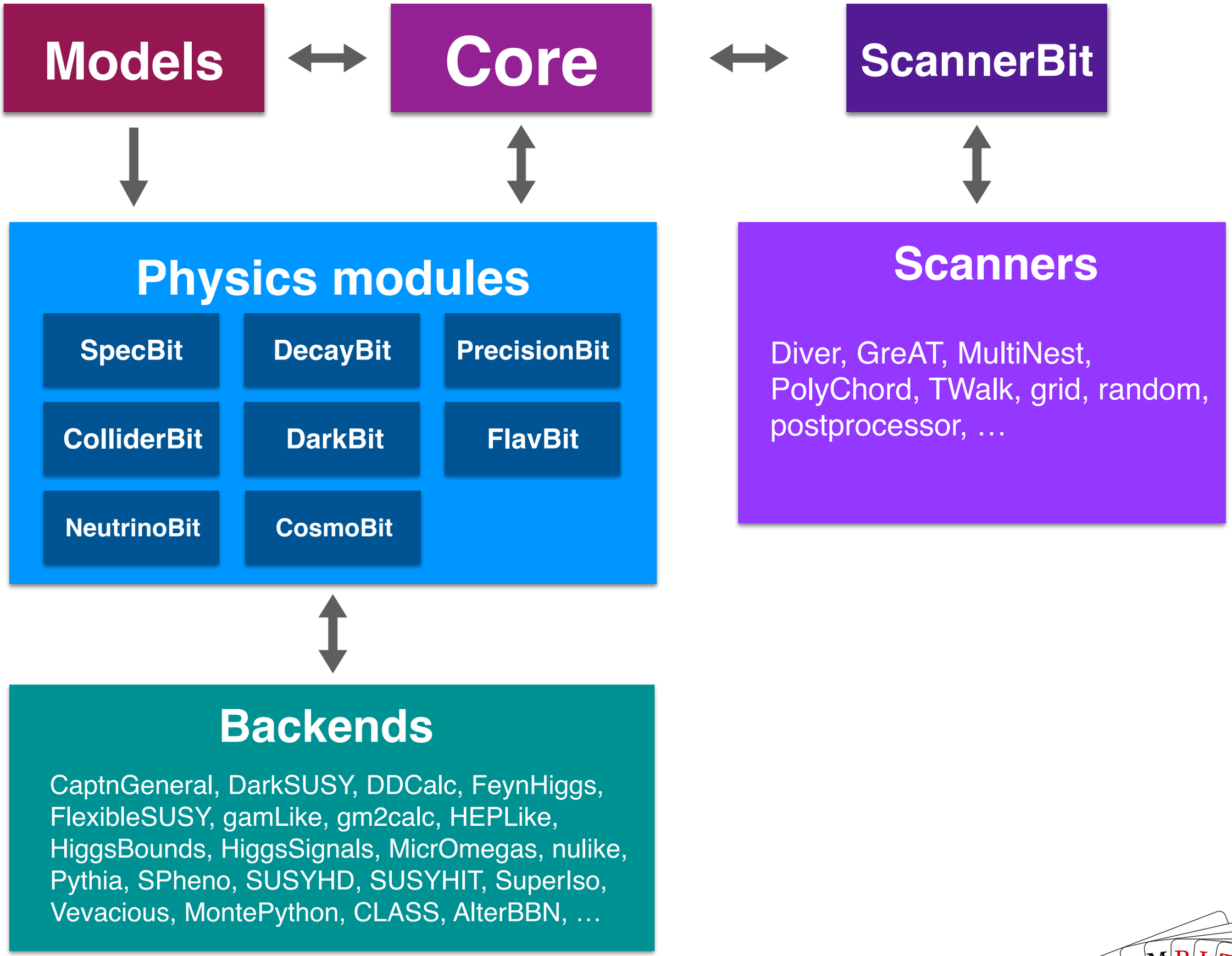






Preliminary results

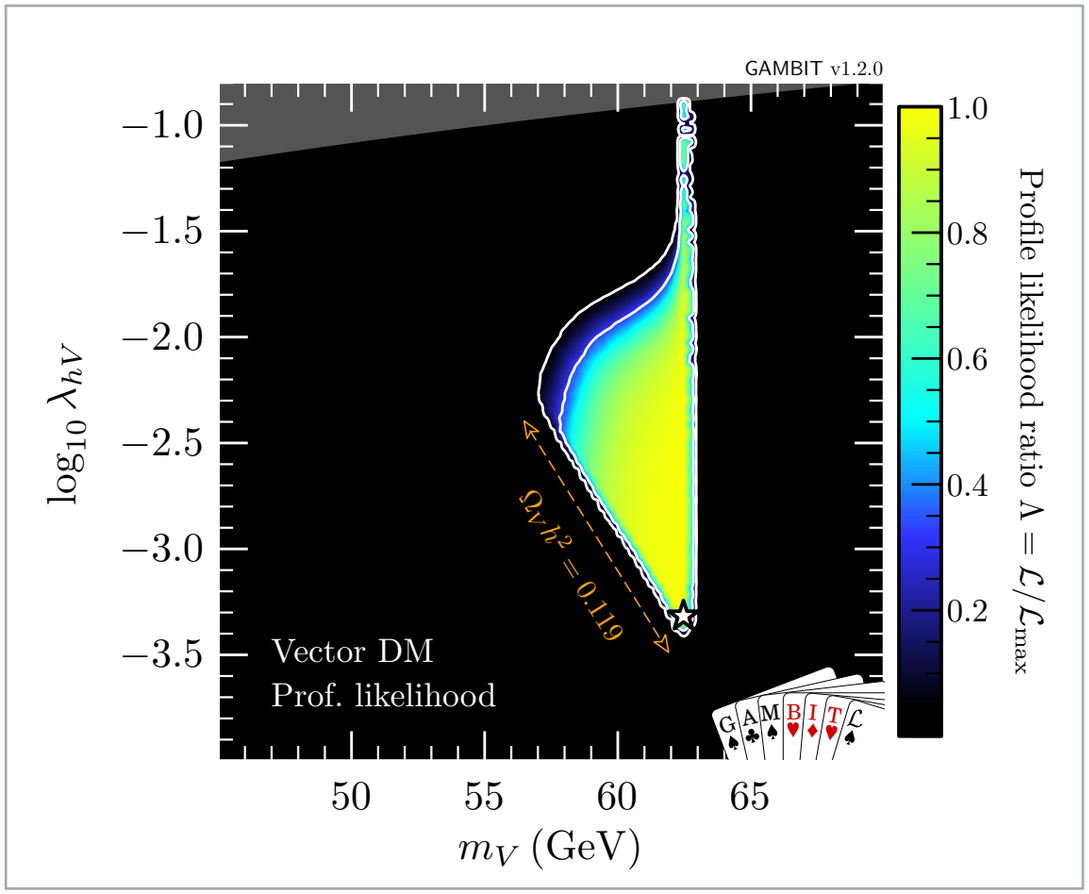


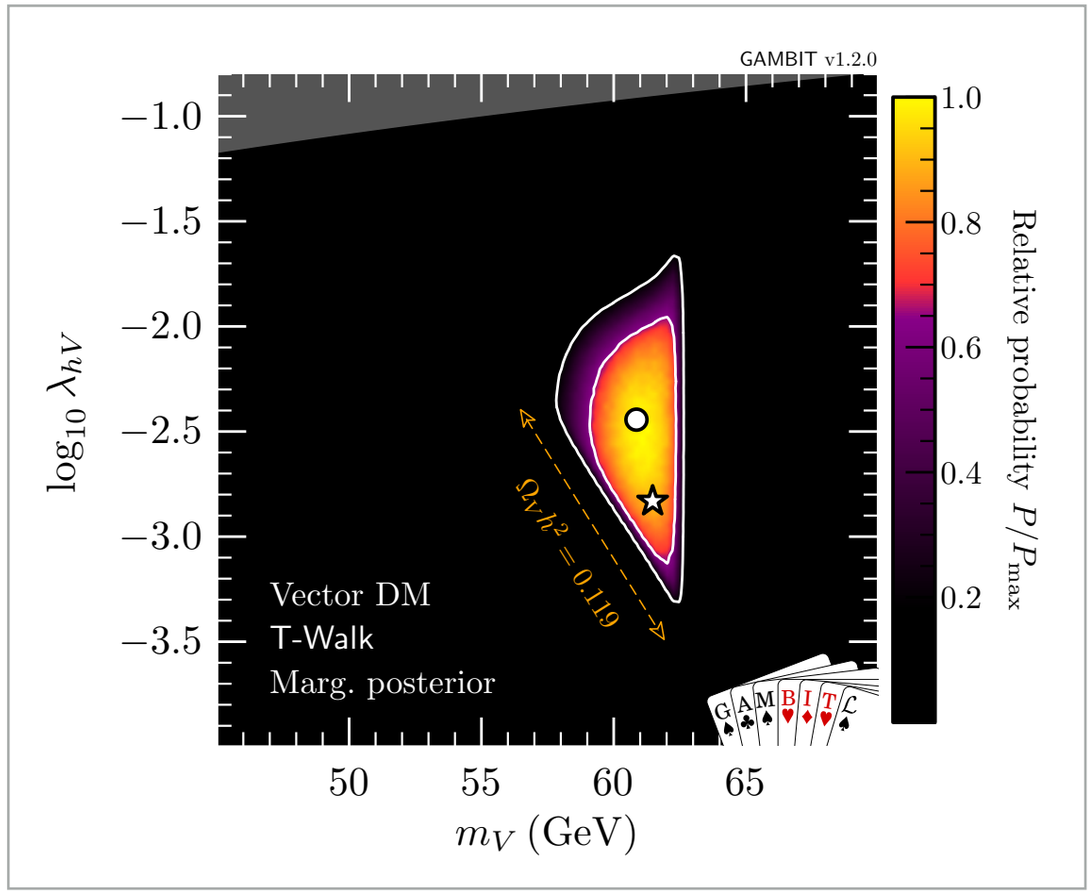

Models
Core
ScannerBit
Physics modules
SpecBit
DecayBit
PrecisionBit
ColliderBit
DarkBit
FlavBit
NeutrinoBit
CosmoBit
Scanners
Diver, GreAT, MultiNest, PolyChord, TWalk, grid, random, postprocessor, …
Backends
CaptnGeneral, DarkSUSY, DDCalc, FeynHiggs, FlexibleSUSY, gamLike, gm2calc, HEPLike, HiggsBounds, 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 **state-of-the-art 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

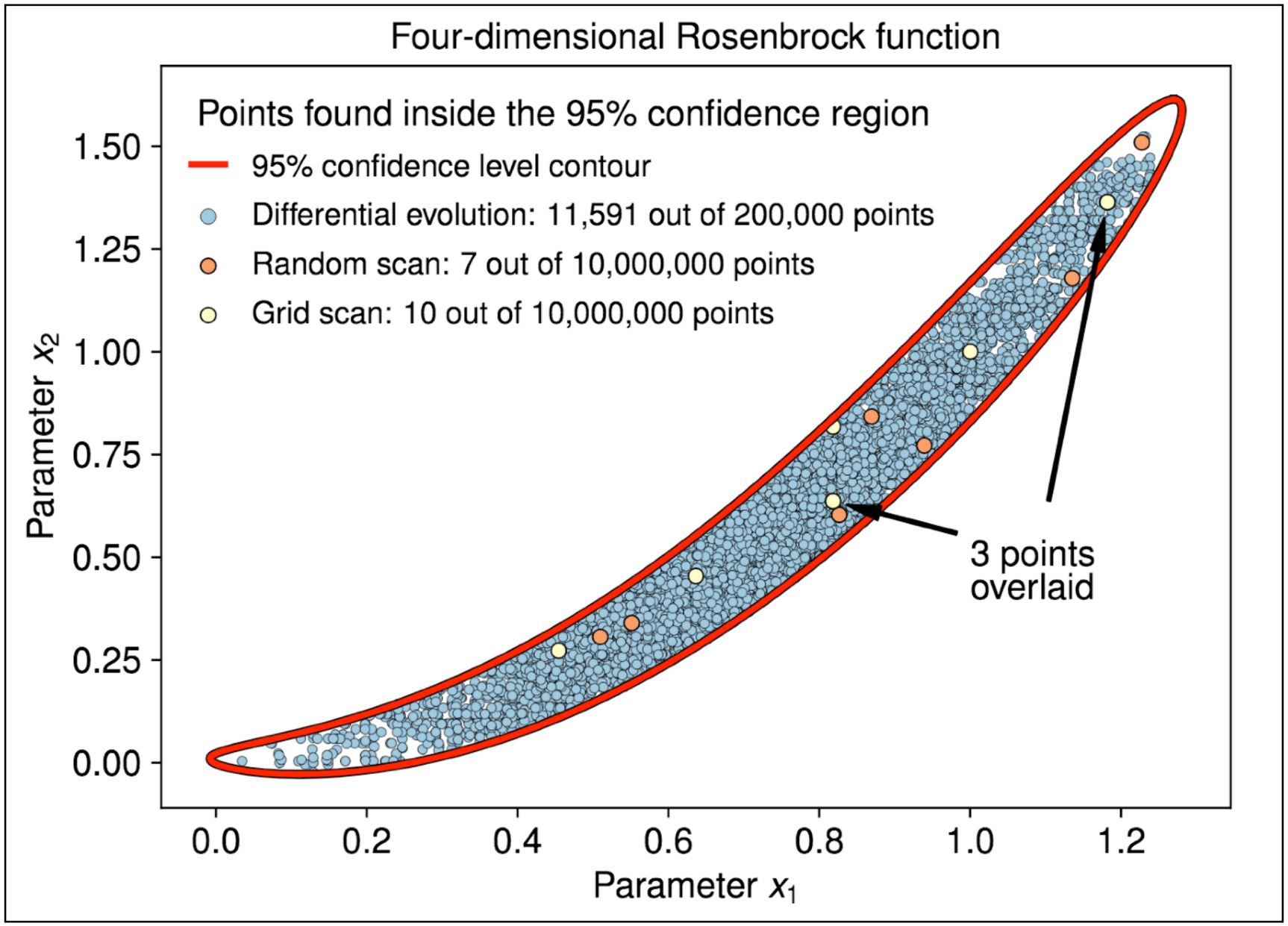
Results usually presented as **profile likelihood** or **posterior density** plots





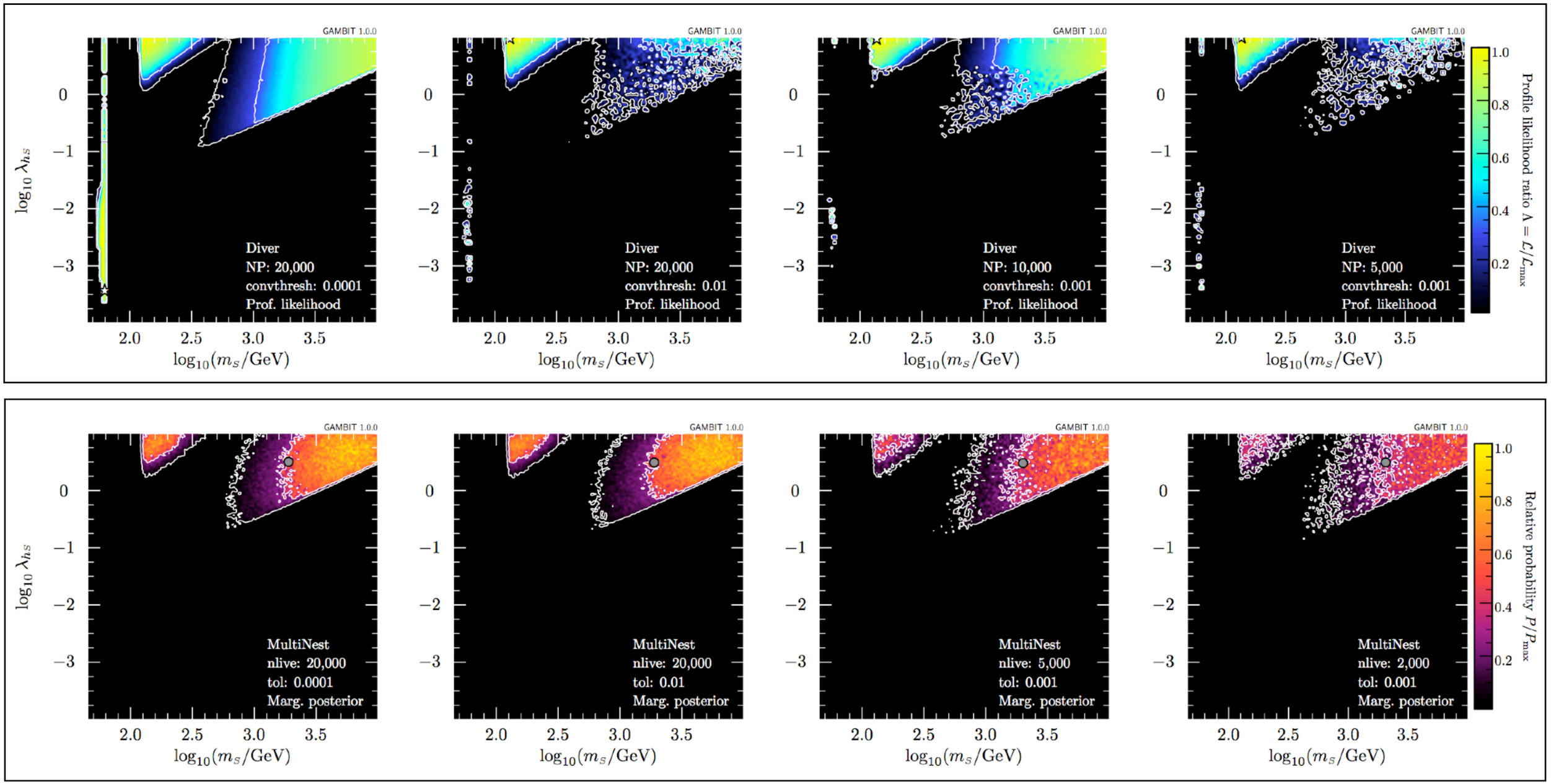
[arxiv:1808.10465]

Parameter space exploration



[arxiv:2012.09874]

Parameter space exploration



[arxiv:1705.07959]

Dependency resolution

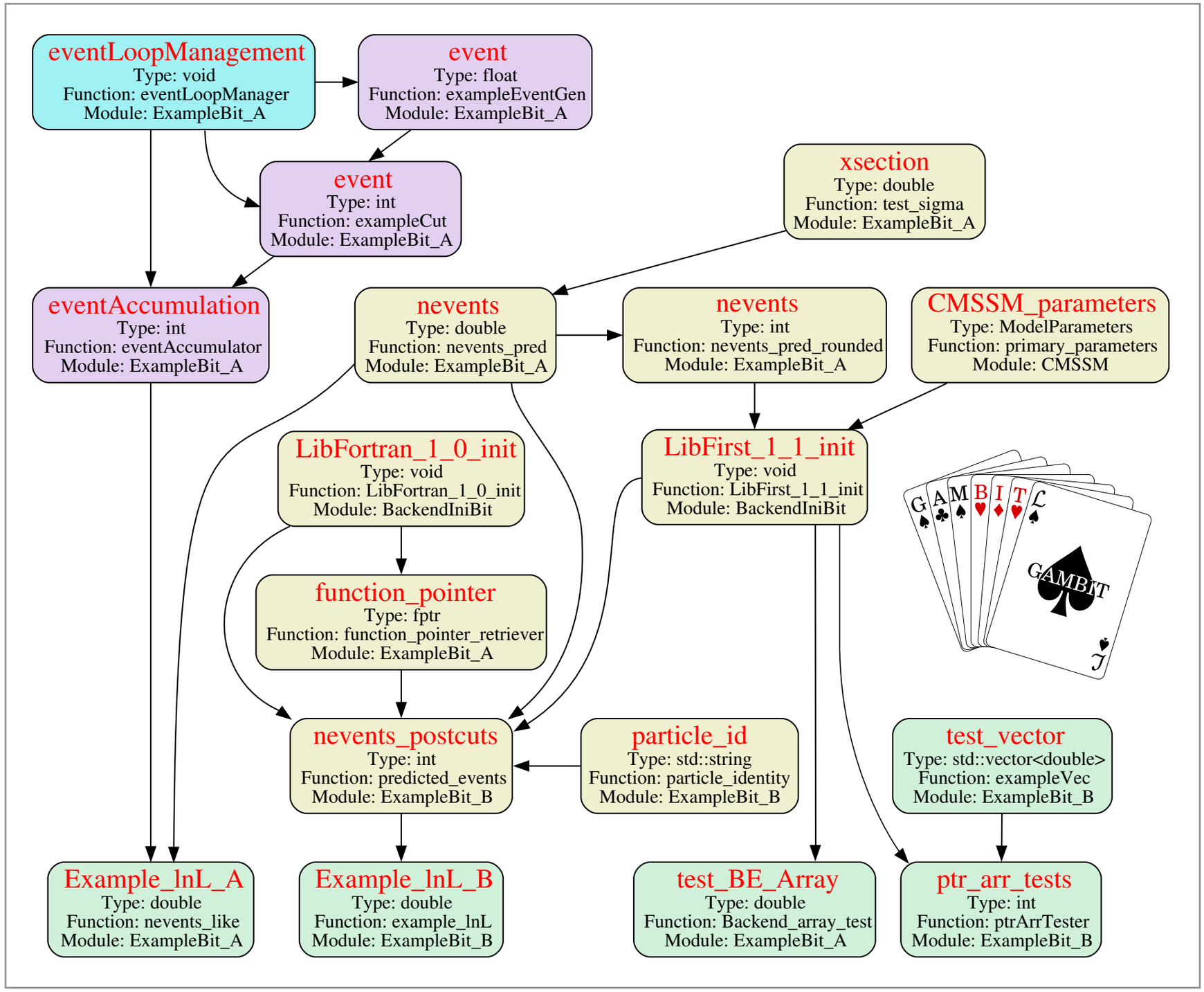
- Basic building blocks: **module functions**
- A physics module: **a collection of module functions** related to the same physics topic
- Each module function has a single **capability** (what it calculates)
- A module function can have **dependencies** on the results of other module functions
- A module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

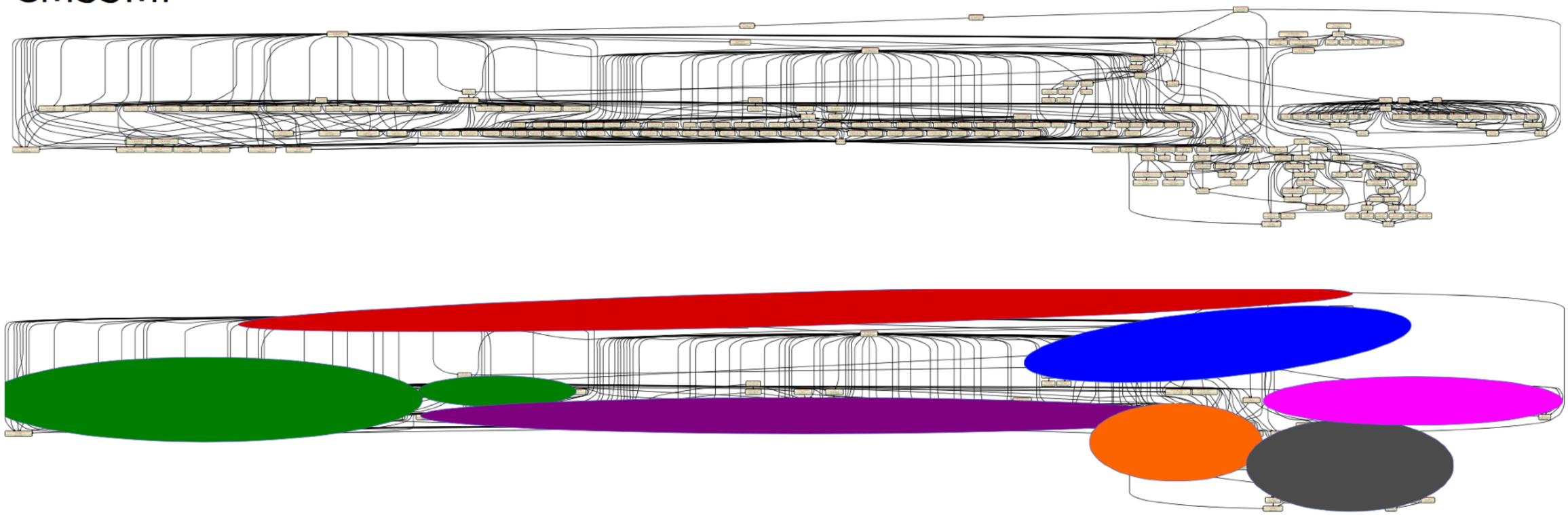
```
/// Br B->tau nu_tau decays
void SI_Btaunu(double &result)
{
  using namespace Pipes::SI_Btaunu;

  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