New (preliminary) GAMBIT results:

LHC impact on SUSY with a light gravitino

Anders Kvellestad, University of Oslo

on behalf of the GAMBIT Collaboration

N-PACT, Stavanger, 18 August, 2022

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Outline

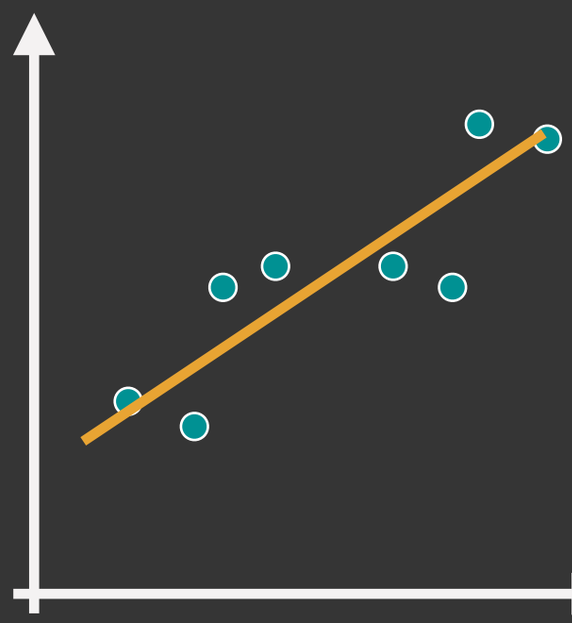
1. GAMBIT and BSM global fits

2. LHC impact on SUSY with a light gravitino

3. Summary

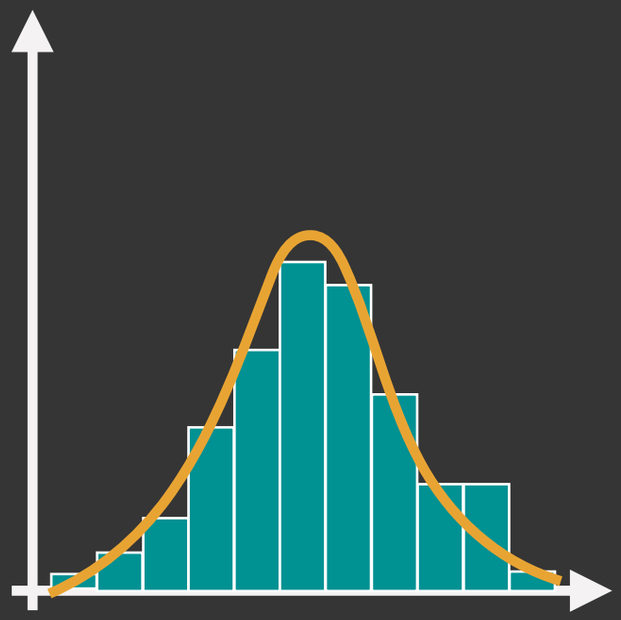
1. GAMBIT and BSM global fits

Statistical fits

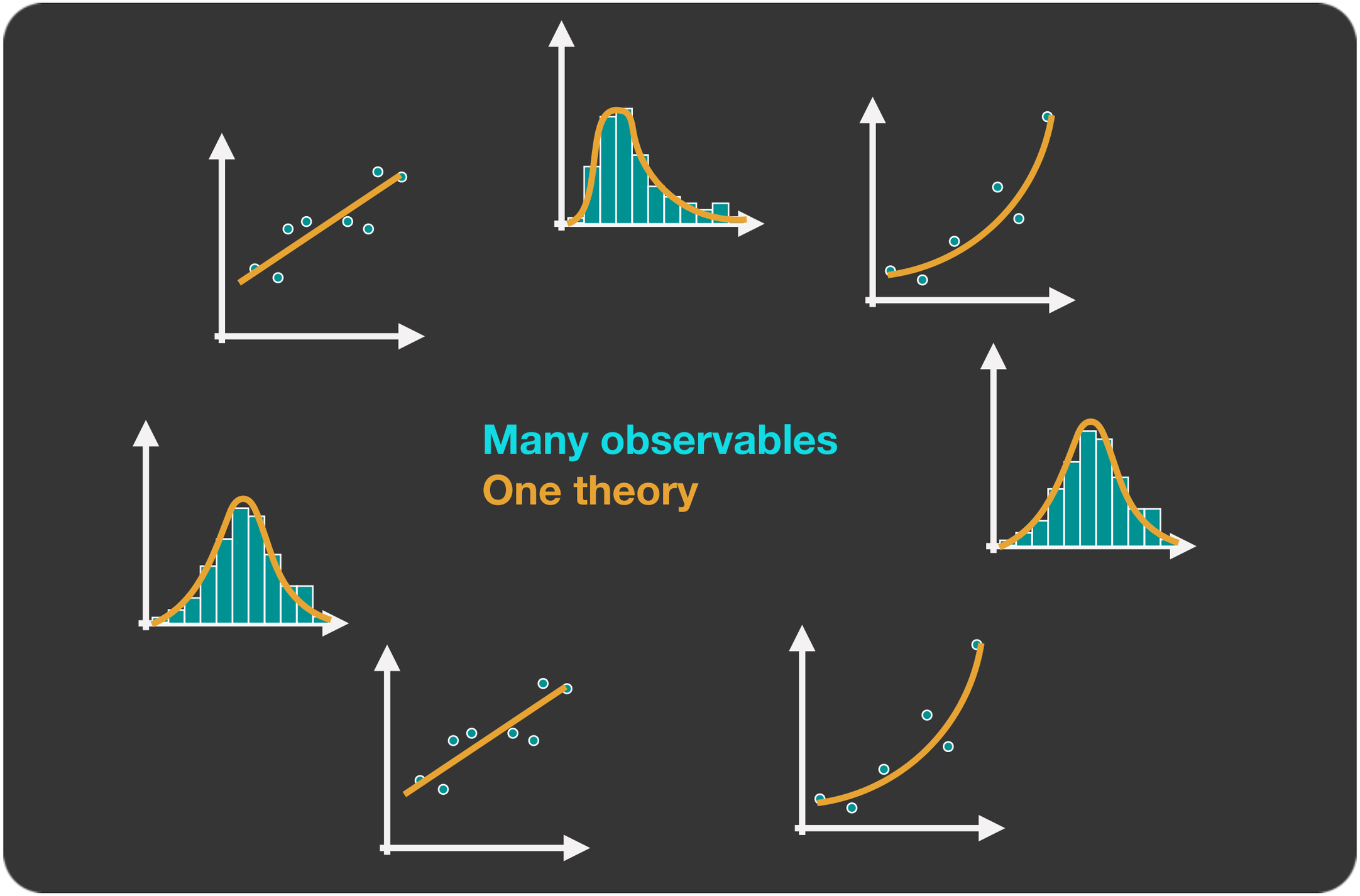


Some observable
Some model

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, +++

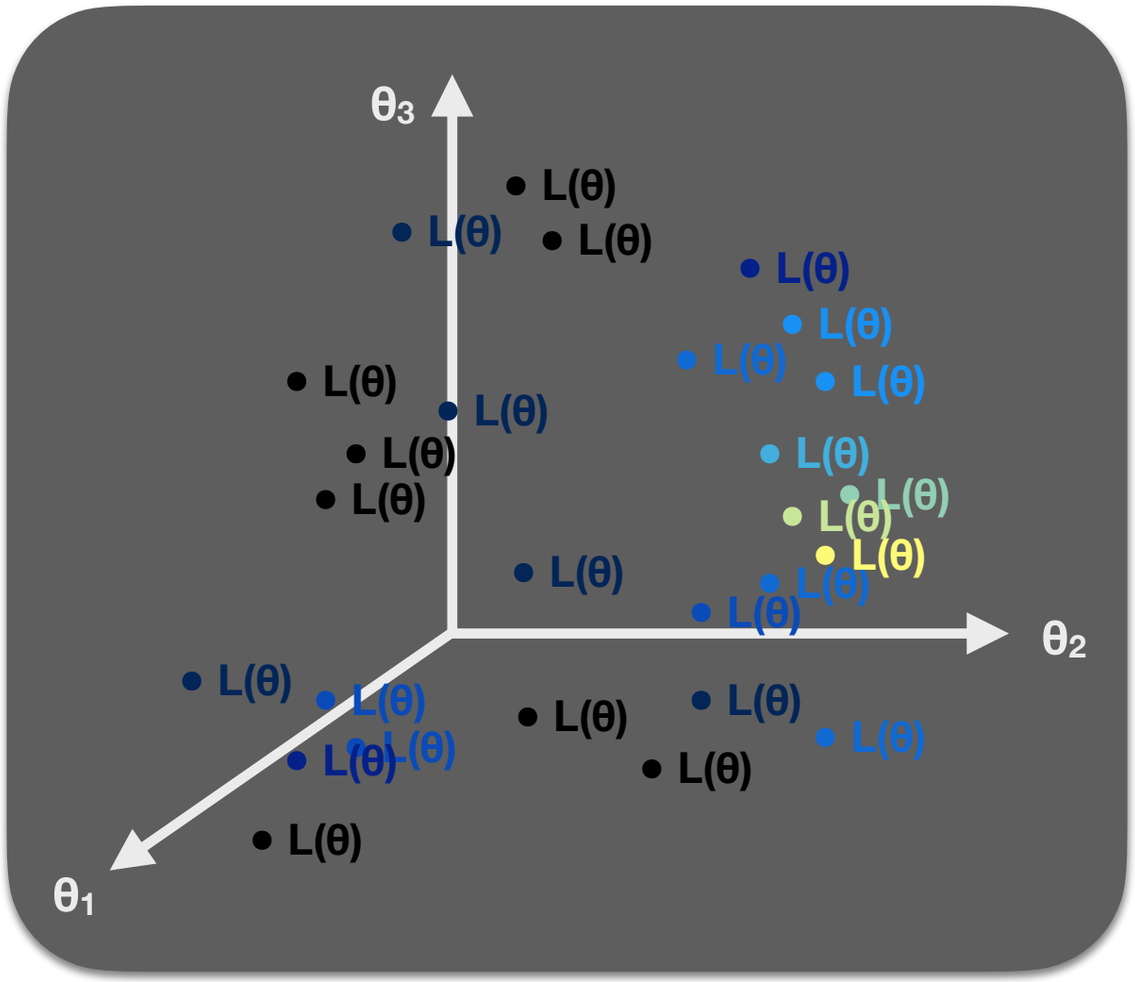
$$\mathcal{L} = \mathcal{L}_{\text{collider}} \mathcal{L}_{\text{DM}} \mathcal{L}_{\text{flavor}} \mathcal{L}_{\text{EWPO}} \cdots$$

- Use **sophisticated scanning techniques** to explore the likelihood function across the parameter space of the theory

- Test **parameter regions** properly — not just single points *(parameter estimation)*

- Test **different theories the same way** *(model comparison)*

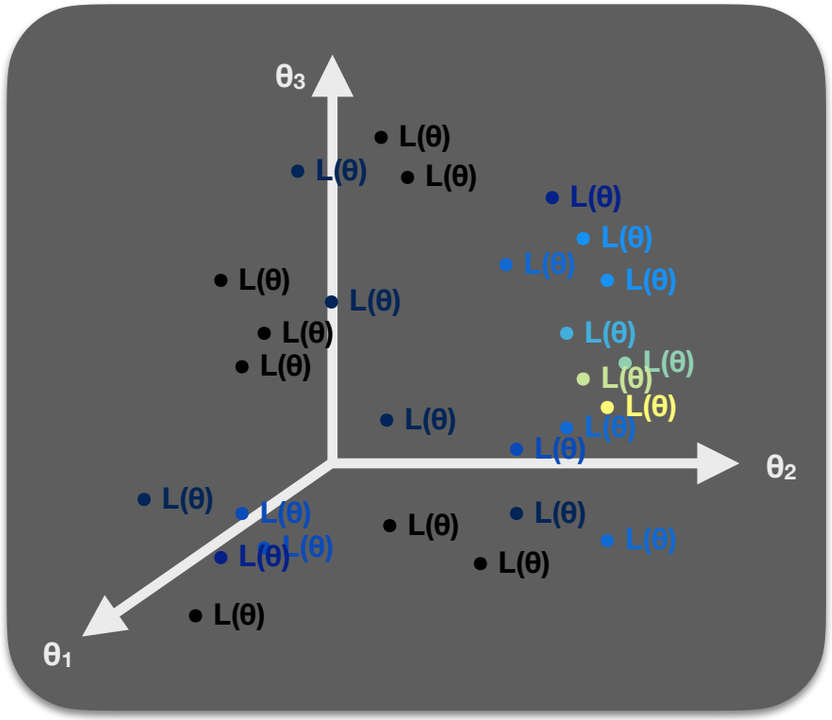
- **Explore the model parameter space** (θ_1, θ_2, θ_3, …)
- At every point θ: **calculate predictions(θ) → evaluate joint likelihood L(θ)**

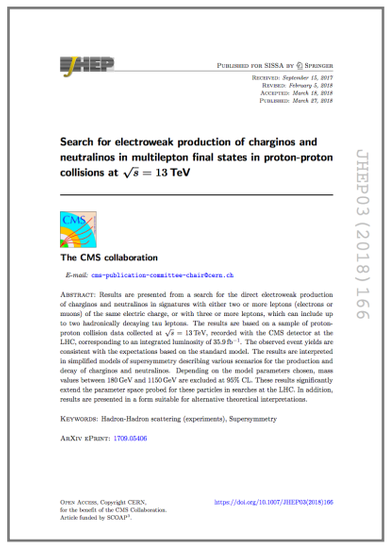


- Region of highest L(θ) or lnL(θ): **model's best simultaneous fit to all data**
  (but not necessarily a *good* fit, or the most probable θ…)

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

JHEP03(2018)166

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

```
// 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 killing your 10,000-CPU scan**…

GAMBIT

GAMBIT: The Global And Modular BSM Inference Tool

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

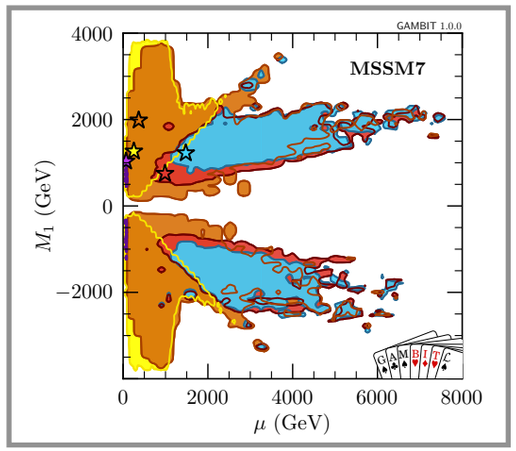
- Extensive model database, beyond SUSY
- Fast definition of new datasets, theories
- Extensive observable/data libraries
- Plug&play scanning/physics/likelihood packages
- Various statistical options (frequentist /Bayesian)
- Fast LHC likelihood calculator
- Massively parallel
- Fully open-source

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

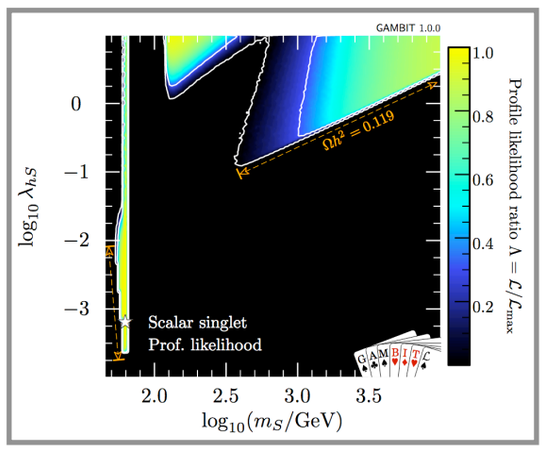
Authors of: BubbleProfiler, Capt'n General, Contur, DarkAges, DarkSUSY, DDCalc, DirectDM, Diver, EasyScanHEP, ExoCLASS, FlexibleSUSY, gamLike, GM2Calc, HEPLike, IsaTools, MARTY, nuLike, PhaseTracer, PolyChord, Rivet, SOFTSUSY, Superlso, SUSY-AI, xsec, Vevacious, WIMPSim

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, ++

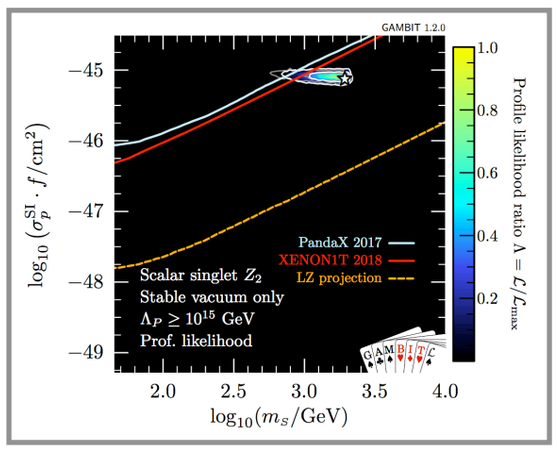
70+ participants in many experiments and numerous major theory codes



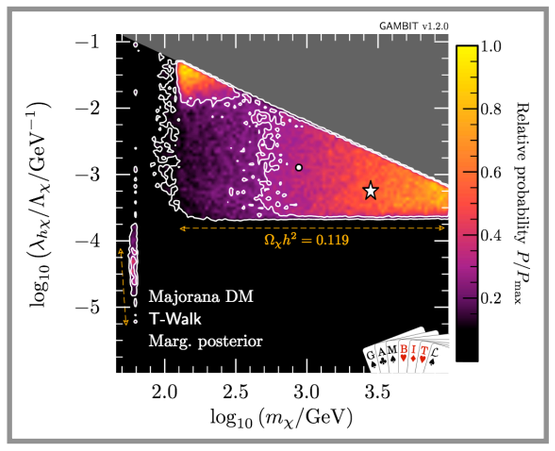
MSSM7: 1705.07917
GUT-scale SUSY: 1705.07935



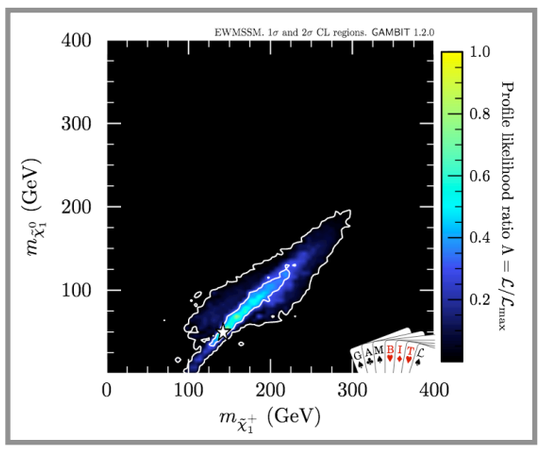
Scalar Higgs portal DM: 1705.07931



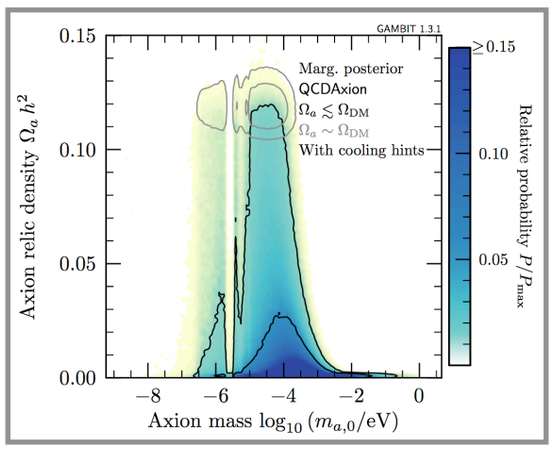
Scalar Higgs portal DM w/ vac. stability: 1806.11281



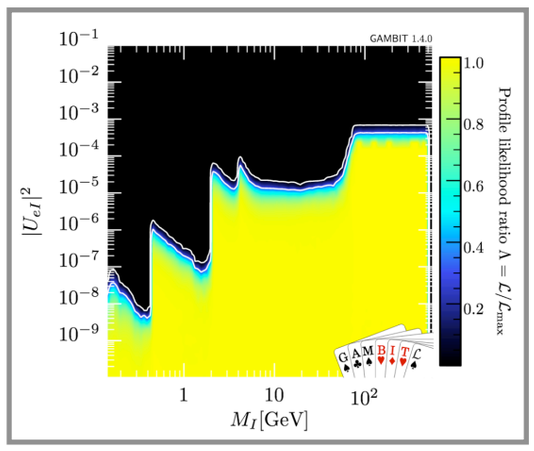
Vector and fermion Higgs portal DM: 1808.10465



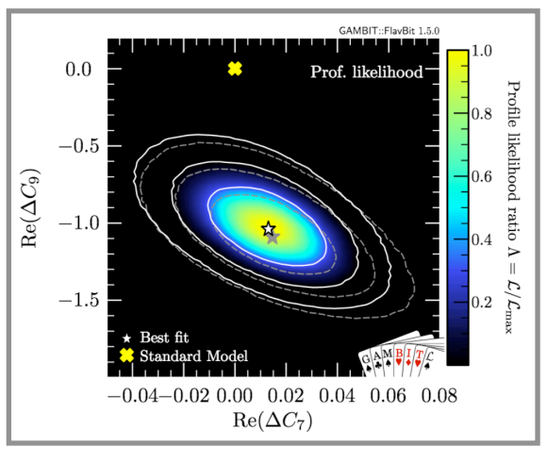
EWMSSM: 1809.02097



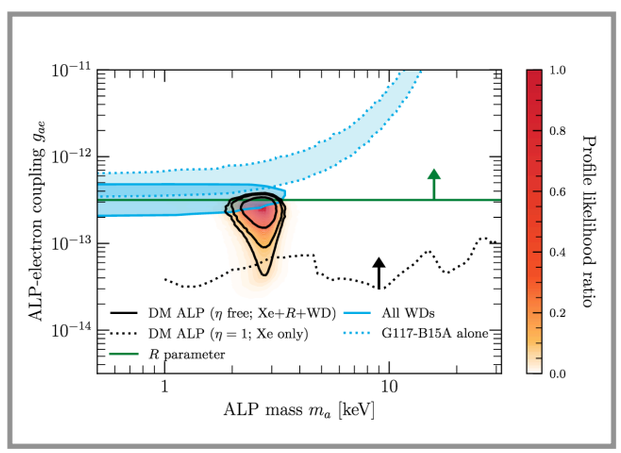
Axion-like particles: 1810.07192



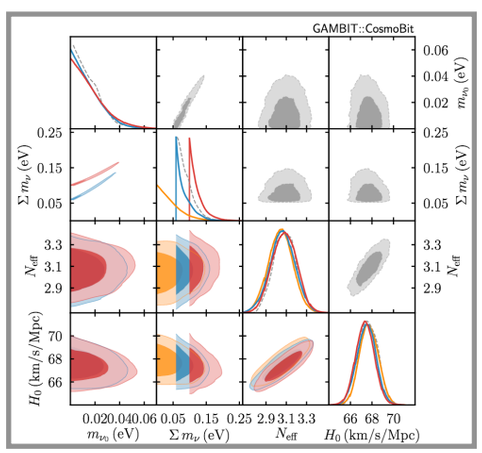
Right-handed neutrinos: 1908.02302



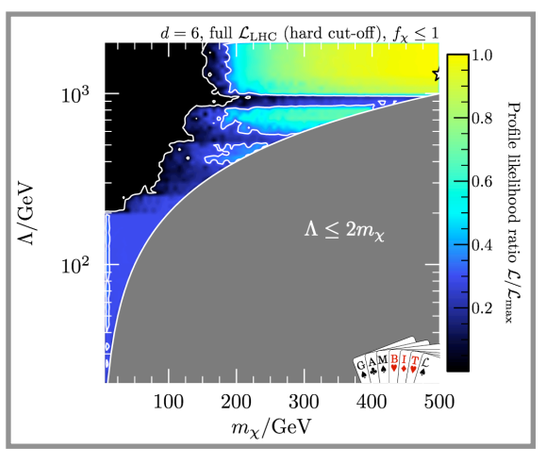
Flavour EFT: 2006.03489



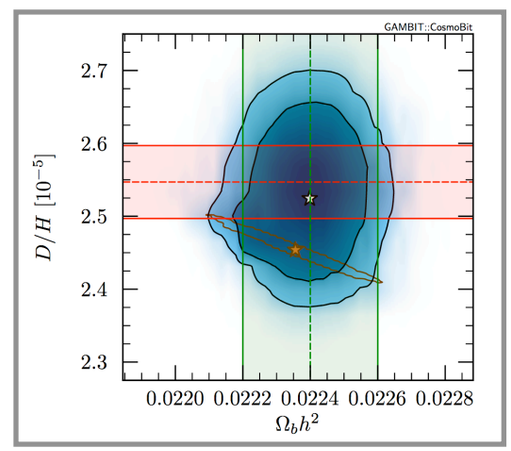
More axion-like particles: 2006.03489



Neutrinos and cosmo: 2009.03287



Dark matter EFTs: 2106.02056



Cosmo ALPs: 2205.13549

2. LHC impact on SUSY with a light gravitino

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]

Model: EWMSSM + light gravitino

- **EWMSSM**: MSSM w/ only the EWinos not decoupled (4 neutralinos, 2 charginos)
- Studied LHC impact on EWMSSM in arXiv:1809.02097
- 4D parameter space: M1, M2, mu, tan beta
- **G-EWMSSM**: EWMSSM + a near massless **gravitino LSP**
  - Extension of ATLAS/CMS simplified models for gravitino searches
  - **Gravitino:**
    - necessary consequence of supergravity
    - gauge-mediated symmetry breaking (GMSB): gravitino likely the LSP
  - Very different collider pheno: **lightest EWino will decay**
  - Gravitino mass fixed to 1 eV → prompt decay of lightest EWino

Parameter space

M_1 M_2 μ $\tan\beta$

Neutralinos

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

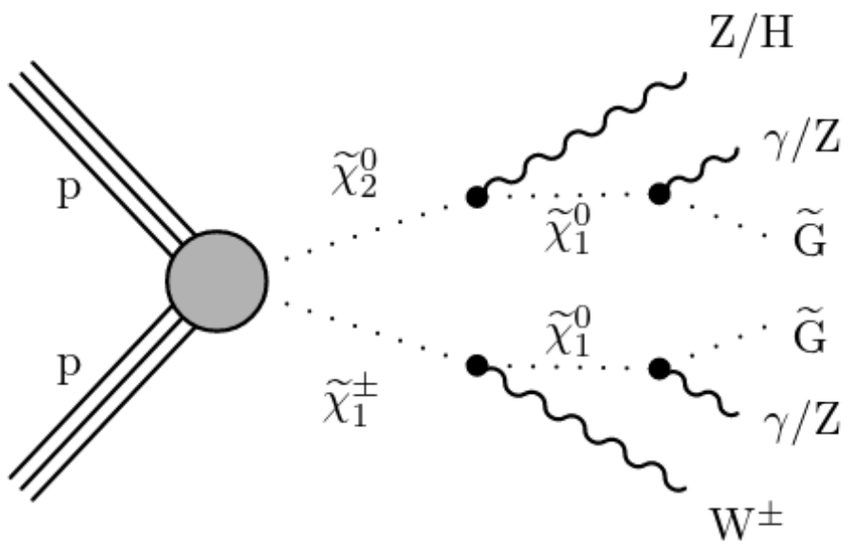
$$M_N = \begin{pmatrix} M_1 & 0 & -\frac{1}{2}g'vc_\beta & \frac{1}{2}g'vs_\beta \\ 0 & M_2 & \frac{1}{2}gvc_\beta & -\frac{1}{2}gvs_\beta \\ -\frac{1}{2}g'vc_\beta & \frac{1}{2}gvc_\beta & 0 & -\mu \\ \frac{1}{2}g'vs_\beta & -\frac{1}{2}gvs_\beta & -\mu & 0 \end{pmatrix}$$

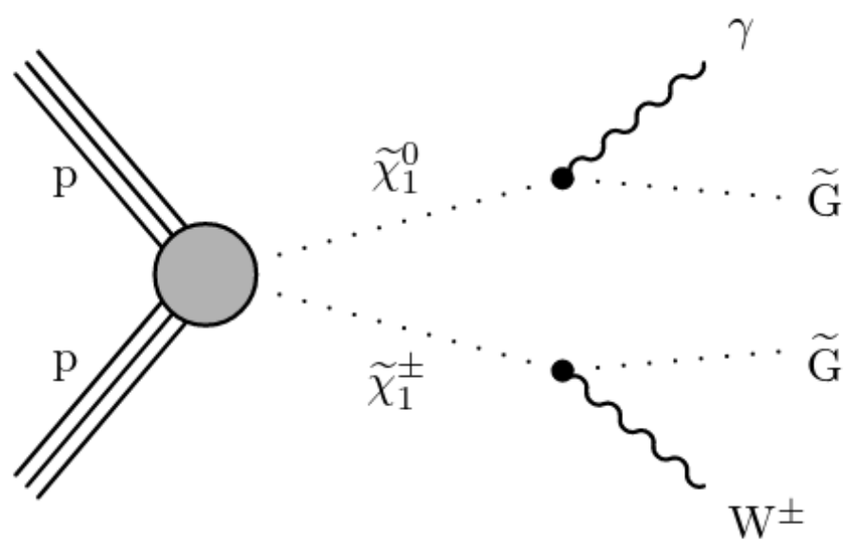
Charginos

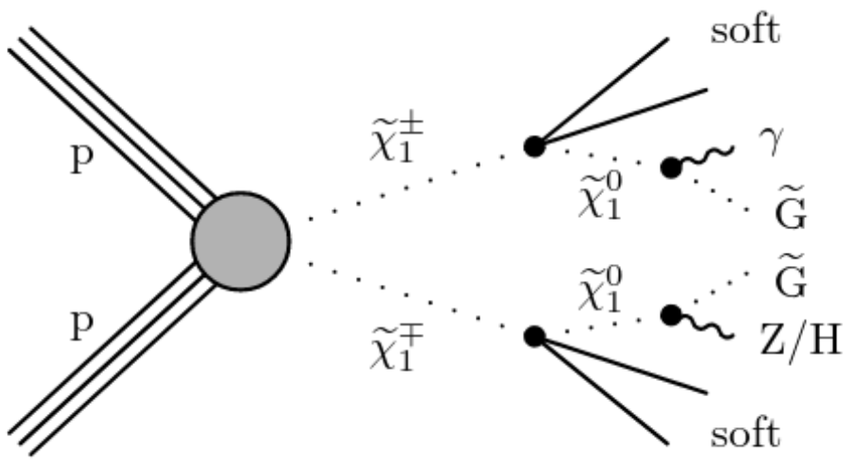
$$\psi^\pm = (\tilde{W}^+, \tilde{H}_u^+, \tilde{W}^-, \tilde{H}_d^-)$$

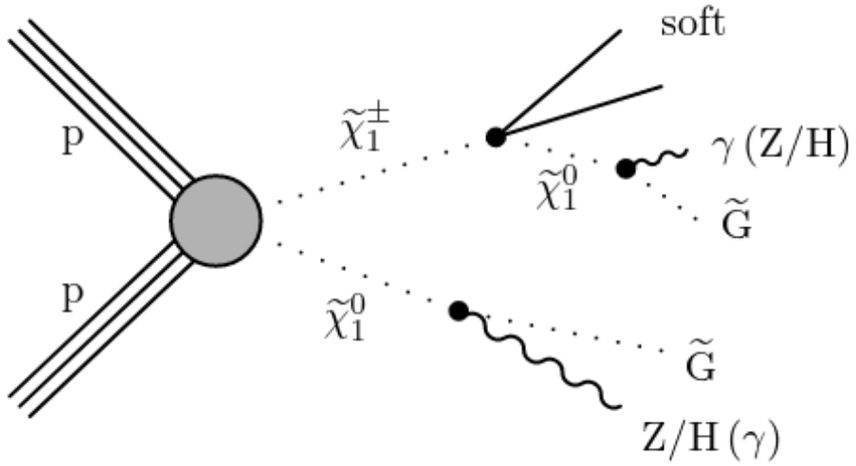
$$M_C = \begin{pmatrix} 0 & X^T \\ X & 0 \end{pmatrix}, \quad \text{where} \quad X = \begin{pmatrix} M_2 & \frac{gvs_\beta}{\sqrt{2}} \\ \frac{gvc_\beta}{\sqrt{2}} & \mu \end{pmatrix}.$$

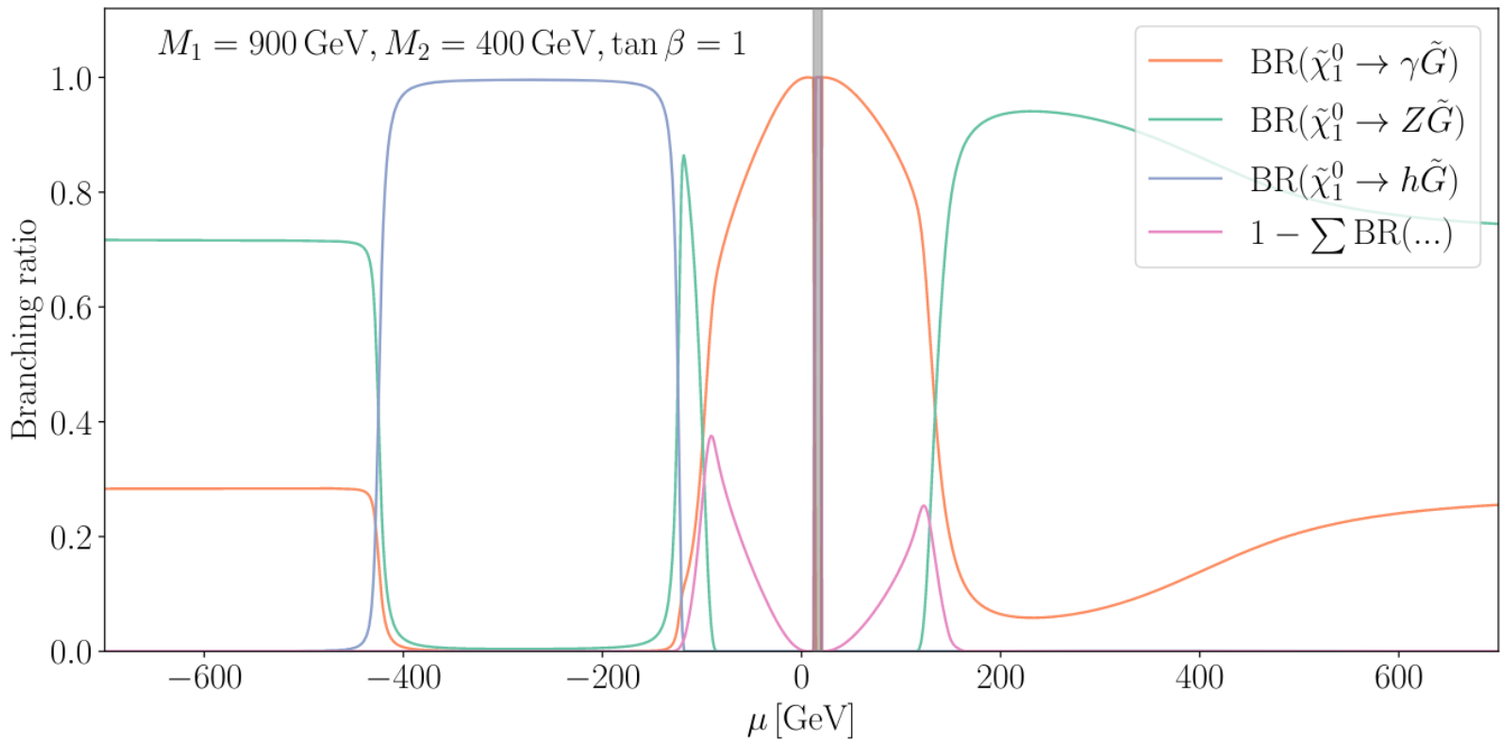
Rich collider pheno:

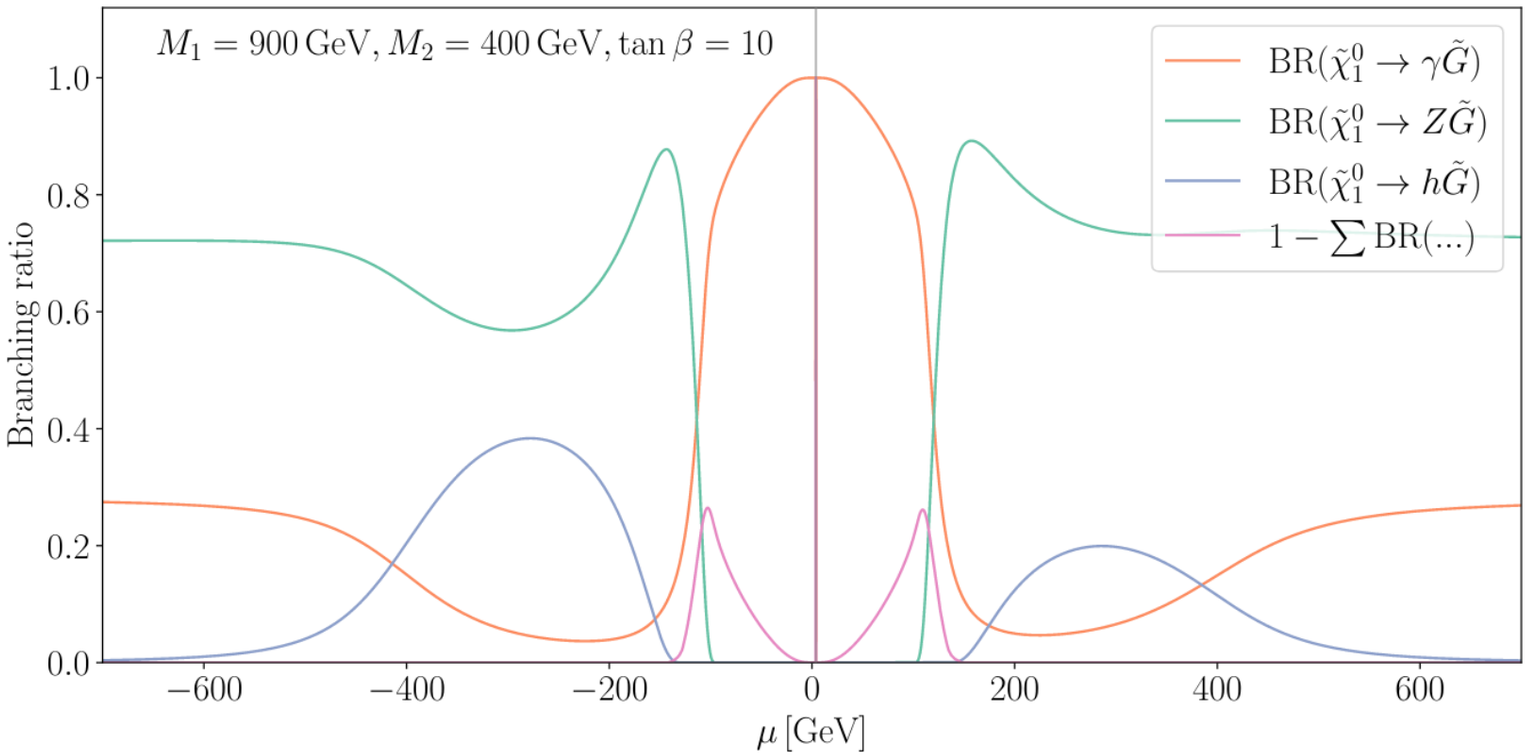









$M_1 = 900\,\mathrm{GeV}, M_2 = 400\,\mathrm{GeV}, \tan\beta = 1$
$\mathrm{BR}(\tilde{\chi}_1^0 \to \gamma\tilde{G})$
$\mathrm{BR}(\tilde{\chi}_1^0 \to Z\tilde{G})$
$\mathrm{BR}(\tilde{\chi}_1^0 \to h\tilde{G})$
$1 - \sum \mathrm{BR}(...)$
Branching ratio
0.0
0.2
0.4
0.6
0.8
1.0
−600
−400
−200
0
200
400
600
μ [GeV]


$M_1 = 900\,\mathrm{GeV}, M_2 = 400\,\mathrm{GeV}, \tan\beta = 10$
$\mathrm{BR}(\tilde{\chi}_1^0 \to \gamma\tilde{G})$
$\mathrm{BR}(\tilde{\chi}_1^0 \to Z\tilde{G})$
$\mathrm{BR}(\tilde{\chi}_1^0 \to h\tilde{G})$
$1 - \sum \mathrm{BR}(...)$
Branching ratio
0.0
0.2
0.4
0.6
0.8
1.0
−600
−400
−200
0
200
400
600
μ [GeV]

Analysis

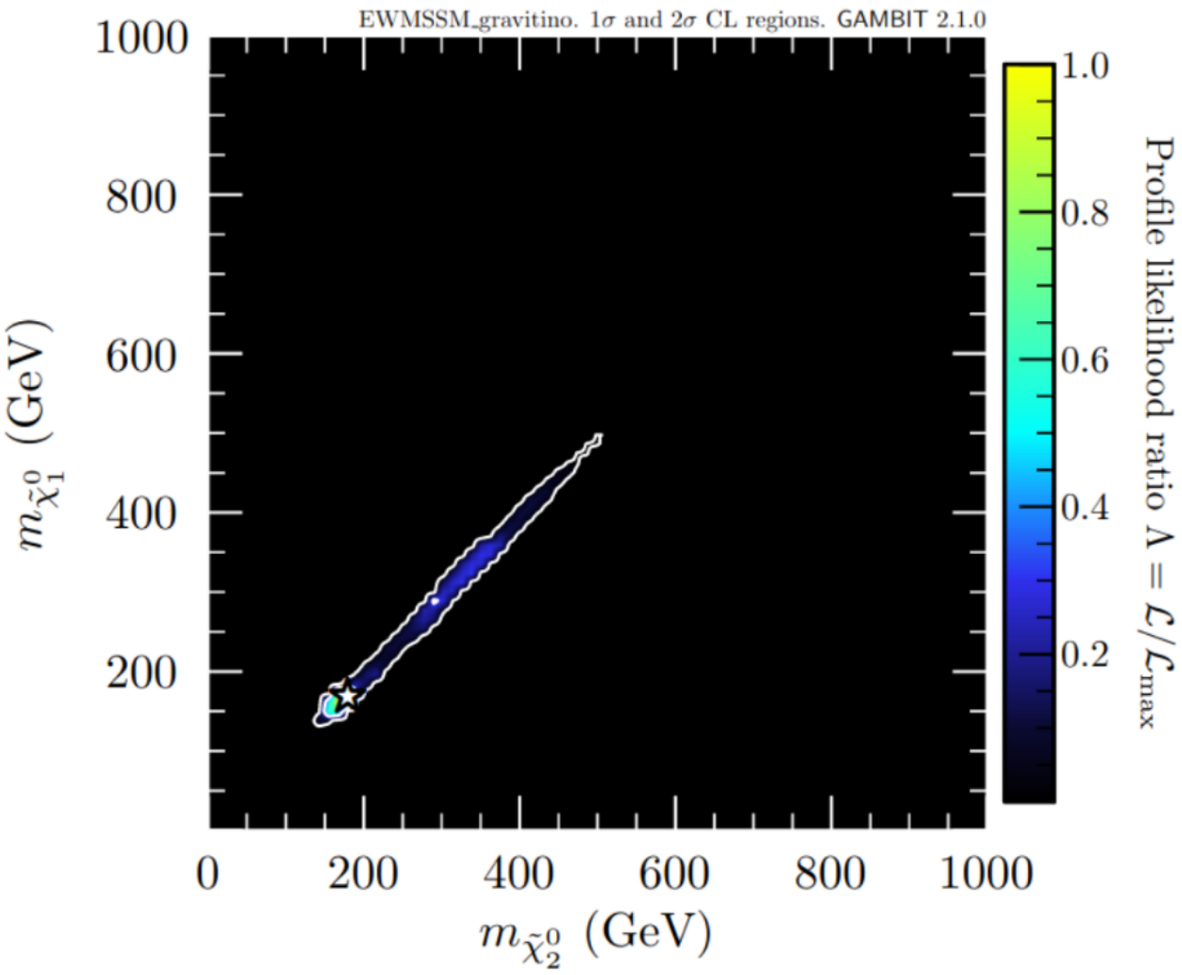
- Series of parameter scans w/ GAMBIT
- Scanner: **Diver** (differential evolution)
- Per point: **simulate 16M SUSY events** (Pythia, via ColliderBit)
- CPU cost: tens of millions of CPU hours…
- **Likelihoods**:
  - simulated **ATLAS/CMS searches** (in ColliderBit)
  - simulated **ATLAS/CMS «SM measurements»**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

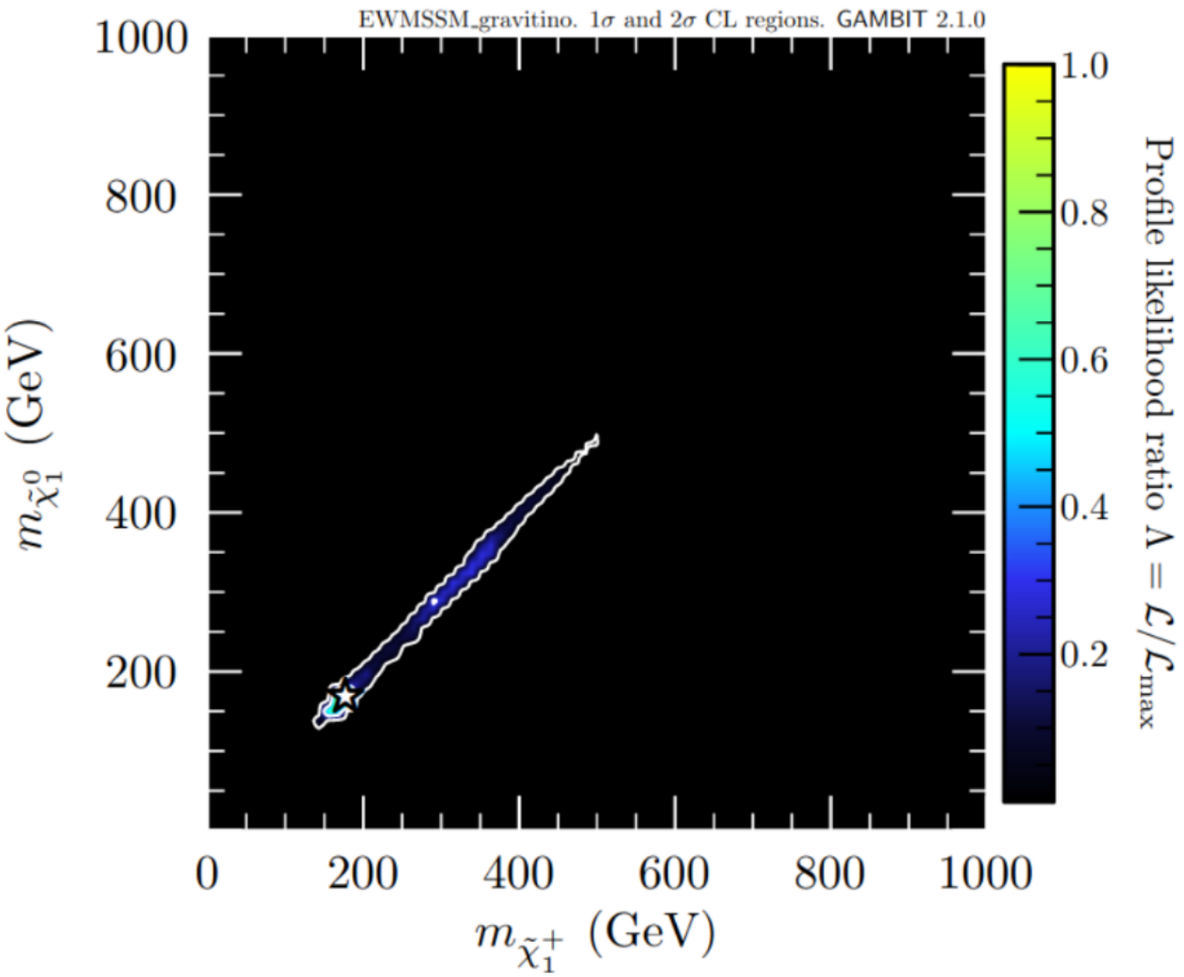
LHC searches:

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

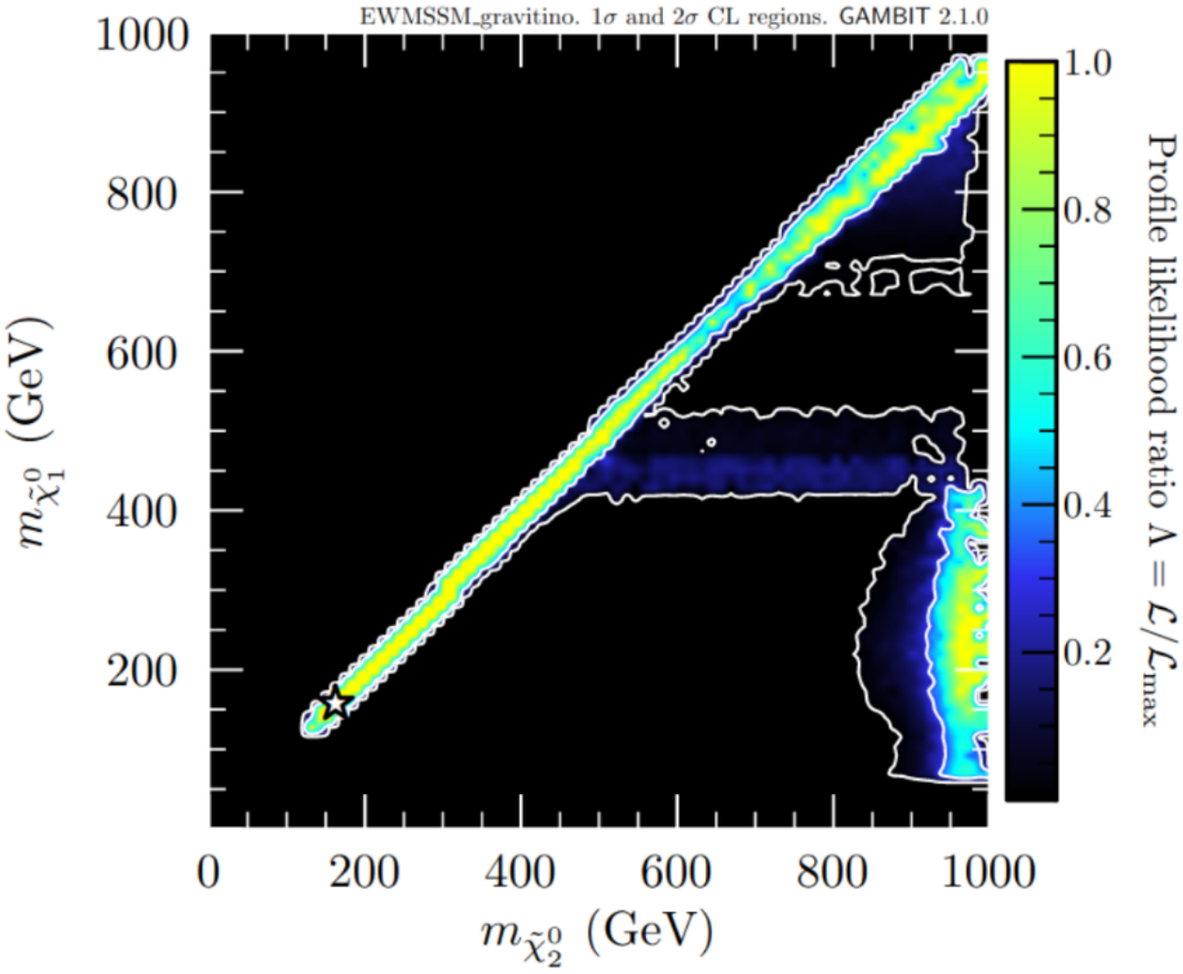
Profile likelihood ratio

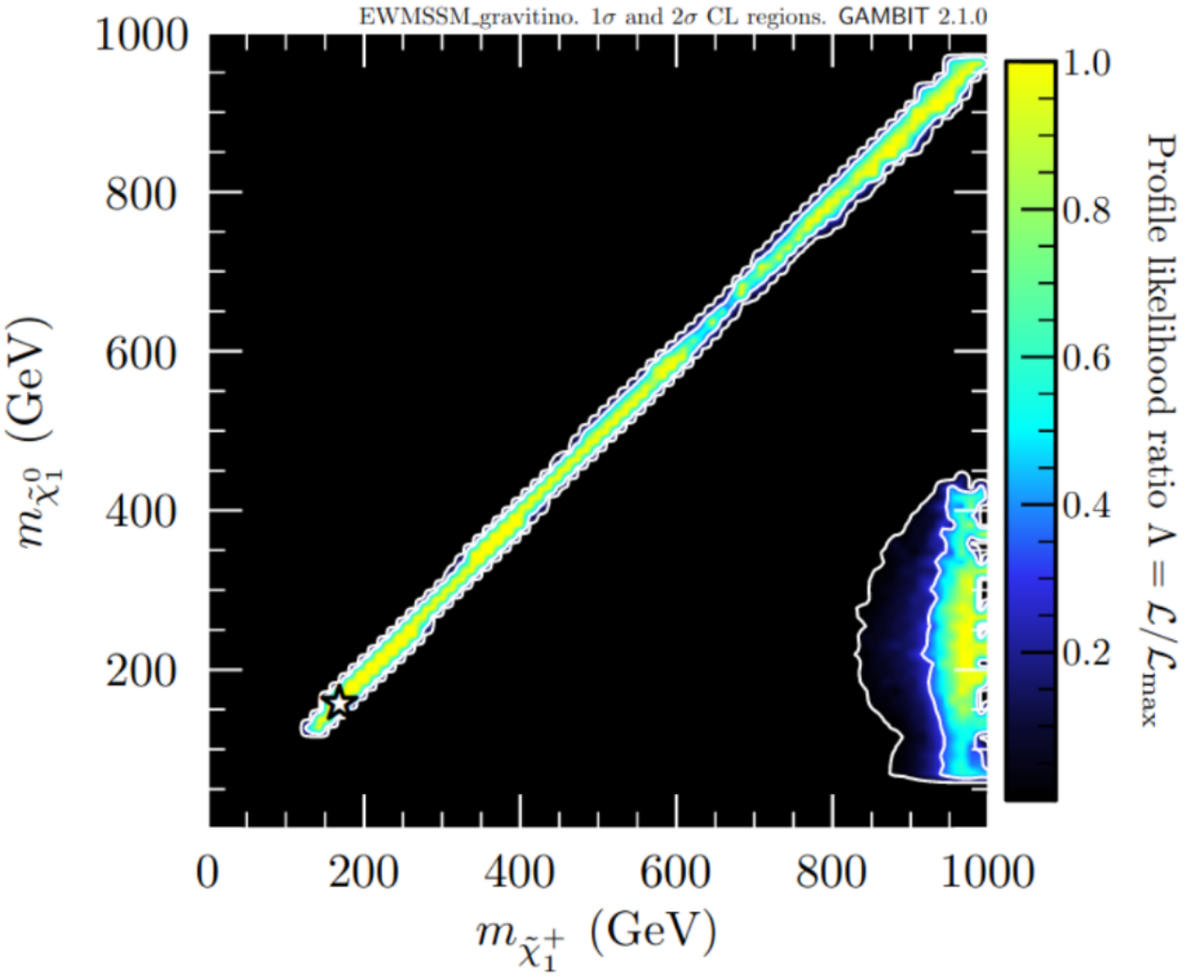




Preliminary results

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

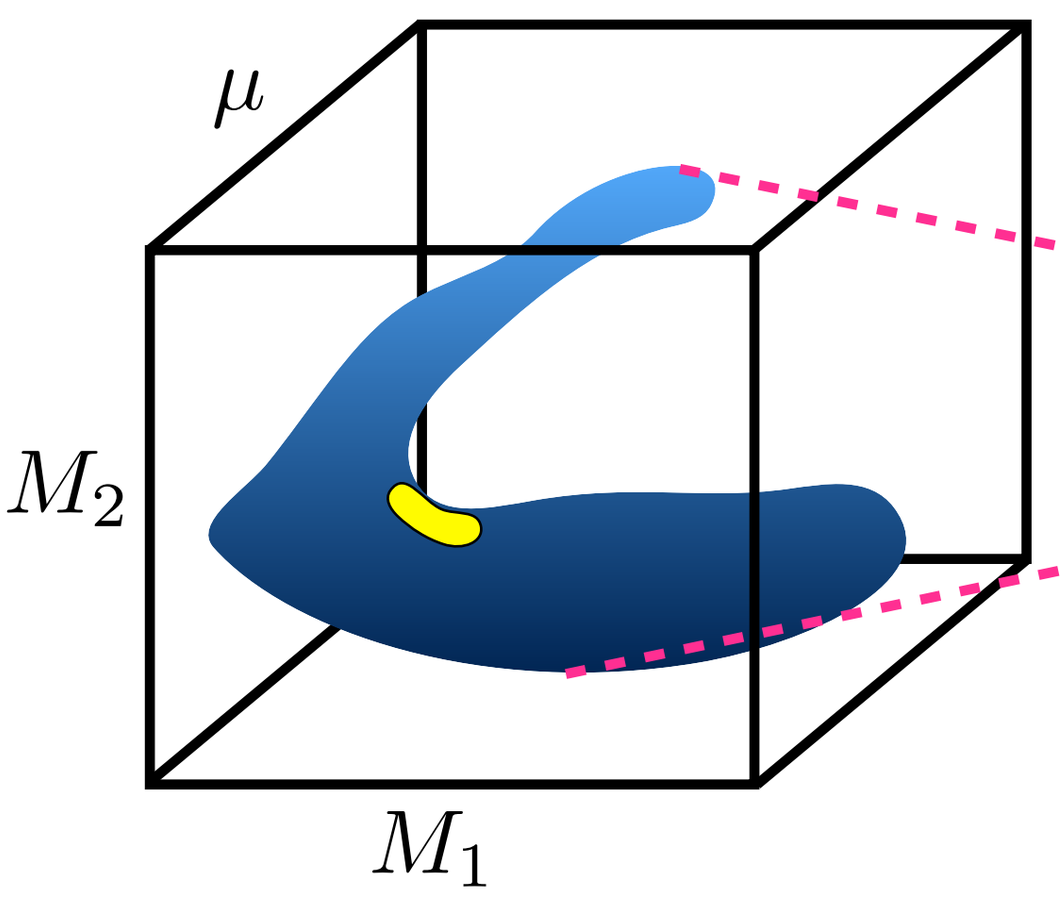


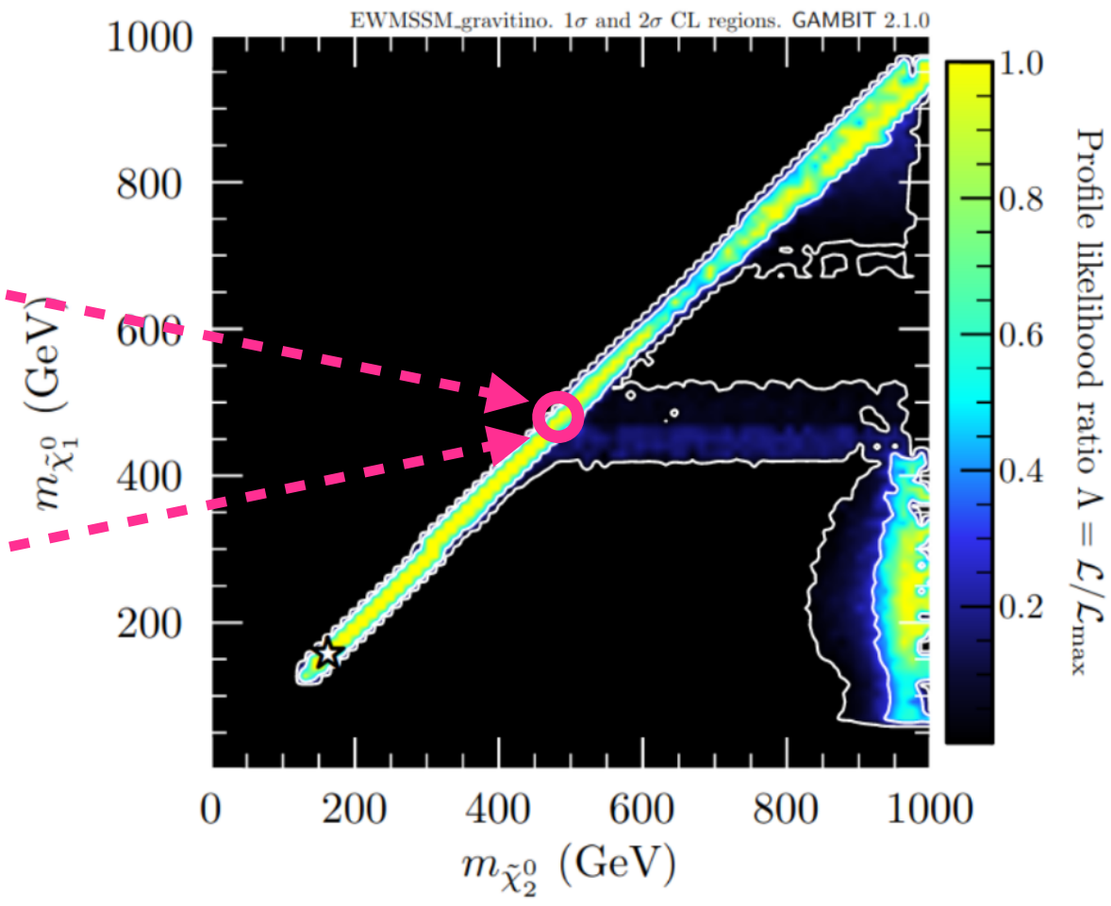


Preliminary results

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.

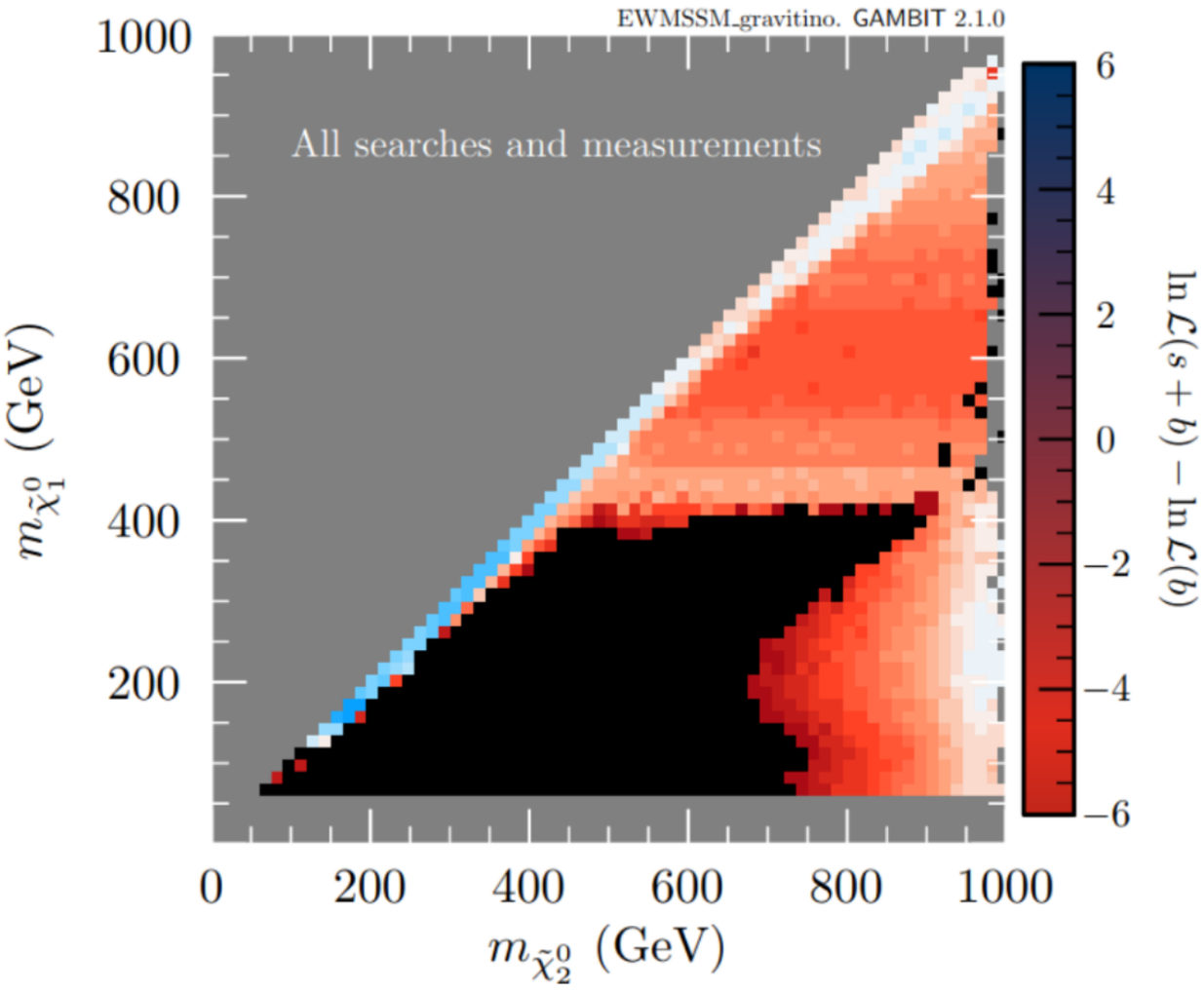
This does not tell us anything about *the size* of the viable parameter space…

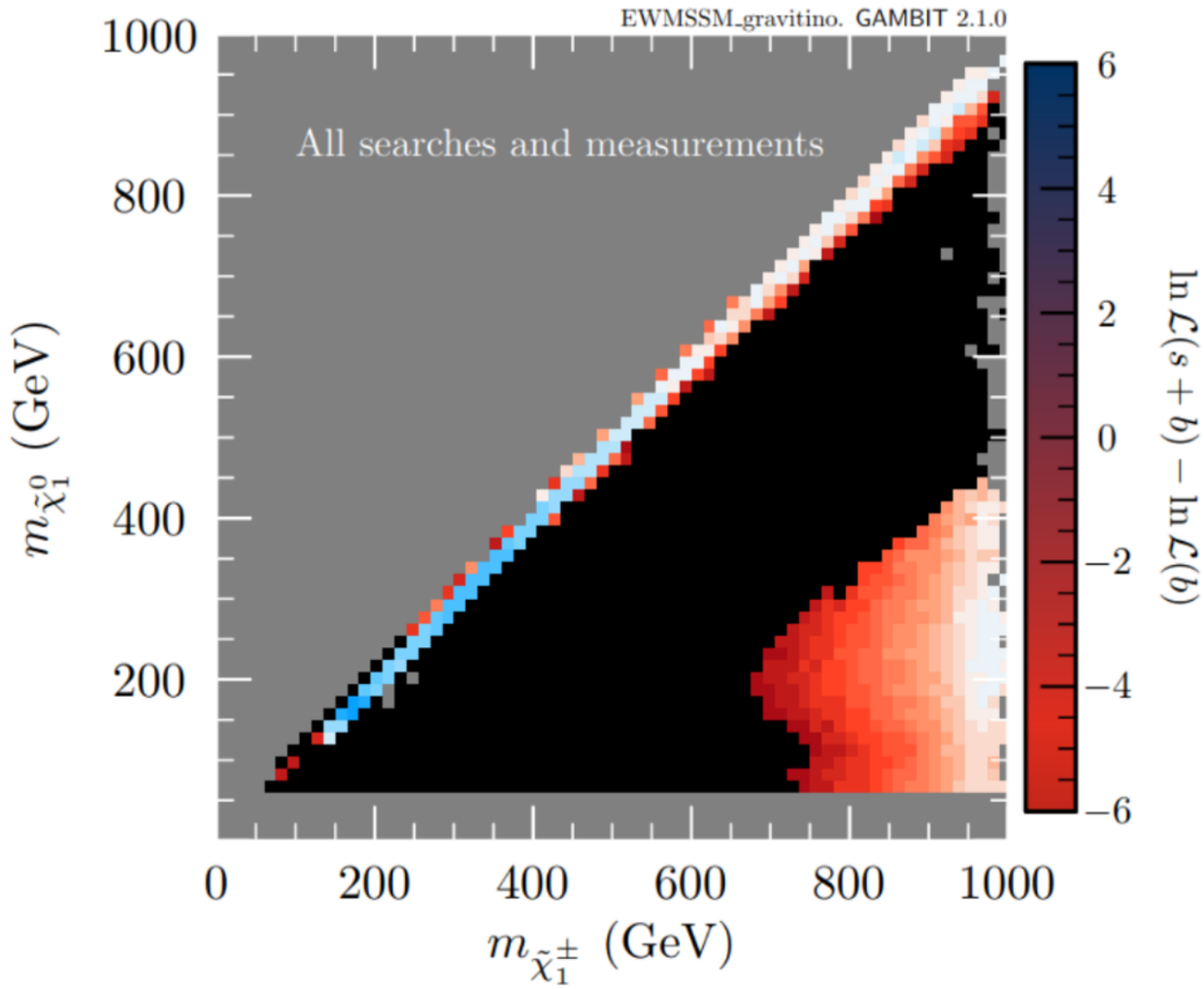




Preliminary results

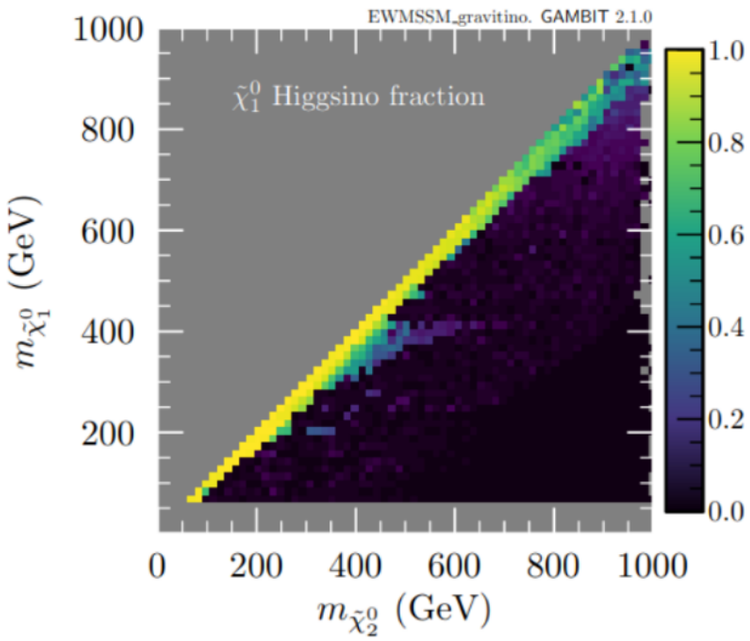
ln L(s+b) - ln L(b)

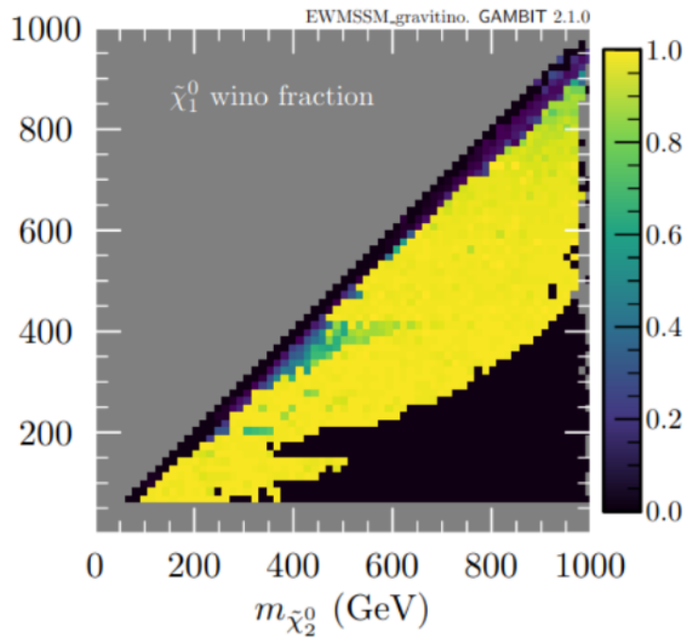


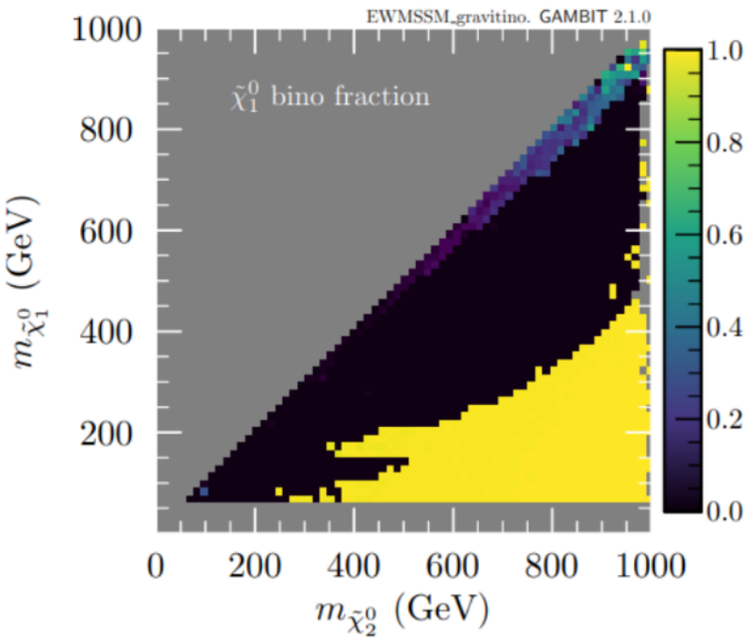


Preliminary results

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

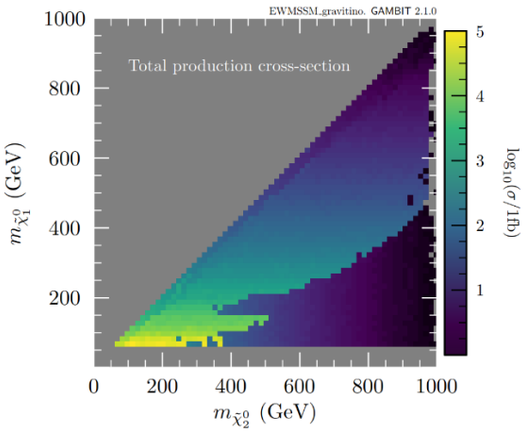


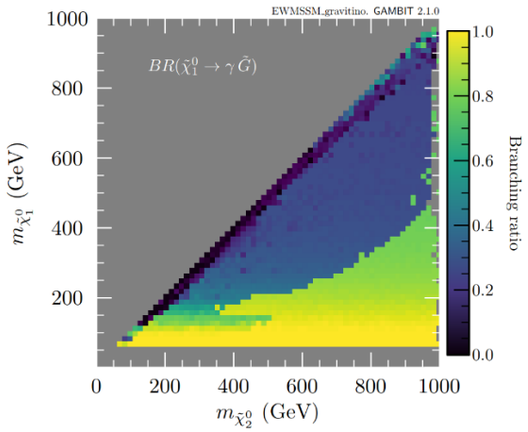


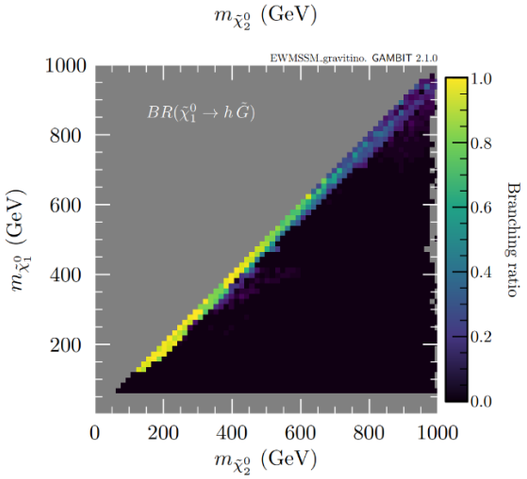


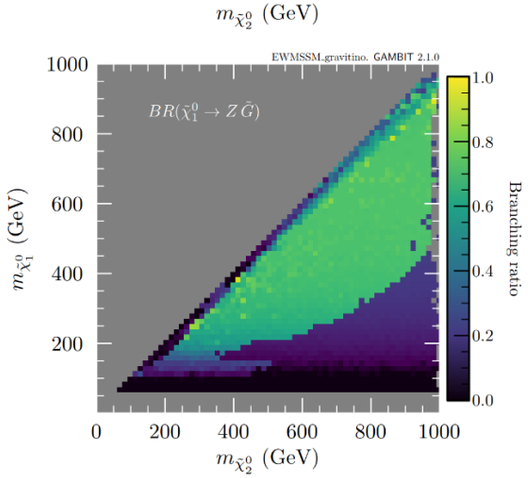
Preliminary results

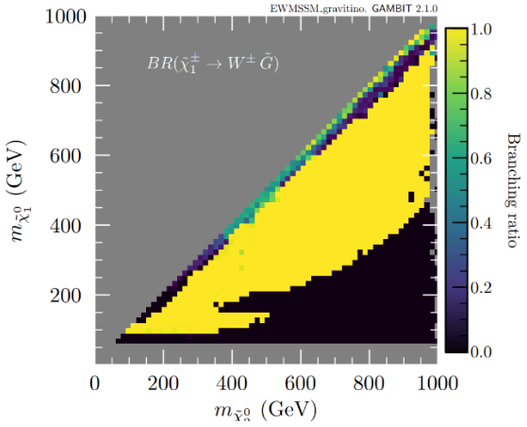
Impact of different classes of searches/measurements

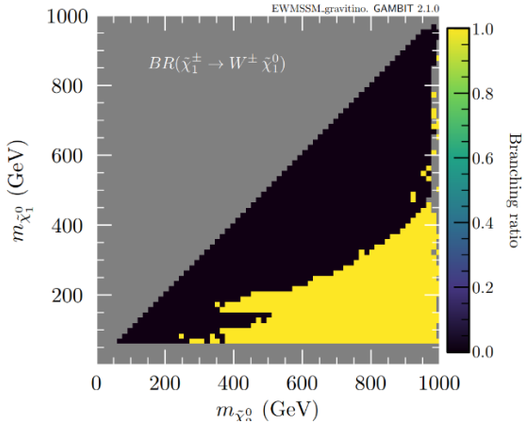


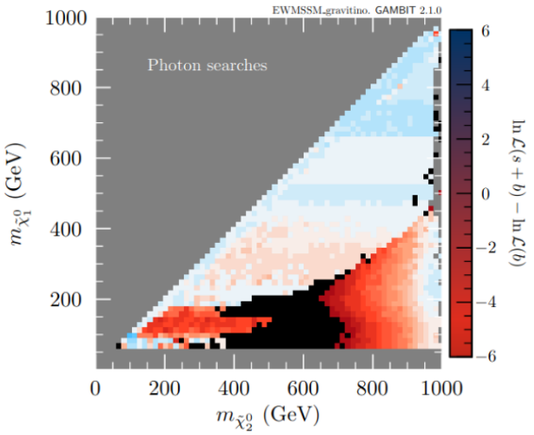


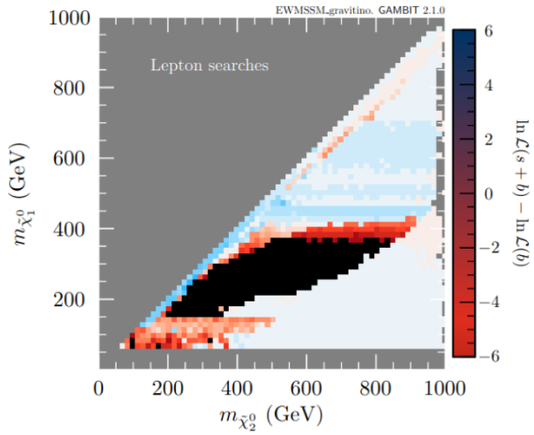


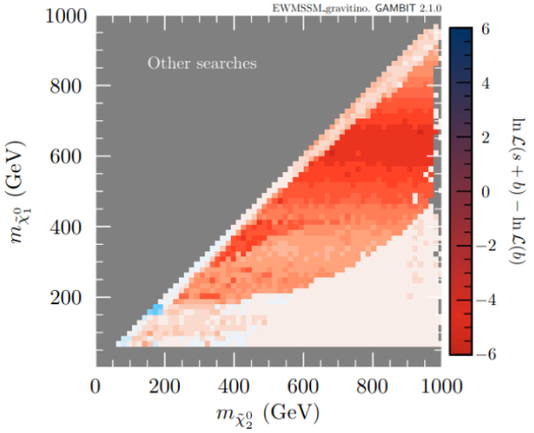


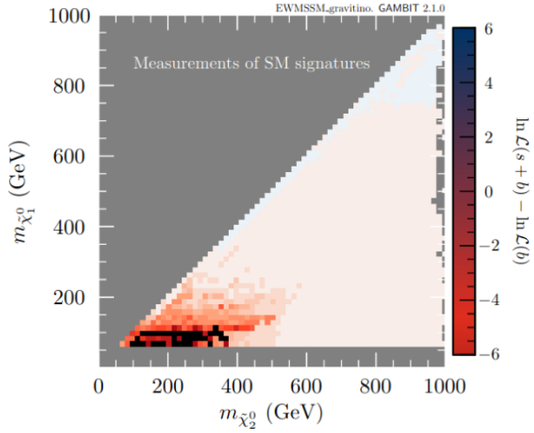






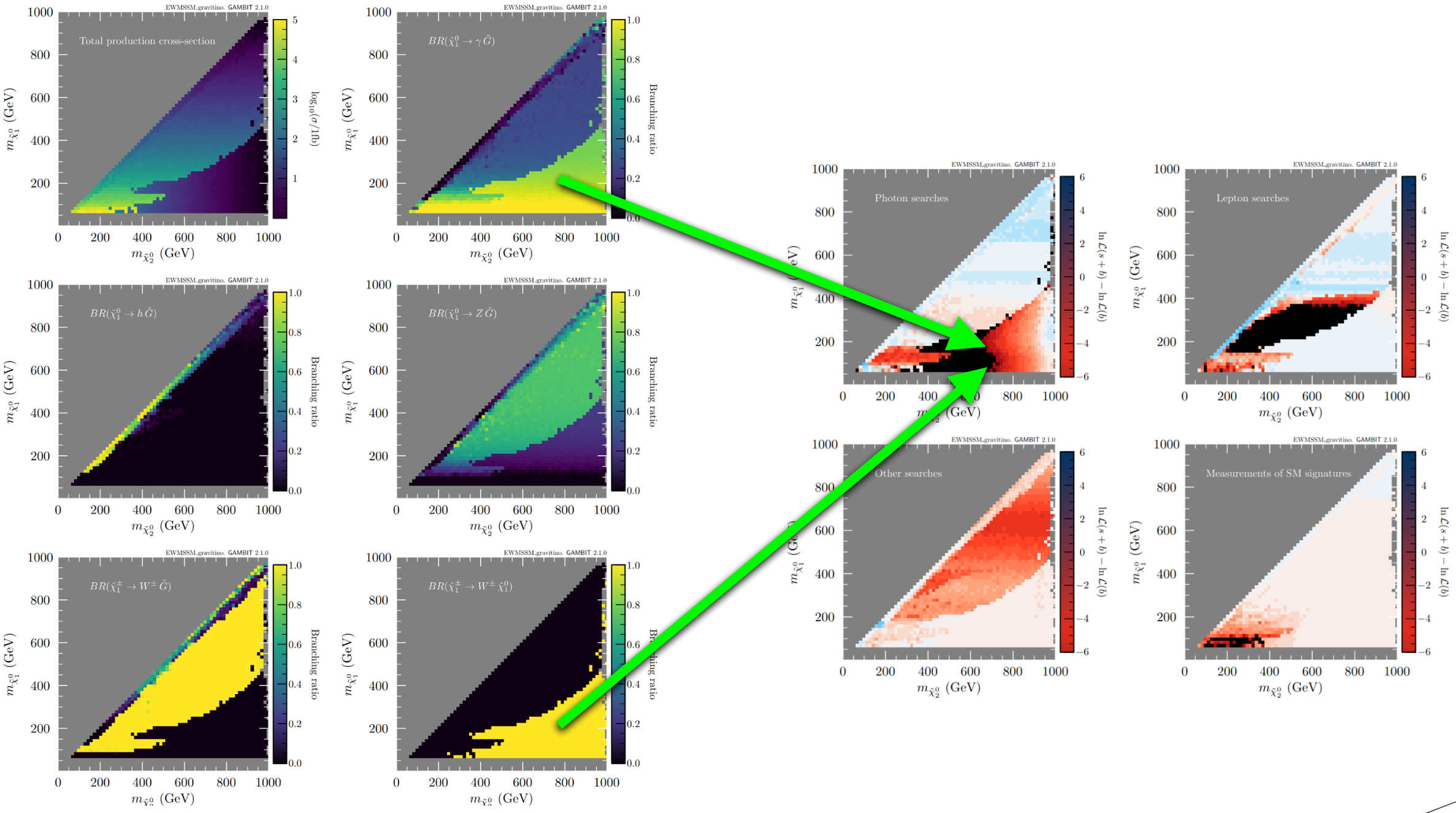






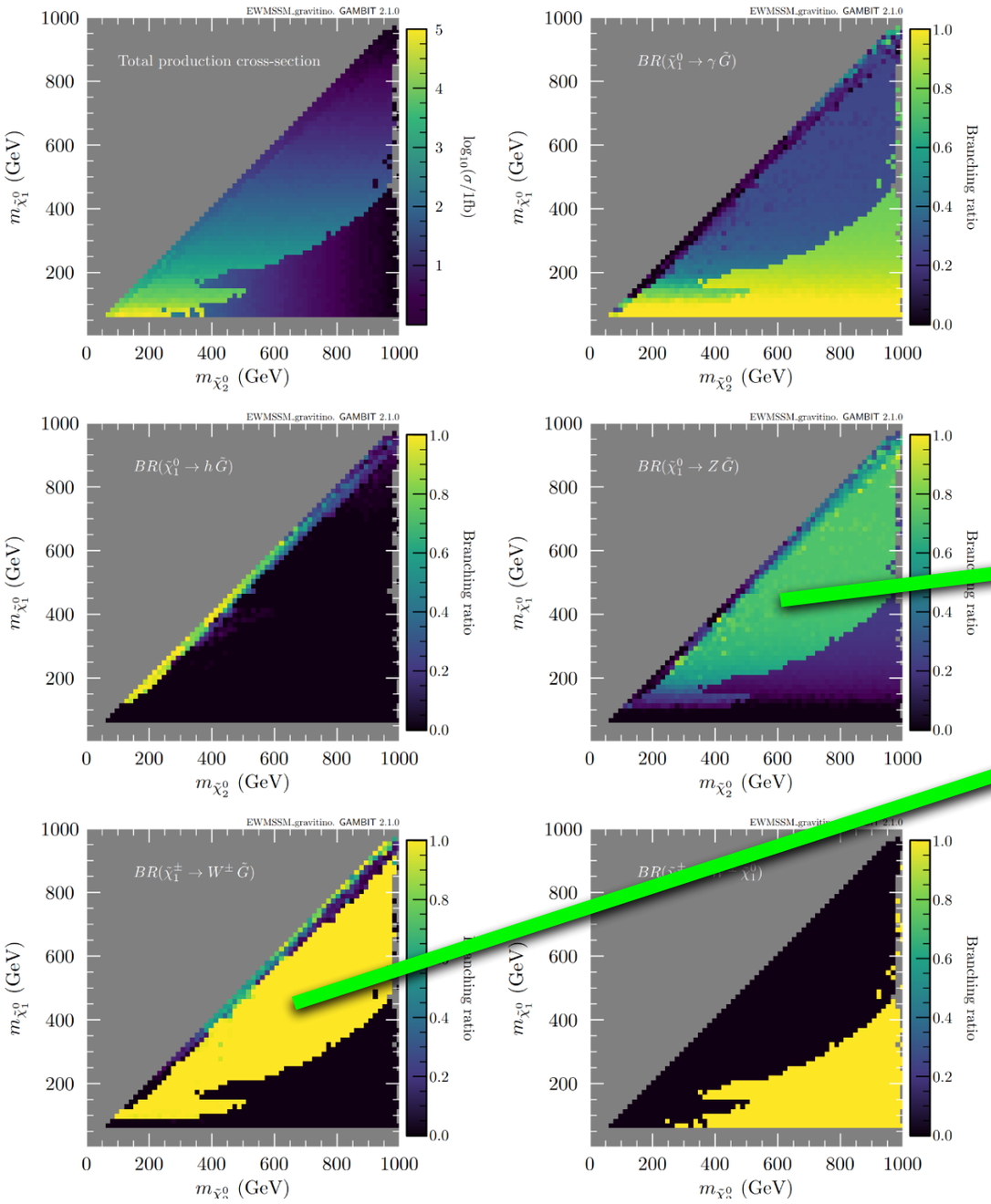
Preliminary results

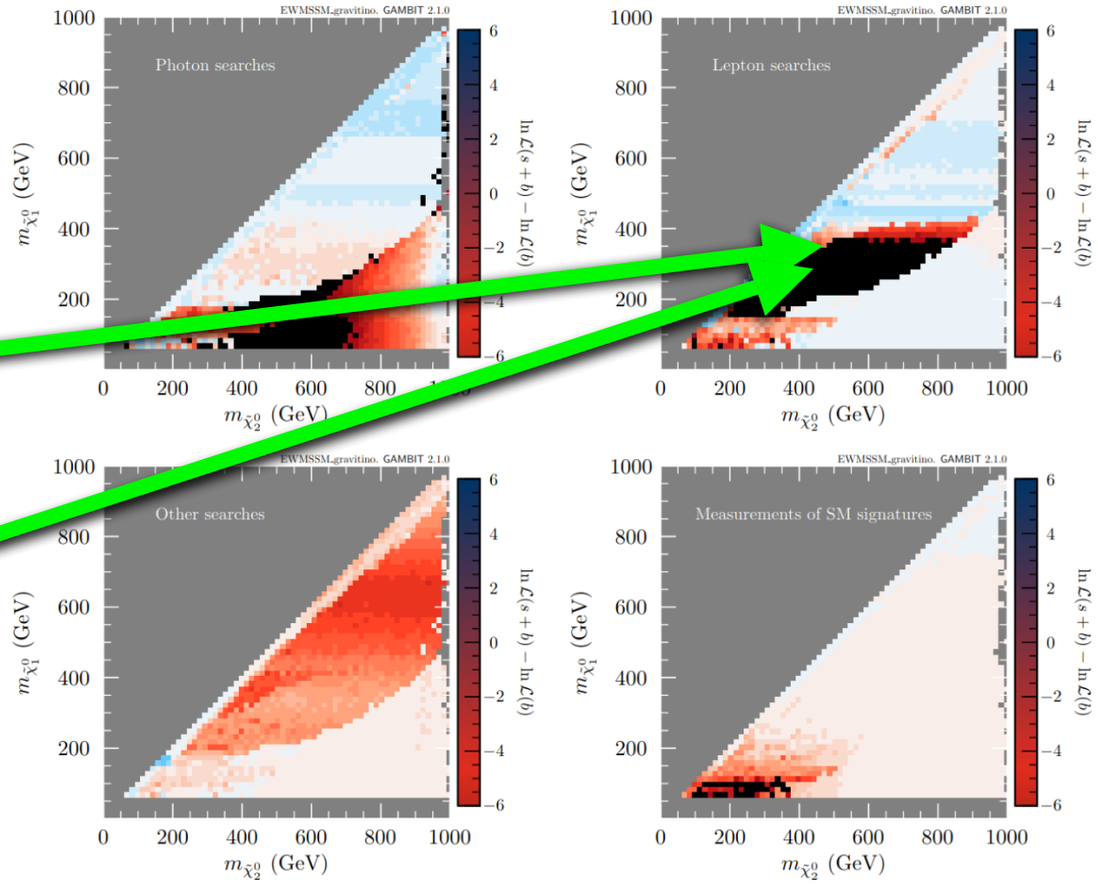
Impact of different classes of searches/measurements



Preliminary results

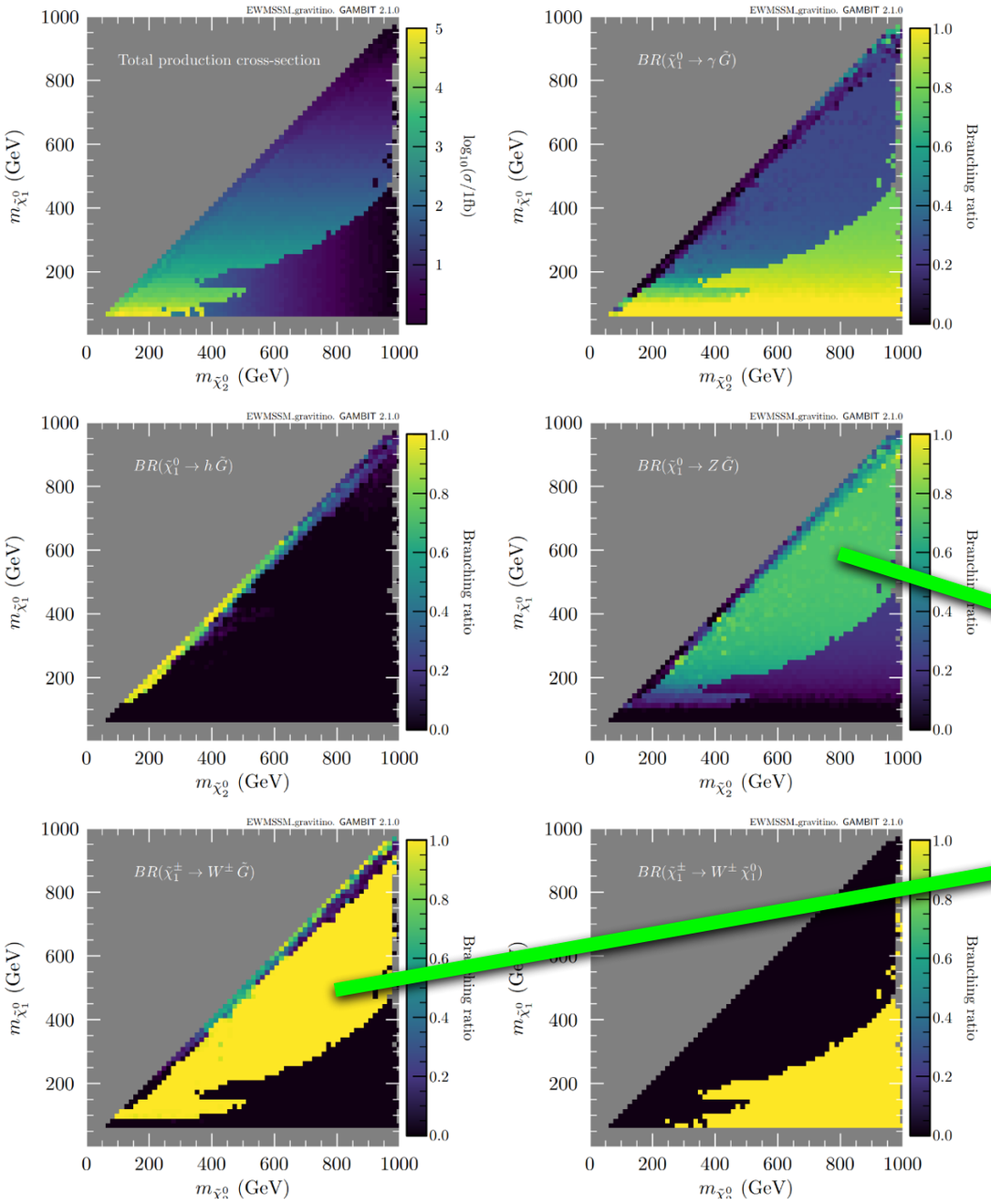
Impact of different classes of searches/measurements

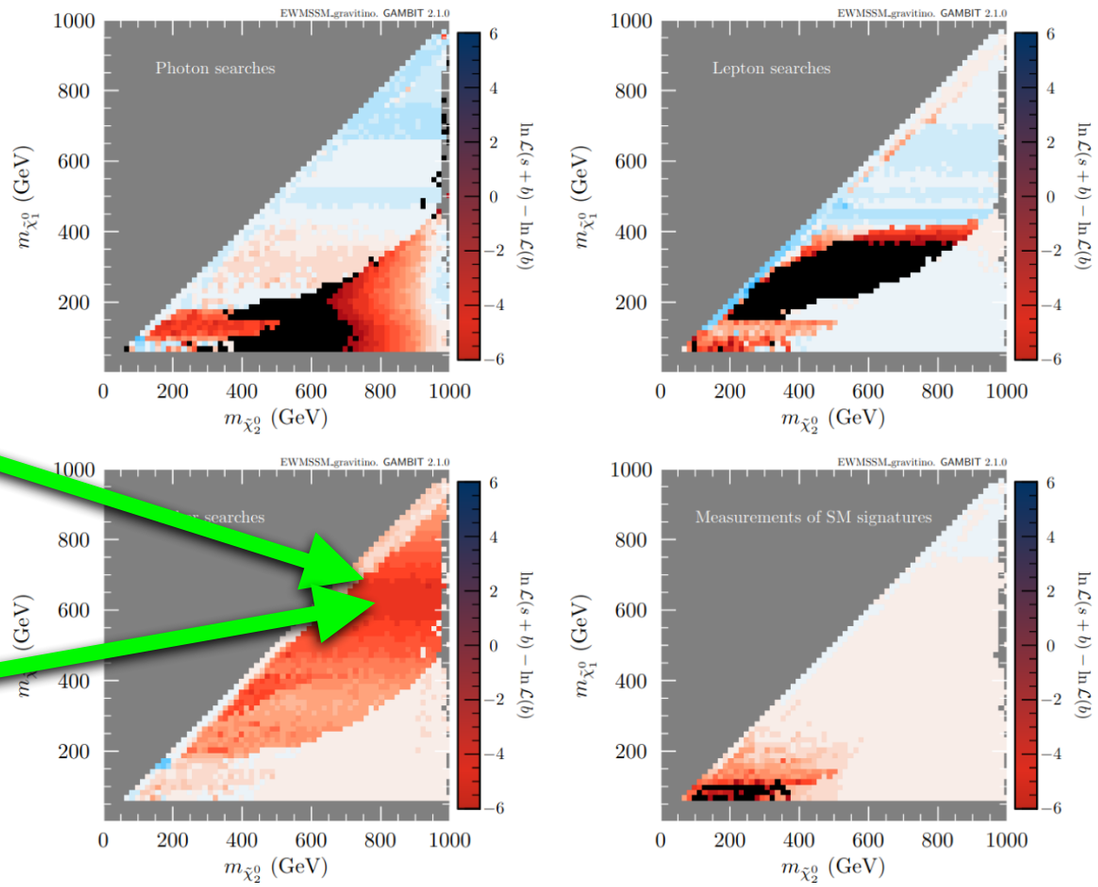




Preliminary results

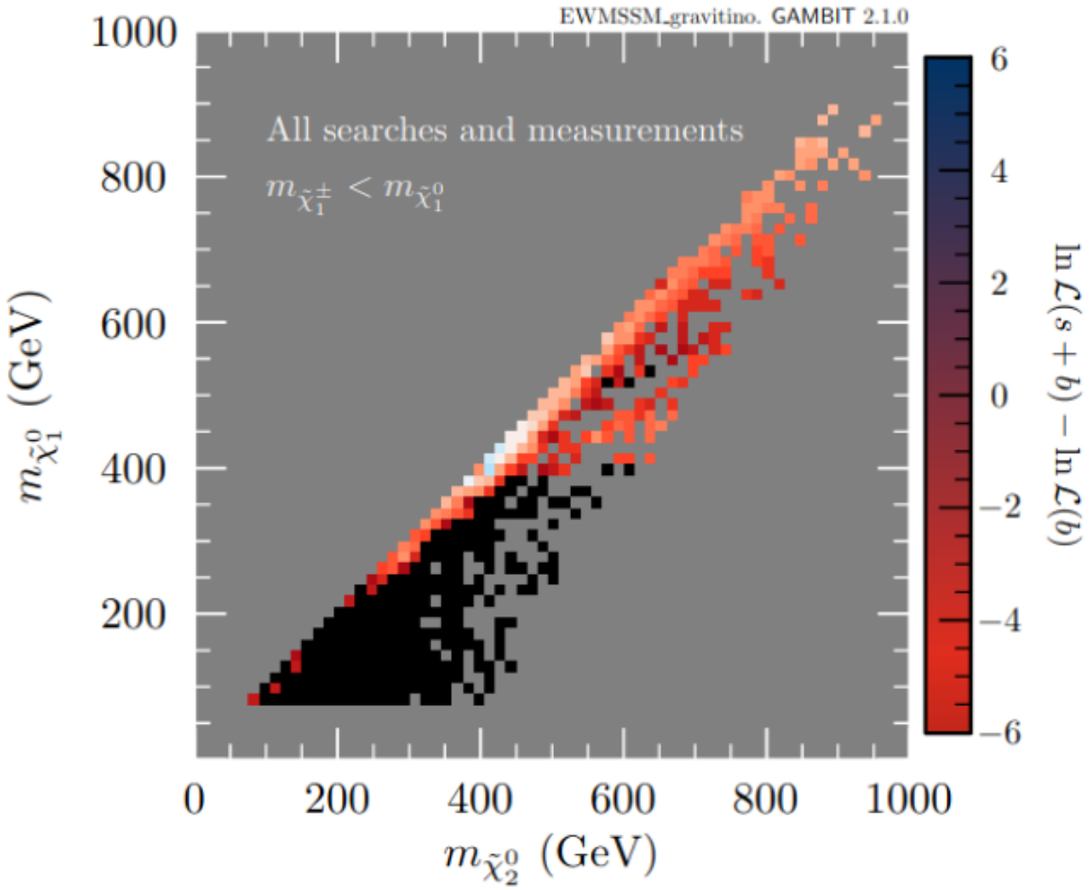
Impact of different classes of searches/measurements

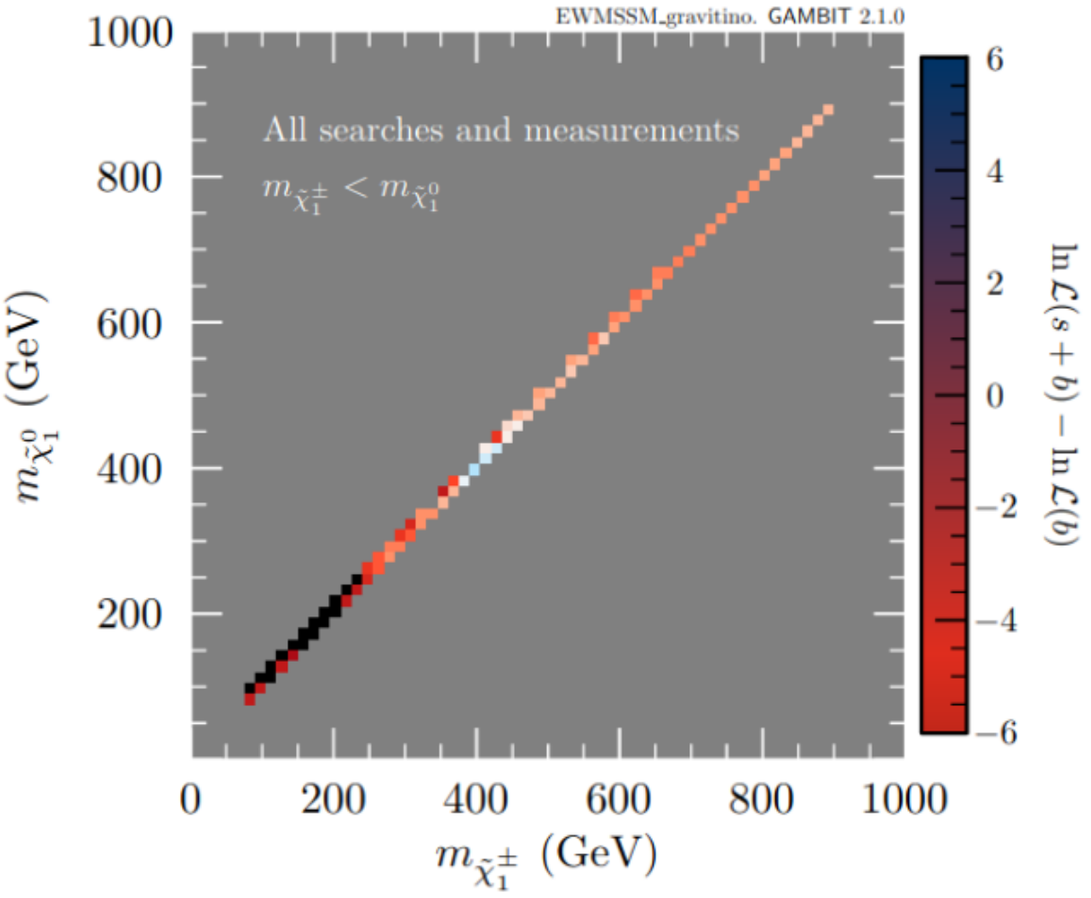




Preliminary results

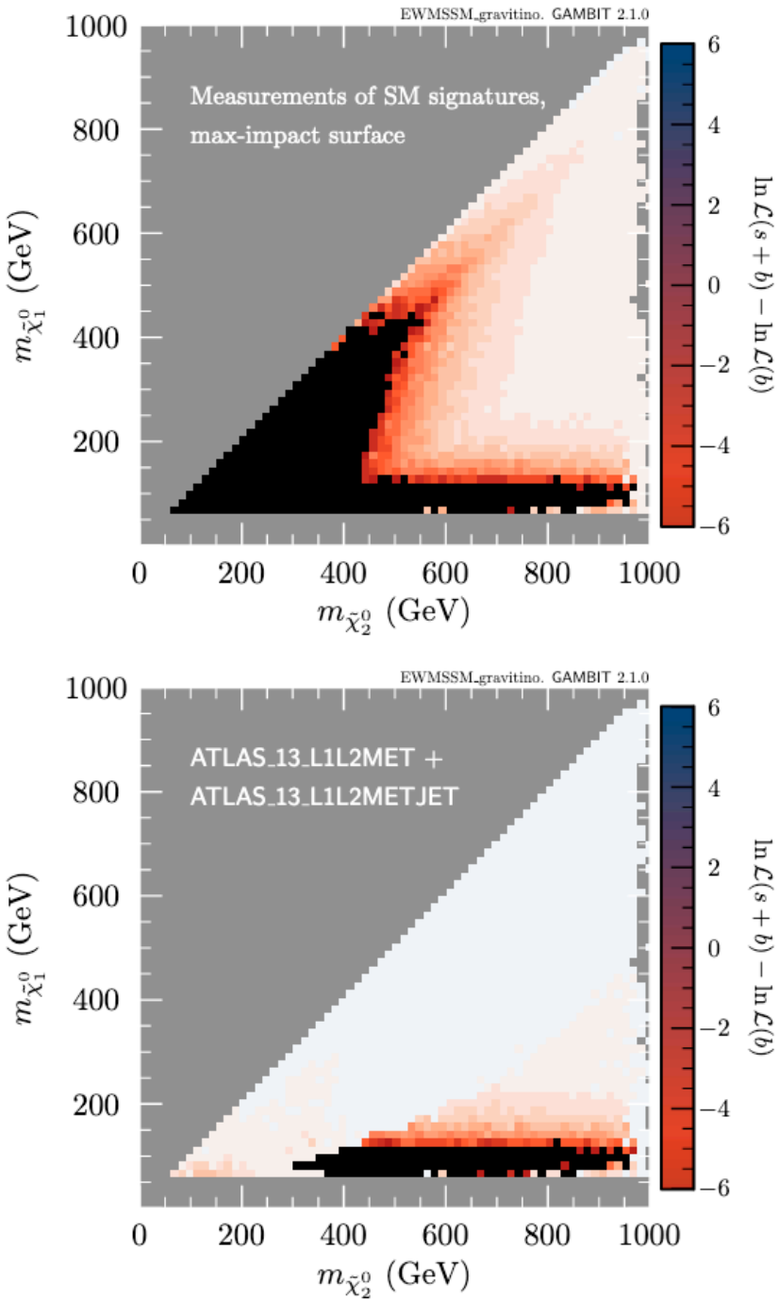
Can have chargino lighter than the lightest neutralino

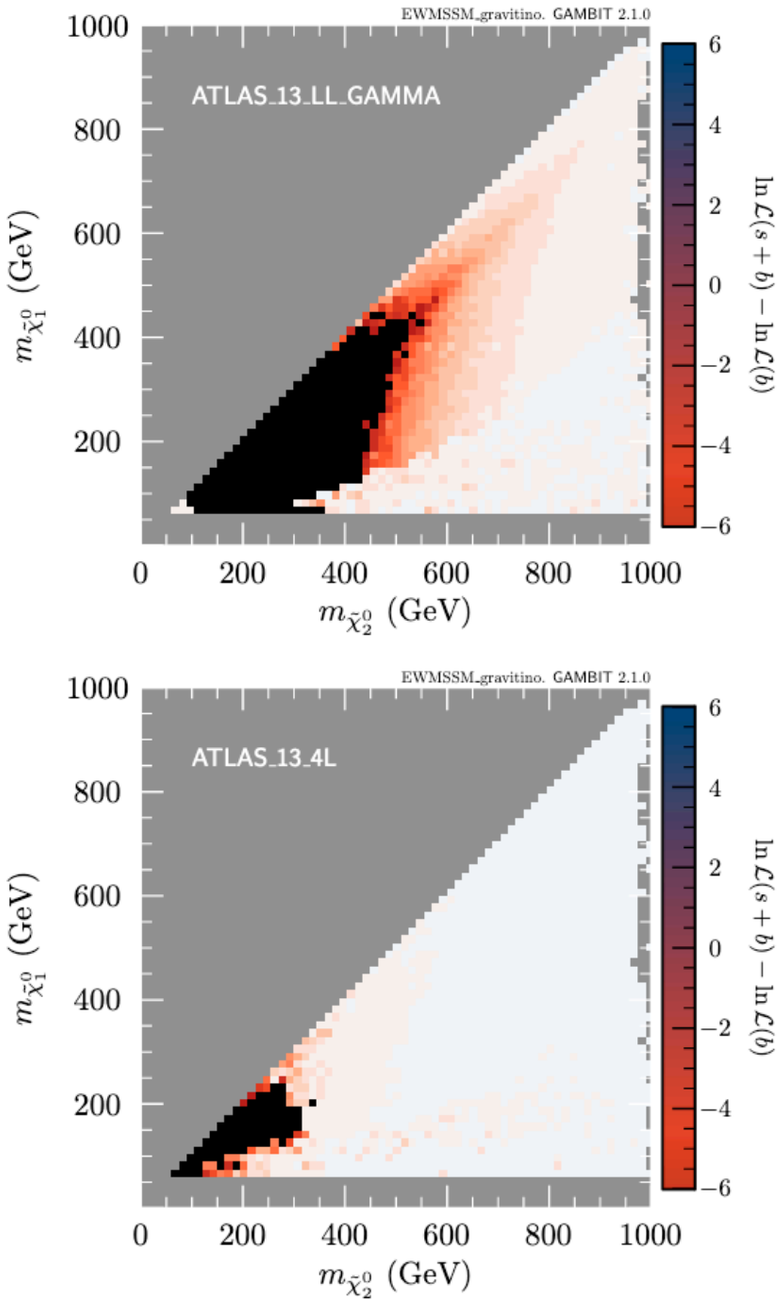




Preliminary results

Points most constrained by the «SM measurements» alone





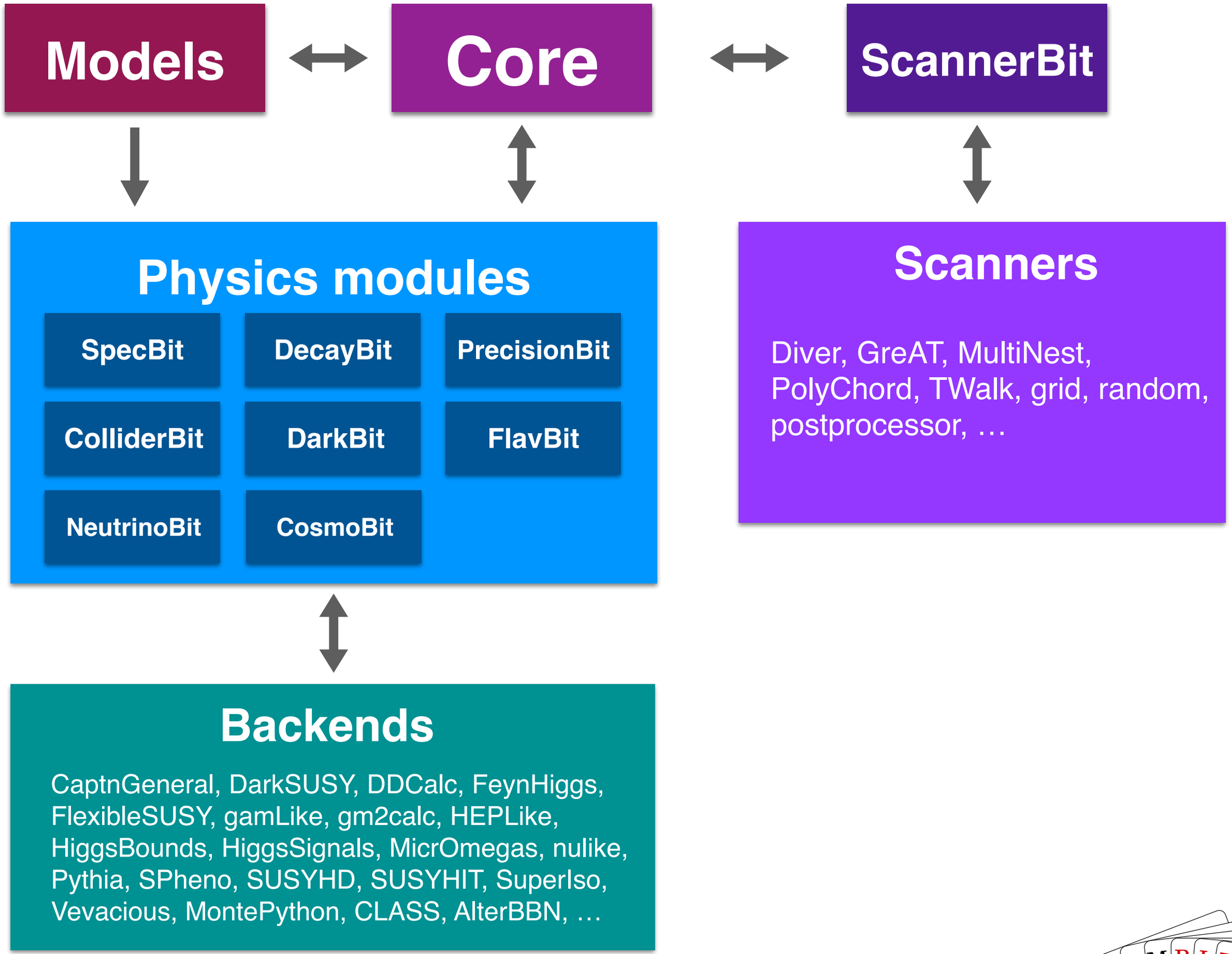
3. Summary

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**
- **New study:** LHC impact on SUSY w/ light gravitino
  - Largest proper global fit with full collider event simulations
  - First time we include simulations of LHC «SM measurements»
  - Weak preference for higgsinos ~ 200 GeV
    (small excesses in MET+leptons/jets searches)
  - Can also have a «light & lonely» bino (very low production cross-section)
  - Large parts of G-EWMSSM parameter space excluded (mostly photon+MET)
  - Difficult to exclude scenarios where the lightest EWinos are mostly, but not pure, higgsino
  - Demonstrates importance of recasting LHC results in non-simplified models


GAMBIT

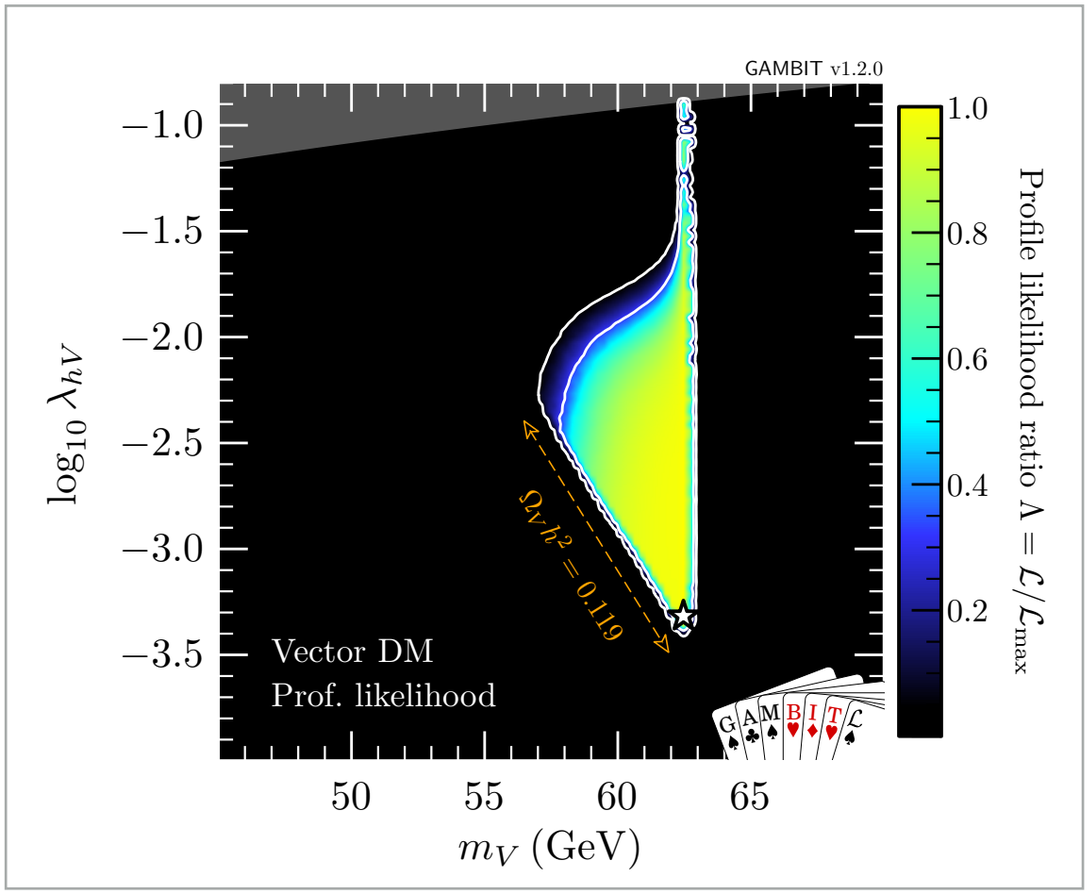
Bonus tracks

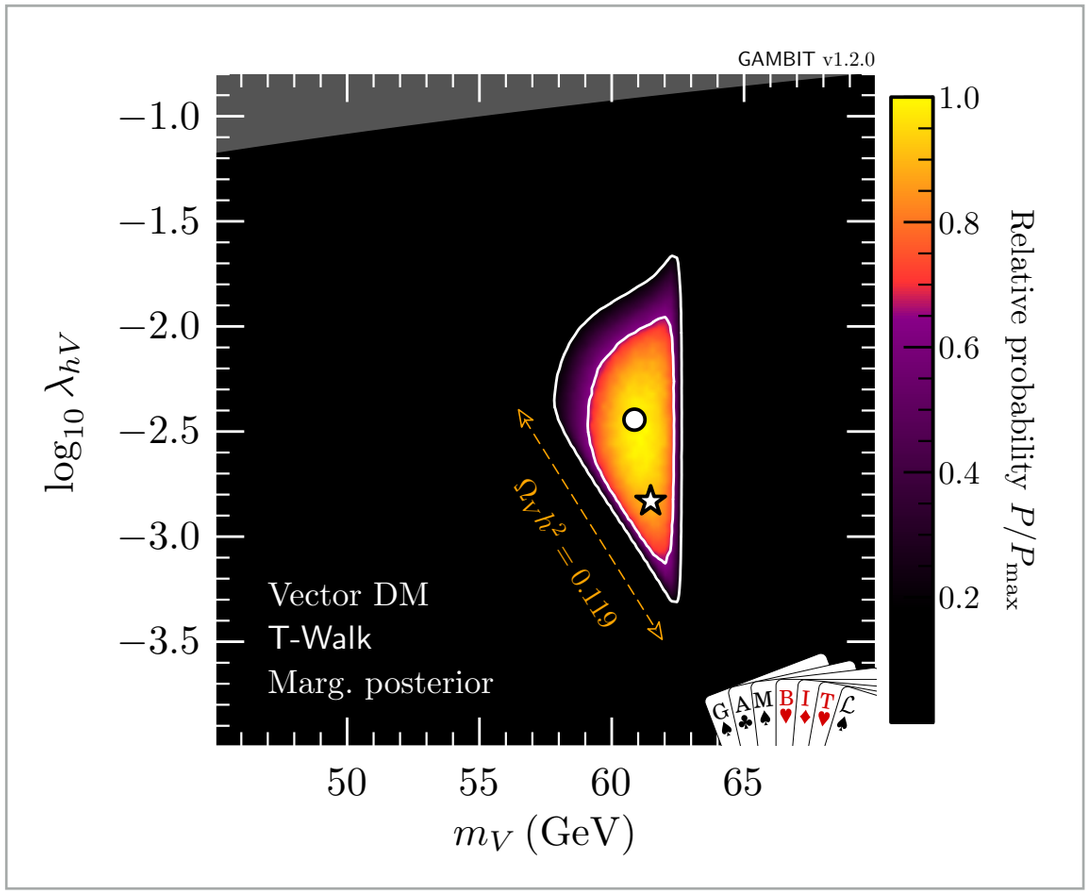

Models
Core
ScannerBit
Physics modules
SpecBit
DecayBit
PrecisionBit
ColliderBit
DarkBit
FlavBit
NeutrinoBit
CosmoBit
Scanners
Diver, GreAT, MultiNest, PolyChord, TWalk, grid, random, postprocessor, …
Backends
CaptnGeneral, DarkSUSY, DDCalc, FeynHiggs, FlexibleSUSY, gamLike, gm2calc, HEPLike, HiggsBounds,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

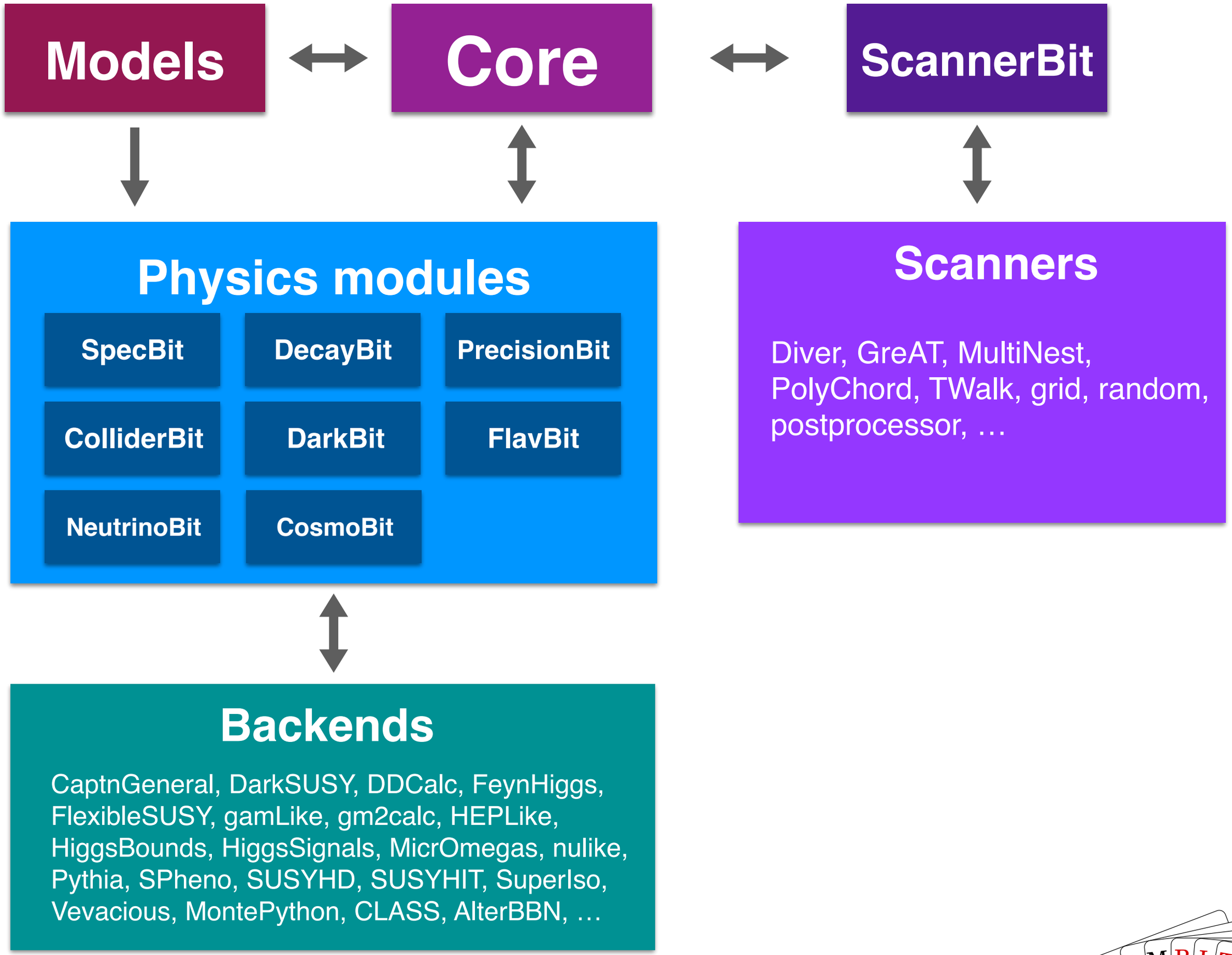




[arxiv:1808.10465]

New project: GAMBIT-light

- **GAMBIT** can be used **beyond particle physics**
- A general tool for **computationally heavy optimisation and parameter estimation** tasks
- Would be useful: a **lightweight** and **physics-free** version of GAMBIT
- **GAMBIT-light:** project starting soon w/ support from dScience/USIT/Sigma2


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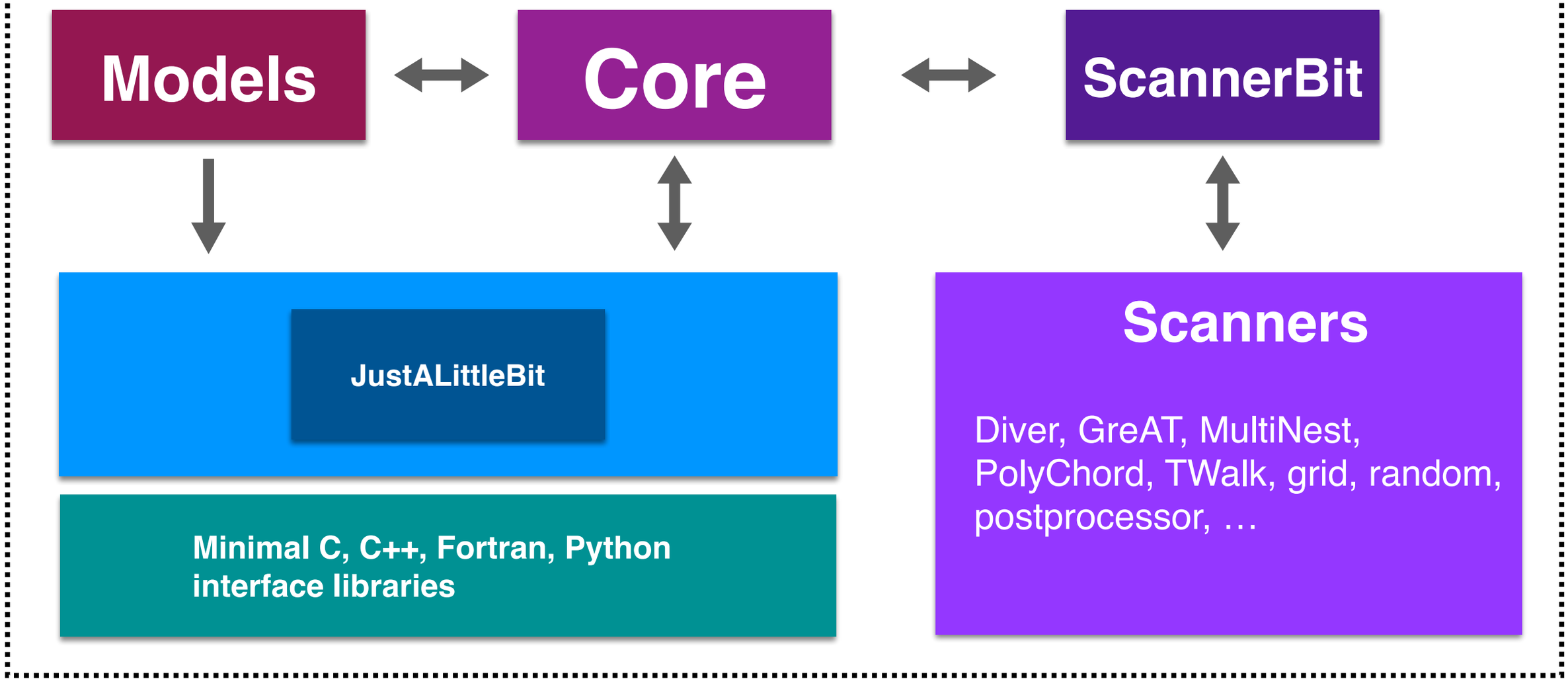
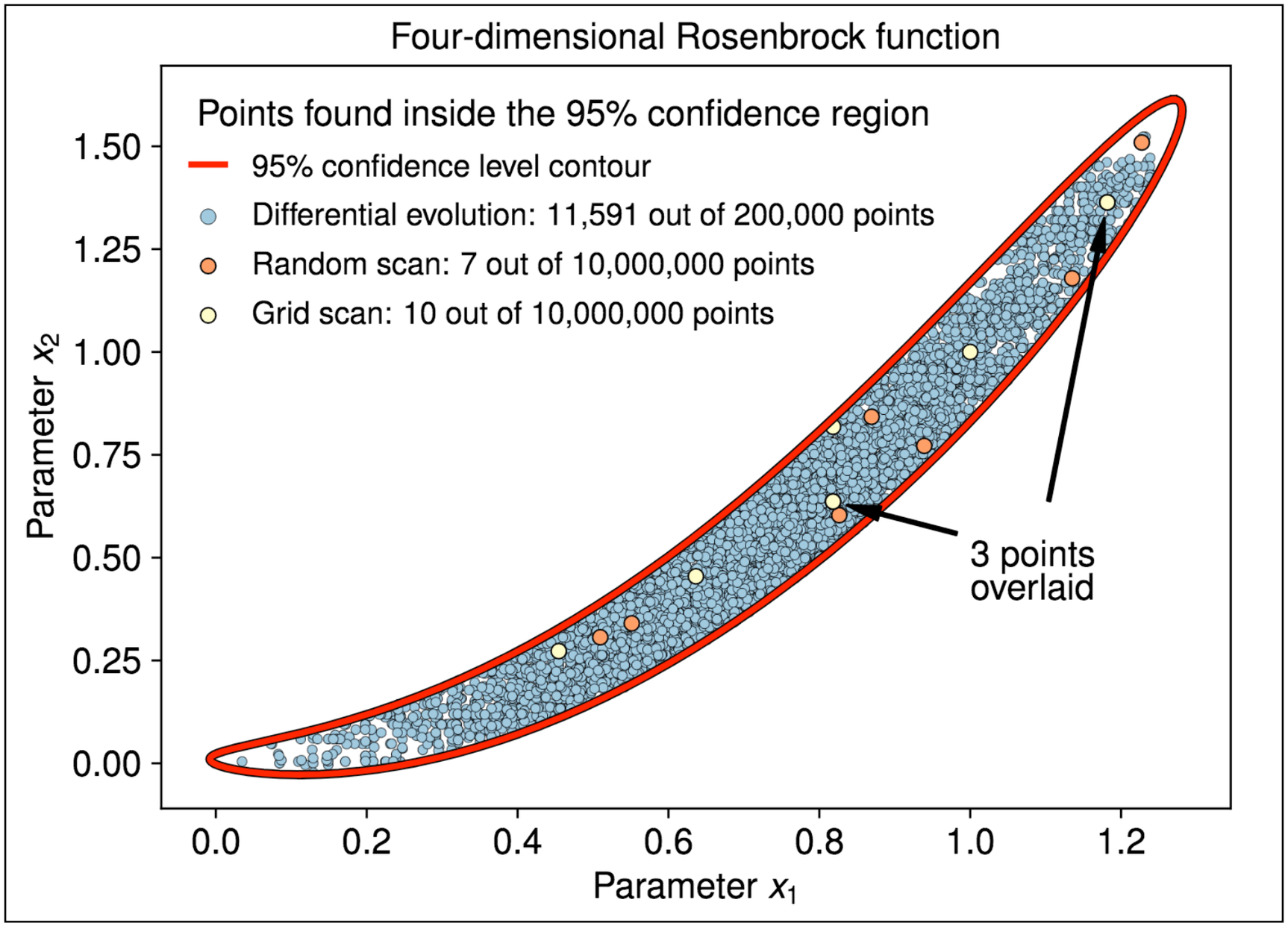
NeutrinoBit
CosmoBit
Scanners
Diver, GreAT, MultiNest, PolyChord, TWalk, grid, random, postprocessor, …
Backends
CaptnGeneral, DarkSUSY, DDCalc, FeynHiggs, FlexibleSUSY, gamLike, gm2calc, HEPLike, HiggsBounds, HiggsSignals, MicrOmegas, nulike, Pythia, SPheno, SUSYHD, SUSYHIT, SuperIso, Vevacious, MontePython,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

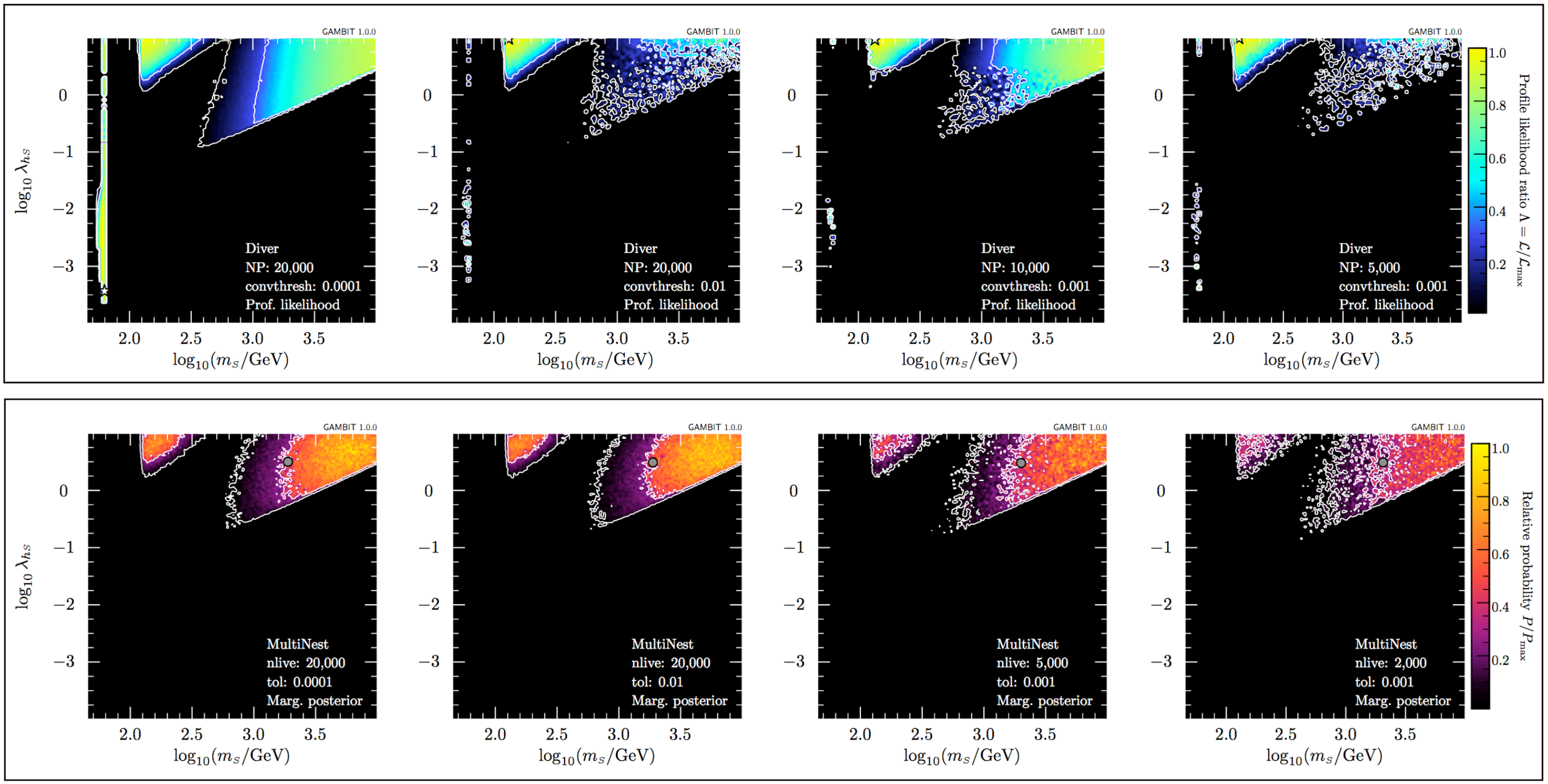

Models
Core
ScannerBit
JustALittleBit
Minimal C, C++, Fortran, Python interface libraries
Scanners
Diver, GreAT, MultiNest, PolyChord, TWalk, grid, random, postprocessor, …
Your target function code here

Parameter space exploration



[arxiv:2012.09874]

Parameter space exploration



[arxiv:1705.07959]

Dependency resolution

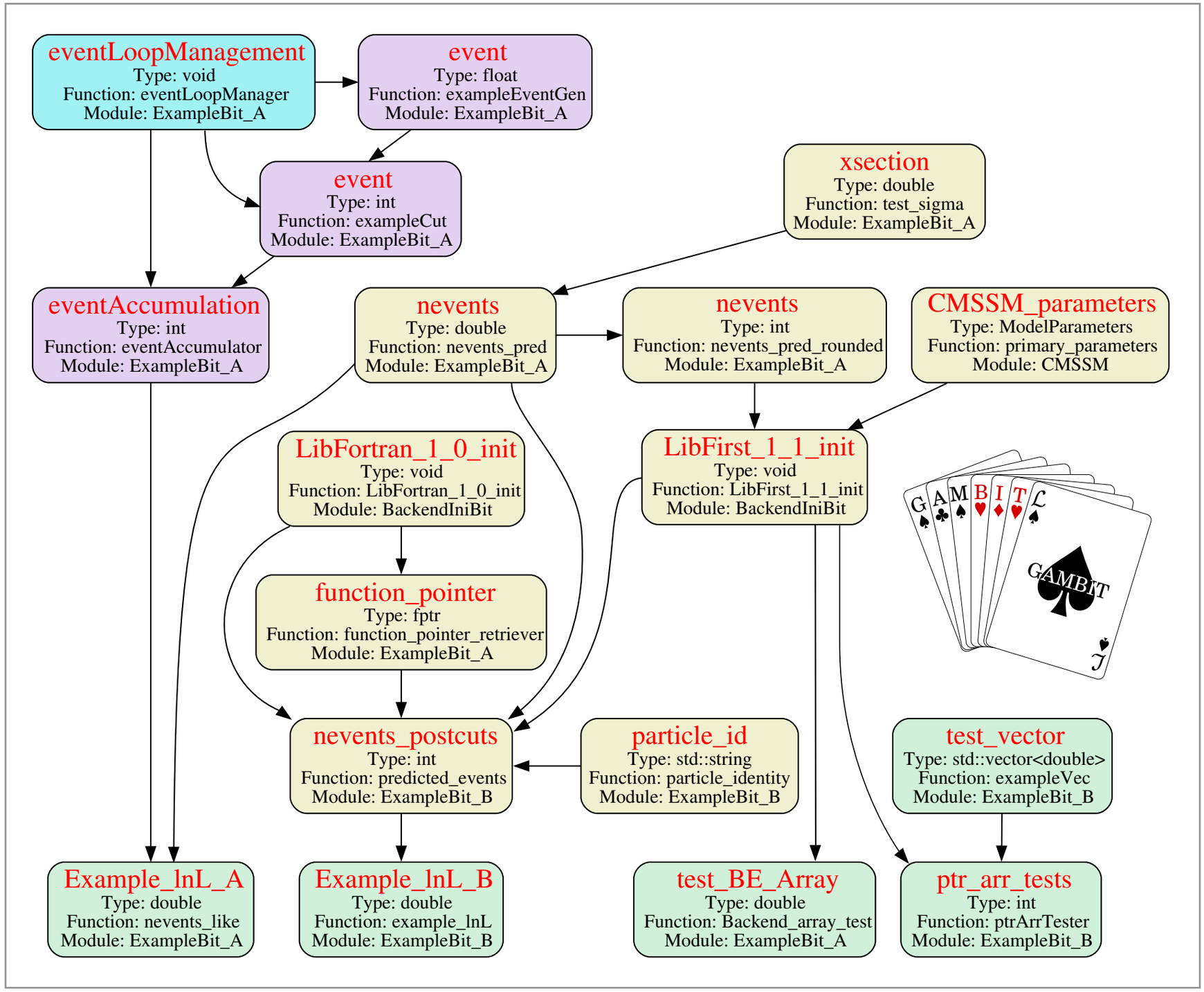
- Basic building blocks: **module functions**
- A physics module: **a collection of module functions** related to the same physics topic
- Each module function has a single **capability** (what it calculates)
- A module function can have **dependencies** on the results of other module functions
- A module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

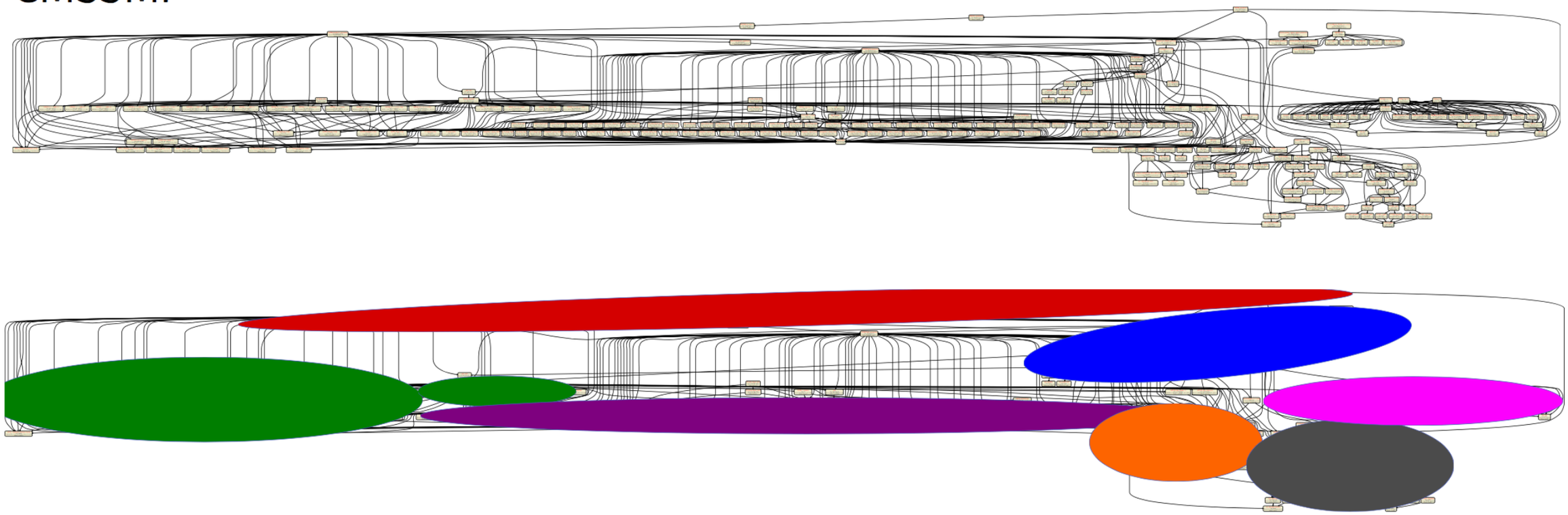
```
  /// Br B->tau nu_tau decays
  void SI_Btaunu(double &result)
  {
    using namespace Pipes::SI_Btaunu;

    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