First SUSY results with GAMBIT

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on behalf of the GAMBIT Collaboration

DESY Theory Workshop 2017 — 27/09/17

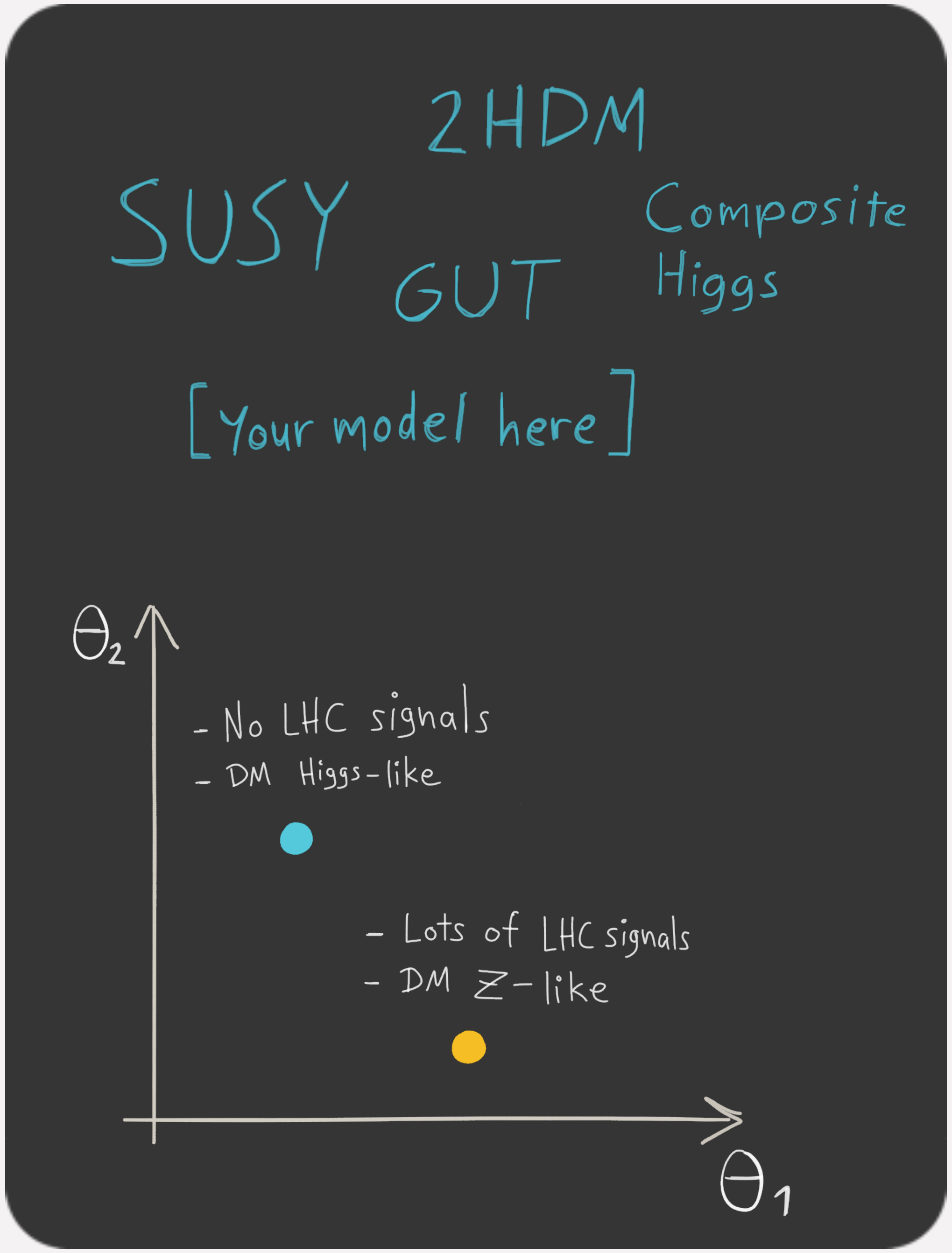
NORDITA

The Nordic Institute for Theoretical Physics

What is GAMBIT?

Comparing BSM theories to data

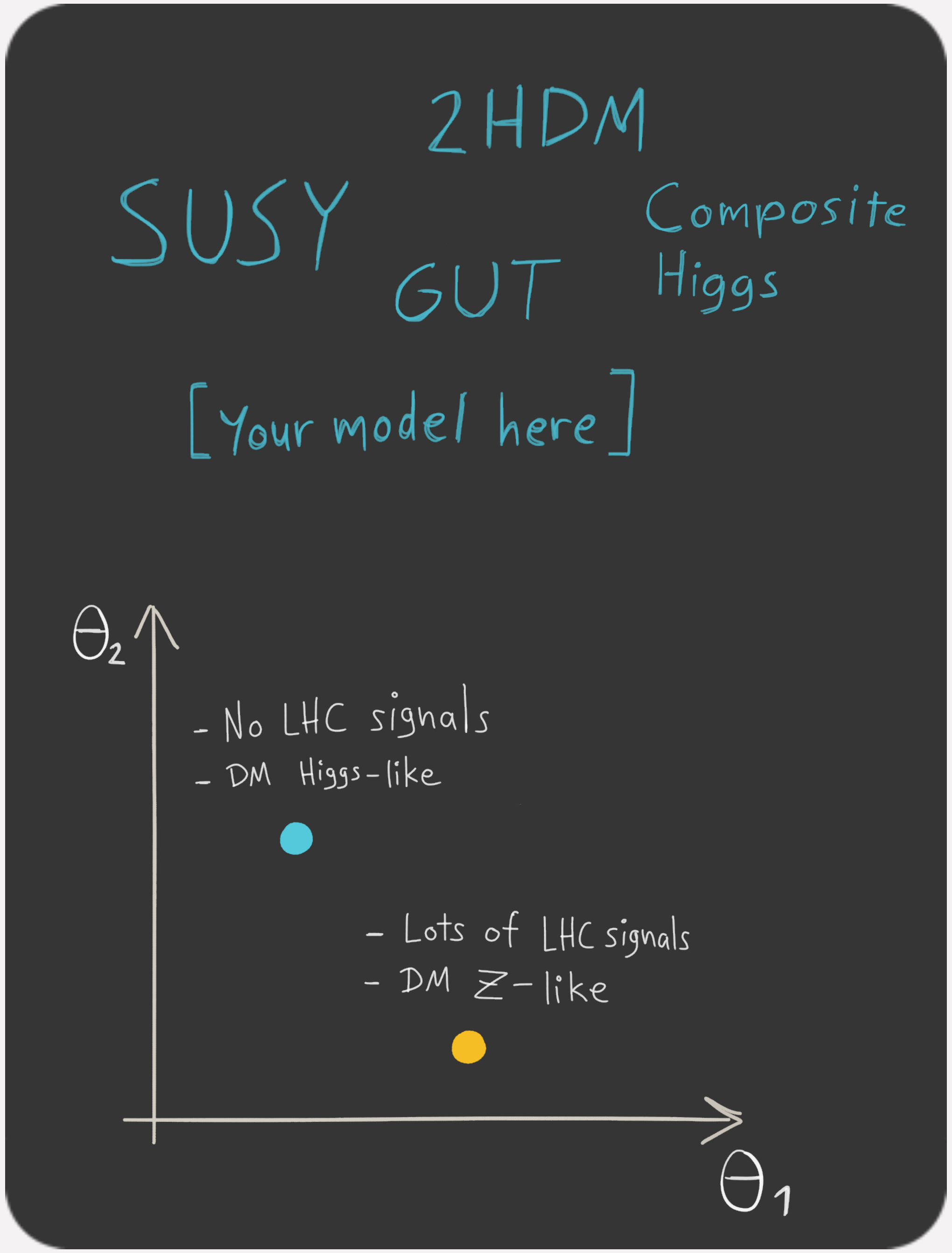
- Lots of theories for BSM physics
- For each theory, a parameter space of varying phenomenology
- Many different experiments can constrain each theory



Comparing BSM theories to data

- Lots of theories for BSM physics
- For each theory, a parameter space of varying phenomenology
- Many different experiments can constrain each theory

*Consistently compare theories against **all** available data: **global fits***



GAMBIT

The Global And Modular BSM Inference Tool

- A new framework for BSM **global fits**
- Fully **open source**
- **Modular design:** easily extended with
  — new models
  — new likelihoods
  — new theory calculators
  — new scanning algorithms
- Use external codes as **runtime plugins**
  — Currently supported: C, C++, Fortran
  — In version 1.1: Mathematica
  — Working on: Python
- **Two-level parallellization** with MPI and OpenMP
- **Hierarchical** model database
- **User friendly** (hopefully!)

gambit.hepforge.org

GAMBIT

What's in the box?

Core

- Models — arXiv:1705.07908

Physics modules

- ColliderBit: *fast* LHC sim, Higgs searches, LEP SUSY limits — arXiv:1705.07919
- DarkBit: relic density, gamma ray signal yields, ID/DD likelihoods — arXiv:1705.07920
- FlavBit: wide range of flavour observables & likelihoods — arXiv:1705.07933
- SpecBit: spectrum objects, RGE running
- DecayBit: decay widths
- PrecisionBit: precision BSM tests

(SpecBit, DecayBit, PrecisionBit) — arXiv:1705.07936

Statistics and sampling

- ScannerBit: stats & sampling (Diver, MultiNest, T-Walk, ++) — arXiv:1705.07959

Backends (external tools)

GAMBIT: The Global And Modular BSM Inference Tool

gambit.hepforge.org

- Fast definition of new datasets and theoretical models
- Plug and play scanning, physics and likelihood packages
- Extensive model database – not just SUSY
- Extensive observable/data libraries
- Many statistical and scanning options (Bayesian & frequentist)
- *Fast* LHC likelihood calculator
- Massively parallel
- Fully open-source

ATLAS	F. Bernlochner, A. Buckley, P. Jackson, M. White
LHCb	M. Chrząszcz, N. Serra
Belle-II	F. Bernlochner, P. Jackson
Fermi-LAT	J. Edsjö, G. Martinez, P. Scott
CTA	C. Balázs, T. Bringmann, M. White
CMS	C. Rogan
IceCube	J. Edsjö, P. Scott
XENON/DARWIN	B. Farmer, R. Trotta
Theory	P. Athron, C. Balázs, S. Bloor, T. Bringmann, J. Cornell, J. Edsjö, B. Farmer, A. Fowlie, T. Gonzalo, J. Harz, S. Hoof, F. Kahlhoefer, A. Kvellestad, F.N. Mahmoudi, J. McKay, A. Raklev, R. Ruiz, P. Scott, R. Trotta, A. Vincent, C. Weniger, M. White, S. Wild

29 Members in 9 Experiments, 12 major theory codes, 11 countries

GAMBIT
First physics results

Scalar singlet dark matter arXiv:1705.07931

GUT-scale MSSM arXiv:1705.07935

- CMSSM
- NUHM1
- NUHM2

Weak-scale MSSM7 arXiv:1705.07917

GUT-scale MSSM results

Parameters and scanning

- Profile likelihood analysis
- Combine samples from scans with different priors and scanners (Diver & MultiNest)
- Additional scans to improve sampling of co-annihilation regions
- In total for all three models: 36 scans, ~280 million viable samples
- Vary 5 nuisance parameters (constrained by gaussian likelihoods

Parameter	Minimum	Maximum	Priors
CMSSM			
m_0	50 GeV	10 TeV	flat, log
$m_{1/2}$	50 GeV	10 TeV	flat, log
A_0	-10 TeV	10 TeV	flat, hybrid
$\tan\beta$	3	70	flat
$\mathrm{sgn}(\mu)$	$-$	$+$	binary
NUHM1 – as per CMSSM plus			
m_H	50 GeV	10 TeV	flat, log
NUHM2 – as per CMSSM plus			
m_{H_u}	50 GeV	10 TeV	flat, log
m_{H_d}	50 GeV	10 TeV	flat, log

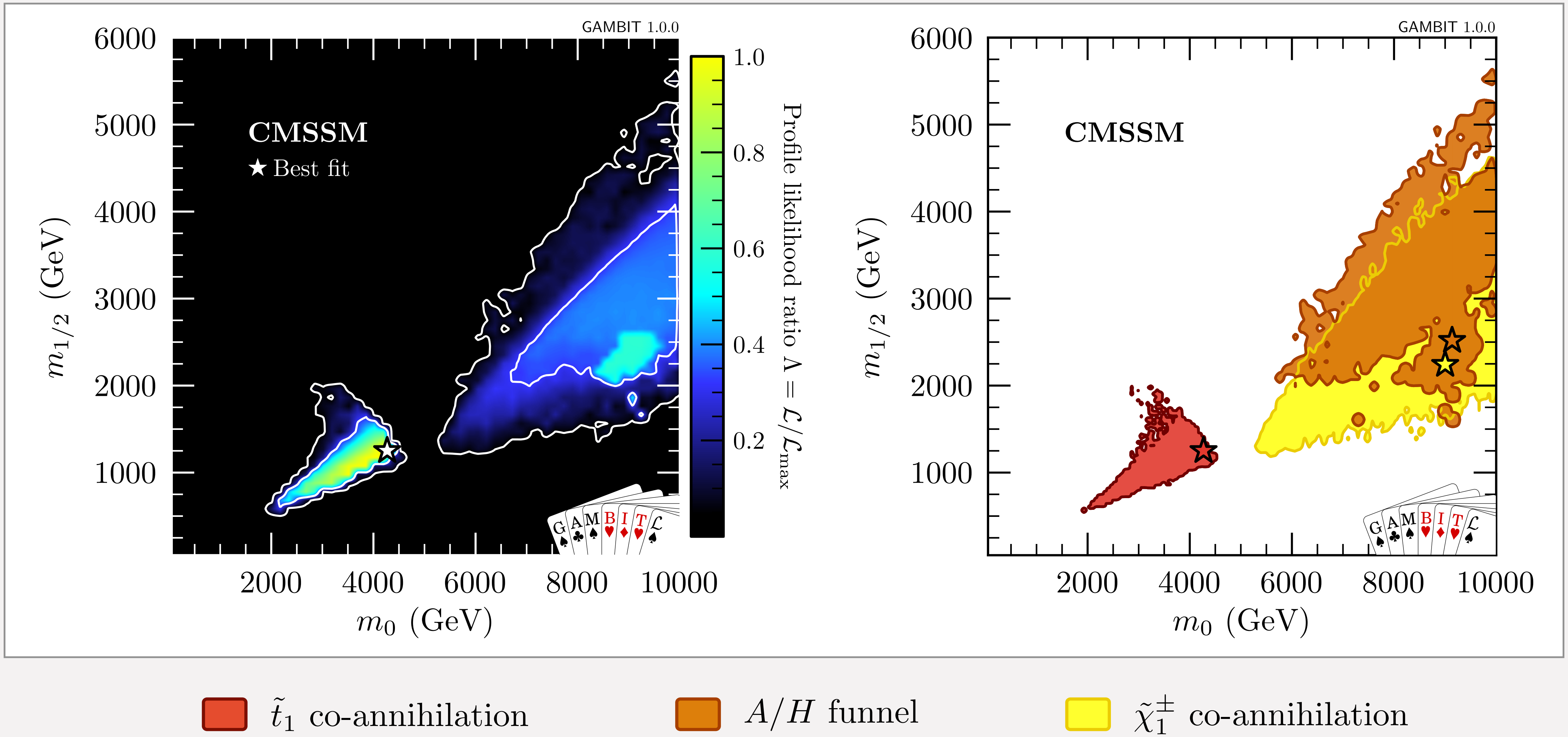
Parameter		Value($\pm$Range)
Varied		
Strong coupling	$\alpha_s^{\overline{MS}}(m_Z)$	0.1185(18)
Top quark pole mass	m_t	173.34(2.28) GeV
Local DM density	ρ_0	0.2–0.8 GeV cm^{-3}
Nuclear matrix el. (strange)	σ_s	43(24) MeV
Nuclear matrix el. (up + down)	σ_l	58(27) MeV

Likelihoods

- Nuisance parameter likelihoods
  (SM, local halo model, nuclear matrix elements)
- DM relic density *as upper bound*
- DM Indirect detection
  - Gamma rays: Fermi-LAT
    (dwarf spheriodal galaxies)
  - Neutrinos from DM annihilation in the Sun:
    IceCube79
- DM Direct detection:
  - XENON100 (2012)
  - LUX (2016)
  - Panda-X (2016)
  - PICO (2015)
  - SuperCDMS (2014)
  - SIMPLE (2014)

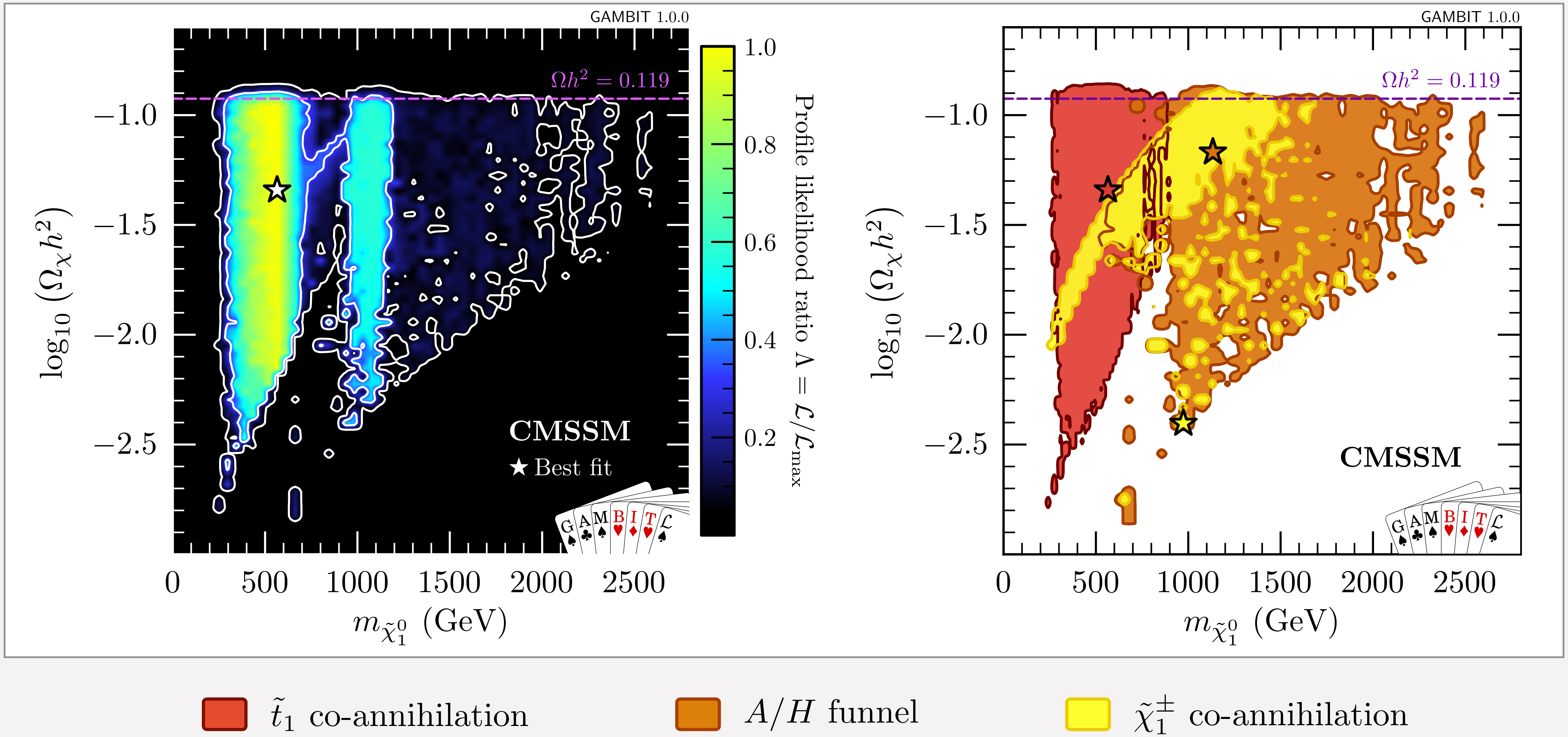
- Electroweak precision observables
  - W mass
  - muon g-2
- 59 flavour observables
- Higgs mass and signal strengths
- SUSY cross section limits from LEP
- SUSY searches at LHC (simulated)
  - 0 lepton searches (Run I & II, ATLAS & CMS)
  - Stop searches (Run I, ATLAS & CMS)
  - 2 & 3 lepton searches (Run I, ATLAS & CMS)
  - Monojet search (Run I, CMS)

CMSSM



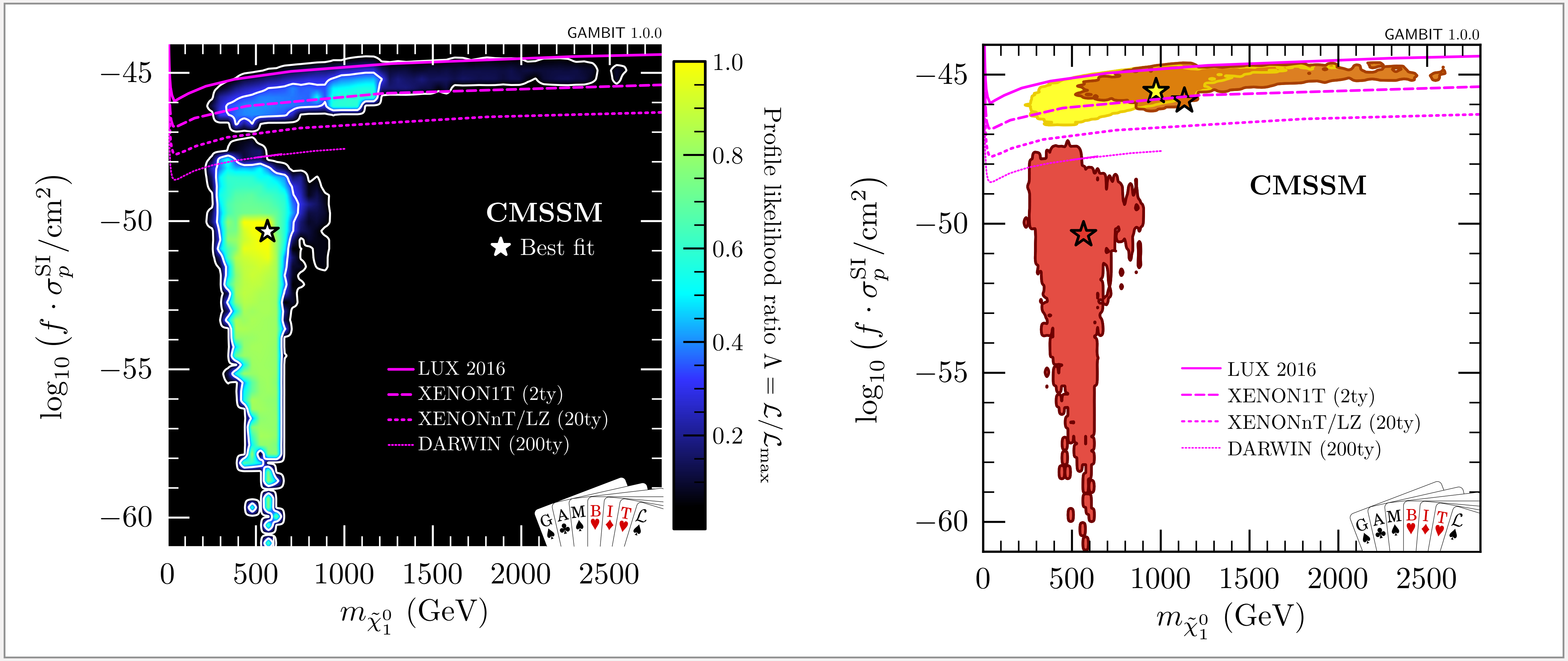
- Three mechanisms to avoid DM overabundance:
  stop co-ann., chargino co-ann., heavy Higgs funnel
- **Stau co-ann. is ruled out at 95% CL** (present at higher CL)
- Overall best fit point in stop co-ann. region (stop/neutralino mass ~600 GeV)

CMSSM



- We impose relic density likelihood as an upper limit
- Higgsino-dominated neutralino saturates relic density for masses ~1 TeV
- Can have combined higgsino co-annihilation and heavy Higgs funnel above 1 TeV

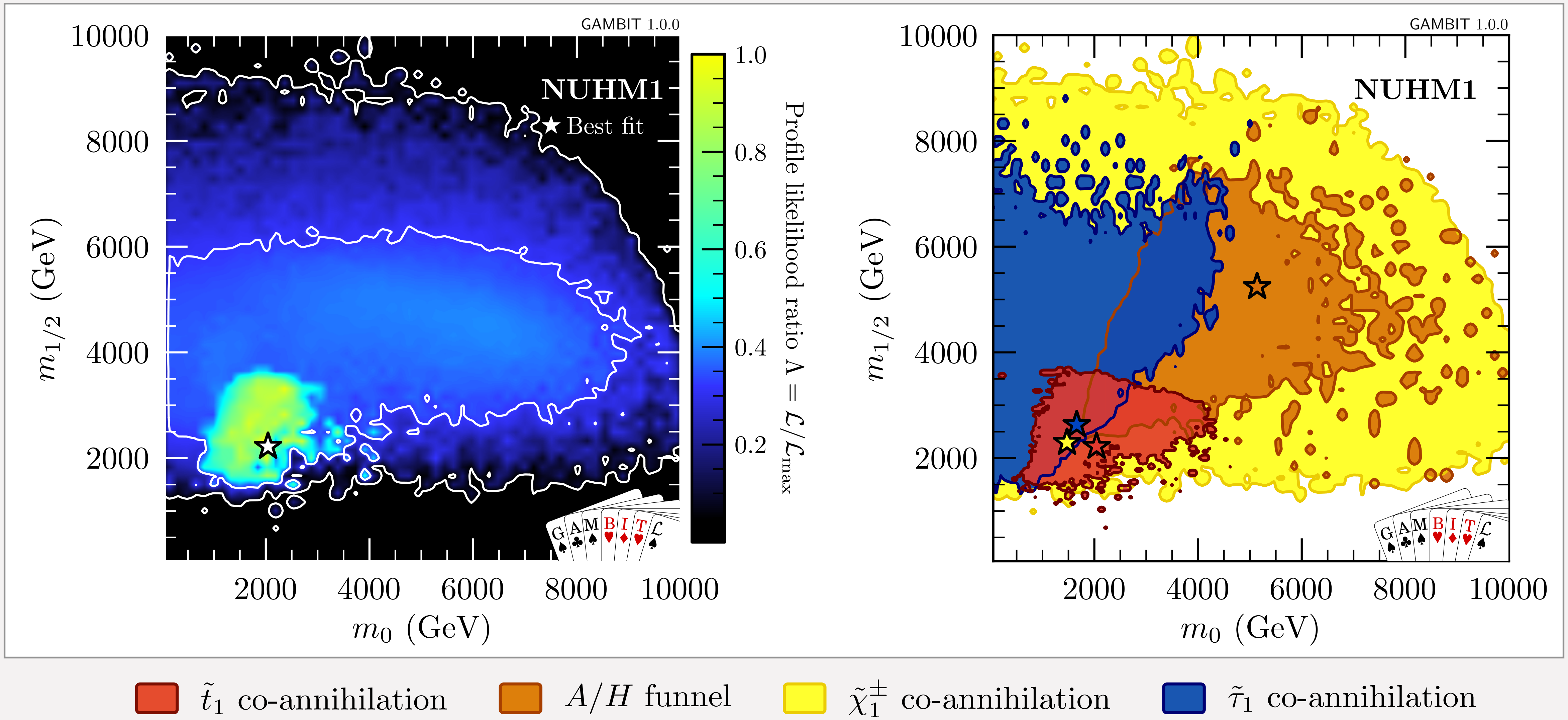
CMSSM



$\tilde{t}_1$ co-annihilation A/H funnel $\tilde{\chi}_1^\pm$ co-annihilation

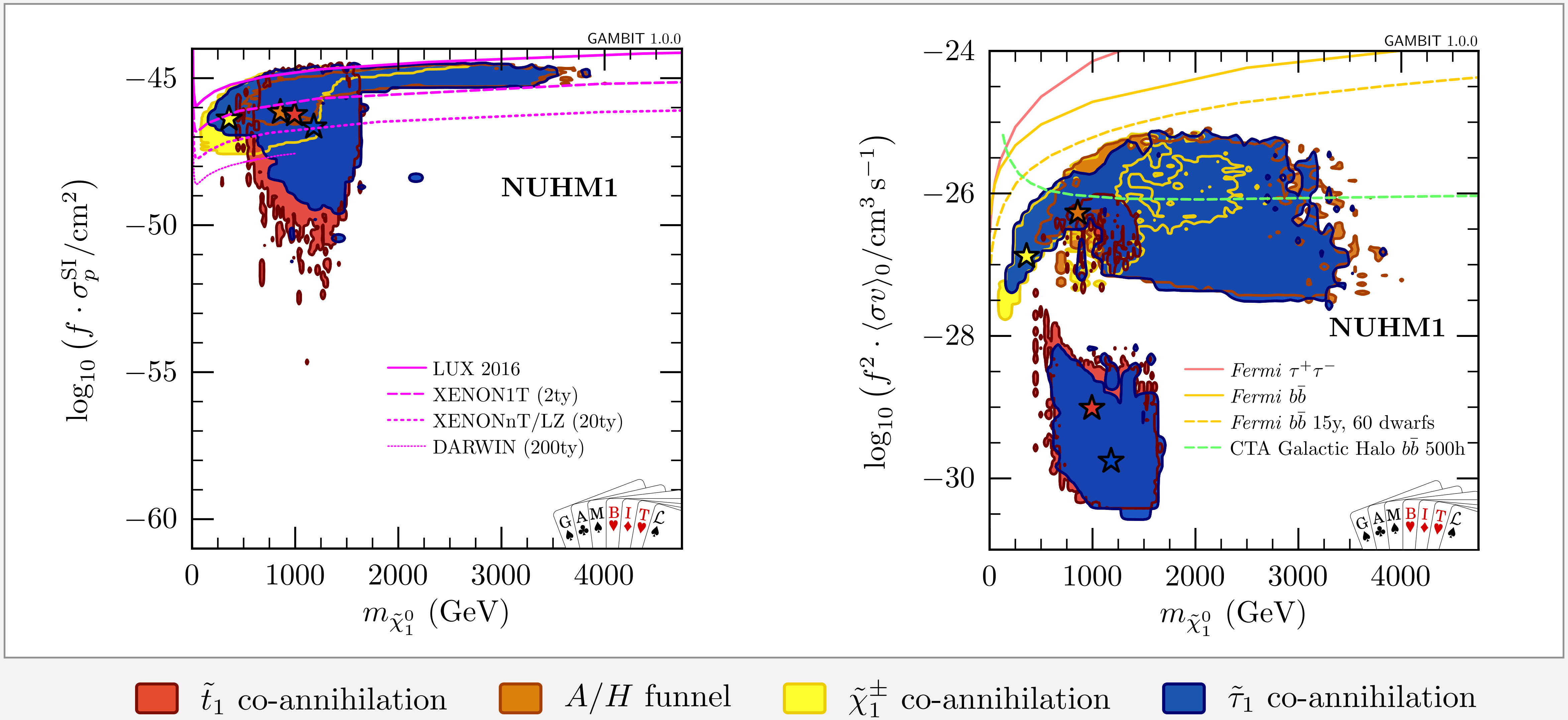
- Cross-section scaled according to predicted relic density
- Chargino co-ann. and Higgs funnel regions can be fully probed by future DD
- Preferred stop co-ann region difficult to probe for DD, ID and LHC
  (Hope to probe low-mass end of the stop-coann region at the LHC)
- Smallest cross-sections due to fine-tuned cancellations in tree-level matrix elements
  (Expect such cancellation to be spoiled by loop corrections)

NUHM I



- Substantially larger allowed regions compared to the CMSSM
- Additional parameter — more freedom to fit Higgs mass
- Stau co-annihilation is back in the 95% CL region
- Overall best fit point in stop co-ann. region (stop & neutralino mass ~1 TeV)

NUHM I



- Preferred region extends to heavier neutralinos than in the CMSSM (~2.5 TeV)
- Chargino co-ann. and Higgs funnel regions will be probed by future DD
- Stop and stau co-ann. regions difficult to fully explore

NUHM2 results qualitatively similar

Weak-scale MSSM results

Parameters and likelihoods

Parameter	Minimum	Maximum	Priors
$A_{u_3}(Q)$	-10 TeV	10 TeV	flat, hybrid
$A_{d_3}(Q)$	-10 TeV	10 TeV	flat, hybrid
$M^2_{H_u}(Q)$	$-(10\,\mathrm{TeV})^2$	$(10\,\mathrm{TeV})^2$	flat, hybrid
$M^2_{H_d}(Q)$	$-(10\,\mathrm{TeV})^2$	$(10\,\mathrm{TeV})^2$	flat, hybrid
$m^2_{\tilde{f}}(Q)$	0	$(10\,\mathrm{TeV})^2$	flat, hybrid
$M_2(Q)$	-10 TeV	10 TeV	split; flat, hybrid
$\tan\beta(m_Z)$	3	70	flat
$\mathrm{sgn}(\mu)$	$+$		fixed
Q	1 TeV		fixed

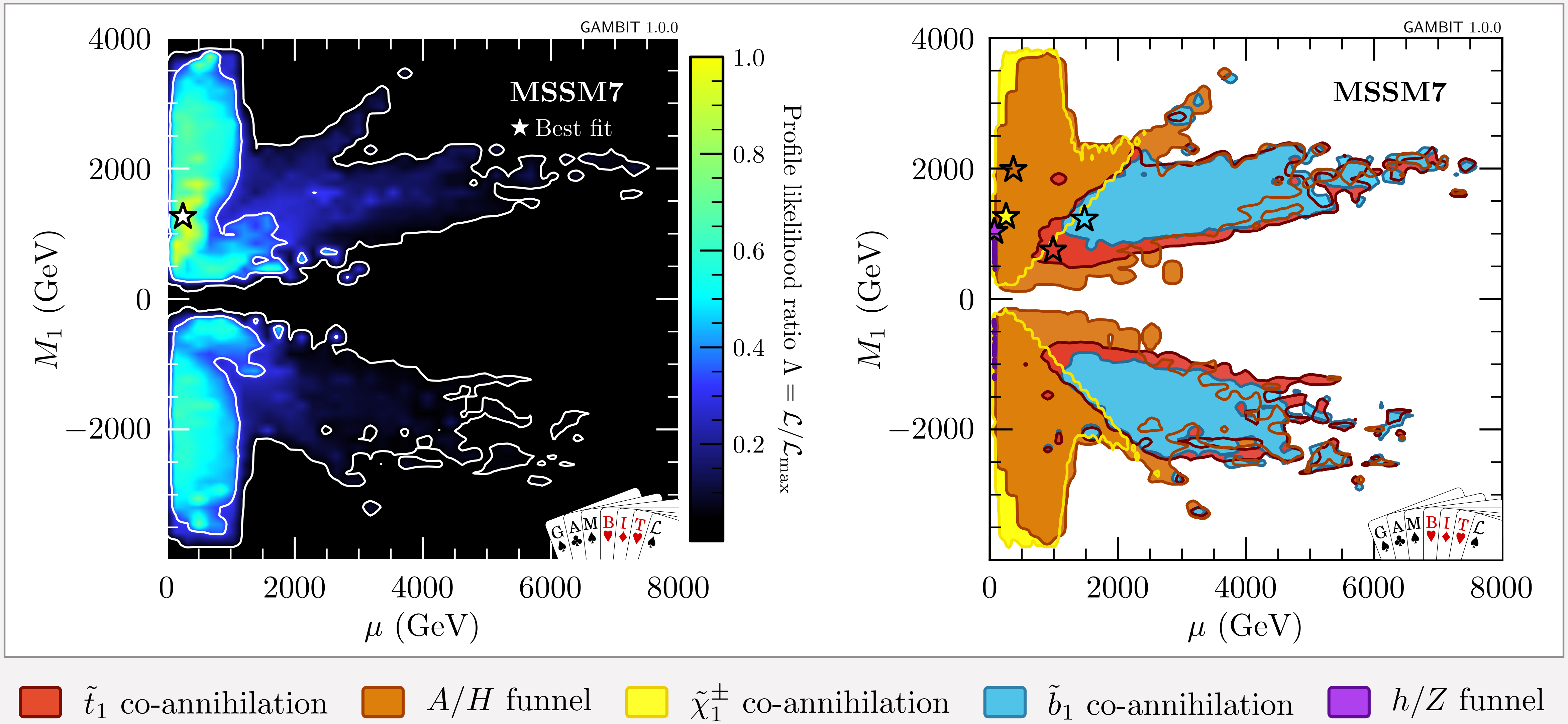
- 7 MSSM parameters + 5 nuisance parameters

- Assume GUT-inspired relation on gaugino mass parameters:

$$\frac{3}{5}\cos^2\theta_\mathrm{W} M_1 = \sin^2\theta_\mathrm{W} M_2 = \frac{\alpha}{\alpha_\mathrm{s}} M_3$$

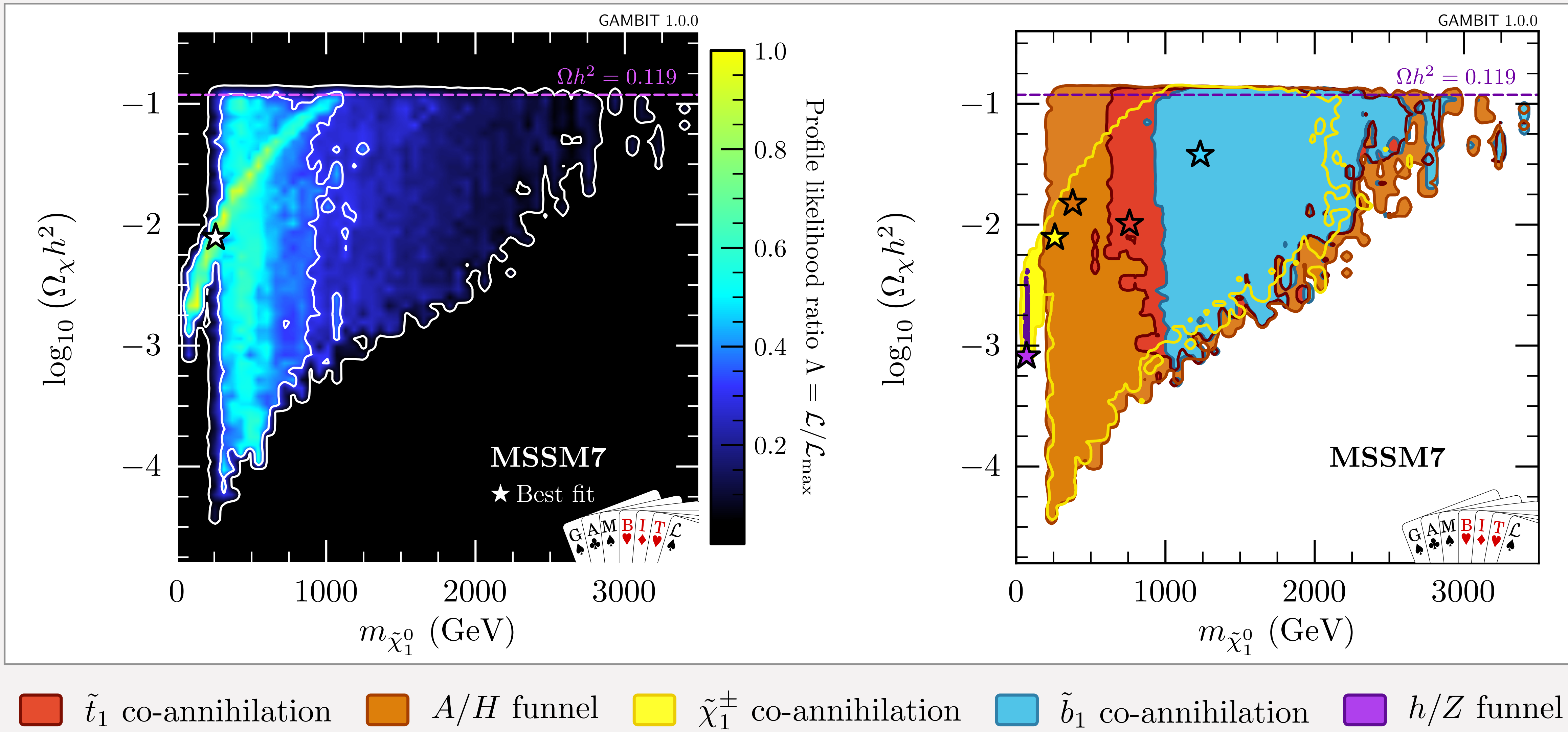
- Same likelihoods as for the GUT-scale models

MSSM 7



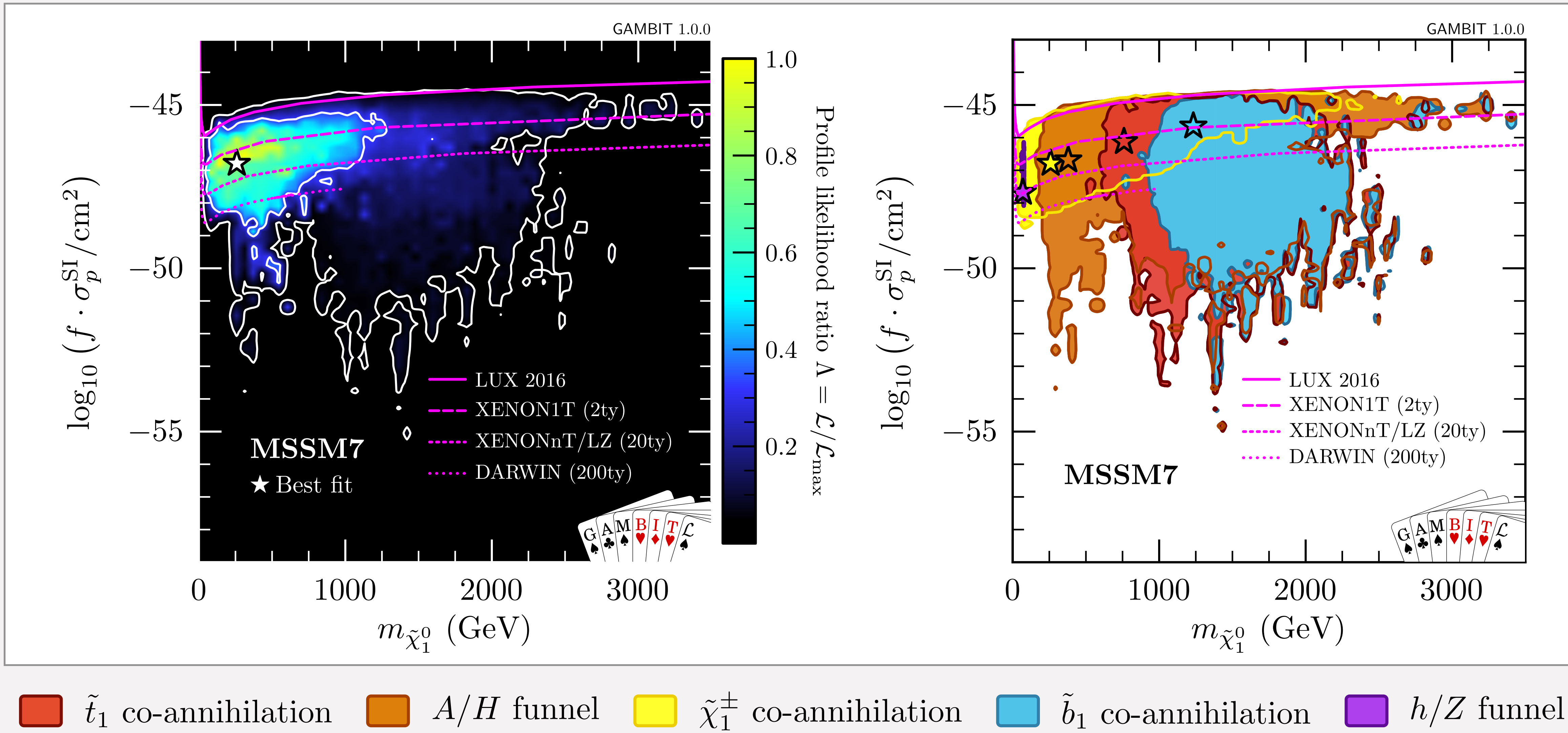
- Three neutralino scenarios: higgsino-dominated, higgsino/bino mix, bino-dominated
- Wino-dominated neutralino not possible due to GUT relation $(M_2 \sim 2M_1)$

MSSM 7



- Best fit point in chargino co-annihilation region (chargino/neutralino mass ~260 GeV)
- Mass difference < 10 GeV (challenging for LHC)
- Under-abundant relic density

MSSM 7



- Entire chargino co-ann. and light Higgs funnel regions will be probed by future DD
- Smallest cross sections again due to cancellations in tree-level matrix elements

Summary

Summary

- **GAMBIT 1.0 is public — try it out!**
  - Includes several stand-alone physics modules
  - 6 code papers and 3 physics papers to appear in EPJC

- **First physics results**
  - Singlet DM
  - GUT-scale SUSY
  - Weak-scale MSSM7

- **More results coming soon**
  - Axions, 2HDMs, Dirac fermion Higgs portal

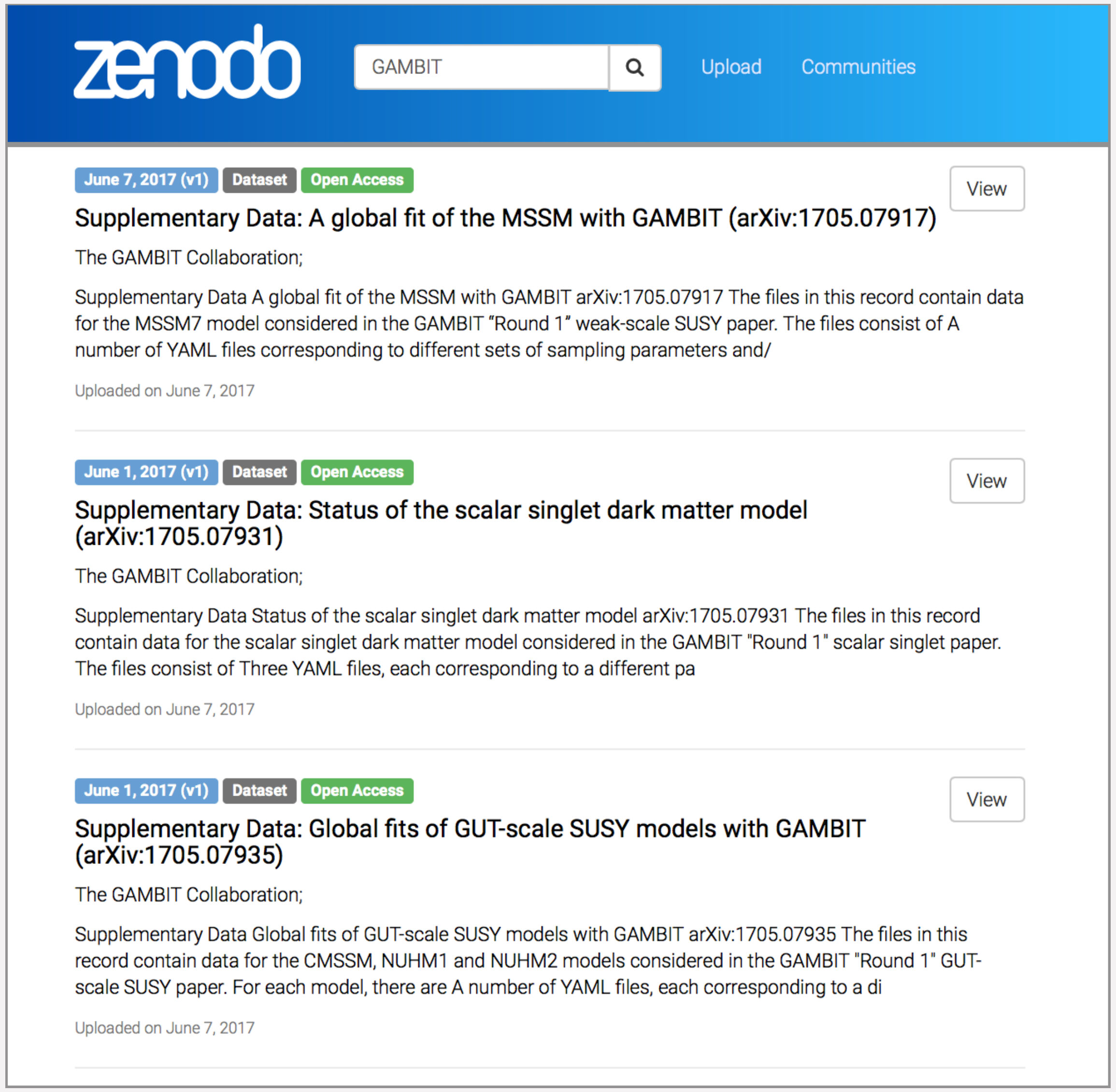
- **Future plans**
  - More models! More likelihoods!
  - GAMBIT 2.0: Interface with Lagrangian-level tools for automatic code generation

All results publicly available

Results available on zenodo.cern.ch

- Parameter point samples (hdf5 files)
- GAMBIT input files for all scans
- Example plotting routines

Links at gambit.hepforge.org/pubs



— Backup slides —

Get started with GAMBIT

Clone git repository from GitHub

- github.com/patscott/gambit_1.0

Download tarballs

- hepforge.org/downloads/gambit

Pre-compilied version with Docker [Sebastian Liem]

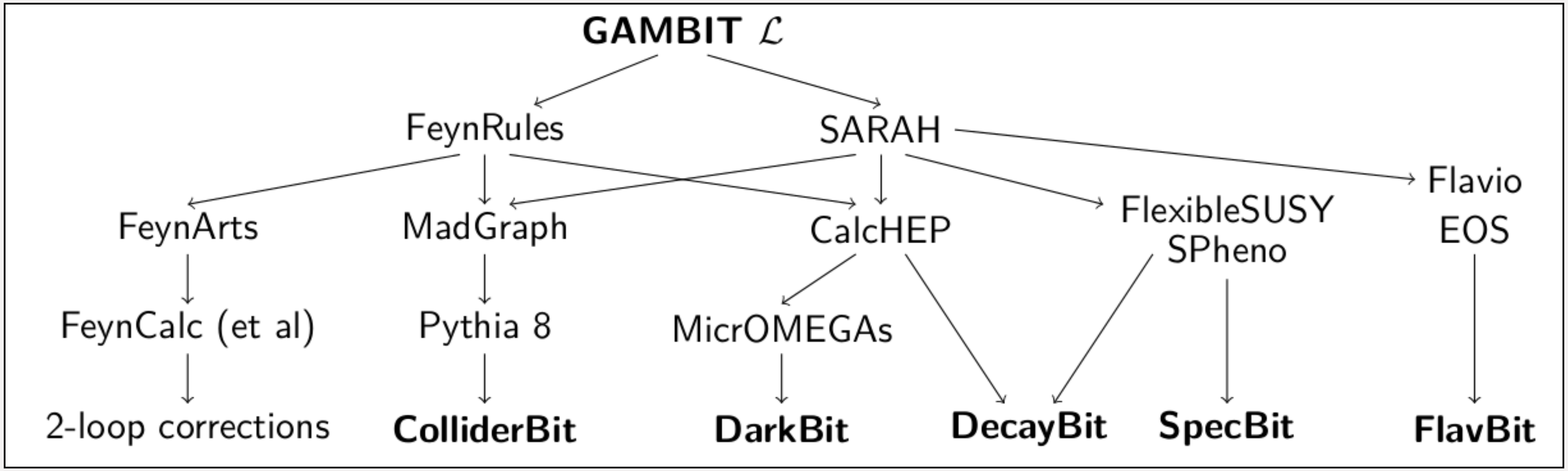
- `docker run -it sliem/gambit`

See quick start guide in arXiv:1705.07908

GAMBIT 2

Extension to model building

- GAMBIT Universal Model (GUM) files
- Interface to Lagrangian-level tools
- Code generation for spectra, cross sections, …



Adding a new model to GAMBIT

(From Pat Scott)

1. Add the model to the **model hierarchy**:
   - Choose a model name, and declare any **parent model**
   - Declare the model's parameters
   - Declare any **translation function** to the parent model

```
#define MODEL NUHM1
#define PARENT NUHM2
  START_MODEL
  DEFINEPARS(M0,M12,mH,A0,TanBeta,SignMu)
  INTERPRET_AS_PARENT_FUNCTION(NUHM1_to_NUHM2)
#undef PARENT
#undef MODEL
```

2. Write the translation function as a standard C++ function:

```
void MODEL_NAMESPACE::NUHM1_to_NUHM2 (const ModelParameters &myP, ModelParameters &targetP)
{
   // Set M0, M12, A0, TanBeta and SignMu in the NUHM2 to the same values as in the NUHM1
   targetP.setValues(myP,false);
   // Set the values of mHu and mHd in the NUHM2 to the value of mH in the NUHM1
   targetP.setValue("mHu", myP["mH"]);
   targetP.setValue("mHd", myP["mH"]);
}
```

3. If needed, declare that existing module functions work with the new model, or add new functions that do.

Adding a new module function is easy:

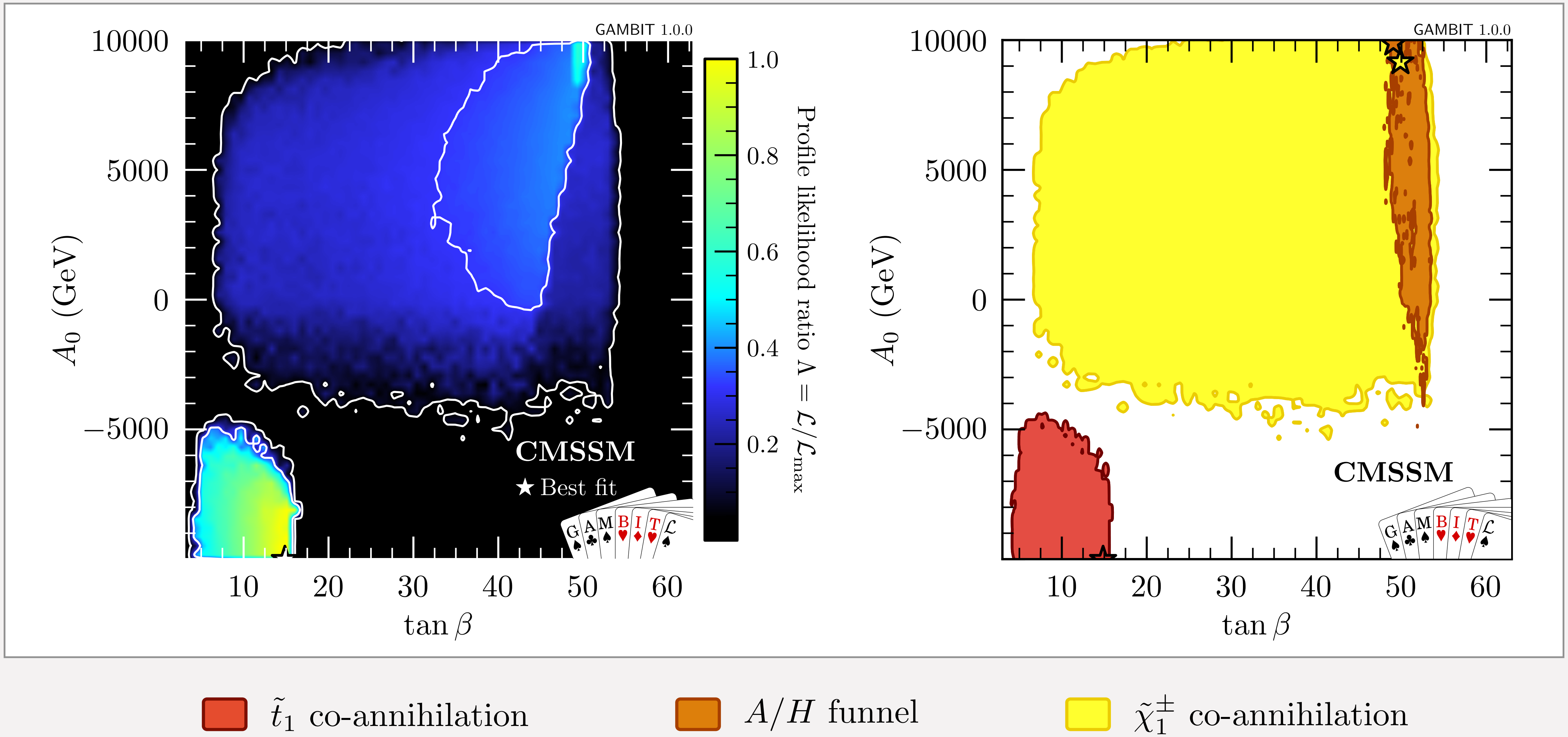
1. Declare the function to GAMBIT in a module's **rollcall header**
   - Choose a capability
   - Declare any **backend requirements**
   - Declare any **dependencies**
   - Declare any specific **allowed models**
   - other more advanced declarations also available

```
#define MODULE FlavBit                            // A tasty GAMBIT module.
START_MODULE

  #define CAPABILITY Rmu                          // Observable: BR(K->mu nu)/BR(pi->mu nu)
  START_CAPABILITY
    #define FUNCTION SI_Rmu                       // Name of a function that can compute Rmu
    START_FUNCTION(double)                        // Function computes a double precision result
    BACKEND_REQ(Kmunu_pimunu, (my_tag), double, (const parameters*)) // Needs function from a backend
    BACKEND_OPTION( (SuperIso, 3.6), (my_tag) )                      // Backend must be SuperIso 3.6
    DEPENDENCY(SuperIso_modelinfo, parameters)    // Needs another function to calculate SuperIso info
    ALLOW_MODELS(MSSM63atQ, MSSM63atMGUT)         // Works with weak/GUT-scale MSSM and descendents
    #undef FUNCTION
  #undef CAPABILITY
```

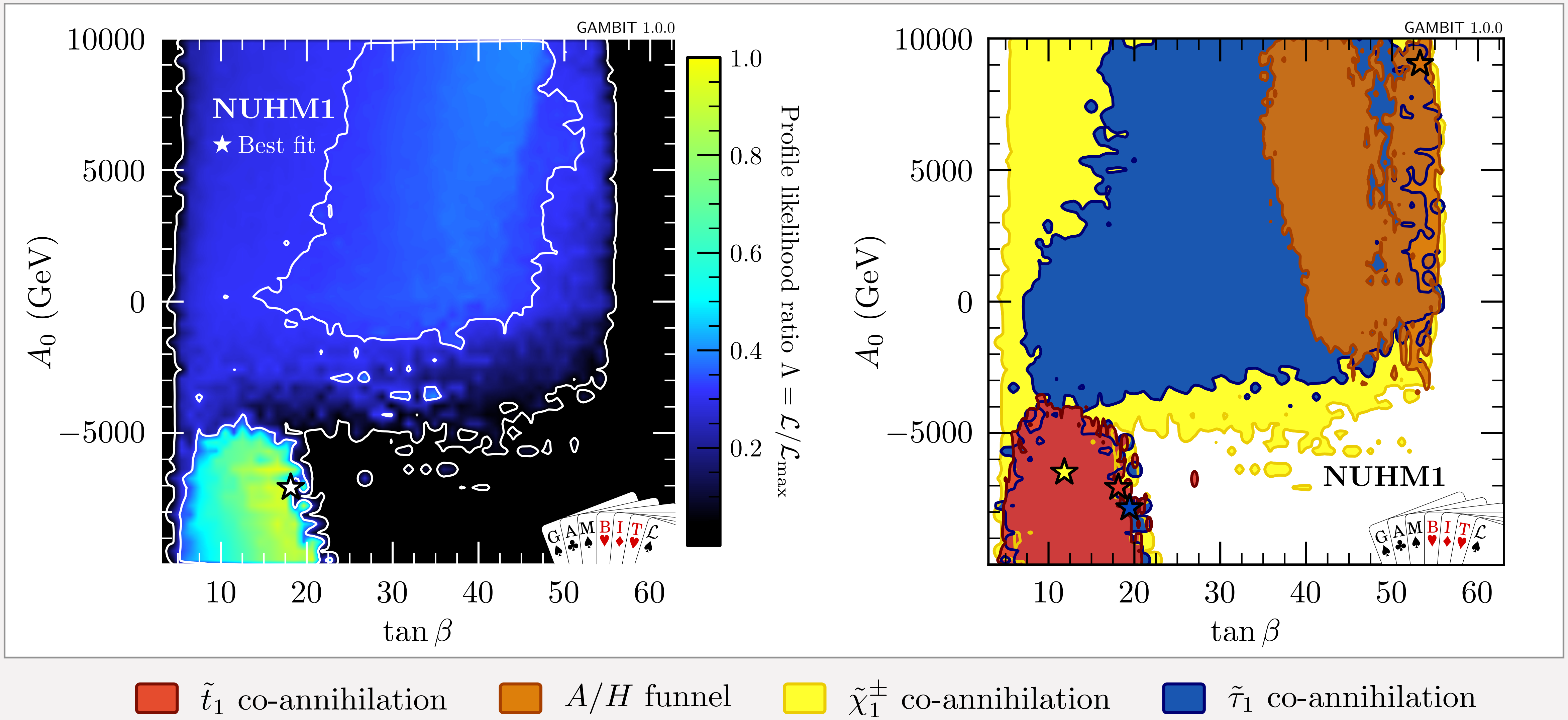
2. Write the function as a standard C++ function (one argument: the result)

CMSSM



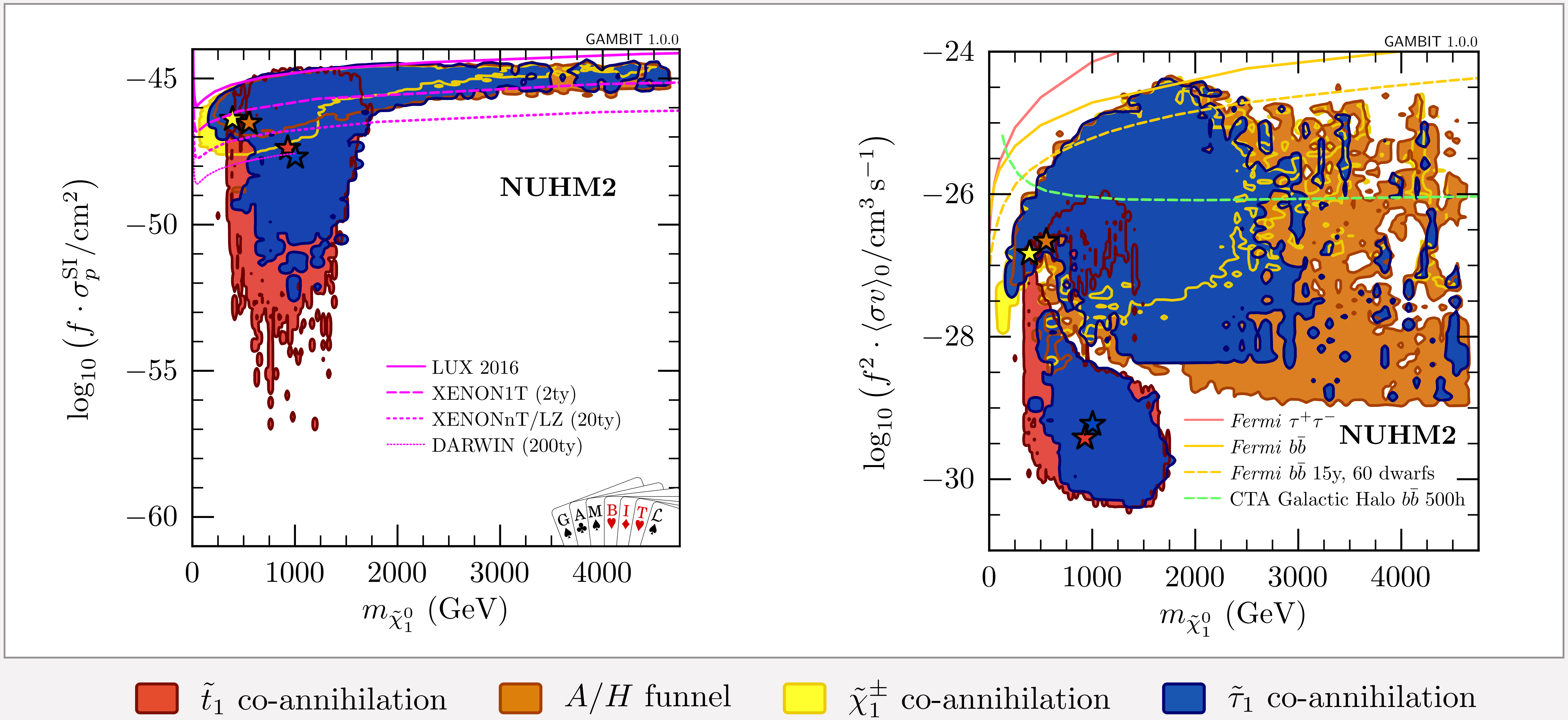
- Stop co-ann. region at large, negative trilinear coupling
- Small impact of (simple) check for charge- and colour-breaking minima

NUHM I



- Substantially larger allowed regions compared to the CMSSM
- Additional parameter — more freedom to fit Higgs mass
- Stau co-annihilation is back in the 95% CL region
- Overall best fit point in stop co-ann. region (stop & neutralino mass ~1 TeV)

NUHM 2



- NUHM2 results qualitatively similar to NUHM1 results
- LHC Run 2 searches for stop & EW gaugino production (not included) may impact low-mass end of preferred regions

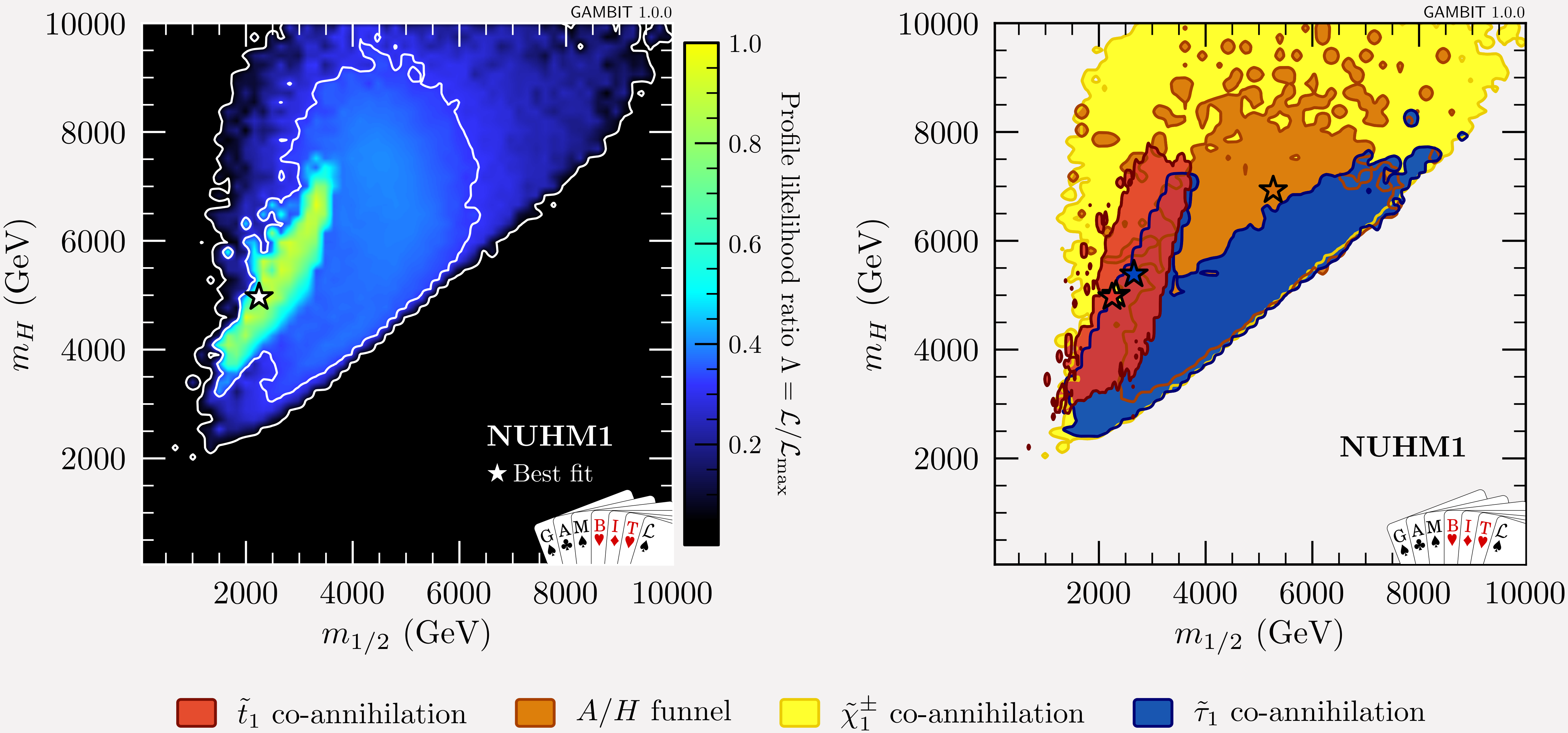
GUT-scale results

Definition of coloured regions

– stau co-annihilation: $m_{\tilde{\tau}_1} \leq 1.2\, m_{\tilde{\chi}_1^0}$,
– stop co-annihilation: $m_{\tilde{t}_1} \leq 1.2\, m_{\tilde{\chi}_1^0}$,
– chargino co-annihilation: $\tilde{\chi}_1^0 \geq 50\%$ Higgsino,
– A/H-funnel: $1.6\, m_{\tilde{\chi}_1^0} \leq m_{\text{heavy}} \leq 2.4\, m_{\tilde{\chi}_1^0}$,

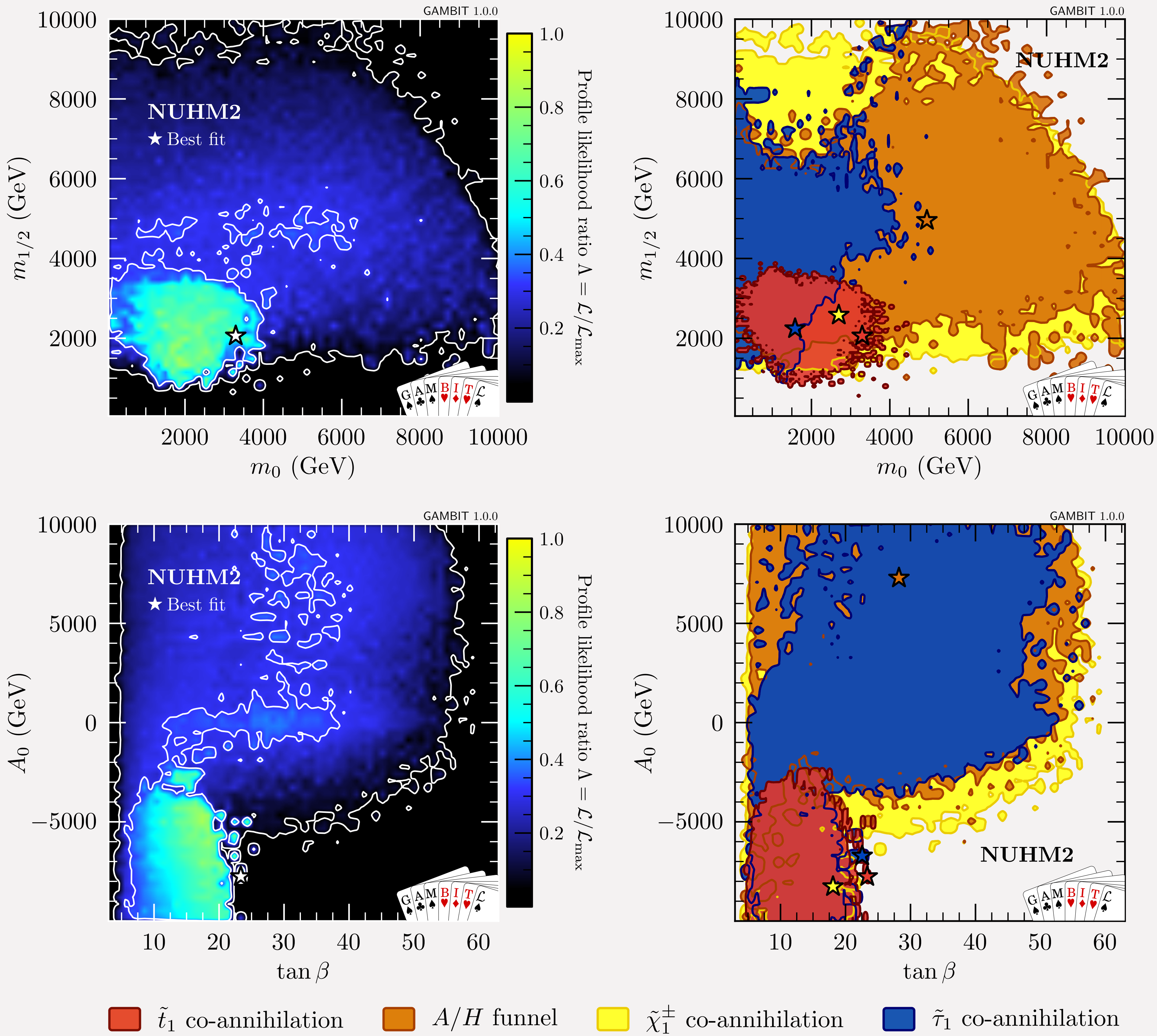
GUT-scale results

NUHM1 parameter planes



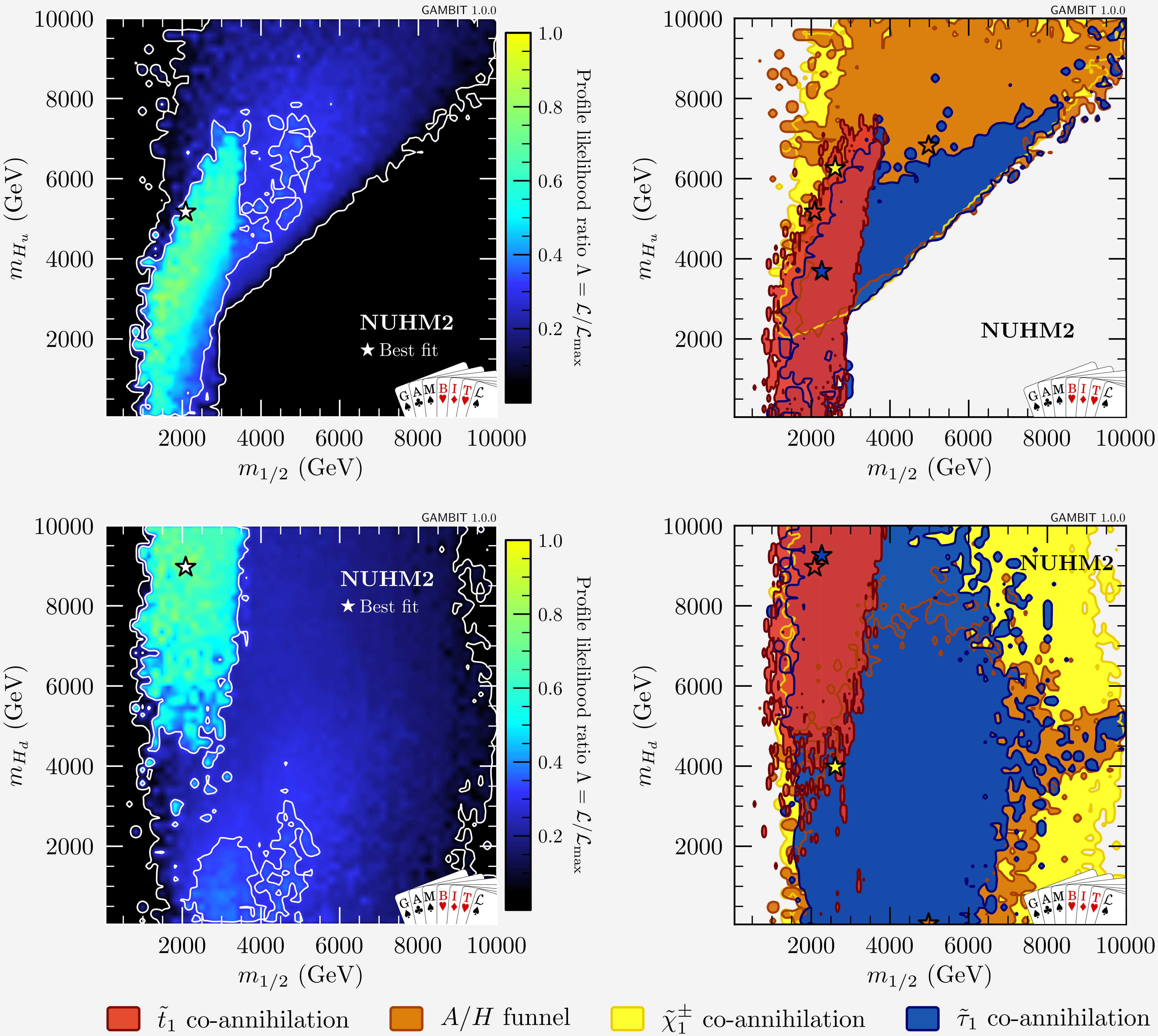
GUT-scale results

NUHM2 parameter planes



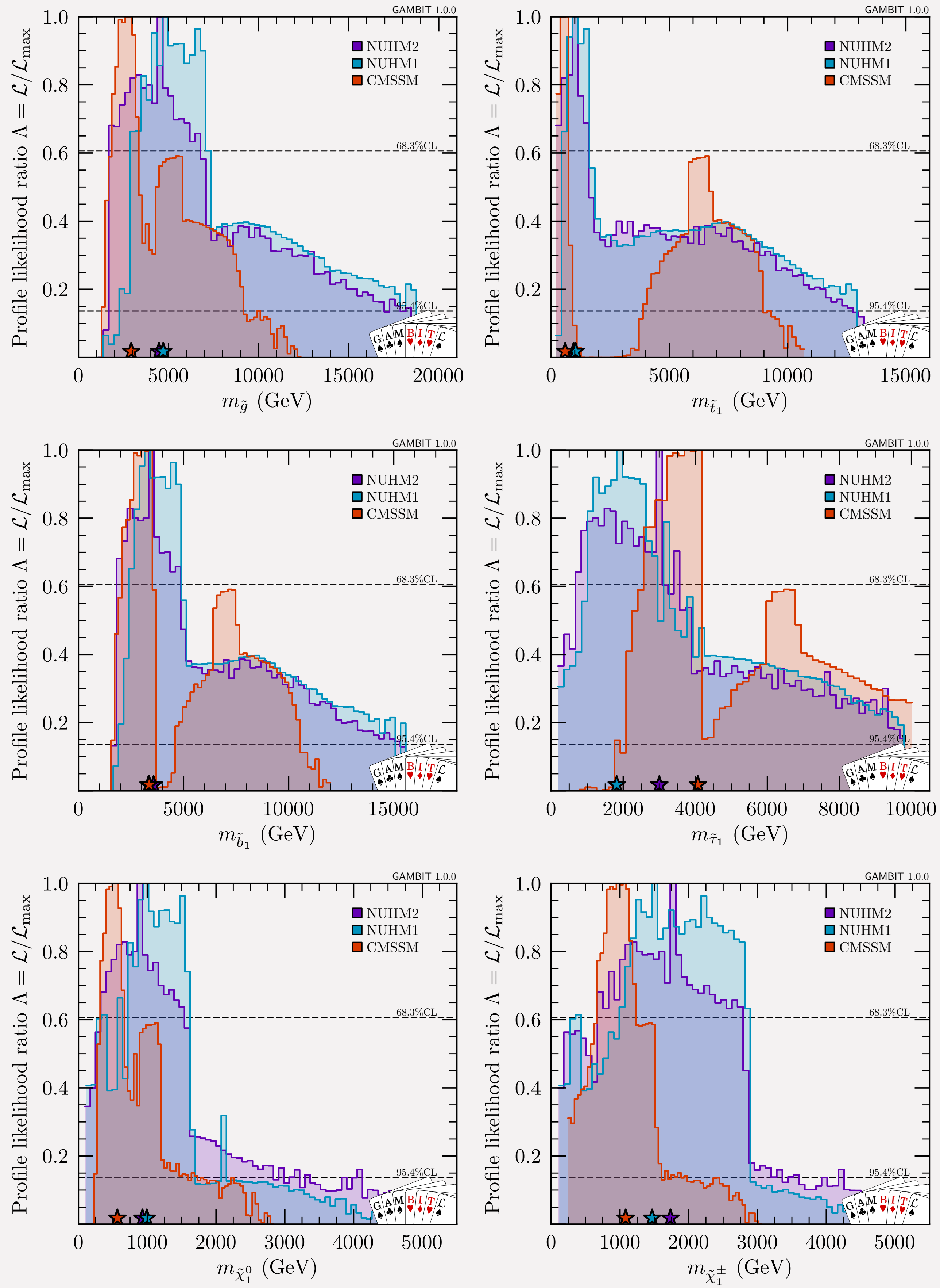
GUT-scale results

NUHM2 parameter planes



GUT-scale results

1D profile likelihood ratios



GUT-scale results

Stop—neutralino mass plane

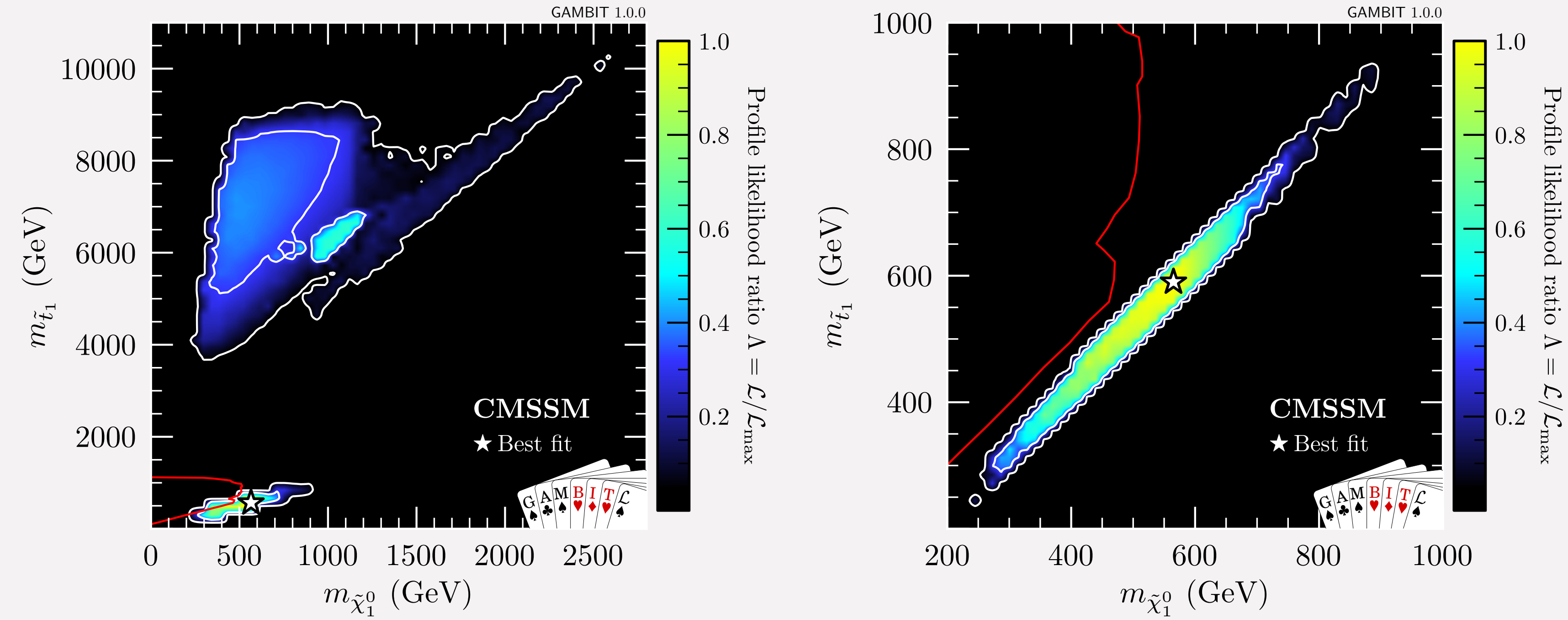
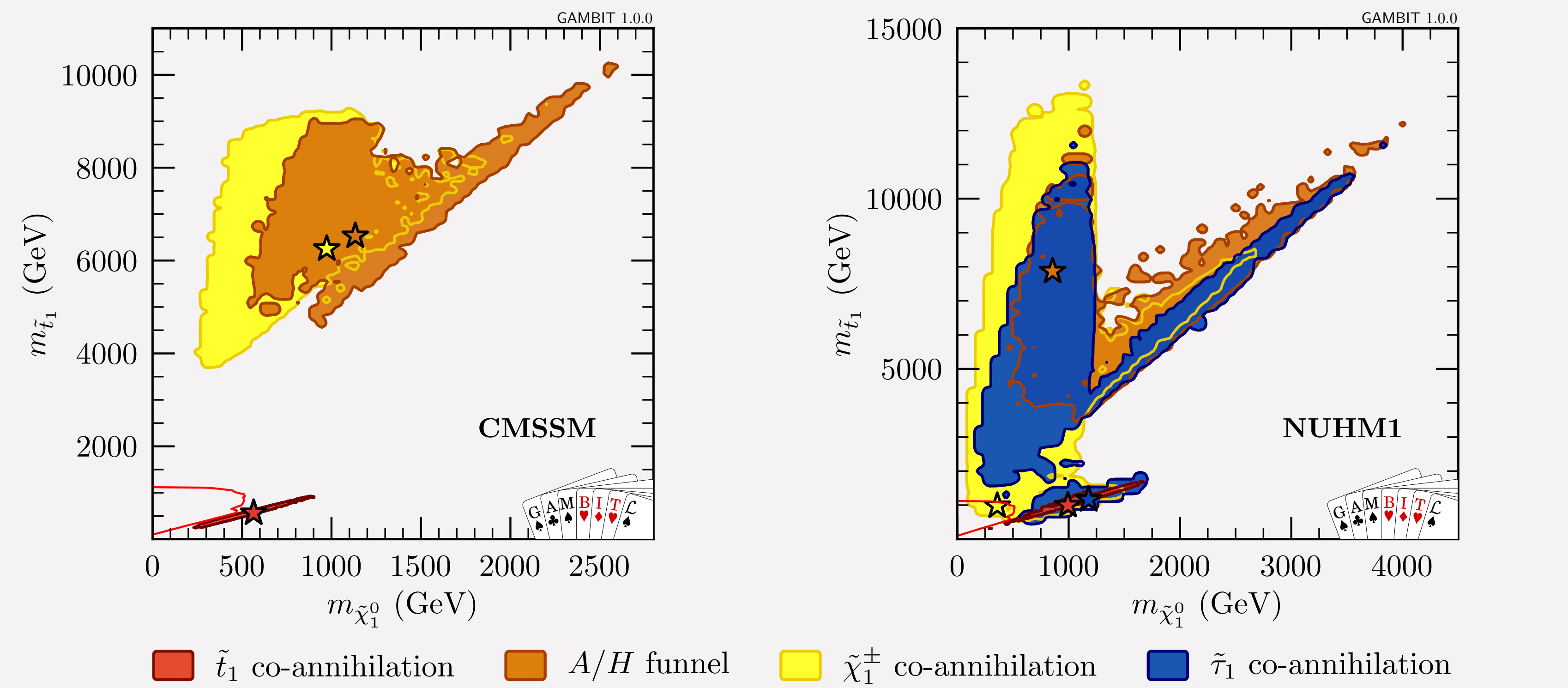


Fig. 14: 2D profile likelihoods for the CMSSM, plotted in the $\tilde{t}_1 - \tilde{\chi}_1^0$ mass plane. *Left:* the full range of neutralino masses present in the combined sample. *Right:* as per the lefthand panle, but zoomed in to focus on the low-mass region. Superimposed in red is the latest CMS Run II simplified model limit for $\tilde{t}_1$ pair production, followed by decay to t quarks and the lightest neutralino [316]. This limit should be interpreted with caution (for details see main text).



GUT-scale results

Chargino—neutralino mass plane

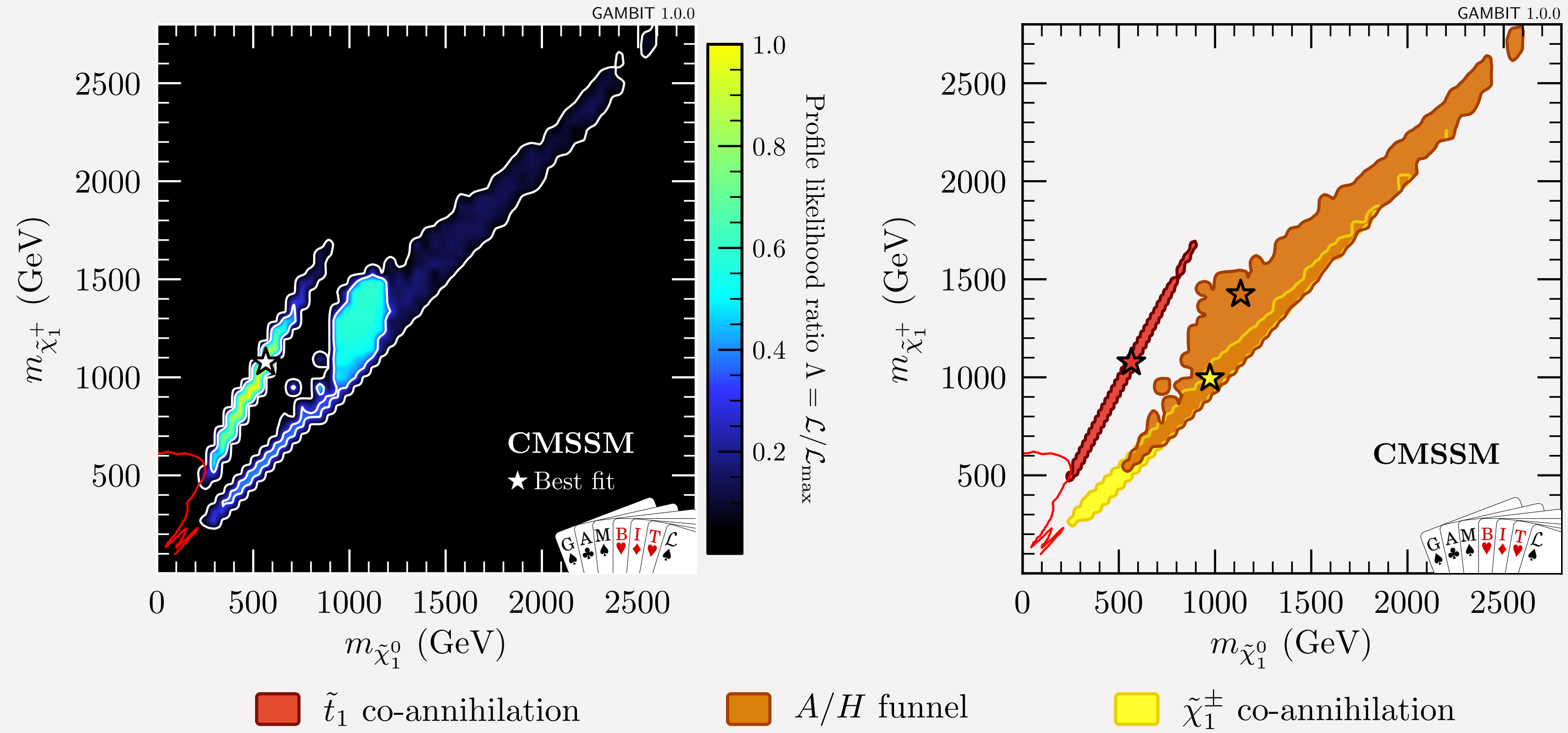
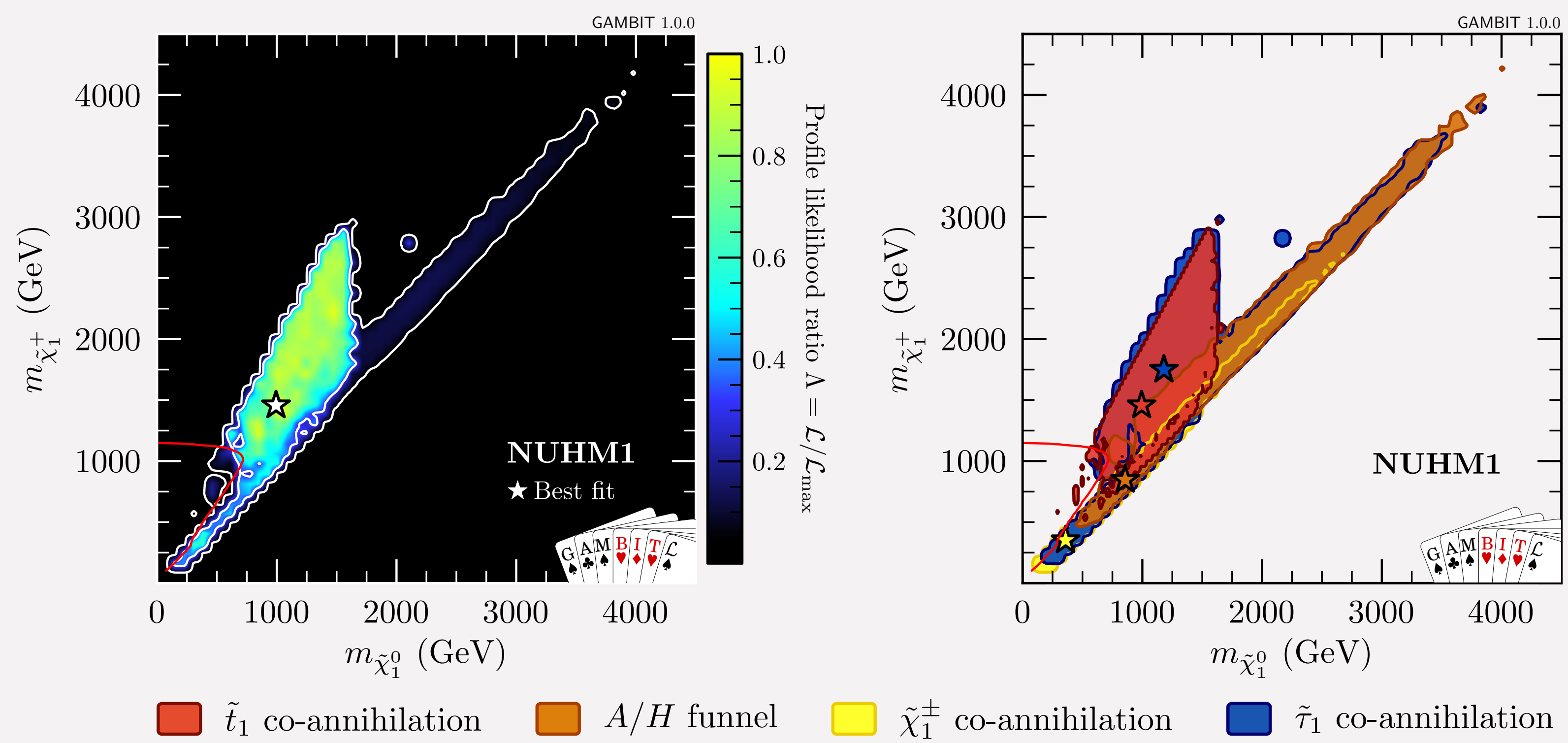
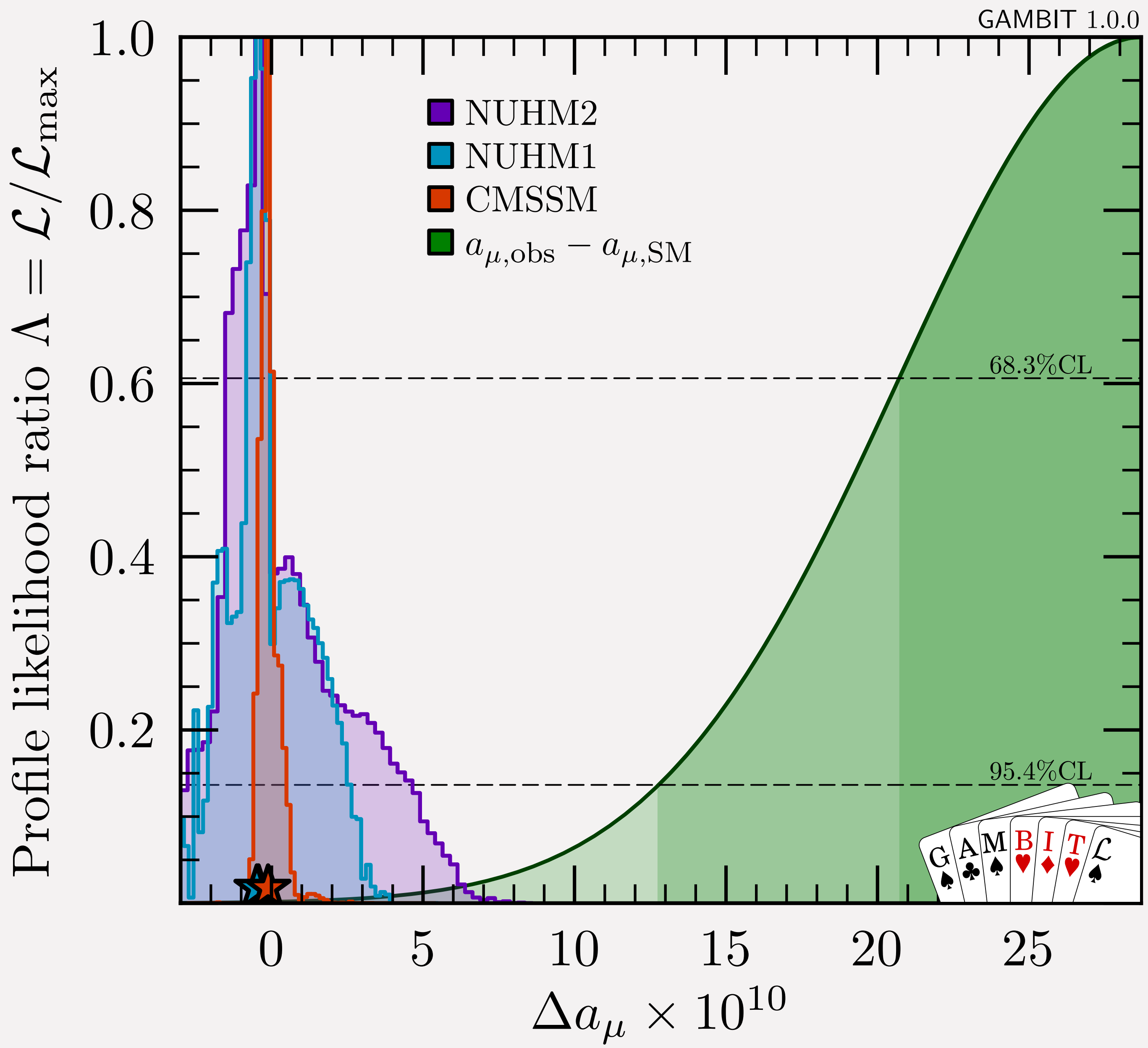


Fig. 16: *Left:* Profile likelihood for the CMSSM in the $\tilde{\chi}_1^\pm - \tilde{\chi}_1^0$ mass plane. *Right:* Colour-coding shows the mechanism(s) that allow models within the 95% CL region to avoid exceeding the observed relic density of DM. Superimposed in red is the latest CMS Run II simplified model limit for $\tilde{\chi}_1^\pm \tilde{\chi}_1^0$ pair production and decay with decoupled sleptons [317]. This limit should be interpreted with caution (for details see main text).



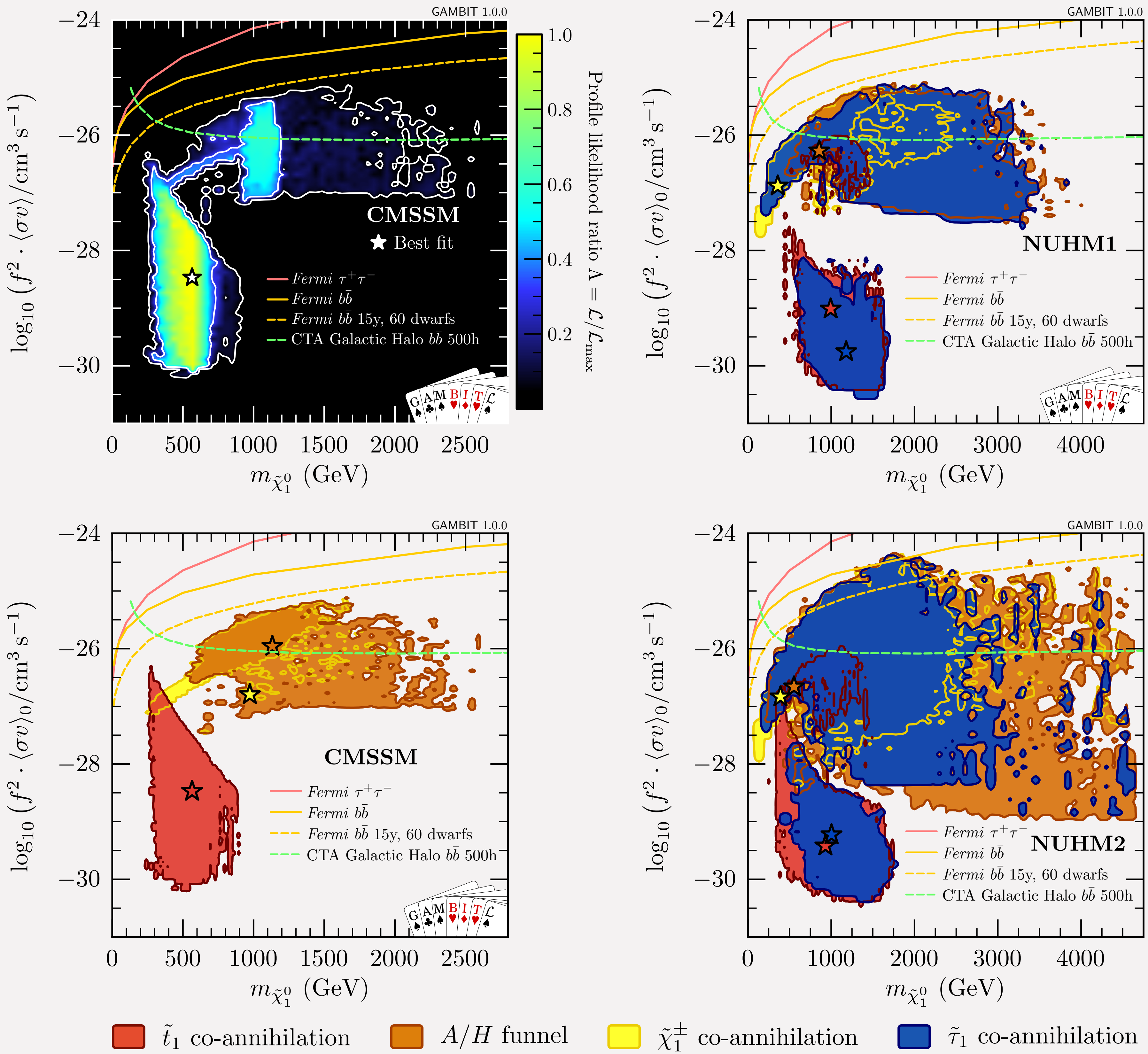
GUT-scale results

Muon g-2



GUT-scale results

Neutralino self-annihilation cross-section

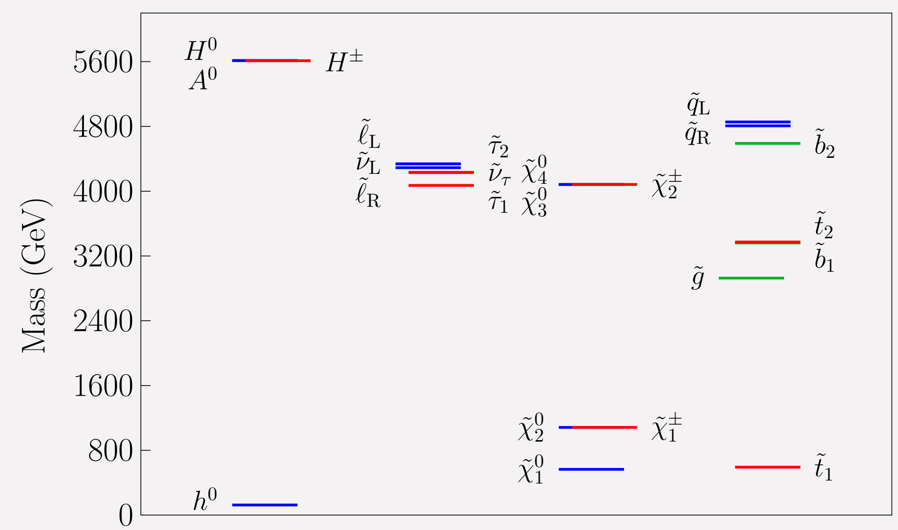


GUT-scale results

CMSSM best fit points

Likelihood term	Ideal	A/H-funnel	$\tilde{\tau}$ co-ann.	$\tilde{t}$ co-ann.	$\tilde{\chi}_1^\pm$ co-ann.	$\Delta \ln \mathcal{L}_{\rm BF}$
LHC sparticle searches	0.000	0.000	0.000	0.000	0.000	0.000
LHC Higgs	−37.734	−37.960	−41.296	−38.042	−38.069	0.308
LEP Higgs	0.000	0.000	0.000	0.000	0.000	0.000
ALEPH selectron	0.000	0.000	0.000	0.000	0.000	0.000
ALEPH smuon	0.000	0.000	0.000	0.000	0.000	0.000
ALEPH stau	0.000	0.000	0.000	0.000	0.000	0.000
L3 selectron	0.000	0.000	0.000	0.000	0.000	0.000
L3 smuon	0.000	0.000	0.000	0.000	0.000	0.000
L3 stau	0.000	0.000	0.000	0.000	0.000	0.000
L3 neutralino leptonic	0.000	0.000	0.000	0.000	0.000	0.000
L3 chargino leptonic	0.000	0.000	0.000	0.000	0.000	0.000
OPAL chargino hadronic	0.000	0.000	0.000	0.000	0.000	0.000
OPAL chargino semi-leptonic	0.000	0.000	0.000	0.000	0.000	0.000
OPAL chargino leptonic	0.000	0.000	0.000	0.000	0.000	0.000
OPAL neutralino hadronic	0.000	0.000	0.000	0.000	0.000	0.000
$B_{(s)} \to \mu^+\mu^-$	0.000	−1.939	−2.739	−2.029	−1.939	2.029
Tree-level B and D decays	0.000	−15.515	−15.491	−15.283	−15.610	15.283
$B^0 \to K^{*0}\mu^+\mu^-$	−184.260	−196.506	−197.469	−196.088	−196.309	11.828
$B \to X_s\gamma$	9.799	9.258	9.525	9.106	9.184	0.693
a_μ	20.266	13.915	14.556	13.977	13.903	6.289
W mass	3.281	3.084	3.093	3.050	3.095	0.231
Relic density	5.989	5.989	5.984	5.989	5.989	0.000
PICO-2L	−1.000	−1.000	−1.000	−1.000	−1.000	0.000
PICO-60 F	0.000	0.000	0.000	0.000	0.000	0.000
SIMPLE 2014	−2.972	−2.972	−2.972	−2.972	−2.972	0.000
LUX 2015	−0.640	−0.676	−0.642	−0.640	−0.727	0.000
LUX 2016	−1.467	−1.539	−1.472	−1.467	−1.646	0.000
PandaX 2016	−1.886	−1.936	−1.889	−1.886	−2.009	0.000
SuperCDMS 2014	−2.248	−2.248	−2.248	−2.248	−2.248	0.000
XENON100 2012	−1.693	−1.675	−1.692	−1.693	−1.651	0.000
IceCube 79-string	0.000	0.000	0.000	0.000	0.000	0.000
γ rays (*Fermi*-LAT dwarfs)	−33.244	−33.421	−33.393	−33.381	−33.394	0.137
ρ_0	1.142	1.141	1.142	1.141	1.141	0.001
σ_s and σ_l	−6.115	−6.115	−6.116	−6.115	−6.117	0.000
$\alpha_s(m_Z)(\overline{MS})$	6.500	6.487	6.479	6.481	6.479	0.019
Top quark mass	−0.645	−0.645	−0.645	−0.649	−0.645	0.004
Total	−226.927	−264.273	−268.287	−263.747	−264.546	36.820

Quantity	A/H-funnel	$\tilde{\tau}$ co-ann.	$\tilde{t}$ co-ann.	$\tilde{\chi}_1^\pm$ co-ann.
A_0	9924.435	−1227.154	−9965.036	9206.079
m_0	9136.379	1476.893	4269.402	9000.628
$m_{1/2}$	2532.163	2422.340	1266.043	2256.472
$\tan\beta$	49.048	48.594	14.857	49.879
sgn(μ)	−	+	−	−
m_t	173.366	173.358	173.267	173.329
$\alpha_s(m_Z)(\overline{MS})$	0.119	0.119	0.119	0.119
ρ_0	0.394	0.401	0.403	0.394
σ_s	42.950	43.031	42.975	43.503
σ_l	57.976	58.544	57.887	58.155
M_1	1140.417	1089.994	556.554	1011.999
μ	−1409.433	2621.118	−4073.398	−983.112
$m_{\tilde{\ell}_1}$	6554.967	3594.650	592.052	6279.661
$m_{\tilde{\tau}_1}$	6590.901	1076.748	4071.458	6407.136
m_A	2292.366	2182.200	5612.268	1953.735
m_h	124.896	124.054	125.007	124.797
$m_{\tilde{\chi}_1^0}$	1133.191	1076.738	565.069	973.418
(%bino, %Higgsino)	(99, 1)	(100, 0)	(100, 0)	(44, 56)
$m_{\tilde{\chi}_2^0}$	1432.774	1999.921	1083.062	−1005.489
(%bino, %Higgsino)	(1, 98)	(0, 1)	(0, 0)	(0, 100)
$m_{\tilde{\chi}_1^\pm}$	1430.811	2000.084	1083.224	1002.018
(%wino, %Higgsino)	(1, 99)	(99, 1)	(100, 0)	(1, 99)
$m_{\tilde{g}}$	5545.587	5017.077	2926.857	5002.109
Ωh^2	6.88×10^{-2}	1.06×10^{-1}	4.62×10^{-2}	4.00×10^{-3}

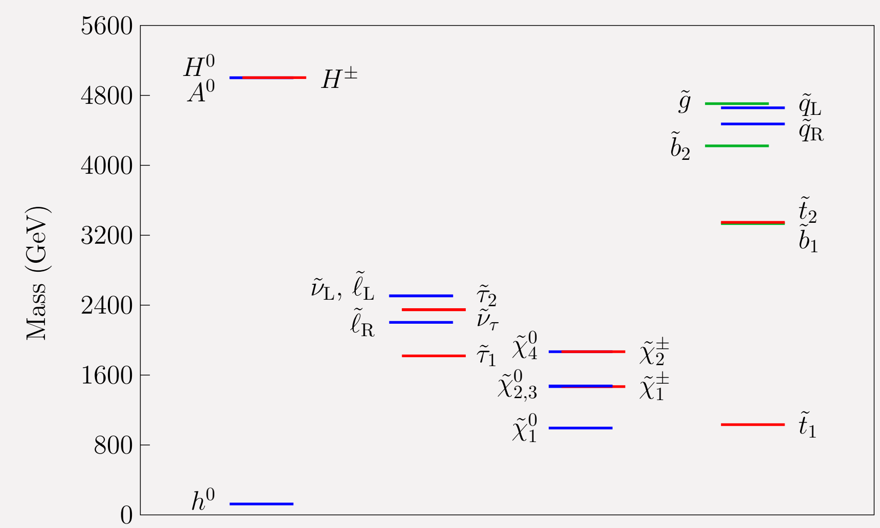


GUT-scale results

NUHM1 best fit points

Likelihood term	Ideal	A/H-funnel	$\tilde{\tau}$ co-ann.	$\tilde{t}$ co-ann.	$\tilde{\chi}_1^{\pm}$ co-ann.	$\Delta \ln \mathcal{L}_{\mathrm{BF}}$
LHC sparticle searches	0.000	0.000	0.000	0.000	0.000	0.000
LHC Higgs	−37.734	−38.646	−38.182	−38.271	−38.531	0.537
LEP Higgs	0.000	0.000	0.000	0.000	0.000	0.000
ALEPH selectron	0.000	0.000	0.000	0.000	0.000	0.000
ALEPH smuon	0.000	0.000	0.000	0.000	0.000	0.000
ALEPH stau	0.000	0.000	0.000	0.000	0.000	0.000
L3 selectron	0.000	0.000	0.000	0.000	0.000	0.000
L3 smuon	0.000	0.000	0.000	0.000	0.000	0.000
L3 stau	0.000	0.000	0.000	0.000	0.000	0.000
L3 neutralino leptonic	0.000	0.000	0.000	0.000	0.000	0.000
L3 chargino leptonic	0.000	0.000	0.000	0.000	0.000	0.000
OPAL chargino hadronic	0.000	0.000	0.000	0.000	0.000	0.000
OPAL chargino semi-leptonic	0.000	0.000	0.000	0.000	0.000	0.000
OPAL chargino leptonic	0.000	0.000	0.000	0.000	0.000	0.000
OPAL neutralino hadronic	0.000	0.000	0.000	0.000	0.000	0.000
$B_{(s)} \to \mu^+\mu^-$	0.000	−1.985	−2.033	−2.032	−2.043	2.032
Tree-level B and D decays	0.000	−15.703	−15.286	−15.286	−15.282	15.286
$B^0 \to K^{*0}\mu^+\mu^-$	−184.260	−196.553	−195.323	−194.855	−194.825	10.595
$B \to X_s\gamma$	9.799	9.272	8.696	8.430	8.351	1.369
a_μ	20.266	14.158	13.837	13.819	13.836	6.447
W mass	3.281	3.095	3.062	3.075	3.096	0.206
Relic density	5.989	5.989	5.989	5.989	5.989	0.000
PICO-2L	−1.000	−1.000	−1.000	−1.000	−1.000	0.000
PICO-60 F	0.000	0.000	0.000	0.000	−0.001	0.000
SIMPLE 2014	−2.972	−2.972	−2.972	−2.972	−2.972	0.000
LUX 2015	−0.640	−0.666	−0.646	−0.659	−0.676	0.019
LUX 2016	−1.467	−1.519	−1.479	−1.504	−1.539	0.037
PandaX 2016	−1.886	−1.921	−1.894	−1.912	−1.936	0.026
SuperCDMS 2014	−2.248	−2.248	−2.248	−2.248	−2.248	0.000
XENON100 2012	−1.693	−1.680	−1.690	−1.684	−1.675	0.009
IceCube 79-string	0.000	−0.014	0.000	0.000	−0.135	0.000
γ rays (*Fermi*-LAT dwarfs)	−33.244	−33.384	−33.364	−33.373	−33.398	0.129
ρ_0	1.142	1.141	1.141	1.140	1.141	0.002
σ_s and σ_l	−6.115	−6.115	−6.135	−6.124	−6.117	0.009
$\alpha_s(m_Z)(\overline{MS})$	6.500	6.491	6.488	6.493	6.494	0.007
Top quark mass	−0.645	−0.647	−0.673	−0.655	−0.645	0.010
Total	−226.927	−264.907	−263.712	−263.629	−264.115	36.702

Quantity	A/H-funnel	$\tilde{\tau}$ co-ann.	$\tilde{t}$ co-ann.	$\tilde{\chi}_1^{\pm}$ co-ann.
A_0	9084.348	−7798.283	−7016.861	−6439.114
m_0	5139.563	1659.858	2042.775	1472.445
$m_{1/2}$	5266.693	2656.510	2245.476	2319.968
m_H	6954.864	5407.626	4990.078	5034.071
$\tan\beta$	53.263	19.430	18.128	11.840
sgn(μ)	+	−	−	−
m_t	173.393	173.522	173.451	173.362
$\alpha_s(m_Z)(\overline{MS})$	0.119	0.118	0.119	0.119
ρ_0	0.403	0.398	0.408	0.396
σ_s	42.776	43.646	43.747	42.478
σ_l	57.737	56.355	57.132	58.024
M_1	2419.401	1184.390	994.971	1023.177
μ	836.283	−1753.895	−1462.491	−351.100
$m_{\tilde{t}_1}$	7902.945	1198.127	1032.608	1012.967
$m_{\tilde{\tau}_1}$	2231.113	1295.803	1819.486	1513.479
m_A	1805.767	5428.634	5002.455	5122.233
m_h	125.026	124.544	124.531	124.903
$m_{\tilde{\chi}_1^0}$	856.207	1179.991	993.716	358.905
(%bino, %Higgsino)	(0, 100)	(100, 0)	(100, 0)	(0, 100)
$m_{\tilde{\chi}_2^0}$	−858.645	1760.580	1467.989	−364.815
(%bino, %Higgsino)	(0, 100)	(0, 98)	(0, 98)	(0, 100)
$m_{\tilde{\chi}_1^{\pm}}$	857.791	1760.608	1467.887	362.366
(%wino, %Higgsino)	(0, 100)	(2, 98)	(2, 98)	(0, 100)
$m_{\tilde{g}}$	10 470.041	5462.593	4705.842	4823.285
Ωh^2	7.03×10^{-2}	5.24×10^{-2}	9.29×10^{-2}	1.59×10^{-2}

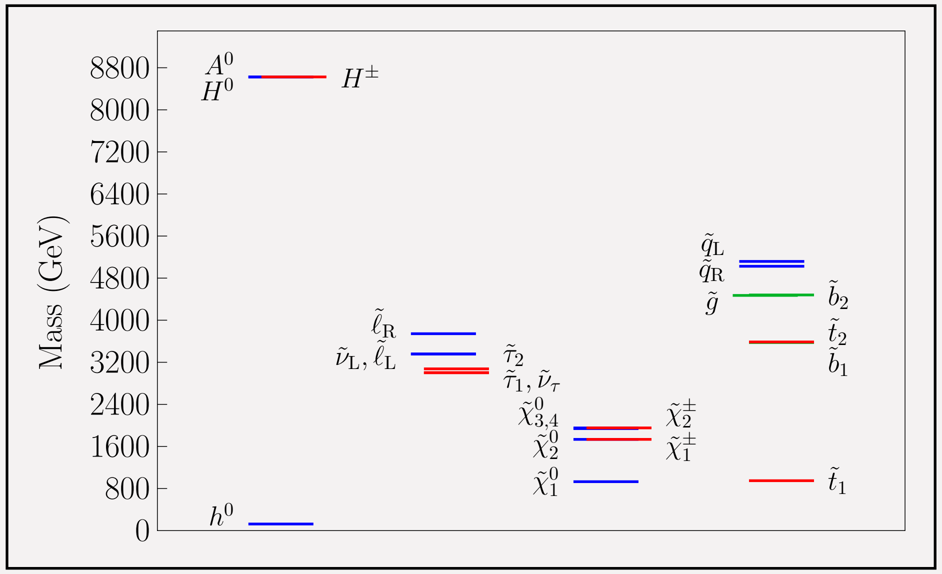


GUT-scale results

NUHM2 best fit points

Likelihood term	Ideal	A/H-funnel	$\tilde{\tau}$ co-ann.	$\tilde{t}$ co-ann.	$\tilde{\chi}_1^{\pm}$ co-ann.	$\Delta \ln \mathcal{L}_{\rm BF}$
LHC sparticle searches	0.000	0.000	0.000	0.000	0.000	0.000
LHC Higgs	−37.734	−38.563	−37.928	−37.980	−38.484	0.246
LEP Higgs	0.000	0.000	0.000	0.000	0.000	0.000
ALEPH selectron	0.000	0.000	0.000	0.000	0.000	0.000
ALEPH smuon	0.000	0.000	0.000	0.000	0.000	0.000
ALEPH stau	0.000	0.000	0.000	0.000	0.000	0.000
L3 selectron	0.000	0.000	0.000	0.000	0.000	0.000
L3 smuon	0.000	0.000	0.000	0.000	0.000	0.000
L3 stau	0.000	0.000	0.000	0.000	0.000	0.000
L3 neutralino leptonic	0.000	0.000	0.000	0.000	0.000	0.000
L3 chargino leptonic	0.000	0.000	0.000	0.000	0.000	0.000
OPAL chargino hadronic	0.000	0.000	0.000	0.000	0.000	0.000
OPAL chargino semi-leptonic	0.000	0.000	0.000	0.000	0.000	0.000
OPAL chargino leptonic	0.000	0.000	0.000	0.000	0.000	0.000
OPAL neutralino hadronic	0.000	0.000	0.000	0.000	0.000	0.000
$B_{(s)} \to \mu^+\mu^-$	0.000	−1.972	−2.037	−2.033	−2.030	2.033
Tree-level B and D decays	0.000	−15.553	−15.283	−15.283	−15.290	15.283
$B^0 \to K^{*0}\mu^+\mu^-$	−184.260	−195.596	−195.475	−195.043	−194.415	10.783
$B \to X_s\gamma$	9.799	8.865	8.797	8.550	8.077	1.249
a_μ	20.266	14.086	13.756	13.842	13.876	6.424
W mass	3.281	3.060	3.078	3.074	3.097	0.207
Relic density	5.989	5.989	5.989	5.989	5.989	0.000
PICO-2L	−1.000	−1.000	−1.000	−1.000	−1.000	0.000
PICO-60 F	0.000	0.000	0.000	0.000	0.000	0.000
SIMPLE 2014	−2.972	−2.972	−2.972	−2.972	−2.972	0.000
LUX 2015	−0.640	−0.657	−0.641	−0.641	−0.671	0.001
LUX 2016	−1.467	−1.501	−1.468	−1.470	−1.529	0.003
PandaX 2016	−1.886	−1.909	−1.887	−1.888	−1.929	0.002
SuperCDMS 2014	−2.248	−2.248	−2.248	−2.248	−2.248	0.000
XENON100 2012	−1.693	−1.685	−1.693	−1.692	−1.678	0.001
IceCube 79-string	0.000	−0.021	0.000	0.000	−0.108	0.000
γ rays (*Fermi*-LAT dwarfs)	−33.244	−33.398	−33.371	−33.369	−33.398	0.125
ρ_0	1.142	1.141	1.137	1.141	1.131	0.001
σ_s and σ_l	−6.115	−6.115	−6.116	−6.115	−6.116	0.000
$\alpha_s(m_Z)(\overline{MS})$	6.500	6.447	6.499	6.496	6.496	0.004
Top quark mass	−0.645	−0.652	−0.661	−0.646	−0.645	0.001
Total	−226.927	−264.255	−263.524	−263.289	−263.855	36.362

Quantity	A/H-funnel	$\tilde{\tau}$ co-ann.	$\tilde{t}$ co-ann.	$\tilde{\chi}_1^{\pm}$ co-ann.
A_0	7337.758	−6666.073	−7706.626	−8213.109
m_0	4945.237	1582.304	3294.531	2697.314
$m_{1/2}$	4981.246	2265.444	2085.463	2607.561
m_{H_u}	6845.748	3714.036	5196.468	6282.001
m_{H_d}	93.459	9285.571	8990.311	4005.580
$\tan\beta$	28.221	22.567	23.345	18.075
sgn(μ)	+	−	−	−
m_t	173.246	173.479	173.388	173.328
$\alpha_s(m_Z)(\overline{MS})$	0.119	0.119	0.119	0.119
ρ_0	0.396	0.388	0.405	0.381
σ_s	43.162	42.562	43.121	43.323
σ_l	57.980	58.022	57.890	57.764
M_1	2277.442	1004.143	925.176	1157.614
μ	537.021	−2480.773	−1928.496	−382.757
$m_{\tilde{t}_1}$	7589.989	1030.595	948.763	1217.299
$m_{\tilde{\tau}_1}$	4633.573	1083.376	3001.595	2261.195
m_A	1176.568	9151.605	8624.785	3808.674
m_h	125.377	124.398	125.173	125.414
$m_{\tilde{\chi}_1^0}$	553.377	1004.076	930.008	391.009
(%bino, %Higgsino)	(0, 100)	(100, 0)	(100, 0)	(0, 100)
$m_{\tilde{\chi}_2^0}$	−555.848	1868.405	1734.260	−396.274
(%bino, %Higgsino)	(0, 100)	(0, 1)	(0, 6)	(0, 100)
$m_{\tilde{\chi}_1^{\pm}}$	554.943	1868.573	1734.450	394.095
(%wino, %Higgsino)	(0, 100)	(99, 1)	(94, 6)	(0, 100)
$m_{\tilde{g}}$	9979.887	4715.895	4471.116	5436.877
Ωh^2	3.06×10^{-2}	6.76×10^{-2}	4.49×10^{-2}	1.81×10^{-2}



MSSM7 results

Definition of coloured regions

- chargino co-annihilation: $\tilde{\chi}_1^0 \geq 50\%$ Higgsino,
- stop co-annihilation: $m_{\tilde{t}_1} \leq 1.2\, m_{\tilde{\chi}_1^0}$,
- sbottom co-annihilation: $m_{\tilde{b}_1} \leq 1.2\, m_{\tilde{\chi}_1^0}$,
- A/H funnel: $1.6\, m_{\tilde{\chi}_1^0} \leq m_{\text{heavy}} \leq 2.4\, m_{\tilde{\chi}_1^0}$,
- h/Z funnel: $1.6\, m_{\tilde{\chi}_1^0} \leq m_{\text{light}} \leq 2.4\, m_{\tilde{\chi}_1^0}$,

MSSM7 results

1D profile likelihood ratios for parameters

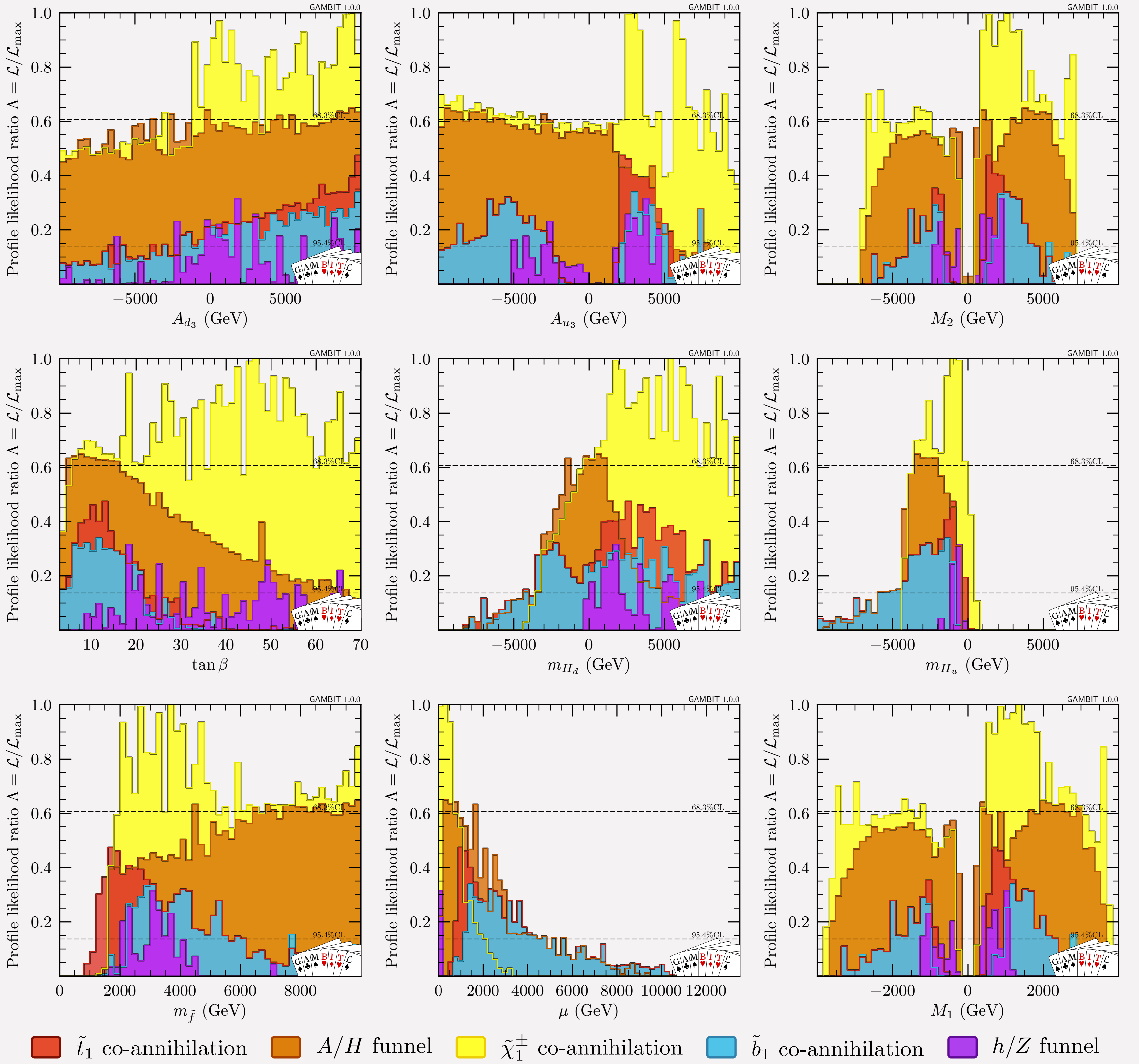


Fig. 2: 1D profile likelihood ratio for the input parameters A_{d_3}, A_{u_3}, M_2, $\tan\beta$, m_{H_d}, m_{H_u} and $m_{\tilde{f}}$, as well as the derived parameters M_1 and μ.

MSSM7 results

1D profile likelihood ratios for masses

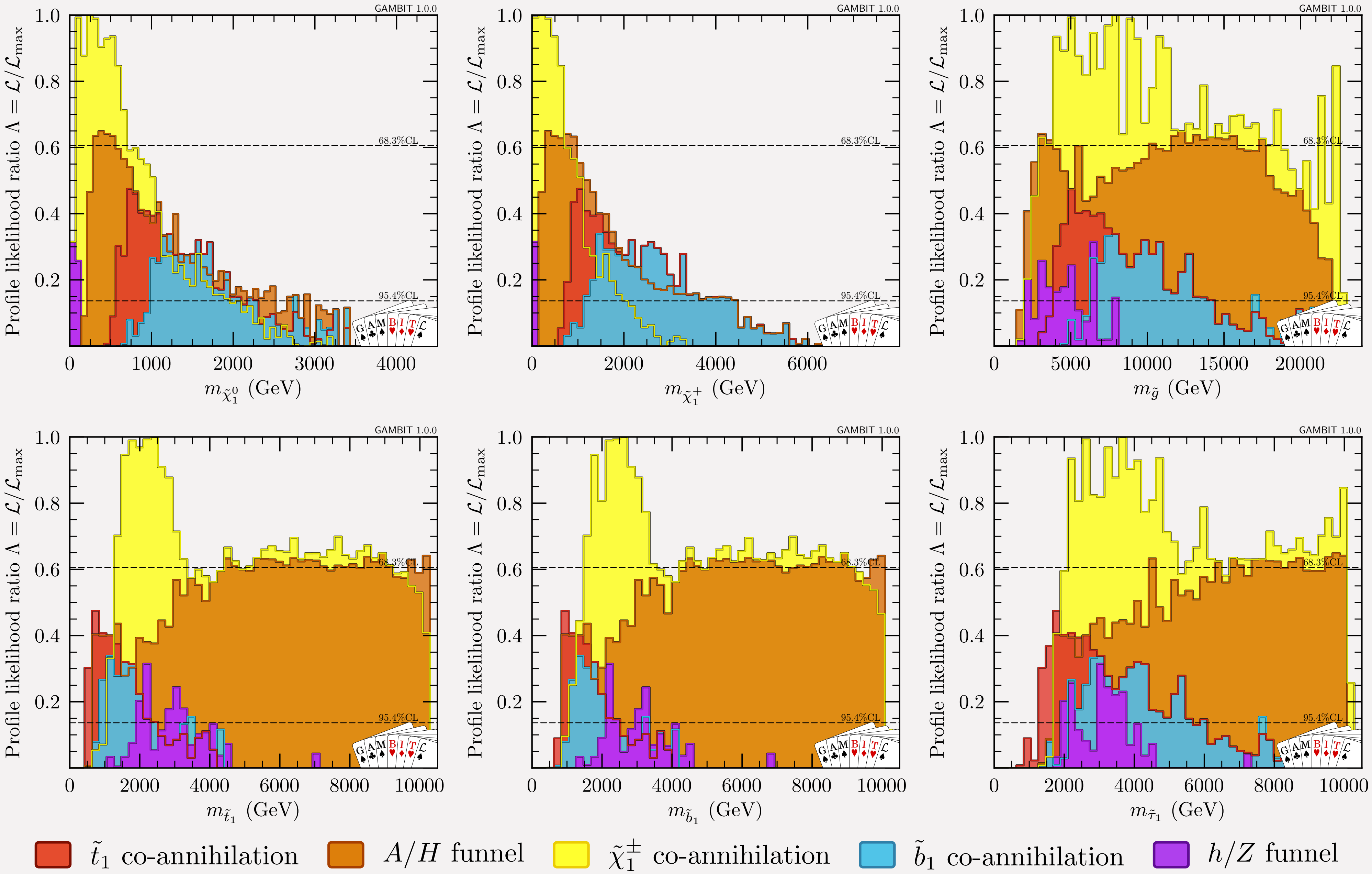
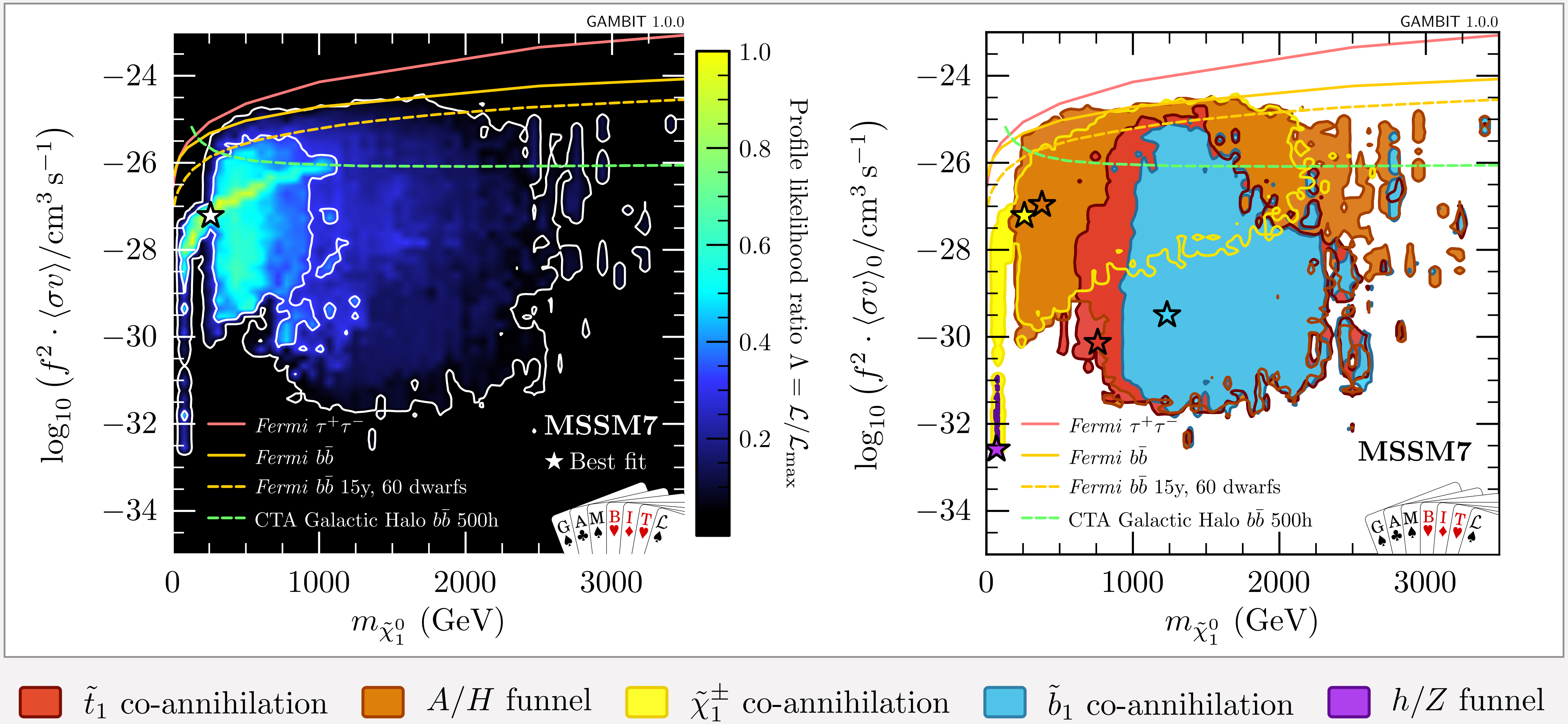


Fig. 7: 1D profile likelihood ratios for the masses $m_{\tilde{\chi}_1^0}$, $m_{\tilde{\chi}_1^+}$, $m_{\tilde{g}}$, $m_{\tilde{t}_1}$, $m_{\tilde{b}_1}$ and $m_{\tilde{\tau}_1}$. We show separate distributions for each mechanism that allows the models to obey the relic density constraint.

MSSM 7



- Future ID will probe parts of the preferred region
- Prospects may be better than indicated here:
    - We have only included gamma ray searches
    - Radiative corrections and Sommefeld enhancement not taken into account

MSSM7 results

Chargino—neutralino mass plane

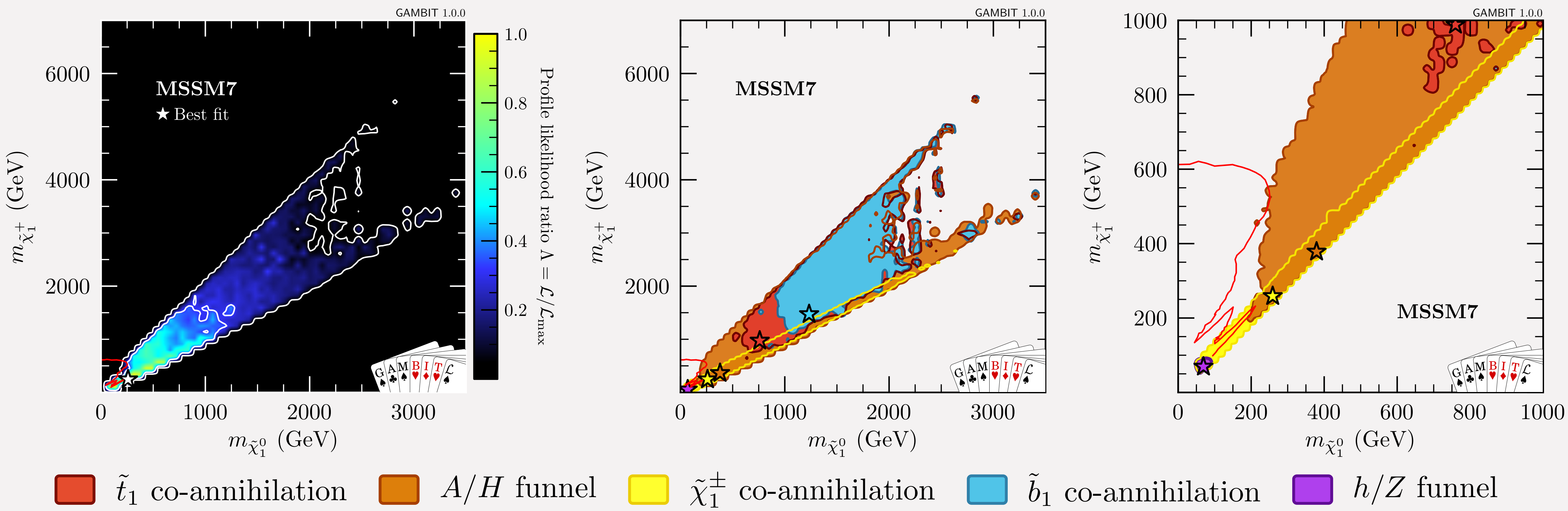


Fig. 8: *Left:* Profile likelihood in the $\tilde{\chi}_1^{\pm} - \tilde{\chi}_1^0$ mass plane. *Centre:* Sub-regions within the 95% CL profile likelihood region, coloured according to mechanisms by which the relic density constraint is satisfied. The regions shown correspond to neutralino co-annihilation with charginos, stops or sbottoms, and resonant annihilation through the light or heavy Higgs funnels. Superimposed in red is the latest CMS Run II simplified model limit for $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^0$ production and decay with decoupled sleptons [210]. This limit should be interpreted with caution (see main text for details). *Right:* The same information as the central plot, but zoomed into the low-mass region. Note that, although the CMS limit appears to have excluded part of the chargino co-annihilation region, this is a binning effect. One should instead refer to the plot of the $\tilde{\chi}_1^{\pm} - \tilde{\chi}_1^0$ mass difference in Fig. 7, which provides finer resolution on the mass difference in this region.

MSSM7 results

Sbottom/stop—neutralino mass planes

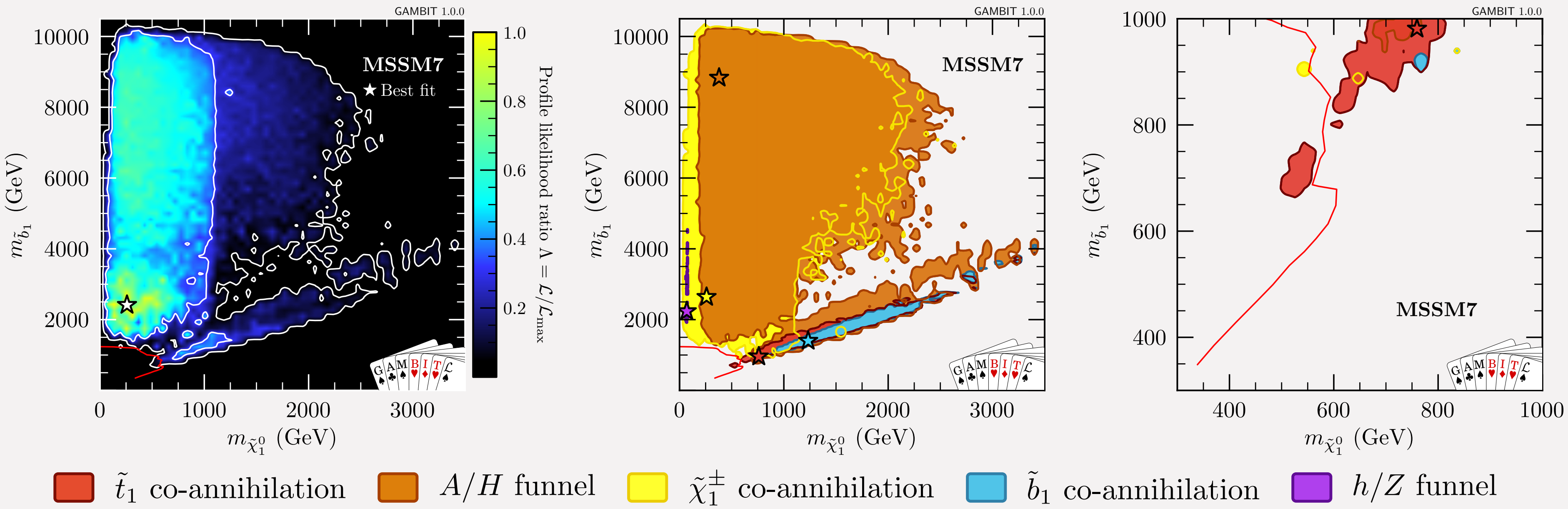


Fig. 10: *Left:* The profile likelihood ratio in the $\tilde{b}_1 - \tilde{\chi}^0_1$ mass plane. *Centre:* Colour-coding shows mechanism(s) that allow models within the 95% CL region to avoid exceeding the observed relic density of DM. The regions shown correspond to neutralino co-annihilation with charginos, stops or sbottoms, and resonant annihilation through the light or heavy Higgs funnels. *Right:* The same information as the central plot, zoomed into the low-mass region.

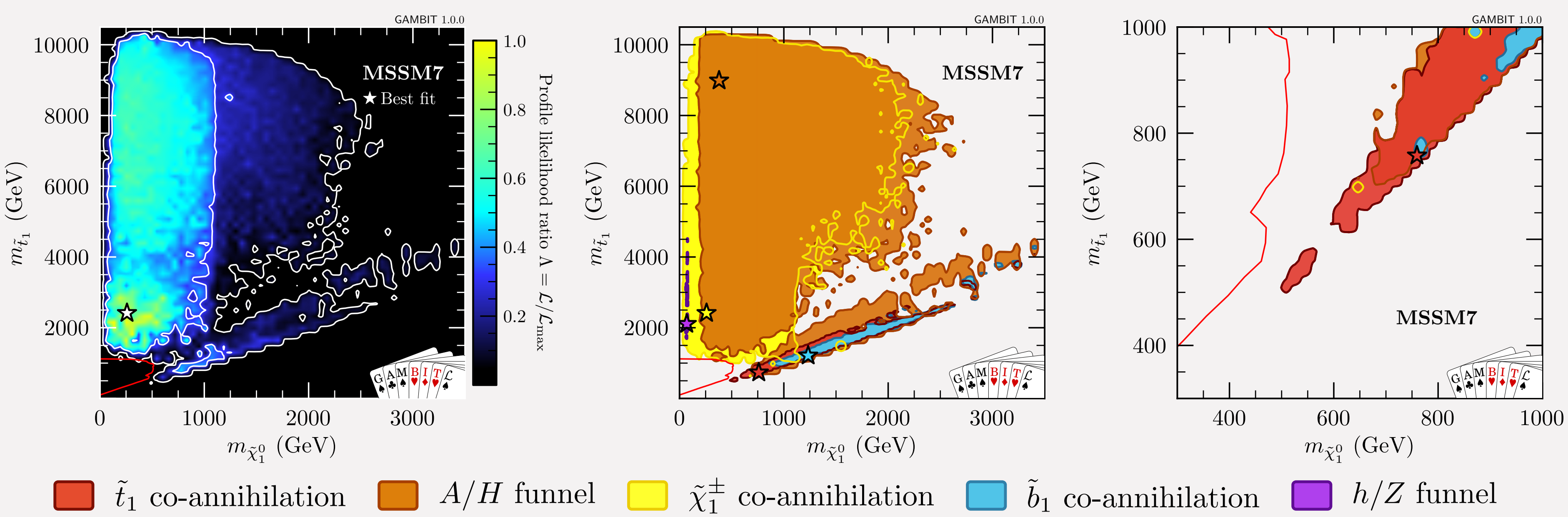
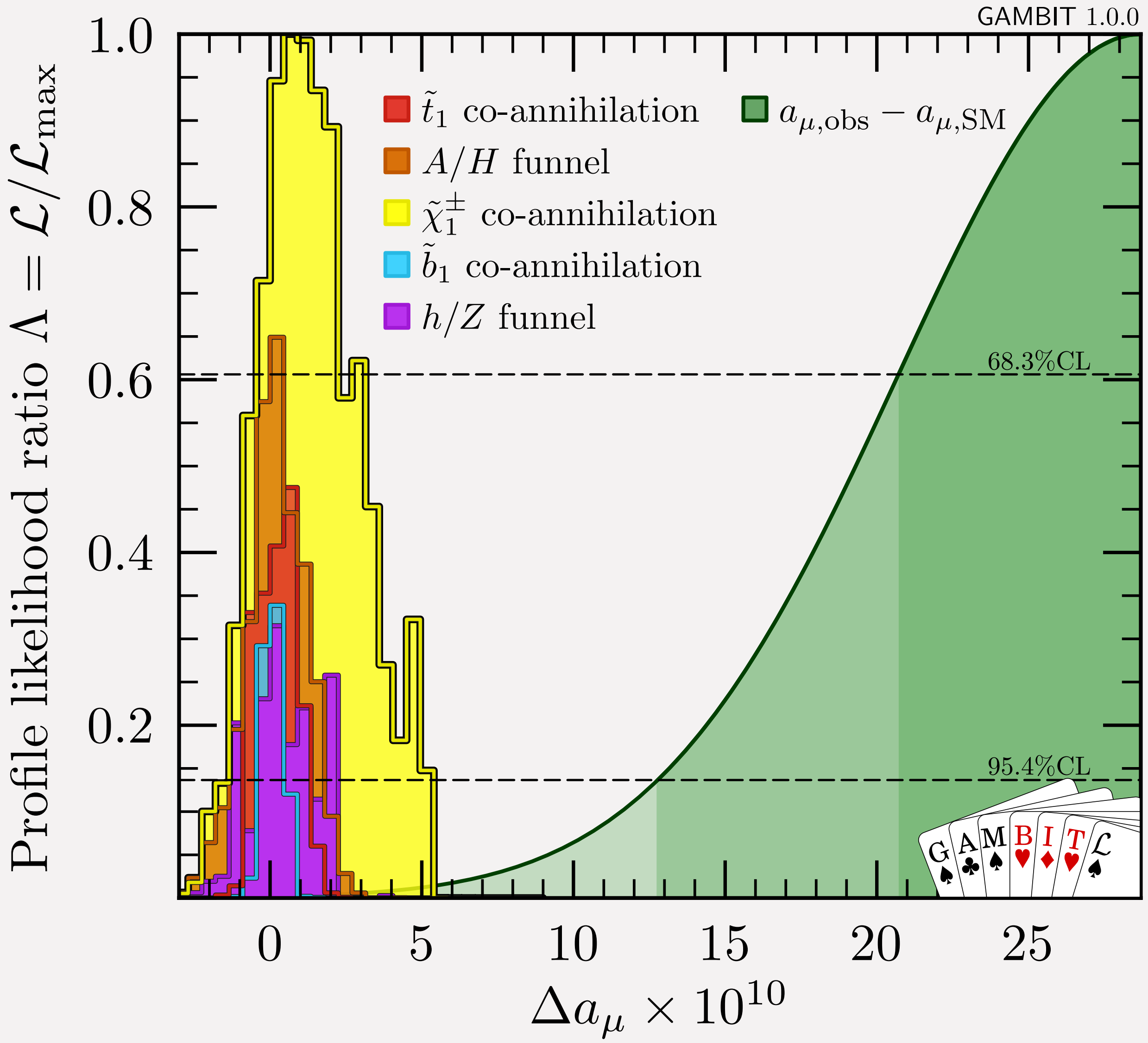


Fig. 11: *Left:* The profile likelihood ratio in the $\tilde{t}_1 - \tilde{\chi}^0_1$ mass plane. *Centre:* Colour-coding shows mechanism(s) that allow models within the 95% CL region to avoid exceeding the observed relic density of DM. The regions shown correspond to neutralino co-annihilation with charginos, stops or sbottoms, and resonant annihilation through the light or heavy Higgs funnels. Superimposed in red is the latest CMS Run II simplified model limit for stop pair production [211]. *Right:* The same information as the central plot, zoomed into the low-mass region.

MSSM7 results

Muon g-2



MSSM7 results

MSSM7 best fit points

Likelihood term	Ideal	A/H-funnel	$\tilde{b}$ co-ann.	$\tilde{t}$ co-ann.	$\tilde{\chi}_1^\pm$ co-ann.	Z/h-funnel	$\Delta \ln \mathcal{L}_{\rm BF}$
LHC sparticle searches	0.000	0.000	0.000	0.000	0.000	0.000	0.000
LHC Higgs	−37.734	−38.657	−38.647	−39.050	−38.347	−38.593	0.613
LEP Higgs	0.000	0.000	0.000	0.000	0.000	0.000	0.000
ALEPH selectron	0.000	0.000	0.000	0.000	0.000	0.000	0.000
ALEPH smuon	0.000	0.000	0.000	0.000	0.000	0.000	0.000
ALEPH stau	0.000	0.000	0.000	0.000	0.000	0.000	0.000
L3 selectron	0.000	0.000	0.000	0.000	0.000	0.000	0.000
L3 smuon	0.000	0.000	0.000	0.000	0.000	0.000	0.000
L3 stau	0.000	0.000	0.000	0.000	0.000	0.000	0.000
L3 neutralino leptonic	0.000	0.000	0.000	0.000	0.000	0.000	0.000
L3 chargino leptonic	0.000	0.000	0.000	0.000	0.000	0.000	0.000
OPAL chargino hadronic	0.000	0.000	0.000	0.000	0.000	0.000	0.000
OPAL chargino semi-leptonic	0.000	0.000	0.000	0.000	0.000	0.000	0.000
OPAL chargino leptonic	0.000	0.000	0.000	0.000	0.000	0.000	0.000
OPAL neutralino hadronic	0.000	0.000	0.000	0.000	0.000	0.000	0.000
$B_{(s)} \to \mu^+\mu^-$	0.000	−2.033	−2.024	−2.021	−1.998	−1.997	1.998
Tree-level B and D decays	0.000	−15.318	−15.284	−15.287	−15.315	−15.333	15.315
$B^0 \to K^{*0}\mu^+\mu^-$	−184.260	−194.316	−195.283	−193.103	−194.734	−195.551	10.474
$B \to X_s\gamma$	9.799	8.030	8.710	6.978	8.334	8.795	1.465
a_μ	20.266	14.027	14.114	14.299	14.269	14.090	5.997
W mass	3.281	3.081	2.813	2.778	3.096	2.643	0.185
Relic density	5.989	5.989	5.989	5.989	5.989	5.989	0.000
PICO-2L	−1.000	−1.000	−1.000	−1.000	−1.000	−1.000	0.000
PICO-60 F	0.000	0.000	0.000	0.000	0.000	−0.001	0.000
SIMPLE 2014	−2.972	−2.972	−2.972	−2.972	−2.972	−2.972	0.000
LUX 2015	−0.640	−0.657	−0.693	−0.670	−0.660	−0.650	0.020
LUX 2016	−1.467	−1.501	−1.574	−1.527	−1.506	−1.487	0.039
PandaX 2016	−1.886	−1.909	−1.960	−1.927	−1.912	−1.899	0.026
SuperCDMS 2014	−2.248	−2.248	−2.248	−2.248	−2.248	−2.248	0.000
XENON100 2012	−1.693	−1.684	−1.667	−1.678	−1.683	−1.688	0.010
IceCube 79-string	0.000	−0.032	0.000	0.000	−0.069	0.000	0.069
γ rays (Fermi-LAT dwarfs)	−33.244	−33.374	−33.367	−33.363	−33.371	−33.255	0.127
ρ_0	1.142	1.139	1.115	1.138	1.142	1.141	0.000
σ_s and σ_l	−6.115	−6.115	−6.117	−6.115	−6.128	−6.116	0.013
$\alpha_s(m_Z)(\overline{MS})$	6.500	6.493	6.427	6.409	6.496	6.457	0.004
Top quark mass	−0.645	−0.647	−0.687	−0.645	−0.654	−0.751	0.009
Total	−226.927	−263.704	−264.354	−264.016	−263.272	−264.426	36.345

Quantity	A/H-funnel	$\tilde{b}$ co-ann.	$\tilde{t}$ co-ann.	$\tilde{\chi}_1^\pm$ co-ann.	Z/h-funnel
A_{d_3} (1 TeV)	9582.567	9669.750	9706.338	9376.461	1639.611
A_{u_3} (1 TeV)	−9389.783	2957.229	2197.287	2923.877	3660.585
M_2 (1 TeV)	3768.368	2404.020	1498.770	2469.296	2032.136
$\tan\beta$ (m_Z)	7.133	11.862	12.743	46.632	19.058
$m^2_{H_u}$ (1 TeV)	$-1.271\cdot10^7$	$-2.490\cdot10^6$	$-9.757\cdot10^5$	$-7.830\cdot10^5$	$-6.077\cdot10^5$
$m^2_{H_d}$ (1 TeV)	$3.748\cdot10^5$	$1.045\cdot10^7$	$7.824\cdot10^6$	$2.729\cdot10^7$	$3.189\cdot10^6$
$m^2_{\tilde{f}}$ (1 TeV)	$9.680\cdot10^7$	$9.229\cdot10^6$	$3.006\cdot10^6$	$1.352\cdot10^7$	$9.574\cdot10^6$
m_t	173.289	173.120	173.325	173.445	172.990
$\alpha_s(m_Z)(\overline{MS})$	0.119	0.119	0.119	0.119	0.119
ρ_0	0.409	0.372	0.390	0.399	0.406
σ_s	42.966	43.242	42.916	44.101	42.591
σ_l	57.987	57.442	58.265	58.773	58.095
$M_1(M_{\rm SUSY})$	2002.225	1242.861	767.869	1283.505	1053.133
$\mu(M_{\rm SUSY})$	367.156	1477.923	987.697	253.479	69.449
$m_{\tilde{t}_1}$	9012.999	1237.689	759.551	2440.084	2132.455
$m_{\tilde{\tau}_1}$	9845.047	3034.359	1730.209	3698.869	3097.127
m_A	793.380	3567.851	2956.071	5348.470	1804.886
m_h	125.099	125.088	123.988	124.731	126.427
$m_{\tilde{\chi}^0_1}$	379.116	1233.050	759.524	258.939	69.247
(%bino, %Higgsino)	(0, 100)	(98, 2)	(98, 2)	(0, 100)	(0, 100)
$m_{\tilde{\chi}^0_2}$	−381.804	−1491.708	994.456	−262.754	−73.665
(%bino, %Higgsino)	(0, 100)	(0, 100)	(2, 97)	(0, 100)	(0, 100)
$m_{\tilde{\chi}^\pm_1}$	380.734	1488.287	990.571	261.179	71.618
(%wino, %Higgsino)	(0, 100)	(1, 99)	(2, 98)	(0, 100)	(0, 100)
$m_{\tilde{g}}$	12 370.525	7920.520	5006.746	8104.365	6711.215
Ωh^2	$1.537\cdot10^{-2}$	$3.890\cdot10^{-2}$	$1.046\cdot10^{-2}$	$8.027\cdot10^{-3}$	$8.382\cdot10^{-4}$