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Minimal SUSY Global Fits with GAMBIT

Peter Athron
On behalf of the GAMBIT community

Outline

- Global Fits and GAMBIT
- Back in time to 2017
  - most recent CMSSM global fit
  - impact of run II LHC data + dark matter, flavour, Higgs, low energy
  - `current' status of the model
- Forward in time to 20XX with CEPC data
  - impact of CEPC measurement
  - Need for precise Higgs decay calculations
- Conclusions

Why Global Fits?

Realistic BSM models have:

- A large multidimensional parameter space
- Many collider & astrophysical observables

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→ Global Fits

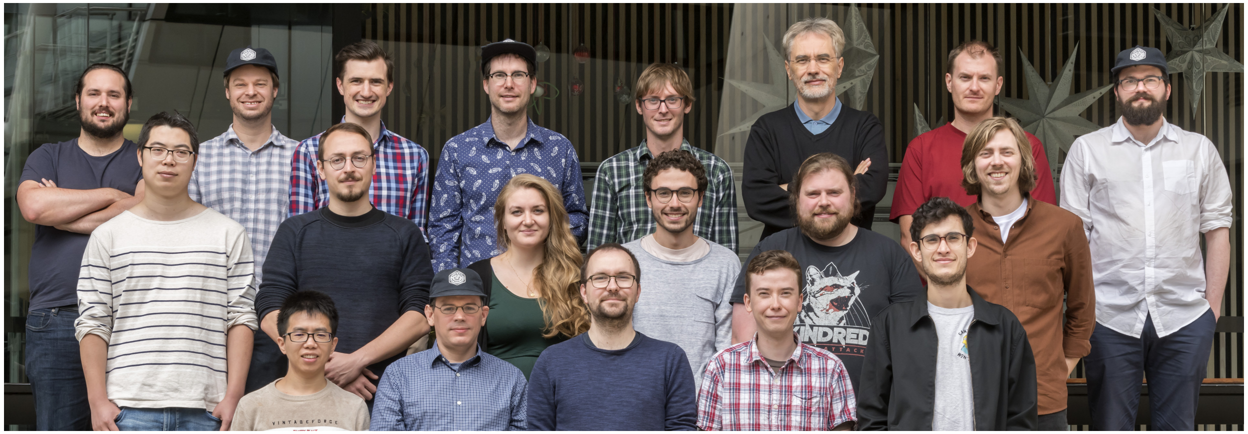
→ GAMBIT

GAMBIT: The Global And Modular BSM Inference Tool

https://gambit.com/GambitBSM/ https://gambitbsm.org

- A BSM global fitting community 80+ participants

Recently Active Members:
V Ananyev, P Athron, N Avis-Kozar, C Balázs, A Beniwal, S Bloor, LL Braseth, T Bringmann, A Buckley, J Butterworth, J-E Camargo-Molina, C Chang, M Chrzaszcz, J Conrad, J Cornell, M Danninger, J Edsjö, T Emken, A Fowlie, T Gonzalo, W Handley, J Harz, S Hoof, F Kahlhoefer, A Kvellestad, M Lecroq, P Jackson, D Jacob, C Lin, FN Mahmoudi, G Martinez, H Pacey, MT Prim, T Procter, F Rajec, A Raklev, JJ Renk, R Ruiz, A Scaffidi, P Scott, N Serra, P Stöcker, W. Su, J Van den Abeele, A Vincent, C Weniger, A Woodcock, M White, Y Zhang ++



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

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, SuperIso, SUSY-AI, xsec, Vevacious, WIMPSim

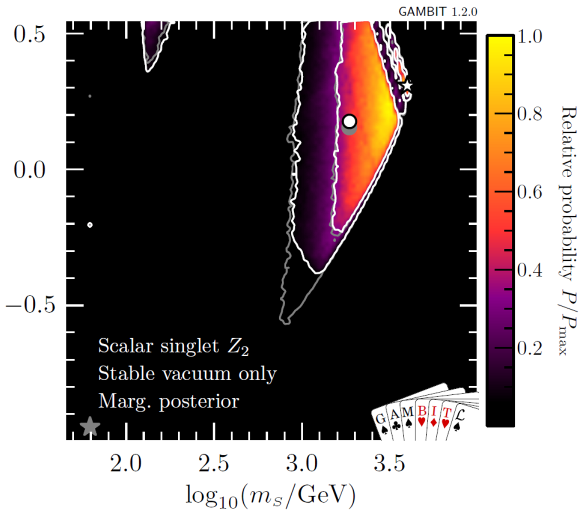
- Public Tool for BSM global fits (MSSM / non-minimal SUSY / non-SUSY)

Fully open source, massively parallel, extensive observable/data libraries and model database, frequentist/bayesian statistical options, Plug & play packages, extendable with new models, observables, fast LHC likelihoods

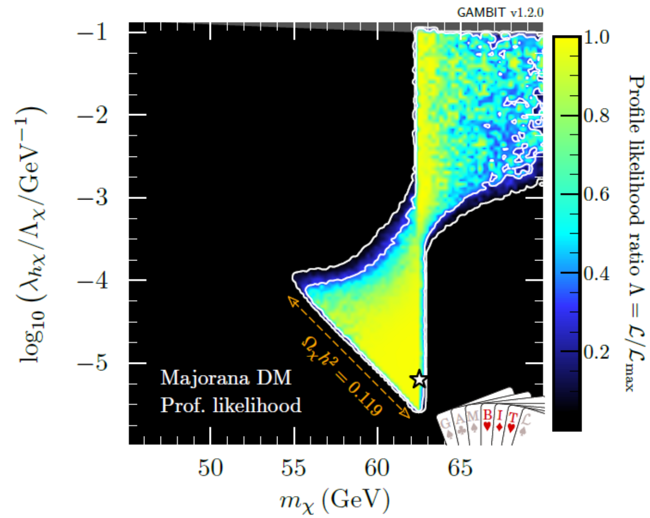
GAMBIT has producued Global fits of many BSM theories

- Collider constraints on electroweakinos in the presence of a light gravitino, Eur. Phys. J. C 83 (2023) 6, 493, arXiv:2303.09082.
  Supplementary data, including samples: DOI 10.5281/zenodo.7704832
- Global fits of simplified models for dark matter with GAMBIT II. Vector dark matter with an s-channel vector mediator, arXiv:2303.08351.
  Supplementary data, including samples: DOI 10.5281/zenodo.7710586
- Fast and accurate AMS-02 antiproton likelihoods for global dark matter fits, arXiv:2303.07362.
  Supplementary data, including samples: DOI 10.5281/zenodo.7952765
- Global fits of simplified models for dark matter with GAMBIT: I. Scalar and fermionic models with s-channel vector mediators, Eur. Phys. J. C 83 (2023) 3, 249, arXiv:2209.13266.
  Supplementary data, including samples: DOI 10.5281/zenodo.6615830
- Cosmological constraints on decaying axion-like particles: a global analysis, JCAP 12 (2022) 027, arXiv:2205.13549.
  Supplementary data, including samples: DOI 10.5281/zenodo.6573347
- Thermal WIMPs and the Scale of New Physics: Global Fits of Dirac Dark Matter Effective Field Theories, Eur. Phys. J. C 81 (2021) 11, 992, arXiv:2106.02056.
  Supplementary data, including samples: DOI 10.5281/zenodo.4836397
- Strengthening the bound on the mass of the lightest neutrino with terrestrial and cosmological experiments, Phys. Rev. D 103 (2021) 12, 123508, arXiv:2009.03287.
  Supplementary data, including samples: DOI 10.5281/zenodo.4005381
- Global fits of axion-like particles to XENON1T and astrophysical data, JHEP 05 (2021) 159, arXiv:2007.05517.
  Supplementary data, including samples: DOI 10.5281/zenodo.4384061
- A model-independent analysis of $b \to s\mu+\mu-$ transitions with GAMBIT's FlavBit, Eur. Phys. J. C 81 (2021), arXiv:2006.03489.
  Supplementary data, including samples: DOI 10.5281/zenodo.5749787
- A frequentist analysis of three right-handed neutrinos with GAMBIT, Eur. Phys. J. C 80 (2020) 6, 569, arxiv:1908.02302.
  Supplementary data, including samples: DOI 10.5281/zenodo.3334971
- Axion global fits with Peccei-Quinn symmetry breaking before inflation using GAMBIT, JHEP 03 (2019) 191, arXiv:1810.07192.
  Supplementary data, including samples: DOI 10.5281/zenodo.1423692
- Combined collider constraints on neutralinos and charginos, Eur. Phys. J. C 79 (2019) 395, arXiv:1809.02097.
  Supplementary data, including samples: DOI 10.5281/zenodo.1410335
- Global analyses of Higgs portal singlet dark matter models using GAMBIT, Eur. Phys. J. C 79 (2019) 38, arXiv:1808.10465.
  Supplementary data, including samples: DOI 10.5281/zenodo.1400654
- Impact of vacuum stability, perturbativity and XENON1T on global fits of Z_2 and Z_3 scalar singlet dark matter, Eur. Phys. J. C 78 (2018) 830, arXiv:1806.11281.
  Supplementary data, including samples: DOI 10.5281/zenodo.1298566
- A global fit of the MSSM with GAMBIT, Eur. Phys. J. C 77 (2017) 879, arXiv:1705.07917.
  Supplementary data, including samples: DOI 10.5281/zenodo.801639
- Global fits of GUT-scale SUSY models with GAMBIT, Eur. Phys. J. C 77 (2017) 824, arXiv:1705.07935.
  Supplementary data, including samples: DOI 10.5281/zenodo.801641
- Status of the scalar singlet dark matter model, Eur. Phys. J. C 77 (2017) 568, arXiv:1705.07931.
  Supplementary data, including samples: DOI 10.5281/zenodo.801510

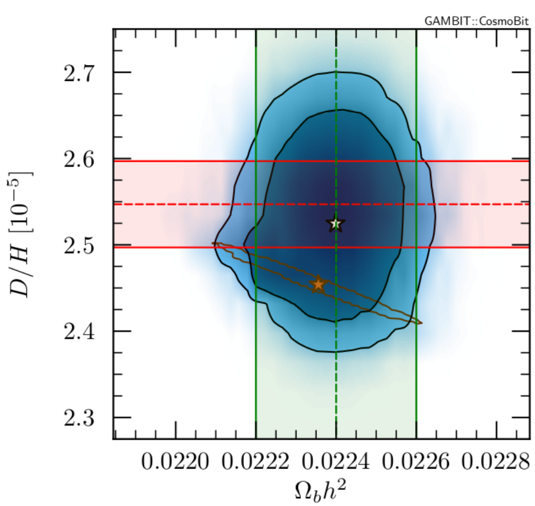
Examples: GAMBIT global fits



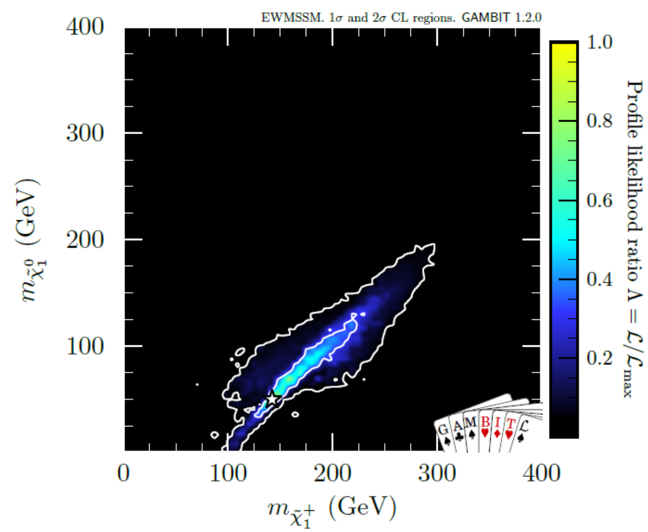
Scalar singlet dark matter
(EPJC 78 (2018) 830)



Fermion and vector Higgs portal dark matter
(EPJC 79 (2019) 38)



Axion like particles
(JCAP 12 (2022) 027)



Electroweakinos
(EPJC 79 (2019) 5, 395, & 83 (2023) 6, 493)

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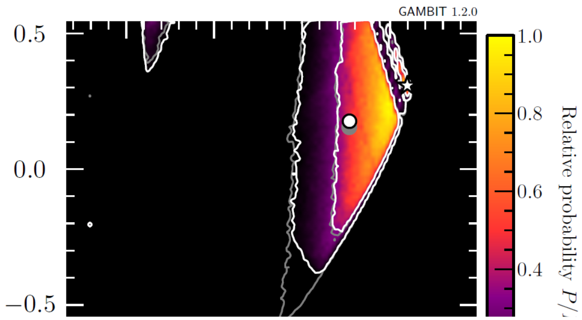
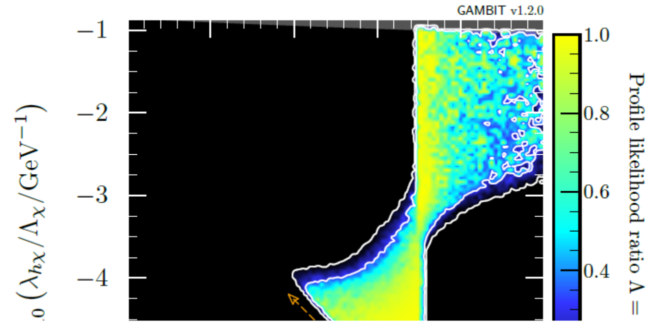
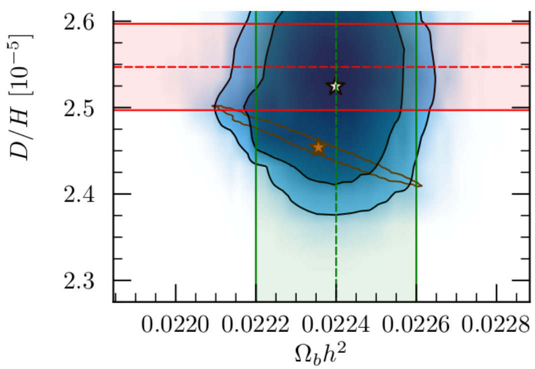
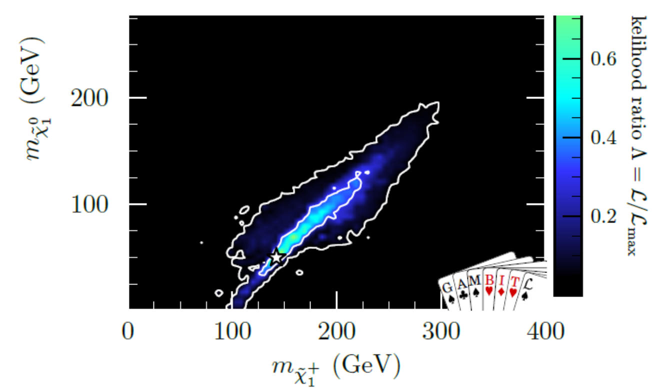




Here I will focus on the CMSSM and other SUSY models as an example of er the impact the CEPC can have.





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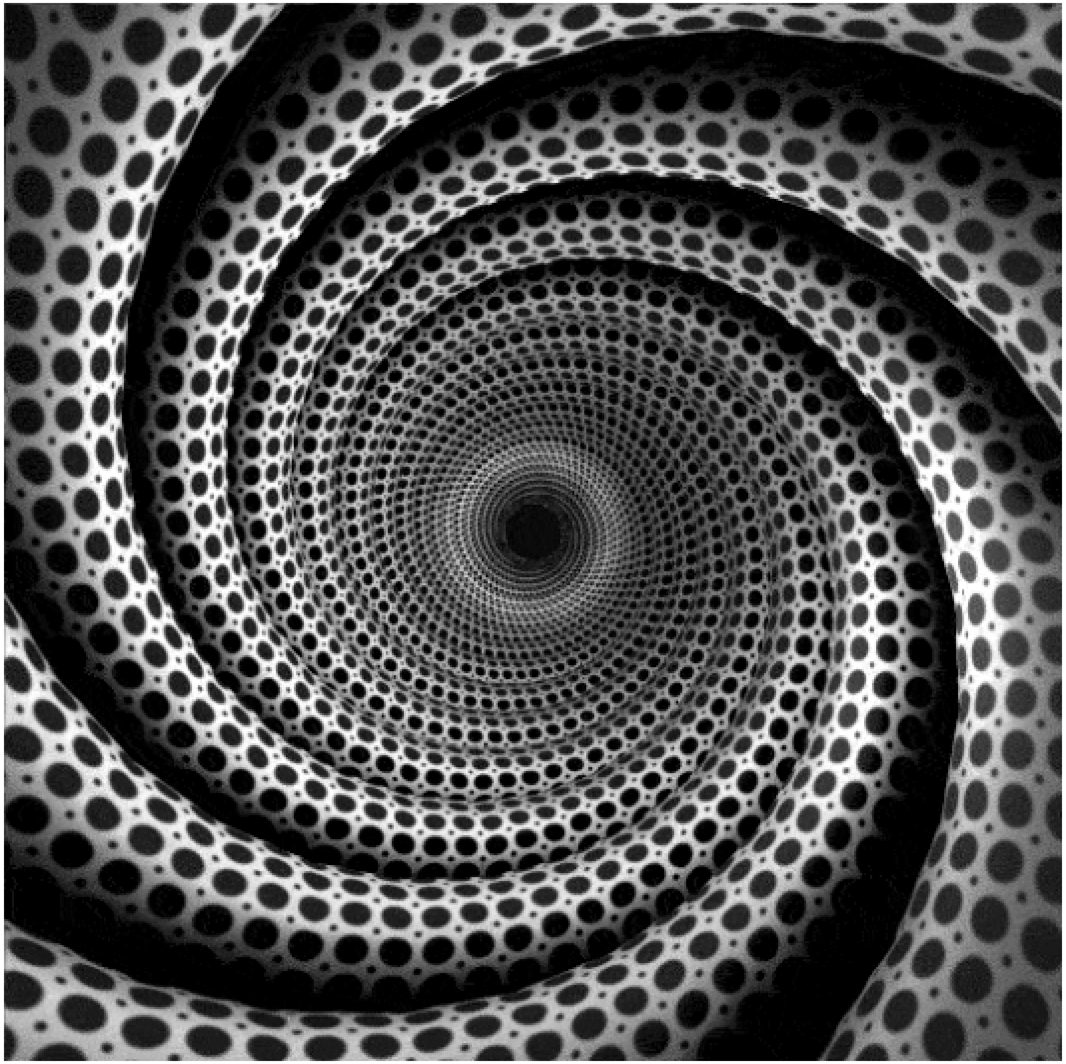
Back in time to 2017



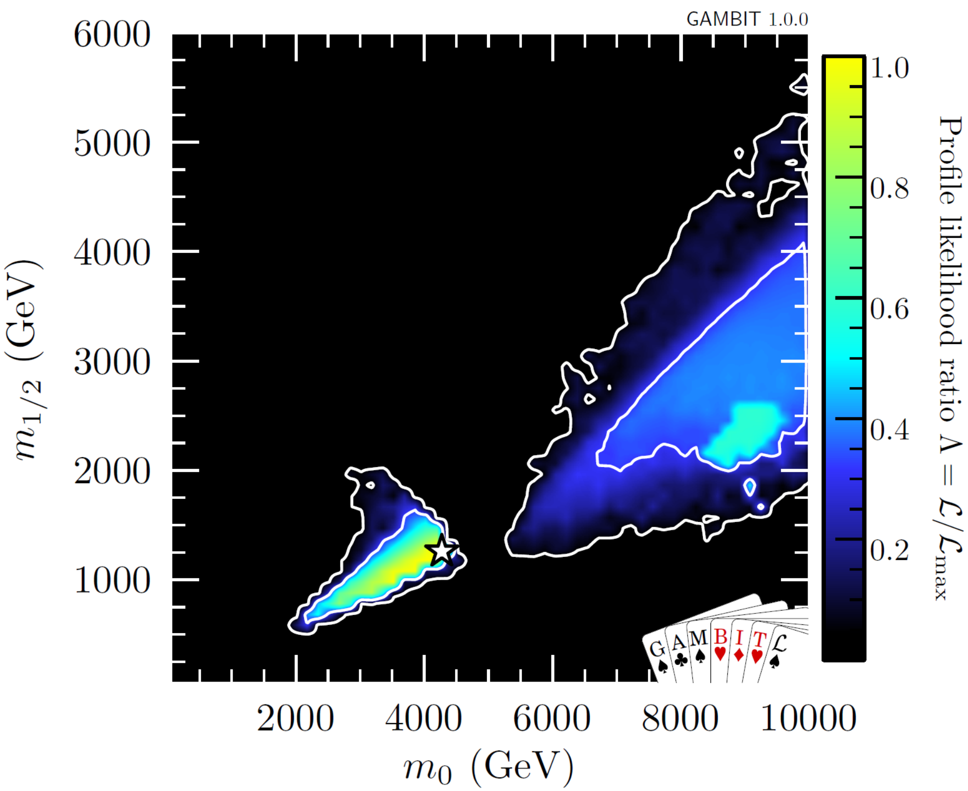
Most recent CMSSM global fit

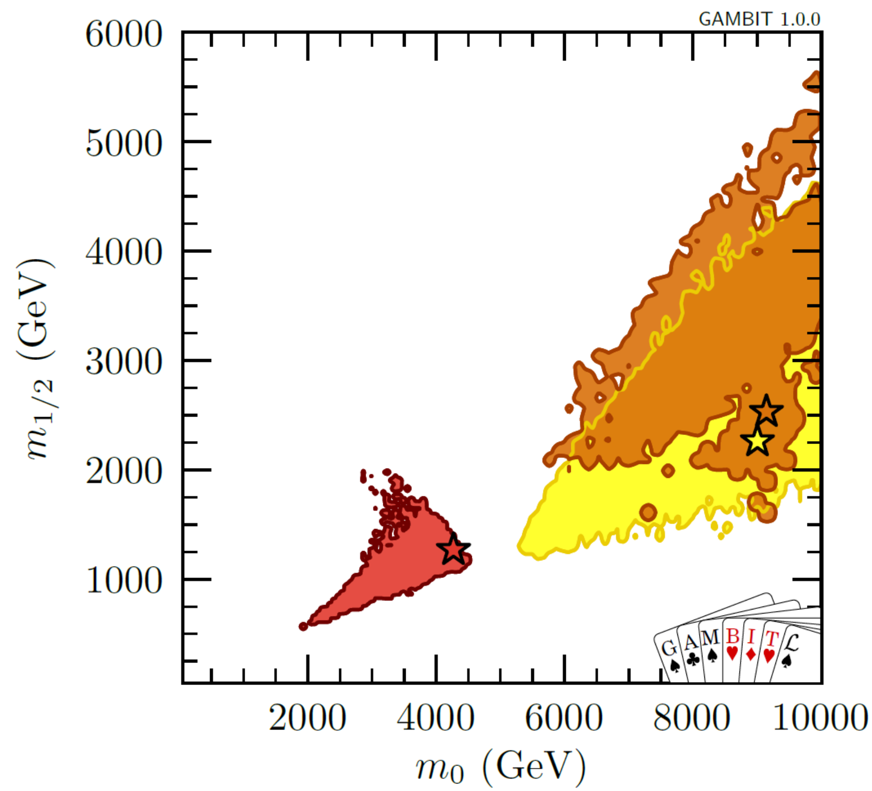
[GAMBIT collaboration, Eur.Phys.J.C 77 (2017) 12, 824]

CMSSM Global Fit

Scan: $m_0, m_{1/2}, A_0, \tan\beta, \mathrm{sign}(\mu)$ + 5 nuisances inc. α_s, m_t

- CMSSM can fit all the data* but it is just pushed to high masses.
- Significant stop co-annihilation region (red) surviving
- Heavy chargino (yellow) and A-funnel (brown) regions with sfermions and gauginos out of reach of the LHC

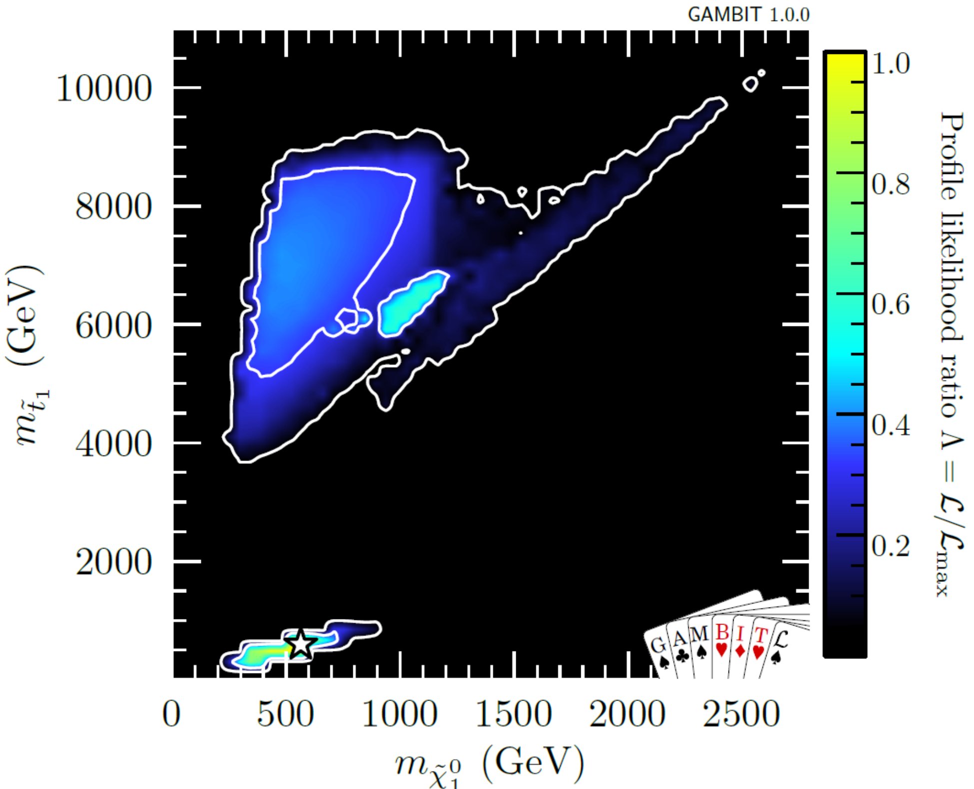


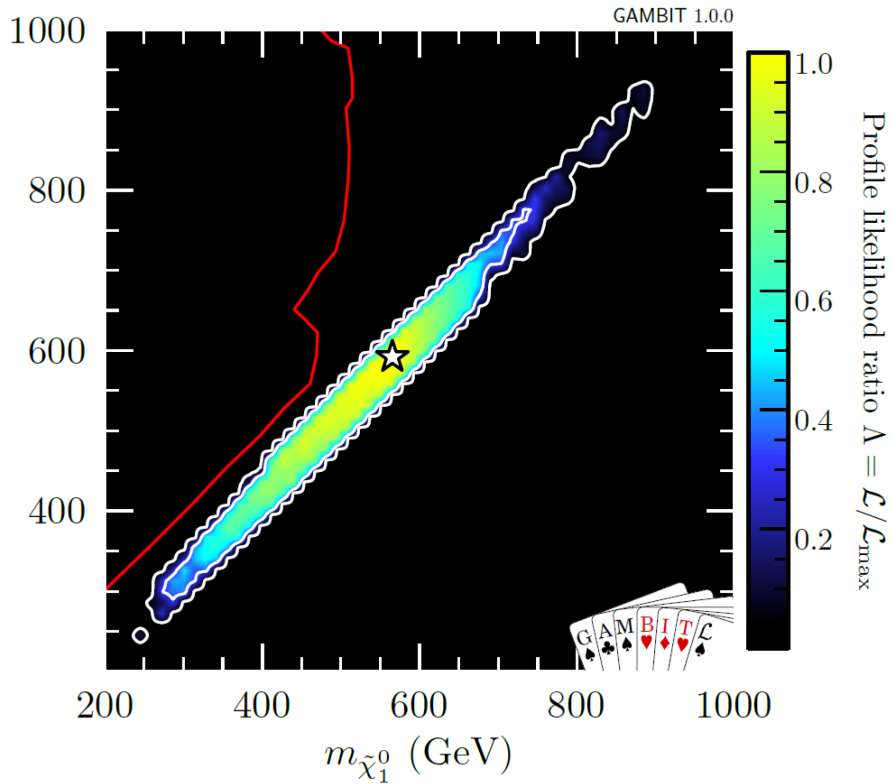


* Doesn't include SM deviations in muon g-2, flavour etc

Masses

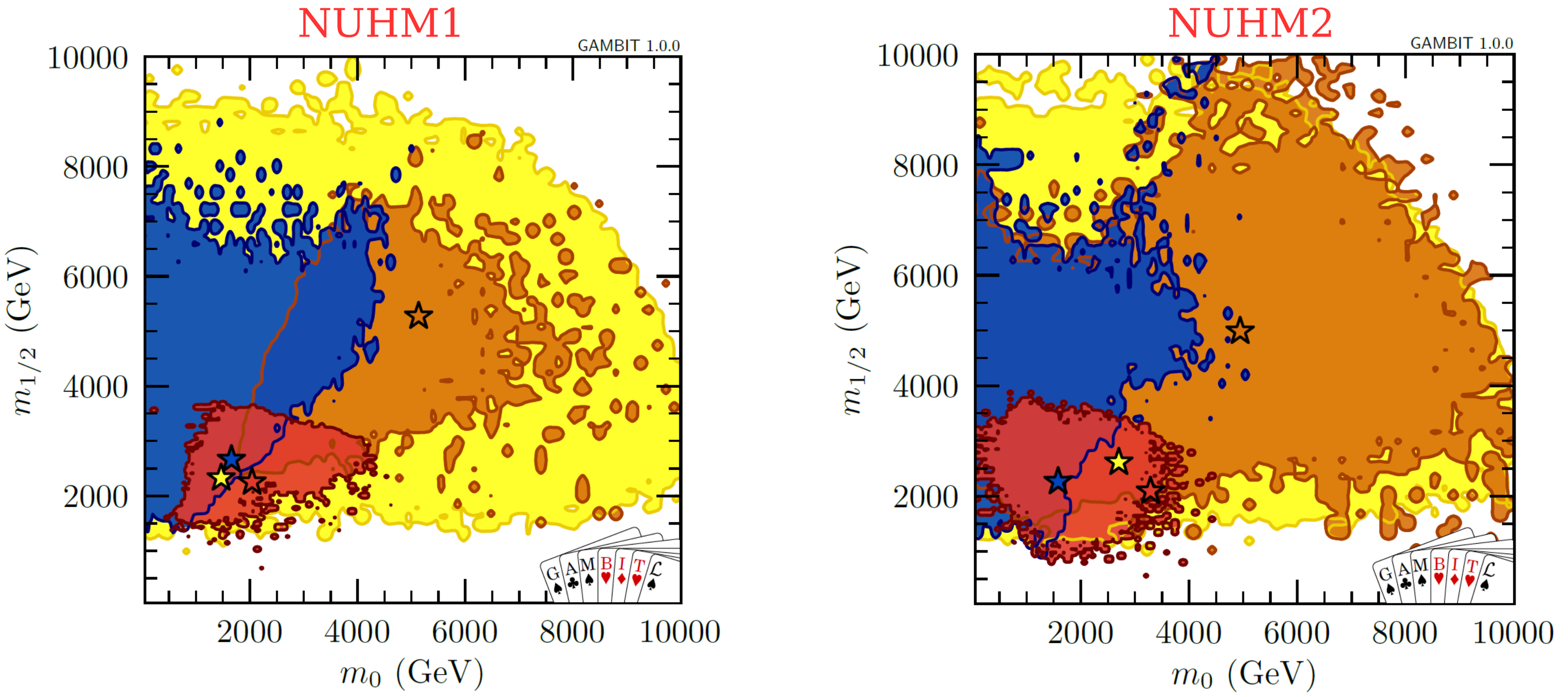
- Masses should be very heavy except in stop co-annihilation region
- Could be under threat by more recent compressed spectra searches - red line indicates 2017 limits from CMS compressed spectra
- Vacuum stability checks also important here



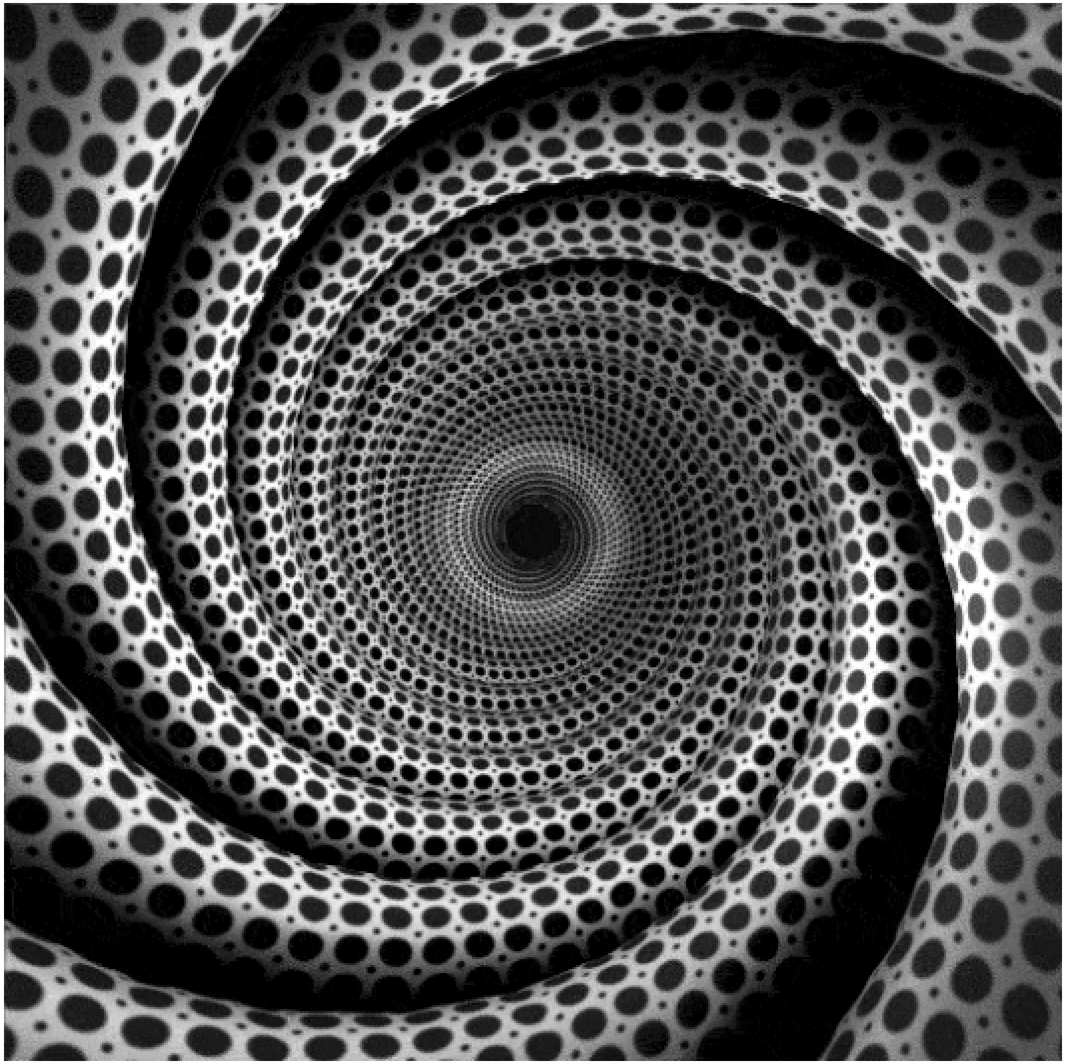


NUHM Global Fits

- Relaxing constraints gives more room for light SUSY states - lighter $1^{st}/2^{nd}$ generations sfermions without stop co-annihilation
- More mechanism for depleting the relic density - Stau co-annihilation region re-emerges
- All our fits here allow underabundent dark matter, allowing sub TeV Higgsino LSPs (but we can fit the relic density in all models)



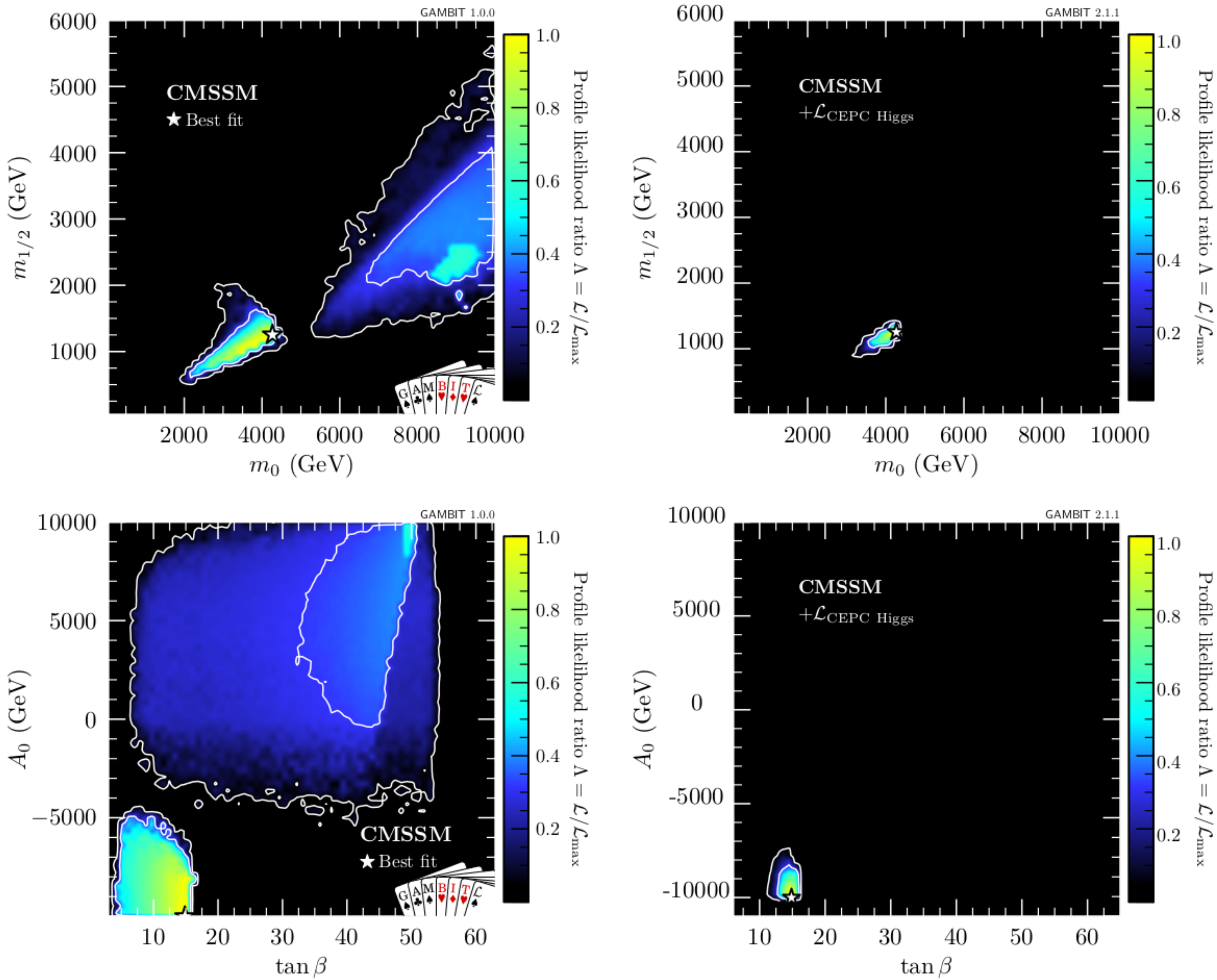
Forward in time to 20XX



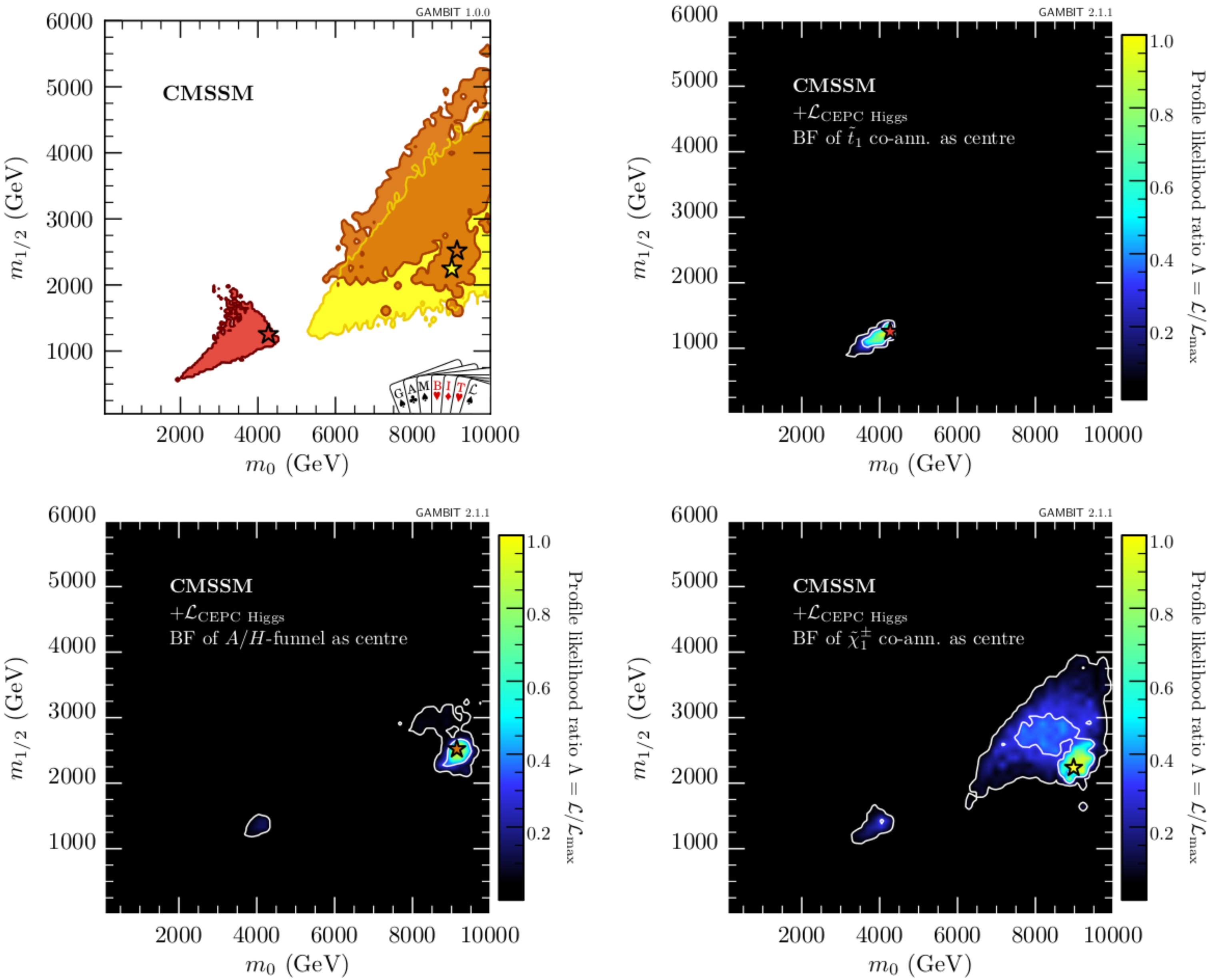
First SUSY global fit with CEPC data

[PA, Csaba Balazs, Andrew Fowlie, Huifang Lv, Wei Su, Lei Wu, Jin Min Yang, Yang Zhang, Phys.Rev.D 105 (2022) 11, 115029]

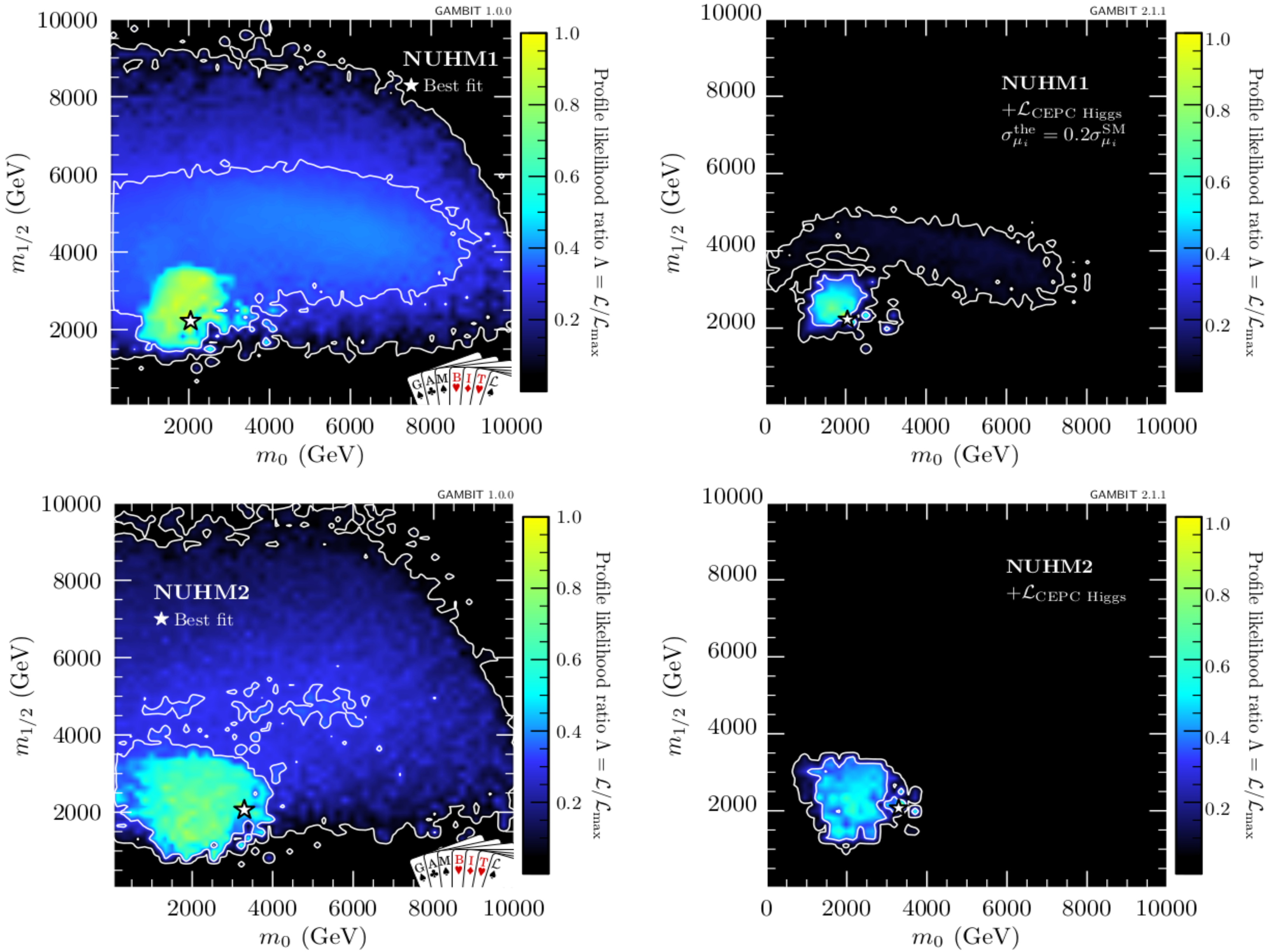
If the best fit CMSSM point stays the same,
a remarkable reduction in parameter space is possible!



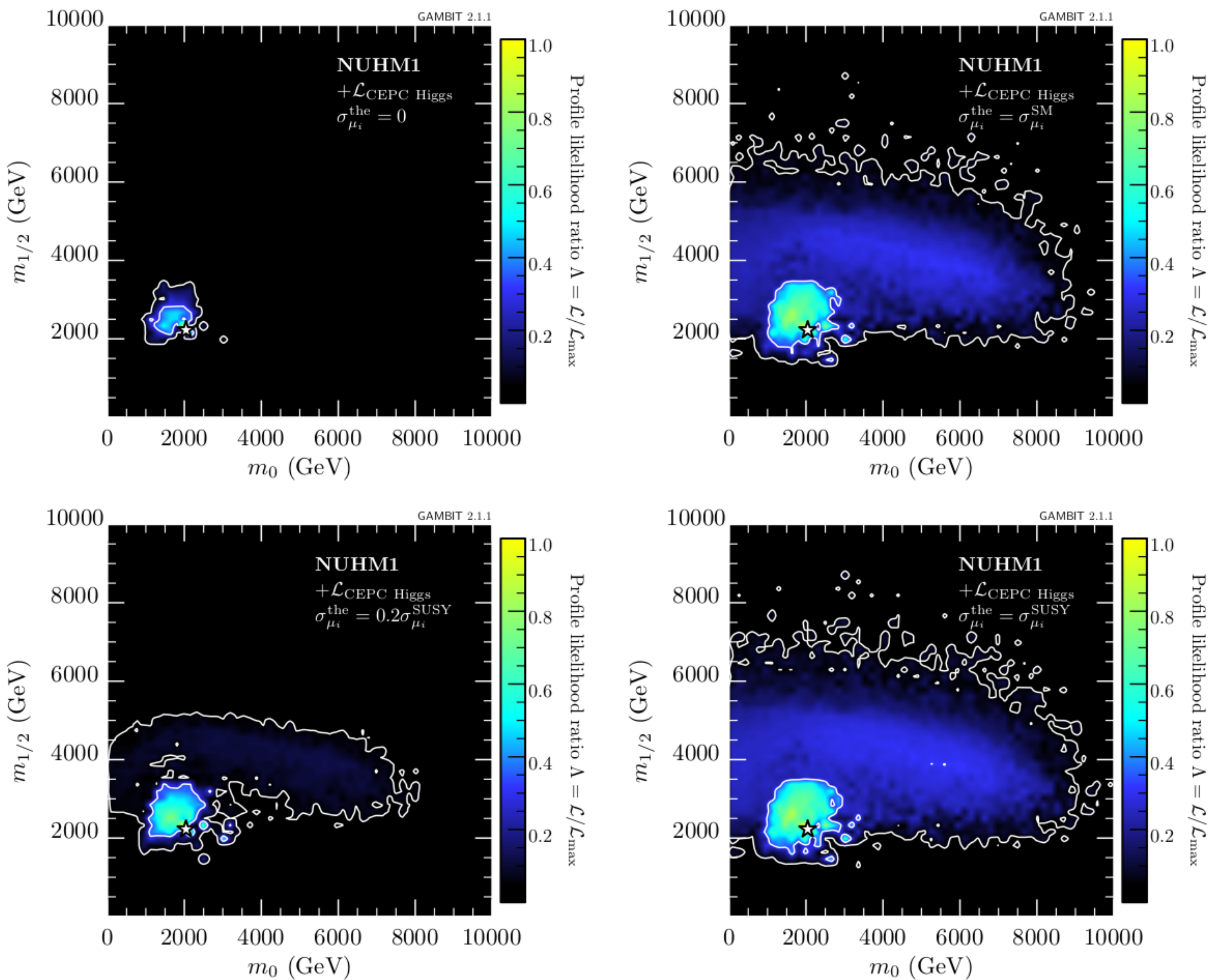
We also see a large reduction in the parameter space for the best fit point in specific sub-regions



And we see a similar impact in NUHM models



Warning: this reduction in parameter space depends crucially on the theory uncertainty in the Higgs couplings!



Needs significant progress on SM and BSM calculations of Higgs BRs

Current situation for BSM decay codes:

CMSSM Predictions for particular benchmark

channel	SUSY-HIT	SOFTSUSY	SARAH/SPheno (DECAY)	SARAH/SPheno (DECAY1L)	FlexibleDecay
$h \to b\bar{b}$	2.662	3.843	2.403	1.541	2.348
$h \to W^+W^-$	$8.342 \cdot 10^{-1}$	$6.751 \cdot 10^{-1}$	$5.887 \cdot 10^{-1}$	—	$8.141 \cdot 10^{-1}$
$h \to \tau\bar{\tau}$	$2.595 \cdot 10^{-1}$	$2.726 \cdot 10^{-1}$	$2.778 \cdot 10^{-1}$	$2.355 \cdot 10^{-1}$	$2.499 \cdot 10^{-1}$
$h \to c\bar{c}$	$1.183 \cdot 10^{-1}$	$2.235 \cdot 10^{-1}$	$1.031 \cdot 10^{-1}$	$1.073 \cdot 10^{-1}$	$1.160 \cdot 10^{-1}$
$h \to ZZ$	$1.060 \cdot 10^{-1}$	$7.606 \cdot 10^{-2}$	$5.882 \cdot 10^{-2}$	—	$1.032 \cdot 10^{-1}$
$h \to gg$	$2.731 \cdot 10^{-1}$	$2.760 \cdot 10^{-1}$	$2.993 \cdot 10^{-1}$	$9.555 \cdot 10^{-2}$	$3.434 \cdot 10^{-1}$
$h \to \gamma\gamma$	$9.439 \cdot 10^{-3}$	$1.052 \cdot 10^{-2}$	$8.580 \cdot 10^{-3}$	$1.024 \cdot 10^{-2}$	$9.940 \cdot 10^{-3}$
$h \to Z\gamma$	$6.316 \cdot 10^{-3}$	$6.779 \cdot 10^{-3}$	—	$4.303 \cdot 10^{-1}$	$6.098 \cdot 10^{-3}$
total width	4.272	5.386	3.741	—	3.993

Table 5.4: Comparison of Higgs boson decay widths in the MSSM as calculated by FlexibleDecay, HDECAY via SUSY-HIT, SOFTSUSY and SARAH/SPheno (for CMSSM SPS1a slope with $m_0 = 1.4$ TeV). All widths in MeV.

[FlexibleDecay manual, PA, A. Buechner, D. Harries, W. Kotlarski, D. Stoeckinger and A. Voigt]

Plenty of room for improvement!

But a very long way to go...

See detailed discussion in A. Arbey, M. Battaglia, A. Djouadi, F. Mahmoudi, M. Muhlleitner, M. Spira, Phys. Rev. D 106, 055002 (2022) for what is needed

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- We similar effects in less constrained versions NUHM1/2 & MSSM7
- However low BSM theory uncertainty is vital for achieving this!
- Precision Higgs decay calculations are very important.
- CEPC could shed light on SUSY or other extensions of the SM through Higgs couplings

謝謝！

BACK UP SLIDES

If we want to have this impact in any BSM extension

Need to focus on the precision on the codes that can apply to arbitrary models: SARAH/SPHENO and FlexibleSUSY/FlexibleDecay

2HDM

channel	2HDECAY	SARAH/SPheno (DECAY)	SARAH/SPheno (DECAY1L)	FlexibleDecay
$h \to b\bar{b}$	2.237	2.110	1.759	2.121
$h \to W^+W^-$	$8.889 \cdot 10^{-1}$	$8.321 \cdot 10^{-1}$	—	$8.504 \cdot 10^{-1}$
$h \to \tau\bar{\tau}$	$2.406 \cdot 10^{-1}$	$2.445 \cdot 10^{-1}$	$2.483 \cdot 10^{-1}$	$2.256 \cdot 10^{-1}$
$h \to c\bar{c}$	$1.210 \cdot 10^{-1}$	$1.014 \cdot 10^{-1}$	$8.894 \cdot 10^{-2}$	$1.164 \cdot 10^{-1}$
$h \to ZZ$	$1.114 \cdot 10^{-1}$	$8.124 \cdot 10^{-2}$	—	$1.084 \cdot 10^{-1}$
$h \to gg$	$3.262 \cdot 10^{-1}$	$3.339 \cdot 10^{-1}$	$1.785 \cdot 10^{-1}$	$3.472 \cdot 10^{-1}$
$h \to \gamma\gamma$	$1.005 \cdot 10^{-2}$	$1.049 \cdot 10^{-2}$	$1.572 \cdot 10^{-2}$	$9.130 \cdot 10^{-3}$
$h \to \gamma Z$	$6.814 \cdot 10^{-3}$	—	< 0	$5.961 \cdot 10^{-3}$
total width	3.944	3.715	—	3.786

MRSSM

channel	SARAH/SPheno (DECAY)	SARAH/SPheno (DECAY1L)	FlexibleDecay
$h \to b\bar{b}$	2.460	2.079	2.433
$h \to W^+W^-$	$7.234 \cdot 10^{-1}$	—	$7.856 \cdot 10^{-1}$
$h \to \tau\bar{\tau}$	$2.851 \cdot 10^{-1}$	$2.601 \cdot 10^{-1}$	$2.587 \cdot 10^{-1}$
$h \to c\bar{c}$	$1.046 \cdot 10^{-1}$	$1.273 \cdot 10^{-1}$	$1.158 \cdot 10^{-1}$
$h \to ZZ$	$7.686 \cdot 10^{-2}$	—	$9.987 \cdot 10^{-2}$
$h \to gg$	$3.186 \cdot 10^{-1}$	$1.353 \cdot 10^{-1}$	$3.462 \cdot 10^{-1}$
$h \to \gamma\gamma$	$8.402 \cdot 10^{-3}$	$1.007 \cdot 10^{-2}$	$9.140 \cdot 10^{-3}$
$h \to \gamma Z$	—	$1.671 \cdot 10^{-1}$	$5.588 \cdot 10^{-3}$
total width	3.979	—	4.056

Global Fits of MSSM models

- GAMBIT code is split up into modules or "Bits"
- User chooses backends - many options with GAMBIT 1.0.0 release

For the MSSM global fits here we used:

ScanBit

Scanning via Diver + MultiNest-3.10

DecayBit

Decay BRs and widths via
SUSYHIT-1.5 (HDECAY & SDECAY)

ColliderBit

Native recast tool for SUSY searches
uses Pythia-8.212 + BuckFast
Higgs searches: HiggsBounds-4.3.1,
HiggsSignals-1.4.0

SpecBit

Spectrum via FlexibleSUSY-1.5.1

PrecisionBit

$(g-2)_\mu$ via GM2Calc-1.3.1
Native likelihoods for MW,

FlavBit

Flavour physics observables
(semi-leptonic B decays, b to s
transitions, leptonic decays of B
and D_s mesons) - SuperIso-3.6

DarkBit

Relic Density – microOMEGAs-3.6.9.2
Direct Detection Cross sections – DarkSUSY 5.1.3
DD Likelihoods – DDCalc-1.0.0
Indirect detection – GamLike, nuLike 1.0.4, DarkSUSY 1.5.3

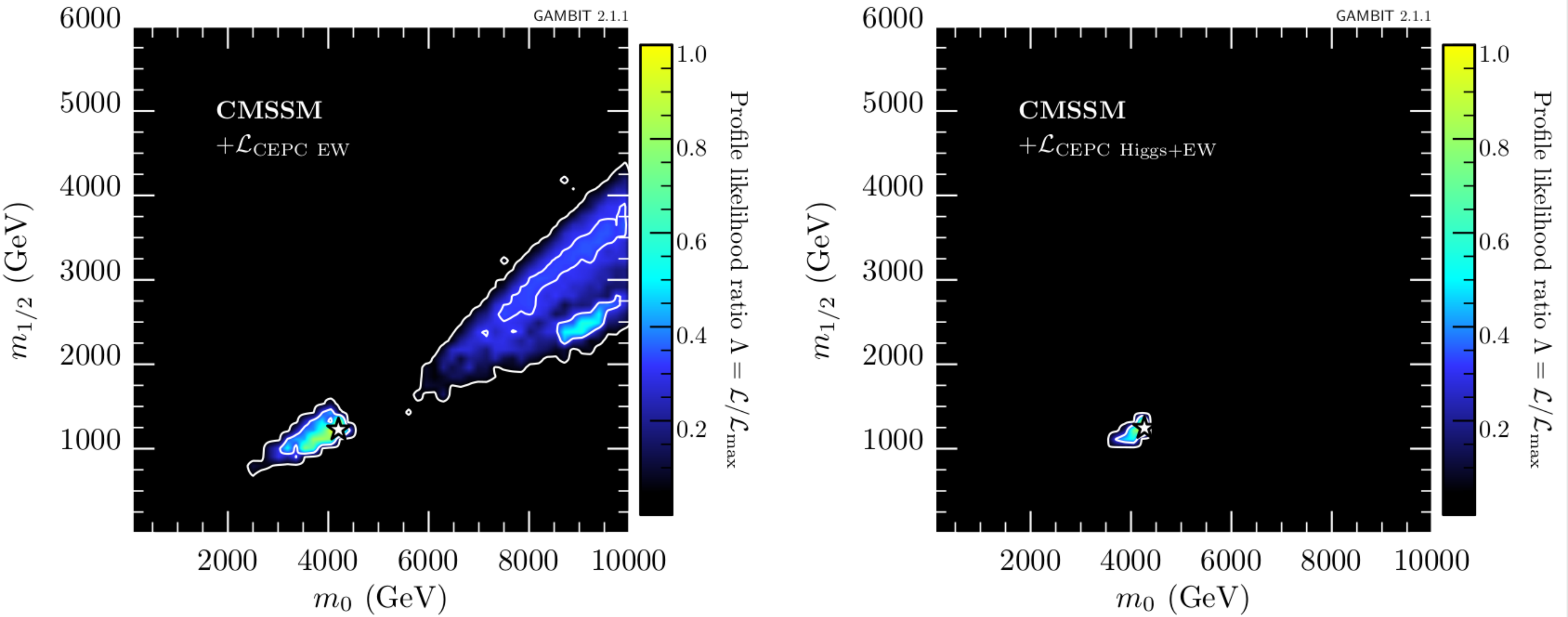
CEPC likelihood: electroweak and Higgs

CEPC likelihoood is included via post processing

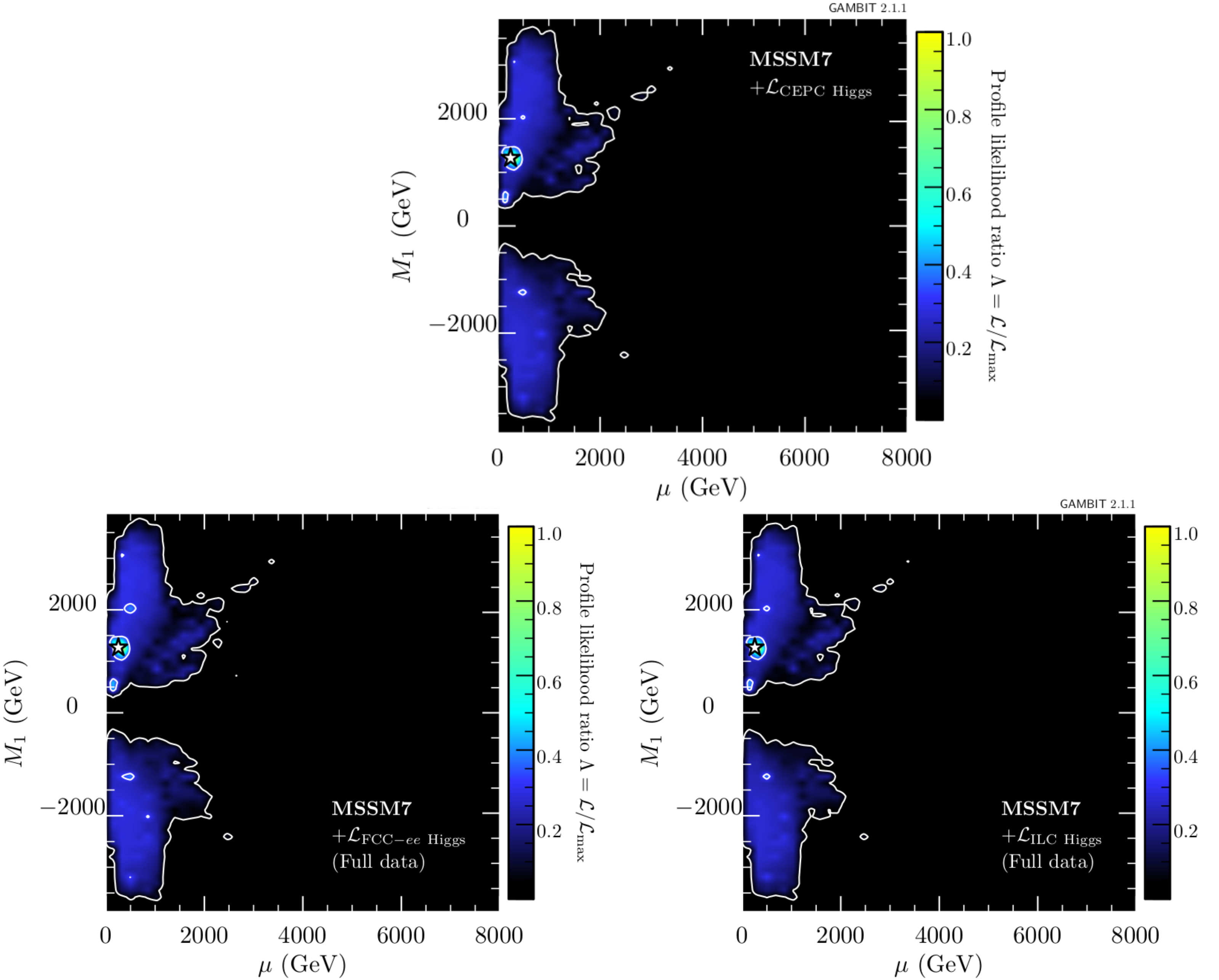
Includes likelihoods for improved measurements of Higgs signals and EW

$$\mathcal{L}_{\text{Total}} = \mathcal{L}^{\text{GAMBIT}}_{2017} \times L^{\text{CEPC}}_{\text{Higgs}} \times L^{\text{CEPC}}_{\text{EW}}$$

The CEPC Higgs measurements are mostly responsible for the drastic reduction in parameter space

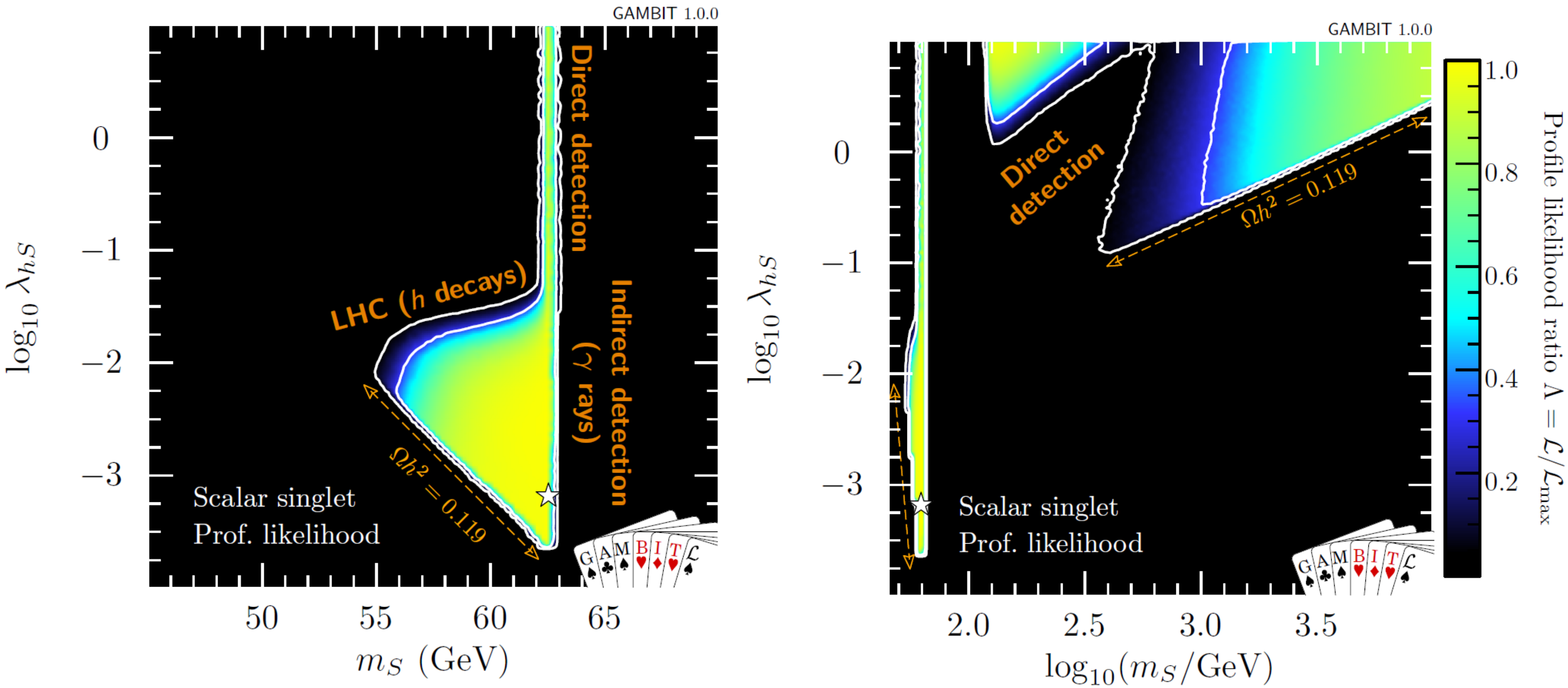


CEPC vs FCC-e and ILC



Scalar Singlet Model and beyond

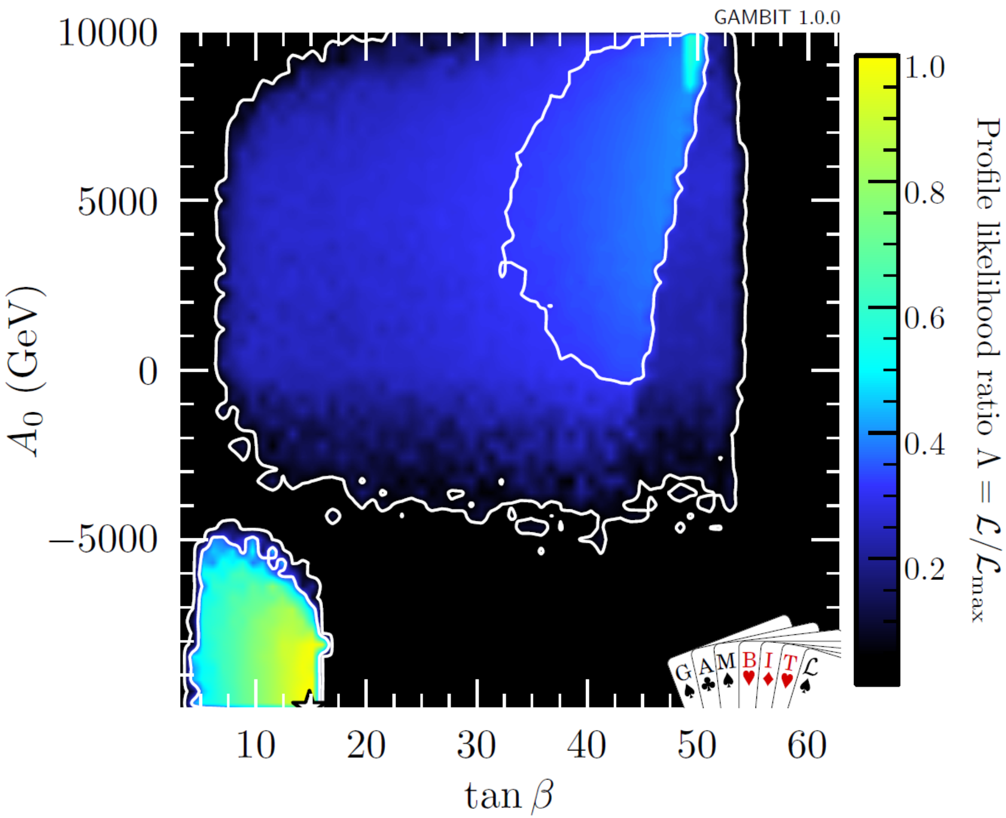
- GAMBIT is not only for minimal SUSY nor just SUSY
- Most thorough and uptodate fit of the scalar singlet model completed and already submitted to EPJC (see plot below)
- Work in progress on two Higgs doublet models, axions, Dirac Fermion Higgs portal DM and many more to come...

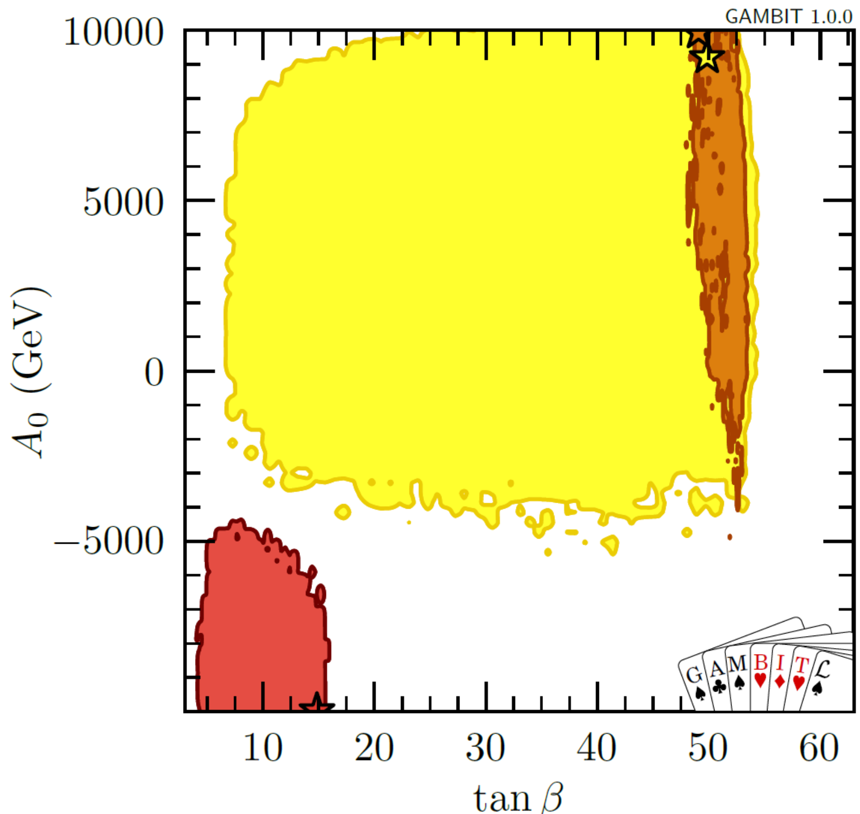


CMSSM Global Fits

Scan: $m_0, m_{1/2}, A_0, \tan\beta, \text{sign}(\mu)$ + 5 nuissances inc. α_s, m_t

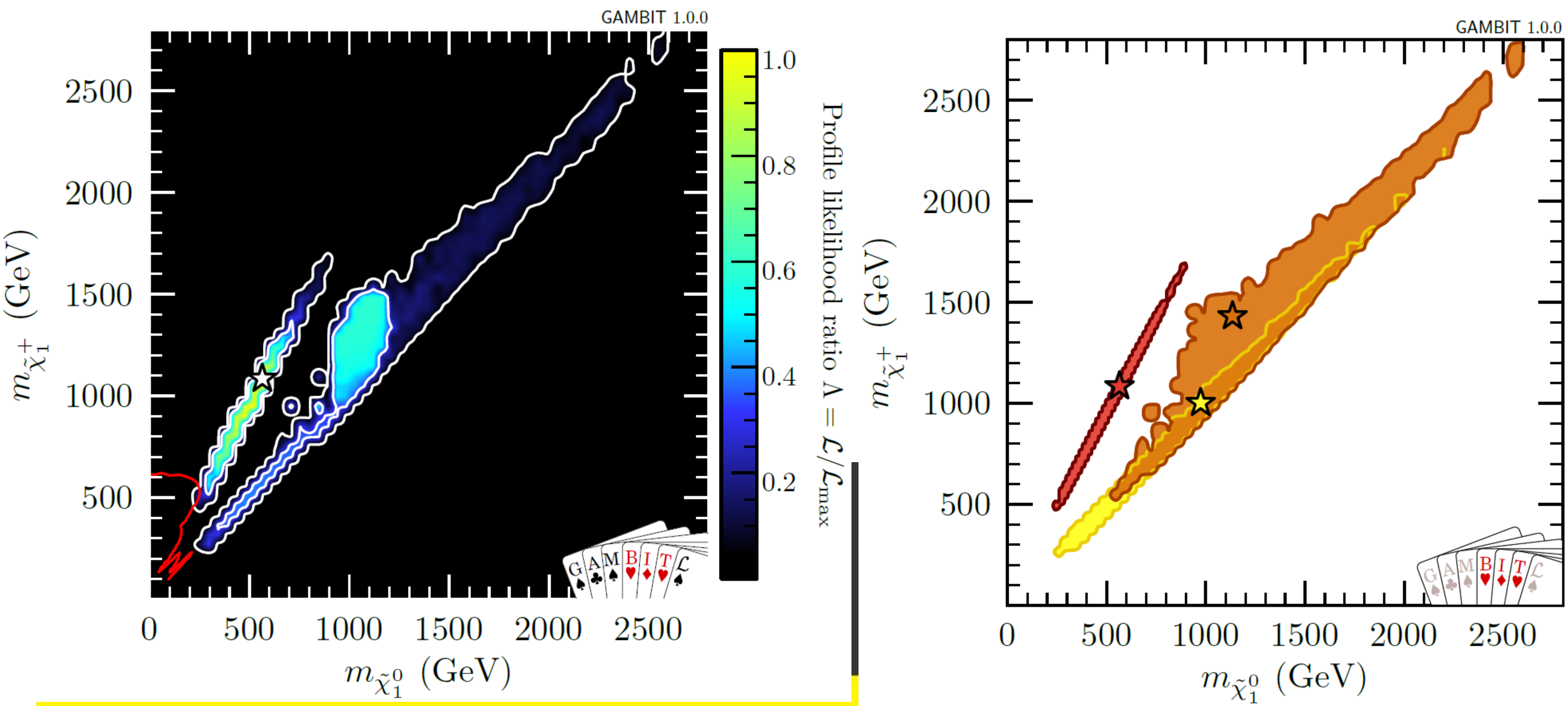
- A-funnel region at very large than beta where b-physics measurements can have an impact
- Stop co-annihilation region restricted to large negative universal trilinear and low tan beta





Electroweakinos

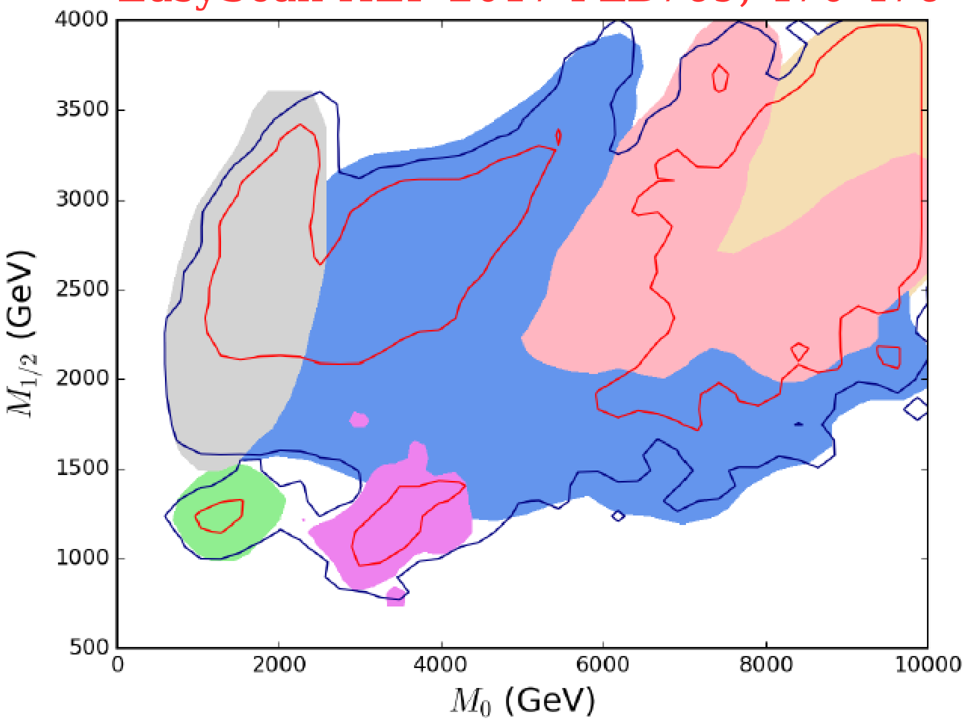
- Don't penalise under abundant relic density → Light Higgsinos
- Mass difference always small → Challenging to detect
- For stop co-annihilation lightest charged wino almost in range

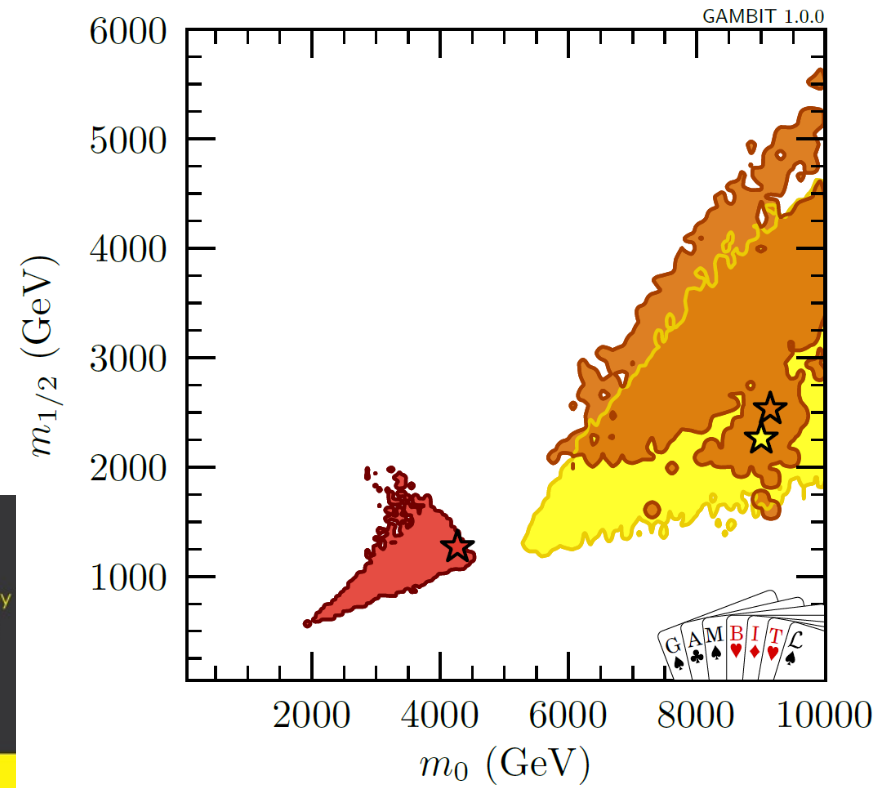


CMSSM Global Fits

- EasyScan HEP also saw the stau co-annihilation region shrink with LHC run II, but not does not disappear (green)
- Also see stop co-annihilatioon region (purple, c.f. red on right pnel)
- Heavy hybrid stau-co-annihilation / A-funnel (grey). GAMBIT finds better Higgs signals fit at high mass suppressing this.
- Lighter A-funnel region (blue, c.f. brown on right panel)

EasyScan HEP 2017 PLB769, 470-476

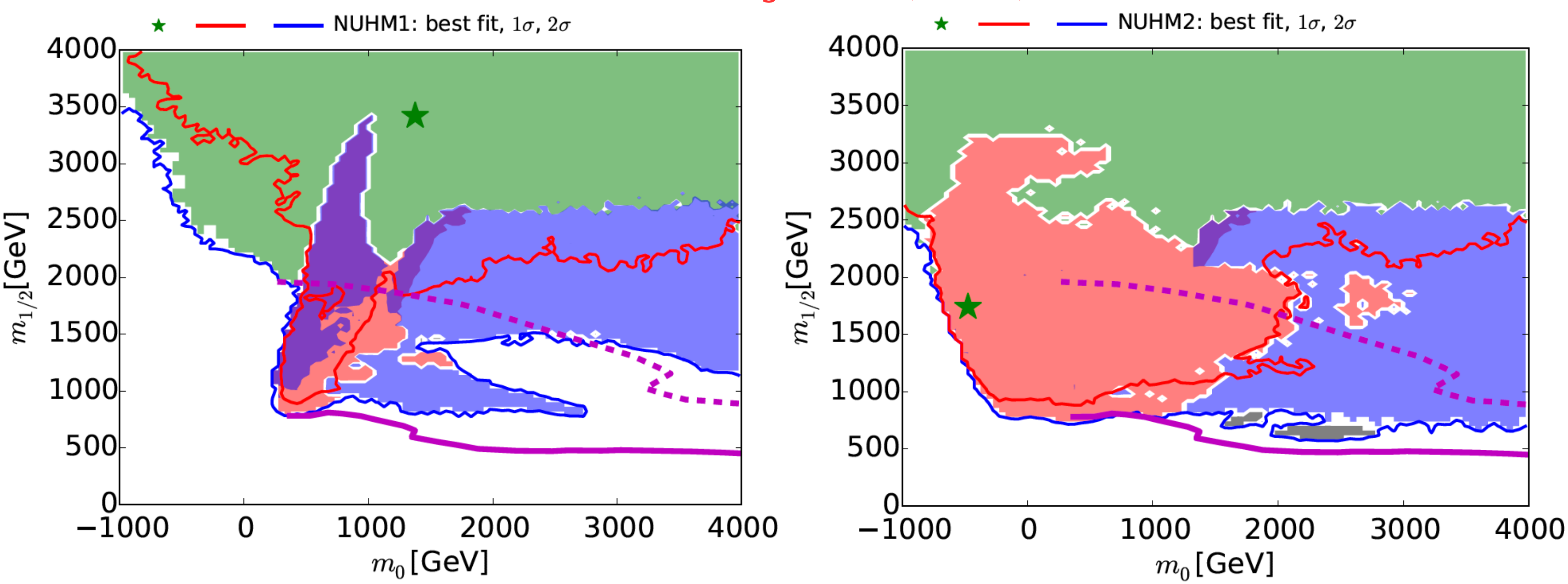




NUHM Global Fits

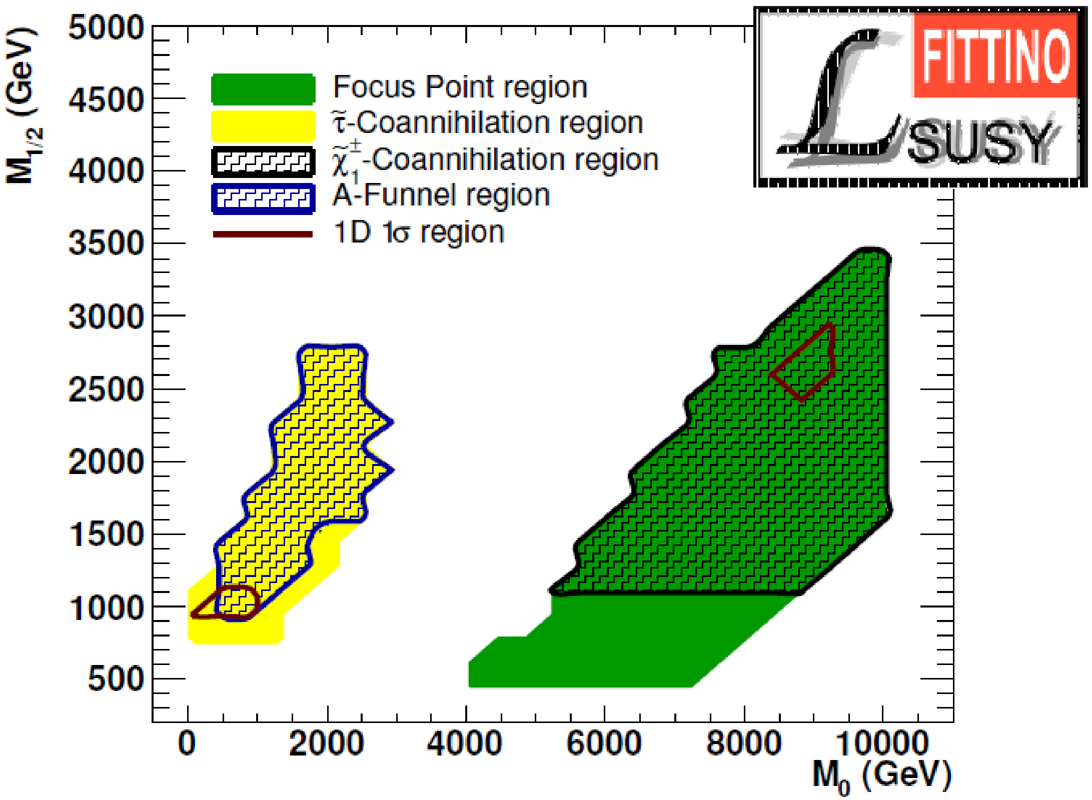
- Mastercode results using LHC run I and LUX 2013
- Mastercode found stau co-annihilation (pink and purple) expand in NUHM2. GAMBIT already saw large expansion in NUHM1.
- GAMBIT has no gap at low m0. Consequence of allowing under-abundant relic density of DM.
- Matercode see no stop co-annihilation, due to smaller range of A0 considered.

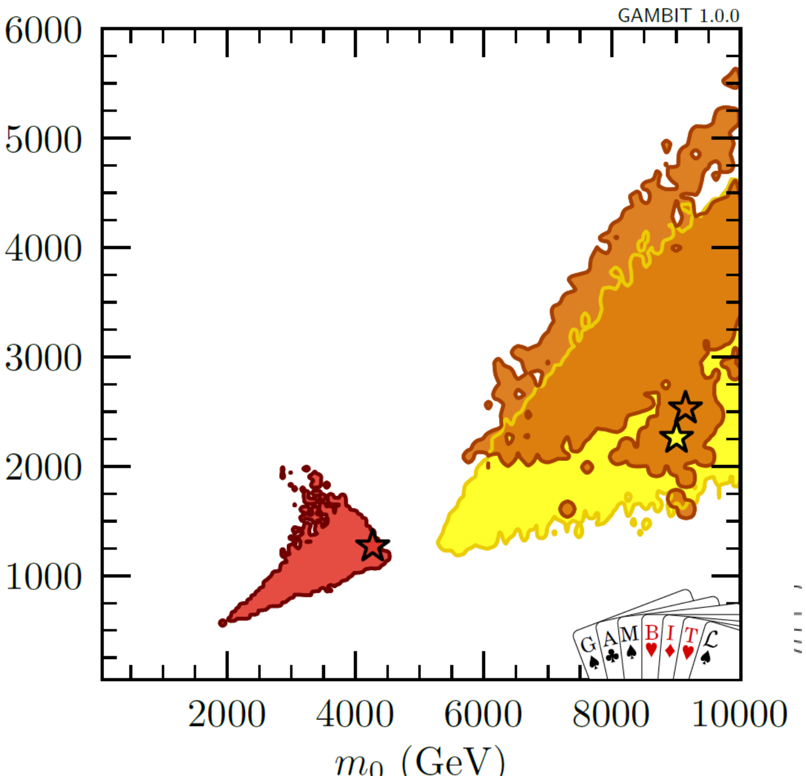
Mastercode: EPJC 75, (2015) 500



CMSSM Global Fits

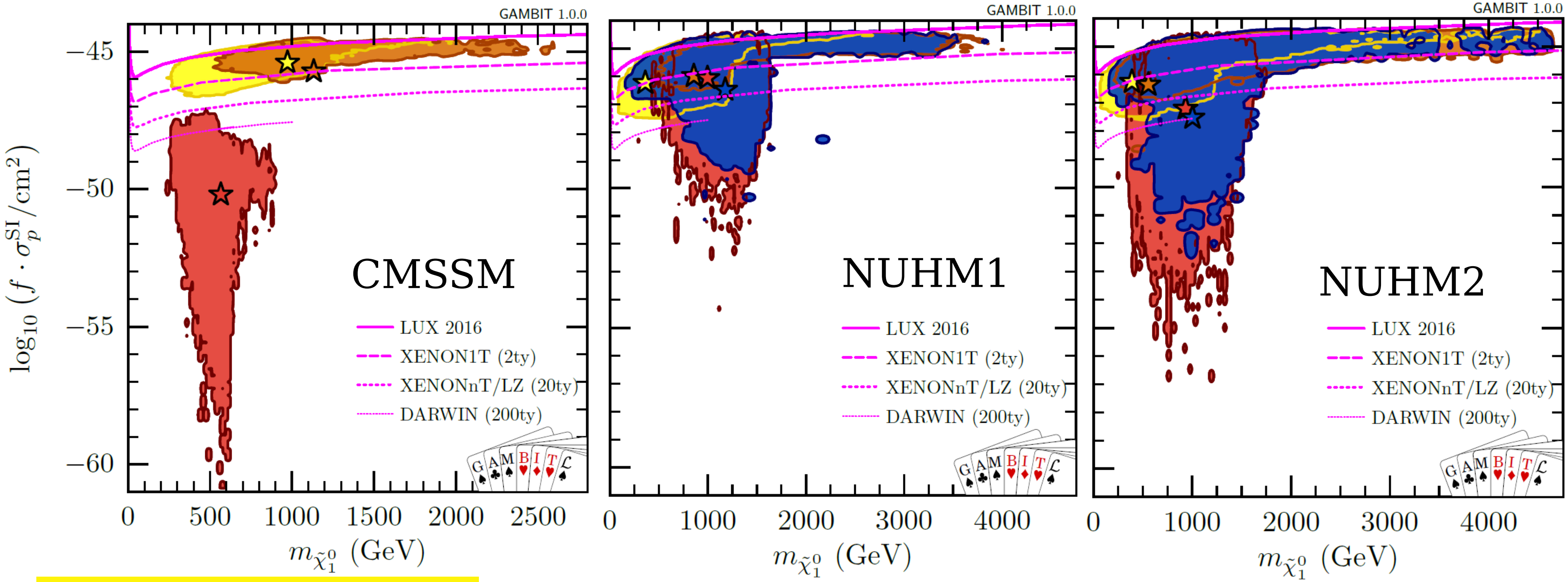
- Fittino with LHC run 1 and LUX 2013
- Large stau co-annihilation strip at lighter masses overlapping with A-funnel
- Heavier chargino co-annihilation region (c.f. yellow on right panel)





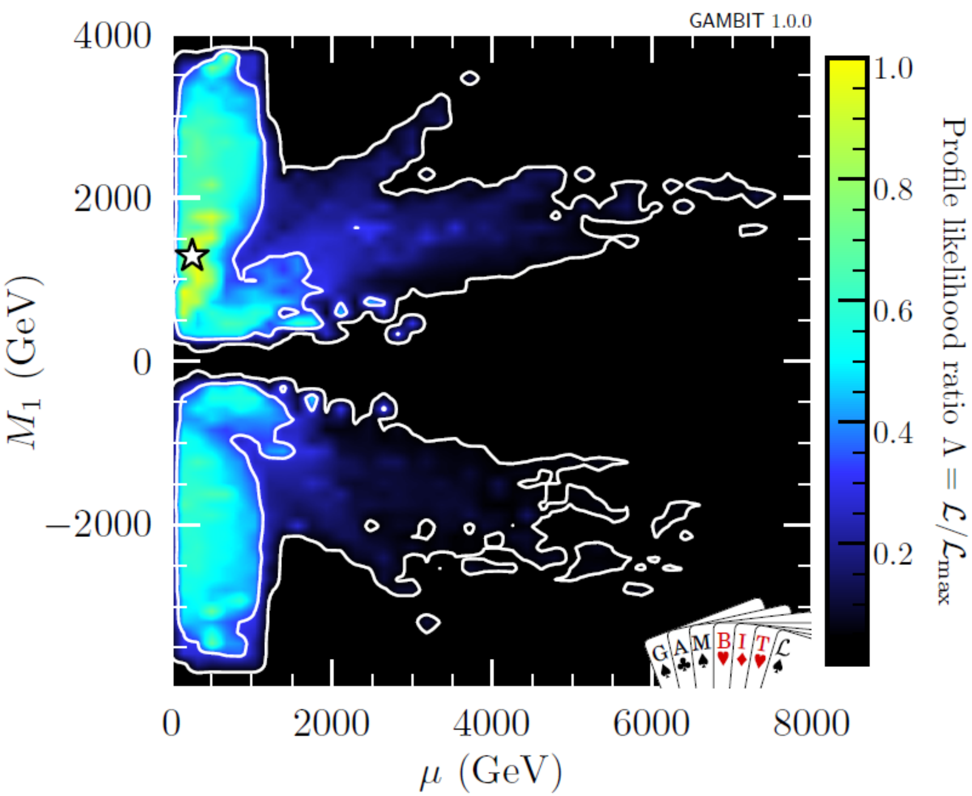
Direct Detection of Dark Matter

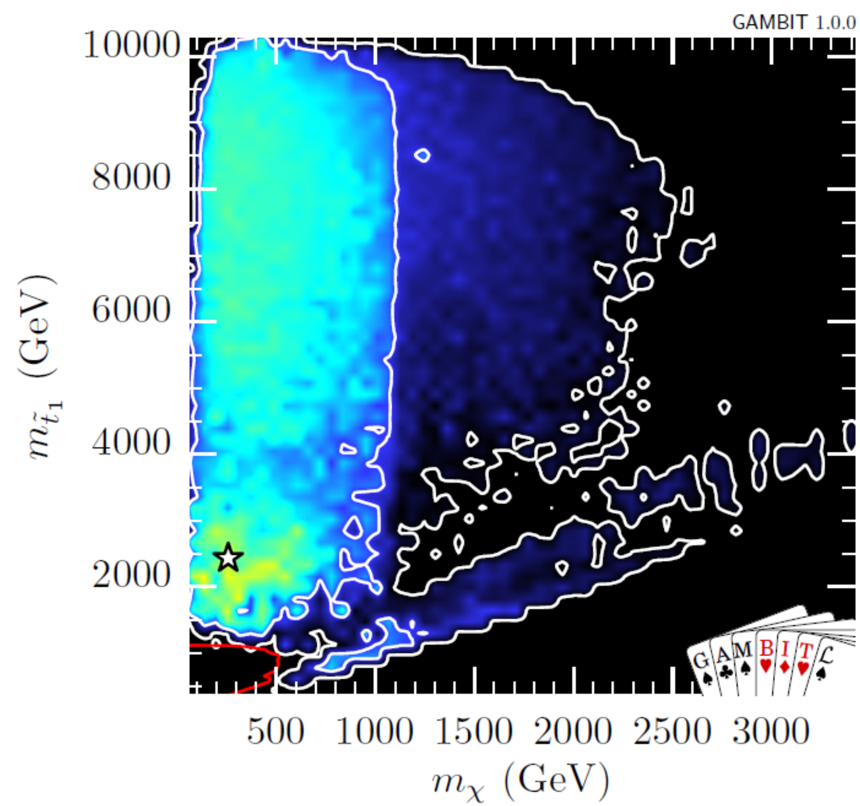
- Xenon1T, nT and LZ will test the entire CMSSM chargino co-annihilation region
- Stop co-annihilation and stau co-annihilation can be well out reach
- Prospects for discovering sfermion co-annihilation in the NUHM models better, but still have many scenarios out of reach
- Collider searches can probe some of the sfermion co-annihilation region so there is complementarity Very challenging to probe the entire region though.



MSSM7 Global Fits

- SUSY scale MSSM can also have lighter spectra including
- We found Higgsino DM $\mu \ll M_1$, bino like DM $\mu \gg M_1$ and well tempered DM $\mu \approx M_1$
- Stop co-annihilation region is also present here.





CMSSM Global Fits

- Mastercode with LHC run 1 and LUX 2013
- stau co-annihilation strip (pink and purple) at lighter masses.
- Extensive A-funnel region with (blue, c.f. brown region on right panel)
- Focus point at large m0 (light blue, c.f. yellow region on right panel)