New Physics Interpretations with GAMBIT

Peter Athron
On behalf of the GAMBIT collaboration

Why Global Fits?

Realistic BSM models have:

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

To understand the impact of BSM searches we need to:

1) Combine experimental results (needs rigorous statistics)
2) Explore the full parameter space (intelligent scanning algorithms)
3) Project onto planes of interest (marginalise / profile)

→ Global Fits

→ GAMBIT

GAMBIT: The Global And Modular BSM Inference Tool

gambit.hepforge.org EPJC **77** (2017) 784 arXiv:1705.07908

- 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

- Fast definition of new datasets and theories
- Plug and play scanning, physics and likelihood packages

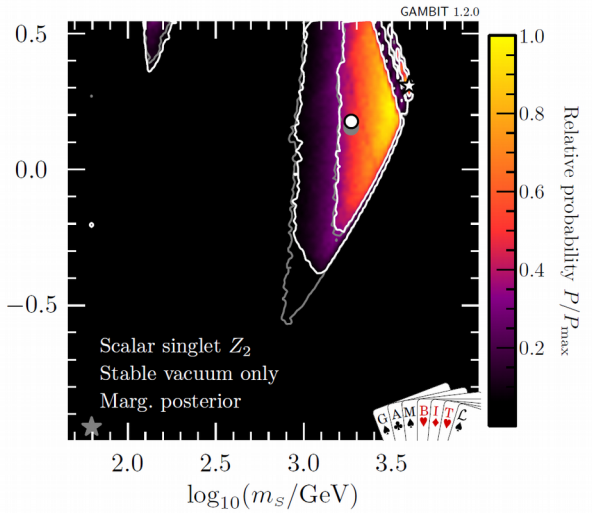
Members of:
ATLAS, Belle-II, CLiC, CMS, CTA, *Fermi*-LAT, DARWIN, IceCube, LHCb, SHiP, XENON

Authors of:
DarkSUSY, DDCalc, Diver, FlexibleSUSY, gamlike, GM2Calc, IsaTols, nulike, PolyChord, Rivet, SoftSUSY, SuperISO, SUSY-AI, WIMPSim

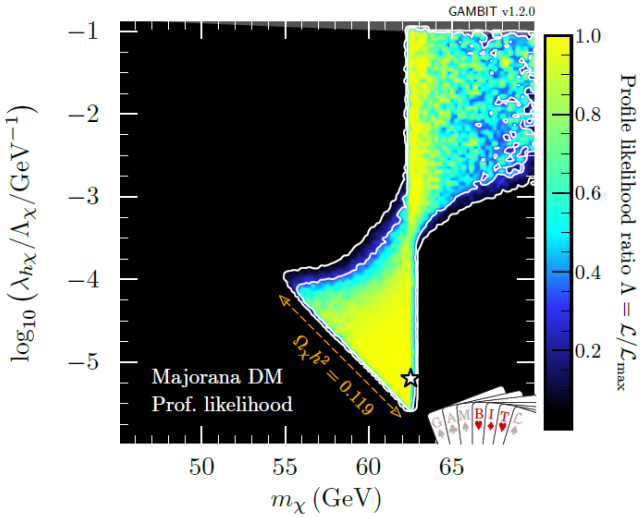
Recent collaborators:
Peter Athron, Csaba Balázs, Ankit Beniwal, Sanjay Bloor, Torsten Bringmann, Andy Buckley, José Eliel Camargo-Molina, Marcin Chrząszcz, Jonathan Cornell, Matthias Danninger, Joakim Edsjö, Ben Farmer, Andrew Fowlie, Tomás E. Gonzalo, Will Handley, Sebastian Hoof, Selim Hotinli, Felix Kahlhoefer, Anders Kvellestad, Julia Harz, Paul Jackson, Farvah Mahmoudi, Greg Martinez, Are Raklev, Janina Renk, Chris Rogan, Roberto Ruiz de Austri, Pat Scott, Patrick Stöcker, Aaron Vincent, Christoph Weniger, Martin White, Yang Zhang

40+ participants in 11 experiments and 14 major theory codes

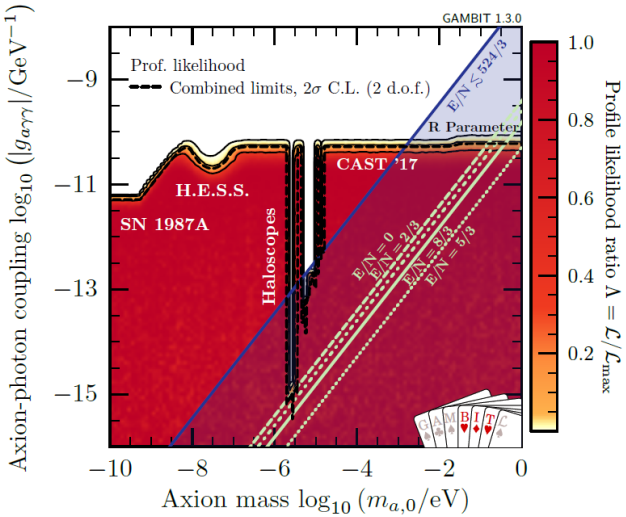
Recent GAMBIT global fits



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



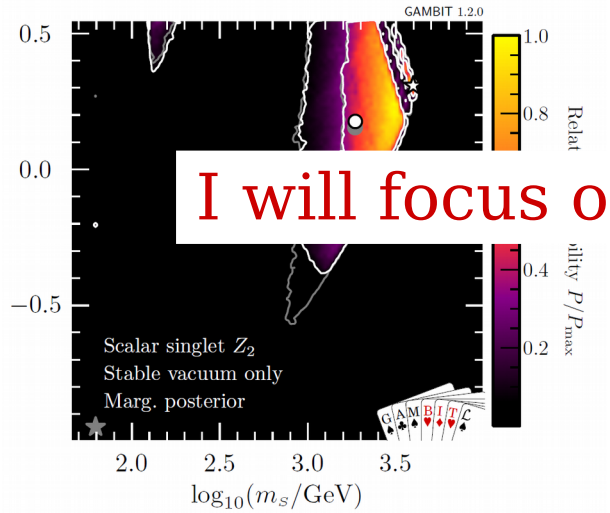
Fermion and vector Higgs portal dark matter
(EPJC 79 (2019) 38)



Axion like particles
(JHEP 03 (2019) 191)

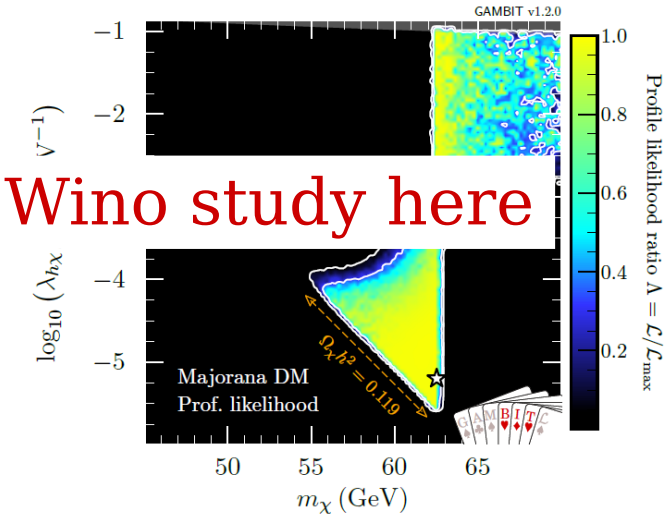
See talk by Ankit Beniwal
Today @ 17:20 DM session

Recent GAMBIT global fits

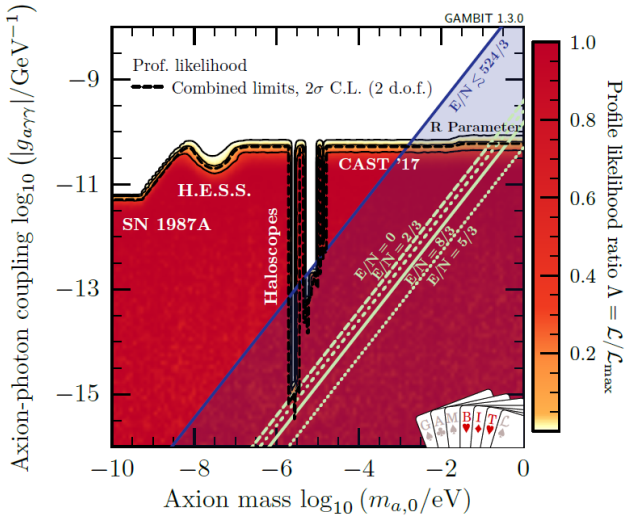


Scalar singlet dark matter
(EPJC 78 (2018) 830)

I will focus on the EWino study here



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



Axion like particles
(JHEP 03 (2019) 191)

?

EWinos
(EPJC 79 (2019) 395)

EWino model

Generic name	Spin	R-parity	Gauge Eigenstates	Mass Eigenstates
Higgs bosons	0	+1	$H_u^0 \; H_d^0 \; H_u^+ \; H_d^-$	$h^0 \; H^0 \; A^0 \; H^\pm$
squarks	0	−1	$\widetilde{u}_L \; \widetilde{u}_R \; \widetilde{d}_L \; \widetilde{d}_R$	(same)
			$\widetilde{s}_L \; \widetilde{s}_R \; \widetilde{c}_L \; \widetilde{c}_R$	(same)
			$\widetilde{t}_L \; \widetilde{t}_R \; \widetilde{b}_L \; \widetilde{b}_R$	$\widetilde{t}_1 \; \widetilde{t}_2 \; \widetilde{b}_1 \; \widetilde{b}_2$
sleptons	0	−1	$\widetilde{e}_L \; \widetilde{e}_R \; \widetilde{\nu}_e$	(same)
			$\widetilde{\mu}_L \; \widetilde{\mu}_R \; \widetilde{\nu}_\mu$	(same)
			$\widetilde{\tau}_L \; \widetilde{\tau}_R \; \widetilde{\nu}_\tau$	$\widetilde{\tau}_1 \; \widetilde{\tau}_2 \; \widetilde{\nu}_\tau$
neutralinos	1/2	−1	$\widetilde{B}^0 \; \widetilde{W}^0 \; \widetilde{H}_u^0 \; \widetilde{H}_d^0$	$\widetilde{\chi}_1^0 \; \widetilde{\chi}_2^0 \; \widetilde{\chi}_3^0 \; \widetilde{\chi}_4^0$
charginos	1/2	−1	$\widetilde{W}^\pm \; \widetilde{H}_u^+ \; \widetilde{H}_d^-$	$\widetilde{\chi}_1^\pm \; \widetilde{\chi}_2^\pm$
gluino	1/2	−1	$\widetilde{g}$	(same)

EWino model

Generic name	Spin	R-parity	Gauge Eigenstates	Mass Eigenstates
Higgs bosons	0	+1	H_u^0 H_d^0 H_u^+ H_d^-	h^0 H^0 A^0 $H^\pm$
			$\widetilde{u}_L$ $\widetilde{u}_R$ $\widetilde{d}_L$ $\widetilde{d}_R$	(same)
squarks	0	−1	$\widetilde{c}_L$ $\widetilde{c}_R$	(same)
			t_L $\widetilde{t}_R$ $\widetilde{b}_L$ $\widetilde{b}_R$	$\widetilde{t}_1$ $\widetilde{t}_2$ $\widetilde{b}_1$ $\widetilde{b}_2$
			$\widetilde{e}_L$ $\widetilde{e}_R$ $\widetilde{\nu}_e$	(same)
sleptons	0	−1	$\widetilde{\mu}_L$ $\widetilde{\mu}_R$ $\widetilde{\nu}_\mu$	(same)
			$\widetilde{\tau}_L$ $\widetilde{\tau}_R$ $\widetilde{\nu}_\tau$	$\widetilde{\tau}_1$ $\widetilde{\tau}_2$ $\widetilde{\nu}_\tau$
neutralinos	1/2	−1	$\widetilde{B}^0$ $\widetilde{W}^0$ $\widetilde{H}_u^0$ $\widetilde{H}_d^0$	$\widetilde{\chi}_1^0$ $\widetilde{\chi}_2^0$ $\widetilde{\chi}_3^0$ $\widetilde{\chi}_4^0$
charginos	1/2	−1	$\widetilde{W}^\pm$ $\widetilde{H}_u^+$ $\widetilde{H}_d^-$	$\widetilde{\chi}_1^\pm$ $\widetilde{\chi}_2^\pm$
gluino	1/2	−1	$\widetilde{g}$	(same)

DECOUPLED

EWino parameters

Neutralinos

$$M_1 \quad M_2 \quad \mu \quad \tan\beta$$

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

$$M_N = \begin{pmatrix} M_1 & 0 & -\frac{1}{2}g' v c_\beta & \frac{1}{2}g' v s_\beta \\ 0 & M_2 & \frac{1}{2}g v c_\beta & -\frac{1}{2}g v s_\beta \\ -\frac{1}{2}g' v c_\beta & \frac{1}{2}g v c_\beta & 0 & -\mu \\ \frac{1}{2}g' v s_\beta & -\frac{1}{2}g v s_\beta & -\mu & 0 \end{pmatrix}$$

Charginos

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

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

Nicked from: Anders Kvellestad

EWino parameters

Neutralinos

$$M_1 \quad M_2 \quad \mu \quad \tan\beta$$

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

$$M_N = \begin{pmatrix} M_1 & 0 & -\frac{1}{2}g' v c_\beta & \frac{1}{2}g' v s_\beta \\ 0 & M_2 & \frac{1}{2}g v c_\beta & -\frac{1}{2}g v s_\beta \\ -\frac{1}{2}g' v c_\beta & \frac{1}{2}g v c_\beta & 0 & -\mu \\ \frac{1}{2}g' v s_\beta & -\frac{1}{2}g v s_\beta & -\mu & 0 \end{pmatrix}$$

M_1 Bino-like neutralino mass

M_2 Wino-like neutralino and chargino masses

μ Higgsino-like neutralino and chargino masses

Charginos

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

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

Nicked from: Anders Kvellestad

Sampling of parameter space

- Scan via Diver 1.0.4 (differential evolution) over parameter ranges:

Parameter	Minimum	Maximum	Priors
$M_1(Q)$	-2 TeV	2 TeV	hybrid, flat
$M_2(Q)$	0 TeV	2 TeV	hybrid, flat
$\mu(Q)$	-2 TeV	2 TeV	hybrid, flat
$\tan\beta(m_Z)$	1	70	flat
Q	3 TeV		fixed
$\alpha_s^{\overline{MS}}(m_Z)$	0.1181		fixed
Top quark pole mass	171.06 GeV		fixed

Plus two targeted scans of lower masses, $|\mu| < 500\,\mathrm{GeV}$ $M_2 < 500\,\mathrm{GeV}$
~ 2.4 million total samples obtained

Monte Carlo statistics limit precision of LHC likelihoods

We used 100k (500k) pythia events per point in full scan (targeted scans)

Post-processed preferred region to reduce MC uncertainty:

2σ region: 4m events, 1σ region: 16m events, 500 best fit points: 64m events

Likelihood Contributions

- LHC searches for Ewinos

Likelihood label	Source
ATLAS_4b	ATLAS Higgsino search [118]
ATLAS_4lep	ATLAS 4ℓ search [119]
ATLAS_MultiLep_2lep_0jet	ATLAS multilepton EW search [114]
ATLAS_MultiLep_2lep_jet	ATLAS multilepton EW search [114]
ATLAS_MultiLep_3lep	ATLAS multilepton EW search [114]
ATLAS_RJ_2lep_2jet	ATLAS recursive jigsaw EW search [115]
ATLAS_RJ_3lep	ATLAS recursive jigsaw EW search [115]
CMS_1lep_2b	CMS Wh search [120]
CMS_2lep_soft	CMS 2 soft opposite-charge lepton search [123]
CMS_2OSlep	CMS 2 opposite-charge lepton search [124]
CMS_MultiLep_2SSlep	CMS multilepton EW search [125]
CMS_MultiLep_3lep	CMS multilepton EW search [125]

Likelihood Contributions

- LEP EWino pair production

Production	Signature	Experiment
$\tilde{\chi}_i^0 \tilde{\chi}_1^0$	$\tilde{\chi}_i^0 \to q\bar{q}\tilde{\chi}_1^0$	OPAL [53]
$(i = 2, 3, 4)$	$\tilde{\chi}_i^0 \to \ell\bar{\ell}\tilde{\chi}_1^0$	L3 [112]
$\tilde{\chi}_i^+ \tilde{\chi}_i^-$	$\tilde{\chi}_i^+ \tilde{\chi}_i^- \to q\bar{q}' q\bar{q}' \tilde{\chi}_1^0 \tilde{\chi}_1^0$	OPAL [53]
$(i = 1, 2)$	$\tilde{\chi}_i^+ \tilde{\chi}_i^- \to q\bar{q}' \ell\nu\tilde{\chi}_1^0 \tilde{\chi}_1^0$	OPAL [53]
	$\tilde{\chi}_i^+ \tilde{\chi}_i^- \to \ell\nu\ell\nu\tilde{\chi}_1^0 \tilde{\chi}_1^0$	OPAL [53], L3 [112]
	ISR γ + missing energy	OPAL [113]

- Higgs and Z Invisible width limits

$\mathrm{BF}(h \to \mathrm{inv.}) \leq 0.19$ (Fit to Higgs data from PRD 88 (2013) 075008)

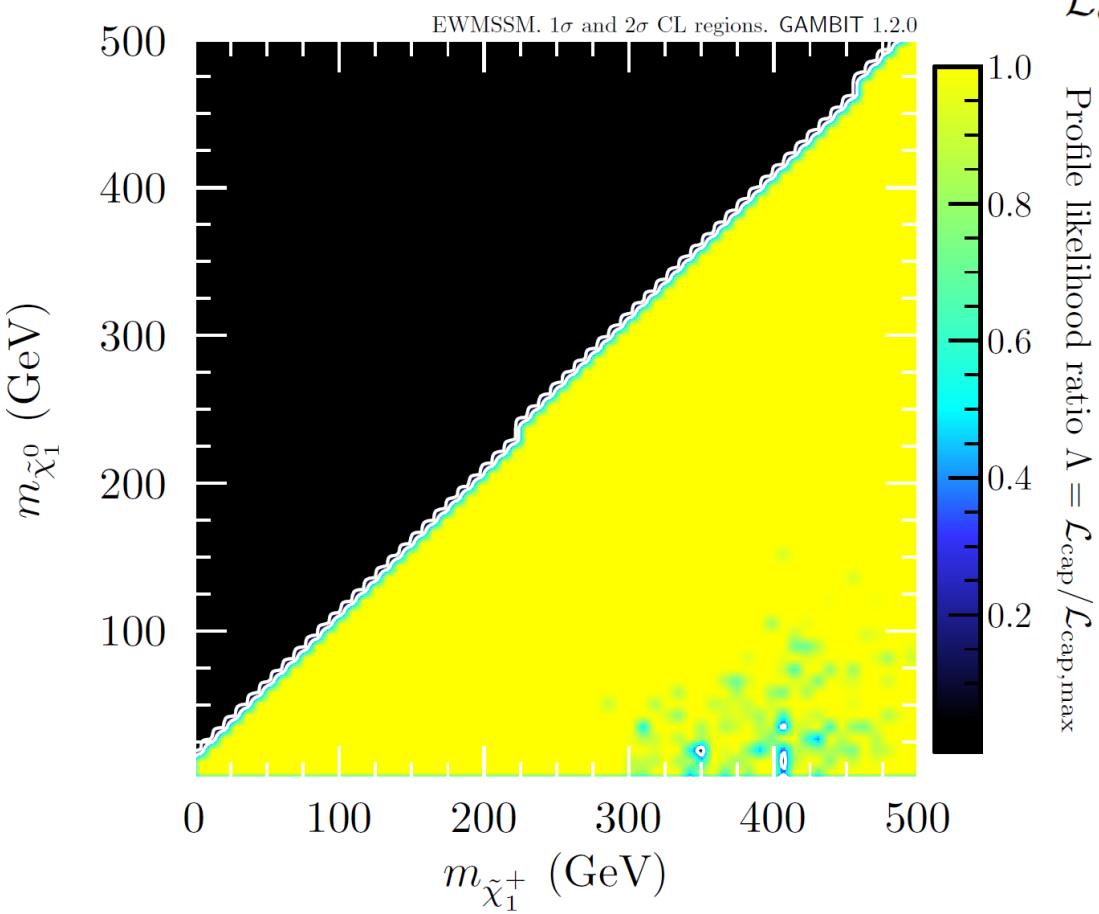
$\Gamma(Z \to \mathrm{inv.}) = 499.0 \pm 1.5\,\mathrm{MeV}$ (Indirect LEP measurements)

Results

- Capped profile Likelihood

  - Don't allow excesses above SM in data
  - 2d profiling over extra dimensions selects highest likelihood point
  - tests if LHC can place general constraint on $m_{\chi_1^0} - m_{\chi_1^\pm}$ plane

$$\mathcal{L}_{\rm cap} = \min[\mathcal{L}_{\rm LHC}(\boldsymbol{s}+\boldsymbol{b}), \mathcal{L}_{\rm LHC}(\boldsymbol{b})]$$



No general constraint on lightest EWinos!

Results

- Capped profile Likelihood

$\Longrightarrow$ For each point in plane, at least one scenario in 4D space fits data well

Says *nothing* about the volume of viable parameter space in 4D space

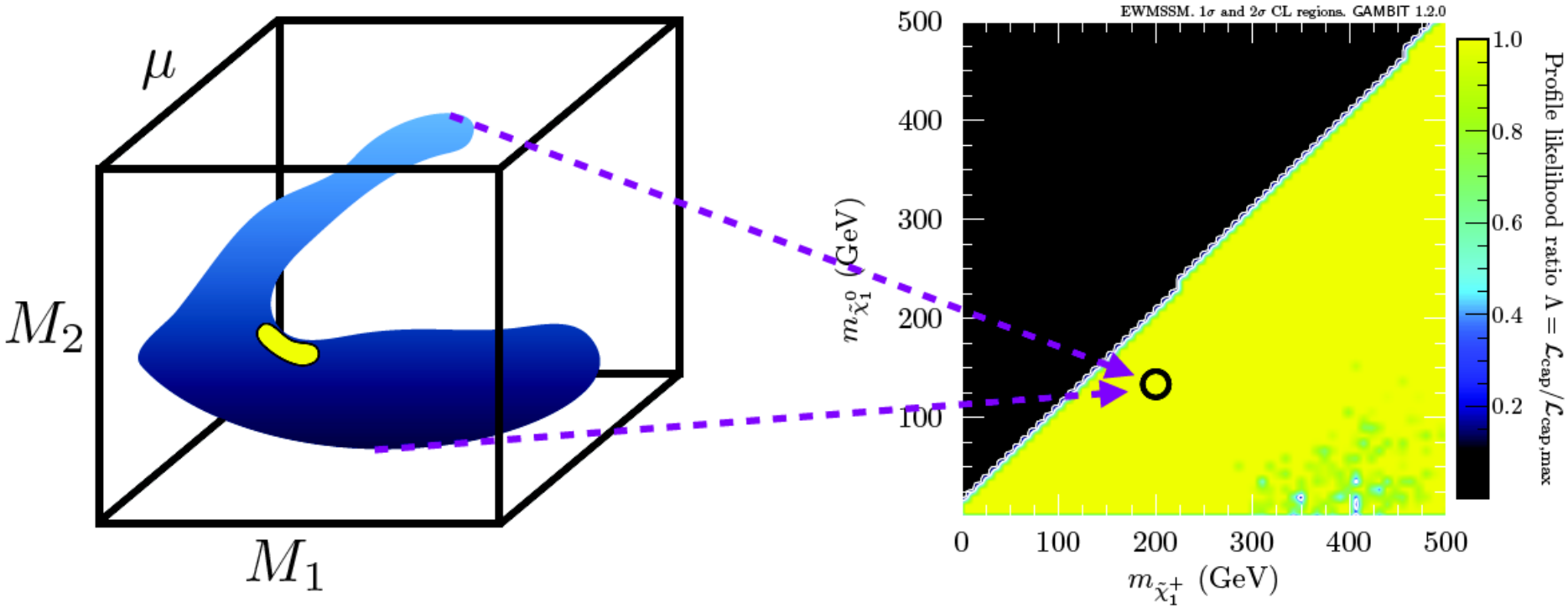
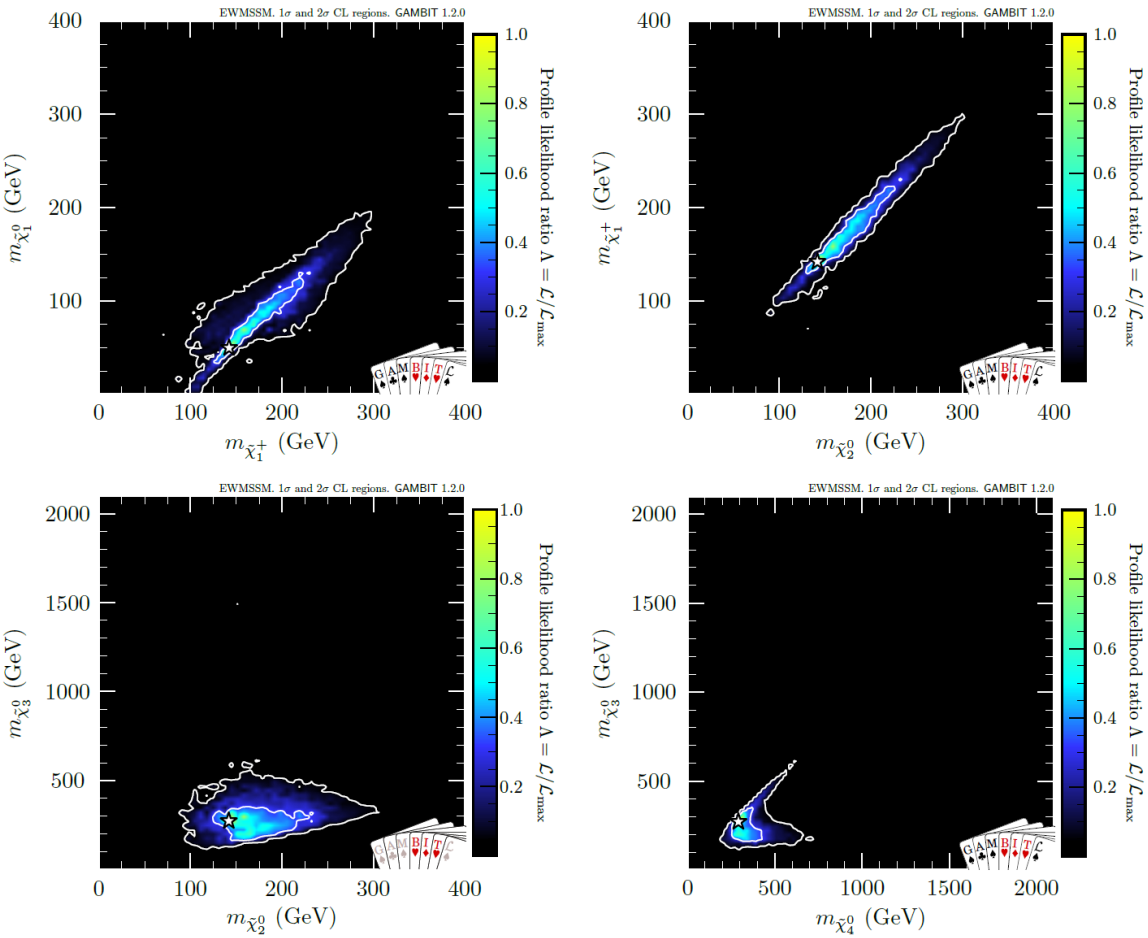


Image: Anders Kvellestad

Results

- Full profile Likelihood

  - Allows one to also fit anomalies
  - shows regions preferred by data without any tampering



- Prefers light EWino
- "Excludes" SM / heavy states
- All EWinos light! (unlike simplified models)
- Bino < winos < Higgsinos or Bino < Higgsinos < winos

So.. have we discovered supersymmetry?

Results

- Statistical significance

Obtain local p-values, using test statistic:

$$q_{\mathrm{LS}} = -2 \log \frac{\mathcal{L}_{\mathrm{joint}}(\mu = 1, \hat{\eta})}{\mathcal{L}_{\mathrm{joint}}(\mu = 0, \hat{\hat{\eta}})},$$

Joint likelihood for signal

Joint likelihood for background only hypothesis

Determine distribution for test statistic by Monte Carlo

Gives best fit point local significances:

13 TeV only: 3.3 sigma

13 TeV plus 8 TeV: 2.9 sigma

Note: local p-values only.

Does not account for look else where effect.

So.. have we discovered supersymmetry?

The combined significance of these anomalies is intriguing...
but not high enough to get so excited.

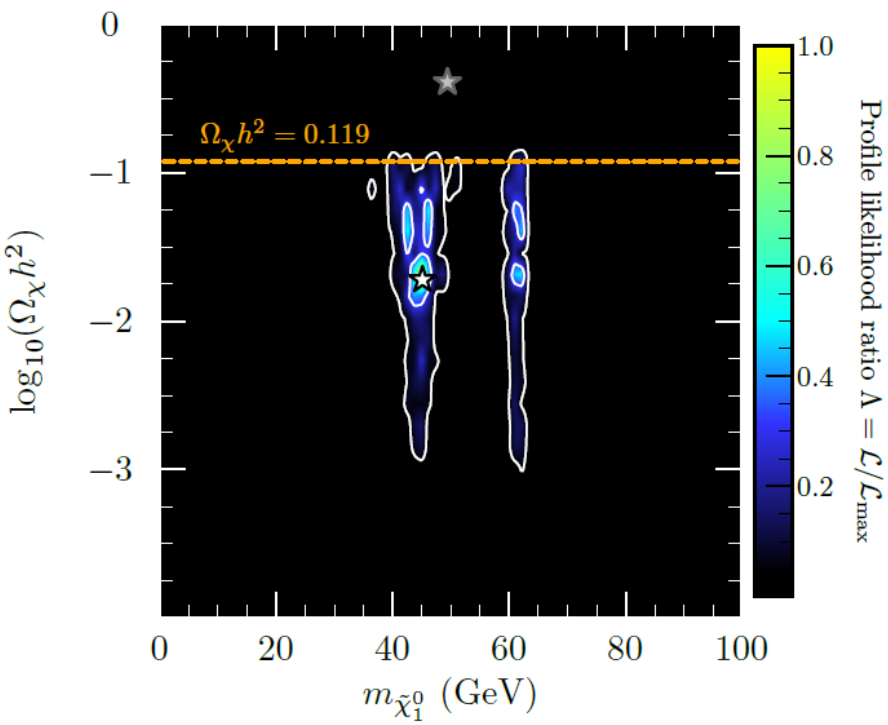
Bonus Result: Dark Matter

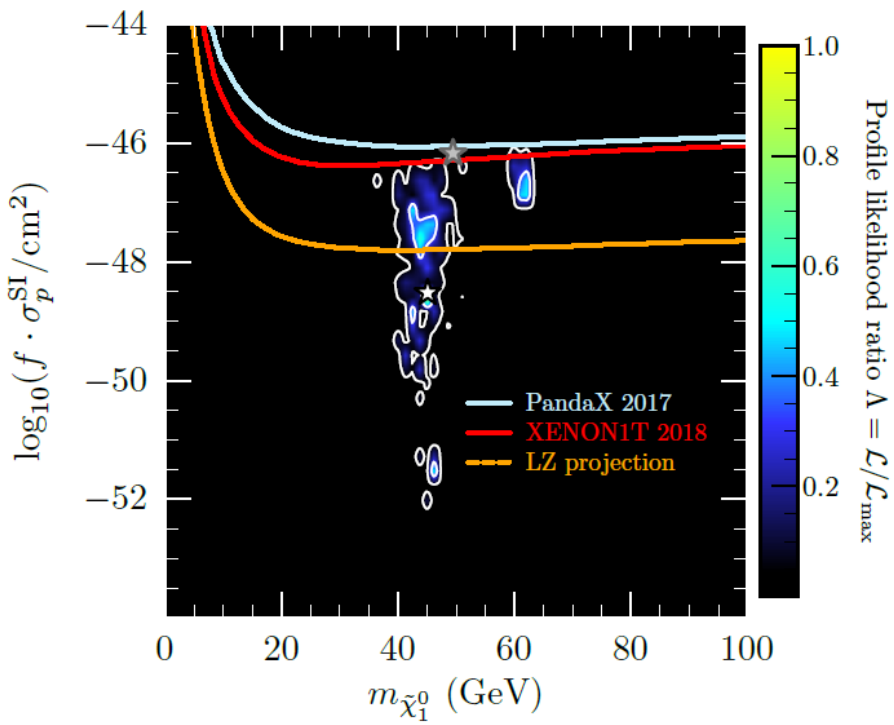
This collider only global fit, prefer a light bino-like LSP.

BSM states that could deplete relic density were decoupled

However bino can be light enough for H/Z funnel mechanisms

Postprocessing more results from collider only fit...





Conclusions

- There is no general exclusion on light electroweakinos from LHC.
- There are some excesses in data that favour certain light EWino scenarios.
- A subset of the scenarios favoured by the collider searches can explain the relic density of dark matter.
- Significance of collider excesses is intriguing but not large enough to celebrate… could easily just be statistical fluctuations.
- Main lesson is we must be careful how we interpret simplified model search results!
- Treating them as general exclusions on non-simplified models can exaggerate limits and even miss significant anomalies in the data!

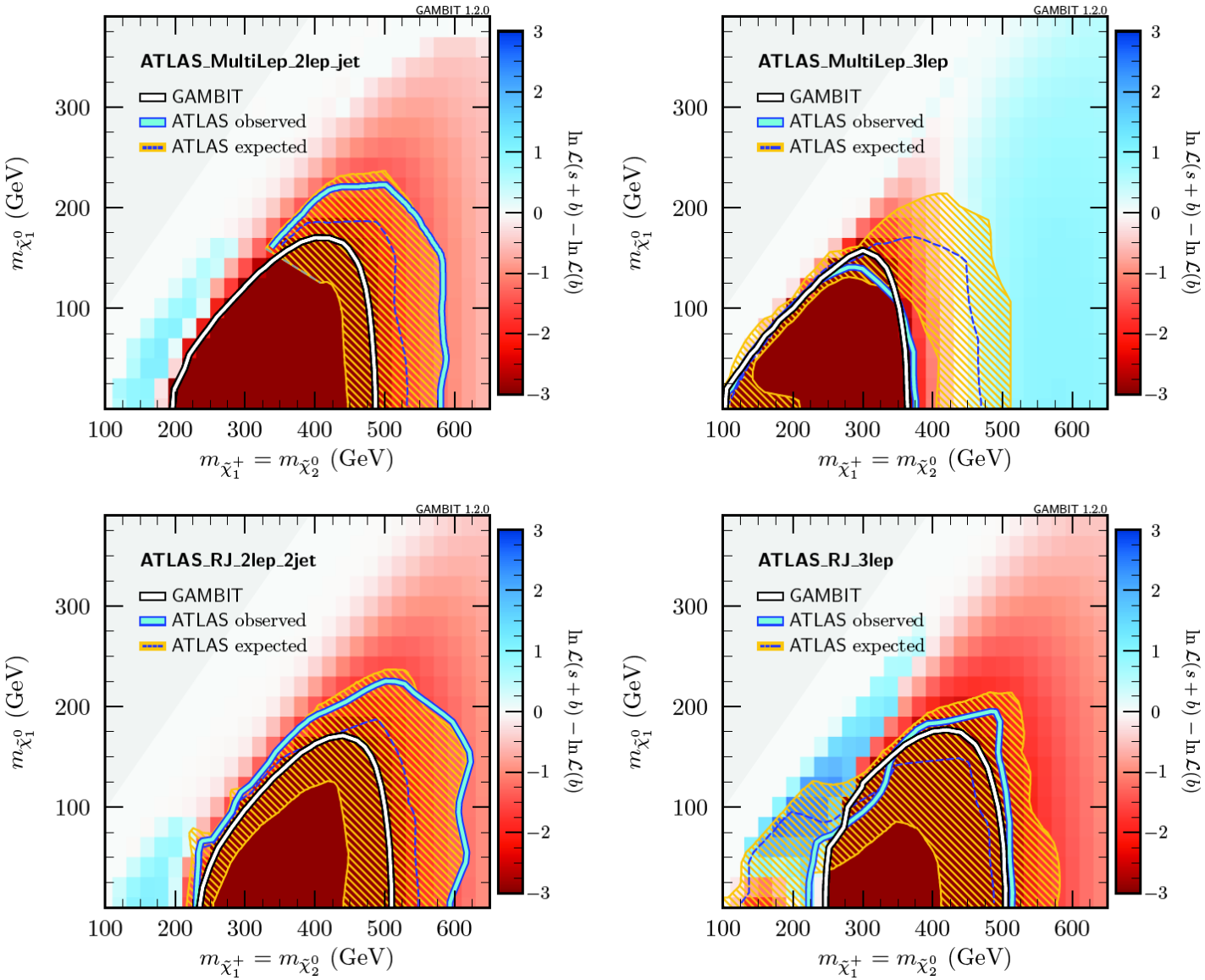
The End

Thanks for listening!

BACK UP SLIDES

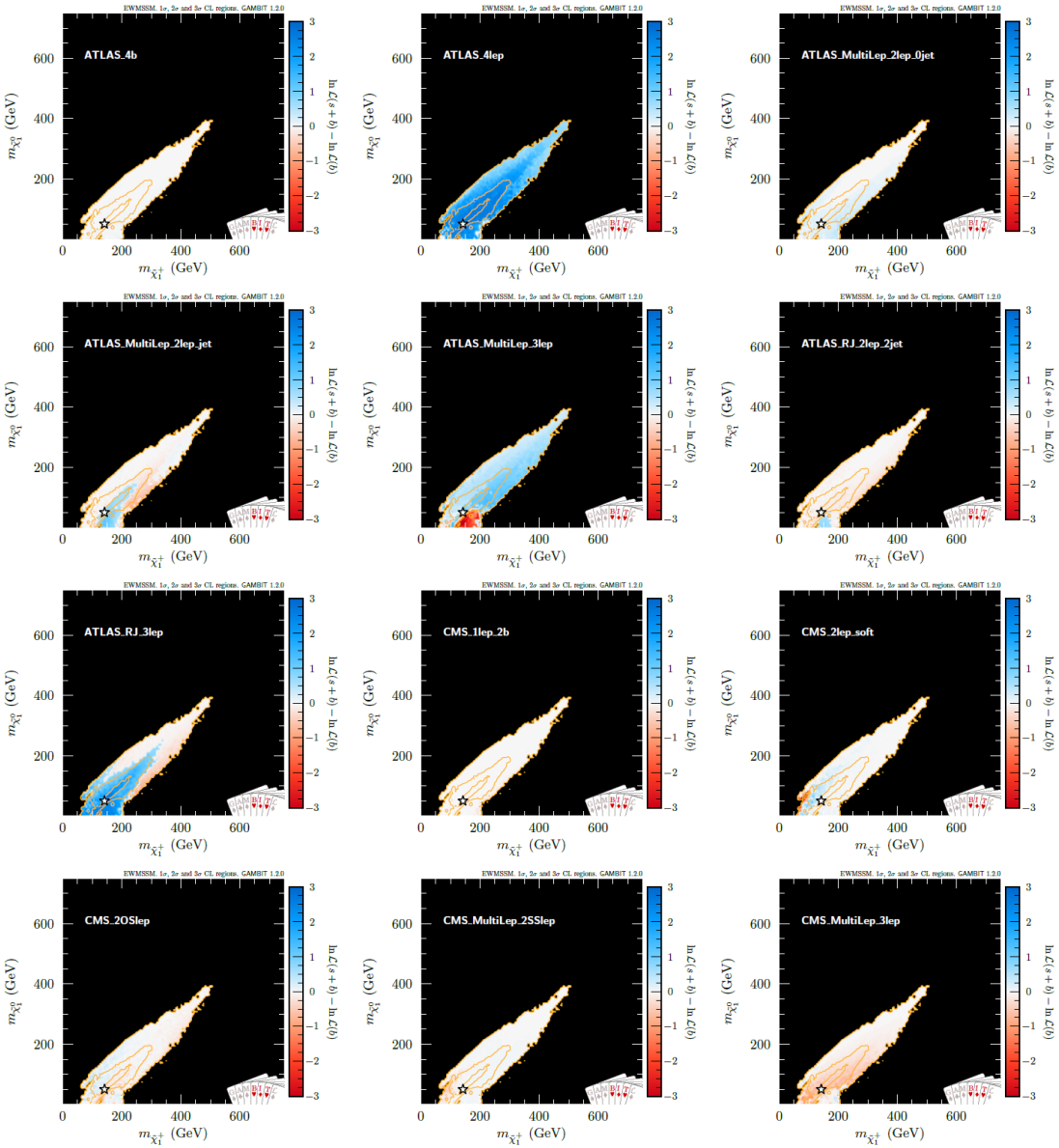
Simplified Model limits

- GAMBIT *does* reproduce ATLAS simplified model limits reasonably well



Results

- Likelihood contributions



- **Contribution from each analysis** to the 1σ, 2σ and 3σ best-fit regions

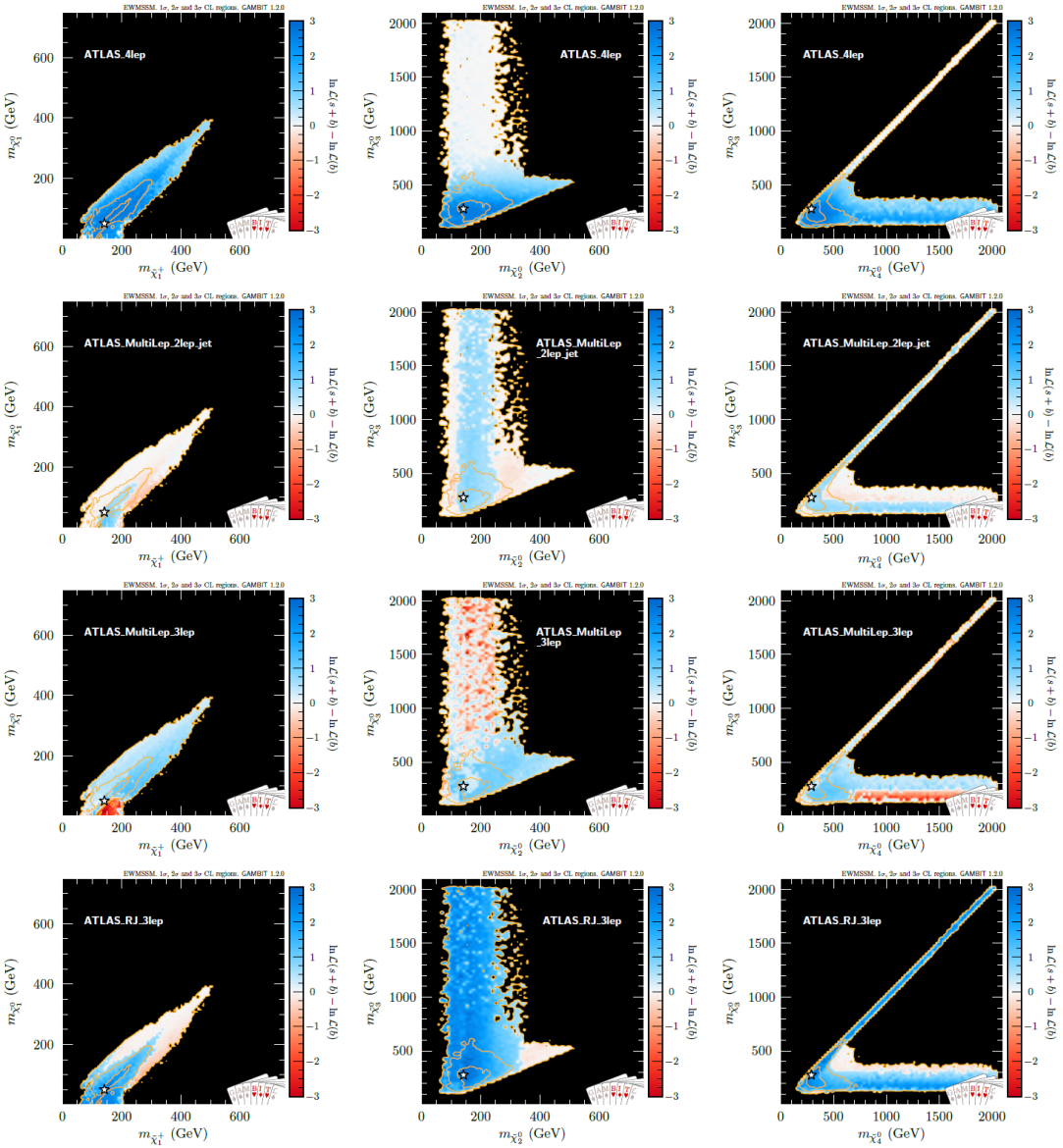
$$\ln \mathcal{L}(s+b) - \ln \mathcal{L}(b)$$

- **Blue**: **better** than background-only
  Red: **worse** than background-only

- Most important contributions to best-fit region:
  - **ATLAS_4lep**
  - **ATLAS_RJ_3lep**
  - **ATLAS_MultiLep_2lep_jet**
  - **ATLAS_MultiLep_3lep**
  - **CMS_MultiLep_3lep**

Results

- Likelihood contributions



- More detailed look on
  - ATLAS_4lep
  - ATLAS_RJ_3lep
  - ATLAS_MultiLep_2lep_jet
  - ATLAS_MultiLep_3lep
- Sudden changes in likelihood due to changes in most sensitive SR
- Light $\tilde{\chi}_3^0$ preferred by ATLAS_4lep and ATLAS_MultiLep_3Lep
- Heavy $\tilde{\chi}_4^0$ disfavoured by ATLAS_MultiLep_2lep_jet and ATLAS_MultiLep_3Lep
- The «expected» tension between ATLAS_MultiLep_3Lep and ATLAS_RJ_3lep observed for heavy $\tilde{\chi}_4^0$ (production of higgsino $\tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_1^\pm$)

Results

- Statistical significance

Including only 13 TeV data for LHC

	Best expected SRs				All SRs; neglect correlations			
Analysis	Local signif. (σ)	SM fit (σ)	EWMSSM fit (σ)	#SRs	Local signif. (σ)	SM fit (σ)	EWMSSM fit (σ)	#SRs
Higgs invisible width	0	0	0	1	0	0	0	1
Z invisible width	0	1.3	1.3	1	0	1.3	1.3	1
ATLAS_4b	0.7	0	0	1	1.5	0	0	2^*
ATLAS_4lep	2.3	1.9	0	1	2.5	1.0	0	4
ATLAS_MultiLep_2lep_0jet	0.9	0.3	0.1	1	1.3	0	0	6
ATLAS_MultiLep_2lep_jet	0	0	0.5	1	0.8	0.5	0.2	3
ATLAS_MultiLep_3lep	1.8	1.5	0.7	1	1.2	0.4	0.3	11
ATLAS_RJ_2lep_2jet	0	0.3	0.5	1	1.5	1.8	1.5	4
ATLAS_RJ_3lep	2.7	2.5	1.1	1	3.4	2.5	0.7	4
CMS_1lep_2b	0.8	0.3	0.3	1	0	0	0	2
CMS_2lep_soft	0.1	0.2	0.2	12	0.1	0.2	0.2	12
CMS_2OSlep	0.1	0.5	0.5	7	0	0.4	0.5	7
CMS_MultiLep_2SSlep	0.2	0	0	1	0.2	0	0	2
CMS_MultiLep_3lep	0	0	0.4	1	0	0	0	6
Combined	3.3	1.4	0.2	31	4.1	1.2	0	65

Results

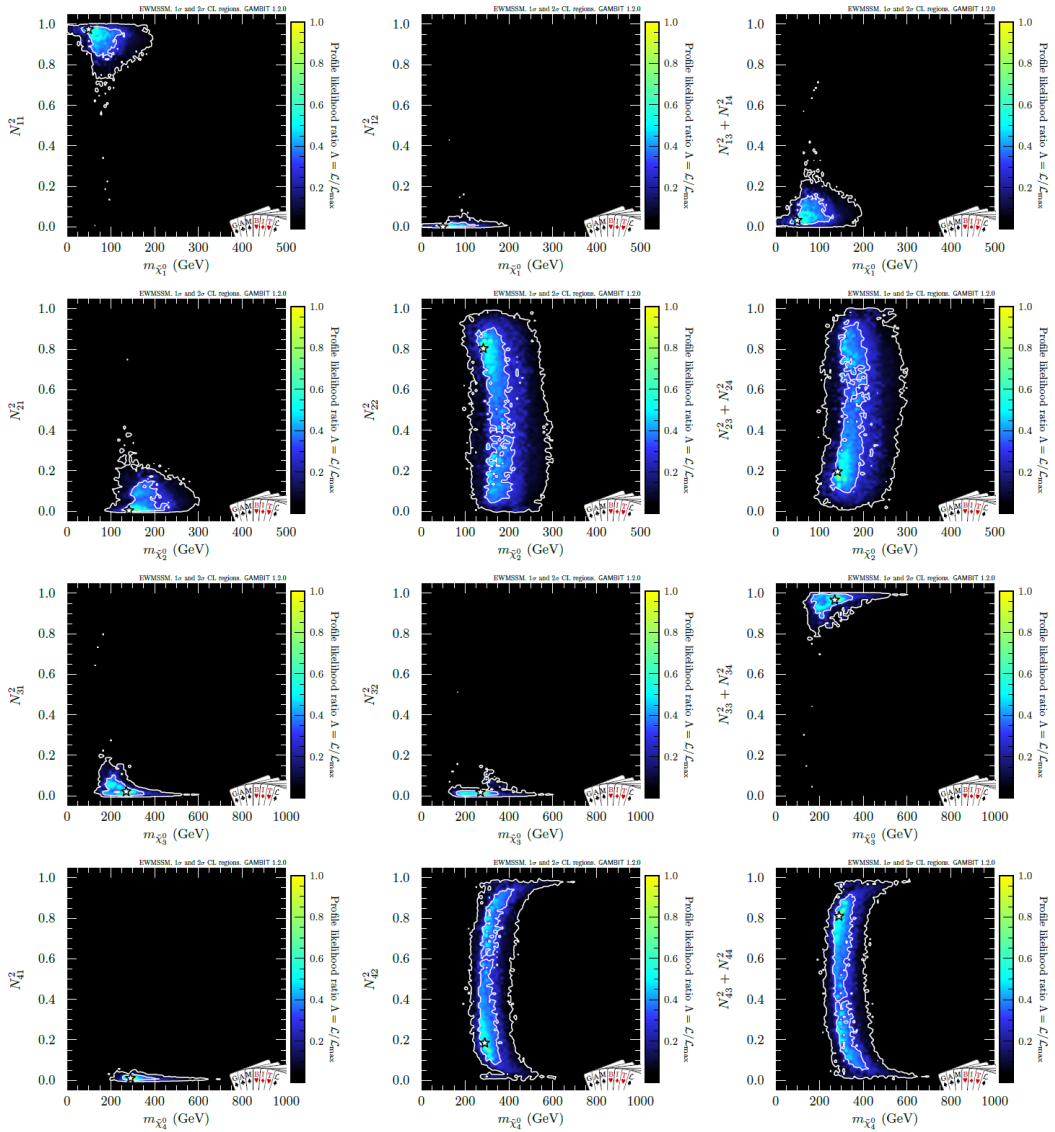
- Statistical significance

Including 8 TeV data significance is reduced slightly

	Best expected SRs				All SRs; neglect correlations			
Analysis	Local signif. (σ)	SM fit (σ)	MSSM4 fit (σ)	#SRs	Local signif. (σ)	SM fit (σ)	MSSM4 fit (σ)	#SRs
Higgs invisible width	0	0	0	1	0	0	0	1
Z invisible width	0	1.3	1.3	1	0	1.3	1.3	1
ATLAS_4b	0.7	0	0	1	1.5	0	0	46
ATLAS_4lep	2.3	1.9	0	1	2.5	1.0	0	4
ATLAS_MultiLep_2lep_0jet	0.9	0.3	0.1	1	1.3	0	0	6
ATLAS_MultiLep_2lep_jet	0	0	0.5	1	0.9	0.5	0.2	3
ATLAS_MultiLep_3lep	1.8	1.5	0.7	1	1.1	0.4	0.3	11
ATLAS_RJ_2lep_2jet	0	0.3	0.5	1	1.5	1.8	1.5	4
ATLAS_RJ_3lep	2.7	2.4	1.1	1	3.4	2.6	0.7	4
CMS_1lep_2b	0.9	0.3	0.3	1	0	0	0	2
CMS_2lep_soft	0.1	0.2	0.2	12	0.1	0.2	0.2	12
CMS_2OSlep	0.1	0.5	0.5	7	0.1	0.5	0.5	7
CMS_MultiLep_2SSlep	0.2	0	0	1	0.2	0	0	2
CMS_MultiLep_3lep	0	0	0.4	1	0	0	0	6
CMS_8TeV_3lep	0	0	0	1	1.1	0	0	108
CMS_8TeV_4lep	0.3	0	0	1	0.3	0	0	12
ATLAS_8TeV_1lep_2b	0	0	0	1	0	0	0	2
ATLAS_8TeV_2lep	0	0	0	1	0	0	0	13
ATLAS_8TeV_3lep	0	0	1.0	1	0.4	0	0	23
Combined	2.9	0.9	0	36	3.6	0	0	267

Results

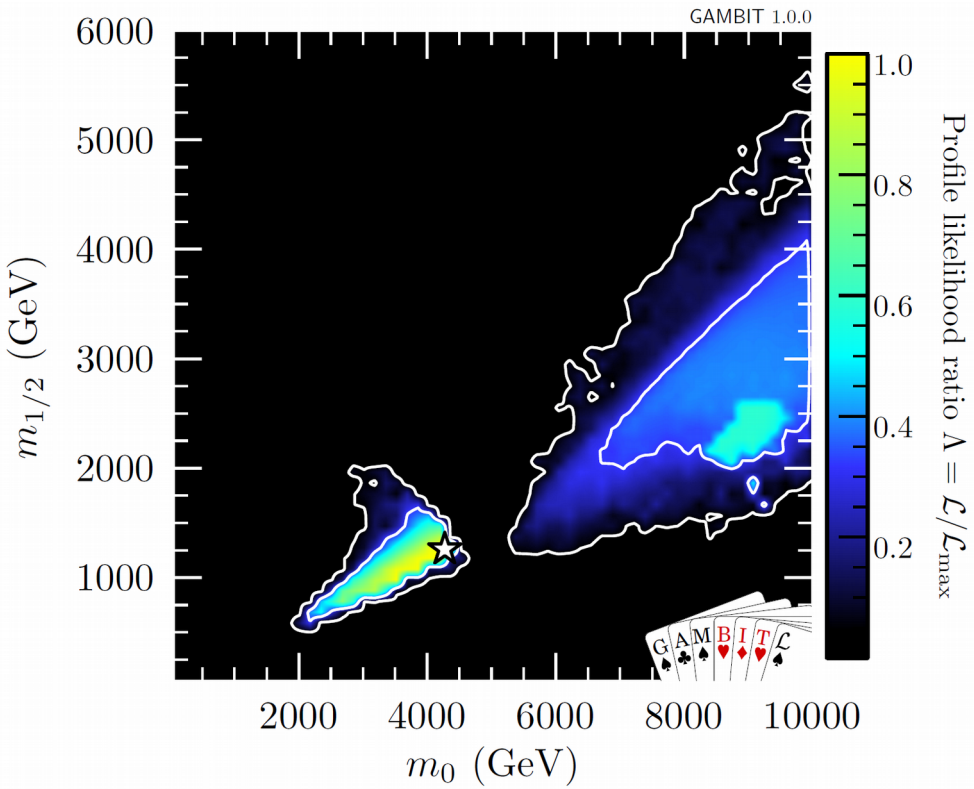
- Neutralino Composition

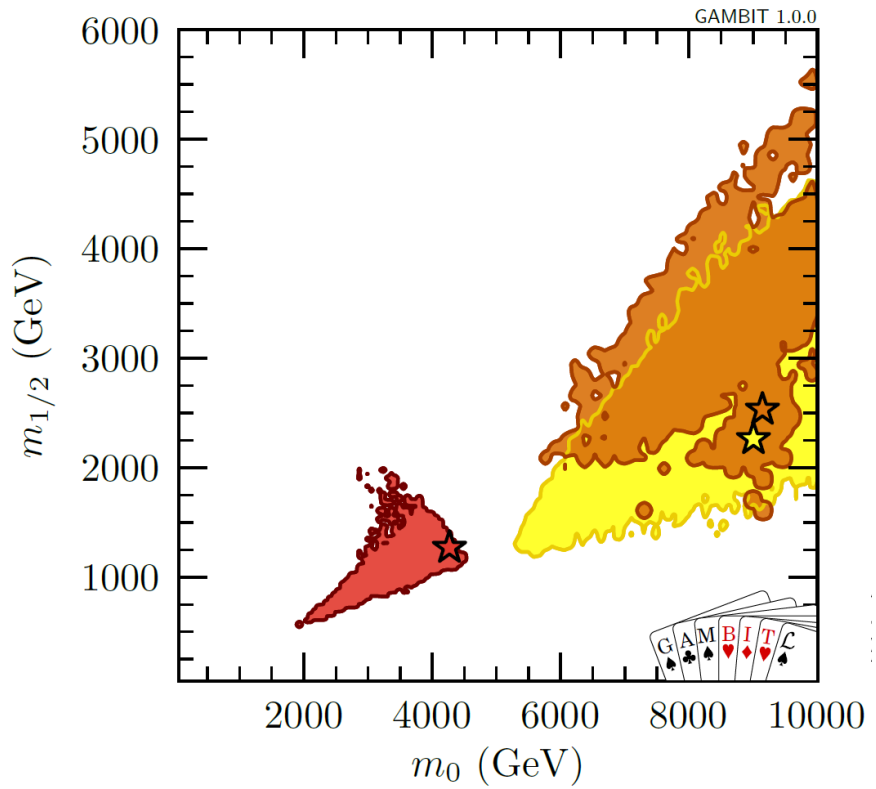


CMSSM Global Fits

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

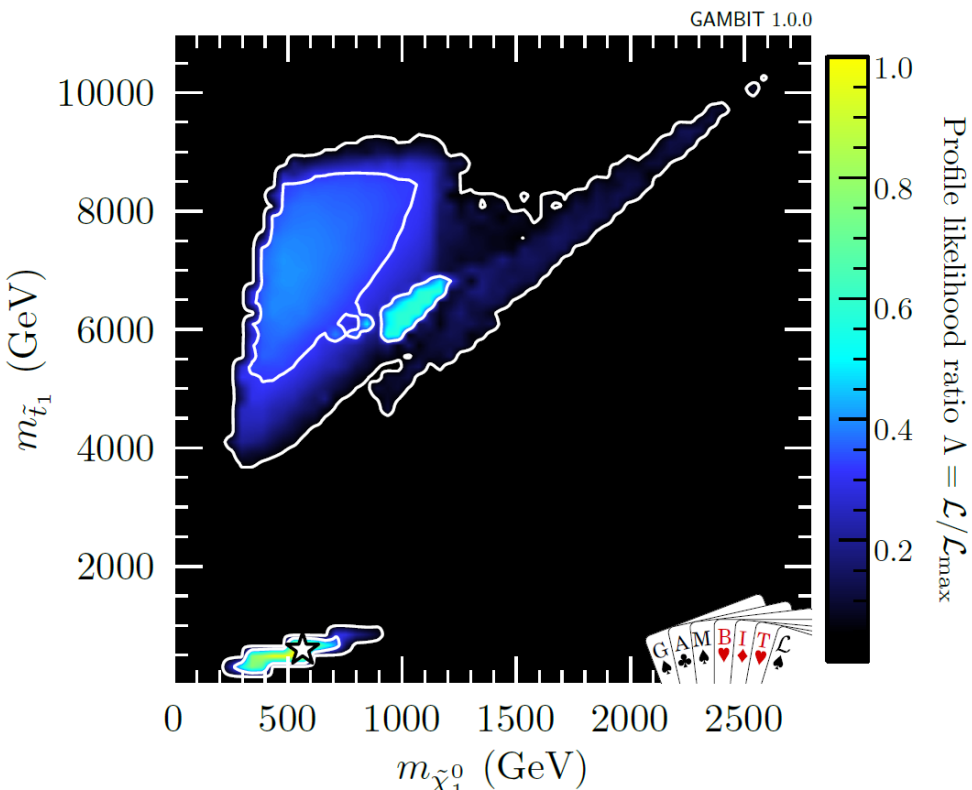
- No stau co-annihilation region within 2 sigma contours after including run II
- Large stop co-annihilation region (red) which survives LHC limits and LUX 2006
- Heavy chargino (yellow) and A-funnel (brown) regions with sfermions and gauginos out of reach of the LHC

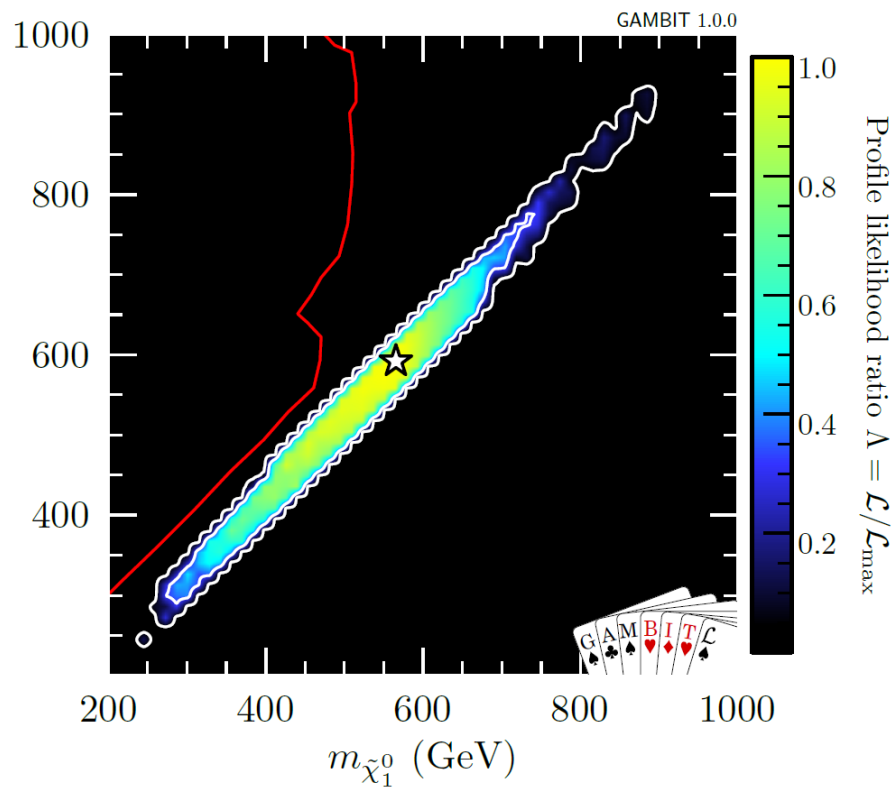




CMSSM stop co-annihilation

- Could be probed by long lived sparticle or compressed spectra searches
- Stop pair production within range for a multi-TeV linear collider
- Red line indicates current limits from CMS compressed spectra
- Some opportunity to probe further at colliders
- Vacuum stability issues exist in this region, requires careful study also involving precise determination of Higgs mass

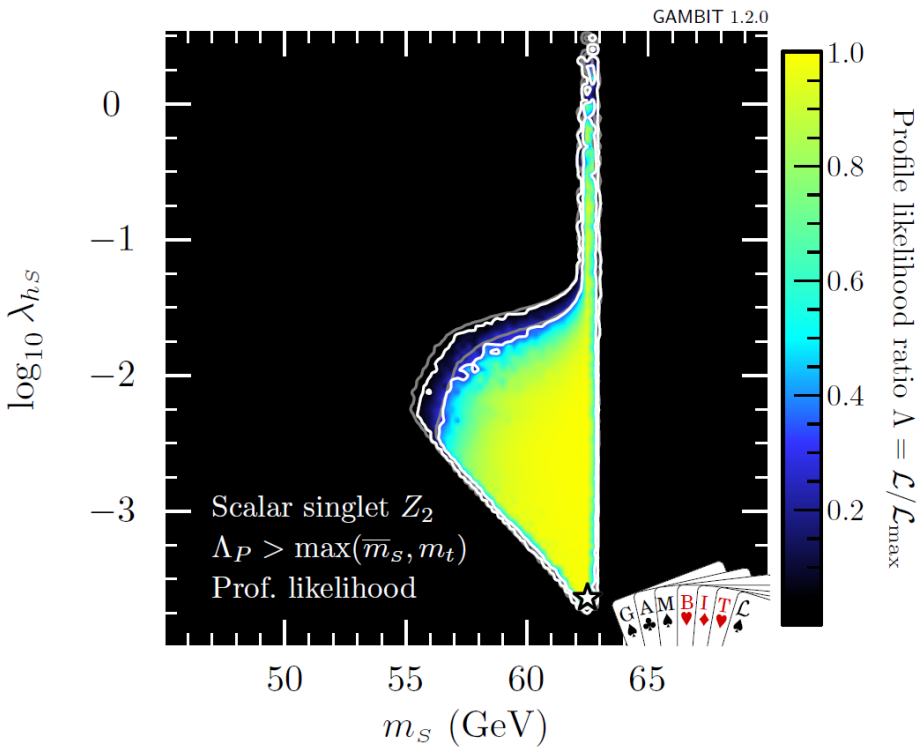


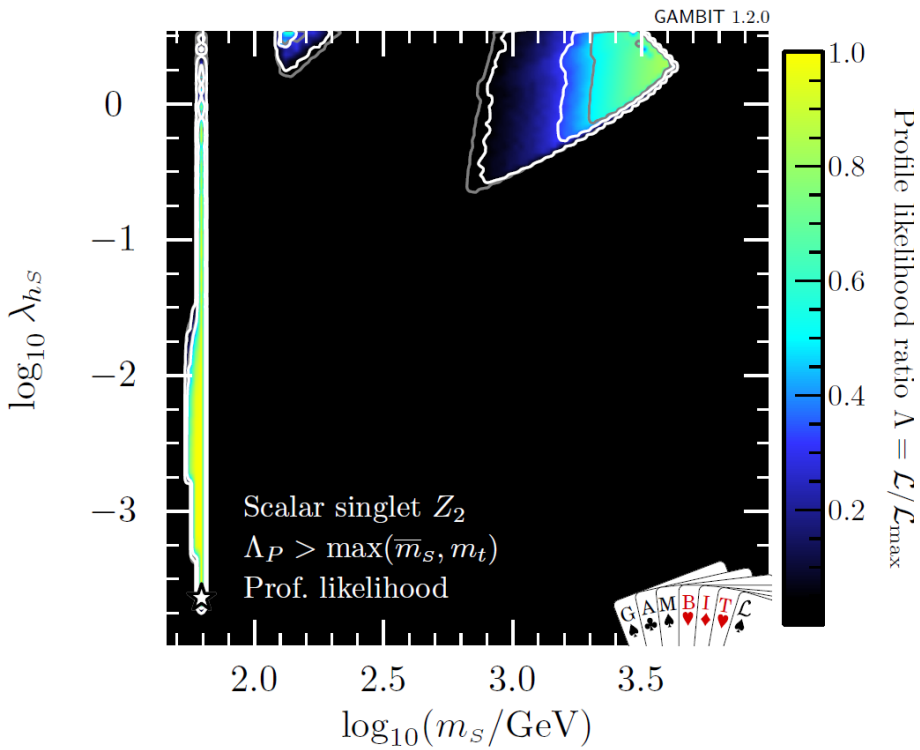


Scalar Singlet DM Profile Likelihood ($\mathbb{Z}_2$)

Reveals three surviving modes: low mass resonance mode (best fit)
small medium mass mode
high mass mode

Note: our relic density likelihood is one-sided
we allow for the possibility of other DM candidates



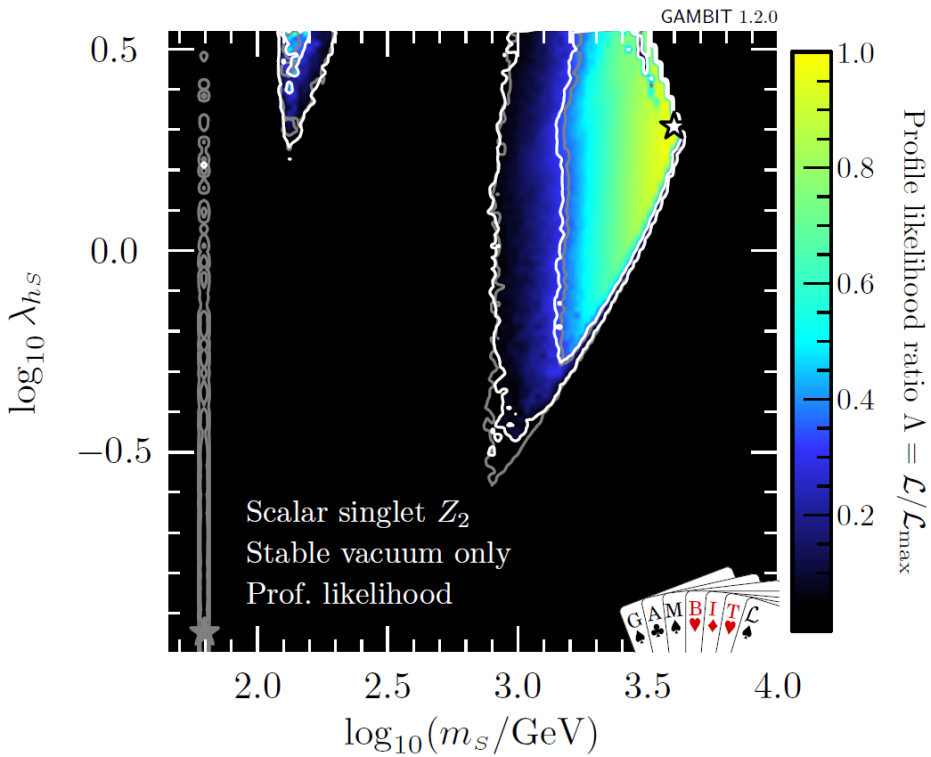


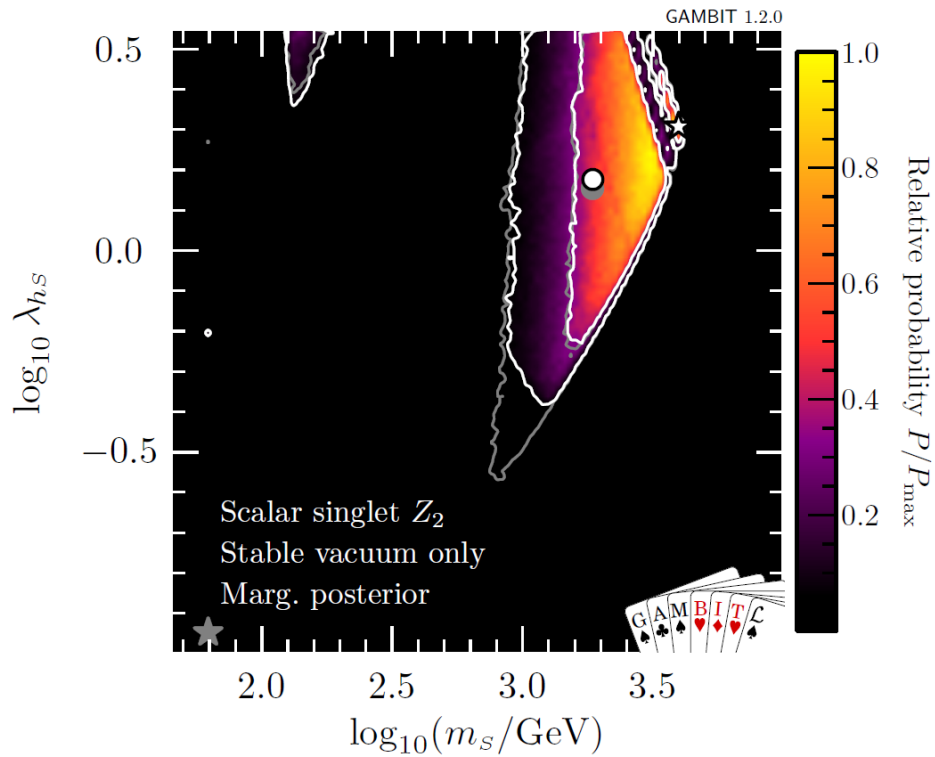
Vacuum Stability in Scalar Singlet DM model ($\mathbb{Z}_2$)

Exclude points where we can show perturbatively that $\lambda_h(Q) < 0$ for some $Q < M_{\rm Pl}$

$\lambda_{hs} \gtrsim 0.2$ to stabalise EW vacuum $\implies$ low mass resoance mostly ruled out

Posterior results similar but medium mass mode relatively disfavoured



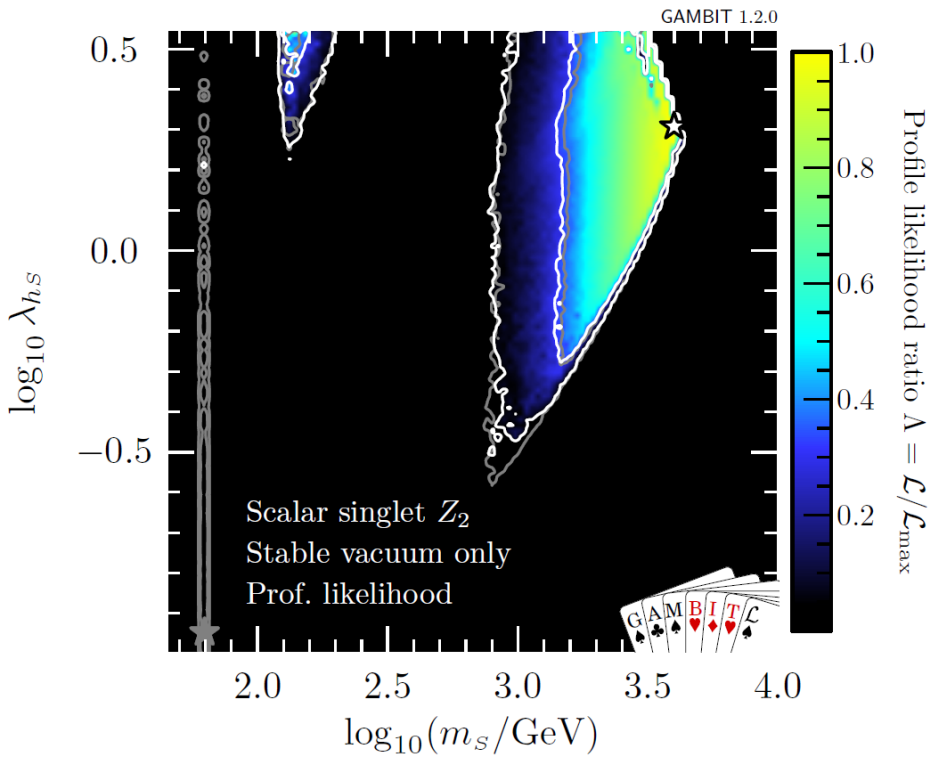


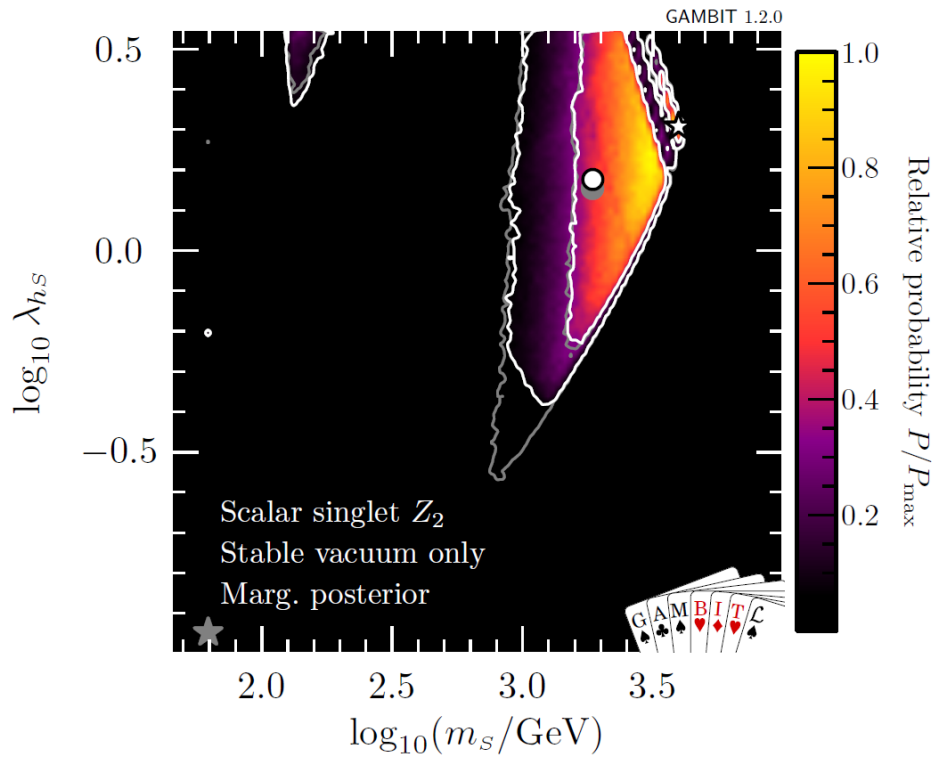
Vacuum Stability in Scalar Singlet DM model ($\mathbb{Z}_2$)

Exclude points where we can show perturbatively that $\lambda_h(Q) < 0$ for some $Q < M_{\rm Pl}$

$\lambda_{hs} \gtrsim 0.2$ to stabalise EW vacuum $\implies$ low mass resoance mostly ruled out

Posterior results similar but medium mass mode relatively disfavoured





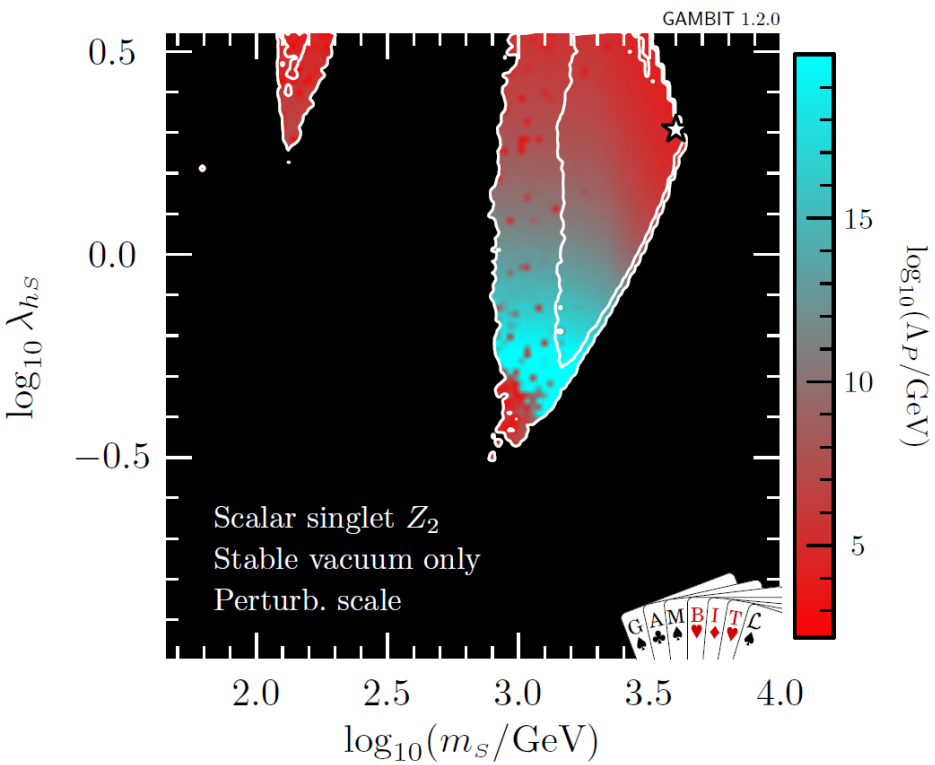
Perturbativity and Vacuum Stability constraints ($\mathbb{Z}_2$)

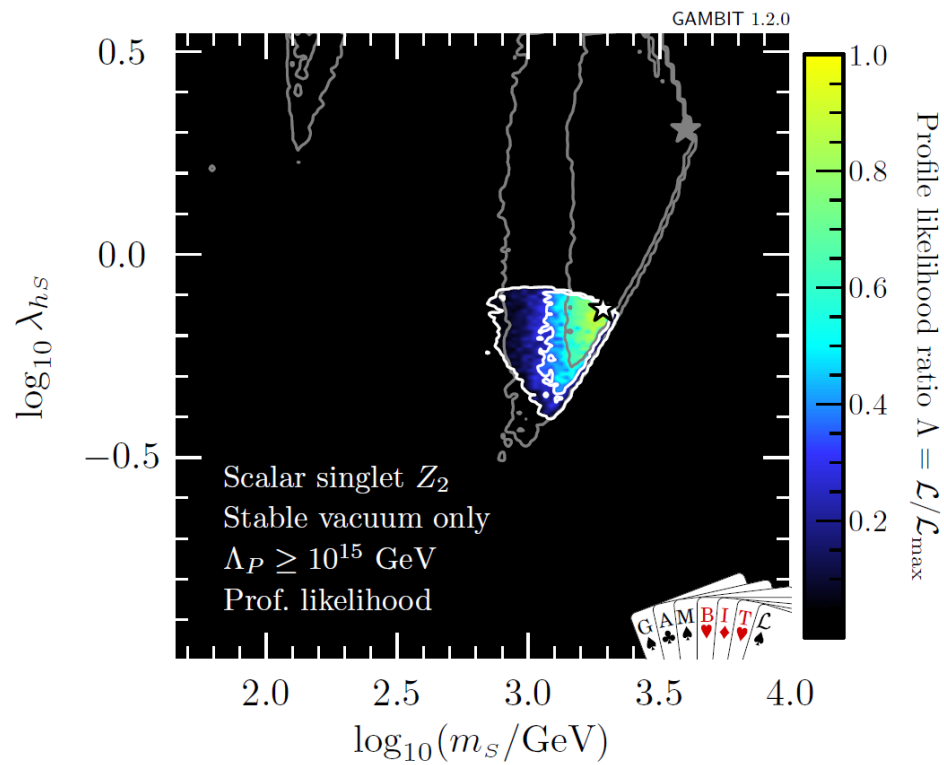
Now require that the couplings remain pertu$\leq \sqrt{4\pi}$e ($Q = M_{Pl}$
to:

$\lambda_s \gtrsim 0.7 \implies$ perturbativity scale low

Medium mass mode has $\lambda_{hs} > 1 \implies$ low perturbativity scale

Large mass mode can remnain perturbative upto $Q = M_{\rm Pl}$
Depends on λ_s and λ_{hs}





End of Back Up Sildes