GAMBIT updates and results

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Reinterpretation Forum 2023, 29 August 2023

Outline

1. GAMBIT
   - ColliderBit
   - Recent updates and work in progress
2. Results
   - EW MSSM with a light gravitino
3. Conclusions

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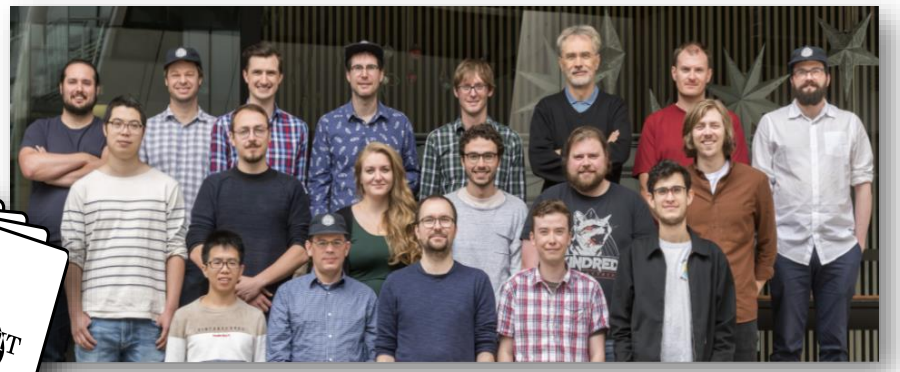
GAMBIT: The Global And Modular BSM Inference Tool

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

Recent collaborators: 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 ++

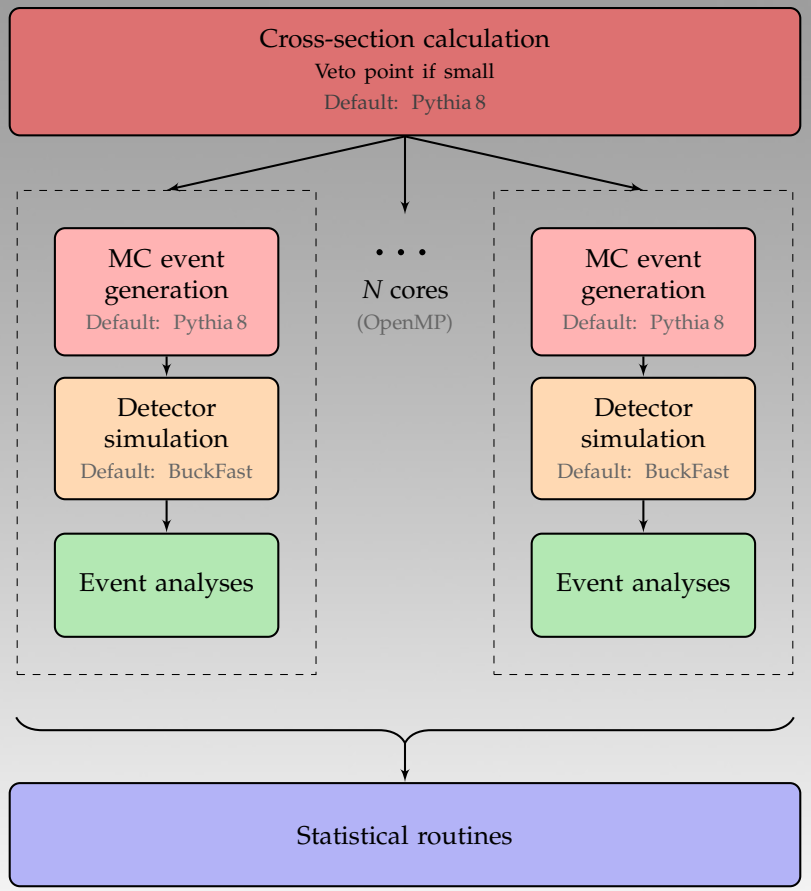
80+ participants in many experiments and numerous major theory codes

Modules (Bits)

- Physics Modules
  - → **ColliderBit**: collider searches [Eur.Phys.J. C77 (2017) no.11, 795]
  - → **DarkBit**: relic density, dd,. . . [Eur.Phys.J. C77 (2017) no.12, 831]
  - → **FlavBit**: flavour observables [Eur.Phys.J. C77 (2017) no.11, 786]
  - → **SpecBit**: spectra, RGE running [Eur.Phys.J. C78 (2018) no.1, 22]
  - → **DecayBit**: decay widths [Eur.Phys.J. C78 (2018) no.1, 22]
  - → **PrecisionBit**: precision tests [Eur.Phys.J. C78 (2018) no.1, 22]
  - → **NeutrinoBit**: neutrino likelihoods [Eur.Phys.J.C 80 (2020) no.6, 569]
  - → **CosmoBit**: cosmological constraints [JCAP 02 (2021) 022]
- **ScannerBit** : stats and sampling [Eur.Phys.J. C77 (2017) no.11, 761]
  - → Diver, GreAT, Multinest, Polychord, . . .
- **Models**: hierarchical model database
- **Core** : dependency resolution [Eur.Phys.J. C78 (2018) no.2, 98]
- **Backends** : External tools to calculate observables
- **GUM**: Autogeneration of code [S. Bloor, TG, P. Scott et. al., soon]

ColliderBit

- Reinterpretation of searches at the LHC
  - → Simulation based (e.g. Pythia) or yield interpolation
  - → 63 implemented analyses (36 ATLAS, 24 CMS)
  - → Homebrew dectector simulation (Buckfast)
  - → SM xsec measurements (Rivet, Contur)
- Likelihoods for (some) LEP searches
- Higgs properties via HiggsBounds and HiggSignals



Updates and work in progress

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Recent updates

- Allowed interpolation of yields from efficiency tables
- Generation of HepMC events and YODA histograms
- Interface to Rivet and Contur
- MadGraph as event generator
- Interface to ATLAS Full likelihoods
- Speed up of fastjet (PACER)

Work in progress

- CBS (ColliderBit Solo)
- Expand event class for long lived particles
- Alternative xsec calculators: Prospino, xsec, salami
- Interface to SModelS
- Move to Pythia 8.3
- Beam dump constraints
- Usage of NN in analyses (Tomek)
- Interface to ATLAS SimpleAnalysis

EW MSSM with a light gravitino

[GAMBIT, Eur.Phys.J.C 83 (2023) 6, 493, arXiv:2303.09082 [hep-ph]]

TTP23-009, KCL-PH-TH/2023-21, gambit-physics-23, MCnet-23-05, ADP-23-08/T1217, CERN-TH-2023-043

Collider constraints on electroweakinos in the presence of a light gravitino

The GAMBIT Collaboration: Viktor Ananyev[1], Csaba Balázs[2], Ankit Beniwal[3], Lasse Lorentz Braseth[1], Andy Buckley[4], Jonathan Butterworth[5], Christopher Chang[6], Matthias Danninger[7], Andrew Fowlie[8], Tomás E. Gonzalo[9,a], Anders Kvellestad[1,b], Farvah Mahmoudi[10,11], Gregory D. Martinez[12], Markus T. Prim[13], Tomasz Procter[4], Are Raklev[1], Pat Scott[14], Patrick Stöcker[15], Jeriek Van den Abeele[1,18], Martin White[16], Yang Zhang[17,19]

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[2] School of Physics and Astronomy, Monash University, Melbourne, VIC 3800, Australia
[3] Theoretical Particle Physics and Cosmology (TPPC), Department of Physics, King's College London, Strand, London, WC2R 2LS, UK
[4] SUPA, School of Physics and Astronomy, University of Glasgow, Glasgow, G12 8QQ, UK
[5] Department of Physics and Astronomy, University College London, Gower St., London, WC1E 6BT, UK
[6] School of Mathematics and Physics, The University of Queensland, St. Lucia, Brisbane, QLD 4072, Australia
[7] Department of Physics, Simon Fraser University, Burnaby BC, V5A 1S6, Canada
[8] Department of Physics, School of Mathematics and Physics, Xi'an Jiaotong-Liverpool University, 111 Ren'ai Road, Suzhou Dushu Lake, Science and Education Innovation District, Suzhou Industrial Park, Suzhou 215123, P.R. China
[9] Institute for Theoretical Particle Physics (TTP), Karlsruhe Institute of Technology (KIT), 76128 Karlsruhe, Germany

ph] 16 Mar 2023

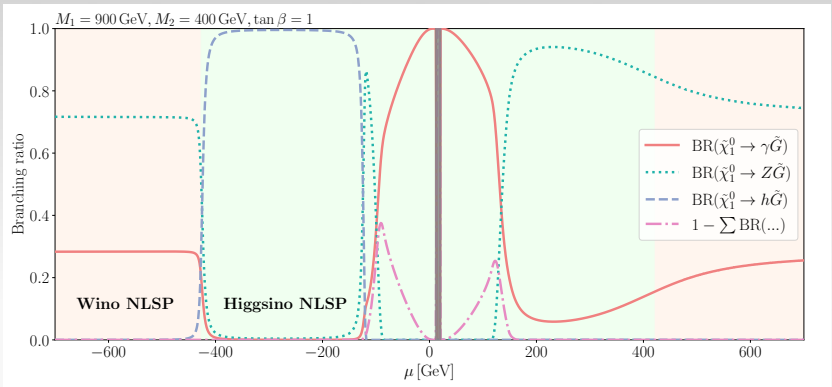
EW MSSM + $\tilde{G}$

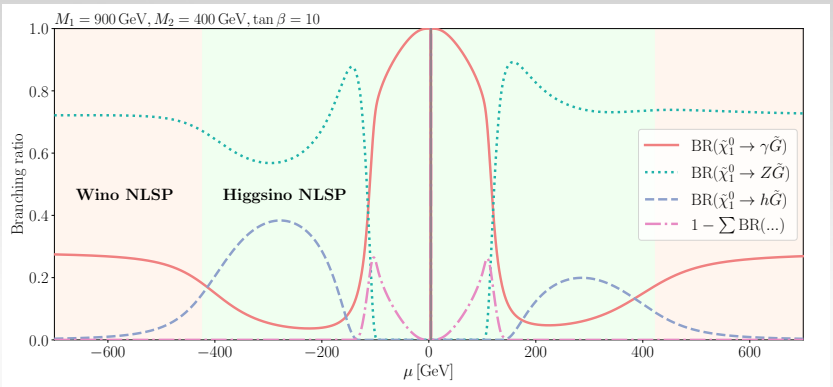
Name	Spin	Gauge ES	Mass ES	Param
Higgs bosons	0	$H_u^0\ H_d^0\ H_u^+\ H_d^-$	$h\ H\ A\ H^\pm$	-
squarks	0	$\tilde{u}_L\ \tilde{u}_R\ \tilde{d}_L\ \tilde{d}_R$	-	-
		$\tilde{c}_L\ \tilde{c}_R\ \tilde{s}_L\ \tilde{s}_R$	-	-
		$\tilde{t}_L\ \tilde{t}_R\ \tilde{b}_R\ \tilde{b}_R$	$\tilde{t}_1\ \tilde{t}_2\ \tilde{b}_1\ \tilde{b}_2$	-
sleptons	0	$\tilde{e}_L\ \tilde{e}_R\ \tilde{\nu}_e$	-	-
		$\tilde{\mu}_L\ \tilde{\mu}_R\ \tilde{\nu}_\mu$	-	-
		$\tilde{\tau}_L\ \tilde{\tau}_R\ \tilde{\nu}_\tau$	$\tilde{\tau}_1\ \tilde{\tau}_2\ \tilde{\nu}_\tau$	-
neutralino	1/2	$\tilde{B}\ \tilde{W}^3\ \tilde{H}_u^0\ \tilde{H}_d^0$	$\tilde{\chi}_1^0\ \tilde{\chi}_2^0\ \tilde{\chi}_3^0\ \tilde{\chi}_4^0$	$M_1, M_2, \mu, \tan\beta$
chargino	1/2	$\tilde{W}^\pm\ \tilde{H}_u^+\ \tilde{H}_d^-$	$\tilde{\chi}_1^\pm\ \tilde{\chi}_2^\pm$	$\mu, M_2, \tan\beta$
gluino	1/2	$\tilde{g}$	-	-
gravitino	3/2	$\tilde{G}$	-	$m_{\tilde{G}} = 1$ eV

- Only 7 SUSY particles below 1 TeV, other decoupled
- 4D theory parameter space: $M_1, M_2, \mu, \tan\beta$
- Light gravitino for prompt decay of lightest neutralino/chargino

EW MSSM + $\tilde{G}$

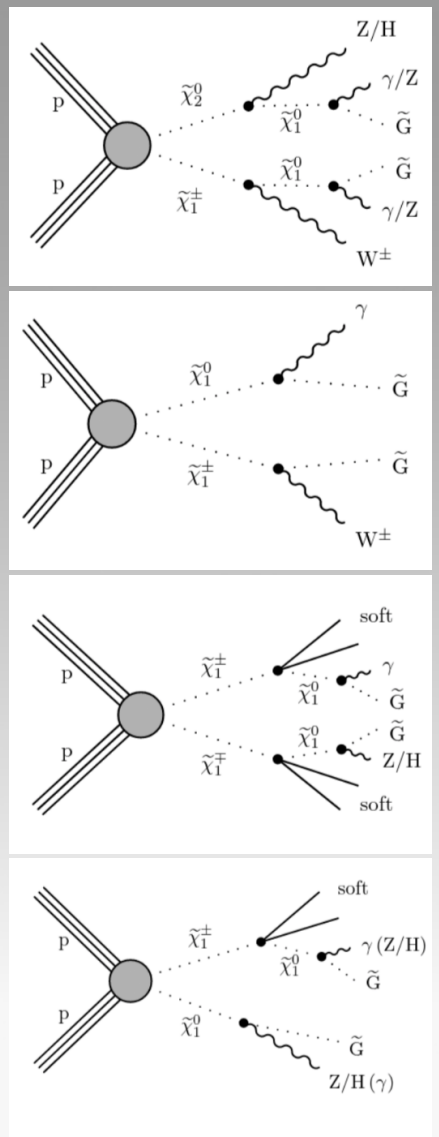
- Three phenomenological scenarios
  - → Wino NLSP: $M_2 < M_1, \mu \quad \rightsquigarrow \quad \tilde{\chi}_1^0 \to \{Z, \gamma\}\tilde{G}, \; \tilde{\chi}_1^\pm \to W^\pm \tilde{G}$
  - → Higgsino NLSP: $\mu < M_1, M_2 \quad \rightsquigarrow \quad \tilde{\chi}_1^0 \to \{Z, h\}\tilde{G}, \; \tilde{\chi}_2^0, \tilde{\chi}_1^\pm \to f^\pm f^{\pm,0} \tilde{\chi}_1^0, \{Z, h, W\}\tilde{G}$
  - → Bino NLSP: $M_1 < M_2, \mu \quad \rightsquigarrow \quad \tilde{\chi}_1^0 \to \gamma \tilde{G}$
- Heavier $\tilde{\chi}_i^0/\tilde{\chi}_i^\pm$ decay to NLSP with multiple $\{Z, W^\pm, h\}$
- Chargino NLSP extremely rare





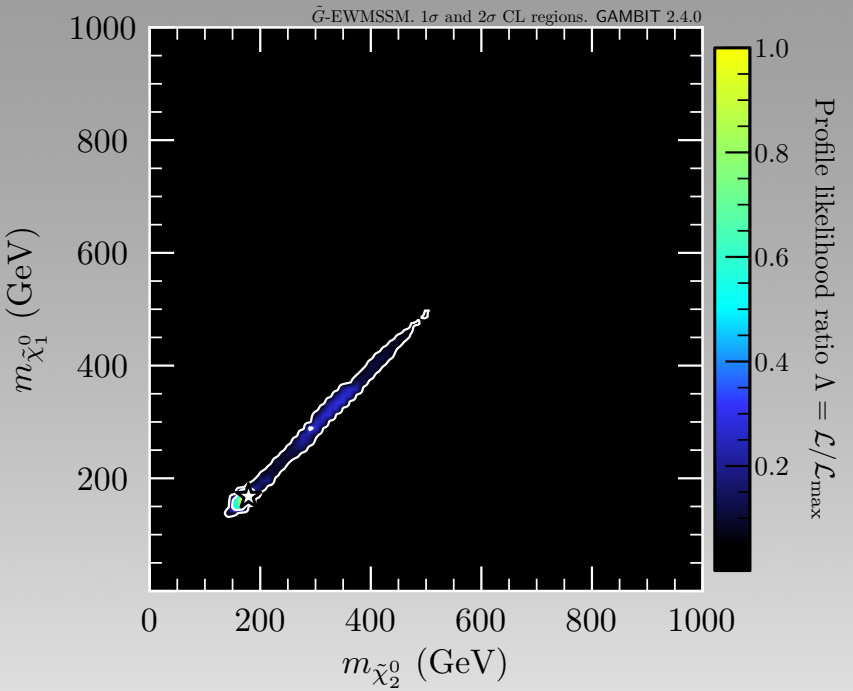
EW MSSM + $\tilde{G}$

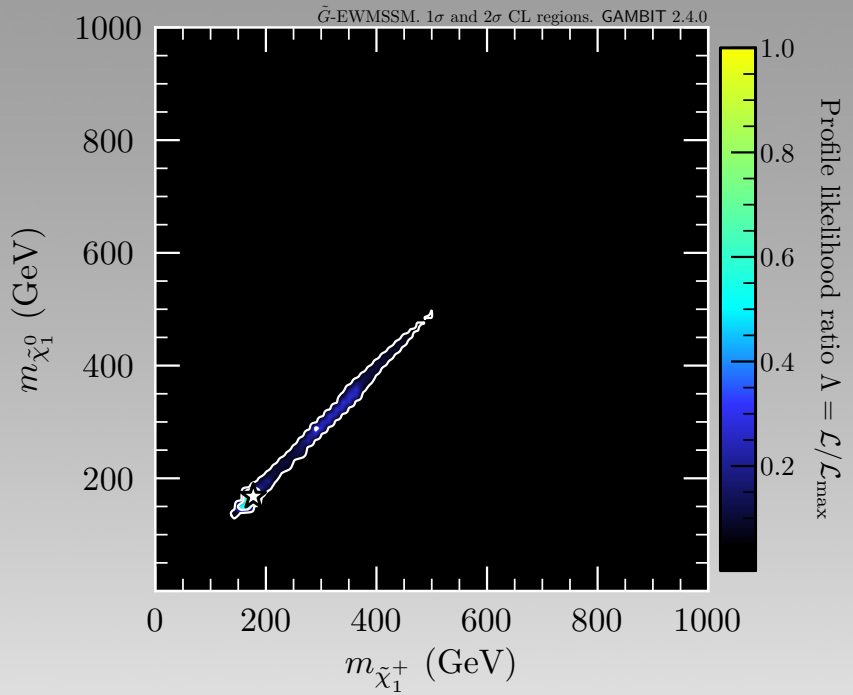
- LHC SUSY searches
  - → 15 ATLAS and 12 CMS Run 2
  - → $\gamma + E_{\mathrm{T}}^{\mathrm{miss}}$
  - → 2/3/4 leptons + $E_{\mathrm{T}}^{\mathrm{miss}}$
  - → 0/1/2 leptons + $\tilde{t}$ + $E_{\mathrm{T}}^{\mathrm{miss}}$
  - → 2/3 b-jets + 0/1 lepton + $E_{\mathrm{T}}^{\mathrm{miss}}$
  - → multiple jets + $E_{\mathrm{T}}^{\mathrm{miss}}$
- LHC "SM" xsec measurements
  - → 22 pools with 45 ATLAS, CMS and LHCb measurements
  - → $pp \to ZZ \to 4l$
  - → $pp \to W^+W^- \to ll'(j) + E_{\mathrm{T}}^{\mathrm{miss}}$
  - → $pp \to Z\gamma \to ll\gamma$
- LEP xsection constraints
  - → $\chi^{\pm} \to \mathrm{SM} + \tilde{G}$
  - → L3 search $\chi^0 \to \gamma + \tilde{G}$



Results

- Profile likelihoods for neutralinos and charginos





$\rightarrow$ Preferred scenario are Higgsino-like, i.e. $\mu < M_1, M_2$

$\rightarrow$ At 2σ, $\mu < 0, \tan\beta \sim 1$, $\Rightarrow$ 140 GeV $< \tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_1^\pm <$ 500 GeV

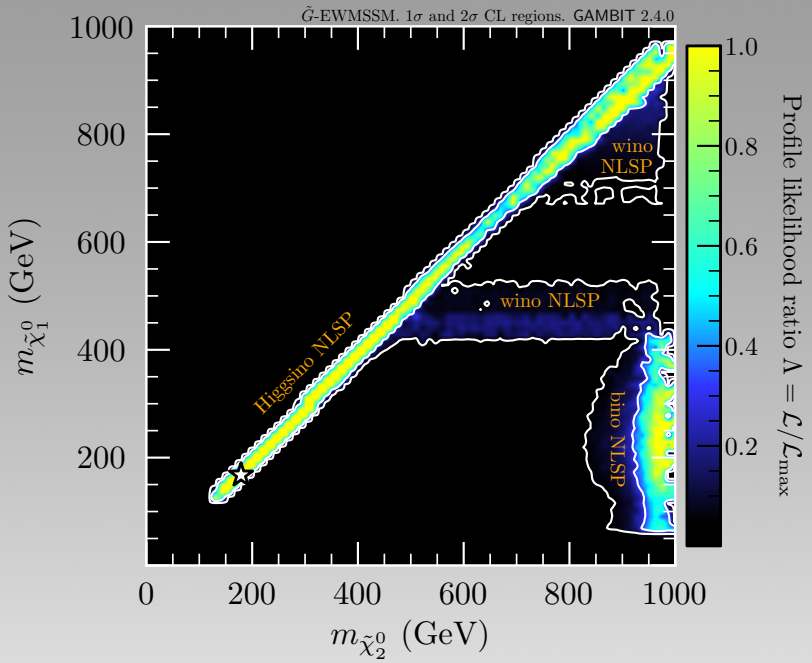
$\rightarrow$ Dominant channels are $\tilde{\chi}_1^0 \rightarrow h\tilde{G}$, $\tilde{\chi}_1^0 \rightarrow Z\tilde{G}$

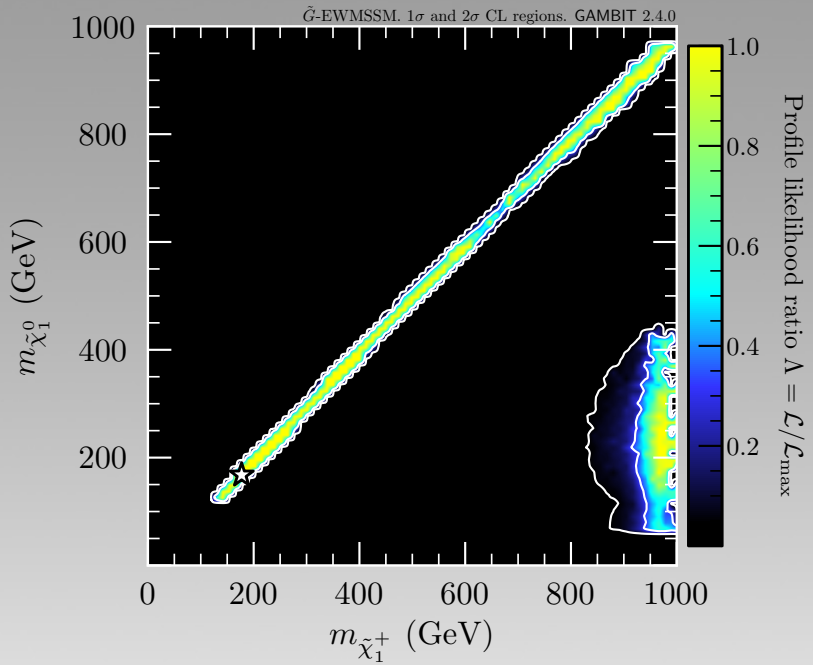
$\rightarrow$ Fits excess is leptons + $E_{\mathrm{T}}^{\mathrm{miss}}$and b-jets + $E_{\mathrm{T}}^{\mathrm{miss}}$searches

$\rightarrow$ Simultaneous fit to multi-lepton and multi-b signal regions

EW MSSM + $\tilde{G}$

- "Capped" likelihood (exclusion-only)





→ Largest suriving region Higgsino NSLP

→ γ + MET searches exclude binos < 800 GeV

→ l + MET excludes wino except at > 600 GeV and ~ 450 GeV due to excesses

→ SM cross section measurements kill lowest masses

Results

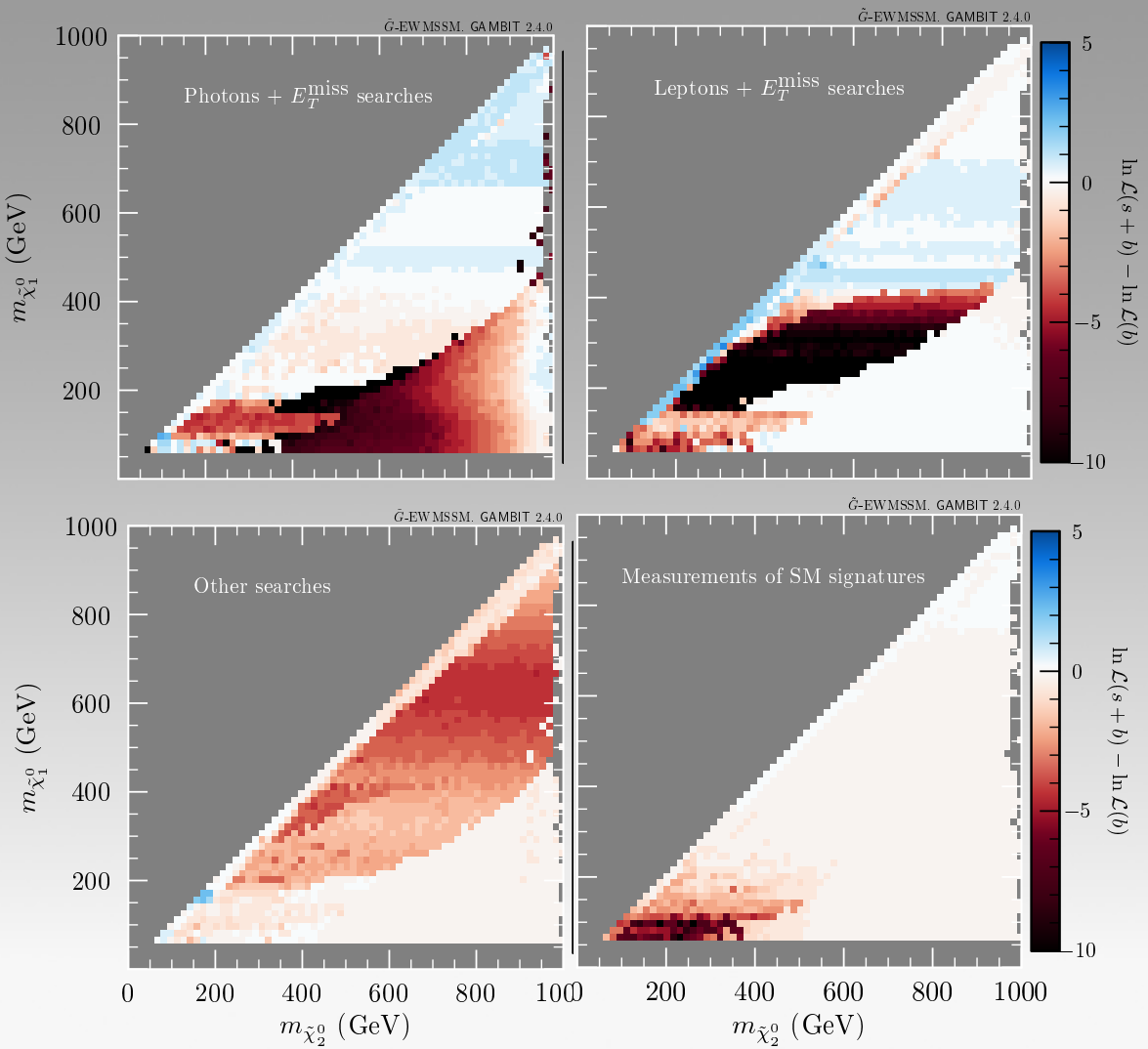
- Impact of searches and measurements

→ Photon searches exclude low mass binos

→ Lepton searches exclude low mass winos

→ Boosted boson searches exclude high mass winos

→ Measurements exclude low mass Higgsino and winos



Conclusions

- GAMBIT updates
  - → Some updates and a lot of work in progress in ColliderBit
  - → Simultaneous search and measurement combination
  - → CBS around the corner (hopefully)
  - → Many recent analyses being implemented right now
- EWMSSM with gravitino
  - → EW MSSM interesting as it remains somewhat unconstrained
  - → Light gravitino motivated by GMSB and interesting phenomenology
  - → First time combining unfolded "SM" measurements with reco-level searches
  - → We find slight preference for light Higgsinos $140 - 500$ GeV
  - → Most parameter space exluded except a few critial regions:
    - * Degenerate Higgsinos, difficult to exclude
    - * Winos at ~ 450 GeV or > 700 GeV
    - * Lonely bino with $m_{\tilde{\chi}_1^0} > 60$ GeV and $m_{\tilde{\chi}_2^0} > 800$ GeV

Backup

Analyses

ATLAS_2BoostedBosons	$139\,\mathrm{fb}^{-1}$	ATLAS hadronic chargino/neutralino search
ATLAS_0lep	$139\,\mathrm{fb}^{-1}$	ATLAS 0-lepton search
ATLAS_0lep_stop	$36\,\mathrm{fb}^{-1}$	ATLAS 0-lepton stop search
ATLAS_1lep_stop	$36\,\mathrm{fb}^{-1}$	ATLAS 1-lepton stop search
ATLAS_2lep_stop	$139\,\mathrm{fb}^{-1}$	ATLAS 2-lepton stop search
ATLAS_2OSlep_Z	$139\,\mathrm{fb}^{-1}$	ATLAS stop search with Z/H final states
ATLAS_2OSlep_chargino	$139\,\mathrm{fb}^{-1}$	ATLAS 2-lepton chargino search
ATLAS_2b	$36\,\mathrm{fb}^{-1}$	ATLAS 2-b-jet stop/sbottom search
ATLAS_3b	$24\,\mathrm{fb}^{-1}$	ATLAS 3-b-jet Higgsino search
ATLAS_3lep	$139\,\mathrm{fb}^{-1}$	ATLAS 3-lepton chargino/neutralino search
ATLAS_4lep	$139\,\mathrm{fb}^{-1}$	ATLAS 4-lepton search
ATLAS_MultiLep_strong	$139\,\mathrm{fb}^{-1}$	ATLAS leptons + jets search
ATLAS_PhotonGGM_1photon	$139\,\mathrm{fb}^{-1}$	ATLAS 1-photon GGM search
ATLAS_PhotonGGM_2photon	$36\,\mathrm{fb}^{-1}$	ATLAS 2-photon GGM search
ATLAS_Z_photon	$80\,\mathrm{fb}^{-1}$	ATLAS Z + photon search
CMS_0lep	$137\,\mathrm{fb}^{-1}$	CMS 0-lepton search
CMS_1lep_bb	$36\,\mathrm{fb}^{-1}$	CMS 1-lepton + b-jets chargino/neutralino search
CMS_1lep_stop	$36\,\mathrm{fb}^{-1}$	CMS 1-lepton stop search
CMS_2lep_stop	$36\,\mathrm{fb}^{-1}$	CMS 2-lepton stop search
CMS_2lep_soft	$36\,\mathrm{fb}^{-1}$	CMS 2 soft lepton search
CMS_2OSlep	$137\,\mathrm{fb}^{-1}$	CMS 2-lepton search
CMS_2OSlep_chargino_stop	$36\,\mathrm{fb}^{-1}$	CMS 2-lepton chargino/stop search
CMS_2SSlep_stop	$137\,\mathrm{fb}^{-1}$	CMS 2 same-sign lepton stop search
CMS_MultiLep	$137\,\mathrm{fb}^{-1}$	CMS multilepton chargino/neutralino search
CMS_photon	$36\,\mathrm{fb}^{-1}$	CMS 1-photon GMSB search
CMS_2photon	$36\,\mathrm{fb}^{-1}$	CMS 2-photon GMSB search
CMS_1photon_1lepton	$36\,\mathrm{fb}^{-1}$	CMS 1-photon + 1-lepton GMSB search

Measurements

ATLAS_13_4L
ATLAS_13_EEJET
ATLAS_13_GAMMA
ATLAS_13_JETS
ATLAS_13_L1L2MET
ATLAS_13_L1L2METJET
ATLAS_13_L1L2MET_GAMMA
ATLAS_13_LLJET
ATLAS_13_LL_GAMMA
ATLAS_13_LMETJET
ATLAS_13_LMET_GAMMA
ATLAS_13_METJET
ATLAS_13_MMJET
ATLAS_13_TTHAD

CMS_13_EEJET
CMS_13_HMDY
CMS_13_JETS
CMS_13_LMETJET
CMS_13_MMETJET
CMS_13_MMJET
CMS_13_TTHAD
LHCB_13_L1L2B

Collider likelihoods

- No background covariance info → SR with best expeted sensitivity

$$\mathcal{L}(s_i, \gamma_i) = \left[\frac{(s_i + b_i + \gamma_i)_i^n e^{-(s_i+b_i+\gamma_i)}}{n_i!} \right] \times \frac{1}{\sqrt{2\pi}\sigma_i} e^{-\frac{\gamma_i^2}{2\sigma_i^2}}$$

- CMS analyses provide covariance matrices for bkg uncertainties

$$\mathcal{L}(\mathbf{s}, \boldsymbol{\gamma}) = \prod_{i=1}^{n_{\mathrm{SR}}} \left[\frac{(s_i + b_i + \gamma_i)_i^n e^{-(s_i+b_i+\gamma_i)}}{n_i!} \right] \times \frac{1}{\sqrt{\det 2\pi \boldsymbol{\Sigma}}} e^{-\frac{1}{2}\boldsymbol{\gamma}^T \boldsymbol{\Sigma}^{-1} \boldsymbol{\gamma}}$$

- SM measurement likelihood

$$\ln \mathcal{L}_{\mathrm{meas}}(\boldsymbol{s}) = - \sum_{i \in \mathrm{activebins}} \left[\frac{y_i^{s+b}(\boldsymbol{s}) - y_i^{\mathrm{obs}}}{\Delta y_i} \right]^2 /2$$

- "Capped" likelihood $\Delta \ln \mathcal{L}^{\mathrm{cap}}(\boldsymbol{s}) = \min[\Delta \ln \mathcal{L}(\boldsymbol{s}), \Delta \ln \mathcal{L}(\boldsymbol{s} = 0)]$

Scan framework

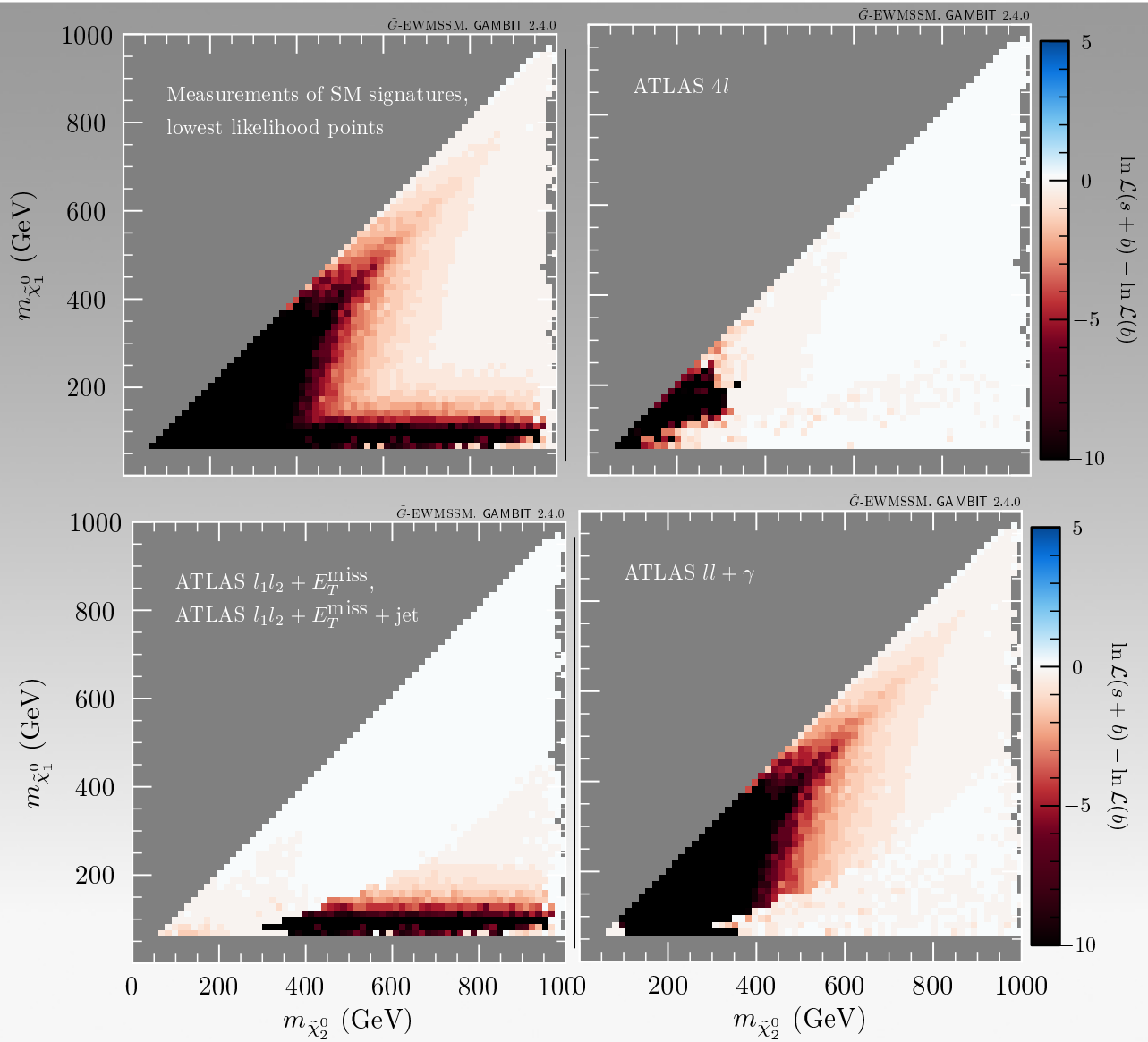
- GAMBIT modules used for the scan
  - → SpecBit ⇝ one-loop spectrum with FlexibleSUSY
  - → DecayBit ⇝ $\tilde{\chi}^{0,\pm} \to \tilde{\chi}^{0,\pm}$ decays with SUSY-HIT
    $\chi^{0,\pm} \to \tilde{G}$ decays native
  - → ColliderBit ⇝ MC event generation with Pythia 8
    detector simulation with BuckFast
    LHC search emulation native
    SM measurements with Rivet and Contur
  - → ScannerBit ⇝ sampling using diver

- Parameter ranges

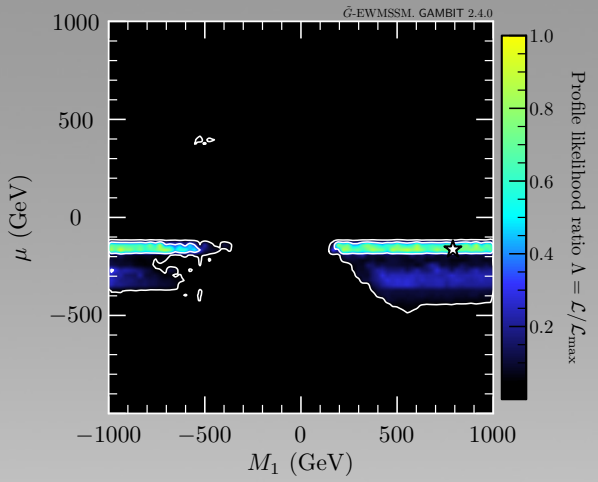
$M_1(Q)$	$[-1, 1]$ TeV	hybrid, flat
$M_2(Q)$	$[0, 1]$ TeV	hybrid, flat
$\mu(Q)$	$[-1, 1]$ TeV	hybrid, flat
$\tan\beta(m_Z)$	$[1, 70]$	log, flat
$m_{\tilde{G}}$	1 eV	fixed

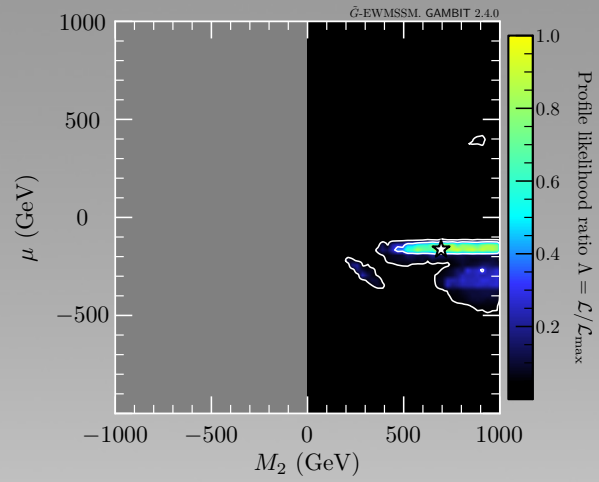
- Scan details
  - → diver 1.0.4 self-adaptive rand/1/bin evolution
  - → 16M MC events for LHC searches
  - → 100k MC events for measurements
  - → 3.1×10^5 parameter samples

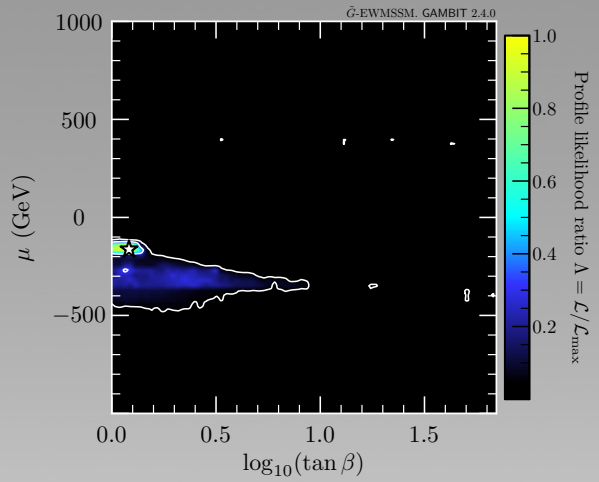
Exclusion power of measurements

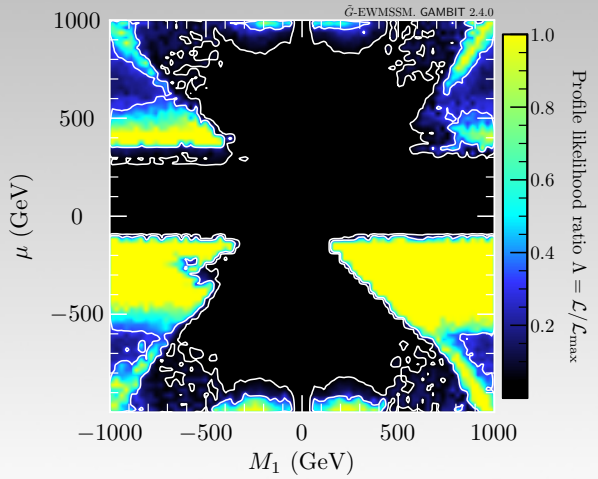


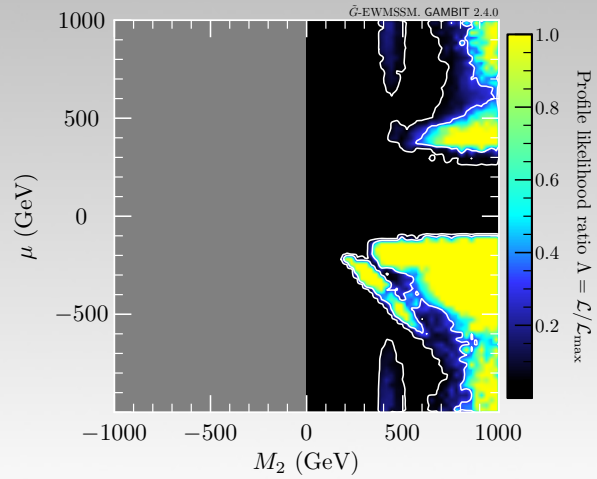
Profile likelihoods

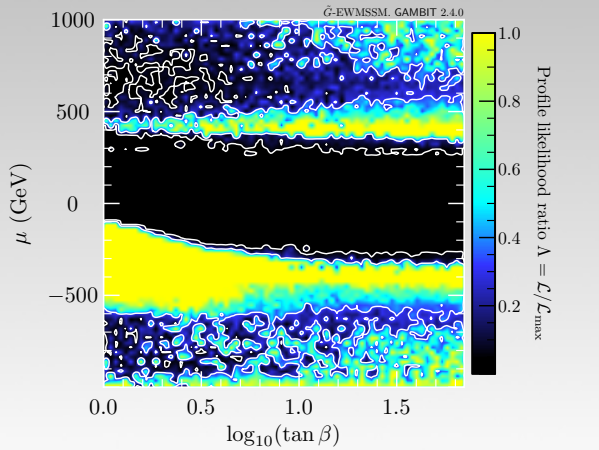








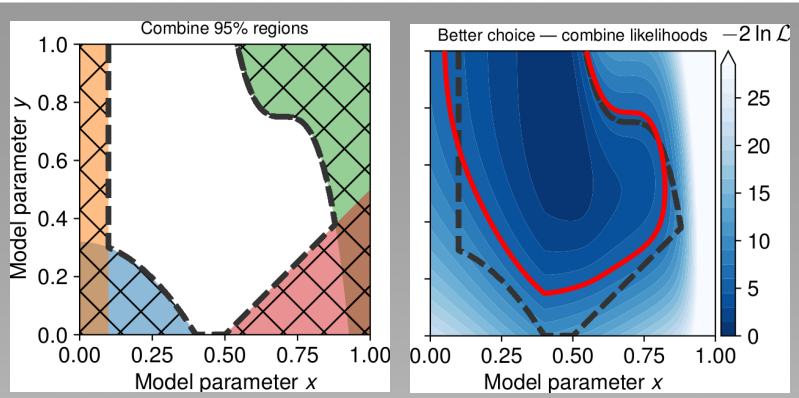




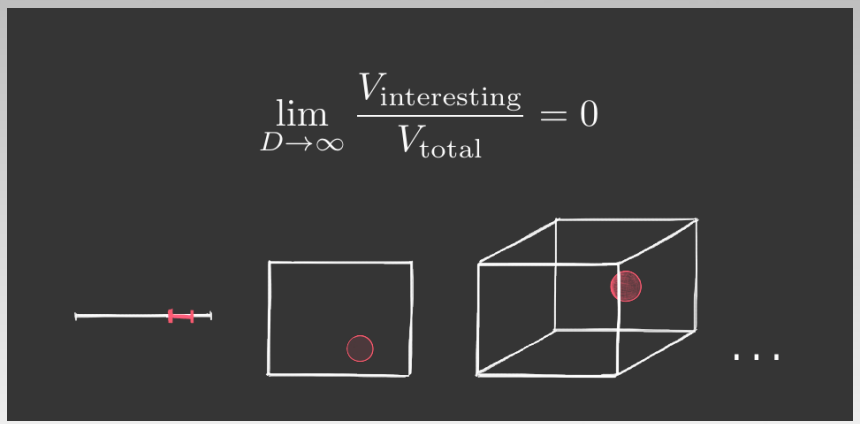
Global Fits

- Many constraints in BSM models
- Exclusion regions do not properly represent the model predictions
- Composite likelihood

$$\mathcal{L} = \mathcal{L}_{Collider}\mathcal{L}_{Higgs}\mathcal{L}_{DM}\mathcal{L}_{Flavour}\cdots$$



[arXiv:2012.09874 [hep-ph]]



- Multitude of parameters
- Hard to find interesting regions
- Random methods are inefficient
- Need smart sampling strategies (differential, nested, genetic,...)

- Rigorous statisical interpretations (frequentist / Bayesian)
- Parameter estimation, goodness-of-fit, model comparison, ...

Core

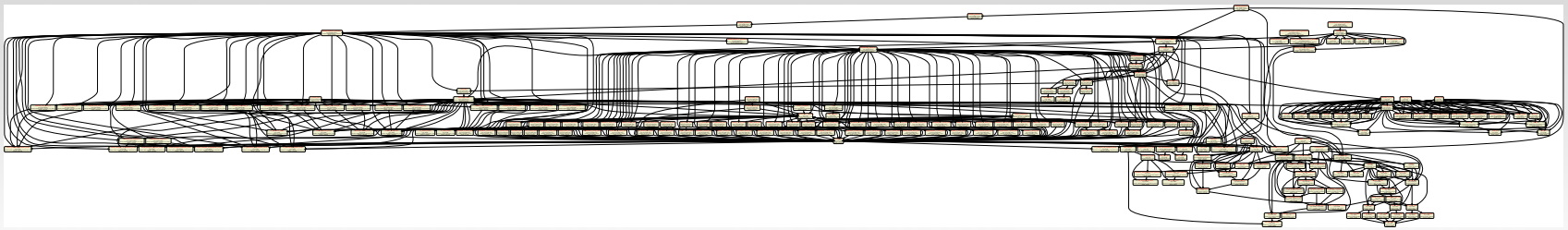
- Each module contains a collection of module functions
- Module functions provide a *capability*
- They have dependencies and backend requirements
- Allowed for specific models
- At run time a dependency tree is generated and resolved

```
// SM-like Higgs mass with theoretical uncertainties
#define CAPABILITY prec_mh
START_CAPABILITY

  #define FUNCTION FH_HiggsMass
  START_FUNCTION(triplet<double>)
  DEPENDENCY(unimproved_MSSM_spectrum, Spectrum)
  DEPENDENCY(FH_HiggsMasses, fh_HiggsMassObs)
  ALLOW_MODELS(MSSM63atQ, MSSM63atMGUT)
  #undef FUNCTION

  #define FUNCTION SHD_HiggsMass
  START_FUNCTION(triplet<double>)
  DEPENDENCY(unimproved_MSSM_spectrum, Spectrum)
  BACKEND_REQ(SUSYHD_MHiggs, (), MReal, (const MList<MReal>&))
  BACKEND_REQ(SUSYHD_DeltaMHiggs, (), MReal, (const MList<MReal>&))
  ALLOW_MODELS(MSSM63atQ, MSSM63atMGUT)
  #undef FUNCTION

#undef CAPABILITY
```

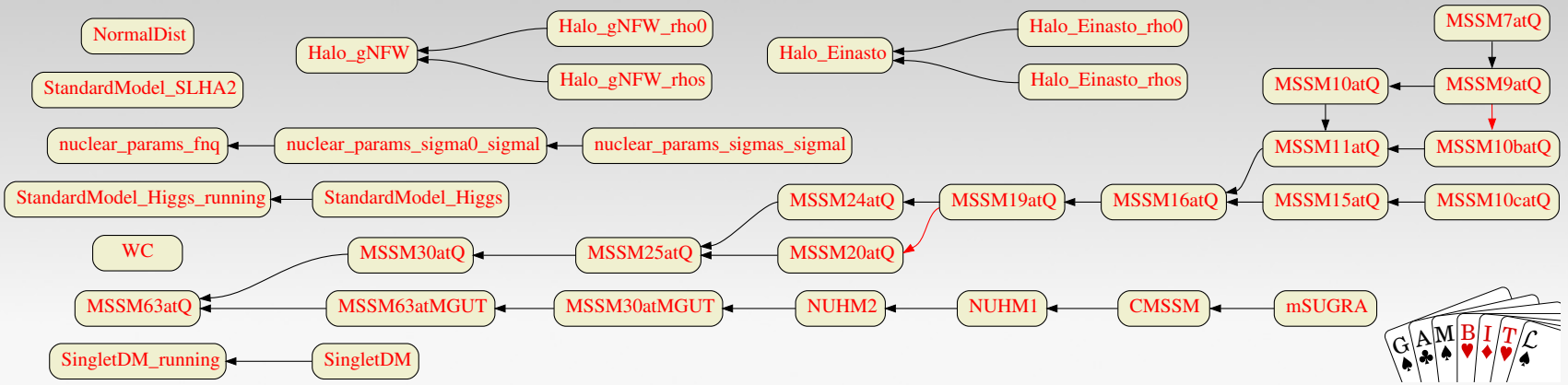


Models

- Extensive model database

SUSY	DM	Cosmo	Others
CMSSM	S, F, V HP Singlet	ΛCDM	SM
NUHM1,2	S, F, V Simplified	$\Delta N_{\rm eff}$	RH neutrinos
MSSM63	Axions	Power-law	WC
MSSM63+mG	DMEFT	inflation	nuisance models

- Parent-daughter hierarchy
- Module functions are activated for each model



Backends

CosmoBit

Acropolis 1.2.1
AlterBBN 2.2
DarkAges 1.2.0
MontePythonLike 3.5.0
MultiModeCode 2.0.0
classy 3.1.0
plc 3.0

DarkBit

CaptnGeneral 2.1
DDCalc 2.3.0
DarkSUSY 6.4.0
DirectDM 2.2.0
MicrOmegas 3.6.9.2
gamLike 1.0.1
nulike 1.0.9
pbarlike 1.0

ColliderBit

Contur 2.1.1
HiggsBounds 4.3.1
HiggsSignals 1.4
Pythia 8.212
Rivet 3.1.5
nulike 1.0.9
phy 0.7

PrecisionBit

FeynHiggs 2.12.0
SUSYHD 1.0.2
gm2calc 1.3.0

SpecBit

FlexibleSUSY 2.0.1
SPheno 4.0.3
Vevacious 1.0

FlavBit

HepLike 2.0
HepLikeData 1.4
SuperISO 3.6

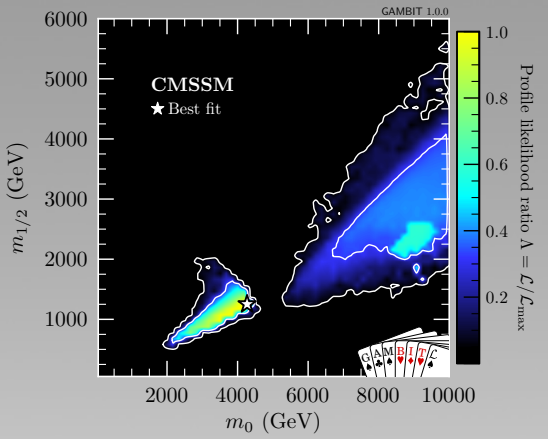
DecayBit

CalcHEP 3.6.27
SUSY_HIT 1.5

Scan framework

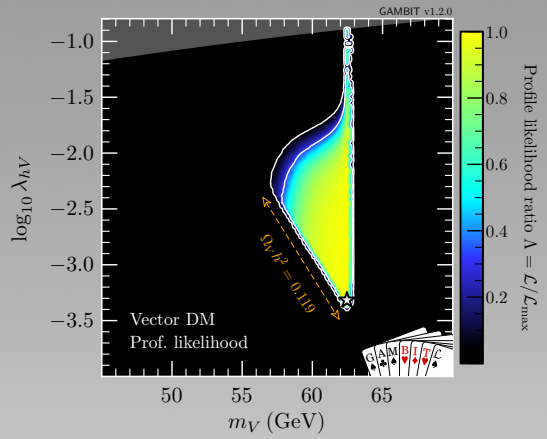
CMSSM

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



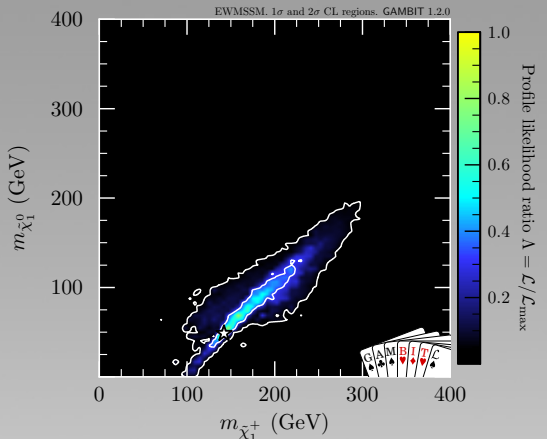
Higgs-portal DM

[Eur.Phys.J.C 79 (2019) 1, 38]



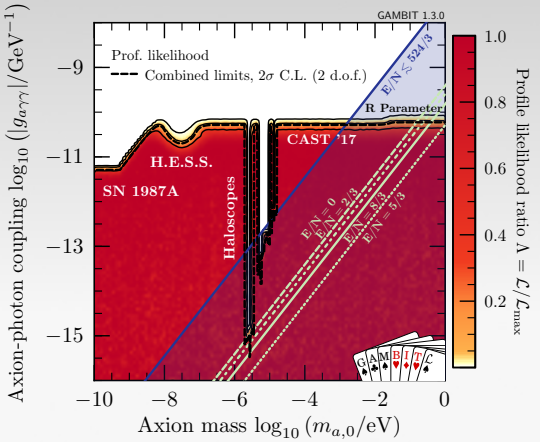
MSSM-EW

[Eur.Phys.J.C 79 (2019) 5, 395]



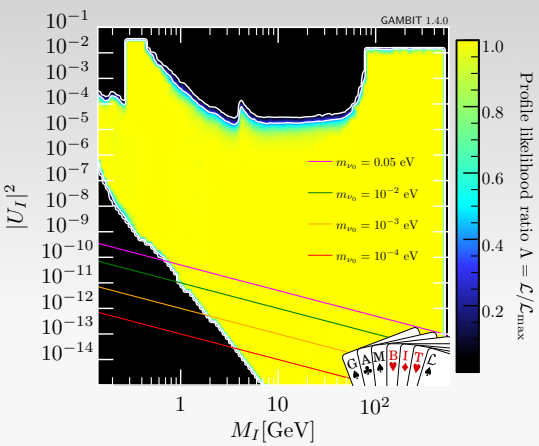
QCD axions

[JHEP 03 (2019) 191]



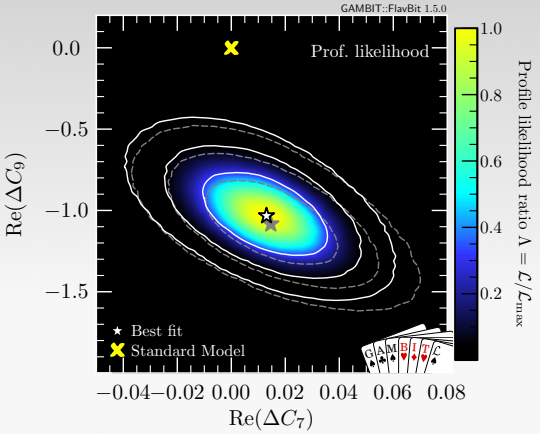
Right-Handed Neutrinos

[Eur.Phys.J.C 80 (2020) 6, 569]



Flavour EFT

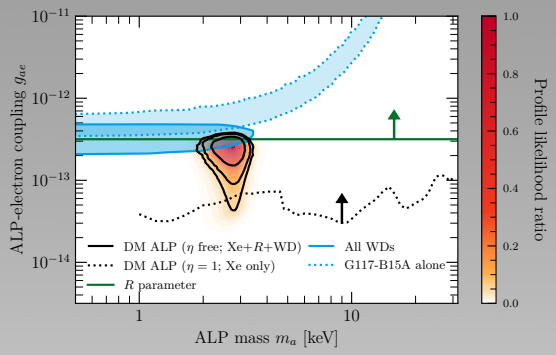
[Eur.Phys.J.C 81 (2021)12,1076]



Scan framework

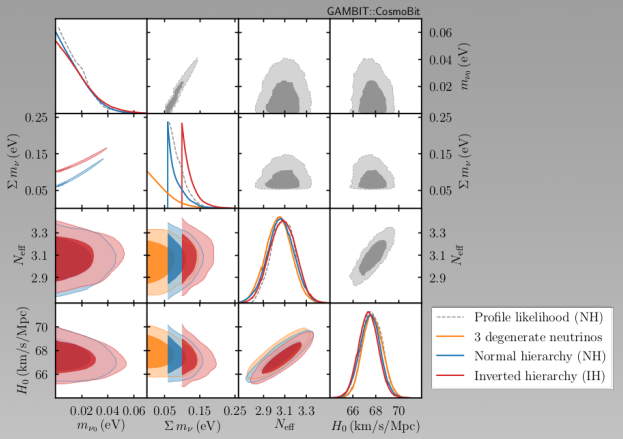
DM ALPs

[JHEP 05 (2021) 159]



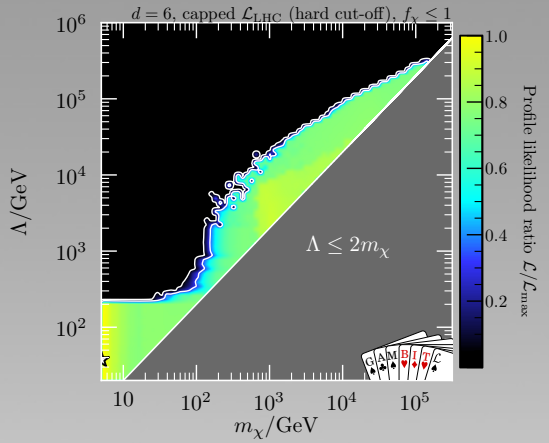
Neutrino Masses

[Phys.Rev.D 103(2021)12,123508]



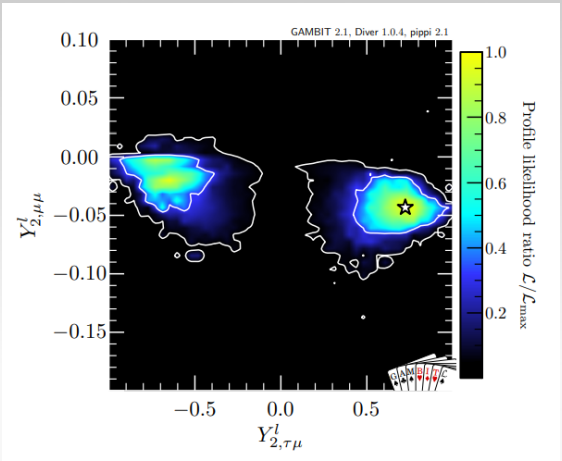
DMEFT

[Eur.Phys.J.C 81 (2021) 11,992]



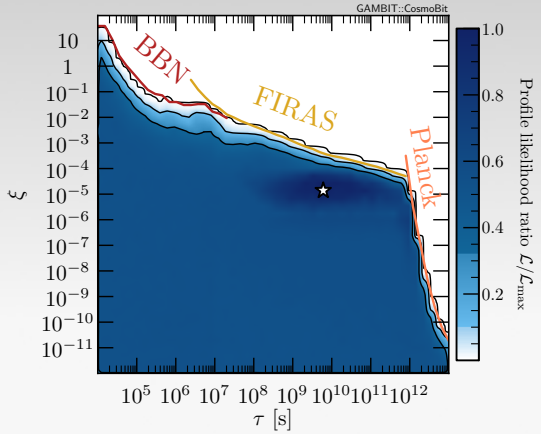
THDM-III

[JHEP 01 (2022) 037]



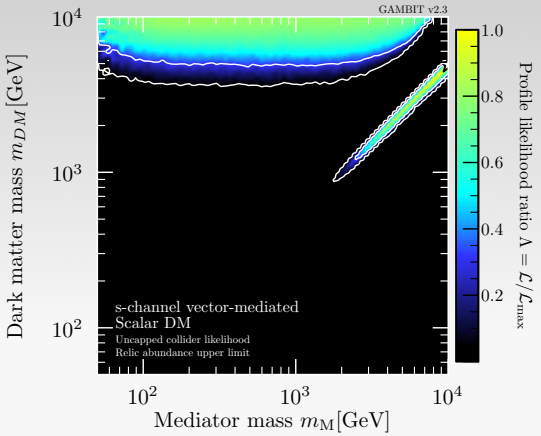
Cosmo ALPs

[JCAP 12 (2022) 027]



S-channel DM

[arXiv:2209.13266 [hep-ph]]



An example run