Status of supersymmetric models with GAMBIT

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on behalf of the GAMBIT collaboration

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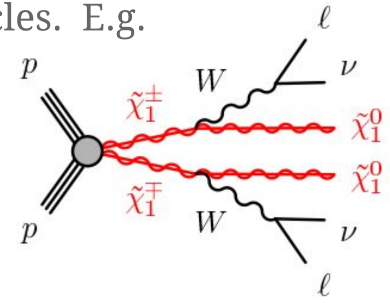
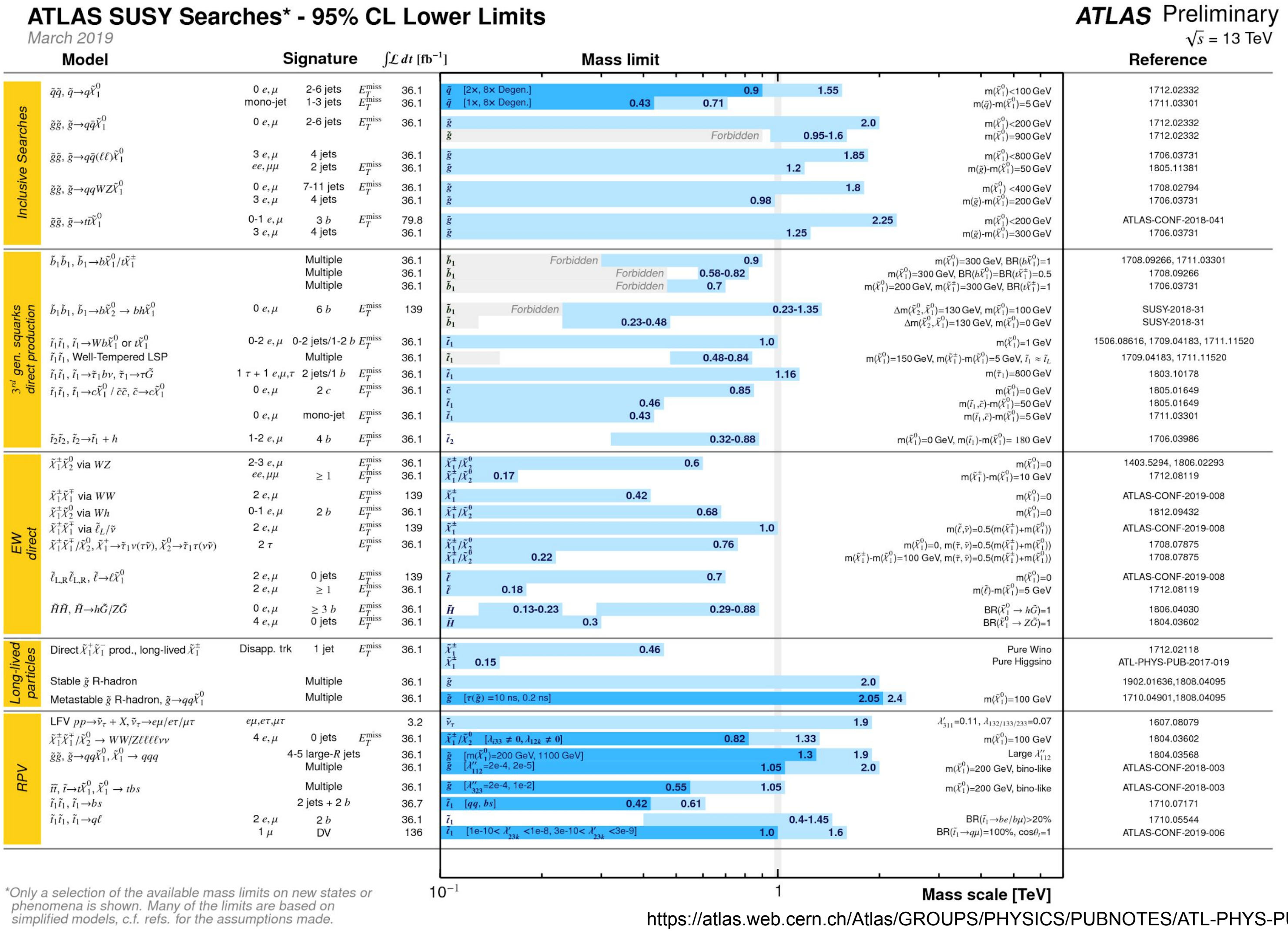
Imperial College London

1. Motivation

- No clear evidence of supersymmetry at LHC
  - ...so set limits on SUSY models
- But, the general MSSM has many free parameters
  - -> very difficult to explore thoroughly
- ATLAS and CMS have opted for a search strategy optimised around "simplified models";
  - simple SUSY-like models where one or two SUSY particles added, with certain assumptions about how they decay to SM particles. E.g.
- What might these searches miss?





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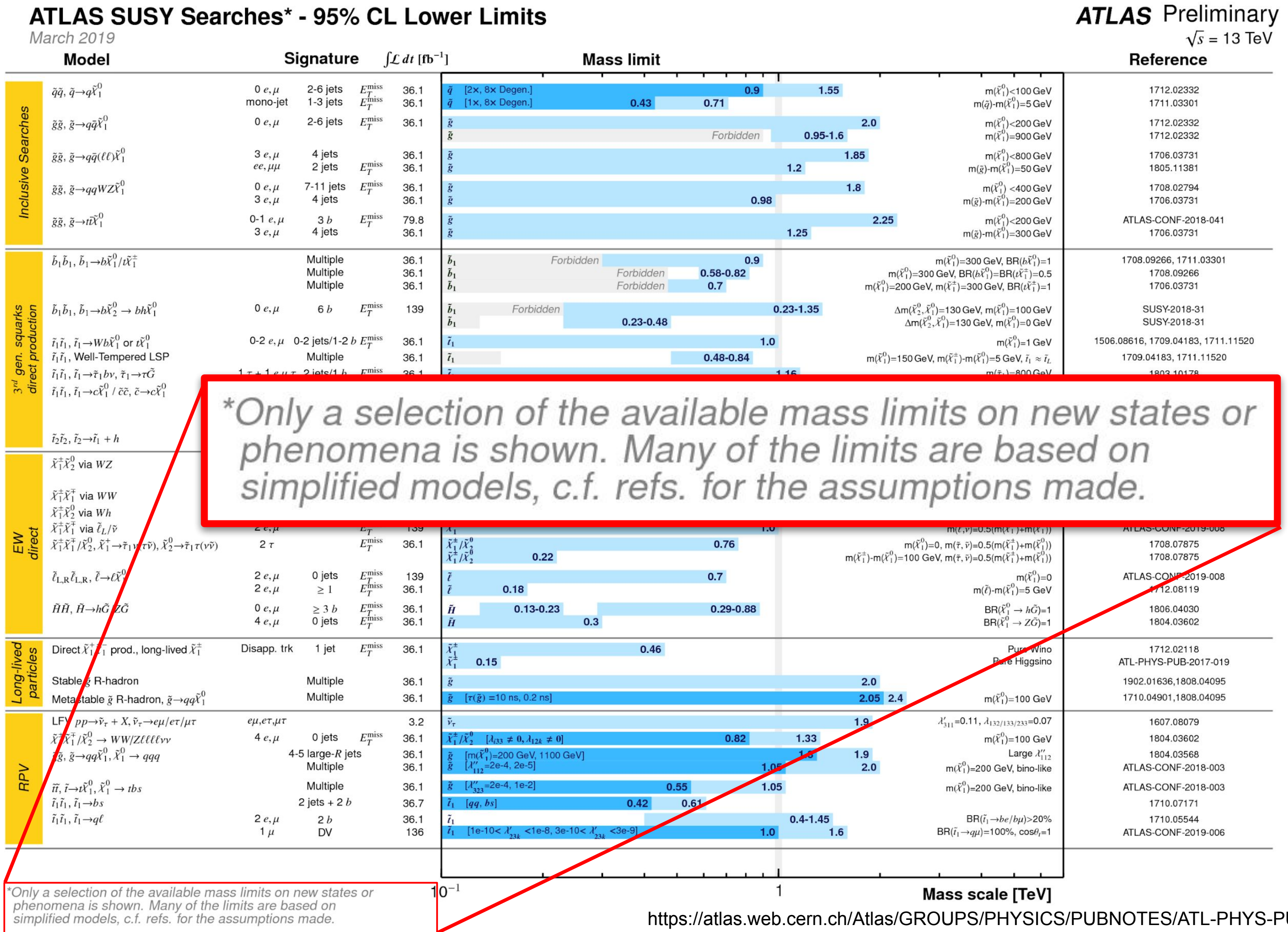
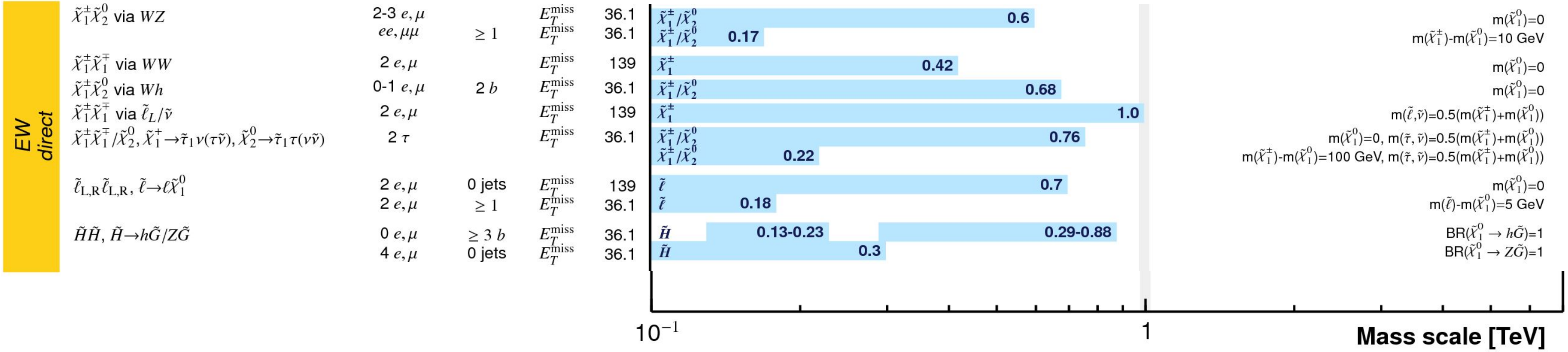


*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2019-012/fig_08.png

How light could the electroweak sector of the MSSM still be?



- **Limits from EW direct production pushing to TeV scale?**

2. Analysis

Light SUSY is alive!

Theory: MSSM particle content

Slide credit: *Anders Kvellestad*

Name	Spin	P_R	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)

Decoupled

Theory: parameter space

M_1 M_2 μ $\tan\beta$

Slide credit: *Anders Kvellestad*

Neutralinos

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

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

Charginos

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

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

Theory: parameter space

M_1 M_2 μ $\tan\beta$

Slide credit: *Anders Kvellestad*

Neutralinos

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

$M_N =$

Rough summary:

M_1 controls the mass of **one neutralino**

M_2 controls the mass of **one neutralino** and **one chargino**

μ controls the mass of **two neutralinos** and **one chargino**

inos

$\tilde{H}_d^-)$

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

"EWMSSM"

- Only electroweak sector of MSSM kept light
- Everything else decoupled
- 4 parameters: $M_1, M_2, \mu, \tan\beta$
  - Manageable! But still a lot of non-trivial physics beyond what simplified models can capture.
  - 6 new particles: 4 neutralinos + 2 charginos

Strategy

- Focus on 13 TeV searches
- Scan 4D EWMSSM parameter space
- ***At every point***: Run MC simulations of 13 TeV searches
- Compute joint likelihood function for all searches

How? -> GAMBIT

gambit.hepforge.org

GAMBIT

The Global And Modular BSM Inference Tool

- An international community with 40+ collaborators (10 experiments, 14 major theory codes)
- A new software framework for global fits developed over the past six years

- First public code release in May 2017, arXiv:1705.07908 (gambit.hepforge.org)
- So far 7 physics studies:
  arXiv:1705.07917, arXiv:1705.07935
  arXiv:1705.07931, arXiv:1806.11281
  arXiv:1808.10465, arXiv:1809.02097,
  arXiv:1810.07192
  + many more in preparation

gambit.hepforge.org

GAMBIT

- Apply **wide ranges of constraints** to a given model
  - Construction of composite likelihoods
  - Efficient scans of multi-dimensional parameter space
  - Consistent treatment of uncertainties and nuisance parameters
- Maximum of **flexibility and modularity** in terms of
  - Fast definition of new data sets and models
  - Plug and play of many popular theory tools* (dynamical adaptation to user's system)
  - Large database of models and observables (+ more to come)
  - Many statistical methods (frequentist & Bayesian)
- **Optimized** for parallel computing & fully open source

* GAMBIT supports backend codes in C/C++, Fortran, Python and Mathematica

Modules

A module provides GAMBIT with a range of capabilities (the ability to calculate a certain quantity)

- **DarkBit** (arXiv:1705.07920) – dark matter observables
- **ColliderBit** (arXiv:1705.07919) – collider observables (Higgs + SUSY searches from ATLAS, CMS, LEP)
- **FlavBit** (arXiv:1705.07933) – flavour physics ($g-2$, $b \rightarrow s\gamma$, B decays)
- **SpecBit** (arXiv:1705.07936) – RGE running, masses, mixings, …
- **DecayBit** (arXiv:1705.07936) – decay widths for all relevant particles
- **PrecisionBit** (arXiv:1705.07936) – SM likelihoods, electroweak precision tests
- **ScannerBit** (arXiv:1705.07959) – manages statistics, sampling and optimisation

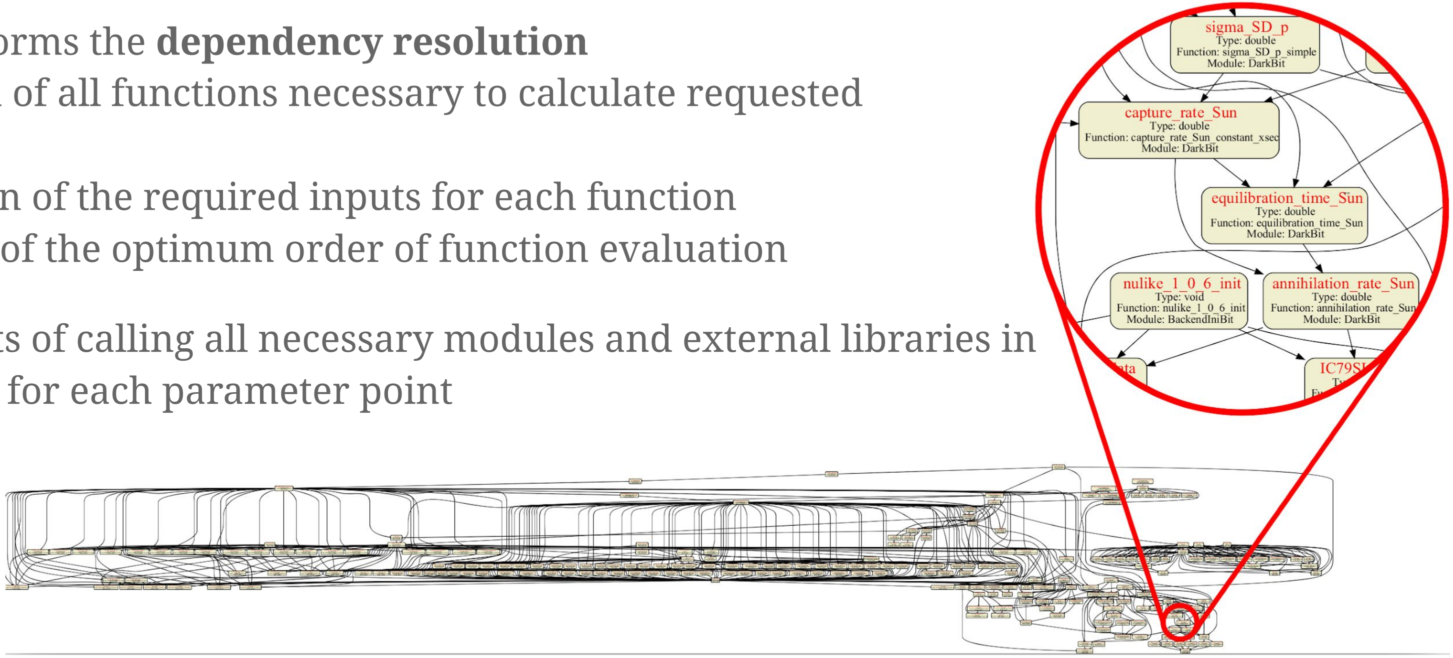
- Coming soon: NeutrinoBit & CosmoBit

gambit.hepforge.org

GAMBIT

How does GAMBIT work?

- User specifies the model, parameter space, observables and scanning technique
- GAMBIT then performs the **dependency resolution**
    - Identification of all functions necessary to calculate requested observables
    - Determination of the required inputs for each function
    - Construction of the optimum order of function evaluation
- A scan then consists of calling all necessary modules and external libraries in the required order for each parameter point



Global fits of GUT-scale SUSY models with GAMBIT

The GAMBIT Collaboration: Peter Athron[1,2,a], Csaba Balázs[1,2], Torsten Bringmann[3], Andy Buckley[4], Marcin Chrząszcz[5,6], Jan Conrad[7,8], Jonathan M. Cornell[9], Lars A. Dal[3], Joakim Edsjö[7,8], Ben Farmer[7,8,b], Paul Jackson[10,2], Abram Krislock[3], Anders Kvellestad[11,c], Farvah Mahmoudi[12,13,*], Gregory D. Martinez[14], Antje Putze[15], Are Raklev
Christopher Rogan[16], Roberto Ruiz de Austri[17], Aldo Saavedra[18,2],
Christopher Savage[11], Pat Scott[19,d], Nicola Serra[5], Christoph Wenig
Martin White[10,2,e]

arXiv: 1705.07935
EPJC 77 (2017) no.12, 824

A global fit of the MSSM with GAMBIT

The GAMBIT Collaboration: Peter Athron[1,2,a], Csaba Balázs[1,2], Torsten Bringmann[3], Andy Buckley[4], Marcin Chrząszcz[5,6], Jan Conrad[7,8], Jonathan M. Cornell[9], Lars A. Dal[3], Joakim Edsjö[7,8], Ben Farmer[7,8], Paul Jackson[10,2], Abram Krislock[3], Anders Kvellestad[11,b], Farvah Mahmoudi[12,13,*], Gregory D. Martinez[14], Antje Putze[15], Are Raklev[3], Christopher Rogan[16], Aldo Saavedra[17,2], Christopher Savage[11], Pat Scott[18,c], Nicola Serra[5], Christoph Weniger[19], Martin White[10,2,d]

arXiv: 1809.02097
EPJC 77 (2017) no.12, 879

Combined collider constraints on neutralinos and charginos

The GAMBIT Collaboration: Peter Athron[1,2], Csaba Balázs[1,2], Andy Buckley[3], Jonathan M. Cornell[4], Matthias Danninger[5], Ben Farmer[6], Andrew Fowlie[1,2,9], Tomás E. Gonzalo[10], Julia Harz[11], Paul Jackson[2,12], Rose Kudzman-Blais[5], Anders Kvellestad[6,10,a], Gregory D. Martinez[13], Andreas Petridis[2,12], Are Raklev[10], Christopher Rogan[14], Pat Scott[6], Abhishek Sharma[2,12], Martin White[2,12,b], Yang Zhang[1,2]

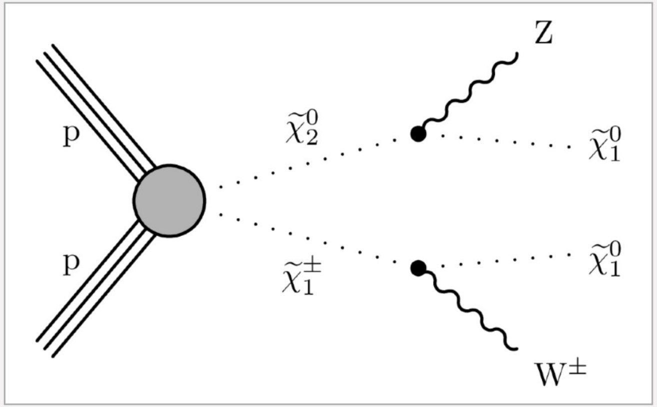
arXiv: 1809.02097
Accepted at EPJC, 3 April 2019

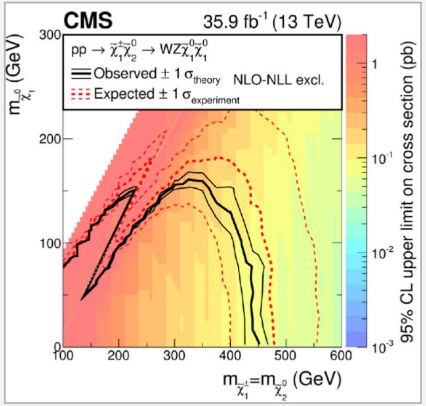
Analysis: EW SUSY searches

13 TeV, 36 fb^{-1}

Slide credit: *Anders Kvellestad*

- ATLAS Higgsino search: **ATLAS_4b**
- ATLAS ≥4 lepton search: **ATLAS_4lep**
- ATLAS multilepton EW search: **ATLAS_MultiLep_* (2lep_0jet**, **2lep_jet**, **3lep**)
- ATLAS recursive jigsaw EW search: **ATLAS_RJ_* (2lep_2jet**, **3lep**)
- CMS Wh search: **CMS_1lep_2b**
- CMS 2 soft opposite-sign lepton search: **CMS_2lep_soft** (including SR correlations)
- CMS 2 opposite-sign lepton search: **CMS_2OSlep** (including SR correlations)
- CMS multilepton EW search: **CMS_MultiLep_* (2SSlep**, **3lep**)





Included likelihoods

- Z and Higgs invisible decays

$$\Gamma(Z \to \text{inv.}) = 499.0 \pm 1.5\,\text{MeV}$$

$$\text{BF}(h \to \text{inv.}) \leq 0.19$$

- LEP cross-section limits

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 [98]
$\tilde{\chi}_i^+ \tilde{\chi}_i^-$	$\tilde{\chi}_i^+ \tilde{\chi}_i^- \to q\bar{q}' q\bar{q}' \tilde{\chi}_1^0 \tilde{\chi}_1^0$	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 [98]
	ISR γ + missing energy	OPAL [99]

- 13 TeV searches for EW SUSY

Likelihood label	Source
ATLAS_4b	ATLAS Higgsino search [104]
ATLAS_4lep	ATLAS 4ℓ search [105]
ATLAS_MultiLep_2lep_0jet	ATLAS multilepton EW search [100]
ATLAS_MultiLep_2lep_jet	ATLAS multilepton EW search [100]
ATLAS_MultiLep_3lep	ATLAS multilepton EW search [100]
ATLAS_RJ_2lep_2jet	ATLAS recursive jigsaw EW search [101]
ATLAS_RJ_3lep	ATLAS recursive jigsaw EW search [101]
CMS_1lep_2b	CMS Wh search [106]
CMS_2lep_soft	CMS 2 soft opposite-charge lepton search [109]
CMS_2OSlep	CMS 2 opposite-charge lepton search [110]
CMS_MultiLep_2SSlep	CMS multilepton EW search [111]
CMS_MultiLep_3lep	CMS multilepton EW search [111]

Joint likelihood

$$L(\mu) = \prod_i L_i(\mu)$$

- Different analyses assumed to be statistically independent
  - (no search region event overlap)
  - Also assumed signal regions with different final states to be independent

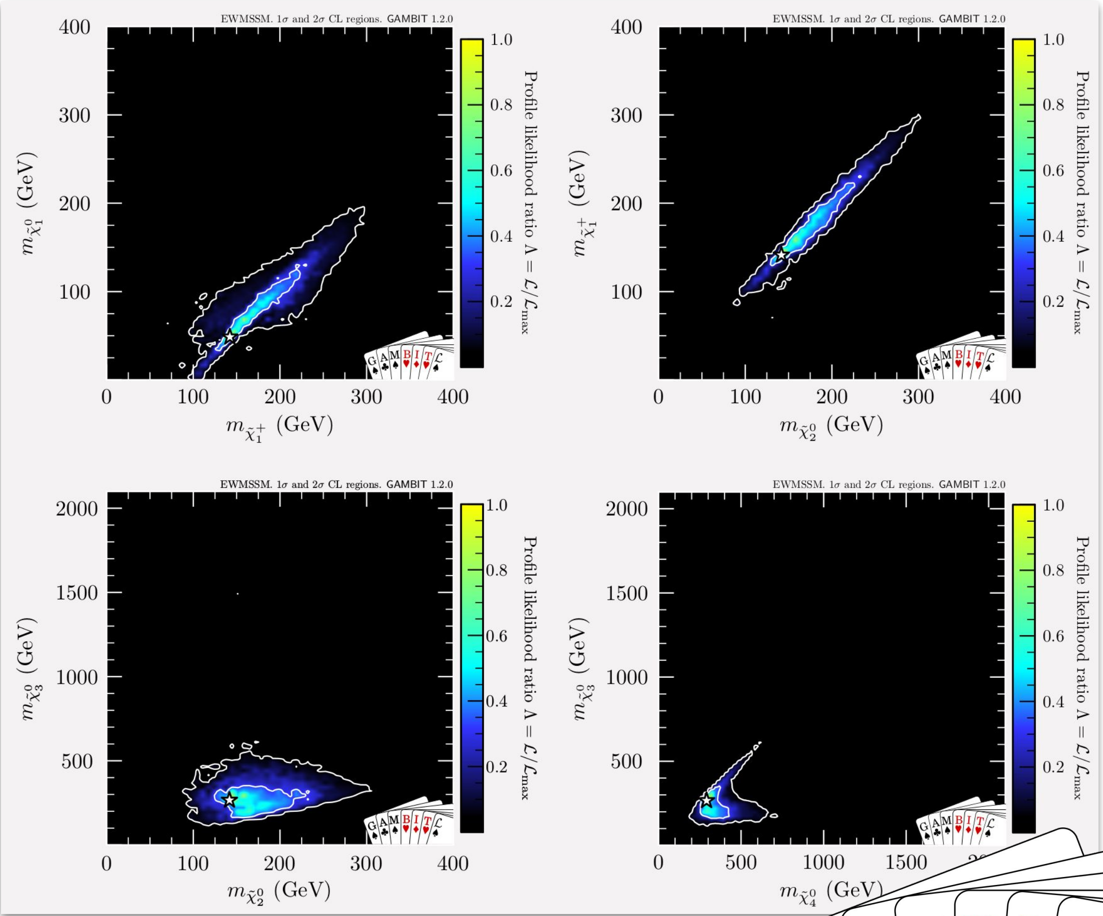
- CMS simplified likelihoods used where available
  - ...but when they aren't, "Best expected" signal region is used*
  - --> reduced exclusion power but not much choice without correlation information.

$$\mathcal{L}(\boldsymbol{s}, \boldsymbol{\gamma}) = \prod_i^{N_{\text{bin}}} \left[\frac{(s_i + b_i + \gamma_i)^{n_i} e^{-(s_i + b_i + \gamma_i)}}{n_i!} \right] \times \frac{1}{\sqrt{\det 2\pi \Sigma}} e^{-\frac{1}{2} \boldsymbol{\gamma}^T \boldsymbol{\Sigma}^{-1} \boldsymbol{\gamma}} .$$

*for p-value tests of best fit point we also combined all signal regions as if they were independent, to check potential impact of un-chosen signal regions.

Results

- Full profile likelihood
- **All** electroweakinos preferred light
- Prefers scenarios with **two large steps** $\gtrsim m_Z$ in neutralino mass hierarchy



Results

Local significance tests

+

"Goodness of fit" tests

	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

- Est. local significance ~ 3.3σ (reduced to ~2.9σ with 8 TeV analyses)
- **Optimistic summary**: Early hint of signal in multilepton final states? (not necessarily SUSY/MSSM)
- **Cool-headed summary**: Very light electroweakinos still allowed in MSSM
- Need to go **beyond simplified models** with one-step decay chains
- **Look forward to updates on ATLAS/CMS multilepton searches!**

Results

A few caveats:

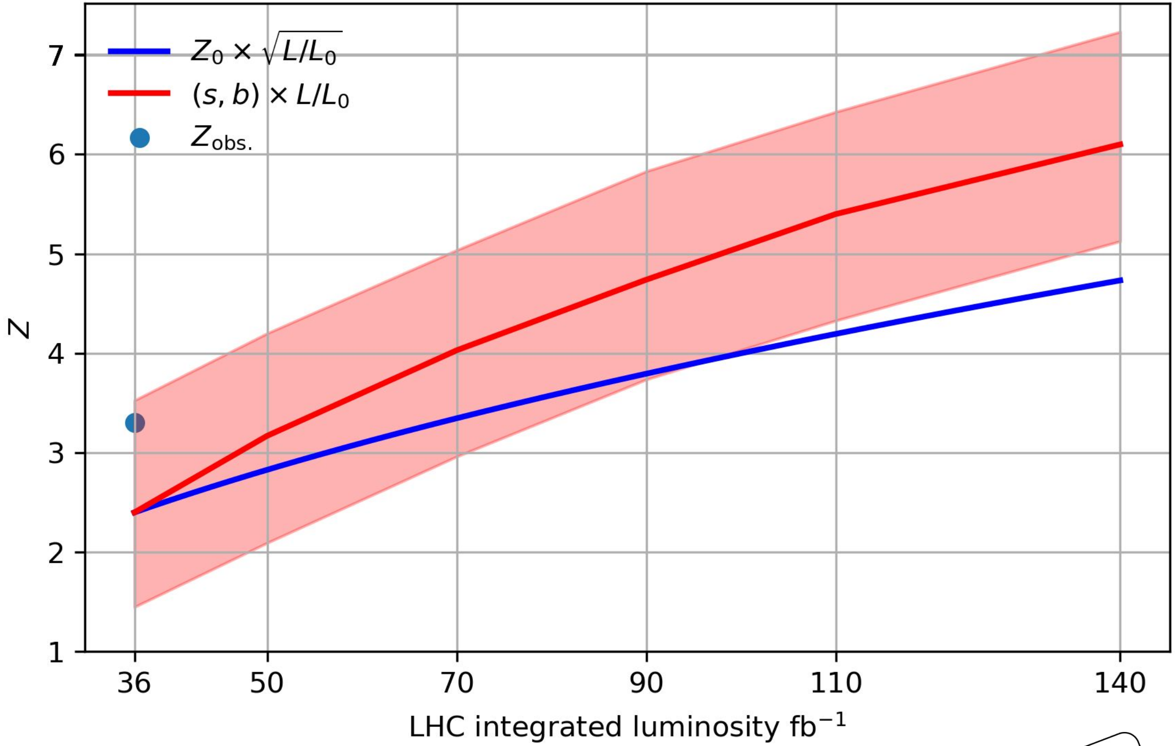
- Only L0+LL cross-sections
  - *Why?* Speed.
- For most analyses can only use one SR per point
  - *Why?* Missing correlation information
- Too weak constraints from CMS multilepton search
  - *Why?* Too many SRs - had to use aggregated SRs
  - CMS have recently provided covariance information - thanks!

Predictions for full Run 2 data!

ATLAS and CMS now have ~140 fb^{-1} of data on disk.

What can we expect under the assumption that our EWMSSM BF point is True?

-> Simple scaling of 36 fb^{-1} 13 TeV analyses. Take with a grain of salt.



Predictions for full Run 2 data!

$36\ \mathrm{fb}^{-1}$

↓

Scaled to

↓

$140\ \mathrm{fb}^{-1}$

	Best expected SRs				All SRs; neglect correlations			
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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
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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
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ATLAS_MultiLep_2lep_jet	2.0	1.7	0	1	2.2	0.9	0	3
ATLAS_MultiLep_3lep	2.0	1.7	0	1	3.8	0.8	0	11
ATLAS_RJ_2lep_2jet	1.6	1.2	0	1	1.6	0	0	4
ATLAS_RJ_3lep	2.8	2.6	0	1	3.6	2.2	0	4
CMS_1lep_2b	0	0	0	1	0	0	0	2
CMS_2lep_soft	0.1	0	0	12	0.1	0	0	12
CMS_2OSlep	1.6	0	0	7	1.6	0	0	7
CMS_MultiLep_2SSlep	0.7	0	0	1	0.9	0	0	2
CMS_MultiLep_3lep	2.2	1.9	0	1	2.8	0.7	0	6
Combined	6.1	1.1	0	29	7.8	0	0	63

Summary

- We have performed a large global fit of the MSSM electroweak sector using GAMBIT
- **Light neutralinos and charginos still allowed** in MSSM
- No necessary tension between ATLAS RJ and conventional multilepton searches
- Combined LHC results prefer scenarios with **all neutralinos and charginos below ~500 GeV**
- Predicts **multi-W/Z/h** final states
- Subset of best-fit regions compatible with dark matter results
- **Interesting times for EW SUSY searches!**

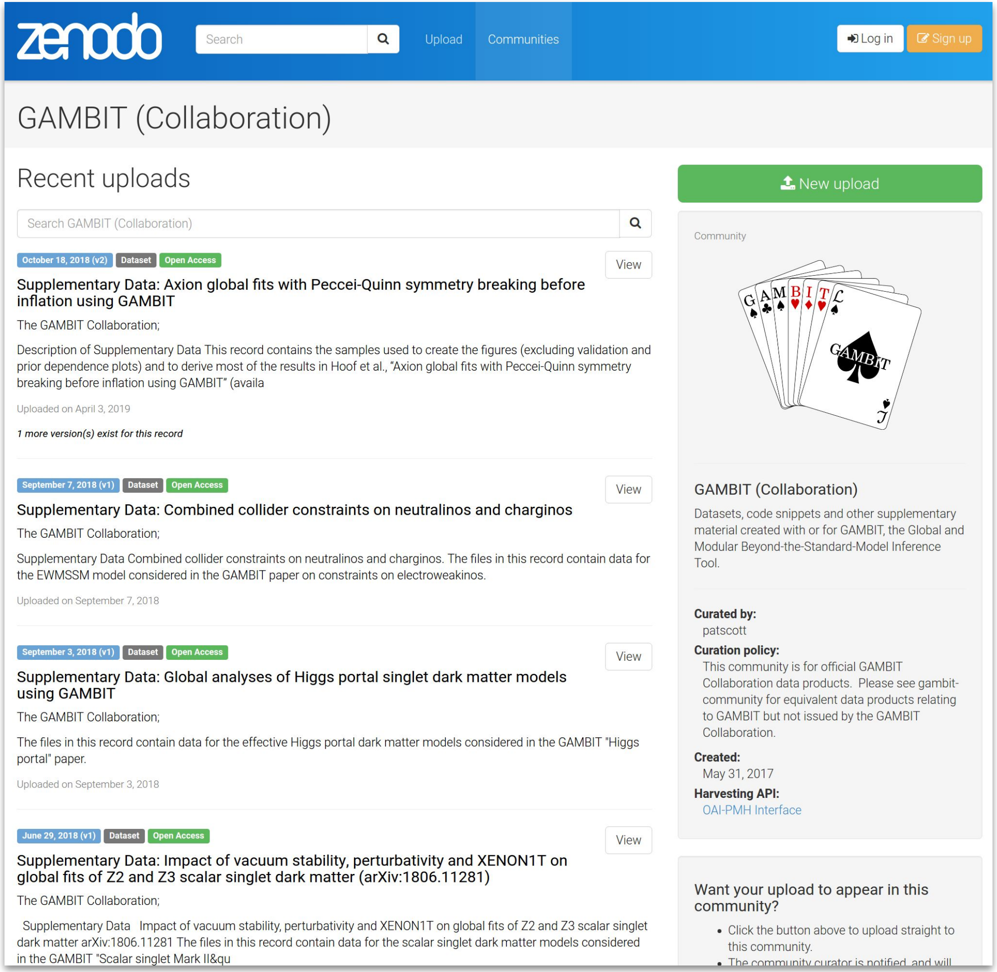
Benchmark points

Parameter	#1 Best fit	#2 Heavy winos	#3 Highest mass	#4 DM
$M_1(Q)$	−50.6 GeV	−79.2 GeV	133.4 GeV	−45.6 GeV
$M_2(Q)$	149.3 GeV	263.0 GeV	243.5 GeV	143.7 GeV
$\mu(Q)$	252.7 GeV	−187.3 GeV	−293.2 GeV	260.8 GeV
$\tan\beta(m_Z)$	28.7	40.4	41.5	16.4
$m_{\tilde{\chi}_1^0}$	−49.4 GeV	−73.9 GeV	129.4 GeV	−45.1 GeV
$m_{\tilde{\chi}_2^0}$	141.6 GeV	165.7 GeV	230.6 GeV	136.5 GeV
$m_{\tilde{\chi}_3^0}$	−270.3 GeV	−208.5 GeV	−308.8 GeV	−277.8 GeV
$m_{\tilde{\chi}_4^0}$	290.2 GeV	292.6 GeV	344.6 GeV	297.2 GeV
$m_{\tilde{\chi}_1^\pm}$	142.1 GeV	168.7 GeV	230.2 GeV	136.8 GeV
$m_{\tilde{\chi}_2^\pm}$	293.9 GeV	294.2 GeV	345.8 GeV	300.5 GeV
Collider log-likelihood	10.8	10.3	9.7	10.4

All results are publically available

- Results available on zenodo.cern.ch
  - Parameter point samples and signal predictions (hdf5 files)
  - GAMBIT input files for all scans
  - SLHA files for benchmark points

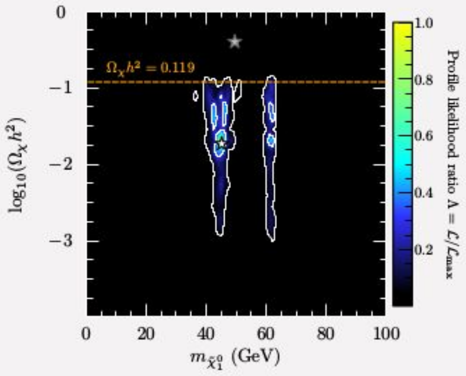
- Links at gambit.hepforge.org/pubs

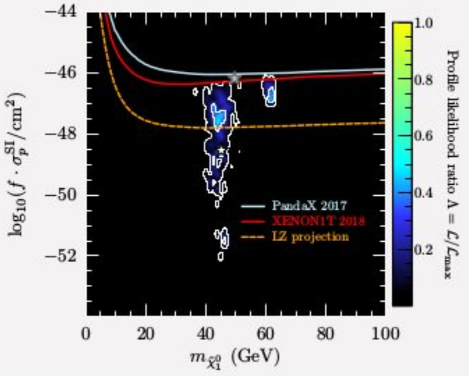


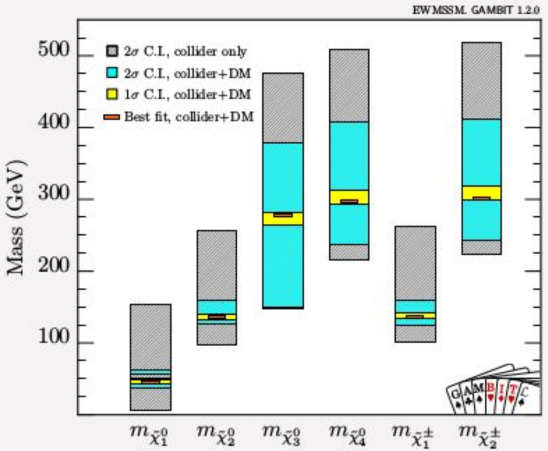
Backup slides

Bonus result: dark matter

- Scan did **not** include DM constraints
- LHC likelihood prefers **light bino LSP** (with non-zero higgsino component)
- **Z/Higgs resonances** can give acceptable relic density
- We post-process all samples with DM likelihoods: **relic density**, **direct detection** and **indirect detection**

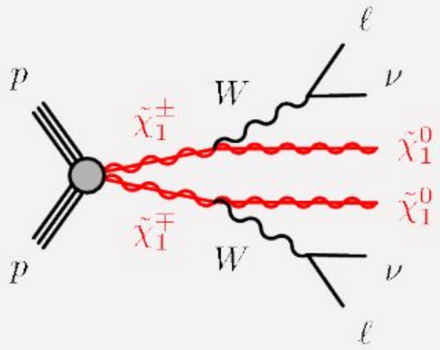




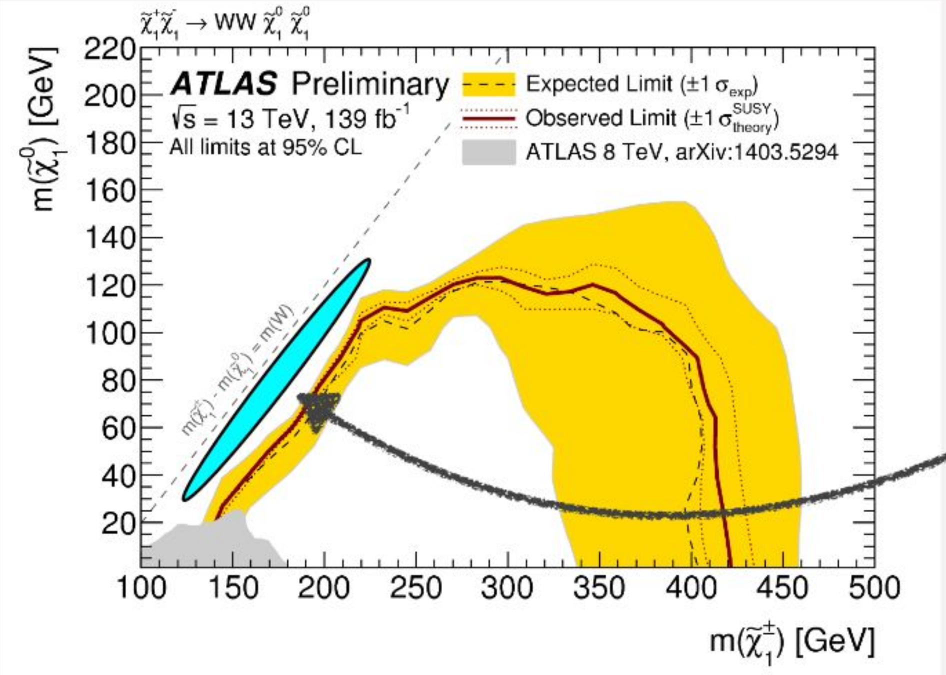


- Subset of our «collider-only» best-fit region also gives acceptable relic density and avoids DD and ID constraints.
- Part of best-fit region accessible to next generation of DD experiments
- *This is only a rough check*: A dedicated scan with both collider and DM likelihoods is needed for complete picture

EW SUSY results with ~140 fb^{-1} starting to appear:
ATLAS search for production of chargino pairs



[ATLAS-CONF-2019-008]



Naive comparison:
Not sensitive to the ~M_Z mass splitting in our best-fit region

Analysis: scan and post-processing

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

Scans

- Diver (differential evolution)
- 100k/500k Pythia events per point for LHC simulations
- ~2.4M parameter point samples (large uncertainty in LHC likelihood)

Post-processing

- Re-run points in preferred parameter regions with higher MC statistics
- 2σ/3σ regions: ≥4M events, 1σ region: ≥16M events, 500 best points: 64M events

~3 hours per point, using 68 CPUs x4 hyperthreading

- ~240k parameter point samples

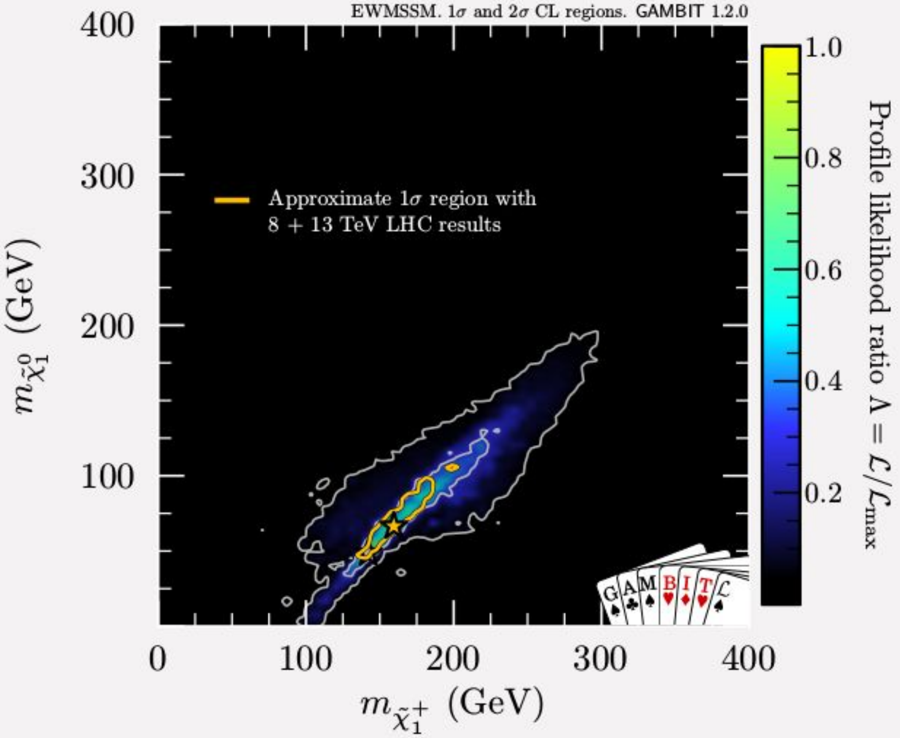
Analysis: impact of 8 TeV searches

Post-processed all samples within the 1-sigma preferred region from 13 TeV.

Included 8 TeV analyses:

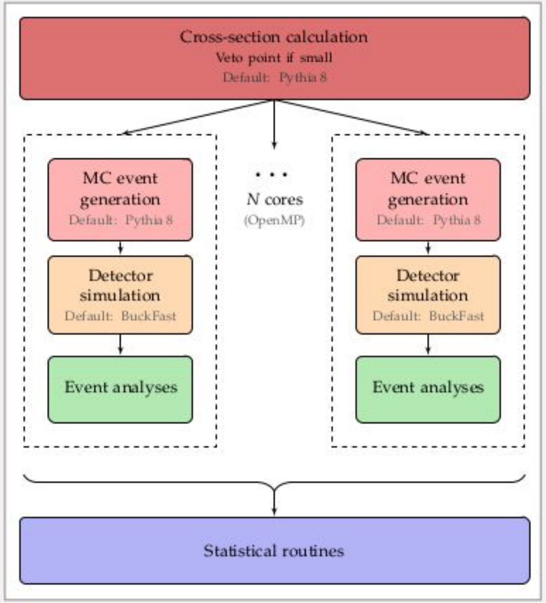
- ATLAS 2 lepton search
- ATLAS 3 lepton search
- ATLAS Wh search (1lep + 2b)
- CMS 3 lepton search
- CMS 4 lepton search

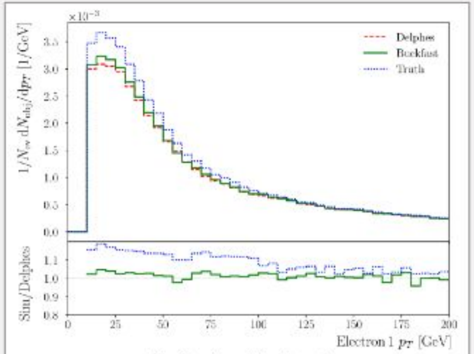
Bino < higgsinos < winos generally less constrained than *bino < winos < higgsinos*



ColliderBit: overview

- The collider physics module of GAMBIT
- **LEP limits (SUSY):** Calculate $\sigma \times BR$ and check against published limits
- **LHC particle searches:** Full Poisson likelihood from fast MC simulation of LHC searches
  - Parallellized MC event generation and analysis loop inside ColliderBit
  - Event generation with Pythia 8
  - Fast detector simulator: BuckFast (4-vector smearing)
- **Focus on speed,** as required for use in global fits

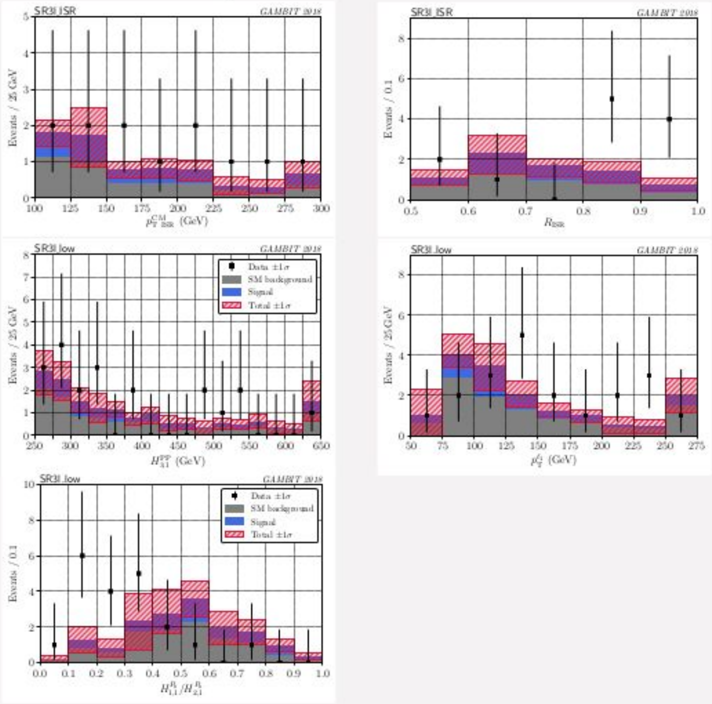




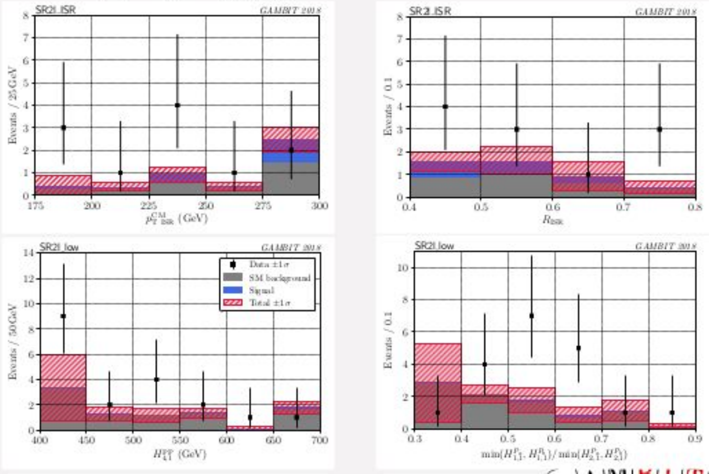
p_T distribution of leading electrons.

Analysis: best-fit point distributions

ATLAS_RJ_3lep

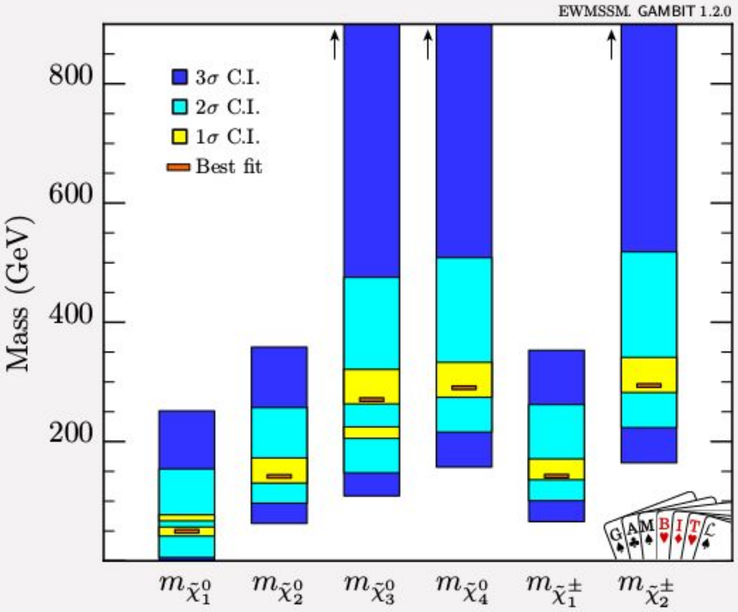


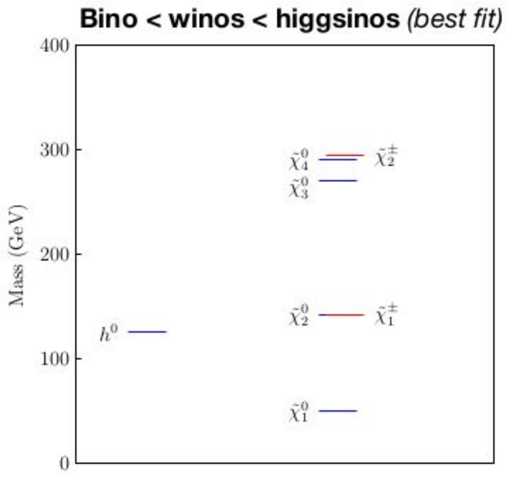
ATLAS_RJ_2lep_2jet

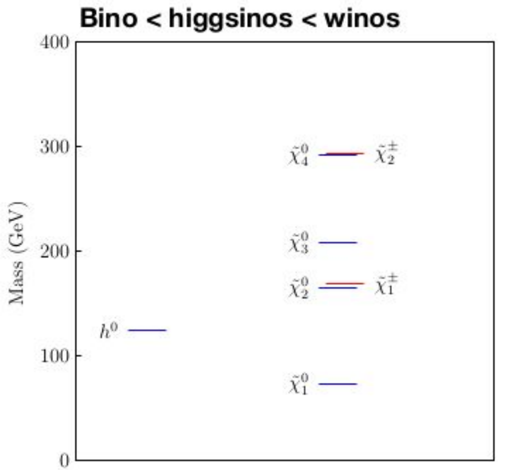


Analysis: results

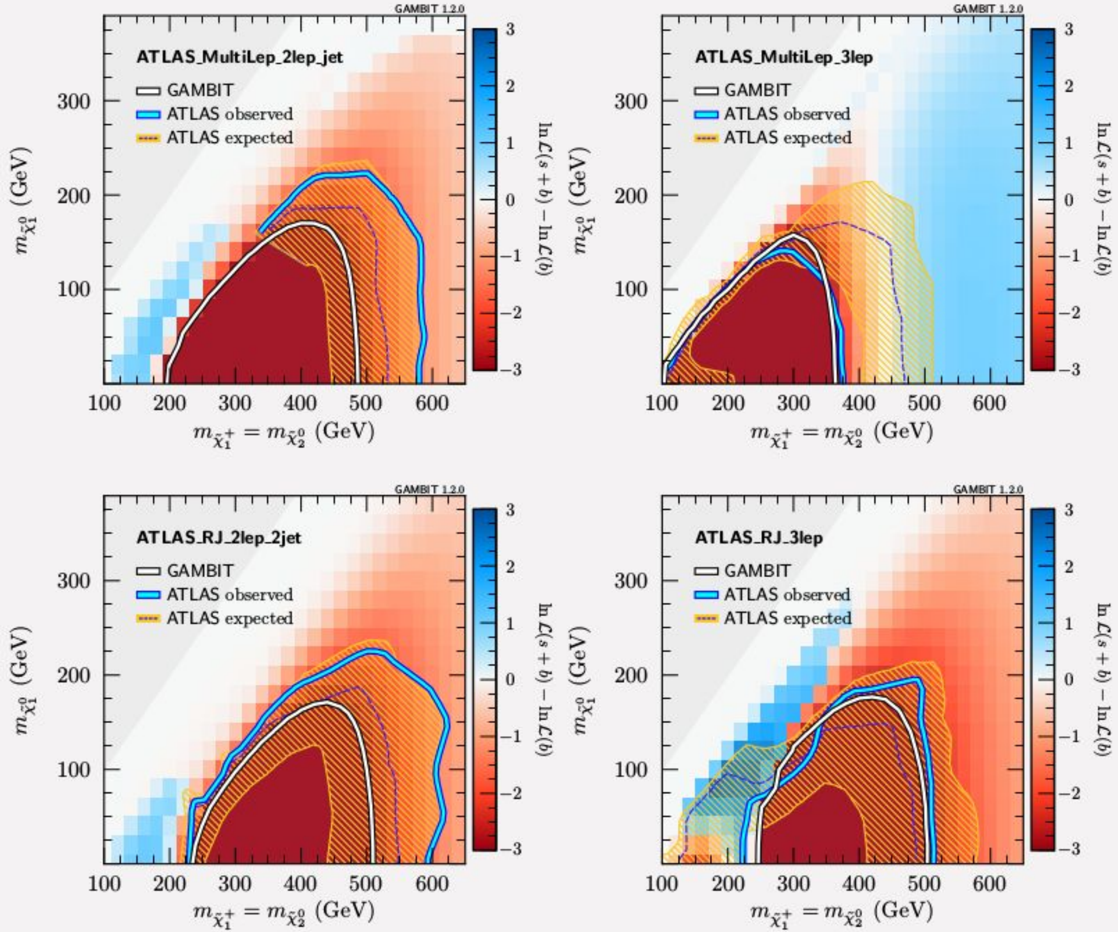
1D confidence intervals







ColliderBit: validation



ColliderBit: validation

Cut	ATLAS	GAMBIT	Ratio
All events	14028	14028	1.00
Trigger, 4 jets ($p_T > 40$ GeV, 2 b-tags)	1455	1906	1.31
≥ 4 b-tags	163.0	161.0	0.99
≥ 2 Higgses	126.4	140.8	1.11
Lepton veto	126.1	140.3	1.11
$X_{Wt} > 1.8$	108.4	132.8	1.23
$X_{hh}^{SR} < 1.6$	53.4	52.47	0.98
SR1: $m_{\text{eff}} > 440$ GeV	37.0	43.58	1.18
SR2: $m_{\text{eff}} > 440$ GeV + $E_T^{\text{miss}} > 150$ GeV	14.2	16.27	1.15

Table 4: Example comparison of GAMBIT and ATLAS [120] cutflows for two signal regions targeting low-mass Higgsinos in a search for new physics in events with two Higgs bosons decaying into $\bar{b}b$. Shown are the numbers of events expected in 24.3 fb^{-1} of 13 TeV ATLAS data for Higgsino pair production with a signal cross-section of 0.577 pb, $m_{\tilde{H}} = 250$ GeV and a massless gravitino, assuming 100% branching fraction for $\tilde{H} \to h\tilde{G}$.

Cut	CMS	GAMBIT	Ratio
All events	172000	172000	1.00
2 reconstructed muons with $5 < p_T < 30$ GeV	1250	1212	0.97
muons oppositely charged	1200	1099	0.91
$p_T(\mu\mu) > 3$ GeV	1176	1067	0.97
$M(\mu\mu) \in [4, 50]$ GeV	1095	1062	1.02
$M(\mu\mu) \in [9, 10.5]$ GeV veto	988.5	1011	0.99
$125 < p_T^{\text{miss}} < 200$ GeV	46.8	46.4	0.98
Trigger efficiency	30.7	30.2	1.07
ISR jet	27.9	29.9	1.17
$H_T > 100$ GeV	23.6	27.7	1.40
$0.6 < p_T^{\text{miss}}/H_T < 1.4$	17.2	24.0	1.42
b-tag veto	14.0	19.8	1.25
$M(\tau\tau)$ veto	12.3	15.4	1.25
$M_T(\mu_x, p_T^{\text{miss}}) < 70$ GeV	9.3	10.3	1.11

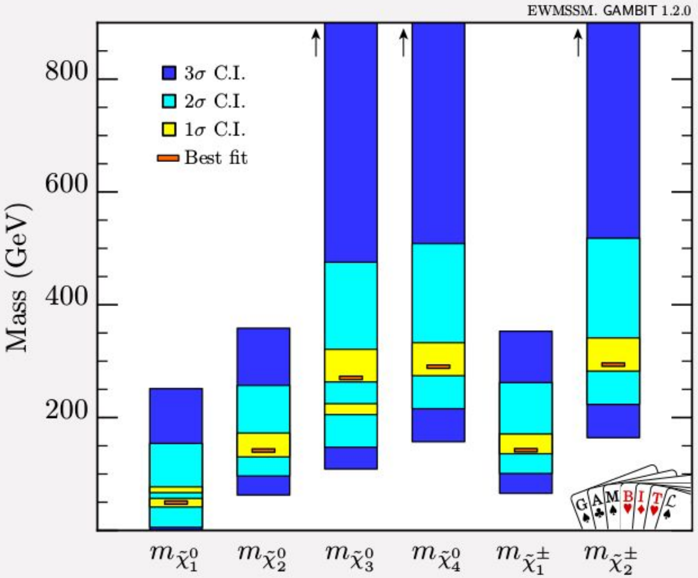
Table 5: Comparison of the GAMBIT and CMS [125] cutflows for a WZ signal model ($m_{\tilde{\chi}_1^\pm} = 150$ GeV, $m_{\tilde{\chi}_1^0} = 130$ GeV) in a search for new physics in events with two low-momentum opposite-sign leptons and missing transverse momentum. Shown are the numbers of events expected in 33.2 fb^{-1} of 13 TeV CMS data for a signal cross-section of 5.18 pb [129]. Both the CMS cutflow and GAMBIT cutflow are generated for production of $\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ in a simplified model with decays via off-shell W/Z.

Cut	CMS	GAMBIT	Ratio
All events	109.35	1084.18	9.91
2 SFOS leptons	24.21	30.00	1.24
Extra lepton vetoes	18.37	25.07	1.36
$m_{\ell\ell} \in [86, 96]$ GeV	14.13	15.97	1.13
2-3 Jets	11.98	9.83	0.82
$\Delta\Phi(E_T^{\text{miss}}, j_{1,2}) > 0.4$	10.95	9.07	0.83
B-tag veto	9.92	8.86	0.89
$M_{T2}(\ell\ell) > 80$ GeV	8.04	7.27	0.90
$M_{\ell\ell} < 150$ GeV	5.62	5.26	0.94
SR1: $E_T^{\text{miss}} > 100$ GeV	5.41	5.05	0.93
SR2: $E_T^{\text{miss}} > 150$ GeV	4.96	4.76	0.96
SR3: $E_T^{\text{miss}} > 250$ GeV	3.59	3.49	0.97
SR4: $E_T^{\text{miss}} > 350$ GeV	1.94	1.95	0.96

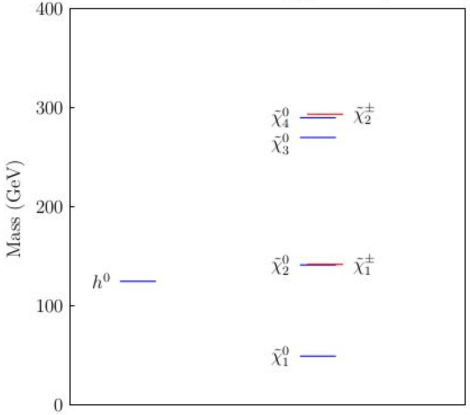
Table 6: Comparison of the GAMBIT and published CMS cutflows [126] in four signal regions of a search for new physics in events with two opposite-charge same-flavor leptons and missing transverse momentum, for a WZ signal model ($m_{\tilde{\chi}_1^\pm} = 550$ GeV, $m_{\tilde{\chi}_1^0} = 200$ GeV). Shown are the numbers of events expected in 35.9 fb^{-1} of 13 TeV CMS data, and the ratio of the GAMBIT and CMS numbers. Note that the CMS cutflow is generated for a $\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ simplified model decaying via W/Z where the Z boson decays leptonically, while the GAMBIT cutflow is generated without specifying Z boson decay mode. This explains the discrepancy at the "All events" cut.

Analysis: results

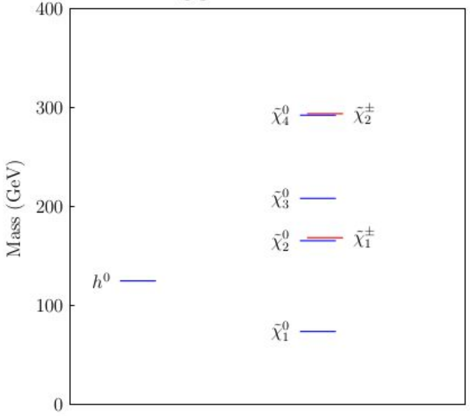
1D confidence intervals



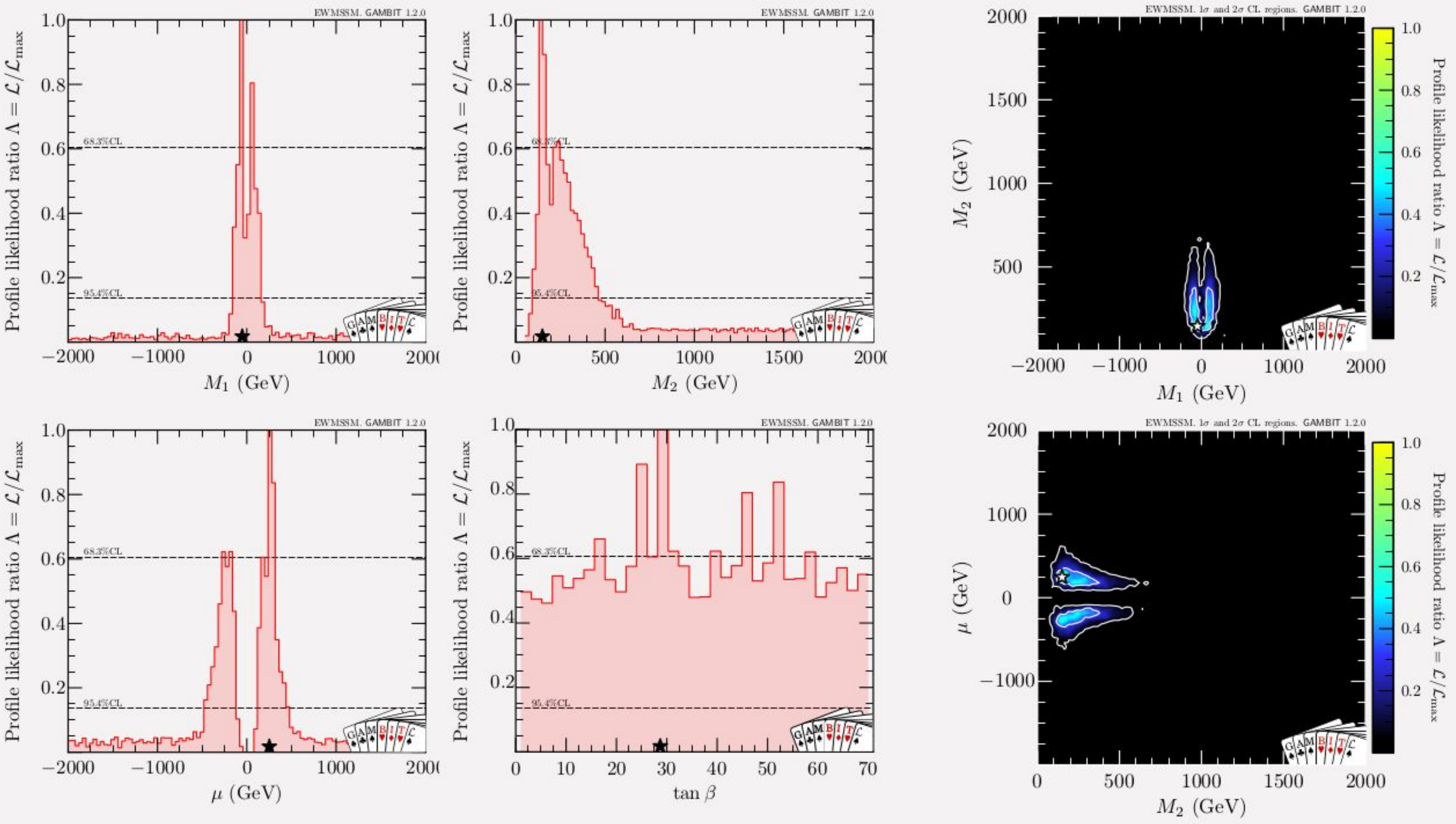
Bino < winos < higgsinos *(best fit)*



Bino < higgsinos < winos

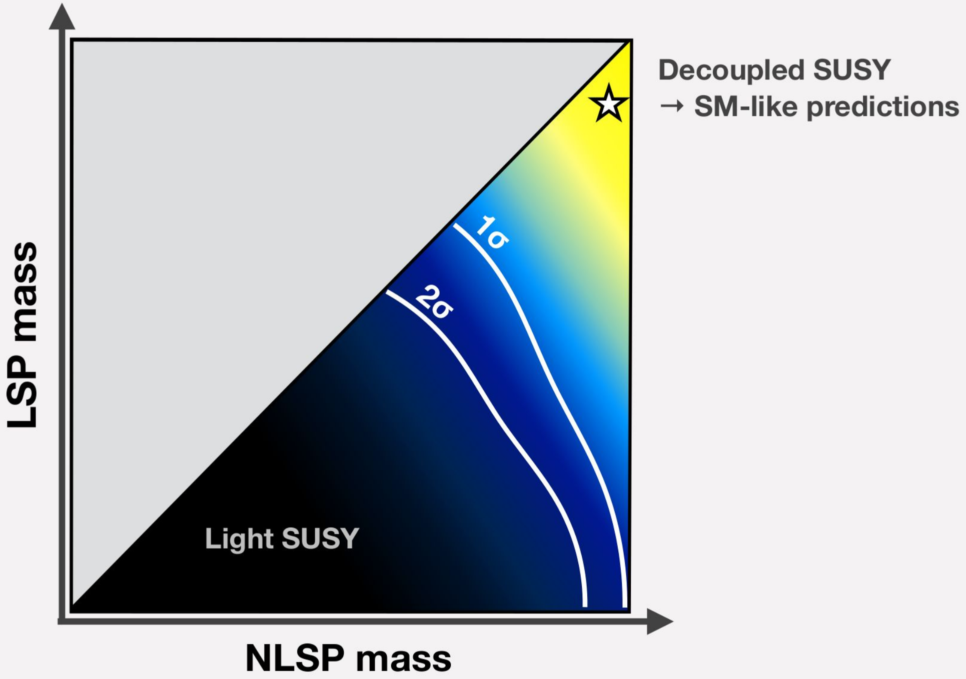


Analysis: Lagrangian parameters



Analysis: profile likelihood maps

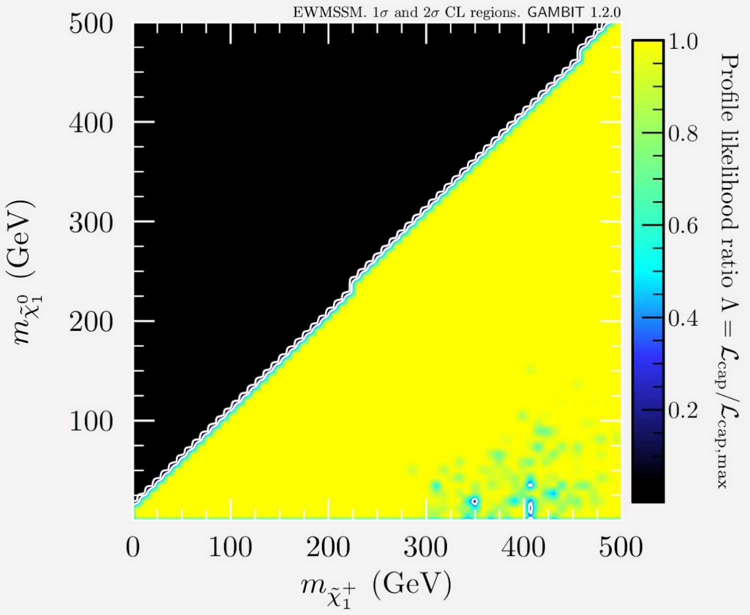
Naive *«light SUSY is dead»* expectation:



Analysis: results

- First: «**capped**» LHC likelihood
- *How much **worse** does a point in the MSSM fit the data compared to the SM?*
- Capping done on **combined** likelihood for all analyses
- If **profile likelihood ratio = 1**: found a point with *either*
    - no sensitivity; *or*
    - all bad fits offset by other good fits
- **No general constraint** on the lightest EWinos

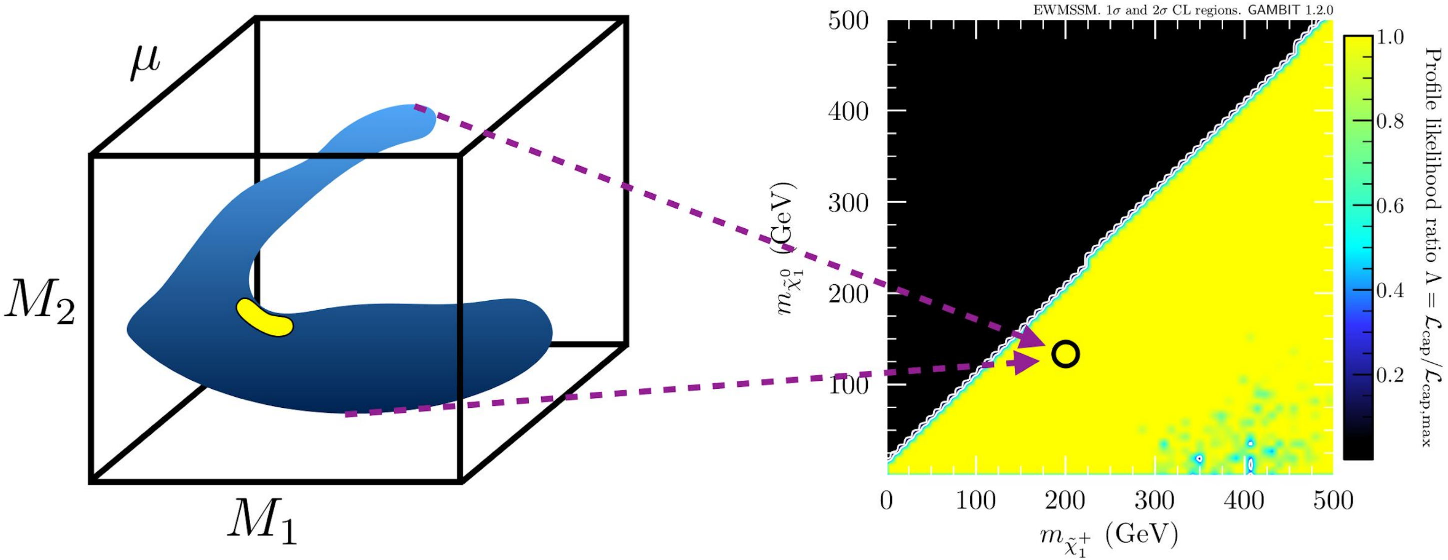
$$\mathcal{L}_{\text{cap}} = \min[\mathcal{L}_{\text{LHC}}(\boldsymbol{s}+\boldsymbol{b}), \mathcal{L}_{\text{LHC}}(\boldsymbol{b})]$$



Analysis: results

Interpretation: For every point in the mass plane, there is *at least one point* in the MSSM parameter space that fits the data as well as (or better than) the SM expectation.

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



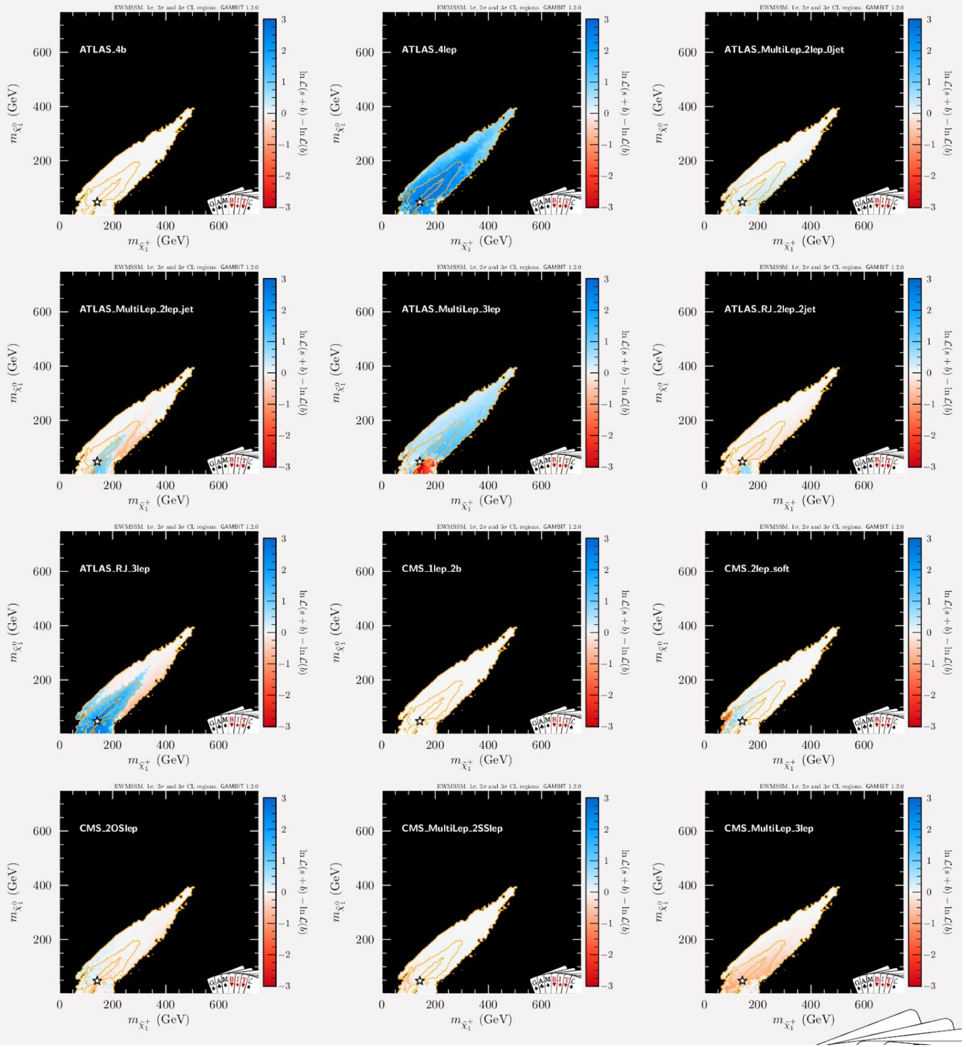
Analysis: results

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

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

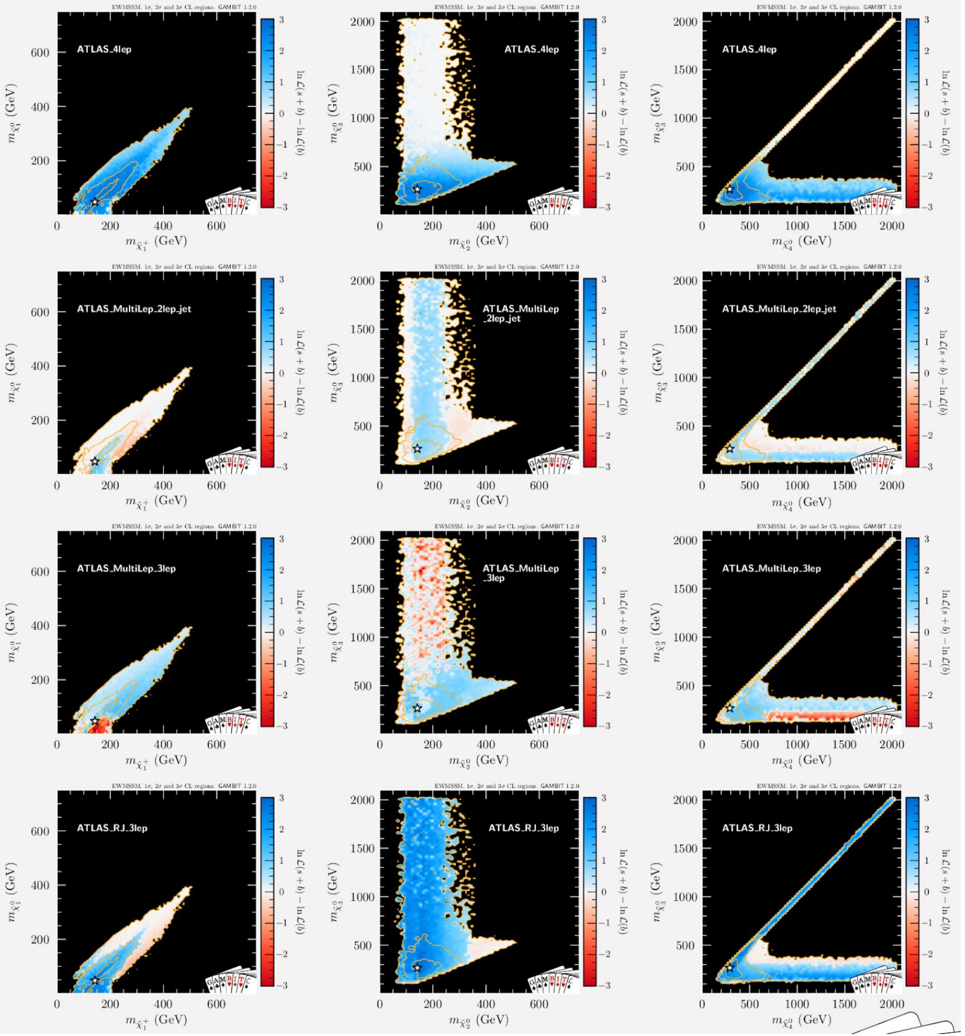
- **Blue**: **better** than background-only
  Red: **worse** than background-only

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



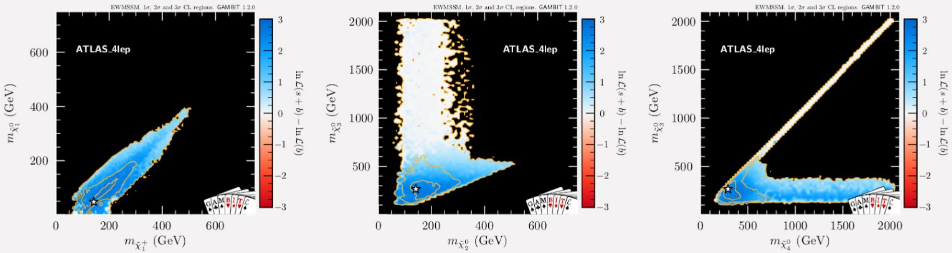
Analysis: results

- 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 $\tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_1^\pm$)



Analysis: results

- More detailed look on
  - **ATLAS_4lep**
  - **ATLAS_RJ_3lep**

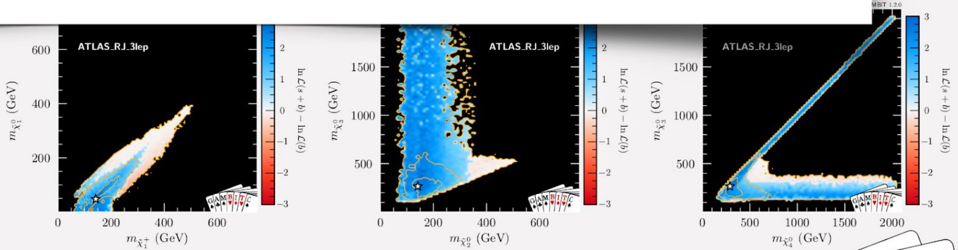


Lots of processes relevant for the best-fit point:

- $\tilde{\chi}_2^0\tilde{\chi}_3^0$ production, with e.g.
  $\tilde{\chi}_2^0 \to Z + \tilde{\chi}_1^0,\ \tilde{\chi}_3^0 \to W^- + \tilde{\chi}_1^+ \to W^- + W^+ + \tilde{\chi}_1^0$
- $\tilde{\chi}_2^\pm\tilde{\chi}_2^\mp$ production, with e.g.
  $\tilde{\chi}_2^\pm \to W^\pm + \tilde{\chi}_2^0 \to W^\pm + Z + \tilde{\chi}_1^0$
- $\tilde{\chi}_2^\pm\tilde{\chi}_3^0$ production, with e.g.
  $\tilde{\chi}_2^\pm \to W^\pm + \tilde{\chi}_1^0,\ \tilde{\chi}_3^0 \to Z + \tilde{\chi}_2^0 \to Z + Z + \tilde{\chi}_1^0$
- $\tilde{\chi}_2^\pm\tilde{\chi}_3^0$ production, with e.g.
  $\tilde{\chi}_2^\pm \to W^\pm + \tilde{\chi}_2^0 \to W^\pm + Z + \tilde{\chi}_1^0,$
  $\tilde{\chi}_3^0 \to W^- + \tilde{\chi}_1^+ \to W^- + W^+ + \tilde{\chi}_1^0$
- $\tilde{\chi}_2^\pm\tilde{\chi}_4^0$ production, with e.g.
  $\tilde{\chi}_2^\pm \to W^\pm + \tilde{\chi}_2^0 \to W^\pm + Z + \tilde{\chi}_1^0,\ \tilde{\chi}_4^0 \to Z + \tilde{\chi}_1^0$
- $\tilde{\chi}_2^\pm\tilde{\chi}_2^0$ production, with e.g.
  $\tilde{\chi}_2^\pm \to h + \tilde{\chi}_1^\pm \to h + W^\pm + \tilde{\chi}_1^0,\ \tilde{\chi}_2^0 \to Z + \tilde{\chi}_1^0$
- $\tilde{\chi}_1^\pm\tilde{\chi}_3^0$ production, with e.g.
  $\tilde{\chi}_1^\pm \to W^\pm + \tilde{\chi}_1^0,\ \tilde{\chi}_3^0 \to W^- + \tilde{\chi}_1^+ \to W^+ + W^- + \tilde{\chi}_1^0$
- $\tilde{\chi}_2^\pm\tilde{\chi}_4^0$ production, with e.g.
  $\tilde{\chi}_2^\pm \to Z + \tilde{\chi}_1^\pm \to Z + W^\pm + \tilde{\chi}_1^0,$
  $\tilde{\chi}_4^0 \to h + \tilde{\chi}_2^0 \to h + Z + \tilde{\chi}_1^0$

...

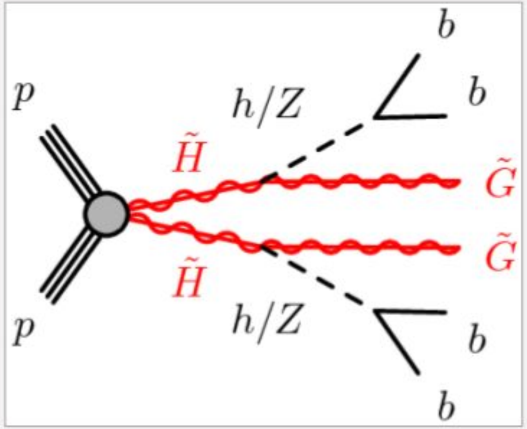
- S… c…
- L… A…
- H… A… A…
- The «expected» tension between **ATLAS_MultiLep_3Lep** and **ATLAS_RJ_3lep** observed for heavy $\tilde{\chi}_4^0$ (production of higgsino $\tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_1^\pm$)

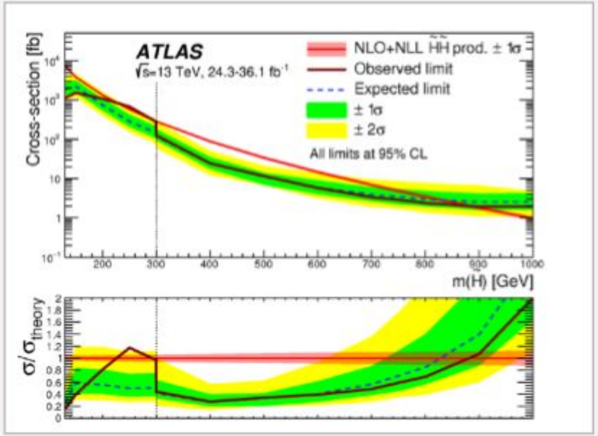


Analysis: EW SUSY searches

13 TeV, 36 fb^{-1}

- ATLAS Higgsino search: **ATLAS_4b**
- ATLAS ≥4 lepton search: **ATLAS_4lep**
- ATLAS multilepton EW search: **ATLAS_MultiLep_*** (**2lep_0jet**, **2lep_jet**, **3lep**)
- ATLAS recursive jigsaw EW search: **ATLAS_RJ_*** (**2lep_2jet**, **3lep**)
- CMS Wh search: **CMS_1lep_2b**
- CMS 2 soft opposite-sign lepton search: **CMS_2lep_soft** (including SR correlations)
- CMS 2 opposite-sign lepton search: **CMS_2OSlep** (including SR correlations)
- CMS multilepton EW search: **CMS_MultiLep_*** (**2SSlep**, **3lep**)





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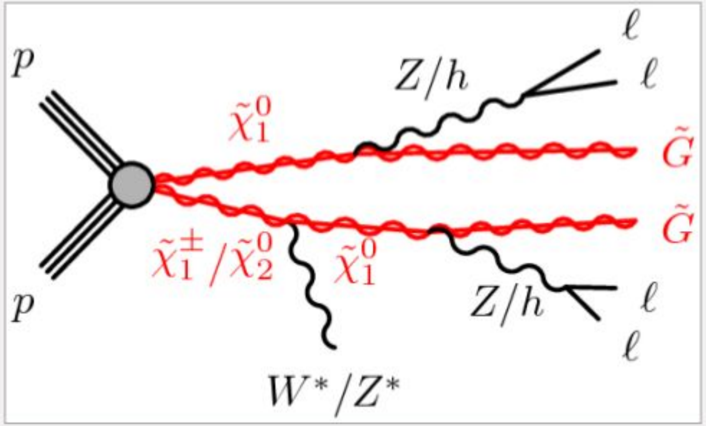

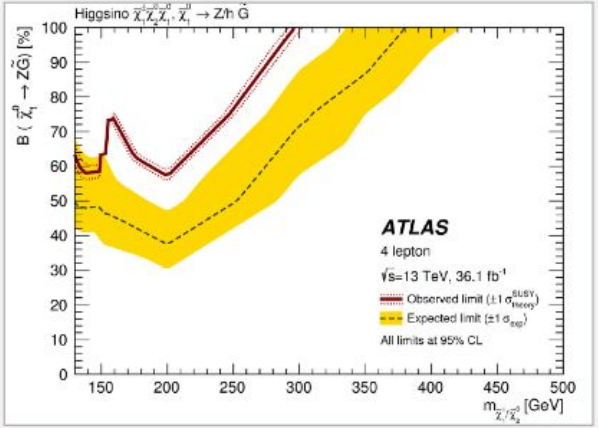

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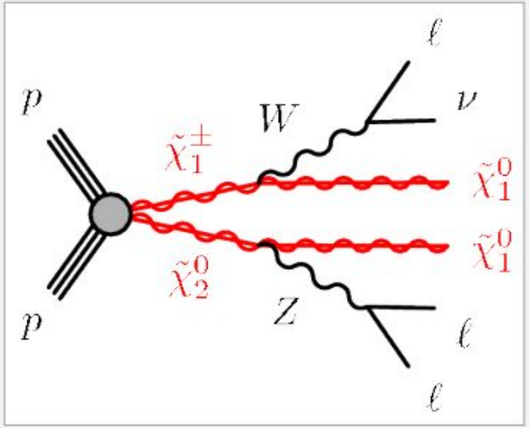

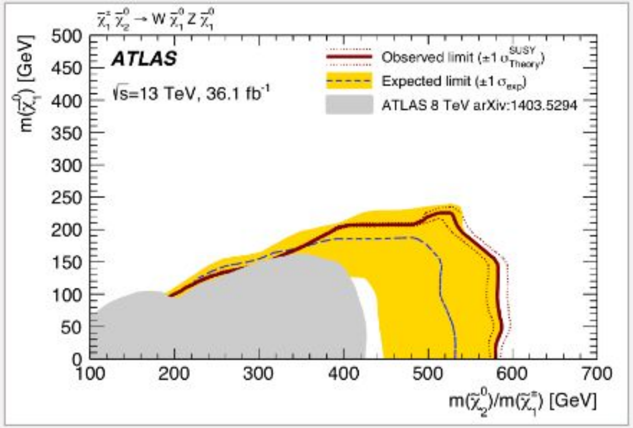

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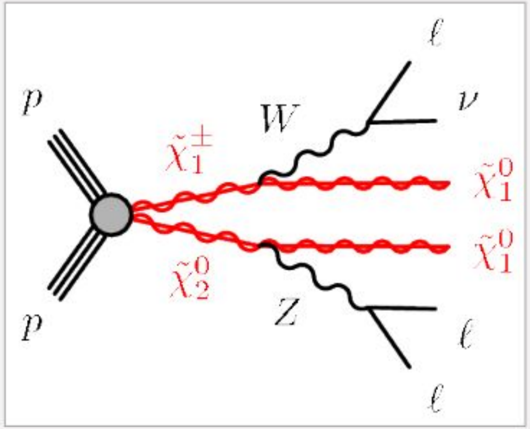

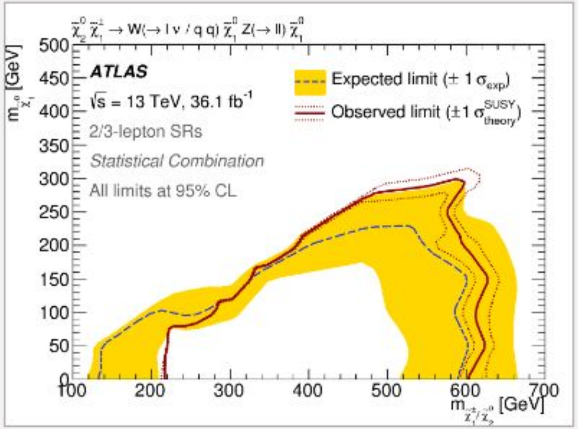

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13 TeV, 36 fb^{-1}

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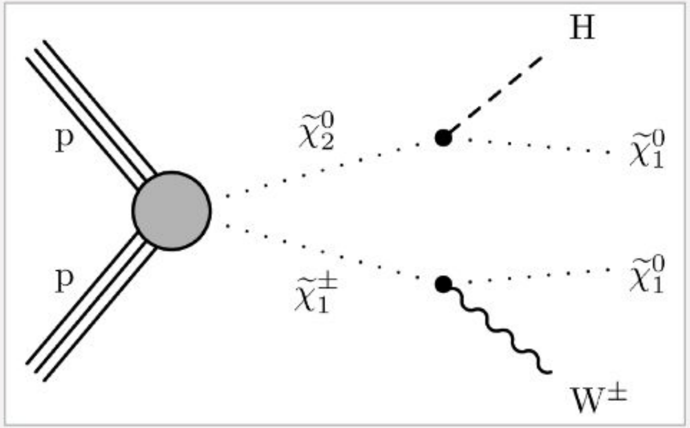

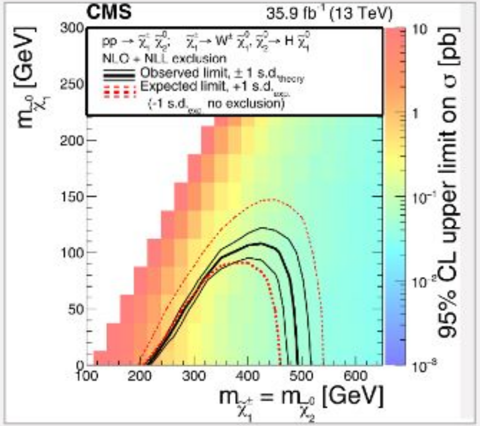

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13 TeV, 36 fb^{-1}

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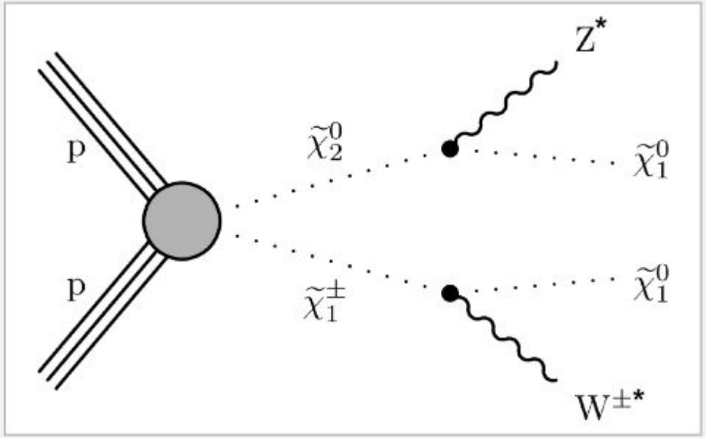
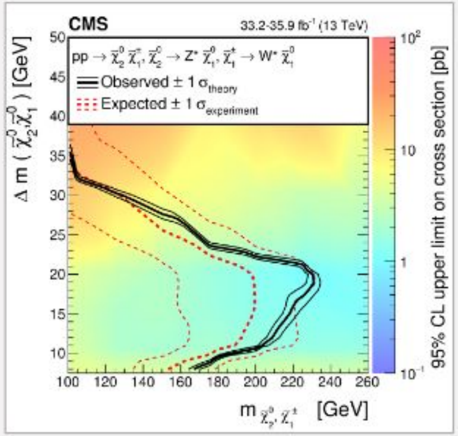
- ATLAS recursive jigsaw EW search: **ATLAS_RJ_*** (**2lep_2jet**, **3lep**)
- CMS Wh search: **CMS_1lep_2b**
- CMS 2 soft opposite-sign lepton search: **CMS_2lep_soft** (including SR correlations)
- CMS 2 opposite-sign lepton search: **CMS_2OSlep** (including SR correlations)
- CMS multilepton EW search: **CMS_MultiLep_*** (**2SSlep**, **3lep**)





Analysis: EW SUSY searches

13 TeV, 36 fb^{-1}

- ATLAS Higgsino search: **ATLAS_4b**
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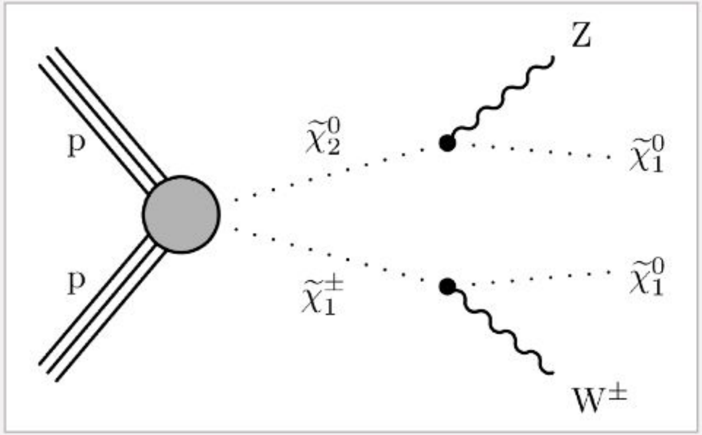

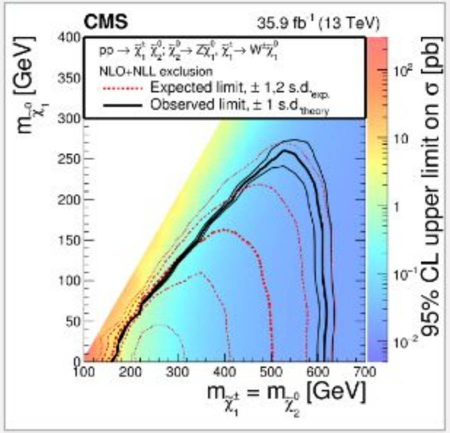

Analysis: EW SUSY searches

13 TeV, 36 fb^{-1}

- ATLAS Higgsino search: **ATLAS_4b**
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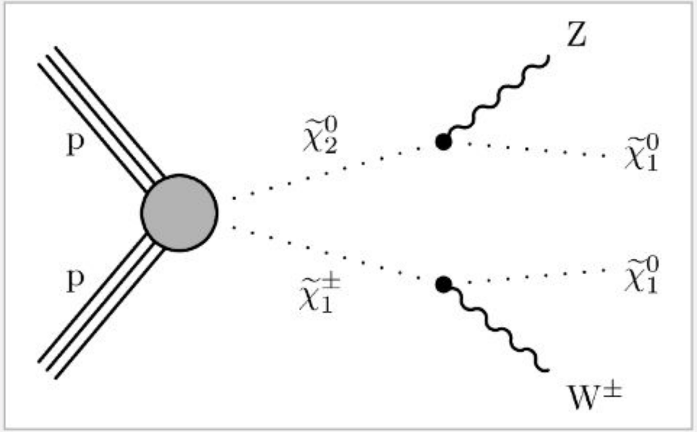
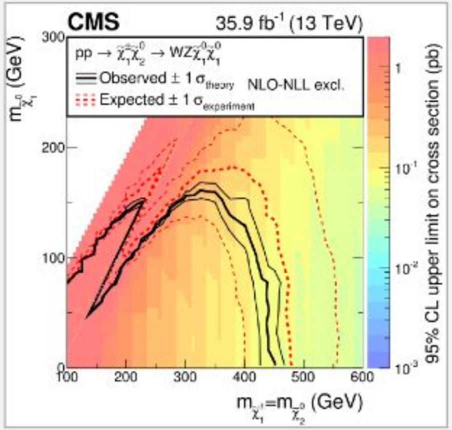
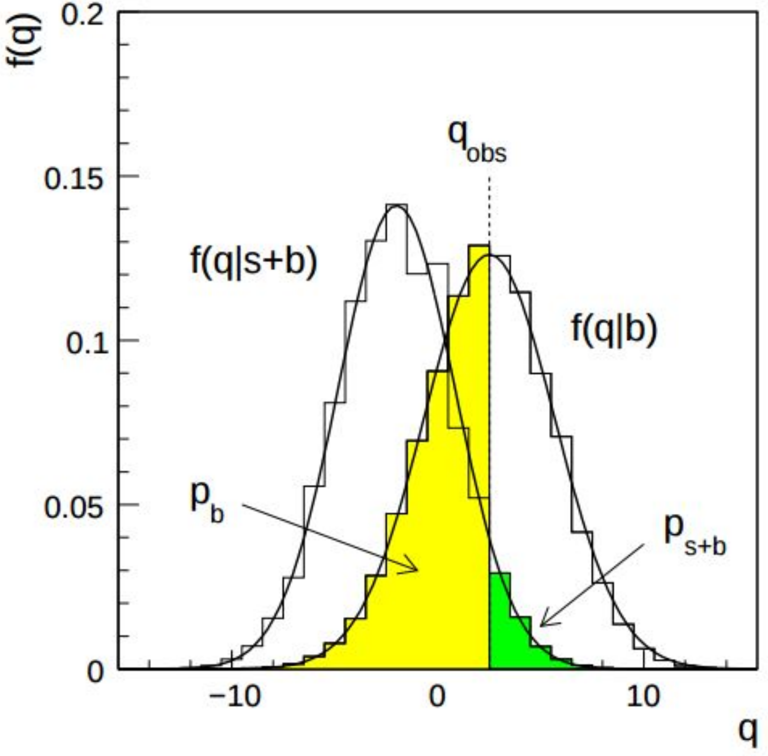




Local p-values



$$q = -2\ln\frac{L_{s+b}}{L_b}\,,$$

$$\lambda_i = \mu s_i(\phi) + b_i + \theta_i$$

$$q = -2\ln\frac{L(\mu=1,\hat{\hat{\boldsymbol{\theta}}}(1))}{L(\mu=0,\hat{\hat{\boldsymbol{\theta}}}(0))}$$

Note: this is where combination comes in! Same whether combining signal regions or whole analyses:

$$L(\mu) = \prod_i L_i(\mu)$$

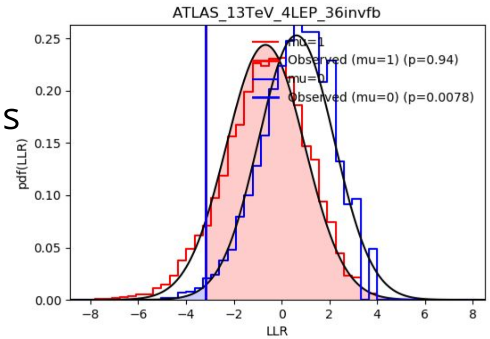
Figure 6: The distribution of the statistic $q = -2\ln(L_{s+b}/L_b)$ under the hypotheses of $\mu = 0$ and $\mu = 1$ (see text).

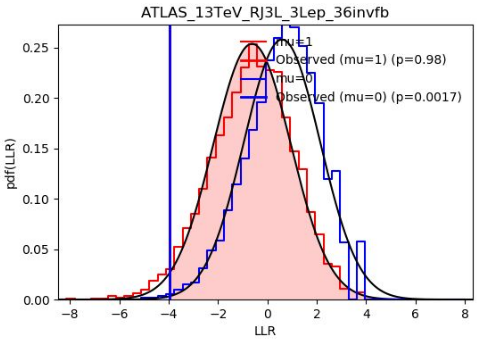
*Note: for simple vs simple hypothesis testing, the likelihood ratio gives the best discrimination (power, **Neyman-Pearson Lemma**)

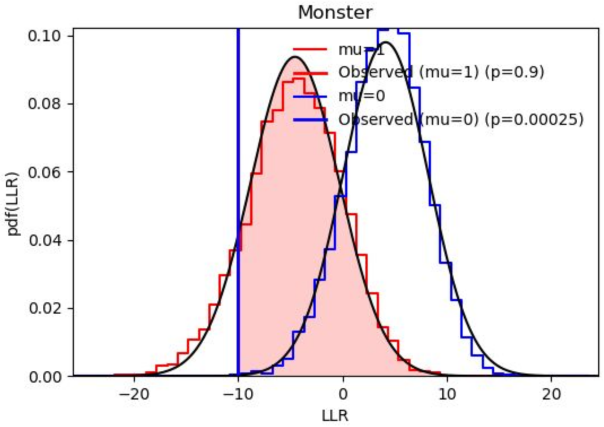
Local p-values

Analysis	Local signif. (σ)
Higgs invisible width	0
Z invisible width	0
ATLAS_4b	0.7
ATLAS_4lep	2.3
ATLAS_MultiLep_2lep_0jet	0.9
ATLAS_MultiLep_2lep_jet	0
ATLAS_MultiLep_3lep	1.8
ATLAS_RJ_2lep_2jet	0
ATLAS_RJ_3lep	2.7
CMS_1lep_2b	0.8
CMS_2lep_soft	0.1
CMS_2OSlep	0.1
CMS_MultiLep_2SSlep	0.2
CMS_MultiLep_3lep	0
Combined	3.3

No correlations







$$q = -2\ln\frac{L_{s+b}}{L_b},$$

$$q = -2\ln\frac{L(\mu=1,\hat{\hat{\theta}}(1))}{L(\mu=0,\hat{\hat{\theta}}(0))}$$

Goodness of fit

$$q_{\mathrm{GOF}} = -2\log\frac{\mathcal{L}_{\mathrm{joint}}(\mathbf{s}(\theta), \hat{\hat{\eta}})}{\mathcal{L}_{\mathrm{joint}}(\hat{\mathbf{s}}, \hat{\eta})}$$

Asymptotic distribution is chi-squared with DOF=#SR

(to test background-only hypothesis, set s(θ)=0)

No look-elsewhere effect*, but test is not very powerful for discovery due to large DOF.

Goodness of fit

	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