Combined collider constraints on neutralinos and charginos

GAMBIT, Eur. Phys. J. **C79**, 395, `arXiv:1809.02097`

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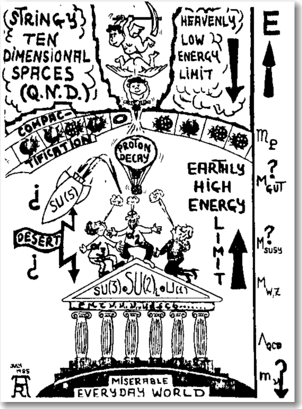
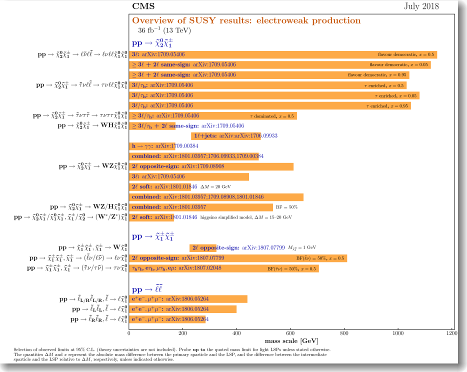
We are in the miserable everyday world!

If we explore above the electroweak scale we might discover the beauty — supersymmetry and grand unification!



The experimental picture

It looks like the miserable everyday world up to the TeV scale!



Let's check the real picture in a global fit of a supersymmetric model. Is it really the miserable everyday world up to the TeV scale?

What is a global fit?

The problem

You have a BSM model with several parameters and experimental data from e.g., the LHC and searches for DM.

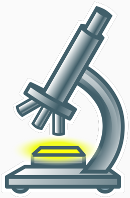
You must find the regions of parameter space that are favored by the data, what is predicts, and judge whether the model is disfavored.

How do we tell what is favored by data?

The solution

Put the model under the microscope with a global fit

This isn't optional — you need this to draw scientific conclusions about models in light of data



Global fit

A statistical analysis of a model and its parameters using all relevant experimental data

The solution

- We call it a global fit as we consider the entire, global parameter space and fit it to experimental data
- Usually includes only estimating the favored parameters of a model, but can include judging whether the model itself is favored or allowed by data
- There are many ingredients — including algorithms, statistics, experiments and predictions from your model

We need statistics

To judge whether a model or parameter point is favored by data, we need statistics

- Global fits are agnostic about statistical methodology — can be Bayesian or frequentist
- But analyses without a coherent methodology — e.g., you just scatter points or identify benchmark points that might be in agreement with data — are not considered reliable
- We must ask and answer questions about a model in a statistically meaningful way

Sounds tricky? ⇒ GAMBIT

We need algorithms

To explore a multi-dimensional parameter space, we require a Monte Carlo algorithm

- Relies on repeated random sampling
- Escapes local minima by permitting backward steps with a particular probability
- Helps escape the curse of dimensionality
- Represents a complicated probability distribution by random samples drawn from it

Common choices are Monte Carlo Markov Chain, nested sampling and evolutionary algorithms

Sounds tricky? $\Rightarrow$ GAMBIT

We need predictions

Regardless of our algorithm, we must go from a point in our model to predictions for experimental observables. Each prediction in a realistic BSM model

- Requires a chain of dedicated computer programs, e.g., `FlexibleSUSY` and micrOMEGAs for predicting the relic density
- Calculated up to a certain order — has an uncertainty
- Depends on a set of so-called nuisance parameters, e.g., the top mass and strong coupling, that should be treated consistently throughout all predictions

Sounds tricky? $\Rightarrow$ GAMBIT

We need experiments

Finally, we must compare our prediction to experiments. Each experimental measurement must be interpreted within a model

- Interpreted through a so-called likelihood function — the probability of obtaining the observed data in a particular model
- Should incorporate relevant statistical and systematic uncertainties
- Potentially extremely complicated

Sounds tricky? $\Rightarrow$ GAMBIT

What is GAMBIT?

gambit.hepforge.org

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

Follows pioneering global fits by Allanach et al, Roszkowski, Trotta & Ruiz et al, `BayesFits`, `MasterCode`, `Fittino` and others, in supersymmetric models that began in the mid 2000s. Global fits 2.0

- A community working towards solving the problems encountered in global fits in high-energy physics
- A public computer program that solves the problems allowing you to perform global fits
- A collaboration developing that software and publishing global fits with it

GAMBIT community

The GAMBIT collaboration expanded into a community. You can join and participate our discussions and workshops, and develop global fits with us

`gambit.hepforge.org/community`

GAMBIT code

GAMBIT software and results are publicly available. This is a powerful suite of tools allowing you to perform comprehensive state-of-the-art global fits of your models

- Many models
- Interfaces to major tools in high-energy physics and new ones
- Massively parallel
- Multiple scanning algorithms and statistical approaches
- Written in `C++` and supports interfaces with `Fortran`, `Python` and `Mathematica`
- Complete datasets from previous studies are available

`gambit.hepforge.org/code`

GAMBIT papers

I will focus on GAMBIT, Eur. Phys. J. **C79**, 395, `arXiv:1809.02097` — collider constraints on electroweakinos

Previously published state-of-the-art fits of

- Constrained and phenomenological supersymmetric models
- Scalar singlet model
- Fermion and vector Higgs portal dark matter models
- Axion-like particles
- Right-handed neutrinos

`gambit.hepforge.org/pubs`

Electroweakinos in the MSSM

Supersymmetry

A space-time symmetry between fermions and bosons

- Solves hierarchy problem
- Natural dark matter candidate
- Ensures gauge coupling unification at the high-scale

Predicts a new superpartner for every known particle, with identical quantum numbers but spin differing by one-half

Electroweakinos — motivation

- Maybe the squarks, sleptons and gluino are very heavy — we haven't seen them
- Perhaps only the neutralinos and charginos (electroweakinos) are visible
- Light electroweakinos are motivated by dark matter
- Retains gauge coupling unification — similar to split supersymmetry
- μ-parameter remains near the weak scale — possibly natural

The LHC favors strong production of sparticles. Look at only the electroweakinos

Electroweakino model

Our model is defined by four parameters:

- Soft-breaking bino and wino masses, M_1 and M_2
- Supersymmetric μ parameter
- Electroweak symmetry breaking output, $\tan\beta = v_u / v_d$

These are the only parameters that appear in the neutralino and chargino mass matrices

We assume that everything else is SM-like — $m_h \simeq 125\,\text{GeV}$ etc

Neutralinos

The four neutralinos are mass eigenstates of bino, wino and neutral higgsinos

$$\tilde{B}, \tilde{W}^0, \tilde{H}_u^0, \tilde{H}_d^0$$

found from diagonalizing the matrix

$$M_\chi = \begin{pmatrix} M_1 & 0 & -c_\beta s_W m_Z & s_\beta s_w m_Z \\ 0 & M_2 & c_\beta c_W m_Z & -s_\beta c_W m_Z \\ -c_\beta s_W m_Z & c_\beta c_w m_Z & 0 & -\mu \\ s_\beta s_W m_Z & -s_\beta c_w m_Z & -\mu & 0 \end{pmatrix}$$

If m_Z can be neglected, the neutralinos are almost exactly bino-like, wino-like and higgsino-like with masses M_1, M_2 and $|\mu|$

Charginos

The two charginos are mass eigenstates of charged wino and charged higgsinos

$$\tilde{W}^+, \tilde{H}_u^+, \tilde{W}^-, \tilde{H}_d^-$$

found from a bi-unitary transformation of the matrix

$$M_{\chi^\pm} = \begin{pmatrix} 0 & X^T \\ X & 0 \end{pmatrix}$$

where

$$X = \begin{pmatrix} M_2 & \sqrt{2} s_\beta m_W \\ \sqrt{2} c_\beta m_W & \mu \end{pmatrix}$$

If m_W can be neglected, the charginos are almost exactly wino-like and higgsino-like with masses M_2 and $|\mu|$

The lightest neutralino

We consider an R-parity conserving scenario and assume that the lightest neutralino is the lightest supersymmetric particle. This means that it's stable

- Sparticles are produced in pairs and decay down to pairs of neutralinos
- The lightest neutralino escapes collider searches, leaving only missing energy
- The lightest neutralino could play the role of dark matter

Global fit with LHC and LEP data

Statistics

We make a frequentist analysis

- We plot confidence regions in the parameters — regions that would contain the true parameters in 68% and 95% of identical repeat experiments
- To judge the evidence for our model, we consider whether data are consistent with the Standard Model. We calculate a p-value — the probability of obtaining data at least as extreme as that obtained, were the Standard Model correct

This requires the combined likelihood from all our experiments

$$\mathscr{L} \equiv \text{Prob}\left(\text{observed data} \,\middle|\, M_1, M_2, \tan\beta, \mu\right)$$

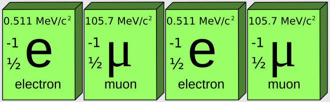
Electroweakino signatures

Missing energy

Pairs of $\chi_1 \chi_1$ escape leaving behind missing energy. They are, however, often accompanied by other clues

Electroweakino signatures

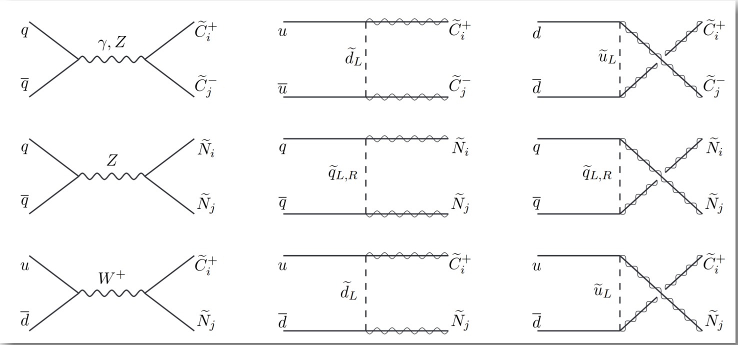
Lepton rich final states



Lepton-rich final states are common from the production and subsequent decays of heavier neutralinos and charginos

Electroweakino signatures

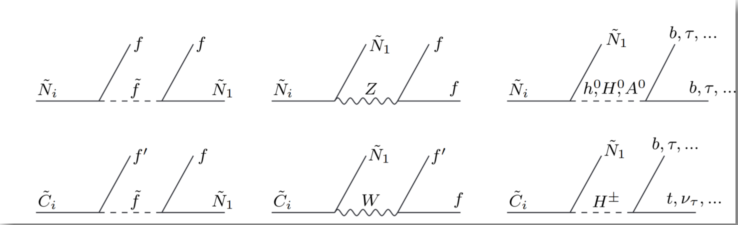
Production at hadron colliders



From ref. [3]

Electroweakino signatures

Subsequent decay



From ref. [3]

LEP searches

LEP searches for electroweakinos remain competitive with LHC

Signature	Experiment
$\tilde{\chi}_i^0\tilde{\chi}_1^0 \to q\bar{q}\tilde{\chi}_1^0\tilde{\chi}_1^0$	OPAL [4]
$\tilde{\chi}_i^0\tilde{\chi}_1^0 \to \ell\bar{\ell}\tilde{\chi}_1^0\tilde{\chi}_1^0$	L3 [5]
$\tilde{\chi}_i^+\tilde{\chi}_i^- \to q\bar{q}'q\bar{q}'\tilde{\chi}_1^0\tilde{\chi}_1^0$	OPAL [4]
$\tilde{\chi}_i^+\tilde{\chi}_i^- \to q\bar{q}'\ell\nu\tilde{\chi}_1^0\tilde{\chi}_1^0$	OPAL [4]
$\tilde{\chi}_i^+\tilde{\chi}_i^- \to \ell\nu\ell\nu\tilde{\chi}_1^0\tilde{\chi}_1^0$	OPAL [4], L3 [5]
$\tilde{\chi}_1^0\tilde{\chi}_1^0$ with ISR γ	OPAL [6]

Invisible widths of h and Z

We must make sure that invisible decays to neutralinos are under control

- The Z boson was well-studied at LEP. From a fit to precision observables [7]

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

  We use a Gaussian likelihood

- The Higgs invisible width is tricky to measure. We only know

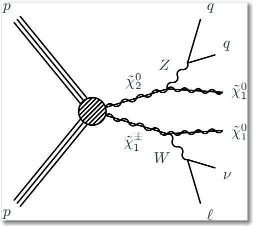
$$\text{BF}(h \to \text{inv.}) \lesssim 0.19$$

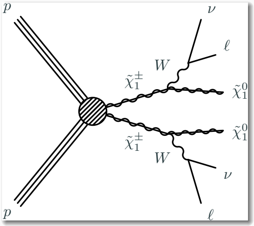
  We use a likelihood from a fit to the Higgs sector [8]

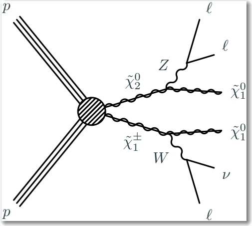
We calculated tree-level decays to neutralinos and two-loop decays to neutrinos

LHC searches

- Electroweakino production cross sections are small
- Most sensitive to final states rich in leptons, poor in jets
- Optimized for simplified models







LHC searches

We consider $\sqrt{s} = 13$ TeV searches with up to 36/fb

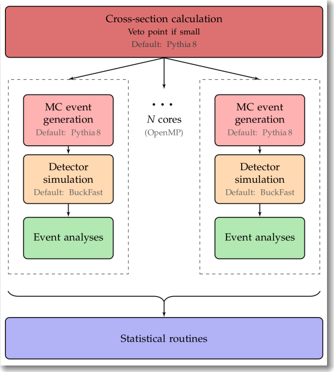
ATLAS_4b	Higgsino search [9]
ATLAS_4lep	4ℓ search [10]
ATLAS_MultiLep_2lep_0jet	Multilepton EW search [11]
ATLAS_MultiLep_2lep_jet	Multilepton EW search [11]
ATLAS_MultiLep_3lep	Multilepton EW search [11]
ATLAS_RJ_2lep_2jet	Recursive jigsaw EW search [12]
ATLAS_RJ_3lep	Recursive jigsaw EW search [12]
CMS_1lep_2b	Wh search [13]
CMS_2lep_soft	Two soft opposite-charge lepton search [14]
CMS_2OSlep	Two opposite-charge lepton search [15]
CMS_MultiLep_2SSlep	Multilepton EW search [16]
CMS_MultiLep_3lep	Multilepton EW search [16]

`ColliderBit` toolchain

For every point

1. Electroweakino masses to one-loop using `FlexibleSUSY`
2. Electroweakino decays `SUSY-HIT` — on-shell three body decays
3. Monte-Carlo at least 500k events with optimized version of `Pythia` — LO + LL
4. Fast detector simulation with `BuckFast`
5. Apply selections with `ColliderBit`
6. Calculate likelihood

We validate our procedure against published cutflows and limits



From Anders Kvellestad

We validate our procedure against published cutflows and limits

LHC likelihoods

For each search region the likelihood is Poisson

$$\mathscr{L} = \frac{\lambda^o e^{-\lambda}}{o!}$$

where o = number of observed events λ = signal + background.

We only simulate the signal; the backgrounds come from the experimentalists.

In some cases, we marginalize (correlated) uncertainties on the backgrounds.

Correlations

In the perfect world, searches would be completely independent. We could just multiply our likelihoods

$$\mathscr{L} = \mathscr{L}_1 \cdot \mathscr{L}_2 \cdots$$

The LHC searches though are correlated as search regions may contain the same events or share common systematics, thus

$$\mathscr{L} \neq \mathscr{L}_1 \cdot \mathscr{L}_2 \cdots$$

When correlation information was published, we used it. When it wasn't, we used the single region with the best expected sensitivity or aggregated regions when recommended.

Flip-flopping and number of MC events

We need to use millions of MC events in `Pythia`

- Electroweakino searches typically suffer from small acceptances — few signal events are expected to pass tight kinematic cuts
- Search regions with similar sensitivity (predata) could result in quite different likelihoods (postdata).
  Thus MC fluctuations in estimates of sensitivity cause flip-flopping between the signal regions and thus in the likelihood

We use more events for more interesting points, ranging from 100k to 64M events. About 250k points were processed with at least 4M events

Scanning

We scanned broadly over light electroweakino masses.

We used the `Diver` differential evolution algorithm to explore the parameter space.

To ensure thorough exploration, we explored it with two choices of metric, obtaining millions of samples.

Scanning

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

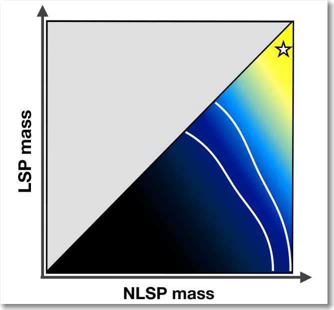
Are any combinations of masses worse than SM?

Look at the lightest neutralino and chargino masses.

Are any combinations of masses definitely worse than the SM?

Are any combinations of masses worse than SM?

If light electroweakinos are under pressure, maybe it looks like this?

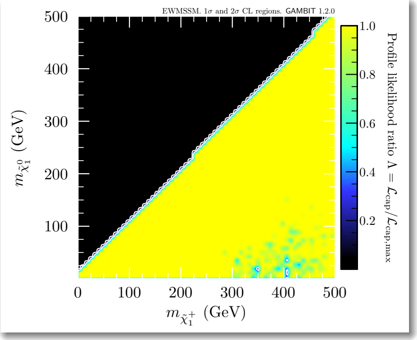


From Anders Kvellestad

Yellow = no worse than SM. Grey = forbidden as $m_\chi > m_{\chi^\pm}$

Only heavy electroweakinos are no worse than the SM?

Are any combinations of masses worse than SM?



Yellow = no worse than SM. Black = forbidden as $m_\chi > m_{\chi^\pm}$

No! We can find parameter combinations for any $(m_\chi, m_{\chi^\pm})$ that are no worse than the SM.

Tension with simplified models?

Does this conflict with ATLAS and CMS results?

No. They are all optimized and interpreted in terms of simplified models

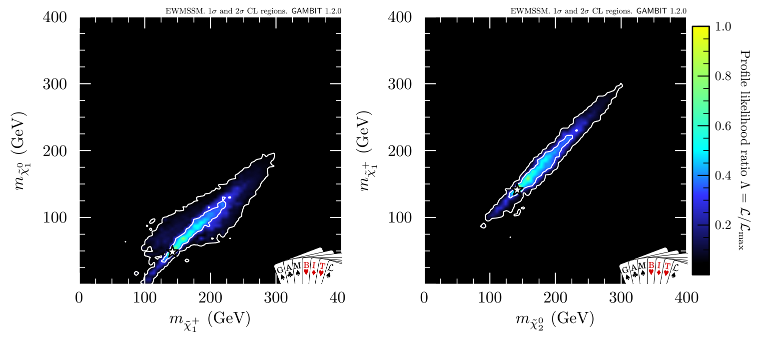
In the real model, there are many possibilities of neutralino masses and composition that change the production cross section and typical final states

Are any masses preferred?

Yes! The combination of searches appears to favor light electroweakinos

Let's look at the 1σ and 2σ regions for the masses

Are any masses preferred?



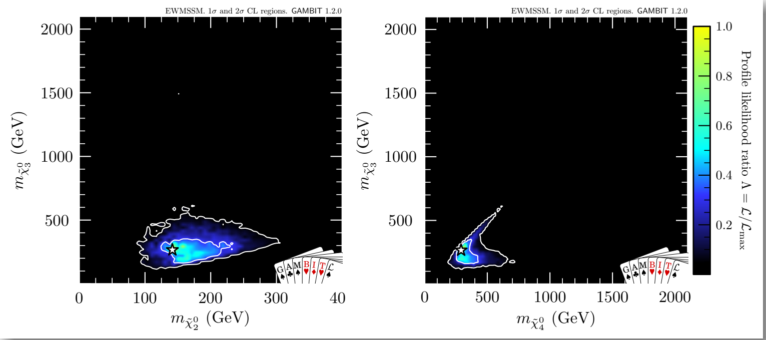
Blue/Yellow = preferred

★ = best fit

Black = very bad

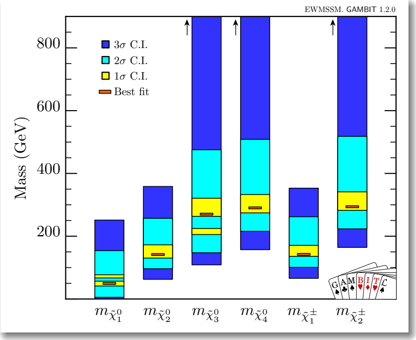
White lines = 1σ and 2σ regions

Are any masses preferred?



Heavier neutralinos — similar story. All electroweakinos are light

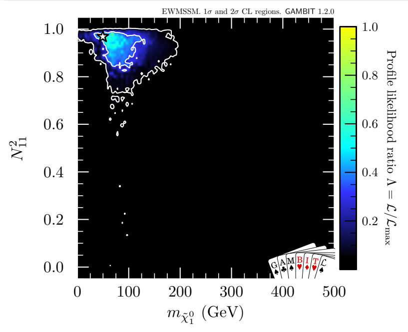
Are any masses preferred?



One-dimensional summary of neutralino and chargino masses

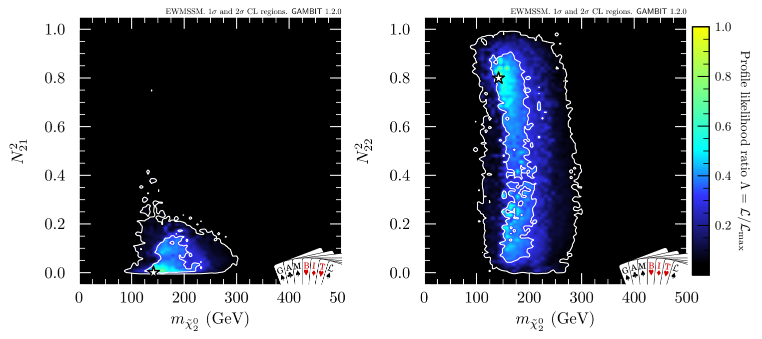
The searches prefer light electroweakinos

Neutralino composition



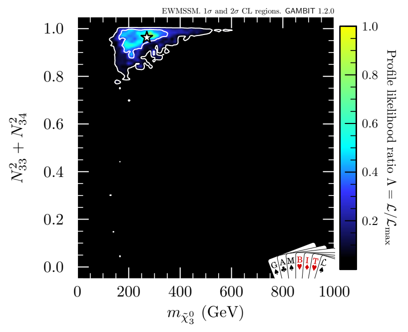
χ_1 is bino-like

Neutralino composition



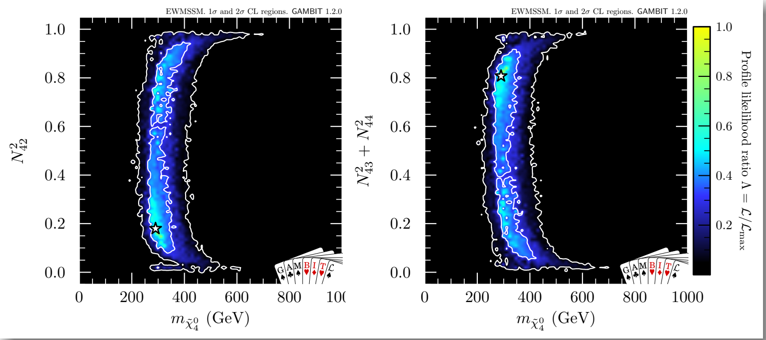
χ_2 is wino/higgsino

Neutralino composition



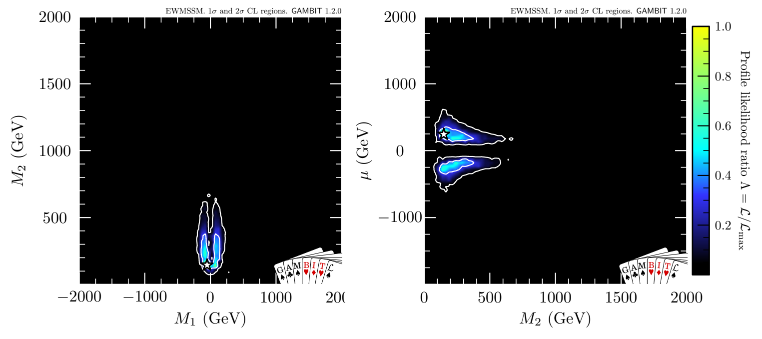
χ_3 is higgsino

Neutralino composition



χ_4 is wino/higgsino

Model parameters



Very particular parameters favored at $\ll 1\,\mathrm{TeV}$

Benchmarks

	Best fit	Heavy winos	Highest mass	Dark matter
M_1	-50.6	-79.2	133.4	-45.6
M_2	149.3	263.0	243.5	143.7
μ	252.7	-187.3	-293.2	260.8
$\tan\beta$	28.7	40.4	41.5	16.4
Neutralino and chargino masses				
χ_1	-49.4	-73.9	129.4	-45.1
χ_2	141.6	165.7	230.6	136.5
χ_3	-270.3	-208.5	-308.8	-277.8
χ_4	290.2	292.6	344.6	297.2
$\chi_1^\pm$	142.1	168.7	230.2	136.8
$\chi_2^\pm$	293.9	294.2	345.8	300.5

Everything in GeV.

Anomaly!?

What drives the preference for light electroweakinos?

ATLAS_4lep

Two reconstructed Z that decay leptonically and missing energy

Simplified models produce charginos — don't have this final state

Backgrounds are diboson production with missing energy from neutrinos/misreconstruction

What drives the preference for light electroweakinos?

ATLAS_MultiLep_3lep

Targets $\chi_1^{\pm}\chi_2$ production with a reconstructed Z that decays leptonically and missing energy

ATLAS analysis contained 1.8σ excess

Backgrounds are diboson production with missing energy from neutrinos/misreconstruction

What drives the preference for light electroweakinos?

ATLAS_RJ_3lep

Targets a reconstructed Z and W that decay leptonically and missing energy

ATLAS analysis contained excesses in four regions of $1.4 - 3\sigma$

Backgrounds are diboson production with missing energy from neutrinos/misreconstruction

Estimating its significance

p-value

The probability of obtaining data at least as extreme as that obtained, were the Standard Model correct

The extremeness of the data defined by a test-statistic

$$\lambda = -2 \ln \frac{\mathscr{L}_\text{Best-fit SUSY}}{\mathscr{L}_\text{SM}}$$

More extreme $\Leftrightarrow$ Likelihood of data greater in our electroweakino model at the best fit point than in the SM

The look-elsewhere effect

We calculated our test-statistic using the best-fit point.

If the data were different, we would have used a different best-fit point. We would have looked elsewhere.

- If we account for this in our calculation of the p-value, it's called a global p-value
- If we don't, it's called a local p-value

Calculating global p-value very hard — ordinary asymptotic approximations do not apply to our case

We only calculated the local p-value through MC simulations.

Local p-value

	Local signifcance	SM fit	SUSY fit
Higgs invisible width	0	0	0
Z invisible width	0	1.3	1.3
ATLAS_4b	0.7	0	0
ATLAS_4lep	2.3	1.9	0
ATLAS_MultiLep_2lep_0jet	0.9	0.3	0.1
ATLAS_MultiLep_2lep_jet	0	0	0.5
ATLAS_MultiLep_3lep	1.8	1.5	0.7
ATLAS_RJ_2lep_2jet	0	0.3	0.5
ATLAS_RJ_3lep	2.7	2.5	1.1
CMS_1lep_2b	0.8	0.3	0.3
CMS_2lep_soft	0.1	0.2	0.2
CMS_2OSlep	0.1	0.5	0.5
CMS_MultiLep_2SSlep	0.2	0	0
CMS_MultiLep_3lep	0	0	0.4
Combined	3.3	1.4	0.2

Combined local significance of 3.3σ. Contributions from several searches.

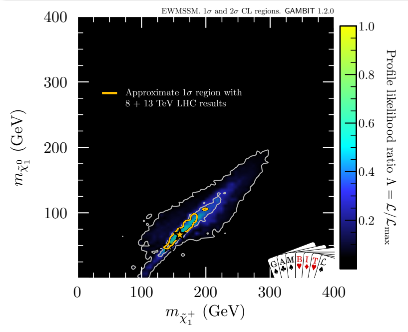
What about 8 TeV?

Did not originally simulate events at 8 TeV — assumed that 13 TeV was most important

In light of the preference for small masses, perhaps we should check?

What about 8 TeV?

Did not originally simulate events at 8 TeV — assumed that 13 TeV was most important



Orange = new 1σ contour

Mild impact. The preference remains but drops in significance to 2.9σ

How about more data?

- Relevant search for chargino pair-production [17] came too late for our study. Contains small hint — could it be related?
- RJ-like analysis with 139/fb already out [18]. Contains small hint — but probably just the excess events from the 35/fb analysis
- We are already making plans to investigate them
- We expect more interesting results soon. Stay tuned

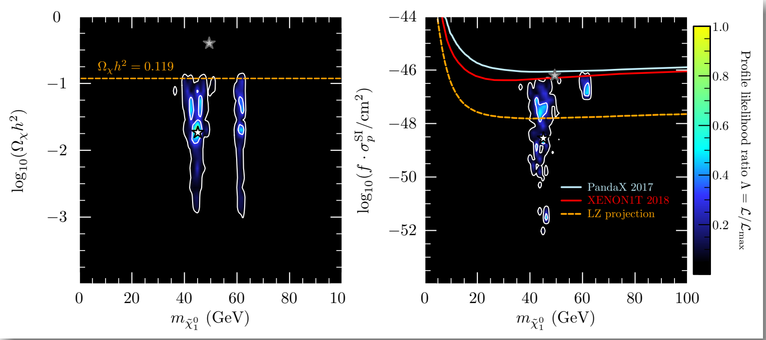
Could points that explain the anomalous results explain dark matter?

We checked relic density, direct and indirect searches for dark matter.

They can.

This isn't a trivial test — the neutralino's properties depend on the admixture of bino, higgsino and wino

The lightest is bino-like and annihilates efficiently through Z and h resonances at $m_\chi \simeq m_Z/2$ and $m_h/2$



A local significance of 3σ is not strong evidence [19] but we hope our study leads to progress in searches for electroweakinos

Conclusions

- LHC constraints on electroweakinos are mild — everything is allowed on profiled $(m_\chi, m_{\chi_1^\pm})$ plane
- A pattern of excesses favor light electroweakinos, $m_\chi \simeq 50\,\text{GeV}$
- The favored scenarios even accommodate dark matter
- However, 3σ local significance is not strong evidence

Careful how you interpret electroweakino searches — the real picture is complicated and the simple picture can miss anomalies and exaggerate limits

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