Combined collider constraints on neutralinos and charginos with **GAMBIT**

Jonathan Cornell, on behalf of the GAMBIT collaboration

GAMBIT: The Global And Modular BSM Inference Tool

A open-source tool for global fits of BSM theories based on the concepts of modularity and flexibility.

- Large (and growing) database of models, SUSY and others
- Extensive library of observables/likelihoods that can easily be enabled or disabled for a particular scan
- Tools for simple interfacing with external codes (Fortran, C, C++, Python, Mathematica)
- Many statistical options – Bayesian/frequentist, likelihood definitions, scanning algorithms
- Massively parallel, both OpenMP and MPI
- Easy to add new models, observables, likelihoods, and scanners!

arXiv:1705.07908
The Bits

• **DarkBit** – WIMP and ALP density calculations, event rates and likelihoods for indirect and direct searches (arXiv:1705.07920)

• **ColliderBit** – LHC and LEP searches for new particle production, Higgs constraints (arXiv:1705.07919)

• **FlavBit** – flavor physics, particularly B decays. Likelihoods from LHCb measurements. (arXiv:1705.07933)

• **SpecBit** – generic BSM spectrum object, providing RGE running, masses, mixings, etc. via interchangeable interfaces to different RGE codes (arXiv:1705.07936)

• **DecayBit** – decay widths for all relevant SM & BSM particles (arXiv:1705.07936)

• **PrecisionBit** – SM likelihoods, muon $g - 2$, precision BSM tests (W mass, etc.) (arXiv:1705.07936)

+ **ScannerBit** – manages stats, sampling and optimization (arXiv:1705.07959)

**Coming soon: CosmoBit and NeutrinoBit!**
The GAMBIT Community


40+ participants, 4 continents, 11 experiments, 14 major theory codes

ATLAS, Belle-II, CliC, CMS, CTA, DARWIN, Fermi-LAT, IceCube, LHCb, SHiP, Xenon
Other Results

Higgs Portal DM  
(arXiv: 1806.11281;  
arXiv: 1808.10465)

Axions  
(arXiv: 1810.07192)

MSSM-7  
(arXiv: 1705.07917)

- $\tilde{t}_1$ co-annihilation
- $A/H$ funnel
- $\tilde{\chi}_1^{\pm}$ co-annihilation
- $\tilde{b}_1$ co-annihilation
- $h/Z$ funnel

Scalar singlet $Z_2$  
$\Delta \rho > \max(m_q, m_t)$  
Prof. likelihood
Question

What are the 13 TeV LHC constraints on the neutralino/chargino sector of the MSSM? (Taking into account all possible signatures, not just those covered by simplified models)

Method

• Scan 4D MSSM electroweakino parameter space.
• At every point: Run MC simulations of 13 TeV searches.
• Calculate joint likelihood function for all searches.

\[ \mathcal{L}_{\text{total}} = \mathcal{L}_{2\ell} \mathcal{L}_{2\ell} + j \mathcal{L}_{3\ell} \cdots \]
The Model

Squarks, sleptons, and gluinos are decoupled, only neutralinos and charginos can be produced at LHC.

**Scan over 4 relevant parameters:**  \( M_1, M_2, \mu, \tan \beta \)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Priors</th>
</tr>
</thead>
<tbody>
<tr>
<td>( M_1(Q) )</td>
<td>(-2 \text{ TeV})</td>
<td>2 \text{ TeV}</td>
<td>hybrid, flat</td>
</tr>
<tr>
<td>( M_2(Q) )</td>
<td>0 \text{ TeV}</td>
<td>2 \text{ TeV}</td>
<td>hybrid, flat</td>
</tr>
<tr>
<td>( \mu(Q) )</td>
<td>(-2 \text{ TeV})</td>
<td>2 \text{ TeV}</td>
<td>hybrid, flat</td>
</tr>
<tr>
<td>( \tan \beta(m_Z) )</td>
<td>1</td>
<td>70</td>
<td>flat</td>
</tr>
<tr>
<td>( Q )</td>
<td></td>
<td>3 \text{ TeV}</td>
<td>fixed</td>
</tr>
</tbody>
</table>

Used to calculate mass spectrum, production cross sections, and decay widths.

2.4M total parameter points. 500k – 64M Pythia events/point.
# Searches Included

<table>
<thead>
<tr>
<th>Likelihood label</th>
<th>Source</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS_4b</td>
<td>ATLAS Higgsino search [120]</td>
<td>arXiv:1806.04030</td>
</tr>
<tr>
<td>ATLAS_4lep</td>
<td>ATLAS 4\ell search [121]</td>
<td>arXiv:1804.03602</td>
</tr>
<tr>
<td>ATLAS_MultiLep_2lep_0jet</td>
<td>ATLAS multilepton EW search [116]</td>
<td>arXiv:1803.02762</td>
</tr>
<tr>
<td>ATLAS_MultiLep_3lep</td>
<td>ATLAS multilepton EW search [116]</td>
<td>CMS-PAS-SUS-16-039</td>
</tr>
<tr>
<td>ATLAS_RJ_2lep_2jet</td>
<td>ATLAS recursive jigsaw EW search [117]</td>
<td>arXiv:1801.01846</td>
</tr>
<tr>
<td>CMS_1lep_2b</td>
<td>CMS Wh search [122]</td>
<td>CMS-PAS-SUS-16-039</td>
</tr>
<tr>
<td><strong>CMS_2lep_soft</strong></td>
<td>CMS 2 soft opposite-charge lepton search [125]</td>
<td><strong>CMS_2OS1lep</strong></td>
</tr>
<tr>
<td><strong>CMS_2OS1lep</strong></td>
<td>CMS 2 opposite-charge lepton search [126]</td>
<td><strong>CMS-MultiLep_2SSlep</strong></td>
</tr>
<tr>
<td>CMS_MultiLep_2SSlep</td>
<td>CMS multilepton EW search [127]</td>
<td>CMS-MultiLep_3lep</td>
</tr>
<tr>
<td>CMS_MultiLep_3lep</td>
<td>CMS multilepton EW search [127]</td>
<td></td>
</tr>
</tbody>
</table>

- All likelihoods determined by considering signal region expected to give the strongest limit, except blue CMS searches, for which correlations between backgrounds in signal regions have been provided.
- Also include limits on production cross sections from LEP, Z and h invisible decay widths.
Results: What can we exclude?

Capped LHC likelihood: \( \mathcal{L}_{\text{cap}} = \min[\mathcal{L}_{\text{LHC}}(s + b), \mathcal{L}_{\text{LHC}}(b)] \leq 1 \)

If \( \mathcal{L}_{\text{cap}} = 1 \) then there is a point in the 4D parameter space where there is either:

- no sensitivity
- all bad fits offset by other good fits

Very little of the mass range is disfavored...
Results: Uncapped

Remove the cap — allow for likelihoods better than the SM

- Preference for all EWinos less than $\sim500$ GeV
- $\chi^0_1$ is Bino-like
- 2 large mass steps ($>m_Z$) preferred
What's driving the low mass preference?

Blue — SUSY improves fit
Red — SUSY makes fit worse

Important Searches:
- ATLAS_4lep
- ATLAS_RJ_3lep
- ATLAS_MultiLep_2lep_jet
- ATLAS_MultiLep_3lep
- CMS_MultiLep_3lep
Dark Matter

Is $\tilde{\chi}_1^0$ a viable DM candidate? Post-process best fit samples with relic density, indirect and direct detection likelihoods.

- Preferred regions have relic density set by resonant annihilation via Z or h.
- Future direct detection experiments should probe much of allowed DM parameter space.
Summary

- Light neutralinos and charginos still allowed in when taking into account full MSSM EWino phenomenology.
- Small excesses in multi-lepton searches lead to preference (3.3σ local significance) for EWinos below 500 GeV (or potentially other BSM models that give multi-lepton final states).
- Subset of best fit region avoids all dark matter constraints.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>#1 Best fit</th>
<th>#2 Heavy winos</th>
<th>#3 Highest mass</th>
<th>#4 DM</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_1(Q)$</td>
<td>−50.6 GeV</td>
<td>−79.2 GeV</td>
<td>133.4 GeV</td>
<td>−45.6 GeV</td>
</tr>
<tr>
<td>$M_2(Q)$</td>
<td>149.3 GeV</td>
<td>263.0 GeV</td>
<td>243.5 GeV</td>
<td>143.7 GeV</td>
</tr>
<tr>
<td>$\mu(Q)$</td>
<td>252.7 GeV</td>
<td>−187.3 GeV</td>
<td>−293.2 GeV</td>
<td>260.8 GeV</td>
</tr>
<tr>
<td>$\tan \beta(m_Z)$</td>
<td>28.7</td>
<td>40.4</td>
<td>41.5</td>
<td>16.4</td>
</tr>
</tbody>
</table>

- $m_{\chi_1^0}$: 49.4 GeV, 73.9 GeV, 129.4 GeV, ·45.1 GeV
- $m_{\chi_2^0}$: 141.6 GeV, 165.7 GeV, 230.6 GeV, 136.5 GeV
- $m_{\chi_3^0}$: 270.3 GeV, 208.5 GeV, 308.8 GeV, 277.8 GeV
- $m_{\chi_4^0}$: 290.2 GeV, 292.6 GeV, 344.6 GeV, 297.2 GeV
- $m_{\chi_1^\pm}$: 142.1 GeV, 168.7 GeV, 230.2 GeV, 136.8 GeV
- $m_{\chi_2^\pm}$: 293.9 GeV, 294.2 GeV, 345.8 GeV, 300.5 GeV

Collider log-likelihood: 10.8, 10.3, 9.7, 10.4
GAMBIT Structure

**Models**
- ColliderBit
- DarkBit
- FlavBit
- PrecisionBit
- SpecBit
- DecayBit

**Core**

**Physics Modules**
- ColliderBit
- DarkBit
- FlavBit
- PrecisionBit
- SpecBit
- DecayBit

**Backends:**
- FlexibleSUSY
- SPheno
- SUSYHD
- FeynHiggs
- HiggsBounds
- HiggsSignals
- Vevacious
- PYTHIA
- SUSYHit
- CaptnGeneral
- DarkSUSY
- micrOMEGAs
- nuLike
- DDCalc*
- gamLike*
- SuperISO
- gm2Calc

**Scanners:**
- MultiNest
- Diver*
- GreAT
- twalk*
- Polychord
  *New!
ColliderBit’s recast chain is designed with a focus on speed:

- Cross-sections are calculated with Pythia (interfaces to MadGraph/CalcHEP in development)
- If cross section is too low, point is vetoed
- Pythia has been parallelized and some options have been turned off

<table>
<thead>
<tr>
<th>Configuration</th>
<th>$t \times 10^5$ events</th>
<th>Speed-up</th>
</tr>
</thead>
<tbody>
<tr>
<td>All</td>
<td>1,841 sec</td>
<td>1</td>
</tr>
<tr>
<td>$\rightarrow$ -MPI</td>
<td>671 sec</td>
<td>2.7</td>
</tr>
<tr>
<td>$\rightarrow$ $-\tau$ correlations</td>
<td>531 sec</td>
<td>3.5</td>
</tr>
</tbody>
</table>
We have written a custom fast detector simulator, **BuckFast**, based on four-vector smearing, which we use by default.

**ColliderBit — LHC**

- Cross-section calculation
  - Veto point if small
  - Default: Pythia 8

MC event generation
- Default: Pythia 8

Detector simulation
- Default: BuckFast

Event analyses

**Statistical routines**

- $\frac{1}{N_{ev} \cdot dN_{obj} / d\pt}$ [1/GeV]
  - $10^{-3}$
  - $3.5$ to $0$

**Electron $p_T$ [GeV]**
- $0$ to $200$

- Delphes
- BuckFast
- Truth

$N_{ev}$

$N_{obj}$

$\pt$ [GeV]
ColliderBit LHC Likelihoods

• We use a Poissonian likelihood marginalized over a rescaling parameter $\xi$ to account for systematic uncertainties:

$$\mathcal{L}(n|s, b) = \int_0^{\infty} \frac{[\xi(s + b)]^n e^{-\xi(b + s)}}{n!} P(\xi) d\xi$$

$$P(\xi|\sigma_\xi) \approx \frac{1}{\sqrt{2\pi}\sigma_\xi} \frac{1}{\xi} \exp \left[ -\frac{1}{2} \left( \frac{\ln \xi}{\sigma_\xi} \right)^2 \right]$$

where

$$\sigma_\xi^2 = \sigma_s^2 + \sigma_b^2$$

• $n$, $s$ and $b$ are for signal region expected to give the strongest limit (i.e. $\Delta \ln \mathcal{L}_{\text{pred}} = \ln \mathcal{L}(n = b | s, b) - \ln \mathcal{L}(n = b | s = 0, b)$ is maximally negative).
ColliderBit LHC Likelihoods

- When correlations between signal regions are provided (for some CMS analyses):

\[ \mathcal{L}(n \mid s, b) = \int \prod_i^{N_{\text{bin}}} \left[ \frac{(s_i + b_i + \gamma_i)^n e^{-(s_i + b_i + \gamma_i)n_i}}{n_i!} \right] P(\gamma \mid \Sigma) d\gamma \]

\[ P(\gamma \mid \Sigma) = \frac{1}{\sqrt{\det 2\pi \Sigma}} e^{-\frac{1}{2} \gamma^T \Sigma^{-1} \gamma} \]
Validation
Determining Local Significance

**Test statistic:**
\[ -2 \log \left( \frac{\mathcal{L}(s(M_1, M_2, \mu, \tan \beta) + b, \hat{\eta})}{\mathcal{L}(b, \hat{\eta})} \right) \]

- \( \hat{\eta} \) and \( \hat{\eta} \) are profiled values of nuisance parameters \( \xi \) and \( \gamma \).

- Distribution of test statistic for best fit point is determined via Monte Carlo simulations

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Local signif. (( \sigma ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Higgs invisible width</td>
<td>0</td>
</tr>
<tr>
<td>Z invisible width</td>
<td>0</td>
</tr>
<tr>
<td>ATLAS_4b</td>
<td>0.7</td>
</tr>
<tr>
<td>ATLAS_4lep</td>
<td>2.3</td>
</tr>
<tr>
<td>ATLAS_MultiLep_2lep_0jet</td>
<td>0.9</td>
</tr>
<tr>
<td>ATLAS_MultiLep_2lep_jet</td>
<td>0</td>
</tr>
<tr>
<td>ATLAS_MultiLep_3lep</td>
<td>1.8</td>
</tr>
<tr>
<td>ATLAS_RJ_2lep_2jet</td>
<td>0</td>
</tr>
<tr>
<td>ATLAS_RJ_3lep</td>
<td>0.7</td>
</tr>
<tr>
<td>CMS_1lep_2b</td>
<td>0.8</td>
</tr>
<tr>
<td>CMS_2lep_soft</td>
<td>0.1</td>
</tr>
<tr>
<td>CMS_2OSlep</td>
<td>0.1</td>
</tr>
<tr>
<td>CMS_MultiLep_2SSlep</td>
<td>0.2</td>
</tr>
<tr>
<td>CMS_MultiLep_3lep</td>
<td>0</td>
</tr>
<tr>
<td><strong>Combined</strong></td>
<td><strong>3.3</strong></td>
</tr>
</tbody>
</table>
Effect of Including 8 TeV Analyses

8 TeV likelihoods calculated for all points within 1σ contours.

Relevant 8 TeV, 20 fb⁻¹ EW analyses:
• ATLAS 1 lepton + 2 b-jet
• ATLAS 2 leptons
• ATLAS 3 leptons
• CMS 3 leptons
• CMS 4 leptons

2.9σ local significance
EW SUSY results with ~140 fb$^{-1}$ starting to appear:
ATLAS search for production of chargino pairs

Naive comparison:
Not sensitive to the ~M$_Z$ mass splitting in our best-fit region
Analysis: EW SUSY searches

- 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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13 TeV, 36 fb⁻¹

Courtesy of Anders Kvellestad
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ATLAS
Vs = 13 TeV, 36.1 fb⁻¹

Expected limit (± 1 σ_{exp})

Observed limit (± 1 σ_{theory})

2/3-lepton SRs

Statistical Combination

All limits at 95% CL

Courtesy of Anders Kvellestad
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