Global fits of supersymmetry — can we still have light neutralino DM?

Are Raklev

Dark Matter @ LHC 2020
Outline

- The electroweak sector of the MSSM (EWMSSM)
- LHC searches (see also previous talk)
- Global fits
- A fit of the EWMSSM
- Conclusions
The EWMSSM
# The MSSM particle content

<table>
<thead>
<tr>
<th>Name</th>
<th>Spin</th>
<th>P&lt;sub&gt;R&lt;/sub&gt;</th>
<th>Gauge Eigenstates</th>
<th>Mass Eigenstates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Higgs bosons</td>
<td>0</td>
<td>+1</td>
<td>( H_u^0 ) ( H_d^0 ) ( H_u^+ ) ( H_d^- )</td>
<td>( h^0 ) ( H^0 ) ( A^0 ) ( H^\pm )</td>
</tr>
<tr>
<td>squarks</td>
<td>0</td>
<td>-1</td>
<td>( \tilde{u}_L ) ( \tilde{u}_R ) ( \tilde{d}_L ) ( \tilde{d}_R )</td>
<td>(same)</td>
</tr>
<tr>
<td>sleptons</td>
<td>0</td>
<td>-1</td>
<td>( \tilde{e}_L ) ( \tilde{e}_R ) ( \tilde{\nu}_e )</td>
<td>(same)</td>
</tr>
<tr>
<td>neutralinos</td>
<td>1/2</td>
<td>-1</td>
<td>( \tilde{B}^0 ) ( \tilde{W}^0 ) ( \tilde{H}_u^0 ) ( \tilde{H}_d^0 )</td>
<td>( \tilde{\chi}_1^0 ) ( \tilde{\chi}_2^0 ) ( \tilde{\chi}_3^0 ) ( \tilde{\chi}_4^0 )</td>
</tr>
<tr>
<td>charginos</td>
<td>1/2</td>
<td>-1</td>
<td>( \tilde{W}^\pm ) ( \tilde{H}_u^+ ) ( \tilde{H}_d^- )</td>
<td>( \tilde{\chi}_1^\pm ) ( \tilde{\chi}_2^\pm )</td>
</tr>
<tr>
<td>gluino</td>
<td>1/2</td>
<td>-1</td>
<td>( \tilde{g} )</td>
<td>(same)</td>
</tr>
</tbody>
</table>
# The MSSM particle content

<table>
<thead>
<tr>
<th>Name</th>
<th>Spin</th>
<th>$P_R$</th>
<th>Gauge Eigenstates</th>
<th>Mass Eigenstates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Higgs bosons</td>
<td>0</td>
<td>+1</td>
<td>$H_u^0$ $H_d^0$ $H_u^+$ $H_d^-$</td>
<td>$h^0$ $H^0$ $A^0$ $H^\pm$</td>
</tr>
<tr>
<td>squarks</td>
<td>0</td>
<td>-1</td>
<td>$\tilde{u}_L$ $\tilde{u}_R$ $\tilde{d}_L$ $\tilde{d}_R$</td>
<td>(same)</td>
</tr>
<tr>
<td>sleptons</td>
<td>0</td>
<td>-1</td>
<td>$\tilde{e}_L$ $\tilde{e}_R$ $\tilde{\nu}_e$</td>
<td>(same)</td>
</tr>
<tr>
<td>neutralinos</td>
<td>1/2</td>
<td>-1</td>
<td>$\tilde{B}^0$ $\tilde{W}^0$ $\tilde{H}_u^0$ $\tilde{H}_d^0$</td>
<td>$\tilde{\chi}_1^0$ $\tilde{\chi}_2^0$ $\tilde{\chi}_3^0$ $\tilde{\chi}_4^0$</td>
</tr>
<tr>
<td>charginos</td>
<td>1/2</td>
<td>-1</td>
<td>$\tilde{W}^\pm$ $\tilde{H}_u^+$ $\tilde{H}_d^-$</td>
<td>$\tilde{\chi}_1^\pm$ $\tilde{\chi}_2^\pm$</td>
</tr>
<tr>
<td>gluino</td>
<td>1/2</td>
<td>-1</td>
<td>$\tilde{g}$</td>
<td>(same)</td>
</tr>
</tbody>
</table>
### The MSSM particle content

<table>
<thead>
<tr>
<th>Name</th>
<th>Spin</th>
<th>P&lt;sub&gt;R&lt;/sub&gt;</th>
<th>Gauge Eigenstates</th>
<th>Mass Eigenstates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Higgs bosons</td>
<td>0</td>
<td>+1</td>
<td>( H_u^0 ) ( H_d^0 ) ( H_u^+ ) ( H_d^- )</td>
<td>( h^0 ) ( H^0 ) ( A^0 ) ( H^\pm )</td>
</tr>
<tr>
<td>squarks</td>
<td>0</td>
<td>-1</td>
<td>( \tilde{u}_L ) ( \tilde{u}_R ) ( \tilde{d}_L ) ( \tilde{d}_R )</td>
<td>(same)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>( \tilde{s}_L ) ( \tilde{s}_R ) ( \tilde{c}_L ) ( \tilde{c}_R )</td>
<td>(same)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>( \tilde{t}_L ) ( \tilde{t}_R ) ( \tilde{b}_L ) ( \tilde{b}_R )</td>
<td>( \tilde{t}_1 ) ( \tilde{t}_2 ) ( \tilde{b}_1 ) ( \tilde{b}_2 )</td>
</tr>
<tr>
<td>sleptons</td>
<td>0</td>
<td>-1</td>
<td>( \tilde{e}_L ) ( \tilde{e}_R ) ( \tilde{\nu}_e )</td>
<td>(same)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>( \tilde{\mu}_L ) ( \tilde{\mu}<em>R ) ( \tilde{\nu}</em>\mu )</td>
<td>(same)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>( \tilde{\tau}_L ) ( \tilde{\tau}<em>R ) ( \tilde{\nu}</em>\tau )</td>
<td>( \tilde{\tau}_1 ) ( \tilde{\tau}<em>2 ) ( \tilde{\nu}</em>\tau )</td>
</tr>
<tr>
<td>neutralinos</td>
<td>1/2</td>
<td>-1</td>
<td>( \tilde{B}^0 ) ( \tilde{W}^0 ) ( \tilde{H}_u^0 ) ( \tilde{H}_d^0 )</td>
<td>( \tilde{\chi}_1^0 ) ( \tilde{\chi}_2^0 ) ( \tilde{\chi}_3^0 ) ( \tilde{\chi}_4^0 )</td>
</tr>
<tr>
<td>charginos</td>
<td>1/2</td>
<td>-1</td>
<td>( \tilde{W}^\pm ) ( \tilde{H}_u^+ ) ( \tilde{H}_d^- )</td>
<td>( \tilde{\chi}_1^\pm ) ( \tilde{\chi}_2^\pm )</td>
</tr>
<tr>
<td>gluino</td>
<td>1/2</td>
<td>-1</td>
<td>( \tilde{g} )</td>
<td>(same)</td>
</tr>
</tbody>
</table>
# The MSSM particle content

<table>
<thead>
<tr>
<th>Name</th>
<th>Spin</th>
<th>P&lt;sub&gt;R&lt;/sub&gt;</th>
<th>Gauge Eigenstates</th>
<th>Mass Eigenstates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Higgs bosons</td>
<td>0</td>
<td>+1</td>
<td>$H_u^0$, $H_d^0$, $H_u^+$, $H_d^-$</td>
<td>$h^0$, $H^0$, $A^0$, $H^\pm$</td>
</tr>
<tr>
<td>squarks</td>
<td>0</td>
<td>-1</td>
<td>$\tilde{u}_L$, $\tilde{u}_R$, $\tilde{d}_L$, $\tilde{d}_R$</td>
<td>(same)</td>
</tr>
<tr>
<td>slepton</td>
<td>0</td>
<td>-1</td>
<td>$\tilde{e}_L$, $\tilde{e}_R$, $\tilde{\nu}_e$</td>
<td>(same)</td>
</tr>
<tr>
<td>neutralinos</td>
<td>1/2</td>
<td>-1</td>
<td>$\tilde{B}^0$, $\tilde{W}^0$, $\tilde{H}_u^0$, $\tilde{H}_d^0$</td>
<td>$\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$, $\tilde{\chi}_3^0$, $\tilde{\chi}_4^0$</td>
</tr>
<tr>
<td>charginos</td>
<td>1/2</td>
<td>-1</td>
<td>$\tilde{W}^\pm$, $\tilde{H}_u^+$, $\tilde{H}_d^-$</td>
<td>$\tilde{\chi}_1^\pm$, $\tilde{\chi}_2^\pm$</td>
</tr>
<tr>
<td>gluino</td>
<td>1/2</td>
<td>-1</td>
<td>$\tilde{g}$</td>
<td>(same)</td>
</tr>
</tbody>
</table>
## The MSSM particle content

<table>
<thead>
<tr>
<th>Name</th>
<th>Spin</th>
<th>P&lt;sub&gt;R&lt;/sub&gt;</th>
<th>Gauge Eigenstates</th>
<th>Mass Eigenstates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Higgs bosons</td>
<td>0</td>
<td>+1</td>
<td>(H_u^0) (H_d^0) (H_u^+) (H_d^-)</td>
<td>(h^0) (H^0) (A^0) (H^\pm)</td>
</tr>
<tr>
<td>squarks</td>
<td>0</td>
<td>-1</td>
<td>(\tilde{u}_L) (\tilde{u}_R) (\tilde{d}_L) (\tilde{d}_R)</td>
<td>(same)</td>
</tr>
<tr>
<td>sleptons</td>
<td>0</td>
<td>-1</td>
<td>(\tilde{e}_L) (\tilde{e}_R) (\tilde{\nu}_e)</td>
<td>(same)</td>
</tr>
<tr>
<td>neutralinos</td>
<td>1/2</td>
<td>-1</td>
<td>(\tilde{B}^0) (\tilde{W}^0) (\tilde{H}_u^0) (\tilde{H}_d^0)</td>
<td>(\tilde{\chi}_1^0) (\tilde{\chi}_2^0) (\tilde{\chi}_3^0) (\tilde{\chi}_4^0)</td>
</tr>
<tr>
<td>charginos</td>
<td>1/2</td>
<td>-1</td>
<td>(\tilde{W}^\pm) (\tilde{H}_u^+) (\tilde{H}_d^-)</td>
<td>(\tilde{\chi}_1^\pm) (\tilde{\chi}_2^\pm)</td>
</tr>
<tr>
<td>gluino</td>
<td>1/2</td>
<td>-1</td>
<td>(\tilde{g})</td>
<td>(same)</td>
</tr>
</tbody>
</table>
## The MSSM particle content

<table>
<thead>
<tr>
<th>Name</th>
<th>Spin</th>
<th>$P_R$</th>
<th>Gauge Eigenstates</th>
<th>Mass Eigenstates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Higgs bosons</td>
<td>0</td>
<td>+1</td>
<td>$H^0_u$ $H^0_d$ $H^+_u$ $H^-_d$</td>
<td>$h^0$ $H^0$ $A^0$ $H^\pm$</td>
</tr>
<tr>
<td>squarks</td>
<td>0</td>
<td>-1</td>
<td>$\tilde{u}_L$ $\tilde{u}_R$ $\tilde{d}_L$ $\tilde{d}_R$</td>
<td>(same)</td>
</tr>
<tr>
<td>sleptons</td>
<td>0</td>
<td>-1</td>
<td>$\tilde{e}_L$ $\tilde{e}_R$ $\tilde{\nu}_e$</td>
<td>(same)</td>
</tr>
<tr>
<td>electroweakinos — EWMSSM</td>
<td></td>
<td></td>
<td>$\tilde{\tau}_L$ $\tilde{\tau}<em>R$ $\tilde{\nu}</em>\tau$</td>
<td>(same)</td>
</tr>
<tr>
<td>neutralinos</td>
<td>1/2</td>
<td>-1</td>
<td>$\tilde{B}^0$ $\tilde{W}^0$ $\tilde{H}^0_u$ $\tilde{H}^0_d$</td>
<td>$\tilde{\chi}^0_1$ $\tilde{\chi}^0_2$ $\tilde{\chi}^0_3$ $\tilde{\chi}^0_4$</td>
</tr>
<tr>
<td>charginos</td>
<td>1/2</td>
<td>-1</td>
<td>$\tilde{W}^\pm$ $\tilde{H}^+_u$ $\tilde{H}^-_d$</td>
<td>$\tilde{\chi}^{\pm}_1$ $\tilde{\chi}^{\pm}_2$</td>
</tr>
<tr>
<td>gluino</td>
<td>1/2</td>
<td>-1</td>
<td>$\tilde{g}$</td>
<td>(same)</td>
</tr>
</tbody>
</table>
Neutralinos & charginos

Neutralinos

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

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

Charginos

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

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

Neutralinos

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

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

Charginos

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

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

Modified from original slide courtesy of Anders Kvellestad
Neutralinos & charginos

Neutralinos

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

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

Charginos

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

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

Neutralinos

$$\psi^0 = (\tilde{B}, \tilde{W}_0, \tilde{H}^0_d, \tilde{H}^0_u)$$

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

Charginos

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

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

Neutralinos

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

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

Charginos

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

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

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

Rough summary:

- \( M_1 \) controls the mass of **one neutralino** (bino)
- \( M_2 \) controls the mass of **one neutralino** and **one chargino** (winos)
- \( \mu \) controls the mass of **two neutralinos** and **one chargino** (higgsinos)
Mass hierarchies

Degenerate wino/higgsino LSPs

higgsinos

\( M_2 \ll M_1, \mu \)

wino

\( \mu \ll M_1, M_2 \)

bino

\( \quad \)

\( \quad \)

\( \quad \)
Mass hierarchies

Degenerate wino/higgsino LSPs

\[ M_2 \ll M_1, \mu \]

\[ \mu \ll M_1, M_2 \]

Wino NLSP(s)  \( \tilde{\chi}_2^0, \tilde{\chi}_1^\pm \)

\[ M_1 < M_2 < \mu \]
Mass hierarchies

Degenerate wino/higgsino LSPs

$\mu \ll M_1, M_2$

Wino NLSP(s) $\tilde{\chi}_2^0, \tilde{\chi}_1^\pm$

Higgsino NLSP(s) $\tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_1^\pm$

$M_2 \ll M_1, \mu$

$M_1 < M_2 < \mu$

$M_1 < \mu < M_2$
# Mass hierarchies

<table>
<thead>
<tr>
<th>Mass Hierarchy</th>
<th>NLSPs</th>
<th>Mass Relations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Degenerate wino/higgsino LSPs</td>
<td></td>
<td>$M_2 \ll M_1, \mu$</td>
</tr>
<tr>
<td>Wino NLSP(s)</td>
<td>$\tilde{\chi}_2^0, \tilde{\chi}_1^\pm$</td>
<td>$M_1 &lt; M_2 &lt; \mu$</td>
</tr>
<tr>
<td>Higgsino NLSP(s)</td>
<td>$\tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_1^\pm$</td>
<td></td>
</tr>
<tr>
<td>Lonely bino</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
LHC searches
The LHC experiments have done a spectacular job of searching for neutralino DM.
LHC searches

- The LHC experiments have done a spectacular job of searching for neutralino DM
LHC searches

• The LHC experiments have done a spectacular job of searching for neutralino DM

[ATL-PHYS-PUB-2020-013]
However...

- Summary plot assumes wino production cross sections (generically smaller for bino & higgsino).
- For each channel a 100% BR is assumed.
- What happens when you join searches instead of overlaying the strongest ones?
- (What happens if you go beyond the MSSM?)
Global fits
Global fits

- Choose your BSM model and parameterisation.

- Calculate a combined consistent likelihood from relevant experimental results:
  \[ \mathcal{L} = \mathcal{L}_{\text{Collider}} \mathcal{L}_{\text{Higgs}} \mathcal{L}_{\text{Flavour}} \mathcal{L}_{\text{DM}} \mathcal{L}_{\text{Precision}} \cdots \]

- Use a sophisticated scanning technique to explore the likelihood function across the parameter space of the model to determine:
  - The best fit regions of parameter space of a particular theory.
  - Which theories give (comparatively) the best fit to the data.

- Sensible statistical interpretation (inference):
  - Not just counting number of points.
  - Choice of approach: frequentist/Bayesian.
Recent results

Chargino coannihilation region starting from $m_{\tilde{\chi}^\pm_1} \sim m_{\tilde{\chi}^0_1} \sim 100$ GeV with degenerate Higgsinos.
Recent results

Chargino coannihilation region starting from $m_{\tilde{\chi}_1^\pm} \sim m_{\tilde{\chi}_1^0} \sim 100$ GeV with degenerate Higgsinos.
A fit of the EWMSSM
Scan setup

[The GAMBIT Collaboration, 1809.02097]

<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 TeV</td>
<td>2 TeV</td>
<td>hybrid, flat</td>
</tr>
<tr>
<td>$M_2(Q)$</td>
<td>0 TeV</td>
<td>2 TeV</td>
<td>hybrid, flat</td>
</tr>
<tr>
<td>$\mu(Q)$</td>
<td>−2 TeV</td>
<td>2 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 TeV</td>
<td>fixed</td>
</tr>
<tr>
<td>$\alpha_s^{MS}(m_Z)$</td>
<td>0.1181</td>
<td>fixed</td>
<td></td>
</tr>
<tr>
<td>Top quark pole mass</td>
<td></td>
<td>171.06 GeV</td>
<td>fixed</td>
</tr>
</tbody>
</table>

Scans

- Diver (differential evolution) scanner (https://diver.hepforge.org/)
- ~2.4M parameter point samples
- Up to 500k Pythia 8 events per point for LHC simulations

Post-processing

- Re-run points in preferred parameter regions with higher MC statistics
- 3σ region: ≥4M events, 1σ region: ≥16M events, 500 best points: 64M events
- ~240k parameter point samples
## LHC likelihoods

<table>
<thead>
<tr>
<th>Likelihood label</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS_4b</td>
<td>ATLAS Higgsino search [116]</td>
</tr>
<tr>
<td>ATLAS_4lep</td>
<td>ATLAS 4\ell search [117]</td>
</tr>
<tr>
<td>ATLAS_MultiLep_2lep_0jet</td>
<td>ATLAS multilepton EW search [112]</td>
</tr>
<tr>
<td>ATLAS_MultiLep_2lep_jet</td>
<td>ATLAS multilepton EW search [112]</td>
</tr>
<tr>
<td>ATLAS_MultiLep_3lep</td>
<td>ATLAS multilepton EW search [112]</td>
</tr>
<tr>
<td>ATLAS_RJ_2lep_2jet</td>
<td>ATLAS recursive jigsaw EW search [113]</td>
</tr>
<tr>
<td>ATLAS_RJ_3lep</td>
<td>ATLAS recursive jigsaw EW search [113]</td>
</tr>
<tr>
<td>CMS_1lep_2b</td>
<td>CMS Wh search [118]</td>
</tr>
<tr>
<td>CMS_2lep_soft</td>
<td>CMS 2 soft opposite-charge lepton search [121]</td>
</tr>
<tr>
<td>CMS_2OSlep</td>
<td>CMS 2 opposite-charge lepton search [122]</td>
</tr>
<tr>
<td>CMS_MultiLep_2SSlep</td>
<td>CMS multilepton EW search [123]</td>
</tr>
<tr>
<td>CMS_MultiLep_3lep</td>
<td>CMS multilepton EW search [123]</td>
</tr>
</tbody>
</table>

All LHC searches included use 13 TeV data (up to 36 fb$^{-1}$). Roughly corresponds to March 2018 status.
Can light neutralinos be excluded?

Use a **capped likelihood** where the model can not do better than the SM background model:

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

If **profile likelihood ratio** = 1, a parameter point with those masses exists which fits just as well as the SM.

[The GAMBIT Collaboration, 1809.02097]
Can light neutralinos be excluded?

Use a **capped likelihood** where the model can not do better than the SM background model:

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

If **profile likelihood ratio = 1**, a parameter point with those masses exists which fits just as well as the SM.

So, virtually no neutralino masses are excluded!
Can light neutralinos be excluded?

**Interpretation of profile likelihood:** For every point in the mass plane, there is at least one point in the EWMSSM parameter space that fits the data as well as the given ratio value.

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

- **$\mu$**
- **$M_1$**
- **$M_2$**

EWMSSM. 1σ and 2σ CL regions. GAMBIT 1.2.0

Profile likelihood ratio $\Lambda = \mathcal{L}_{\text{cap}}/\mathcal{L}_{\text{cap,max}}$
Can light neutralinos be excluded?

EWMSSM. $1\sigma$ and $2\sigma$ CL regions. GAMBIT 1.2.0

Profile likelihood ratio $\Lambda = \frac{L_{\text{cap}}}{L_{\text{cap,max}}}$

[The GAMBIT Collaboration, 1809.02097]
Can light neutralinos be excluded?

EWMSSM. 1σ and 2σ CL regions. GAMBIT 1.2.0

Profile likelihood ratio $\Lambda = \frac{\mathcal{L}}{\mathcal{L}_{\text{cap,max}}}$

$\tilde{\chi}_{1}^{0}$ (GeV)

$m_{\tilde{\chi}_{1}^{\pm}}$ (GeV)

[The GAMBIT Collaboration, 1809.02097]
What is going on?

**Wino NLSP(s)** $\tilde{\chi}^0_2, \tilde{\chi}^{\pm}_1$

**Higgsino NLSP(s)** $\tilde{\chi}^0_2, \tilde{\chi}^0_3, \tilde{\chi}^{\pm}_1$

Total relevant production cross sections ~2-3 times smaller for Higgsino NLSPs

*Graphs show NLO cross section [fb] as a function of $m_{\tilde{\chi}^\pm}$ [GeV].*

- **Wino NLSP**
  - $\sqrt{s} = 13$ TeV
  - $M_1 = 100$ GeV
  - $\mu = 1$ TeV
  - $\tan \beta = 10$

- **Higgsino NLSP**
  - $\sqrt{s} = 13$ TeV
  - $M_1 = 100$ GeV
  - $M_2 = 1$ TeV
  - $\tan \beta = 10$
What is going on?

Assumptions of 100% BR.

For Wino NLSPs, when $m_{\tilde{\chi}^0_2} > m_{\tilde{\chi}^0_1} + m_h$, the $\tilde{\chi}^0_2$ BR to h and Z can be flipped between ~0.9 and ~0.1 by switching the sign of $\mu$
Can light neutralinos be excluded now?

EWMSSM. 1σ and 2σ CL regions. GAMBIT 1.2.0

Profile likelihood ratio $\Lambda = \frac{\mathcal{L}}{\mathcal{L}_{\text{cap}}}$

$WZ$

ATLAS March 2018
Can light neutralinos be excluded now?

EWMSSM. 1σ and 2σ CL regions. GAMBIT 1.2.0

Profile likelihood ratio $\Lambda = \frac{\mathcal{L}_{\text{cap}}}{\mathcal{L}_{\text{cap,max}}}$

$\tilde{m} \tilde{\chi}_1^0$ (GeV)

$\tilde{m} \tilde{\chi}_1^+$ (GeV)
Can light neutralinos be excluded now?

EWMSSM. $1\sigma$ and $2\sigma$ CL regions. GAMBIT 1.2.0

$\bar{\chi}_0^1$ (GeV)

Profile likelihood ratio $\Lambda = L_{\text{cap}} / L_{\text{cap, max}}$
Conclusions

- Important to go beyond simplified models to reach firm conclusions about the possibilities of light neutralino DM.

- A global fit of the MSSM electroweak sector using GAMBIT showed (as of March 2018) no model independent absolute bounds on neutralinos from the LHC.
  
  - Recent increases in luminosity from 36 fb\(^{-1}\) up to 140 fb\(^{-1}\) may change this conclusion, however, bounds in all probability much weaker in full parameter space.

- Since capacity of the experiments to analyse all possible full models is limited, the reinterpretation of results is crucial for the community.
  
  - Strong bounds need detailed information, e.g. full likelihoods, correlations between signal regions etc.

[LHC Reinterpretation Forum, 2003.07868]
Bonus material
ColliderBit validation

GAMBIT 1.2.0

ATLAS MultiLep
2lep
jet

ATLAS MultiLep
3lep

ATLAS RJ
2lep
2jet

ATLAS RJ
3lep

\[ m_{\tilde{\chi}^0_1} = m_{\tilde{\chi}^0_2} \] (GeV)

\[ \ln L(\text{s+b}) - \ln L(b) \]

\[ m_{\tilde{\chi}^0_1} = m_{\tilde{\chi}^0_2} \] (GeV)

\[ m_{\tilde{\chi}^0_1} = m_{\tilde{\chi}^0_2} \] (GeV)
With an **uncapped likelihood** we have closed $2\sigma$ contours

Preference for $m_{\tilde{\chi}_2^0} \sim m_{\tilde{\chi}_1^\pm} \sim m_{\tilde{\chi}_1^0} + m_Z$
DM properties
DM properties

DM relic density bound is satisfied through Higgs- and Z-funnels.
Adding DM likelihoods

DM likelihoods: Planck DM density (upper limit), direct detection searches from LUX, PandaX, XENON1T, CDMSlite, CRESST-II, PICO-60, DarkSide-50, and IceCube, indirect detection gamma-ray limits from Fermi-LAT observations of 15 Milky Way dwarf spheroidal galaxies.

[The GAMBIT Collaboration, 1809.02097]
LEP likelihoods

<table>
<thead>
<tr>
<th>Production</th>
<th>Signature</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tilde{\chi}_i \tilde{\chi}_1$</td>
<td>$\tilde{\chi}_i^0 \rightarrow q\bar{q}\tilde{\chi}_1^0$</td>
<td>OPAL [53]</td>
</tr>
<tr>
<td>($i = 2, 3, 4$)</td>
<td>$\tilde{\chi}_i^0 \rightarrow \ell \bar{\ell} \tilde{\chi}_1^0$</td>
<td>L3 [98]</td>
</tr>
<tr>
<td>$\tilde{\chi}_i \tilde{\chi}_i$</td>
<td>$\tilde{\chi}_i^+ \tilde{\chi}_i^- \rightarrow q\bar{q}' q\bar{q}' \tilde{\chi}_1^0 \tilde{\chi}_1^0$</td>
<td>OPAL [53]</td>
</tr>
<tr>
<td>($i = 1, 2$)</td>
<td>$\tilde{\chi}_i^+ \tilde{\chi}_i^- \rightarrow q\bar{q}' \ell \nu \tilde{\chi}_1^0 \tilde{\chi}_1^0$</td>
<td>OPAL [53]</td>
</tr>
<tr>
<td></td>
<td>$\tilde{\chi}_i^+ \tilde{\chi}_i^- \rightarrow \ell \nu \nu \tilde{\chi}_1^0 \tilde{\chi}_1^0$</td>
<td>OPAL [53], L3 [98]</td>
</tr>
<tr>
<td>ISR $\gamma +$ missing energy</td>
<td></td>
<td>OPAL [99]</td>
</tr>
</tbody>
</table>

Invisible width likelihoods

$\Gamma(Z \rightarrow \text{inv.}) = 499.0 \pm 1.5 \text{ MeV}$  \hspace{1cm} (LEP)

$\text{BF}(h \rightarrow \text{inv.}) \leq 0.19$  \hspace{1cm} (LHC)
Most important contributions:

- ATLAS_4lep
- ATLAS_RJ_3lep
- ATLAS_MultiLep_2lep_jet
- ATLAS_MultiLep_3lep
- CMS_MultiLep_3lep

Individual analysis contributions to the 3σ best-fit region:

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

Blue: better than background-only
Red: worse than background-only
Local significance & goodness-of-fit

Optimist view: Early hint of a signal in multi-lepton states?

Realist view: Very light electroweakinos still allowed in the MSSM

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Best expected SRs</th>
<th>All SRs; neglect correlations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Local signif. (σ)</td>
<td>SM fit (σ)</td>
</tr>
<tr>
<td>Higgs invisible width</td>
<td>0.9</td>
<td>0.3</td>
</tr>
<tr>
<td>Z invisible width</td>
<td>0</td>
<td>1.3</td>
</tr>
<tr>
<td>ATLAS_4b</td>
<td>0.7</td>
<td>0</td>
</tr>
<tr>
<td>ATLAS_4lep</td>
<td>2.3</td>
<td>2.0</td>
</tr>
<tr>
<td>ATLAS_MultiLep_2lep_0jet</td>
<td>0.9</td>
<td>0.3</td>
</tr>
<tr>
<td>ATLAS_MultiLep_2lep_jet</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>ATLAS_MultiLep_3lep</td>
<td>1.8</td>
<td>1.6</td>
</tr>
<tr>
<td>ATLAS_RJ_2lep_2jet</td>
<td>0</td>
<td>0.3</td>
</tr>
<tr>
<td>ATLAS_RJ_3lep</td>
<td>2.8</td>
<td>2.4</td>
</tr>
<tr>
<td>CMS_1lep_2b</td>
<td>0.9</td>
<td>0.3</td>
</tr>
<tr>
<td>CMS_2lep_soft</td>
<td>0.4</td>
<td>0.2</td>
</tr>
<tr>
<td>CMS_2OSlep</td>
<td>0</td>
<td>0.4</td>
</tr>
<tr>
<td>CMS_MultiLep_2SSlep</td>
<td>0.2</td>
<td>0</td>
</tr>
<tr>
<td>CMS_MultiLep_3lep</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Combined</td>
<td>3.5</td>
<td>1.5</td>
</tr>
</tbody>
</table>
Beyond the MSSM

- **EWMSSM + light gravitino (prompt NLSP decay)**
  - Extra Z, γ, or h from decay of NLSP changes which searches are sensitive

- **NMSSM**
  - Singlino component in neutralinos can reduce cross sections and open decays to further Higgs states
Excess in gravitino model?

July 2018

ATLAS Preliminary

$\sqrt{s}=13$ TeV, 36.1 fb$^{-1}$

$pp \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_1^- , \tilde{\chi}_1^\pm \tilde{\chi}_1^0 , \tilde{\chi}_1^\pm \tilde{\chi}_2^0 , \tilde{\chi}_1^0 \tilde{\chi}_2^0$ (Higgsino)

$\tilde{\chi}_1^0 \rightarrow h \tilde{G}$ or $Z \tilde{G}$

- Expected limits
- Observed limits

All limits at 95% CL

4b, arXiv:1806.04030
4L, arXiv:1804.03602
GAMBIT: The Global And Modular BSM Inference Tool

gambit.hepforge.org

Recent collaborators:

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

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

40+ participants in 11 experiments and 14 major theory codes

- 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

EPJC 77 (2017) 784  arXiv:1705.07908
Public results

- Documentation for open source codebase: gambit.hepforge.org

- All physics results publicly available on zenodo.cern.ch, including:
  - GAMBIT input yaml files for scans
  - Parameter point chains (hdf5 files)
  - SLHA1 and SLHA2 files for the best-fit point in each subregion of each fit
  - Plotting routines
Public results

- Documentation for open source codebase: gambit.hepforge.org

- All physics results publicly available on zenodo.cern.ch, including:
  - GAMBIT input yaml files for scans
  - Parameter point chains (hdf5 files)
  - SLHA1 and SLHA2 files for the best-fit point in each subregion of each fit
  - Plotting routines
How to start using GAMBIT

- Clone the git repository
  
github.com/patscott/gambit_1.4

- Or download tarball from: gambit.hepforge.org

- Compiles with CMake using gcc or intel compilers

- Or get the pre-compiled docker version (around 6 GB)
  
docker run -it gambitbsm/gambit-pippi

- Run with
  
gambit -f yaml_files/CMSSM.yaml