pMSSM Studies with ATLAS and CMS

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On behalf of the ATLAS and CMS collaborations
14 June 2016
How do we interpret the impact of experimental searches on SUSY?
Simplified Models

- Most searches interpret results in terms of simplified models
- These consider a single production and decay process
- Not representative of more complex SUSY phenomenology

Is there a more generic way of understanding limits on SUSY?
The Phenomenological MSSM

Subset of 120 parameter MSSM

Key Constraints
- 1st gen. sfermion degenerate with corresponding 2nd gen. sfermion
- No CP violation beyond CKM
- No FCNC

- Constraints are motivated by experiments
- No assumption made about nature of SUSY breaking
- ATLAS and CMS use the 19-parameter pMSSM
- Lightest neutralino, $\tilde{\chi}_1^0$ is the LSP
Both ATLAS and CMS have produced large scale studies summarising the impact of Run-1 SUSY searches:

ATLAS: JHEP 10 (2015) 134
CMS: CMS-PAS-SUS-15-010

New today! 1606.03577 (update of PAS note)

Find points in pMSSM space: sets of parameters

Both apply relevant experimental constraints, such as:

- Heavy Flavour
- Higgs Mass
- LEP chargino
- Heavy Flavour Precision Measurement

\[ b \rightarrow W^+ t \rightarrow W^- Z \rightarrow \mu^+ \mu^- \]
\[ H \]
\[ g-2 \]
Similarities and Differences

- Both employed flat priors to restrict the parameter space, e.g., all sparticles have mass less than 4 (3) TeV for ATLAS (CMS)

**ATLAS**
- Employed uniform sampling
- Sampled \( 500 \times 10^6 \) points
- Dark Matter constraint: \( \Omega h^2 (\tilde{\chi}_1^0) < \text{Planck} \)
- Simulated 300k models
- Combined 22 searches

**CMS**
- Bayesian approach & MCMC
- Sampled \( 20 \times 10^6 \) points
- No DM constraint
- Simulated 7k models
- Combined 11 searches
Results (CMS)

CMS preliminary, pMSSM

- Prior from non-DCS data
- Combined, 7 TeV
- Combined, 7 + 8 TeV
- Combined, 7 + 8 TeV, LHC Higgs data
- $\mu=0.5$
- $\mu=1.0$
- $\mu=1.5$

After CMS

7+8 TeV

Before CMS

After CMS + Higgs BR

$\log_{10}(\text{cross-section}) / \text{fb}$
Cross-section

Impact: Most probable cross-section reduced by order of magnitude

Sensitivity to models with x-section of 1 fb

\[ \log_{10}(\text{cross-section}) / \text{fb} \]
Gluinos: Before LHC

- Model density (prior)
- White squares mean no models
- Similarity between the two approaches
• Impact of searches
• No models with $m(\tilde{g}) < 500$ GeV remain
Models with $m(\tilde{t}_1) < 500$ GeV are rare in the pMSSM

- Rare due to requirement $m(h) \approx 125$ GeV
- Models with light stops are still viable
Higgs to Invisibles

- If $m(\tilde{\chi}_1^0) \lesssim \frac{1}{2} m(h)$ then (invisible) $h \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0$ occurs
- Light neutralinos under threat from Higgs branching ratio constraints

Will Fawcett (University of Oxford)
Dark Matter

Key difference between the ATLAS and CMS approaches:

Constraint from PLANCK: $\Omega_{CDM} h^2 < 0.1208$

These models are not considered by ATLAS.
pMSSM: summary

Mass [GeV]
0 500 1000 1500 2000

Sparticle
$g \sim 1$
t$\sim 2$
t$\sim 1$
b$\sim 2$
b$\sim q \sim 0$
$\chi \sim 0$
$\chi \sim 0$
$\chi \sim 0$
$\tau \sim 2$
$\tau \sim l \sim \pm$
$\chi \sim \pm$

ATLAS
$\sqrt{s} = 8$ TeV, 20.3 fb$^{-1}$

Fraction of Models Excluded
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
First interpretation of 13 TeV results

Uses ATLAS model information

- Theorists have combined 6 ATLAS 13 TeV searches
- Considerable sensitivity increase of Run-2 searches
- 1605.09502
Summary

- pMSSM captures of the phenomenology of the full MSSM
- ATLAS: random scan, CMS: Bayesian approach
- Large swathes of pMSSM parameter space untouched by searches
- Plenty of work to do in Run-2!
Backup
pMSSM and the $Z+{E_T}^{miss}$ excess

Uses ATLAS model information

- $3\sigma$ excess in $Z$+jets+$E_T^{miss}$ search (ATLAS)  EPJC 75, 10, 463 (2015)
- Yet no excess from a similar CMS search  JHEP 04 (2015) 124
- pMSSM can provide a candidate model: study using ATLAS pMSSM models  1604.02959
Machine Learning and the pMSSM

Uses ATLAS model information

- Study done by theorists taking the ATLAS model set and using this as training for a Machine Learning Algorithm. “BSM AI project” 1605.02797
- Takes parameters of pMSSM model from SLHA input
- 93% accurate in determining if the model is excluded

True classification  Prediction by classifier  Difference between classification and prediction
Models Evading Run-1: ATLAS

1602.06194

- ATLAS scan of the pMSSM revealed classes of models evading searches
- Built a simplified model to emulate this class
- Optimised a search to fill gap
- See Antonia’s talk
Models Evading Run-1: CMS

- Set of “principal topologies” defined
- Most common production and decay modes
- Each colour corresponds to a different topology
- Each line a different model
The pMSSM is:

19 parameters subset of the 120 parameter MSSM

- MSSM too complex to explore directly
- Imposing following constraints:
  1. No CP violation beyond CKM
  2. No FCNC
  3. Degeneracy of $1^{st}/2^{nd}$ gen. squarks (& sleptons)
- Assume $R$-parity conservation
- neutralino-1 is the LSP

The pMSSM is small enough to explore with available computing resources but large enough to incorporate non-LHC constraints.
### ATLAS: pMSSM Scan Range

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
<th>Parameter</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_1$</td>
<td>[-4000:4000]</td>
<td>$m(\tilde{q}<em>{1L} = \tilde{q}</em>{2L})$</td>
<td>[200:4000]</td>
</tr>
<tr>
<td>$M_2$</td>
<td>[-4000:-70], [70:4000]</td>
<td>$m(\tilde{u}_R = \tilde{c}_R)$</td>
<td>[200:4000]</td>
</tr>
<tr>
<td>$M_3$</td>
<td>[200:4000]</td>
<td>$m(\tilde{d}_R = \tilde{s}_R)$</td>
<td>[200:4000]</td>
</tr>
<tr>
<td>$\mu$</td>
<td>[-4000:-80], [80:4000]</td>
<td>$m(\tilde{\nu}_3L)$</td>
<td>[100:4000]</td>
</tr>
<tr>
<td>$\tan \beta$</td>
<td>[1:60]</td>
<td>$m(\tilde{b}_R)$</td>
<td>[100:4000]</td>
</tr>
<tr>
<td>$M_A$</td>
<td>[100:4000]</td>
<td>$m(\tilde{t}_R)$</td>
<td>[100:4000]</td>
</tr>
<tr>
<td>$A_\tau$</td>
<td>[-4000:4000]</td>
<td>$m(\tilde{e}_L = \tilde{\mu}_L)$</td>
<td>[90:4000]</td>
</tr>
<tr>
<td>$A_b$</td>
<td>[-4000:4000]</td>
<td>$m(\tilde{e}_R = \tilde{\mu}_R)$</td>
<td>[90:4000]</td>
</tr>
<tr>
<td>$A_t$</td>
<td>[-8000:8000]</td>
<td>$m(\tilde{\tau}_L)$</td>
<td>[90:4000]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$m(\tilde{\tau}_R)$</td>
<td>[90:4000]</td>
</tr>
</tbody>
</table>

**Table:** pMSSM parameter scan ranges. Note mass units are in GeV.

Note, the upper bound of 4 TeV forces all sparticles to be below that limit and we therefore do not explore parts of the pMSSM where most particles are heavy, i.e. split SUSY like scenarios.
## ATLAS: Non-ATLAS Search Constraints

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Constraint</th>
</tr>
</thead>
<tbody>
<tr>
<td>(m(h))</td>
<td>124–128 GeV</td>
</tr>
<tr>
<td>(g_\mu - 2)</td>
<td>([-1.77 : 4.38] \times 10^{-9})</td>
</tr>
<tr>
<td>(BF(b \to s\gamma))</td>
<td>([0.269 : 0.387] \times 10^{-3})</td>
</tr>
<tr>
<td>(BF(B_d \to \mu\mu))</td>
<td>(&lt; 9.4 \times 10^{-10})</td>
</tr>
<tr>
<td>(BF(B_s \to \mu\mu))</td>
<td>([1.6 : 4.2] \times 10^{-9})</td>
</tr>
<tr>
<td>(BF(B^+ \to \tau\nu\tau))</td>
<td>([64 : 161] \times 10^{-6})</td>
</tr>
<tr>
<td>(\Gamma_{\text{invis.}}(Z))</td>
<td>(&lt; 2,\text{MeV})</td>
</tr>
<tr>
<td>(\Delta\rho)</td>
<td>([-0.0005 : 0.0017])</td>
</tr>
<tr>
<td>Relic density</td>
<td>(\Omega h^2 &lt; \text{Planck} + 10%)</td>
</tr>
<tr>
<td>Direct SI</td>
<td>(&lt; 4\times\text{LUX})</td>
</tr>
<tr>
<td>Direct SD, p</td>
<td>(&lt; 4\times\text{COUPP})</td>
</tr>
<tr>
<td>Direct SD, n</td>
<td>(&lt; 4\times\text{Xenon})</td>
</tr>
<tr>
<td>Charged sparticles</td>
<td>(&gt; 100,\text{GeV})</td>
</tr>
<tr>
<td>Chargino</td>
<td>(m(\tilde{\nu}) &gt; 160,\text{GeV}) and (\Delta m(\tilde{\chi}^\pm_1, \tilde{\chi}^0_1) &gt; 2,\text{GeV})</td>
</tr>
</tbody>
</table>

- Use 2\(\sigma\) union of expt.+theory uncertainty everywhere, ex. \(g - 2\)
- For DM measurements, \(\sigma\) scaled down by a factor of 4 to account for nucleon form factor uncertainties
- Planck limit is upper bound only, models would be very different if lower bound applied
- \(m(h)\) centered on 126 GeV (ATLAS value at time of model generation). Results insensitive to small change.
- We remove models outside the ranges and treat any model inside on equal footing.
## ATLAS: Sampling by LSP type

<table>
<thead>
<tr>
<th>LSP type</th>
<th>Definition</th>
<th>Sampled</th>
<th>Simulated Number</th>
<th>Simulated Fraction</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>‘Bino-like’</td>
<td>( N_{11}^2 &gt; \max(N_{12}^2, N_{13}^2 + N_{14}^2) )</td>
<td>480 \times 10^6</td>
<td>104,201</td>
<td>35%</td>
<td>1/24</td>
</tr>
<tr>
<td>‘Wino-like’</td>
<td>( N_{12}^2 &gt; \max(N_{11}^2, N_{13}^2 + N_{14}^2) )</td>
<td>{ 20 \times 10^6 }</td>
<td>80,239</td>
<td>26%</td>
<td>1</td>
</tr>
<tr>
<td>‘Higgsino-like’</td>
<td>( (N_{13}^2 + N_{14}^2) &gt; \max(N_{11}^2, N_{12}^2) )</td>
<td>{ 126,769 }</td>
<td>126,769</td>
<td>39%</td>
<td>1</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td>500 \times 10^6</td>
<td><strong>311,209</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

• Categorisation of the 311,209 models by the type of the LSP

• Split according to the neutralino mixing matrix parameters \( N_{ij} \)
  - first index indicates the neutralino mass eigenstate
  - second indicates its nature in the lexicographical order \((\tilde{B}, \tilde{W}, \tilde{H}_1, \tilde{H}_2)\)
ATLAS: Resulting model distributions

Model distributions after other experimental and theoretical constraints, but before ATLAS searches

- Relic density constraint shapes these distributions
- E.g. two spikes in neutralino distribution for bino-LSP models “Z and h funnels”
### ATLAS: Searches included

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Reference</th>
<th>Category</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0\ell$, 2-6 jets</td>
<td>ATLAS-SUSY-2013-02</td>
<td></td>
</tr>
<tr>
<td>$0\ell$, 7-10 jets</td>
<td>ATLAS-SUSY-2013-04</td>
<td></td>
</tr>
<tr>
<td>$1\ell$, 2-6 jets</td>
<td>ATLAS-SUSY-2013-20</td>
<td></td>
</tr>
<tr>
<td>$1-2\tau$, jets</td>
<td>ATLAS-SUSY-2013-10</td>
<td>Inclusive</td>
</tr>
<tr>
<td>$2\ell$ SS/3$\ell$</td>
<td>ATLAS-SUSY-2013-09</td>
<td></td>
</tr>
<tr>
<td>3 $b$-jet</td>
<td>ATLAS-SUSY-2013-18</td>
<td></td>
</tr>
<tr>
<td>Exotics mono-jet</td>
<td>ATLAS-EXOT-2013-13</td>
<td></td>
</tr>
<tr>
<td>$0\ell$, stop</td>
<td>ATLAS-SUSY-2013-16</td>
<td></td>
</tr>
<tr>
<td>$1\ell$, stop</td>
<td>ATLAS-SUSY-2013-15</td>
<td>Third generation</td>
</tr>
<tr>
<td>$2\ell$, stop</td>
<td>ATLAS-SUSY-2013-19</td>
<td></td>
</tr>
<tr>
<td>Stop to charm, monojet</td>
<td>ATLAS-SUSY-2013-21</td>
<td></td>
</tr>
<tr>
<td>Stop with Z boson</td>
<td>ATLAS-SUSY-2013-08</td>
<td></td>
</tr>
<tr>
<td>Two $b$-jet</td>
<td>ATLAS-SUSY-2013-05</td>
<td></td>
</tr>
<tr>
<td>$tb+\text{MET},\text{stop}$</td>
<td>TBA</td>
<td>TBA</td>
</tr>
<tr>
<td>$\ell h$, electroweak</td>
<td>ATLAS-SUSY-2013-23</td>
<td></td>
</tr>
<tr>
<td>$2\ell$, electroweak</td>
<td>ATLAS-SUSY-2013-11</td>
<td>Electroweak</td>
</tr>
<tr>
<td>$2\tau$, electroweak</td>
<td>ATLAS-SUSY-2013-14</td>
<td></td>
</tr>
<tr>
<td>$3\ell$, electroweak</td>
<td>ATLAS-SUSY-2013-12</td>
<td></td>
</tr>
<tr>
<td>$4\ell$</td>
<td>ATLAS-SUSY-2013-13</td>
<td></td>
</tr>
<tr>
<td>Disappearing Track</td>
<td>ATLAS-SUSY-2013-01</td>
<td></td>
</tr>
<tr>
<td>Long-lived sparticles</td>
<td>ATLAS-SUSY-2013-22</td>
<td>Other</td>
</tr>
<tr>
<td>$H/A \rightarrow \tau^+\tau^-$</td>
<td>ATLAS-HIGG-2013-31</td>
<td></td>
</tr>
</tbody>
</table>
## CMS: Searches included

<table>
<thead>
<tr>
<th>Analysis</th>
<th>$\sqrt{s}$ [TeV]</th>
<th>$L$ [fb$^{-1}$]</th>
<th>Likelihood</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hadronic HT + MHT search [46]</td>
<td>7</td>
<td>4.98</td>
<td>counts</td>
</tr>
<tr>
<td>Hadronic HT + MET + $b$-jets search [47]</td>
<td>7</td>
<td>4.98</td>
<td>counts</td>
</tr>
<tr>
<td>Leptonic search for EW prod. of $\tilde{\chi}^0, \tilde{\chi}^{\pm}, \tilde{\ell}$ [48]</td>
<td>7</td>
<td>4.98</td>
<td>counts</td>
</tr>
<tr>
<td>Hadronic HT + MHT search [49]</td>
<td>8</td>
<td>19.5</td>
<td>counts</td>
</tr>
<tr>
<td>Hadronic MT2 search [50]</td>
<td>8</td>
<td>19.4</td>
<td>$\chi^2$</td>
</tr>
<tr>
<td>Hadronic HT + MET + $b$-jets search [51]</td>
<td>8</td>
<td>19.4</td>
<td>binary</td>
</tr>
<tr>
<td>Monojet searches [52, 53]</td>
<td>8</td>
<td>19.4</td>
<td>counts</td>
</tr>
<tr>
<td>Hadronic stop search [54]</td>
<td>8</td>
<td>19.4</td>
<td>counts</td>
</tr>
<tr>
<td>Opposite sign di-lepton (OS ll) search [55] (count experiment only)</td>
<td>8</td>
<td>19.4</td>
<td>counts</td>
</tr>
<tr>
<td>Like-sign di-lepton (LS ll) search [56] (only channels w/o 3rd lepton veto)</td>
<td>8</td>
<td>19.5</td>
<td>counts</td>
</tr>
<tr>
<td>Leptonic search for EW prod. of $\tilde{\chi}^0, \tilde{\chi}^{\pm}, \tilde{\ell}$ [57] (only ss, 3l, and 4l channels)</td>
<td>8</td>
<td>19.5</td>
<td>counts</td>
</tr>
<tr>
<td>Combination of 7 TeV searches</td>
<td>7</td>
<td>-</td>
<td>binary</td>
</tr>
<tr>
<td>Combination of 8 TeV searches</td>
<td>8</td>
<td>-</td>
<td>binary</td>
</tr>
<tr>
<td>Combination of 7 and 8 TeV searches</td>
<td>7,8</td>
<td>-</td>
<td>binary</td>
</tr>
</tbody>
</table>
CMS prior (non-CMS constraints)

\[
p_{\text{non-DCS}}(\theta) \propto \left[ \prod_j L(D_{j\text{non-DCS}}^{\text{non-DCS}}|\mu_j(\theta)) \right] p(c\tau(\tilde{\chi}^\pm) < 10\text{mm}|\theta)p(\text{theory}|\theta)p_0(\theta)
\]

\(p_0(\theta):\) flat prior in scan range:

\[
|M_1|, |M_2|, \mu \leq 3 \text{ TeV} \\
0 \leq M_3, M_A \leq 3 \text{ TeV} \\
2 \leq \tan \beta \leq 60 \\
0 \leq \tilde{Q}_{1,2}, \tilde{U}_{1,2}, \tilde{D}_{1,2}, \tilde{L}_{1,2}, \tilde{E}_{1,2}, \tilde{Q}_3, \tilde{U}_3, \tilde{D}_3, \tilde{L}_3, \tilde{E}_3 \leq 3 \text{ TeV} \\
-7 \text{ TeV} \leq A_t, A_b, A_\tau \leq 7 \text{ TeV}
\]
$p(\text{theory}|\theta)$ imposes the following constraints:

- Spectrum free of tachyons
- No colour or charge breaking in the scalar potential
- EWSB is consistent and Higgs potential bounded from below
- LSP is lightest neutralino

$p(c\tau(\tilde{\chi}^{\pm}) < 10\text{mm}|\theta)$ removes long-lived charginos
$L(D_{j}^{\text{non-DCS}}|\mu_{j}(\theta))$ Results from precision and pre-LHC measurements

| $i$ | Observable $\mu_{i}(\theta)$ | Constraint $D_{i}^{\text{non-DCS}}$ | Likelihood function $L(D_{i}^{\text{non-DCS}}|\mu_{i}(\theta))$ | comment |
|-----|--------------------------------|-------------------------------------|------------------------------------------------|---------|
| 1   | $BR(b \rightarrow s\gamma)$ [40] | $(3.43 \pm 0.21^{\text{stat}} \pm 0.24^{\text{th}} \pm 0.07^{\text{sys}}) \times 10^{-4}$ | Gaussian | reweight |
| 2   | $BR(B_{s} \rightarrow \mu\mu)$ [41] | $(2.9 \pm 0.7 \pm 0.29^{th}) \times 10^{-9}$ | Gaussian | reweight |
| 3   | $R(B_{u} \rightarrow \tau\nu)$ [40] | $1.04 \pm 0.34$ | Gaussian | reweight |
| 4   | $\Delta a_{\mu}$ [42] | $(26.1 \pm 6.3^{\exp} \pm 4.9^{\text{SM}} \pm 10.0^{\text{SUSY}}) \times 10^{-10}$ | Gaussian | reweight |
| 5   | $m_{t}$ [43] | $173.20 \pm 0.87^{\text{stat}} \pm 1.3^{\text{sys}} \text{ GeV}$ | Two-sided Gaussian | |
| 6   | $m_{b}(m_{b})$ [44] | $4.19^{+0.18}_{-0.06} \text{ GeV}$ | Gaussian | |
| 7   | $\alpha_{S}(M_{Z})$ [44] | $0.1184 \pm 0.0007$ | Gaussian | |
| 8   | $m_{h}$ | LHC: $m_{h}^{\text{low}} = 120, m_{h}^{\text{up}} = 130$ | $1$ if $m_{h}^{\text{low}} \leq m_{h} \leq m_{h}^{\text{up}}$ \[0\] if $m_{h}^{\text{low}} < m_{h}$ or $m_{h} > m_{h}^{\text{up}}$ | reweight |
| 9   | $\mu_{h}$ | CMS and ATLAS in LHC RunI, Tevatron | Lilith1.01 [36, 37] | post-MCMC |
| 10  | sparticle masses | LEP [45] (via micrOMEGAs [29–31]) | $1$ if allowed \[0\] if excluded | |
ATLAS: Sbottoms

\[ \tilde{b}_1 \rightarrow b\tilde{\chi}_1^0 \quad [1308.2631] \]

\( \sqrt{s} = 8 \text{ TeV}, 20.3 \text{ fb}^{-1} \)
SUSY models typically over-produce dark matter, unless there is some special mechanism to reduce the relic abundance.
Wino and Higgsino models get this special mechanism ‘for free’ as they have a compressed chargino.

\[ \tilde{\chi}^\pm_1 \rightarrow \chi^0_1 + W^\pm \]

\[ \Omega_{\chi_1} h^2 \]

\[ \text{pMSSM: } \tilde{\chi}^0 \text{-like LSP} \]

\[ \text{ATLAS: Dark Matter} \]

\[ \text{Wino and Higgsino models get this special mechanism ‘for free’ as they have a compressed chargino.} \]
ATLAS: Dark Matter

pMSSM: ̄B-like LSP

Z/h funnel

Ω_{\tilde{\chi}_1^0} h^2

ATLAS
Before ATLAS Run 1

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

Z/H funnel

h^0/Z^0

\tilde{\chi}_1^0

\tilde{\chi}_1^0

Will Fawcett (University of Oxford)
Most bino-LSP models require a co-annihilator to reduce the relic abundance. This is models with mostly bino-LSPs have compressed sparticles.
ATLAS: Sleptons

Impact of electroweak searches only

ATLAS

pMSSM: $\tilde{\chi}^0_1$ LSP

$\sqrt{s}=8$ TeV, 20.3 fb$^{-1}$

Electroweak searches

Will Fawcett (University of Oxford)
ATLAS: Bino-LSP mass distribution

ATLAS

- A Funnel
- Gaugino
- Light Flavour
- Third Gen.
- Slepton

Fraction of Models / 40 GeV

\[ m(\tilde{\chi}_1^0) \text{ [GeV]} \]