HERE BE DRAGONS:
THE UNEXPLORED CONTINENTS OF
THE CMSSM

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with Jay Wacker

arXiv:13XX.soon

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Disclaimer

This is not a talk on light dark matter, but dark matter phenomenology plays a central role.
Outline

I) Motivation
II) CMSSM Cartography
III) Circumnavigating the CMSSM
IV) Conclusions
Motivation
The MSSM in the Era of Higgs Discovery

• A SM-like Higgs has been discovered at 125 GeV.

• This measurement is “consistent” with the MSSM (and its extensions).
  • Stops can lie from \( \mathcal{O}(100) \) GeV to \( \mathcal{O}(100) \) TeV.

ATLAS [arXiv:1207.7214]
CMS [arXiv:1207.7235]
The MSSM in the Era of Higgs Discovery

• A SM-like Higgs has been discovered at 125 GeV.

• This measurement is “consistent” with the MSSM (and its extensions).
  • Stops can lie from $O(100)$ GeV to $O(100)$ TeV.

• The motivation for weak-scale superpartners still stands:
  • Solves the hierarchy problem;
  • Explains the dark matter;
  • Predicts gauge coupling unification.
The MSSM in the Era of Higgs Discovery

- The parameter space of the MSSM is enormous.
  - The soft supersymmetry breaking Lagrangian includes more than 120 new dimensionful terms.

- How can we map out all possible signatures?
  - Simplified models: isolate particles responsible for the signature of interest. The parameter space becomes tractable; there are typically only a few masses and branching ratios to specify.
    
    \begin{itemize}
    \item Alwall, Le, Listanti, Wacker [arXiv:0809.3264]; Alwall, Schuster, Toro [arXiv:0810.3921];
    \item LHC New Physics Working Group [arXiv:1105.2838]
    \end{itemize}

  - pMSSM: phenomenologically motivated reduction to 19 parameters.
    
    \begin{itemize}
    \item Berger, Gainer, Hewett, Rizzo [arXiv:0812.0980]
    \end{itemize}

  - CMSSM/mSUGRA: 4 parameters.
    
    \begin{itemize}
    \item Chamseddine, Arnowitt, Nath [PRL 49 (1982)]; Barbieri, Ferrara, Savoy [PLB (1982)];
    \item Hall, Lykken, Weinberg [PRD (1983)]
    \end{itemize}

- 4 parameters is potentially tractable.
- Can we understand all predictions of the CMSSM ansatz?
A simple ansatz - a wide range of dynamics

- The CMSSM is a four dimensional subspace of the $R$-parity conserving MSSM.
- It is defined at the GUT scale by the following (real) inputs:
  - The unified scalar soft mass, $M_0$.
  - The unified gaugino mass: $M_{1/2}$.
  - The unified $A$-term: $A_0$.
  - The ratio of the Higgs vevs: $\tan \beta$ (traded for the $B_\mu$ term).
A simple ansatz - a wide range of dynamics

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  • The unified $A$-term: $A_0$.
  • The ratio of the Higgs vevs: $\tan \beta$ (traded for the $B_\mu$ term).
• These parameters are evolved to the weak scale using the renormalization group equations (RGEs).
• The $\mu$ -term is determined by requiring that the Z-boson mass match the measured value.
• Since the RGEs are integrated over 14 orders of magnitude, the relation between the low energy parameters and the inputs is highly non-linear.
The state of the art

- Both ATLAS and CMS put limits on the CMSSM:

- They exclude a region of the $M_{1/2}$ versus $M_0$ plane for a fixed choice of $A_0$ and $\tan \beta$. 
The state of the art

- Both ATLAS and CMS put limits on the CMSSM:

- They exclude a region of the $M_{1/2}$ versus $M_0$ plane for a fixed choice of $A_0$ and $\tan \beta$.
- What is the Higgs mass?
- Does the neutralino overclose the Universe?
Our approach to the CMSSM

• We will require that the Higgs mass is \( \sim 125 \) GeV and the neutralino comprises all of the dark matter.

• “Quadrants” are defined by the \( \text{sign}(A_0) \) and the \( \text{sign}(\mu) \).

• Schematically, the RGEs for \( A \) and \( B \) terms are given by

\[
16 \pi^2 \frac{d}{dt} A = A \left( |y|^2 - g^2 \right) + y g^2 M, \\
16 \pi^2 \frac{d}{dt} B = B \left( |y|^2 - g^2 \right) + \mu \left( A y^\dagger + g^2 M \right),
\]

• The low energy behavior can be very different depending on these signs.
Classification

- What process determines the relic abundance?
  - “light $\tilde{\chi}^0$”: annihilation is dominated by the $Z^0$ and $h$ poles.
  - “well-tempered”: annihilation via Higgsino/Bino mixing to $W^+ W^-$. 
  - “$A^0$ pole”: annihilation is dominated by an s-channel $A^0$ resonance.
  - “stau coannihilation”
  - “stop coannihilation”
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\[
\tilde{\chi}^0 \rightarrow \tau^\pm \rightarrow \tilde{\tau}^\pm \rightarrow Z^0
\]
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```
chi --|-- t

|  
|  
|  

~t --|-- g
```
The CMSSM should be compact

- Requiring a 125 GeV Higgs boson implies that one can not take $M_0$ to be arbitrarily large.

- Relic density
  - The pure Bino limit bounds $M_{1/2}$.
    - The lightest gaugino is the Bino.
    - As one decouples the scalars, the Bino becomes inert.
    - Its early Universe annihilation cross section goes to zero.
    - It freezes out with too large a relic density.
  - The pure Higgsino limit bounds $M_0$.
    - As one decouples the gauginos, the LSP becomes Higgsino like.
    - If the mass of a pseudo-Dirac Higgsino is greater than ~1 TeV, it freezes out with too large a relic density.

- Requiring the lifetime of our vacuum be longer than the age of the Universe bounds $A_0$.

- Perturbativity of the bottom Yukawa coupling bounds $\tan \beta$. 
CMSSM CARTOGRAPHY
Tools

• SoftSUSY v3.3.7 computes the low energy spectrum from the CMSSM inputs.  Allanach [arXiv:hep-ph/0104145]
  • The two loop MSSM RGEs are included (leading log decoupling is accounted for by the inclusion of all 1-loop finite terms).
  • The two loop contributions to the Higgs potential are included.

• DarkSUSY v5.1.1 computes the relic density and direct detection cross sections.
  • All 2-2 scattering processes are included.

• SUSY-HIT v1.3 computes the decay tables.

• We have had 186+ cores running for roughly 4 continuous months.
Constraints

• We take a 3 GeV error for the theoretical prediction for the Higgs mass:
  \[ 122 \text{ GeV} < m_h < 128 \text{ GeV} \]

• We require the relic density be in the range:
  \[ 0.08 < \Omega h^2 < 0.14 \]

• We require that the lifetime for the vacuum to decay to a charge/color breaking minimum be longer than the age of the Universe:
  \[ |a_t|^2 < (7.5 m_{q_3}^2 + 7.5 m_{u_3}^2 + 3 (m_{H_u}^2 + |\mu|^2)) \]

• We require that the chargino mass satisfy a naive LEP bound:
  \[ \tilde{m}_{\chi^+} > 100 \text{ GeV} \]
Charting the CMSSM

- light $\tilde{\chi}^0$
- Well-tempered
- $A^0$ pole
- stau coann
- stop coann
Charting the CMSSM

- light $\tilde{\chi}^0$
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Charting the CMSSM

• light $\tilde{\chi}^0$
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• coann

\[
\text{Sign}(\mu) \times M_{1/2} \text{ [GeV; } A_0/M_0 \text{]}
\]
Charting the CMSSM

- light $\tilde{\chi}^0$
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- stop coann
Lessons

• The CMSSM is compact.

• The size of the allowed parameter space is huge!
• Our classification scheme is a useful way to organize the CMSSM.

• There is a range of possible low energy signatures.
• The rest of this talk will be devoted to exploring them.
CIRCUMNAVIGATING THE CMSSM

Light $\tilde{\chi}^0$
Setting sail for light $\tilde{\chi}^0 \iff \tilde{m}_{\chi^0} < 75$ GeV

- light $\tilde{\chi}^0$
- Well-tempered
- $A^0$ pole
- stau
- coann

- $2 \text{ TeV} \lesssim M_0 \lesssim 12 \text{ TeV}$
- $5 \lesssim \tan \beta \lesssim 50$
Light $\tilde{\chi}^0$ implies light gluinos

\begin{figure}
\centering
\begin{tikzpicture}
\begin{axis}[
width=\textwidth,
height=0.8\textwidth,
axis lines=left,
xtick={300,400,500,600,700,800},
xticklabels={300,400,500,600,700,800},
ytick={4000,5000,6000,7000,8000,9000,10000,11000,12000},
yticklabels={4000,5000,6000,7000,8000,9000,10000,11000,12000},
\]
\addplot[only marks,mark size=0.5pt,draw=gray] table [x=m_{\text{gluino}}, y=m_{\text{squark}}] {data.csv};
\end{axis}
\end{tikzpicture}
\end{figure}
Has the LHC excluded this region?

• Take as a benchmark:
  - Squarks and sleptons are heavier than 5 TeV.
  - The gluino is 409 GeV and the LSP is 57 GeV.

\[ \tilde{g} \rightarrow q + \bar{q} + Z^0 + \tilde{\chi}_0 \]
  - The 7 TeV CMS search yields \( \sigma \times \text{BR} \lesssim 1 \).  
    CMS [arXiv:1204.3774]
  - The 7 TeV prediction is \( \sigma \times \text{BR} \simeq 1.0 \text{ pb} \).

\[ \tilde{g} \rightarrow q + \bar{q} + \tilde{\chi}^0 \]
  - The 7 TeV CMS Razor search does not exclude this channel.

\[ \tilde{g} \rightarrow q + \bar{q}' + W^\pm + \tilde{\chi}_0 \]
  - The 7 TeV ATLAS search for (requiring same sign \( W^\pm \)) does not exclude this channel.  
    ATLAS [arXiv:1208.0949]

• So the exclusion is borderline at 7 TeV without performing any combinations.
• Likely excluded at 8 TeV (unless efficiency drops for low masses; no detailed efficiency plots are public yet).
CIRCUMNAVIGATING THE CMSSM

Well-tempered
Setting sail for well-tempered

- light $\tilde{\chi}^0$
- Well-tempered
- $A^0$ pole
- stau coann
- stop coann

- $4 \text{ TeV} \lesssim M_0 \lesssim 20 \text{ TeV}$
- $5 \lesssim \tan \beta \lesssim 50$
Will direct detection exclude this region?

- A 1-ton Xenon experiment can reach spin-independent cross sections of $5 \times 10^{-12}$ pb at 300 GeV.

[Dark matter limit plotter](http://dmtools.brown.edu/)
Will direct detection exclude this region?

- A 1-ton Xenon experiment can reach spin-independent cross sections of \(5 \times 10^{-12}\) pb at 300 GeV.

[Dark matter limit plotter](http://dmtools.brown.edu/)
What about the LHC?
What about the LHC?

- The LHC will have little impact on the well-tempered spectra.
CIRCUMNAVIGATING THE CMSSM

$A^0$ pole annihilation
Setting sail for $A^0$ pole annihilation

- light $\tilde{\chi}^0$
- Well-tempered
- $A^0$ pole
- stau coann
- stop coann

\begin{align*}
500 \text{ GeV} & \lesssim M_0 \lesssim 16 \text{ TeV} & [\mu > 0] \\
200 \text{ GeV} & \lesssim M_{1/2} \lesssim 7 \text{ TeV} & [\mu > 0] \\
5 \text{ TeV} & \lesssim M_0 \lesssim 10 \text{ TeV} & [\mu < 0] \\
300 \text{ GeV} & \lesssim M_{1/2} \lesssim 2 \text{ TeV} & [\mu < 0]
\end{align*}
The squark-gluino plane

- 1st quadrant is similar.
Direct detection

$A^0$ pole annihilation (2$^\text{nd}$ quadrant)

- 1$^{\text{st}}$ quadrant is similar but 4$^{\text{th}}$ quadrant extends below $10^{-14}$ pb.
CIRCUMNAVIGATING THE CMSSM

Stau coannihilation
Setting sail for stau coannihilation

- light $\tilde{\chi}^0$
- Well-tempered
- $A^0$ pole
- stau coann
- stop coann

$200 \text{ GeV} \lesssim M_0 \lesssim 3 \text{ TeV}$
$5 \lesssim \tan \beta \lesssim 60$
A 1-ton Xenon experiment can reach spin-independent cross sections of at 300 GeV. Direct detection can probe all of the 2nd quadrant.
Stau-coann: direct detection

- A 1-ton Xenon experiment can reach spin-independent cross sections of $5 \times 10^{-12}$ pb at 300 GeV. Dark matter limit plotter [http://dmtools.brown.edu/]
- Direct detection can probe all of the 2nd quadrant.
Stau-coann: squark-gluino plane

Stau–coannihilation (3\textsuperscript{rd} quadrant)

$m_{\text{squark}}$ [TeV] vs. $m_{\text{gluino}}$ [TeV]
Stau-coann: squark-gluino plane

Are these spectra discoverable at the 14 TeV LHC?
A stau-coann benchmark (3rd quad)

<table>
<thead>
<tr>
<th>Input parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_0$</td>
</tr>
<tr>
<td>259.515</td>
</tr>
</tbody>
</table>

- The LSP is 383.52 GeV; the lighter stau is 383.8 GeV.
- The stau lifetime is $O\left(10^{-2} \text{ s}\right)$. Probed via long-lived stau searches?

*Citron, Ellis, Luo, Marrouche, Olive, Vries* [arXiv:1212.2886]
A stau-coann benchmark (3rd quad)

The LSP is 383.52 GeV; the lighter stau is 383.8 GeV.
- The stau lifetime is $O\left(10^{-2} \text{s}\right)$. Probed via long-lived stau searches? Citron, Ellis, Luo, Marrouche, Olive, Vries [arXiv:1212.2886]

The gluino is 1980 GeV.

The squark masses are

<table>
<thead>
<tr>
<th>$m$ [GeV]</th>
<th>$\tilde{q}$</th>
<th>$\tilde{b}_1$</th>
<th>$\tilde{b}_2$</th>
<th>$\tilde{t}_1$</th>
<th>$\tilde{t}_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1780.8</td>
<td>1529.9</td>
<td>1715.3</td>
<td>1067.2</td>
<td>1562.9</td>
<td></td>
</tr>
</tbody>
</table>

The gluino branching ratios are
- $\tilde{g} \rightarrow \tilde{t}_{1,2} + \tilde{t}$ [52%]
- $\tilde{g} \rightarrow \tilde{b}_{1,2} + \tilde{b}$ [20%]
- $\tilde{g} \rightarrow \tilde{q} + \tilde{q}$ [28%]

Probed via gluino pair production?
CIRCUMNAVIGATING THE CMSSM

Stop coannihilation
Setting sail for stop coannihilation

- light $\tilde{\chi}^0$
- Well-tempered
- $A^0$ pole
- stau coann
- stop coann

- $2 \text{ TeV} \lesssim M_0 \lesssim 12 \text{ TeV}$
- $\tan \beta \lesssim 50$
Stop-coannihilation phenomenology

Stop–coannihilation (3rd quadrant)

$M_{\text{squark}}$ [TeV] vs $m_{\text{gluino}}$ [TeV]

$\sigma \Gamma$ [pb] vs $m_{\chi}$ [GeV]

Timothy Cohen (SLAC)
Stop-coannihilation phenomenology

A large portion of these spectra will require a machine beyond the 14 TeV LHC.
Almost Home

Conclusions
Conclusions

• The CMSSM provides a simple ansatz which allows one to explore the phenomenology of the full parameter space.
• We provide a map of the CMSSM which is consistent with a Higgs at 125 GeV and thermal dark matter comprised of neutralinos.
• We demonstrate that the parameter space is compact.
• What regions will remain unconstrained after LHC14 and 1 Ton scale spin-independent direct detection?
  • The 4th quadrant of $A^0$-pole annihilation;
  • Large portions of the stop coannihilation regions.
• Note we need LHC results to be presented as generally as possible so it is easy to interpret bound for non-trivial models.