SUSY and Exotica

by

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Talk outline

• SUSY Fits
• Impact of LHC data
• SUSY Tactics
• Exotica and $A_{FB}(t\bar{t})$

Please ask questions while I’m talking
A Problem With the Higgs Boson

The Higgs boson mass receives quantum corrections from heavy particles in the theory:

\[ \lambda h - h - h - \sim - \frac{a\lambda^2}{16\pi^2} \int \frac{d^n k}{k^2 - m_F^2} + \ldots \]

Quantum correction to Higgs mass:

\[ m_h^{\text{phys}} = 126 \text{ GeV} / c^2 = m_h^{\text{tree}} + \mathcal{O}(m_F / 100). \]

\[ m_F \sim 10^{19} \text{ GeV} / c^2 \] is heaviest mass scale present.
Electroweak Breaking

Both Higgs get vacuum expectation values:

\[
\begin{pmatrix}
H_1^0 \\
H_1^-
\end{pmatrix}
\rightarrow
\begin{pmatrix}
v_1 \\
0
\end{pmatrix}
\quad \begin{pmatrix}
H_2^+
\\
H_2^0
\end{pmatrix}
\rightarrow
\begin{pmatrix}
0 \\
v_2
\end{pmatrix}
\]

and to get \( M_W \) correct, match with \( v_{SM} = 246 \text{ GeV} \):

\[
\tan \beta = \frac{v_2}{v_1}
\]

\[
\mathcal{L} = h_t \bar{t}_L H_2^0 t_R + h_b \bar{b}_L H_1^0 b_R + h_\tau \bar{\tau}_L H_1^0 \tau_R
\]

\[
\frac{m_t}{\sin \beta} = \frac{h_t v_{SM}}{\sqrt{2}}, \quad \frac{m_{b,\tau}}{\cos \beta} = \frac{h_{b,\tau} v_{SM}}{\sqrt{2}}.
\]
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Implementation

We use

- **95% C.L. direct search constraints**
- $\Omega_{DM} h^2 = 0.1143 \pm 0.02$ micrOMEGAs
- $\delta(g - 2)_{\mu}/2 = (29.5 \pm 8.8) \times 10^{-10}$ Stöckinger et al
- $B -$physics observables including SusyBSG
  $BR[b \to s\gamma]_{E_\gamma > 1.6 \text{ GeV}} = (3.52 \pm 0.38) \times 10^{-4}$,
  $BR(B_s \to \mu\mu) < 1.1 \times 10^{-8}$ micrOMEGAs
- Electroweak data W Hollik, A Weber et al

$$2 \ln L = - \sum_i \chi_i^2 + c = \sum_i \frac{(p_i - e_i)^2}{\sigma^2_i} + c$$
Additional observables

\[ \delta \frac{(g - 2)}{2} \mu \sim 13 \times 10^{-10} \left( \frac{100 \text{ GeV}}{M_{\text{SUSY}}} \right)^2 \tan \beta \]

\[ BR[b \rightarrow s\gamma] \propto \tan \beta (M_W / M_{\text{SUSY}})^2 \]
Again, we assume $A_0\cdot\tan\beta$ independence and interpolate across $m_0$ and $m_{1/2}$. CMS $35\,\text{pb}^{-1}$, ATLAS $35\,\text{pb}^{-1}$, CMS $1\,\text{fb}^{-1}$.
CMS/ATLAS Weighted Fits

Incl. ATLAS
Excl. CMS/ATLAS
Incl. CMS

Allanach, Khoo, Lester and Williams, Mar 2011
Prospects for SUSY

Still look good! $5\text{fb}^{-1}$ expected before christmas

Allanach, Khoo, Lester and Williams, Mar 2011
pMSSM Fits

25 pMSSM input parameters are: $M_{1,2,3}$, $A_{t,b,\tau,\mu}$, $m_{H_{1,2}}$, $\tan \beta$, $m_{\tilde{d}_{R,L}} = m_{\tilde{s}_{R,L}}$, $m_{\tilde{u}_{R,L}} = m_{\tilde{c}_{R,L}}$, $m_{\tilde{\ell}_{R,L}} = m_{\tilde{\mu}_{R,L}}$, $m_{\tilde{t},\tilde{b},\tilde{\tau}_{R,L}}$, $m_t$, $m_b(m_b)$ $\alpha_s(M_Z)^{\overline{MS}}$, $\alpha^{-1}(M_Z)^{\overline{MS}}$, $M_Z$. Combined Bayesian fit:

\begin{table}[h]
\begin{tabular}{lcccc}
  Observable & Measurement & Fit (Log) & $\sigma_{\text{meas}}$ & $\sigma_{\text{fit}}$ \\
  \hline
  $m_t$ (GeV) & 174.49 $\pm$ 0.25 & 173.62 & 0.26 & 0.17 \\
  $\Gamma_Z$ (GeV) & 2.4952 $\pm$ 0.0025 & 2.4964 & 0.0026 & 0.0014 \\
  $\sin^2 \theta_W$ & 0.2324 $\pm$ 0.0012 & 0.2314 & 0.0013 & 0.0008 \\
  $\delta_{(g-2)} \times 10^9$ & 30.20 $\pm$ 9.02 & 26.74 & 9.03 & 4.57 \\
  $R^T_1$ & 20.767 $\pm$ 0.025 & 20.760 & 0.025 & 0.0127 \\
  $R_\gamma$ & 0.21629 $\pm$ 0.00066 & 0.21662 & 0.0007 & 0.0003 \\
  $R_\ell$ & 0.1721 $\pm$ 0.0030 & 0.1723 & 0.003 & 0.0015 \\
  $A_{t_0}$ & 0.1513 $\pm$ 0.0021 & 0.1483 & 0.0022 & 0.0011 \\
  $A_t$ & 0.0923 $\pm$ 0.020 & 0.0935 & 0.021 & 0.0105 \\
  $A_{b_0}$ & 0.670 $\pm$ 0.027 & 0.685 & 0.028 & 0.0137 \\
  $A_b$ & 0.0992 $\pm$ 0.0016 & 0.1040 & 0.0017 & 0.0009 \\
  $A_{\tau_0}$ & 0.071 $\pm$ 0.035 & 0.074 & 0.036 & 0.0181 \\
  $BR(B \to X_s \gamma) \times 10^4$ & 3.55 $\pm$ 0.42 & 3.42 & 0.42 & 0.22 \\
  $R_{B_{(s)\to \mu^+\mu^-}}$ & 1.11 $\pm$ 0.32 & 1.00 & 0.32 & 0.17 \\
  $R_{B_s \to \mu^+\mu^-}$ & 1.15 $\pm$ 0.40 & 1.00 & 0.40 & 0.20 \\
  $\Delta_{\nu}$ & 0.0375 $\pm$ 0.0269 & 0.0748 & 0.027 & 0.0147 \\
  $\epsilon_{\text{exp}}$ & 0.11 $\pm$ 0.02 & 0.13 & 0.02 & 0.01 \\
\end{tabular}
\end{table}

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Spectrum

Obtained with Multinest\textsuperscript{a} algorithm in 16 CPU years. Prior dependence is useful: which predictions are robust?

\textsuperscript{a} Feroz, Hobson arXiv:0704.3704
Collider SUSY Production

Strong sparticle production and decay to dark matter particles.

Any (light enough) dark matter candidate that couples to hadrons can be produced at the LHC.
\[ \alpha_T, \text{MET, } M_{T_2} \text{ Searches} \]

CMS: jets and missing energy \texttt{arXiv:1101.1628}

\[ \mathcal{L} = 35 \text{ pb}^{-1}. \quad H_T = \sum_{i=1}^{N_{\text{jet}}} |p_T^j| > 350 \text{ GeV}. \]

(1) \[ \Delta H_T \equiv \sum_{j_i \in A} |p_T^{j_i}| - \sum_{j_i \in B} |p_T^{j_i}|. \]

One then calculates

(2) \[ \alpha_T = \frac{H_T - \Delta H_T}{2 \sqrt{H_T^2 - \mathcal{H}_T^2}} > 0.55 \]

where \[ \mathcal{H}_T = \sqrt{\left(\sum_{i=1}^{N_{\text{jet}}} p_x^{j_i}\right)^2 + \left(\sum_{i=1}^{N_{\text{jet}}} p_y^{j_i}\right)^2}. \]
Cue $M_{T2}$

\[
m_T^2(i)(p_T(i), q_T(i)) \equiv 2 \left| p_T(i) \right| \left| q_T(i) \right| - 2 p_T(i) \cdot q_T(i)
\]

where $q_T(i)$ is the missing transverse momentum from $i$. The variable $M_{T2}$ is defined by:

\[
M_{T2}(p_T^{(1)}, p_T^{(2)}, p_T) \equiv \min \sum q_T = p_T \left\{ \max \left( m_T^{(1)}, m_T^{(2)} \right) \right\}
\]

The minimization is over all values of $q_T^{(1,2)}$ consistent with $\sum q_T = p_T$. For the SUSY search, the unknown undetected particle masses are set to zero in $M_{T2}$. 

*SUSY and Exotica*
$M_{T2}$ Search

Figure 1: Only cuts: $N_j > 1$, $p_T > 50$ GeV, $\mathcal{L} = 100\,pb^{-1}$ at $\sqrt{s} = 7$ TeV. Barr, Gwenlan PRD80 (2009) 074007.
$M_{T2} \, v \, E_{T}^{miss}$

BCA, Barr, Dafinca, Gwenlan, JHEP 1107 (2011) 104,

arXiv:1105.1024

Figure 6: $\log_{10}$[luminosity (pb)$^{-1}$ needed for discovery] with the combined optimal $M_{T2}$ and MET based strategy at $\sqrt{s} = 14$ TeV in the $(\Delta m, m_{\text{lightest sparton}})$ plane, $\Delta m$ is the mass difference between the lightest sparton and the LSP. The $M_{T2}$ based strategy was optimized for an integrated luminosity of 1 fb$^{-1}$. Systematic uncertainties in the background have been neglected.
**Compressed Spectra**

FIG. 1: The masses of the most relevant superpartners for the class of models defined in subsection III A, as a function of the compression parameter \( c \), for fixed \( M_{\tilde{g}} = 700 \) GeV. The case \( c = 0 \) corresponds to an mSUGRA-like model.

FIG. 2: The distributions before cuts of \( E_{T}^{\text{miss}} \) (left panel) and \( m_{\text{eff}} \) with 3 jets included (right panel) for models described in subsection III A with \( M_{\tilde{g}} = 700 \) GeV and \( c = 0.0, 0.3, 0.6, \) and 0.9, from right to left.
Compressed Spectra II

LeCompte, Martin, arXiv:1105.4304
Benchmarks

Currently we are devising SUSY benchmark models. It’s imminent.

- CMSSM, NUHM, mAMSB, mGMSB, RPV and some simplified models (via pMSSM) are defined.
- Defining interesting parameter planes: identifying important parameters which control the masses of sparticles in each case.
- Discrete set of points along monotonic lines: next point for the experiments to study is defined as the lightest one that is not ruled out to 95% CL.

\[
A_{FB}(t\bar{t})
\]

\[
A_{FB} = \frac{N(y_t > y_{\bar{t}}) - N(y_{\bar{t}} > y_t)}{N(y_t > y_{\bar{t}}) + N(y_{\bar{t}} > y_t)}
\]

\[
A_{FB}(CDF)_{lj+ll} = (20.9 \pm 6.6)\%,
\]

\[
A_{FB}(D0)_{lj} = (19.6 \pm 6.5)\%,
\]

**Positive Asymmetry**

**Negative Asymmetry**

**NLO QCD:** \( A_{fb} \approx 5 - 6\% \)
CDF

Seems to be increasing with mass. Lepton charge is nice verification.
$M_{t\bar{t}}$

**Forward-Backward Top Asymmetry, %**

**Reconstruction Level**

$m_{t\bar{t}} < 450$ GeV

- **DØ, 5.4 fb$^{-1}$**
  - 7.8 ± 4.8

- **CDF, 5.3 fb$^{-1}$**
  - -2.2 ± 4.3

$m_{t\bar{t}} > 450$ GeV

- **DØ, 5.4 fb$^{-1}$**
  - 11.5 ± 6.0

- **CDF, 5.3 fb$^{-1}$**
  - 26.6 ± 6.2

*S. Frixione and B.R. Webber, JHEP 06, 029 (2002)*
A_{FB} \textbf{Exotica}

![Diagram of tree level t\bar{t} production with mediator M exchange.](image)

**Figure 1:** Tree level t\bar{t} production diagram with mediator M exchange.

Must **not** disturb $\sigma_{t\bar{t}}$ or $d\sigma_{t\bar{t}}/dM_{t\bar{t}}$

- axigluons$^a$
- $Z'/W'^b$

\cite{Frampton et al}
LHC Asymmetry

Defined LHC charge asym

\[ A_C = \frac{N(|y_t| > |y\bar{t}|) - N(y\bar{t} > |y_t|)}{N(|y_t| > |y\bar{t}|) + N(y\bar{t} > |y_t|)} \]

SM discovery would take 60 fb\(^{-1}\) at 5\(\sigma\), but new physics quicker (\(Z'\) takes 2 fb\(^{-1}\))

\[ A_C^{\text{CMS}} = -1.6 \pm 3 \pm 1\% \quad A_C^{\text{ATLAS}} = -2.4 \pm 1.6 \pm 2.3\% \]
Models

- **$Z'$ model** is rather odd: only contains a vertex coupling $utZ'$, eg $M_{Z'} = 800$ GeV, $g_Z = 3.4$: predicts significant *same sign tops*.

- **$W'$ models** also covered by LHC experiments by now.

- Heavy **axigluon models** eg 2 TeV, $g_q = -g_t = 2.4$ are ruled out by LHC $m_{jj}$ searches

- Recent proposal: axigluons $g = 0.4-0.8$, $M = 50 - 90$ GeV. They evade jet data because the have masses *below* current limits. Non-resonant production suppresses new physics contribution to $\sigma_{t\bar{t}}$. 

*Krnjaic, arXiv:1109.0648*
Shopping List

Things that the CMS/ATLAS always provide that we need:

- Cuts and numbers of events observed past them
- Expected background numbers with systematic errors

We could really do with:

- Keeping in mind: we can’t combine analyses that use the same events: much better to keep the events disjoint. Doesn’t preclude fully inclusive analysis, but make the others as disjoint as possible.
- Likelihood versus predicted number of events past cuts (before efficiency correction). Ideally, sanitized RooStats
Failing that, then we must calculate the likelihood:

- **Systematic errors on signals**: perhaps at least a range over parameter space in one model. Ideally, it would be parameterised in terms of important quantities.

- **Other contours** (e.g. 1/5 sigma exclusion contours) so we can check our likelihood away from 95% excluded region.

- **Numbers in histogram plots** attached to arXiv publication
Summary

- LHC analyses providing a nice amount of information for interpretation of data. There’s always room for improvement...

- SUSY is late to the party, but not late enough to be reported missing

- CMSSM *could well be discovered this/next year*

- Current searches reach squark and gluino masses of 980 GeV. This will be extended to $\sim 1100$ GeV next year, covering much of the good-fit region.

- $t\bar{t}$ asymmetry situation extremely *murky*. Many heavy axigluon models now ruled out.
CMS $\alpha_T$ Search

CMS: jets and missing energy \texttt{arXiv:1101.1628}

$\mathcal{L} = 35 \text{ pb}^{-1}$. $H_T = \sum_{i=1}^{N_{\text{jet}}} |p_T^j| > 350 \text{ GeV}$.

(3) $\Delta H_T \equiv \sum_{j_i \in A} |p_T^j| - \sum_{j_i \in B} |p_T^j|$.

One then calculates

(4) $\alpha_T = \frac{H_T - \Delta H_T}{2\sqrt{H_T^2 - \overline{H_T}^2}} > 0.55$

where $\overline{H_T} = \sqrt{(\sum_{i=1}^{N_{\text{jet}}} p_x^j)^2 + (\sum_{i=1}^{N_{\text{jet}}} p_y^j)^2}$.
Results
ATLAS 0-lepton, jets and $\not{p}_T$

\[ m_{\text{eff}} = \sum p_T^{(j)} + \not{p}_T, \]

\[ m_T^{(i)}^2 (p_T^{(i)}, \not{q}_T^{(i)}) \equiv 2 \left| p_T^{(i)} \right| \left| \not{q}_T^{(i)} \right| - 2 p_T^{(i)} \cdot \not{q}_T^{(i)} \]

where $\not{q}_T^{(i)}$ is the transverse momentum of particle $(i)$. For each event, it is a lower bound on $m(NLSP)$.

\[ M_{T2}(p_T^{(1)}, p_T^{(2)}, \not{p}_T) \equiv \min \sum \not{q}_T = \not{p}_T \left\{ \max \left( m_T^{(1)}, m_T^{(2)} \right) \right\} \]
Candidate Event: High $E_T(j)$
MSSM Exclusion: Simplified Model

<table>
<thead>
<tr>
<th>Signal region A</th>
<th>Signal region B</th>
<th>Signal region C</th>
<th>Signal region D</th>
</tr>
</thead>
<tbody>
<tr>
<td>QCD</td>
<td>$7^{+8}_{-7}[u+j]$</td>
<td>$0.6^{+0.7}_{-0.6}[u+j]$</td>
<td>$9^{+10}_{-9}[u+j]$</td>
</tr>
<tr>
<td>W+jets</td>
<td>$50 \pm 11[u]^{+14}_{-10}[j] \pm 5[\mathcal{L}]$</td>
<td>$4.4 \pm 3.2[u]^{+1.5}_{-0.8}[j] \pm 0.5[\mathcal{L}]$</td>
<td>$35 \pm 9[u]^{+10}_{-9}[j] \pm 4[\mathcal{L}]$</td>
</tr>
<tr>
<td>Z+jets</td>
<td>$52 \pm 21[u]^{+15}_{-12}[j] \pm 6[\mathcal{L}]$</td>
<td>$4.1 \pm 2.9[u]^{+2.1}_{-1.8}[j] \pm 0.5[\mathcal{L}]$</td>
<td>$27 \pm 12[u]^{+10}_{-10}[j] \pm 3[\mathcal{L}]$</td>
</tr>
<tr>
<td>$t\bar{t}$ and $t$</td>
<td>$10 \pm 0[u]^{+3}_{-2}[j] \pm 1[\mathcal{L}]$</td>
<td>$0.9 \pm 0.1[u]^{+0.4}_{-0.3}[j] \pm 0.1[\mathcal{L}]$</td>
<td>$17 \pm 1[u]^{+6}_{-5}[j] \pm 2[\mathcal{L}]$</td>
</tr>
<tr>
<td>Total SM</td>
<td>$118 \pm 25[u]^{+32}_{-23}[j] \pm 12[\mathcal{L}]$</td>
<td>$10.0 \pm 4.3[u]^{+4.0}_{-1.9}[j] \pm 1.0[\mathcal{L}]$</td>
<td>$88 \pm 18[u]^{+26}_{-17}[j] \pm 9[\mathcal{L}]$</td>
</tr>
<tr>
<td>Data</td>
<td>87</td>
<td>11</td>
<td>66</td>
</tr>
</tbody>
</table>

Table 2: Expected and observed numbers of events in the four signal regions. Uncertainties shown are due to "MC statistics, statistics in control regions, other sources of uncorrelated systematic uncertainty, and also the jet energy resolution and lepton efficiencies" [u], the jet energy scale [j], and the luminosity [\mathcal{L}].

![Squark-gluino-neutralino model, $m(\chi^0_1) = 0$ GeV](image)

**ATLAS** Preliminary

Combined: $\text{CL}_s$ observed 95% C.L. limit

CL$_s$ median expected limit

Expected limit ±1$\sigma$

ATLAS EPS 2011

[$L = 4.7 \pm 1 fb^{-1}, \sqrt{s} = 7$ TeV]

$\sigma_{quark} = 7$ fb

$\sigma_{quark} = 10$ fb

$\sigma_{quark} = 100$ fb