Searches for new physics at the LHC: some frustration, but no despair...

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Outline

- Summary of beyond the Standard Model searches at the LHC
- Global fits of constrained supersymmetric models
- Where could supersymmetry hide?
- Bosonic supersymmetry? Searches for models with extra dimensions
- Summary and conclusions
Summary of BSM searches at the LHC: limits, limits and more limits...

95% C.L. upper limit on $-3 \times 10^{-2}$ and $10^{-1}$ times $10^{1}$ times $10^{2}$ times $10^{1}$ times $10^{0}$ times $10^{1}$ times $10^{2}$ (GeV)

- gluino mass [GeV]: 400, 500, 600, 700, 800, 900, 1000, 1100

- LSP mass [GeV]: 100, 200, 300, 400, 500, 600, 700, 800

- Expected Limit theory $\pm$ NLO+NLL

T" = 8 TeV, $L^{-1}$, 3.9 fb$^{-1}$

CMS Preliminary
Summary of BSM searches at the LHC: no indications for new physics

ATLAS SUSY Searches* - 95% CL Lower Limits (Status: Dec 2012)

*Only a selection of the available mass limits on new states or phenomena shown.
All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.
Summary of BSM searches at the LHC: no indications for new physics

**ATLAS Exotics Searches** - 95% CL Lower Limits (Status: HCP 2012)

<table>
<thead>
<tr>
<th>Mass scale [TeV]</th>
<th>M_0 (δ=2)</th>
<th>M_0 (δ=3, NLO)</th>
<th>M_0 (δ=6)</th>
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<tr>
<td>1.0 fb^-1</td>
<td>4.37 TeV</td>
<td>4.18 TeV</td>
<td>4.71 TeV</td>
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<td>2.5 TeV</td>
<td>4.49 TeV</td>
<td>4.48 TeV</td>
<td>4.16 TeV</td>
</tr>
</tbody>
</table>

*Only a selection of the available mass limits on new states or phenomena shown*
Summary of BSM searches at the LHC: no indications for new physics

- coloured SUSY particles probed up to $\mathcal{O}(1.5 \text{ TeV})$
- third generation squarks probed up to $\mathcal{O}(500 \text{ GeV})$
- electroweak SUSY particles probed up to $\mathcal{O}(300 \text{ GeV})$
- exotic particles ($Z'$ etc.) probed up to $\mathcal{O}(2 \text{ TeV})$

"probed up to" $\neq$ "excluded": it is important to read the fine print!
Why physics beyond the Standard Model?

- **The problem of mass:**
  What is the origin of particle masses? Is it the Higgs boson?
  What stabilizes the Higgs mass?
  What sets the scale of fermion masses?

- **The problem of unification:**
  Is there a simple framework for unifying all particle interactions?

- **The problem of flavour:**
  Why are there so many types of quarks and leptons?
  What is the origin of CP-violation?

- **Cosmological problems:**
  What is the origin of the baryon-antibaryon asymmetry?
  What is the nature of dark matter and dark energy?
Why new physics at the LHC?

The naturalness problem: why is $M_{\text{Higgs}} \ll M_{\text{Planck}}$?

\[ \delta M_H^2 \sim \frac{3 \lambda_t^2}{8 \pi^2} \Lambda_{\text{UV}}^2 \sim (0.3 \Lambda_{\text{UV}})^2 \]

→ need new coloured (top) partners with mass below about 500 GeV
New physics at the LHC?

A dark matter connection?

The new physics should

stabilize the Higgs mass
decouple from EWK physics

Solution: impose a discrete parity
→ all interactions require pairs of new particles;
→ the lightest new particle is stable and provides a dark matter candidate.

A weakly interacting massive particle (WIMP) with mass $\sim \mathcal{O}(100)$ GeV provides the correct dark matter relic abundance.

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New physics models that address the naturalness problem and the origin of dark matter generically predict a spectrum of new particles at the TeV-scale with a weakly interacting & stable particle (← discrete parity).

A generic LHC new physics signature is thus cascade decays with $E_{T,\text{miss}}$

Supersymmetry is a prime example for this class of models.
Supersymmetry

A symmetry between fermions and bosons:  
\[ Q|\text{boson}\rangle = |\text{fermion}\rangle \]
\[ Q|\text{fermion}\rangle = |\text{boson}\rangle \]
with algebra \( \{Q_\alpha, Q^\dagger_\beta\} = (\sigma^\mu)_{\alpha\beta} P_\mu \)

- SUSY is the unique maximal external symmetry in Nature.
- Weak-scale SUSY provides a solution to the hierarchy problem.
- SUSY allows for gauge coupling unification, radiative EWSB, and provides dark matter candidates.

To describe SUSY breaking phenomenologically and to preserve the solution to the hierarchy problem one introduces “soft” SUSY breaking terms \( \rightarrow 124 \) parameters in the MSSM.

SUSY searches are often interpreted in more specific models, like the constrained MSSM, with a universal scalar mass \( M_0 \), gaugino mass \( M_{1/2} \), and trilinear coupling \( A_0 \) at \( M_{\text{GUT}} \), and with \( \tan \beta = \frac{v_2}{v_1} \) and \( \text{sign}(\mu) \).
The mass spectrum of the CMSSM

The SUSY masses at the weak scale are determined through the RGE:

\[
\begin{align*}
    \left( \frac{\mu}{\text{GeV}} \right)^2 + m_{H_d}^2 & \Rightarrow M_1 \\
    \left( \frac{\mu}{\text{GeV}} \right)^2 + m_{H_u}^2 & \Rightarrow M_2 \\
    M_1 & \Rightarrow M_3 
\end{align*}
\]

Typical mass pattern e.g. from

\[
\frac{M_1(\mu)}{\alpha_1(\mu)} = \frac{M_2(\mu)}{\alpha_2(\mu)} = \frac{M_3(\mu)}{\alpha_3(\mu)}
\]

\[
\Rightarrow M_3(M_Z) : M_2(M_Z) : M_1(M_Z) \approx 7 : 2 : 1
\]

Thus, in the CMSSM the sparticle masses are strongly correlated.
SUSY searches

SUSY models are constrained through

- **loop-induced effects**: rare decays of $B$ mesons, $(g - 2)_\mu$, ewk observables
- **astrophysical observations**: $\Omega_{DM}$, direct and indirect DM detection limits
- **direct sparticle and Higgs boson search limits from colliders**:
  LEP and Tevatron bounds and LHC exclusions from jets+$E_{Tmiss}$ searches
- **the LHC Higgs signal**

Global SUSY fits are trying to address the following questions:

- What is the most probable SUSY parameter space including all low-energy observations, astrophysical constraints and collider data?
- To what extent are the various observations and constraints in mutual agreement?

[see e.g. Mastercode (arXiv:1207.7315), SuperBayes (arXiv:1206.0264), and Fittino (arXiv:12044199), and further references in arXiv:1109.3859]
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CMSSM fits as of spring 2012 predicted

- sparticles and $H, A, H^\pm$ beyond the current LHC reach:
branching ratios of the light Higgs $h$ close to the SM values:
CMSSM fits as of spring 2012 predicted

- the branching ratio for $B_s \to \mu\mu$ close to the SM value:

![Fitting SUSY SPRING 2012](image)

\begin{align*}
\alpha_{\mu} - \alpha_{\mu}^{SM} &\approx (2.9 \pm 0.8 \pm 0.2) \times 10^{-9} & 0.3 \times 10^{-9} \\
\text{BR}(b \to s\gamma) &\approx (3.55 \pm 0.26 \pm 0.23) \times 10^{-4} & 2.88 \times 10^{-4} \\
\text{BR}(B \to \tau\nu) &\approx (1.67 \pm 0.39) \times 10^{-4} & 0.99 \times 10^{-4} \\
\text{BR}(B_s \to \mu^+\mu^-) &< (4.50 \pm 0.30) \times 10^{-9} & 3.61 \times 10^{-9} \\
\Delta m_s (\text{ps}^{-1}) &\approx 17.78 \pm 0.12 \pm 5.20 & 20.58 \\
\sin^2 \theta_{\text{eff}} &\approx 0.23113 \pm 0.00021 & 0.23138 \\
m_W (\text{GeV}) &\approx 80.385 \pm 0.015 \pm 0.010 & 80.386 \\
m_h (\text{GeV}) &\approx 126.0 \pm 2.0 \pm 3.0 & 124.4 \\
LHC & & \\
\Omega_{\text{CDM}}^h &\approx 0.1123 \pm 0.0035 \pm 0.0112 & 0.1112 \\
\sigma^{\text{SI}} (\text{pb}) &\approx 2.44 \times 10^{-11} &
\end{align*}
CMSSM fits as of spring 2012 predicted

- no dark matter signal in current direct or indirect searches:

XENON100:
- $m_{\chi^0} = 270.6$ GeV
- $\sigma_{SI} = 7.28 \times 10^{-10}$ pb

LHC, XENON100: 2D 95% CL, XENON100
LHC, XENON100 goal: 2D 95% CL, XENON100 goal
LHC, XENON1T: 2D 95% CL, XENON1T
LHC, XENON1T: 1D 68% CL, XENON1T

- LHC, XENON100 Best Fit
- LHC, XENON100 goal Best Fit
- LHC, XENON1T Best Fit
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- no dark matter signal in current direct or indirect searches ✓

Future global SUSY fits should

- include the measured Higgs couplings in the fits; ✓
- calculate the $p$-value using toy fits; ✓
- address more general models, in particular those with a different connection between the coloured and uncoloured sparticle sector;
- include a larger set of LHC observables and proper combinations thereof.

However,

- just from exclusions it is hard to constrain a larger set of SUSY parameters;
- we need fast and accurate implementations of the LHC results.
Where could SUSY hide?

$
\begin{align*}
\text{95\% C.L. upper limit on} & \quad (\text{GeV}) \\
\text{gluino mass} \quad m_{\tilde{g}} & \quad 400, 500, 600, 700, 800, 900, 1000, 1100 \\
\text{LSP mass} \quad m_{\tilde{\chi}^0_1} & \quad 100, 200, 300, 400, 500, 600, 700, 800 \\
\text{Expected Limit} & \quad \pm \text{NLO+NLL} \\
T & = 8 \text{ TeV, } -1, 3.9 \text{ fb}^{\text{sCL}} \\
\text{CMS Preliminary}
\end{align*}$

$\tilde{g} \gg \tilde{\chi}^0_1 + \text{LSP; } m_{\tilde{g}} \to m_{\tilde{\chi}^0_1}, g \to p p$

$\text{Experimental Uncertainty} \pm \text{(b)}$
Where could SUSY hide?

Compared to the CMSSM, the true SUSY model could have a

- **split spectrum** and thus reduced production cross section:
  - "natural" SUSY with light stops;
  - "unnatural" SUSY with heavy scalars, Higgsino and gravitino;
  - light Higgsinos from anomaly mediation or higher-dim. GUTs;
  - supersoft SUSY;
  - ...

- **different decay pattern**:
  - compressed spectrum;
  - R-parity violation;
  - models with gravitino dark matter;
  - stealth SUSY;
  - ...

Compressed spectra

SUSY models with a compressed mass spectrum could have escaped the standard searches:

[Conley et al.]

A nightmare waiting to happen...

Heavy LSP + all $\lesssim 1$ TeV
Compressed spectra

If the spectrum is compressed, all momentum is carried by the LSP → the event is invisible

One can use initial state radiation to search for these events.

[Alwall et al., LeCompte, Martin; Izaguirre et al., Gunion, Mrenna; Drees et al., Carena et al., Belanger et al., Rolbieki, Sakurai; Dreiner, MK, Tattersall, ...]
We consider three simplified models to capture the extreme scenarios:

(a) squark degenerate with LSP ($\Delta m = 1 - 100$ GeV), gluino decoupled;

(b) gluino degenerate with LSP ($\Delta m = 1 - 100$ GeV), squark decoupled;

(c) squark and gluino degenerate with LSP ($\Delta m = 1 - 100$ GeV).
Compressed spectra

It is essential to properly describe the initial state radiation by matching matrix element calculations and parton showers:

- The uncertainty of the parton shower prediction has been estimated by using different shower settings and is very large.
- The MLM and CKKW-L matching schemes give consistent results with a small uncertainty.
Compressed spectra

We have implemented a variety of SUSY and mono-jet searches into the RIVET analysis package and set limits on the three simplified models.

The CMS razor and mono-jet searches provide the best limits:

We find the following limits:

(a1) stop degenerate with LSP, squarks & gluino decoupled: \( m_{\tilde{t}} > 200 \text{ GeV} \)

(a2) squark degenerate with LSP, gluino decoupled: \( m_{\tilde{q}} > 340 \text{ GeV} \)

(b) gluino degenerate with LSP, squark decoupled: \( m_{\tilde{g}} > 500 \text{ GeV} \)

(c) squark and gluino degenerate with LSP: \( m_{\tilde{q}} \approx m_{\tilde{g}} > 650 \text{ GeV} \)
Consider **minimal universal extra dimension model** [Appelquist, Cheng, Dobrescu]

- 4D flat space time & one extra dimensions of size $R$
- tower of massive Kaluza-Klein partners for all Standard Model particles
- The SM particles and their KK partners have:
  - identical spins
  - identical couplings
- discrete symmetry (KK-parity)
  $\rightarrow$ lightest KK particle is stable and provides a dark matter candidate
- predicts jets + $E_{T\text{miss}}$ signatures qualitatively similar to supersymmetry
Supersymmetry or universal extra dimensions?

- **SUSY**
- **UED**
  - $n = 3$
  - $n = 2$
  - $n = 1$
  - $n = 0$

- **Spins** differ by 1/2
- **Higher levels** no
- Same as SM yes

---

Bosonic supersymmetry? Searches for models with extra dimensions
Search for resonances from the production and decay of 2nd KK modes:

strong production:

⊗ decay:
Production cross sections at the LHC (8 TeV) [Edelhäuser, Flacke, MK]

(A) KK-number conserving production
(B) KK-number violating direct production: A^{(2)}
(B) KK-number violating direct production: Z^{(2)}
(B) KK-number violating direct production: G^{(2)}
(C) KK-number violating associated production

$\sigma$/pb vs $R^{-1}$/GeV
Bosonic supersymmetry? Searches for models with extra dimensions

Limits from comparison with CMS-PAS-EXO-12-061 [Edelhäuser, Flacke, MK]

\[
\rightarrow R^{-1} \gtrsim 700 \text{ GeV and } M_{KK}^{(2)} \gtrsim 1.5 \text{ TeV}
\]
Conclusions

The LHC7/8 has started to cut heavily into the landscape of new physics at the TeV-scale

- there is no sign of new physics so far;
- canonical searches with jets and MET have pushed limits on squark and gluino masses beyond 1 TeV;
- very constrained models like the CMSSM are by now disfavoured.

However, the LHC searches need to

- be optimized for and interpreted in a wider class of BSM models;
- focus on third generation and electroweak sparticles;
- be extended to more general and complex scenarios, e.g. compressed spectra.

Unfortunately, the (canonical) BSM searches are running out of steam; it will be crucial to upgrade the LHC energy towards 14 TeV.
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The landscape of new physics

...Anthropic big desert up to the Planck scale
The landscape of new physics

...or a natural supersymmetric Garden Eden?

courtesy of Isabell M.-P.
Thank you!