Recent Beyond the SM Results from ATLAS and CMS

Yuri Gershtein
LHC is exploring Electroweak Scale

We are here

Yuri Gershtein

Monday, May 5, 14
What’s so Exciting

**Exploring Electroweak Symmetry Breaking Scale**

- had to find something - and already have
  - something that looks a lot like a **fundamental scalar** - more in *Halladjian and Bortoletto talks*

- is the small Higgs mass anthropic or a consequence of some new symmetry? The answer is likely to lie at O(EWSB scale)

- every time we produce a Higgs (or a W, or a Z at large $\sqrt{s}$) at the LHC we learn more about EWSB

**Are there more fundamental scalars?**

- *SUSY never looked more attractive*

**Can we produce Dark Matter at the LHC?**

- *especially given hints of indirect detection of DM with preferential coupling to the third generation*

**LHC probes Unknown territory - have to watch out for new things:** *Occama razor has a terrible record in our field*
LHC is exploring Electroweak Scale

More on $10^{16}$ scale on Wednesday

We are here
In Torrential Detail

For the full picture see

- SUSY and Exotics at https://twiki.cern.ch/twiki/bin/view/AtlasPublic/
- SUS, EXO and B2G at https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults
In this talk

My personal pick of “most interesting” and links to a more complete set of results

- Dark Matter searches
  - Most searches are carried out at both ATLAS and CMS and have ~same sensitivity
- Exotica
  - extra dimensions, extra gauge bosons, vector quarks
- Supersymmetry
  - “Classic”, “Natural”, RPV violating
- Higgs as a new physics tag
  - Higgsino searches
- Summary / Outlook
Dark Matter Searches

If DM interacts more than gravitationally, it could be made in perceptible numbers at the LHC

To be observable at the LHC, it has to be associated production with SM particles (that would also tell us about the DM couplings)

- mono-jet / mono-photor
- mono W/Z
- mono top / top pairs
- ...

Interpretation

- model independent cross section times acceptance measurement / limits
- Effective Field Theory approach for heavy DM force mediator
- Specific model (i.e. Higgs portal, etc)

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### EFT Operators

*Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu arXiv:1008.1783*

<table>
<thead>
<tr>
<th>Name</th>
<th>Operator</th>
<th>Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1</td>
<td>$\bar{\chi}\chi\bar{q}q$</td>
<td>$m_q/M_\ast^3$</td>
</tr>
<tr>
<td>D2</td>
<td>$\bar{\chi}\gamma^5\chi\bar{q}q$</td>
<td>$im_q/M_\ast^3$</td>
</tr>
<tr>
<td>D3</td>
<td>$\bar{\chi}\chi\bar{q}\gamma^5q$</td>
<td>$im_q/M_\ast^3$</td>
</tr>
<tr>
<td>D4</td>
<td>$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5q$</td>
<td>$m_q/M_\ast^3$</td>
</tr>
<tr>
<td>D5</td>
<td>$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma^\mu q$</td>
<td>$1/M_\ast^2$</td>
</tr>
<tr>
<td>D6</td>
<td>$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$</td>
<td>$1/M_\ast^2$</td>
</tr>
<tr>
<td>D7</td>
<td>$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma^\mu\gamma^5q$</td>
<td>$1/M_\ast^2$</td>
</tr>
<tr>
<td>D8</td>
<td>$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma^\mu\gamma^5q$</td>
<td>$1/M_\ast^2$</td>
</tr>
<tr>
<td>D9</td>
<td>$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$</td>
<td>$1/M_\ast^2$</td>
</tr>
<tr>
<td>D10</td>
<td>$\bar{\chi}\sigma^{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\alpha\beta}q$</td>
<td>$i/M_\ast^2$</td>
</tr>
<tr>
<td>D11</td>
<td>$\bar{\chi}\chi G_{\mu\nu}\bar{G}^{\mu\nu}$</td>
<td>$\alpha_\ast/4M_\ast^3$</td>
</tr>
<tr>
<td>D12</td>
<td>$\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$</td>
<td>$i\alpha_\ast/4M_\ast^3$</td>
</tr>
<tr>
<td>D13</td>
<td>$\bar{\chi}\chi G_{\mu\nu}\bar{G}^{\mu\nu}$</td>
<td>$i\alpha_\ast/4M_\ast^3$</td>
</tr>
<tr>
<td>D14</td>
<td>$\bar{\chi}\gamma^5\chi G_{\mu\nu}\bar{G}^{\mu\nu}$</td>
<td>$\alpha_\ast/4M_\ast^3$</td>
</tr>
</tbody>
</table>

**TABLE I:** Operators coupling WIMPs to SM particles. The operator names beginning with D, C, R apply to WIMPS that are Dirac fermions, complex scalars or real scalars respectively.
CMS-EXO-13-004
leptonic W decay

ATLAS-EXOT-2012-27
hadronic W/Z decay

Mono W/Z

Interference effects

D5 (SI): \[ \frac{1}{\Lambda^2} \bar{X} \gamma \mu X \cdot \bar{\zeta} q_i \gamma \mu q_i \]

Mass of “fat” jet

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Associated top

CMS-B2G-12-022

http://feynrules.irmp.ucl.ac.be/wiki/Monotops

Lepton + 3 jets
Veto events with fourth jet above 25 GeV
Veto events with extra leptons

Exclude vector (scalar) DM masses below 655 (327) GeV

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Higgs Portal

If the DM couples to Higgs and is lighter than 125/2, then Higgs would have increased rate of invisible decays.

CMS-HIG-13-030

See also ATLAS Z(\ell)+H(inv)
ATLAS-HIGG-2013-03


\[
\Delta L_S = -\frac{1}{2} m_S^2 S^2 - \frac{1}{4} \lambda_S S^4 - \frac{1}{4} \lambda_{hSS} H^\dagger H S^2 ,
\]

\[
\Delta L_V = \frac{1}{2} m_V V^\mu V^\mu + \frac{1}{4} \lambda_V (V^\mu V^\mu)^2 + \frac{1}{4} \lambda_{VVV} H^\dagger H V^\mu V^\mu ,
\]

\[
\Delta L_f = -\frac{1}{2} m_f \chi \chi - \frac{1}{4} \lambda_{hf} \frac{H^\dagger H \chi \chi} .
\]

If the Dark Sector is complex, some of the dark cascade can “come back”: long-lived neutral particles.

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Large number of well-motivated scenarios predict long-lived particles

- hidden valley models
- rare Higgs decays (the one at 125 GeV or a new one) - if there are HVs, Higgs may the particle that senses them most: $H \rightarrow XX$, $X \rightarrow ff$
- GMSB SUSY $\tilde{\chi}_1^0 \rightarrow \tilde{G}Z(\rightarrow jj)$
- RPV SUSY $\tilde{q} \rightarrow q\chi^0(\rightarrow \ell^+\ell^−\nu)$ (or H cascade) $\tilde{t} \rightarrow jb$

New!

CMS-EXO-12-037

great reach at low masses!

much lower sensitivity for masses <100 GeV

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Long-Lived Particles decaying into leptons
observe no events for IP significance > 12σ
Long-Lived Particles decaying into leptons observe no events for IP significance > 12σ

Probing $H(125)$ branchings down to $10^{-4}$
Long-Lived Particles decaying into leptons

observe no events for IP significance $> 12\sigma$

Probing sub-femtobarn cross sections
Long-Lived Particles

for ~recent results also see

Stopped particles: ATLAS-SUSY-2013-03 CMS-EXO-11-020
“slow” charged particles: ATLAS-CONF-2013-058; ATLAS-EXOT-2012-10; ATLAS-EXOT-2011-11; CMS-EXO-12-026
Extra Gauge bosons

ATLAS-CONF-2014-017: \( qq \to W' \to lv \)

ATLAS Preliminary

\( \sqrt{s} = 8 \text{ TeV} \)

\( \mathcal{L} dt = 20.3 \text{ fb}^{-1} \)

W' \to ev

\[
\begin{array}{c}
\text{Data 2012} \\
\text{W' (500)} \\
\text{W' (1000)} \\
\text{W' (3000)} \\
\text{W} \\
\text{Z} \\
\text{Top quark} \\
\text{Diboson} \\
\text{Multijet}
\end{array}
\]

ATLAS-CONF-2014-015

CMS-EXO-12-025

CMS-EXO-12-061: \( qq \to Z' \to ll \)

CMS Preliminary, 8 TeV, 19.6 fb\(^{-1}\)

DATA

\( \gamma Z' \to e^+ e^- \)

\( tt, tW, WW, WZ, ZZ, \tau \tau \)

jets (data)

W', Z' limits \(~3 \text{ TeV assuming SSM}\)

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Extra Dimensions

- Randall-Sundrum model with a wrapped extra dimension
- Geometric way out of the Naturalness problem
- G*: first KK excitation of a graviton
  - Decays into $t\bar{t}$, WW, ZZ, hh, $\gamma\gamma$, l$^+$$^-$, ...

CMS-EXO-12-022

Fat jet with sub-structure

Excludes G* below 700 GeV for $k/M_{Pl}=1$
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mini black holes

One of most striking consequences of $\sim$TeV Planck scale
◆ require at least three high $E_T$ objects, one of them - an electron or a muon

Limits on $M_{th}$ of 5-6 TeV depending on assumptions

See Also: ATLAS-EXOT-2013-003
CMS-EXO-12-009

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Vector-like quarks

- Supersymmetry is not the only symmetry that can protect the Higgs mass
- the 125 GeV boson could be a pseudo-Goldstone boson from a spontaneous breaking of a global symmetry
- several attractive models exist with new strong dynamics and vector-like quarks. Exotic charges (i.e. can be a 5/3)


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Supersymmetry

Complexity of the final state can be staggering

What happens to the neutralino $\chi_1^0$?

- R-parity conserved and SUSY broken at high scale:
  - Dark Matter candidate!
- R-parity conserved and SUSY broken at low scale:
  - gravitino is LSP (DM component)
  - $\chi_1^0$ decays to gravitino plus a photon, Z, or Higgs
  - long lived decays are possible
- R-parity is not conserved:
  - decay chains with little or no MET
  - 3-rd generation if MFV
  - long lived decays are possible
  - Can make ~any final state (great for signature generation)

Cascade from strong production

If colored partners are inaccessible, can produce EWKly interacting partners (lower cross sections and more SM-like events)
In the “expected” version of SUSY with R-parity conservation at the LHC, squarks and gluinos were strongly produced, resulting in light flavor jets + MET signature. Z/W + jets dominant background. MET tails under control. Constrained models ~dead.

\[ \tilde{q}\tilde{q} \text{ production, } \tilde{q} \rightarrow q \tilde{\chi}_1^0 \]
Search methodology

- The phenomenology is very rich even in simple and simplified models
- Need to make results re-castable into many models
- Move away from making kinematic cuts beyond base selection
  - instead make multiple kinematic regions - some dominated by specific SM backgrounds, some - with potentially clean BSM signals

36 kinematic regions of the SUS-13-012 jets+MET search
Tops in SUSY cascades

Even if SUSY “hides” in a complex long decay chains, it should have lots of tops in them - gives extra handles for searches

- with all Run 1 data, it’s almost impossible to miss a gluino below a TeV
Gauge Mediated SUSY

- Diphotons + MET: "classic" GMSB Bino
- Strong and EWK production

ATLAS-CONF-2014-001
“Natural” SUSY

How heavy can SUSY be without making fine tuning too large?
- recall the Sun and the Moon have same size: $10^{-2}$ tuning

The criteria of Naturalness are squishy, but wholistically:
- higgsino should not be too heavy (200-500 GeV)
- at least one stop should be not too heavy (500-1000 GeV)
- gluino should not be much heavier than 1.5 TeV

Some requirements are “easy” to relax
- i.e. if gluino is a Dirac fermion, then a 3 TeV mass can be perfectly natural
- light higgsino is the least squishy attribute of Naturalness
- if bino/wino are much heavier they decouple, and the three higgsinos are almost mass degenerate (~GeV splitting)
“Natural” SUSY: Stop

Limits ~ 600-700 GeV

Notable hole:

- $m(\text{stop}) - m(\text{neutralino}) \sim m(\text{top})$

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**ATLAS** Preliminary

- Observed limits
- Expected limits

All limits at 95% CL

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see also

CMS-SUS-13-004
CMS-SUS-13-011
CMS-SUS-13-009

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Status: Moriond 2014
Stop + Stau in GMSB

- Expansion of the di-lepton + b + MET stop analysis (MT2)
- add low mass region sensitivity by constructing MT2 variable for (jet-l) pairs

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Stop + Higgsino in GMSB

- Events with two higgses and at jets from stop cascades
- use di-photon higgs decay mode: low Br but very clean

CMS, $\sqrt{s} = 8$ TeV, $\int L \, dt = 19.7$ fb$^{-1}$

Events per GeV

CMS-SUS-13-014

For Z final states use lepton channel

see also SUS-13-022, SUS-13-021 for different stop-higgs topologies

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Higgs as New Physics Tag

New physics (SUSY?) cascades may produce higgses as copiously as W’s and Z’s - but the SM Higgs cross section is tiny compared to W/Z

- single W: $10^5$ pb
- W+lots of jets (aka top): $10^3$ pb
- single h: 20 (50) pb
- h + lots of jets (tth): 0.1 (0.6) pb

requiring higgs production is a New Physics booster

even paying $2 \cdot 10^{-3}$ penalty for $\gamma\gamma$
branching one gets ~reasonable number of events

$5/fb \cdot 1pb \cdot 2 \cdot 10^{-3} = 10$ events

Impact way beyond just SUSY - every time you produce a Higgs you explore EWSB: SUSY here is just a great way to “generate signatures” with Higgs + stuff.

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Impact way beyond just SUSY - every time you produce a Higgs you explore EWSB: SUSY here is just a great way to “generate signatures” with Higgs + stuff.
Electroweak production

- Quiet events, small cross sections
- Even combining a lot of channels does not exclude a lot of parameter space

Complementary to diphotons and multileptons: sensitive to higher masses

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CMS-SUS-13-022

control region  signal region
Summary

- Extensive program of searches for BSM
  - now getting results from really tough final states
  - exclude huge portions of BSM models’ parameter space - and we have not run at nominal energy yet

- Although no new sign of BSM yet, we barely started exploring the TeV scale
  - i.e. Natural SUSY is still perfectly viable

- Stay tuned for more Run 1 results and 13 TeV data next year!

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Comparison with multileptons

Higgs decays into leptons
- mostly though WW and $\tau\tau$
- $\text{Br}[h\rightarrow 1 \ e/\mu]\approx 11\%$, $\text{Br}[h\rightarrow 2 \ e/\mu]\approx 1.8\%$
- $\text{Br}[hh\rightarrow 3 \ e/\mu]\approx 0.4\%$ - comparable to $\eta\eta$
- in reality, a little less sensitive - soft leptons from $\tau$, $W^*$ and larger background (no mass peak!)