Searches for New Physics at the Energy Frontier

John Alison

University of Chicago
Disclaimer:
Impossible to cover all the interesting BSM physics in 30 min. Won’t try.

Over 40 talks at this conference related to new physics at LHC.

Aim to:
Outline the overall program.
Give coherent picture of general strategy.
Try to put the other talks in context.
Outline

Introduction
- Motivations
- Challenges

Lessons learned in Run-1

Highlights of Run-1 Program

Anomalies in the current dataset

What we might know by DPF 2017
Motivation for New Physics at LHC

- We are at the frontier.
  - Doing things that have never been done...
    - Probing physics at unexplored energies
    - Unprecedented rates of pp collisions
- We are at the frontier.
  - Doing things that have never been done...
    - Probing physics at unexplored energies
    - Unprecedented rates of pp collisions
  - Using state-of-the-art tools.
    - Detectors / Trigger(!)
    - Computing / Analysis Techniques / Monte Carlo Predictions
Motivation for New Physics at LHC

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- **Recipe for discovery:** Expect the unexpected
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- Recipe for discovery: Expect the unexpected

- Guiding principles hinting that the TeV scale is special.
  - Naturalness/Hierarchy Problem  (*Why is the higgs light?*)
  - Dark Matter  (*TeV scale WIMP can explain observed abundance*)
Challenge in Finding New Physics at the LHC

- Don’t know where to look.
  - Have good guesses.
  - Cast as wide a net as possible.
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  - Many different detector signatures.
  - Large range of masses.
  - Large span in production rates.
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Need to cope with large levels of Standard Model background.

Example: SUSY
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Standard Model Production Cross Section Measurements

Theory | Observed
--- | ---
LHC pp $\sqrt{s} = 7$ TeV | 4.5 – 4.9 fb$^{-1}$
LHC pp $\sqrt{s} = 8$ TeV | 20.3 fb$^{-1}$
Challenge in Finding New Physics at the LHC

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<table>
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LHC pp $\sqrt{s} = 7$ TeV

Theory

Observed 4.5 – 4.9 fb$^{-1}$

LHC pp $\sqrt{s} = 8$ TeV

Theory

Observed 20.3 fb$^{-1}$

Expected range of sensitivity to New Physics
Challenge in Finding New Physics at the LHC

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### Standard Model Production Cross Section Measurements

**Status: March 2015**

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**Expected range of sensitivity to New Physics**

500 GeV stop / 1 TeV gluino

1 event every 10 minutes
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### Standard Model Production Cross Section Measurements

**Total rate billion events/s**

- **LHC pp** \( \sqrt{s} = 7 \) TeV
  - **Observed**: 4.5 – 4.9 fb
  - **Theory**:

- **LHC pp** \( \sqrt{s} = 8 \) TeV
  - **Observed**: 20.3 fb
  - **Theory**:

**Expected range of sensitivity to New Physics**

- 500 GeV stop / 1 TeV gluino
  - 1 event every 10 minutes

**Summary**

- Theory vs. Observed:
- ATLAS Preliminary
- Run 1 \( \sqrt{s} = 7, 8 \) TeV

**Dataset**

- **Planck**
- **LHC pp**
- **LHC pp**
- **LHC pp**
- **LHC pp**

**Expected Sensitivity**

- **LHC pp**
- **LHC pp**
- **LHC pp**
- **LHC pp**

**Analysis**

- **Expected Sensitivity**
- **Planck**
- **LHC pp**
- **LHC pp**
- **LHC pp**

**Signatures**

- **Wbab**
- **Zbab**
- **Wbab**
- **Zbab**
- **Wbab**

**Expected**

- **LHC pp**
- **LHC pp**
- **LHC pp**
- **LHC pp**

**Production**

- **Wbab**
- **Zbab**
- **Wbab**
- **Zbab**
- **Wbab**

**Total**

- **LHC pp**
- **LHC pp**
- **LHC pp**
- **LHC pp**
- **LHC pp**

**Observed**

- **LHC pp**
- **LHC pp**
- **LHC pp**
- **LHC pp**
- **LHC pp**

**Theory**

- **LHC pp**
- **LHC pp**
- **LHC pp**
- **LHC pp**
- **LHC pp**

**Limit**

- **LHC pp**
- **LHC pp**
- **LHC pp**
- **LHC pp**
- **LHC pp**

**Background**

- **LHC pp**
- **LHC pp**
- **LHC pp**
- **LHC pp**
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| pp total | Jets $R=0.4\ | y|<3.0$ | Dijets $R=0.4\ | y|<3.0$ | W total | Z total | $t\bar{t}$ total | $t\bar{t}$-chan total | WW total | $\gamma\gamma$ total | Wt total | H total | WZ total | ZZ total | $W^+W^-$ total | $W^+\gamma$ total | $W^+Z$ total | $Z\gamma$ total | $t\bar{t}W$ total | $t\bar{t}Z$ total | $t\bar{t}\gamma$ total | $Z_{jj}$ total | $W_{\gamma\gamma}$ total | $W^{+}\gamma^{\pm}$ total | $t\bar{t}$-chan total |
| 10^11 | 10^10 | 10^9 | 10^8 | 10^7 | 10^6 | 10^5 | 10^4 | 10^3 | 10^2 | 10^1 | 10^{-1} | 10^{-2} | 10^{-3} | 10^{-4} | 10^{-5} | 10^{-6} | 10^{-7} | 10^{-8} | 10^{-9} | 10^{-10} | 10^{-11} | 10^{-12} | 10^{-13} |

Total rate billion events/s

100-GeV jets: 10 kHz

500 GeV stop / 1 TeV gluino
1 event every 10 minutes

Expected range of sensitivity to New Physics

**LHC pp**

$\sqrt{s} = 7, 8$ TeV

**Theory**

ATLAS Preliminary

Run 1

$\sigma = 10^{34}$ cm$^{-2}$ s$^{-1}$

$\mathcal{L} = 10^{34}$ cm$^{-2}$ s$^{-1}$

$\sqrt{s} = 8$ TeV
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**Expected range of sensitivity to New Physics**

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**Total rate billion events/s**

- **ATLAS** Preliminary
  - Run 1 $\sqrt{s} = 7, 8$ TeV

- **LHC pp** $\sqrt{s} = 8$ TeV
  - Observations:
    - $W$ bosons: $4.5 - 4.9$ fb$^{-1}$
    - $Z$ bosons: $20.3$ fb$^{-1}$

- **Theory**

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<td>$t\bar{t}$</td>
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<tr>
<td>$W^+W^-$</td>
<td>$\sigma = 10^{-2}$</td>
</tr>
<tr>
<td>$ttW$</td>
<td>$\sigma = 10^{-1}$</td>
</tr>
<tr>
<td>$H\rightarrow\gamma\gamma$</td>
<td>$\sigma = 10$</td>
</tr>
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<td>$H\rightarrow WW$</td>
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<td>$H\rightarrow ZZ\rightarrow 4\ell$</td>
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**Theory and Observed Cross Sections**

- **Observed**
  - $W$ bosons: $4.5 - 4.9$ fb$^{-1}$
  - $Z$ bosons: $20.3$ fb$^{-1}$

- **Theory**
  - $W$ bosons: $1$ kHz
  - $Z$ bosons: $10$ kHz

**Total Rate per Billion Events/s**

- **Total rate billion events/s**
  - $\sigma = 10^{-3}$ fb$^{-1}$
  - $\sigma = 10^{-2}$ fb$^{-1}$
  - $\sigma = 10^{-1}$ fb$^{-1}$
  - $\sigma = 10$ fb$^{-1}$
  - $\sigma = 10^2$ fb$^{-1}$
  - $\sigma = 10^3$ fb$^{-1}$

**Expected range of sensitivity to New Physics**

- **Expected range of sensitivity**
  - $500$ GeV stop / $1$ TeV gluino
  - 1 event every 10 minutes
Challenge in Finding New Physics at the LHC

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<td>Top quarks: 1 event/s</td>
<td></td>
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<td>100-GeV jets: 10 kHz</td>
<td>1 kHz</td>
<td></td>
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**Expected range of sensitivity to New Physics**

- 500 GeV stop / 1 TeV gluino
- 1 event every 10 minutes
Lessons from Run-1
- There is a higgs sector.
  - It’s approximately standard model like.
  - Could have been clear signs of new physics here.
  - Now an obvious lamppost to look under.
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- No clear indications of new physics.
Lessons from Run-1

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  - Now an obvious lamppost to look under.

- No clear indications of new physics.

- Excellent understanding of:
  - Detectors / Reconstruction / Calibration
  - Standard Model physics
Highlights from Run-1 Program:

- Using Naturalness as a Guide
- Searching for Dark Matter
- Looking for the Unexpected
Using Naturalness as a Guide
Using Naturalness as a Guide

- Supersymmetry SUSY

- New cut-off scale:
  - Extra dimensions
  - Higgs compositeness

*In general top partners emerge.*

*Recent theme: “Filling in the Holes.”*
Naturalness suggests “light” top partners: below ~TeV

Stops strongly produced:
- Come in pairs
- Relatively large cross sections
- Decay to undetected L.S.P.

Rich phenomenology depending on various mass splittings (next slide)
Stop Search

\[ \Delta m \equiv m_{\text{stop}} - m_{\chi^0} \]

\[ \Delta m < 0 \]

\[ (m_W + m_b) < \Delta m < m_{\text{top}} \]

\[ \Delta m > m_{\text{top}} \]
Stop Search

\[ \Delta m \equiv m_{\text{stop}} - m_{\tilde{\chi}^0} \]

**ATLAS**
- \( \tilde{t} \rightarrow t\tilde{\chi}^0 \)
- \( \tilde{t} \rightarrow t\tilde{\chi}_1 \)
- \( \tilde{t} \rightarrow t\tilde{\chi}_2 \)

\( \sqrt{s} = 8 \) TeV, 20 fb\(^{-1}\)

Observed limits

Expected limits

All limits at 95\% CL

\( \Delta m < (m_{W} + m_{b}) < \Delta m < m_{\text{top}} \)

Diagram of \( t\bar{t} + \text{MeT} \) search

stop search

\[ \Delta m < 0 \]
Stop Search

\[ \Delta m = m_{\text{stop}} - m_{\tilde{\chi}^0} \]

\[ \sqrt{s} = 8 \text{ TeV, } 20 \text{ fb}^{-1} \]

- \( \tilde{t}_1 \rightarrow t \tilde{\chi}^0 \)
- \( \tilde{t}_1 \rightarrow t \tilde{\chi}_1 \)
- \( \tilde{t}_1 \rightarrow t \tilde{\chi}_1 \) combined
- \( \tilde{t}_1 \rightarrow W b \tilde{\chi}^0 \)

\[ m_{\tilde{\chi}^0} \text{ [GeV]} \]

\[ m_{\tilde{t}_1} \text{ [GeV]} \]

\[ \Delta m < 0 \]

\[ \Delta m < (m_W + m_b) \]

bbWW+ MeT search

- Observed limits
- Expected limits

\[ \tilde{t} \rightarrow W b \tilde{\chi}^0 \]

\[ \tilde{t} \rightarrow W b \tilde{\chi}^0 \]

\[ \tilde{t} \rightarrow W b \tilde{\chi}^0 \]

\[ \tilde{t} \rightarrow W b \tilde{\chi}^0 \]
The figure shows the stop search results from the ATLAS experiment. The plot displays the mass limits on the stop mass, $m_{t_1}$, for various decay modes andino mass, $m_{\tilde{\chi}_1^0}$, using mono-Jet + charm tags. The observed limits are indicated by the shaded regions, with the region where the limit is not observed marked with a gray area. The figure highlights the significance of considering the stop's mass in the phenomenology of supersymmetric models. Several possible dependencies on SUSY parameters arise, such as the lightest chargino, which can be characterized by the three-body decay $t_1 \rightarrow W b \tilde{\chi}_1^0$. The diagram does not show "mixed" decays, in which the two pair-produced third-generation quark states decay differently.

The inset diagram illustrates the mono-Jet + charm tags analysis, with different decay modes represented by arrows. The plot includes contributions from $W b \tilde{\chi}_1^0$, $t_1 \rightarrow W b \tilde{\chi}_1^0$, and other decay modes, with the ATLAS experiment's color-coded regions indicating the observed limits at 95% CL. The mass limits are shown in different colors, with lighter shades indicating less stringent limits. The figure is a simplified model of the ATLAS experiment's search for supersymmetry, focusing on the stop and the lightest chargino.
Stop Search

**ATLAS**

- \( \tilde{t}_1 \to t \tilde{\chi}_1^0 \)
- \( \tilde{t}_1 \to t \tilde{\chi}_1^+ \)
- \( \tilde{t}_1 \to W b \tilde{\chi}_1^0/b f f' \tilde{\chi}_1^0 \)
- \( \tilde{t}_1 \to W b \tilde{\chi}_1^0 \)
- \( \tilde{t}_1 \to c \tilde{\chi}_1^- \)
- \( \tilde{t}_1 \to b f f' \tilde{\chi}_1^0 \)

\( \Delta m < 0 \)

- t\bar{t} di-lepton channel
- (think \( H \to WW \))

\( \sqrt{s}=8 \text{ TeV}, 20 \text{ fb}^{-1} \)

- t0L/t1L combined
- t2L, SC
- WW
- t1L, t2L
- tc
- tc, t1L

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

\( m_{\tilde{t}_1} \) [GeV]
Stop Search: ATLAS

\[ \tilde{t}_1 \tilde{t}_1 \text{ production, } \tilde{t}_1 \rightarrow b f f' \tilde{\chi}_1^0 / \tilde{t}_1 \rightarrow c \tilde{\chi}_1^0 / \tilde{t}_1 \rightarrow W b \tilde{\chi}_1^0 / \tilde{t}_1 \rightarrow \tilde{t} \tilde{\chi}_1^0 \]

**ATLAS**

- \( \tilde{t}_1 \rightarrow t \tilde{\chi}_1^0 \)
- \( \tilde{t}_1 \rightarrow t \tilde{\chi}_1^0 \)
- \( \tilde{t}_1 \rightarrow W b \tilde{\chi}_1^0 / b f f' \tilde{\chi}_1^0 \)
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- \( \tilde{t}_1 \rightarrow b f f' \tilde{\chi}_1^0 \)

\( \sqrt{s} = 8 \) TeV, 20 fb\(^{-1}\) 
- t0L/t1L combined 
- t2L, SC 
- WW 
- t1L, t2L 
- tc 
- tc, t1L

---

Observed limits 
---

Expected limits
---

All limits at 95\% CL

---

arXiv:1506.08616 
CMS-SUS-13-009 
CMS-SUS-13-011 
CMS-SUS-13-015 
CMS-SUS-14-011
Limits on other SUSY Production

- Each colored line here is a separate analysis/talk.

- General Message: Strongly produced particles excluded to ~TeV
  EW produced particles excluded up to 100s of GeV.

- Many caveats in all SUSY limits! Need to read fine print.
Searching for Dark Matter

- ATLAS/CMS not designed to detect Dark Matter.

- Sensitive to processes w/Dark Matter produced in association other SM particles.
Mono-Jet Search

Workhorse Analysis.
- Constrain WIMP models over broad mass range.
- Sensitivity to many other BSM models.
Mono-Jet Search

Workhorse Analysis.
- Constrain WIMP models over broad mass range.
- Sensitivity to many other BSM models.

Dark Matter produced new mediator or other new physics process.
- WIMPs escape detection, detect transverse boost of recoil system
- Infer presence of Dark Matter from $P_T$ imbalance.

\begin{align*}
\text{Diagram 1:} & \quad g \rightarrow q\chi \\
\text{Diagram 2:} & \quad g \rightarrow Z\chi
\end{align*}
Search for signal in tail of missing $E_T$ distribution

Workhorse Analysis:
- Constrain WIMP models over broad mass range
- Sensitivity to many other BSM models.

Dark Matter:
- WIMPs escape detection
- Infer presence of Dark Matter from $P_T$ imbalance.

Mono-Jet Search

Jet 0,
- $et = 921.98$
- $eta = -0.463$
- $phi = 2.508$

MET 0,
- $pt = 913.68$
- $eta = 0.000$
- $phi = -0.657$

CMS PAS EXO-12-055
arXiv:1502.01518
Mono-Jet Search

Workhorse Analysis.
- Constrain WIMP models over broad mass range.
- Sensitivity to many other BSM models.

Dark Matter produced new mediator or other new physics process.
- WIMPs escape detection, detect transverse boost of recoil system
- Infer presence of Dark Matter from $P_T$ imbalance.

Search for signal in tail of missing $E_T$ distribution.
Mono-Jet Search

Workhorse Analysis
- Constraints
- Sensitivity

Dark Matter
- WIMP
- Infer properties

Search for

\( t\bar{t} + \text{single top} \)
\( \text{Di-boson} \)
\( \text{Multi-jet} \)
\( \text{W(} \to l\nu) + \text{jets} \)
\( \text{Z(} \to \ell\ell) + \text{jets} \)
\( \text{D5} \)
\( \tilde{G} + q\bar{q} \quad \text{M}_{q\bar{q}} = 1 \text{ TeV}, \quad \text{M}_G = 10^{-4} \text{ eV} \)

\[ \sqrt{s} = 8 \text{ TeV}, \quad 20.3 \text{ fb}^{-1} \]

Data 2012
SM uncertainty
\( Z(\to \nu\nu) + \text{jets} \)
\( W(\to l\nu) + \text{jets} \)
Di-boson
\( t\bar{t} + \text{single top} \)
Multi-jet
\( Z(\to \ell\ell) + \text{jets} \)

\( \slashed{E}_T \) > 150 GeV
Mono-Jet Search

Irreducible SM Background

- WIMPs
- Infer parameters

ATLAS
\( \sqrt{s} = 8 \text{ TeV, } 20.3 \text{ fb}^{-1} \)
\( E_T^{\text{miss}} > 150 \text{ GeV} \)

Data 2012
SM uncertainty
Z\((\rightarrow \nu \nu)\)+jets
W\((\rightarrow l\nu)\)+jets
Di-boson
tf + single top
Multi-jet
Z\((\rightarrow ll)\)+jets
D5 \( M = 100 \text{GeV}, M_s = 670 \text{GeV} \)
ADD \( n = 2, M_D = 3 \text{TeV} \)
\( \tilde{G} + \tilde{q}/\tilde{g} \) \( M_{\tilde{q}/\tilde{g}} = 1 \text{TeV}, M_G = 10^{-4} \text{eV} \)
Mono-Jet Search

ATLAS

\[ \sqrt{s} = 8 \text{ TeV}, \ 20.3 \text{ fb}^{-1} \]

\[ E_T^{\text{miss}} > 150 \text{ GeV} \]

Data 2012
- SM uncertainty
- \( \ell \ell \) + jets
- Di-boson
- \( t\bar{t} + \text{ single top} \)
- Multi-jet
- \( Z(\rightarrow \nu\nu) + \text{ jets} \)
- \( W(\rightarrow l\nu) + \text{ jets} \)
- ADD \( n=2, M_D = 3 \text{ TeV} \)
- \( D5 M = 100 \text{ GeV}, M_* = 670 \text{ GeV} \)
- \( \tilde{g} + \tilde{q} \tilde{g} M_{\tilde{q}} = 1 \text{ TeV}, M_G = 10^{-4} \text{ eV} \)

Mono-Jets already hit “neutrino floor”

WIMP Mass [GeV/c^2]

WIMP-nucleon cross-section [pb]

WIMP-nucleon cross-section [cm^2]

Mono-Jet Search

Data 2012
- SM uncertainty
- \( \ell \ell \) + jets
- Di-boson
- \( t\bar{t} + \text{ single top} \)
- Multi-jet
- \( Z(\rightarrow \nu\nu) + \text{ jets} \)
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- \( D5 M = 100 \text{ GeV}, M_* = 670 \text{ GeV} \)
- \( \tilde{g} + \tilde{q} \tilde{g} M_{\tilde{q}} = 1 \text{ TeV}, M_G = 10^{-4} \text{ eV} \)

Mono-Jets already hit “neutrino floor”

WIMP Mass [GeV/c^2]

WIMP-nucleon cross-section [pb]

WIMP-nucleon cross-section [cm^2]
Beyond Mono-Jet

- mono-everything (...anything)

mono-\(\gamma\):

mono-W/Z/h/\(\gamma\):

VBF + MeT:

- Trade background rejection for model dependence.
- Even here typically largest backgrounds irreducible \(Z \rightarrow \nu\nu\) production.
DM Searches in Context

Many caveats! Need to read fine print.
DM Searches in Context

Many caveats! Need to read fine print.
Searching for the Unexpected
Searching for the Unexpected

Look for deviations from Standard Model.

Exploit distributions with simple well-defined SM behavior:
- mass / Angular distributions / $H_T$ / ...
- bump hunt / tail hunt.

Search in regions with little or no predicted SM events.
- many leptons / displaced objects / like charge / ...
Searching for the Unexpected

Look for deviations from Standard Model.

Exploit distributions with simple well-defined SM behavior:
- mass / Angular distributions / $H_T$ / ...
- bump hunt / tail hunt.

Search in regions with little or no predicted SM events.
- many leptons / displaced objects / like charge / ...

Highlight a few of the mass searches in the following
Searching for the Unexpected

\( v_e \quad v_\mu \quad v_\tau \quad u \quad c \quad t \quad g \quad \gamma \quad W \quad Z \quad h \quad e \quad \mu \quad \tau \quad d \quad s \quad b \)
Searching for the Unexpected

\[ \nu_e, \nu_\mu, \nu_\tau, \quad u, c, t, \quad d, s, b, \quad g, \gamma, W, Z, h \]

**CMS**: di-\(e\) / di-\(\mu\)

**ATLAS**: di-\(\tau\)au

**arXiv**: 1405.4123, 1412.6302

**arXiv**: 1502.07177

**CMS-PAS-EXO-12-046**

![Graphs](image-url)
Searching for the Unexpected

\[ \nu_e \quad \nu_\mu \quad \nu_\tau \quad u \quad c \quad t \quad d \quad s \quad b \quad g \quad \gamma \quad W \quad Z \quad h \]

ATLAS: di-jet  \hspace{2cm} arXiv:1407.1376

CMS: di-b-tagged-jet  \hspace{2cm} arXiv:1501.04198
Searching for the Unexpected

\[ \nu_e \quad \nu_\mu \quad \nu_\tau \quad u \quad c \quad t \quad g \quad \gamma \quad W \quad Z \quad h \]

ATLAS: di-top

CMS: di-\gamma

arXiv:1505.07018
arXiv:1506.03062

arXiv:1504.05511
CMS-PAS-EXO-12-045
A novel aspect of the boosted technique presented here is the use of track-jets satisfying a set of hit and impact parameter criteria to make sure that those tracks are consistent with the energy and mass scales is applied as a function of trimming algorithm reconstructs subjets within the large-impact of energy depositions due to pile-up and the underlying event, the jets are trimmed are shown as dashed lines.

Two simulated signal to the predicted background (solid histograms). The filled blocks represent the combined statistical and systematic uncertainty in the total background estimate. Two potential signals, 

\[ m_{4j} / 20 \text{ GeV} \]

\[ \text{Data} / \text{Bkgd} \]

\[ \int \text{Data} = 8 \text{ TeV} \]

\[ \text{Ldt} = 19.5 \text{ fb}^{-1} \]

\[ \text{Events} / 20 \text{ GeV} \]

\[ \text{Events} / 100 \text{ GeV} \]

\[ \text{Significance} (\text{stat} + \text{syst}) \]

\[ \text{Significance} (\text{stat}) \]

\[ \text{Significance (stat)} \]

\[ \text{Significance (stat + syst)} \]

\[ \text{WZ Selection} \]

\[ \text{Data} \]

\[ \text{Background model} \]

\[ 1.5 \text{ TeV EGM W', c = 1} \]

\[ 2.0 \text{ TeV EGM W', c = 1} \]

\[ 2.5 \text{ TeV EGM W', c = 1} \]

\[ \text{Significance (stat)} \]

\[ \text{Significance (stat + syst)} \]

\[ \text{WZ Selection} \]

\[ \text{Data} \]

\[ \text{Background model} \]

\[ 1.5 \text{ TeV EGM W', c = 1} \]

\[ 2.0 \text{ TeV EGM W', c = 1} \]

\[ 2.5 \text{ TeV EGM W', c = 1} \]

\[ \text{Significance (stat)} \]

\[ \text{Significance (stat + syst)} \]
A novel aspect of the boosted technique presented here is the use of track-jets satisfying a set of hit and impact parameter criteria to make sure that those tracks are consistent with measurements. The impact of energy depositions due to pile-up and the underlying event, the jets are trimmed. Further calibration of both algorithms with radius parameter to identify the presence of signal events, background events in dijet mass bin. Also, a log-normal distribution for the nuisance parameters, 1.5, 2.0, or 2.5 TeV or to an RS graviton with 1.5, 2.0, or 2.5 TeV Bulk G, µτ, and ττ.

ATLAS: di-higgs (4b)  

ATLAS: di-vector boson (hadronic)

arXiv:1506.00285  
arXiv:1503.04114  
arXiv:1506.00962  
Anomalies in the current dataset
2 TeV Di-boson Resonance

- Bump hunt all-hadronic diboson mass
- Uses jet sub-structure tag W/Z
  - sub-jet Pt balance / Trk. Multi.
- Relatively poor W/Z separation correlated WW, ZZ, WZ signal regions

**WZ Selection**

**local p-values**

- WZ-ch: 3.4 σ
- WW-ch: 2.6 σ
- ZZ-ch: 2.9 σ

*(statistically correlated!)*
2 TeV Di-boson Resonance

- Bump hunt all-hadronic diboson mass
- Uses jet sub-structure tag W/Z
  - sub-jet Pt balance / Trk. Multi.
- Relatively poor W/Z separation
correlated WW, ZZ, WZ signal regions

**ATLAS**

\( \sqrt{s} = 8 \text{ TeV}, 20.3 \text{ fb}^{-1} \)

Events / 100 GeV

Data

Background model

1.5 TeV EGM W', c = 1
2.0 TeV EGM W', c = 1
2.5 TeV EGM W', c = 1
Significance (stat)
Significance (stat + syst)

**WZ Selection**

Local p-values

- WZ-ch: 3.4 \( \sigma \)
- WW-ch: 2.6 \( \sigma \)
- ZZ-ch: 2.9 \( \sigma \)

(statistically correlated!)

**CMS excesses in similar regions**

More on next slides
**2 TeV Di-boson Resonance**

**Consistent with WZ?**

**ATLAS: WZ→JJ**

**CMS: WZ → JJ**

---

**Figure 6:**

<table>
<thead>
<tr>
<th>Resonance mass (TeV)</th>
<th>ATLAS Observed 95% CL</th>
<th>ATLAS Expected 95% CL</th>
<th>ATLAS ± 1σ uncertainty</th>
<th>ATLAS ± 2σ uncertainty</th>
<th>EGM W', c = 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.4</td>
<td>$10^{-1}$</td>
<td>$10^{-2}$</td>
<td>$10^{-3}$</td>
<td>$10^{-4}$</td>
<td></td>
</tr>
<tr>
<td>1.6</td>
<td>$10^{-1}$</td>
<td>$10^{-2}$</td>
<td>$10^{-3}$</td>
<td>$10^{-4}$</td>
<td></td>
</tr>
<tr>
<td>1.8</td>
<td>$10^{-1}$</td>
<td>$10^{-2}$</td>
<td>$10^{-3}$</td>
<td>$10^{-4}$</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>$10^{-1}$</td>
<td>$10^{-2}$</td>
<td>$10^{-3}$</td>
<td>$10^{-4}$</td>
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</tr>
<tr>
<td>2.2</td>
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<td>$10^{-2}$</td>
<td>$10^{-3}$</td>
<td>$10^{-4}$</td>
<td></td>
</tr>
<tr>
<td>2.4</td>
<td>$10^{-1}$</td>
<td>$10^{-2}$</td>
<td>$10^{-3}$</td>
<td>$10^{-4}$</td>
<td></td>
</tr>
<tr>
<td>2.6</td>
<td>$10^{-1}$</td>
<td>$10^{-2}$</td>
<td>$10^{-3}$</td>
<td>$10^{-4}$</td>
<td></td>
</tr>
<tr>
<td>2.8</td>
<td>$10^{-1}$</td>
<td>$10^{-2}$</td>
<td>$10^{-3}$</td>
<td>$10^{-4}$</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>$10^{-1}$</td>
<td>$10^{-2}$</td>
<td>$10^{-3}$</td>
<td>$10^{-4}$</td>
<td></td>
</tr>
</tbody>
</table>

---

**Figure 7:**

<table>
<thead>
<tr>
<th>Resonance mass (TeV)</th>
<th>Expected (95%)</th>
<th>Expected (68%)</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.4</td>
<td>$10^{-1}$</td>
<td>$10^{-2}$</td>
<td>$10^{-3}$</td>
</tr>
<tr>
<td>1.6</td>
<td>$10^{-1}$</td>
<td>$10^{-2}$</td>
<td>$10^{-3}$</td>
</tr>
<tr>
<td>1.8</td>
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<td>$10^{-2}$</td>
<td>$10^{-3}$</td>
</tr>
<tr>
<td>2</td>
<td>$10^{-1}$</td>
<td>$10^{-2}$</td>
<td>$10^{-3}$</td>
</tr>
<tr>
<td>2.2</td>
<td>$10^{-1}$</td>
<td>$10^{-2}$</td>
<td>$10^{-3}$</td>
</tr>
<tr>
<td>2.4</td>
<td>$10^{-1}$</td>
<td>$10^{-2}$</td>
<td>$10^{-3}$</td>
</tr>
<tr>
<td>2.6</td>
<td>$10^{-1}$</td>
<td>$10^{-2}$</td>
<td>$10^{-3}$</td>
</tr>
<tr>
<td>2.8</td>
<td>$10^{-1}$</td>
<td>$10^{-2}$</td>
<td>$10^{-3}$</td>
</tr>
<tr>
<td>3</td>
<td>$10^{-1}$</td>
<td>$10^{-2}$</td>
<td>$10^{-3}$</td>
</tr>
</tbody>
</table>

---

We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWFW and institutions without whom ATLAS could not be operated.
2 TeV Di-boson Resonance

Consistent with WZ?

**ATLAS: WZ → JJ**

**CMS: WZ → JJ**

---

**ATLAS**

\[ \sqrt{s} = 8 \text{ TeV}, 20.3 \text{ fb}^{-1} \]

- Observed 95% CL
- Expected 95% CL
- ± 1σ uncertainty
- ± 2σ uncertainty
- EGM \( W' \), \( c = 1 \)

**CMS**

\[ \text{CMS, } L = 19.7 \text{ fb}^{-1}, \sqrt{s} = 8 \text{ TeV} \]

- Observed
- Expected (68%)
- Expected (95%)

---

**Figure 6:** The red line in each figure displays the predicted cross section for the mass.

**Figure 7:** Expected and observed 95% CL limits on the production cross section as a function of resonance mass for (upper left) qW resonances, (upper right) qZ resonances, and (bottom) \( W^\prime \) resonances, compared to their predicted cross sections for the corresponding benchmark models.

---

**Summary**

The ATLAS and CMS collaborations have used data collected with their respective detectors at the LHC to search for di-boson resonances with masses between 1.3 and 1.5 TeV, and for the 2 TeV Di-boson Resonance. The data are consistent with the Standard Model predictions within the uncertainties.

---

**arXiv:1506.00962**

2 TeV Di-boson Resonance

Consistent with WZ?

ATLAS: WZ→JJ

CMS: WZ → JJ

\[ \text{Observed 95\% CL} \]
\[ \text{Expected 95\% CL} \]

\[ +1\sigma \text{ uncertainty} \]
\[ \pm 2\sigma \text{ uncertainty} \]

\[ \text{EGM W}', c = 1 \]

\[ \sigma(p p \rightarrow W') \times BR(W' \rightarrow WZ) \text{ [fb]} \]

\[ \sqrt{s} = 8 \text{ TeV}, 20.3 \text{ fb}^{-1} \]

arXiv:1506.00962


\[ \text{CMS, L = 19.7 fb}^{-1}, \sqrt{s} = 8 \text{ TeV} \]

\[ \sigma \times B(W' \rightarrow WZ) \text{ [pb]} \]

\[ 1 \text{ TeV}, 1.5 \text{ TeV}, 2 \text{ TeV}, 2.5 \text{ TeV}, 3 \text{ TeV} \]

Resonance mass (TeV)
2 TeV Di-boson Resonance

Consistent with WZ?

**ATLAS: WZ → JJ**

**ATLAS: WZ → ℓνJ**

![Graph showing cross section vs. resonance mass](image)

- Observed 95% CL
- Expected 95% CL
- ± 1σ uncertainty
- ± 2σ uncertainty

*TITL 1506.00962*

**ATLAS**

\[ \int \frac{\sigma(pp \to W') \times BR(W' \to WZ)}{m_{W'}} [pb] \]

- Expected 95% CL
- Observed 95% CL

- EGM W', c = 1

**ARXIV:1503.04677**
2 TeV Di-boson Resonance

Consistent with WZ?

ATLAS: WZ → JJ

ATLAS: WZ → ℓνJ

arXiv:1503.04677
2 TeV Di-boson Resonance

Consistent with WZ?

**ATLAS: WZ → JJ**

**ATLAS: WZ → ℓνJ**

*Play same game under WW or ZZ hypothesis ⇒ similar results*
2 TeV Di-boson Resonance

- Hard to tell a consistent story.

- Rate of ATLAS excess in tension with observed CMS exclusions.

- Leptons channels do not corroborate excess.
SS leptons + bs + H_T + E_T^{Miss.}

**ATLAS**

Same-sign di-leptons  (P_T ≥ 25 GeV)
H_T > 700 GeV

**SR7:**
N_{bjet} ≥ 3
E_T^{Miss.} > 40 GeV

12 obs
4.3 ± 1.6 exp

**SR6:**
N_{bjet} = 2
E_T^{Miss.} > 100 GeV

6 obs
1.1 ± 1 exp

\[ \sqrt{s} = 8 \text{ TeV, 20.3 fb}^{-1} \]
SS leptons + bs + $H_T + E_T^{\text{Miss.}}$

### ATLAS

**Same-sign di-leptons**  \( (P_T \geq 25 \text{ GeV}) \)

- **$H_T > 700$ GeV**

### CMS

**Same-sign di-leptons**  \( (P_T \geq 20 \text{ GeV}) \)

- **$H_T > 400$ GeV**
- **$N_{\text{bjet}} \geq 2$**

#### SR7:

- **$N_{\text{bjet}} \geq 3$**
- **$E_T^{\text{Miss.}} > 40$ GeV**

<table>
<thead>
<tr>
<th>$N_{\text{jet}}$: 2-3</th>
<th>$N_{\text{jet}} \geq 4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>12 obs</td>
<td>6 obs</td>
</tr>
<tr>
<td>4.3 ± 1.6 exp</td>
<td>1.1 ± 1 exp</td>
</tr>
<tr>
<td>$E_T^{\text{Miss.}}$: 50-120 GeV</td>
<td>1 obs.</td>
</tr>
<tr>
<td>1.0 ± 0.5 exp.</td>
<td>2.8 ± 1.2 exp</td>
</tr>
</tbody>
</table>

#### SR6:

- **$N_{\text{bjet}} = 2$**
- **$E_T^{\text{Miss.}} > 100$ GeV**

<table>
<thead>
<tr>
<th>$N_{\text{jet}}$: 2-3</th>
<th>$N_{\text{jet}} \geq 4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 obs</td>
<td>2 obs</td>
</tr>
<tr>
<td>0.8 ± 0.5 exp.</td>
<td>2.2 ± 1.0 exp</td>
</tr>
</tbody>
</table>

**ATLAS**

Same-sign di-leptons \((P_T \geq 25 \text{ GeV})\)

\(H_T > 700 \text{ GeV}\)

**SR7:**

\(N_{\text{bjet}} \geq 3\)

\(E_T^{\text{Miss.}} > 40 \text{ GeV}\)

12 obs

\(4.3 \pm 1.6 \text{ exp.}\)

**SR6:**

\(N_{\text{bjet}} = 2\)

\(E_T^{\text{Miss.}} > 100 \text{ GeV}\)

6 obs

\(1.1 \pm 1 \text{ exp.}\)

**CMS**

Same-sign di-leptons \((P_T \geq 20 \text{ GeV})\)

\(H_T > 400 \text{ GeV}\)

\(N_{\text{bjet}} \geq 2\)

**N\text{jet}: 2-3**

\(E_T^{\text{Miss.}} : 50-120 \text{ GeV}\)

1 obs

\(1.0 \pm 0.5 \text{ exp.}\)

\(7 \text{ obs}\)

\(2.8 \pm 1.2 \text{ exp}\)

**N\text{jet} \geq 4**

\(E_T^{\text{Miss.}} \geq 120 \text{ GeV}\)

1 obs

\(0.8 \pm 0.5 \text{ exp.}\)

2 obs

\(2.2 \pm 1.0 \text{ exp}\)
What have we missed?
What have we missed?

“If there is new physics .... ALL of it”
- C. Delaunay
What have we missed?

“If there is new physics .... ALL of it”
- C. Delaunay

Several ways of hiding New Physics:
- Compressed scenarios
- Long-Lived Particles
- R-parity violation
- Signatures w/soft leptons
- ...
What have we missed?

“If there is new physics .... ALL of it”
- C. Delaunay

Several ways of hiding New Physics:
- Compressed scenarios
- Long-Lived Particles
- R-parity violation
- Signatures w/soft leptons
- ...

Plugging these holes is hard.
Becoming a more important piece of the program.
13 TeV is Here

Run: 266904
Event: 25855182
2015-06-03 13:41:48 CEST

Peak Luminosity per Fill [10^{-23} cm^{-2} s^{-1}]

Total Integrated Luminosity [pb]

Total Delivered: 113 pb^{-1}
Total Recorded: 100 pb^{-1}

ATLAS Online Luminosity

\[ \sqrt{s} = 13 \text{ TeV} \]

LHC Delivered
ATLAS Recorded

ATLAS Online Luminosity

Peak Lumi: \(1.6 \times 10^{33} \text{ cm}^{-2} \text{s}^{-1}\)
Run-2 Physics Program Underway

CMS*Run–2*dijet*mass*spectrum*15"EPS/Vienna"25/07/2015"15"

- **Mass spectrum fit** using a 4 parameter function.
- **For illustrative purposes:**
  - In blue: signal of a $q^*$ resonance at $M = 4.5$ TeV.
  - **Highest dijet mass event:** $M = 5$ TeV.

**CMS Preliminary**

37 pb$^{-1}$ (13 TeV)

$|\eta| < 2.5$, $|\Delta\eta| < 1.3$

$M_{jj} > 1.1$ TeV

Wide Jets

**ATLAS Preliminary**

$\sqrt{s} = 13$ TeV, 78 pb$^{-1}$

Dilepton Search Selection

Data

- $Z/\gamma^*$
- Top Quarks
- Diboson

**Dimuon Invariant Mass [GeV]**

Events

(Data-Fit)/$\sigma$
Run-2 Projections

- Expect more data in run-2 \((100/\text{fb} \, vs \, 20/\text{fb} \, \text{for Run-1})\)
- Larger cross sections from pdf with increased \(\sqrt{s}\)

- Run-2: \(\approx 5 \times (100 \, \text{fb}/20 \, \text{fb}) \approx 25 \times \text{Run-1}\) for pair production at 500 GeV
- \(\approx 15 \times (100 \, \text{fb}/20 \, \text{fb}) \approx 75 \times \text{Run-1}\) for pair production at 1 TeV
Di-jet Resonance

Post/pre-dictions for excited quark exclusion reach

- Extrapolations
- Reference (ATLAS)
- ATLAS
- CMS
- CDF

Reach for $m_{q^*}$ [TeV] vs. integrated lumi [fb$^{-1}$]

- 14 TeV
- 13 TeV
- 8 TeV
- 7 TeV
- 1.96 TeV, pp
Run-2 Projections

Di-jet Resonance

Post/pre-dictions for excited quark exclusion reach

Reach for $m_{q^*}$ [TeV]

Integrated lumi [fb$^{-1}$]

Log scale!
Run-2 Projections

Di-jet Resonance

Post/predictions for excited quark exclusion reach

reach for $m_{q^*}$ [TeV] vs. integrated lumi [fb$^{-1}$]

- Extrapolations
- Reference (ATLAS)
- ATLAS
- CMS
- CDF

1/fb (Run-2) ≈ 200/fb (Run-1)
Run-2 Projections

Gluino

Post/pre-dictions for gluino exclusion reach

- extrapolations
- reference (ATLAS)
- ATLAS
- CMS

reach for $2m_{\tilde{g}}$ [TeV]

integrated lumi [fb$^{-1}$]

Stop

Post/pre-dictions for stop exclusion reach

- extrapolations
- reference (ATLAS)
- ATLAS
- CMS

reach for $2m_{\tilde{t}}$ [TeV]

integrated lumi [fb$^{-1}$]

Salam, Weiler
collider-reach.web.cern.ch
Run-2 Projections

Electroweak SUSY

\[ \sqrt{s} = 14 \text{ TeV} \]

3-lepton channel

\[ \tilde{\chi}_1^{\pm} \tilde{\chi}_2^0 \rightarrow W^{\pm} \tilde{\chi}_1^0 Z \tilde{\chi}_1^0 \]

\[ m_{\tilde{\chi}_1^\pm} = m_{\tilde{\chi}_2^0} \]

\[ m_{\tilde{\chi}_1^0} < m_{\tilde{\chi}_2^0}, \quad m_{\tilde{\chi}_3^0} - m_{\tilde{\chi}_1^0} = m_Z \]

\[ \sigma_{\text{bkg}} = 30\% \]

ATLAS Simulation Preliminary

\( \int L \, dt = 3000 \, \text{fb}^{-1}, \mu = 140, 95\% \) CL exclusion

\( \int L \, dt = 3000 \, \text{fb}^{-1}, \mu = 140, 5\sigma \) discovery

\( \int L \, dt = 300 \, \text{fb}^{-1}, \mu = 60, 95\% \) CL exclusion

\( \int L \, dt = 300 \, \text{fb}^{-1}, \mu = 60, 5\sigma \) discovery

8 TeV, \( \int L \, dt = 20.3 \, \text{fb}^{-1}, 95\% \) CL exclusion

Run-2 discovery

Run-2 exclusion

ATL-PHYS-PUB-2014-010
CMS-PAS-SUS-14-012
Run-2 Take Away

- Run-2 brings significant jump in sensitivity.

- Reach in Run-2:
  - Strong production up to ~2 TeV.
  - Weakly produced sensitivity ~500 GeV.
  - Even higher for more exotic models (eg: q* or black-holes).

- Sensitivity front loaded.
  - Most significant gains with first few 100/fb.
  - Next two years most interesting for new physics searches.
Conclusions

Reasons to expect physics beyond the Standard Model.

Broad search program at the LHC.
- *From* inclusive surveys of basic event topologies,
- *to* dedicated searches ruling out corners of phase space.

Run-2 is here:
- Signal production: \( \sim 75 \times \text{Run-1} \) (or more at higher mass.).

*Now is the time to be looking for new physics at the LHC!*
Back-up
# ATLAS Exotics Searches - 95% CL Exclusion

**Status: July 2015**

<table>
<thead>
<tr>
<th>Model</th>
<th>$\ell$, $\gamma$</th>
<th>Jets</th>
<th>$E^{\text{miss}}_T$</th>
<th>$\mathcal{L} dt$ [fb$^{-1}$]</th>
<th>Limit</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADD $G_{KX} + g/q$</td>
<td>–</td>
<td>$\geq 1J$</td>
<td>Yes</td>
<td>20.3</td>
<td>$M_0$</td>
<td>5.25 TeV</td>
</tr>
<tr>
<td>ADD non-resonant $t\bar{t}$</td>
<td>$2e, \mu$</td>
<td>–</td>
<td></td>
<td></td>
<td></td>
<td>4.7 TeV</td>
</tr>
<tr>
<td>ADD QbH $\rightarrow e\gamma$</td>
<td>$1e, \mu$</td>
<td>1</td>
<td>$J$</td>
<td>20.3</td>
<td></td>
<td>5.2 TeV</td>
</tr>
<tr>
<td>ADD QbH $\rightarrow e\gamma$</td>
<td>$1e, \mu$</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td>5.2 TeV</td>
</tr>
<tr>
<td>ADD BH high $N_{\text{ch}}$</td>
<td>$2\mu$ (SS)</td>
<td>–</td>
<td></td>
<td>20.3</td>
<td>$M_0$</td>
<td>4.7 TeV</td>
</tr>
<tr>
<td>ADD BH high $g^{\text{inv}}$</td>
<td>$\geq 1J$</td>
<td>$\geq 2J$</td>
<td></td>
<td>20.3</td>
<td>$M_0$</td>
<td>5.8 TeV</td>
</tr>
<tr>
<td>RS1 $G_{KX} + \gamma$</td>
<td>$2e, \mu$</td>
<td>–</td>
<td></td>
<td>20.3</td>
<td>$G_{KX}$ mass</td>
<td>2.69 TeV</td>
</tr>
<tr>
<td>RS1 $G_{KX} + \gamma$</td>
<td>$2\gamma$</td>
<td>–</td>
<td></td>
<td></td>
<td></td>
<td>2.69 TeV</td>
</tr>
<tr>
<td>Bulk RS $G_{KX} \rightarrow ZZ \rightarrow q\bar{q}g$</td>
<td>$2e, \mu$</td>
<td>1</td>
<td>$J$</td>
<td>20.3</td>
<td>$W$ mass</td>
<td>760 GeV</td>
</tr>
<tr>
<td>Bulk RS $G_{KX} \rightarrow WW \rightarrow q\bar{q}g$</td>
<td>$1e, \mu$</td>
<td>1</td>
<td>$J$</td>
<td>20.3</td>
<td></td>
<td>760 GeV</td>
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<tr>
<td>Bulk RS $G_{KX} \rightarrow HH \rightarrow bb\bar{b}b$</td>
<td>$1e, \mu$</td>
<td>2</td>
<td></td>
<td>19.5</td>
<td></td>
<td>500-720 GeV</td>
</tr>
<tr>
<td>Bulk RS $G_{KX} \rightarrow t\bar{t}$</td>
<td>$1e, \mu$</td>
<td>$\geq 1b$, $\geq 1J/2$</td>
<td>Yes</td>
<td>20.3</td>
<td>$G_{KX}$ mass</td>
<td>$2.2$ TeV</td>
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<tr>
<td>Extra dimensions</td>
<td>$2e, \mu$ (SS)</td>
<td>$\geq 1b$, $\geq 1J$</td>
<td>Yes</td>
<td>20.3</td>
<td></td>
<td>960 GeV</td>
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<tr>
<td>SSM $Z' \rightarrow \ell\ell$</td>
<td>$2e, \mu$</td>
<td>–</td>
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<td>20.3</td>
<td>$Z'$ mass</td>
<td>2.9 TeV</td>
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<tr>
<td>SSM $Z' \rightarrow \tau\tau$</td>
<td>$2\tau$</td>
<td>–</td>
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<td>2.02 TeV</td>
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<td>SSM $W' \rightarrow \ell\nu$</td>
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<td>19.5</td>
<td>$W'$ mass</td>
<td>3.24 TeV</td>
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<td>EGM $W'$</td>
<td>$3e, \mu$</td>
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<td>$\geq 2J$</td>
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<td>1.52 TeV</td>
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<td>$J$</td>
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<td>$W'$ mass</td>
<td>1.58 TeV</td>
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<tr>
<td>EGM $W'$</td>
<td>$2e, \mu$</td>
<td>2</td>
<td>$J$</td>
<td>20.3</td>
<td>$W'$ mass</td>
<td>1.58 TeV</td>
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<tr>
<td>HVT $W' \rightarrow WH \rightarrow t\bar{b}b$</td>
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<td>2</td>
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<td>$W$ mass</td>
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<td>LRSM $W' \rightarrow t\bar{b}$</td>
<td>$1e, \mu$</td>
<td>2</td>
<td>$b$, $01J$</td>
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<td>$W'$ mass</td>
<td>1.82 TeV</td>
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<tr>
<td>LRSM $W' \rightarrow t\bar{b}$</td>
<td>0</td>
<td>$e, \mu$</td>
<td>$\geq 1b$, $\geq 1J$</td>
<td>Yes</td>
<td></td>
<td>1.76 TeV</td>
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<tr>
<td>Cl $qq\gamma$</td>
<td>–</td>
<td>$2J$</td>
<td></td>
<td>20.3</td>
<td>$A$</td>
<td>12.0 TeV</td>
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<tr>
<td>Cl $qq\ell\nu$</td>
<td>$2e, \mu$</td>
<td>–</td>
<td></td>
<td>20.3</td>
<td>$A$</td>
<td>21.6 TeV</td>
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<td>Cl $uutt$</td>
<td>$2e, \mu$ (SS)</td>
<td>$\geq 1b$, $\geq 1J$</td>
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<td>20.3</td>
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<td>4.3 TeV</td>
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<td>DM EFT D5 operator (Dirac)</td>
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<td>$e, \mu$ (SS)</td>
<td>$\geq 1b$, $\geq 1J$</td>
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<td></td>
<td>574 GeV</td>
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<tr>
<td>DM EFT D9 operator (Dirac)</td>
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<td>$e, \mu$ (SS)</td>
<td>$\geq 1b$, $\geq 1J$</td>
<td>Yes</td>
<td></td>
<td>574 GeV</td>
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<tr>
<td>LQ Scalar LQ $1^{\text{st}}$ gen</td>
<td>$2e$</td>
<td>$\geq 2J$</td>
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<td>20.3</td>
<td>$LQ$ mass</td>
<td>1.06 TeV</td>
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<tr>
<td>LQ Scalar LQ $2^{\text{nd}}$ gen</td>
<td>$2\mu$</td>
<td>$\geq 2J$</td>
<td>Yes</td>
<td>20.3</td>
<td>$LQ$ mass</td>
<td>1.0 TeV</td>
</tr>
<tr>
<td>LQ Scalar LQ $3^{\text{rd}}$ gen</td>
<td>$1e, \mu$</td>
<td>$\geq 1b$, $\geq 1J$</td>
<td>Yes</td>
<td>20.3</td>
<td>$LQ$ mass</td>
<td>1.0 TeV</td>
</tr>
<tr>
<td>Heavy quarks VLO $T^+ \rightarrow H^+ + X$</td>
<td>$1e, \mu$</td>
<td>$\geq 2b$, $\geq 3J$</td>
<td>Yes</td>
<td>20.3</td>
<td>$T$ mass</td>
<td>855 GeV</td>
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<tr>
<td>VLO $Y^+ \rightarrow W^+ b + X$</td>
<td>$1e, \mu$</td>
<td>$\geq 1b$, $\geq 1J$</td>
<td>Yes</td>
<td>20.3</td>
<td>$Y$ mass</td>
<td>770 GeV</td>
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<td>VLO $B^+ \rightarrow H^+ b + X$</td>
<td>$1e, \mu$</td>
<td>$\geq 2b$, $\geq 3J$</td>
<td>Yes</td>
<td>20.3</td>
<td>$B$ mass</td>
<td>735 GeV</td>
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<td>VLO $BB^+ \rightarrow Z^+ b + X$</td>
<td>$2e, 3\mu$</td>
<td>$\geq 2b$, $\geq 1J$</td>
<td>Yes</td>
<td>20.3</td>
<td>$B$ mass</td>
<td>755 GeV</td>
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<tr>
<td>VLO $T^+ \rightarrow W^+ b$</td>
<td>$1e, \mu$</td>
<td>$\geq 1b$, $\geq 3J$</td>
<td>Yes</td>
<td>20.3</td>
<td>$W^+$ mass</td>
<td>840 GeV</td>
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<tr>
<td>Excited fermions Excited quark $q^* \rightarrow q\gamma$</td>
<td>$1\gamma$</td>
<td>$1J$</td>
<td></td>
<td>20.3</td>
<td>$q^*$ mass</td>
<td>3.9 TeV</td>
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<tr>
<td>Excited quark $b^* \rightarrow W^+ t$</td>
<td>$1e, \mu$</td>
<td>$2b$, $1J$</td>
<td>Yes</td>
<td>4.7</td>
<td>$b^*$ mass</td>
<td>4.09 TeV</td>
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<tr>
<td>Excited lepton $e^* \rightarrow \ell W^+ + X$</td>
<td>$2e, \mu$</td>
<td>$1J$</td>
<td></td>
<td>20.3</td>
<td>$e^*$ mass</td>
<td>870 GeV</td>
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<tr>
<td>Excited lepton $\nu^* \rightarrow \nu W^+ + X$</td>
<td>$3e, \mu$, $\tau$</td>
<td>–</td>
<td></td>
<td>13.0</td>
<td></td>
<td>2.2 TeV</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.6 TeV</td>
</tr>
<tr>
<td>Other LSCT $\chi \rightarrow WY$</td>
<td>$1e, \mu$, $1\gamma$</td>
<td>–</td>
<td></td>
<td>20.3</td>
<td>$\chi$ mass</td>
<td>960 GeV</td>
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<td>LRS Majorana $\nu$</td>
<td>$2e, \mu$ (SS)</td>
<td>–</td>
<td></td>
<td>20.3</td>
<td>$N_1$ mass</td>
<td>2.0 TeV</td>
</tr>
<tr>
<td>Higgs triplet $H^{++} \rightarrow \ell\ell$</td>
<td>$2e, \mu$ (SS)</td>
<td>–</td>
<td></td>
<td>20.3</td>
<td>$H^{++}$ mass</td>
<td>551 GeV</td>
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<td>Higgs triplet $H^{++} \rightarrow \ell\ell$</td>
<td>$3e, \mu$ (SS)</td>
<td>–</td>
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<td>20.3</td>
<td>$H^{++}$ mass</td>
<td>400 GeV</td>
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<tr>
<td>Monopole (non-res prod)</td>
<td>$1e, \mu$</td>
<td>1</td>
<td>$b$</td>
<td>Yes</td>
<td></td>
<td></td>
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<tr>
<td>Multi-charged particles</td>
<td>–</td>
<td>–</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Magnetic monopole</td>
<td>–</td>
<td>–</td>
<td></td>
<td></td>
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</tbody>
</table>

*Only a selection of the available mass limits on new states or phenomena is shown.*
**ATLAS SUSY Searches** - 95% CL Lower Limits

**Status:** July 2015

<table>
<thead>
<tr>
<th>Model</th>
<th>$\ell$, $\tau$, $\gamma$, $\mu$, or $\tau$</th>
<th>Jets</th>
<th>$E_T^{	ext{miss}}$</th>
<th>$\int L , dt [ \text{nb}^{-1}]$</th>
<th>Mass limit</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Inclusive Searches</strong></td>
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<tr>
<td>MSUGRA/CMSSM</td>
<td>0-3 $\ell$, $\mu$, or $\tau$, 2-10 jets/3 b</td>
<td>Yes</td>
<td>20.3</td>
<td>1.8 TeV</td>
<td></td>
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<tr>
<td>$\tilde{g}$, $\tilde{ \chi}_1^0$, or $\tilde{ \chi}_2^0$ (compressed)</td>
<td>0-2 jets</td>
<td>Yes</td>
<td>20.3</td>
<td>850 GeV</td>
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<tr>
<td>2 $\ell$, (off-Z)</td>
<td>0-1 jet</td>
<td>Yes</td>
<td>20.3</td>
<td>780 GeV</td>
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<tr>
<td>$\tilde{q}$, $\tilde{q}$, $\tilde{g}$, or $\tilde{W}^\pm$</td>
<td>0-1 jet</td>
<td>Yes</td>
<td>20.3</td>
<td>1.33 TeV</td>
<td></td>
</tr>
<tr>
<td>2 $\ell$, (off-Z)</td>
<td>0-2 jets</td>
<td>Yes</td>
<td>20.3</td>
<td>1.32 TeV</td>
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</tr>
<tr>
<td>$\tilde{\chi}_1^0$</td>
<td>1-2 $\ell$, 0-1 t</td>
<td>Yes</td>
<td>20.3</td>
<td>1.26 TeV</td>
<td></td>
</tr>
<tr>
<td><strong>Gravitino LSP</strong></td>
<td>0-1 jet</td>
<td>Yes</td>
<td>20.3</td>
<td>1.34 TeV</td>
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</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Model</th>
<th>$\ell$, $\tau$, $\gamma$, $\mu$, or $\tau$</th>
<th>Jets</th>
<th>$E_T^{	ext{miss}}$</th>
<th>$\int L , dt [ \text{nb}^{-1}]$</th>
<th>Mass limit</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>3rd gen squarks and med.</strong></td>
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</tr>
<tr>
<td>$\tilde{t}_3$, $\tilde{t}_1$, or $\tilde{b}_3$</td>
<td>0-2 b</td>
<td>Yes</td>
<td>20.3</td>
<td>1.25 TeV</td>
<td></td>
</tr>
<tr>
<td>2 $\ell$, (SS)</td>
<td>0-2 b</td>
<td>Yes</td>
<td>20.3</td>
<td>1.1 TeV</td>
<td></td>
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<tr>
<td>1-2 $\ell$, 2 b</td>
<td>Yes</td>
<td>4.7</td>
<td>1.1 TeV</td>
<td></td>
<td></td>
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<tr>
<td>0-2 $\ell$, 2-2 b</td>
<td>Yes</td>
<td>4.7</td>
<td>1.2 TeV</td>
<td></td>
<td></td>
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<tr>
<td>2 $\ell$, (off-Z)</td>
<td>0-2 jets/1-2 b</td>
<td>Yes</td>
<td>20.3</td>
<td>1.34 TeV</td>
<td></td>
</tr>
<tr>
<td>$\tilde{\chi}_1^0$ (natural GMSB)</td>
<td>2 $\ell$, Z</td>
<td>Yes</td>
<td>20.3</td>
<td>1.3 TeV</td>
<td></td>
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<tr>
<td>$\tilde{\chi}_1^0$ (compressed)</td>
<td>2-2 jets</td>
<td>Yes</td>
<td>20.3</td>
<td>1.3 TeV</td>
<td></td>
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</table>

<table>
<thead>
<tr>
<th>Model</th>
<th>$\ell$, $\tau$, $\gamma$, $\mu$, or $\tau$</th>
<th>Jets</th>
<th>$E_T^{	ext{miss}}$</th>
<th>$\int L , dt [ \text{nb}^{-1}]$</th>
<th>Mass limit</th>
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<tbody>
<tr>
<td><strong>E W direct</strong></td>
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<td></td>
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</tr>
<tr>
<td>$\tilde{t}_1$, $\tilde{t}_2$, $\tilde{t}_3$, $\tilde{b}_1$</td>
<td>0-2 b</td>
<td>Yes</td>
<td>20.3</td>
<td>1.34 TeV</td>
<td></td>
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<tr>
<td>$\tilde{t}_1$, $\tilde{t}_2$, $\tilde{t}_3$, $\tilde{b}_1$</td>
<td>0-2 b</td>
<td>Yes</td>
<td>20.3</td>
<td>1.26 TeV</td>
<td></td>
</tr>
<tr>
<td>2 $\ell$, (off-Z)</td>
<td>0-2 jets</td>
<td>Yes</td>
<td>20.3</td>
<td>1.34 TeV</td>
<td></td>
</tr>
<tr>
<td>$\tilde{\chi}_1^0$</td>
<td>2 $\ell$, Z</td>
<td>Yes</td>
<td>20.3</td>
<td>1.34 TeV</td>
<td></td>
</tr>
<tr>
<td>$\tilde{\chi}_1^0$</td>
<td>2 $\ell$, Z</td>
<td>Yes</td>
<td>20.3</td>
<td>1.34 TeV</td>
<td></td>
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</table>

<table>
<thead>
<tr>
<th>Model</th>
<th>$\ell$, $\tau$, $\gamma$, $\mu$, or $\tau$</th>
<th>Jets</th>
<th>$E_T^{	ext{miss}}$</th>
<th>$\int L , dt [ \text{nb}^{-1}]$</th>
<th>Mass limit</th>
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<tbody>
<tr>
<td><strong>Direct</strong></td>
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<td></td>
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<tr>
<td>$\tilde{t}_1$, $\tilde{t}_2$, $\tilde{t}_3$, $\tilde{b}_1$, $\tilde{b}_2$</td>
<td>0-2 b</td>
<td>Yes</td>
<td>20.3</td>
<td>1.34 TeV</td>
<td></td>
</tr>
<tr>
<td>$\tilde{t}_1$, $\tilde{t}_2$, $\tilde{t}_3$, $\tilde{b}_1$, $\tilde{b}_2$</td>
<td>0-2 b</td>
<td>Yes</td>
<td>20.3</td>
<td>1.26 TeV</td>
<td></td>
</tr>
<tr>
<td>2 $\ell$, (off-Z)</td>
<td>0-2 jets</td>
<td>Yes</td>
<td>20.3</td>
<td>1.34 TeV</td>
<td></td>
</tr>
<tr>
<td>$\tilde{\chi}_1^0$</td>
<td>2 $\ell$, Z</td>
<td>Yes</td>
<td>20.3</td>
<td>1.34 TeV</td>
<td></td>
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<tr>
<td>$\tilde{\chi}_1^0$</td>
<td>2 $\ell$, Z</td>
<td>Yes</td>
<td>20.3</td>
<td>1.34 TeV</td>
<td></td>
</tr>
</tbody>
</table>

$^*$Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1\sigma theoretical signal cross section uncertainty.
Filling Stop Gaps

ATLAS

\( \sqrt{s} = 7 \text{ TeV}, 4.6 \text{ fb}^{-1} \)

\( \sqrt{s} = 8 \text{ TeV}, 20 \text{ fb}^{-1} \)

\( \tilde{t}_1 \rightarrow t^{(*)} \chi_1^0, m(\chi_1^0) = 1 \text{ GeV} \)

95% CL limit on signal strength \( \mu \)

ATLAS

Expected limit \( \pm 1 \sigma_{\text{exp}} \)

Observed limit \( \pm 1 \sigma_{\text{SUSY theory}} \)

Obs. -1\( \sigma \), \( m = 175.0 \text{ GeV} \)

Obs. -1\( \sigma \), \( m = 173.5 \text{ GeV} \)
Stop Search

\( \tilde{t}_1 \tilde{t}_1 \) production, \( \tilde{t}_1 \rightarrow t \tilde{\chi}_1^0 \) / b \( \tilde{\chi}_1^\pm \), \( \tilde{\chi}_1^\pm \rightarrow W^{(*)} \tilde{\chi}_1^0 \), \( m_{\tilde{\chi}_1} = 2 m_{\tilde{\chi}_1^0} \)

**ATLAS** Preliminary

\[ \int L \, dt = 20 \, \text{fb}^{-1}, \sqrt{s} = 8 \, \text{TeV} \]

0/1L + jets + \( E_T^{\text{miss}} \)

- Expected limits
- Observed limits

All limits at 95% CL

\[ x = \text{BR}(\tilde{t}_1 \rightarrow t \tilde{\chi}_1^0) \]

- \( x = 0\% \)
- \( x = 25\% \)
- \( x = 50\% \)
- \( x = 75\% \)
- \( x = 100\% \)

**Expected limits**

- \( m_{\tilde{\chi}_1} < m_{\tilde{t}_1} \)
- \( m_{\tilde{\chi}_1} < m_{t} + m_{\tilde{\chi}_1} \) (\( m_{\tilde{\chi}_1} = 2 m_{\tilde{\chi}_1^0} \))
Vector-like Quarks

Predicted in models many model motivated by naturalness

Strong pair production of heavy top bottom partners

Flavor changing decays.

Rich phenomenology at the LHC
“Excluding Triangles, not points”
“Excluding Triangles, not points”

\[ \text{higgs + top + X} \]
\[ \text{Select top+bb} \]
\[ \text{Search in } H_T \]
“Excluding Triangles, not points”

**higgs + top + X**
Select top+bb
Search in $H_T$

**Same-sign Leptons (eμ)**
Select Bjets / Large $H_T$
“Excluding Triangles, not points”

**higgs + top + X**
Select top+bb
Search in \( H_T \)

**Z(\rightarrow \ell\ell) + X**
Select top+Z\( \rightarrow \ell \ell \) (e/\mu)
Search in \( m_{Zb} \)

**Same-sign Leptons (e\mu)**
Select Bjets / Large \( H_T \)
“Excluding Triangles, not points”

**higgs + top + X**
Select top+bb
Search in $H_T$

**Same-sign Leptons (eμ)**
Select Bjets / Large $H_T$

**$Z(\rightarrow \ell\ell)t + X$**
Select top+$Z\rightarrow \ell\ell$ (e/μ)
Search in $m_{Zb}$

**$Wb + X$**
Select $W+b$
Search in $m_{wb}$
“Excluding Triangles, not points”
Figure 12: 90% CL upper limits on the spin-independent DM-nucleon or pair annihilation cross-sections assuming a scalar (left) or pseudoscalar (right) mediator with a mass of 125 GeV. The limits are given separately for each of the three categories, the two V-tagged categories combined (Mono V) and the full combination. Limits are also shown assuming the mediator couples to fermions only.
Anomalies in the current dataset

CDF reported an excess in the 120-160 GeV mass range in $W+2$ jets based on $4.3 \text{ fb}^{-1}$.

The analysis has been recently extended to $7.3 \text{ fb}^{-1}$ (http://www-cdf.fnal.gov/physics/ewk/2011/wjj/7_3.html).

Using the same analysis methods, the excess increases from $3.2\sigma$ to $4.1\sigma$.

Exactly 2 jets with $p_T > 30$

Exactly one isolated lepton with $p_T > 20$

Lepton veto, $Z$ veto

$M_T(W) > 30$

$|\Delta\eta(jj)| < 2.5$

Cross section of the excess: $3.0 \pm 0.7 \text{ pb}$

https://indico.cern.ch/event/129980/
WW All Hadronic ATLAS

tagging requirements

Figure 1:

- **ATLAS Simulation**
  - $\sqrt{s} = 8$ TeV
  - EGM $W' \rightarrow WZ (m_{W'} = 1.8$ TeV)
  - Pythia QCD dijet

- **Jet** $\langle \eta \rangle$
  - $|\Delta y| < 1.2$
  - $|\eta_j| < 2$
  - $1.62 \leq m_j < 1.98$ TeV
  - $60 \leq m_j < 110$ GeV

- **Jet ungroomed** $n_{trk}$
  - $|\Delta y| < 1.2$
  - $|\eta_j| < 2$
  - $1.62 \leq m_j < 1.98$ TeV
  - $\langle \eta \rangle > 0.45$

**grooming cut**
2 TeV Di-boson Resonance

Consistent with WW?

ATLAS: WW → JJ

CMS: WW → JJ

arXiv:1506.00962

2 TeV Di-boson Resonance

Consistent with WW?

**ATLAS: WW → JJ**

Observed 95% CL

Expected 95% CL

± 1σ uncertainty

± 2σ uncertainty

Bulk $G_{RS}$ $k/\sqrt{s} = 1$

**CMS: WW → JJ**

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

Observed

Expected (68%)

Expected (95%)

$G_{bulk} \rightarrow WW$ ($k/\sqrt{s} = 0.5$)
2 TeV Di-boson Resonance

Consistent with WW?

ATLAS: WW → JJ

CMS: WW → ℓνJJ

arXiv:1506.00962

arXiv:1405.3447
2 TeV Di-boson Resonance

Consistent with WW?

ATLAS: WW→JJ

CMS: WW→ℓνJ

\( \sqrt{s} = 8 \text{ TeV}, 20.3 \text{ fb}^{-1} \)

\[ \sigma(pp \rightarrow G_{RS} \rightarrow WW) \times BR(G_{RS} \rightarrow WW) \] [fb]

\[ \sigma(pp \rightarrow G_{RS} \rightarrow WW) \times BR(G_{RS} \rightarrow WW) \] [pb]

arXiv:1506.00962

arXiv:1405.3447
2 TeV Di-boson Resonance

Consistent with ZZ?

ATLAS: ZZ → JJ

CMS: ZZ → JJ

arXiv:1506.00962

2 TeV Di-boson Resonance

Consistent with ZZ?

ATLAS: ZZ → JJ

CMS: ZZ → JJ


arXiv:1506.00962
2 TeV Di-boson Resonance

Consistent with ZZ?

ATLAS: ZZ → JJ

CMS: ZZ → ℓℓJJ

\[ \frac{\sigma(pp \rightarrow G_{RS}) \times BR(G_{RS} \rightarrow ZZ)}{fb} \]

- Observed 95% CL
- Expected 95% CL

\[ \sqrt{s} = 8 \text{ TeV}, 20.3 \text{ fb}^{-1} \]

\[ \pm 1\sigma \text{ uncertainty} \]

\[ \pm 2\sigma \text{ uncertainty} \]

Bulk G_{RS} k/\sqrt{M_{Pl}} = 1
2 TeV Di-boson Resonance

Consistent with ZZ?

ATLAS: ZZ→JJ

CMS: ZZ → ℓℓJJ

\[ \sigma(pp \rightarrow G_{RS} \rightarrow ZZ) \times \text{BR}(G_{RS} \rightarrow ZZ) \text{ [fb]} \]

\[ \sqrt{s} = 8 \text{ TeV}, 20.3 \text{ fb}^{-1} \]

- Observed 95% CL
- Expected 95% CL

\[ \pm 1\sigma \text{ uncertainty} \]
\[ \pm 2\sigma \text{ uncertainty} \]

Bulk G_{RS} k/\sqrt{\text{Pl}} = 1

\[ \text{ATLAS} \]

arXiv:1506.00962

\[ \text{CMS} \]

arXiv:1405.3447

\[ \text{at } \sqrt{s} = 8 \text{ TeV} \]

\[ \text{Expected 95\% CL} \]

\[ \text{Observed 95\% CL} \]
**2 TeV Di-boson Resonance**

**Consistent with ZZ ?**

**ATLAS: ZZ→JJ**

---

**ATLAS: ZZ → ℓℓJ**

---

**ATLAS**

\( \sqrt{s} = 8 \text{ TeV}, 20.3 \text{ fb}^{-1} \)

\[
\int L \, dt = 20.3 \text{ fb}^{-1}
\]

\[
\sigma(pp \to G) \times \text{BR}(G \to ZZ) [\text{pb}]
\]

---

**Expected 95% CL**

- Bulk RS graviton \( k/\overline{M}_{Pl} = 1 \)
- Bulk RS graviton \( k/\overline{M}_{Pl} = 0.5 \)
- Expected 95% CL
- Observed 95% CL

**± 1σ uncertainty**

**± 2σ uncertainty**

---

**Graphical representation**

- Observed 95% CL
- Expected 95% CL
- ± 1σ uncertainty
- ± 2σ uncertainty

---

**Graphical representation**

- Observed 95% CL
- Expected 95% CL
- ± 1σ uncertainty
- ± 2σ uncertainty
2 TeV Di-boson Resonance

Consistent with ZZ?

ATLAS: ZZ → JJ

ATLAS: ZZ → ℓℓJ
2 TeV Di-boson Resonance

Consistent with WW?

**ATLAS: WW → JJ**

![Graph showing cross section and branching ratio as a function of resonance mass.](Image)

**ATLAS: WW → ℓνJ**

![Graph showing cross section and branching ratio as a function of resonance mass.](Image)
**SS leptons + bs + HT + MeT**

**ATLAS Search**

**Common Selection**

- Same-sign di-leptons \( (P_T \geq 25 \text{ GeV}) \)
- \( HT > 700 \text{ GeV} \)
- \( NJet \geq 2 \)

<table>
<thead>
<tr>
<th>Model</th>
<th>SRVLQ6/SR4t3</th>
<th>SRVLQ7/SR4t4</th>
</tr>
</thead>
<tbody>
<tr>
<td>( ttW/Z )</td>
<td>( 2.46 \pm 0.11 \pm 1.06 )</td>
<td>( 0.57 \pm 0.05 \pm 0.25 )</td>
</tr>
<tr>
<td>( ttH )</td>
<td>( 0.44 \pm 0.04 \pm 0.06 )</td>
<td>( 0.08 \pm 0.02 \pm 0.02 )</td>
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<tr>
<td>Dibosons</td>
<td>( 0.04 \pm 0.12 \pm 0.03 )</td>
<td>( 0.00 \pm 0.12 \pm 0.00 )</td>
</tr>
<tr>
<td>Fake/Non-prompt</td>
<td>( 0.00 \pm 1.02 \pm 0.28 )</td>
<td>( 0.04 \pm 0.83 \pm 0.24 )</td>
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<tr>
<td>Q mis-Id</td>
<td>( 1.09 \pm 0.14 \pm 0.34 )</td>
<td>( 0.30 \pm 0.09 \pm 0.10 )</td>
</tr>
<tr>
<td>Other bkg.</td>
<td>( 0.23 \pm 0.08 \pm 0.05 )</td>
<td>( 0.14 \pm 0.08 \pm 0.08 )</td>
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<tr>
<td>Total bkg.</td>
<td>( 4.3 \pm 1.1 \pm 1.1 )</td>
<td>( 1.1 \pm 0.9 \pm 0.4 )</td>
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<tr>
<td>Data</td>
<td>( 12 )</td>
<td>( 6 )</td>
</tr>
<tr>
<td>( p )-value</td>
<td>( 0.029 )</td>
<td>( 0.036 )</td>
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</table>
SS leptons + bs + HT + MeT

<table>
<thead>
<tr>
<th>Type</th>
<th>N_j</th>
<th>H_T [GeV]</th>
<th>E_T^{miss} [GeV]</th>
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</thead>
<tbody>
<tr>
<td>e^-e^-</td>
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<td>807</td>
<td>171</td>
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<tr>
<td>e^+e^+</td>
<td>5</td>
<td>862</td>
<td>268</td>
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<tr>
<td>e^+e^+</td>
<td>5</td>
<td>868</td>
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<tr>
<td>μ^-e^-</td>
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<tr>
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<td>810</td>
<td>106</td>
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<tr>
<td>e^-μ^-</td>
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<tr>
<td>μ^+μ^+</td>
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<td>888</td>
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</table>

<table>
<thead>
<tr>
<th>Type</th>
<th>N_j</th>
<th>N_b</th>
<th>H_T [GeV]</th>
<th>E_T^{miss} [GeV]</th>
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<td>239</td>
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<td>μ^-μ^+μ^-</td>
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<td>4</td>
<td>1072</td>
<td>176</td>
</tr>
</tbody>
</table>
More Excesses

\[ Z + \geq 2 \text{ jets} / \text{MeT} \geq 225 / HT \geq 600 \]

ATLAS
\[ \sqrt{s} = 8 \text{ TeV}, 20.3 \text{ fb}^{-1} \]

SR-Z \( ee \)

ATLAS
\[ \sqrt{s} = 8 \text{ TeV}, 20.3 \text{ fb}^{-1} \]

SR-Z \( \mu \mu \)

Not seen in CMS.
But analysis different selection estimate.

arXiv:1503.03290

arXiv:1502.06031
Post/pre-dictions for excited quark exclusion reach

Post/pre-dictions for sequential Z' exclusion reach

Salam, Weiler

collider-reach.web.cern.ch