Searches for New Physics at the Energy Frontier

John Alison

University of Chicago
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

- Naturalness/Hierarchy Problem
  (Why is the higgs light?)

- Dark Matter
  (TeV scale WIMP can explain observed abundance)
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
  - Using state-of-the-art tools.
    - Detectors / Trigger(!)
    - Computing / Analysis Techniques / Monte Carlo Predictions
- We are at the frontier.
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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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Example: SUSY

arXiv:1206.2892
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### Standard Model Production Cross Section Measurements

**LHC pp \(\sqrt{s} = 7\) TeV**

- ATLAS Preliminary
- Run 1 \(\sqrt{s} = 7, 8\) TeV

**LHC pp \(\sqrt{s} = 8\) TeV**

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**Standard Model Production Cross Section Measurements**

- Status: March 2015
- ATLAS Preliminary
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Standard Model Production Cross Section Measurements

**ATLAS** Preliminary
Run 1 \( \sqrt{s} = 7, 8 \text{ TeV} \)

Expected range of sensitivity to New Physics.
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**LHC pp**

$$\sqrt{s} = 7 \text{ TeV}$$

Theory

Observed

4.5 - 4.9 fb

**LHC pp**

$$\sqrt{s} = 8 \text{ TeV}$$

Theory

Observed

20.3 fb

Expected range of sensitivity to New Physics

500 GeV stop / 1 TeV gluino

1 event every 10 minutes
**Challenge in Finding New Physics at the LHC**

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**Total rate billion events/s**

- **Expected range of sensitivity to New Physics**
  - 500 GeV stop / 1 TeV gluino
  - 1 event every 10 minutes

**Status: March 2015**

**ATLAS Preliminary**

Run 1 $\sqrt{s} = 7, 8$ TeV

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

$\sqrt{s} = 8$ TeV
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\[ \sqrt{s} = 7, 8 \text{ TeV} \]

**Expected range of sensitivity to New Physics**

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

**Standard Model Production Cross Section Measurements**

**Total rate billion events/s**

- 100-GeV jets: 10 kHz

**Theory**

**Observed**

\[ \mathcal{L} = 10^{34} \, \text{cm}^{-2} \text{s}^{-1} \]

\[ \sqrt{s} = 8 \text{ TeV} \]
Challenge in Finding New Physics at the LHC

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**Standard Model Production Cross Section Measurements**

- Total rate billion events/s
- 100-GeV jets: 10 kHz
- W bosons: 1 kHz

**Expected range of sensitivity to New Physics**

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

**ATLAS Preliminary**

- Run 1 \( \sqrt{s} = 7 \), 8 TeV
- \( L = 10^{34} \text{ cm}^{-2} \text{ s}^{-1} \)
- \( \sqrt{s} = 8 \text{ TeV} \)

**Observed**

- 4.5 – 4.9 fb
- 20.3 fb

**Theory**

- \( 35 \text{ pb}^{-1} \)

**Observed**

- \( \sigma = 10^{-3} \text{ pb} \)
- \( \sigma = 10^{-2} \text{ pb} \)
- \( \sigma = 10^{-1} \text{ pb} \)
- \( \sigma = 10^{0} \text{ pb} \)
- \( \sigma = 10^{1} \text{ pb} \)

**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
Lessons from Run-1
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- 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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Lessons from Run-1

- There is a higgs sector.
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  - Could have been clear signs of new physics here.
  - 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.”
Stop Search

Naturalness suggests “light” top partners: below $\sim$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

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

\[ m_{\tau_1} \] [GeV]

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

\[ \Delta m < 0 \]

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

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

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

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

- \( \tilde{t}_{1} \rightarrow t \tilde{\chi}_{1}^{0} \)
- \( t0L/t1L \) combined
- t2L, SC

\( \Delta m < 0 \)

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

Observed limits

Expected limits

All limits at 95% CL

ttbar + MeT search

Diagrams of

\[ \chi \sim \chi_0, \chi_1 \]

chargino almost degenerate with the neutralino, a chargino almost degenerate with the squark, or a chargino almost degenerate with the neutralino, a chargino almost degenerate with the squark, or a char-
Stop Search

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

\[ \Delta m < 0 \]

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

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

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

Expected limits

**bbWW+ MeT search**
Stop Search

ATLAS

Mono-Jet (more later)

Observed limits

Not observed

m < 0

[Graph and Table]
Stop Search

\[ \Delta m < 0 \]

ATLAS

- \( \tilde{t}_1 \rightarrow t \tilde{\chi}_1^0 \)
- \( \tilde{\chi}_1^0 \rightarrow W b \tilde{\chi}_1^0 \)
- \( \tilde{t}_1 \rightarrow \tilde{\tau}_1 \tilde{\chi}_1^0 \)
- \( \tilde{t}_1 \rightarrow \tilde{c} \tilde{c} \)
- \( \tilde{t}_1 \rightarrow b f f \tilde{\chi}_1^0 \)

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

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

**ttbar Spin Analysis:**
- ttbar di-lepton channel
- \((\text{think } H \rightarrow WW)\)

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

\[ m_{t_1} \text{ [GeV]} \]
Stop Search: ATLAS

\[ \tilde{t}_1 \rightarrow b f^* \tilde{\chi}^0_1 / \tilde{t}_1 \rightarrow c \tilde{\chi}^0_1 / \tilde{t}_1 \rightarrow W b \tilde{\chi}^0_1 / \tilde{t}_1 \rightarrow t \tilde{\chi}^0_1 \]

**ATLAS**

- \( \tilde{t}_1 \rightarrow b f^* \tilde{\chi}^0_1 \)
- \( \tilde{t}_1 \rightarrow t \tilde{\chi}^0_1 \)
- \( \tilde{t}_1 \rightarrow W b \tilde{\chi}^0_1 / b f^* \tilde{\chi}^0_1 \)
- \( \tilde{t}_1 \rightarrow W b \tilde{\chi}^0_1 / t \tilde{\chi}^0_1 \)
- \( \tilde{t}_1 \rightarrow c \tilde{\chi}^0_1 \)
- \( \tilde{t}_1 \rightarrow t c \)
- \( t_1L, t_2L \)

- Observed limits
- Expected limits
- All limits at 95% CL

\( m_{\tilde{\chi}^0_1} \) vs. \( m_{t_1} \)

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

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 with 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

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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.
Mono-Jet Search

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.

Search for signal in tail of missing $E_T$ distribution

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

MET 0,
- $pt = 913.68$
- $\eta = 0.000$
- $\phi = -0.657$
Mono-Jet Search

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

Workhorse Analysis
- Constraints
- Sensitivities

Dark Matter
- WIMPs
- Infer properties

Search for signals in tail of missing $E_T$

Events / GeV

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

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

ATLAS

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

\( E_T^{\text{miss}} > 150 \text{ GeV} \)

- WIMPs
- Infer particles

Irreducible SM Background

- Multi-jet
- Di-boson
- Single top
- Jet + single top
- \( Z(\rightarrow \nu\nu) + \text{jets} \)
- \( W(\rightarrow l\nu) + \text{jets} \)
- ADD model

Data 2012

SM uncertainty

Search for signal in tail of missing \( E_T^{\text{miss}} \)

\( \Delta \) mass and a factorization scale

\( g+\tilde{g} \) \( M_{\tilde{g}} = 1 \text{ TeV}, M_G = 10^{-4} \text{ eV} \)

Events / 0.1

Events / GeV

\( E_T^{\text{miss}} \) vs. Events

Data/SM

\( E_T^{\text{miss}} \) [GeV]
Fig. 6

The results are translated into limits on the parameters of the theoretical model predictions is indicated by the shaded regions, with model references included. For example, the WIMP model over broad mass range demonstrates the capability to confirm or deny an indication of a WIMP signal from another experiment.

The uncertainties due to theoretical model predictions are indicated by the shaded regions, with model references included. The limits are used to obtain the final results.

For instance, the limits on the WIMP mass and cross-section are presented in the context of various experiments and detection methods, including SuperCDMS, CoGeNT, and others, which are expected to operate over the next decade. Also, shown is an approximate scale for the neutrino floor, which is important for setting limits on WIMP signals.

The figures and diagrams illustrate the sensitivity of the Mono-Jet Search to WIMP signals, with particular emphasis on the neutrino floor. The search is designed to be sensitive to a variety of WIMP signatures, including those mediated by extra spatial dimensions, large extra spatial dimensions, and others.

The results are presented in the context of the ATLAS collaboration, with a focus on the Mono-Jet Search at the LHC, which is being used to explore the parameter space of WIMP models.
Beyond Mono-Jet

- mono-everything (...anything)

mono-\(\gamma\):

\[
\begin{array}{c}
\gamma \\
\chi \\
\chi
\end{array}
\]

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

\[
\begin{array}{c}
V \\
\chi \\
V
\end{array}
\]

mono-b: (mono-t)

\[
\begin{array}{c}
b \\
\chi \\
\chi
\end{array}
\]

VBF + MeT:

\[
\begin{array}{c}
v \\
\chi \\
v
\end{array}
\]

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

19.7 fb^{-1} (8 TeV)

$\sigma_{SI}$ (cm^2)

$\sigma_{SI}$ vs $m_{DM}$ (GeV)

- Monojet
- Boosted
- Resolved
- V-tagged
- Combination

CMS Preliminary

$g_{DM} = g_{SM} = 1$

$m_{med} = 2000$ GeV

"Spin Independent"

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

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Exploit distributions with simple well-defined SM behavior:
- **mass** / Angular distributions / $H_T$ / ...
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Search in regions with little or no predicted SM events.
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*Highlight a few of the mass searches in the following*
Searching for the Unexpected

$\nu_e \, \nu_\mu \, \nu_\tau \quad u \, c \, t \quad g \, \gamma \, W \, Z \, h$

$e \, \mu \, \tau \quad d \, s \, b$
Searching for the Unexpected

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

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

ATLAS: di-\(\tau\)au

\[ e^+e^- \]

\[ \mu^+\mu^- \]

Figure 7: Obs. / exp.

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

\[ m_{T}^{\text{tot}}(l, \tau_{\text{had-vis}}, E_{T}^{\text{miss}}) \text{ [GeV]} \]

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

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

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

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

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

Data

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

\(t\bar{t}, tW, WW, WZ, ZZ, \tau\tau\)

Jets (data)

Data

\(\gamma/Z \to \mu^+\mu^-\)

\(t\bar{t}, tW, WW, WZ, ZZ, \tau\tau\)

Jets (data)

\[ m_{\text{ee}} \text{ [GeV]} \]

\[ m_{\mu\mu} \text{ [GeV]} \]

\[ \text{Acceptance (dashed lines with empty markers)} \]

\[ \text{Acceptance}\times\text{efficiency} \times \text{[\%]} \]

\[ \text{Obs.} / \text{exp.} \]

\[ \text{Uncertainty} \]

\[ \text{Total systematic and negative} \]

\[ \text{Total systematic} \]

\[ \text{Statistical} \]

\[ \text{Systematic} \]
Searching for the Unexpected

\[ v_e, v_\mu, v_\tau, u, c, t, d, s, b, g, \gamma, W, Z, h \]

**ATLAS:** di-jet  
**CMS:** di-b-tagged-jet

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

CMS 
\[ \int \mathcal{L} dt = 19.7 \text{ fb}^{-1} (8 \text{ TeV}) \]

**ATLAS:**
- Data
- Fit
- \( q^*, m = 0.6 \text{ TeV} \)
- \( q^*, m = 2.0 \text{ TeV} \)
- \( q^*, m = 3.5 \text{ TeV} \)

**CMS:**
- Data
- Fit
- Wide jets (\( R = 1.1 \))
- \( |\eta| < 2.5 \) & \(|\Delta\eta| < 1.3 \)
- \( b^* (1.8 \text{ TeV}) \)
- \( Z' (2.2 \text{ TeV}) \)
- \( G (2.8 \text{ TeV}) \)
- \( Z' (3.2 \text{ TeV}) \)
Searching for the Unexpected

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

**ATLAS**: di-top  
**CMS**: di-\( \gamma \)

![Graph showing data and SM expected distributions for diphoton, photon+jet, and jet+jet and SM diphoton](image.png)  
**ATLAS**:  
**CMS** - Preliminary

arXiv:1505.07018  
arXiv:1506.03062  
arXiv:1504.05511  
CMS-PAS-EXO-12-045

![Graph showing data and SM expected distributions for diphoton, photon+jet, and jet+jet and SM diphoton](image.png)  
19.5 fb^{-1} (8 TeV)  
**CMS** - Preliminary

arXiv:1504.05511  
CMS-PAS-EXO-12-045
Searching for the Unexpected

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

**ATLAS**: di-higgs (4b)  

**ATLAS**: di-vector boson (hadronic)

\[
\int_0^{\infty} \frac{\mathrm{d}L}{\mathrm{d}t} = 19.5 \text{ fb}^{-1}
\]

**ATLAS**

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

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<tr>
<th>Signal Region</th>
<th>Data</th>
<th>Multijet</th>
<th>t\bar{t}</th>
<th>Syst+Stat Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**ATLAS**

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

**WZ Selection**

**Significance**

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

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

\[ m_{jj} \text{ [GeV]} \]

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

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

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

\[ m_{jj} \text{ [GeV]} \]

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

\[ m_{jj} \text{ [GeV]} \]

arXiv:1506.00285  
arXiv:1503.04114  
arXiv:1506.00962  
Searching for the Unexpected

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

**ATLAS**: di-higgs (4b)  
**ATLAS**: di-vector boson (hadronic)

\[ \int \sqrt{s} = 8 \text{ TeV} \quad L_{\text{int}} = 19.5 \text{ fb}^{-1} \]

![Graph showing data and background prediction for di-jet mass distribution](image)

- **Signal Region**
- **Data**
- **Multijet**
- **Syst+Stat Uncertainty**
- **G*(700), k/M_{Pl} = 1.0**
- **G*(1000), k/M_{Pl} = 1.0, \times 3**

![Graph showing significance for WZ selection](image)

**WZ Selection**

- **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)**

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

**ATLAS**

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

**Figure 5:**

After tagging with the correlated WW, ZZ, WZ signal regions

- sub-jet Pt balance / Trk. Multi.
- Relatively poor W/Z separation

**Figure 6:**

Events / 100 GeV

**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**

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

<table>
<thead>
<tr>
<th>Events / 100 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \times 10^4 )</td>
</tr>
</tbody>
</table>

**CMS excesses in similar regions**

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

(Statistically correlated!)

Local p-values

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

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

More on next slides
2 TeV Di-boson Resonance

Consistent with WZ?

ATLAS: WZ→JJ

CMS: WZ → JJ

\[ \sigma(pp \rightarrow W') \times BR(W' \rightarrow WZ) \ [fb] \]

\[ m_{W'} \ [TeV] \]

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

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

\[ m_{W'} \ [TeV] \]

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

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

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

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

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

\[ \text{Observed} \]

\[ \text{Expected (68\%) } \]

\[ \text{Expected (95\%)} \]

\[ W' \rightarrow WZ \]

arXiv:1506.00962

2 TeV Di-boson Resonance

Consistent with WZ?

ATLAS: WZ→JJ

 CMS: WZ → JJ

arXiv:1506.00962


Observed 95% CL

Expected 95% CL

± 1σ uncertainty

± 2σ uncertainty

EGM W', c = 1
2 TeV Di-boson Resonance

Consistent with WZ?

ATLAS: $WZ \rightarrow JJ$

CMS: $WZ \rightarrow JJ$

![Graph](image-url)

**ATLAS**

$\sqrt{s} = 8$ TeV, 20.3 fb$^{-1}$

- Observed 95% CL
- Expected 95% CL
- $\pm 1\sigma$ uncertainty
- $\pm 2\sigma$ uncertainty
- EGM $W'$, $c = 1$

**CMS**

$\sigma \times \text{BR}(W' \rightarrow WZ)$ (pb)

- Observed
- Expected (68%)
- Expected (95%)
- $W' \rightarrow WZ$

![Graph](image-url)

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

**arXiv:1506.00962**

2 TeV Di-boson Resonance

Consistent with WZ?

ATLAS: WZ → JJ

ATLAS: WZ → ℓνJ

![Graph showing cross section vs. mass for WZ resonance](Image)

arXiv:1506.00962

arXiv:1503.04677
2 TeV Di-boson Resonance

Consistent with WZ ?

ATLAS: WZ→JJ

ATLAS: WZ→ℓνJ

arXiv:1503.04677

arXiv:1506.00962
2 TeV Di-boson Resonance

Consistent with WZ?

ATLAS: WZ → JJ

ATLAS: WZ → ℓνJ

Play same game under WW or ZZ hypothesis ⇒ similar results

(see back-up)
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 + $H_T + E_T^{\text{Miss.}}$

**ATLAS**

Same-sign di-leptons (P_T $\geq$ 25 GeV)

$H_T > 700$ GeV

**SR7:**

$N_{\text{bjet}} \geq 3$

$E_T^{\text{Miss.}} > 40$ GeV

12 obs

4.3 ± 1.6 exp

**SR6:**

$N_{\text{bjet}} = 2$

$E_T^{\text{Miss.}} > 100$ GeV

6 obs

1.1 ± 1 exp

Figure 3: Expected background and observed data events in various signal regions.

Uncertainties include both the statistical and systematic errors. The difference between data and expectations is quantified by the means of the significance, computed from the p-values in tables 8 and 9.

Limits on $T_5/3$ production are set for pair production only, and for the sum of pair and single production for two different values of the coupling $\lambda$ of the $T_5/3$ to $W_t$ ($\lambda = 0.5$ and 1.0) [84]. This coupling is related to the mixing parameter $g^*$ used by the model in refs. [85, 86]:

$\lambda = \frac{m_{T_5/3}^2 g^*}{m_{W}^2 \sqrt{2}}$. The pair-production limits are shown in figure 10a, and correspond to a mass limit of 0.74 TeV (0.81 TeV expected). The limits on pair plus single production with $\lambda = 0.5$ are shown in figure 10b, where the observed mass limit is 0.75 TeV and the expected limit is 0.81 TeV. Finally, limits on pair plus single production with $\lambda = 1.0$ are shown in figure 10c, where again the observed mass limit is 0.75 TeV and the expected limit is 0.81 TeV.

The upper limit on the cross section for four-top-quark production is 70 fb assuming SM kinematics, and 61 fb for production with a BSM-physics contact interaction (expected limits are respectively 27 fb and 22 fb). The cross-section limit for the contact interaction case is lower than for the SM since the contact interaction tends to result in final-state objects with larger $p_T$, which increases the selection efficiency. The limits are also interpreted in the context of specific BSM physics models. For the contact interaction model,
### ATLAS

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

**HT > 700 GeV**

<table>
<thead>
<tr>
<th><strong>SR7:</strong></th>
<th><strong>SR6:</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>( N_{bjet} \geq 3 )</td>
<td>( N_{bjet} = 2 )</td>
</tr>
<tr>
<td>( E_T^{\text{Miss.}} &gt; 40 \text{ GeV} )</td>
<td>( E_T^{\text{Miss.}} &gt; 100 \text{ GeV} )</td>
</tr>
<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>
</tbody>
</table>

### CMS

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

**HT > 400 GeV**

<table>
<thead>
<tr>
<th><strong>N_{jet}: 2-3</strong></th>
<th><strong>N_{jet} \geq 4</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ET^{Miss.}:</strong></td>
<td><strong>ET^{Miss.}:</strong></td>
</tr>
<tr>
<td>50-120 GeV</td>
<td>( \geq 120 \text{ GeV} )</td>
</tr>
<tr>
<td>1 obs</td>
<td>1 obs.</td>
</tr>
<tr>
<td>1.0 ± 0.5 exp.</td>
<td>0.8 ± 0.5 exp.</td>
</tr>
<tr>
<td>7 obs</td>
<td>2 obs</td>
</tr>
<tr>
<td>2.8 ± 1.2 exp</td>
<td>2.2 ± 1.0 exp</td>
</tr>
</tbody>
</table>
SS leptons + bs + H_T + E_T^{Miss.}

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

<table>
<thead>
<tr>
<th>SR7:</th>
</tr>
</thead>
</table>
| N_{bjet} ≥ 3 | 12 obs | 4.3 ± 1.6 exp  
| E_T^{Miss.} > 40 GeV |  

<table>
<thead>
<tr>
<th>SR6:</th>
</tr>
</thead>
</table>
| N_{bjet} = 2 | 6 obs | 1.1 ± 1 exp  
| E_T^{Miss.} > 100 GeV |  

**CMS**  
Same-sign di-leptons (P_T ≥ 20 GeV)  
H_T > 400 GeV  
N_{bjet} ≥ 2

<table>
<thead>
<tr>
<th>N_{jet}: 2-3</th>
<th>N_{jet} ≥ 4</th>
</tr>
</thead>
</table>
| E_T^{Miss.}:  
50-120 GeV | 1 obs | 1.0 ± 0.5 exp. | 7 obs | 2.8 ± 1.2 exp  
| ≥ 120 GeV | 1 obs. | 0.8 ± 0.5 exp. | 2 obs | 2.2 ± 1.0 exp  

arXiv:1504.04605  
arXiv:1311.6736
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

ATLAS Online Luminosity
\[ \sqrt{s} = 13 \text{ TeV} \]

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

ATLAS Online Luminosity
\[ \sqrt{s} = 13 \text{ TeV} \]

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

Total Integrated Luminosity [pb]:

- LHC Delivered
- ATLAS Recorded

Day in 2015
Run-2 Physics Program Underway

For illustration purposes:
In blue: signal of a $q^* qg$ resonance at $M = 4.5$ TeV

Highest dijet mass event: $M = 5$ TeV $\sqrt{s} = 13$ TeV, 78 pb$^{-1}$

CMS*Run*2–*dijet*mass*spectrum

• Mass spectrum fitted using a 4 parameter function.

Wide Jets

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

$M_J > 1.1$ TeV

Data

*Z/\gamma^*

Top Quarks

Diboson

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

Dilepton Search Selection

**ATLAS** Preliminary

(Data-Fit)/σ

Events

10

100

1,000

10

100

200

300

400

500

600

700

800

900

1,000

Dimuon Invariant Mass [GeV]

1500 2000 2500 3000 3500 4000 4500 5000

Dijet Mass (GeV)
Run-2 Projections

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

- **Run-2: is** \(\approx 5 \times (100 \text{ fb}/20 \text{ fb}) \approx 25 \times \text{Run-1} \) for pair production at 500 GeV
  \(~15 \times (100 \text{ fb}/20 \text{ fb}) \approx 75 \times \text{Run-1} \) for pair production at 1 TeV
Run-2 Projections

Di-jet Resonance

Post/pre-dictions for excited quark exclusion reach

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

- extrapolations
- open circle reference (ATLAS)
- filled circle ATLAS
- filled square CMS
- filled triangle CDF

7 TeV
8 TeV
13 TeV
14 TeV

1.96 TeV, $p\bar{p}$

Salam, Weiler

collider-reach.web.cern.ch
Run-2 Projections

Di-jet Resonance

Post/pre-dictions for excited quark exclusion reach

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

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

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

log scale!
Run-2 Projections

Di-jet Resonance

Post/pre-dictions 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

**Stop**

Post/pre-dictions for stop exclusion reach

- Extrapolations
- Reference (ATLAS)
- ATLAS
- CMS

References:

- CERN
- CMS
- ATLAS
- Reference (ATLAS) extrapolations

CERN reference (CMS)

Salam, Weiler

collider-reach.web.cern.ch
Run-2 Projections

Electroweak SUSY

\( \sqrt{s} = 14 \text{ TeV} \)

3-lepton channel

\( \tilde{\chi}_1^\pm \tilde{\chi}_2^0 \rightarrow W^\pm \tilde{\chi}_1^0 Z \tilde{\chi}_1^0 \)

\( m_{\tilde{\chi}_1^\pm} = m_{\tilde{\chi}_2^0} \)

### 8 TeV

\[ \int L dt = 20.3 \text{ fb}^{-1}, \text{95% CL exclusion} \]

### 14 TeV

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

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

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

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

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

---

**ATLAS Simulation Preliminary**

---

CMS-PAS-SUS-14-012

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ATL-PHYS-PUB-2014-010
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.
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: $\sim 75 \times$ 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**

#### Model

| Model | $\ell, \gamma$ | Jets | $E_{T}^{miss}$ | $|\mathcal{L}|dt$ [fb$^{-1}$] | Limit | Reference |
|-------|----------------|------|----------------|----------------|-------|-----------|
| ADD $g_{X}+g/q$ | $\ell, \gamma$ | $\geq 1$ | Yes | 20 | $M_{0}$ | 5.25 TeV | 1502.01518 |
| ADD non-resonant $\ell\ell$ | $2e, \mu$ | - | - | 20 | $M_{0}$ | 4.7 TeV | 1407.2410 |
| ADD QBH $\rightarrow q\ell$ | $1e, \mu$ | 1 | | 20 | $M_{0}$ | 5.2 TeV | 1311.2006 |
| ADD $Q^{2}$ | $2e, \mu$ | 2 | 20 | 3 | $M_{0}$ | 4.7 TeV | 1405.2576 |
| ADD BH high $N_{b}$ | $2\mu$ (SS) | - | - | 20 | $M_{0}$ | 5.8 TeV | 1308.4075 |
| ADD BH high $\Sigma_{T}$ | $\geq 1$ | $\geq 2$ | Yes | 20 | $M_{0}$ | 5.8 TeV | 1405.4254 |
| ADD BH high multijet | $\geq 1$ | $\geq 2$ | Yes | 20 | $M_{0}$ | 5.8 TeV | 1503.08988 |
| RS1 $G_{X} \rightarrow \gamma\ell$ | $2e, \mu$ | - | - | 20 | $G_{X}$ mass | 2.68 TeV | 1504.4123 |
| RS1 $G_{X} \rightarrow \gamma\ell$ | $2\gamma$ | - | - | 20 | $G_{X}$ mass | 2.68 TeV | 1504.5551 |
| Bulk RS $G_{X} \rightarrow Z\gamma \rightarrow q\bar{q}\ell\ell$ | $2e, \mu$ | $2|/1J$ | Yes | 20 | $W$ mass | 760 GeV | 1409.6190 |
| Bulk RS $G_{X} \rightarrow WW \rightarrow q\bar{q}\ell\ell$ | $2e, \mu$ | $2|/1J$ | Yes | 20 | $W$ mass | 760 GeV | 1503.04677 |
| Bulk RS $G_{X} \rightarrow H\gamma \rightarrow b\bar{b}bb$ | $4e, \mu$ | - | - | 20 | $G_{X}$ mass | 500-720 GeV | 1506.06020 |
| Bulk RS $G_{X} \rightarrow H\gamma \rightarrow \ell\ell$ | $1e, \mu$ | $\geq 1b, \geq 1J$ | Yes | 20 | $G_{X}$ mass | 2.2 TeV | 1507.07018 |
| 2UED | $2e, \mu$ | $\geq 1b, \geq 1J$ | Yes | 20 | $G_{X}$ mass | 960 GeV | 1504.0605 |
| SSM $Z' \rightarrow \ell\ell$ | $2e, \mu$ | - | - | 20 | $Z'$ mass | 2.9 TeV | 1405.1413 |
| SSM $Z' \rightarrow \tau\tau$ | $2\tau$ | - | - | 20 | $Z'$ mass | 2.02 TeV | 1407.749 |
| SSM $W' \rightarrow \ell\ell$ | $2e, \mu$ | - | - | 20 | $W'$ mass | 2.32 TeV | 1403.6456 |
| EGM $W' \rightarrow Z\ell\ell$ | $3e, \mu$ | $1\ell$ | Yes | 20 | $W$ mass | 5.82 TeV | 1409.6190 |
| EGM $W' \rightarrow Z\ell\ell$ | $2e, \mu$ | $2|/1J$ | Yes | 20 | $W$ mass | 5.58 TeV | 1506.0096 |
| LRS $W'_r \rightarrow tb$ | $1e, \mu$ | $2b, 0|/1|$ | Yes | 20 | $W$ mass | 1.92 TeV | 1410.4103 |
| LRS $W'_r \rightarrow tb$ | $0e, \mu$ | $\geq 1b, 1|/1$ | Yes | 20 | $W$ mass | 1.76 TeV | 1408.0866 |
| CI $q\bar{q}\ell\ell$ | $2\ell$ | | | 20 | $A$ | $\sqrt{s} = 1$ | 1504.00357 |
| CI $q\bar{q}\ell\ell$ | $2\ell$ | | | 20 | $A$ | $\sqrt{s} = 1$ | 1407.2410 |
| CI $u\bar{u}tt$ | $2e, \mu$ | $\geq 1b, 1J$ | Yes | 20 | $A$ | $\sqrt{s} = 1$ | 1504.0605 |
| DM EFT5 operator (Dirac) | $0e, \mu$ | $\geq 1b, 1J$ | Yes | 20 | $M_{s}$ | 974 GeV | 1502.01518 |
| DM EFT5 operator (Dirac) | $0e, \mu$ | $1\ell, 1J$ | Yes | 20 | $M_{s}$ | 4.3 TeV | 1309.4017 |
| Scalar LQ 1st gen | $2e, \mu$ | $\geq 2$ | Yes | 20 | $LQ$ mass | 1.05 TeV | Preliminary |
| Scalar LQ 2nd gen | $2e, \mu$ | $\geq 2$ | Yes | 20 | $LQ$ mass | 1.0 TeV | Preliminary |
| Scalar LQ 3rd gen | $2e, \mu$ | $\geq 2b, 1J$ | Yes | 20 | $LQ$ mass | 640 GeV | Preliminary |
| VLO $TT \rightarrow Ht + X$ | $1e, \mu$ | $\geq 2b, 3|/1$ | Yes | 20 | $T$ mass | 855 GeV | 1505.04306 |
| VLO $VVY \rightarrow Wb + X$ | $1e, \mu$ | $\geq 2b, 3|/1$ | Yes | 20 | $V$ mass | 770 GeV | 1505.04306 |
| VLO $BB \rightarrow Hb + X$ | $1e, \mu$ | $\geq 2b, 3|/1$ | Yes | 20 | $B$ mass | 735 GeV | 1505.04306 |
| VLO $BB \rightarrow Zb + X$ | $2e, \mu$ | $\geq 2b, 1b$ | Yes | 20 | $B$ mass | 750 GeV | 1505.04306 |
| VLO $W_{L} \rightarrow W_{L} + X$ | $1e, \mu$ | $\geq 2b, 3|/1$ | Yes | 20 | $B$ mass | 840 GeV | 1505.04306 |
| Excited fermions | $1\gamma$ | $1|/1$ | Yes | 20 | $m_{X}$ mass | 3.5 TeV | 1309.3230 |
| Excited fermions | $1\nu$ | $1|/1$ | Yes | 20 | $m_{X}$ mass | 3.5 TeV | 1407.2376 |
| Excited fermions | $1\bar{b}$ | $1|/1$ | Yes | 20 | $m_{X}$ mass | 870 GeV | 1311.5083 |
| Excited fermions | $1\nu$ | $1|/1$ | Yes | 20 | $m_{X}$ mass | 4.05 TeV | 1313.1864 |
| Excited fermions | $1\bar{b}$ | $1|/1$ | Yes | 20 | $m_{X}$ mass | 1.6 TeV | 1411.2921 |
| LSTC | $2e, \mu$ | $\geq 1y, 1y$ | Yes | 20 | $M_{0}$ mass | 960 GeV | 1407.7410 |
| LSTC Majorana $\nu$ | $2e, \mu$ | 2 | | 20 | $M_{0}$ mass | 2.0 TeV | 1506.06020 |
| Higgs triplet $h^{++} \rightarrow \ell\ell$ | $2e, \mu$ (SS) | - | - | 20 | $H_{0}^{++}$ mass | 551 GeV | 1412.0237 |
| Higgs triplet $h^{++} \rightarrow \ell\ell$ | $3e, \mu$ | - | - | 20 | $H_{0}^{++}$ mass | 400 GeV | 1411.2921 |
| Higgs triplet $h^{++} \rightarrow \ell\ell$ | $3e, \mu$ | - | - | 20 | $H_{0}^{++}$ mass | 511 GeV | 1410.5404 |
| Monopole (non-res prod) | $1e, \mu$ | $1b$ | Yes | 20 | $M_{0}$ mass | 657 GeV | 1504.04188 |
| Multi-charged particles | - | - | Yes | 20 | $M_{0}$ mass | 765 GeV | 1411.2921 |
| Monopole mass | - | - | Yes | 20 | $M_{0}$ mass | 1.34 TeV | 1411.2921 |

*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

#### Model

<table>
<thead>
<tr>
<th>Model</th>
<th>$e, \mu, \tau, \gamma$, Jets</th>
<th>$E_{\text{miss}}$</th>
<th>$\mathcal{L}$ ( fb$^{-1}$ )</th>
<th>Mass limit</th>
<th>$\sqrt{s} = 7$ TeV</th>
<th>$\sqrt{s} = 8$ TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Inclusive Searches</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MSUGRA/CMSSM</td>
<td>$0-3$ $e, \mu, \tau$ ($\ell$)</td>
<td>$2-1$ jets/3 $h$</td>
<td>Yes</td>
<td>$20.3$</td>
<td>$\sqrt{s} = 7$ TeV</td>
<td>$\sqrt{s} = 8$ TeV</td>
</tr>
<tr>
<td>0</td>
<td>2-6 jets</td>
<td>Yes</td>
<td>$20.3$</td>
<td>$100-400$ GeV</td>
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#### $\nu$-like dark matter

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#### Long-lived particles

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<td>$m_{l}$</td>
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<tr>
<td>0</td>
<td>1</td>
<td>$m_{k}$</td>
<td>$m_{l}$</td>
<td>$\gamma = \sqrt{s} - 7$ TeV</td>
<td>$\gamma = \sqrt{s} - 8$ TeV</td>
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*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.*
Filling Stop Gaps

\[ \sqrt{s} = 7 \text{ TeV}, \ 4.6 \text{ fb}^{-1} \]
\[ \sqrt{s} = 8 \text{ TeV}, \ 20 \text{ fb}^{-1} \]
\[ \tilde{t}_1 \rightarrow t^* \tilde{\chi}_1^0, \ m(\tilde{\chi}_1^0) = 1 \text{ GeV} \]

- Expected limit ±1\( \sigma_{\text{exp}} \)
- Observed limit ±1\( \sigma_{\text{SUSY \ theory}} \)
- Obs. -1\( \sigma \), \( m = 175.0 \text{ GeV} \)
- Obs. -1\( \sigma \), \( m = 173.5 \text{ GeV} \)

\( m_{\tilde{t}_1} [\text{GeV}] \) vs. 95% CL limit on signal strength \( \mu \).
Stop Search

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

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
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

![Feynman Diagrams](image_url)
“Excluding Triangles, not points”
“Excluding Triangles, not points”

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

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

**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(→ℓℓ)t + X**
Select top+$Z\rightarrow\ell\ell$ (e/μ)
Search in $m_{Zb}$
“Excluding Triangles, not points”

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

**Same-sign Leptons (e/\(\mu\))**
- Select Bjets / Large \(H_T\)

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

**Wb + X**
- Select W+b
- Search in \(m_{wb}\)
“Excluding Triangles, not points”
Dark Matter

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+2jets based on 4.3 fb$^{-1}$. The analysis has been recently extended to 7.3 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

$\text{MET} > 25$

$p_T(jj) > 40$

$M_T(W) > 30$

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

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

https://indico.cern.ch/event/129980/
tagging requirements

**Figure 1:** Distribution of the boson-tagging variables. The plots show the fraction of jets within a mass window, consistent with the ATLAS data. The left plot compares ATLAS Simulation with EGM W' → WZ (m_W' = 1.8 TeV) and Pythia QCD dijet predictions. The right plot shows the fraction of jets / 3 for ATLAS Simulation with EGM W' → WZ (m_W' = 1.8 TeV) and Pythia QCD dijet predictions. The grooming cut is indicated by the arrow.

**ATLAS Simulation**

- **ATLAS Simulation:** 
  - EGM W' → WZ (m_W' = 1.8 TeV)
  - Pythia QCD dijet

**Plot Details:**
- Jet |\Delta y| < 1.2
- Jet |\eta| < 2
- 1.62 ≤ m_j < 1.98 TeV
- 60 ≤ m_j < 110 GeV
- 20 ≤ m_j < 60 GeV
- |\Delta y| > 0.45
- |\eta| > 2
- |\Delta y| > 1.2

**Tagging Requirements:**
- Events are removed if they contain a prompt electron candidate with 99% C.
- Event selection being studied.
- Jet's mass must fall within either the 0.05 to 0.15 or 0.15 to 0.25 or 0.25 to 0.35 or 0.35 to 0.45 mass window, consistent with the bulk G.

**Grooming Cut:**
- Jets with reconstructed missing transverse momentum exceeding 350 GeV are also removed, as these are used in searches sensitive to diboson resonances with a mass window consistent with the ATLAS data (c).
2 TeV Di-boson Resonance

Consistent with WW ?

ATLAS: WW → JJ

CMS: WW → JJ

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

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

- Observed 95% CL
- Expected 95% CL

- ± 1\sigma uncertainty
- ± 2\sigma uncertainty

Bulk \( G_{RS} k/M_{Pl} = 1 \)

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

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

\( G_{bulk} \rightarrow WW (k/M_{Pl} = 0.5) \)

arXiv:1506.00962

**2 TeV Di-boson Resonance**

**Consistent with WW?**

**ATLAS: WW → JJ**

**CMS: WW → JJ**

![Graphs showing ATLAS and CMS results for WW resonances](image)

*ATLAS*:

- Observed 95% CL
- Expected 95% CL
- ± 1σ uncertainty
- ± 2σ uncertainty
- Bulk $G_{RS}$ $k/M_{Pl} = 1$

*CMS*:

- Observed
- Expected (68%)
- Expected (95%)
- $G_{bulk} → WW (k/M_{Pl} = 0.5)$

*arXiv:1506.00962*  

*arXiv:1405.1994*
2 TeV Di-boson Resonance

Consistent with WW?

ATLAS: WW→JJ

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

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

- Observed 95% CL
- Expected 95% CL
- ± 1σ uncertainty
- ± 2σ uncertainty
- Bulk \(G_{RS}\) k/\(M_{Pl}\) = 1

CMS: WW→ℓνJ

arXiv:1506.00962

arXiv:1405.3447
2 TeV Di-boson Resonance

Consistent with WW?

ATLAS: WW → JJ

CMS: WW → ℓνJ

Observed 95% CL
Expected 95% CL
± 1σ uncertainty
± 2σ uncertainty
Bulk $G_{RS} \ k/\sqrt{s} = 1$

$\sqrt{s} = 8$ TeV, 20.3 fb$^{-1}$

arXiv:1506.00962

arXiv:1405.3447
2 TeV Di-boson Resonance

Consistent with ZZ?

ATLAS: ZZ→JJ

CMS: ZZ→JJ

ATLAS

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

- Observed 95% CL
- Expected 95% CL

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

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

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

\[
\text{Bulk } G_{RS} k/M_{Pl} = 1
\]

CMS, L = 19.7 fb\(^{-1}\), \(\bar{s} = 8 \text{ TeV}\)

\[
\sigma \times BR(G_{bulk} \rightarrow ZZ) \text{ [pb]}
\]

- Observed
- Expected (68%)
- Expected (95%)
- \(G_{bulk} \rightarrow ZZ (k/M_{Pl} = 0.5)\)

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
2 TeV Di-boson Resonance

Consistent with ZZ?

ATLAS: ZZ → JJ

CMS: ZZ → ℓℓJJ

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

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

\[ \bullet \] Observed 95\% CL

\[ \cdots \cdots \] Expected 95\% CL

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

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

\[ \text{Bulk } G_{RS} \frac{k}{M_{Pl}} = 1 \]
2 TeV Di-boson Resonance

Consistent with ZZ?

**ATLAS: ZZ → JJ**

![Graph showing cross section in ATLAS ZZ → JJ channel](image)

**ATLAS: ZZ → ℓℓJ**

![Graph showing cross section in ATLAS ZZ → ℓℓJ channel](image)
2 TeV Di-boson Resonance

Consistent with ZZ ?

**ATLAS: ZZ → JJ**

**ATLAS: ZZ → ℓℓJ**

\[
\sigma(pp \to G^*) \times BR(G^* \to ZZ) \text{ [fb]}
\]

- **Observed 95% CL**
- **Expected 95% CL**
- **± 1σ uncertainty**
- **± 2σ uncertainty**
- **Bulk G_{RS} k/\bar{M}_P = 1**

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

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

**ATLAS**

- **Bulk RS graviton k/\bar{M}_P = 1**
- **Bulk RS graviton k/\bar{M}_P = 0.5**
- **Expected 95% CL**
- **Observed 95% CL**
- **± 1σ uncertainty**
- **± 2σ uncertainty**

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

\[
\text{Observed mass distributions in the}
\]

\[
\text{theoretical framework of an Extended}
\]

\[
\text{Standard Model background expectation was found.}
\]

In summary, a search for narrow, heavy resonances producing either leptons or di-bosons in the decay mode \(G^* \to ZZ\) or \(G^* \to M/M^*\) was performed with the ATLAS detector at the LHC at the centre-of-mass energy of 8 TeV. The data were collected corresponding to an integrated luminosity of 20.3 fb\(^{-1}\). No significant signal was observed, and upper limits on the cross section times branching fraction are derived for a wide range of masses of the resonances. The limits on the cross section times branching fraction are compared with the predictions of the Minimal Supersymmetric Standard Model and other models.

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

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

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

\[
\text{± 1σ uncertainty}
\]

\[
\text{± 2σ uncertainty}
\]

\[
\text{Bulk RS graviton k/\bar{M}_P = 1}
\]

\[
\text{Bulk RS graviton k/\bar{M}_P = 0.5}
\]

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

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

\[
\text{± 1σ uncertainty}
\]

\[
\text{± 2σ uncertainty}
\]
2 TeV Di-boson Resonance

Consistent with $WW$ ?

**ATLAS: $WW \rightarrow JJ$**

**ATLAS: $WW \rightarrow \ell \nu J$**

![Graph showing expected and observed cross sections for $gg\rightarrow WW$ as a function of the resonance mass, with limits on the cross section times branching fraction for $WW$ and $G*$ production.](image)
SS leptons + bs + HT + MeT

ATLAS Search

Common Selection
- Same-sign di-leptons ($p_T \geq 25$ GeV)
- $HT > 700$ GeV
- $NJet \geq 2$
- $MeT > 100$ GeV
- $MeT > 40$ GeV

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SS leptons + bs + HT + MeT

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</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Type</th>
<th>$N_j$</th>
<th>$N_b$</th>
<th>$H_T$ [GeV]</th>
<th>$E_T^{\text{miss}}$ [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^+ e^+$</td>
<td>4</td>
<td>3</td>
<td>709</td>
<td>298</td>
</tr>
<tr>
<td>$e^+ e^+$</td>
<td>6</td>
<td>3</td>
<td>800</td>
<td>137</td>
</tr>
<tr>
<td>$e^+ \mu^+$</td>
<td>5</td>
<td>3</td>
<td>744</td>
<td>216</td>
</tr>
<tr>
<td>$e^+ \mu^+$</td>
<td>4</td>
<td>3</td>
<td>888</td>
<td>155</td>
</tr>
<tr>
<td>$\mu^+ e^+$</td>
<td>3</td>
<td>3</td>
<td>1439</td>
<td>239</td>
</tr>
<tr>
<td>$\mu^- \mu^+ \mu^-$</td>
<td>4</td>
<td>4</td>
<td>1072</td>
<td>176</td>
</tr>
</tbody>
</table>
More Excesses

More Excesses

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

Not seen in CMS.
But analysis different selection estimate.
Run-2 Projections

Di-jet Resonance

Z-prime

Post/pre-dictions for excited quark exclusion reach

Post/pre-dictions for sequential Z' exclusion reach

- extrapolations
- reference (ATLAS)
- ATLAS
- CMS
- CDF

14 TeV

13 TeV

8 TeV

7 TeV

1.96 TeV, pp

14 TeV

13 TeV

8 TeV

7 TeV

1.96 TeV, pp

Salam, Weiler

collider-reach.web.cern.ch