Searches for new phenomena with the ATLAS detector

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On behalf of the ATLAS Collaboration

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After the observation of Higgs boson in 2012 at ATLAS and CMS experiments, all the elementary particles predicted by the Standard Model (SM) have been observed.

The SM works extremely well…but…

Phenomena not explained

- Gravity
- Dark Matter & Dark Energy
- Neutrino Mass
- …

Naturalness Questions

- The hierarchy problem
- The strong CP-problem
- …
Many theories beyond the Standard Model (BSM), providing solutions to these problems, predict new phenomena accessible by the LHC

Exotic searches:

- Dark Matter
- Extended Gauge Groups
- Extra dimensions
- Vector like Quarks
- Contact Interaction
- Leptoquarks
- Excited fermions

Beyond the Standard Model Searches

* red: covered in this talk

### ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

**Status:** July 2018

<table>
<thead>
<tr>
<th>Model</th>
<th>( \ell, \gamma )</th>
<th>Jets</th>
<th>( E_{T}^{miss} )</th>
<th>Limit</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADD GMSB + ( g/\gamma )</td>
<td>( 0,\gamma )</td>
<td>1 - 4</td>
<td>Yes</td>
<td>36.1</td>
<td>7.7 TeV</td>
</tr>
<tr>
<td>ADD non-resonant ( g/\gamma )</td>
<td>( 2,\gamma )</td>
<td>2 - 3</td>
<td>Yes</td>
<td>36.7</td>
<td>8.6 TeV</td>
</tr>
<tr>
<td>ADD QRH</td>
<td>( 0,\gamma )</td>
<td>2 - 3</td>
<td>Yes</td>
<td>37.0</td>
<td>9.5 TeV</td>
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<tr>
<td>ADD BH high ( \Sigma \gamma )</td>
<td>( 1,\gamma \geq 2 )</td>
<td>2 - 3</td>
<td>Yes</td>
<td>3.2</td>
<td>9.05 TeV</td>
</tr>
<tr>
<td>ADD BH multijet</td>
<td>( 1,\gamma \geq 2 )</td>
<td>2 - 3</td>
<td>Yes</td>
<td>3.6</td>
<td>9.05 TeV</td>
</tr>
<tr>
<td>RS1 GMSB ( \mu \rightarrow \gamma \gamma )</td>
<td>( 2,\gamma )</td>
<td>2 - 3</td>
<td>Yes</td>
<td>36.7</td>
<td>4.1 TeV</td>
</tr>
<tr>
<td>Bulk RS GMSB ( \mu \rightarrow \gamma \gamma )</td>
<td>( 2,\gamma )</td>
<td>2 - 3</td>
<td>Yes</td>
<td>36.7</td>
<td>4.1 TeV</td>
</tr>
<tr>
<td>2UED / RPP</td>
<td>( 1,\gamma \geq 1 )</td>
<td>2 - 3</td>
<td>Yes</td>
<td>36.7</td>
<td>4.1 TeV</td>
</tr>
</tbody>
</table>

**Extra dimensions**

- **Gauge bosons**
  - \( Z \rightarrow \ell \ell \)
  - \( Z \rightarrow \gamma \gamma \)
  - Leptophobic \( Z' \rightarrow b \bar{b} \)
  - Leptophobic \( Z' \rightarrow \ell \ell \)
  - \( W' \rightarrow \ell \ell \)
  - \( W' \rightarrow \gamma \gamma \)
  - \( H' \rightarrow VV \rightarrow \ell \ell \gamma \gamma \)
  - \( H' \rightarrow VV \rightarrow \ell \ell \gamma \gamma \)

**Cl**

- Axial-vector mediator (Direct DM) | \( 0,\gamma \) | 1 - 4 | Yes | 36.1 | 7.7 TeV |
- Colored scalar mediator (Direct DM) | \( 0,\gamma \) | 1 - 4 | Yes | 36.1 | 7.7 TeV |
- \( V_{T}\gamma \) EFT (Direct DM) | \( 0,\gamma \) | 1 - 4 | Yes | 36.1 | 7.7 TeV |

**DM**

- Scalar LO 1st gen | \( 2,\gamma \) | \( \geq 1 \) | Yes | 36.1 | 7.7 TeV |
- Scalar LO 2nd gen | \( 2,\gamma \) | \( \geq 1 \) | Yes | 36.1 | 7.7 TeV |
- Scalar LO 3rd gen | \( 2,\gamma \) | \( \geq 1 \) | Yes | 36.1 | 7.7 TeV |

**LO**

- VLo Qb \( \rightarrow Z/\gamma B \rightarrow \gamma \ell \gamma \)
- VLo Qb \( \rightarrow Wb \rightarrow \ell \mu \)
- VLo Qb \( \rightarrow Ws \rightarrow \ell \tau \)
- VLo Qb \( \rightarrow Ws \rightarrow \ell \tau \)
- VLo Qb \( \rightarrow Ws \rightarrow \ell \tau \)
- VLo Qb \( \rightarrow Ws \rightarrow \ell \tau \)
- VLo Qb \( \rightarrow Ws \rightarrow \ell \tau \)
- VLo Qb \( \rightarrow Ws \rightarrow \ell \tau \)
- VLo Qb \( \rightarrow Ws \rightarrow \ell \tau \)
- VLo Qb \( \rightarrow Ws \rightarrow \ell \tau \)

**Tevatron**

- Type II Seesaw | \( 1,\gamma \) | \( \geq 2 \) | Yes | 36.1 | 7.7 TeV |
- LSRM Majorana | \( 2,\gamma \) | 2 - 3 | Yes | 36.1 | 7.7 TeV |
- Higgs triplets \( h^{\pm} \rightarrow V \gamma \) | \( 2,\gamma \) | \( \geq 1 \) | Yes | 36.1 | 7.7 TeV |
- Higgs triplets \( h^{\pm} \rightarrow V \gamma \) | \( 2,\gamma \) | \( \geq 1 \) | Yes | 36.1 | 7.7 TeV |
- Monopole (non-robust) | \( 1,\gamma \) | 1 - 3 | Yes | 36.1 | 7.7 TeV |
- Multi-charged particles | \( 1,\gamma \) | 1 - 3 | Yes | 36.1 | 7.7 TeV |
- Magnetic monopoles | \( 1,\gamma \) | 1 - 3 | Yes | 36.1 | 7.7 TeV |

**Other**

- \( V_{T} \gamma = 8 \) TeV
- \( V_{T} = 13 \) TeV

*Only a selection of the available mass limits on new states or phenomena is shown.

1 Small-radius (large-radius) jets are denoted by the letter (j).
Dark Matter

A Mystery in the Universe
Dark Matter Searches

Evidences of Dark Matter (DM)
- galaxy rotation curves
- gravitational lensing
- cosmic microwave background
- ...

The newest result (2018) from Plank gives out that 26.4% of our universe is dark matter. [arxiv:1807.06209](https://arxiv.org/abs/1807.06209)

Searches
- Direct detection: the measurement of elastic scattering of DM with nuclei in a detector;
- Indirect detection: the detection of standard model (SM) particles produced in the annihilations or decays of DM in the universe;
- **Searches in colliders: production of DM particles at colliders**;

A weak-interaction massive particle (WIMP) is a compelling candidate of DM.
Signal Models Overview

Simplified models — new particle(s) mediate(s) the interaction of DM with the SM particles

- dark sector is composed of a single particle
  - spin 1: vector or axial-vector DM models
  - spin 0: scalar or pseudo-scalar DM models

- dark sector is composed of an extended-Higgs sector plus an additional mediator
  - Two-Higgs-doublet models with a vector / pseudo-scalar mediator

- EFT models of scalar dark energy

Other models like those can provide a viable WIMP DM candidate are not summarized here
Searches for invisible final states

- If WIMPs are produced at the LHC, they are invisible to the detector.
  - Missing transfers momentum (MET)
- To tag the event and measure the recoiling MET
  - Additional particle(s) X produced in association with DM

**experimental final states: MET + X**

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**Example diagrams for invisible final states**

Analyses: **MET + jet / γ / V(qq) / Z(ll) / h(bb) / h(γγ) / top**
Signal Model(s)

- 4 free parameters: WIMP mass; mediator mass; coupling of the mediator to quarks (g_q); coupling to WIMPs (g_x);

Event Selection

- a large MET (MET > 250 GeV)
- jets (leading jet pT > 250 GeV, ...)
- separation between MET and jets (∆φ(MET, jet) > 0.4), suppress multi-jet background

Background estimation

- W+jets, Z+jets, top-quark-related background are constrained using MC samples in control regions
- multi-jet background, non-collision background are also estimated, small contribution / negligible
- background fit — constrain the normalization of dominant background, reduce the uncertainties

Systematic Uncertainties ...
Searches for visible final states

- The mediators couple to SM particles — interpreting the DM models in resonance searches is also interesting

The visible final states searches

- Dijet: high mass resonance search, \( m(jj) > 1.1 \) TeV
- Trigger-level dijet analysis (TLA): using only trigger level jets to reach lower \( m_{jj} \)
- Boosted dijet + ISR analysis: light resonances boosted via recoil from high-pT ISR photon or jet
  - Di-bjet
  - Di-lepton
  - \( tt \)bar resonance
  - 4 top

Dijet background estimated by the falling \( m(jj) \) distribution. A sliding-window fitting technique is used.

Example diagrams for visible final states

\[ \text{ATLAS Paper EXOT 2017-032} \]
The Complementarity of Dijet Searches

Bounds in the Coupling-Mediator plane

ATLAS Preliminary July 2018 $\sqrt{s} = 13$ TeV, 3.6-37.0 fb$^{-1}$

95% CL upper limits
- Observed
- Expected

Dijet 8 TeV
- 20.3 fb$^{-1}$
- 36.1 fb$^{-1}$
  - arXiv: 1801.08769

Large-$R$ jet + ISR
- 3.6-29.7 fb
  - Dijet + ISR ($\gamma$)
  - ATLAS-CONF-2016-070
- 15.5 fb$^{-1}$
  - ATLAS-CONF-2016-070

Di-b-jet
- 24.3-36.1 fb$^{-1}$
  - arXiv: 1805.09299

Dijet TLA
- 3.6-29.7 fb$^{-1}$
  - arXiv: 1804.03496

Dijet
- 37.0 fb$^{-1}$

Axial vector mediator
Dirac Dark Matter
$m_{DM} = 10$ TeV

$|y_{12}| < 0.3$

Dijet TLA, $|y_{12}| < 0.6$
Axial-Vector Mediator $g(q) = 0.25$, $g(l) = 0$, $g(DM) = 1$
Vector Mediator $g(q) = 0.1$, $g(l) = 0.01$, $g(DM) = 1$
Compared with Direct Detection (Model Dependent)

Vector mediator, Dirac DM

\[ g_q = 0.25, \quad g_i = 0, \quad g_{\text{DM}} = 1 \]

ATLAS limits at 95% CL, direct detection limits at 90% CL
## Extended Gauge Groups

<table>
<thead>
<tr>
<th>Extended Gauge Group</th>
<th>Predictions</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSM $Z' \rightarrow \ell \ell$</td>
<td>$2e, \mu$</td>
</tr>
<tr>
<td>SSM $Z' \rightarrow \tau \tau$</td>
<td>$2\tau$</td>
</tr>
<tr>
<td>Leptophobic $Z' \rightarrow bb$</td>
<td>$- \quad 2b$</td>
</tr>
<tr>
<td>Leptophobic $Z' \rightarrow tt$</td>
<td>$1e, \mu \geq 1b, \geq 1J/2j$</td>
</tr>
<tr>
<td>SSM $W' \rightarrow lv$</td>
<td>$1e, \mu$</td>
</tr>
<tr>
<td>SSM $W' \rightarrow \tau \nu$</td>
<td>$1\tau$</td>
</tr>
<tr>
<td>HVT $V' \rightarrow WV \rightarrow qqqq$ model B</td>
<td>$0e, \mu$</td>
</tr>
<tr>
<td>HVT $V' \rightarrow WH/ZH$ model B</td>
<td>multi-channel</td>
</tr>
<tr>
<td>LRSM $W'_{R} \rightarrow tb$</td>
<td>multi-channel</td>
</tr>
</tbody>
</table>

### Results

- $Z'$ mass: 4.5 TeV
- $W'$ mass: 5.6 TeV
- $V$ mass: 4.15 TeV
- $f/m = 1\%$
- $g_V = 3$

**References:**
- ATLAS-CONF-2018-017
- ATLAS-CONF-2018-016
$Z' \rightarrow bb$ in Di-bjets Searches

- The sequential standard model (SSM) the $Z'$ boson has the **same couplings** to SM fermions as the SM $Z$ boson
- The leptophobic $Z'$ model having **vanishing couplings** to leptons
- A simplified dark matter model with $Z'$ axial-vector mediator

**Di-bjet background** estimated by the falling $m(jj)$ distribution. A sliding-window fitting technique is used.
\( Z' \rightarrow \text{ttbar in Top Quark Pair Searches} \)

- A leptophobic \( Z' \) model
  - Topcolor-assisted-technicolor (TC2)
  - Only couples to first- and third-generation quarks
- Simplified dark matter models with \( Z' \) vector/axial-vector mediator

Considering the leptons-plus-jets topology
- \( t \rightarrow Wb \)
- \( W \rightarrow e\nu/\mu\nu \) or \( W \rightarrow \tau\nu \) if the \( \tau \) decays leptonically
  - The other \( W \) boson decays into quarks
- \( \sim 30\% \) of \( \text{ttbar} \) events decays in this way
The sequential standard model (SSM) the $W'$ boson has the same couplings to SM fermions as the SM $W$ boson.

- Search for $W'$ decaying into a lepton (electron /muon) and MET
- using 2015+2016+2017 data (79.8 fb$^{-1}$ in total)
Several models with extra-dimension(s) provide solutions to the hierarchy problem

<table>
<thead>
<tr>
<th>Model</th>
<th>$\ell, \gamma$</th>
<th>Jets$^\dagger$</th>
<th>$E_{\text{miss}}^T$</th>
<th>$\int L , dt [\text{fb}^{-1}]$</th>
<th>Limit</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADD $G_{KK} + g/q$</td>
<td>$0, e, \mu$</td>
<td>$1 - 4 , j$</td>
<td>Yes</td>
<td>36.1</td>
<td>$M_D$</td>
<td>7.7 TeV</td>
</tr>
<tr>
<td>ADD non-resonant $\gamma\gamma$</td>
<td>$2 \gamma$</td>
<td>$-</td>
<td>-</td>
<td>36.4</td>
<td>$M_A$</td>
<td>8.6 TeV</td>
</tr>
<tr>
<td>ADD OBH</td>
<td>$-</td>
<td>$2 , j</td>
<td>-</td>
<td>37.0</td>
<td>$M_8$</td>
<td>8.9 TeV</td>
</tr>
<tr>
<td>ADD BH high $\sum p_T$</td>
<td>$\geq 1, e, \mu$</td>
<td>$\geq 2 , j$</td>
<td>-</td>
<td>3.2</td>
<td>$M_{88}$</td>
<td>8.2 TeV</td>
</tr>
<tr>
<td>ADD BH multijet</td>
<td>$-</td>
<td>$\geq 3 , j$</td>
<td>-</td>
<td>3.8</td>
<td>$M_{88}$</td>
<td>9.55 TeV</td>
</tr>
<tr>
<td>RS1 $G_{KK} \rightarrow \gamma\gamma$</td>
<td>$2 \gamma$</td>
<td>$-$</td>
<td>-</td>
<td>36.7</td>
<td>$G_{KK}$ mass</td>
<td>4.1 TeV</td>
</tr>
<tr>
<td>Bulk RS $G_{KK} \rightarrow WW/ZZ$</td>
<td>multi-channel</td>
<td>-</td>
<td>-</td>
<td>36.1</td>
<td>$G_{KK}$ mass</td>
<td>2.3 TeV</td>
</tr>
<tr>
<td>Bulk RS $g_{KK} \rightarrow tt$</td>
<td>$1, e, \mu$</td>
<td>$\geq 1 , b, \geq 1 , J/\ell$</td>
<td>Yes</td>
<td>36.1</td>
<td>$g_{KK}$ mass</td>
<td>3.8 TeV</td>
</tr>
<tr>
<td>2UED / RPP</td>
<td>$1, e, \mu$</td>
<td>$\geq 2 , b, \geq 3 , j$</td>
<td>Yes</td>
<td>36.1</td>
<td>KK mass</td>
<td>1.8 TeV</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$n = 2$

$n = 3$ H1Z NLO
$n = 6$

$n = 6, M_D = 3$ TeV, rot BH
$n = 6, M_D = 3$ TeV, rot BH

$k/M_{KK} = 0.1$
$k/M_{KK} = 1.0$
$\Gamma/m = 15\%$

Tier (1,1), 2J(A^{(1,1)} \rightarrow tt) = 1
Large Extra Dimension Model

- Large extra dimension model (ADD model) — product spacetime

With \( n \) extra spatial dimensions of size \( R \), the plank scale in \( 4+n \) dimensions given by,

\[
M_{Pl} \sim M_D^{2+n} R^n
\]

where \( M_D \) is the fundamental scale

e.g. with 2 extra dimensions whose size is \( 10^{16} \text{ TeV}^{-1} \) (~1mm scale), \( M_D \) is at TeV scale large compared with the Plank scale (\( 10^{-35} \text{ m} \))

Lower Limits of \( M_D \) from mono jet + MET analysis

---

\( M_{Pl} \sim M_D^{2+n} R^n \)

\( M_D \) is the fundamental scale

\( M_{Pl} \) is at TeV scale large compared with the Plank scale (\( 10^{-35} \text{ m} \))
Randall-Sundrum Models

A warped external dimension in which

- only gravity propagates — RS1 scenario
- both gravity and all SM fields propagate — bulk RS scenario

Mass term suppressed exponentially, without introducing new hierarchy problem

Limits on $G_{kk}$ (Kaluza-Klein excitations of gravitons), from VV resonance searches where $V$ is W/Z boson, VV combination includes 5 leptonic and hadronic final states from $\ell\ell\ell\ell$ to $qqqq$

$\sigma(pp \rightarrow G_{kk}) \times B(G_{kk} \rightarrow WW + ZZ)$

$\sigma(pp \rightarrow G_{kk}) \times B(G_{kk} \rightarrow WW + ZZ)$

$\sigma(pp \rightarrow G_{kk}) \times B(G_{kk} \rightarrow WW + ZZ)$

Almost same exclusion range to 36.1 fb$^{-1}$ VV combination results
Vector Like Quarks

predicted by many BSM models aimed at solving the hierarchy problem
Vector-like Quarks (VLQ)

Vector-like quarks are predicted by many BSM models aimed at solving the hierarchy problem, e.g. little Higgs, Composite Higgs

- color-triplet spin-\(\frac{1}{2}\) fermions
- left- and right-hand particles have same quantum numbers
- could be singlet, doublet or triplet of \(T, B, X\) or \(Y\)
  - \(T (2/3e), B(-1/3e), X(5/3e), Y(-4/3e)\)
  - \(T, B, (X,T), (T,B), (B,Y), (X,T,B), (T,B,Y)\)
- couples to preferentially to third-generation quarks
  assuming: couples to SM particles only (No \(T\rightarrow WB\))

Decay
\[
\begin{align*}
T & \rightarrow Wb, Zt, Ht \\
B & \rightarrow Wt, Zb, Hb
\end{align*}
\]

Single Production

Pair Production
A Combination of ATLAS pair-product VLQ searches

- The focus was on **pair production** in the past years
  - ✓ strong production (larger cross-section)
  - ✓ model independence

**Strategy for pair-production is to target different final states with optimized analyses**

<table>
<thead>
<tr>
<th>Analysis</th>
<th>$T\bar{T}$ decay</th>
<th>$B\bar{B}$ decay</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H(bb)t + X$</td>
<td>$HtH\bar{t}$</td>
<td>-</td>
</tr>
<tr>
<td>$W(\ell\nu)b + X$</td>
<td>$WbW\bar{b}$</td>
<td>-</td>
</tr>
<tr>
<td>$W(\ell\nu)t + X$</td>
<td>-</td>
<td>$WtW\bar{t}$</td>
</tr>
<tr>
<td>$Z(\nu\nu)t + X$</td>
<td>$ZtZ\bar{t}$</td>
<td>-</td>
</tr>
<tr>
<td>$Z(\ell\ell)t/b + X$</td>
<td>$ZtZ\bar{t}$</td>
<td>$ZbZ\bar{b}$</td>
</tr>
<tr>
<td>tril./s.s. dilepton</td>
<td>$HtH\bar{t}$</td>
<td>$WtW\bar{t}$</td>
</tr>
<tr>
<td>fully-hadronic</td>
<td>$HtH\bar{t}$</td>
<td>$HbH\bar{b}$</td>
</tr>
</tbody>
</table>

*Mass limits of doublet $T$, where $Ht+X$ limits are the strongest (situation would change with different branch ratio, 2D plots in next page)*
Model Independent Lower Mass Limits

Assuming

\[
\text{Br}(T \rightarrow Ht) + \text{Br}(T \rightarrow Zt) + \text{Br}(T \rightarrow Wb) = 1
\]
\[
\text{Br}(B \rightarrow Hb) + \text{Br}(B \rightarrow Zb) + \text{Br}(B \rightarrow Wt) = 1
\]

★ Excluding T(B) mass below 1.31(1.03) TeV for ANY combination of branching ratio.

⇒ With the limit above 1 TeV, the attention is recently shifting towards single production, which is dominant at higher VLQ masses (depending on the model parameters).

\text{arxiv:1808.02343}
Summary

ATLAS is looking for BSM signals in a large variety of final states

Though no new physics is find, limits are improved a lot (or set for the first time) in these analyses. The limits are guiding us for future analysis.

With new techniques and full Run-2 data been used in more and more analysis teams, we expect to have improved results in next years and are looking forward to see new signals.
Back Up
A combination of $VV$, $VH$, $ll$, $lv$ searches for

- Heavy flavor triplet model (HVT)
  - model A: Drell-Yan, weak coupling
  - model B: Drell-Yan, strong coupling
  - model C: VBF (no exclusion region find)
- Randall-Sundrum model (Page 20)
- narrow heavy scalar resonance

Table 2: Signal models, resonances, and decay modes considered in the combination.

<table>
<thead>
<tr>
<th>Model \ Decay mode</th>
<th>$WW$</th>
<th>$WZ$</th>
<th>$ZZ$</th>
<th>$WH$</th>
<th>$ZH$</th>
<th>$ll$</th>
<th>$\ell\nu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>HVT</td>
<td>$Z'$</td>
<td>$W'$</td>
<td></td>
<td>$W'$</td>
<td>$Z'$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bulk RS</td>
<td>$G_{KK}$</td>
<td>$G_{KK}$</td>
<td></td>
<td>$Z'$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scalar</td>
<td>Scalar</td>
<td>Scalar</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
$V'$ — Combination of searches for heavy resonance in bosonic and leptonic final states

arxiv:1808.02380
Lower mass limit (TeV)

- singlet $T$ : 1.31
- doublet $T$ : 1.37
- singlet $B$ : 1.22
- $B$ in $(T, B)$ : 1.37
- $B$ in $(B, Y)$ : 1.14