ATLAS results on searches for exotic new particles

Sara Alderweireldt
on behalf of the ATLAS Collaboration

Aspen 2018 – The Particle Frontier
Aspen, CO
March 28, 2018
**Introduction**

- Many BSM theories:
  - Grand Unification Theory
  - Sequential Standard Model
  - Extra dimensions
  - Dark sector extensions
  - Gravitons
  - Two-Higgs-doublet model
  - ...

- Many final states and many regions of phase space to consider
  - Search for any deviation from the SM prediction

- Pushing limits both at high and low mass

- 2015+2016 dataset: 36.1 fb⁻¹

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

#### Status: July 2017

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<thead>
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<th>Jets</th>
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#### Reference

- ATLAS-CONF-2016-030
- ATLAS-CONF-2016-070
- ATLAS-CONF-2017-027
- ATLAS-CONF-2017-055
- ATLAS-CONF-2017-051

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### ATLAS Online Luminosity

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<td>2017</td>
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### DM Simplified Exclusions

- Dijet
- Dijet 8 TeV
- Dijet 13 TeV
- Dijet + ISR
- Dijet TLA
- Dijet + ISR
- $E_{\text{miss}}$ + jet
- $E_{\text{miss}}$ + Z
- $E_{\text{miss}}$ + $W$
<table>
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Higgs decays to light bosons \( H(125) \rightarrow XX \rightarrow 4l \)

- **motivation**: higgs portal models, hidden sectors, dark matter
  → setting upper limits on the Higgs boson branching ratio to BSM particles

- three analysis regions targetting different processes
  - \( H(125) \rightarrow ZX \rightarrow 4l \) (2l2e and 2l2\( \mu \))
  - \( H(125) \rightarrow XX \rightarrow 4l \), \( m(X) \in [15,60] \) GeV (4e, 2e2\( \mu \) and 4\( \mu \))
  - \( H(125) \rightarrow XX \rightarrow 4l \), \( m(X) \in [1,15] \) GeV (4\( \mu \))

- \( X \) is new vector boson \( Z_d \) or pseudoscalar \( a \) with low mass
Higgs decays to light bosons $H(125) \rightarrow XX \rightarrow 4l$

- set 95% CL upper limits on the fiducial cross section for $H \rightarrow ZX \rightarrow 4l$ & $H \rightarrow XX \rightarrow 4l$ (model independent)
- upper limits are applicable to any model with $H(125)$ decays to 4 leptons via two intermediate, on-shell, narrow, promptly-decaying bosons

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EXOT-2016-22

S. Alderweireldt ATLAS results on searches for exotic new particles (28/Mar 2018)
Doubly Charged Higgs \( pp \rightarrow H^{++}H^{--} \rightarrow l^+l^-l^+l^- \)

- dedicated 2-, 3-, and 4-lepton channels to optimize signal acceptance
- fit invariant mass
  - invariant mass of same-charge lepton pair in 2- and 3-lepton channels
  - average mass in 4-lepton channel
- dominant systematic uncertainties
  - fake leptons
  - charge misidentification
  - background estimation

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S. Alderweireldt

ATLAS results on searches for exotic new particles (28/Mar 2018)
Doubly Charged Higgs

\[ pp \rightarrow H^{++} H^{--} \rightarrow l^+ l^- l^- \]

- set lower limit on \( m(H^{\pm\pm}) \) at 95% CL
- \( B(H^{\pm\pm} \rightarrow e^+ e^-) + B(H^{\pm\pm} \rightarrow e^+ \mu^-) + B(H^{\pm\pm} \rightarrow \mu^+ \mu^-) = B(H^{\pm\pm} \rightarrow l^+ l^-) \)
- mass limit derived for all combinations of the partial branching ratios
  - lower limit above 770 (450) GeV for \( B(H^{\pm\pm} \rightarrow l^+ l^-) = 100(10)\% \) for \( H_L^{\pm\pm} \)
  - lower limit above 670 (320) GeV for \( B(H^{\pm\pm} \rightarrow l^+ l^-) = 100(10)\% \) for \( H_R^{\pm\pm} \)
Doubly Charged Higgs

\[ pp \rightarrow H^{++} H^{--} \rightarrow \ell^{+} \ell^{+} \ell^{-} \ell^{-} \]

- the muon channel is the most powerful, but the differences are small
- minimum limit as a function of \( B(H^{\pm \pm} \rightarrow l^{\pm} l^{\pm}) \)
- limits derived for \( H^{\pm \pm}_L \) and \( H^{\pm \pm}_R \)
  - lower limit above 770 (450) GeV for \( B(H^{\pm \pm} \rightarrow l^{\pm} l^{\pm}) = 100(10)\% \) for \( H^{\pm \pm}_L \)
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| Search for Higgs decays to beyond the standard model light gauge bosons in **four-lepton events** with the ATLAS detector at $\sqrt{s} = 13$ TeV  | $H(125) \rightarrow XX \rightarrow 4l$ | EXOT-2016-22 | leptonic | low mass |
| Search for doubly charged Higgs boson production in **multi-lepton final states** with the ATLAS detector using proton–proton collisions at $\sqrt{s} = 13$ TeV  | $pp \rightarrow H^{++}H^{--}
\rightarrow l^+l^+\nu\nu$I | EXOT-2016-07 | leptonic | high mass |
| Search for heavy resonances decaying into a W or Z boson and a Higgs boson in final states with **leptons and b-jets** in 36 fb$^{-1}$ of $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector  | $V' \rightarrow VH
\rightarrow (l\nu/l\nu/\nu\nu)bb$ | EXOT-2016-10 | semi-leptonic | intermediate/high mass |
| Search for WW/WZ resonance production in **lvqq final states** in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector  | $X \rightarrow WV \rightarrow lvqq$ | EXOT-2016-28 | semi-leptonic | intermediate/high mass |
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Heavy resonance $\rightarrow$ VH in semi-leptonic decays

$W'/Z'/ggF \ A/\bbA \rightarrow \ VH \rightarrow (l\nu/ll/\nu\nu)\bb$

- **motivation:** heavy resonances, 2HDM, heavy vector triplets, ...

- analysis setup using dedicated categories
  - 0-2 lepton channels
  - resolved or merged bb regimes (small- and large-R jets)
  - various multiplicities of main and additional b-jets

- reconstructed resonance mass dependent on channel: $m_{Vh}$ and $m_{T,Vh}$

![Graphs showing data and backgrounds for different channels and mass distributions.](image)

- resolved, 1 lep, 2+ jets, 1 b-tag
- resolved, 2 lep, 2+ jets, 2 b-tags
- merged, 0 lep, 1+ large-R jet, 2+0 b-tags

ATLAS results on searches for exotic new particles (28/Mar 2018)
Heavy resonance → VH in semi-leptonic decays

$W'/Z'/ggF \ A/\bb A \rightarrow VH \rightarrow (l\nu/ll/\nu\nu)\bb$

- 95% CL upper limits for $Z'\rightarrow Zh$ & $W'\rightarrow Wh$ production
- observed exclusion contours in the HVT parameter space
- 95% CL upper limits for $A\rightarrow Zh$ with $h\rightarrow \bb$
- interpretations following various models available in the paper
Heavy resonance → WV in semi leptonic decays

\[ X \rightarrow WV \rightarrow lvqq \]

- **motivation:** composite H, extra dimensions, heavy vector triplets, ...
- **analysis using dedicated categorization**
  - merged (lvJ) or resolved (lvjj) quark pair
  - low- or high purity boson tagging (D\(_2\))
  - WW or WZ signal
  - DY or VBF production

![Resolved SR (WW)](image1)

![Resolved SR (WZ)](image2)

![Resolved CR](image3)

![Merged CR](image4)

![D\(_2\) variable](image5)
Heavy resonance $\rightarrow$ WV in semi leptonic decays

$X \rightarrow WV \rightarrow l\nu qq$

- **motivation:** composite H, extra dimensions, heavy vector triplets, ...
- **analysis using dedicated categorization**
  - merged (lvj) or resolved (lvjj) quark pair
  - low- or high purity boson tagging (D2)
  - WW or WZ signal
  - DY or VBF production
- **perform simultaneous binned ML fit to m(WV) distributions**

**Data**

- merged, VBF, WW, high-purity
- merged, ggF, WZ, low-purity
- resolved, VBF, WW

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S. Alderweireldt

ATLAS results on searches for exotic new particles (28/Mar 2018)
Heavy resonance $\rightarrow$ WV in semi-leptonic decays

$X \rightarrow WV \rightarrow l\nu qq$

- 95% CL upper limits for various models; more in the paper
- largest excess $2.7\sigma$ local

**VBF, HVT model $Z'$**

**VBF, Heavy-scalar model**

**ggF, HVT model $W'$**

**ggF, graviton model**
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<td><strong>A search for high-mass resonances decaying to $\tau\nu$</strong> in pp collis-</td>
<td>$W' \rightarrow \tau\nu$</td>
<td>EXOT-2017-06</td>
<td>hadronic</td>
<td>high mass</td>
</tr>
<tr>
<td>sions at $\sqrt{s} = 13$ TeV with the ATLAS detector</td>
<td></td>
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</tr>
</tbody>
</table>
Light resonances decaying to boosted quark pairs

- **motivation:** many models with mediators coupling to quarks & gluons
  - look at lower mass with ISR \( m_{Z'} < 200 \text{ GeV} \)
  - ISR allows highly efficient triggering at lower masses
    (compared to regular triggering on the resonance decay products)

- **topologies:**
  - 1 isolated \( \gamma \) + 1 large-R jet
  - 1 small-R jet + 1 large-R jet

- making use of \( \tau_{21} \) substructure variable and Designed Decorrelated Tagger (DDT; removing dependence of \( \tau_{21} \) on jet mass and \( p_T \))
  - \( \tau_N \) a measure of a jet’s compatibility with being fully aligned along N axes
  - \( \tau_{21} = \tau_2 / \tau_1 \) differentiates two-particle jets from the decay of
    a boosted resonance & a single-particle jet
  - aim to separate large-R signal jets and QCD \( \gamma \)+jet background

- background estimate using transfer factor method
Light resonances decaying to boosted quark pairs

ISR(γ/j) + boosted jj

- fit of large-R jet mass in jet & photon channels
  - background estimated separately per candidate mass
- 95% CL limits on the Z' cross section
- channels combined for limit on coupling g_q
- largest excess in the jet (γ) channel at m_{Z'} = 150 (140) GeV with local significance 2.5 (2.2)σ
Monojets and missing transverse momentum

- **motivation:** dark matter, compressed SUSY, extra dimensions, ...
  - many possible diagrams

- **requiring:** large missing transverse energy + 1 high-$p_T$ jet + ≤3 more jets ($p_T > 30$ GeV) + no leptons

- background is constrained using a likelihood fit to the $E_T^{miss}$ distribution in a set of control regions, taking into account systematic uncertainties

S. Alderweireldt

ATLAS results on searches for exotic new particles (28/Mar 2018)
Monojets and missing transverse energy

- setting model-independent limits using inclusive signal regions
- providing exclusion limits for a wide range of models (more in the paper)

### ATLAS

**F = 13 TeV, 36.1 fb⁻¹**
- Axial-Vector Mediator
- Dirac Fermion DM
- \( g_q = 0.25, g_b = 1.0 \)
- 95% CL limits

### ATLAS

**F = 13 TeV, 36.1 fb⁻¹**
- Axial-Vector Mediator
- Dirac Fermion DM
- \( g_q = 0.25, g_b = 1.0 \)
- 90% CL limits

### Number of extra dimensions

- 2
- 3
- 4
- 5
- 6
- 7
- 8
- 9
- 10
- 11

### Lower limit on \( M_{\text{extr}} \)

- Observed limit: \( \sigma = 2 \pm 1 \sigma_{\text{exp}} \)
- Expected limit: \( \sigma = 1 \pm 1 \sigma_{\text{exp}} \)
- Observed limit: \( \sigma = 2 \pm 1 \sigma_{\text{exp}} \)
- Expected limit: \( \sigma = 1 \pm 1 \sigma_{\text{exp}} \)

### ATLAS

**\( m_T = 13 TeV, 36.1 fb⁻¹ \)**
- 95% CL limits, \( E_{\text{T}}^{miss} > 400 \text{ GeV} \)
- Observed limit: \( \sigma = 1 \pm 1 \sigma_{\text{exp}} \)
- Expected limit: \( \sigma = 2 \pm 1 \sigma_{\text{exp}} \)
- ATLAS **\( m_T = 13 TeV, 3.2 fb⁻¹ \)**

### hadronic MONOJETS and missing transverse energy **monojet + \( E_{\text{T}}^{miss} \)**
Pair production of vector-like quarks

$T\bar{T} \rightarrow Ht + X$

- **motivation:** alternative for 4th generation quarks; hierarchy problem decays to vector bosons and 3rd generation quarks
- **approach:** 0/1-lepton + (many) jets, some b-tagged
  - 1-lepton = lepton + jets: sensitive to $T \rightarrow tH(bb)$ (12 regions)
  - 0-lepton = jets + MET: sensitive to $T \rightarrow tZ(\nu\nu)$ (22 regions)
- make use of Higgs and top tagging: categorize using $N(H)$, $N(t)$, $N(b)$, $N(j)$ multiplicities
- ML fit of effective mass
- derive 95% CL limit on production cross section

### Data / Bkg

<table>
<thead>
<tr>
<th>Events</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-lepton</td>
<td>2.0</td>
<td>1.5</td>
<td>1.0</td>
<td>0.5</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>1-lepton</td>
<td>3.0</td>
<td>2.5</td>
<td>2.0</td>
<td>1.5</td>
<td>1.0</td>
<td>0.5</td>
</tr>
</tbody>
</table>

### Top-tagged jet multiplicity

<table>
<thead>
<tr>
<th>Fraction of events</th>
<th>0</th>
<th>0.2</th>
<th>0.4</th>
<th>0.6</th>
<th>0.8</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top-tagged jet multiplicity</td>
<td>0</td>
<td>2</td>
<td>4</td>
<td>6</td>
<td>8</td>
<td>10</td>
</tr>
</tbody>
</table>

### Effective Mass Distribution

**ATLAS Simulation Preliminary**

- $\sqrt{s} = 13$ TeV
- 0-lepton
- $\geq 7j$, $\geq 2b$
- Total background
- $T\bar{T}$ doublet (1 TeV)
- $T\bar{T}$ singlet (1 TeV)
- $T\bar{T}$ → ZZ (1 TeV)

**ATLAS Preliminary**

- $\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$
- Search regions
- Post-fit (Bkg-only)

**Events**

- 1-lepton
- 0-lepton
- $E + light$-jets
- $E + 1c$
- $E + 21b$
- $E + 1b$
- Non-$E$
- Total Bkg unc.

**ATLAS Preliminary**

- $\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$
- 1-lepton + 0-lepton combination
- $SU(2)$ doublet

Theoretical (NNLO prediction ±1σ) vs 95% CL observed limit vs 95% CL expected limit
**Hadronic \( W' \rightarrow tb \)**

- **motivation**: universal extra dimensions, little Higgs, top assisted technicolor, Kaluza-Klein gravitons, …
  - \( tb \) final state sensitive to right handed \( W' \)s
- **topology**: 1 high-\( p_T \) b-jet + 1 large-R top-jet (bqq)
- **categorize**:
  - 0 or 1 b-tag
  - 6 regions each based on b- and top tagging criteria
- making use of shower deconstruction top tagger


Hadronic $W' \rightarrow tb$

- fit reconstructed $m_{tb}$ in signal and validation regions
- derived 95% CL limits on the cross section
- largest excess at $m = 2.25$ TeV with local significance of 2.0$\sigma$

ATLAS results on searches for exotic new particles (28/Mar 2018)
Heavy resonances decaying to taus

- **motivation**: $W'$ preferential coupling to 3rd gen as explanation for anomalies, mass hierarchy, …
  - might not appear in $e/\mu$ final states and therefore requires targeted $\tau$ search
- selecting events with taus and large missing transverse energy
- deriving model-independent 95% CL limits
- interpretations in SSM and non-universal $G(221)$
Summary

- presented 9 recent ATLAS exotics searches using the 2015+2016 dataset (36.1 fb⁻¹)
- results covering many final states and a wide range of masses
- derivation of model-independent limits as well as interpretations testing a large number of models
- no hints of new physics yet

- for the future
  - more data to be analysed (2017+2018)
  - several more results in the pipeline
  - all public results at: [https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults](https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults)
Backup
Jet substructure

- crucial tool in searches for resonances decaying to highly boosted quark pairs, SM bosons, top quarks
- $\tau_{21}$ and $D_2$ variables to track two-pronged signal jets \cite{2},\cite{3}
- designed decorrelated tagger (DDT) \cite{4} to remove dependence on mass & $p_T$
- important for
  - ISR + boosted quark pair
  - $W' \rightarrow tb$
  - $X \rightarrow WV \rightarrow l\nu qq$

\cite{1} R. Jansky

\cite{2} EXOT-2017-01
Jet substructure

jet mass: \[ \sqrt{\left( \sum_{i \in J} E_i \right)^2 - \left( \sum_{i \in J} \vec{p}_i \right)^2} \]

- currently mostly using calorimeter-based jet substructure
- gain from including tracker information in substructure measurements
Jets

Resolved

Boosted/merged

Small-radius jets

Large-radius jet

Boosted jets: Increasing transverse momentum, $p_T$

[1] R. Jansky

S. Alderweireldt

ATLAS results on searches for exotic new particles  (28/Mar 2018)