Results on searches for Exotic phenomena with the ATLAS Detector

N. Chr. Benekos (NTUA)
On behalf of ATLAS collaboration

Only selected new highlights are to be discussed here

LQ candidate

Apologies if your favorite BSM search is not shown in this talk!
Excellent LHC performance in 2016!

- more data than all other years combined!
- Peak \( L = 1.4 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1} \) (exceeded design)
- higher pileup conditions

ATLAS: High data taking efficiency (>92%) and data quality efficiency (93-95%)

- **New physics sensitivity climbs**

### ATLAS Detector – Run 2

#### ATLAS pp 25ns run: April-October 2016

<table>
<thead>
<tr>
<th>Ecm</th>
<th>Year</th>
<th>Luminosity used in analyses</th>
<th>Uncertainty on luminosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sqrt{s} = 7 \text{ TeV} )</td>
<td>2011</td>
<td>4.5 fb(^{-1})</td>
<td>1.8% final</td>
</tr>
<tr>
<td>( \sqrt{s} = 8 \text{ TeV} )</td>
<td>2012</td>
<td>20.3 fb(^{-1})</td>
<td>2.8% final</td>
</tr>
<tr>
<td>( \sqrt{s} = 13 \text{ TeV} )</td>
<td>2015</td>
<td>3.2 fb(^{-1})</td>
<td>2.1% final</td>
</tr>
<tr>
<td>( \sqrt{s} = 13 \text{ TeV} )</td>
<td>2016</td>
<td>32.9 fb(^{-1})</td>
<td>3.2% prelim</td>
</tr>
</tbody>
</table>

**Luminosity weighted relative detector uptime and good data quality efficiencies (in %) during stable beam in pp collisions with 25ns bunch spacing at \( \sqrt{s} = 13 \text{ TeV} \) between April-October 2016, corresponding to an integrated luminosity of 35.9 fb\(^{-1}\). The toroid magnet was off for some runs, leading to a loss of 0.7 fb\(^{-1}\). Analyses that don’t require the toroid magnet can use that data.**
- Heavy boson resonances: $W'/Z'$
- Di-jet resonances / Dark Matter
- Di-boson resonances
- VH resonances
- $\gamma\gamma$ resonances

Final states:
- Leptons, Photons
- Hadrons (resolved, boosted)
- Decays with missing energy

Candidate event displays at the backup slides

Large diversity of theoretical models:
(Extra-Dimensions (ED), Sequential SM (SSM), Lepto-Quark, ...) giving alternative solutions to the hierarchy problem, weakness of gravity dark matter, grand unification, etc.

All results available on the ATLAS Exotics webpage:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults
BSM models introduce new heavy charged spin-1 gauge-bosons $W'$:

- Benchmark model: SSM
  - Same fermion coupling as the SM $W$,
  - no coupling to $W,Z$
  - Interference between $W$ and $W'$ neglected

- Analysis Strategy: exactly one high- $p_T$ lepton and large $E_T^{\text{miss}}$
  - Compare transverse mass distribution ($m_T$) to SM predictions

\[ m_T = \sqrt{2p_T E_T^{\text{miss}}(1 - \cos \phi_{\ell\nu})}, \]

Amongst others, need to control extremely well:
- Muon scale and resolution
- Electron fake-levels
- Isolation

**LEPTON + $E_T^{\text{miss}}$ RESONANCES**

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**ATLAS-CONF-2017-016**

**10 May 2017**

N. Chr. Benekos – NTUA on behalf of ATLAS Collaboration
Lepton + $E_T^{\text{miss}}$ resonances

**ATLAS-CONF-2017-016**

<table>
<thead>
<tr>
<th>Decay</th>
<th>$m_{W'}$, lower limit [TeV]</th>
<th>Expected</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W' \rightarrow e\nu$</td>
<td>5.09</td>
<td>5.22</td>
<td></td>
</tr>
<tr>
<td>$W' \rightarrow \mu\nu$</td>
<td>4.70</td>
<td>4.45</td>
<td></td>
</tr>
<tr>
<td>$W' \rightarrow \ell\nu$</td>
<td>5.22</td>
<td>5.11</td>
<td></td>
</tr>
</tbody>
</table>

Limit set on $\sigma\text{Br}$ for $W'$
A SSM $W'$ is excluded up to 5.22 TeV
(3.2 TeV in Run-1)

Limits improved by $\sim 1$ TeV wrt previous analysis based on 3.2 fb$^{-1}$

*Phys. Lett. B 762 (2016) 334*
Straightforward analysis, looking for a di-lepton pairs
Selection:
\[ \geq e (\mu) \text{ with } E_T(p_T) > 30 \text{ GeV} \]
Isolation and quality criteria
\[ \varepsilon_{\text{tot}} = 73\% (44\%) \text{ for } ee(\mu\mu) \text{ channel for } m_{Z'} = 3 \text{ TeV} \]

Backgrounds with two real leptons:
• DrellYan (dominant), \textit{tt}, single-top,\textit{WW} , \textit{WZ} , and \textit{ZZ} by MC

Background due to jet faking electrons:
• \textit{W} +jets and multi-jet events estimated from data

New physics could alter the \textit{ee} and \textit{\mu\mu} mass distributions in two ways:
- a new resonance (Z') would create a bump
- non-resonant effects could change the shape (contact interaction)

The NNLO QCD corrections are a factor of \(~ 0.98\) at \(m_{Z'} = 3 \text{ TeV}\)
Search for narrow resonance with binning optimized wrt detector resolution from 120 GeV to 5 TeV

No significant excess is observed

\[ \sqrt{s} = 13 \text{ TeV}, \ 36.1 \text{ fb}^{-1} \]

\[ \text{Observed } p_{\text{t}}', Z'_{\chi} \rightarrow \ell\ell \]

\[ \text{Local significance} \]

\[ \text{Global significance for largest excess} \]

\[ M_{Z'} \ [\text{TeV}] \]

\[ \sigma_B [\text{pb}] \]

**Z' \Psi** (0.5% width) > 3.36 TeV

**Z'_{SSM}** (3% width) > 4.05 TeV

Limit Increased by 700 GeV wrt limit obtained with 3.2 fb\(^{-1}\)
Contact Interaction (CI): use an effective Lagrangian with 4-lepton couplings depending on a scale

\[ \mathcal{L} = \frac{g^2}{\Lambda^2} \left[ \eta_{LL}(q_L \gamma_{\mu} q_L) (\bar{\ell}_L \gamma_{\mu} \ell_L) + \eta_{RR}(q_R \gamma_{\mu} q_R) (\bar{\ell}_R \gamma_{\mu} \ell_R) + \eta_{LR}(q_L \gamma_{\mu} q_L) (\bar{\ell}_R \gamma_{\mu} \ell_R) + \eta_{RL}(q_R \gamma_{\mu} q_R) (\bar{\ell}_L \gamma_{\mu} \ell_L) \right] \]

- Different chiral structures tested:
  - Helicities left-right , left-left, right-rights
    - \( \eta_{LR\text{(RL)}} = \pm 1 \)
    - \( \eta_{LL\text{(RR)}} = \pm 1 \)
    - the others to zero
  - (con)destructive interference of signal model with SM QCD
    \[ \eta_{ij} = -1(+1) \]

**Exclusion limits on CI**

Limits on the llqq CI energy scale range between 23.5 TeV and 40.1 TeV

\[ \frac{\text{data}}{3.2 \text{ fb}^{-1}} \]

Limits on the llqq CI energy scale range between 16.7 TeV and 25.2 TeV @2015

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**ATLAS-CONF-2017-027**
Several models are constrained by 2e or 2μ final states
Doubly charged Higgs occur in many BSM models: Doubly charged Higgs within L-R symmetric models, Little Higgs, Higgs triplet, Type II seesaw, etc..

**ATLAS-CONF-2016-051**

**Same flavor same sign (ee, μμ)**

[Graph showing same-sign di-lepton final states with mass limits at 95% C.L.]

\[
\begin{align*}
H^{++/-} & > 420 \text{ GeV} \\
H^{++/-} & > 570 \text{ GeV (Run-1: m(H_R)>370 GeV, m(H_L)>550 GeV)}
\end{align*}
\]
Highly sensitive channel for new neutral resonance with LFV decays

- Require different flavor leptons
- Main background from $t\bar{t} \rightarrow W^+W^-$
- Test for LFV in $Z'$ models and QBH in RS and ADD models.
- No excess observed.

<table>
<thead>
<tr>
<th>Model</th>
<th>Expected limit (TeV)</th>
<th>Observed limit (TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$e\mu$</td>
<td>$e\tau$</td>
</tr>
<tr>
<td>$Z'$</td>
<td>3.2</td>
<td>2.7</td>
</tr>
<tr>
<td>RPV SUSY $\tilde{\nu}_\tau$</td>
<td>2.5</td>
<td>2.1</td>
</tr>
<tr>
<td>QBH ADD $n=6$</td>
<td>4.6</td>
<td>4.1</td>
</tr>
<tr>
<td>QBH RS $n=1$</td>
<td>2.5</td>
<td>2.2</td>
</tr>
</tbody>
</table>

Heavy bosons and Extra Dimension interpretation

New scalar decaying in 2 photons predicted by several models (ED, additional Higgs fields,...)

\[ m_{\gamma\gamma} \sim 750 \text{ GeV}, \ 3.9\sigma \ (\text{local})/2.1\sigma \ (\text{global}) \]

**ATLAS-CONF-2016-059**

**JHEP 09 (2016) 1**

\[ \sqrt{s} = 13 \text{ TeV}, \ 2015, \ 3.2 \text{ fb}^{-1} \]

\[ \sqrt{s} = 13 \text{ TeV}, \ 15.4 \text{ fb}^{-1} \]
Unfortunately, no signal at $m(\gamma\gamma) \sim 750$ GeV…despite 2016 data (lumi x10)
Diboson resonances searches

Vast range of decay channels and various experimental signature categories to explore
- $WW$: $l\nu l\nu$, $l\nu qq$, $qqqq$
- $WZ$: $l\nu l\nu$, $l\nu qq$, $llqq$, $qqqq$
- $ZZ$: $l\nu l\nu$, $llvv$, $llqq$, $qqqq$, $vvqq$
- Experimental signature of the “merged” outgoing jets from boson decays: large-$R$ jets (boosted jets)

- Spin property, polarization effect

Many inspiring models and effective theory interpretations: HVT, RS graviton, 2HDM, etc.

Largely overlap the Higgs searches and SM measurements with similar final states
Inspired by Run-1 excess ($\sim 2$TeV)

Looking in leptonic/hadronic decay channels using different topologies for hadronic decays:
- Resolved: two small-$R$ jets ($j_1; j_2$).
- Boosted: single large-$R$ jet ($J$).

*JHEP 12 (2015) 55*
Searches in Diboson final states using fat-Jet (J) substructure based V tagger (i.e. W&Z)

Models: RS Graviton or heavy scalar boson decay to WW/ZZ, Heavy Vector Triplet (HVT)

Excess from Run-1 not confirmed in Run-2 (1.9 σ local)
Follow up with more data

High-momentum → boosted topology:
→ anti-kT R=1.0,|η|<2
→ pT>200GeV,m>30GeV after trimming
→ Boson-tagging:
  mass window of 15 GeV around W or Z mass
  pT-dependent cut on D2(beta=1)

N(tracks)<30 - improves the sensitivity by ~20-30%
**Diboson Resonance Searches (with leptons)**

**ZV (with Z to dilepton)**
- $2e$ or $2\mu,$ $Z(\ell\ell)+V(qq),$: resolved+boosted
- **Most sensitive at lower mass** (also VBF channel)

**ZV (with Z to $\nu\nu$)**
- $\nu$ MET $>200$ GeV + topo cuts

**WV (with W to $l\nu$)**
- $1\ e/\mu$ MET $>100$ GeV
- Z($\nu\nu$)+V(qq), W($l\nu$)+V(qq): competitive with all-hadronic at high-mass. Only boosted channels in this iteration.

Enhance *sensitivity* by adding “low-purity” signal regions (mass-tagged, not boson-tagged)
Summary of Diboson resonance searches

\( \sqrt{s} = 13 \text{ TeV}, 13.2-15.5 \text{ fb}^{-1} \)

ATLAS Preliminary

95% C.L. exclusion limits

- HVT model \( A g_V = 1 \)
- Observed
- Expected
- \( qqqq \)
- \( l\nuqq \)
- \( l\nuqq \)
- \( vqqq \)

Limit on \( W' \) cross-section \( \times \) BR(WZ) from various decay modes

RS Graviton mass limit up to 2 TeV
HVT \( W' \) mass limit up to 2.4 TeV

ATLAS-CONF-2016-055
ATLAS-CONF-2016-062
ATLAS-CONF-2016-082
Dark Matter (DM) : Strategy

1. Look for the initial state radiation to tag DM pair production
   → Mono-X, with $X = \text{jet, } \gamma, W/Z; \ t/b \ or \ H$.
2. Look directly for the mediator (dijet resonance)

Mediator couples to DM with $g_{DM}$, to SM quarks with $g_q$

- DM cannot be reconstructed in detector:
  Look for accompanying signature (mono–X)
- Mediator can also decay into quark (Jet) pairs

Di–jet resonance signature

Direct mediator searches contributing to DM interpretations

ATLAS searches assume that Dark Matter (DM) is a Weakly Interacting Massive Particle (WIMP)
- Di-jets final states sensitive to a broad class of new phenomena, though generic features of BSM signals:
  - Sensitive to new particles in s- and t-channels, respectively
    - any new particle produced at the LHC must couple to quarks/gluons
    - dijet search is sensitive to all such particles
- Main background: SM dijet production

**Resonances searches**

- Bump hunt in the falling standard model $m_{jj}$ spectrum
- Sensitive to narrow resonance:
  - Quantum Black Hole (QBH), Excited quark ($q^*$), $W'$, excited $W^*$
Searches for di-jet high-mass resonances

Jet selections:
- Single jet trigger (HLT) $p_T > 380$ GeV
- $p_T (j_1) > 440$ GeV, $p_T (j_2) > 60$ GeV

Multi-jet background (t-channel scattering) reduced with requirement on rapidity difference $|y^*| = |(y_1 - y_2)/2| < 0.6$ (1.2 for $W^*$)

$m_{jj} > 1.1$ TeV (1.7 TeV for $W^*$)

Smooth QCD background from a Sliding Window Fit

Search for a localized excess:
- BumpHunter algorithm looks for the most discrepant region
- Pseudo-data used to evaluate the significance of the output

Limits on Models: $q^*$, QBH, $W'$, $W^*$, $Z'$ (Dark Matter mediator)

<table>
<thead>
<tr>
<th>Model</th>
<th>95% CL exclusion limit</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Observed</td>
</tr>
<tr>
<td>Quantum black hole</td>
<td>8.9 TeV</td>
</tr>
<tr>
<td>$W'$</td>
<td>3.6 TeV</td>
</tr>
<tr>
<td>$W^*$</td>
<td>3.4 TeV</td>
</tr>
<tr>
<td></td>
<td>3.77 TeV - 3.85 TeV</td>
</tr>
<tr>
<td>Excited quark</td>
<td>6.0 TeV</td>
</tr>
<tr>
<td>$Z'$ ($g_q = 0.1$)</td>
<td>2.1 TeV</td>
</tr>
<tr>
<td>$Z'$ ($g_q = 0.2$)</td>
<td>2.9 TeV</td>
</tr>
<tr>
<td>Contact interaction ($\eta_{LL} = -1$)</td>
<td>21.8 TeV</td>
</tr>
<tr>
<td>Contact interaction ($\eta_{LL} = +1$)</td>
<td>13.1 TeV</td>
</tr>
</tbody>
</table>

$\sigma \times A \times BR [pb]$}

No evidence of a localized contribution from BSM phenomena
Improved limits from 7% to 40% wrt analysis based on 3.2fb$^{-1}$
Dijet summary on DM mediator coupling

Combination of various dijet channels targeting different mass ranges

Sensitive to the parameter space for the leptophobic $Z'$ model
Select events with high $p_T$ jet(s) and $E_T^{\text{miss}}$

Trigger fully efficient for $E_T^{\text{miss}} > 250$ GeV

Dominant bkg $Z(\rightarrow \nu\nu)+\text{jets}$, $W(\rightarrow \ell\nu)+\text{jets}$ constrained in control regions (CRs) with leptons

Several signal regions with $E_T^{\text{miss}}$ cuts 250 - 700 GeV

Simultaneous fit to CRs and signal region (SR)

No excess $\rightarrow$ limits on several models

ADD for Large Extra-Dimensions, squark pairs production, WIMPs

Limits set in 2D Dark Matter/axial vector mediator masses space
Dijet and mono-X combined results for the leptophobic axial-vector model.

Complementary approaches to probe the DM parameter space:
- Dijet probes mediators production
- Mono-X searches cover mediators to DM

Limits Results highly depend on choice of coupling parameters

$g_q = 0.25$, $g_{DM} = 1$

previous $\gamma + X$ result, new one covers a much wider region

Dijet searches

- Di-jets final states sensitive to a broad class of new phenomena, though generic features of BSM signals:
  - Sensitive to new particles in s- and t-channels, respectively
    - any new particle produced at the LHC must couple to quarks/gluons
    - dijet search is sensitive to all such particles
- Main background: SM dijet production

**Di-jets angular distributions** anomalies:

\[ \chi = e^{2|\eta^*|} \approx \frac{1 + \cos \theta^*}{1 - \cos \theta^*} \]

- BSM give more isotropic signature wrt to QCD
- Deviations in angular variables from prediction
  - Contact interactions at compositeness scale \(\Lambda\)

New particles decaying to dijets

\[ W^' Z^' W^* \]

\[ q^* \]

\[ \Lambda \]
High-mass di-jet angular search

- Use CLs method to look for deviations in $\chi$
- Combined fit in 7 signal region above 3.4 TeV $\rightarrow$ sensitivity to the evolution in $m_{jj}$
- Test compatibility of data to SM and BSM models
Limit set on the compositeness scale of CI:
\[ \Lambda_{CI(DI)} > 19.9(12.6) \text{ TeV for constructive (destructive) interference with SM} \]
Events classified according to a number of isolated electrons, muons, photons, jets, b-jets and $E_T^{\text{miss}}$.

- SM background taking from simulation
- Look for a deviation from the SM in:

$$m_{bc}^2 = (p_b + p_c)^2$$

$$M_{\text{eff}} = E_T^{\text{missing}} + \sum_i |p_T^{\text{jet}_i}|$$

After classification, 639 event classes are found with at least one data event or a SM expectation greater than 0.1 events.
- Pseudo-data generated according to the SM and SM+signal expectation
- Tested sensitivity of this search to different signals
- Lowest p-value in data ($5 \cdot 10^{-4}$ in $1\mu 1e4b2j$) consistent at 70% level with the SM expectation → no significant excess observed

ATLAS-CONF-2017-001
**Summary of ATLAS exotics – now**

ATLAS has an extensive search program to prove or discard models.

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

**Status:** August 2016

<table>
<thead>
<tr>
<th>Model</th>
<th>$\ell, \gamma$</th>
<th>Jets†</th>
<th>$E_{\text{T}}^{\text{miss}}$</th>
<th>$\int \mathcal{L} dt$ [fb$^{-1}$]</th>
<th>Limit</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADD $G_{\text{VX}} + e/e'q$</td>
<td>–</td>
<td>$\geq 1j$</td>
<td>Yes</td>
<td>3.2</td>
<td>$M_{\text{max}}$</td>
<td>6.58 TeV</td>
</tr>
<tr>
<td>ADD non-resonant $\ell\ell$</td>
<td>$2, \mu$</td>
<td>–</td>
<td>–</td>
<td>20.3</td>
<td>$M_{\text{max}}$</td>
<td>4.9 TeV</td>
</tr>
<tr>
<td>ADD GGH $\rightarrow e\gamma$</td>
<td>$1, e, \mu$</td>
<td>$\geq 1j$</td>
<td>–</td>
<td>20.3</td>
<td>$M_{\text{max}}$</td>
<td>6.13 TeV</td>
</tr>
<tr>
<td>ADD Higgs $\rightarrow e\gamma$</td>
<td>$2j$</td>
<td>–</td>
<td>–</td>
<td>15.7</td>
<td>$M_{\text{max}}$</td>
<td>8.7 TeV</td>
</tr>
<tr>
<td>ADD $\text{BB}$ high $\sqrt{s}$</td>
<td>$\geq 1\ell, \mu$</td>
<td>–</td>
<td>–</td>
<td>3.2</td>
<td>$M_{\text{max}}$</td>
<td>6.2 TeV</td>
</tr>
<tr>
<td>ADD $\text{BB}$ multijet</td>
<td>–</td>
<td>$\geq 3j$</td>
<td>–</td>
<td>3.6</td>
<td>$M_{\text{max}}$</td>
<td>9.55 TeV</td>
</tr>
<tr>
<td>$\text{SR1}_{\text{GG}}$ $\rightarrow \ell\gamma$</td>
<td>$2\gamma$</td>
<td>–</td>
<td>–</td>
<td>2.8</td>
<td>$M_{\text{max}}$</td>
<td>12 TeV</td>
</tr>
<tr>
<td>Bulk $\text{RS}_{\text{GKK}} + WW \rightarrow q\bar{q}e\gamma$</td>
<td>$1, e, \mu$</td>
<td>1, $j$</td>
<td>Yes</td>
<td>12.2</td>
<td>$M_{\text{GKK}}$</td>
<td>1.24 TeV</td>
</tr>
<tr>
<td>Bulk $\text{RS}_{\text{GKK}} + WW \rightarrow bb\gamma$</td>
<td>$4b$</td>
<td>–</td>
<td>–</td>
<td>13.3</td>
<td>$M_{\text{GKK}}$</td>
<td>360–850 GeV</td>
</tr>
<tr>
<td>Bulk $\text{RS}_{\text{GKK}} + tt$</td>
<td>$1, e, \mu\geq 1j, b, 1j, j\gamma$</td>
<td>Yes</td>
<td>20.5</td>
<td>3.2</td>
<td>$M_{\text{max}}$</td>
<td>1.46 TeV</td>
</tr>
<tr>
<td>$\text{SU2HDM}_{\text{PP}}$</td>
<td>$1, e, \mu\geq 2j, 4j$</td>
<td>Yes</td>
<td>3.2</td>
<td>$M_{\text{max}}$</td>
<td>4.05 TeV</td>
<td></td>
</tr>
<tr>
<td>$\text{SSM}_{2}$ $\rightarrow \ell\ell$</td>
<td>$2, e, \mu$</td>
<td>–</td>
<td>–</td>
<td>13.3</td>
<td>$M_{\text{max}}$</td>
<td>2.03 TeV</td>
</tr>
<tr>
<td>$\text{SSM}_{2}$ $\rightarrow \ell\gamma$</td>
<td>2</td>
<td>–</td>
<td>–</td>
<td>10.5</td>
<td>$M_{\text{max}}$</td>
<td>1.5 TeV</td>
</tr>
<tr>
<td>Leptophobic $Z''$ $\rightarrow bb$</td>
<td>–</td>
<td>2 $b$</td>
<td>–</td>
<td>3.2</td>
<td>$M_{\text{max}}$</td>
<td>4.74 TeV</td>
</tr>
<tr>
<td>$\text{HVT}_{\text{W}}$ $\rightarrow WW + e$</td>
<td>$0, e, \mu$</td>
<td>1</td>
<td>Yes</td>
<td>13.2</td>
<td>$M_{\text{max}}$</td>
<td>2.47 TeV</td>
</tr>
<tr>
<td>$\text{HVT}_{\text{W}}$ $\rightarrow WW + \text{other}$</td>
<td>–</td>
<td>3</td>
<td>Yes</td>
<td>15.5</td>
<td>$M_{\text{max}}$</td>
<td>8.6 TeV</td>
</tr>
<tr>
<td>$\text{HVT}_{\text{W}} + WW + ZH$ model</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>3.2</td>
<td>$M_{\text{max}}$</td>
<td>2.31 TeV</td>
</tr>
<tr>
<td>$\text{LRSM}_{\text{W}} + \ell\ell$</td>
<td>$1, e, \mu$</td>
<td>2, $b, 1j, 1j\gamma$</td>
<td>Yes</td>
<td>20.3</td>
<td>$M_{\text{max}}$</td>
<td>1.92 TeV</td>
</tr>
<tr>
<td>$\text{LRSM}_{\text{W}} + \ell\ell$</td>
<td>$0, e, \mu\geq 1j$</td>
<td>–</td>
<td>–</td>
<td>20.3</td>
<td>$M_{\text{max}}$</td>
<td>1.76 TeV</td>
</tr>
</tbody>
</table>

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### ATLAS Preliminary

\[ \int \mathcal{L} dt = (3.2 - 20.3) \text{ fb}^{-1} \]

\[ \sqrt{s} = 8, 13 \text{ TeV} \]

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*Only a selection of the available mass limits on new states or phenomena is shown. Lower bounds are specified only when explicitly not excluded.

†Small-radius (large-radius) jets were studied by the later (1,l)
Conclusions

• The LHC is performing extremely well – beyond expectations
  – LHC delivered excellent data in 2016
  – All data consistent with SM expectations...No hint of new physics found...this year.
  – New limits significantly extend the Run 1 results: Limits set on many key BSM searches significantly extended beyond Run-1 (e.g. $W'_{\text{SSM}}$ by 1.5 TeV, etc...)

For a complete description of these results see the ATLAS public webpage: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/Winter201713TeV
Exciting future

- This dataset represents only about 1.2% of full LHC data at 13 TeV
- In run-2 we expect ~120-150 fb$^{-1}$ and by 2035 expect ~3000 fb$^{-1}$ of data
- LHC experiments are key for BSM searches.
  - Therefore LHC BSM searches are indispensable and should be continued in the new energy regime and with increasing statistics.
- Current dataset corresponds to only 2% of full LHC data

Are we looking at the right place?
Time for more effort in thinking of complementary searches?
Thank you
BACK UP SLIDES
The ATLAS Detector

General purpose detector
- excellent tracking in central region & muon spectrometer
- good energy measurements with fine segmented calorimeters

Muon Spectrometers

ex) Jet

Hadron Calorimeter

Electromagnetic Calorimeter

Inner Tracker
(Mag. field = 2T)

Muon measurements
**ATLAS Experimental challenges**

**ATLAS Preliminary**

$\sqrt{s} = 13$ TeV, $L = 3.1$ (2015) + 33.9 (2016) fb$^{-1}$

$|\eta| < 2.47$, $p_T > 27$ GeV

- Electrons from $Z\rightarrow ee$, 2015 data
- Electrons from $Z\rightarrow ee$, 2016 data

**EGAM-2017-002**

**ATLAS Preliminary**

$\sqrt{s} = 13$ TeV, 33.3 fb$^{-1}$

No TRT selection applied

**MUON-2017-001**

**ATLAS Preliminary**

$\sqrt{s} = 13$ TeV, 28 fb$^{-1}$

$60 < p_T < 300$ GeV

Anti-$k_T$, $R=0.4$ calorimeter jets

**EGAM-2017-002**

ATLAS performance close to or exceeding design specs in all compartments

**JETM-2016-003**

**JETM-2016-010**
After Higgs discovery, the Standard Model (SM) is a self-consistent theory. So far in good agreement with data.

13 TeV data are particularly interesting for searching of new heavy states.
Beyond the Standard Model Searches

- There are many big questions beyond the SM to be answered at TeV scale
- Big Ideas are constrained from theory and observed phenomena

“Exotic” basically cover the searches of any BSM new physics signatures at ATLAS, except: SUSY and BSM Higgs (not covered in this talk)

Big questions request a better and bigger ideas, as well as broader analysis topics at the TeV scale hadron colliders to explore the new phenomena of the “unknowns”

- Model guidance
- Signature driven
- Benchmark model interpretation

See arxiv:1311.0299
> Standard Model (SM):
  - An effective theory → has worked very well at energy scales probed so far

> Standard Model, Standard problems: Several limitations, many involving fine-tuning:
  - What happened to antimatter?
  - No explanation of masses, coupling constants
  - Why three families?
  - Hierarchy Problem / Gravity: Reconciling $m_W$ and $m_Z$ with $m_{\text{Planck}}$
  - Electroweak Symmetry Breaking: How does it really work?
  - Dark Matter: What is it?
  - Flavor
  - Strong CP Problem
  - …

> Because we can with the Large Hadron Collider (LHC)
Searches for new resonances

Neutral

dilepton

Charged

dijet

top

diphoton
diboson

new fermions
top partners

W(Z,H)
Discrimination of different models requires measurement of
  - cross section: limits with very little data
  - mass: exact value requires a visible peak
  - width: about same amount of data as for mass
  - backward-forward asymmetry: requires high statistics in order to divide events in categories

Backgrounds
  - relatively clean with good S/B
  - mostly tails of SM processes

Experimental challenges
  - detector resolution can be a key player
    - 1.3% - 2.4% for electrons and 7% for muons at 1 TeV mass

extra care for energy/momentum reconstruction above 1 TeV
**Searches for New Physics**

**Strategy:**
- Define selection based on signal signatures and background (bkg) kinematics.
- Compare data to SM bkg (MC + data driven) and MC signal predictions → data consistent with bkg+signal would be evidence for new physics.

**Background estimation**
- Irreducible background estimated using data in control region (CR) and extrapolated from CR to SR with Monte Carlo.
- Reducible background (fake/non isolated leptons, charge flip) estimated using data.
- Minor backgrounds estimated with pure Monte Carlo.

**No evidence for new physics:**
- Limits typically set on cross-section x branching fraction ($\sigma \times BR$).
- Comparisons provided for specific models, but usually possible for reader to constrain additional models.
• **Jets:**
  - Reconstructed from calorimeter energy clusters using the anti-$k_T$ algorithm with radius parameter $R = 0.4$
  - Jets are reclustered with $R = 1$ to search for boosted top quarks
  - Corrected for avg. energy deposition from pile-up (= multiple collisions, averaging 14 in 2015)
  - Jet energy scale calibrated with detector response from MC and 8 TeV data
  - Event rejected if contains jet identified as due to noise or non-collision

• **b-jets:**
  - Tagged by multivariate algorithm using the impact parameters of tracks in the jet, and the presence and flight paths of displaced vertices from b/c hadrons

• **Electrons:**
  - Matching EM calorimeter clusters to inner-detector tracks & TRT threshold

• **Muons:**
  - Matching tracks in the muon spectrometer and inner detector
Event Selection Inputs

- **Physics-object overlap removal:**
  - If 2 objects (e, μ, jet, or b-jet) are nearby, indicating mis-identification, one of them is discarded according to an optimized algorithm

- **Missing transverse energy:**
  \[
  \vec{p}_T^{\text{miss}} = - \left[ \sum_{\text{physics objects}} \vec{p}_T + \sum_{\text{other PV tracks}} \vec{p}_T \right]
  \]

  \[
  \text{MET} \equiv E_T^{\text{miss}} = |\vec{p}_T^{\text{miss}}|
  \]

- **Scalar } p_T \text{ sum**
  \[
  H_T = \sum_{\text{physics objects}} p_T
  \]

- **Effective mass:**
  \[
  m_{\text{eff}} = \sum_{\text{physics objects}} p_T + E_T^{\text{miss}}
  \]
Common Analysis procedures

• Define signal regions (SRs)
  – Based on $N_{\text{leptons}}, N_{\text{jets}}, N_{b-jets}$ with $T$ cuts, $H_T$, MET, $m_{\text{eff}}$, etc.
  – Targeting different regions in SUSY parameter space

• Estimate background for each SR in control regions (CRs)
  – Usually using Monte Carlo distributions to relate CR yields to SR yields
  – Background estimate from CRs validated using validation regions (VRs)
  – Smaller backgrounds often obtained from MC

• If no excess, set limits using the CLs prescription, accounting for systematic uncertainties:
  – Finite MC statistics
  – Theory, e.g., models used for background shapes
  – Jet energy scale and resolution
  – Lepton / b-jet ID efficiencies and purities
- Dark matter particles do not interact in the detector
  \[\rightarrow \text{Observed particles will have a large imbalance of } p_T.\]

Search strategies based on looking for events with high $E_{\text{miss}}$. 

M. Strassler 2015
A wide range of final states can be investigated exploiting the full potential of LHC experiments.
Dijet summary on DM mediator coupling

**Di-jet + ISR**

**ISR γ/jet -> trigger**

search in m_{jj} of dijet

arXiv:1703.09127

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**ATLAS-CONF-2016-030**

**Trigger Level Analysis**

- partial info stored
- ad-hoc calibration
- huge statistics

* fit technique more complicated

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High-mass di-jet (previous analysis)

ATLAS Preliminary March 2017

\( \sqrt{s} = 13 \text{ TeV}; 3.4-37.0 \text{ fb}^{-1} \)

\[ m_{Z'} \text{ for the leptophobic Z'} \text{ model} \]

arXiv:1703.09127

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**ATLAS-CONF-2016-060**

**γ+jet on 3.2/fb @ 13 TeV**

**JHEP 03 (2016) 041**

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**Record jets reconstructed at trigger level but do not record the rest of the event:**

High rate possible due to small size of event
Mono-Z(→ ll) searches

$Z \rightarrow ll$, $l = e, \mu$ - clean signature

$E_T^{\text{miss}} > 90$ GeV - reduce $Z+$jet bkg

Dominant and irreducible bkg $ZZ$ → Monte Carlo based

Limits set in 2D Dark Matter/vector mediator masses space

Main observable: Imbalanced $E_T^{\text{miss}}$

\[ \text{No excess of events observed so far} \]

\[ \text{ATLAS-CONF-2016-056} \]
ATLAS Highest transverse mass in $\mu$ channel

$p_T \, 2.01 \text{ TeV GeV}$

$E_{\text{miss}} \, 1.05 \text{ TeV}$
Candidate event: high mass di-lepton

ATLAS Highest dielectron invariant mass 2.38 TeV

$E_T$ 889 GeV

$E_T$ 868 GeV
Candidate event $e^+\mu^-$

- Electron pT of 1164 GeV, $\eta$ of -2.8.
- Antimuon has an pT of 617 GeV, $\eta$ of 0.4.
- MET of the event = 72 GeV.
- Mass(electron-antimuon) = 2089 GeV.
Dijet searches

- the two central high-p\text{T} jets each have transverse momenta of 3.79 TeV,
- |y*| of 0.38 and their invariant mass is 8.12 TeV.
- The event passes both the resonance and angular selections.
  - $E_{\text{T}}^\text{miss}$ in this event is 44 GeV.
### ATLAS Exotics Searches* - 95% CL Exclusion

**Status: July 2015**

#### Summary of ATLAS exotics – Run 1

| Model | $\ell, \gamma$ | Jets | $E_{\text{miss}}$ | $|\mathcal{L}| dt$ (fb$^{-1}$) | Limit |
|-------|----------------|------|------------------|-------------------------------|-------|
| ADD $G_{WW} + q \bar{q}$ | $\ell, \gamma$ | $J$ | Yes | 20.3 | $m_{\ell} = 5.25$ TeV |
| ADD non-resonant $tt$ | $2e, \mu$ | $\ell$ | Yes | 20.3 | $m_{\ell} = 4.7$ TeV |
| ADD $G_{QB} \rightarrow \ell \gamma$ | $2\mu$ | $J$ | Yes | 20.3 | $m_{\ell} = 5.2$ TeV |
| ADD $G_{BB}$ | $2\mu$ | $J$ | Yes | 20.3 | $m_{\ell} = 5.2$ TeV |
| ADD $BH_{WW}$ | $2\mu$ | $J$ | Yes | 20.3 | $m_{\ell} = 4.7$ TeV |
| ADD $BH_{\mu \\tau}$ | $2e, \mu$ | $J$ | Yes | 20.3 | $m_{\ell} = 5.2$ TeV |
| ADD $BH_{d}$ | $2\mu$ | $J$ | Yes | 20.3 | $m_{\ell} = 5.2$ TeV |
| RS1 $\gamma \\gamma$ | $\ell, \gamma$ | $J$ | Yes | 20.3 | $m_{\ell} = 5.2$ TeV |
| BS $\gamma \\gamma$ | $\ell, \gamma$ | $J$ | Yes | 20.3 | $m_{\ell} = 5.2$ TeV |
| BS $\ell \ell$ | $\ell, \gamma$ | $J$ | Yes | 20.3 | $m_{\ell} = 5.2$ TeV |
| 2UED / RPP | $2e, \mu$ | $J$ | Yes | 20.3 | $m_{\ell} = 5.2$ TeV |

**Extra dimensions**

| Model | $\ell, \gamma$ | Jets | $E_{\text{miss}}$ | $|\mathcal{L}| dt$ (fb$^{-1}$) | Limit |
|-------|----------------|------|------------------|-------------------------------|-------|
| SSM $Z' \rightarrow \ell \ell$ | $2\ell$ | $J$ | Yes | 20.3 | $m_{\ell} = 3.02$ TeV |
| SSM $Z' \rightarrow t \bar{t}$ | $2t$ | $J$ | Yes | 20.3 | $m_{\ell} = 2.02$ TeV |
| SSM $W' \rightarrow \ell \ell$ | $2\ell$ | $J$ | Yes | 20.3 | $m_{\ell} = 2.02$ TeV |
| SSM $W' \rightarrow t \bar{t}$ | $2t$ | $J$ | Yes | 20.3 | $m_{\ell} = 2.02$ TeV |

**Gaugino bosons**

| Model | $\ell, \gamma$ | Jets | $E_{\text{miss}}$ | $|\mathcal{L}| dt$ (fb$^{-1}$) | Limit |
|-------|----------------|------|------------------|-------------------------------|-------|
| EGQ $W^{\pm} \rightarrow \ell \ell$ | $2\ell$ | $J$ | Yes | 20.3 | $m_{\ell} = 1.52$ TeV |
| EGQ $W^{\pm} \rightarrow \ell \ell$ | $2\ell$ | $J$ | Yes | 20.3 | $m_{\ell} = 1.52$ TeV |
| EGQ $W^{\pm} \rightarrow \ell \ell$ | $2\ell$ | $J$ | Yes | 20.3 | $m_{\ell} = 1.52$ TeV |
| EGQ $W^{\pm} \rightarrow \ell \ell$ | $2\ell$ | $J$ | Yes | 20.3 | $m_{\ell} = 1.52$ TeV |

**Heavy quarks**

| Model | $\ell, \gamma$ | Jets | $E_{\text{miss}}$ | $|\mathcal{L}| dt$ (fb$^{-1}$) | Limit |
|-------|----------------|------|------------------|-------------------------------|-------|
| VLO $TT \rightarrow Ht + X$ | $1e, 1\mu$ | $J$ | Yes | 20.3 | $m_{\ell} = 856$ GeV |
| VLO $YV \rightarrow Wb + X$ | $1e, 1\mu$ | $J$ | Yes | 20.3 | $m_{\ell} = 770$ GeV |
| VLO $BB \rightarrow Hb + X$ | $1e, 1\mu$ | $J$ | Yes | 20.3 | $m_{\ell} = 735$ GeV |
| VLO $BB \rightarrow Zb + X$ | $1e, 1\mu$ | $J$ | Yes | 20.3 | $m_{\ell} = 755$ GeV |

**Other**

| Model | $\ell, \gamma$ | Jets | $E_{\text{miss}}$ | $|\mathcal{L}| dt$ (fb$^{-1}$) | Limit |
|-------|----------------|------|------------------|-------------------------------|-------|
| LBG $\ell \ell$ | $1e, 1\mu$ | $J$ | Yes | 20.3 | $m_{\ell} = 960$ GeV |
| LBG $\ell \ell$ | $2e, 2\mu$ | $J$ | Yes | 20.3 | $m_{\ell} = 2.0$ TeV |
| LBG $\ell \ell$ | $2e, 2\mu$ | $J$ | Yes | 20.3 | $m_{\ell} = 2.0$ TeV |
| LBG $\ell \ell$ | $2e, 2\mu$ | $J$ | Yes | 20.3 | $m_{\ell} = 2.0$ TeV |
| LBG $\ell \ell$ | $2e, 2\mu$ | $J$ | Yes | 20.3 | $m_{\ell} = 2.0$ TeV |

**References**

- [1502.01518](https://arxiv.org/abs/1502.01518)
- [1407.2410](https://arxiv.org/abs/1407.2410)
- [1306.4545](https://arxiv.org/abs/1306.4545)
- [1409.6190](https://arxiv.org/abs/1409.6190)
- [1503.09898](https://arxiv.org/abs/1503.09898)
- [1500.02958](https://arxiv.org/abs/1500.02958)
- [1500.07018](https://arxiv.org/abs/1500.07018)
- [1504.04555](https://arxiv.org/abs/1504.04555)
- [1405.4123](https://arxiv.org/abs/1405.4123)
- [1502.01655](https://arxiv.org/abs/1502.01655)
- [1407.2410](https://arxiv.org/abs/1407.2410)
- [1406.4456](https://arxiv.org/abs/1406.4456)
- [1409.6190](https://arxiv.org/abs/1409.6190)
- [1503.09898](https://arxiv.org/abs/1503.09898)
- [1410.4103](https://arxiv.org/abs/1410.4103)
- [1408.0398](https://arxiv.org/abs/1408.0398)

**Legend**

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

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

10 May 2017

N. Chr. Benekos – NTUA on behalf of ATLAS Collaboration

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