ATLAS results on new physics searches

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On behalf of the ATLAS Collaboration
LHC and ATLAS

Excellent performance of LHC and ATLAS in Run2:

- 13 TeV c.m. energy, \(\sim 1.1 \times 10^{34}\) cm\(^{-2}\)s\(^{-1}\) peak luminosity, 25 ns bunch spacing
- \(\sim 3.2\) fb\(^{-1}\) integrated luminosity in 2015
- >25 fb\(^{-1}\) so far in 2016, \(\sim 100\) fb\(^{-1}\) by the end of Run2

Results reported so far in 2016 with 3-15 fb\(^{-1}\)

**ATLAS Online Luminosity**

- 2011 pp \(\sqrt{s} = 7\) TeV
- 2012 pp \(\sqrt{s} = 8\) TeV
- 2015 pp \(\sqrt{s} = 13\) TeV
- 2016 pp \(\sqrt{s} = 13\) TeV
General strategy for new physics searches

- Event selection performed through sensitive observables (e.g. missing transverse energy, invariant mass, etc.) to maximize signal from background discrimination ➔ “Signal Regions” (SRs)
- Compare data to background ➔ data driven estimates or by MC, normalized through fit to dedicated “Control Regions” (CRs):
  - New physics would produce deviations from background predictions
  - If no deviation ➔ set limits on new physics cross sections\(\times BR\)
- Results interpreted in specific signal models

Searches rely on accurate modeling of the Standard Model backgrounds

Large number of new physics analyses, only few selected new results from ATLAS shown here, e.g. they don’t include:
- Long Lived Particles, Mediator through dijets (see R. Rosten’s talk at TeVPA2016)
- EW SUSY production, SUSY R-Parity Violation, Multi-Charged Particles, Magnetic Monopoles,…

Whole list of analyses (SUSY, Exotics, Higgs) in
- [https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SusyPublicResults](https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SusyPublicResults)
- [https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults](https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults)
- [https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults](https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults)
Dark Matter (DM) searches at LHC

- If DM couples to Standard Model (SM) particles very weakly (WIMPs), it may be observed as directly pair-produced at a collider ➔ Signature at LHC: **triggerable object X** ($\gamma$, jet, W, Z, H, etc.) recoiling against **invisible DM $\chi\chi$** resulting in missing transverse energy $E_T^{\text{Miss}}$ (energy imbalance in detector)

- Collider searches are complementary to direct (WIMP-nucleon scattering) and indirect (WIMP annihilation) detection

<table>
<thead>
<tr>
<th>Search</th>
<th>Data</th>
<th>Reference paper</th>
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<tbody>
<tr>
<td>$E_T^{\text{miss}} + \text{jet}$</td>
<td>2015</td>
<td>Paper: EXOT-2015-03</td>
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<td>Paper: EXOT-2015-05</td>
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<td>$E_T^{\text{miss}} + Z (\rightarrow \ell\ell)$</td>
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<tr>
<td>$E_T^{\text{miss}} + t\bar{t} (2\ell)$</td>
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13 TeV Results in this talk:
- Mono-photon
- Mono-jet
- Mono $W/Z$
- Mono $H$ ($\rightarrow \gamma\gamma, bb$)
Dark Matter through Mono-X
Mono-X searches in ATLAS: models

- $\chi\chi$ interpretation inside:
  - More complete models (e.g. SUSY R-parity conserving, WIMPS as SUSY Lightest particles)
  - “Simplified” models $\Rightarrow$ mediator (med) exchanged in s-channel, DM particle is a stable Dirac fermion $\chi$, 5 parameters: $M_{\text{med}}, \Gamma_{\text{med}}, m_\chi, g_q, g_\chi$
  - Effective Field Theory (EFT) $\Rightarrow$ (Run1 approach) 2 parameters, $m_\chi$ and mass of the very heavy mediator $M_*$, valid only when $M_*$ is much larger than the energy of the interaction (not always true at LHC)

Common effort between the ATLAS and CMS Collaborations and the theory community (DM Forum) to direct the DM searches in Run2 to benchmark simplified models, improved analysis techniques, common rules to present results (arXiv:1507.00966, arXiv: 1506.03116v3)
Mono-photon search (JHEP06 (2016) 059)

- **Clean signature**: High $p_T$ photon (>150 GeV) + $E_T^{\text{Miss}}$ (>150 GeV) + $\Delta \phi(\gamma - E_T^{\text{Miss}})$ > 0.4 + veto on l and jets

- **Main backgrounds**: $Z \rightarrow \nu\nu+\gamma$ (irreducible), $W \rightarrow l\nu+\gamma$, $\gamma+jets$, fake photons (electrons, jets)

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**Simplified Models** (Dirac DM, axial-vector mediator couplings $g_q = 0.25$ and $g_\chi = 1$): 95% CL excluded $m_\chi < 150$ GeV for $m_{\text{med}} \sim 700$ GeV

<table>
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<tr>
<th></th>
<th>SR</th>
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<tr>
<td>Observed events</td>
<td>264</td>
</tr>
<tr>
<td>Fitted Background</td>
<td>295±34</td>
</tr>
</tbody>
</table>

- $Z(\rightarrow \nu\nu)\gamma$: 171±29
- $W(\rightarrow l\nu)\gamma$: 58±9
- $Z(\rightarrow \ell\ell)\gamma$: 3.3±0.6
- $\gamma+jets$: 15±4
- Fake photons from electrons: 22±18
- Fake photons from jets: 26±12
- Pre-fit background: 249±29

**Comparison with Direct Detection**: 90% CL limits on spin-dependent WIMP-proton cross section $\sigma_{SD}(\chi-p)$: $\sigma_{SD}(\chi-p) < 10^{-41}$ cm$^2$ for $m_\chi < \sim 150$ GeV

**Direct Production complement Direct Detection** (through DM-nucleon scattering in deep underground detectors) below 10 GeV

Prescription in arXiv:1603.04156
Mono-jet search (arXiv:1604.07773v1)

- More complex signature but larger x-section (compared to Mono-photon): High $p_T$ jet (>250 GeV)+$E_T^{\text{Miss}}$ (>250 GeV)+max 4 Jets with $p_T$ > 30 GeV+$\Delta\phi(p_T \text{ jet} - E_T^{\text{Miss}})$>0.4+lepton veto

- Main backgrounds: $Z \rightarrow \nu\bar{\nu}(\tau\tau)$+jets (irreducible), $W \rightarrow l\nu$+jets

- Multiple SRs:

<table>
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<tr>
<th>Inclusive signal region</th>
<th>IM1</th>
<th>IM2</th>
<th>IM3</th>
<th>IM4</th>
<th>IM5</th>
<th>IM6</th>
<th>IM7</th>
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<tbody>
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<td>&gt;250</td>
<td>&gt;300</td>
<td>&gt;350</td>
<td>&gt;400</td>
<td>&gt;500</td>
<td>&gt;600</td>
<td>&gt;700</td>
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<td>$E_T^{\text{miss}}$ (GeV)</td>
<td>[250-300]</td>
<td>[300-350]</td>
<td>[350-400]</td>
<td>[400-500]</td>
<td>[500-600]</td>
<td>[600-700]</td>
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</table>

95% CL Exclusion limits in simplified Models: Dirac DM, axial-vector mediator, couplings $g_q=0.25$ and $g_\chi=1$: exclude $m_\chi < 250$ GeV for $m_A \sim 1$ TeV

Comparison with direct detection: 90% CL limits on spin-dependent WIMP-proton cross section $\sigma_{SD}(\chi$-p): $\sigma_{SD}(\chi$-p) < $10^{-42}$ cm$^2$ for $m_\chi < 300$ GeV

DM relic density (Planck, Wmap) line crosses the excluded region
- below relic abundance curve: DM over production
- above relic abundance curve: DM under production

- **Signature:** Large R jet (R=1) with 2 substructures for boson tagging and $p_T > 200$ GeV + $E_T^{\text{miss}} (>200$ GeV)
- **Main backgrounds:** Z+jets, W+jets, ttbar
- **Complements** mono-jet search with different production modes. Hadronic channel has strong sensitivity.

Exclusion limits in **simplified Models:** vector mediator, couplings $g_q=0.25$ and $g_\chi=1$, 95% CL limits on signal strength $\mu$ in $(m_{\text{med}},m_\chi)$ plane

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**Mono-Z (Z → ll)**

- **Signature:** very clean, but low statistics
- **Main Background:** ZZ → $\nu\nu$+ll (irreducible)

95% CL limits: exclude $m_{\text{med}} < \sim 400$ GeV
Mono-H(H → γγ) search (ATLAS-CONF-2016-087)

- **Low BR, but clean signature**: at least 2 photons (105 < m_{γγ} < 160 GeV) + E_T^{Miss} (>100 GeV)
- **Backgrounds**: γγ, γ+jet, evaluated directly from data-driven fit
- **No excess** found in data

Limits in **simplified Models**: Dirac DM, vector mediator couplings g_q = 1/3 and g_χ = 1: 95%CL exclusion limit on σ(pp → Hχχ) × BR(H → γγ) vs m_{med} (3fb@50 GeV)
DM (Mono-X+Di-jets) ATLAS Summary

- **95%CL exclusion** in \((m_\chi, m_{\text{med}})\) plane by Mono-Photon, Mono-Jet and Di-jet DM searches

- **Dirac DM, axial-vector mediator**

- Di-jet searches (see R. Rosten’s talk) in the context of DM: DM mediator also give rise to di-jet events. Results highly depend on choice of coupling parameters

- **Complementarity** between di-jet and Mono-X searches

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Mono-photon and Mono-jet interpretation in other New Physics scenarios in backup slides
Supersymmetry
SUSY searches in ATLAS

- **Supersymmetry** is a favoured, non-exotic, SM extension.
- Introduces a superpartner for each SM particle, with spin altered by $\frac{1}{2}$ and 5 Higgs bosons.
- Provides a possible DM candidate (Lightest SUSY particle, LSP) assuming R-parity conservation.

Large $E_T^{\text{Miss}}$:

$$R = (-1)^{3(B-L)+2S}$$

- **Models:** Minimal SUSY Standard Model (MSSM) has more than 100 parameters → a huge phase space to look into, with many possible signatures.

**Strong production:**
- targeting gluinos and 1st and 2nd generation squarks, largest cross-sections

**3rd generation:**
- targeting stop and sbottoms, the lowest mass squarks

**Electroweak production:**
- targeting Electroweakinos, Sleptons

**RPV/LL:**
- targeting R-parity violating models and long lived sparticles
- More exotic model

Only focus on few searches in this talk.
Strong production: Gluino and squarks, 0-leptons+jets+$E_T^{\text{Miss}}$

(ATLAS-CONF-2016-078)

- **Model:** inclusive final state, only gluinos (or 1\textsuperscript{st} and 2\textsuperscript{nd} generation squarks) and LSP ($\chi_1^0$) in the model
- **Selection:** based on cuts on $E_T^{\text{Miss}}$ and $m_{\text{eff}} = E_T^{\text{Miss}} + \Sigma_{\text{jet}} p_T$ (large activity expected in the event), and on Recursive Jigsaw Reconstruction (RJR) techniques
- **Signal Regions:** 30 SRs in total

95% CL Exclusion limits in simplified Models: exclude $m_\tilde{g} < 1.86$ TeV and $m_\tilde{q} < 1.35$ TeV for $m_{\text{LSP}} = 0$ GeV.
3rd Generation: Stop decays – 1 lepton (e, \(\mu\))

- **Decays**: stop decays in \(t\tilde{\chi}_1^0\) and \(b\tilde{\chi}_1^\pm\),

- **DM scenario with a spin-0 med. (scalar or pseudo-scalar)**

- **Main Background**: \(t\bar{t}, Wt, W+jets, t\bar{t}+Z(\rightarrow \nu\nu)\)

- **Multiple SRs**: \(\geq=1\) b-jet and based on cuts on \(E_T^{\text{miss}}, m_T(l-E_T^{\text{miss}}), m_{T2}\)

**Summary for stop decays in neutralino**

95% CL Exclusion limits in simplified Models:
- exclude \(m_{\text{stop}} < 830\) GeV for \(m_{\text{LSP}} = 0\) GeV and BRs = 100%
New resonances

More on New Resonances, TeV-scale gravity and Quantum Black Holes, GUT, Beyond SM Higgs… in backup slides
Di-photon search (ATLAS-CONF-2016-059)

- Many theories beyond the SM predict narrow resonances or broad non-resonant deviations from the SM excess in sensitive observables (invariant mass, …)

- Models for di-\(\gamma\) final states \(\Rightarrow\) Spin-0 (e.g. predicted in models with Extended Higgs Sector) and Spin-2 (Randall-Sundrum graviton, RSG)

- Signature: 2 isolated \(\gamma\)

- Main Background: \(\gamma\gamma, \gamma+\text{jet}, \text{jet}+\text{jet}\), modelled with a fit to data for Spin-0 and a shape prediction (NLO) for Spin-2

- Results from 2015 Data: Broad excesses around \(m_{\gamma\gamma} = 750\) GeV in both analyses (width \(\sim 45\) GeV), 3.8-3.9\(\sigma\) local significances, 2.1\(\sigma\) global significance

No significant excess in 2016 data  Spin-0 analysis
Search for heavy di-boson resonances (ATLAS-CONF-2016-055,062,082,083)

- Narrow charged or neutral resonances (500-3000 GeV) decaying to WW/WZ/ZZ/WH/ZH
- Signatures: $\nu\nu, l\nu, l\ell q, q\bar{q}q, q\bar{q}b\bar{b}$ in final states, $W/Z \rightarrow q\bar{q}$ identified through Large R jet
- Models:
  - model with a new heavy scalar in the extended Higgs sector
  - simplified model with a spin-1 heavy vector-boson triplet (HVT) $W'(Z') \rightarrow WZ$ (WW)
  - bulk Randall-Sundrum model with heavy spin-2 graviton (RSG), $G_* \rightarrow WW,ZZ$
- Results from Run1 Data: Broad excesses around $m_{jj} = 2$ TeV in full hadronic channel, local significances of 2.6-3.4$\sigma$, global significance of 2.5$\sigma$, not confirmed in Run 2 (2015 + 2016 13 TeV data)

**Run2 Data**

95% CL exclude scalar singlet with $m<3$ TeV in Unsupp. scenario, $G_*$ with $m<1.2$ TeV, HVT $W'$ with $m<\sim 2.5$ TeV
Conclusions and outlook

- Intensive searches for Dark Matter and new physics at LHC Run2

- No evidences were found (…but it could be around the corner!)

- Several limits improved with 2015 and 2016 data, but a larger statistics is expected before the end of the year (>30 fb⁻¹)

- The high energy regime and amount of data promise good sensitivity to large scale physics and the opportunity to learn more about our universe

Thank you for your attention
# ATLAS SUSY Searches* - 95% CL Lower Limits

Status: August 2016

<table>
<thead>
<tr>
<th>Model</th>
<th>$e, \mu, \tau, \gamma$</th>
<th>Jets</th>
<th>$E_{miss}^T$</th>
<th>$\mathcal{L}$ [fb$^{-1}$]</th>
<th>Mass limit $\sqrt{s} = 7, 8$ TeV</th>
<th>Mass limit $\sqrt{s} = 13$ TeV</th>
<th>Reference</th>
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</thead>
<tbody>
<tr>
<td>MSUGRA/CMSSM</td>
<td>$0.3 \ e, 1/2 \ 1 - 2$</td>
<td>10 jets/3 b</td>
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<tr>
<td>GMSB (N LSNP)</td>
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<td>3 jets</td>
<td>Yes</td>
<td>3.2</td>
<td>608 GeV</td>
<td>m($\tilde{g}$) $&gt;$ 400 GeV</td>
<td>1504.07773</td>
</tr>
<tr>
<td>GGM (bino NLSNP)</td>
<td>$2 \ e, 1 - 3 \ 1$</td>
<td>3 jets</td>
<td>Yes</td>
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<td>1.05 TeV</td>
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## Inclusive Searches

### 3$\gamma$, $g$, $\bar{g}$, $\tilde{g}$, $\tilde{b}$

<table>
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<td>$\tilde{t}_R \tilde{t}_R$</td>
<td>$2 \ e, 1 - 3 \ 1$</td>
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## EW direct

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<td>$\tilde{g} \tilde{g}$</td>
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## Other

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* Only a selection of the available mass limits on new states or phenomena is shown.
Backup slides
Mono-H(H→bb) search (ATLAS-CONF-2016-019)

- More complex signature but more statistics than H→γγ: high p_T bbbar (resolved or merged in a large R jet) + E_T^{Miss} + p_T^{Miss} + lepton veto

- Backgrounds: Z+jets, W+jets, ttbar

95%CL Exclusion limits in simplified Models:
lepto-phobic $Z'$ vector mediator (U1)\textsubscript{B},
couplings $g_q=1/3$ and $g_{\chi} = 1$, $\sin\theta = 0.3$,
exclude $m_{Z'} < 900$ GeV in $(m_{Z'},m_\chi)$ plane

95%CL Exclusion limits in simplified Models:
$Z'$ – 2HDM with 2 Higgs doublets, tan$\beta$=1,
$Z'\rightarrow hA$, pseudoscalar $A\rightarrow \chi\chi$,
exclude $m_A < 500$ GeV in $(m_{Z'},m_A)$ plane for a wide interval of $m_{Z'}$. 
Interpretation of Mono-X searches in other New Physics scenarios  

- Mono-(Photon,Jet) interpretation within ADD (Arkani-Hamed, Dimopoulos, Dvali) Large Extra Space Dimensions → 95% CL lower limits on $M_D$, fundamental Planck scale in 4+n dimensions:
  - $M_D > 6.58$ TeV for $n=2$; $M_D > 4.31$ TeV for $n=6$ (Mono-Jet)
  - $M_D > 2.3$ TeV for $n=2$; $M_D > 2.8$ TeV for $n=6$ (Mono-Photon)

- Mono-Jet interpretation within squark production model in SUSY compressed scenarios → squark pair production with $\Delta m = m(\tilde{q}) - m(\tilde{\chi}_1^0)$ small:
  - Stop
  - Sbottom
  - Squark ($q=u,d,s,c$)
Models in 4+n dimensions: allow strong gravity at a fundamental gravitational scale $M_D \sim$ EW scale

- production of microscopic black holes above fundamental gravity scale $M_D$

Signature: semi-classical microscopic BH equally produce any particle $\Rightarrow$ high multiplicity final states, QBH (scale $\sim M_D @\text{TeV}$) are instead dominated by 2-bodies final states at the LHC

Main Background: W/Z+jets, QCD multi-jets, ttbar (depending on the final state)

- Multi-particle final state: $l+$jets or multi-jets
- 2-body final state with different flavour leptons

95% CL Exclusion limits on semi-classical BH with $n=6 @M_D=5 \text{TeV}$: exclude $M < 7.4 \text{TeV}$ ($l+$jets) and $M < 9 \text{TeV}$ (multi-jets)

95% CL Exclusion limits on QBH with $n=6$ ADD: $m_{QBH} > 4.5 \text{TeV}$ ($> 8.7$ for dijet analysis, $> 6.2$ for $\gamma$-jet analysis)
Limits on new physics from high mass di-jet and angular distribution (ATLAS-CONF-2016-069)

<table>
<thead>
<tr>
<th>Model</th>
<th>95% CL Exclusion limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quantum black holes, ADD (BlackMax generator)</td>
<td>8.7 TeV 8.7 TeV</td>
</tr>
<tr>
<td>Excited quark</td>
<td>5.6 TeV 5.5 TeV</td>
</tr>
<tr>
<td>$W'$</td>
<td>2.9 TeV 3.3 TeV</td>
</tr>
<tr>
<td>$W^*$</td>
<td>3.3 TeV 3.3 TeV</td>
</tr>
<tr>
<td>Contact interactions ($\eta_{LL}=+1$)</td>
<td>12.6 TeV 13.7 TeV</td>
</tr>
<tr>
<td>Contact interactions ($\eta_{LL}=-1$)</td>
<td>19.9 TeV 23.7 TeV</td>
</tr>
</tbody>
</table>

Limits on new physics from di-lepton (ATLAS-CONF-2016-045)

- Benchmark Sequential Standard Model: $Z'^{SSM}$ M > 4.05 TeV
- Grand Unified E6 - motivated models: $Z'^{E6}$ M > 3.36-3.66 TeV

Limits on scalar Leptoquarks (LQ): GUTs & models with substructure (arXiv:1605.06035)

- $m_{LQ1} > 1.10$ TeV
- $m_{LQ2} > 1.05$ TeV
Model independent upper limits on σxBR:
- ggH limits: 2.0-0.013 pb for m_A=200-1200 GeV
- bbH limits: 2.1-0.014 pb for m_A=200-1200 GeV

**Beyond Standard Model Higgs: MSSM H/A → ττ (ATLAS-CONF-2016-085)**

- Limits on σxBR:
  - 2.0-0.008 pb for m_{H^±} = 200-2000 GeV
  - 95%CL exclusion in hMSSM: tan β >42-60 for m_{H^±} = 200-540 GeV

**Beyond Standard Model Higgs: H^± → ττ (ATLAS-CONF-2016-088)**

**Beyond Standard Model Higgs: H^± → tb (ATLAS-CONF-2016-089)**

95%CL exclusion in MSSM m_{h^{mod±}}:
- tan β <1.7-0.5 @ m_{H^±} = 300-855 GeV
Impressive agreement between data and theory up to NNLO + NNLL

SM cross section measurements: 7, 8, 13 TeV

Inclusive Jet cross sections shows that QCD works well and fits data over 10 order of magnitude
DM Models

Complete Models

More complete/more parameters

MSSM, Composite Higgs, Extra-Dim...

Simplified Models

Integrate out the UV physics connecting DM-SM and describe interactions with eff. ops.

Effective Theories

Other Benchmarks?

less complete/less parameters
Large R jets and W/Z (had) tagging

Large R jets provide efficient reconstruction of massive boosted objects whose decay products are sufficiently collimated

Trimming: recluster kt subjects, remove those with $p_T^{Ti}/p_T^{jet} < f_{cut}$

- Improve resolution of jet mass of W/Z vs multijets
- No dependence of jet mass vs Npv after trimming

Criteria adopted in mono-W/Z (had):

- Large R-jets: Antikt with R=1
- Trimmed with $R_{sub}=0.2$, $f_{cut}=0.05$
- Using $p_T$ dependent selection on jet mass and jet substructure variable D2 that selects jets with 2 concentrations of energy
- D2 selection provides constant efficiency of 50% for W/Z
Di-jet resonances searches

Look for resonance in dijet spectrum
- More sensitive than mono-X searches over wider range of mediator masses.
- But an observed excess not necessarily related to DM (Excited quarks, new heavy gauge bosons, quantum black holes and contact interaction can be probed)

Three search strategies
1) High mass dijet search
   - High rate -> high threshold required
   - Probe mediator mass > 1.5 TeV
   (ATLAS-CONF 2016-069)
2) Low mass dijet search performed with trigger objects
   (ATLAS-CONF 2016-030)
3) Select ISR photon or jet to probe lower Masses avoiding high jet trigger thresholds
   (ATLAS-CONF 2016-070)
SUSY models

SUSY breaking
Gravity, Gauge, Anomaly,
Dilaton/Moduli, Mirage, Gaugino,
D-term, Z-prime, ...

R-Parity conservation

SUSY models possibly with extra matter/gauge bosons
NMSSM, USSM,
μvSSM, E6SSM,
PQNMSSM, ...

Various forms of SUSY spectra
MSSM, mSUGRA,
NUHM, Natural, Split,
Compressed, Stealth, ...

LSP?
Neutralino, SM,
Gravitino, Axino, ...
Transverse mass $m_T$

$$m_T^2(p_T^1, p_T^2) = [E_T^1 + E_T^2]^2 - [p_T^1 + p_T^2]^2$$

- $m_T \equiv m_T(\ell, E_T^{\text{miss}}) = \sqrt{2p_T^\ell E_T^{\text{miss}} \left[1 - \cos \Delta \phi(p_T^\ell, p_T^{\text{miss}})\right]}$ bounded by $m_W$: reduce $WW, Wt, t\bar{t}$

Transverse mass $m_{T2}$

- generalization of $m_T$ to pair decay with final state consisting of 2 visible objects and $E_T^{\text{miss}}$

$$m_{T2}(p_T^1, p_T^2, q_T) = \min_{q_T^1 + q_T^2 = q_T} \left\{ \max[m_T(p_T^1, q_T^1), m_T(p_T^2, q_T^2)] \right\}$$

- $m_{T2} \equiv m_{T2}(p_T^1, p_T^2, p_T^{\text{miss}})$ bounded by $m_W$: reduce $WW, Wt, t\bar{t} \rightarrow 2\ell$
- $a m_{T2}$ bounded by $m_t$: reduce $t\bar{t} \rightarrow 2\ell$ with a lost lepton
- $m_{T2}^\tau$ bounded by $m_W$: reduce $t\bar{t} \rightarrow \ell\bar{\ell}^{\text{had}}$
Recusive Jigsaw Reconstruction (RJR) technique: method used as a basis to define the kinematic variables on an event-by-event basis -> given external constraints on the invisible system, exploits minimizations of the masses of intermediate particle states with respect to unknown quantities.

- The RJR algorithm fix rules for resolving combinatorics
- A four-momentum hypothesis is assigned to each invisible state. The RJR variable construction involves, for each level in the decay tree, kinematic variables in the rest frame
- For the correct decay tree topology, variables from different rest frames should encode different information
3rd Generation: Stop decays – excess in 1 lepton channel (ATLAS-CONF-2016-050)

**Graphs:**
- **Graph 1:** Plot showing events vs. $m_T$ [GeV] with different channels and backgrounds.
- **Graph 2:** Plot showing $E_T^{miss}$ [GeV] with different channels and backgrounds.
- **Graph 3:** Plot showing $m_A$ [GeV] vs. $m_Z$ [GeV] with observed and expected limits.

**Table:**

<table>
<thead>
<tr>
<th>Signal region</th>
<th>SR1</th>
<th>cN.high</th>
<th>bC2x_diag</th>
<th>bC2x_med</th>
<th>bC3b</th>
<th>DM_low</th>
<th>DM_high</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed</td>
<td>37</td>
<td>5</td>
<td>37</td>
<td>14</td>
<td>7</td>
<td>35</td>
<td>21</td>
</tr>
<tr>
<td>Total background</td>
<td>24</td>
<td>3.8</td>
<td>22</td>
<td>23</td>
<td>7.4</td>
<td>17</td>
<td>15</td>
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<tr>
<td>$t\bar{t}$</td>
<td>8.4</td>
<td>0.60</td>
<td>6.5</td>
<td>4.3</td>
<td>0.26</td>
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<td>3.3</td>
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<tr>
<td>$W+jets$</td>
<td>2.5</td>
<td>0.15</td>
<td>1.2</td>
<td>0.63</td>
<td>0.54</td>
<td>3.1</td>
<td>3.4</td>
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<tr>
<td>Single top</td>
<td>3.1</td>
<td>0.57</td>
<td>5.3</td>
<td>0.24</td>
<td>1.9</td>
<td>1.3</td>
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<tr>
<td>$t\bar{t}+V$</td>
<td>7.9</td>
<td>1.6</td>
<td>2.7</td>
<td>0.12</td>
<td>6.4</td>
<td>5.5</td>
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<tr>
<td>Diboson</td>
<td>1.2</td>
<td>0.61</td>
<td>0.42</td>
<td>1.1</td>
<td>1.5</td>
<td>1.4</td>
<td></td>
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<tr>
<td>$Z+jets$</td>
<td>0.59</td>
<td>0.03</td>
<td>0.32</td>
<td>0.08</td>
<td>0.22</td>
<td>0.16</td>
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<tr>
<td>$t\bar{t}$ NF</td>
<td>1.03</td>
<td>0.07</td>
<td>0.89</td>
<td>0.95</td>
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<tr>
<td>$W+jets$ NF</td>
<td>0.76</td>
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<td>0.87</td>
<td>0.85</td>
<td>0.97</td>
<td>0.94</td>
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<tr>
<td>Single top NF</td>
<td>1.07</td>
<td>0.30</td>
<td>1.26</td>
<td>0.97</td>
<td>1.0</td>
<td>1.02</td>
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<td>$t\bar{t}+W/Z$ NF</td>
<td>1.43</td>
<td>0.21</td>
<td>1.40</td>
<td>1.40</td>
<td>1.44</td>
<td>1.42</td>
<td></td>
</tr>
</tbody>
</table>

**Legend:**
- **$\chi^2_{limit}$**
- **$N_{low-SM}$** (95% CL) exp.
- **$N_{low-SM}$** obs. (95% CL)
- **$m_A$ [GeV]**
- **$m_Z > 2 m_H$**

**Units:**
- $m_T$ [GeV]
- $E_T^{miss}$ [GeV]
- $m_A$ [GeV]
**SUSY prospects** *(ATLAS-PHYS-PUB-2014-010)*

- ATLAS studied long term prospects for the (HL-)LHC with 300, 3000 fb$^{-1}$ at 14 TeV.
- Discovery potential up to 2.5 TeV gluinos, 1.3 TeV squarks/sbottom and 800 GeV Electroweakinos.
Di-photon models

- Spin 0: Extended Higgs sector?
  - Example: 2HDM
  - 5 physical states: h^0, H^0, A^0, H^±
    - scalars and/or pseudo-scalars can have sizable BR to di-photons

- Spin 2: Randall-Sundrum graviton?
  - Predicts tower of Kaluza-Klein (KK) graviton excitations with first states at TeV mass scale
  - Phenomenology:
    - m_{Φ}^p: mass of lightest KK excitation
    - κ/M_{π}^p: dimensionless coupling to SM fields
      - κ: curvature scale of extra dimension
      - M_{π}^p: reduced Planck scale

- Hundred's of theory papers
  - cascading heavy quarks, new gauge bosons Z'+/X, quarks, hidden valleys...

- Mostly about a new heavy resonance:
  - Dark matter mediators, technquarks, Goldstone, Axions, Ricksons/gravitons, gravitons/any spin 2, Higgs bosons, ...

- Some SUSY possibilities:
  - Enhanced MSSM, sneutrino in RPV, sgoldstinos and other SUSY, ...

Upper limits on σxBR in 2 photons of a spin-0 particle as a function of its mass, for different values of the width.
Vector-like quarks, Leptoquarks, simple SM extension models

- Compositeness models remain among the few naturally motivated models not yet excluded. One prediction is **vector-like quarks**
  - Couple to 3rd generation quarks
  - Permit flavour-changing neutral current decays
- Second potential consequence (also consequence of GUTs) is **leptoquarks**
  - Essentially fill in the holes of the SU(5) matrix. Mediate interactions between leptons & quarks of same generation.
  - Pair-produced at LHC; decay gives \( LQ \)
  - Another GUT consequence is additional standard-model like **heavy vector bosons**, \( W' \) and \( Z' \)
    - Simplest are “sequential standard model” SSM: same couplings as SM \( W \) and \( Z \) with larger masses

**LQ pair production**: 2 leptons (ATLAS: exactly 2 e or \( \mu \)) and \( \geq 2 \) jets. Discriminating variable: **minimum \( m_{LQ} \)**, lepton-jet pairs chosen for smallest mass difference