Search for new phenomena with the ATLAS detector

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New phenomena: why?

• Higgs boson was the last missing piece predicted by the Standard Model: observed in 2012 by ATLAS & CMS

• **But**: Standard Model is NOT the complete theory of Nature

• Dark matter, baryogenesis, neutrino masses and oscillations: we have observed clear signs of Beyond the Standard Model physics.

• New particles or new particle phenomena are most likely behind these extraordinary observations.

• Particle physics enters a new era, where theory is of limited guidance, and as many and as new, unconventional as possible experimental results need to be pursued.
How to find new phenomena @ colliders

We need to expand the set of measurements we do at the LHC and include as many final states as possible.

It is possible that so far new physics escaped our detection because our detection or trigger techniques have not been enough wide-reaching.
Un-conventional

Search for particles that display long lifetime and still leave some signs within the detector volume.

Multiple search strategies can be applied to one physics model, depending on the lifetime (exp. distribution with constant $c\tau$, proper lifetime).
ATLAS detector and data used

Muon Spectrometer
ATLAS analyses presented here

- Search for the production of a long-lived neutral particle decaying within the ATLAS hadronic calorimeter in association with a Z boson
- Search for heavy Majorana or Dirac neutrinos and right-handed W gauge bosons in final states with two charged leptons and two jets
- Search for long-lived particles in final states with displaced dimuon vertices
- Search for long-lived particles that decay to displaced hadronic jets in the ATLAS muon spectrometer

these are all examples of recent new searches that are sensitive to theoretical models providing explanations for the big observations we have in particle physics
Search for the production of a long-lived neutral particle decaying within the ATLAS hadronic calorimeter in association with a Z boson

extends previous ATLAS result [1,2]:
• consider an intermediate particle to be general scalar $\Phi$
• consider hadronic final state for dark vector boson $Z_d$, with long lifetime (lower coupling strength)

$Z_d$ decays in Tile Calorimeter ($2m<r<4m$), and hence signature is a jet with little deposit in Lar Calorimeter and no tracks in Inner Detector

Selection and backgrounds

Event selection:

- $66 \text{ GeV} < \text{Mass (ll)} < 116 \text{ GeV}$
- jet $p_T > 40 \text{ GeV}$, $|\eta| < 2.0$, calorimeter ratio $\log_{10}(E_{\text{Tile}}/E_{\text{Lar}}) > 1.2$, no ghost tracks with $p_T > 1 \text{ GeV}$. Timing applied to jet to reject out-of-time pile-up and beam induced background.
- Main background: $Z+jet$ (jet mimics the $Z_d$ hadronic decay), data-driven estimated. $W+jets$ and $tt$ less important, MC estimated.

$Z+jet$ background estimation:

- determine the probability for a jet to pass the calorimeter ratio cut, on jets in a $W+jets$ data sample. Apply the probability to the selected sample of $Z->ll + njets$, calculate the amount of events expected to have 1 jet identified as $Z_d$ hadronic decay.
Results

Main errors:
• statistical uncertainty of the W+jets sample 2-8%
• potential quark/gluon difference between the W and Z samples 7-20%
• uncertainty on assumption “jets in W evts = jets in Z evts” 10%
Search for heavy Majorana or Dirac neutrinos and right-handed W gauge bosons in final states with two charged leptons and two jets

Type I see-saw or inverse see-saw mechanism in Left Right Symmetric Models, with new sector parallel to SM, with W bosons with coupling to right-handed particles, and right-handed neutrinos

\[ M_{WR} > M_{NR} : \text{llqq invariant mass sensitive to } M_{WR} \]

\[ M_{WR} < M_{NR} : \text{qq invariant mass sensitive to } M_{WR} \]

\( N_R \) can be Majorana or Dirac particle. Opposite Sign charge channel is sensitive to Majorana and Dirac nature, Same Sign charge channel is sensitive to Majorana only. No flavour mixing is considered in the search.
Selections

Event selection

- single or double lepton trigger + offline $p_T > 25(30)$ GeV for Opposite Sign, OS (Same Sign, SS) charge selection of the two leptons. Leptons are isolated.

- two jets $p_T > 100$ GeV

<table>
<thead>
<tr>
<th>Region</th>
<th>Control region</th>
<th>Validation region</th>
<th>Signal region</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CR($\ell^+\ell^-$)</td>
<td>CR($\ell^+\ell^+$)</td>
<td>VR($\ell^+\ell^-$)</td>
</tr>
<tr>
<td>Channel</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>$m_{ee}$ [GeV]</td>
<td>[60, 110]</td>
<td>—</td>
<td>[110, 300]</td>
</tr>
<tr>
<td>$m_{\mu\mu}$ [GeV]</td>
<td>[60, 110]</td>
<td>—</td>
<td>[60, 300]</td>
</tr>
<tr>
<td>$m_{e\mu}$ [GeV]</td>
<td>—</td>
<td>&gt; 400</td>
<td>—</td>
</tr>
<tr>
<td>$H_T$ [GeV]</td>
<td>&gt; 400</td>
<td>&gt; 400</td>
<td>—</td>
</tr>
<tr>
<td>$m_{jj}$ [GeV]</td>
<td>&gt; 110</td>
<td>&gt; 110</td>
<td>—</td>
</tr>
<tr>
<td>Jet $p_T$ [GeV]</td>
<td>&gt; 100</td>
<td>&gt; 100</td>
<td>&gt; 50</td>
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</table>

OS OS SS OS SS OS SS

CR: used to scale some of the backgrounds, VR: used to validate the backgrounds, SR: used to set limits
Backgrounds and systematics

- **OS**: main backgrounds are Z+jets and tt. MC Z+jets mjj spectrum is reweighted using CR data.

- **SS**: main backgrounds are Z+jets (misidentified e charge, CR used to scale MC) and diboson in ee, μ μ final state. Additionally, “fakes” from misidentified or non-prompt leptons is a large component.

- Fake factor method where identification or isolation is inverted, and a transfer (“fake”) factor is measured in independent, fake-enriched regions.
Results

Improves on previous ATLAS results [1], pushing limits on $M_{WR}$ up by 1-2 TeV. Also, investigates $M_{NR}>M_{WR}$ for first time.

Search for long-lived particles in final states with displaced dimuon vertices

\[ c\tau_X \sim 16 \pi F_0^2/m_X^5, \quad F_0: \text{scale new physics} \]
\[ F_0 \sim 10^6-10^8 \text{ TeV} \rightarrow \text{long-lived} \]

\[ c\tau_{Z_D} \sim 1/\varepsilon^2, \quad \varepsilon: \text{mixing } Z-Z_D \]
\[ \varepsilon \sim 10^{-5} \rightarrow \text{long-lived} \]

<table>
<thead>
<tr>
<th>Signal type</th>
<th>Trigger</th>
<th>Description</th>
<th>Thresholds</th>
</tr>
</thead>
<tbody>
<tr>
<td>High mass</td>
<td>$E_T^\text{miss}$ single muon</td>
<td>missing transverse momentum single muon restricted to the barrel region</td>
<td>$E_T^\text{miss} &gt; 110$ GeV $\mu$on $</td>
</tr>
<tr>
<td>Low mass</td>
<td>collimated dimuon trimuon</td>
<td>two muons with small angular separation three muons</td>
<td>$p_T$ of muons &gt; 15 and 20 GeV and $\Delta R_{\mu\mu} &lt; 0.5$ $p_T &gt; 6$ GeV for all three muons</td>
</tr>
</tbody>
</table>

muons exclusively found in the Muons Spectrometer
Selections

<table>
<thead>
<tr>
<th>Selection</th>
<th>Low mass</th>
<th>High mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T^\mu$ [GeV]</td>
<td>$&gt; 10$</td>
<td>$&gt; 20$</td>
</tr>
<tr>
<td>$m_{\mu\mu}$ [GeV]</td>
<td>15–60</td>
<td>$&gt; 60$</td>
</tr>
<tr>
<td>Dimuon transverse boost</td>
<td>–</td>
<td>$&gt; 2$</td>
</tr>
<tr>
<td>SR$_\text{low}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SR$_\text{high}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Muon candidates</td>
<td>both MSOnly</td>
<td>both MSOnly</td>
</tr>
<tr>
<td>Muon candidate charge</td>
<td>opposite charge</td>
<td>opposite charge</td>
</tr>
</tbody>
</table>

background estimate: solely data driven, via ABCD method

use SS mainly for non-prompt component (cosmics, beam induced background, fake tracks, $\pi/K$ decays). $R^q =$ charge ratio

use OS for prompt component (DY)

signal region (OS) = $N_A^{\text{non-prompt}} + N_A^{\text{prompt}}$

$N_A^{\text{non-prompt}} = N_A^{\text{SS}} \times R^q$

$N_A^{\text{prompt}} = \left[N_B' \times N_C' / N_D'\right]_{\text{OS}}$

$N_B' = N_B^{\text{OS}} - N_B^{\text{SS}} \times R^q$, and similar for C, D
Results

$r_{vtx}=2.2$ cm,
$z_{vtx}=-8.2$ cm,
$m=21$ GeV
Results substantially extend the range of lifetimes probed
Search for long-lived particles that decay to displaced hadronic jets in the ATLAS muon spectrometer sensitive to scalar hidden sectors, or stealth susy (no missing energy)

significantly extends the mean proper lifetime ($\tau$) range of the ATLAS search for a light scalar boson decaying into long-lived neutral particles [1] and extends the range of excluded proper lifetimes [2]. Focuses on Muon Spectrometer (MS) muons

<table>
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<tr>
<th>Strategy</th>
<th>Basic event selection</th>
<th>Benchmarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>2MSVx</td>
<td>At least 2 MS vertices</td>
<td>Scalar portal, Higgs portal baryogenesis, Stealth SUSY</td>
</tr>
<tr>
<td>1MSVx+Jets</td>
<td>Exactly 1 MS vertex At least 2 jets with $E_T &gt; 150$ GeV</td>
<td>Stealth SUSY</td>
</tr>
<tr>
<td>1MSVx+$E_T^{miss}$</td>
<td>Exactly 1 MS vertex $E_T^{miss} &gt; 30$ GeV</td>
<td>Scalar portal with $m_\Phi = 125$ GeV, Higgs portal baryogenesis</td>
</tr>
</tbody>
</table>

Selection and backgrounds

Event passes Muon RoI Cluster trigger
Event has a PV with at least two tracks with $p_T > 400$ MeV
Event has at least one MS vertex
MS vertex matched to triggering muon RoI cluster ($\Delta R(\text{vertex, cluster}) < 0.4$).
For 2MSVx strategy: in the case of 2 muon RoI clusters, the second vertex should be matched to the second cluster.

300 $\leq n_{MDT} < 300$

<table>
<thead>
<tr>
<th>Barrel</th>
<th>Endcaps</th>
</tr>
</thead>
</table>
| MS vertex with $|\eta_{vtx}| < 0.7$ | MS vertex with $1.3 < |\eta_{vtx}| < 2.5$
| $n_{RPC} \geq 250$ | $n_{TRGC} \geq 250$ |

Validation region: SR, invert one jet $p_T$ … or invert number MDT+RPC hits

TRIG-2012-02

2MSVx:
- vtx's isolated from tracks and jets

1MSVx+jets:
- vtx isolated from tracks and jets, 2 jets $p_T > 150$ GeV

1MSVx+MET:
- vtx isolated from tracks and jets, MET>30 GeV, $|\Delta\phi(\text{MET,MSVx})|<1.2$

background determination:

predicted background with two MSVx

measured on Muon RoI Cl. trigger data with only one Muon Cl. and one MSVx

measured on zero-bias trigger data with no Muon Cl. bias and one MSVx

Validation region: SR, invert one jet $p_T$ … or invert number MDT+RPC hits
Results

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Region</th>
<th>A</th>
<th>Expected background</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>1MSVx+Jets</td>
<td>Barrel</td>
<td>14</td>
<td>15 ± 3 (stat.) ± 3 (syst.)</td>
<td>2,057</td>
<td>25</td>
<td>3,414</td>
</tr>
<tr>
<td></td>
<td>Endcaps</td>
<td>4</td>
<td>11 ± 3 (stat.) ± 9 (syst.)</td>
<td>560</td>
<td>15</td>
<td>761</td>
</tr>
<tr>
<td>1MSVx+E_{T}^{miss}</td>
<td>Barrel</td>
<td>224</td>
<td>243 ± 38 (stat.) ± 29 (syst.)</td>
<td>42</td>
<td>132,000</td>
<td>22,800</td>
</tr>
<tr>
<td></td>
<td>Endcaps</td>
<td>489</td>
<td>497 ± 51 (stat.) ± 30 (syst.)</td>
<td>94</td>
<td>165,800</td>
<td>31,390</td>
</tr>
</tbody>
</table>

\[ 2\text{MSVx} : \]

0 observed, 0.027±0.011 expected

Improves the cross-section sensitivity for some of the $\Phi \to ss$ decays by about an order of magnitude compared to the ATLAS Run 1 result.

Extends the sensitivity for the Stealth SUSY model to higher gluino masses that could not be reached with ATLAS Run 1 result.
Conclusions

There are extraordinary beyond Standard Model physics observations: dark matter, baryogenesis, neutrino oscillations. The origin of these phenomena are the big questions in particle physics now.

We are at the start of an era where theory does not provide clear guidelines to the answers, only wide and unconventional experimental searches can. To quote J. Beacham: The nightmare scenario at the LHC is not no-new-physics; it’s: “You didn’t keep the right events and didn’t do the right searches.” We must reduce this chance to as small as possible.

ATLAS is expanding more and more the range of searches for new physics, starting at the trigger level, focusing on high mass and on low mass and low interaction strength scenarios. New peculiar characteristics, such as long-lived particles, are receiving a renewed focus.

First results on Run-2 partial dataset are presented. They extend results from Run-1 notably in all cases. Three times more Run-2 data are still to be analyzed. They will certainly bring exciting updates!