Exotics searches with ATLAS

Andrii Tykhonov on behalf of ATLAS collaboration

Jozef Stefan Institute, Ljubljana, Slovenia

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The ATLAS detector

Electromagnetic and hadronic calorimeters

Inner tracker:
- Silicon detectors
- Transition radiation detector

Principle of operation
Outline

A wealth of exotics analyses at ATLAS – impossible to cover everything in a 15 min talk! – selection of results is presented:

- **Extra dimensions** – solution to hierarchy problem
- **Dark matter** – WIMPs, gravitinos, hidden sectors?
- **Origin of neutrino masses** – seesaw mechanism?
- **Vector-like quarks** – a non-SUSY solution to naturallness problem

![Image of ATLAS Experiment results]

- $m_{\mu\mu} = 1.8$ TeV
- $m_{tt} = 2.6$ TeV
Models of extra dimensions:

- **4 +1** – one warped extra dimension – RS model:
  - *ttbar resonances* (via Kaluza-Klein excitations of gluon); dilepton or diphoton resonances.

- **4 + n** – n large flat extra dimensions – ADD models:
  - *Microscopic black holes;*
  - *Heavy KK excited states of graviton* (escape the detector, giving raise to significant missing transverse momentum)

- Extra dimensions are compactified at some scale, leading the weakness of gravity in 4 space-time dimensions → apparent Planck scale is 19 orders of magnitude higher than electroweak scale.

- The ``truth’’ Planck scale in 4+n dimensions is postulated to be of the order of electroweak scale.
Extra dimensions

- **Search for heavy resonances**
  - Dielectron and dimuon
  - Di-tau
  - Di-photon
  - ttbar
  - jet-jet
  - Jet-photon
  - photon-photon
  - ZZ-resonances

  *Also sensitive to GUT models, technicolor, extended Higgs sectors, etc.*

- **Multi-track (e.g. microscopic black holes)**

- **Mono-object with high missing transverse momentum**
  - Mono-jet
  - Mono-photon
  - Mono-W(Z)

  *Also sensitive to WIMP dark Matter and SUSY gravitinos*
Extra dimensions

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- **Multi-track (e.g. microscopic black holes)** *New!*

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  *Also sensitive to WIMP dark Matter and SUSY gravitinos*
The extremely high pile-up of about 20 $pp$ collisions per bunch crossing in 2012!

Pile-up represents a challenge for top-quark reconstruction. Advanced jet “grooming” is applied

- Subjets are formed with $R=0.3$; soft subjets with less than a certain fraction of the original jet $p_T$ are removed;
- $\text{JVF} > 0.5$.

$\text{JVF}$ is the summed transverse-momentum $p_T$ of all tracks matched to the jet from the primary vertex divided by the summed $p_T$ of all matched tracks from all vertices.

<table>
<thead>
<tr>
<th>Background</th>
<th>$2400 \pm 500$</th>
<th>$3300 \pm 700$</th>
<th>$5600 \pm 1200$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>2177</td>
<td>2945</td>
<td>5122</td>
</tr>
</tbody>
</table>

ATLAS-CONF-2013-052, arxiv:1306.4945
If one assumes the fundamental Planck $M_D$ scale in n+4 dimensions order of 1 TeV, microscopic black holes with TeV-scale mass could exist and be produced at LHC!

Black Hole (BH) production has a continuous mass distribution ranging from $M_D$ to pp mass; **BH are produced when the impact parameter of the two colliding protons is smaller than the higher-dimensional event horizon of a black hole with mass equal to pp mass.**

- BH evaporate by emitting Hawking radiation
- BH events are expected to have a high multiplicity of high-momentum particles!

No deviation from SM prediction $\rightarrow$ BH mass below 5 TeV are excluded at 95% CL

<table>
<thead>
<tr>
<th>Source</th>
<th>Signal Region</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu+$fake</td>
<td>$0.21 \pm 0.09 \pm 0.09$</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>$0.22 \pm 0.08 \pm 0.04$</td>
</tr>
<tr>
<td>Diboson</td>
<td>$0.12 \pm 0.08 \pm 0.03$</td>
</tr>
<tr>
<td>Total</td>
<td>$0.55 \pm 0.15 \pm 0.10$</td>
</tr>
<tr>
<td>Data</td>
<td>0</td>
</tr>
<tr>
<td>Signal</td>
<td>$14.2 \pm 1.3 \pm 2.7$</td>
</tr>
</tbody>
</table>
Dark matter

WIMP dark matter

- \( pp \rightarrow \chi \chi + g / \gamma / W / Z \) – pair of WIMPs (with mass below few TeV) are produced in association either with single gluon or photon or W(Z) gauge boson
- WIMPs escape detection giving rise to significant missing transverse momentum

These analyses are also sensitive to gravitino DM production

Non-standard WIMP scenarios: hidden-sectors

Assumption of Arkani-Hamed et.al.:
WIMP-like Dark Matter is charged under the hidden-sector gauge group, which is broken at a GeV scale

Provides an elegant explanation of Fermi / Pamela/AMS electron (positron) anomaly
Dark matter: lepton-jets

The conventional WIMP models can’t address the PAMELA anomaly for two main reasons:

1. Annihilation rate of dark matter should be a few orders of magnitude larger than the annihilation rate that produces the correct DM relic abundance;

2. Dark Matter should annihilate predominantly into leptons and not hadrons.

**Hidden sectors models feature massive gauge U(1) boson – dark photon with mass < 2 GeV:**

1. Annihilation cross-section is enhanced via Sommerfeld mechanism:

   - **Sommerfeld enhancement**

   - **No enhancement**

   - **Manifest itself at hadron colliders through the lepton jets** – collimated sets of electrons/muons/pions

   - **Branching fraction of dark photon w.r.t. its mass**

   Depending on the strength of mixing between dark photon and SM photon, lepton jets can be either prompt (originating from interaction point) or displaced.

   - **e⁺e⁻**
   - **μ⁺μ⁻**
   - **Hadrons**

   - BR

   - Mass [GeV]
Lepton jets can be produced in the decays of Higgs boson:

possibly from 2 to about ten leptons per lepton-jet

Advanced signal/background discriminating parameters are used: $f_{CH}$ – fraction of jet energy deposited in the calorimeter cells within a cone of $R = 0.2$ around each of the tracks associated with the jet

... or directly in the SUSY cascade (f. ex. through squark or neutrino channels):

Backgrounds:
- multi-jet
- photon + jet

Background yield is determined from data using ABCD-likelihood method

<table>
<thead>
<tr>
<th></th>
<th>2 e-jets</th>
<th>1 μ-jet</th>
<th>2 μ-jets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>15</td>
<td>7</td>
<td>3</td>
</tr>
<tr>
<td>All backgrounds</td>
<td>15.2±2.7</td>
<td>3.0±1.0</td>
<td>0.5±0.3</td>
</tr>
</tbody>
</table>

arxiv:1302.4403, 1210.0435

arxiv:1212.5409
Origin of neutrino masses: multilepton

Seesaw mechanism $\rightarrow$ light neutrino masses are generated by adding new massive particles to the model

... these are f.ex. New heavy fermions $N^0, N^+, N^-$, in type-III seesaw models

Decays of new heavy particles result in events with more than two energetic, prompt and isolated charged leptons

Irreducible SM backgrounds: WZ, ZZ where both bosons decay leptonically, tt+W(Z), Drell-Yan

Reducible SM backgrounds: semi-leptonic decays of $b$- or $c$-hadrons, jets penetrating muon spectrometer, etc. – determined from the data using the fake factor method – up to 50% systematic uncertainty

4 signal regions:

<table>
<thead>
<tr>
<th>Flavor Chan.</th>
<th>Z Chan.</th>
<th>Expected</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\geq 3e/\mu$</td>
<td>off-Z</td>
<td>$260 \pm 10 \pm 40$</td>
<td>280</td>
</tr>
<tr>
<td>$2e/\mu + \geq 1\tau_{had}$</td>
<td>off-Z</td>
<td>$1200 \pm 10 \pm 290$</td>
<td>1193</td>
</tr>
<tr>
<td>$\geq 3e/\mu$</td>
<td>on-Z</td>
<td>$3100 \pm 40 \pm 500$</td>
<td>3199</td>
</tr>
<tr>
<td>$2e/\mu + \geq 1\tau_{had}$</td>
<td>on-Z</td>
<td>$17000 \pm 40 \pm 4000$</td>
<td>14733</td>
</tr>
</tbody>
</table>

ATLAS-CONF-2013-070
**Vector-like quarks**

Vector-like quarks emerge as a characteristic feature of many non-SUSY natural models.

Vector-like quarks: both chiralities have the same transformation properties under SM SU(2) x U(1).

**Vector-like top-partner quark T plays a key role in cancelling the quadratic divergences in the Higgs boson mass (induced by t-quark)**

T quark mixes preferentially with the 3rd generation quarks → signal events feature high multiplicity of jets plus isolated prompt leptons.

Decays of T-quark involve W,Z or Higgs boson → many complementary analyses are performed:

<table>
<thead>
<tr>
<th>Analysis</th>
<th>leptons</th>
<th>jets</th>
<th>b-jets</th>
<th>$E_{T}^{miss}$</th>
<th>Preprint</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ht + X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Same-sign dilepton</td>
<td>$e^{\pm} e^{\pm}$ / $\mu^{\pm} \mu^{\pm}$</td>
<td>≥ 6</td>
<td>≥ 2</td>
<td>40 GeV</td>
<td>ATLAS-CONF-2013-018</td>
</tr>
<tr>
<td>Zb/t + X</td>
<td>$Z \rightarrow ee (\mu\mu)$</td>
<td>≥ 2</td>
<td>≥ 1</td>
<td></td>
<td>ATLAS-CONF-2013-051</td>
</tr>
<tr>
<td>Wb + X</td>
<td>$e/\mu$</td>
<td>≥ 4</td>
<td>≥ 2</td>
<td>20 GeV</td>
<td>ATLAS-CONF-2013-056</td>
</tr>
</tbody>
</table>
Vector-like quarks

95% confidence level exclusion contours with respect to branching fractions and for different masses of vector-like T quark:

Vector-like T quarks with masses in the range 350–550 GeV are completely excluded
Summary of Exotics searches

Mass reach for various ATLAS exotics analyses:

- Dark blue lines indicate 8 TeV results
- Fundamental Planck scale in Large extra dimensions (ADD models) below 1.9 TeV is excluded
Conclusions

- A plethora of Exotics analysis is underway at ATLAS:
  - 20 conference notes with 2012 data
  - 53 papers published with 2011 data

- New physics was not around the corner...
  ... however, not all analyses unblinded their 2012 data → surprises with 8 TeV data are still possible!

- Preparing for the 14 TeV run → a non-exhaustive list of challenges:
  - Reconstruction of TeV leptons
  - Boosted objects (W, top-quarks)
  - Investigate less obvious signatures, f.ex. lepton jets and displaced decays
Thank you for your attention!

To be continued...