Search for DM pair production with W & Z boson

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DM at Collider, Chicago
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Why looking for Dark Matter with W/Z?

- **Typical search channel:**
  - mono-jet,
  - mono-photon
- **mono-W** small rate exp.
  - same couplings up/down-type quarks
- **W boson emission may become dominant**
  - opposite sign couplings
- **Largest BR for hadronic decay**

Y. Bai, T. Tait; arXiv:1208.4361
Isospin Violating DM

- $f_n/f_p =$ ratio of proton/neutron coupling
- For $-0.72 < f_n/f_p < -0.66$ the DAMA- and CoGeNT-favored regions overlap and the sensitivity of XENON is sufficiently reduced to be consistent with these signals
Dataset

<table>
<thead>
<tr>
<th>2011/12</th>
<th>Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>7 TeV / 8 TeV</td>
</tr>
<tr>
<td>Bunch Spacing</td>
<td>50 ns / 25 ns</td>
</tr>
<tr>
<td>Luminosity</td>
<td>3.6 / 8 x 10^{33} cm^{-2} s^{-1} / 10^{34} cm^{-2} s^{-1}</td>
</tr>
<tr>
<td>Pile-Up</td>
<td>~20 / 40</td>
</tr>
</tbody>
</table>

Analysis uses **full 2012 ATLAS data set (20.3 fb^{-1})**
Wimp Signal

- Using **Effective Field Theory**
- **C1, D1** (scalar), **D5** (destructive), **D52** (vector) (constructive, mono-W only) and **D9** (tensor) with $M^*=1\text{TeV}$
- $m_{\text{DM}} = 1, 50, 100, 200, 400, 700, 1000, 1300$
- Sensitive possibly as well to e.g.: $H \rightarrow \text{inv}$ decays ($Wh, Zh$)

<table>
<thead>
<tr>
<th>Coupling Group</th>
<th>Operator</th>
<th>Operator Structure</th>
<th>Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scalar quark</td>
<td>D1</td>
<td>$\chi \chi \bar{q} q$</td>
<td>$m_q / M_*^3$</td>
</tr>
<tr>
<td>Vector quark</td>
<td>D5</td>
<td>$\chi \gamma^\mu \chi \bar{q} \gamma_\mu q$</td>
<td>$1 / M_*^2$</td>
</tr>
<tr>
<td>Tensor quark</td>
<td>D9</td>
<td>$\chi \sigma^{\mu\nu} \chi \bar{q} \sigma_{\mu\nu} q$</td>
<td>$1 / M_*^2$</td>
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Selection

- **Jets boosted**, reconstructed as single large radius jet

- Using ‘**Cambridge-Aachen**’ algorithm for jet reconstruction
  - $p_T > 250$ GeV, $|\eta| < 1.2$
  - $50$ GeV < $M_{\text{jets}}$ < 120 GeV
  - $\sqrt{(y)} < 0.4$, where $\sqrt{(y)} < \min(p_T^1, p_T^2) \Delta R_{1,2} / M_{\text{jets}}$ (balancing of two leading subjets)

- **Further selections**:
  - $\leq 1$ anti-$k_T$ 0.4 jet with $p_T > 40$, $|\eta| < 4.5$
  - separated from large radius jet and $E_T^{\text{miss}}$
  - Signal Regions: $E_T^{\text{miss}} > 350, 500$ GeV
Background Selection

- **MC simulations:**
  - ttbar
  - single top
  - diboson

- **Top-CR region:**
  - 1 b-tag, 2 narrow jet, 1 large jet

- **Dominant bkgd:**
  - Z(vv)+jets, W(lv)+jets and Z(ll)+jets

- **Data-driven method**
  - muon: signal selection + $\mu$
Control Regions

- **W-CR**: $250 < E_T^{\text{miss}} < 350$ GeV
- **Z-CR**: $2\mu$, $E_T^{\text{miss}} > 350$ GeV
- Good agreement in all validation regions
Event yield

<table>
<thead>
<tr>
<th>Process</th>
<th>$E_T^{\text{miss}} &gt; 350$ GeV</th>
<th>$E_T^{\text{miss}} &gt; 500$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z \rightarrow \nu\bar{\nu}$</td>
<td>$400^{+39}_{-34}$</td>
<td>$54^{+8}_{-10}$</td>
</tr>
<tr>
<td>$W \rightarrow \ell^\pm \nu$, $Z \rightarrow \ell^\pm \ell^\mp$</td>
<td>$210^{+20}_{-18}$</td>
<td>$22^{+4}_{-5}$</td>
</tr>
<tr>
<td>$WW, WZ, ZZ$</td>
<td>$57^{+11}_{-8}$</td>
<td>$9.1^{+1.3}_{-1.1}$</td>
</tr>
<tr>
<td>$t\bar{t}$, single $t$</td>
<td>$39^{+10}_{-4}$</td>
<td>$3.7^{+1.7}_{-1.3}$</td>
</tr>
<tr>
<td>Total</td>
<td>$710^{+48}_{-38}$</td>
<td>$89^{+9}_{-12}$</td>
</tr>
<tr>
<td>Data</td>
<td>$705$</td>
<td>$89$</td>
</tr>
</tbody>
</table>

- **W/Z+jets dominant (85%)**
  - **QCD negligible** in hadronic W/Z selection
- Uncertainties dominated by limited CR statistics
Results

Unfortunately no excess over SM found
Limits on Mediator Mass

Individual limits on Mediator Mass

Scalar

Vector (destr)

Tensor

Complete scalar

Vector (constr)
Limits on WIMP-Nucleon xsec

- Converting into limits on WIMP-Nucleon scattering cross section
- Spin independent limits improve by three orders of magnitude if up/down have opposite sign
Limits on $H \rightarrow \text{inv}$.

SR: $E_T^{\text{miss}} > 350$ GeV

$\sigma_{(W/Z \, H \rightarrow \text{inv} \, \text{inv})} / \sigma_{\text{total SM}(W/Z \, H)}$

ATLAS 20.3 fb$^{-1}$ $\sqrt{s} = 8$ TeV

$m_H [\text{GeV}]$

Limits on $\text{Higgs} \rightarrow \text{inv}$
Fiducial regions:
- $W$ or $Z$ $p_T > 250$ GeV, $|\eta| < 1.2$, $\sqrt{y} > 0.4$
- $p_T(\chi\chi) > 350$ GeV or 500 GeV
- Reco efficiency is 50%

Model independent limits as function of $W$-boson fraction
Conclusion

- **First WIMP search using ‘mono-W/Z’**
- **In case of constructive interference** between up- and down quarks, the results set the strongest limits on $M^*$
- There is **no significant excess** observed in these signal regions.
- **Exclusion limits are extracted** on mono-W and mono-Z signals.
- Please see **ATLAS-CONF-2013-073** for details
Backup
Figure 4: Summary of observed limits on the effective theory mass scale $M_\ast$ at 90% CL for various operators from combined single $W$/$Z$ boson signals. Values below these lines are excluded.

**Definitions:**
- For parton level, $p_T > 250 \text{ GeV}$, $|\theta| < 1$.
- Two quarks with $p_T > 0$.
- $p_T > 350$ or $500 \text{ GeV}$.

The upper limit on cross section times reconstruction efficiency is 3 fb (1.5 fb) at 95% C.L. for $p_T > 350$ (500 GeV). The reconstruction efficiency for these events is $50 \pm 1\%$, with modest dependence on the dark-matter production model.

In conclusion, this paper reports the first LHC limits on dark-matter production in events with a hadronically decaying $W$ or $Z$ boson and large missing transverse momentum. In the case of constructive interference between up-type and down-type contributions, the results set the strongest limits on the mass scale of $M_\ast$ of the unknown mediating interaction.

**References**

C/A Jets

- For highly boosted objects, decay products have narrow $dR$ distribution
- To recover efficiency & resolution:
  - Use a single large $R$ Cambridge/Aachen jet encompassing all decay products
  - Revert last step of clustering and look for two low mass, symmetric sub-jets
  - Recluster constituents of sub-jets, keep 3 hardest new sub-jets
- Process greatly improves jet mass measurement, QCD separation