Search for Dark Matter and Extra Dimensions
In ATLAS

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on behalf of the ATLAS collaboration

Large Hadron Collider Physics Conference
New York City, June 3rd, 2014
Why Dark Matter & Extra Dimension?

- Dark Matter (DM) firmly established signal of new physics
- DM likely to be ‘non-baryonic cold dark matter’
- Global fit of cosmological parameters, $\Lambda$CDM:
  \[ \Omega\Lambda \approx 0.68, \quad \Omega_{DM} \approx 0.27, \quad \Omega_b \approx 0.05 \]

- Underground dark matter searches measure nuclear recoil
- There may very well be more phenomena we do not yet understand → parametrize effective scales

arXiv:1303.5062

kinematic limitations at low masses

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Principle of Collider DM searches

- DM likely to be ‘non-baryonic cold dark matter’ → ‘WIMP Miracle’ → BSM physics
- Properties of low mass DM
  - Pair produced (stable)
  - Mediating particle (M*) not directly observed → Effective Field Theory (EFT)

- Sensitive to spin-dependent and independent dark matter nucleon interactions and low masses

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<table>
<thead>
<tr>
<th>Name</th>
<th>Initial state</th>
<th>Type</th>
<th>Operator</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1</td>
<td>$qq$</td>
<td>scalar</td>
<td>$\frac{m_q}{M^*_X} \bar{X} q q$</td>
</tr>
<tr>
<td>D5</td>
<td>$qq$</td>
<td>vector</td>
<td>$\frac{1}{M^*<em>X} \bar{X} \gamma^\mu \chi \bar{q} \gamma</em>\mu q$</td>
</tr>
<tr>
<td>D8</td>
<td>$qq$</td>
<td>axial-vector</td>
<td>$\frac{1}{M^*_X} \bar{X} \gamma^\mu \gamma^5 \chi \bar{q} \gamma^5 q$</td>
</tr>
<tr>
<td>D9</td>
<td>$qq$</td>
<td>tensor</td>
<td>$\frac{1}{M^*<em>X} \bar{X} \sigma^{\mu\nu} \chi \bar{q} \sigma</em>{\mu\nu} q$</td>
</tr>
<tr>
<td>D11</td>
<td>$gg$</td>
<td>scalar</td>
<td>$\frac{1}{4 M^*<em>X} \bar{X} \chi q (G^a</em>{\mu\nu})^2$</td>
</tr>
</tbody>
</table>

Ref: arxiv:1008.1783v2
The LHC & Atlas

**Inner Detector (|η|<2.5)**: Si pixel, SCT, TRT Tracking and vertexing

\[ \sigma(pT)/pT \sim 0.038\% \ pT \ (GeV) \oplus 1.5\% \]

**Muon spectrometer (|η|<2.7)**: air-cores toroids with gas-based chambers.
Momentum resolution <10% up to \( E_\mu \sim 1 \) TeV \( \sigma(pT)/pT \sim 0.038\% \ pT \ (GeV) \oplus 1.5\% \)

**EM calorimeter (|η|<3.2)**: Pb/LAr
\[ \sigma(E)/E \sim 10\% / \sqrt{E} \ (GeV) \oplus 0.7\% \]

**HAD calorimeter (|η|<5)**: Fe/scintillator tiles (central), Cu/W LAr (fwd), T \( \sigma(E)/E \sim 50\% / \sqrt{E} \ (GeV) \oplus 3\% \)
• Extending mono-jet/photon final states to new signatures
• see Thursday’s plenary talks
• W boson emission may become dominant for opposite sign couplings
• $f_n/f_p$ = ratio of proton/neutron coupling
• For $-0.72 < f_n/f_p < -0.66$ DAMA- and CoGeNT, and XENON are consistent

- Selection
  - maximal one $dR=0.4$ jet
  - separated from large radius jet and $E_T^{miss}$
  - Signal Regions: $E_T^{miss} > 350, 500$ GeV

Y. Bai, T. Tait; arXiv:1208.4361
Feng et al.; arXiv:1102.4331

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Dark Matter with W/Z

- Unfortunately no excess over SM found
- Converting into limits on WIMP-Nucleon scattering cross section
- Spin independent limits improve by three orders of magnitude if up/down have opposite sign
- See also ATLAS-CONF-2014-017 for W→lν channel
DM with Z (→ll)

- Associated DM+Z production
- Consider EFT and UV complete models

Event selection:
- Single- or Dilepton Trigger
- m(ll) within Z window
- $E_T^{\text{miss}}$ and $p_T(\ell\ell)$ well separated
- Central production: $|\eta(\ell\ell)|<2.5$
- Balanced: $|p_T(\ell\ell)-E_T^{\text{miss}}|/p_T(\ell\ell)<0.5$
- 4 SRs: $E_T^{\text{miss}}>150, 250, 350, 450 \text{ GeV}$

TABLE I. The power dependence of 1/N dN/E

<table>
<thead>
<tr>
<th>Power</th>
<th>1/N dN/E [1/150 GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>0.5</td>
</tr>
<tr>
<td>3</td>
<td>0.12</td>
</tr>
<tr>
<td>4</td>
<td>0.023</td>
</tr>
</tbody>
</table>

TABLE II. Summary of the systematic uncertainties for the

<table>
<thead>
<tr>
<th>Uncertainty Source</th>
<th>Total [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>36</td>
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<tr>
<td></td>
<td>38</td>
</tr>
<tr>
<td></td>
<td>43</td>
</tr>
</tbody>
</table>

TABLE III. Observed yields and expected SM backgrounds

<table>
<thead>
<tr>
<th>m$_X$ [GeV]</th>
<th>200</th>
<th>400</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield</td>
<td>90</td>
<td>40</td>
</tr>
<tr>
<td>Expected</td>
<td>90</td>
<td>40</td>
</tr>
</tbody>
</table>

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DM with Z ($\rightarrow ll$)

- Unfortunately no excess over SM found
- Converting into limits on WIMP-Nucleon scattering cross section
- Also limits on coupling strength in mediator mass - DM plane are presented

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Extending to ADD & general CI

- Extend dilepton selection to high masses \( m_{ll} > 80 \) GeV and allow inclusive final states (jets and leptons)

- Consider EFT and UV complete model

- **Contact Interaction (CI):**
  Search using \( \cos \Theta \gtrsim 0 \) and \( m_{ll} = [400, \ldots, 4500] \) GeV

\[
\frac{\sigma}{d m_{ll}} = \frac{d \sigma_{DY}}{d m_{ll}} - \frac{F_{I}(m_{ll})}{\Lambda^{2}} + \frac{F_{C}(m_{ll})}{\Lambda^{4}}
\]

- Models of large extra dimensions: provide solution to hierarchy problem

  - **Arkani-Hamed, Dimopoulos, Dvali (ADD)**
    - Gravity propagates in (4+n)-dim bulk space
    - SM fields confined to 4d

- Propagation of LED results in Kaluza-Klein Modes

- As well DM signal candidate but at higher energies

- Search using \( m_{ll} > 1900 \) GeV
Extending to ADD and general CI

- Discriminating variables agree well
Extending to ADD and general CI

- **Good agreement** is observed between both, data and background model in mass and $A_{FB}$ distributions

- Setting **best limits** on various ADD models
BH→l+jets

- LED may lower Gravity scale to EW scale
- Grav. scale $M_D < M_{Pl}$; if $M_D \sim$ TeV
  → strong production of mini Black Holes (BH) at LHC
- DM produced at $M_{th} \sim 2xM_D$
- Different BH evolution and decay modes considered
  - Gravitons
    → approaching $M_D$ → ‘Final burst’ remnants
      (high mult. states)
  - Hawking Radiation

<table>
<thead>
<tr>
<th>Generator</th>
<th>Angular Mom.</th>
<th>Description</th>
<th>$n$ considered</th>
</tr>
</thead>
<tbody>
<tr>
<td>CHARYBDIS</td>
<td>Non-rotating</td>
<td>Black holes: High multiplicity remnant</td>
<td>2, 4, 6</td>
</tr>
<tr>
<td></td>
<td>Rotating</td>
<td>Black holes: High multiplicity remnant</td>
<td>2, 4, 6</td>
</tr>
<tr>
<td></td>
<td>Rotating</td>
<td>Black holes: Low multiplicity remnant</td>
<td>2, 4, 6</td>
</tr>
<tr>
<td></td>
<td>Rotating</td>
<td>Production loss model (gravitons)</td>
<td>2, 4, 6</td>
</tr>
<tr>
<td>CHARYBDIS</td>
<td>Non-rotating</td>
<td>String balls</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>Rotating</td>
<td>String balls</td>
<td>6</td>
</tr>
<tr>
<td>BLACKMAX</td>
<td>Non-rotating</td>
<td>Black holes: High multiplicity remnant</td>
<td>2, 4, 6</td>
</tr>
<tr>
<td></td>
<td>Rotating</td>
<td>Black holes: High multiplicity remnant</td>
<td>2, 4, 6</td>
</tr>
<tr>
<td></td>
<td>Non-rotating</td>
<td>Black holes with graviton</td>
<td>2, 4, 6</td>
</tr>
<tr>
<td></td>
<td>Rotating</td>
<td>10% Production loss model (photons)</td>
<td>2, 4, 6</td>
</tr>
<tr>
<td></td>
<td>Rotating</td>
<td>Lepton number conservation</td>
<td>4</td>
</tr>
</tbody>
</table>

$M_{Pl}^2 \sim M_{Pl}^{2+n}(4+n) R^n$
Further extend this signature by requiring only one lepton, and large jet multiplicities (>2 high $p_T$ final state objects)

\[ \sum p_T = \sum_{i=\text{objects}} p_T,i \]

Signal selection:
- $\sum p_T > 2000$ GeV
- At least three objects with $p_T > 100$ GeV
- At least one lepton with $p_T > 100$ GeV

Using MC and data driven methods for background

Interpolate via analytical function to very high $p_T$
BH→l+jets

- Limits agree again well expectation
- Limits are set on wide range of \textcolor{red}{black hole} and \textcolor{red}{string ball} models
- Strongest existing bounds along with CMS
Conclusion

- At the LHC make a strong statement regarding ‘cosmological’ phenomena
- Using Effective Theories to explore new Frontiers
- Extending DM searches to unexplored low mass region
- Set strongest bounds on Extra Large Dimensions and Microscopic Black Holes
- Extending these analyses to new final states and probing wider phase space
- Use of new experimental tools (boosted jets)
- Looking forward to even higher energies
Backup
Typical Collider Backgrounds

**V+jets**: Data driven or MC with data corrections

**Diboson, Single Top, Top Pair**: Simulations

**Multijet**: Data driven
### The LHC & ATLAS

<table>
<thead>
<tr>
<th></th>
<th>2011/12</th>
<th>Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>7 / 8 TeV</td>
<td>14 TeV</td>
</tr>
<tr>
<td>Bunch Spacing</td>
<td>50 ns</td>
<td>25(50) ns</td>
</tr>
<tr>
<td>Luminosity</td>
<td>3.6/8 x 10^10</td>
<td>10</td>
</tr>
<tr>
<td>Pile-Up</td>
<td>~20/40</td>
<td>~50(100)</td>
</tr>
</tbody>
</table>
The LHC & ATLAS
Dark Matter with W/Z

- **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)
Example of Present Searches

- Mono-jet
Selection Requirements

• $E_T^{\text{miss}}$ trigger

• Monojet (8 TeV, 10.5 fb$^{-1}$)
  - $E_T^{\text{miss}}$, $p_T(\text{jet}) > 120, 220, 350, 500$ GeV
  - 1 or 2 jets
  - $|\Delta \varphi( E_T^{\text{miss}}, j_2)| > 0.5$

• ATLAS-CONF-2012-147
Validation Regions

$W \rightarrow e \nu + \text{jets}$

$W \rightarrow \mu \nu + \text{jets}$

$Z \rightarrow \mu \mu + \text{jets}$
Monojet Signal Region

- Expected and observed number of events agree
- Set limits on coupling strength of heavy mediator
Direct Detection Limits

spin-dependent

spin-independent

![Graph](image_url)

**ATLAS**

\[ \sigma = 7 \text{ TeV}, 4.7 \text{ fb}^{-1}, 90\% \text{CL} \]

**ATLAS**

\[ \sigma = 7 \text{ TeV}, 4.7 \text{ fb}^{-1}, 90\% \text{CL} \]
Direct Detection Limits

- **Spin-Dependent** (SIMPLE, Picasso)
  Atlas limits stronger for axial vector (D8) and tensor (D9) couplings

- **Spin-Independent** (XENON100, CDMSII, CoGent)
  Atlas limits stronger for scalar (D1) and vector (D5) at low $m_\chi$
Indirect Detection Limits

- Comparing to annihilations from galactic high energy gamma ray observations by FERMI LAT
Indirect Detection Limits

- Comparing to annihilations from galactic high energy gamma ray observations by FERMI LAT
**Monophoton limits**

**spin-dependent**

- Cross sections for mono-photon suppressed by ratio of strong and electromagnetic fine structure constants as well as a color factor

- Relative size of excesses in mono-photon vs. mono-jets is sensitive to whether the operator dominating the signal involves up or down quarks, due to their different electric charges

- Some operators (e.g. gg) won’t produce mono-photon signals

**spin-independent**

**ATLAS** $\sqrt{s}=7$ TeV, $\int L dt = 4.6$ fb$^{-1}$

- 90% CL, Spin-Independent
  - CDF, D5, $q\bar{q} \rightarrow j(\chi \bar{\chi})_{\text{Dirac}}$
  - CMS (5 fb$^{-1}$), D5, $q\bar{q} \rightarrow \gamma(\chi \bar{\chi})_{\text{Dirac}}$
  - ATLAS, D1, $q\bar{q} \rightarrow \gamma(\chi \bar{\chi})_{\text{Dirac}}$
  - ATLAS, D5, $q\bar{q} \rightarrow \gamma(\chi \bar{\chi})_{\text{Dirac}}$
  - ATLAS -1 $\sigma_{\text{theory}}$

**ATLAS** $\sqrt{s}=7$ TeV, $\int L dt = 4.6$ fb$^{-1}$

- 90% CL, Spin Dependent
  - CDF, D8, $q\bar{q} \rightarrow j(\chi \bar{\chi})_{\text{Dirac}}$
  - CMS (5 fb$^{-1}$), D8, $q\bar{q} \rightarrow \gamma(\chi \bar{\chi})_{\text{Dirac}}$
  - ATLAS, D8, $q\bar{q} \rightarrow \gamma(\chi \bar{\chi})_{\text{Dirac}}$
  - ATLAS, D9, $q\bar{q} \rightarrow \gamma(\chi \bar{\chi})_{\text{Dirac}}$
  - ATLAS -1 $\sigma_{\text{theory}}$
Principles of Particle Detection

“To see ‘nothing’ you have to understand everything.”

HAD calorimeter

EM calorimeter

Muon System

Muon Spectrometer

Solenoid magnet

Transition Radiation Tracker

Pixel/SCT detector

The dashed tracks are invisible to the detector

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b-tagging in ATLAS

- Long life-time of b/c-hadrons → displaced vertex
- ATLAS uses multivariate method, exploiting information of displaced vertex, track impact and PV association probability
- Typically 50-60% efficient for 0.5-1.5% fake rate
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
Limits on $H \rightarrow \text{inv.}$

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

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

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

Limits on $Higgs \rightarrow \text{inv}$
Model independent limits as function of W-boson fraction