Dark Jet Resonance Search
Status and Outlook

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Eva Hansen on behalf of the analysis team:
Dilia Portillo, Jannik Geisen, Nathan Lalloué,
Marie-Hélène Genest, Caterina Doglioni
Motivation: Composite Dark Matter

- Direct and indirect **WIMP searches have come up empty** so far
- Cosmological simulations allow self-interacting dark matter (DM)
  - E.g. composite DM arising from a hidden sector with confinement ("dark QCD")
- Combined with asymmetric production, composite DM could explain mass and number density of DM and Baryons
- Requires heavy mediator linking hidden sector to visible sector
  - Perhaps we can **produce and detect hidden sector particles at the LHC!**
"Dark QCD"

- Hidden sector with confinement coupled to SM through a heavy mediator
- Showering and hadronisation happens in the dark sector
- The lightest baryon is stable and a DM candidate
- Some mesons might decay back to SM according to specific model
Benchmark Signal Models

- Different realisations can lead to very different detector signatures
- Composition of **visible** and **invisible** partons in the jet dependent on parameter choice:
  - Exotic I: Displaced vertices, emerging jets
  - Exotic II: Semi-visible jets
  - **We target SM QCD-like models**
    - With $s$-channel mediator decaying to two dark quarks

- Four models implemented in Pythia Hidden Valley process
  - **All have larger confinement scales than SM QCD**
    - Based on arXiv:1712.09279
Search strategy

- Dominant background is Standard Model dijet events
  - Invariant mass spectrum is a smoothly falling
- Larger dark $\alpha_s$ means wider jets with larger particle multiplicity

- Strategy:
  - Reconstruct large-radius jets using Anti-kt algorithm with R=1.0
  - Select signal-like dijet events based on **substructure variables**
  - Look for a bump in the dijet invariant mass spectrum
Signal Selection

- Charged track multiplicity $n_{\text{trk}}$ is strongest discriminating variable for a most models
  - But not for Model B!
- Two signal regions:
  - **SR1**: High sensitivity, very pure, based on strict $n_{\text{trk}}$ cut
  - **SR2**: More inclusive, less sensitive based on softer cuts on $n_{\text{trk}}$ and $EM_{\text{frac}}$
Signal Region 1: Challenge

- Best sensitivity for a range of models obtained with very strict cut
- Strict $n_{\text{trk}}$ cut significantly sculpts the background dijet mass spectrum
- Solution: Decorrelate $n_{\text{trk}}$-cut efficiency from dijet mass!

**ATLAS Simulation Work in Progress**

- $n_{\text{trk}} > 85$
- Bkg eff: 0.003 %
- Sig eff: 5 %
"Fixed-efficiency-regression" decorrelates a discriminating variable from other variables. Described and tested in for $W$-tagging in ATL-PHYS-PUB-2017-004.

- For each jet, the new decorrelated observable is computed as $n_{\text{trk}}^\varepsilon = n_{\text{trk}} - p^{\varepsilon=0.5\%}$.
- Here $n_{\text{trk}}^\varepsilon$ is defined from data in a control region with signal efficiency $\sim 0.4\%$. 

ATLAS Work in Progress

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1/3/20

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Signal Region 1: Results (preliminary)

- Gives a smoothly falling spectrum up to ~5 TeV in MC
- Breaks down at higher m_{jj} because of too low statistics in data sample
- Cut: Leading and sub-leading jet n_{trk,ε} > 0
  - Background efficiency: 0.03 %
  - Signal efficiency (all tested models): 31 %
Background description

- The background contribution is determined by fitting data with the parametric function:
  \[
  \frac{dn}{dx} = p_1 (1-x)^{p_2-\xi} x^{-p_3}
  \]

- Currently validating the fitting strategy on dijet MC samples doing
  - "Signal injection test"
  - "Spurious signal test"

The background only fit: No signal injected
Conclusion and outlook

• Lots of uncovered phase space in hidden sector models
  − We can probe (a small) part of it by searching for dark jets
  − Fun challenges for jet substructure fans!

• Ongoing task:
  − Complete validation of background estimation
  − Optimise binning
  − Evaluate systematic uncertainties on signal and background

• Long term:
  − Optimise choice of jet definition and pile-up removal
  − Study more features, such as muons in jets and missing Et aligned with a jet
  − Combine efforts with emerging jets and semi-invisible jets searches
Backup

- Table of benchmark models

<table>
<thead>
<tr>
<th></th>
<th>$N_d$</th>
<th>$n_f$</th>
<th>$\Lambda_d$ (GeV)</th>
<th>$\tilde{m}_{d'}$ (GeV)</th>
<th>$m_{\pi_d}$ (GeV)</th>
<th>$m_{\rho_d}$ (GeV)</th>
<th>$\pi_d$ Decay Mode</th>
<th>$\rho_d$ Decay Mode</th>
</tr>
</thead>
<tbody>
<tr>
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<td>3</td>
<td>2</td>
<td>15</td>
<td>20</td>
<td>10</td>
<td>50</td>
<td>$\pi_d \rightarrow c\bar{c}$</td>
<td>$\rho_d \rightarrow \pi_d\pi_d$</td>
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<tr>
<td>B</td>
<td>3</td>
<td>6</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>4.67</td>
<td>$\pi_d \rightarrow s\bar{s}$</td>
<td>$\rho_d \rightarrow \pi_d\pi_d$</td>
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<tr>
<td>C</td>
<td>3</td>
<td>2</td>
<td>15</td>
<td>20</td>
<td>10</td>
<td>50</td>
<td>$\pi_d \rightarrow \gamma'\gamma'$ with $m_{\gamma'} = 4.0$ GeV</td>
<td>$\rho_d \rightarrow \pi_d\pi_d$</td>
</tr>
<tr>
<td>D</td>
<td>3</td>
<td>6</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>4.67</td>
<td>$\pi_d \rightarrow \gamma'\gamma'$ with $m_{\gamma'} = 0.7$ GeV</td>
<td>$\rho_d \rightarrow \pi_d\pi_d$</td>
</tr>
</tbody>
</table>
in all models, $\gamma \rightarrow q\bar{q} q\bar{q} (B_R \approx 1)$ and $q\bar{q}$ and $q\bar{q} \rightarrow p\bar{v} v$ and $\rho\bar{v} v$ with $\rho\bar{v} \rightarrow p\bar{v} v$ (BR=1.)

Model A: $p\bar{v} \rightarrow c\bar{c}$ (BR=1.)

Model B: $p\bar{v} \rightarrow s\bar{s}$ (BR=1.)

Model C: $p\bar{v} \rightarrow \gamma\gamma\gamma \gamma\gamma$ (BR=1.)
$\gamma\gamma \rightarrow d\bar{d}$ (BR=0.22)
$u\bar{u}$ (BR=0.06)
$s\bar{s}$ (BR=0.06)
$c\bar{c}$ (BR=0.22)
$e^+e^-$ (BR=0.17)
$\mu^+\mu^-$ (BR=0.17)
$\tau^+\tau^-$ (BR=0.10)

Model D: $p\bar{v} \rightarrow \gamma\gamma\gamma \gamma\gamma$ (BR=1.)
$\gamma\gamma \rightarrow e^+e^-$ (BR=0.15)
$\mu^+\mu^-$ (BR=0.15)
$\pi^+\pi^-$ (BR=0.70)
• Sensitivity distribution of $ntrk^{kNN}$
• Cut at peak sensitivity does not leave enough background events to fit
Signal Region 1: Decorrelation method

- "Fixed-efficiency-regression" decorrelates a discriminating variable from other variables
  - Described and tested in for $W$-tagging in ATL-PHYS-PUB-2017-004

- Principal:
  - Choose a substructure variable with good classification power (here $n_{trk}$)
  - Decide on a fixed background single jet efficiency $\epsilon$ (0.5%, giving a signal eff. of 30%)
  - Evaluate the cut value on $n_{trk}$ that gives desired bkg. eff. in bins of $p_T$ and $m_{jj}$
  - Fit the distribution using the $k$-nearest neighbours (kNN) algorithm
  - For each jet, the new decorrelated observable is computed as $n_{trk}^\epsilon = n_{trk} - p^{\epsilon=0.5\%}$

- Here $n_{trk}^\epsilon$ is defined from data in a control region with signal efficiency $\sim 0.4\%$
Backup

- Some Hidden Valley papers

- Astro papers that investigate self-interacting DM: