Mediator-Induced Decay Chains and Multi-Jet Signatures of Non-Minimal Dark Sectors at Colliders

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Based on work done in collaboration with:

- Keith Dienes, Doojin Kim, Huayang Song, Shufang Su, and David Yaylali
  [arXiv:1910.01129]

PHENO 2021, May 24th, 2021
Portals to the Dark Sector

• Dark matter communicates with the visible sector through gravity, but the hope is that it also communicates with the visible sector in other ways.

• One possibility is that the dark sector couples to the visible sector via some mediator particle, which provides a non-gravitational portal through which the two sectors can communicate.

Visible Sector  Mediator ($\phi$)  DM Particle ($\chi$)
Portals to the Dark Sector

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• One possibility is that the dark sector couples to the visible sector via some mediator particle, which provides a non-gravitational portal through which the two sectors can communicate.

• The situation can become far richer in scenarios involving not merely a single dark-matter particle, but an entire dark sector.

• For example, consider the case wherein there exist multiple dark-sector fields with similar quantum numbers which can couple to the mediator.

In such scenarios, the mediator not only facilitates interactions via which the \( \chi_n \) can be produced experimentally/cosmologically, but also generically gives rise to decay processes which render the heavier \( \chi_n \) unstable.

Striking signatures at colliders and beyond!
An Example Model

• For concreteness, let’s consider an example model in which the $\chi_n$ are SM-singlet Dirac fermions which couple to SM quarks $q$ via a mediator $\phi$ which is a Lorentz scalar and a triplet under $SU(3)$ color.

• To suppress flavor-changing effects, we take $\phi$ to be a triplet under the approximate $U(3)_u$ flavor symmetry of the right-handed up-type quarks and assume that $\phi$ and these quarks share a common mass eigenbasis.

Mass eigenstates $\{\phi_u, \phi_c, \phi_t\}$ essentially each couple to a single flavor.

\[
\mathcal{L}_{\text{int}} = \sum_{q \in \{u, c, t\}} \sum_{n=0}^{N-1} \left[ c_{nq} \phi_q^\dagger \chi_n P_R q + \text{h.c.} \right]
\]

• For simplicity, we take $m_{\phi_u} \ll m_{\phi_c}, m_{\phi_t}$ for now, so only $u$ matters (we’ll revisit this later). For simplicity, we’ll refer to $\phi_u$ as “$\phi$” and $m_{\phi_u}$ as “$m_{\phi}$”.

• In practice, this is tantamount to taking $c_{nc} = c_{nt} = 0$, while $c_n = c_{nu} \neq 0$.

Decay:
An Example Model

- The masses and couplings for the individual $\chi_n$ are not arbitrary, but determined by scaling relations that hold across the dark sector.

\[ m_n = m_0 + n^\delta \Delta m \]  

- Masses

\[ c_n = c_0 \left( \frac{m_n}{m_0} \right)^\gamma \]  

- Couplings

- Scaling relations of this sort arise in many top-down scenarios with extended dark sectors. [Dienes, BT: 1107.0721; Dienes, Fennick, Kumar BT: 1601.05094, 1712.09919; Buyukdag, Dienes, Gherghetta, BT: 1912.10588]

- For simplicity, take $N$ such that all possible states with $m_n < m_\phi$ given by the mass-scaling relation exist, but no states with $m_n \geq m_\phi$.

Free parameters: \( \{m_\phi, m_0, \Delta m, c_0, \delta, \gamma\} \)
Collider Phenomenology

• Once a heavy dark-sector particle is produced at a collider, it precipitates a series of decays.

Striking signals involving large numbers of hadronic jets and missing energy!
Production Channels

• Several different processes contribute to the overall production rate for mediator-induced decay chains. There are three main classes:

1. $pp \rightarrow \chi_m \bar{\chi}_n$
   (no on-shell mediators)
   $\sigma(pp \rightarrow \chi_m \chi_n) \propto c_0^4$

2. $pp \rightarrow \chi_m \phi$
   (one on-shell mediator)
   $\sigma(pp \rightarrow \chi_m \chi_n) \propto c_0^2$

3. $pp \rightarrow \phi^\dagger \phi$
   (two on-shell mediators)
   $\sigma(pp \rightarrow \chi_m \chi_n) \propto 1$

   i.e., independent of $c_0$
Production Cross-Sections

- Different production channels dominate the production rate in different regions of parameter space.

- Define the *total* cross-sections for each channel:

$$
\sigma_{\chi\chi} \equiv \sum_{m,n=0}^{N-1} \sigma(pp \rightarrow \chi_m \chi_n) \quad \sigma_{\phi\chi} \equiv \sum_{n=0}^{N-1} \sigma(pp \rightarrow \phi \chi_n) \quad \sigma_{\phi\phi} \equiv \sigma(pp \rightarrow \phi\phi)
$$

---

**Graphical Representation**

- **Legend:**
  - $\sigma(pp\rightarrow\chi\chi)$
  - $\sigma(pp\rightarrow\chi\phi)$
  - $\sigma(pp\rightarrow\phi\phi)$

- **Parameters**
  - $m_0 = 500 \text{ GeV}$
  - $\Delta m = 50 \text{ GeV}$
  - $\delta = 1$
  - $c_0 = 0.1$

- **Equation:**
  - $\gamma = 3$
  - $\gamma = 1$

---

**Note:** The graph shows the cross-sections as a function of $m_\phi$ for different values of $N$. As $N$ increases, the cross-sections change accordingly.
Decay Lengths

- The collider phenomenology of this scenario also depends on the lifetimes $\tau_n$ (or decay lengths $c\tau_n$) of the individual $\chi_n$. 

![Diagram showing decay lengths and corresponding regimes](image)
Decay Lengths

• The collider phenomenology of this scenario also depends on the lifetimes $\tau_n$ (or decay lengths $c\tau_n$) of the individual $\chi_n$.

Multijet Decay Cascades

- $\chi_3$, $\chi_2$, $\chi_1$
- Prompt Decay
- Displaced Vertices
- LLP Regime

$\chi_0$

- Cosmologically Stable

$\log_{10}(c\tau/m)$

$\bar{c}\tau = 1\text{cm}$

In this talk, we’ll focus on the case in which all $\chi_n$ with $n > 0$ decay promptly ($c\tau_n \lesssim 1\text{ cm}$), while $\chi_0$ is at least collider-stable. Places an effective upper bound on $c_0$ for any combination of $m_\phi$, $m_0$, $\Delta m$, $\delta$, and $\gamma$. 
Decay Lengths

• The collider phenomenology of this scenario also depends on the lifetimes \( \tau_n \) (or decay lengths \( c\tau_n \)) of the individual \( \chi_n \).

![Diagrams of decay cascades and displaced vertices]

- In this talk, we’ll focus on the case in which all \( \chi_n \) with \( n > 0 \) decay **promptly** \( (c\tau_n \lesssim 1 \text{ cm}) \), while \( \chi_0 \) is at least collider-stable. Places an effective upper bound on \( c_0 \) for any combination of \( m_\phi, m_0, \Delta m, \delta, \) and \( \gamma \).

- However, the case in which one or more of the \( \chi_n \) have characteristic decay lengths in the **displaced-vertex regime** is interesting too!
Decay Chains: Statistical Properties

- The mediator-induced decay chains which arise in this scenario can in principle give rise to collider signatures involving large jet multiplicities.

- In practice, however, having a sizable population of signal events depends of the statistical properties of these decay chains.

- These properties are ultimately dictated by the branching fractions for the individual decay steps:

  \[
  \text{BR}_{\phi n} \equiv \frac{\Gamma(\phi \rightarrow q\chi_n)}{\Gamma_\phi} \\
  \text{BR}_{n\ell} \equiv \frac{\Gamma(\chi_n \rightarrow qq\ell)}{\Gamma_n}
  \]

- Since we’re interested in extended decay chains with many decays, we want decays with small \(n - \ell\) to dominate.
Decay Chains: Statistical Properties

- Let’s now consider the statistical properties of sequences of decays.

- The probability that a decay chain has precisely $S$ steps may be written schematically as

$$\hat{P}(S) = \sum_{n_0, n_1, \ldots, n_{S-1}} BR_{n_0}^{\text{prod}} BR_{n_0, n_1} \ldots BR_{n_{S-1}, 0}$$

- The probability that a decay chain will yield $N_{\text{jet}}$ SM quarks is then

$$P(N_{\text{jet}}) = \sum_{S_1=0}^{(N_{\text{jet}} - \zeta)/2} \hat{P}(S_1) \hat{P}\left(\frac{N_{\text{jet}}}{2} - \frac{\zeta}{2} - S_1\right)$$

- Indeed, at least at the parton level, mediator-induced decay chains routinely give rise to events with large numbers ($N_{\text{jet}} > 10$) of “jets.”
When You’re a Jet, Are You a Jet All the Way?

- Of course, in going from the parton level to the detector level, a lot of effects can modify the distribution of \( N_{\text{jet}} \) (and other collider variables).

- In order to examine how things are modified at the detector level, we define three benchmark points within our model-parameter space.

Parameter-Space Benchmarks

<table>
<thead>
<tr>
<th>Benchmark</th>
<th>( m_{\phi} )</th>
<th>( m_0 )</th>
<th>( \Delta m )</th>
<th>( \delta )</th>
<th>( \gamma )</th>
<th>( c_0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1 TeV</td>
<td>500 GeV</td>
<td>50 GeV</td>
<td>1</td>
<td>1</td>
<td>0.1</td>
</tr>
<tr>
<td>B</td>
<td>1 TeV</td>
<td>500 GeV</td>
<td>50 GeV</td>
<td>1</td>
<td>3</td>
<td>0.1</td>
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<tr>
<td>C</td>
<td>2 TeV</td>
<td>500 GeV</td>
<td>50 GeV</td>
<td>1</td>
<td>1.5</td>
<td>0.1</td>
</tr>
</tbody>
</table>

- Note that a different production channel dominates the event rate for each of these three benchmarks.
$N_{\text{jet}}$ Distributions

- We’ll begin with a comparison of the $N_{\text{jet}}$ distributions. Contributions from all channels are included and weighted by their cross-sections.

- **Parton level**: Each quark, gluon which passes cuts counts as a “jet.” No additional cuts on $p_{Tj}$, $\eta_j$, etc., or separation $\Delta R_{jj}$ from other “jets.”

- **Detector level**: Jets require to satisfy $p_{Tj} > 20$ GeV, $|\eta_j| < 5$, and separation of at least $\Delta R_{jj} > 0.4$ from all more energetic jets.

**The Upshot**: $N_{\text{jet}}$ distributions at the detector level are smoother and slightly broader, but not drastically different.
Event-Selection: Multi-Jet Channel

• Searches wherein events are selected primarily on the basis of $E_T$ and $N_{\text{jet}}$ are ideal for probing our parameter-space region of interest. For our **multi-jet search** along these lines, we impose the following cuts:

  (Modeled after Sirunyan et al.: 1708.02794)

  - Basic trigger cuts: $p_{Tj} > 50$ GeV, $|\eta_j| < 5$, $\Delta R_{jj} > 0.4$
  
  - $\frac{E_T}{\sqrt{H_T}} > 5$ GeV$^{1/2}$
    
    Use only $|\eta_j| < 4.5$ in computing $\not{E}_T$
  
    Use only $p_{Tj} > 40$ GeV, $|\eta_j| < 2.8$ in computing $H_T$

  - No heavy-flavor tagging.

• We also define the parameters:

  - $N_{\text{jet}}^{50}$: # of jets with $p_{Tj} > 50$ GeV
  
  - $N_{\text{jet}}^{80}$: # of jets with $p_{Tj} > 80$ GeV

  ... and perform an inclusive search within the signal regions

  \[
  N_{\text{jet}}^{50} \geq \{8, 9, 10, 11\} \quad N_{\text{jet}}^{80} \geq \{7, 8, 9\}
  \]
Event-Selection: Monojet Channel

• We must also be careful in our analysis to ensure that our model isn’t already excluded by searches in other detection channels.

• One of these is the **monojet + $\not{E}_T$ channel**:

  e.g., from

  ![Diagram of monojet + $\not{E}_T$ channel](image)

  with $m = n = 0$

• We adopt the following cuts in assessing the event rate in the monojet channel:  
  (Modeled after Aaboud et al.: arXiv:1711.03301)

  - Basic trigger cuts: $p_{Tj} > 50 \text{ GeV}, |\eta_j| < 5, \Delta R_{jj} > 0.4$
  - $\not{E}_T > 250 \text{ GeV}$
  - $p_{Tj} > 250 \text{ GeV}, |\eta_j| < 2.4$ for leading jet
  - No more than 4 jets with $p_{Tj} > 30 \text{ GeV}, |\eta_j| < 2.8$

• In addition, we also consider constraints from multi-jet searches with more **moderate jet multiplicities** ($N_{\text{jet}} = 2 – 6$) and large $\not{E}_T$. 
Contributions from Individual Processes

- We begin by examining the cross-sections for the individual production processes $pp \rightarrow \phi \chi_m$ and $pp \rightarrow \chi_m \bar{\chi}_n$ for our three benchmarks after each set of cuts is applied.
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Aggregate Contributions

• We now compare the total cross-sections for our benchmark points for each of the three main production channels, before and after cuts.

<table>
<thead>
<tr>
<th>Benchmark</th>
<th>Before Cuts</th>
<th>After Monojet Cuts</th>
<th>After Multi-Jet Cuts</th>
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<tbody>
<tr>
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<td>$\sigma_{XX} \ (fb)$</td>
<td>$\sigma_{\phi \chi} \ (fb)$</td>
<td>$\sigma_{\phi \phi} \ (fb)$</td>
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<tr>
<td>A</td>
<td>0.28</td>
<td>4.19</td>
<td>4.29</td>
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<tr>
<td>B</td>
<td>9.72</td>
<td>23.9</td>
<td>4.29</td>
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<td>C</td>
<td>3.06</td>
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<td>LHC Limit</td>
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$\epsilon_1$ and $\epsilon_N$: cut efficiencies for monojet and multi-jet channels

Current (as of April, 2020) limit from LHC searches (in fb)

• All three benchmarks are consistent with LHC limits from both monojet and multi-jet searches, yet a different process dominates for each one.

The upshot: Despite stringent limits, there is still potential for mediator-induced decay chains to manifest themselves at colliders.
Results

- We perform a parameter-space survey, varying $\gamma$ and $m_\phi$ and holding all other parameters fixed.

$$m_0 = 500 \text{ GeV} \quad \delta = 1$$
$$\Delta m = 50 \text{ GeV} \quad c_0 = 0.1$$

--- Multi-jet search limit
--- Moderate $N_{\text{jet}}$ search limit

(Monojet searches not constraining here)
Results

- We perform a parameter-space survey, varying $\gamma$ and $m_{\phi}$ and holding all other parameters fixed.

**What the Entries Mean:**

$N_{jet}^{10\%}$: max value of $N_{jet}$ for which at least 10% of signal events have $N_{jet} > N_{jet}^{10\%}$
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$N_{\text{jet}}^{10\%}$: max value of $N_{\text{jet}}$ for which at least 10% of signal events have $N_{\text{jet}} > N_{\text{jet}}^{10\%}$ at parton level (no cuts)

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<td>Multi-Jet Trigger</td>
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<td>$N_{\text{jet}} \geq 5$, $p_T &gt; 45 \text{ GeV, }</td>
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Results

We perform a parameter-space survey, varying $\gamma$ and $m_\phi$ and holding all other parameters fixed.

**What the Entries Mean:**

$N_{\text{jet}}^{10\%}$: max value of $N_{\text{jet}}$ for which at least 10% of signal events have $N_{\text{jet}} > N_{\text{jet}}^{10\%}$

$N_{\text{jet}}^{10\%}$ at parton level ($p_T > 20$ GeV, $|\eta| < 2.8$)

$N_{\text{jet}}^{10\%}$ at parton level (no cuts)

$\chi\phi > xx > \phi\phi$
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$N_{\text{jet}}^{10\%}$ at detector level ($p_{Tj} > 20$ GeV, $|\eta| < 2.8$)

$\chi_\phi > xx > \phi\phi$ at detector level ($p_{Tj} > 45$ GeV, $|\eta| < 2.4$, $N_{\text{jet}} \geq 5$)

Multi-jet search limit

Moderate $N_{\text{jet}}$ search limit

(Monojet searches not constraining here)

$10^9$ $10^9$

$\chi_{\phi} > \chi_{\chi}$

$\phi > \phi > xx$

$xx > \phi > \phi$

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$xx > \phi > \phi$

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$N_{\text{jet}}^{10\%}$ at parton level ($p_T > 20$ GeV, $|\eta| < 2.8$)

$N_{\text{jet}}^{10\%}$ at detector level ($p_T > 20$ GeV, $|\eta| < 2.8$)

$N_{\text{jet}}^{10\%}$ at detector level ($p_T > 45$ GeV, $|\eta| < 2.4$, $N_{\text{jet}} \geq 5$)

Relative size of parton-level cross-sections
Results

- We perform a parameter-space survey, varying $\gamma$ and $m_\phi$ and holding all other parameters fixed.

$$m_0 = 500 \text{ GeV} \quad \delta = 1$$
$$\Delta m = 50 \text{ GeV} \quad c_0 = 0.1$$

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Multi-jet search limit

Moderate $N_{jet}$ search limit

(Monojet searches not constraining here)
Summary

• In a variety of dark-matter scenarios, interactions between the dark-matter particle and the fields of the visible sector are facilitated by a mediator particle.

• In the context of non-minimal dark sectors, mediators not only provide a portal between the visible and dark sectors, but also can render the dark-sector states unstable.

• These mediators can give rise to extended decay chains at coliders involving large numbers of SM particles.

• We have examined the multi-jet signatures which arise from decay chains of this sort in the case in which the SM particles which couple to the mediator are light quarks.

• While constraints on mediator-induced decay chains are quite stringent, there is still a discovery window for such processes at the LHC.

• In addition, the lightest dark-sector state in these scenarios can potentially serve as a dark-matter candidate.