Non-Minimal Dark Sectors: Mediator-induced Decay Chains and Multi-Jet Collider Signatures

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Most traditional hidden sector scenarios for dark matter have a mediator which connects the visible and dark sectors to each other. What happens if the dark sector is not minimal, e.g. containing many independent dark matter components?
Main point of this talk

As long as you have a non-minimal dark sector and you have a mediator that connects the visible world to this dark sector, then (barring special symmetries) you generally have mediator-induced decay chains and therefore you also have multi-jet collider signatures.

In this talk we will study the resulting "jet avalanches" in the context of a particular "non-minimal dark sector".
We consider an ensemble consisting of $N$ Dirac fermions $\chi_n$, $n = 0, 1, \ldots, N - 1$, and assume that the masses $m_n$ scale according to a general relation of the form

$$m_n = m_0 + n^\delta \Delta m$$

We shall assume that each of the $\chi_n$ couples to a colored heavy scalar $\phi$ of mass $m_\phi$

$$\mathcal{L}_{\text{int}} = \sum_{n=0}^{N-1} (c_{nq} \phi^\dagger \chi_n P_R q + \text{h.c.})$$

where we restrict our attention to the case $q$ denotes only up-quark. And we also assume that the $c_{nq}$ scale according to the power-law relation

$$c_{nq} = c_{0q} \left( \frac{m_n}{m_0} \right)^\gamma, \quad (c_{0q} > 0)$$
Production

\[ p \rightarrow \phi \rightarrow q, \bar{\chi}_n, \chi_m, \bar{q} \]
The overall cross-section scales with the number of kinematically accessible components $\chi_n$ within the ensemble.
Production

\[ \sigma(pp \rightarrow \chi \chi) = 2.78 \times 10^{-2} \text{ fb} \]

\[ m_0 = 500 \text{ GeV}, \Delta m = 50 \text{ GeV}, c_0 = 0.1, \text{ and } \delta = 1 \]

Solid \( \gamma = 1 \), Dash \( \gamma = 3 \)

\[ N = \left[ 1 + \left( \frac{m_\phi - m_0 - m_q}{\Delta m} \right)^{1/\delta} \right] \]
Once some heavier ensemble constituent $\chi_n$ is produced, it decays to successively lighter constituents, thereby forming a decay chain.
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\[ \chi_n \rightarrow q \bar{q} \rightarrow \chi_{n_1} \rightarrow \phi^\dagger \rightarrow \chi_{n_2} \rightarrow \phi^\dagger \rightarrow \chi_{n_3} \rightarrow \cdots \rightarrow \chi_{n_{S-1}} \rightarrow \phi^\dagger \rightarrow \chi_{n_S} \]

The branching fraction $BR(\chi_n \rightarrow q \bar{q} \chi_\ell)$ is plotted against $m_\ell$ [GeV] for different values of $\gamma$: $\gamma = -1$, $\gamma = 0$, $\gamma = 1$, and $\gamma = 2$. The parameters used are $m_\phi = 1$ TeV, $m_0 = 100$ GeV, $\Delta m = 10$ GeV, $\delta = 1$, and $c_0 = 0.1$. The $BR(\chi_n \rightarrow q \bar{q} \chi_\ell)$ values are given for specific masses $m_\ell$: 100, 200, 300, 400, 500, 600, 700, and 800 GeV.
The probability $P(N_{\text{jet}})$ for obtaining a total number $N_{\text{jet}}$ of jets (i.e., quarks or anti-quarks) at the parton level from the decay of a pair of parent particles $\phi$ and $\phi^\dagger$

**Diagram:**

- $p p \rightarrow \phi \phi^\dagger \rightarrow \chi_0 \chi_0 + \text{jets}$
- $m_\phi = 1$ TeV
- $m_0 = 100$ GeV
- $\Delta m = 10$ GeV
- $\delta = 1$
- $c_0 = 0.1$
Constraining the parameter space

Perturbativity ($c_n \lesssim 4\pi$)

Prompt-decay ($c_{\tau n} \lesssim O(1\text{ cm})$ for all $n > 0$)

\begin{tabular}{|c|c|c|c|c|c|c|}
\hline
$m_0$ & $300$ & $500$ & $1000$ & $2000$ & $5000$ & $10^5$ & $5^5$ & $1$ & $0.5$ & $0.05$ & $0.01$ \\
\hline
$\Delta m$ & $10$ & & & & & & & & & & \\
\hline
$\delta$ & $1$ & & & & & & & & & & \\
$\gamma$ & & $0$ & & & & & & & & & \\
$\gamma$ & & $0.5$ & & & & & & & & & \\
$\gamma$ & & $1.0$ & & & & & & & & & \\
$\gamma$ & & $1.5$ & & & & & & & & & \\
$\gamma$ & & $2.0$ & & & & & & & & & \\
\hline
\end{tabular}

$m_\phi [\text{GeV}]$
Constraining the parameter space

- Perturbativity ($c_n \lesssim 4\pi$)
- Prompt-decay ($c\tau_n \lesssim \mathcal{O}(1\text{cm})$ for all $n > 0$)
Constraining the parameter space

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![Graph showing parameter space constraints](image)

- \( c_0 \)
- \( m_\phi \) [GeV]
- \( m_0 = 100 \text{ GeV} \)
- \( \Delta m = 10 \text{ GeV} \)
- \( \delta = 1 \)
Current constraints at the LHC

- Mono-jet with $\mathcal{E}_T$ (JHEP 1801 (2018) 126)
- 2-6 jets with $\mathcal{E}_T$ (Phys.ReV. D97 (2018) 97.112001)
- Multi-jet with $\mathcal{E}_T$ (JHEP 1712 (2017) 034)

$m_0 = 500$ GeV, $\Delta m = 50$ GeV, $c_0 = 0.1$ and $\delta = 1$
Current constraints at the LHC
Summary

- The mediator connecting non-minimal dark sectors to the visible sector will generally induce long decay chains within the dark sector and thereby result in multi-jet collider signatures, or even jet avalanches.
- Current collider experiments have already given constraints on such non-minimal dark sector scenarios, but there is still room for new physics to be explored.
The mediator connecting non-minimal dark sectors to the visible sector will generally induce long decay chains within the dark sector and thereby result in multi-jet collider signatures, or even jet avalanches.

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Related issues: we are currently exploring

- Jet avalanches with soft jets
- Multiple displaced vertices arising from the same decay chain
- Boosted objects from non-trivial mass spectrum in the ensemble
**Backup**

**Benchmark A** \( (m_\phi = 1 \text{ TeV}, m_0 = 500 \text{ GeV}, \Delta m = 50 \text{ GeV}, \delta = 1, \gamma = 1, \text{ and } c_0 = 1) \)
Benchmark A \((m_\phi = 1\ \text{TeV}, m_0 = 500\ \text{GeV}, \Delta m = 50\ \text{GeV}, \delta = 1, \gamma = 1, \text{ and } c_0 = 1)\)
Benchmark A

Production cross-sections before and after cuts for the processes $pp \rightarrow \phi \chi_m$ and $pp \rightarrow \chi_m \chi_n$ at the $\sqrt{s} = 13$ TeV LHC

Before cuts

After monojet cuts

After multi-jet cuts
Backup

**Benchmark B**  \((m_\phi = 1 \text{ TeV}, \ m_0 = 500 \text{ GeV}, \ \Delta m = 50 \text{ GeV}, \ \delta = 1, \ \gamma = 3, \ \text{and} \ \ c_0 = 1)\)
**Benchmark B** \((m_\phi = 1\ \text{TeV}, \ m_0 = 500\ \text{GeV}, \ \Delta m = 50\ \text{GeV}, \ \delta = 1, \ \gamma = 3, \ \text{and} \ c_0 = 1)\)
Benchmark B

Production cross-sections before and after cuts for the processes $pp \rightarrow \phi \chi_m$ and $pp \rightarrow \chi_m \bar{\chi}_n$ at the $\sqrt{s} = 13$ TeV LHC
The inclusive cross-sections at the $\sqrt{s} = 13$ TeV LHC

| Benchmark | Before Cuts | After Monojet Cuts | After Multi-Jet Cuts |
|-----------|-------------|--------------------|---------------------|
|           | $\sigma_{\chi\chi}$ (fb) | $\epsilon_1\sigma_{\chi\chi}$ (fb) | $\epsilon_N\sigma_{\chi\chi}$ (fb) |
| A         | 0.28        | 0.015              | 0.76 $\times 10^{-4}$ |
| B         | 9.72        | 0.32               | 0.10                |
|           | $\sigma_{\phi\chi}$ (fb) | $\epsilon_1\sigma_{\phi\chi}$ (fb) | $\epsilon_N\sigma_{\phi\chi}$ (fb) |
| A         | 4.19        | 0.41               | 0.058               |
| B         | 23.9        | 0.77               | 0.87                |
|           | $\sigma_{\phi\phi}$ (fb) | $\epsilon_1\sigma_{\phi\phi}$ (fb) | $\epsilon_N\sigma_{\phi\phi}$ (fb) |
| A         | 4.29        | 0.32               | 0.12                |
| B         | 4.29        | 0.10               | 0.24                |
$\gamma$

None | Basic Trigger | Multi–Jet Trigger
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None | $p_T>20$ GeV, $|\eta|<2.8$ | $N_{\text{jet}}\geq5$, $p_T>45$ GeV, $|\eta|<2.4$

$\chi\chi$ | $\chi\chi$ | $\chi\phi$
$\chi\phi$ | $\chi\phi$ | $\chi\phi$
$\phi\phi$ | $\phi\phi$ | $\phi\phi$

$m_\phi$ [TeV]