Is there a Higgs mechanism in the dark sector?
Mengchao Zhang
IBS Center for Theoretical Physics of the Universe


A light dark matter with self interaction is favored by current observations (direct search, small scale structure problem, Sommerfeld enhancement...).

Generally, one can consider a toy model with a U(1) gauge group:
\[ L' = \chi (q - m_{\chi} + ig' A') \chi + \frac{1}{4} F_{\mu\nu}F^{\mu\nu} + \frac{1}{2} m_{\chi}^2 A' \chi A' - \frac{1}{2} m_{\chi}^2 \chi \chi \]

Here, \( A' \) is gauge boson of U(1) (called dark photon).
\( \epsilon \) is the kinetic mixing between photon and dark photon.

In a collider, if energetic dark matter can be produced, then dark photon radiated from dark matter will result in dark parton shower. Dark photon then decay back to SM particles through kinetic mixing. The most sensitive signal is lepton jet:

In vector-like case, longitudinal polarization can be just ignored in shower process. But in chiral case, longitudinal polarization is replaced by the goldstone boson eaten by dark photon. Then splitting kernel become:
\[ P_{X \rightarrow A'} (x,t) = \frac{1}{2} \left( a^2 + b^2 \right) + x^2 + \frac{1}{2} (a - b)^2 m_{\chi}^2 / m_{A'}^2 \]

So the shower pattern of chiral model and vector-like model will be different even with the same \( m_{X}, m_{A'}, \alpha' \)

Consider 3 points:

<table>
<thead>
<tr>
<th>Benchmark Points (BP)</th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>( m_{\chi} ) (GeV)</td>
<td>0.3</td>
<td>0.15</td>
<td>0.075</td>
</tr>
<tr>
<td>( m_{A'} ) (GeV)</td>
<td>0.7</td>
<td>1.0</td>
<td>1.4</td>
</tr>
<tr>
<td>( m_{\chi} ) (GeV)</td>
<td>0.4</td>
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</tbody>
</table>

Combination of current limits and signal number requirement at 3000 fb-1 HL-LHC, for both strong dark shower and weak shower:

Distinguishing ability by 200 signal events. The region on the right side of black dash line can be distinguished at 2 sigma sig. level:

One can ask two more questions:

1. Dark photon is massive, so it has longitudinal polarization mode. But why is the longitudinal polarization shower ignored in previous study?

2. What if the dark matter is not vector-like but chiral, and its mass comes from a “dark Higgs mechanism”?

Actually, these two questions are closely related.

Consider a chiral dark matter model with a dark Higgs:
\[ L' = \chi (q - m_{\chi} + ig' A') \chi + \frac{1}{4} F_{\mu\nu}F^{\mu\nu} + \frac{1}{2} m_{\chi}^2 A' \chi A' \]

(ignoring chiral anomaly temporarily)

After spontaneous symmetry breaking:
\[ L' = \chi (q - m_{\chi} + g' A') \chi + \frac{1}{4} F_{\mu\nu}F^{\mu\nu} - \frac{1}{2} g' (g' g' - 1) \phi^2 \phi^2 A' A' - \frac{1}{2} m_{\chi}^2 \phi^2 + \cdots \]

with \( m_{\chi} = g' \sqrt{2} \), \( m_{A'} = (a - b) g' \phi \)

Maybe we can use the distribution of \( H_{T(l)} \) to distinguish the nature of dark matter and the mass origin of dark sector. Then we need to consider:

1. What is the parameter space allowed by current limit (A recast to dijet and lepton-jet reports)
2. Sufficient signal should be produced at future collider. An efficient cut-flow need to be used to cut BKG.

Cut-flow for future search:
lepton-jet, isolation, mass window of lepton jet, \( H_{T(l)} \) cut.

Here is the \( H_{T(l)} \) distribution after front cut:

Such case has been studied by JHEP 07(2015) 045