Theory overview on dark showers

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LHCP 2024
Why dark showers?

dark showers are a feature/signature of confining dark sectors

weakly coupled dark sector  strongly coupled dark sector
Why dark showers?

dark showers are a feature/signature of confining dark sectors

Hidden Valley models/QCD-like dark sectors

→ sector of SM neutral particles connected via a portal

– produced in SM collision
– include states that decay within 1 s lifetime
– have self interactions
– unusual collider pheno

Strassler, Zurek ‘06
Hidden Valley models

QCD-like Dark Sector

$G_{SM} \times SU(N_D)_D$

$n_D$ dark quarks $Q_D$

$N_D$ dark colours
Hidden Valley models

QCD-like Dark Sector

\( \mathcal{G}_{SM} \times SU(N_{D})_{D} \)

\( n_{D} \) dark quarks \( Q_{D} \)

\( N_{D} \) dark colours

\[ \text{Portal} \]

\[ \text{5- channel} \]

\[ \rightarrow \text{connection to flavor} \]

\[ \text{neutral meson mixing} \]

\[ B \rightarrow k\pi_{D}, B \rightarrow \pi\pi_{D}, \]

\[ k \rightarrow \pi\pi_{D}, \pi \rightarrow \pi\pi_{D} \]
Hidden Valley Models: dark pions

\[ \mathcal{L}_{dQCD} = \bar{Q}_\alpha \left( i \not{\! D} - m_Q \delta_{\alpha,\beta} \right) Q_\beta - \frac{1}{4} g^{\mu \nu}_{D} G_{D}^{\mu \nu} \]

for small \( m_Q \): approximate \( SU(3)_{dL} \times SU(3)_{dR} \)

\[ \downarrow \]

broken by dark quark condensate to \( SU(3)_V \)

\[ \downarrow \]

8 pseudo-Nambu-Goldstone bosons

<table>
<thead>
<tr>
<th>Dark Pion</th>
<th>Dark Quark Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \pi_D^{(1,2)} )</td>
<td>( \bar{Q}<em>{D2} Q</em>{D1} )</td>
</tr>
<tr>
<td>( \pi_D^{(1,3)} )</td>
<td>( \bar{Q}<em>{D3} Q</em>{D1} )</td>
</tr>
<tr>
<td>( \pi_D^{(2,3)} )</td>
<td>( \bar{Q}<em>{D3} Q</em>{D2} )</td>
</tr>
<tr>
<td>( \pi_D^3 )</td>
<td>( \frac{1}{\sqrt{2}} \left[ \bar{Q}<em>{D1} Q</em>{D1} - \bar{Q}<em>{D2} Q</em>{D2} \right] )</td>
</tr>
<tr>
<td>( \pi_D^8 )</td>
<td>( \frac{1}{\sqrt{6}} \left[ \bar{Q}<em>{D1} Q</em>{D1} + \bar{Q}<em>{D2} Q</em>{D2} - 2 \bar{Q}<em>{D3} Q</em>{D3} \right] )</td>
</tr>
</tbody>
</table>

\[ Q_D^{(1)}, Q_D^{(2)}, Q_D^{(3)} \]

dark confinement \( \Lambda_D \)

\[ pD, \ldots \]

annihilation

\[ \pi_D^{i,j} \]

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Dark Showers: Theory overview
Dark jets

$q \quad Q_D$

Dark sector shower

Dark sector hadronization

Dark hadron decay

SM shower

SM hadronization

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**Dark jets**

QCD-like: $SU(N)$ with $F \ll 3N$
- $m \lesssim \Lambda \rightarrow$ understood, pythia fine
- $m \gtrsim \Lambda \rightarrow$ somewhat understood, not in pythia

Less QCD-like: $SU(N)$ with $F \gg 3N$
- equal $m \rightarrow$ somewhat understood, not in pythia
- unequal $m$ (many large some small) \(\rightarrow\) understood, not in pythia yet

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poster by Joshua Lockyer
Dark jets

- non-perturbative, unknown
- Lund string fragmentation in pythia

\[ f(z) = \frac{1}{z \left(1 + r_{Q_D} b_{m_{Q_D}}^2 \right)} (1 - z)^{a_L} \exp \left( - \frac{b^2}{m_{Q_D}^2} \right) \]

- observables can depend on hadronization parameter choice

Cohen, Roloff, CS ‘23’
Dark hadronization

- changing hadronization parameters can change observables
- Lund jet plane useful to separate hadronization dependent region

Dreyer, Salam, Soyez ‘18

\[ m_Q = 0.5 \text{ GeV}, \quad m_{\tau} = 10 \text{ GeV}, \quad m_p = 20 \text{ GeV} \]

\[ m_Q = 3.75 \text{ GeV}, \quad m_{\tau} = 6.5 \text{ GeV}, \quad m_p = 6.5 \text{ GeV} \]
Dark hadronization

- changing hadronization parameters can change signature
- Lund jet plane useful to separate hadronization dependent region
- allows to construct hadronization independent observables

Dreyer, Salam, Soyez

Cohen, Roloff, CS ’23
Dark jets

• model dependent
• calculate and implement

→ pythia ok
Dark jets

- SM shower understood
  → pythia ok
- SM hadronization non-perturbative, but (mostly) known
  → pythia ok
Signatures

- semi-visible jets
- lepton jets
- emerging jets
- soft unclustered energy patterns (SUEPs)
- quirks
- ...
Semi-visible jets

- multiple neutral particles decaying to SM
- stable ones $\rightarrow$ MET

\[ \text{Shower Strength} \quad \text{Invisible ratio} \]

<table>
<thead>
<tr>
<th>$\alpha_d(1\text{TeV})$</th>
<th>$r_{inv}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>larger $\alpha_d(\Lambda)$</td>
<td>larger $r_{inv}$</td>
</tr>
</tbody>
</table>

Cohen, Lisanti, Lou '15
Cohen et al '17
Emerging jets

- multiple neutral particles decaying to SM
- stable ones $\rightarrow$ MET
- displaced vertices
SUEPs

• coupling close to confinement scale
→ gluon radiation at larger angles

Knapen et al ‘16
Summary

• realistic dark sectors are rich, but complicated
• collider pheno done piecewise
• difficult to capture full breadth

• great progress on simulation and experimental side!
Flavor pheno

Dark Showers: Theory overview

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Dark pions from top decays

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Dark pion dark matter

F = 4 \rightarrow \text{stable dark pions in t-channel models}
Lund Jet Plane

\[ p_a + p_b + p_c \]

\[ \ln(k_t/\text{GeV}) \]

\[ \ln(R/\Delta R) \]

\[ (\Delta R_{a,b}, k_{tb}) \]

\[ (\Delta R_{ab,c}, k_{tc}) \]
Using Lund Jet Plane for searches

different hadronization parameter choices give very different Lund Jet Planes

→ can translate into large differences in variables, e.g. number of tracks