Theory and Phenomenology of BSM Dark Mesons

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Irrelevant portal: the suppressed coupling with the SM is introduced by a heavy scale (~TeV is a good conjecture).

Comprehensively easy, well-motivated, rich phenomenology.

Long-lived particle (LLP) is a natural outcome of suppressed interactions. The displaced decays of dark hadrons give striking collider signals.

Dark QCD makes dark hadrons experience dark showers and form jet-like structures (a.k.a. "emerging jets").

Introduction

Energy Frontier

SM

HV

(hL-1) LHC and ...

h/Z

Displaced

Inaccessibility

Int. Frontier
The Minimal Dark Pion Theory

Quadratically Heavy than $O(\text{TeV})$

\[
- \mathcal{L}_{\text{UV}} = \bar{Q}_L Y \psi_R H + \bar{Q}_R \tilde{Y} \psi_L H + \bar{Q}_L \omega Q_R + \bar{\psi}_L \omega \psi_R + \text{h.c.},
\]

- Light SM singlet dark quarks $\psi$
- Heavy SM doublet mediators $Q$

Small mass, dark pions can be very light ($< \text{GeV}$)

Indirect constraints, e.g., EW precision tests (oblique $T$ parameter) and CP violation (electron EDM) push the scale of $M > 1$-$2 \text{ TeV}$. 

\[
\mathcal{L}_{\text{EFT}} = \frac{1}{2} \bar{\psi}_R Y^T M^{-2} Y \left[ \left( H^2 i D + i \gamma^\mu H^\dagger D_{\mu} H \right) \psi_R + \text{h.c.} \right] + \frac{1}{2} \bar{\psi}_L \tilde{Y}^T M^{-2} \tilde{Y} \left[ \left( H^2 i D + i \gamma^\mu H^\dagger D_{\mu} H \right) \psi_L + \text{h.c.} \right] + \bar{\psi}_L \omega \psi_R + \bar{\psi}_L \tilde{Y}^T M^{-1} \tilde{Y} \psi_R |H|^2 + \text{h.c.}
\]
Dark Pions as Composite ALPs

CP-odd dark pions behave as ALPs by mixing with the longitudinal component of $Z$, with an effective decay constant $f_a$.

$$\hat{\Pi}_{1,3} \sim Z \gamma \gamma \gamma$$

$m_\pi < m_\eta'$: dimuon mode dominates. Important for phenomenology since muon can be clearly reconstructed.

For generic dark pion parameters and TeV scale mediators, decay lifetimes settle between 0.1 mm – 100 m: typical scales of detector sizes.

$m_\pi > m_\eta'$: PPP modes (mostly SM $\pi^+\pi^-\pi^0$) comes from the $\rho\pi\pi$ coupling.

SM isospin suppressed modes

CP-even dark pion decays via the higgs portal, the modes are the same as the singlet scalar mixing with higgs, parameterized by a single mixing angle.

$$\mathcal{L}_a = \frac{1}{2} (\partial_\mu a)^2 - \frac{1}{2} m_a^2 a^2 - \frac{\partial_\mu a}{f_a} \sum_f c_f \bar{\gamma} \gamma_5 f$$
Most straightforward strategy: if dark pion decays to dimuon largely, simply count the number of displaced dimuon vertexes

LHCb current limits on the 650 MeV benchmark, also run 3 and HL-LHC projections

Phenomenology of Exotic Z Decays

References