Theory and Phenomenology of BSM Dark Mesons

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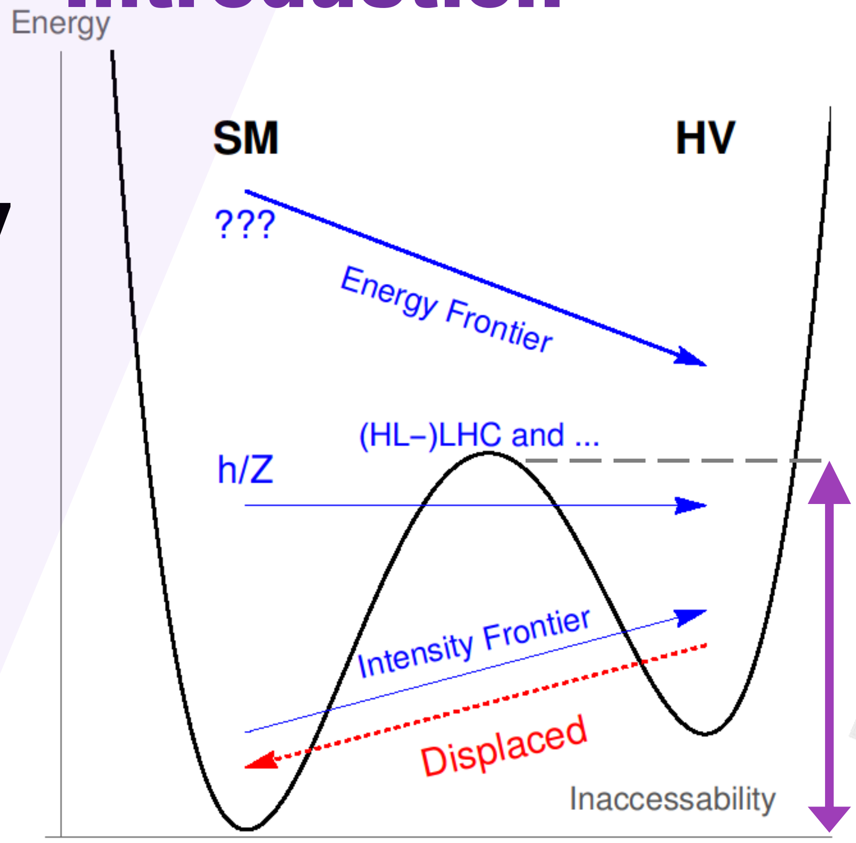
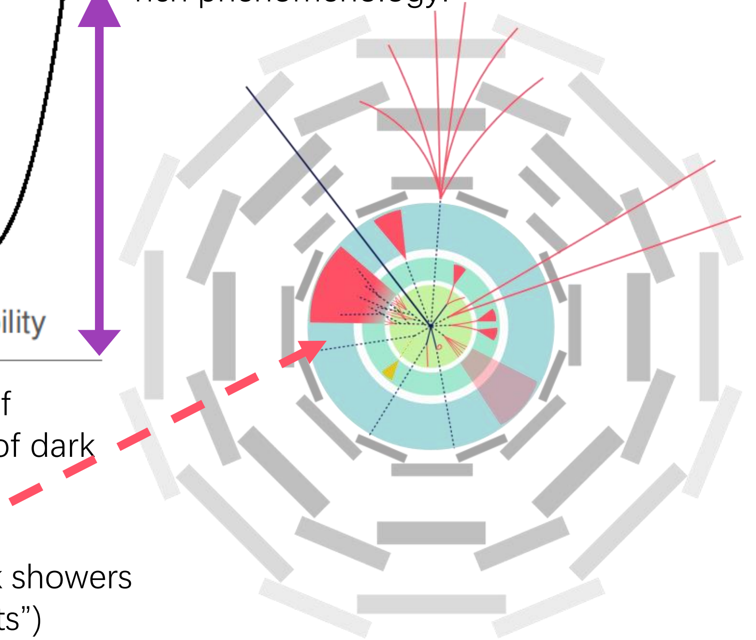
Introduction



Hidden Valley: Weakly interacting with SM and strongly self-coupled (dark hadrons).

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")

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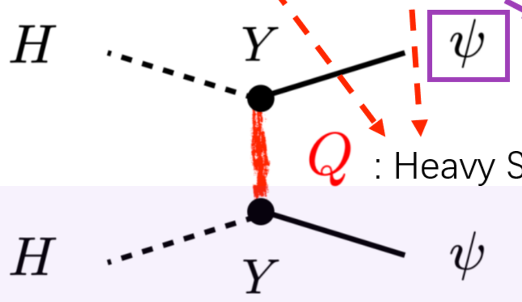
The Minimal Dark Pion Theory

Q heavier than O(TeV)

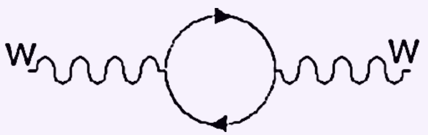
$$-\mathcal{L}_{\rm UV} = \overline{Q}_L \mathbf{Y} \psi_R H + \overline{Q}_R \widetilde{\mathbf{Y}} \psi_L H + \overline{Q}_L \mathbf{M} Q_R + \overline{\psi}_L \boldsymbol{\omega} \psi_R + \text{h.c.},$$

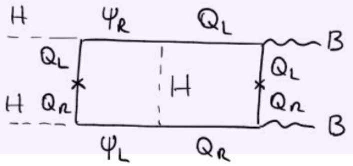


ψ : Light SM singlet dark quarks

Q : Heavy SM doublet mediators

Small mass, dark pions can be very light (< GeV)



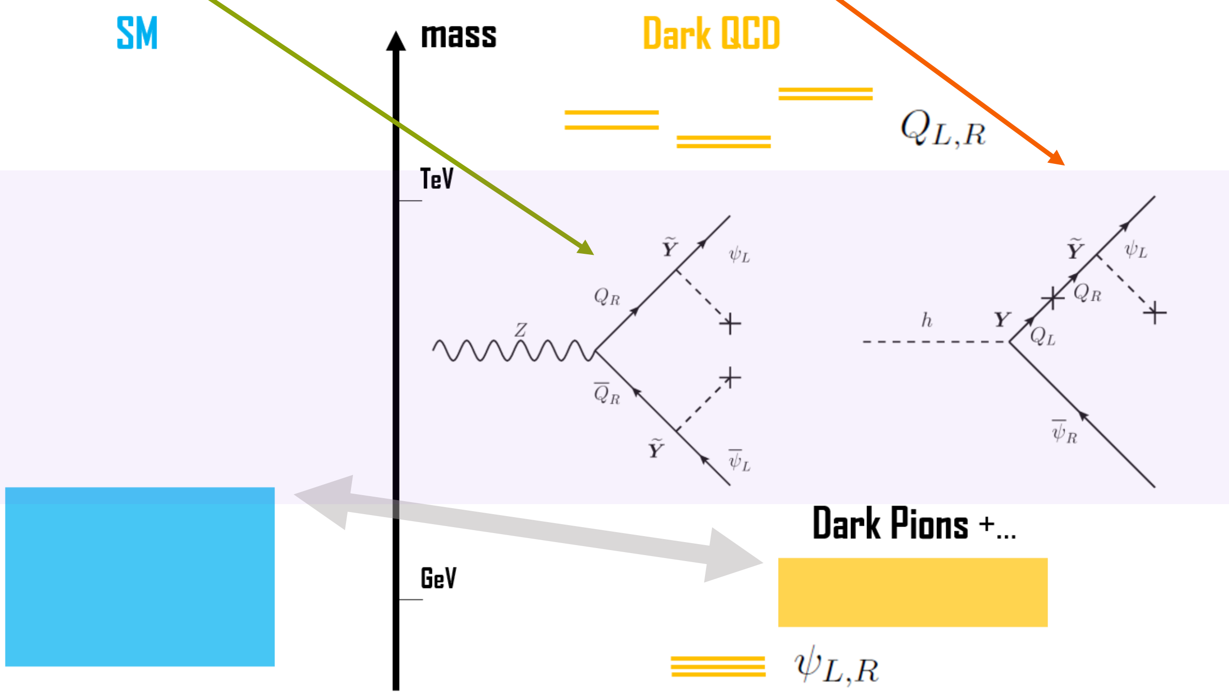


Indirect constraints, e.g., EW precision tests (oblique T parameter) and CP violation (electron EDM) push the scale of M > 1-2 TeV.

$$\begin{aligned}\mathcal{L}_{\rm EFT} = &\ \frac{1}{2}\overline{\psi}_R \mathbf{Y}^\dagger \mathbf{M}^{-2} \mathbf{Y} \left[|H|^2 i\not{D} + i\gamma^\mu H^\dagger D_\mu H\right] \psi_R + \text{h.c.} \\ &+ \frac{1}{2}\overline{\psi}_L \widetilde{\mathbf{Y}}^\dagger \mathbf{M}^{-2} \widetilde{\mathbf{Y}} \left[|H|^2 i\not{D} + i\gamma^\mu H^\dagger D_\mu H\right] \psi_L + \text{h.c.} \\ &- \overline{\psi}_L \boldsymbol{\omega} \psi_R + \overline{\psi}_L \widetilde{\mathbf{Y}}^\dagger \mathbf{M}^{-1} \mathbf{Y} \psi_R |H|^2 + \text{h.c.},\end{aligned}$$

Dimension-6 Z portal couplings

Dimension-5 Higgs portal coupling



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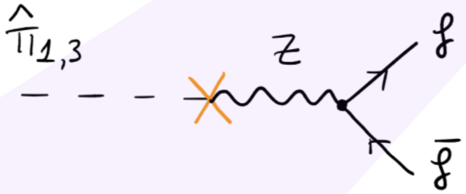
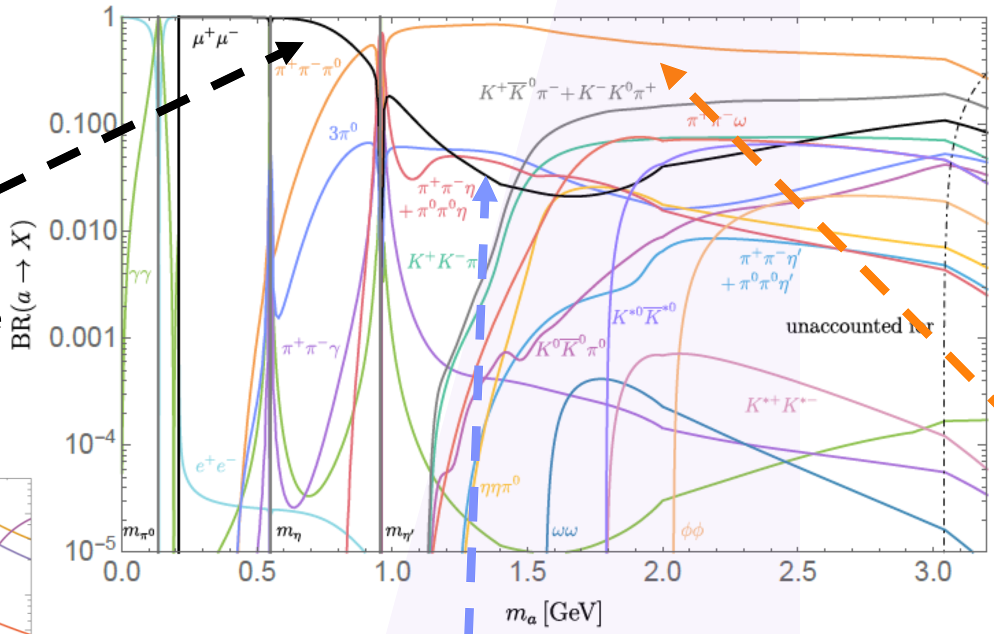
Dark Pions as Composite ALPs

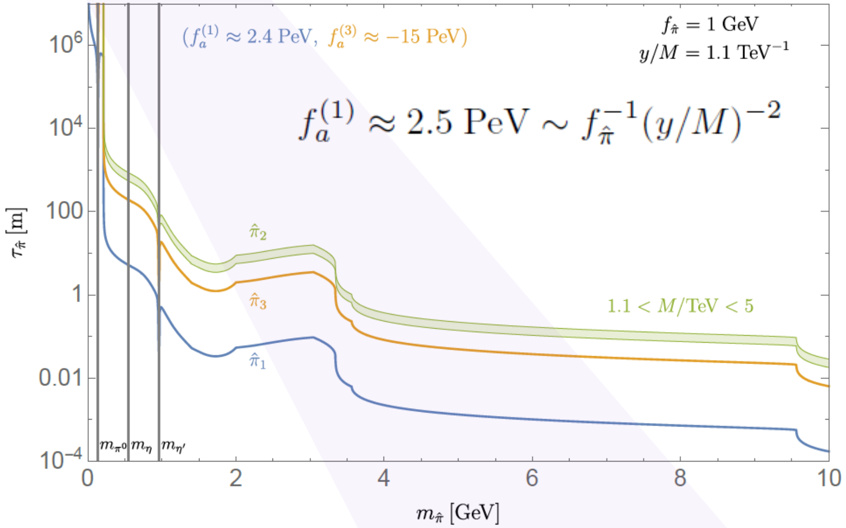
CP-odd dark pions behave as ALPs by mixing with the longitudinal component of Z, with an effective decay constant f_a

$$\mathcal{L}_a = \frac{1}{2}(\partial_\mu a)^2 - \frac{1}{2}m_a^2 a^2 - \frac{\partial_\mu a}{f_a}\sum_f c_f \bar{f}\gamma^\mu \gamma_5 f$$





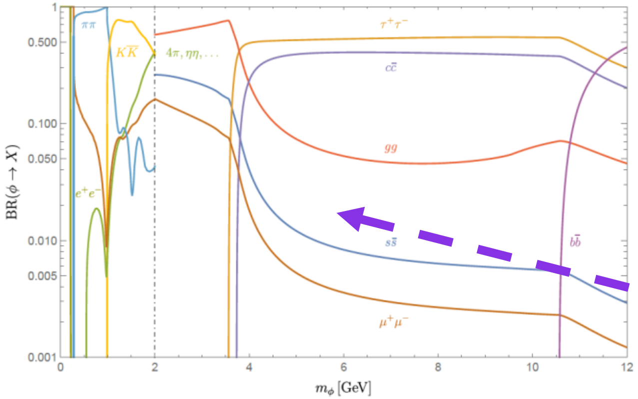
$m_\pi < m_{\eta'}$: dimuon mode dominates
Important for phenomenology since muon can be clearly reconstructed

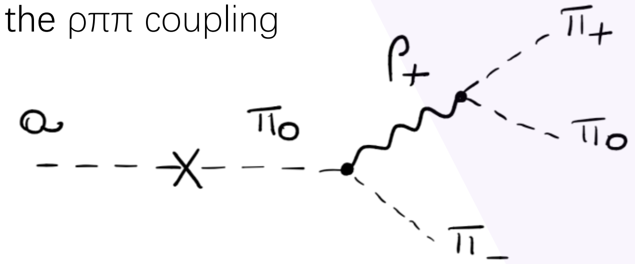


For generic dark pion parameters and TeV scale mediators, decay lifetimes settle between 0.1 mm – 100 m: typical scales of detector sizes

$m_\pi > m_{\eta'}$: 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

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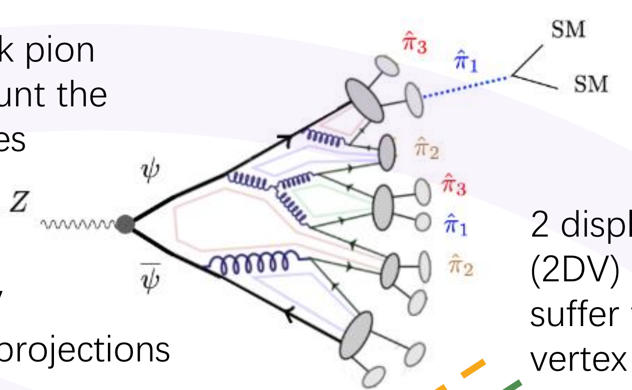
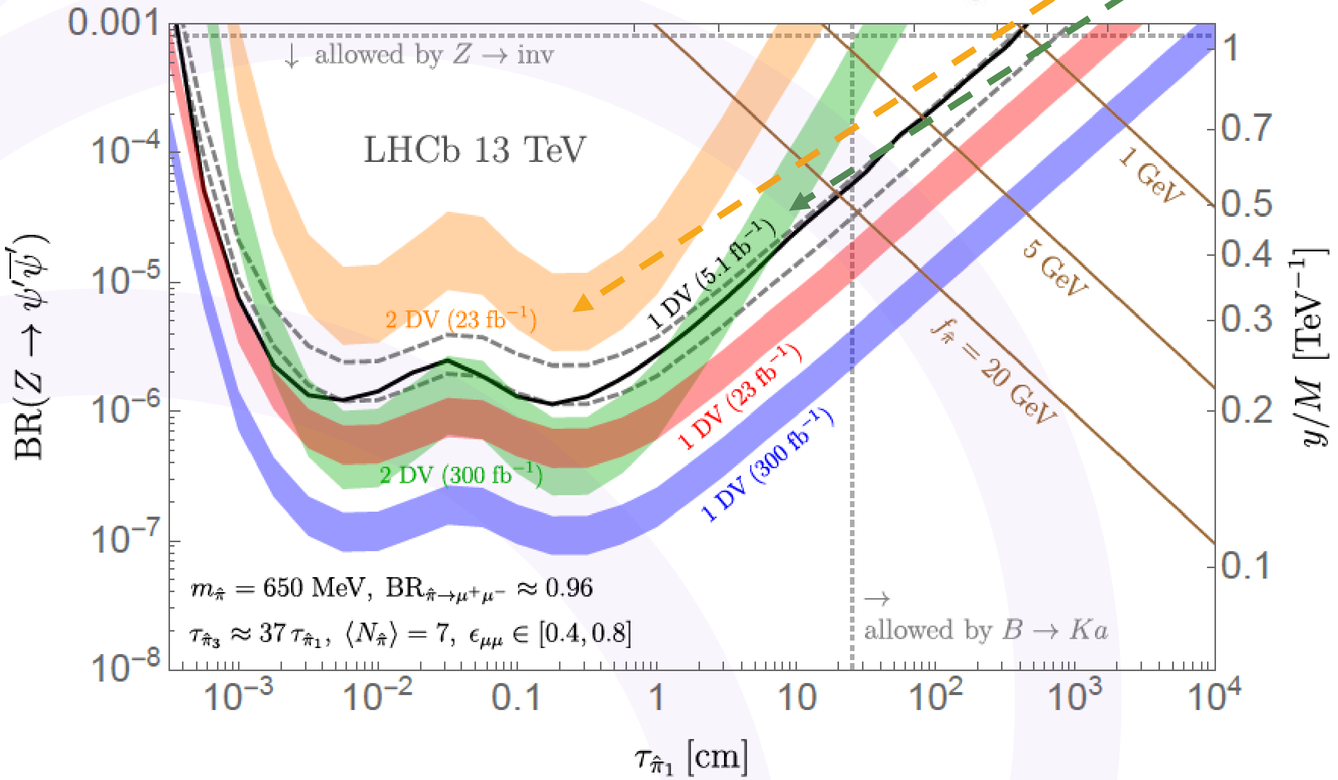
Phenomenology of Exotic Z Decays

Most straightforward strategy: if dark pion decays to dimuon largely, simply count the number of displaced dimuon vertexes

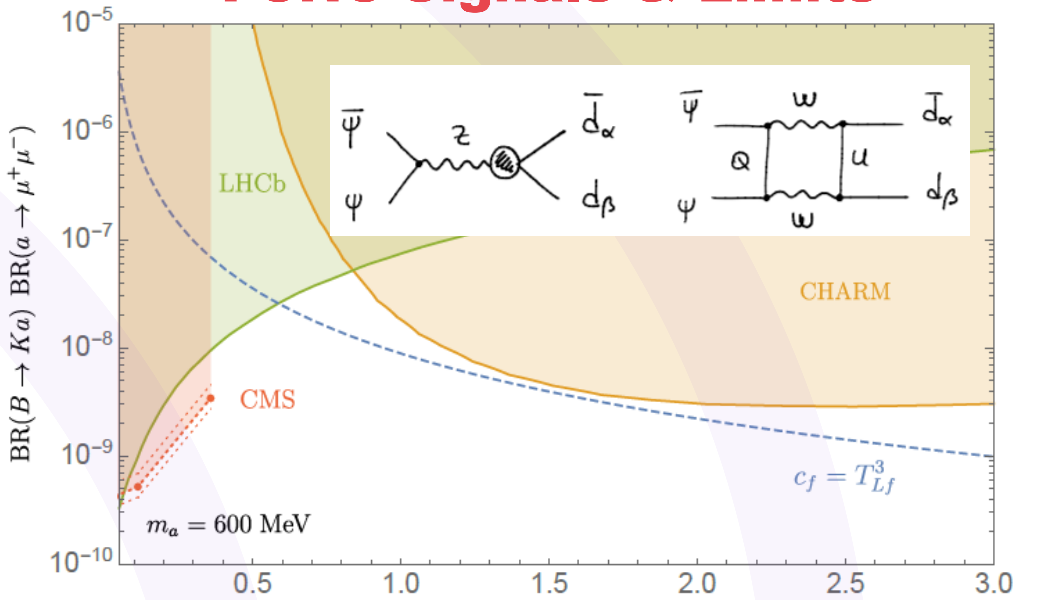


LHCb current limits on the 650 MeV benchmark, also run3 and HL-LHC projections

2 displaced vertexes (2DV) or beyond suffer from low vertex efficiency.



FCNC Signals & Limits



$$\mathrm{BR}(B^{\{+,0\}} \to \{K^+\hat\pi_b, K^{*0}\hat\pi_b\}) \approx \{0.92,\, 1.1\} \times 10^{-8} \left(\frac{10^3\ \mathrm{TeV}}{f_a^{(b)}}\right)^2 \{\lambda_{K\hat\pi}^{1/2}, \lambda_{K^*\hat\pi}^{3/2}\}$$

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