Strongly coupled dark sector and dark pions

Lingfeng Li (Brown U.)

29, Oct, TeVPA 2021, Cheng Du

2110.10691 w/ H-C. Cheng and E. Salvioni

See also:

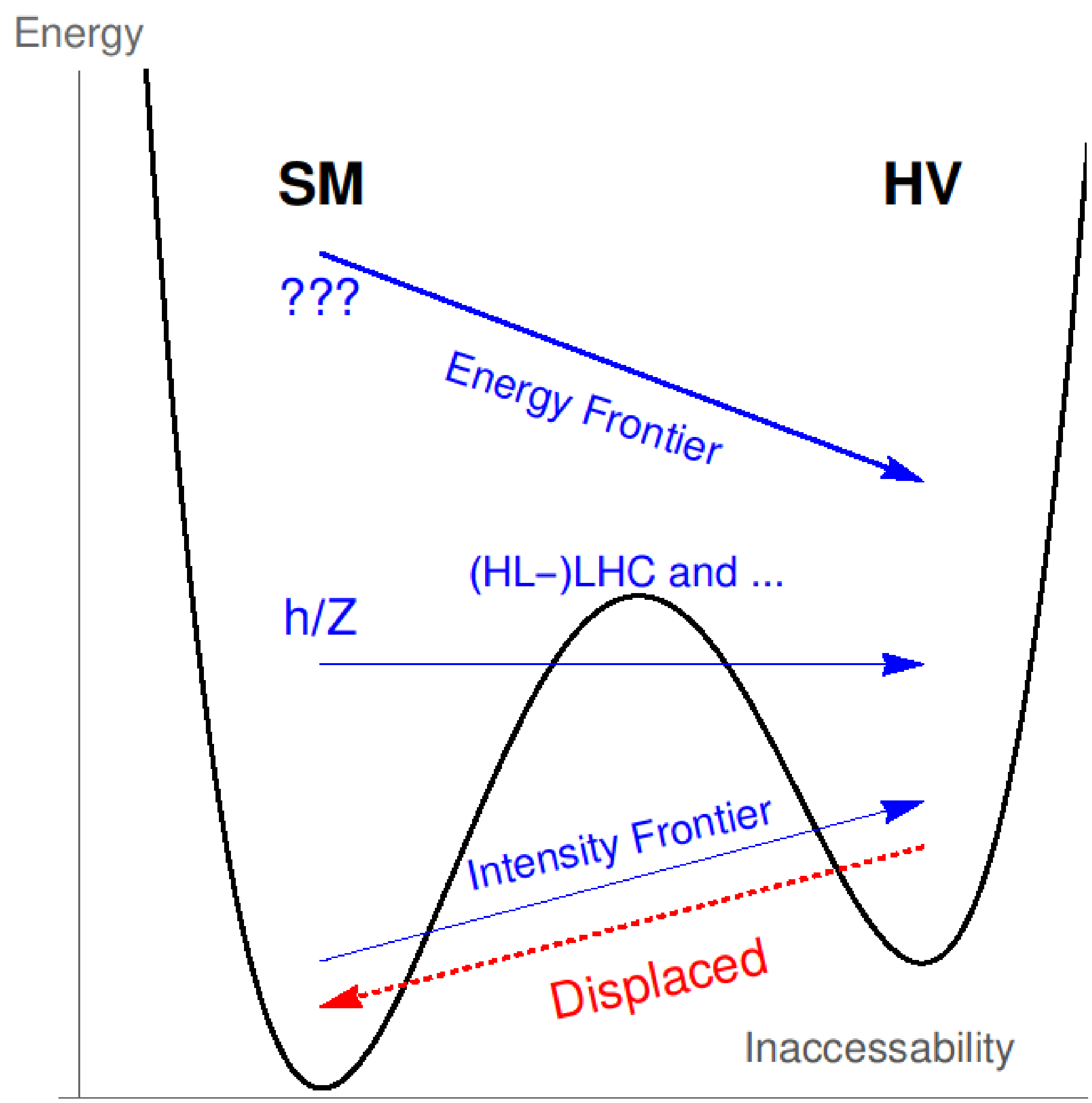
1803.03561 w/ H-C. Cheng, E. Salvioni and C. Verhaaren

1905.03772 w/ H-C. Cheng, E. Salvioni and C. Verhaaren

The Paths to the Hidden Valley

The overview of this talk

- Why a confined light hidden sector: two motivating cases
- The dark pion model
- The irrelevant portal (Z and h) phenomenology
- Several benchmark long-lived particle (LLP) searches
- Comments on cosmology

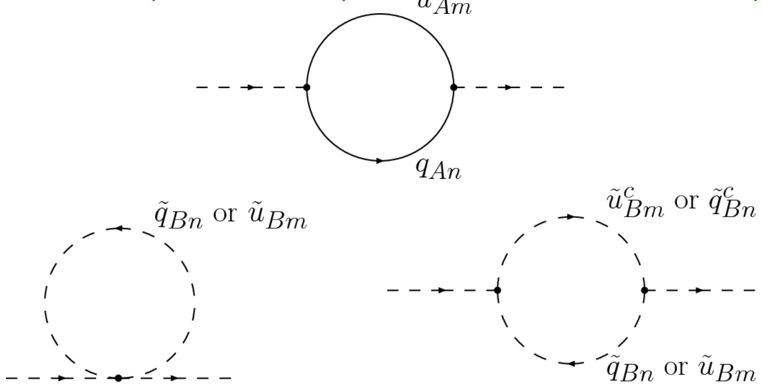


Motivating Scenario I: Neutral Naturalness

Top partners gauged under hidden SU(3) to avoid strong bounds

Folded SUSY

[G. Burdman, Z. Chacko, H.S, Goh and R. Harnik, 0609152]

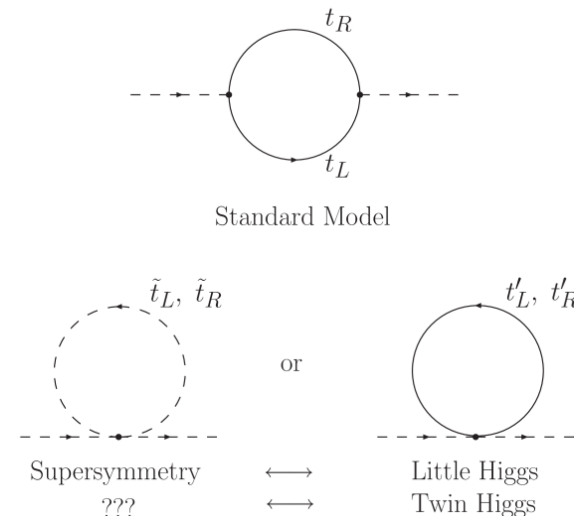


See also Tripled Top (TT) model

[H-C. Cheng, LL, E. Salvioni, and C. Verhaaren, 1803.03561]

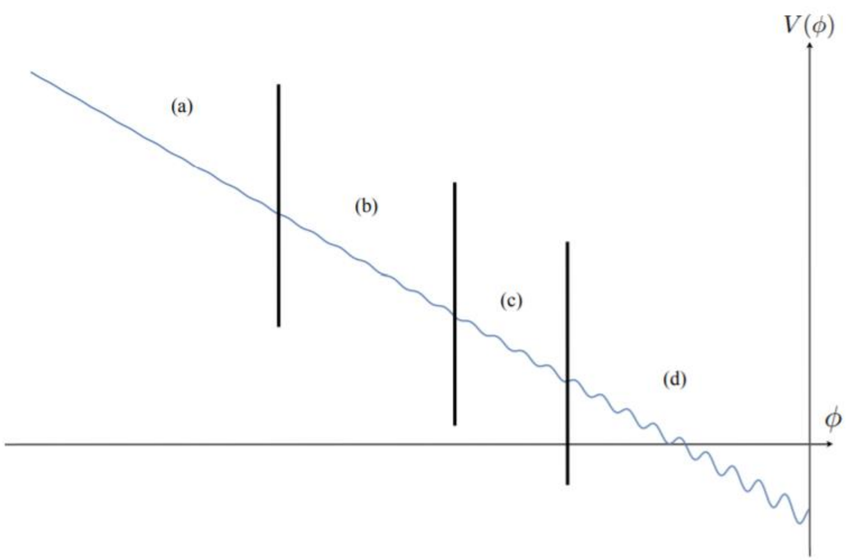
Twin Higgs

[Z. Chacko, H.-S. Goh, and R. Harnik, 0506256]



Motivating Scenario II: Relaxion

The hidden SU(3) confinement generates the necessary backreaction potential



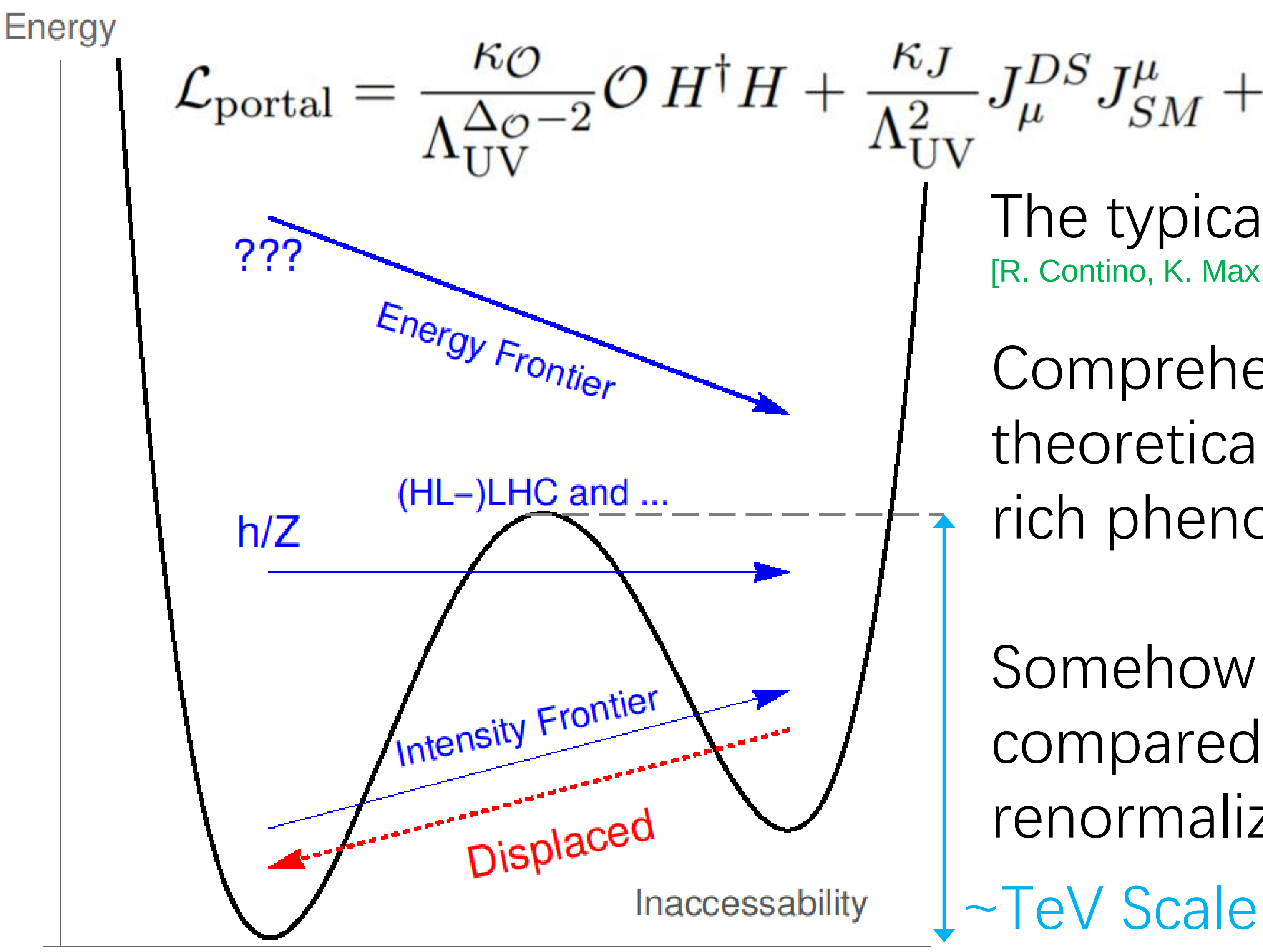
[P. W. Graham, D. E. Kaplan, and S. Rajendran, 1504.07551].

If the potential comes from the dark sector, the model avoids strong CP bounds.

See also: [O. Antipin and M. Redi, 1508.01112]. [H. Beauchesne, E. Bertuzzo and, G. Grilli di Cortona, 1705.06325].

Irrelevant Portal

$$\mathcal{L}_{\rm portal} = \frac{\kappa_{\mathcal{O}}}{\Lambda_{\rm UV}^{\Delta_{\mathcal{O}}-2}}\mathcal{O}\, H^\dagger H + \frac{\kappa_J}{\Lambda_{\rm UV}^2} J_\mu^{DS} J_{SM}^\mu + \frac{\kappa_T}{\Lambda_{\rm UV}^4} T_{DS}^{\mu\nu} O_{\mu\nu}^{SM} \ \ldots$$



The typical form

[R. Contino, K. Max and R. K. Mishra, 2012.08537].

Comprehensively easy, theoretically motivated, rich phenomenology.

Somehow overlooked compared to renormalizable ones.

Irrelevent Portal Dark Pions

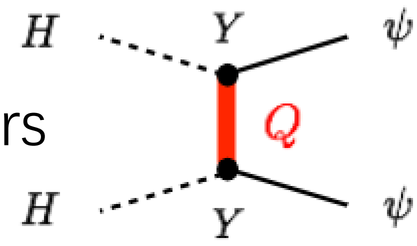
A simple theory having N(>1) dark flavors:

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

$\boldsymbol{\omega}, \boldsymbol{M}, \boldsymbol{Y}, \widetilde{\boldsymbol{Y}}$: N by N mass/Yukawa matrixes

$Q_{L,R}$: Heavy (mass~M~TeV) doublet fermion mediators

$\psi_{L,R}$: Light SM singlet fermions that give dark pions



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

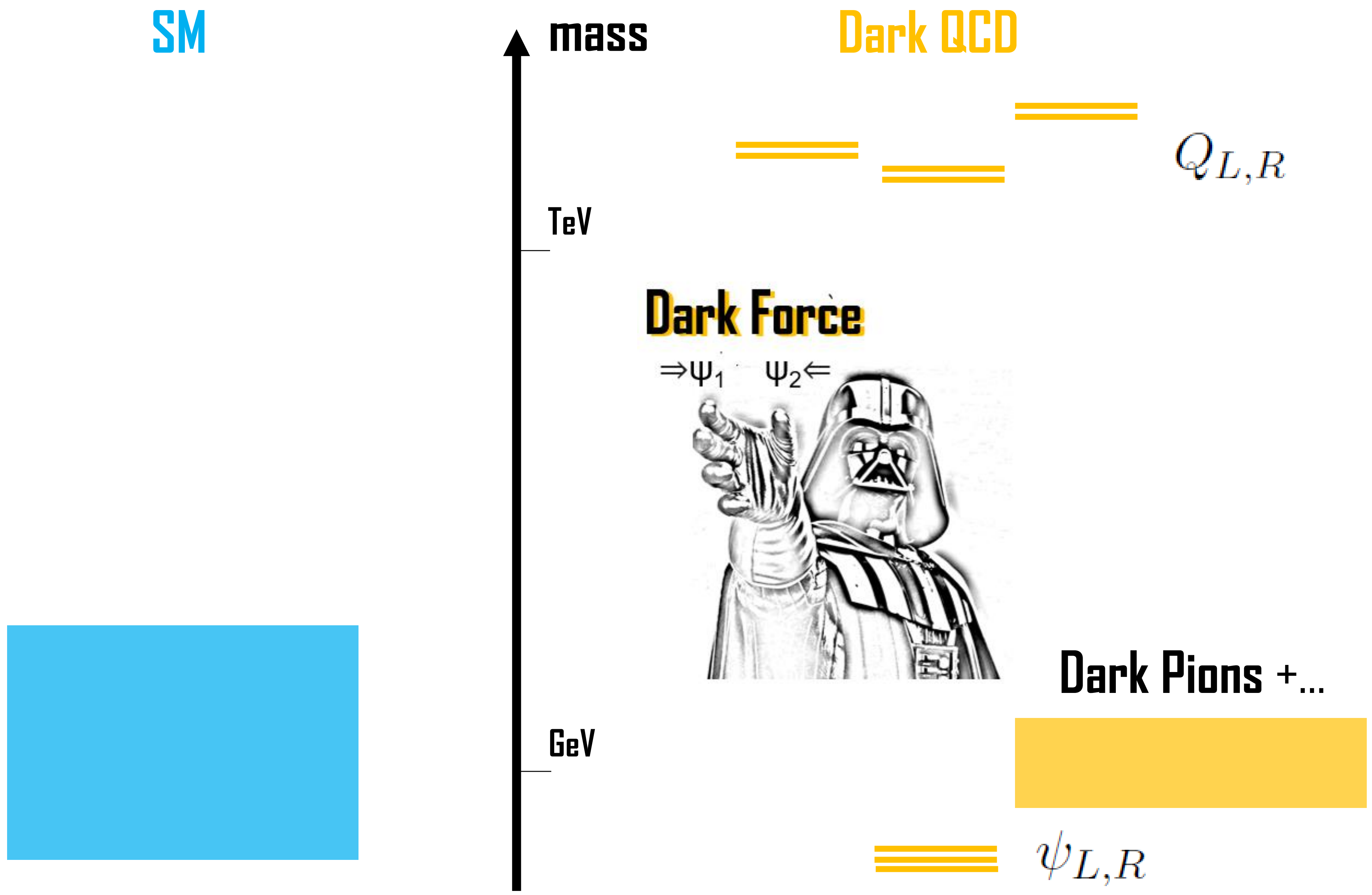
Dimension-6 Z portal couplings

Dimension-5 Higgs portal coupling

We focus on dark pions with mass ~ O(GeV)

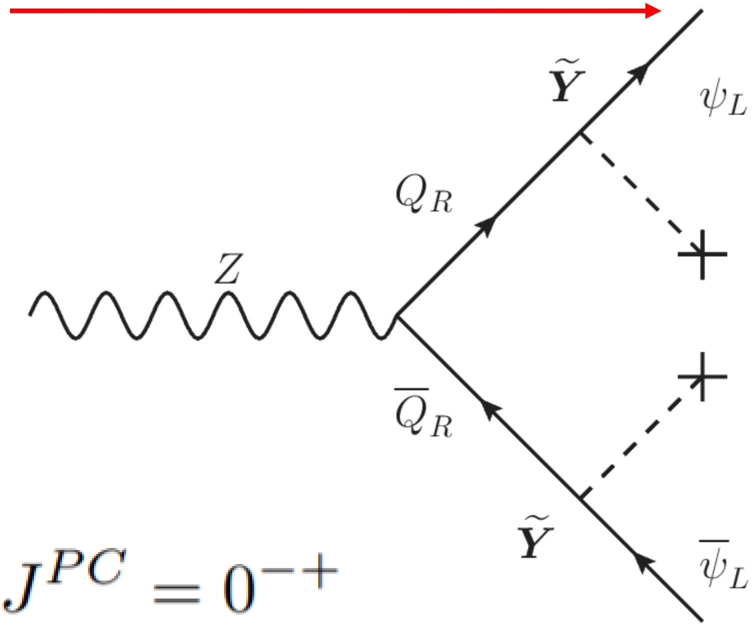
Lingfeng Li (Brown U.) arXiv: 2110.10691

The Cartoon of Dark Spectrum



Two Flavor, Three Dark Pions

Z portal dark pion production



$J^{PC} = 0^{-+}$

Z portal dark pion decay

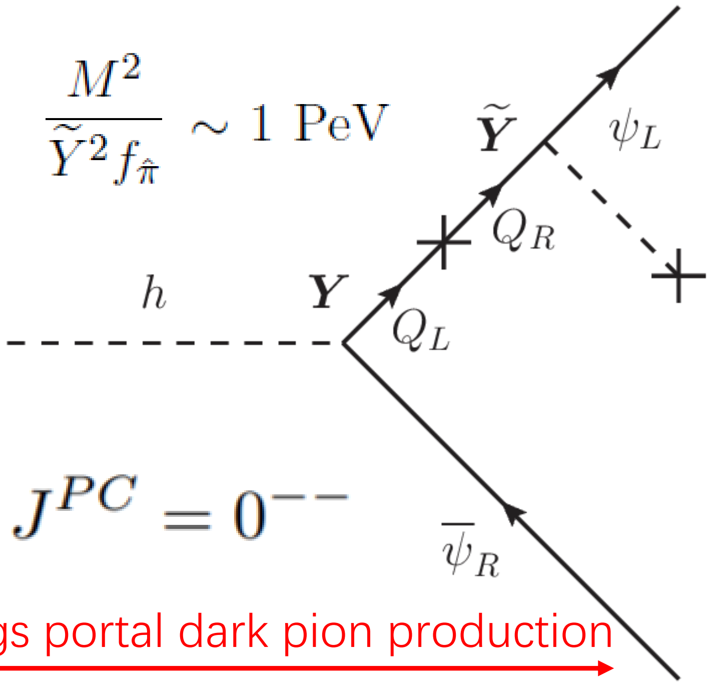
Dark pions rearrange into CP eigenstates (like K_S and K_L in the SM)

The π_1 and π_3 decay via Z portal, behave like ALP (axion-like-particle) with a large ALP decay constant:

$$f_a \sim \frac{M^2}{Y^2 f_{\hat{\pi}}} \quad \text{or} \quad \frac{M^2}{\widetilde{Y}^2 f_{\hat{\pi}}} \sim 1\ \text{PeV}$$

The π_2 decay via its mixing with the Higgs since it's CP-even, well described by the mixing angle:

$$s_\theta^{(2)} \sim 2\pi f_{\hat{\pi}}^2 \frac{v}{m_h^2} \frac{Y\widetilde{Y}}{M} \sim 10^{-6} \left(\frac{Y\widetilde{Y}/M}{10^{-2}\ \text{TeV}^{-1}} \right) \left(\frac{f_{\hat{\pi}}}{\text{GeV}} \right)^2$$



$J^{PC} = 0^{--}$

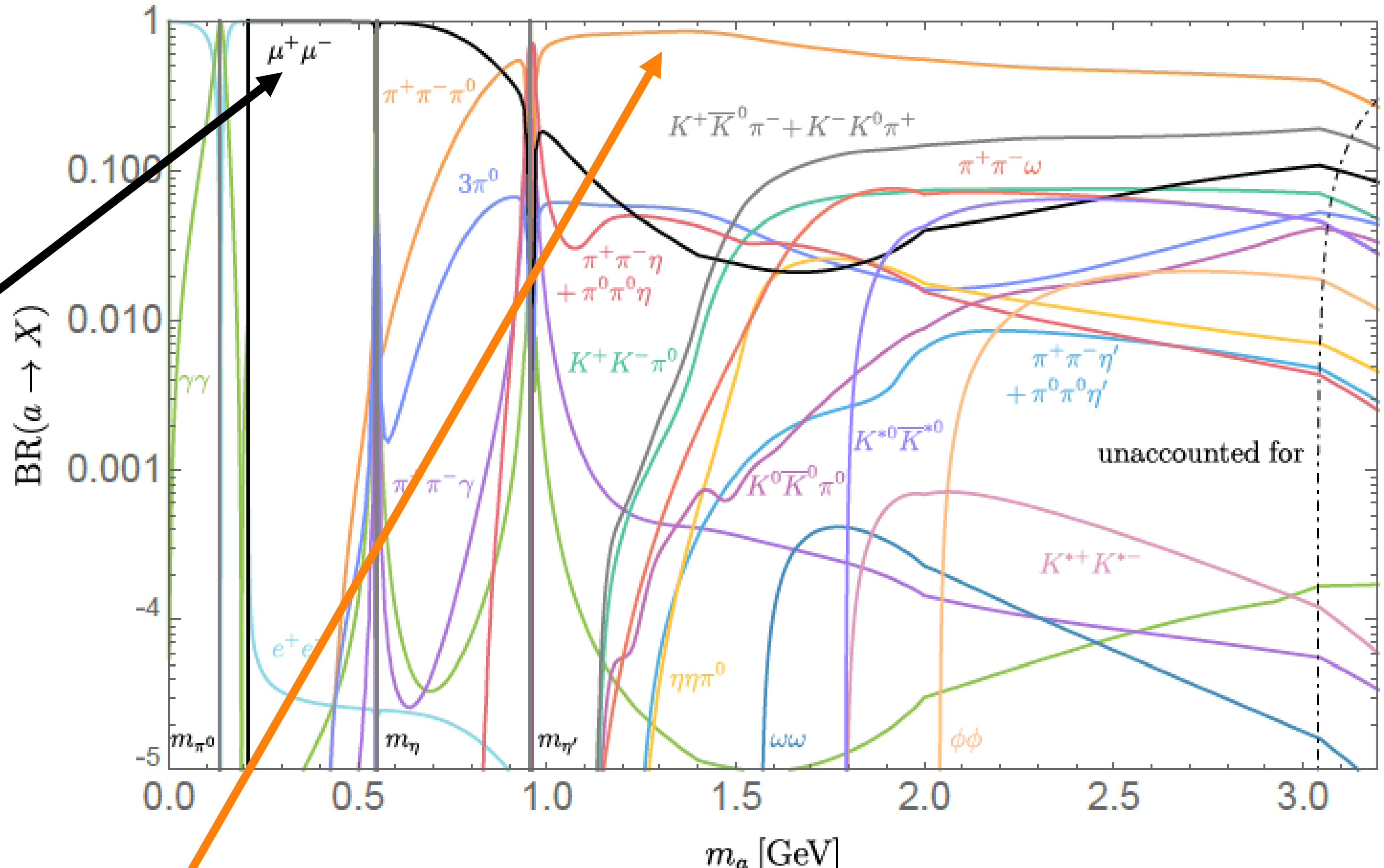
Higgs portal dark pion production

Higgs portal dark pion decays

Dark Pion Decays (ALP-Like)

ALP with arbitrary flavor diagonal couplings, a step forward from [D. Aloni, Y. Soreq and M. Williams, 1811.03474],

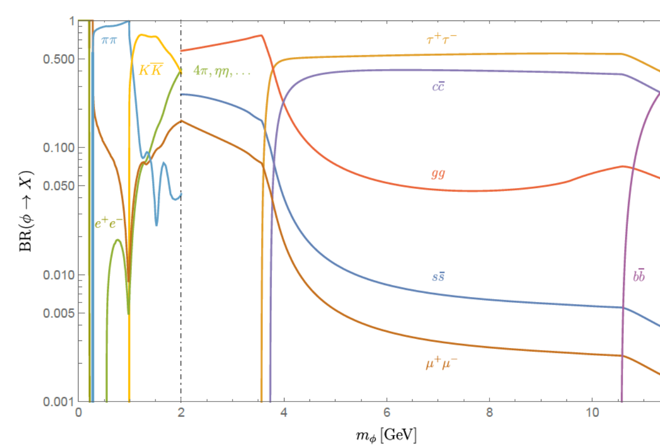
$m_\pi < m_{\eta'}$: dimuon mode



A.1 $a \to \gamma\gamma$
A.2 $a \to \pi^+\pi^-\gamma$
A.3 $a \to \pi^+\pi^-\pi^0$
A.4 $a \to 3\pi^0$
A.5 $a \to \pi^0\pi^0\eta, \pi^+\pi^-\eta$
A.6 $a \to \pi^0\pi^0\eta', \pi^+\pi^-\eta'$
A.7 $a \to \eta\eta\pi^0$
A.8 $a \to K^0\overline{K}^0\pi^0$
A.9 $a \to K^+K^-\pi^0$
A.10 $a \to K^+\overline{K}^0\pi^-, K^-K^0\pi^+$
A.11 $a \to \omega\omega, \phi\phi, K^{*+}K^{*-}, K^{*0}\overline{K}^{*0}$
A.12 $a \to \pi^+\pi^-\omega$

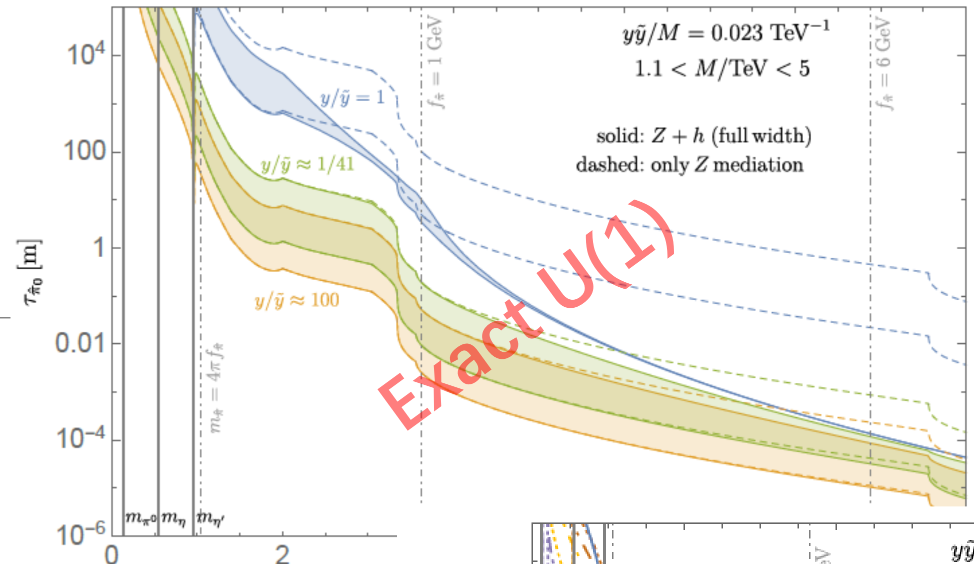
$m_\pi > m_{\eta'}$: PPP modes (mostly SM $\pi^+\pi^-\pi^0$)

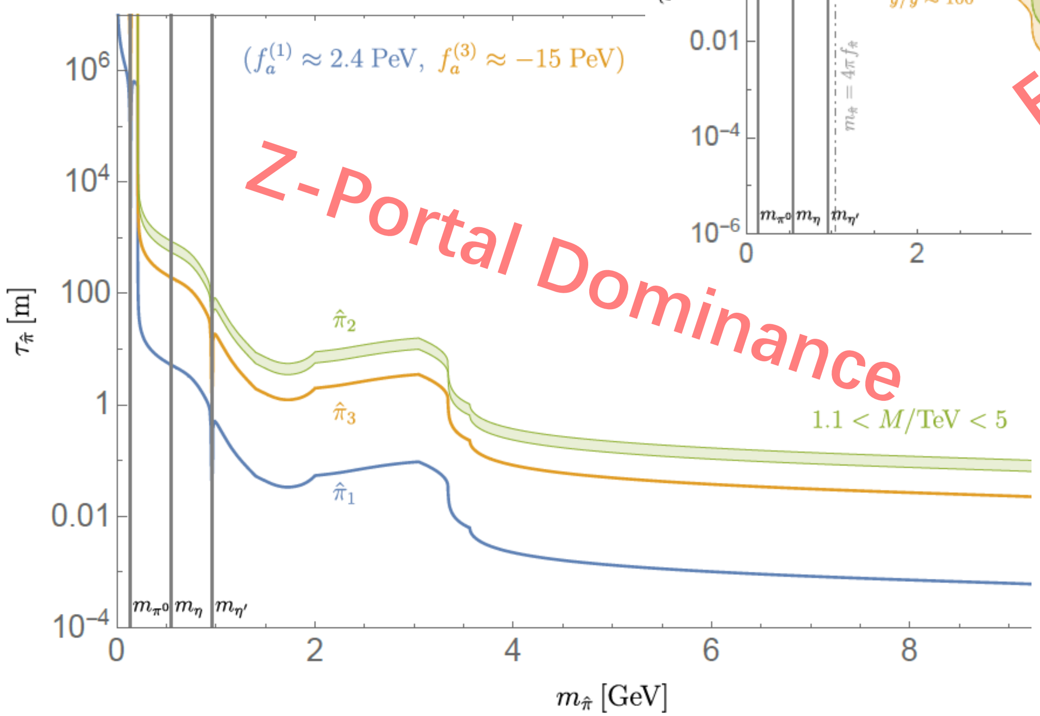
Higgs portal decay follows [M. W. Winkler, 1809.01876]

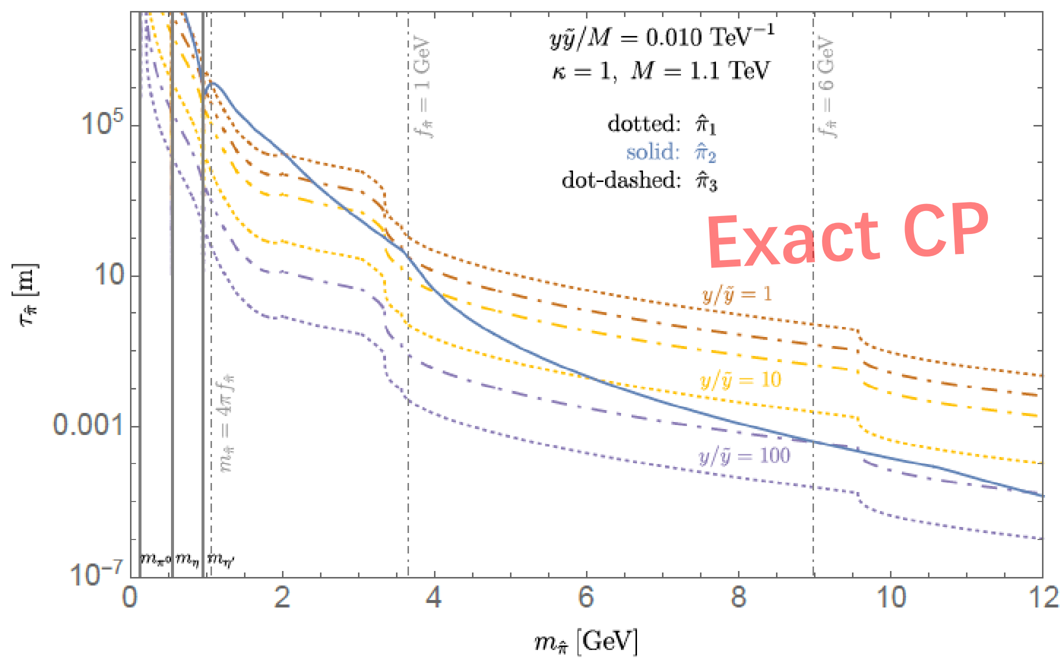


Dark Pion as Long-lived Particles

Lifetime between 1mm to >10m







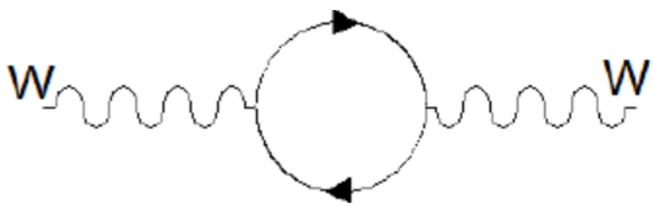
Easy LLP with strong parameter dependence

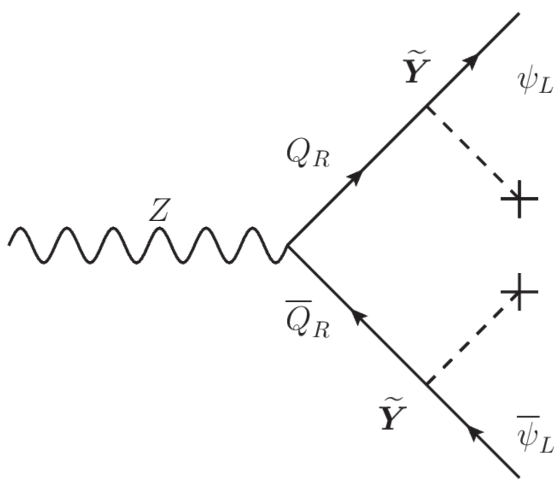
Lingfeng Li (Brown U.) arXiv: 2110.10691

Indirect/Precision Constraints

$$M \gtrsim 0.9\,\mathrm{TeV}\; Y^2 \left(\frac{N_d N}{6}\right)^{1/2}$$

From EW oblique parameter T < O(10^{-3})



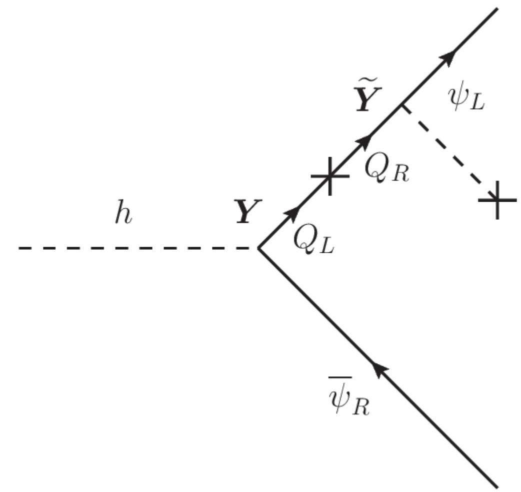


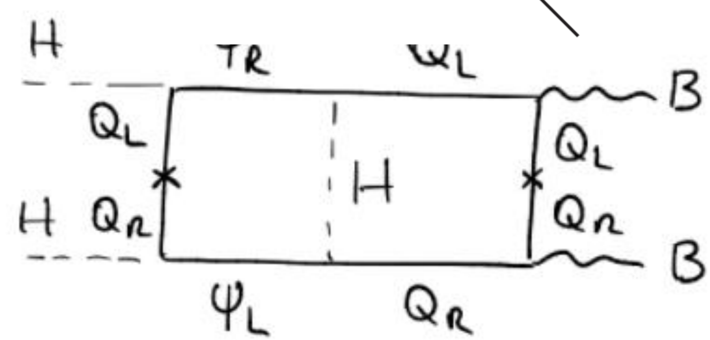
$$M \gtrsim 0.8\,\mathrm{TeV}\; Y \left(\frac{N_d N}{6}\right)^{1/4}$$

From Z invisible decay width <~2 MeV

$$M \gtrsim 0.4\ \mathrm{TeV} \left(\frac{N_d \mathrm{Tr}(\mathbf{Y}\mathbf{Y}^\dagger \widetilde{\mathbf{Y}}\widetilde{\mathbf{Y}}^\dagger)}{3\times 10^{-4}}\right)^{1/2}$$

From Higgs invisible decay BR < 13%





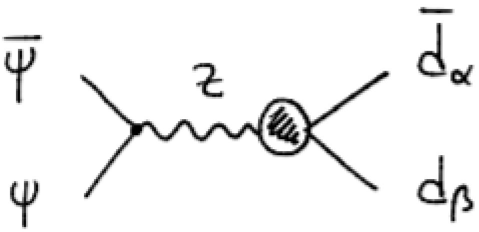
$$M \gtrsim 1.5\ \mathrm{TeV}\ \ Y\tilde{Y}$$

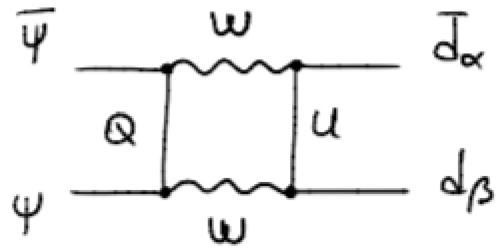
From electron EDM if CP is violated maximally

Dark Pion from SM FCNC

Although suppressed by the small CKM and loop factors, FCNC meson decays are still relevant as the FCCC SM heavy flavor decays are suppressed by $(M_W)^{-4}$ already.

$$\mathcal{L}_{\rm eff} \sim \bar{d}_{L\alpha} d_{L\beta} \bar{\psi}' \psi', \qquad \alpha < \beta$$





Amplitude can be fully adapted from ds→ νν results in [Inami, Lim 1980]

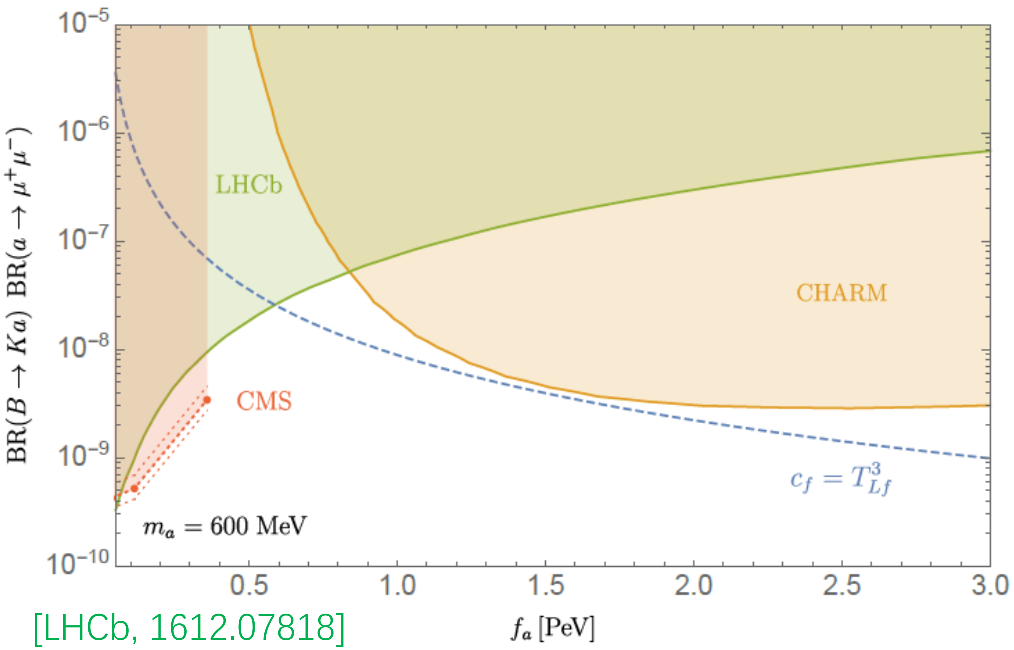
The four-fermion interaction then followed by the factorization, which should be exact for dark QCD vs. QCD.

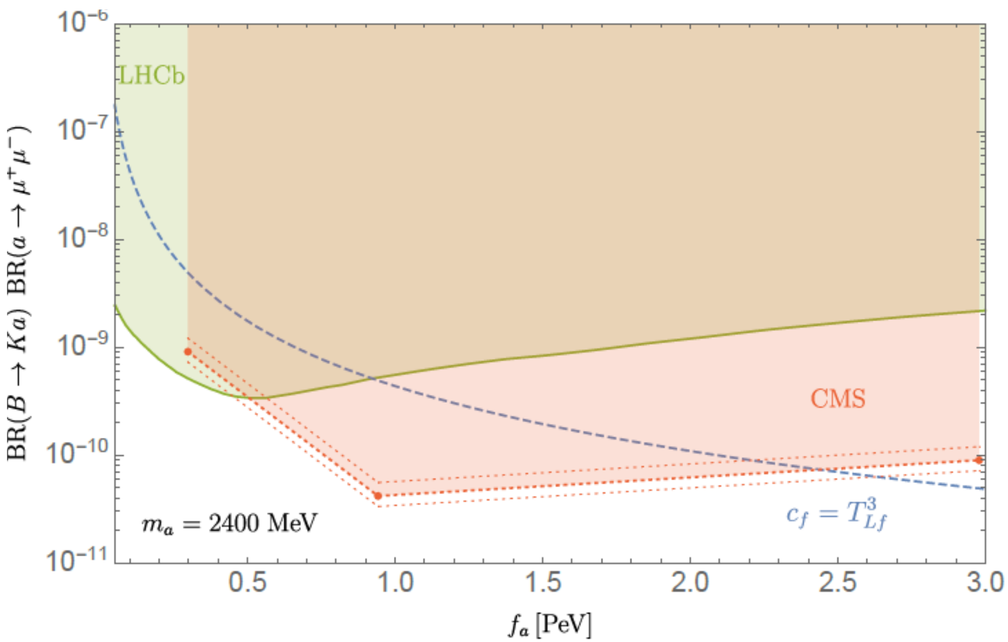
$$\langle \hat{\pi}_a X | \mathcal{H}_{\rm eff} | B \rangle = \langle \hat{\pi}_a | \langle X | \mathcal{H}_{\rm eff} | 0 \rangle | B \rangle = \frac{i g^2}{64\pi^2} V_{ts}^* V_{tb} \langle X | \bar{s}_L \gamma_\mu b_L | B \rangle \frac{p^\mu_{\hat{\pi}}}{f_a^{(a)}} \left[\frac{m_t^2}{m_W^2} \left(\log \frac{M^2}{m_t^2} - 2 \right) + 3 \right]$$

Current FCNC Bounds

The bound as long as the experimental Ecm > the BB/KK thresholds
Limits coming from LHC, ee colliders and beam dump experiments.

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





[LHCb, 1612.07818]
[CHARM, Phys. Lett. B 157 (1985) 458. & 1810.11336]
[CMS, CMS-PAS-EXO-20-014]

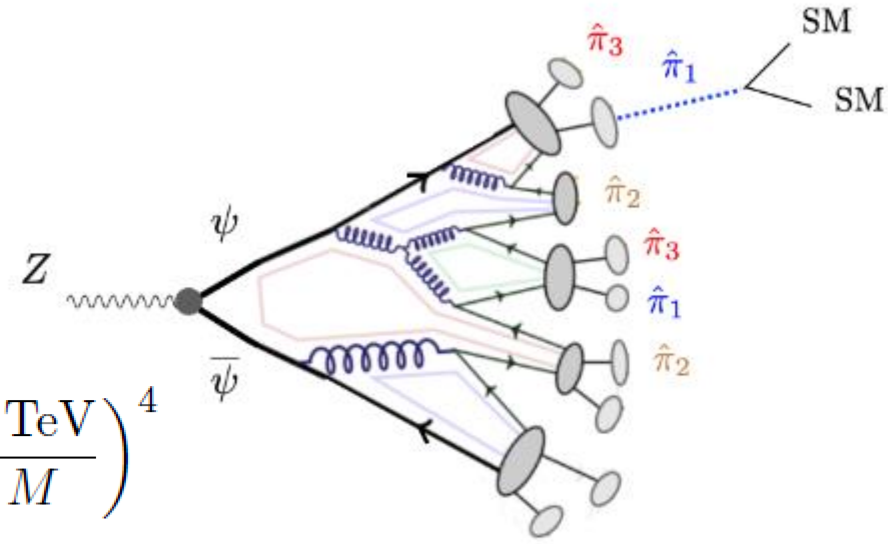
Probing f_a ~ PeV already
Reaching O(10) PeV in future experiments

Kaon FCNC invisible modes give similar constraints as the LLP mode.
[NA48/2 1612.04723]

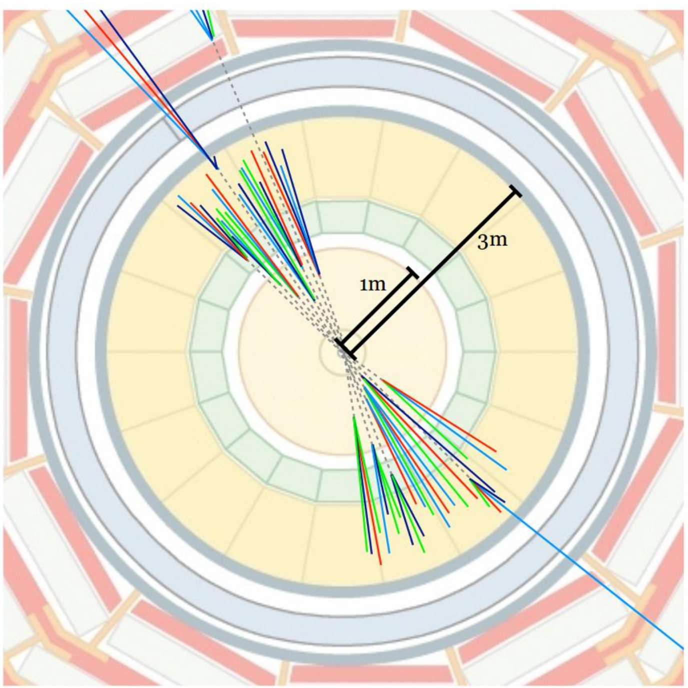
$$\mathrm{BR}(K^+ \to \pi^+\hat{\pi}^{(b)}) \approx 3.9 \times 10^{-11} \left(\frac{10^3\ \mathrm{TeV}}{f_a^{(b)}}\right)^2 \lambda_{\pi\hat{\pi}}^{1/2}$$

Phenomenology @ the LHC

Z exotic decays to dark quarks with BR:



$$1.8 \times 10^{-4} \left(\frac{N_d \mathrm{Tr}(\boldsymbol{Y}\boldsymbol{Y}^\dagger \boldsymbol{Y}\boldsymbol{Y}^\dagger) + (\boldsymbol{Y} \to \tilde{\boldsymbol{Y}})}{3} \right) \left(\frac{1\,\mathrm{TeV}}{M} \right)^4$$



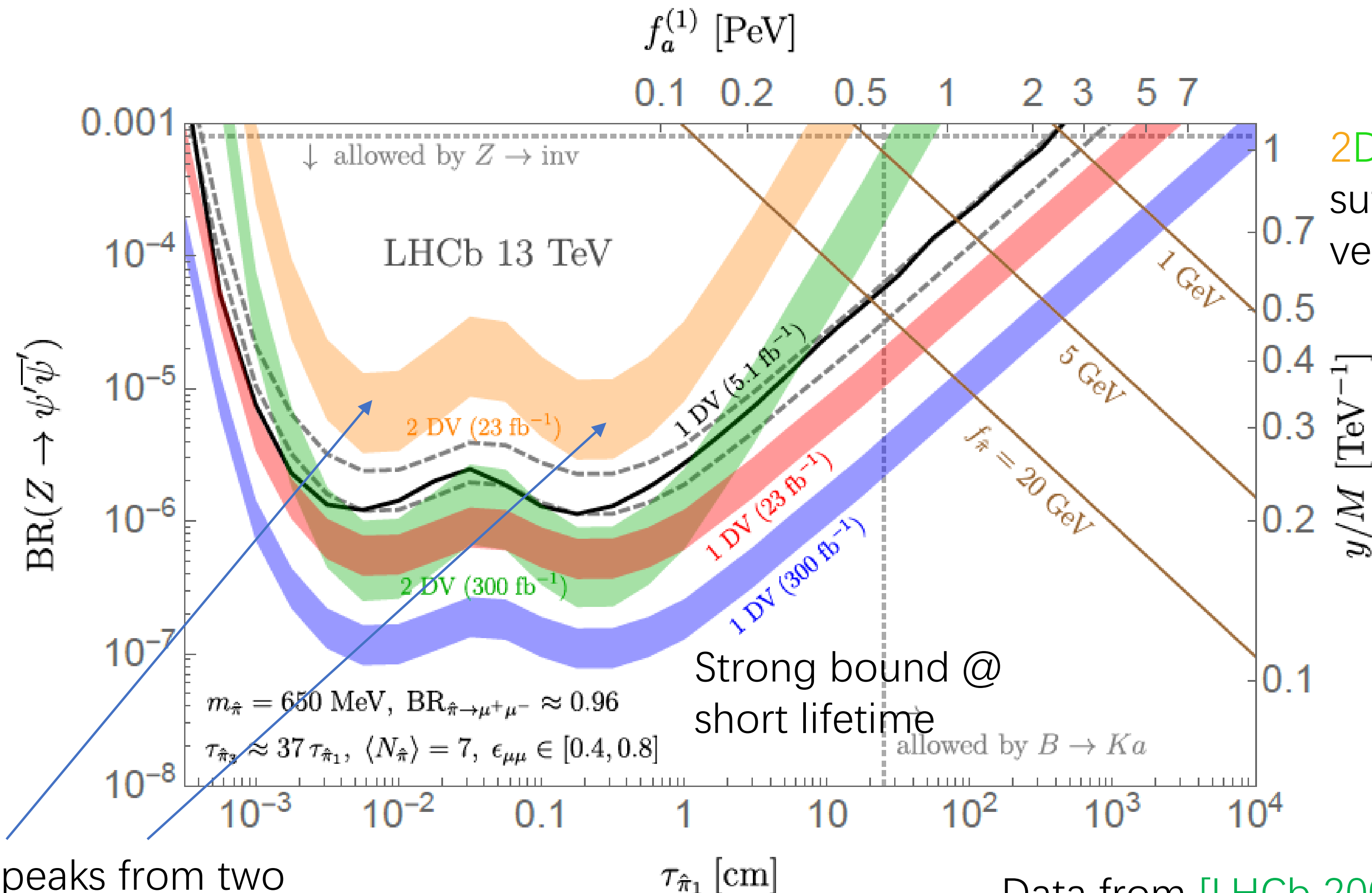
Dark quarks hadronize into many dark pions, forming dark jets.

If any dark pion is a LLP $\longrightarrow$ The case often referred to as “emerging jets”

[P. Schwaller, D. Stolarski and A. Weiler, 1502.05409]
[CMS, 1810.10069]

Example: Dimuon Search @ LHCb

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



2DV or beyond suffer from low vertex efficiency.

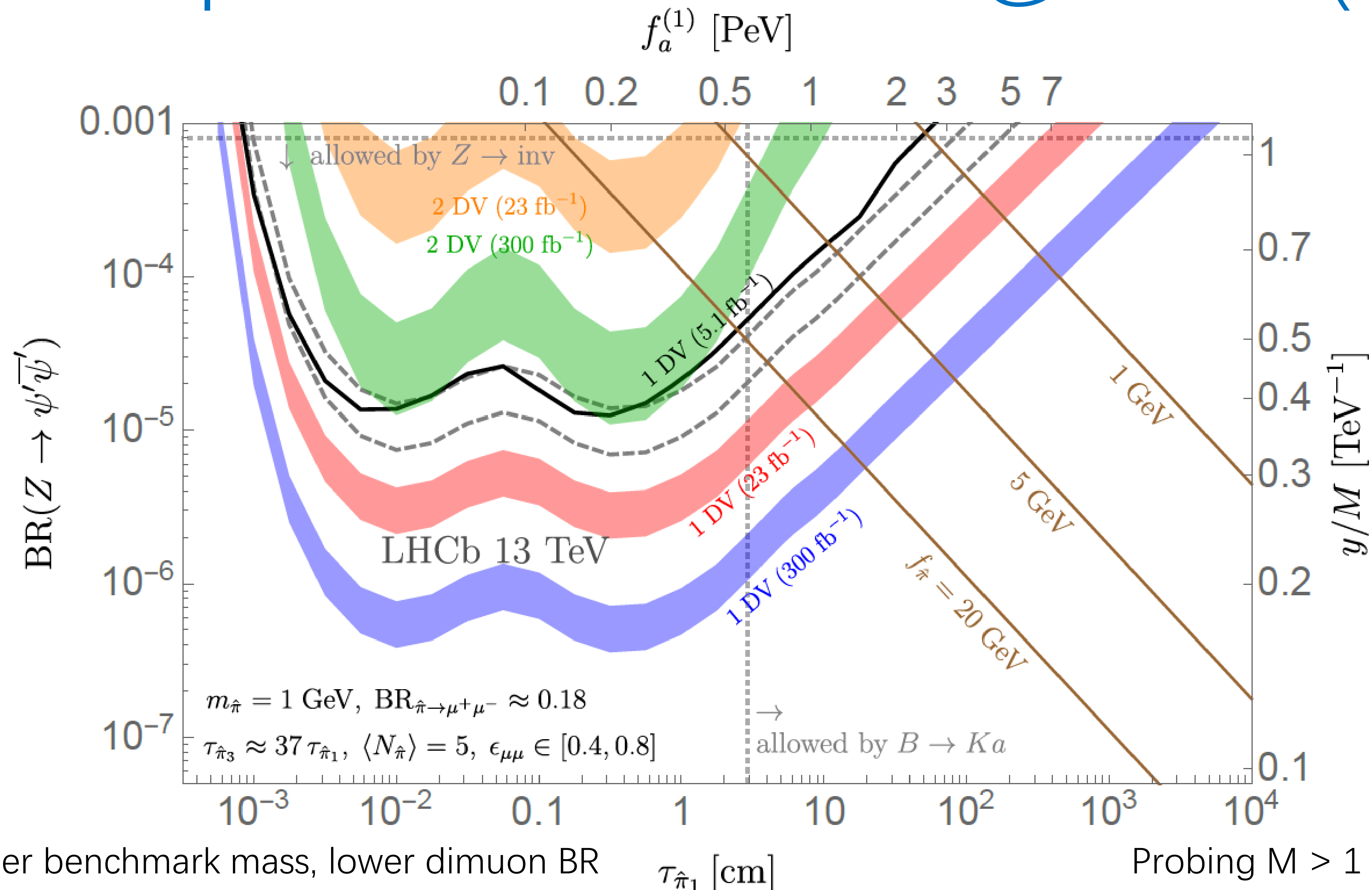
Strong bound @ short lifetime

Two peaks from two different pion widths 1:37

Data from [LHCb 2007.03923]

Lingfeng Li (Brown U.) arXiv: 2110.10691

Example: Dimuon Search @ LHCb (II)

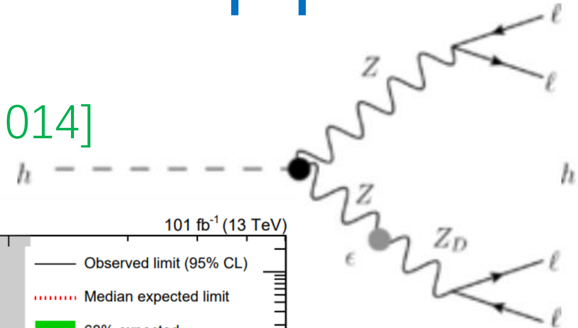


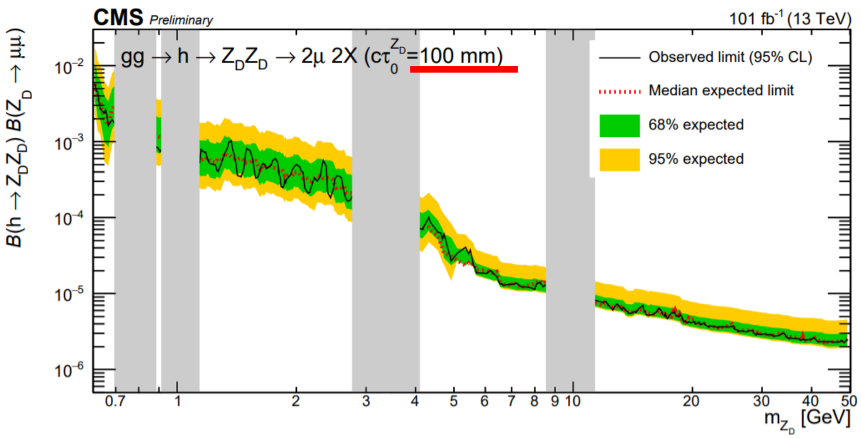
Larger benchmark mass, lower dimuon BR compensated by shorter lifetimes

Probing M > 1 TeV for both benchmarks

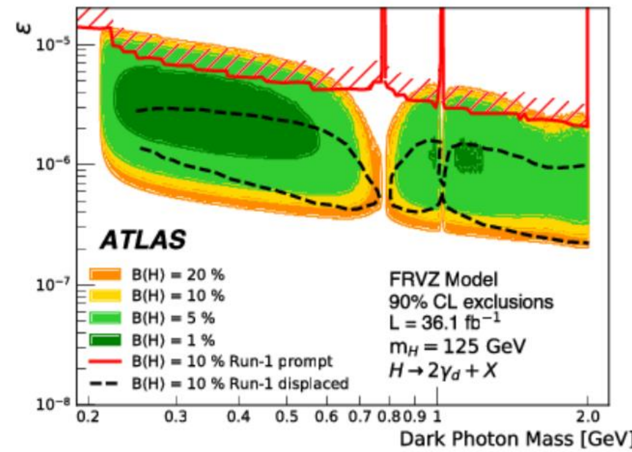
Further Opportunities @ LHC

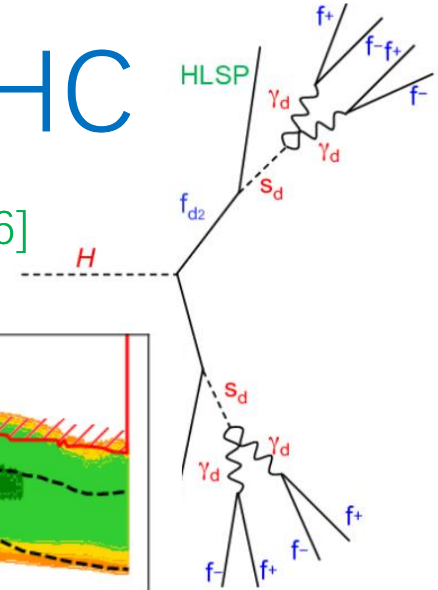
[CMS: CMS-PAS-EXO-20-014]



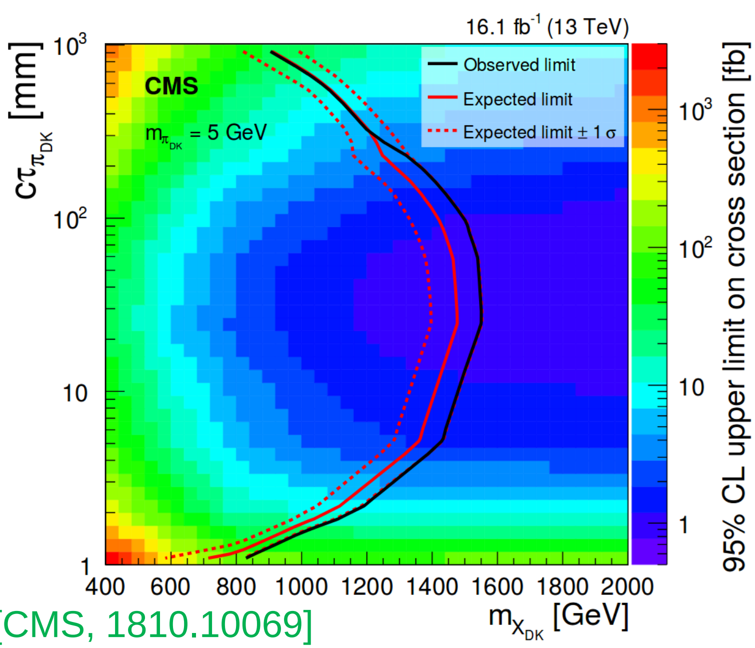


[ATLAS: 1909.01246]

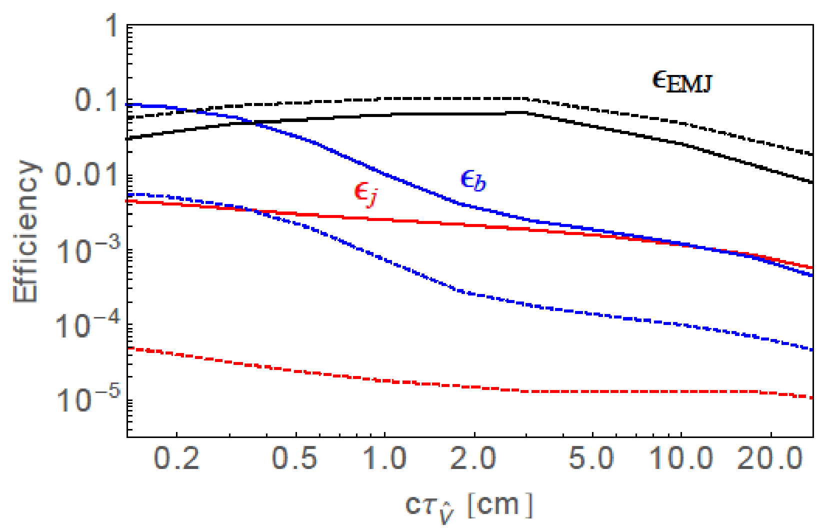




The dark pion searches at ATLAS/CMS benefit from larger luminosities and decay volume. Reprojection are non-trivial. LLP oriented triggers? [Y. Gershtein and S. Knapen, 1907.00007]



[CMS, 1810.10069]



Emerging jet efficiencies for the one-flavor case [H-C. Cheng, LL, E. Salvioni and C. Verhaaren, 1905.03772]

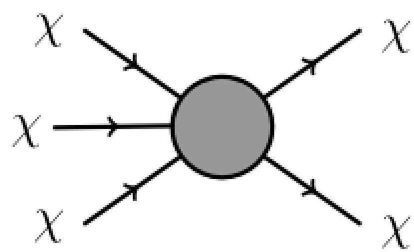
⇐A fully inclusive emerging jet search will be sensitive to heavier dark pions.

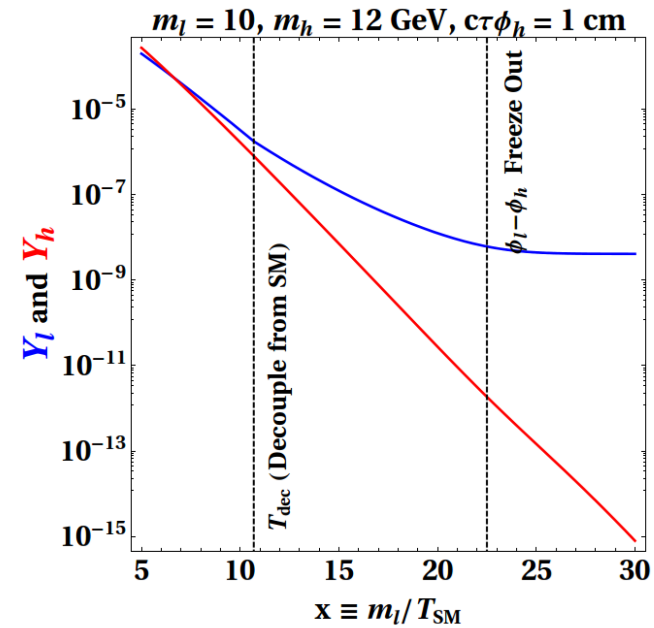
Comments on Cosmology

Our vanilla dark pion model is not strongly constrained by astrophysical/cosmological observations.

If isospin is exact, all dark pions are stable.
For N(flavor)>2 case, reducing number density from WZW interactions (SIMP DM-like): [Y. Hochberg, E. Kuflik, H. Murayama, T. Volansky and J. G. Wacker,1411.3727] +……

Need extra mediators to dump the entropy generated.





As long as a dark pion is unstable, the number density depletion is fast via pion scattering. Small relics and weak bounds. See also [Y. Tsai and LL,1901.09936]

The DM possibilities are still wide open with non-minimal dark components. For example, asymmetric baryonic DM or mesino/glueballino DM in SUSY UV completions.

Summary

- Dark mesons are common and well motivated. From simple UV structures, there will be rich phenomenology.
- A theory of dark pion that gives LLP. Dedicated calculations for mass < 3 GeV cases.
- Phenomenology from current data shows that an M ~ a few TeV is achievable.
- Open fields (LHC upgrades, future colliders, intensity frontier, cosmology) remain to be fully explored.

Backup Slides

Symmetries of the Dark Pion Model

Depending on forms of $\omega, M, Y, \widetilde{Y}$, the symmetry of the model varies. We consider 3 benchmarks:

Symmetries possessed			Decay portals		
$\widetilde{Y}=0$	exact $U(1)$	exact CP	$\hat{\pi}_1$	$\hat{\pi}_2$	$\hat{\pi}_3$
✓	✗	✗	Z	Z	Z
✗	✓	✗	stable	stable	Z, h
✗	✗	✓	Z	h	Z

The U(1) subgroup of the SU(2) isospin is exact if everything is diagonal

The CP is conserved in the dark sector if all couplings are real.

The Higgs portal is greatly suppressed if either Y or $\widetilde{Y}$ =0