Dark Z' and Dark Pions

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w/ Xuhui Jiang, Lingfeng Li and Ennio Salvioni, in progress
and HC, Lingfeng Li and Ennio Salvioni, arXiv:2110.10691

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Introduction

- Hidden sectors are motivated by many physics questions:
    - Solutions to the hierarchy problem, e.g., neutral naturalness, cosmological relaxation, …
    - Dark matter
    - Baryon asymmetry
    - Other theoretical puzzles and experimental anomalies.
- Hidden sector physics also provides new signatures, new targets and challenges for experimental searches.

Introduction

- Confining non-abelian gauge groups (dark QCDs) are common in hidden sectors. If there are light fermions (dark quarks) charged under the dark QCD, the lightest dark hadrons are expected to be pseudo scalars (dark pions).

- The properties of dark pions largely determine the phenomenology of the dark sector.

  - If they are stable, they could be part of the dark matter (e.g. SIMP)

  - If they are unstable and decay back to SM through some portals, we need to know their lifetimes and decay products.

Introduction

- Some common portals:
    - Dark photon kinetically mixed with photon: Only transverse mode mixing while dark pions need to decay through the longitudinal mode.
    - Higgs boson: Only CP even states may decay through Higgs if no CP violation. Decay lengths are long for dark pions lighter than ~3 GeV.
    - New heavy states connecting the dark quarks and SM: Constrained by experimental searches (typically $\gtrsim$ TeV). The production is suppressed and decay lengths of dark pions are also typically very long compared to collider scale.

Z-portal

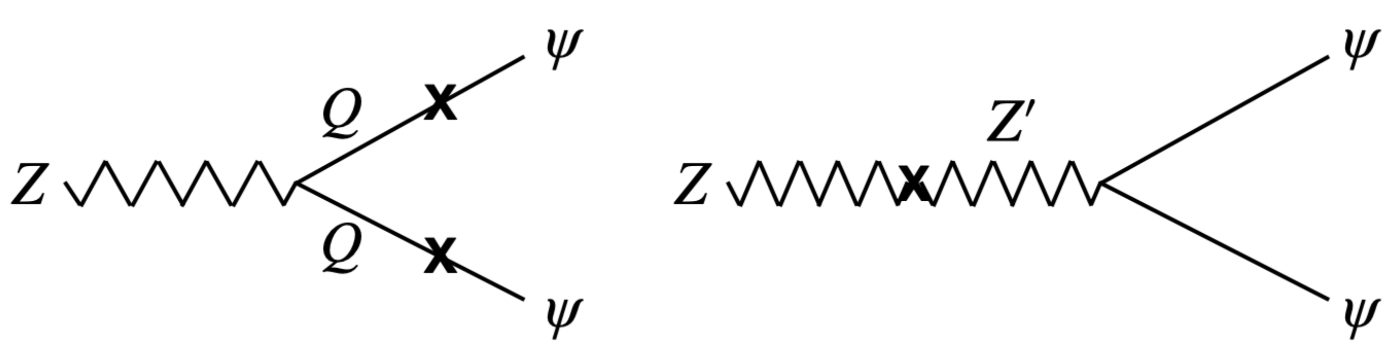
- Z-portal provides an interesting scenario which is less studied.
  - Z decays can be the dominant production mechanism for hidden sector states at colliders.
  - Dark pions can decay through the longitudinal mode of the Z boson back to SM.

Z-portal

- Light dark quarks should be neutral under SM. How do they couple to Z?

1. Light dark quarks mix with heavy SM EW doublet fermions. (HC, L. Li, E. Salvioni, C.B. Verhaaren, 1906.02198, HC, L. Li, E. Salvioni, 2110.10691)

2. Light dark quark are charged under a dark U(1) which mix with Z after EW breaking.



Dark $Z' - Z$ Mixing

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{Z'} + \mathcal{L}_{\rm mix},$$

$$\mathcal{L}_{\rm SM} = -\frac{1}{4}\hat{B}_{\mu\nu}\hat{B}^{\mu\nu} - \frac{1}{4}\hat{W}^3_{\mu\nu}\hat{W}^{3\mu\nu} + \frac{1}{2}\hat{M}_Z^2\hat{Z}_\mu\hat{Z}^\mu$$

$$- \hat{e}\sum_i \left[\bar{f}_{Li}\gamma^\mu\left(\frac{1}{\hat{c}_W}Y_L^i\hat{B}_\mu + \frac{1}{\hat{s}_W}T^3_{Li}\hat{W}^3_\mu\right)f_{Li} + \bar{f}_{Ri}\gamma^\mu\left(\frac{1}{\hat{c}_W}Y_R^i\hat{B}_\mu\right)f_{Ri}\right],$$

$$\mathcal{L}_{Z'} = -\frac{1}{4}\hat{Z}'_{\mu\nu}\hat{Z}'^{\mu\nu} + \frac{1}{2}\hat{M}^2_{Z'}\hat{Z}'_\mu\hat{Z}'^\mu - \hat{g}_D\sum_i\left(\overline{\psi}_{Li}\gamma^\mu x_{Li}\psi_{Li} + \overline{\psi}_{Ri}\gamma^\mu x_{Ri}\psi_{Ri}\right)\hat{Z}'_\mu,$$

$$\mathcal{L}_{\rm mix} = -\frac{\sin\chi}{2}\hat{Z}'_{\mu\nu}\hat{B}^{\mu\nu} + \delta\hat{M}^2\hat{Z}_\mu\hat{Z}'^\mu,$$

f : SM fermions, ψ : dark fermions, x : dark U(1) charge

$\sin\chi$: kinetic mixing

$\delta\hat{M}^2$: mass mixing, can arise from a second Higgs doublet which carries the dark U(1) charge

Dark $Z' - Z$ Mixing

- Neutral gauge boson eigenstates

Remove kinetic mixing: $\begin{pmatrix} \hat{B}_\mu \\ \hat{Z}'_\mu \end{pmatrix} = \begin{pmatrix} 1 & -\tan\chi \\ 0 & 1/\cos\chi \end{pmatrix} \begin{pmatrix} B_\mu \\ Z'_\mu \end{pmatrix}$

Rotation to remove mass mixing:

$$\tan 2\xi = \frac{-2\cos\chi(\delta\hat{M}^2 + \hat{M}_Z^2 \hat{s}_W \sin\chi)}{\hat{M}_{Z'}^2 - \hat{M}_Z^2\cos^2\chi + \hat{M}_Z^2\hat{s}_W^2\sin^2\chi + 2\delta\hat{M}^2\hat{s}_W\sin\chi},$$

$$\begin{pmatrix} A_\mu \\ Z_{1\mu} \\ Z_{2\mu} \end{pmatrix} = L^{-1}\cdot\begin{pmatrix} \hat{A}_\mu \\ \hat{Z}_\mu \\ \hat{Z}'_\mu \end{pmatrix}, \qquad L = \begin{pmatrix} 1 & -\hat{c}_W\sin\xi\tan\chi & -\hat{c}_W\cos\xi\tan\chi \\ 0 & \cos\xi + \hat{s}_W\sin\xi\tan\chi & -\sin\xi + \hat{s}_W\cos\xi\tan\chi \\ 0 & \frac{\sin\xi}{\cos\chi} & \frac{\cos\xi}{\cos\chi} \end{pmatrix},$$

(Following Babu, Kolda, March-Russell, hep-ph/9710441)

$$L^{-1} = \begin{pmatrix} 1 & 0 & \hat{c}_W\sin\chi \\ 0 & \cos\xi & -\hat{s}_W\cos\xi\sin\chi + \sin\xi\cos\chi \\ 0 & -\sin\xi & \cos\xi\cos\chi + \hat{s}_W\sin\xi\sin\chi \end{pmatrix}$$

Dark Z'

- The constraints on such a dark Z' from direct searches are rather mild above the Υ mass (DELPHI,CDF, ATLAS, & CMS DM searches). The strongest constraints come from EW precision measurements.

- Z-pole interaction (to leading order in $\xi, \sin\chi$): $Z_1 = Z, Z_2 = Z'$

$$\mathcal{L}_{Z_1-\mathrm{SM}} = -\frac{e}{s_W c_W}\bar{f}_i\gamma^\mu\left[1+\frac{\xi^2}{2}\left(\frac{M_{Z_2}^2}{M_{Z_1}^2}-2\right)+\xi s_W\tan\chi\right](T_{Li}^3 - s_*^2 Q_i)P_{L(R)}f_i Z_{1\mu},$$

where $$s_*^2 \equiv \sin^2\theta_* = s_W^2 - \frac{s_W^2 c_W^2}{c_W^2 - s_W^2}\xi^2\left(\frac{M_{Z_2}^2}{M_{Z_1}^2}-1\right) + s_W^2 c_W^2 \xi \tan\chi$$

Compared with
$$\mathcal{L}_{Z_1-\mathrm{SM}} = -\frac{e}{s_W c_W}\left(1+\frac{\alpha T}{2}\right)\bar{f}_i\gamma^\mu(T_{Li}^3 - s_*^2 Q_i)P_{L(R)}f_i Z_{1\mu},$$
$$s_*^2 = s_W^2 - \frac{1}{c_W^2 - s_W^2}\left(\frac{1}{4}\alpha S - s_W^2 c_W^2 \alpha T\right)$$
$$\frac{M_W^2}{M_{Z_1}^2} = c_W^2 + \frac{\alpha c_W^2}{c_W^2 - s_W^2}\left(-\frac{S}{2} + c_W^2 T + \frac{c_W^2 - s_W^2}{4 s_W^2}U\right)$$

EW constraints on Dark Z'

$$\alpha S = -4 s_W^2 c_W^2 \xi^2 + 4 s_W c_W^2 \xi \tan\chi,$$

$$\alpha T = \xi^2 \left(\frac{M_{Z_2}^2}{M_{Z_1}^2} - 2 \right) + 2 \xi s_W \tan\chi,$$

$$\alpha U = 4 s_W^2 c_W^2 \xi^2.$$

(Different from Babu, Kolda, March-Russell, hep-ph/9710441)

PDG global fit:

$$S = -0.02 \pm 0.10$$
$$T = \quad 0.03 \pm 0.12$$
$$U = \quad 0.01 \pm 0.11$$

puts constraints on $\xi - \tan\chi$ plane.

For $\sin\chi = 0$, $|\,\xi\,| \lesssim 0.02$

EW constraints on Dark Z'

- If the dark Z' is lighter than Z, it can give enhanced contribution to low-energy non-Z-pole observables. The strongest constraint comes from atomic parity violation (APV).

- Low-energy EFT after integrating out Z, Z':

$$L_{\text{eff}} = -\frac{4G_F}{\sqrt{2}}\rho_*(0)\left[j_3^\mu - s_*^2(0)J_Q^\mu\right]^2 + \epsilon(J_Q^\mu)^2$$

$$\rho_*(0) = \rho_*(M_Z^2) + \frac{M_{Z_1}^2}{M_{Z_2}^2}\left[\xi^2 - 2s_W\xi\tan\chi + s_W^2\tan^2\chi\right]$$

$$s_*^2(0) = s_*^2(M_Z^2) + \frac{M_{Z_1}^2}{M_{Z_2}^2}\left[-s_W c_W^2\xi\tan\chi + s_W^2 c_W^2\tan^2\chi\right]$$

Atomic Parity Violation

$$Q_W(Z,N) \equiv -2\left[Z(g_{AV}^{ep} + 0.00005) + N(g_{AV}^{en} + 0.00006)\right]\left(1 - \frac{\alpha}{2\pi}\right)$$

For $^{133}_{78}$Cs, $Z = 55$, $N = 78$, $\quad \dfrac{\Delta Q_W}{Q_W} \simeq \Delta\rho_* + 2.9\Delta s^2\,.$

$$Q_W = -\,72.82 \pm 0.26_{\mathrm{exp}} \pm 0.33_{\mathrm{th}}$$

SM prediction: $\quad -73.23 \pm 0.01$

For $\sin\chi = 0$, $\xi = 0.02$, $M_{Z_2} \gtrsim 20$ GeV

(M_{Z_2} can be lighter for smaller ξ.)

Dark Pion Decays

- Dark pions decay through interaction between dark current and SM current. Only the axial part contributes.

$$\mathcal{L}_{\rm eff} = -\frac{1}{2}\begin{pmatrix}\hat{e}J^\mu_{\rm EM} & \hat{g}_Z\hat{J}^\mu_Z & \hat{g}_D J^\mu_D\end{pmatrix}\cdot L\cdot\begin{pmatrix}0 & 0 & 0\\ 0 & \frac{1}{M^2_{Z_1}} & 0\\ 0 & 0 & \frac{1}{M^2_{Z_2}}\end{pmatrix}\cdot L^T\cdot\begin{pmatrix}\hat{e}J_{{\rm EM}\,\mu}\\ \hat{g}_Z\hat{J}_{Z\mu}\\ \hat{g}_D J_{D\mu}\end{pmatrix}$$

$$\langle 0|j^\mu_{5a}(0)|\hat{\pi}_b(p)\rangle = -\,i\delta_{ab}f_{\hat{\pi}}\,p^\mu \qquad j^\mu_{5q} = j^\mu_{Rq} - j^\mu_{Lq}\,, \qquad j^\mu_{L,R\,q} = \overline{\psi}'_{L,R}\gamma^\mu\frac{\sigma_q}{2}\psi'_{L,R}$$

where ψ' are mass eigenstates, $\psi_{L,R} = U_{L,R}\psi'_{L,R}$

$$\mathcal{L}_{\hat{\pi}\,\rm decay} = \frac{1}{2}\hat{g}_Z\hat{g}_D\left(\frac{L_{22}L_{32}}{M^2_{Z_1}} + \frac{L_{23}L_{33}}{M^2_{Z_2}}\right){\rm Tr}(\sigma_b X'_A)f_{\hat{\pi}}\partial_\mu\hat{\pi}_b\sum_i T^3_{Li}(\bar{f}_i\gamma^\mu\gamma_5 f_i)$$
$$= \frac{\partial_\mu\hat{\pi}_b}{f_a^{(b)}}\sum_i T^3_{Li}(\bar{f}_i\gamma^\mu\gamma_5 f_i).$$

$$J^\mu_D = \overline{\psi}\gamma^\mu X_L P_L\psi + \overline{\psi}\gamma^\mu X_R P_R\psi,$$

$$X'_A = \frac{1}{2}(X'_R - X'_L), \quad X'_L = U^\dagger_L X_L U_L, \quad X'_R = U^\dagger_R X_R U_R.$$

$$X_L = \begin{pmatrix}x_{1L} & 0 & \cdots\\ 0 & x_{2L} & \\ \vdots & & \ddots\end{pmatrix}, \quad X_R = \begin{pmatrix}x_{1R} & 0 & \cdots\\ 0 & x_{2R} & \\ \vdots & & \ddots\end{pmatrix}$$

Dark U(1) charge matrix in mass eigenstate basis

Dark Pion Decays

$$\frac{1}{f_a^{(b)}} = \frac{\hat{g}_Z \hat{g}_D}{2} \left(\frac{L_{22} L_{32}}{M_{Z_1}^2} + \frac{L_{23} L_{33}}{M_{Z_2}^2} \right) \mathrm{Tr}(\sigma_b X'_A) f_{\hat{\pi}} = -\frac{\hat{g}_Z \hat{g}_D \delta \hat{M}^2}{2 M_{Z_1}^2 M_{Z_2}^2 \cos^2 \chi} \mathrm{Tr}(\sigma_b X'_A) f_{\hat{\pi}}$$

- Dark pions decay requires mass mixing, $\delta\hat{M}^2 \neq 0$.
- If no CP violation in the dark sector,
  - $\hat{\pi}_1, \hat{\pi}_3$ CP-odd, decay through Z, Z'
  - $\hat{\pi}_2$ CP-even, decays through Higgs

For $\sin\chi = 0$, $M_{Z_2}^2 \ll M_{Z_1}^2$,

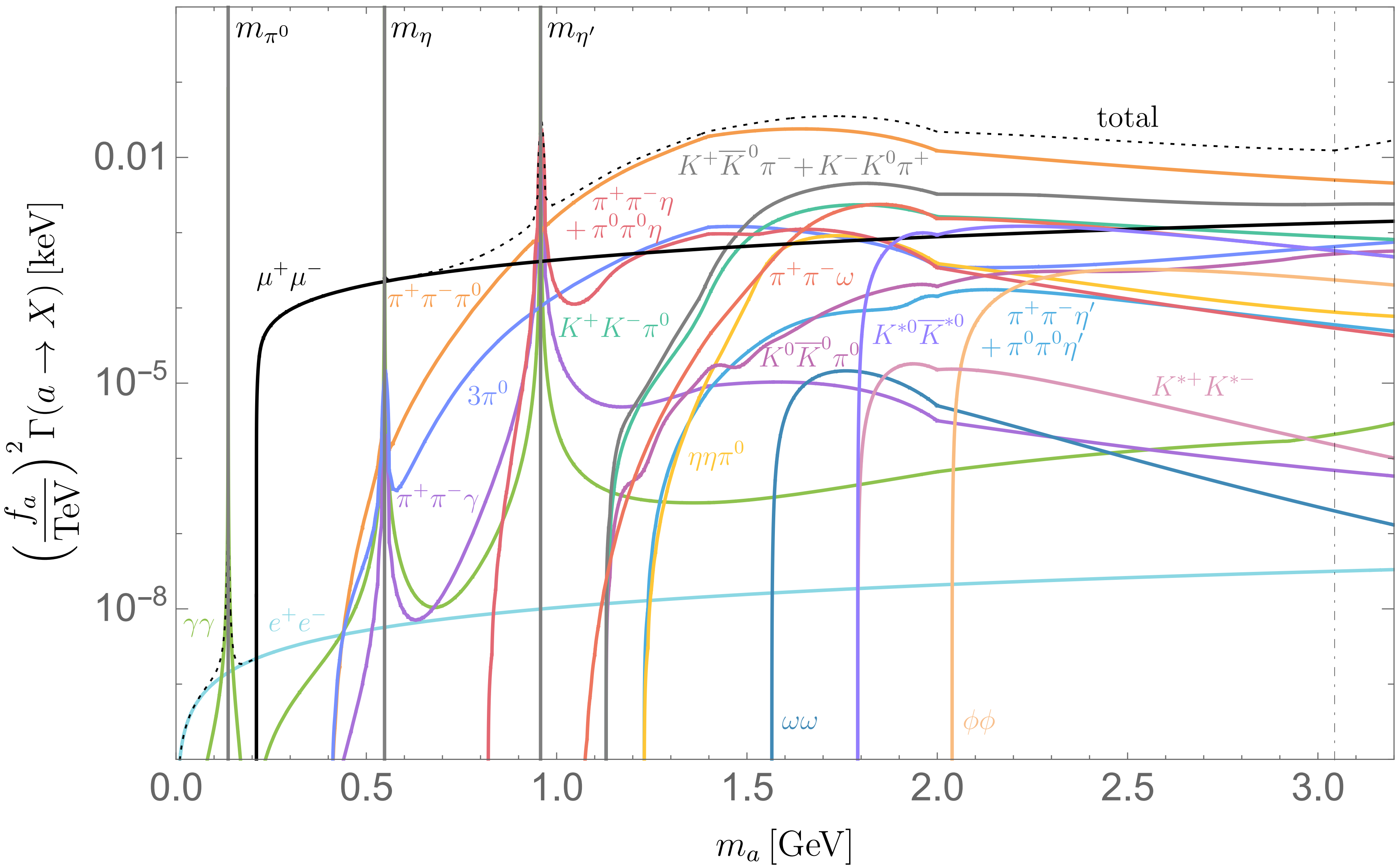
$$\frac{1}{f_a^{(b)}} \approx \frac{1}{1.1\ \text{PeV}} \left(\frac{\hat{g}_D \mathrm{Tr}(\sigma_b X'_A)}{0.1} \right) \left(\frac{|\xi|}{10^{-2}} \right) \left(\frac{f_{\hat{\pi}}}{1\ \text{GeV}} \right) \left(\frac{20\ \text{GeV}}{M_{Z_2}} \right)^2$$

Replaced by M_{Z_1} if $M_{Z_2} \gg M_{Z_1}$

Dark Pion Decays

Exclusive decay rates from the data driven method

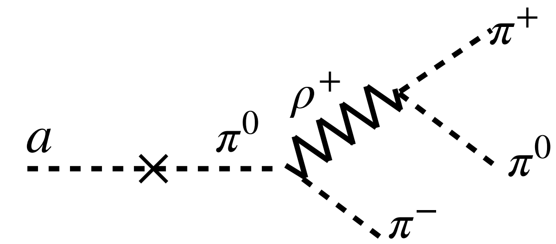
(HC, Li, Salvioni, 2110.10691)



For $m_{\hat{\pi}} = 650$ MeV, $f_a = 1$ PeV, $c\tau \approx 70$ cm,

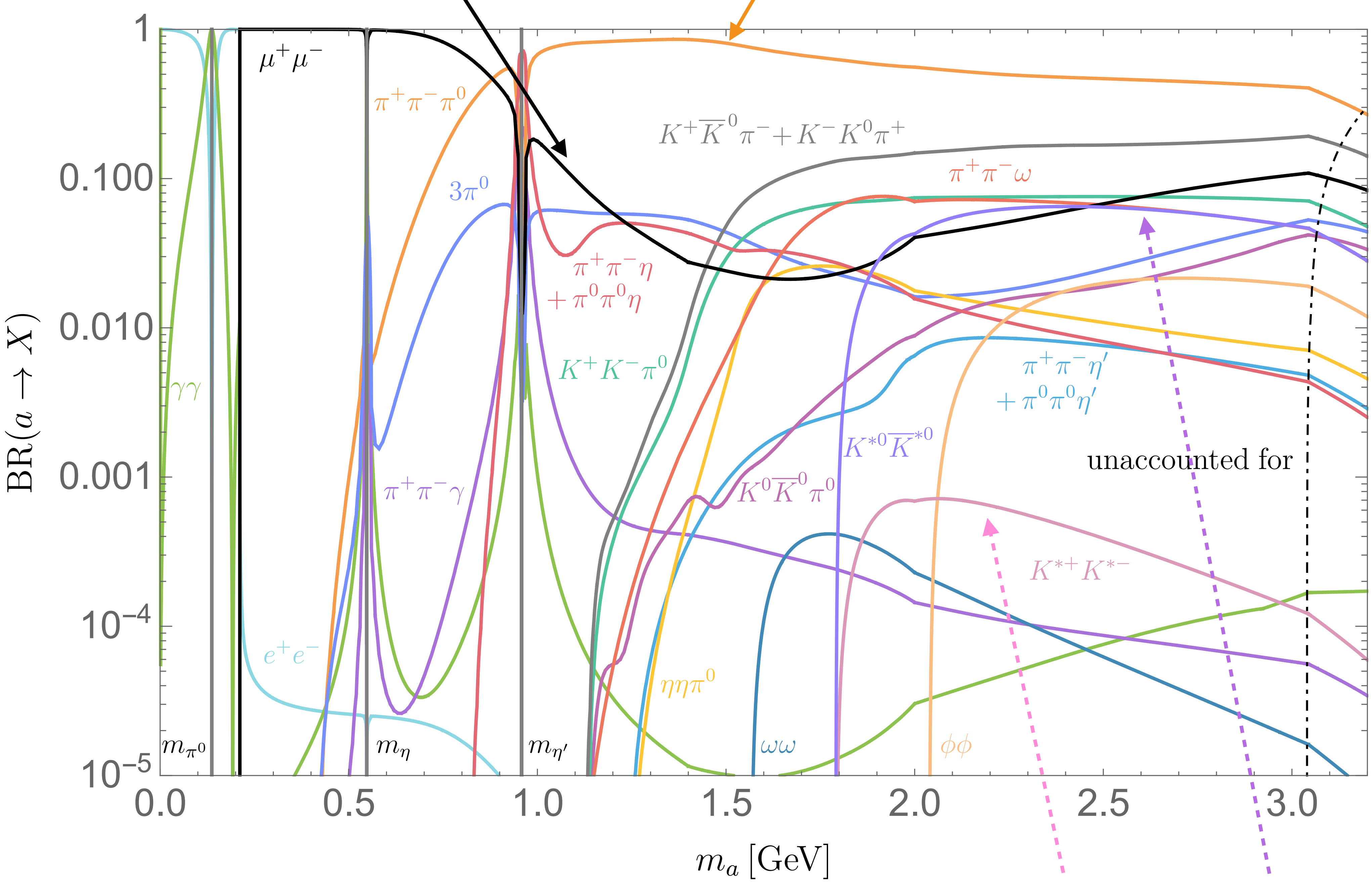
Dark Pion Decays

- Branching ratios:



$\mu^+\mu^-$ is always > few % below 3 GeV

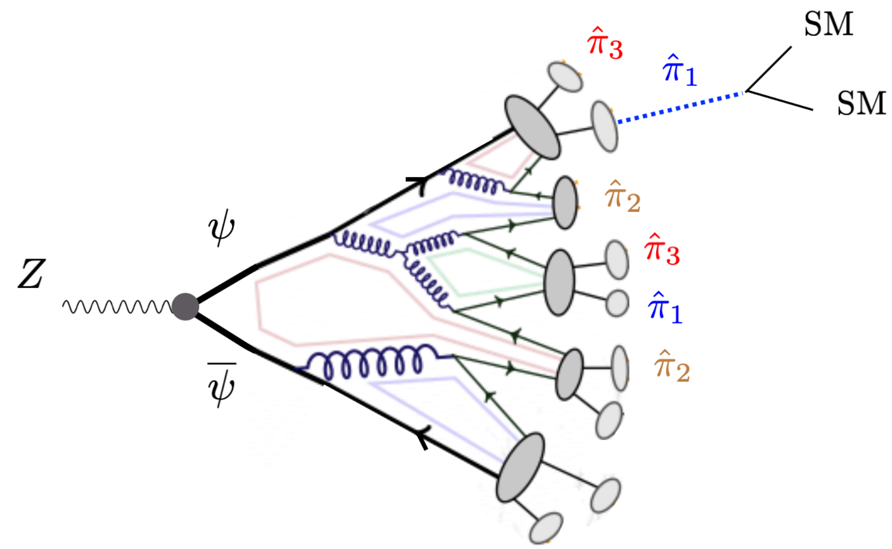
$\pi^+\pi^-\pi^0$ dominates above 900 MeV



$\Gamma(a \to K^{*+}K^{*-}) \ll \Gamma(a \to K^{*0}\overline{K}^{*0})$

Dark Pion Production

- Z and Z' decays: dark showers at LHC and future colliders

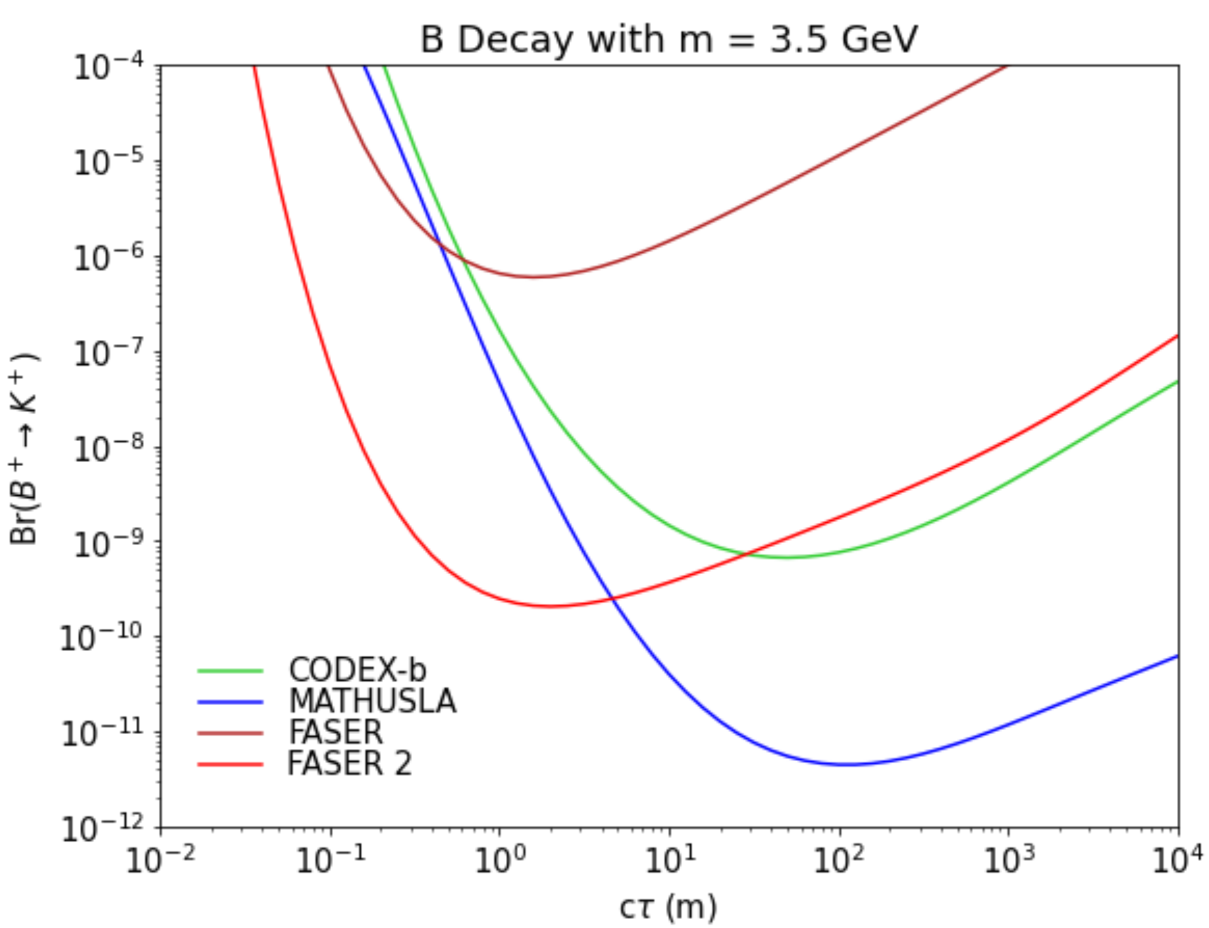


- Meson (B, D, K) FCNC decays for light enough dark pions, e.g., $B \to K^{(*)}(\chi \to \mu\mu)$ with long-lived $\chi(=\hat{\pi})$
  - Beam dump experiment (CHARM)
  - LHCb
  - CMS data scouting

Meson FCNC Decays

- $2m_\mu \lesssim m_a \lesssim 0.6$ GeV: $f_a \gtrsim 1.3 - 1.9$ PeV (CHARM)
- 0.6 GeV $\lesssim m_a \lesssim 1.1$ GeV: $f_a \gtrsim 0.6 - 0.8$ PeV (LHCb)
- 1.1 GeV $\lesssim m_a \lesssim 2.8$ GeV: $f_a \gtrsim 1.3 - 2.8$ PeV (CMS)

- Proposed LLP experiments (FASER 2, CODEX-b, MATHUSLA) can extend the reaches.



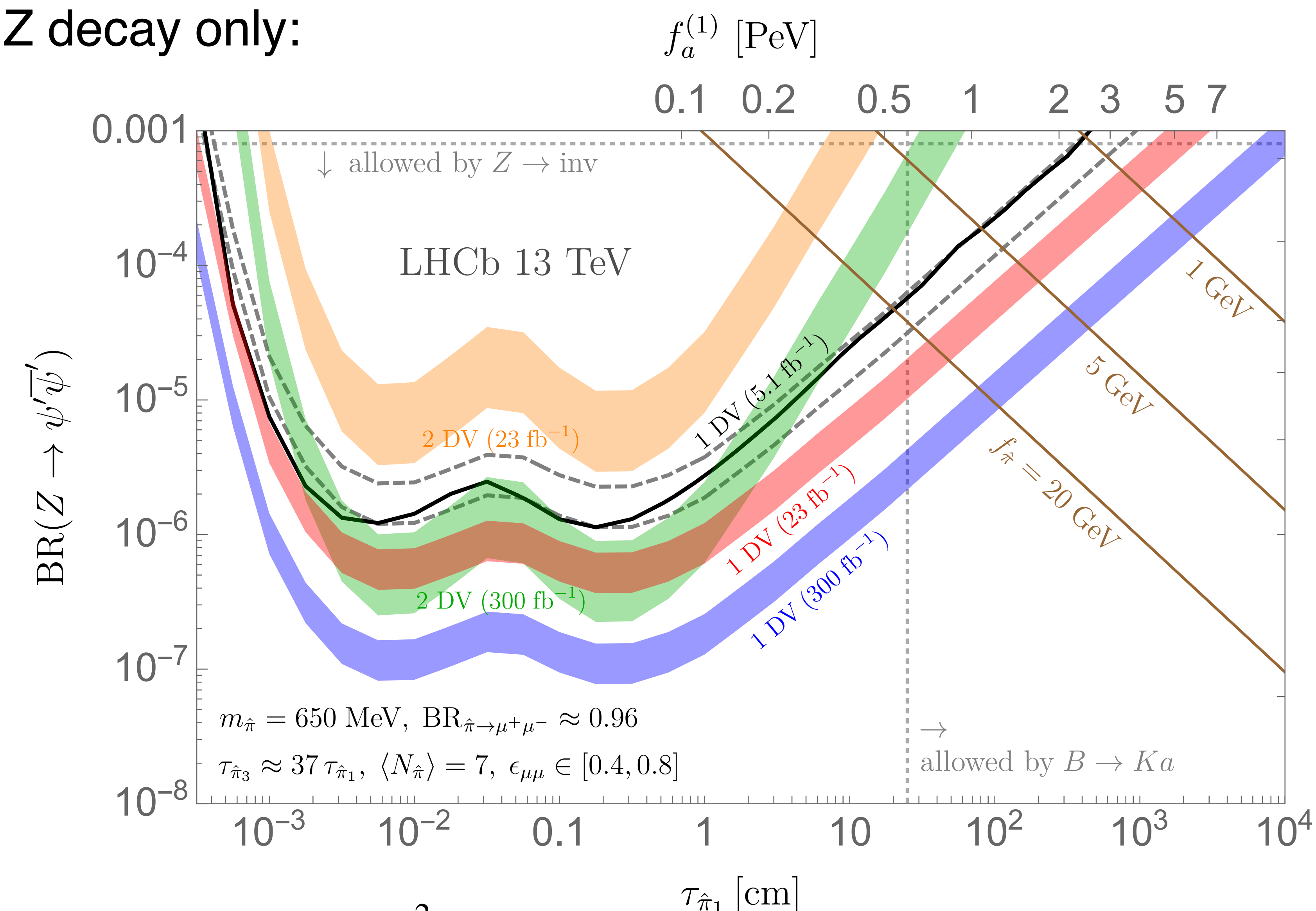
$$\mathrm{BR}\left(B^{\{+,0\}} \to \{K^+\hat{\pi}_b, K^{*0}\hat{\pi}_b\}\right) \approx \{0.92, 1.1\} \times 10^{-8} \left(\frac{10^3\ \mathrm{TeV}}{f_a^{(b)}}\right)^2 \{\lambda_{K\hat{\pi}}^{1/2}, \lambda_{K^*\hat{\pi}}^{3/2}\}$$

$$\lambda_{X\hat{\pi}} = \left(1 - \frac{(m_X + m_{\hat{\pi}})^2}{m_B^2}\right)\left(1 - \frac{(m_X - m_{\hat{\pi}})^2}{m_B^2}\right)$$

Dark Showers from Z decays

- LHCb search for displaced $X \to \mu\mu$ (LHCb:2007.03923).

From Z decay only:



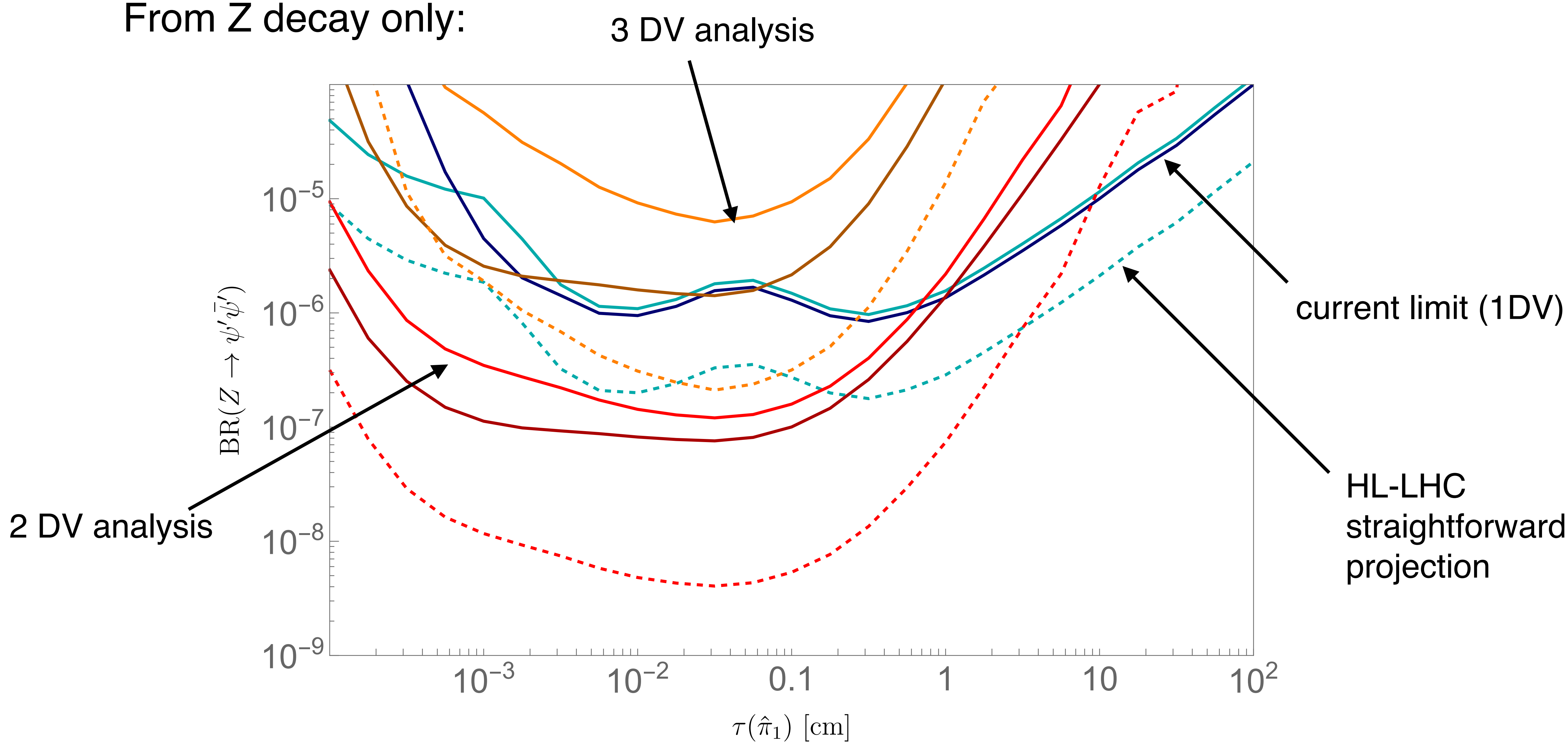
$$\mathrm{BR}(Z \to \psi\bar\psi) = 0.27\xi^2 \left(\frac{g_D}{g_Z}\right)^2 \sum_i (x_{iL}^2 + x_{iR}^2)$$

- It tests a different combinations of model parameters from f_a, which is constrained by FCNC decays.

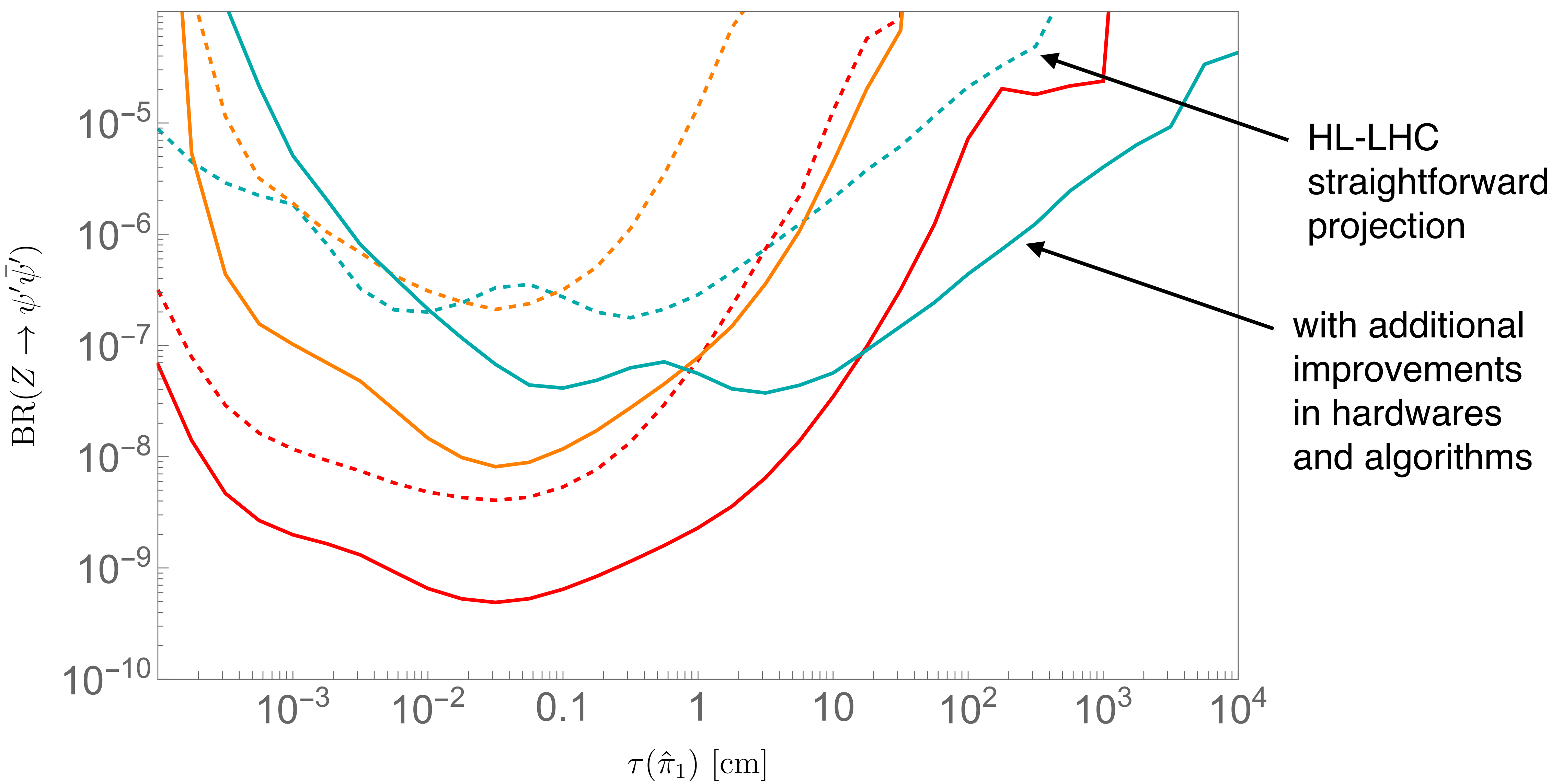
Dark Showers from Z decays

- At LHC, the dark shower events from Z decays are relatively soft without hard objects. They are hard to trigger at ATLAS and CMS.
- CMS data scouting search for displaced $X \to \mu\mu$ (2112.13769).

From Z decay only:



Dark Showers from Z decays



* Z' decays are still under study.

Summaries

- The constraints a dark Z' in the range of a few tenth to a few hundred GeV are rather mild. It can be an interesting target for upcoming searches.

- The dark $Z' - Z$ mixing can be responsible for dark pion decays, which give interesting collider signals, including dark showers and displaced decays.