Z-Portal Dark Pion Dark Matter and Dark Showers

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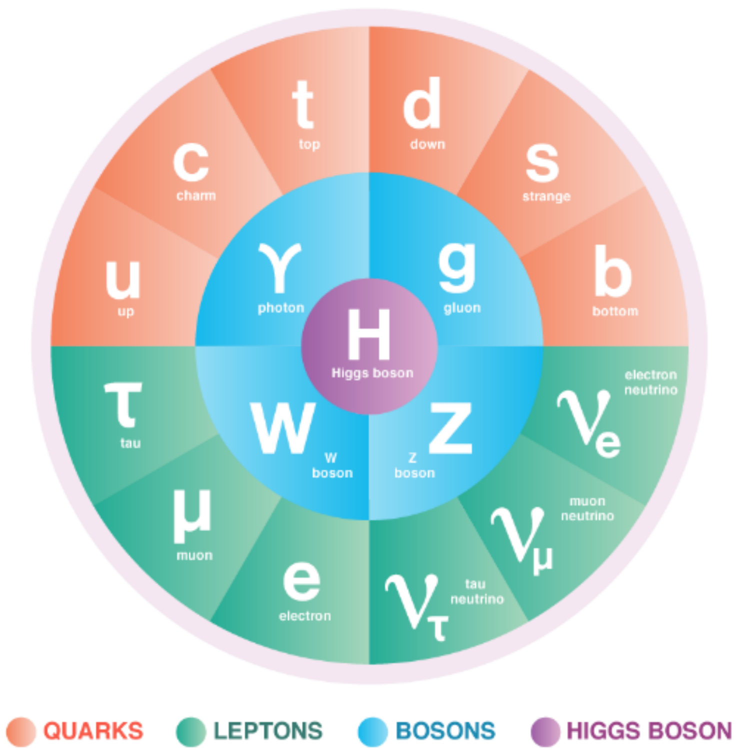
Introduction

SM



portals

Dark sector

$G^a_{D,\mu\nu}$, ψ

Dark QCD

- Dark sector with a confining gauge group is motivated by important physics questions, e.g., naturalness of EW scale (neutral naturalness, cosmological relaxation, …). It's also a natural place to host the dark matter.

- Novel experimental signatures (semi-visible jets, emerging jets with displaced vertices, missing energies): new targets and challenges for experimental searches.

Dark Matter Candidates in Dark QCD

- Dark baryons: may need dark baryon asymmetry, which could be related to the baryon asymmetry in SM.

- Dark pions: likely to be the lightest dark hadrons if there are light dark quarks. Some dark pions could be protected by symmetries to be stable, hence constituting the DM, while other dark pions decay back to SM, giving interesting collider signatures.

- Dark glueballs if there is no light dark quark.
(e.g., Carenza et al, 2306.09510)

Dark Pion Dark Matter

- In a QCD-like theory, if isospin is a good symmetry, dark pions and dark kaons will be stable. On the other hand, dark η is a singlet, not protected by the symmetry, may decay back to SM through portal interactions.

- We consider a more minimal setup, based on the coset SU(3)/SO(3), but with similar features: 3 light fermions ψ_1, ψ_2, ψ_3, transforming as fundamentals of a confining $SO(N_d)$ $(N_d \geq 4)$ gauge group, with $\langle \psi_i \psi_j \rangle \propto \delta_{ij}$

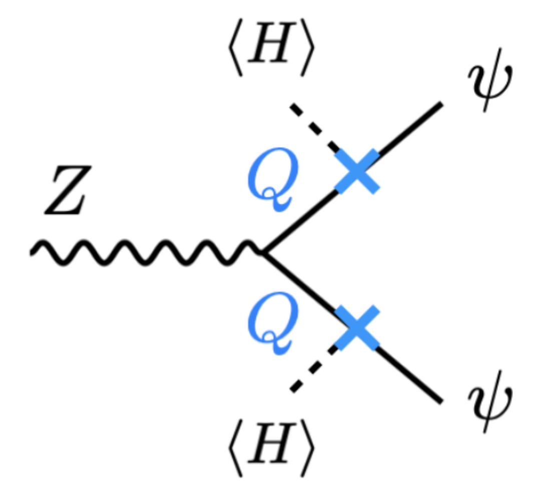
SU(3)/SO(3) Model

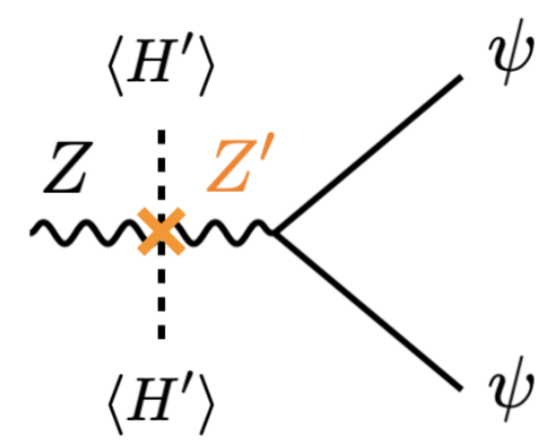
- 5 PNGBs, corresponding to broken generators $T_i = \lambda_i/2, i = 1,3,4,6,8$ (λ_i: Gell-Mann matrices)
- Dark quark mass : $m_1(\psi_1\psi_1 + \psi_2\psi_2) + m_3\psi_3\psi_3$,which preserves the U(1) generated by T_2.
- Under the $U(1)_{T_2}$ symmetry, the PNGBs can be classified as
  - $\pi^{\pm}$ corresponding to $(T_3 \pm iT_1)/\sqrt{2}$,
  - $K^{\pm\frac{1}{2}}$ corresponding to $(T_4 \pm iT_6)/\sqrt{2}$,
  - η^0 corresponding to T_8.
- Assume $m_3 > m_1$, we expect $m_\eta > m_K > m_\pi$, with $3m_\eta^2 + m_\pi^2 = 4m_K^2$ at the lowest order χPT.

Z-portal

- $\pi^{\pm}, K^{\pm\frac{1}{2}}$ are stable, can be dark matter (dominantly $\pi^{\pm}$).
- η^0 can decay back to SM through the Z-portal.

- Light dark quarks should be neutral under SM. How do they couple to Z?
  1. Light dark particles mix with heavy EW doublet fermions. (HC, L. Li, E. Salvioni, C.B. Verhaaren, 1906.02198, HC, L. Li, E. Salvioni, 2110.10691)
  2. Light dark particle are charged under a dark U(1) which mixes with Z after EW breaking. (HC, X.-H. Jiang, L. Li, E. Salvioni, 2401.08785)





Z-portal

Vector-like heavy dark quarks (> TeV): fundamentals under $SO(N_d)$

$Q^{\pm\frac{1}{2}}, Q_3 : \bar{\mathbf{2}}_{-\frac{1}{2}}$ under $SU(2)_W \times U(1)_Y$

$Q^{c\pm\frac{1}{2}}, Q_3^c : \mathbf{2}_{+\frac{1}{2}}$ under $SU(2)_W \times U(1)_Y$

$$\begin{aligned}
-\mathscr{L} \supset\, & M_{Q_1}\left(Q^{c+\frac{1}{2}}Q^{-\frac{1}{2}} + Q^{c-\frac{1}{2}}Q^{+\frac{1}{2}}\right) + M_{Q_3}Q_3^c Q_3 \\
& + y_1 H\left(Q^{+\frac{1}{2}}\psi^{-\frac{1}{2}} + Q^{-\frac{1}{2}}\psi^{+\frac{1}{2}}\right) + y_3 H Q_3 \psi_3 \\
& + \tilde{y}_1 \tilde{H}\left(Q^{c+\frac{1}{2}}\psi^{-\frac{1}{2}} + Q^{c-\frac{1}{2}}\psi^{+\frac{1}{2}}\right) + \tilde{y}_3 \tilde{H} Q_3^c \psi_3
\end{aligned}$$

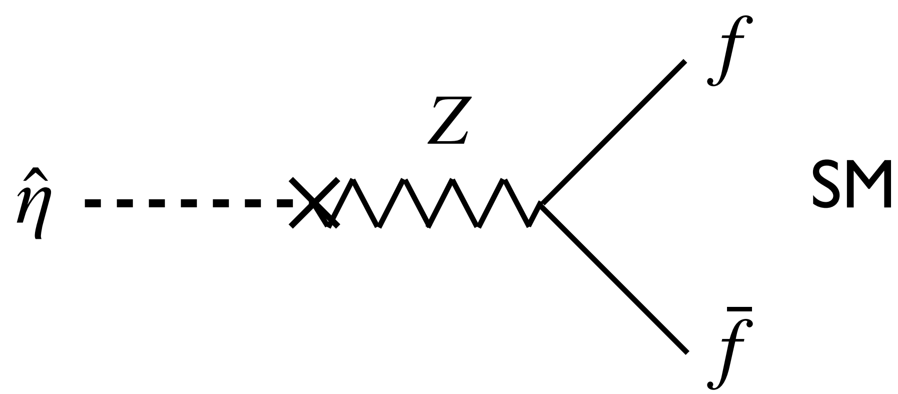
Integrating out Q, Q^c we obtain Z coupling to dark quarks ψ,

$$\frac{g_z v^2}{4M_{Q_1}^2}\,\overline{\Psi}\,\gamma^\mu\,\mathbf{A}\,\Psi\,Z_\mu \quad \text{where} \quad \mathbf{A} = \mathrm{diag}\left((y_1^2 - \tilde{y}_1^2),\,(y_1^2 - \tilde{y}_1^2),\,(y_3^2 - \tilde{y}_3^2)\frac{M_{Q_1}^2}{M_{Q_3}^2}\right)$$

Match to the chiral Lagrangian, $$D_\mu\Sigma = \partial_\mu\Sigma + i\frac{g_z v^2}{4M_{Q_1}^2}Z_\mu\left(\mathbf{A}\Sigma + \Sigma\mathbf{A}^\dagger\right)$$

Z-portal

- $\frac{f^2}{4}\mathrm{Tr}\left[D_\mu\Sigma^\dagger D^\mu\Sigma\right] \supset Z^\mu\partial_\mu\eta \Rightarrow \eta$ decays through the longitudinal mode of Z, with an ALP-like coupling to SM.



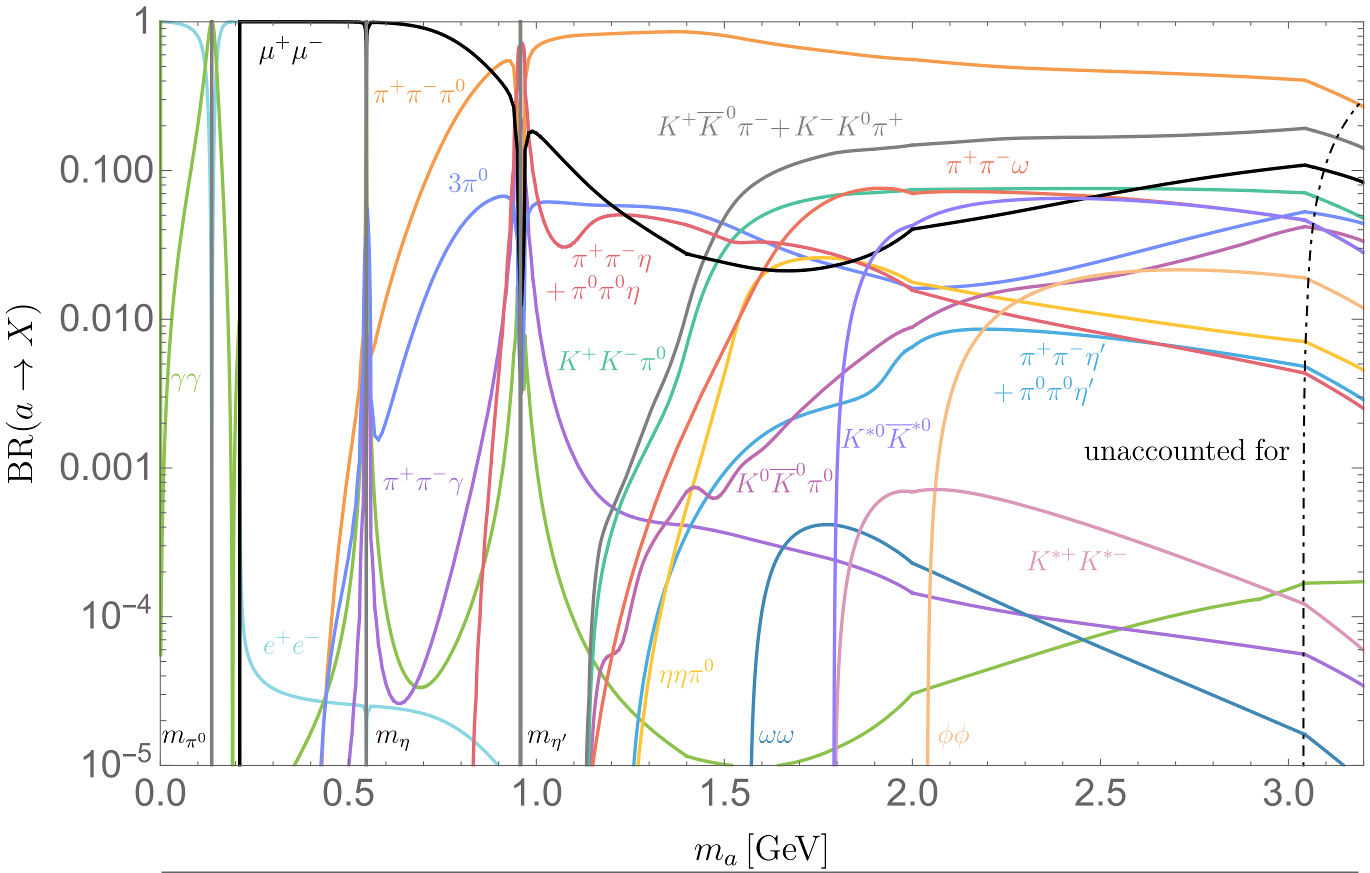
$$\mathcal{L}_{\hat{\eta}f\bar{f}} = -\frac{\partial_\mu\hat{\eta}}{f_a}\sum_f a_f\bar{f}\gamma^\mu\gamma_5 f$$

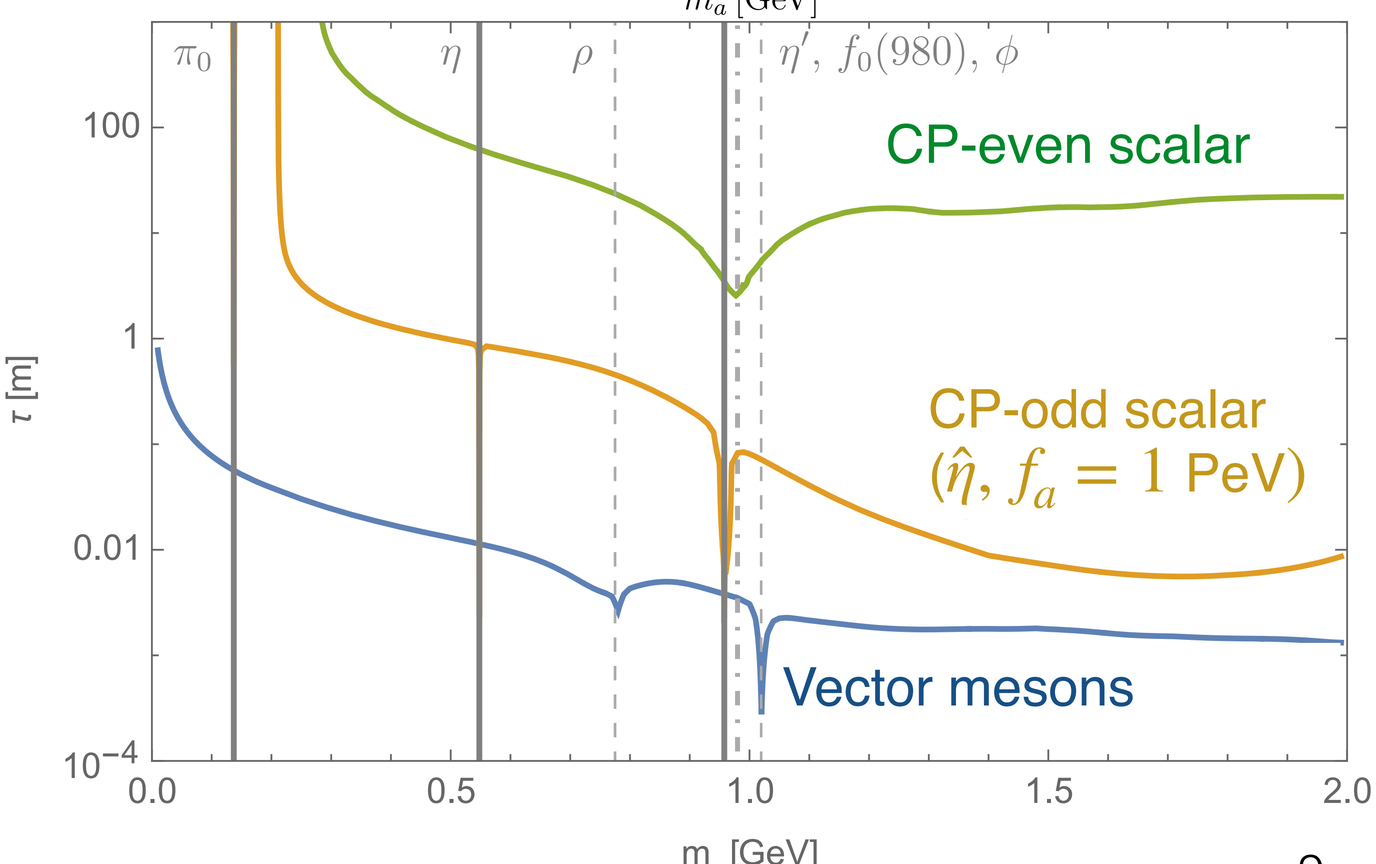
$$f_a \sim \frac{M_Q^2}{y^2 f} \gtrsim \text{PeV}$$

- No PNGB bilinears (i.e., $\pi\partial_\mu\pi$) couple to Z due to $\psi_1 \leftrightarrow \psi_2$ exchange symmetry $\Rightarrow$ Both direct and indirect detections of dark matter are suppressed.

- Higgs mediated interaction $\propto y\tilde{y}$, will be suppressed if $\tilde{y} \sim 0$ (or $y \sim 0$).

Dark Eta Decays





HC, Li, Salvioni, 2110.10691, using data driven method (Aloni et al, 1811.03474)

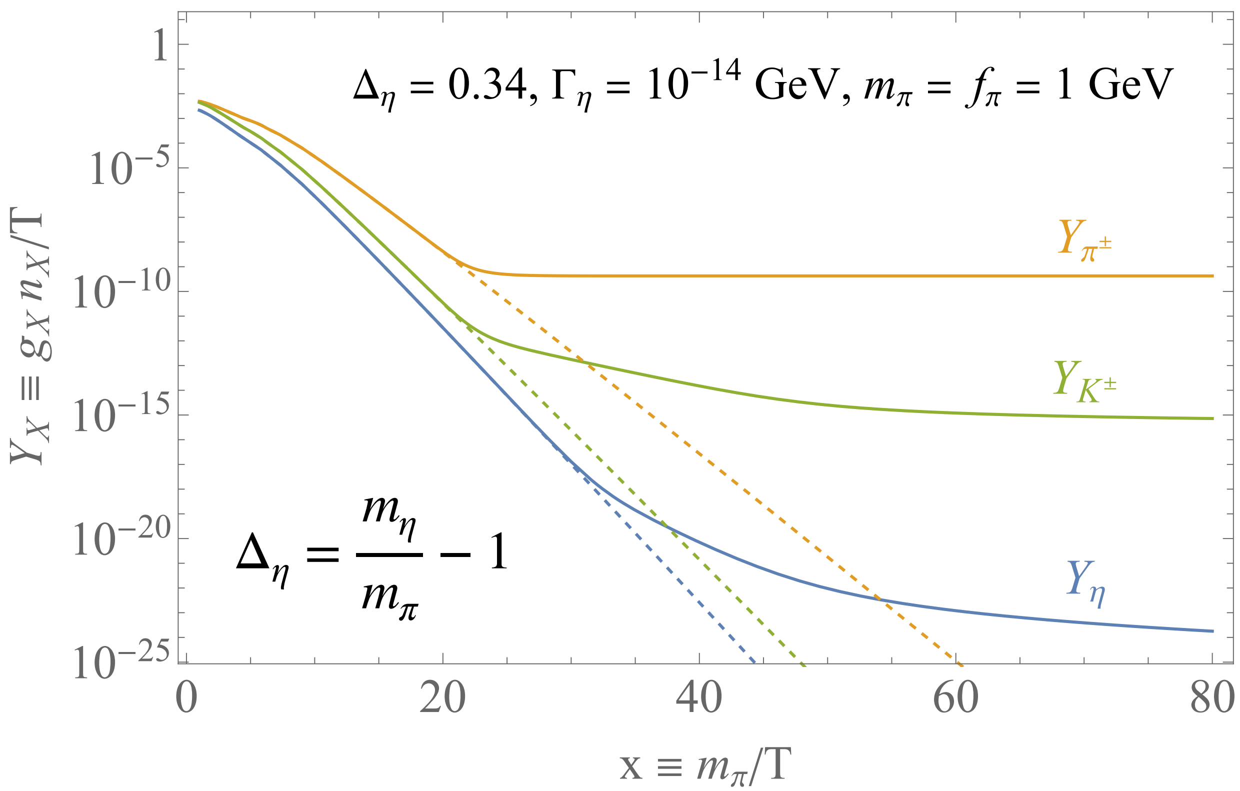
$\mathrm{Br}(\hat{\eta} \to \mu^+\mu^-) \gtrsim$ few% for $2m_\mu < m_{\hat{\pi}} \lesssim 3$ GeV

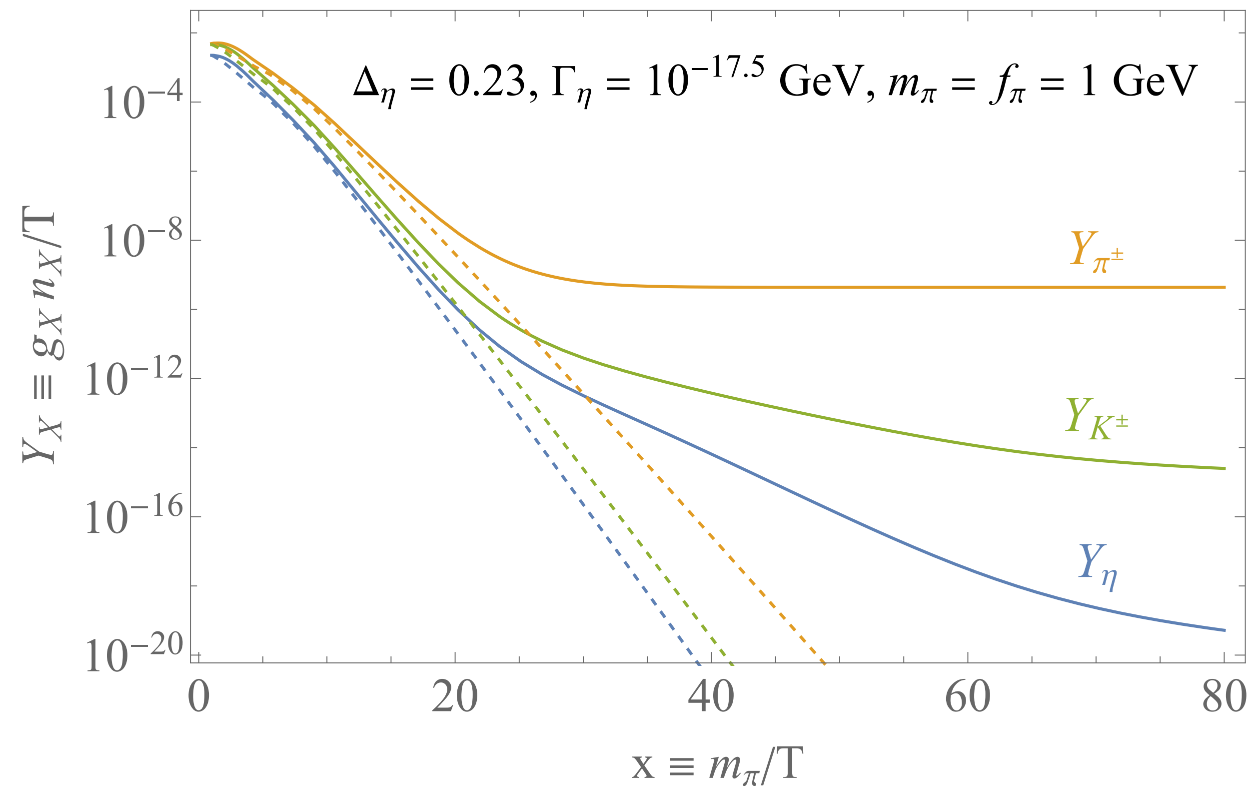
For $2m_\mu < m_{\hat{\eta}} < 3$ GeV, $f_a \sim 1$ PeV, dark eta decays through Z-portal have decay lengths in the most interesting range of few mm to 100 m at colliders.

Boltzmann's Equations

- Relevant interactions in the Boltzmann's equations for the relic calculation:
  - 2↔2 processes, e.g., $\pi^+\pi^- \leftrightarrow K^{+\frac{1}{2}}K^{-\frac{1}{2}}, \eta\eta$; $\pi^{\pm}K^{\mp\frac{1}{2}} \leftrightarrow K^{\pm\frac{1}{2}}\eta$; $K^{\pm\frac{1}{2}}K^{\pm\frac{1}{2}} \leftrightarrow \pi^{\pm}\eta$; $K^{+\frac{1}{2}}K^{-\frac{1}{2}} \leftrightarrow \eta\eta$.
  - 3↔2 processes from WZW term, e.g., $\pi\pi K \leftrightarrow K\eta$ etc, not important in our parameter space of this model.
  - $\eta \leftrightarrow$ SM decay and inverse decay.
- Temperature equilibrium between the dark sector and SM is maintained by decay and inverse decay, no need for a light dark photon like in the SIMP scenario.

Relic Density



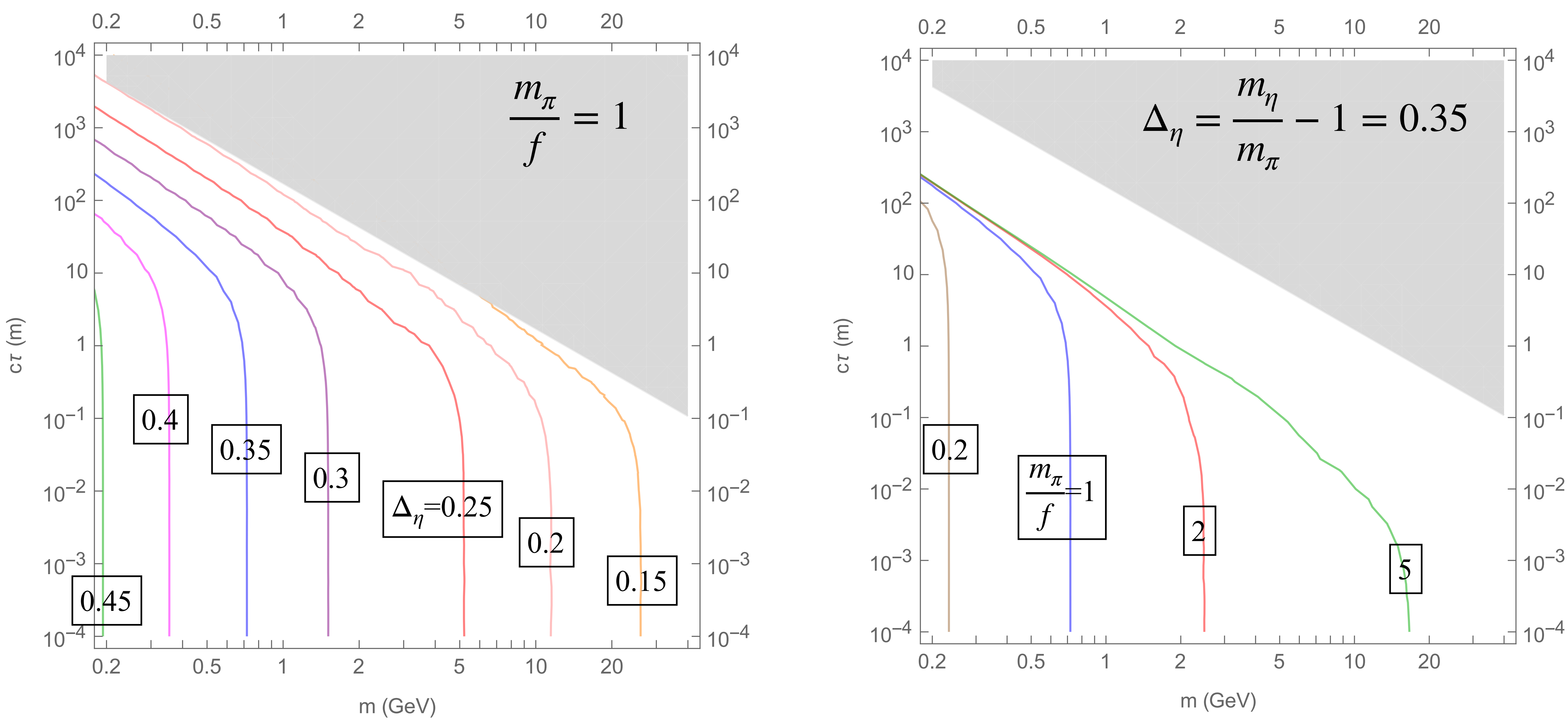


For large decay width, the relic density is determined by the freeze-out of the forbidden process $\pi^\pm K^{\mp\frac{1}{2}} \leftrightarrow K^{\pm\frac{1}{2}}\eta$.

For smaller decay width, the relic density is determined by the decoupling of decay and inverse decay of η.

Relic Density

- Parameter space for correct dark matter density

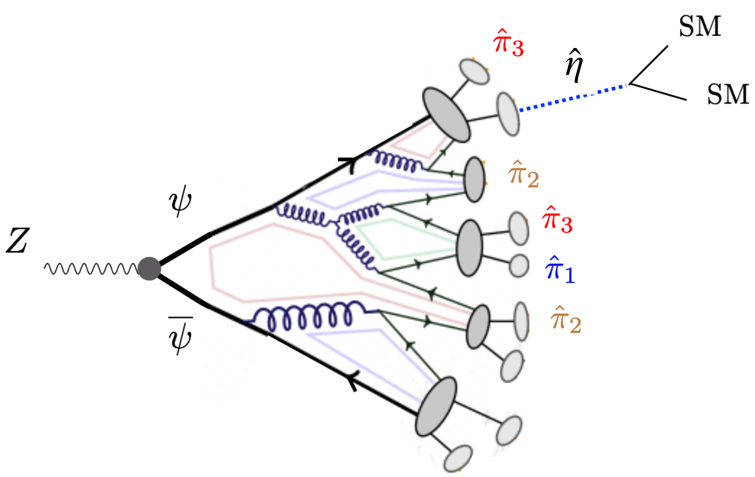


The temperature equilibrium between the dark sector and the SM may not be maintained by the decay and inverse decay in the shaded region.

Dark Matter Signals

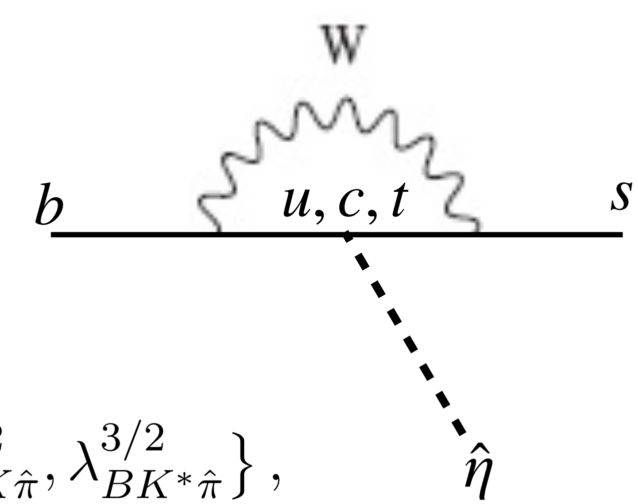
- Both direct and indirect detections are not effective for this model. Dark η productions and decays at accelerators may provide the best chances.

- Productions of dark hadrons:



  - Z decay: $\Delta \mathrm{BR}(Z \to \text{inv}) \lesssim 10^{-3}$

$$\mathrm{BR}(Z \to \psi\psi) \approx 3 \times 10^{-4} \left(\frac{N_d}{5}\right) \left(\frac{1\ \mathrm{TeV}}{M_{Q_1}}\right)^4 \mathrm{Tr}\mathbf{A}^2$$

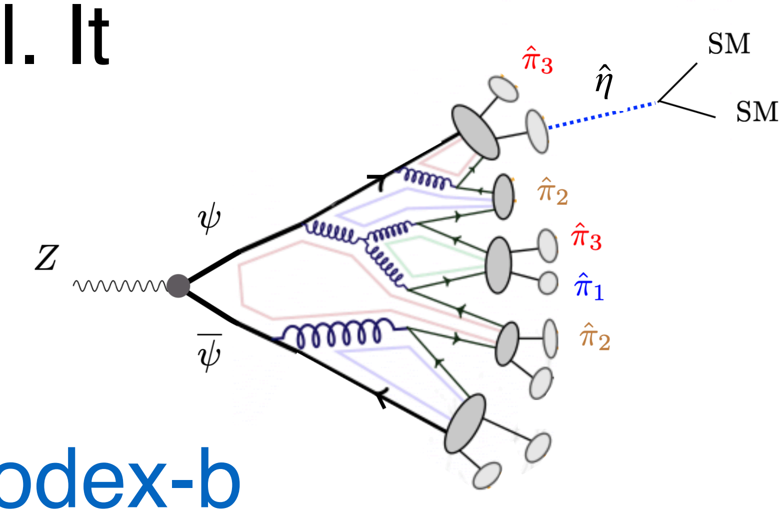


  - FCNC meson decays:

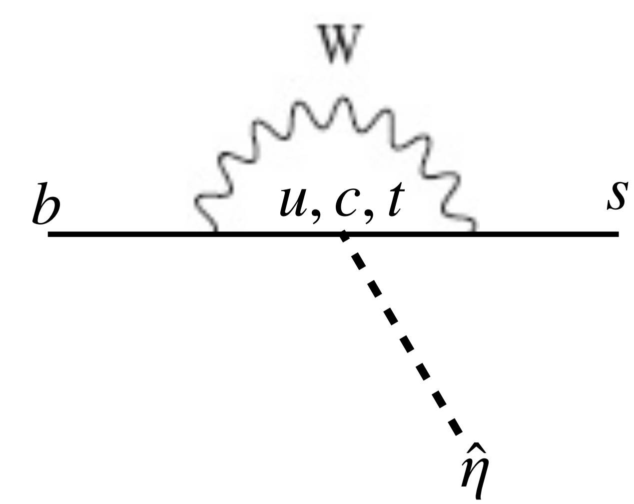
$$\mathrm{BR}(B^{+,0} \to \{K^+\hat{\pi}_b, K^{*0}\hat{\pi}_b\}) \approx \{0.92, 1.1\} \times 10^{-8} \left(\frac{1\ \mathrm{PeV}}{f_a^{(b)}}\right)^2 \left(\frac{\mathcal{K}_t}{10}\right)^2 \{\lambda^{1/2}_{BK\hat{\pi}}, \lambda^{3/2}_{BK^*\hat{\pi}}\},$$

Dark Meson Decay Searches

- The dark η is typically long-lived with Z portal. It can be searched at
  - Data scouting at CMS
  - LHCb with excellent VELO
  - Auxiliary detectors such as MATHUSLA, Codex-b
  - Future Z factories

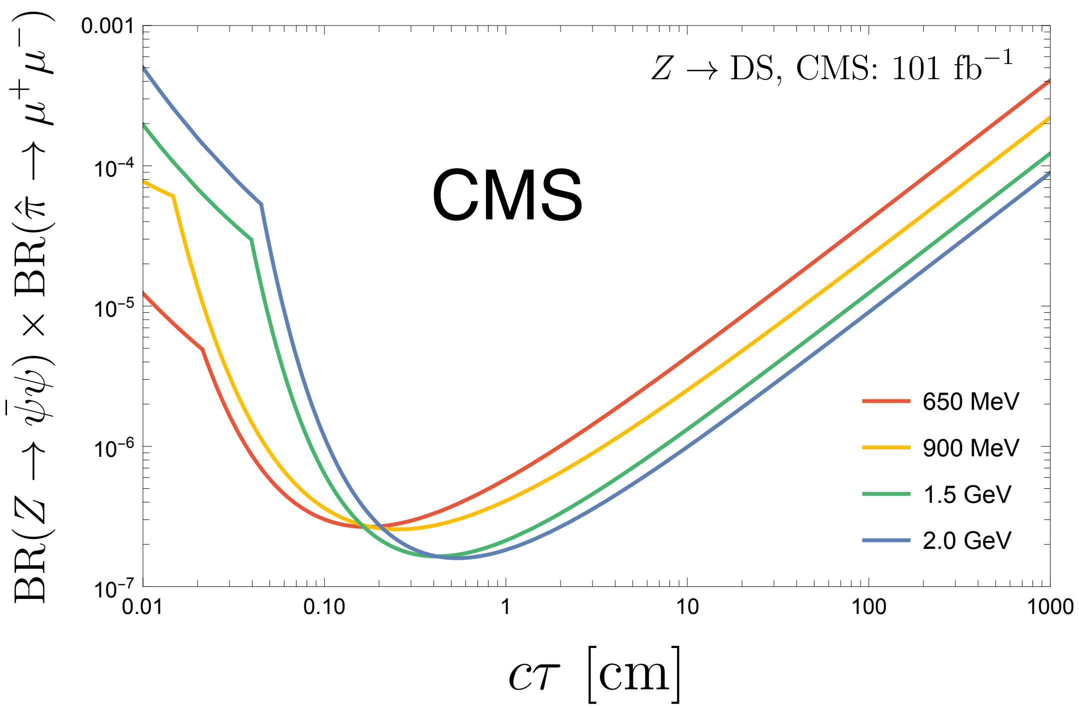


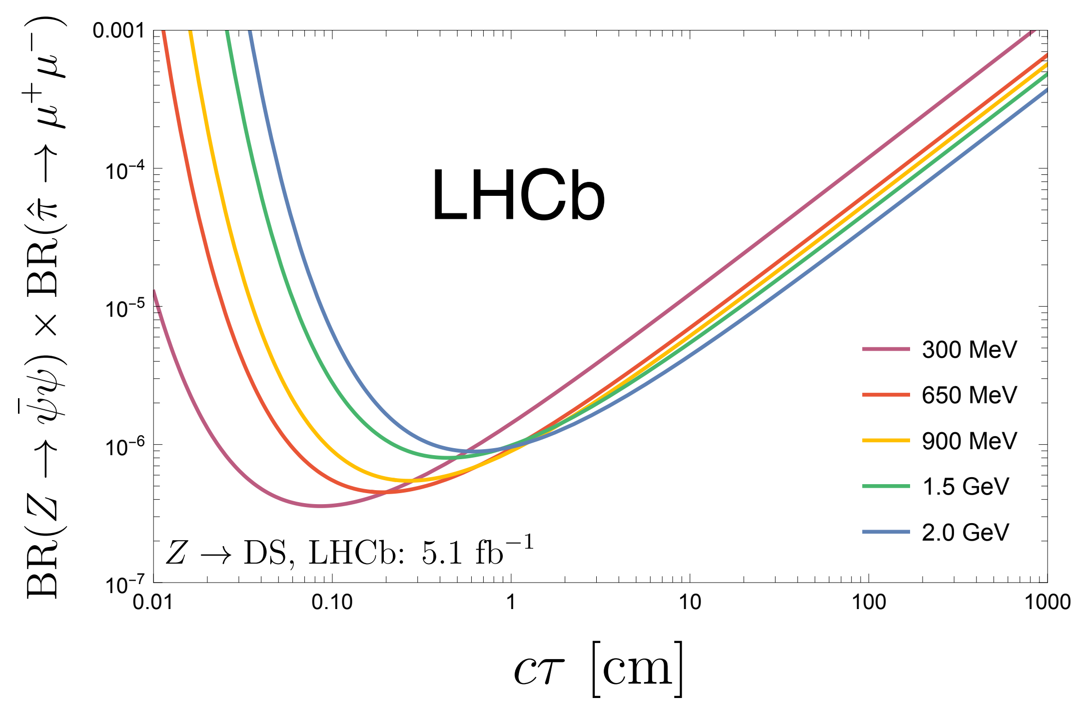
- The meson FCNC decays to light dark hadrons provide complementary tests. They can be searched or constrained, in addition to the above experiments, at
  - LHC forward detectors, e.g., FASER, FASER 2
  - Flavor factories, e.g., Belle II
  - Fixed-target or beam dump experiments, e.g., CHARM



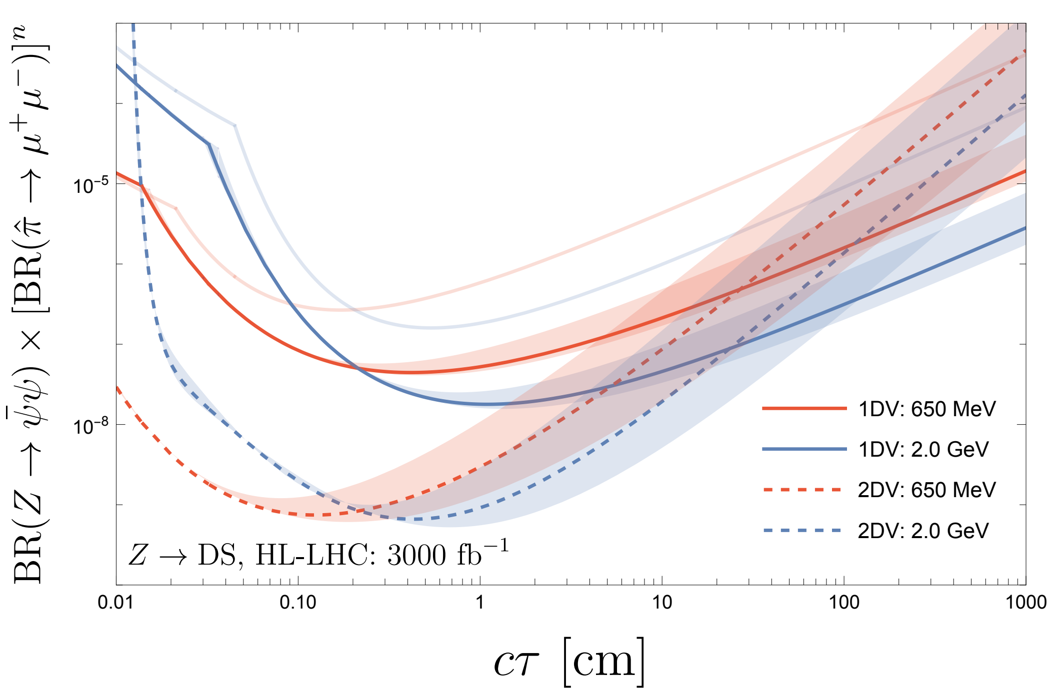
CMS Scouting and LHCb Search

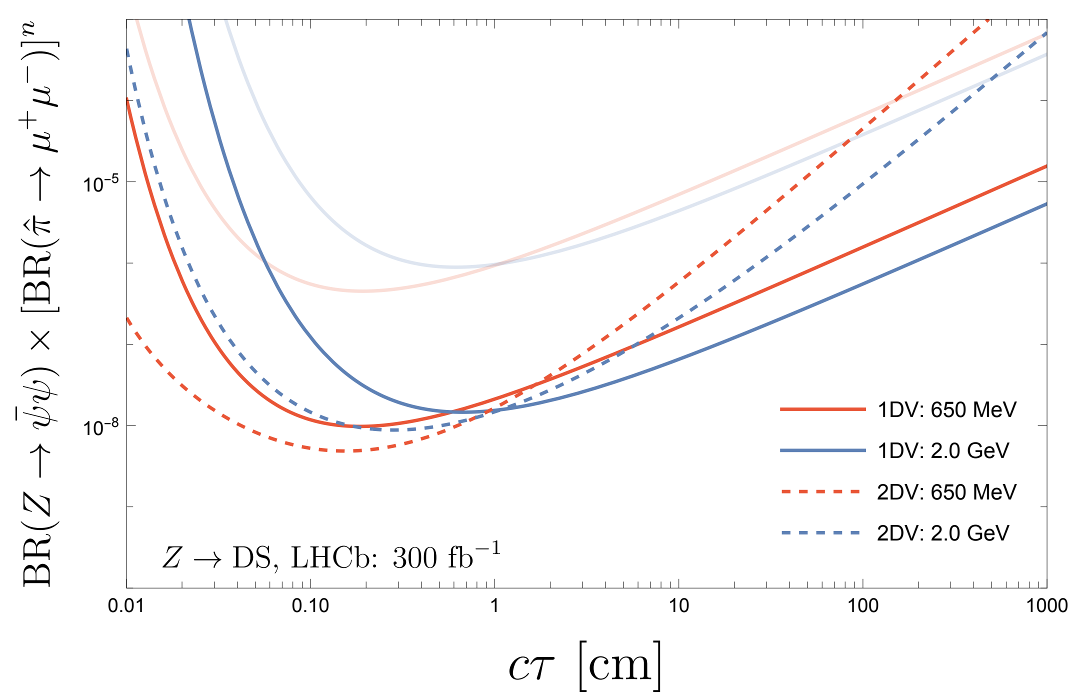
Recast current searches for dark showers with 1DV





HL-LHC projections (with 1DV and 2 DV)

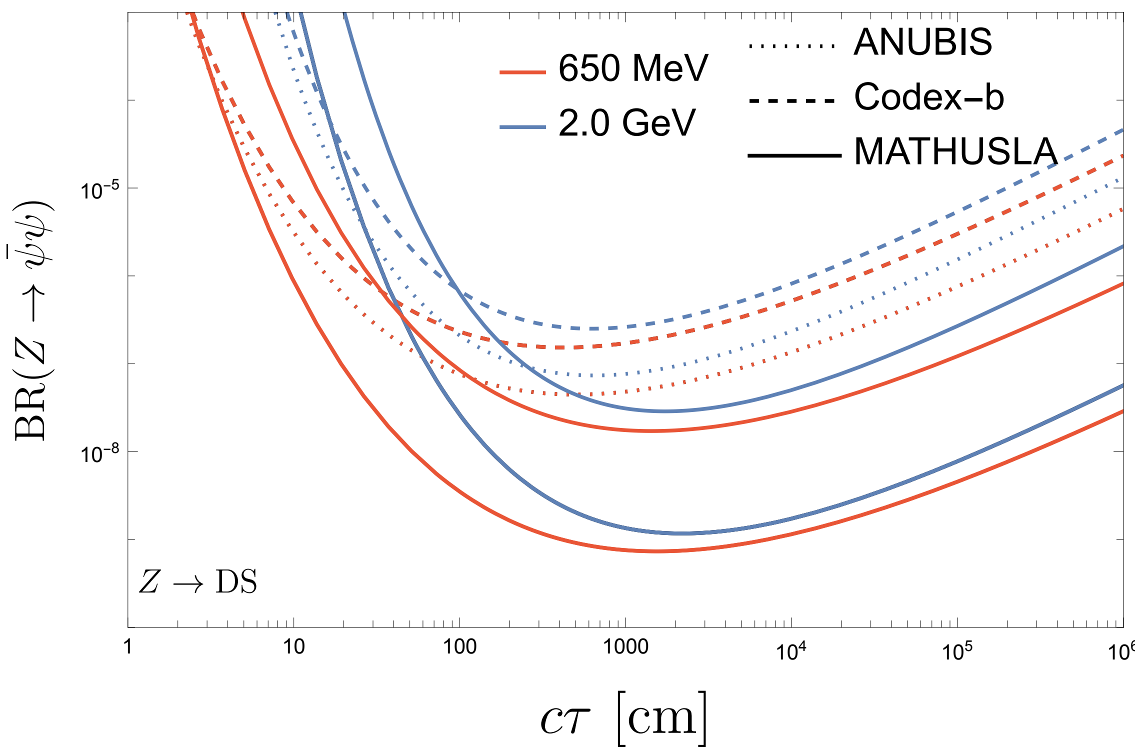


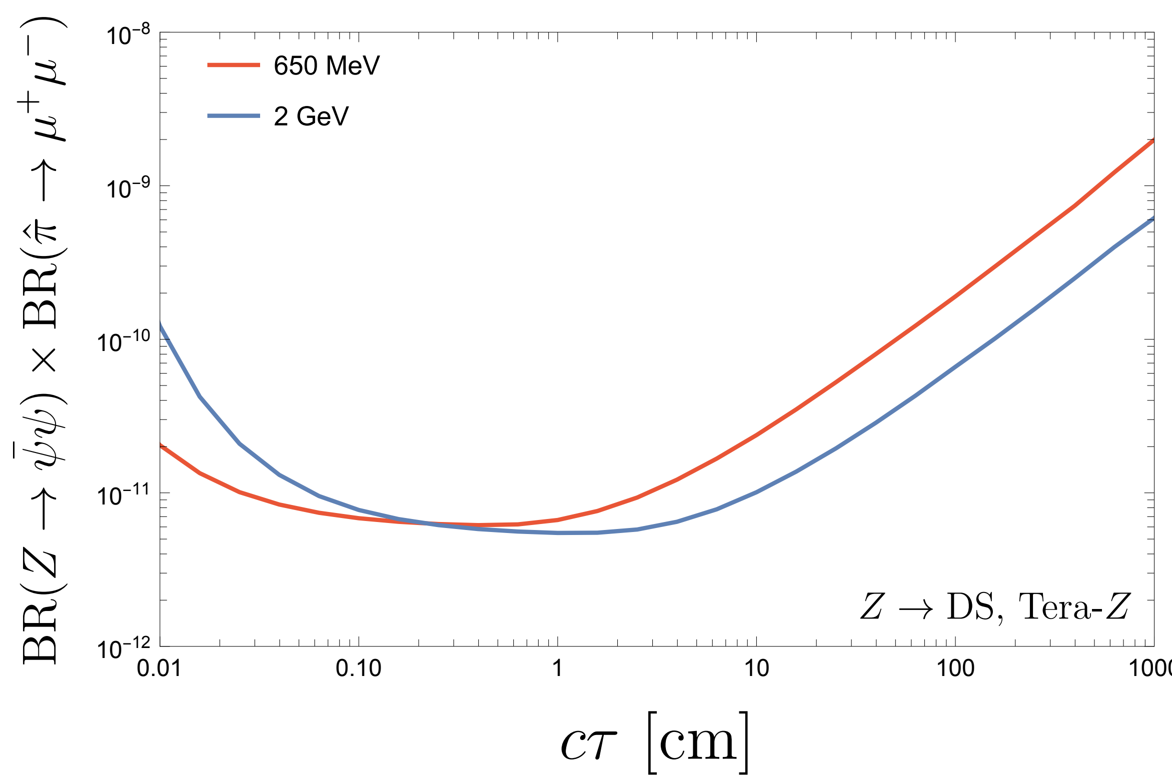


HC, X.-H. Jiang, L. Li, 2408.13304

Auxiliary Detectors and Z factory

Detector	Geometry	Displacement (m)	Volume (m)	Luminosity (fb^{-1})
FASER [42]	Cylinder	0, 0, 480	0.2, 1.5	300
FASER 2 [42]	Cylinder	0, 0, 480	2, 5	3000
MATHUSLA(original) [28]	Box	75, 0, 118	30, 100, 100	3000
MATHUSLA(updated) [67]	Box	88.5, 0, 90	17, 40, 40	3000
Codex-b [68]	Box	31, 2, 10	10, 10, 10	300
ANUBIS (Shaft) [31]	Cylinder	1.7, 51.5, 13.25	17.5, 57	3000





More than 10^{12} Z are expected at a future Z factory, ideal for studying Z-induced dark showers.

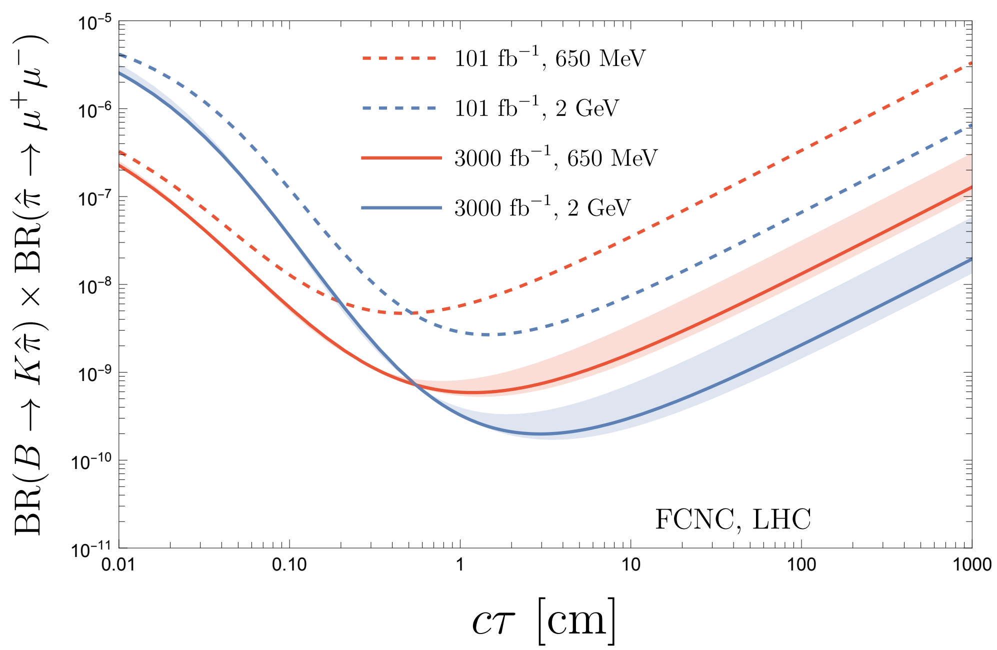
Cuts: $p_{T,\mu} > 0.5$ GeV, $|p_\mu| > 10$ GeV $\quad p_{T,\mu\mu} > 2$ GeV and $|\eta_\mu| < 5$

$l_{xy} \in [0.5, 100]$ cm $\quad m_{\mu\mu} \in [0.99\, m_{\hat{\pi}}, 1.01 m_{\hat{\pi}}]$

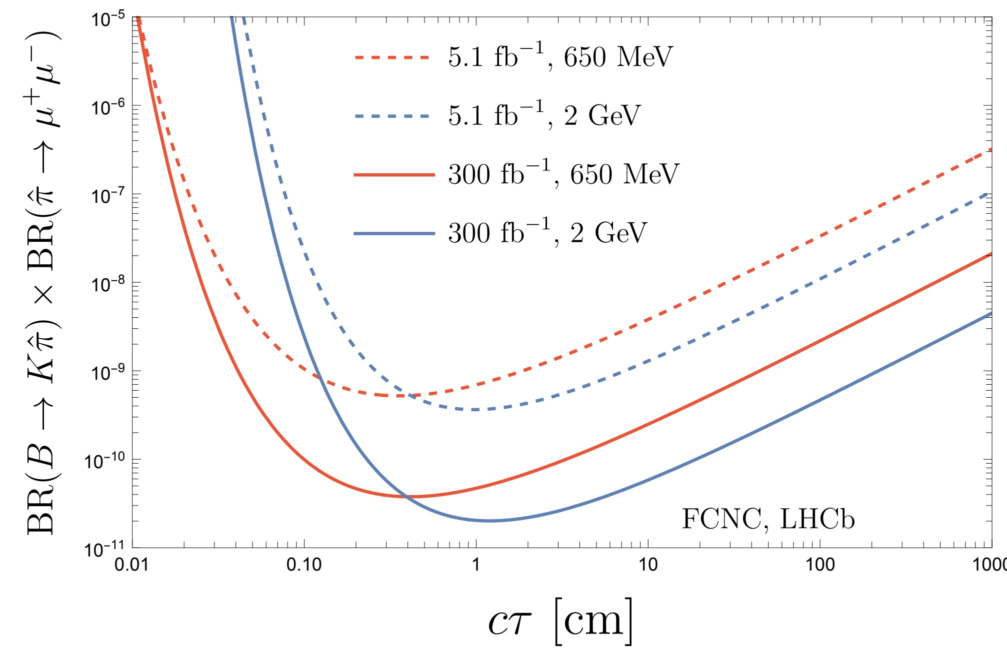
FCNC Reaches

Long-lived dark hadrons produced from FCNC decays can be searched in the similar ways as dark showers

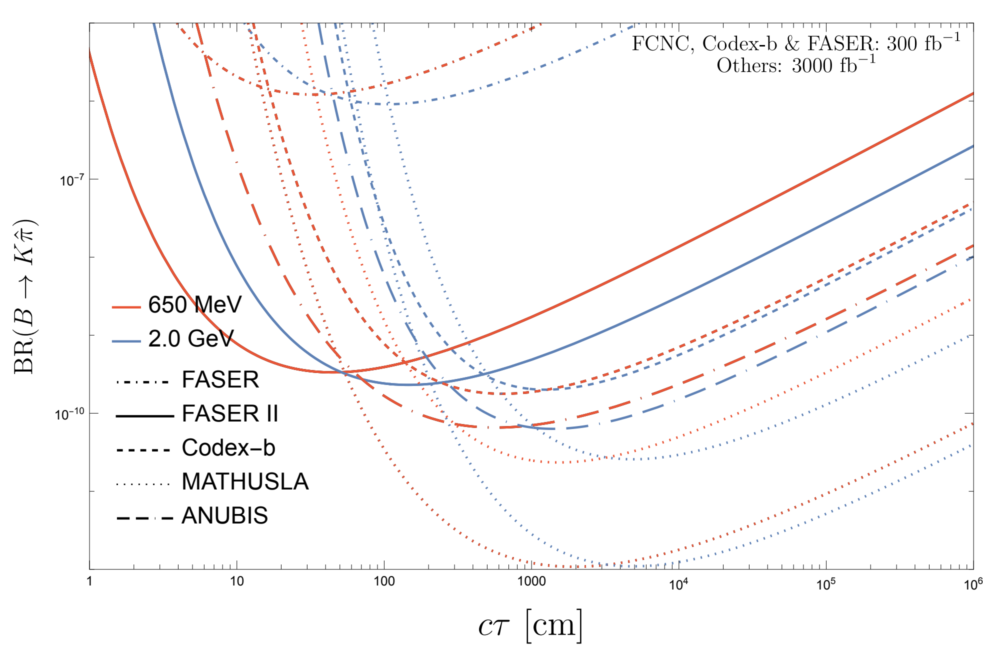
CMS Scouting



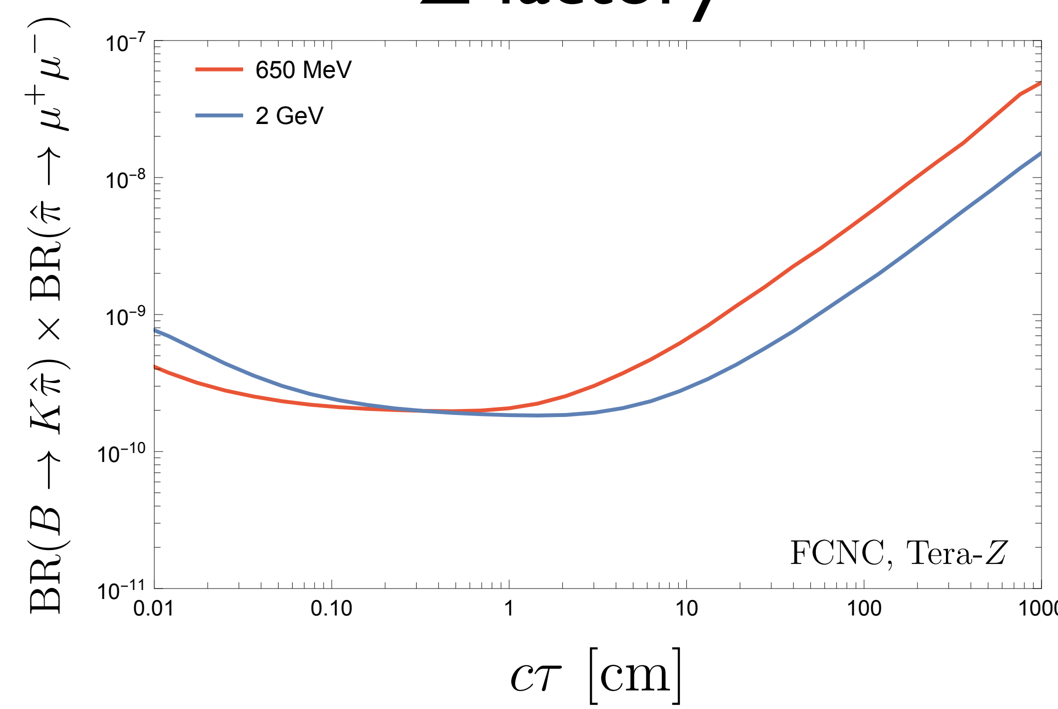
LHCb



Auxiliary detectors



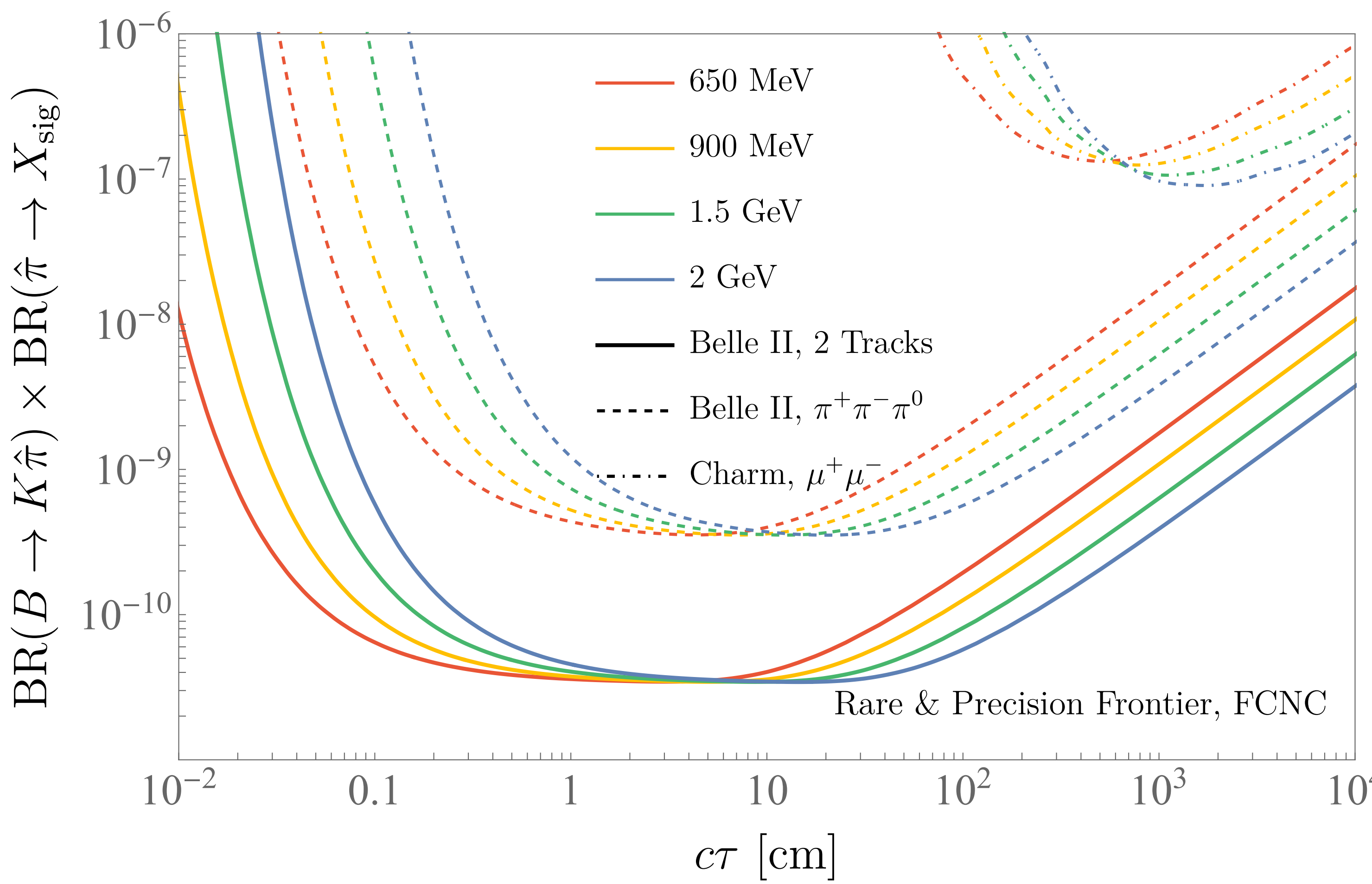
Z-factory



FCNC Reaches

B-factories and fixed target experiments producing large number of B hadrons are also powerful probes of the long-lived dark hadrons from the B hadron decays. Hadronic decays modes, such as (SM) $K^+K^-, \pi^+\pi^-, \pi^+\pi^-\pi^0$ may also be used.

B-factory and fixed target exp



Conclusions

- Dark pions in a dark QCD sector can be a good dark matter candidate. If some dark mesons decay back to SM, the DM relic density is determined by the forbidden annihilation or the decay of the heavier meson.

- In this model the decay is mediated by the Z-portal, with a lifetime naturally in the range mm - 100 m. There is no bilinear dark pion coupling to Z, making direct and indirect detections ineffective.

- The experimental signals come from the dark meson decay. Dark mesons are produced from the Z decays or FCNC SM meson decays. They can be searched at CMS, with scouting and parking data, LHCb, auxiliary detectors located far away from the collisions, intensity frontier experiments, and future Z factories. They can have very good reaches for the model parameters.