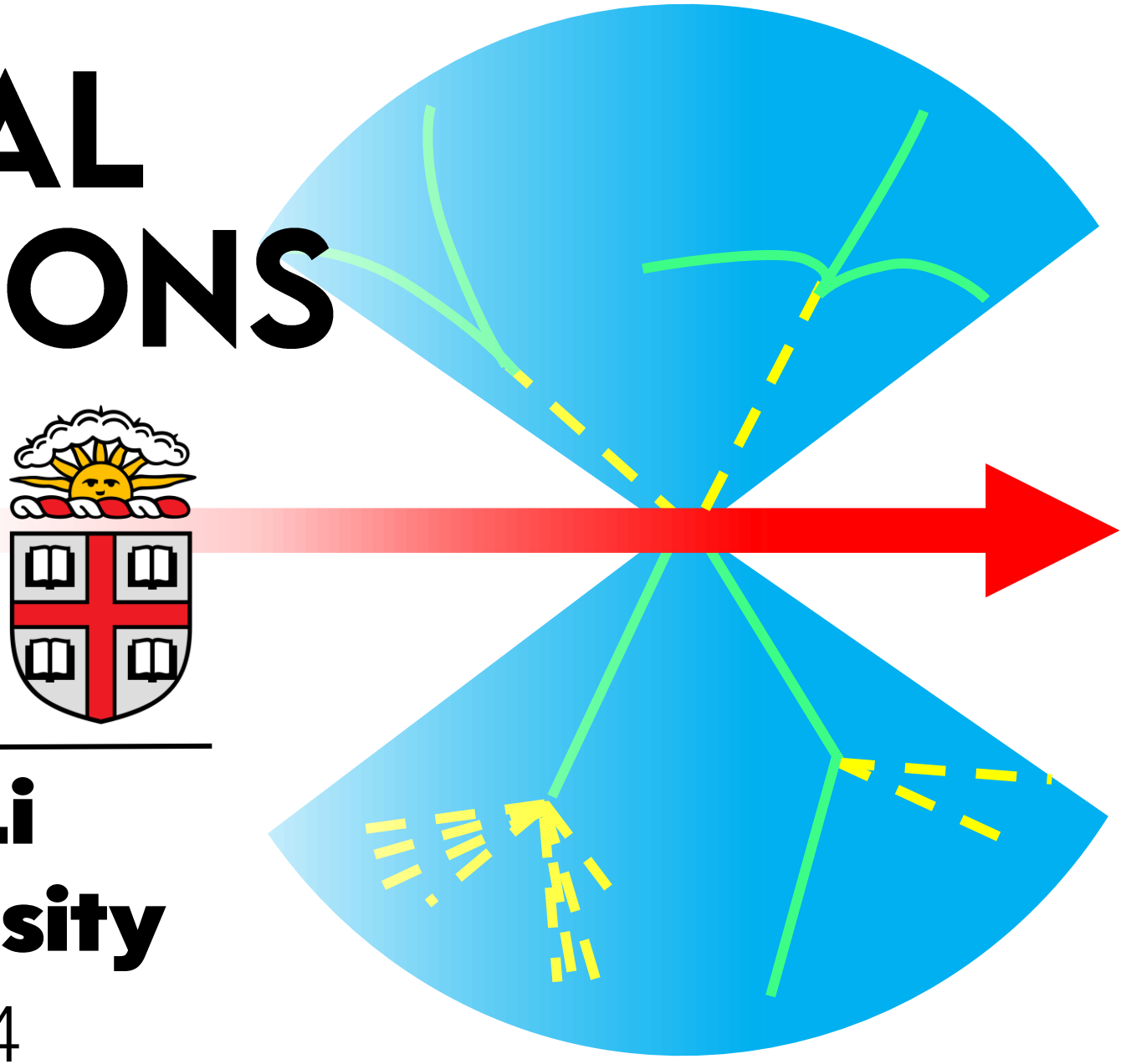
Z PORTAL DARK PIONS

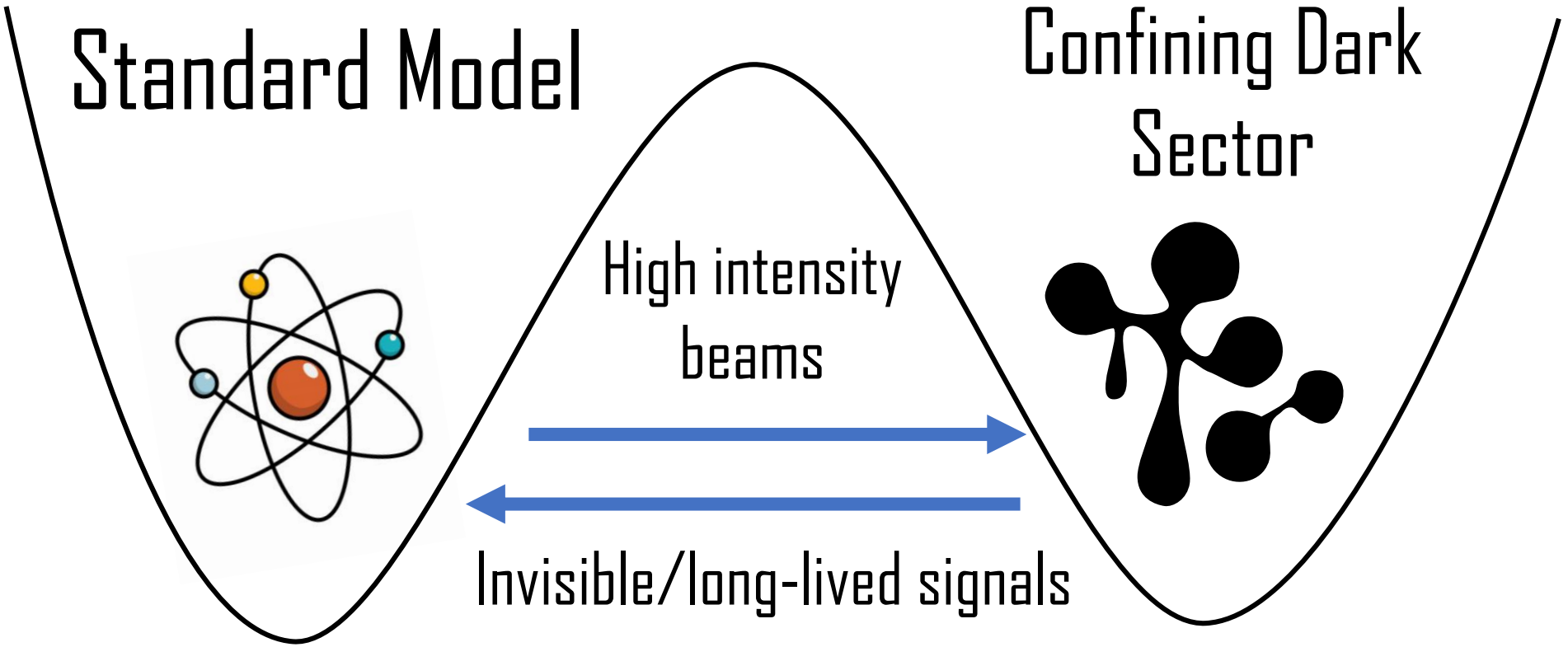


Lingfeng Li
Brown University

Feb. 29, 2024

7th FPF Meeting

Hidden Valley Models



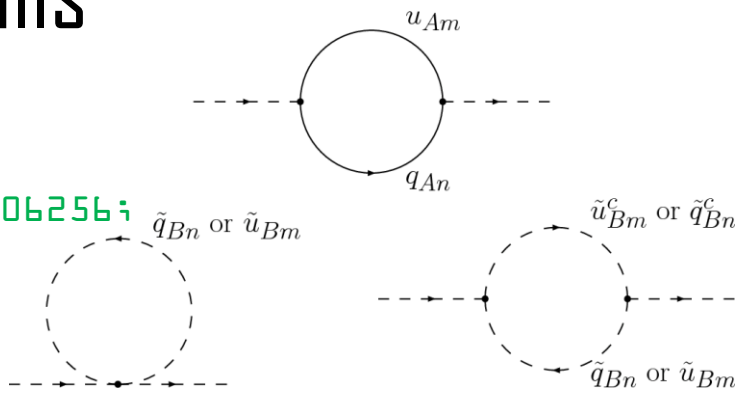
$\epsilon \mathcal{O}_{\rm SM} J_{\rm Dark}$ **Relevant portal:** small couplings to keep the valley hidden

$\frac{1}{\Lambda^n} \mathcal{O}_{\rm SM} J_{\rm Dark}$ **Irrelevant portal:** Hidden behind EFTs

The Dark Force for Confinement

- Neutral naturalness calls for a non-QCD color

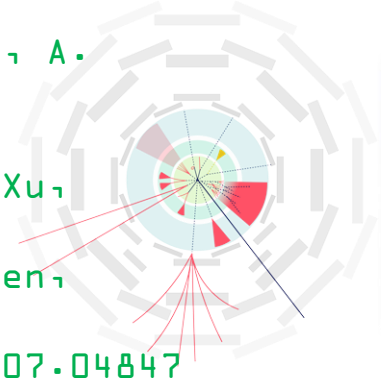
Z. Chacko, H.-S. Goh, and R. Harnik, 0506256;
G. Burdman, Z. Chacko, H.S. Goh and R. Harnik, 0609152;
H-C. Cheng, LL, E. Salvioni, and C. Verhaaren, 1803.03561



- Makes good dark matter candidate

Y. Hochberg, E. Kuflik, H. Murayama, T. Volansky, J. Wacker, 1411. 3727;
A.Katz, E. Salvioni, and B. B. Shakya, 2006.15148;
H-C. Cheng, X. Jiang, LL, E. Salvioni, In Prep.

P. Schwaller, D. Stolarski, A. Weiler, 1502.05409;
CMS, 1810.10069;
S. Knapen, J. Shelton, D. Xu, 2103.01238;
S. Born, R. Karur, S. Knapen, J. Shelton, 2303.04167;
J. Carrosco, J. Zirita, 2307.04847

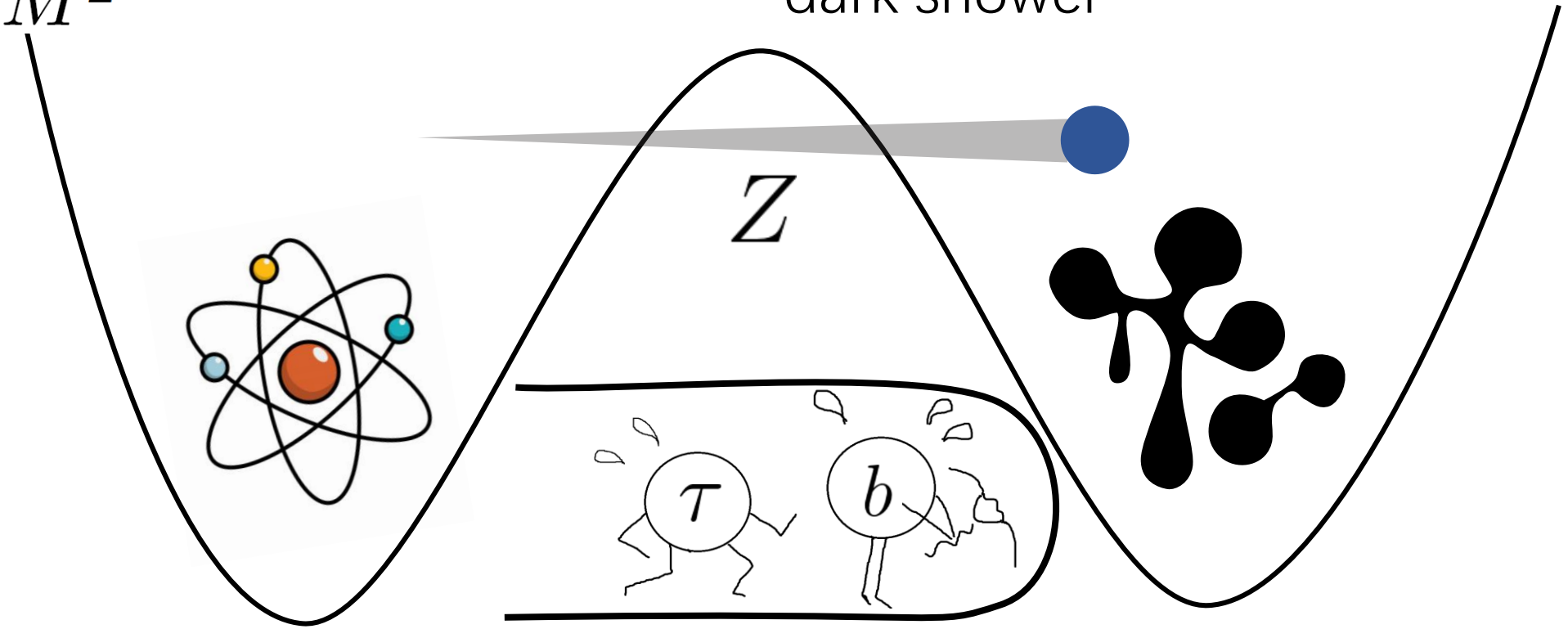


- Rich collider phenomeonolgy

The Z (& Flavor) Portal

$$\frac{c}{M^2}(iH^\dagger \overleftrightarrow{D}_\mu H)(\overline{\psi}\gamma^\mu\psi)$$

Tree level, meson decay and dark shower

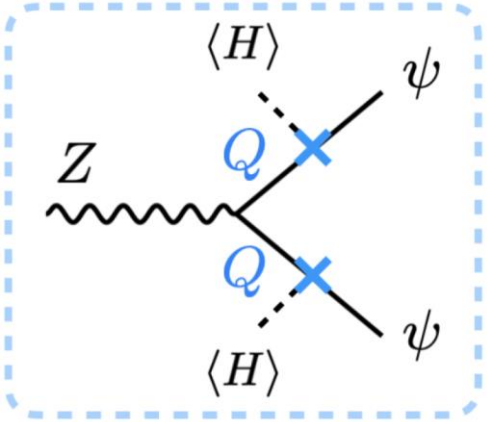


$$\frac{\mathcal{K}}{M^2}(\bar{d}_i\gamma^\mu d_j)(\bar{\psi}\gamma_\mu\psi)$$

One loop, complementary at lower energies, respects MFV

The Z Portal: $\frac{c}{M^2}(iH^\dagger \overleftrightarrow{D}_\mu H)(\overline{\psi}\gamma^\mu\psi)$ from Two UV Models

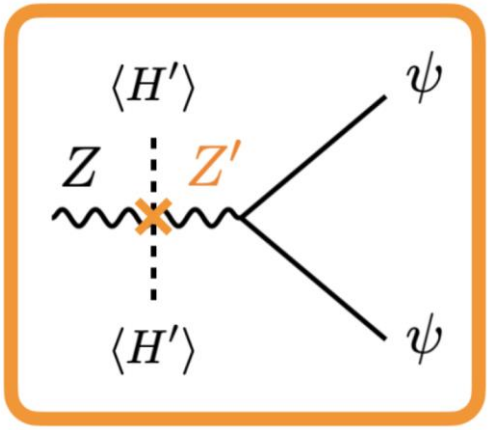
$$\mathcal{L}_{\rm UV} \supset \overline{Q} Y \psi H \longrightarrow \frac{c}{M^2} \sim \frac{Y^2}{M_Q^2}$$



Heavy fermion doublet model: a heavy scale above TeV

H-C. Cheng, LL, E. Salvioni, 2110.10691

$$\mathcal{L}_{\rm UV} \supset \delta \hat{M}^2 Z^\mu Z'_\mu \longrightarrow \frac{c}{M^2} \sim \frac{g_D^2 \delta \hat{M}^2}{m_Z^2 m_{Z'}^2}$$

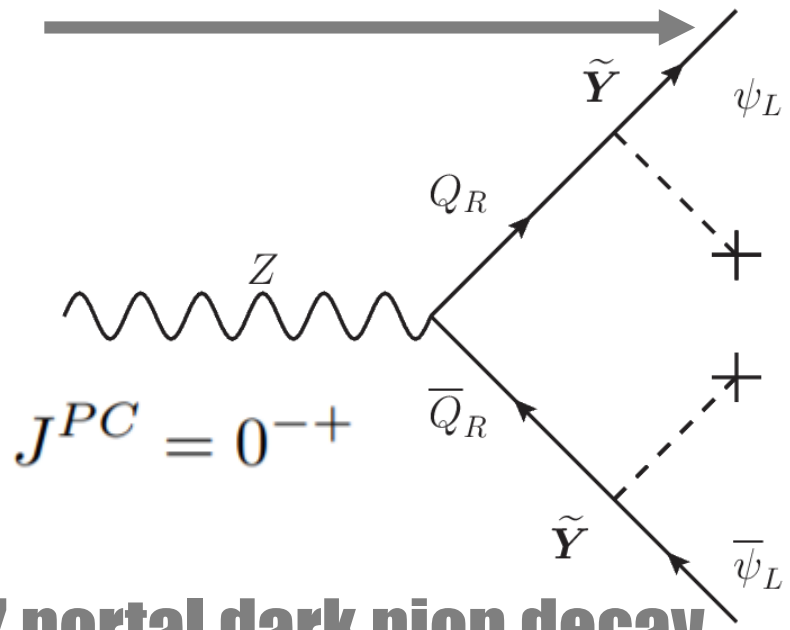


Dark Z' model: a Z' heavier or lighter(!) than Z, must have a mass mixing

H-C. Cheng, X. Jiang, LL, E. Salvioni, 2401.08785

Two Flavor, Three Dark Pions

Z portal dark pion production



Z portal dark pion decay

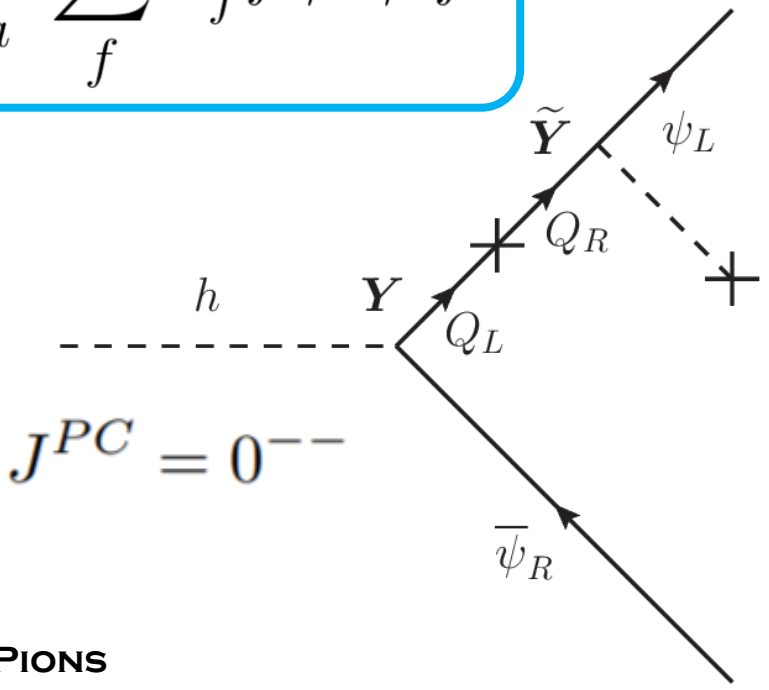
Dark pions rearrange into CP eigenstates (like K_S and K_L in the SM)

The π_1 and π_3 decay via Z portal, ALP-like (axion-like-particle) with effective ALP decay constants:

$$\mathcal{L}_a \supset -\frac{\partial_\mu a}{f_a} \sum_f T_f^3 \bar{f} \gamma^\mu \gamma^5 f$$

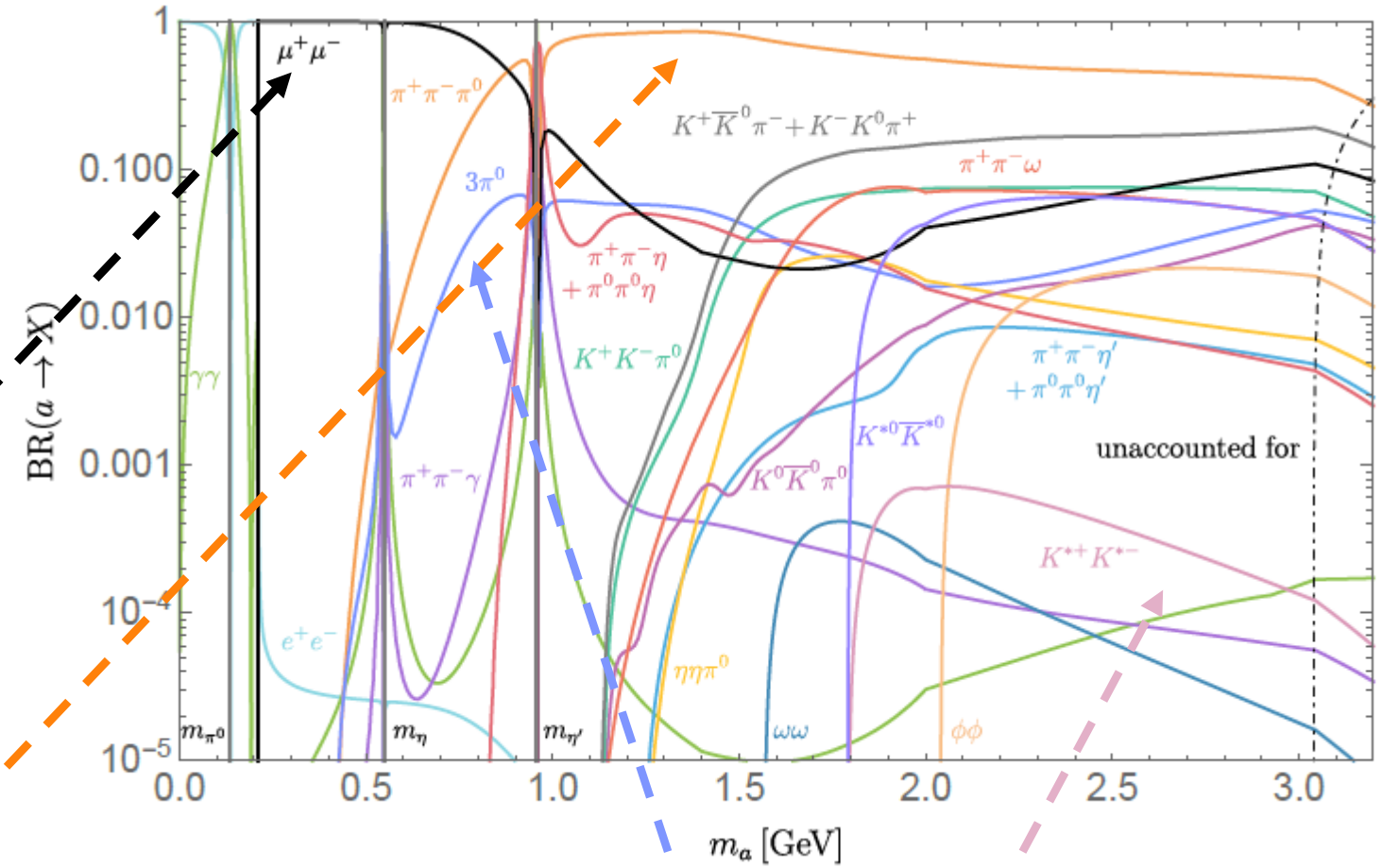
The π_2 mix with the Higgs since it's CP-even, with mixing angle:

$$\mathcal{L}_s \supset -\sin\theta_s \frac{m_f}{v} s \bar{f} f \ , \ \theta_s \lesssim 10^{-6}$$



Dark Pion Decays (ALP-Like)

ALP with arbitrary flavor diagonal couplings



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

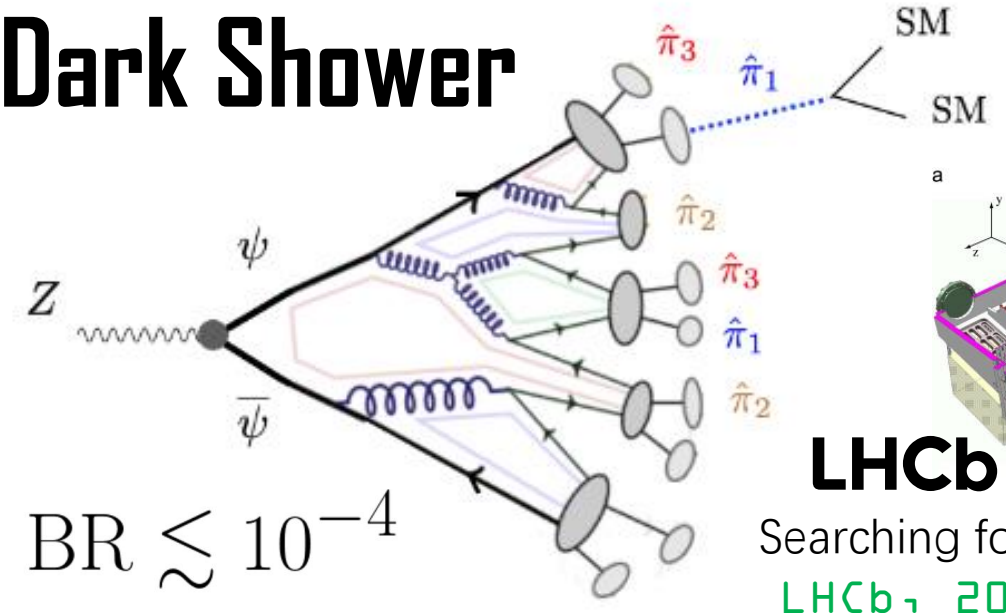
SM isospin suppressed modes

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

$$f_a \sim \frac{M^2}{f_{\hat{\pi}} Y^2} \text{ or } \frac{m_Z^2 m_{Z'}^2}{f_{\hat{\pi}} \delta M^2} \sim \mathcal{O}(\text{PeV})$$

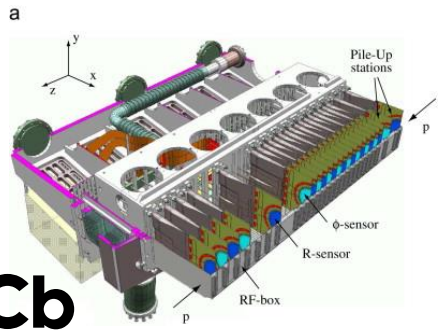
LHC Phenomenology

Dark Shower

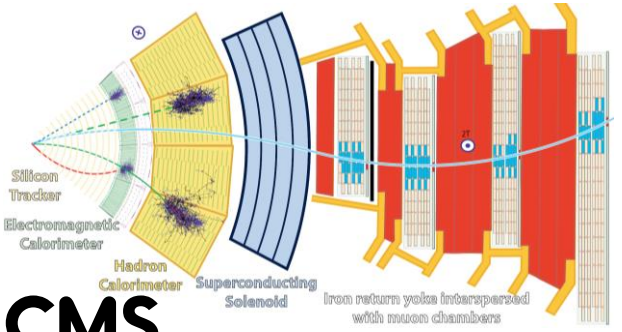


$$\mathrm{BR} \lesssim 10^{-4}$$

Signal: Muon rich jet-like structure with long-lived tracks &MET



LHCb



CMS

Searching for displaced dimuon resonances (one or more)

LHCb, 2007.03923; CMS, 2112.13769

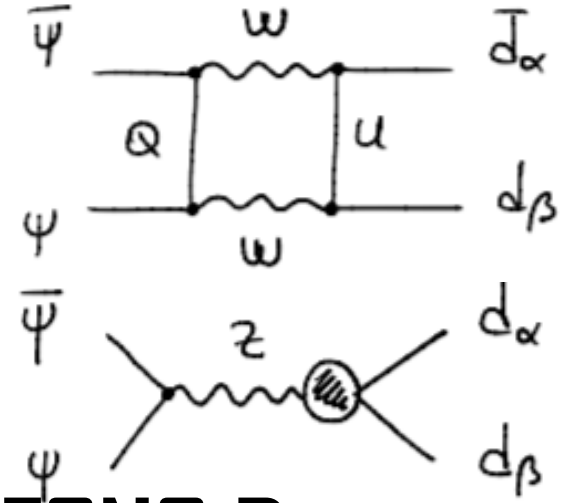
CODEX-b

MATHUSLA

FASER

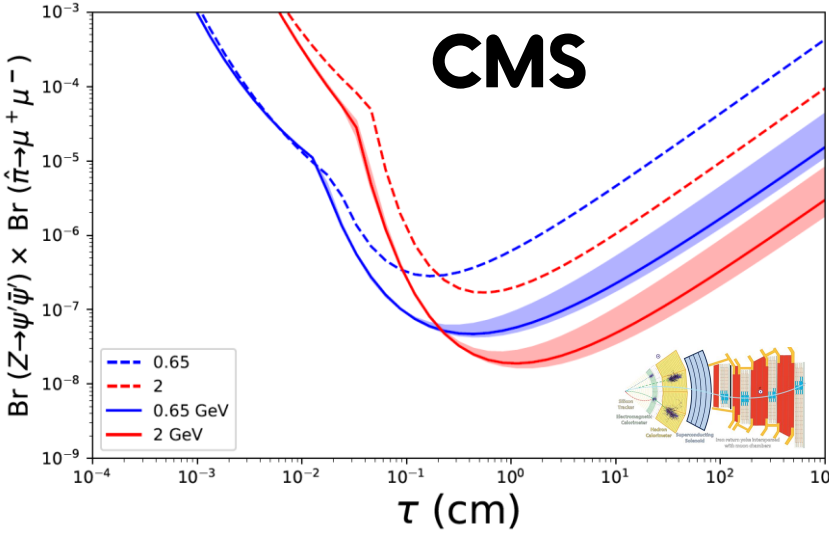
FPF Forward Physics Facility

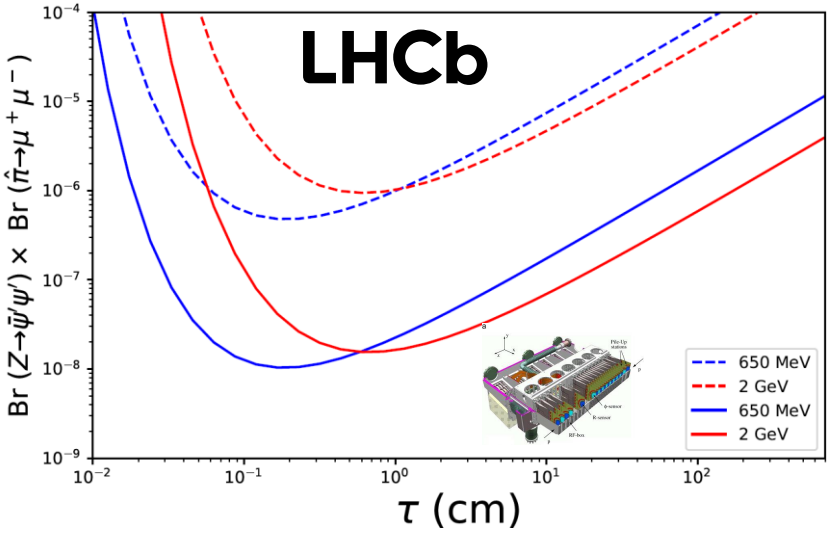
$$\mathrm{BR} \approx 10^{-8} \left(\frac{1\ \mathrm{PeV}}{f_a} \right)^2$$



FCNC Decays

Model-Independent Limits



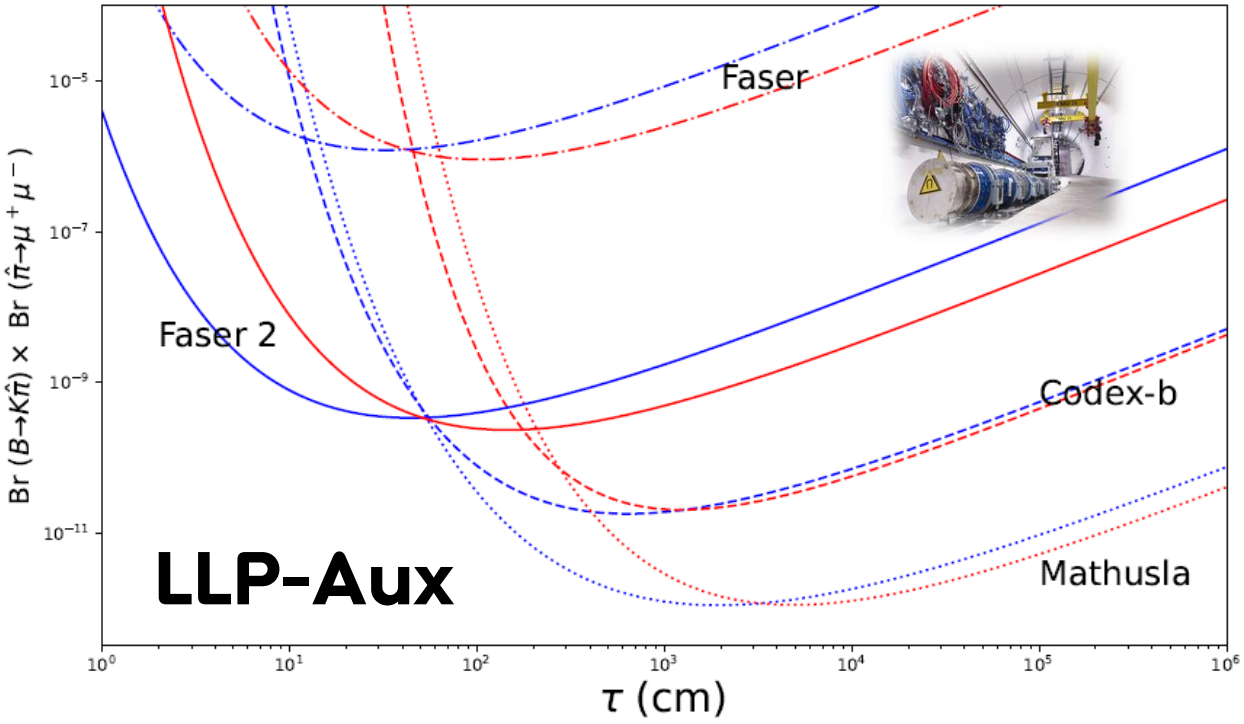


- Z boson initiated dark shower limits at LHC

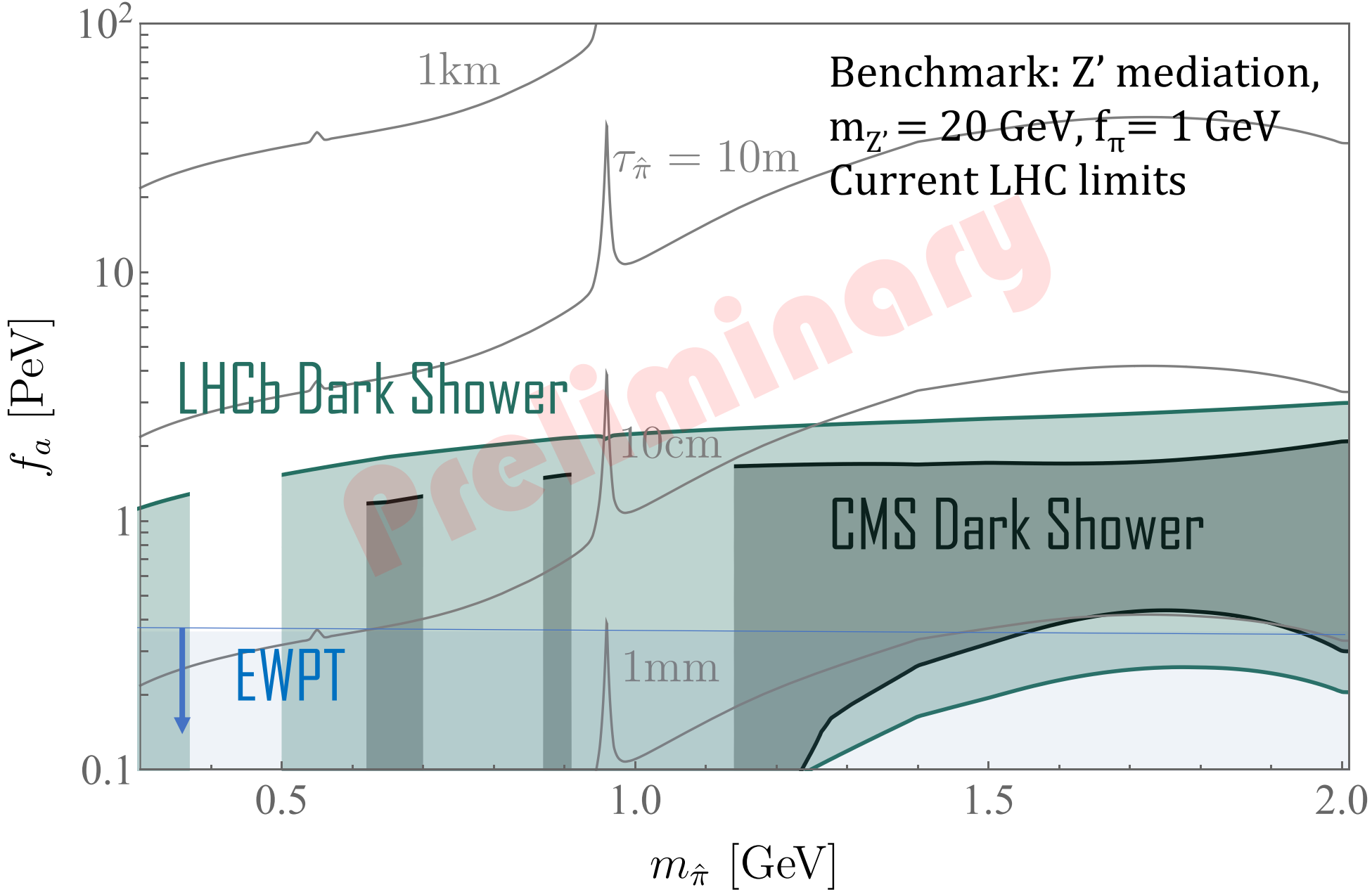
------ : Current

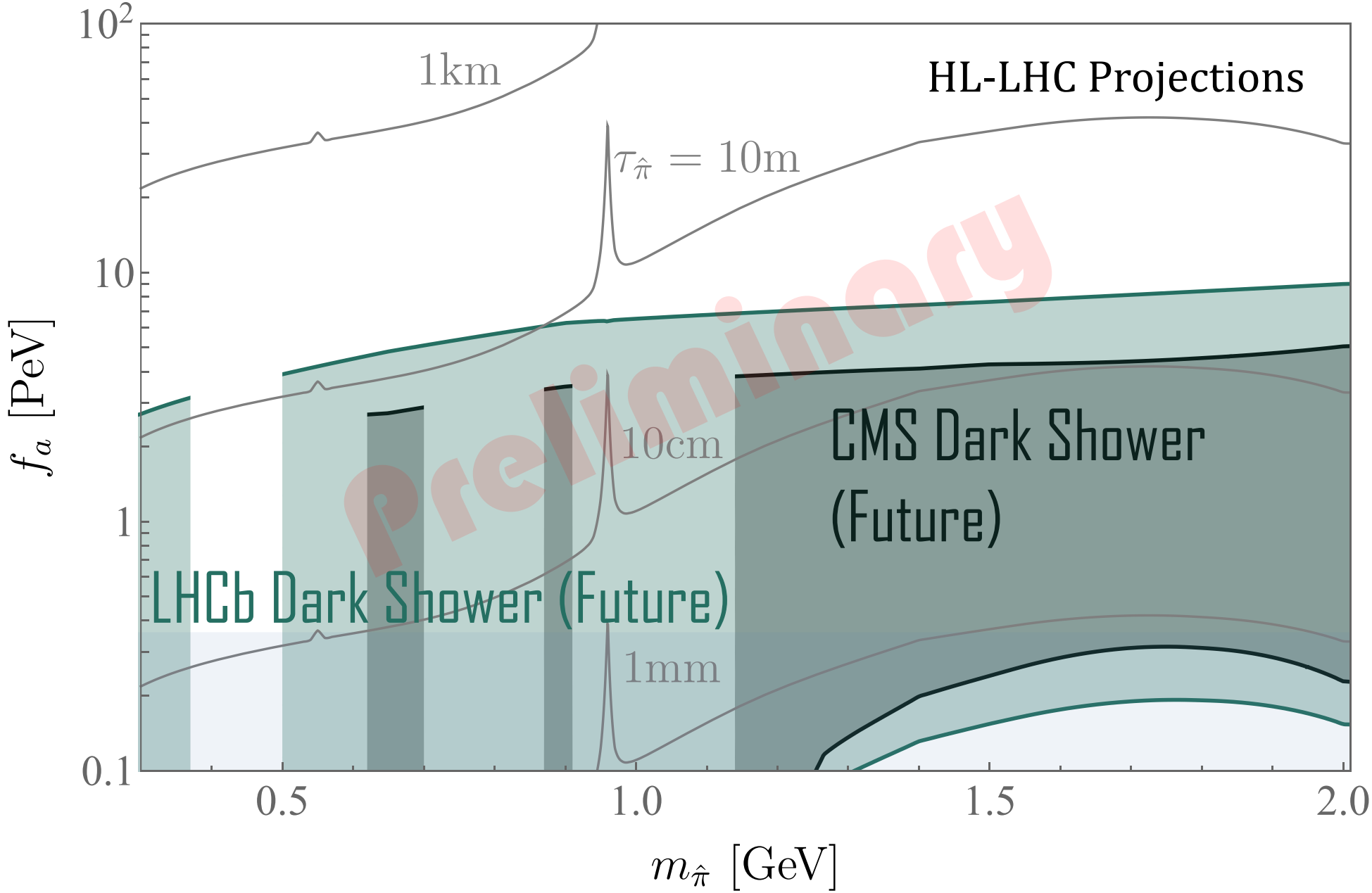
——— : Future

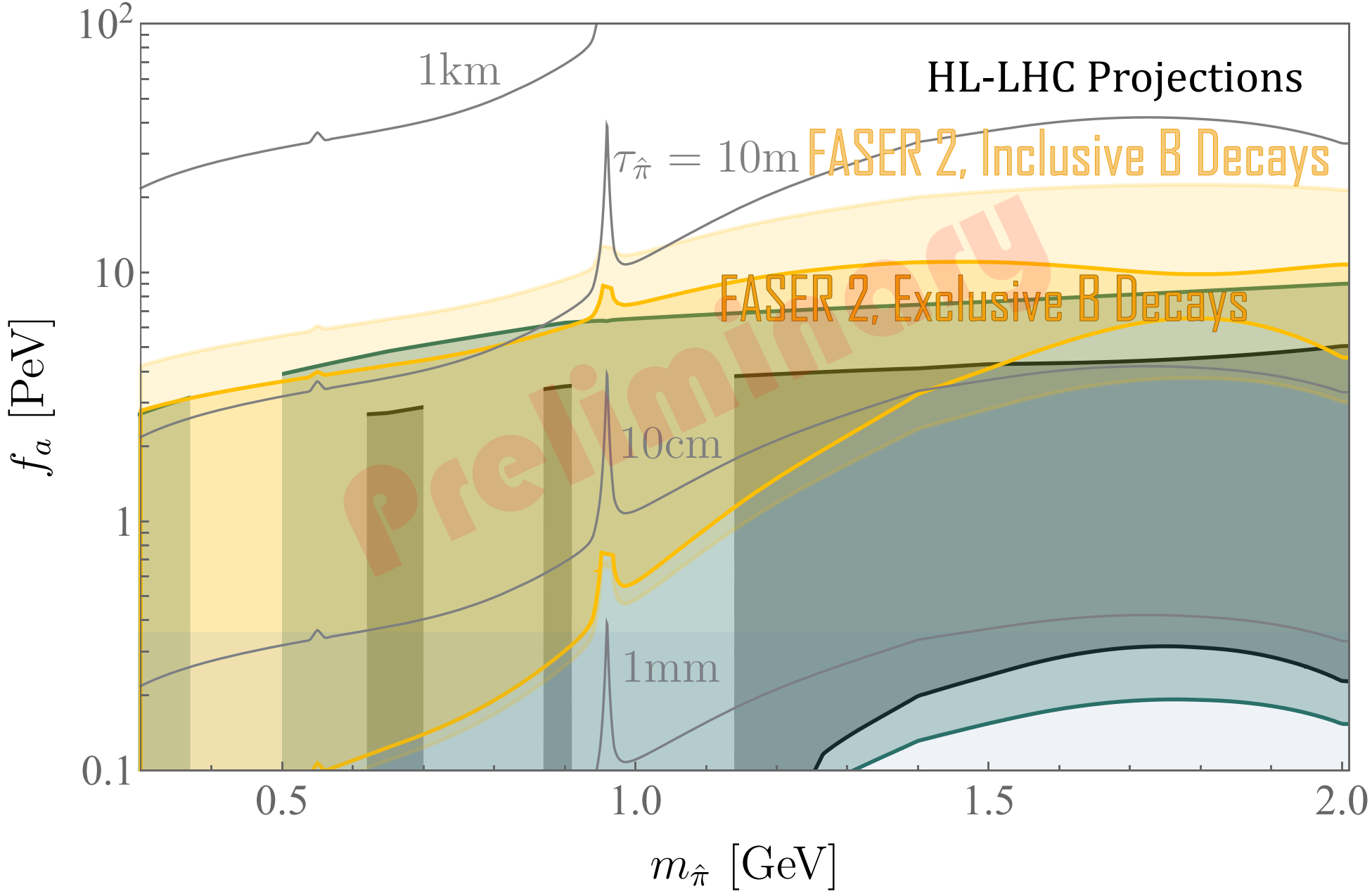
- Exclusive B FCNC limits at various auxiliary LLP detectors, even more when include more final states



Model-Dependent Constraints




HL-LHC Projections
1km
$\tau_{\hat{\pi}} = 10\text{m}$
10cm
1mm
CMS Dark Shower (Future)
LHCb Dark Shower (Future)
Preliminary
10^2
10
1
0.1
f_a [PeV]
0.5
1.0
1.5
2.0
$m_{\hat{\pi}}$ [GeV]


HL-LHC Projections
FASER 2, Inclusive B Decays
FASER 2, Exclusive B Decays
Preliminary
1km
$\tau_{\hat{\pi}} = 10\text{m}$
10cm
1mm
10^2
10
1
0.1
f_a [PeV]
0.5
1.0
1.5
2.0
$m_{\hat{\pi}}$ [GeV]

Summary

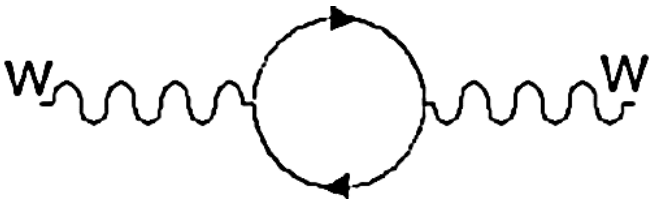
- Dark shower from the Z portal gives rise to decaying dark pions having lifetimes within collider reach, making the dark shower more visible (and likely muon rich)
- We describe two classes of underlying theories: doublet fermion and light Z' portal
- Recasted LHC limits and future limits from main and auxiliary limits
- FCNC decays offer complementary probes, good target for forward LLP detectors

Backup Slides

Indirect/Precision Constraints

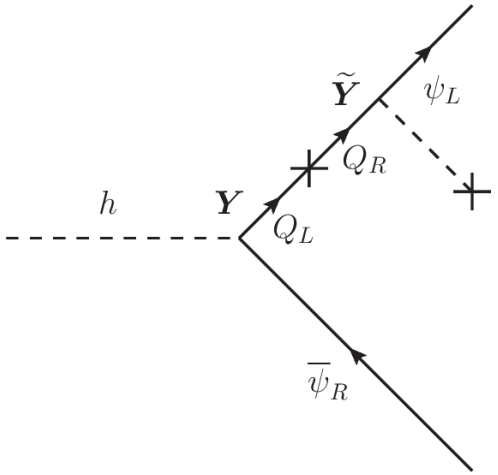
$$M \gtrsim 0.9\,\mathrm{TeV}\; Y^2 \left(\frac{N_d N}{6}\right)^{1/2}$$

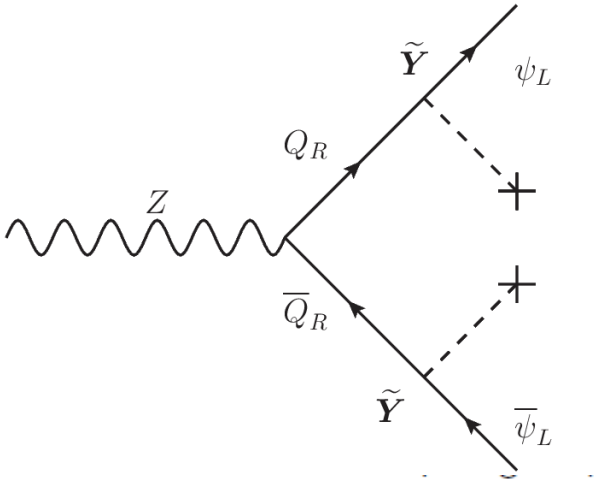
From EW oblique parameter T < O(10^{-3})



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

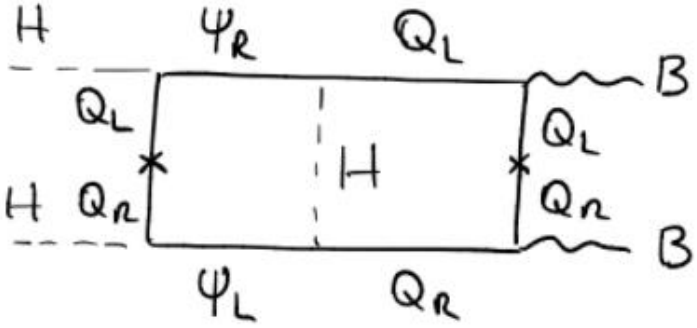
From Higgs invisible decay BR < 13%





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

From Z invisible decay width <~2 MeV



$$M \gtrsim 1.5\;\mathrm{TeV}\;\; Y\widetilde{Y}$$

From electron EDM
if CP is violated maximally