



# ChpT and BSM dark pions

---

Lingfeng Li (Brown U.)

Nov. 17, 2021, CD2021

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

See also:

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

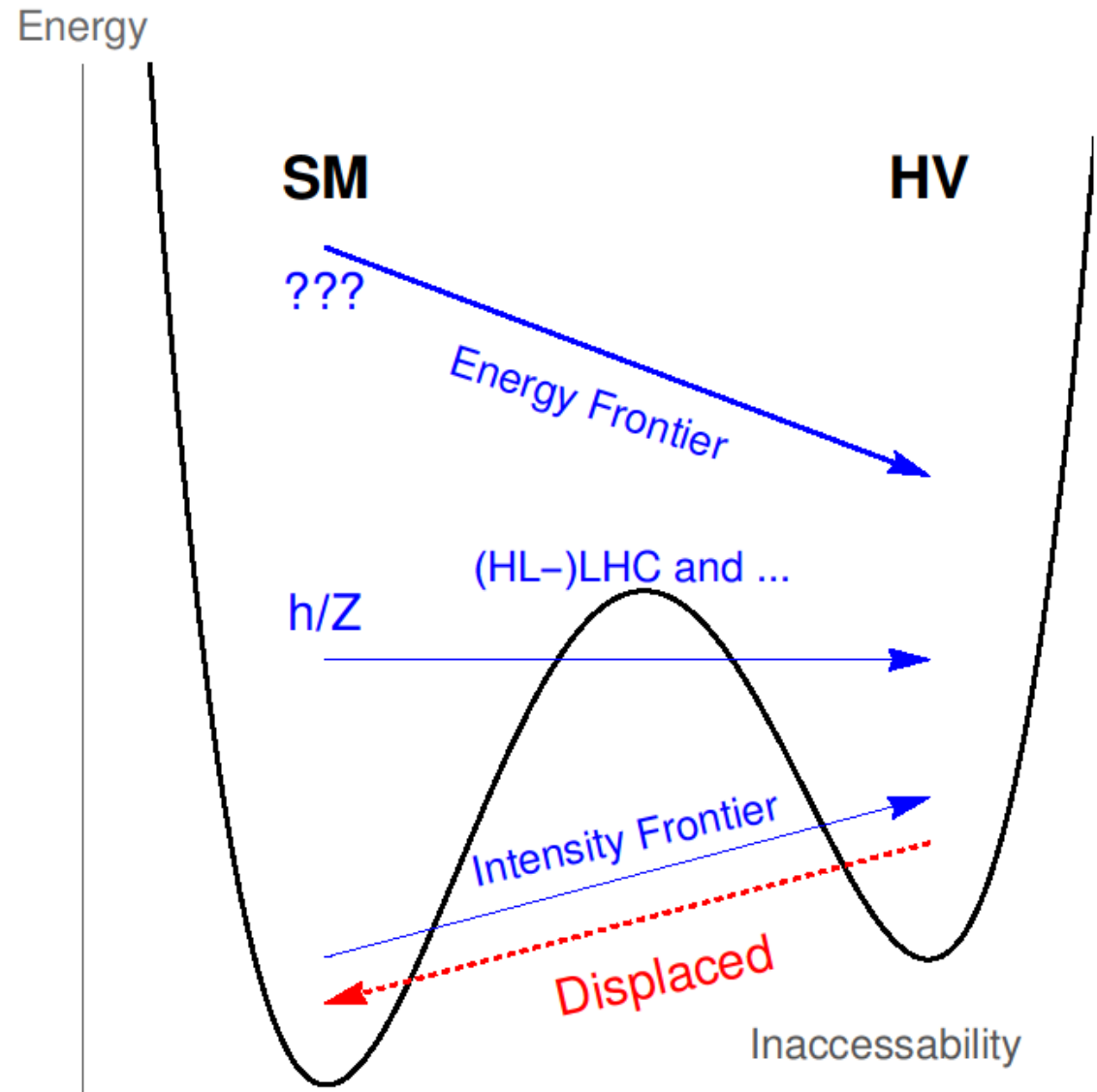
1905.03772 w/ H-C. Cheng, E. Salvioni and C. Verhaaren



# 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 benchmarks, focusing on long-lived particle (LLP) searches

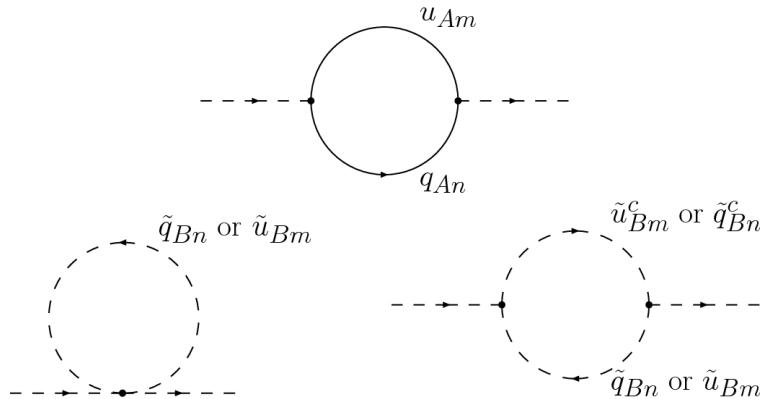


# Motivating Scenario I: Neutral Naturalness

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

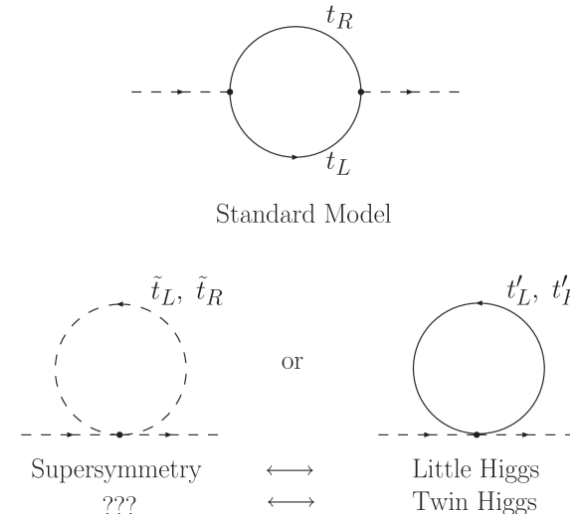
## Folded SUSY

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



## Twin Higgs

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

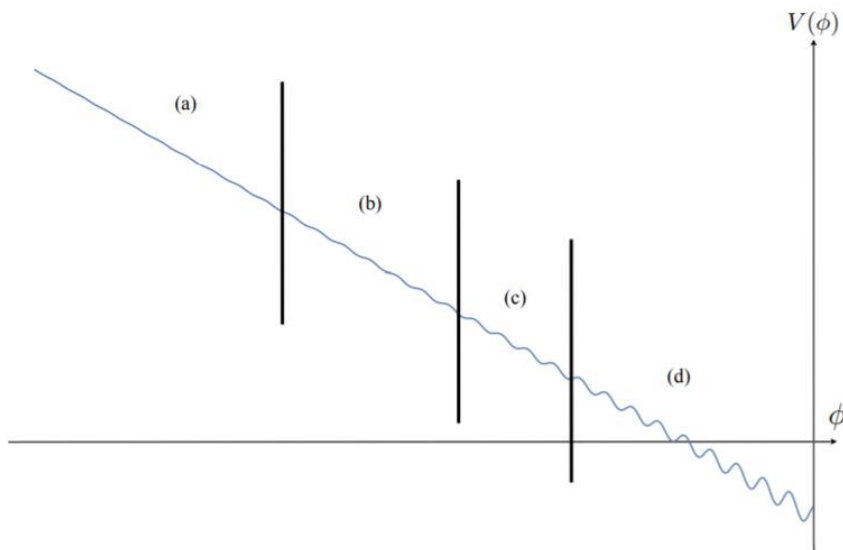


## See also Tripled Top (TT) model

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

# Motivating Scenario II: Relaxion

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

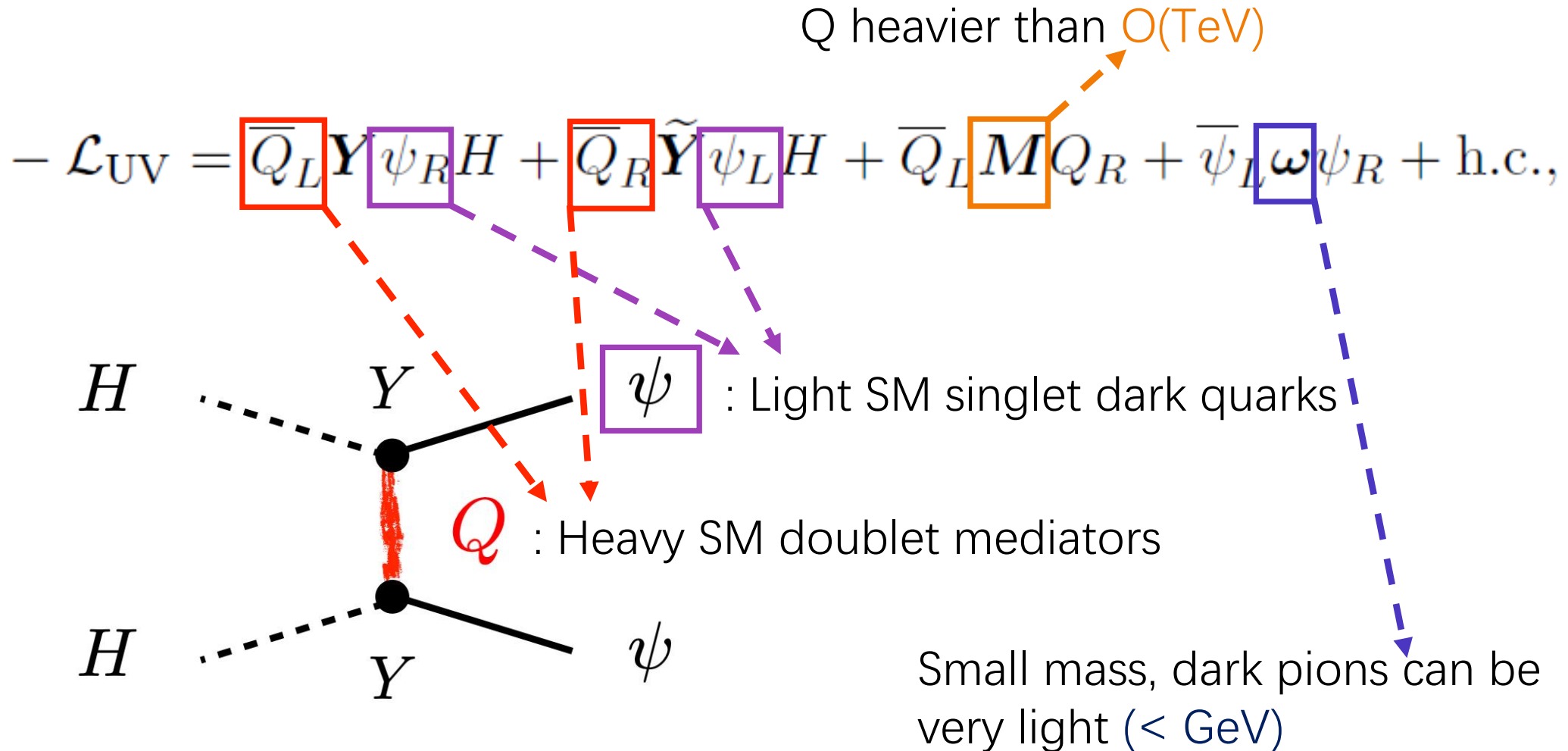


If the potential comes from the dark sector, the model avoids strong CP bounds.

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

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

# Irrelevant Portal Dark Pions



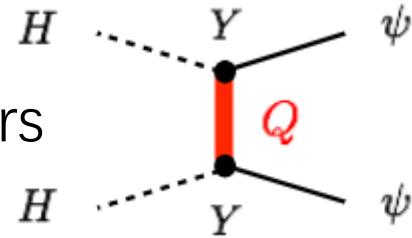
# Irrelevant Portal Dark Pions (II)

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

$\omega, \mathbf{M}, \mathbf{Y}, \tilde{\mathbf{Y}}$  : N by N mass/Yukawa matrixes

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

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



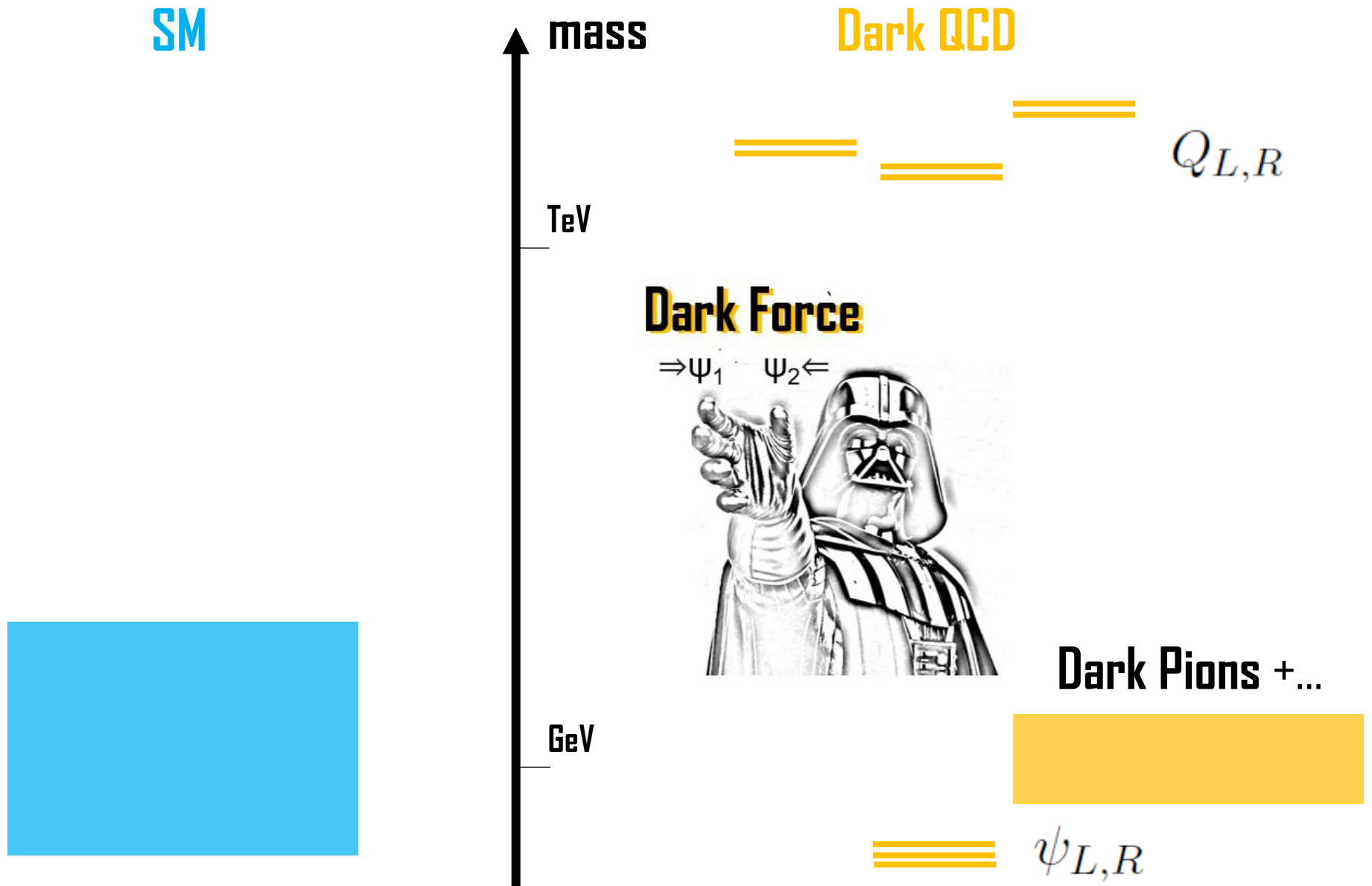
$$\begin{aligned} \mathcal{L}_{\text{EFT}} = & \frac{1}{2} \bar{\psi}_R \mathbf{Y}^\dagger \mathbf{M}^{-2} \mathbf{Y} \left[ |H|^2 i \not{D} + i \gamma^\mu H^\dagger D_\mu H \right] \psi_R + \text{h.c.} \\ & + \frac{1}{2} \bar{\psi}_L \tilde{\mathbf{Y}}^\dagger \mathbf{M}^{-2} \tilde{\mathbf{Y}} \left[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

Dimension-6 Z portal couplings

Dimension-5 Higgs portal coupling

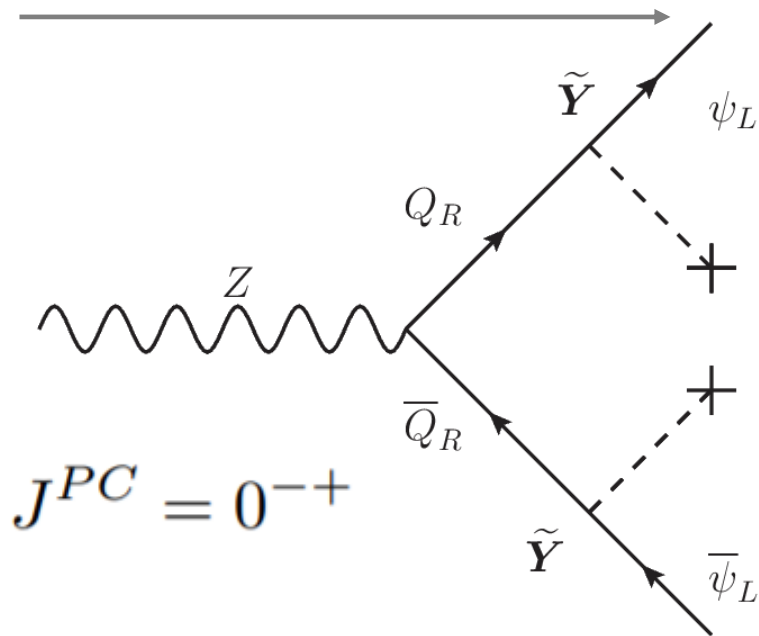
$$\omega, \frac{Y \tilde{Y} v^2}{M} \ll \Lambda \quad \rightarrow \quad (N^2 - 1) \text{ pNGBs}$$

# The Cartoon of Dark Spectrum



# Two Flavor, Three Dark Pions

Z portal dark pion production



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

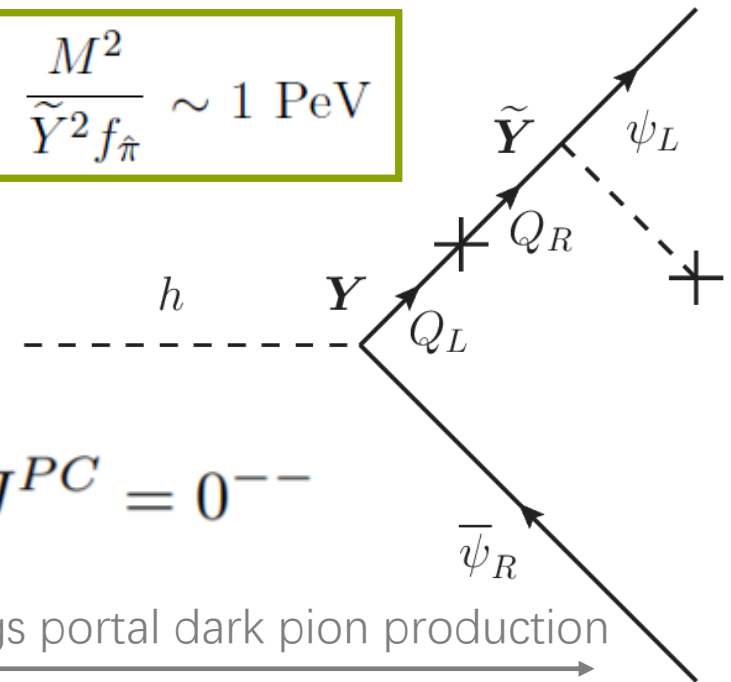
The  $\pi_1$  and  $\pi_3$  decay via Z portal, ALP-like (axion-like-particle) with **large ALP decay constants**:

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

Z portal dark pion decay

The  $\pi_2$  mix with the Higgs since it's CP-even, with **mixing angle**:

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

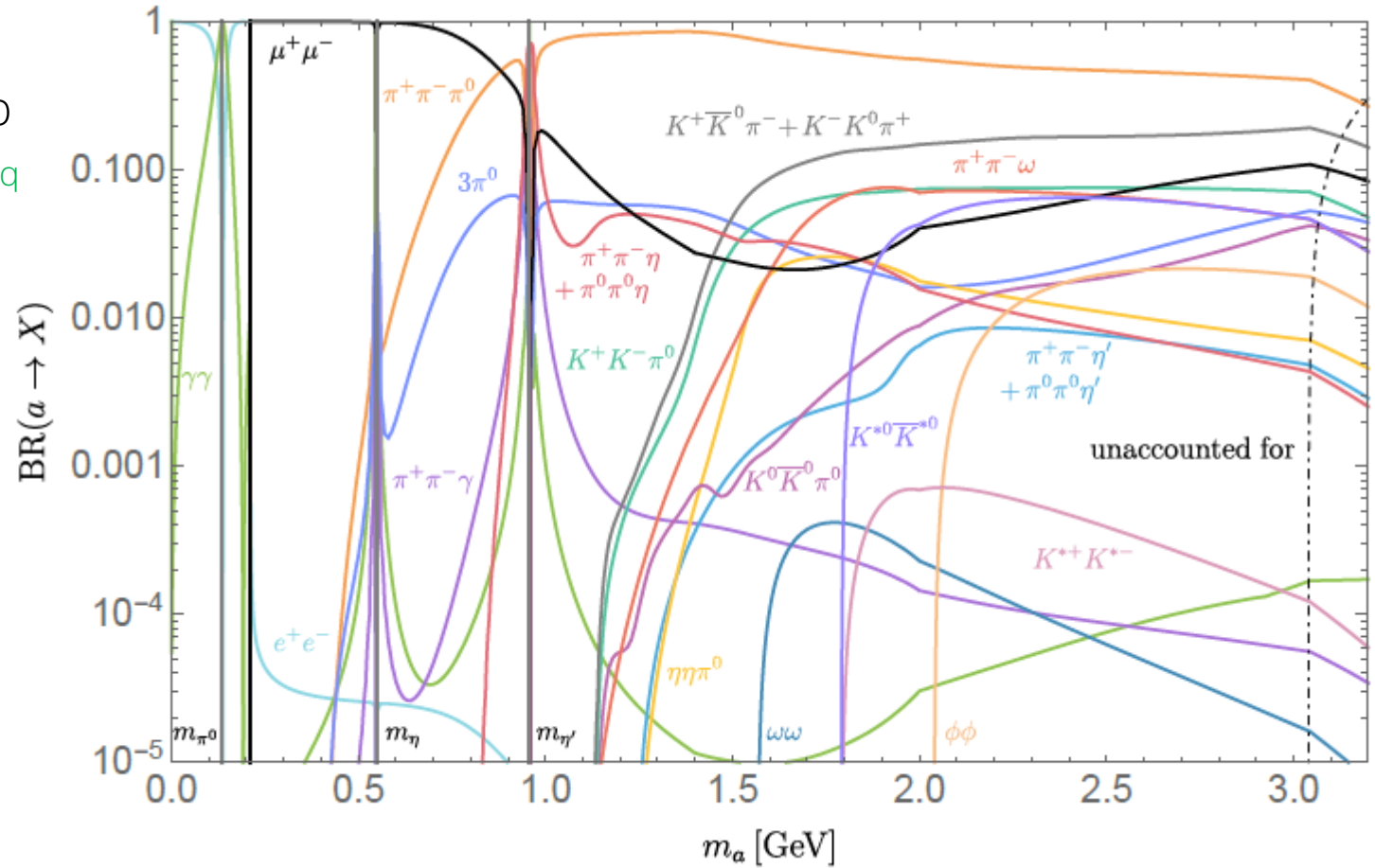


Higgs portal dark pion production

Higgs portal dark pion decays

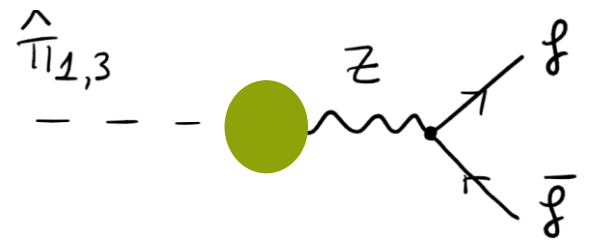
# Dark Pion Decays (ALP-Like)

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



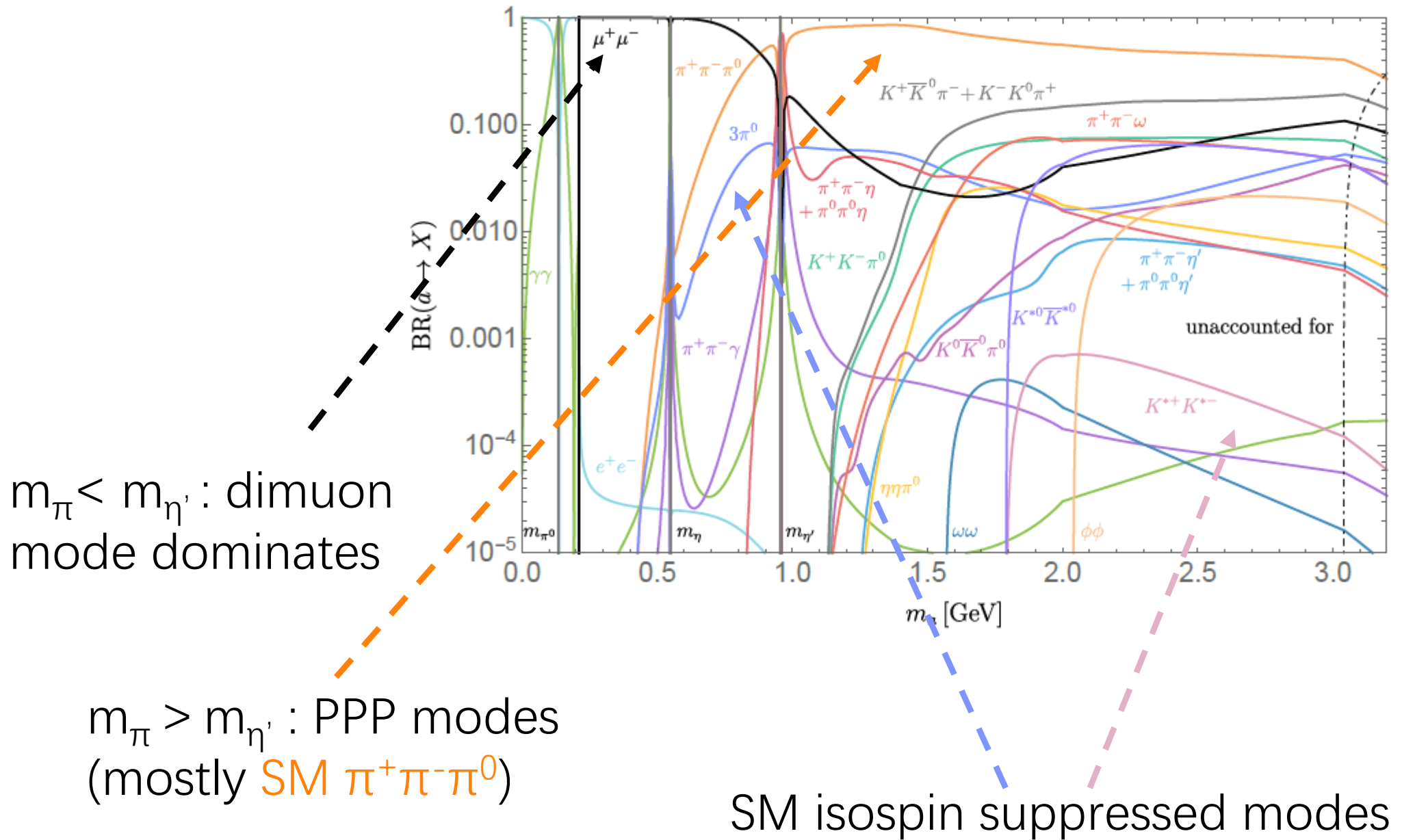
- A.1  $a \rightarrow \gamma\gamma$
- A.2  $a \rightarrow \pi^+\pi^-\gamma$
- A.3  $a \rightarrow \pi^+\pi^-\pi^0$
- A.4  $a \rightarrow 3\pi^0$
- A.5  $a \rightarrow \pi^0\pi^0\eta, \pi^+\pi^-$
- A.6  $a \rightarrow \pi^0\pi^0\eta', \pi^+\pi^-$
- A.7  $a \rightarrow \eta\eta\pi^0$
- A.8  $a \rightarrow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

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



Lingfeng Li (Brown U.) arXiv: 2110.10691

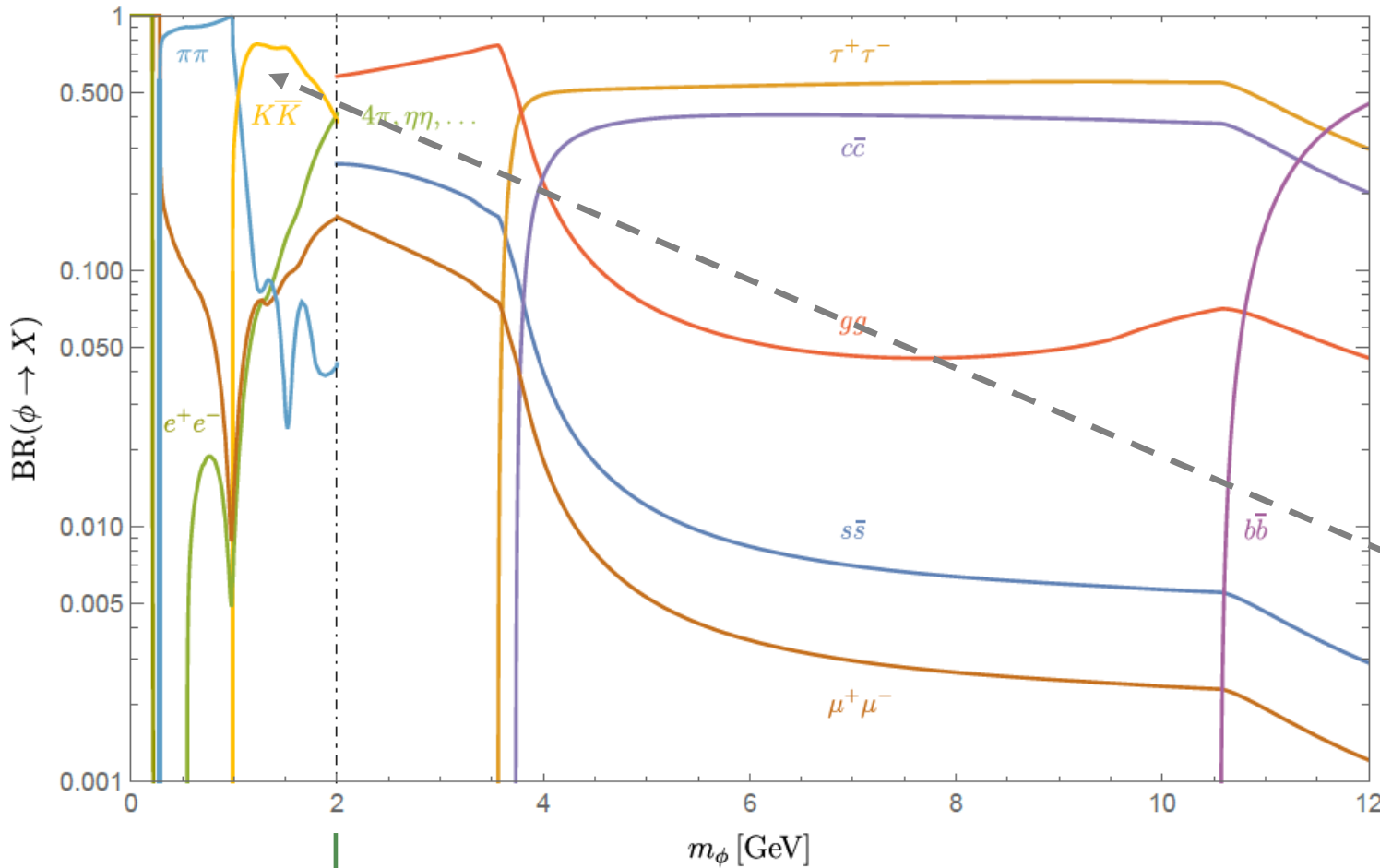
# Dark Pion Decays (ALP-Like, II)



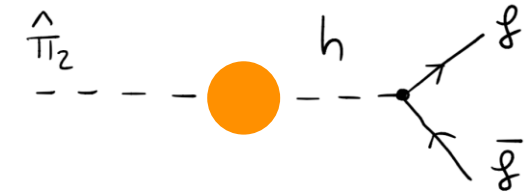


# Higgs Portal Decays

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



$$\mathcal{L}_{\text{eff}} \sim -s_\theta \frac{m_f}{v} \hat{\pi} f \bar{f}$$



$\pi\pi$  or  $KK$   
dominate  
low mass  
region

Perturbative QCD results

Hadronic Exclusives

Lingfeng Li (Brown U.) arXiv: 2110.10691

# Dark Chiral perturbation Theory

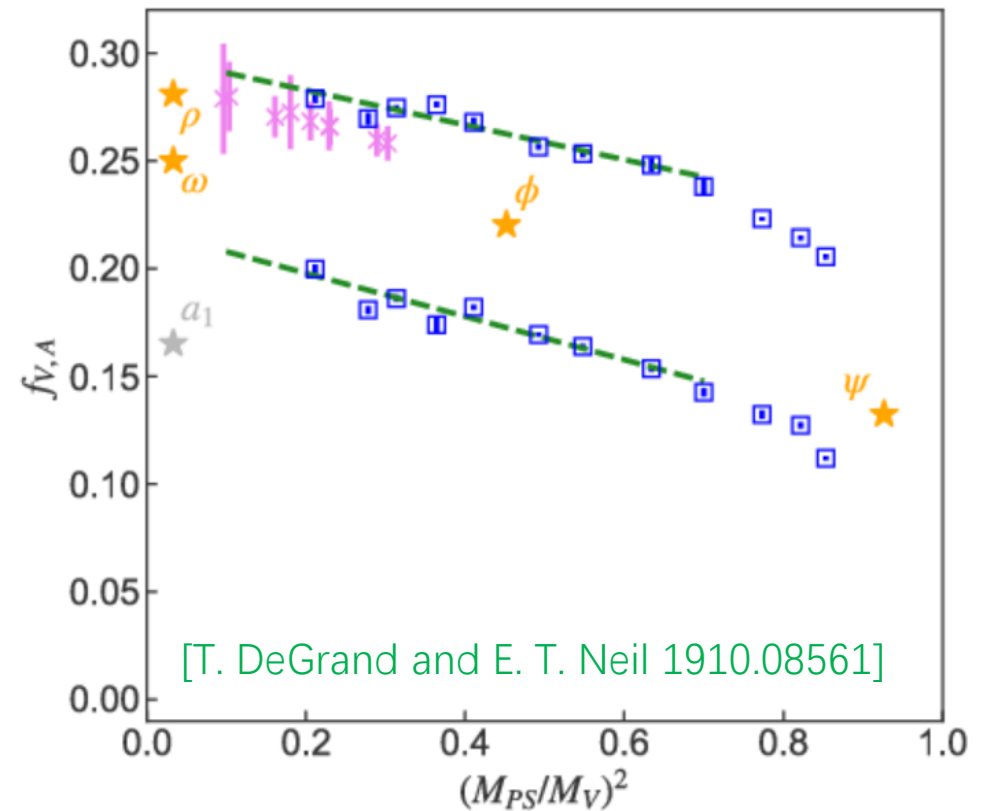
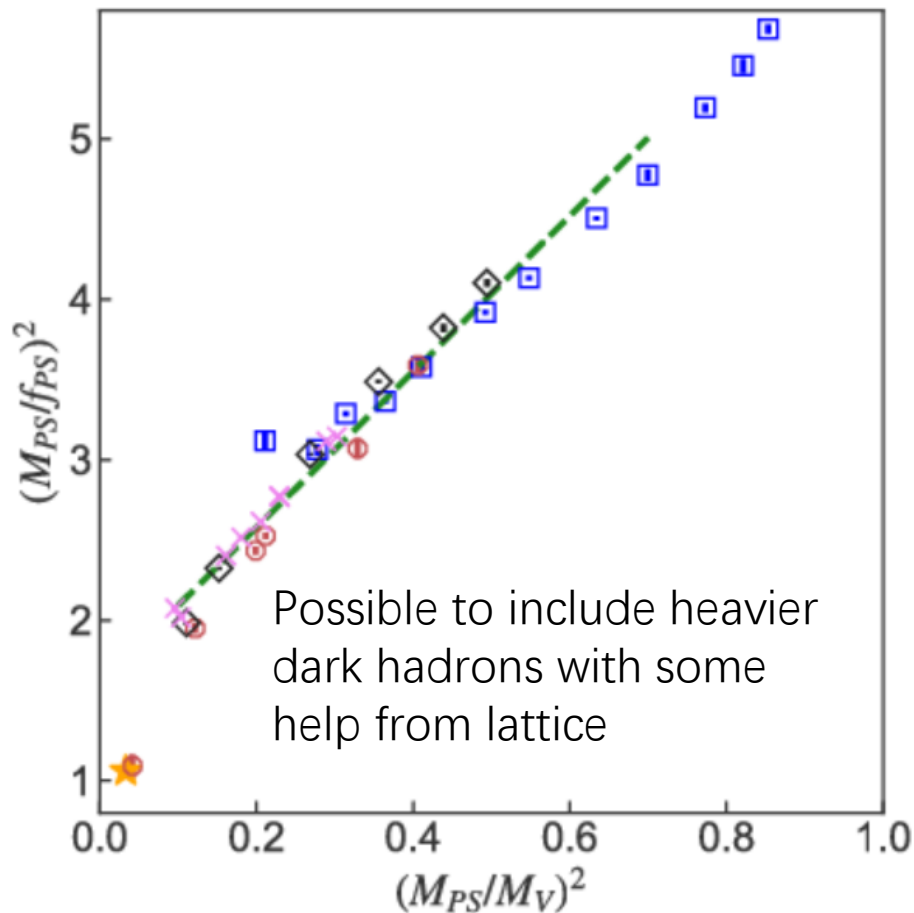
Dark ChpT describe more complicated interaction patterns and dark isospin breaking. Useful at  $E \ll m_Z$

$$U = \exp\left(i \frac{\sigma_a \hat{\pi}^a}{f_{\hat{\pi}}}\right)$$

$$\mathcal{L}_{\hat{\pi}}^{(2)} \supset \frac{f_{\hat{\pi}}^2}{4} \text{Tr}[(D^\mu U)^\dagger D_\mu U] + \frac{\hat{B}_0 f_{\hat{\pi}}^2}{2} \text{Tr}[U \widehat{m}_{\psi'}^\dagger + \widehat{m}_{\psi'} U^\dagger]$$

$$\widehat{m}_{\psi'} = m_{\psi'} - Bh$$

$$D_\mu U = \partial_\mu U - i \frac{g_Z}{2} (\mathbf{A}U - U \tilde{\mathbf{A}}) Z_\mu$$



# Dark Pion from SM FCNC

Although suppressed by CKM and loop, still relevant since  $\Gamma_{B,K}$  are suppressed by  $(M_W)^{-4}$  in SM.

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

Amplitude can be fully adapted from  $ds \rightarrow \nu\nu$  results in [Inami, Lim 1980]

The four-fermion interaction then followed by the factorization

Finite terms introduces a numerical suppression  $\sim 3$

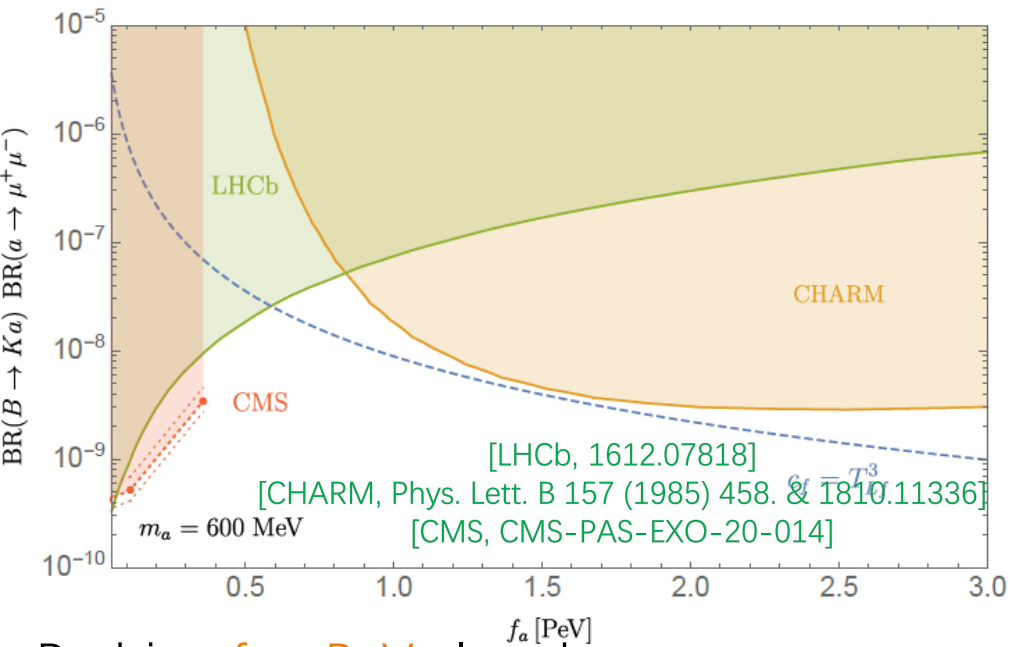
$$\langle \hat{\pi}_a X | \mathcal{H}_{\text{eff}} | B \rangle = \langle \hat{\pi}_a | \langle X | \mathcal{H}_{\text{eff}} | 0 \rangle | B \rangle = \frac{ig^2}{64\pi^2} V_{ts}^* V_{tb} \langle X | \bar{s}_L \gamma_\mu b_L | B \rangle \frac{p_{\hat{\pi}}^\mu}{f_a^{(a)}} \left[ \frac{m_t^2}{m_W^2} \left(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

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

Experimentally achievable if dark pions are LLP

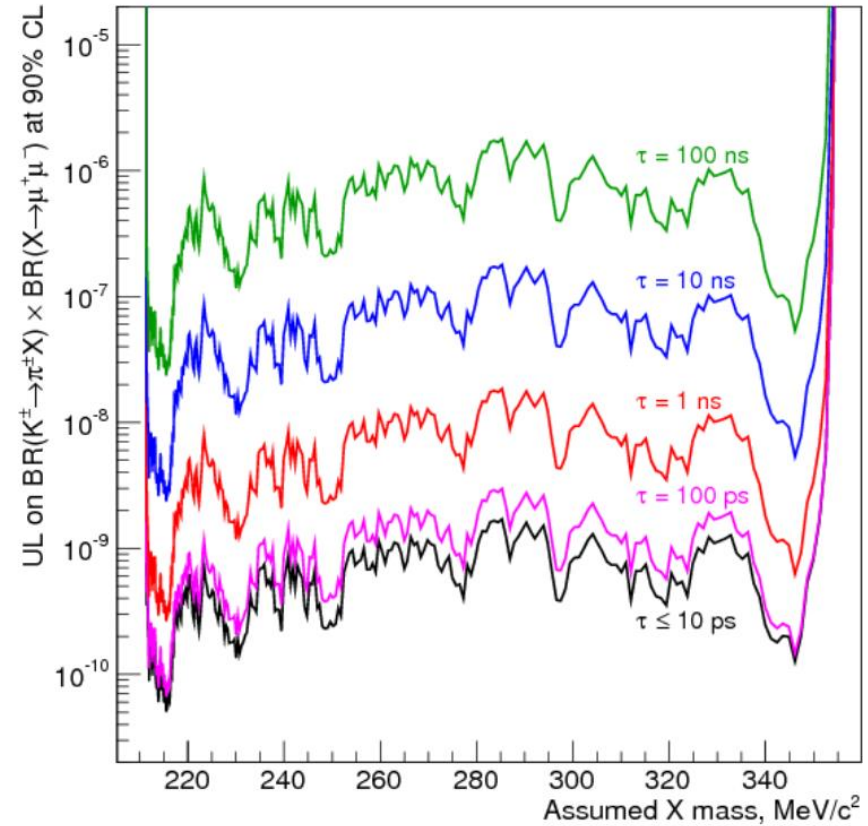
# Current FCNC Bounds (B,K decay)

The bound as long as the experimental  $E_{cm} >$  the BB/KK thresholds  
Limits coming from LHC, ee colliders and beam dump experiments.



Probing  $f_a \sim \text{PeV}$  already

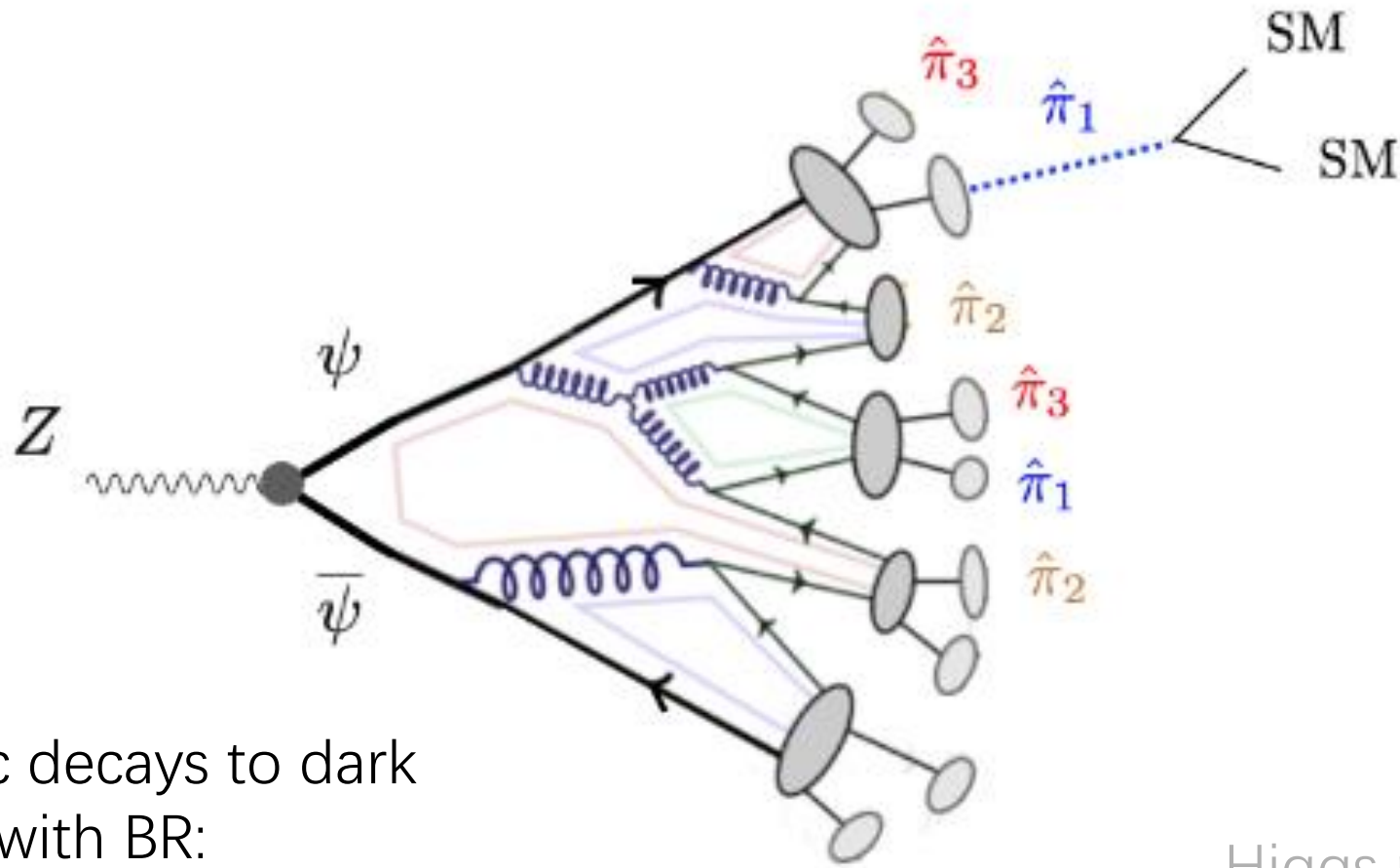
Reaching  $O(8-60) \text{ PeV}$  for future experiments



Kaon FCNC + LLP mode probes  
 $f_a \sim \text{PeV}$  also. [NA48/2 1612.04723]

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

# Phenomenology @ the EW Scale



Z exotic decays to dark quarks with BR:

$$1.8 \times 10^{-4} \left( \frac{N_d \text{Tr}(\mathbf{Y}\mathbf{Y}^\dagger\mathbf{Y}\mathbf{Y}^\dagger) + (\mathbf{Y} \rightarrow \tilde{\mathbf{Y}})}{3} \right) \left( \frac{1 \text{ TeV}}{M} \right)^4$$

Usually dominates the phenomenology because of large statistics:

>  $10^{11}$  Z Bosons @ HL-LHC

Higgs portal only relevant when both  $\mathbf{Y}$ ,  $\tilde{\mathbf{Y}}$  are large

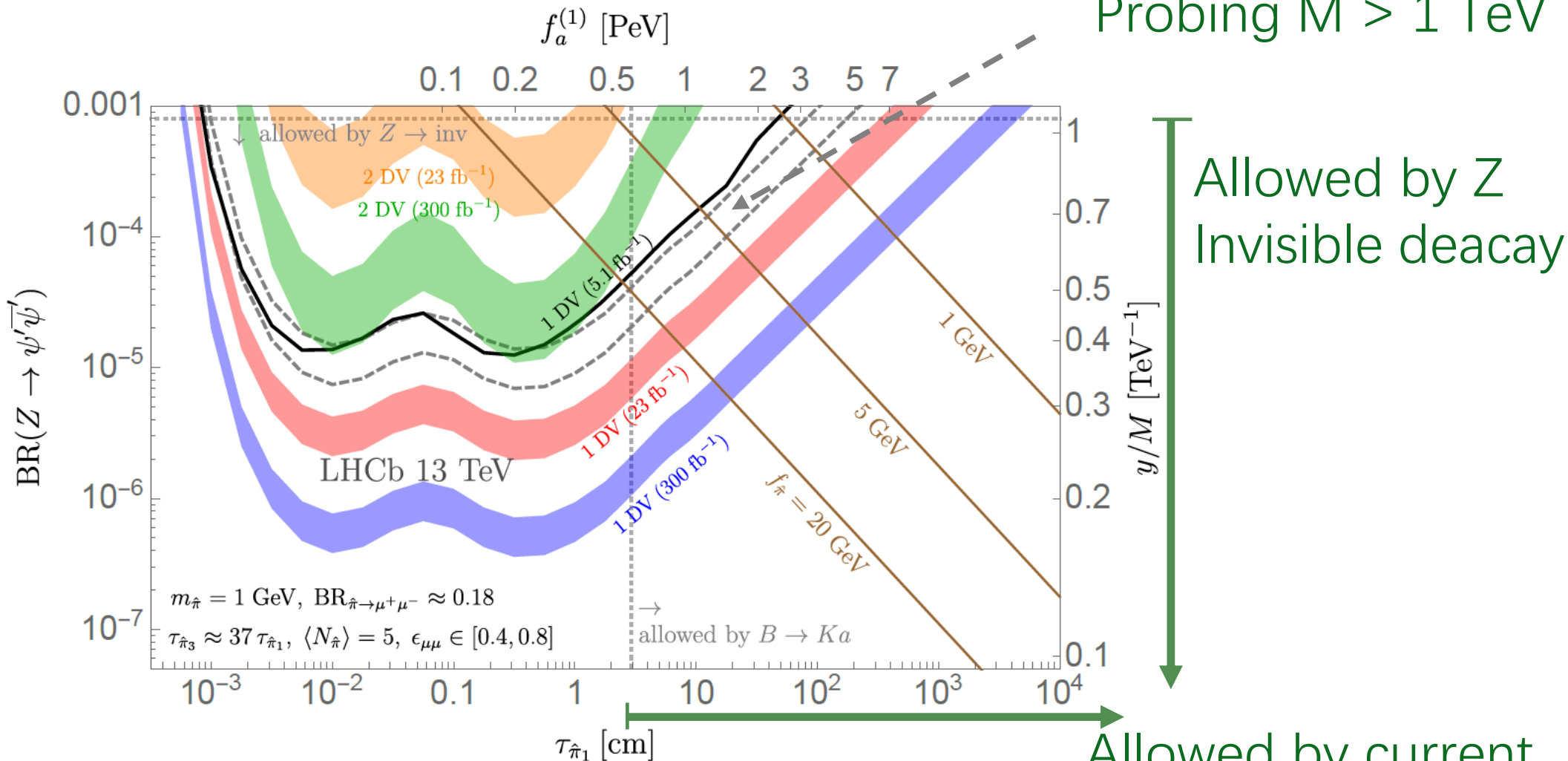
$$\sigma_Z \approx 55 \text{ nb}$$

$$\sigma_h \approx 49 \text{ pb}$$

# Example: Dimuon Search @ LHCb

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

Probing  $M > 1$  TeV



Allowed by Z  
Invisible decay

Allowed by current  
FCNC bounds

# 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  $M \sim$  a few TeV is achievable.
- Open fields (other dark mesons, intensity frontier, cosmology) remain to be fully explored.

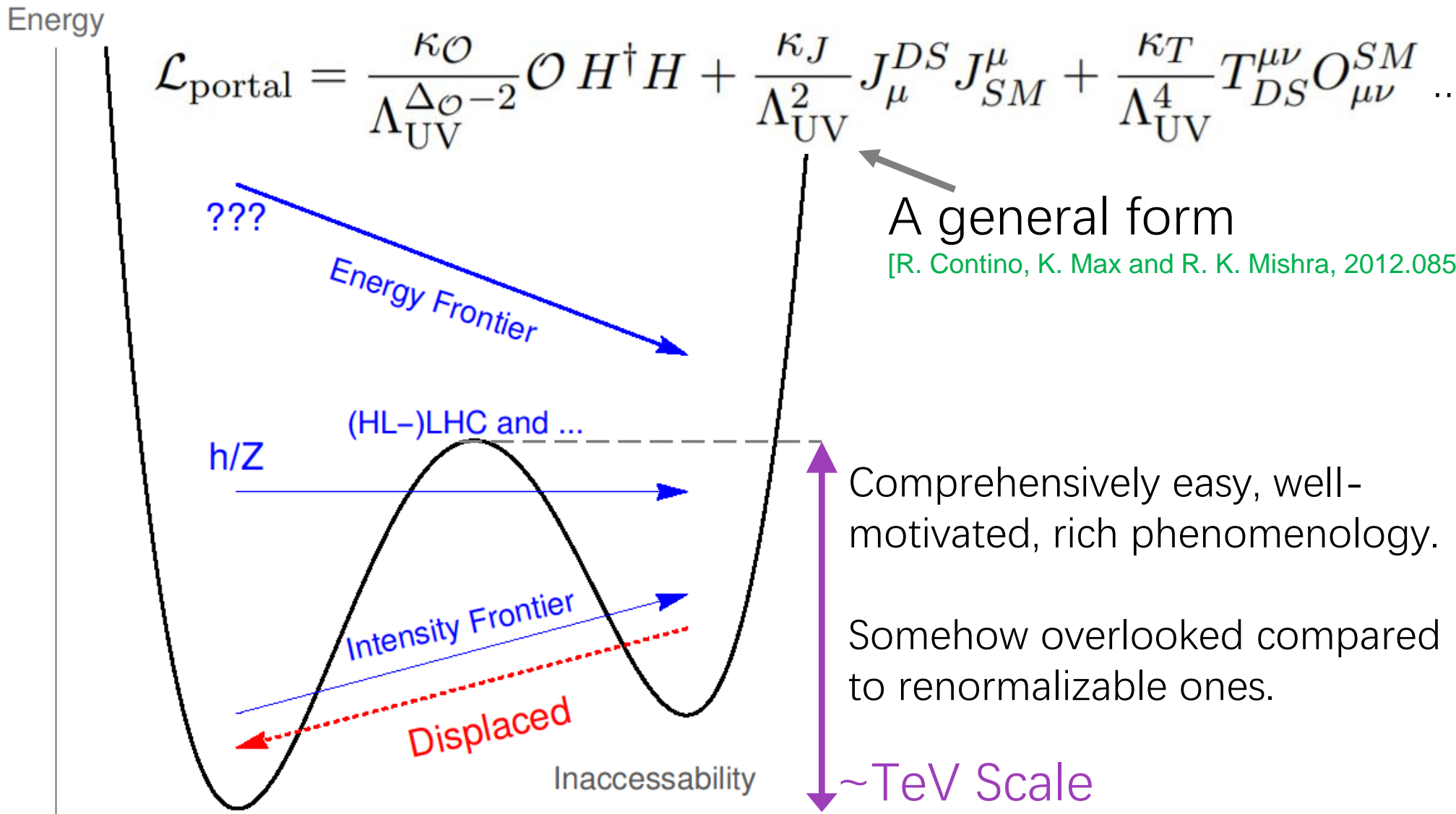
# Backup Slides

# The Irrelevant Portal

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

A general form

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



# Alternative Tripled Top (TT) Model

The superpotential :

$$W'_{Z_3} = y_t(\underbrace{Q_A H u_A^c}_{\text{A}} + \underbrace{Q_B H u_B^c}_{\text{B}} + \underbrace{Q_C H u_C^c}_{\text{C}}) + \omega(u'_B u_B^c + u'_C u_C^c) + M(Q_B Q'_B + Q_C Q'_C)$$

Arbitrarily light

A few TeV

**A, B & C:** 3 sectors charged under different SU(3),

The soft breaking term:

A few TeV ( $\approx M$ )

$$V_s = \tilde{m}^2 (|\tilde{Q}_A|^2 + |\tilde{u}_A^c|^2) - \tilde{m}^2 (|\tilde{u}_B^c|^2 + |\tilde{u}_C^c|^2) .$$

A Folded SUSY-like spectrum realized in 4D

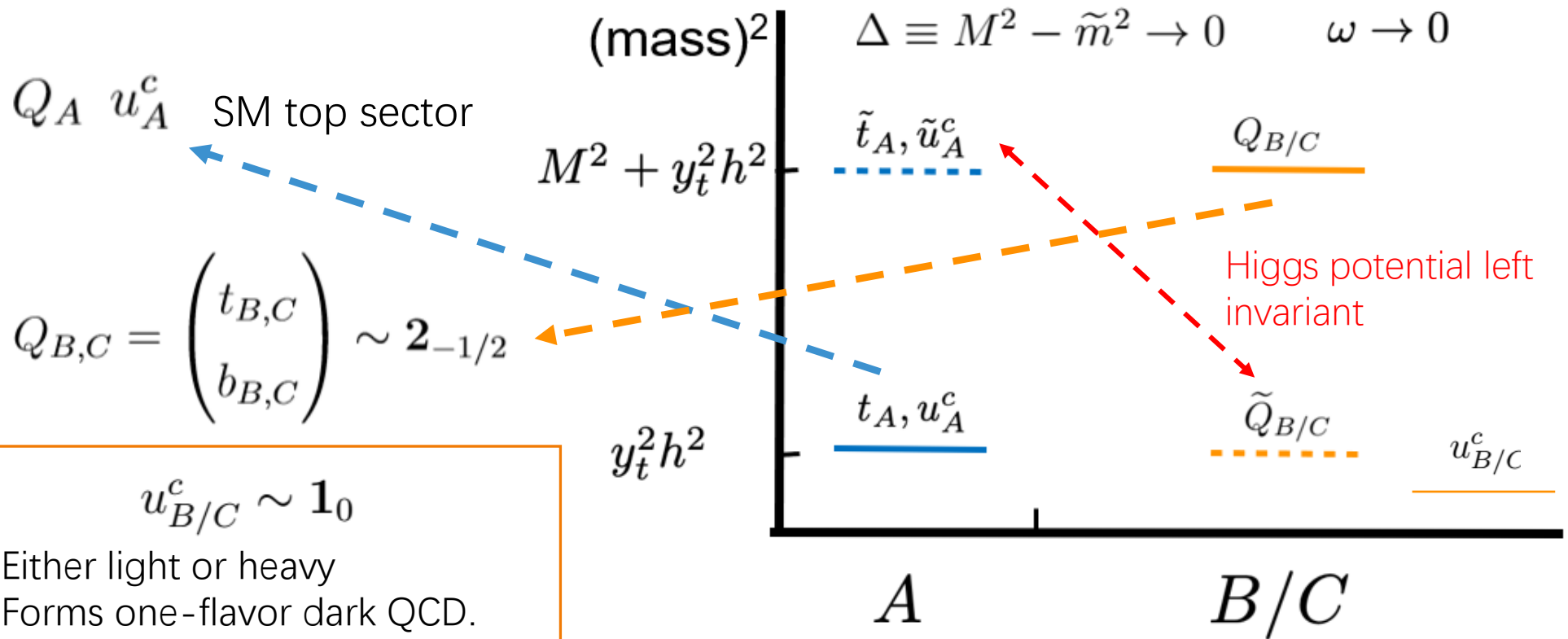
For details of the original model, see [H-C.Cheng, LL, E.Salvioni and C. Verhaareen 1803.03561]

1803.03651 1905.03772 20xy.ijklm

# Alternate Tripled Top (TT) Model & Accidental SUSY

$$W'_{Z_3} = y_t(Q_A H u_A^c + Q_B H u_B^c + Q_C H u_C^c) + \omega(u'_B u_B^c + u'_C u_C^c) + M(Q_B Q'_B{}^c + Q_C Q'_C{}^c)$$

$$V'_s = \tilde{m}^2(|\tilde{Q}_A|^2 + |\tilde{u}_A^c|^2) - \tilde{m}^2(|\tilde{Q}_B|^2 + |\tilde{Q}_C|^2)$$

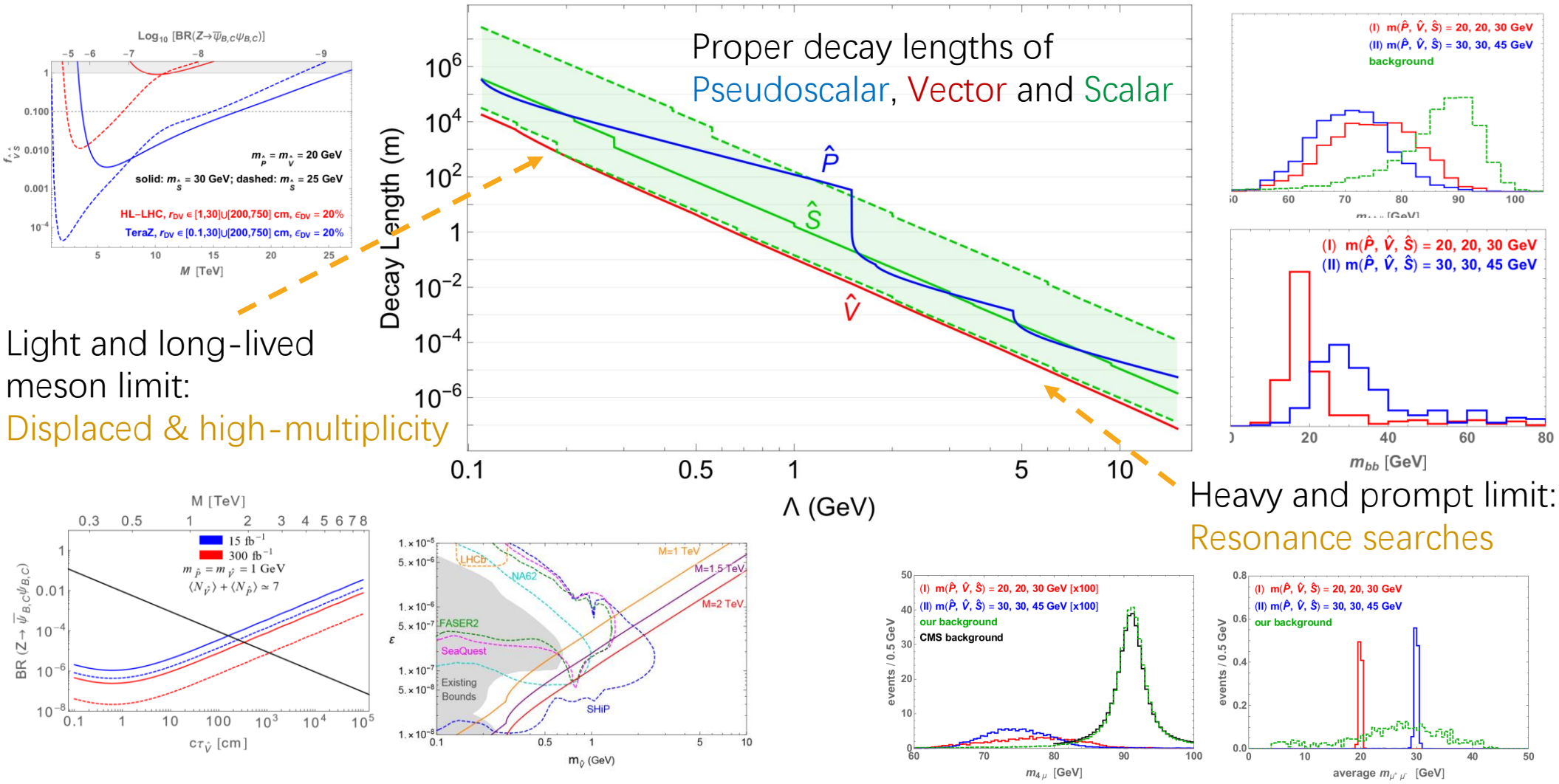


$u_{B/C}^c \sim 1_0$

Either light or heavy  
Forms one-flavor dark QCD.  
Dark hadrons:  
Pseudoscalar, Vector and Scalar

1803.03651 1905.03772 20xy.ijklm

# Dark Meson Phenomenology: (One flavor Dark QCD- No Dark Pions)

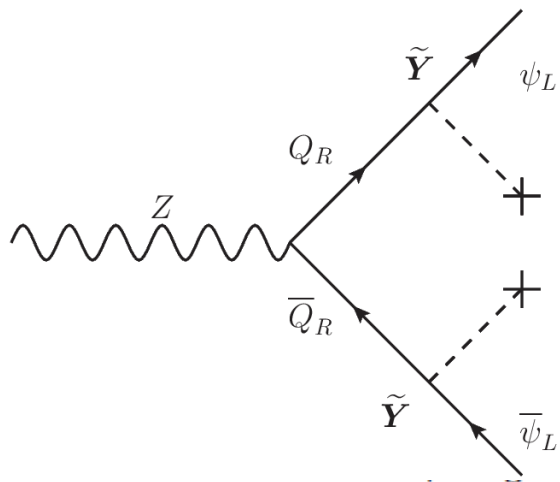
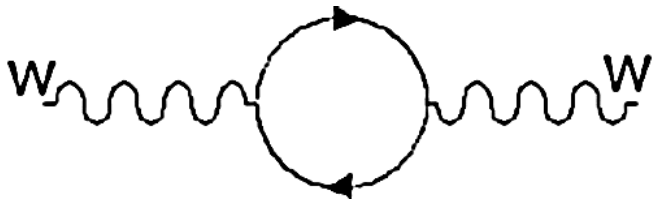


Details of phenomenology : [H-C.Cheng, LL, E.Salvioni and C. Verhaaren 1905.03772]

# Indirect/Precision Constraints

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

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

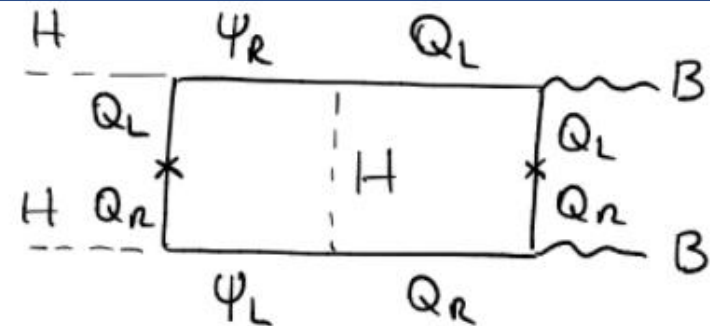
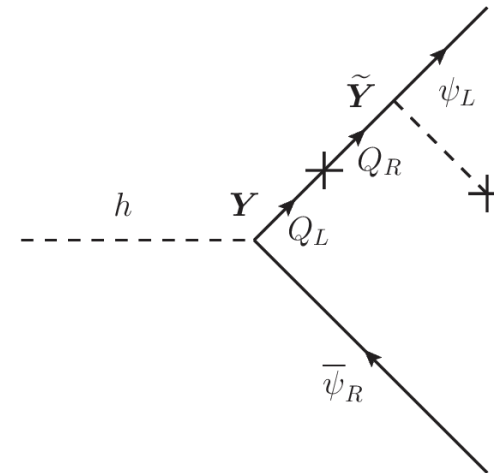


$$M \gtrsim 0.8 \text{ TeV } Y \left( \frac{N_d N}{6} \right)^{1/4}$$

From Z invisible decay width  $< \sim 2 \text{ MeV}$

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

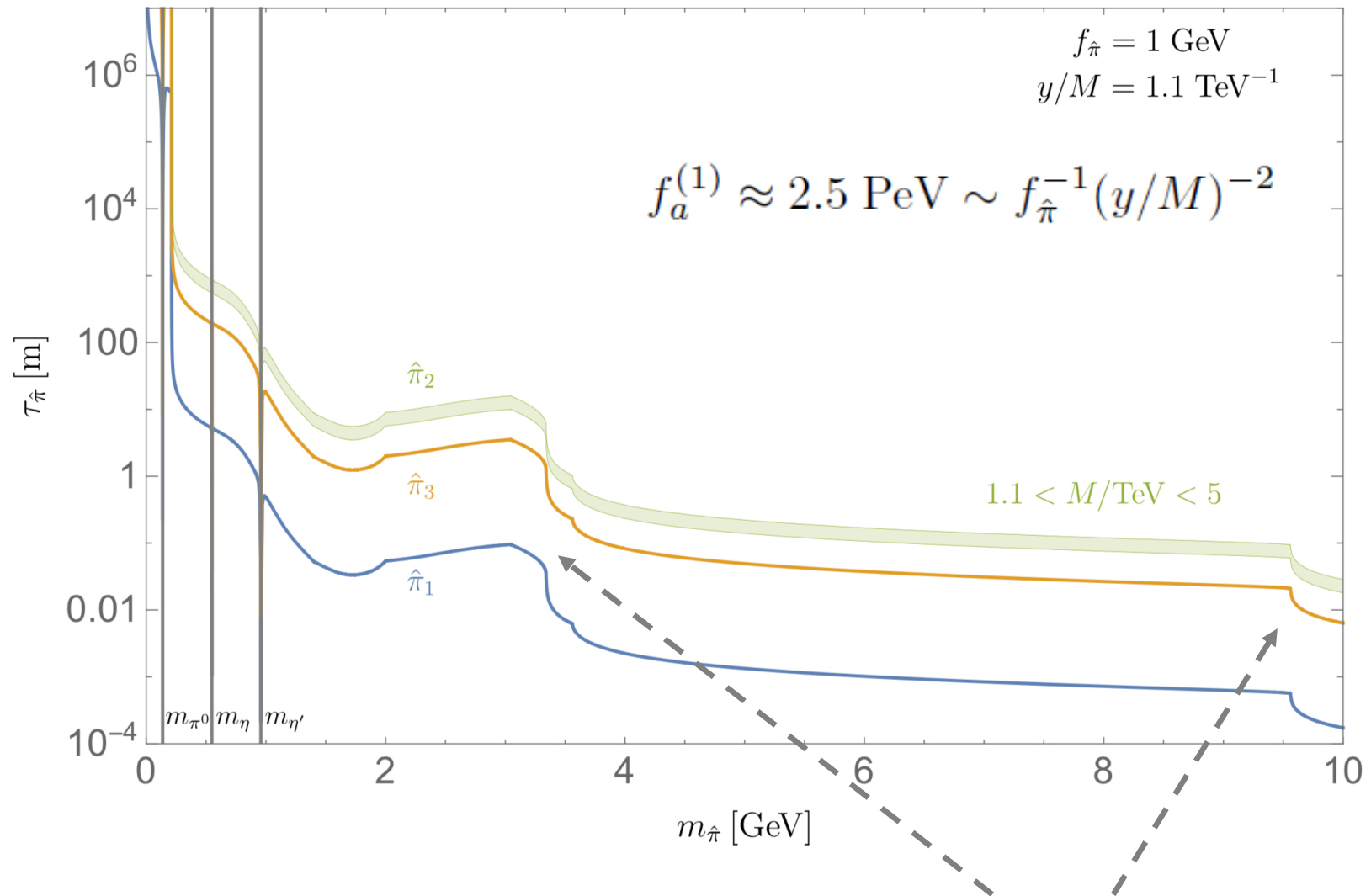
From Higgs invisible decay BR  $< 13\%$



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

From electron EDM  
if CP is violated maximally

# LLP in the Z Portal Dominance

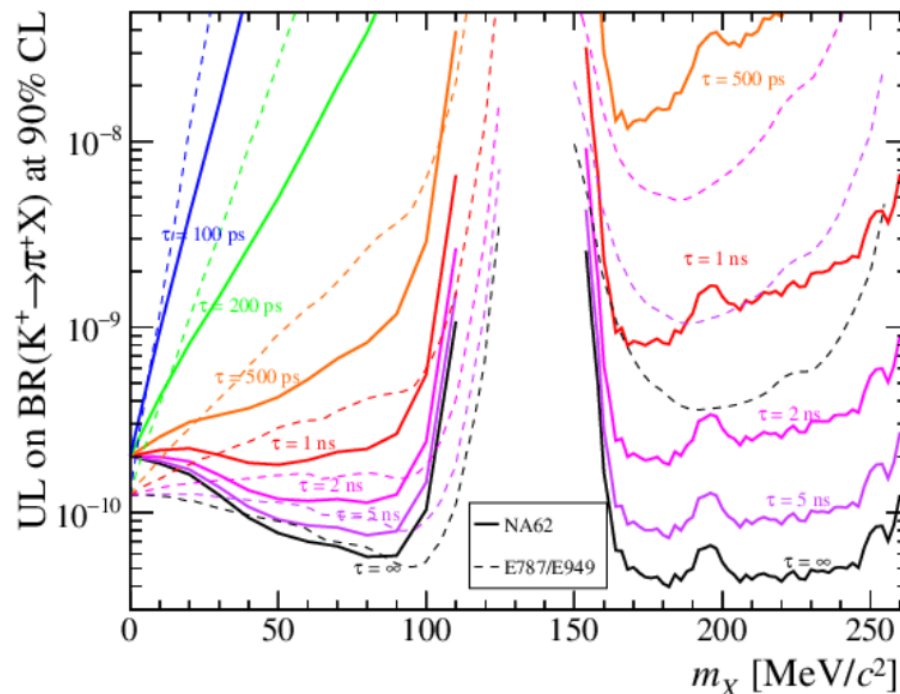
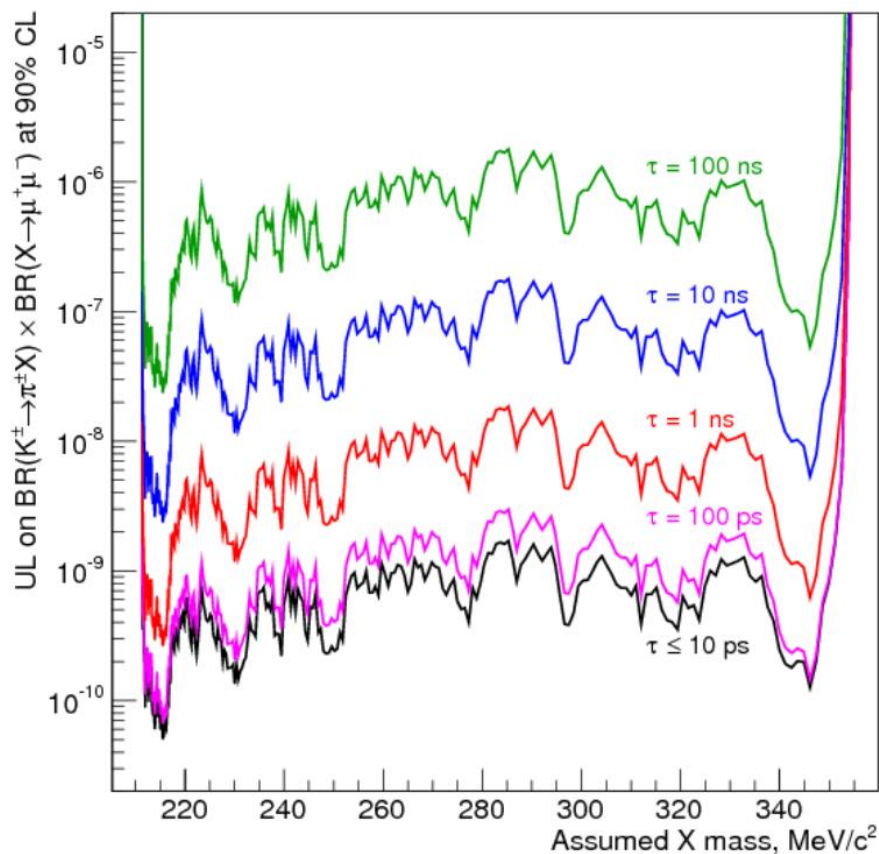


# Current FCNC Bounds (K decay)

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

Kaon FCNC + LLP mode probes

$f_a \sim \text{PeV}$  also. [NA48/2 1612.04723]



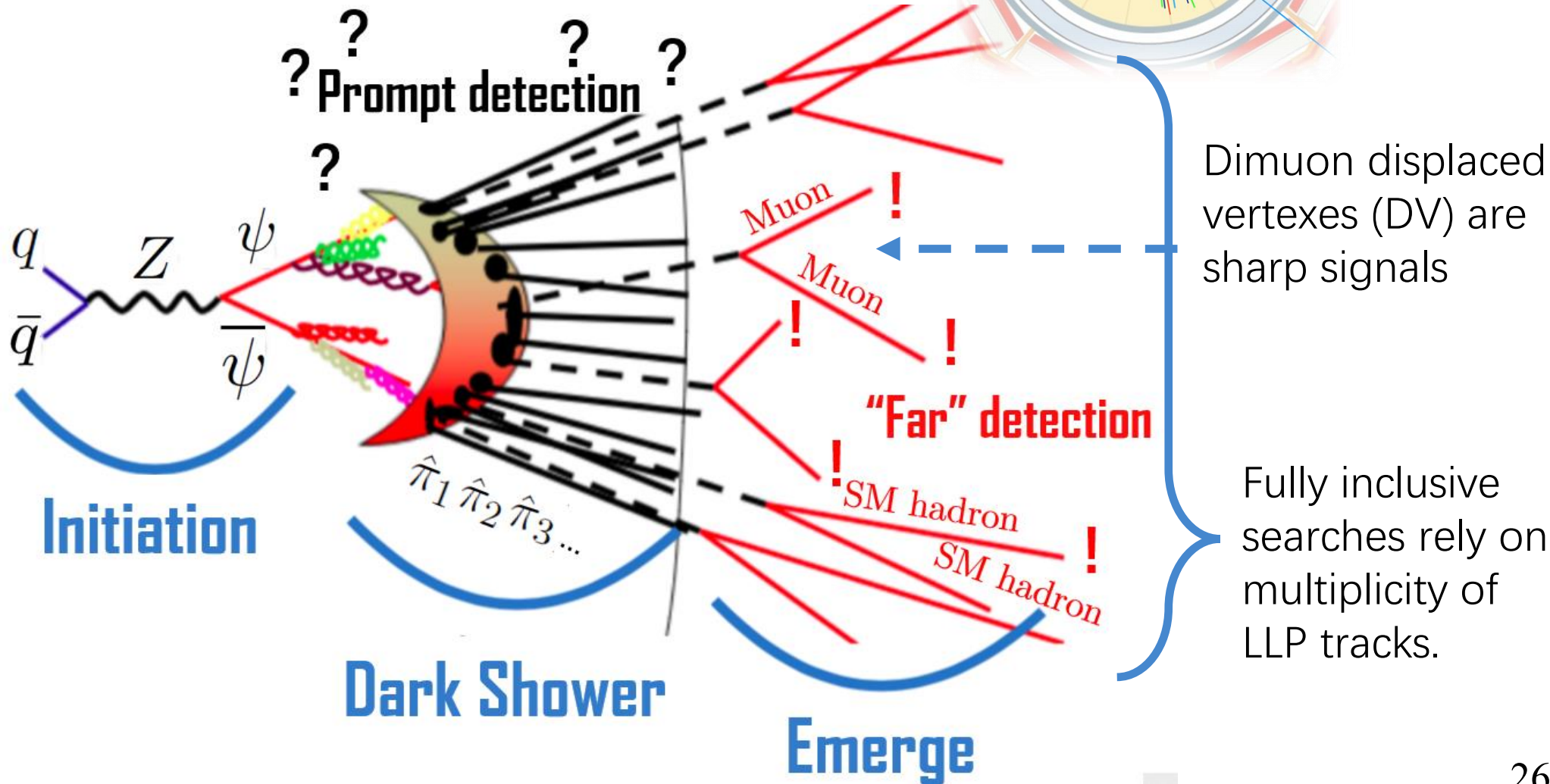
Kaon FCNC invisible modes give similar constraints as the LLP mode. [NA62 2011.11329]

# EW Scale Phenomenology @ LHC

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

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

[CMS, 1810.10069]



# Symmetries of the Dark Pion Model

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

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

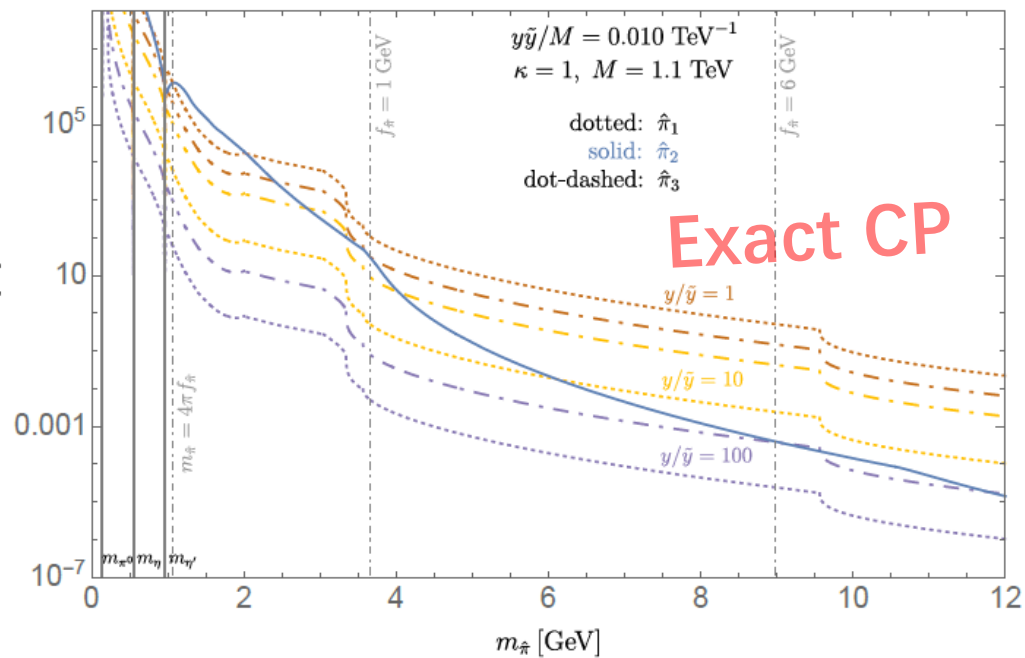
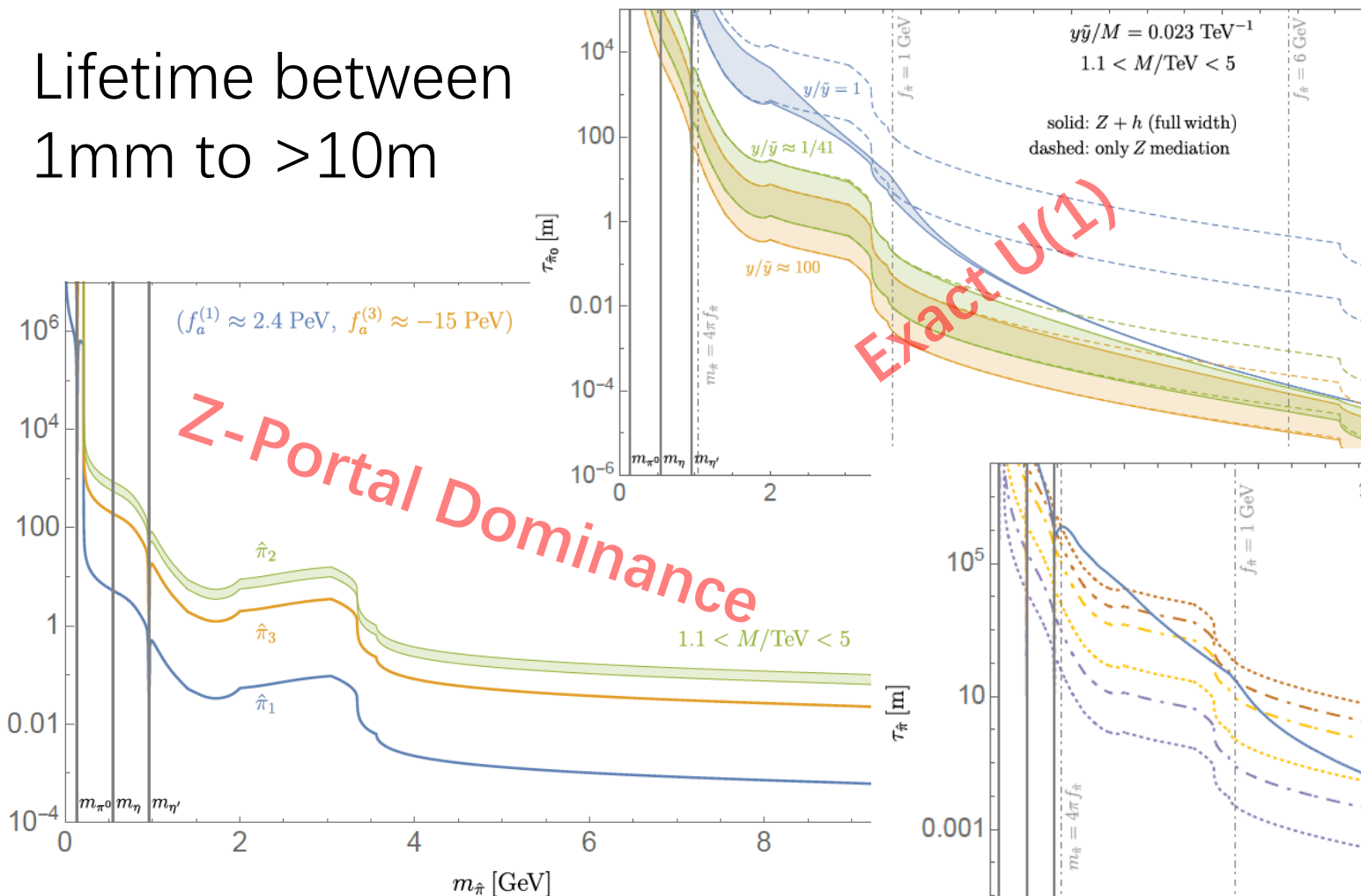
The  $U(1)$  subgroup of the  $SU(2)$  isospin is exact if everything is diagonal

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

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

# Dark Pion as Long-lived Particles

Lifetime between 1mm to >10m



Easy LLP with strong parameter dependence

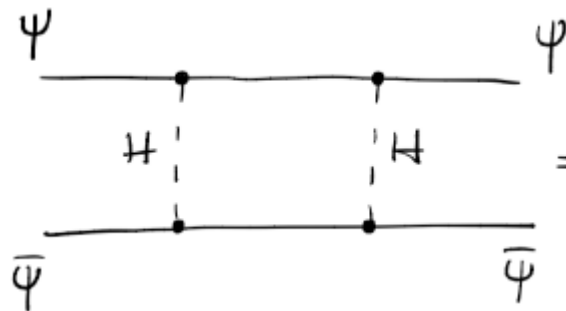
# Case Study: Z Portal Dominance

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

Higgs invisible decay width constraints irrelevant

$$\mathbf{Y} = \begin{pmatrix} y_{11} & y_{12} e^{i\alpha} \\ y_{21} & y_{22} \end{pmatrix}$$

For N=2 case, contains a free CP phase



$\Rightarrow \pi_2$  decays via the CP-violating mixing with  $\pi_1$

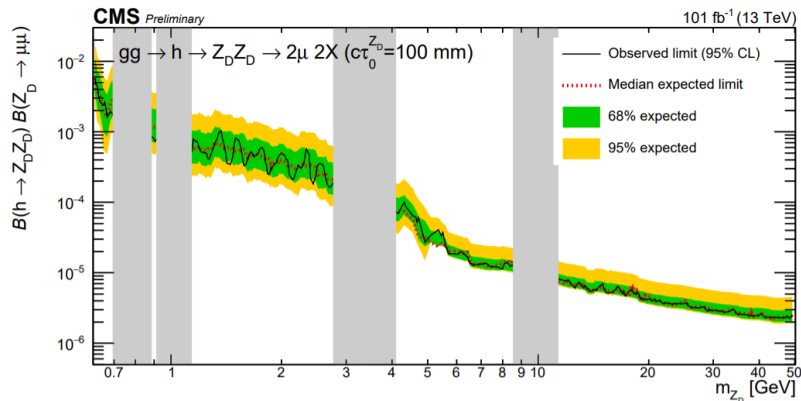
$$\tan 2\theta_{12} \approx \frac{0.20}{1 + 0.036 \left(\frac{4\pi v}{M}\right)^2}$$

$$\rightarrow \Gamma_{\hat{\pi}_2} \approx \sin^2 \theta_{12} \Gamma_{\hat{\pi}_1}$$

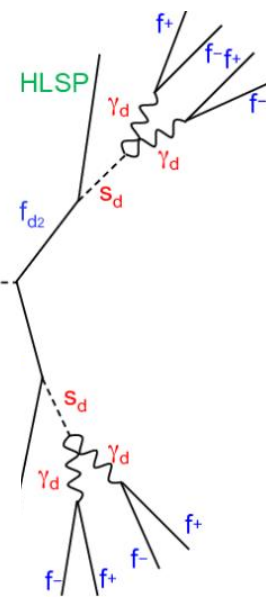
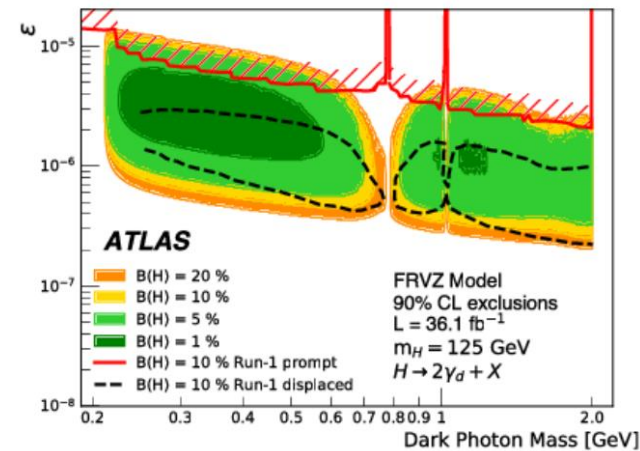
# Further Opportunities @ LHC

ATLAS/CMS benefit from larger luminosities and decay volume.

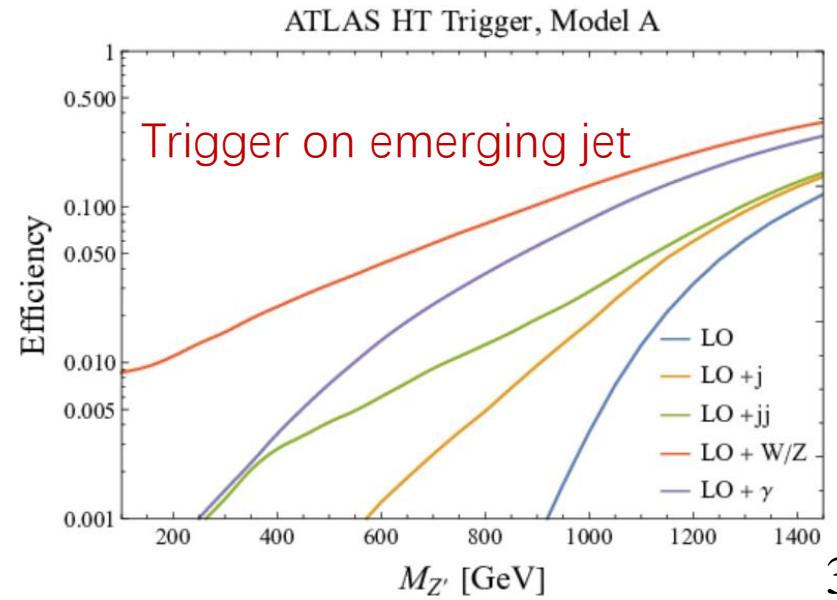
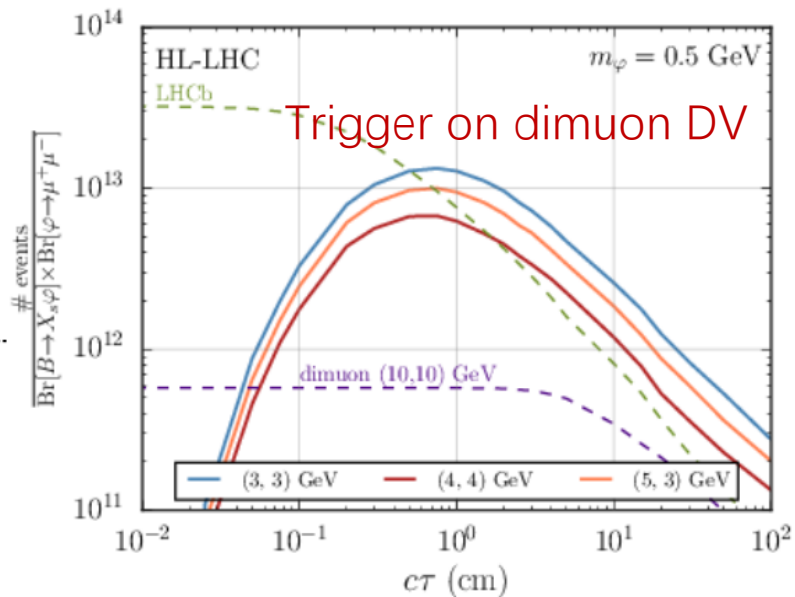
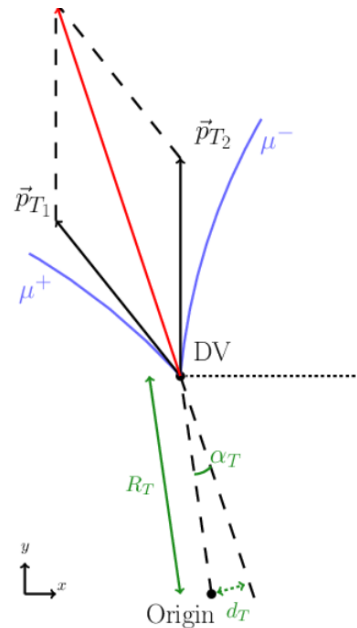
[CMS: CMS-PAS-EXO-20-014]



[ATLAS: 1909.01246]

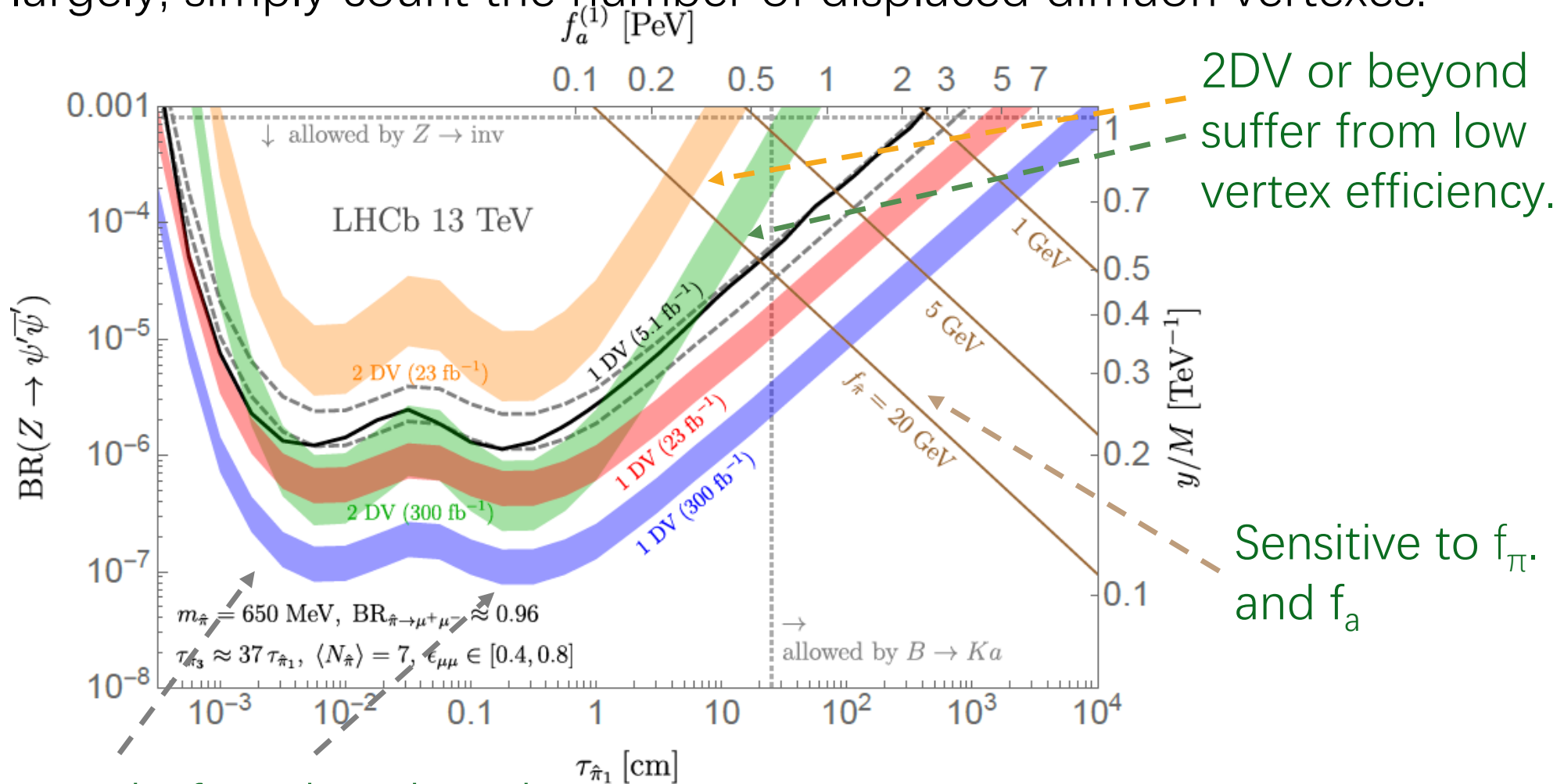


LLP oriented triggers? [Y. Gershtein and S. Knapen, 1907.00007, D. Linthorne and D. Stolarski, 2103.08620]



# Example: Dimuon Search @ LHCb

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



Two peaks from benchmark pion width ratio 1:37

Data from [LHCb 2007.03923]

Lingfeng Li (Brown U.) arXiv: 2110.10691

# TeV Scale Phenomenology @ LHC

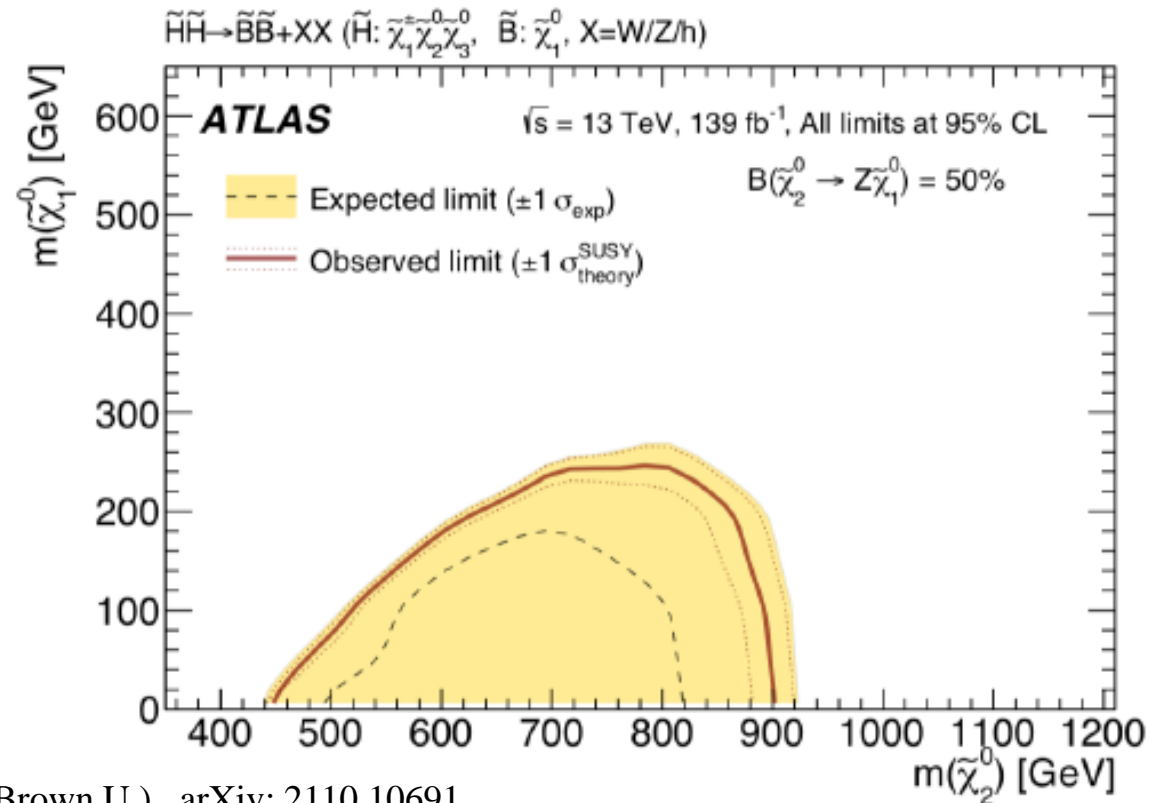
Direct production of heavy EW doublets:

$$\hat{\sigma}(u\bar{d} \rightarrow Q_u\bar{Q}_d) = \frac{N_d \pi \alpha_W^2}{N_c 6\hat{s}} \frac{\hat{s}^2}{(\hat{s} - m_W^2)^2} \left(1 - \frac{4M^2}{\hat{s}}\right)^{1/2} \left(1 + \frac{2M^2}{\hat{s}}\right)$$

⇒ Diboson + emerging jet signals

If dark pions are invisible, similar with SUSY electroweakino searches.

Estimated limit:  $M > 1.3$  TeV @ HL-LHC



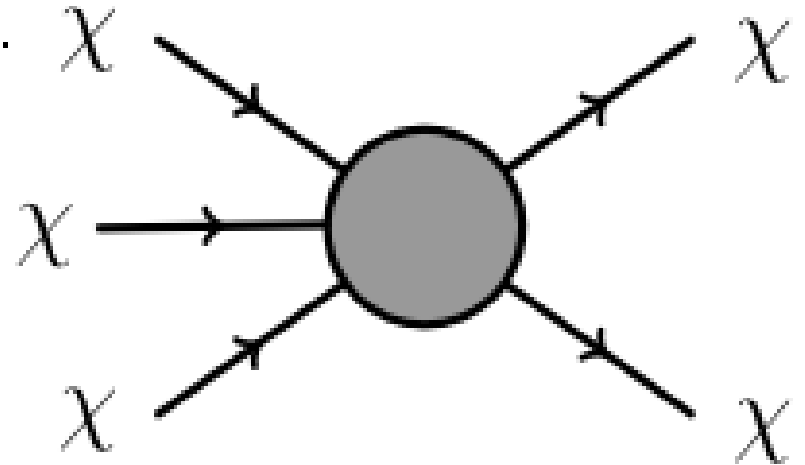
# Comments on Cosmology

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

If isospin is exact, all dark pions are stable.

$N > 2$  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 keep the dump the entropy generated.



The DM possibilities are still wide open with non-minimal dark components.

e.g., asymmetric baryonic DM or dark mesino/glueballino (dark R-hadrons) in SUSY UV completions.