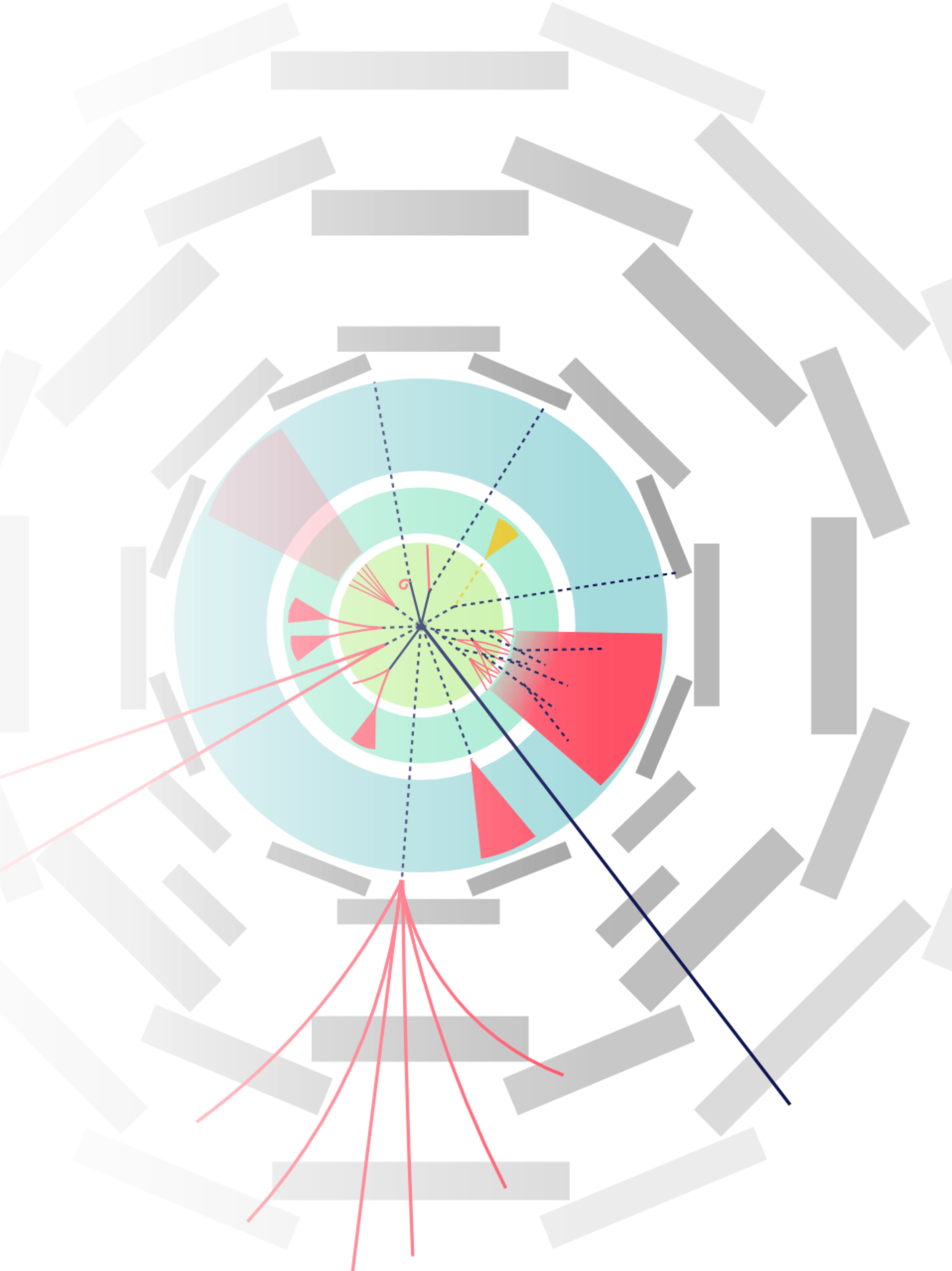
A Theory of Dark Pions



Lingfeng Li (Brown U.)

Mar 02 2022
Mini WS on BSM at ILC

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

See also:

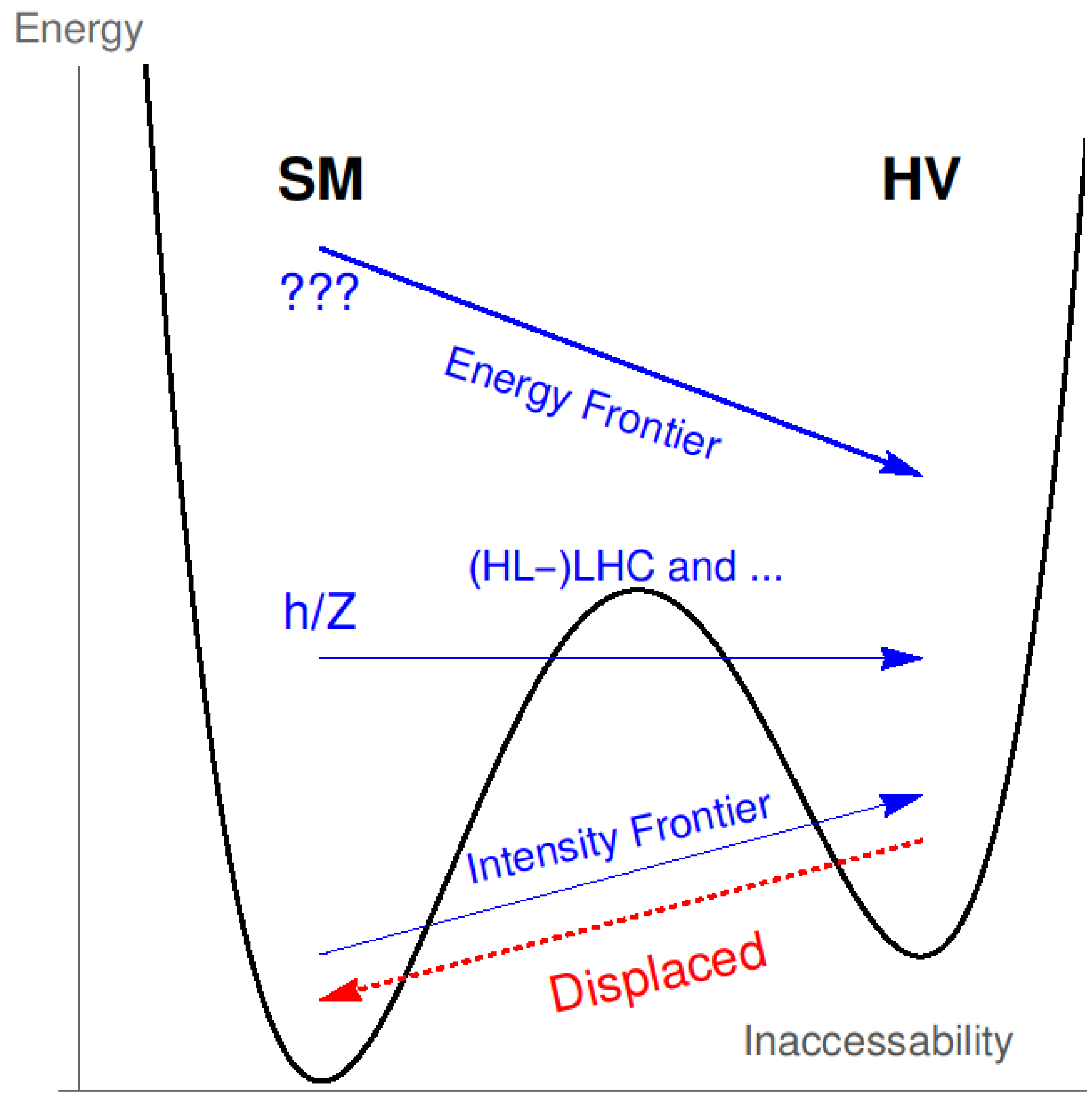
1803.03561 w/ H-C. Cheng, E. Salvioni and C. Verhaaren

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

The Paths to the Hidden Valley

The overview of this talk

- ➢ The dark pion model
- ➢ The irrelevant portal (Z and h) phenomenology
- ➢ Several benchmarks, focusing on long-lived particle (LLP) searches
- ➢ Future prospect at future colliders.



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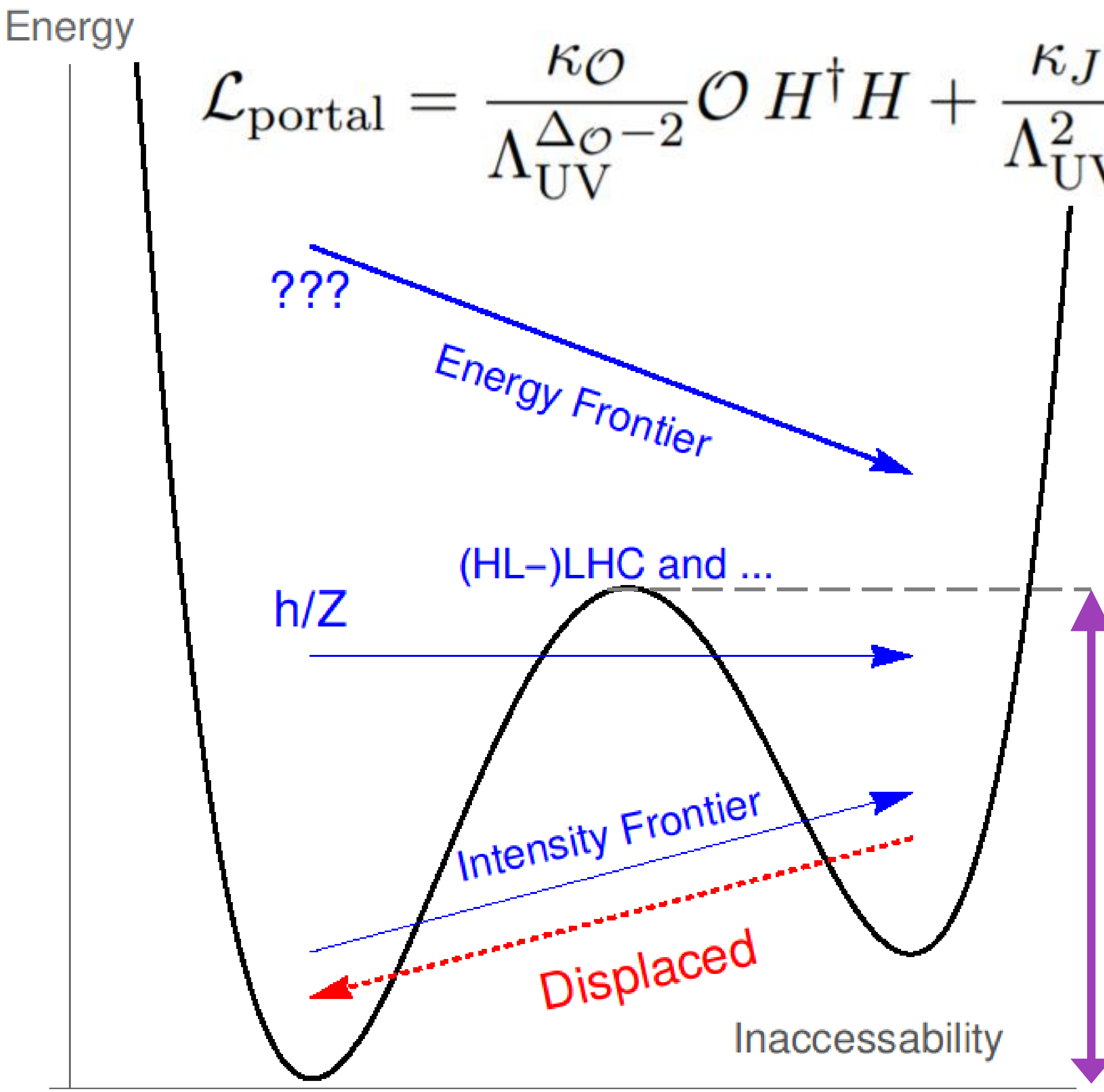
Irrelevant Portal to Hidden Valley

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



A general form

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

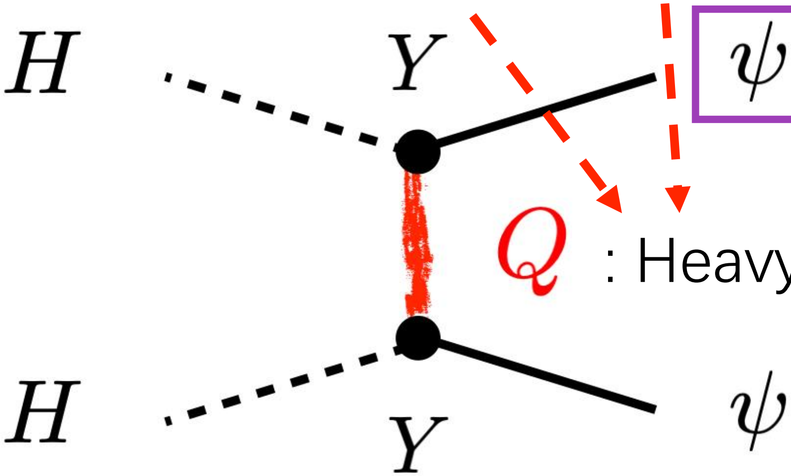
Suppressed HV-SM coupling from the ~TeV scale

Comprehensively easy, well-motivated, rich phenomenology but somehow overlooked.

Irrelevent Portal Dark Pions

Q heavier than O(TeV)

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



ψ : Light SM singlet dark quarks

Q : Heavy SM doublet mediators

Small mass, dark pions can be very light (< GeV)

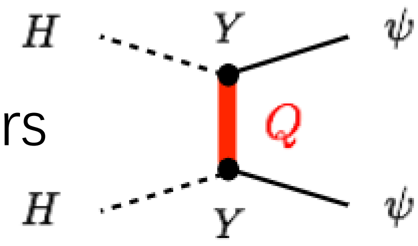
Irrelevent Portal Dark Pions (II)

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

$\boldsymbol{\omega}, \boldsymbol{M}, \boldsymbol{Y}, \widetilde{\boldsymbol{Y}}$: 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



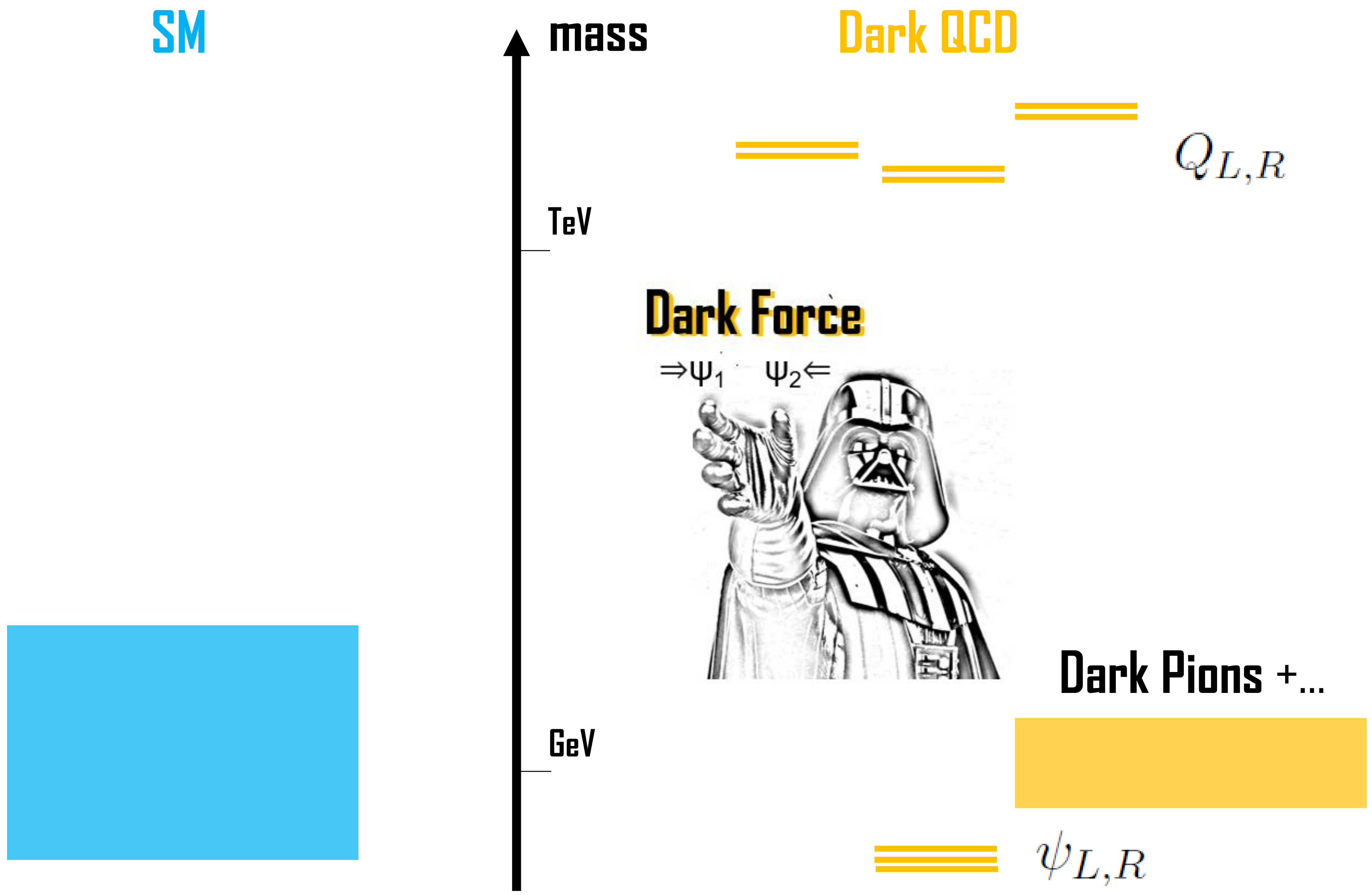
$$\begin{aligned}\mathcal{L}_{\rm EFT} =& \frac{1}{2}\overline{\psi}_R \boldsymbol{Y}^\dagger \boldsymbol{M}^{-2} \boldsymbol{Y} \left[|H|^2 i\not{D} + i\gamma^\mu H^\dagger D_\mu H\right] \psi_R + \text{h.c.} \\ &+ \frac{1}{2}\overline{\psi}_L \widetilde{\boldsymbol{Y}}^\dagger \boldsymbol{M}^{-2} \widetilde{\boldsymbol{Y}}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

Dimension-6 Z portal couplings

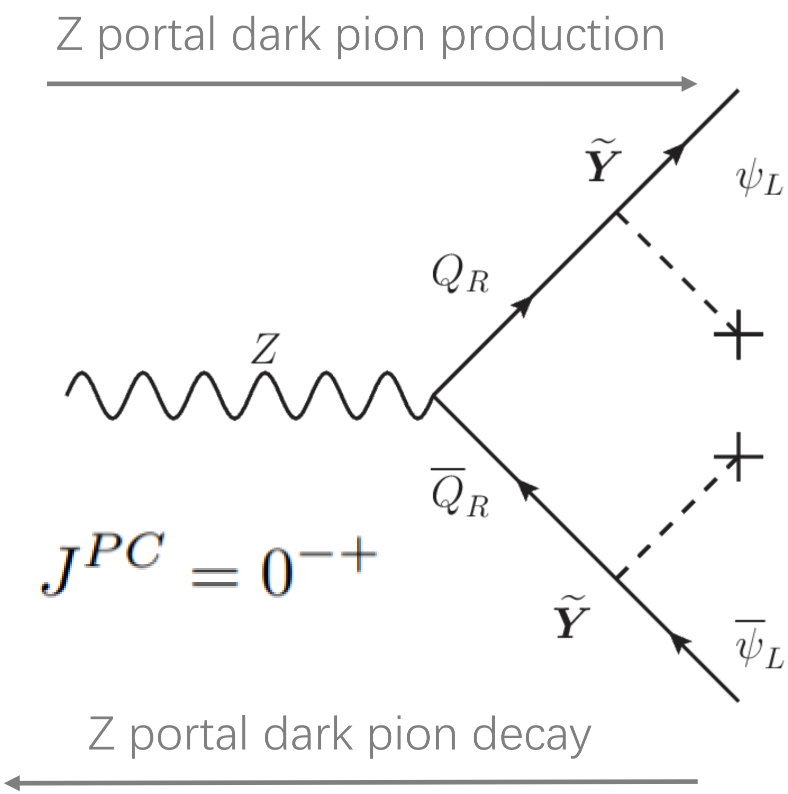
Dimension-5 Higgs portal coupling

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

The Cartoon of Dark Spectrum



Two Flavor, Three Dark Pions



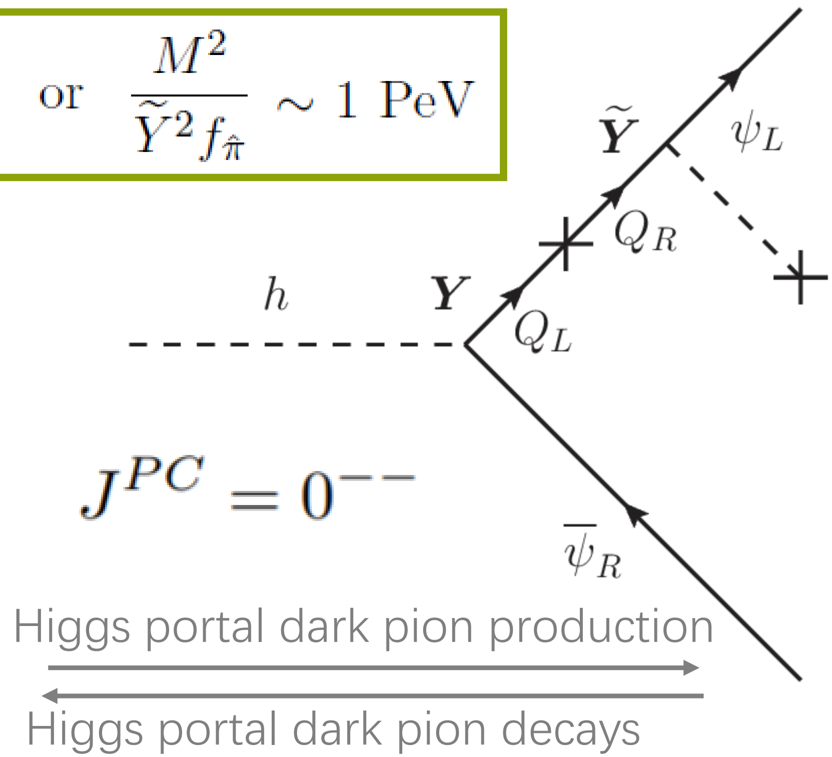
Dark pions rearrange into CP eigenstates (like K_S and K_L in the SM)

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

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

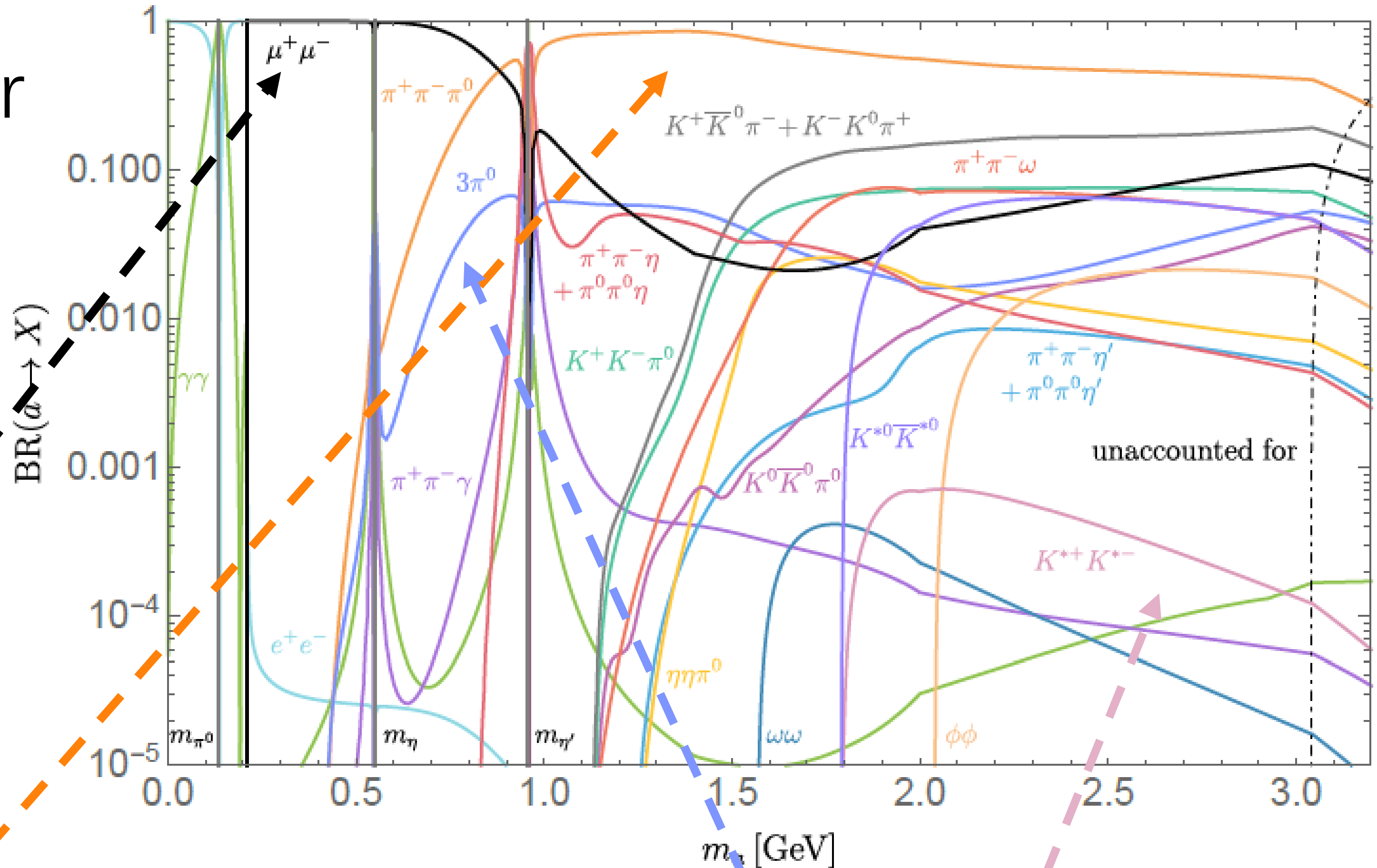
The π_2 mix with the Higgs since it's CP-even, with mixing angle:

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



Dark Pion Decays (ALP-Like)

Results good for generic flavor diagonal ALP couplings



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

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

SM isospin suppressed modes

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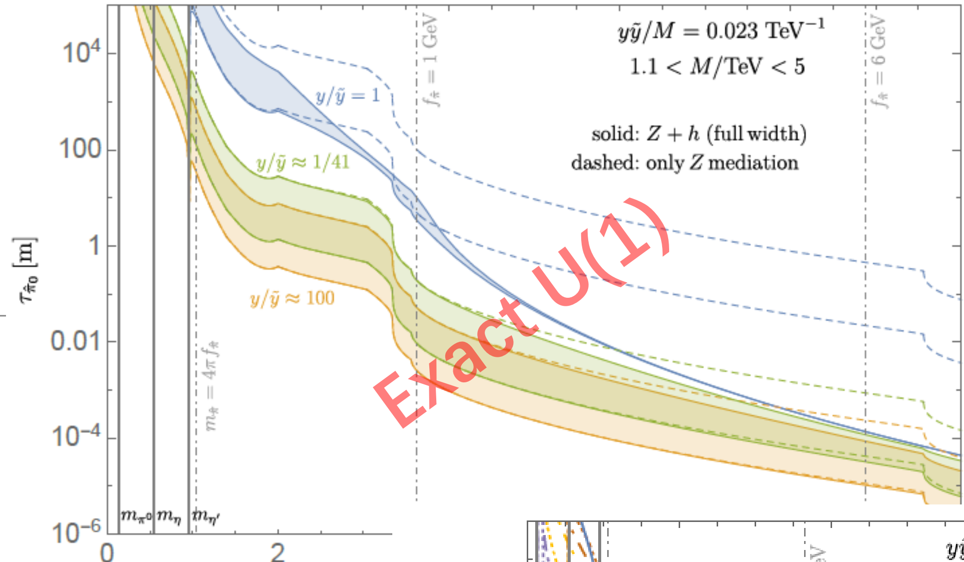
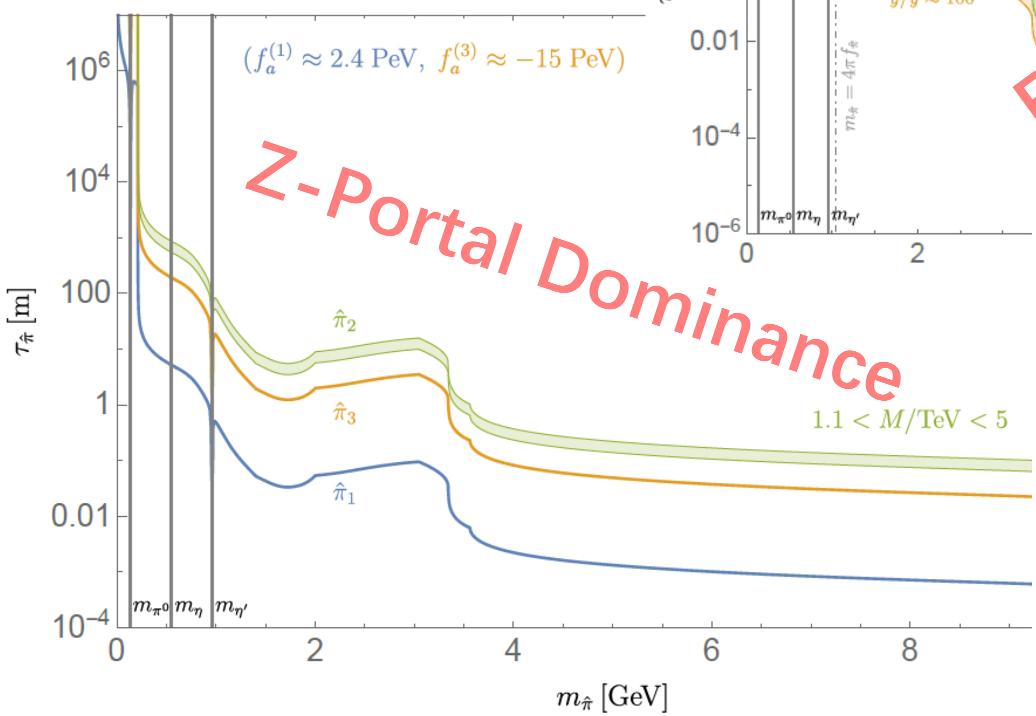
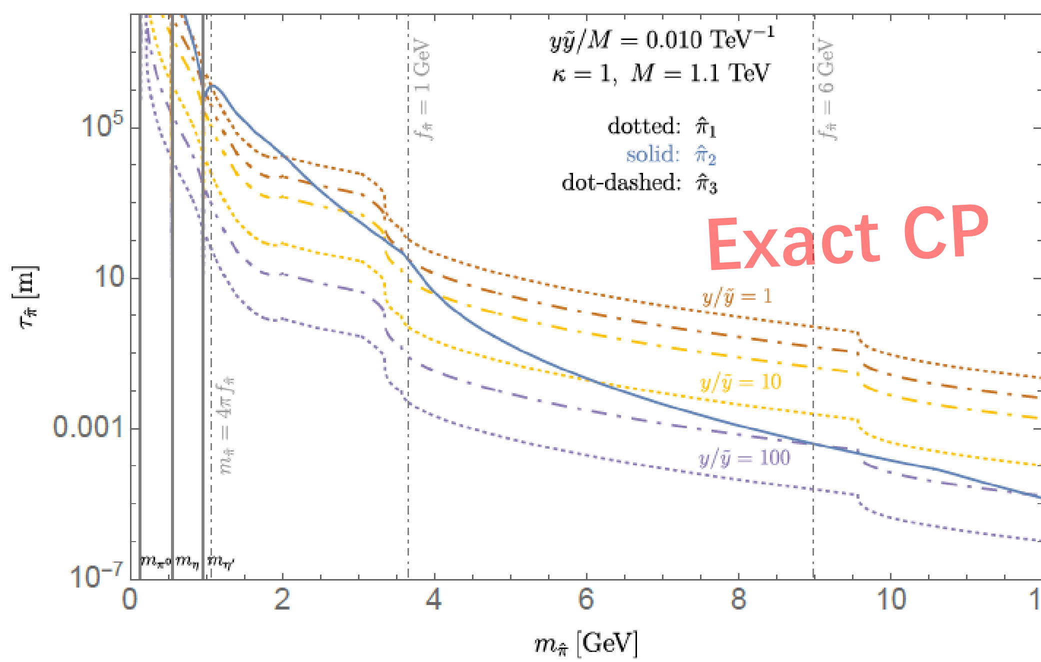
Dark Pion as Long-lived Particles

Lifetime between 1mm to >10m







Easy LLP with strong parameter dependence

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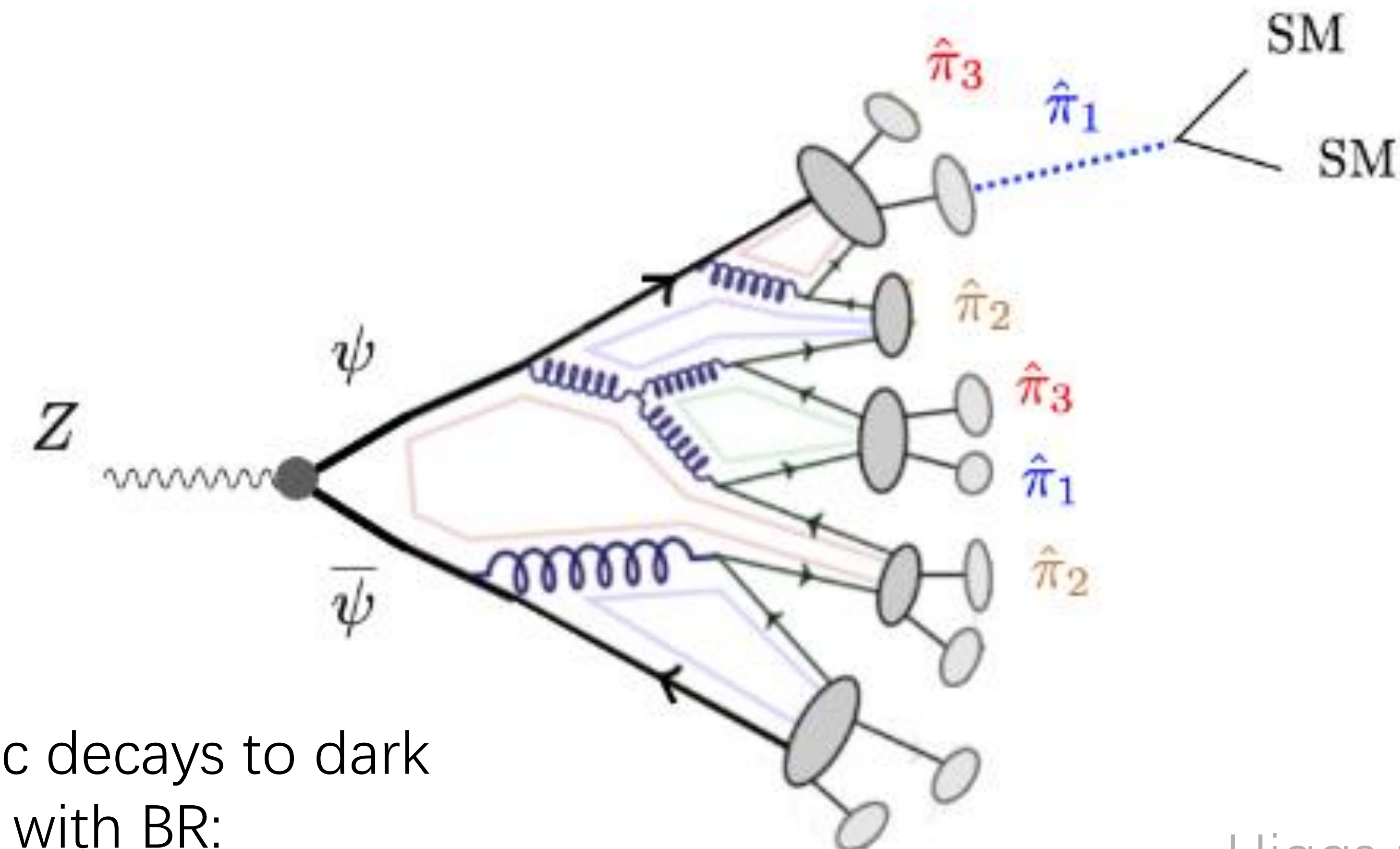
Phenomenology @ the EW Scale



Z exotic decays to dark quarks with BR:

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

Usually dominates the phenomenology because of large stastics:

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

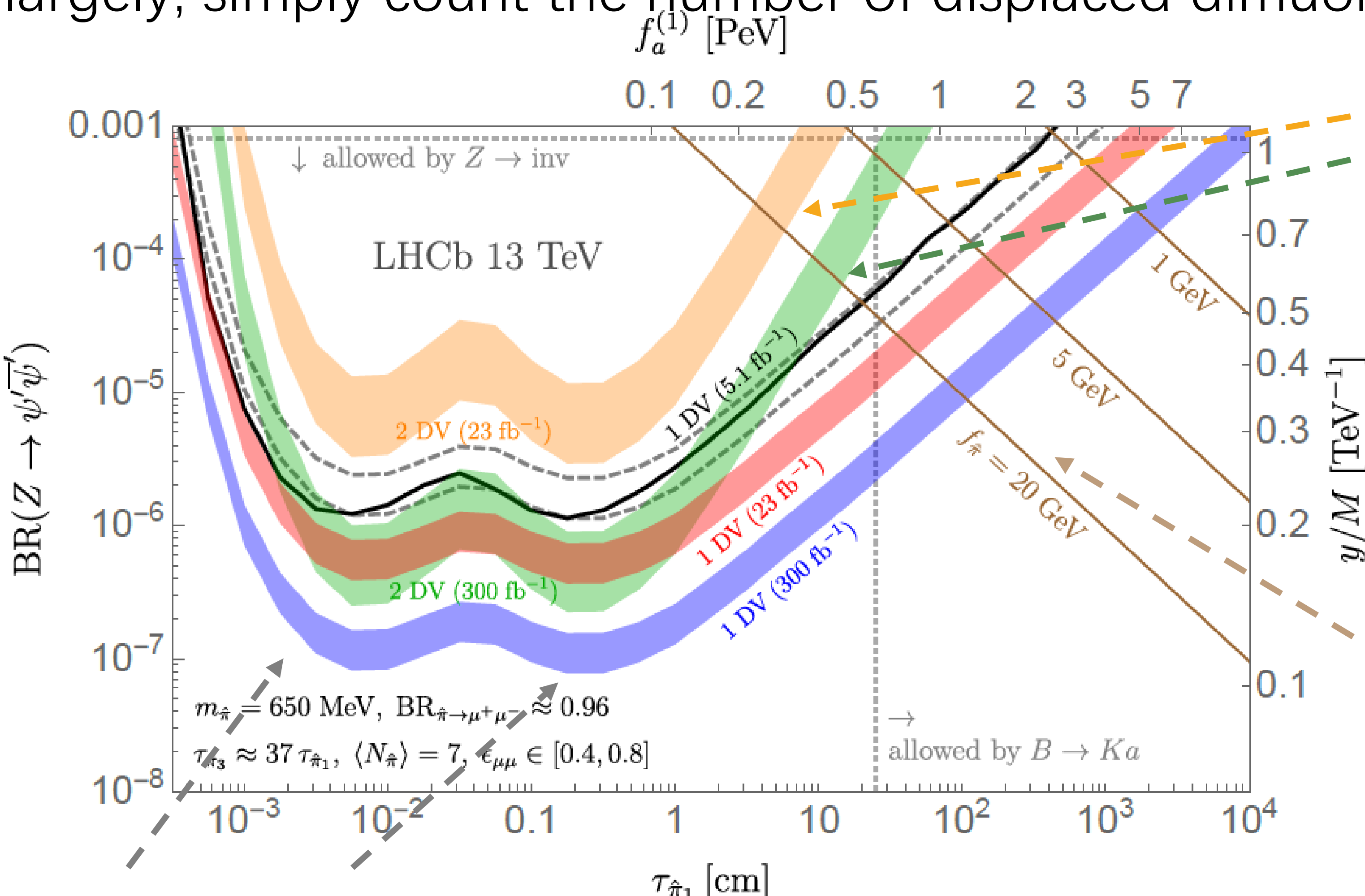
Higgs portal only relevant when both $\mathbf{Y}$, $\widetilde{\mathbf{Y}}$ are large

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

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

Example: Dimuon Search @ LHCb

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



2DV or beyond suffer from low vertex efficiency.

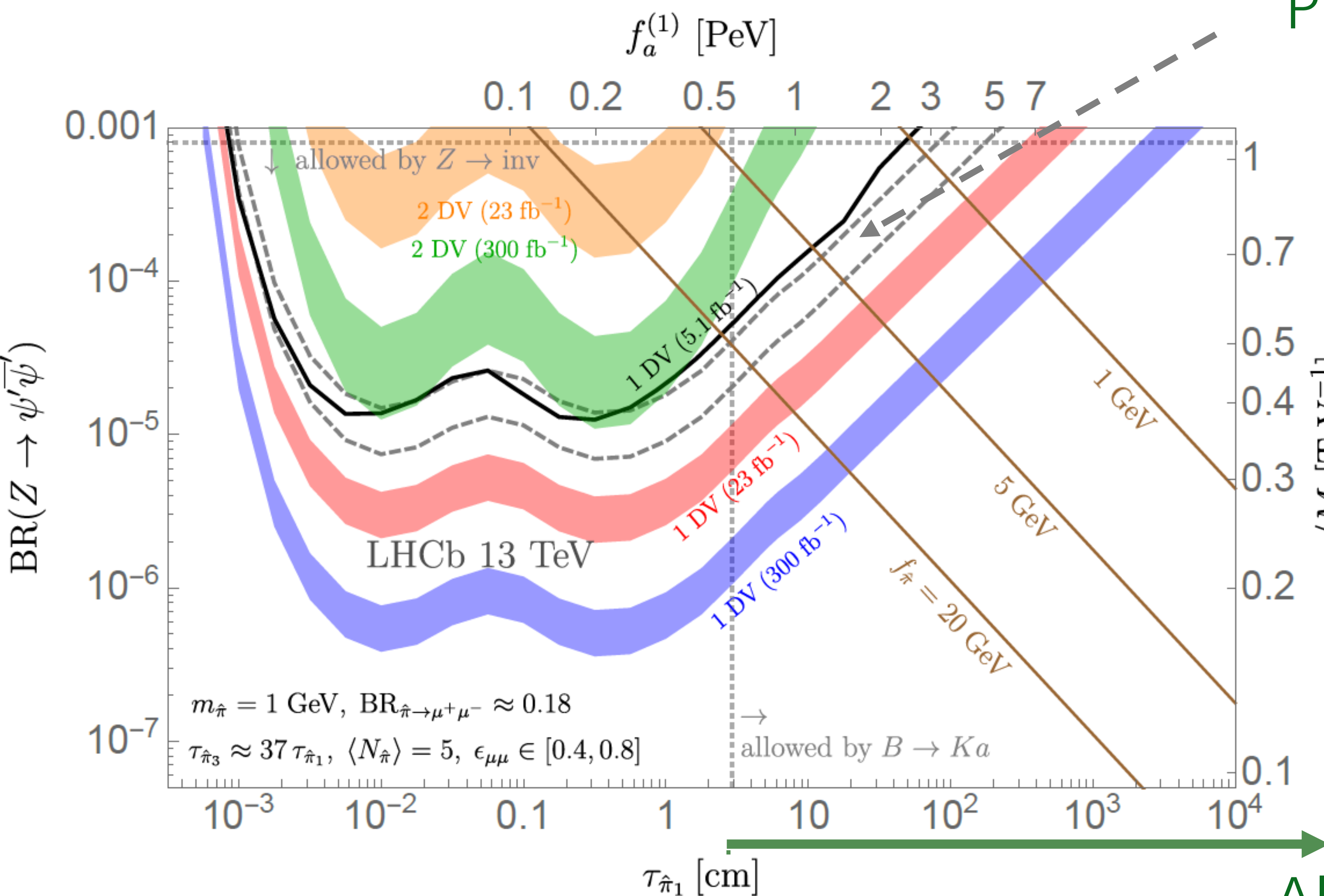
Sensitive to f_π. and f_a

Two peaks from benchmark pion width ratio 1:37

Data from [LHCb 2007.03923]

Example: Dimuon Search @ LHCb

Another benchmark with 1 GeV dark pions



Probing M > 1 TeV

Allowed by Z Invisible deacay

Allowed by current FCNC bounds

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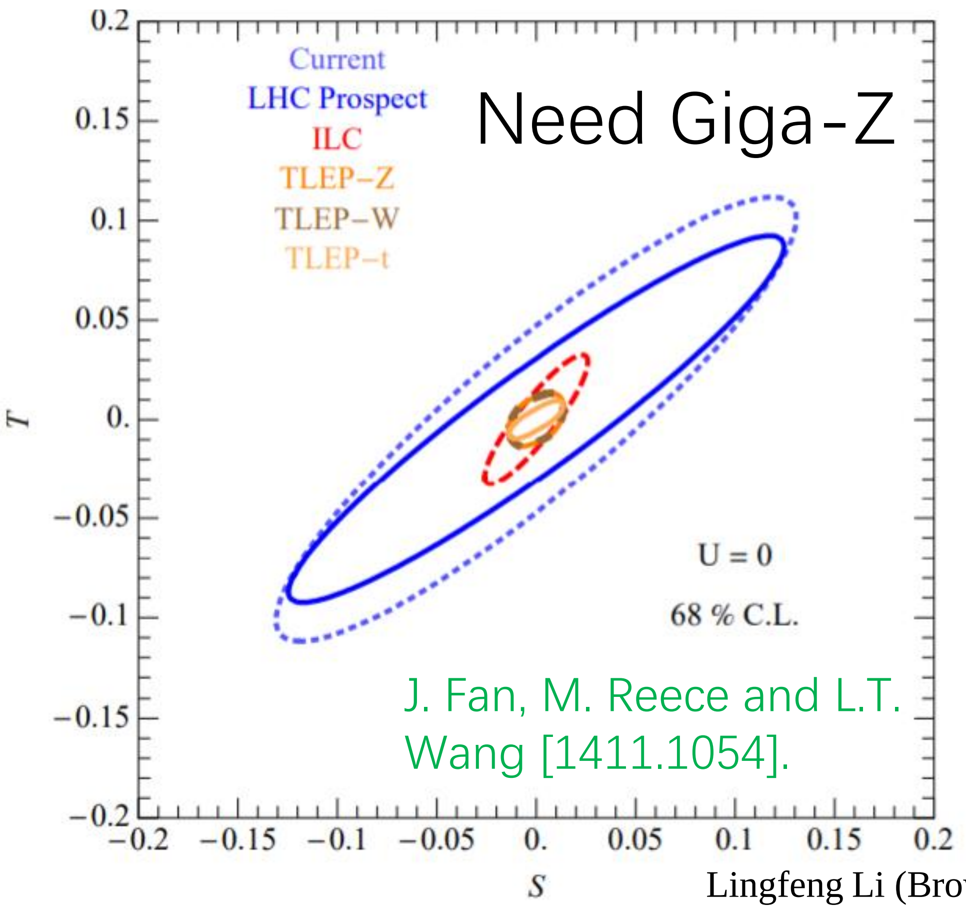
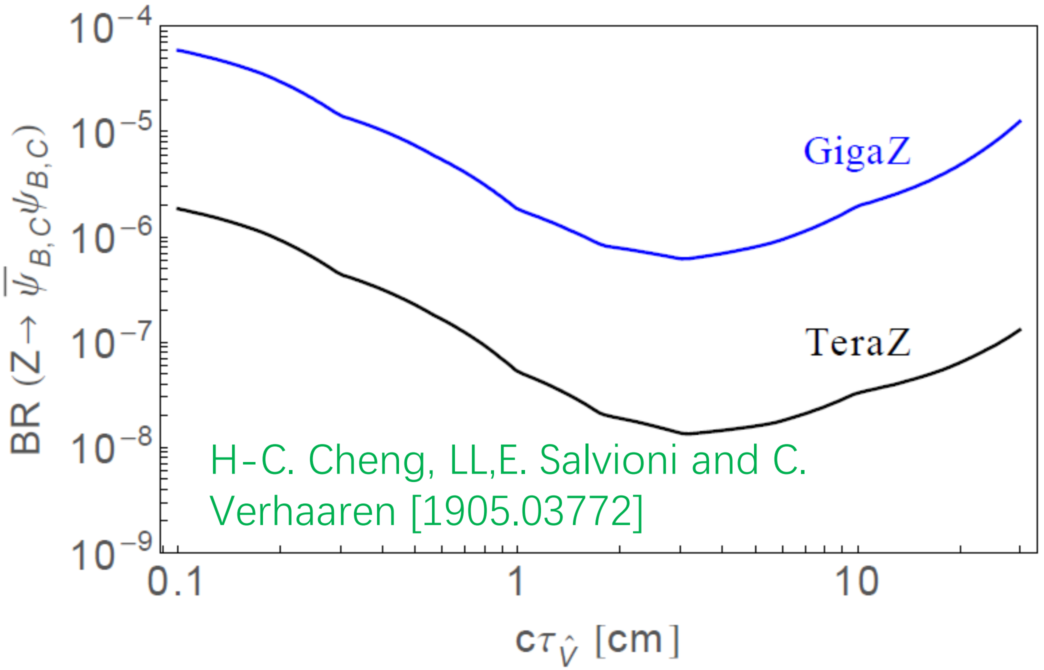
Prospect at Future Colliders

Indirect/Intensity (EWPT), Shifting the T parameter:

$$\widehat{T} \simeq \frac{N_d}{16\pi^2}\sum_{i=1}^{N}\frac{v^2}{3M_i^2}\left(y_i^4+\tilde{y}_i^4+\frac{1}{2}y_i^2\tilde{y}_i^2\right)$$



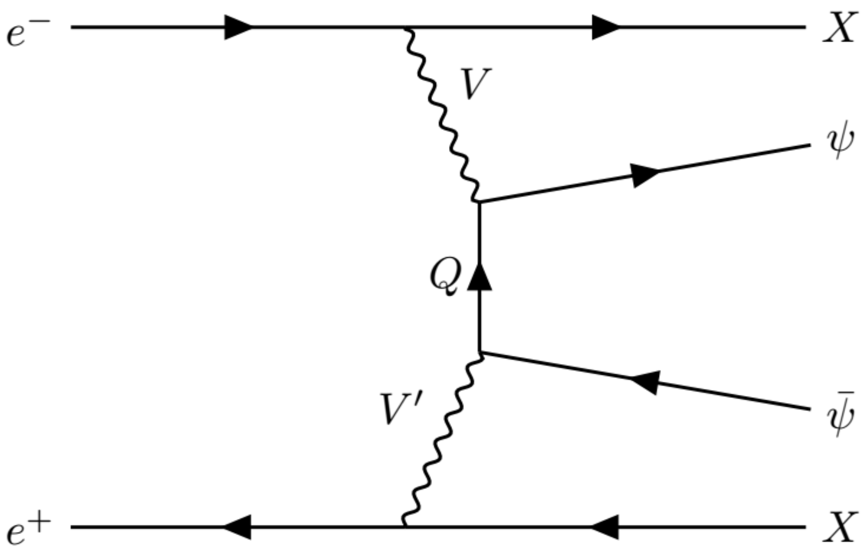
Direct search in H/Z decays:



(VERY conservative) limits on exotic $Z \to$ dark shower decays but with a DIFFERENT model:

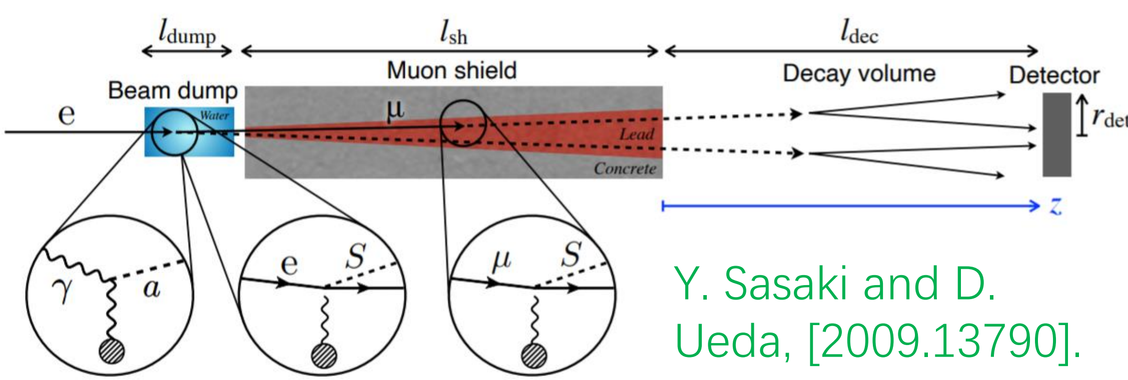
- Vector meson dominance
- Inclusive strategy w/o much vertexing
- Same resolutions as the current LHC···

Prospect at Future Colliders (II)



Energy-frontier searches:

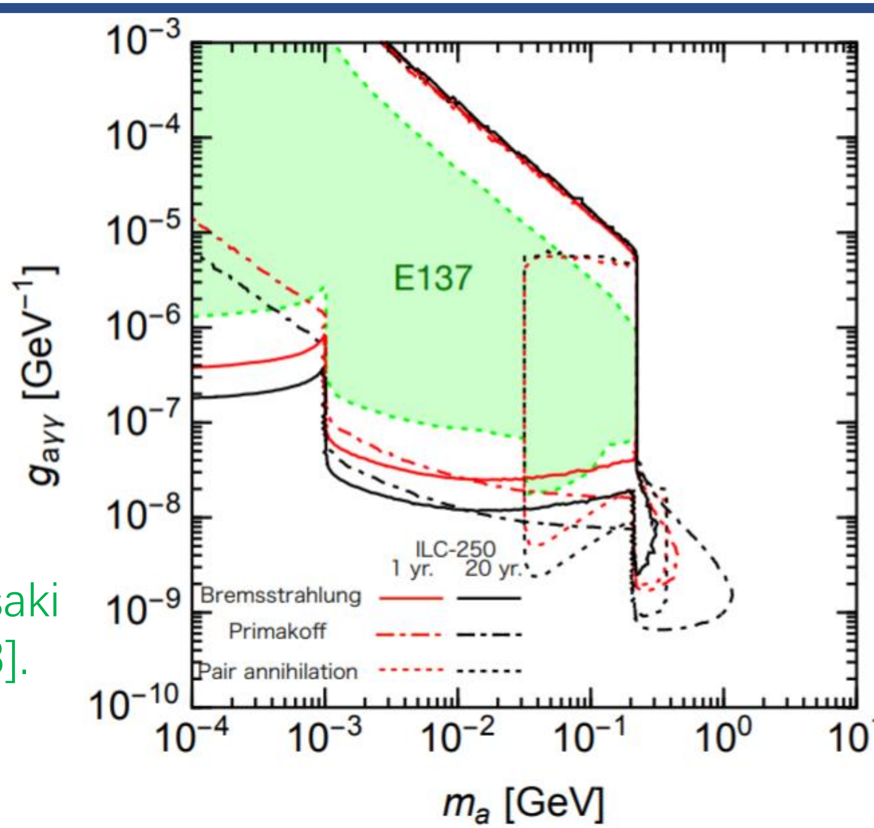
- VBF pair production
- s-channel pair production
- Indirect, non-resonance modulations
- ...



Y. Sasaki and D. Ueda, [2009.13790].

Intensity-frontier approach: searching in the beam dump:

K. Asai, S. Iwamoto, Y. Sasaki and D. Ueda, [2105.13768].



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. Bright future prospects.
- Open fields (other dark mesons, intensity frontier, cosmology) remain to be fully explored.

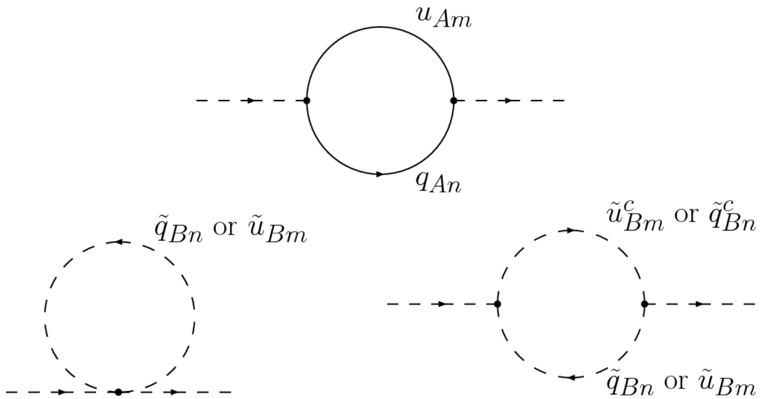
Backup Slides

Motivating Scenario I: Neutral Naturalness

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

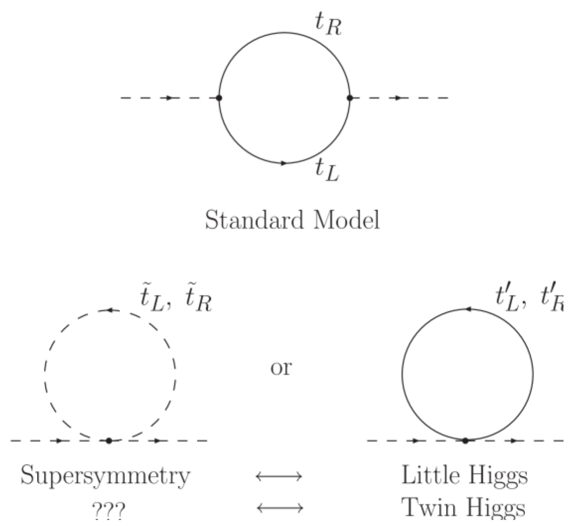
Folded SUSY

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



Twin Higgs

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

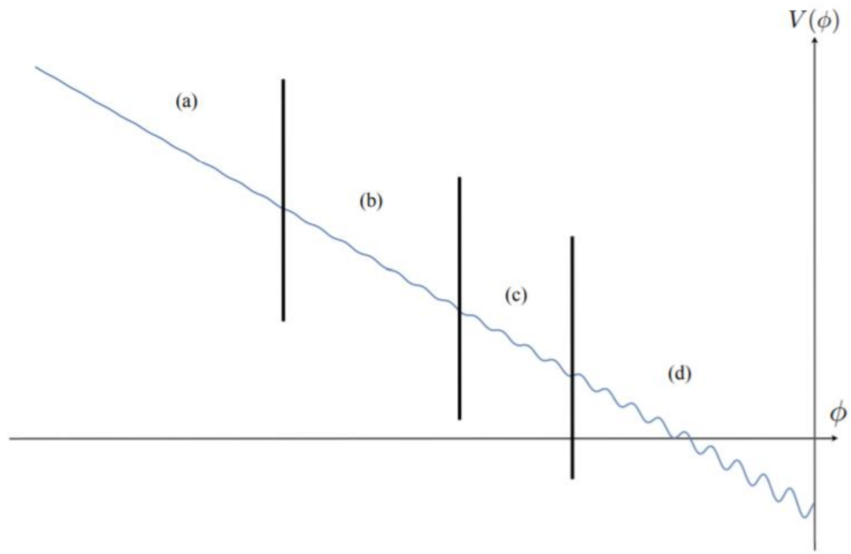


See also Tripled Top (TT) model

[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].

Alternative Tripled Top (TT) Model

Arbitrarily light

A few TeV

The superpotential :

$$W'_{Z_3} = y_t(Q_A H u^c_A + Q_B H u^c_B + Q_C H u^c_C) + \omega(u'_B u^c_B + u'_C u^c_C) + M(Q_B Q'^c_B + Q_C Q'^c_C)$$

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

The soft breaking term:

A few TeV (≈M)

$$V_s = \widetilde{m}^2 \left(|\widetilde{Q}_A|^2 + |\widetilde{u}^c_A|^2\right) - \widetilde{m}^2 \left(|\widetilde{u}^c_B|^2 + |\widetilde{u}^c_C|^2\right) .$$

A Folded SUSY-like spectrum realized in 4D

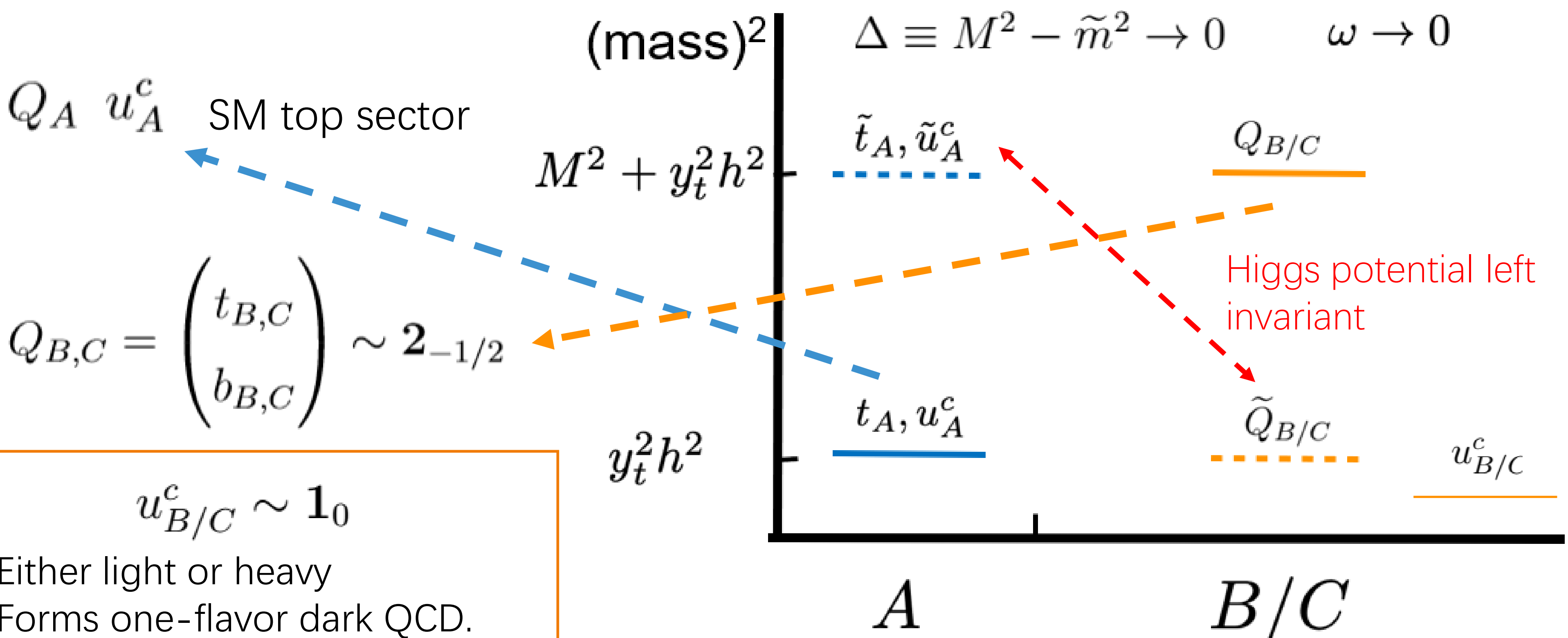
For details of the original model, see [H-C.Cheng, LL, E.Salvioni and C. Verhaareen 1803.03561]

1803.03651 1905.03772 20xy.ijklm

Alternate Tripled Top (TT) Model & Accidental SUSY

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

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

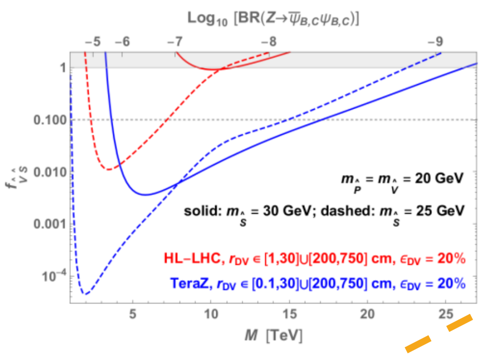


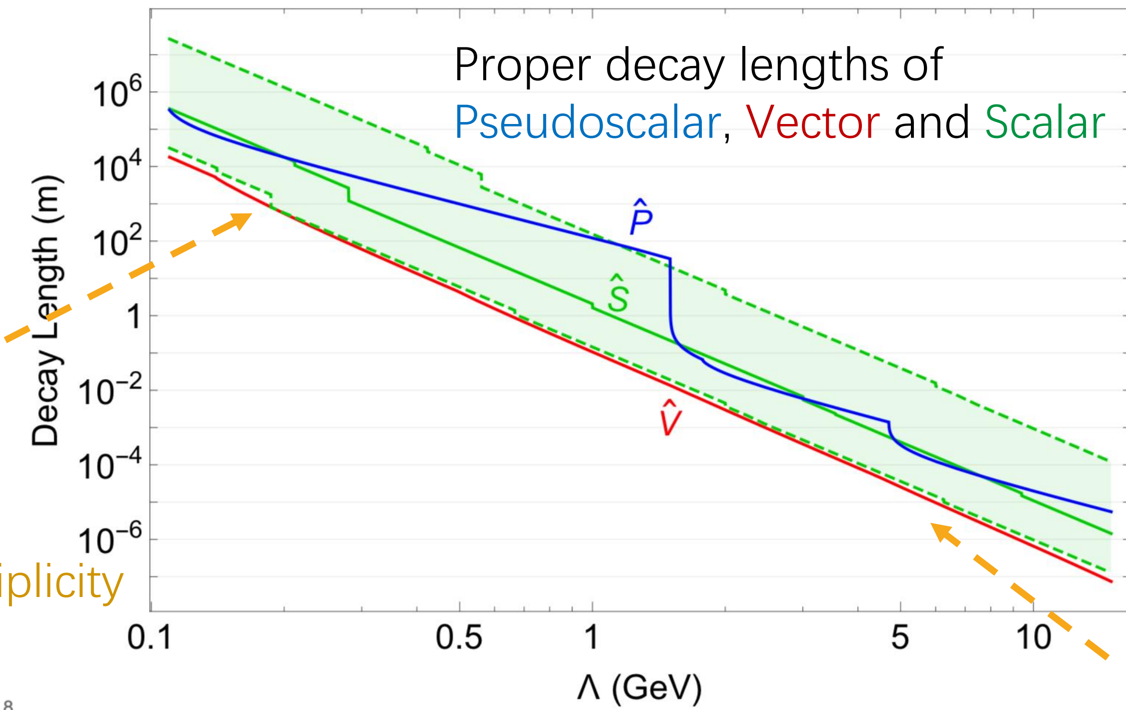
$u_{B/C}^c \sim \mathbf{1}_0$

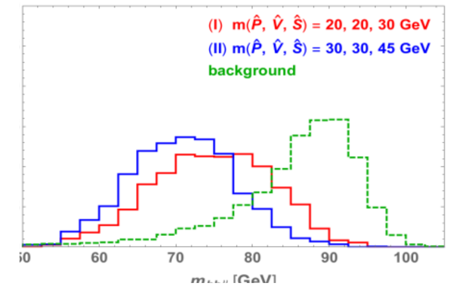
Either light or heavy
Forms one-flavor dark QCD.
Dark hadrons:
Pseudoscalar, Vector and Scalar

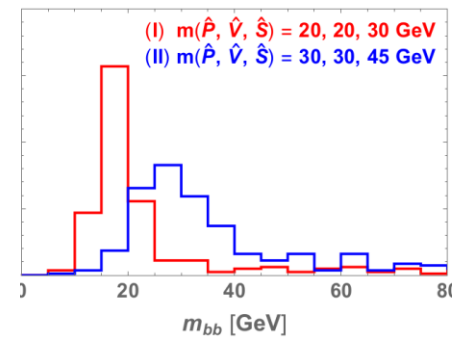
1803.03651 1905.03772 20xy.ijklm

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



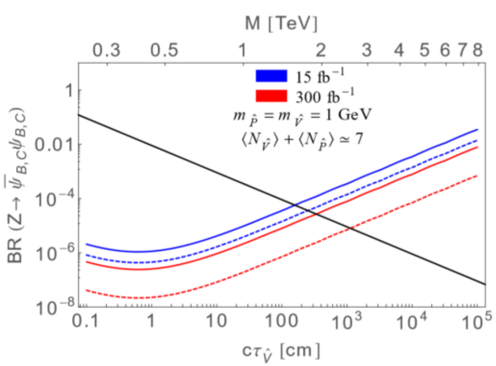


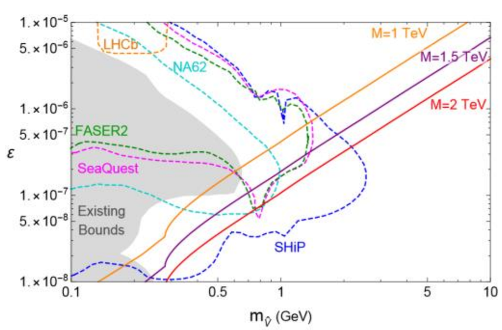


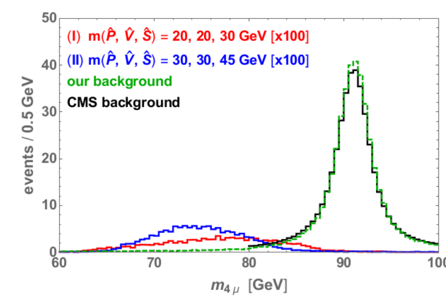


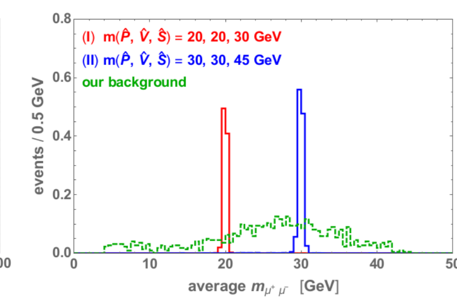
Light and long-lived meson limit:
Displaced & high-multiplicity

Heavy and prompt limit:
Resonance searches







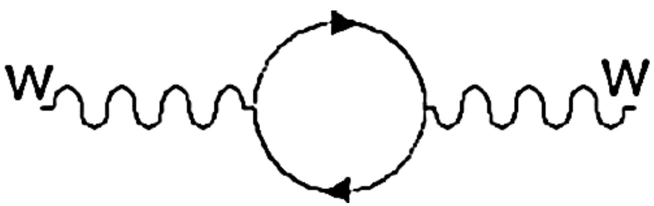


Details of phenomenology : [H-C.Cheng, LL, E.Salvioni and C. Verhaareen 1905.03772]

Indirect/Precision Constraints

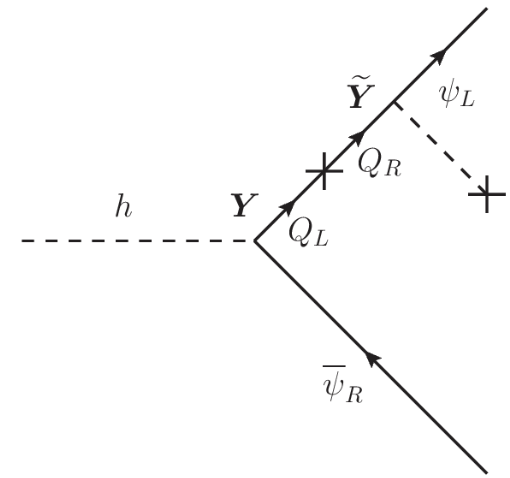
$$M \gtrsim 0.9\,\mathrm{TeV}\; Y^2 \left(\frac{N_d N}{6}\right)^{1/2}$$

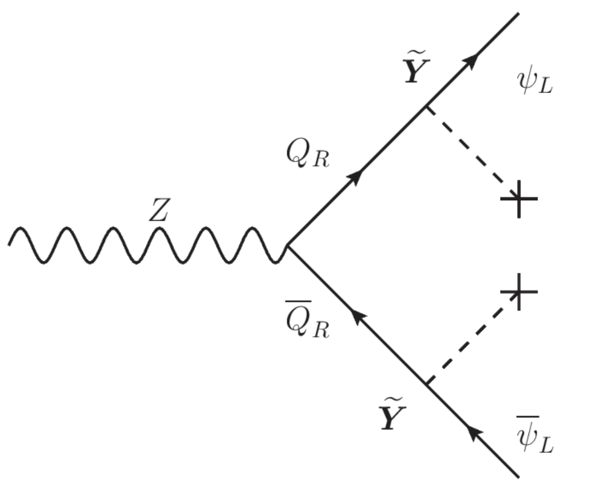
From EW oblique parameter T < O(10^{-3})



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

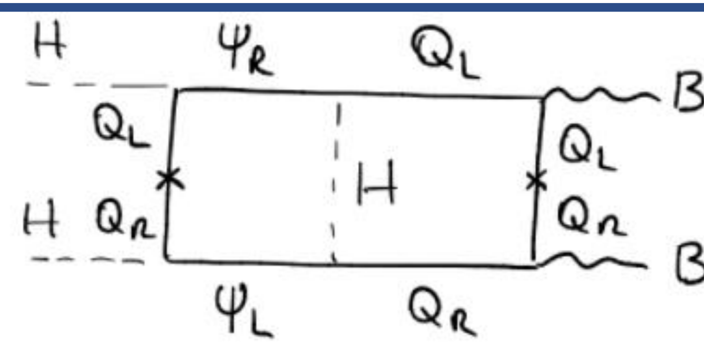
From Higgs invisible decay BR < 13%





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

From Z invisible decay width <~2 MeV



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

From electron EDM
if CP is violated maximally

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 $a \to \gamma\gamma$

A.2 $a \to \pi^+\pi^-\gamma$

A.3 $a \to \pi^+\pi^-\pi^0$

A.4 $a \to 3\pi^0$

A.5 $a \to \pi^0\pi^0\eta, \pi^+\pi^-$

A.6 $a \to \pi^0\pi^0\eta', \pi^+\pi$

A.7 $a \to \eta\eta\pi^0$

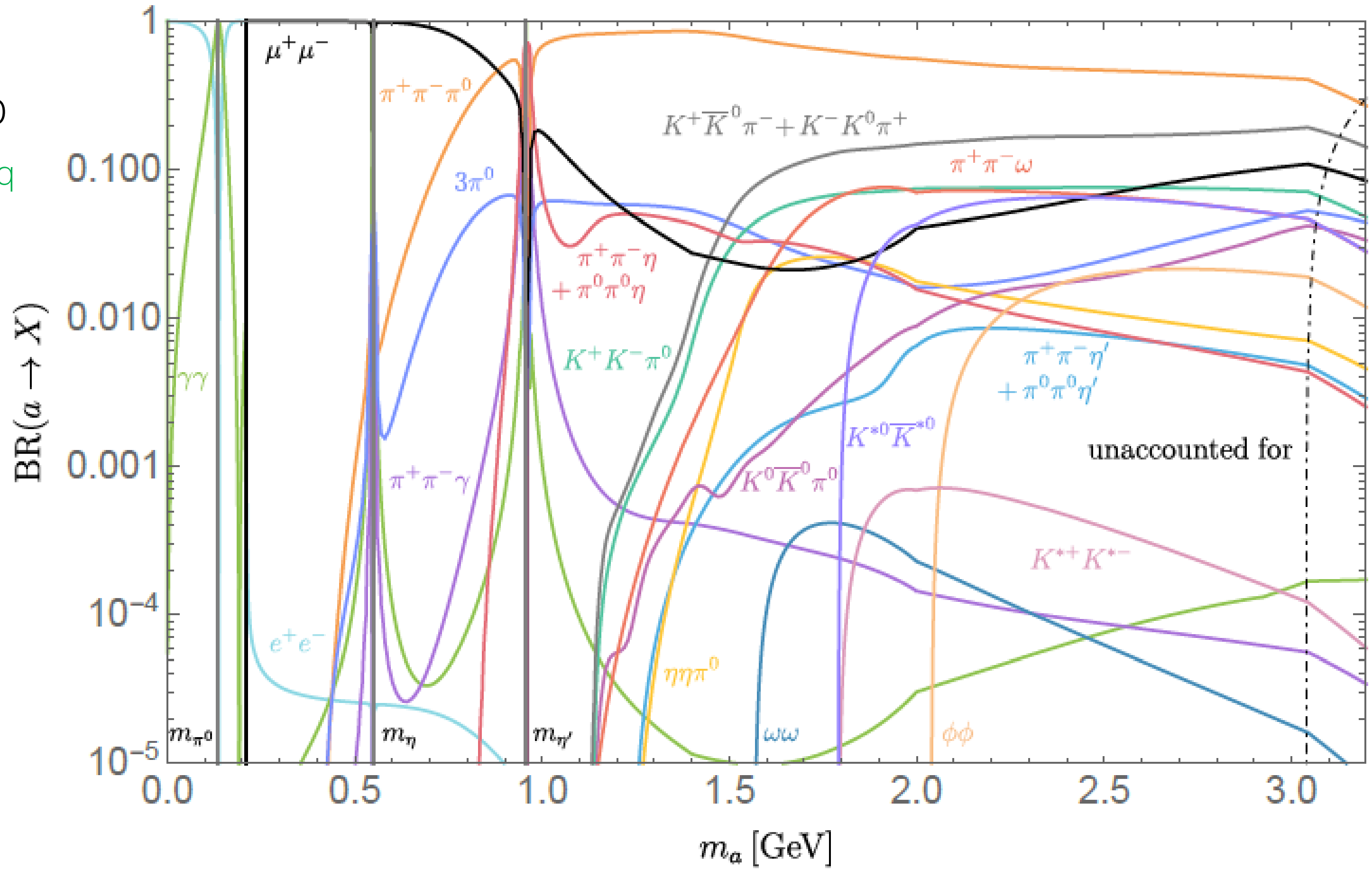
A.8 $a \to K^0\overline{K}^0\pi^0$

A.9 $a \to K^+K^-\pi^0$

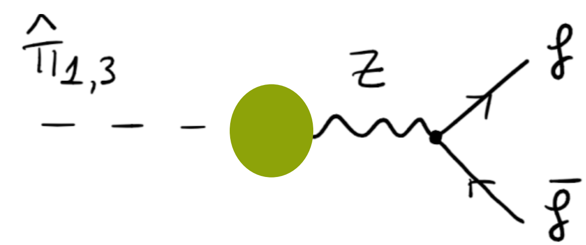
A.10 $a \to K^+\overline{K}^0\pi^-, K^-K^0\pi$

A.11 $a \to \omega\omega, \phi\phi, K^{*+}K^{*-}, K^{*0}\overline{K}^{*0}$

A.12 $a \to \pi^+\pi^-\omega$



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



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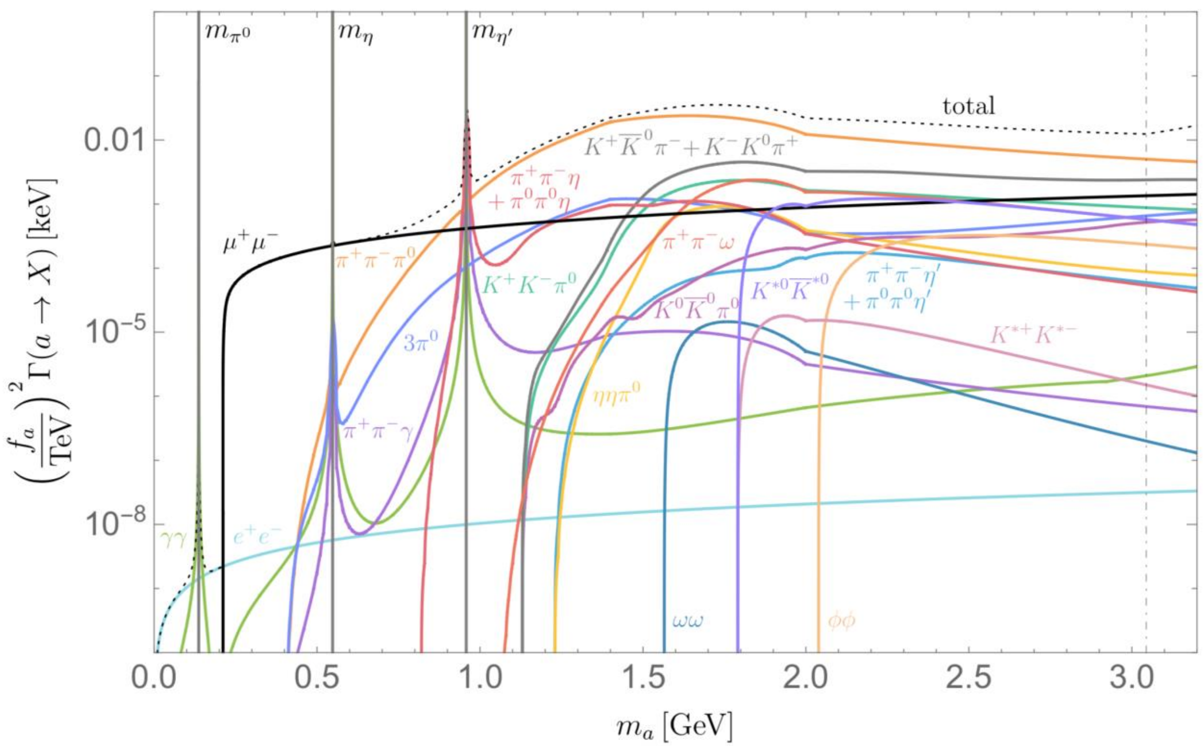
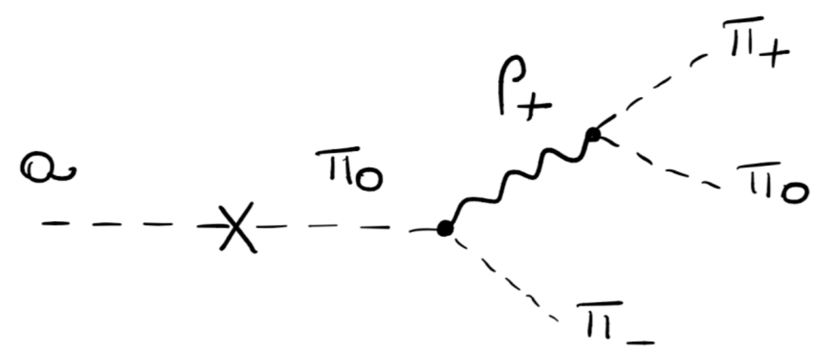
Dark Pion Decays (ALP-Like, III)





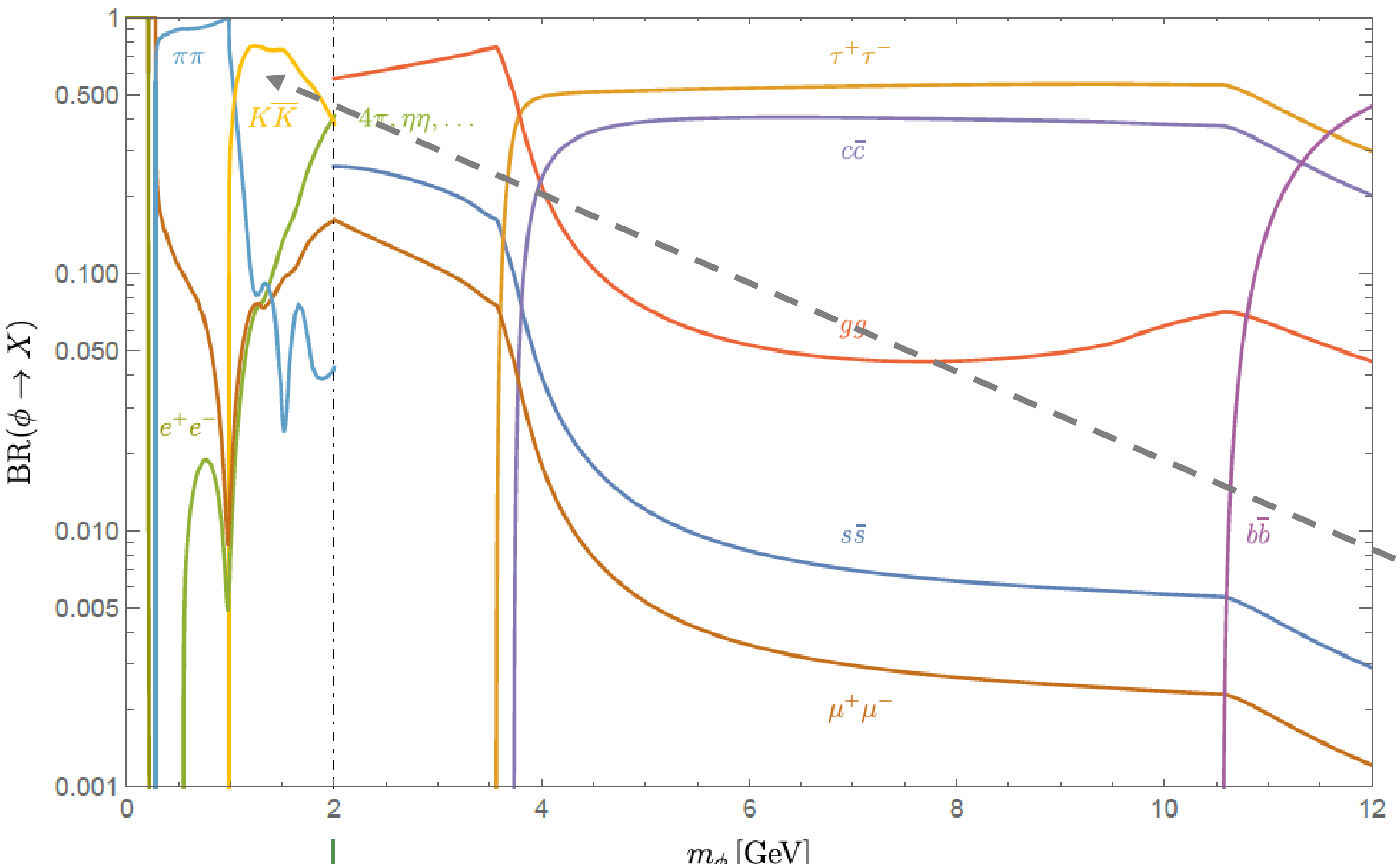
The dominant mode $\pi^+\pi^-\pi^0$ comes from the ρππ coupling

$$\mathcal{M} = \mathcal{M}_{\text{ChPT}} + \mathcal{M}_{\text{VMD}} + \mathcal{M}_\sigma + \mathcal{M}_{f_0} + \mathcal{M}_{f_2}$$

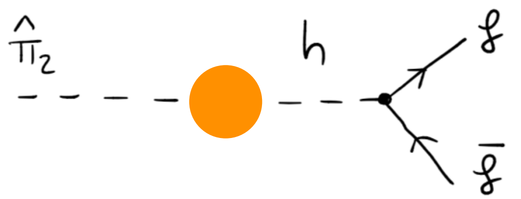
$$\mathcal{M}_{\text{VMD}} = \frac{\langle \boldsymbol{a\pi_0} \rangle}{f_a}\Big\{ g^2 f_\pi \big[(2m_{12}^2 + m_{23}^2 - m_a^2 - 3m_\pi^2)\text{BW}_\rho(m_{23}^2)$$
$$+ (2m_{12}^2 + m_{13}^2 - m_a^2 - 3m_\pi^2)\text{BW}_\rho(m_{13}^2)\big]\mathcal{F}_V(m_a) - \frac{1}{2f_\pi}(3m_{12}^2 - m_a^2 - 3m_\pi^2)\Theta(m_{\eta'} - m_a)\Big\},$$

Higgs Portal Decays

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



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

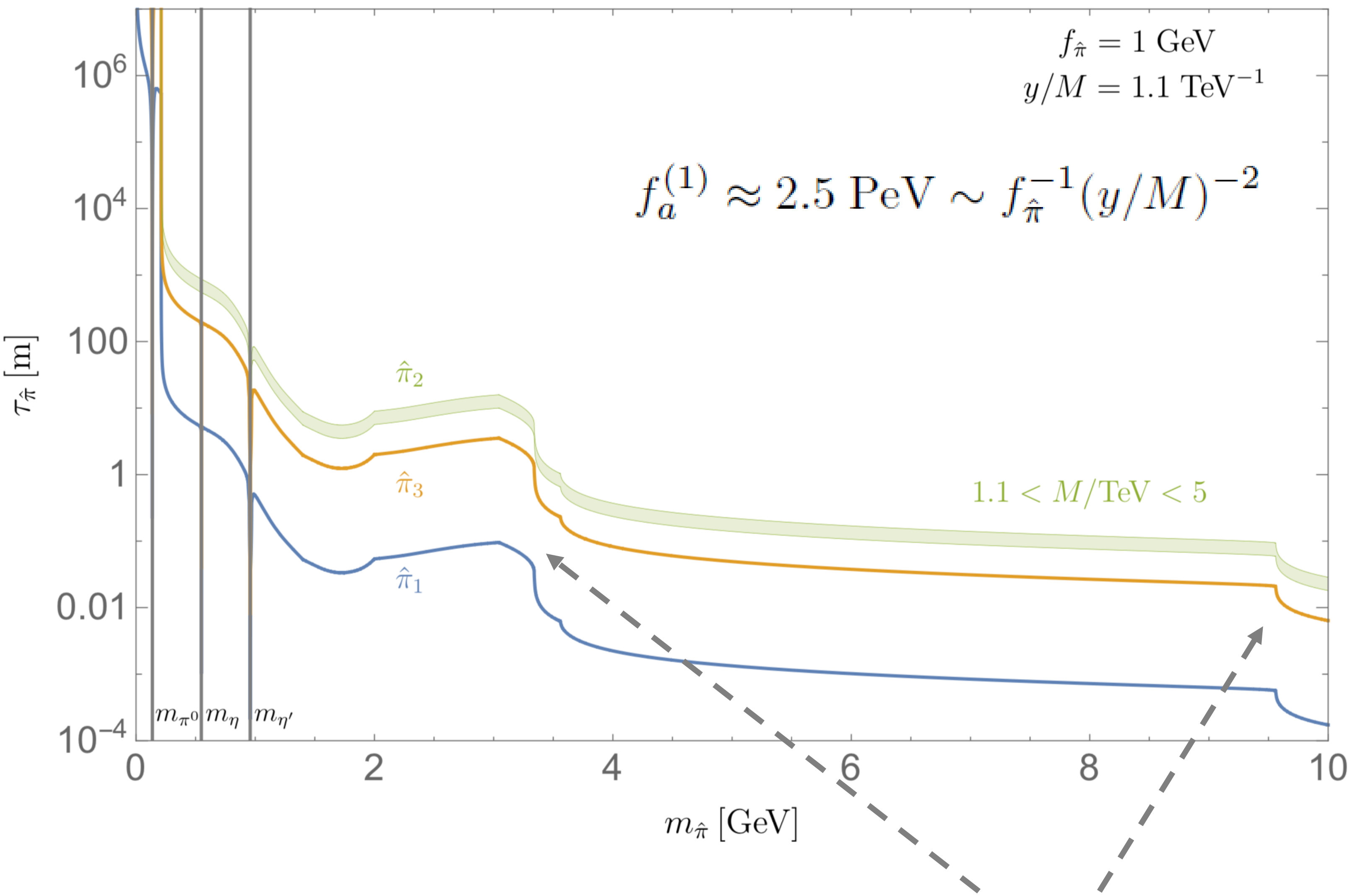


$\pi\pi$ or KK dominate low mass region

Perturbative QCD results

Hadronic Exclusives

LLP in the Z Portal Dominance



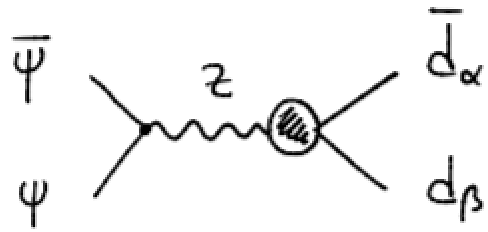
Lingfeng Li (Brown U.) arXiv: 2110.10691

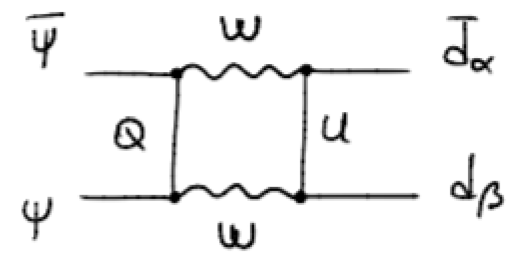
Dark Pion from SM FCNC

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

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

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





The four-fermion interaction then followed by the factorization

Finite terms introduces a numerical suppression ~3

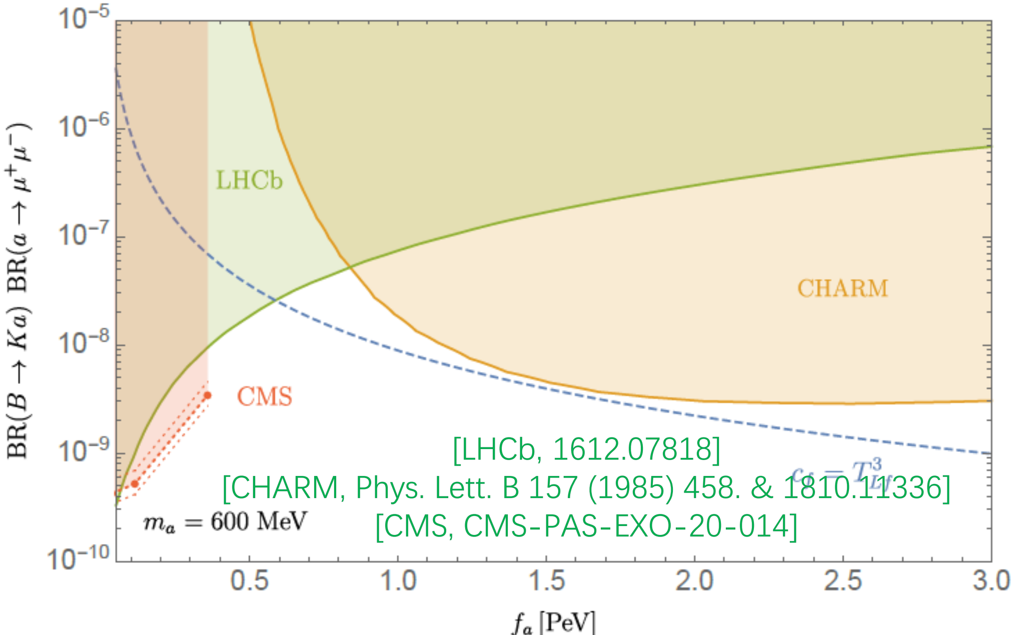
$$\langle \hat{\pi}_a X | \mathcal{H}_{\rm eff} | B \rangle = \langle \hat{\pi}_a | \langle X | \mathcal{H}_{\rm eff} | 0 \rangle | B \rangle = \frac{i g^2}{64\pi^2} V_{ts}^* V_{tb} \langle X | \bar{s}_L \gamma_\mu b_L | B \rangle \frac{p^\mu_{\hat{\pi}}}{f_a^{(a)}} \left[\frac{m_t^2}{m_W^2} \left(\log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

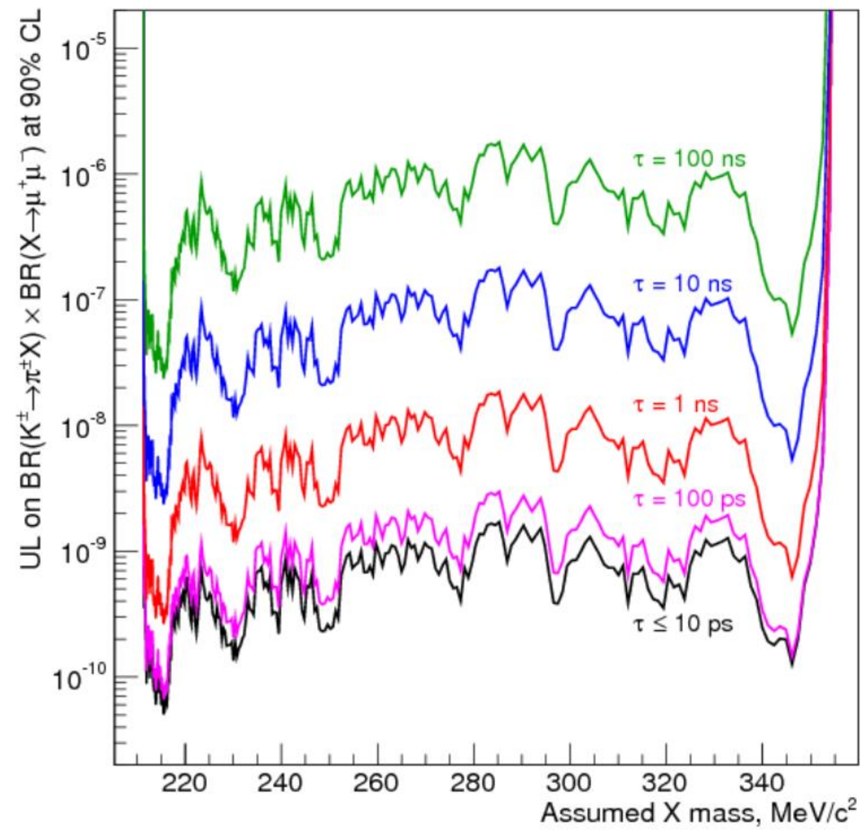
$$\mathrm{BR}(B^{\{+,0\}} \to \{K^+ \hat{\pi}_b, K^{*0} \hat{\pi}_b\}) \approx \{0.92,\ 1.1\} \times 10^{-8} \left(\frac{10^3\ \mathrm{TeV}}{f_a^{(b)}} \right)^2 \{\lambda_{K\hat{\pi}}^{1/2}, \lambda_{K^*\hat{\pi}}^{3/2}\}$$

Experimentally achievable if dark pions are LLP

Current FCNC Bounds (B,K decay)

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





Probing f_a ~ PeV already
Reaching O(8-60) PeV for future experiments

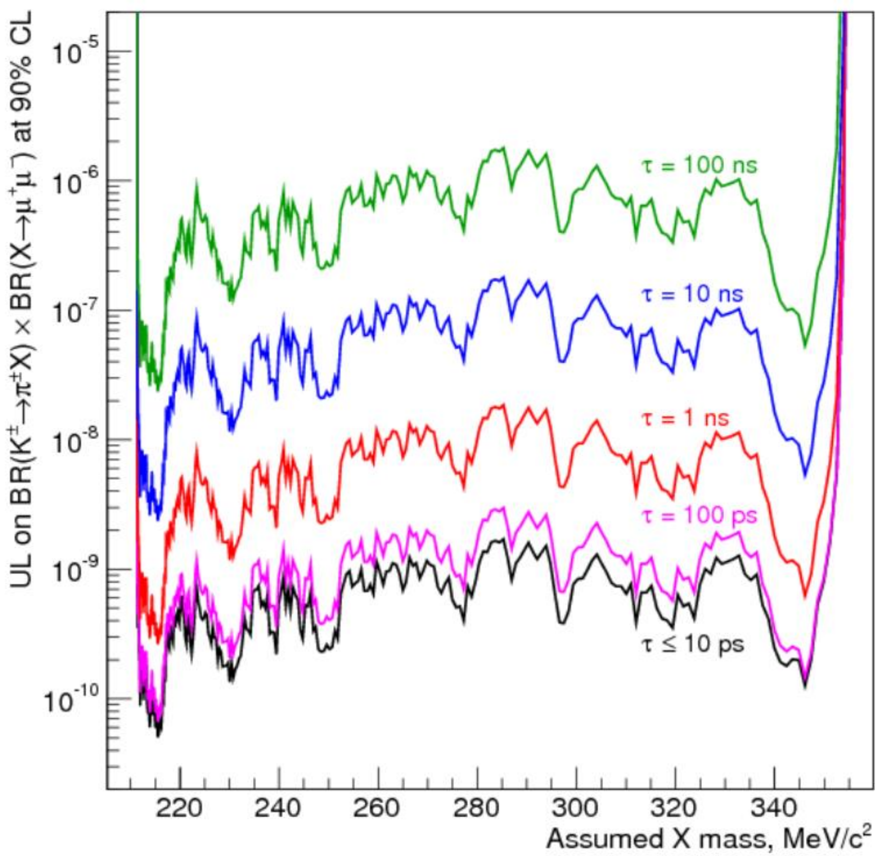
$$\mathrm{BR}(K^+ \to \pi^+ \hat{\pi}^{(b)}) \approx 3.9 \times 10^{-11} \left(\frac{10^3\ \mathrm{TeV}}{f_a^{(b)}} \right)^2 \lambda_{\pi\hat{\pi}}^{1/2}$$

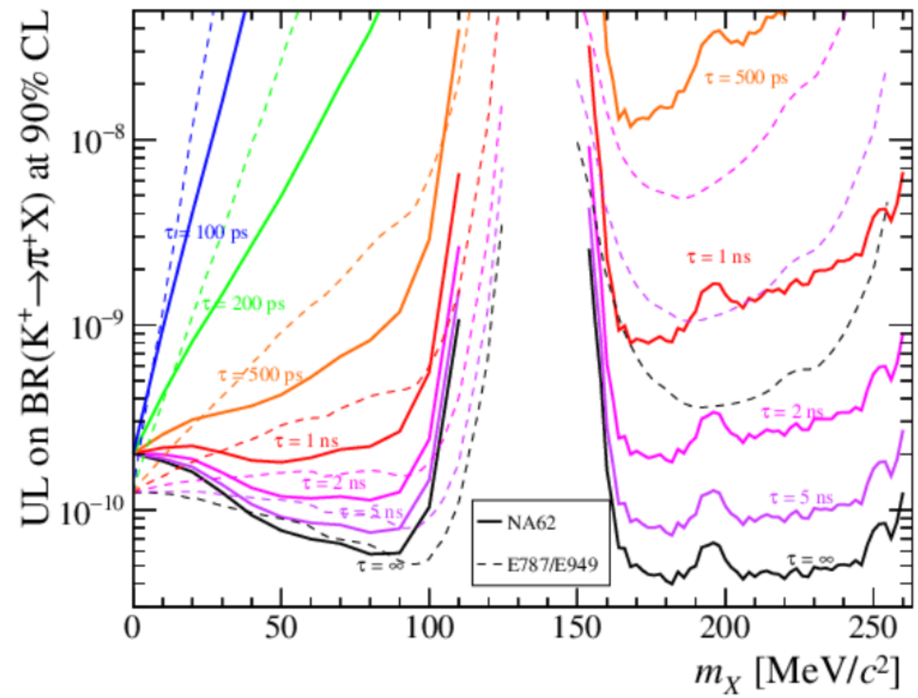
Kaon FCNC + LLP mode probes f_a ~ PeV also. [NA48/2 1612.04723]

Current FCNC Bounds (K decay)

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

Kaon FCNC + LLP mode probes f_a ~ PeV also. [NA48/2 1612.04723]





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

Dark Chiral perturbation Theory

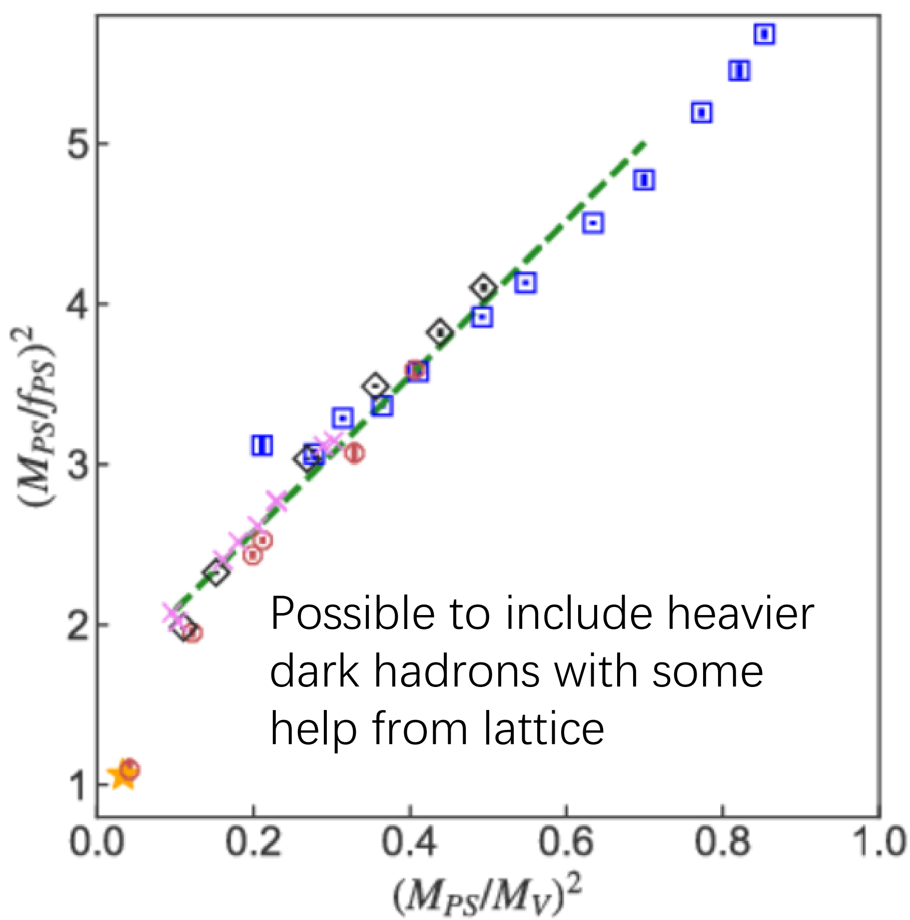
Dark ChpT describe more complicated interaction patterns and dark isospin breaking. Useful at E<<m_Z

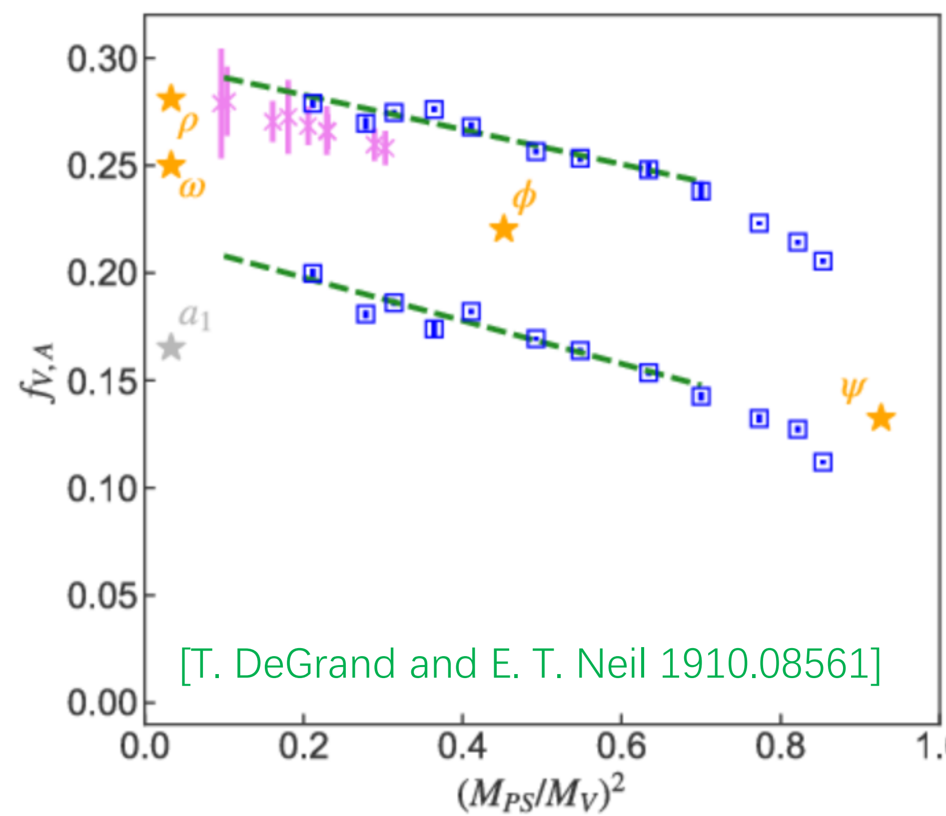
$$U = \exp\left(i\frac{\sigma_a \hat{\pi}^a}{f_{\hat{\pi}}}\right)$$

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

$$\widehat{\boldsymbol{m}}_{\psi'} = \boldsymbol{m}_{\psi'} - \boldsymbol{B}h$$

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



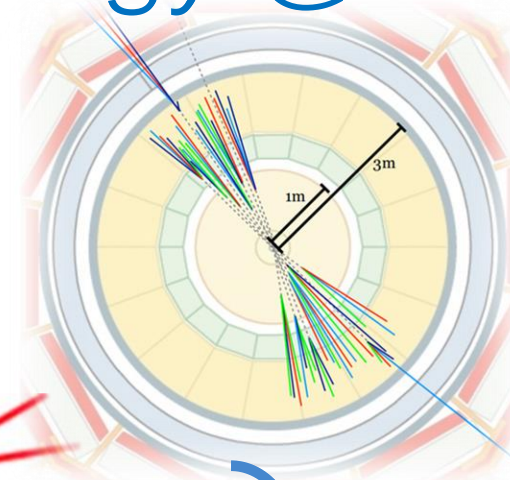


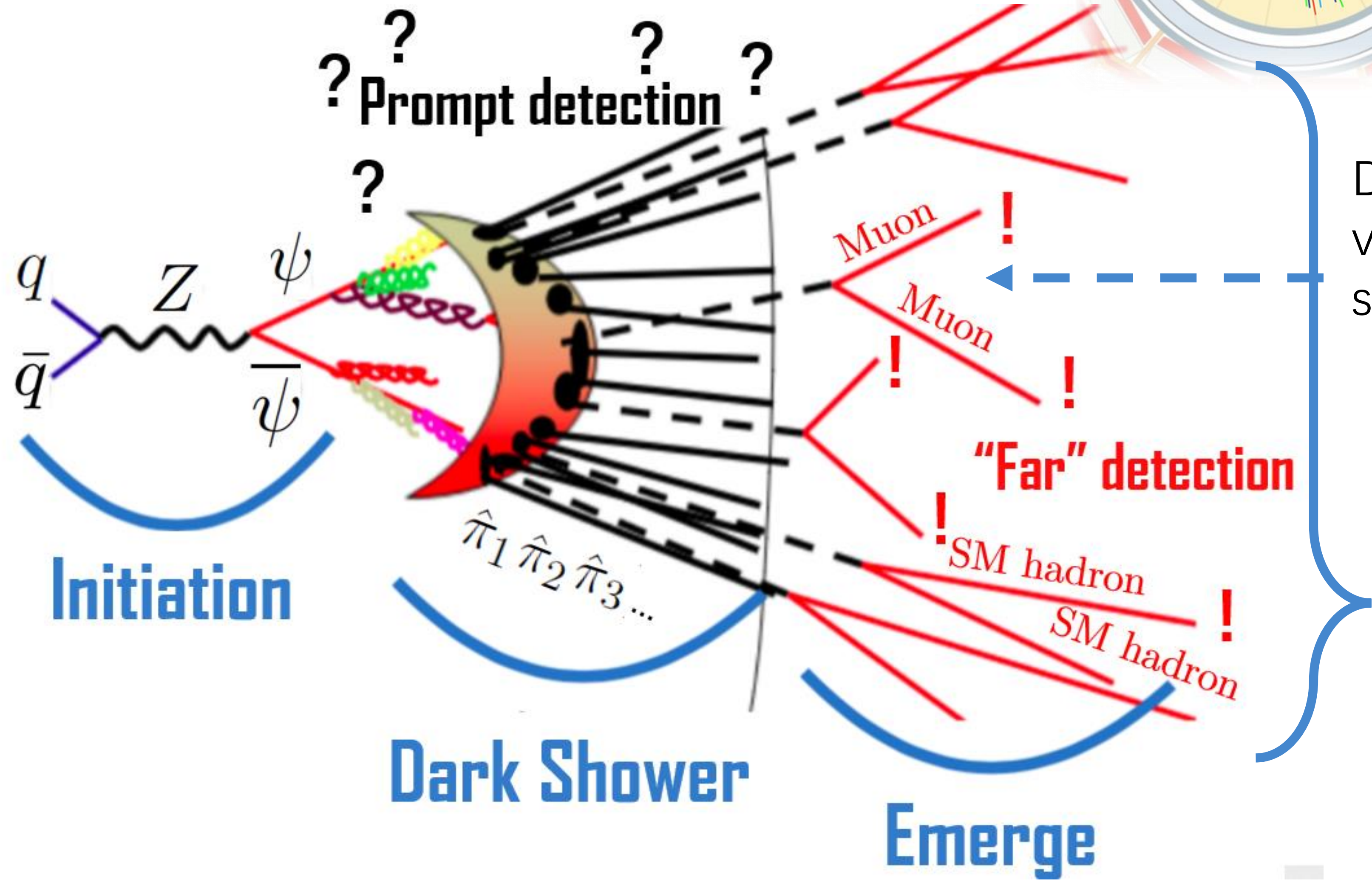
EW Scale Phenomenology @ LHC

If any dark pion is a LLP → The case often referred to as "emerging jets"

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

[CMS, 1810.10069]





Dimuon displaced vertexes (DV) are sharp signals

Fully inclusive searches rely on multiplicity of LLP tracks.

Symmetries of the Dark Pion Model

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

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

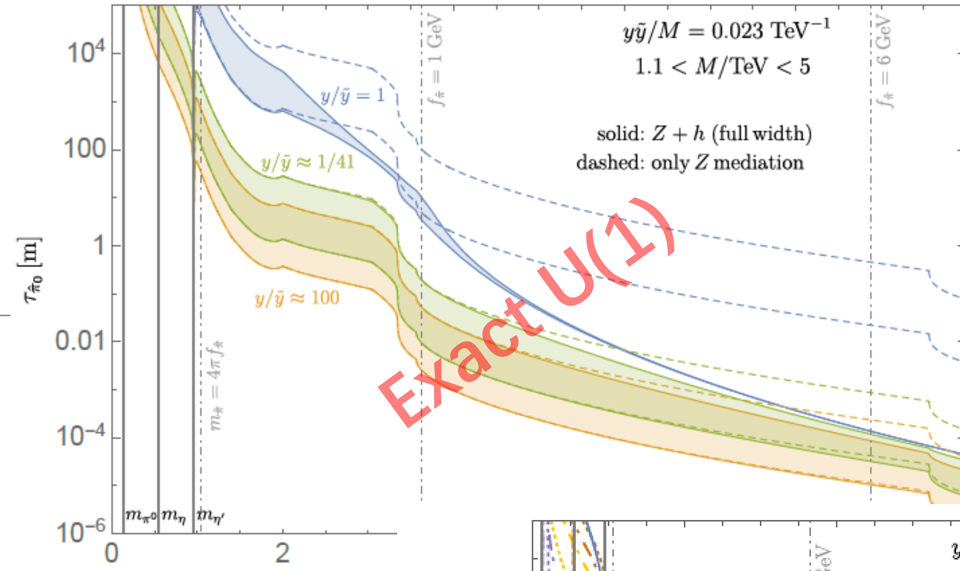
The U(1) subgroup of the SU(2) isospin is exact if everything is diagonal

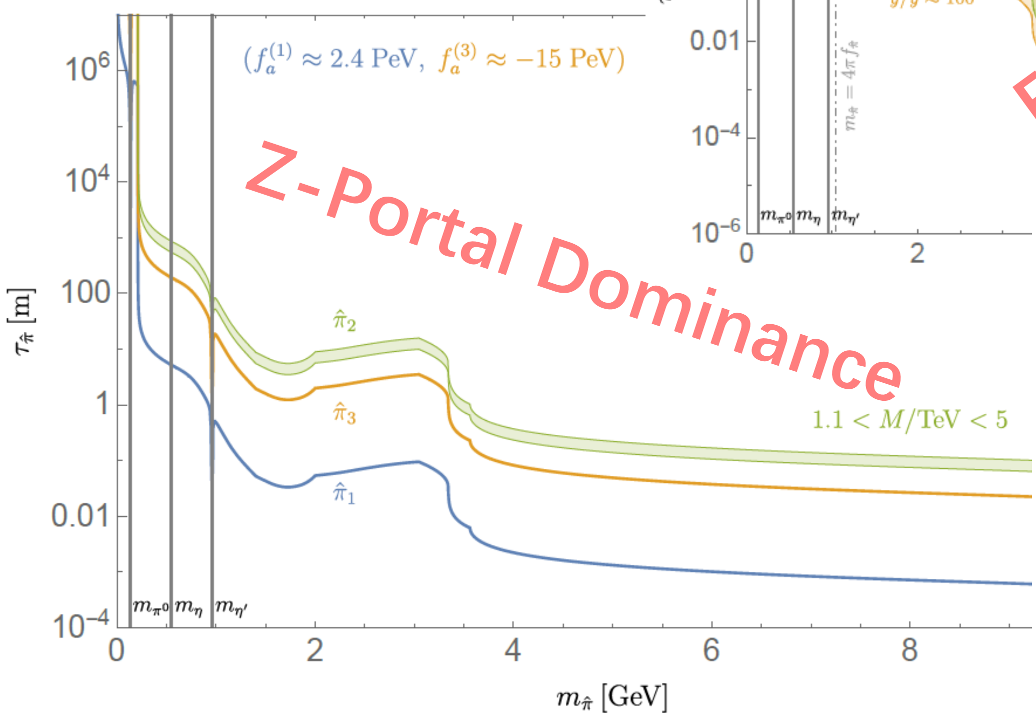
The CP is conserved in the dark sector if all couplings are real.

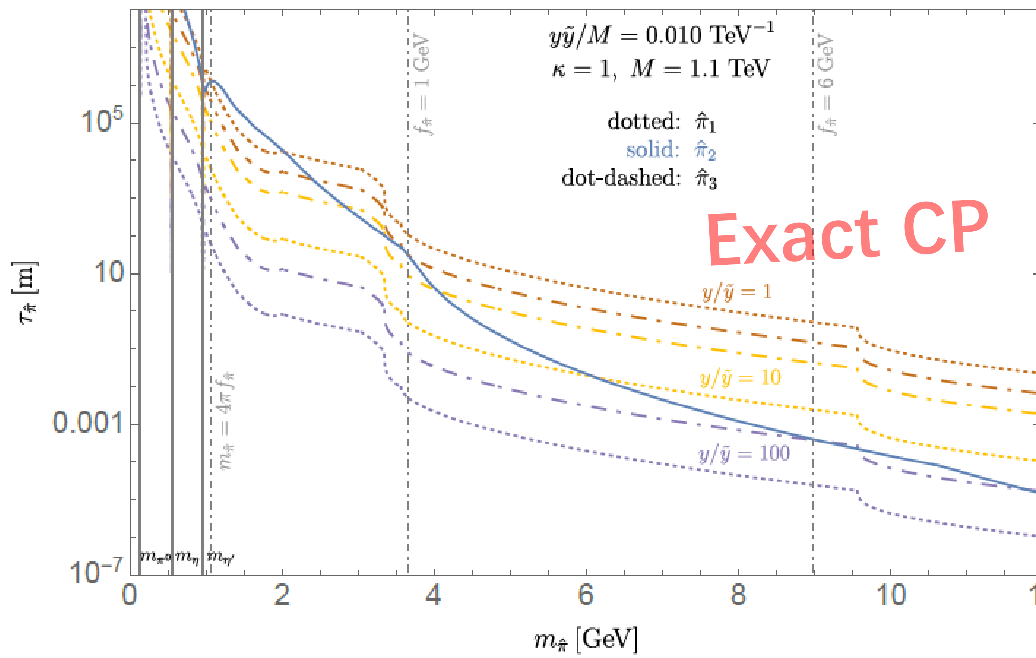
The Higgs portal is suppressed if either $\boldsymbol{Y}$ or $\widetilde{\boldsymbol{Y}}$=0

Dark Pion as Long-lived Particles

Lifetime between 1mm to >10m







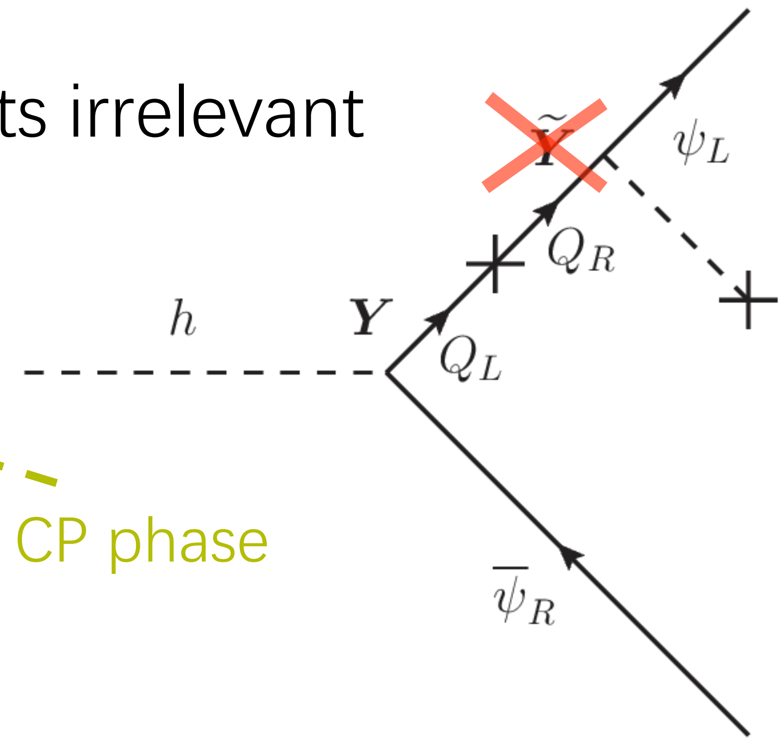
Easy LLP with strong parameter dependence

Lingfeng Li (Brown U.) arXiv: 2110.10691

Case Study: Z Portal Dominance

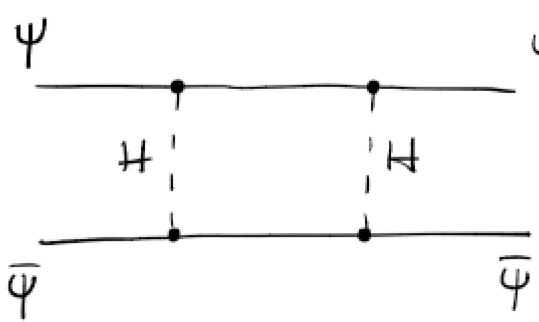
$$-\mathcal{L}_{\rm UV} = \overline{Q}_L \boldsymbol{Y} \psi_R H + \overline{Q}_R \widetilde{\boldsymbol{Y}} \psi_L H + \overline{Q}_L \boldsymbol{M} Q_R + \overline{\psi}_L \boldsymbol{\omega} \psi_R + \text{h.c.},$$

Higgs invisible decay width constraints irrelevant



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

For N=2 case, contains a free CP phase

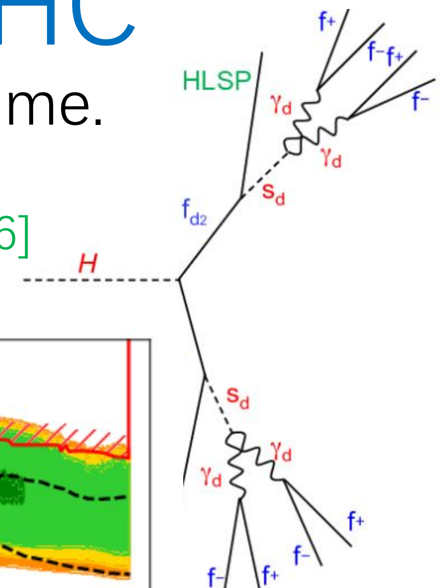


⇒ π_2 decays via the CP-violating mixing with π_1

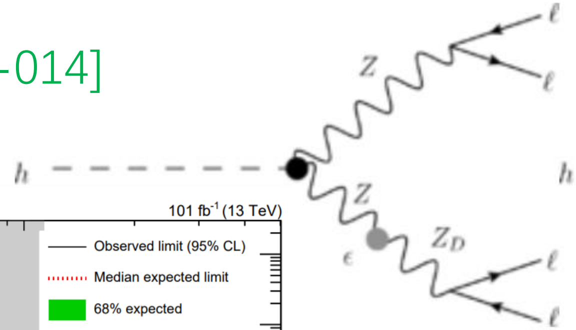
$$\tan 2\theta_{12} \approx \frac{0.20}{1 + 0.036 \left(\frac{4\pi v}{M}\right)^2} \quad \rightarrow \quad \Gamma_{\hat{\pi}_2} \approx \sin^2 \theta_{12} \, \Gamma_{\hat{\pi}_1}$$

Further Opportunities @ LHC

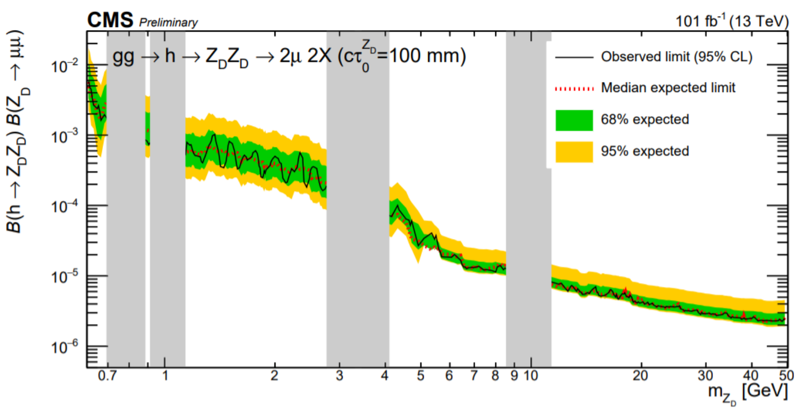
ATLAS/CMS benefit from larger luminosities and decay volume.

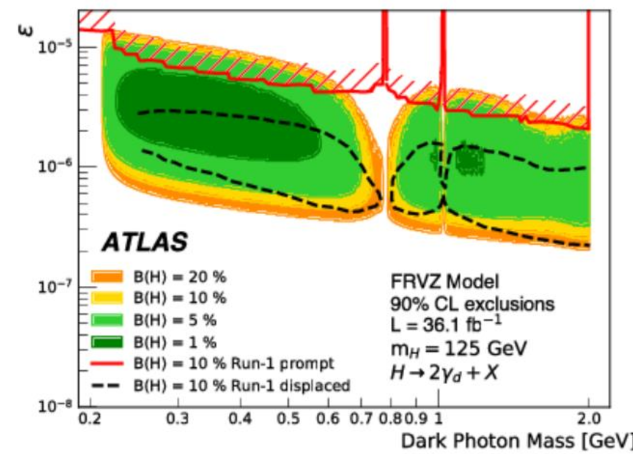


[CMS: CMS-PAS-EXO-20-014]

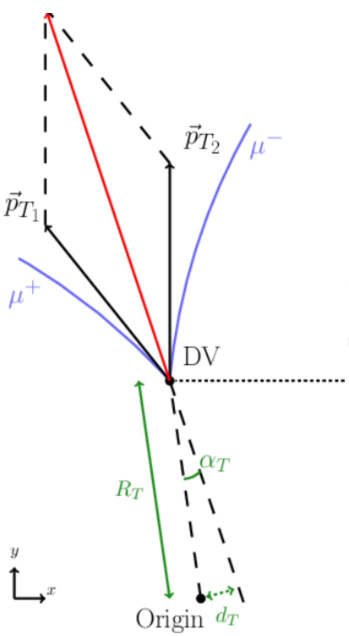


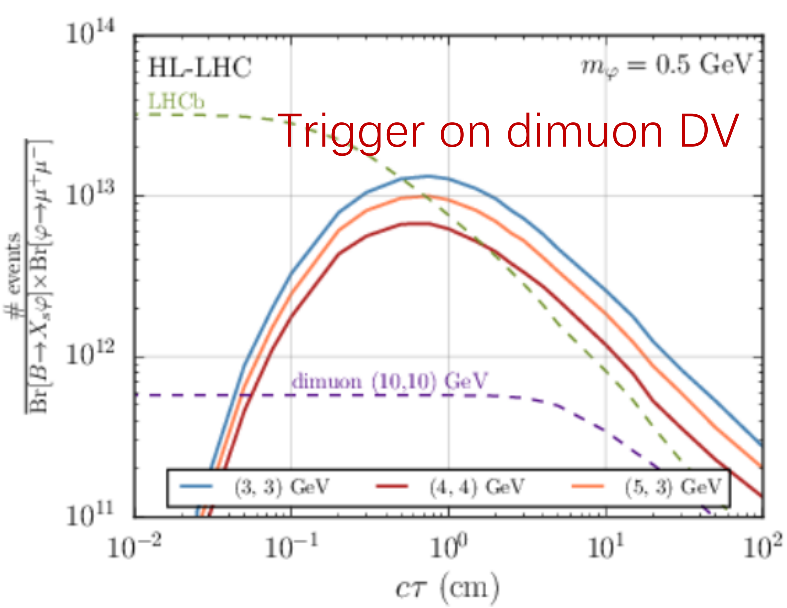
[ATLAS: 1909.01246]

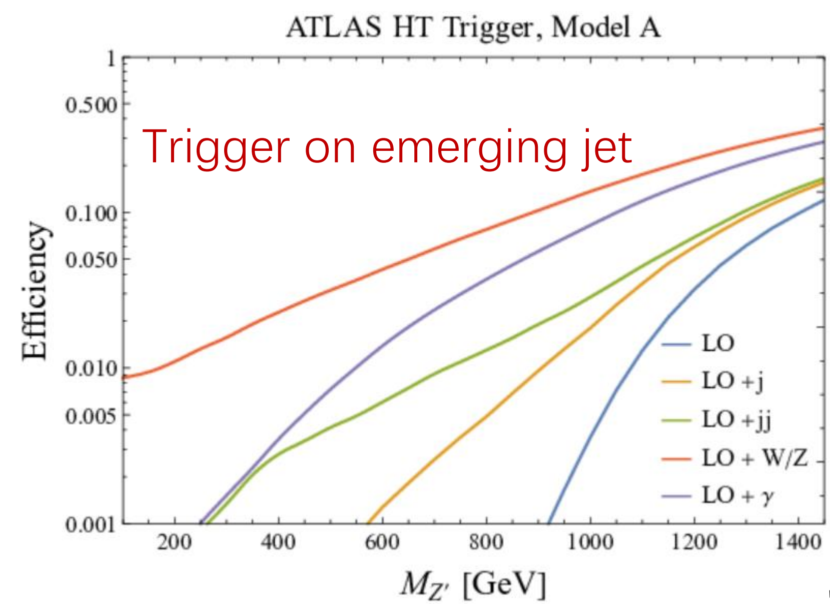




LLP oriented triggers? [Y. Gershtein and S. Knapen, 1907.00007, D. Linthrone and D. Stolarski, 2103.08620]

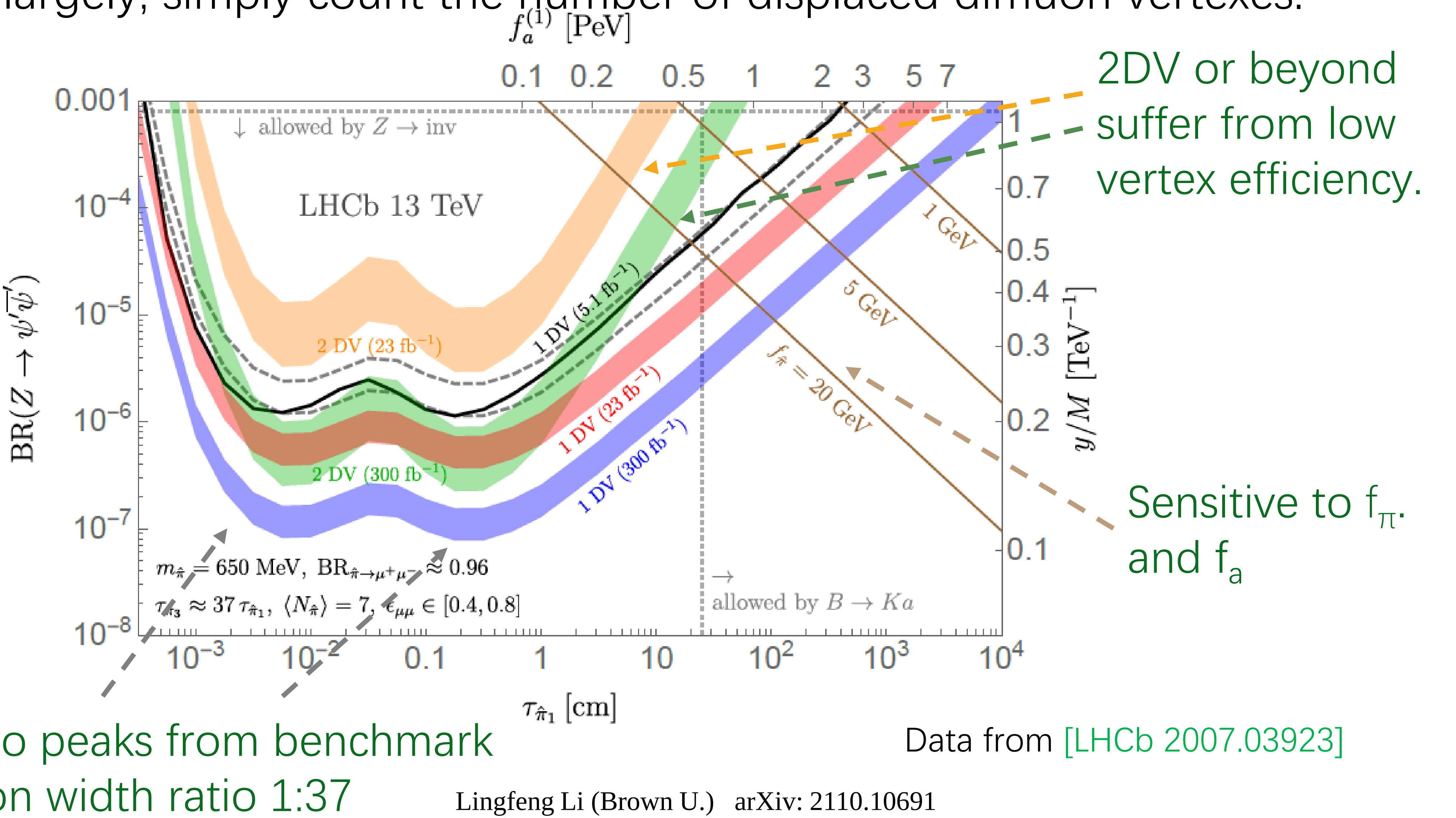






Example: Dimuon Search @ LHCb

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



Data from [LHCb 2007.03923]

TeV Scale Phenomenology @ LHC

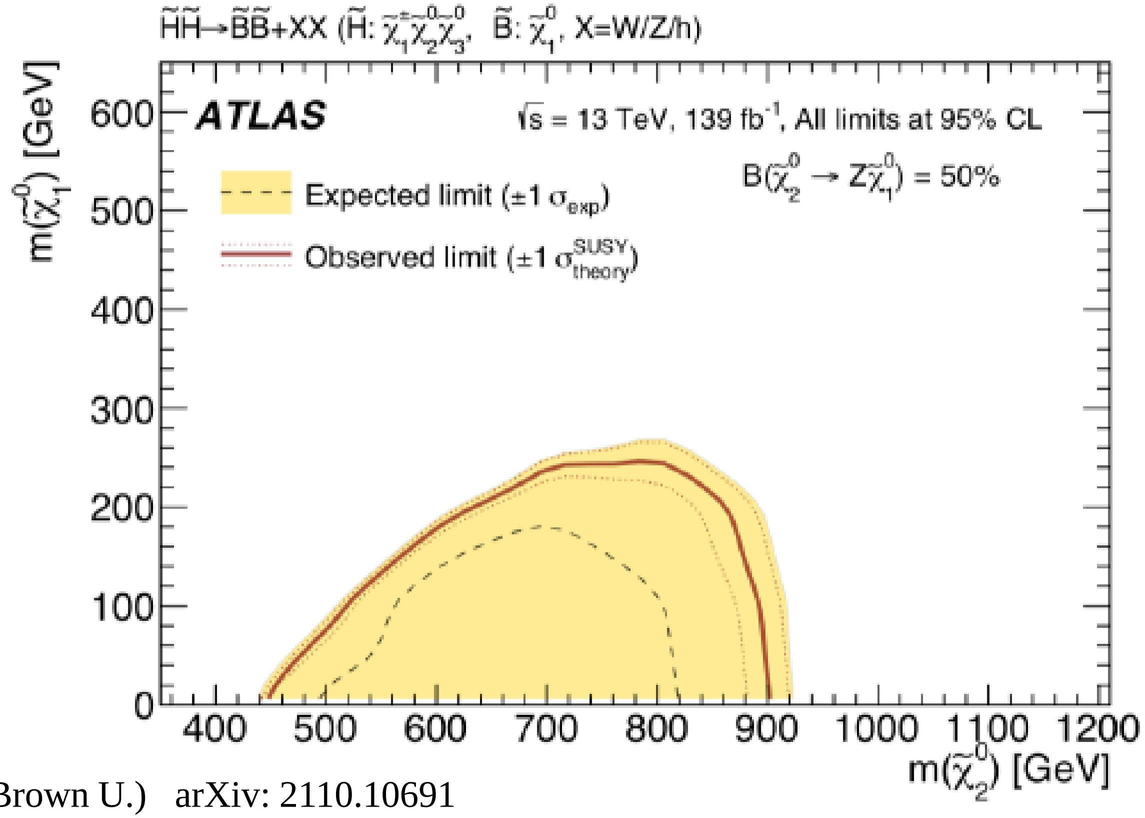
Direct production of heavy EW doublets:

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

⇒Diboson + emerging jet signals

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

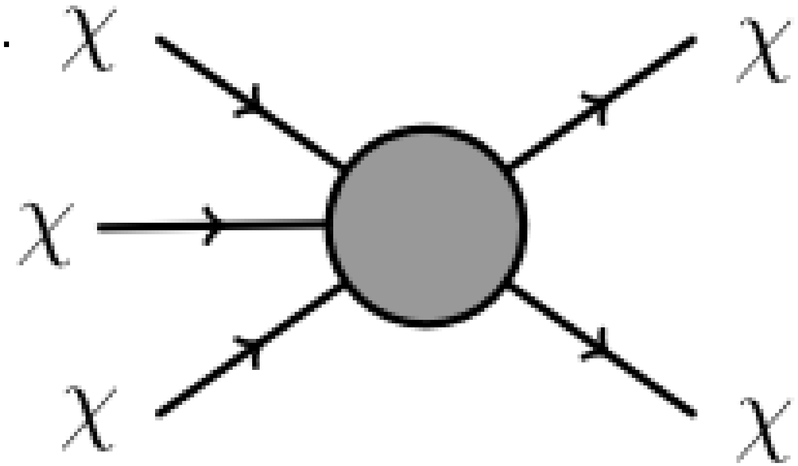
Estimated limit: M>1.3 TeV @ HL-LHC



Lingfeng Li (Brown U.) arXiv: 2110.10691

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.