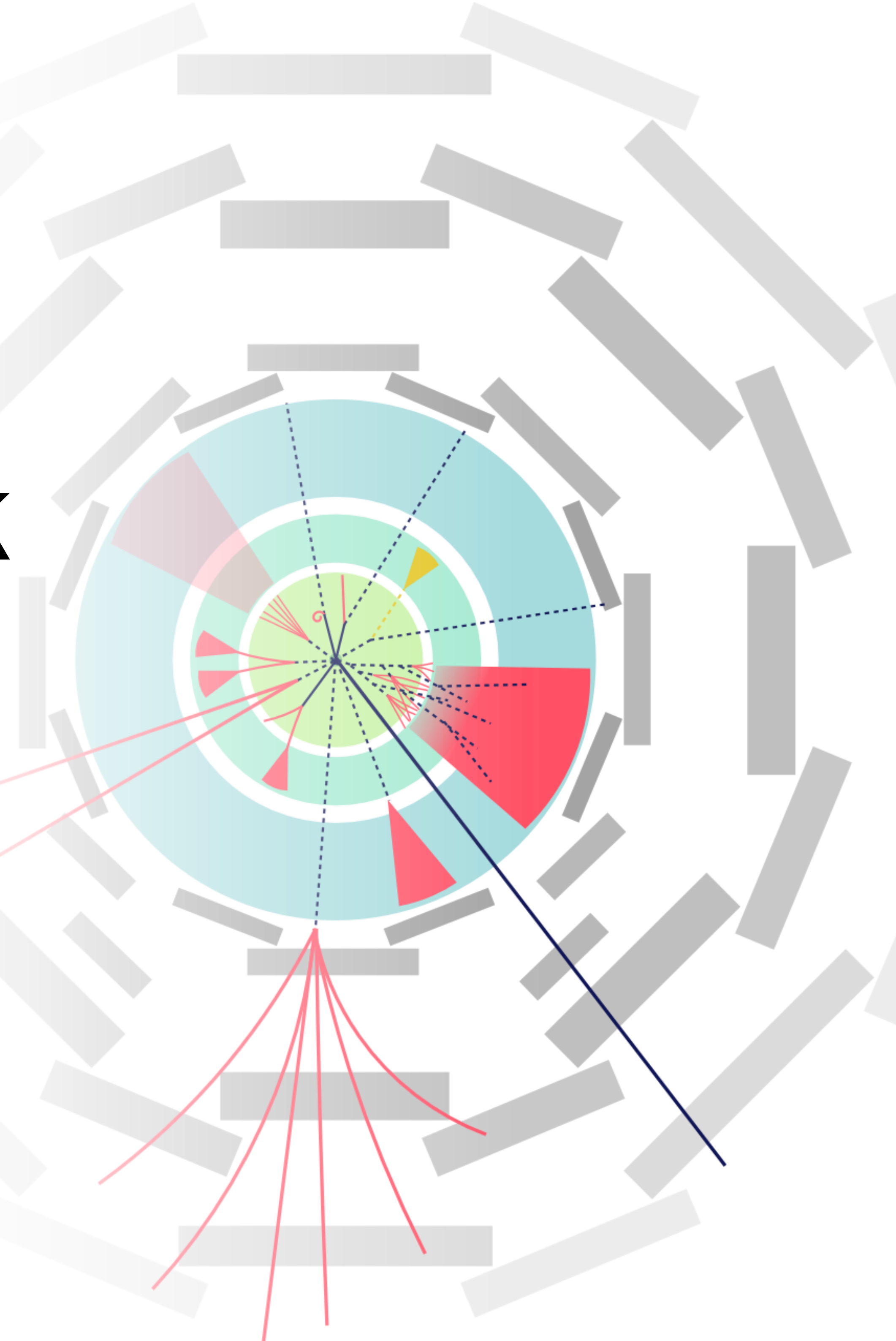
Higgs-Electroweak Portal to the Dark Sector



Lingfeng Li (Brown U.)

Nov. 10 2022
Higgs 2022, PISA

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

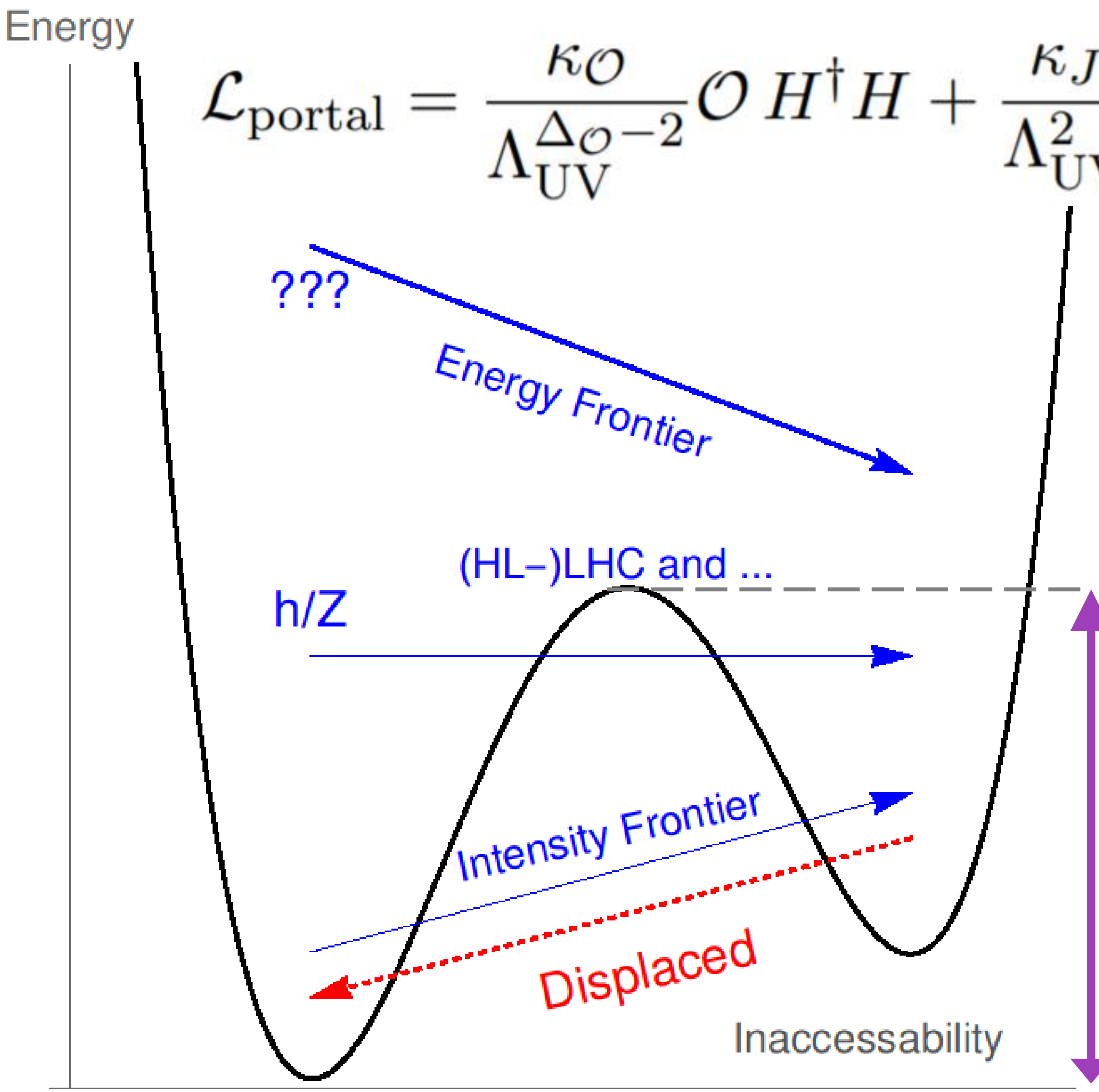
See also:

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

1905.02198 w/ H-C. Cheng, E. Salvioni and C. Verhaaren

Irrelevant Portal to Hidden Valley

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



A general form

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

Suppressed HV-SM coupling from the ~TeV scale

Other possibilities include: Higgs/dark photon/SM photon/axion portals

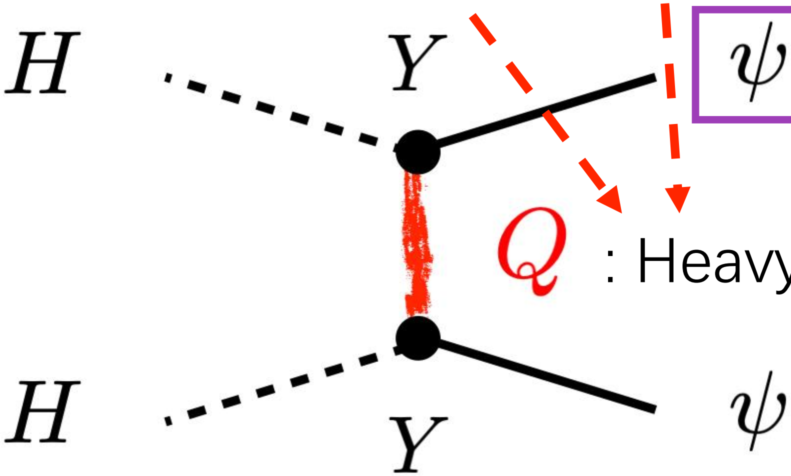
[S. Knapen, J. Shelton, D. Xu 2103.01238]

[G. Albouy et al, 2203.09503]

Irrelevent Portal Dark Pions

Q heavier than O(TeV)

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



ψ : Light SM singlet dark quarks

Q : Heavy SM doublet mediators

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

$\boldsymbol{\omega}, \boldsymbol{M}, \boldsymbol{Y}, \widetilde{\boldsymbol{Y}}$: N×N mass/Yukawa matrixes

Irrelevent Portal Dark Pions (II)

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

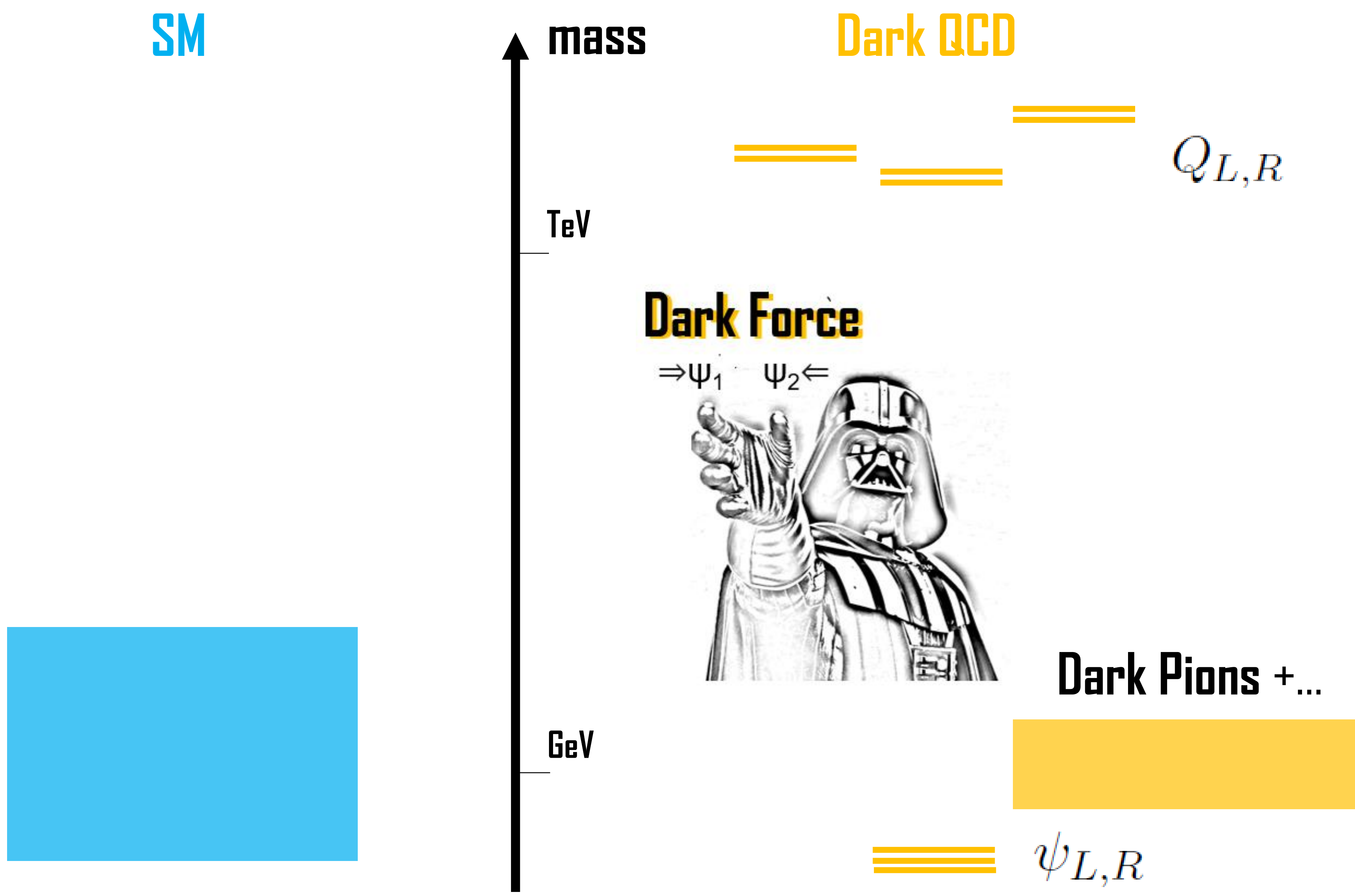
Dimension-6 Z portal couplings

Dimension-5 Higgs portal coupling

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

In the special case N_{flavor} = 1, no isospin symmetry, thus no pNGBs, the dark sector has a heavy psdudoscalar (P), a vector (V) and a scalar (S) as ground states with comparable masses.

The Cartoon of Dark Spectrum



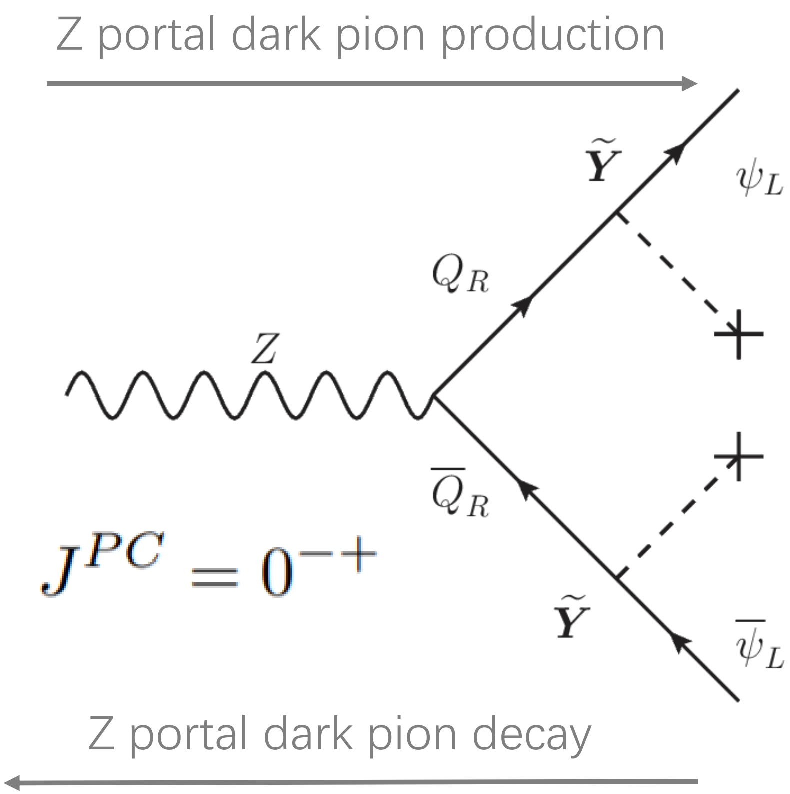
Lingfeng Li (Brown U.) arXiv: 2110.10691

Two Flavor, Three Dark Pions

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

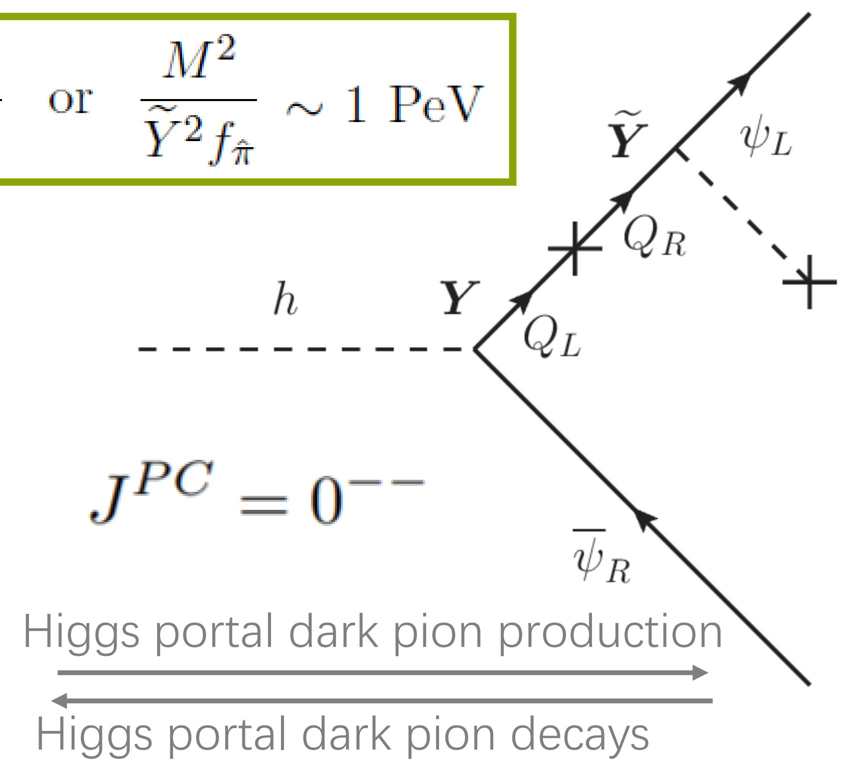
The π_1 and π_3 decay via Z portal, ALP-like (axion-like-particle) with large ALP decay constants:

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



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

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

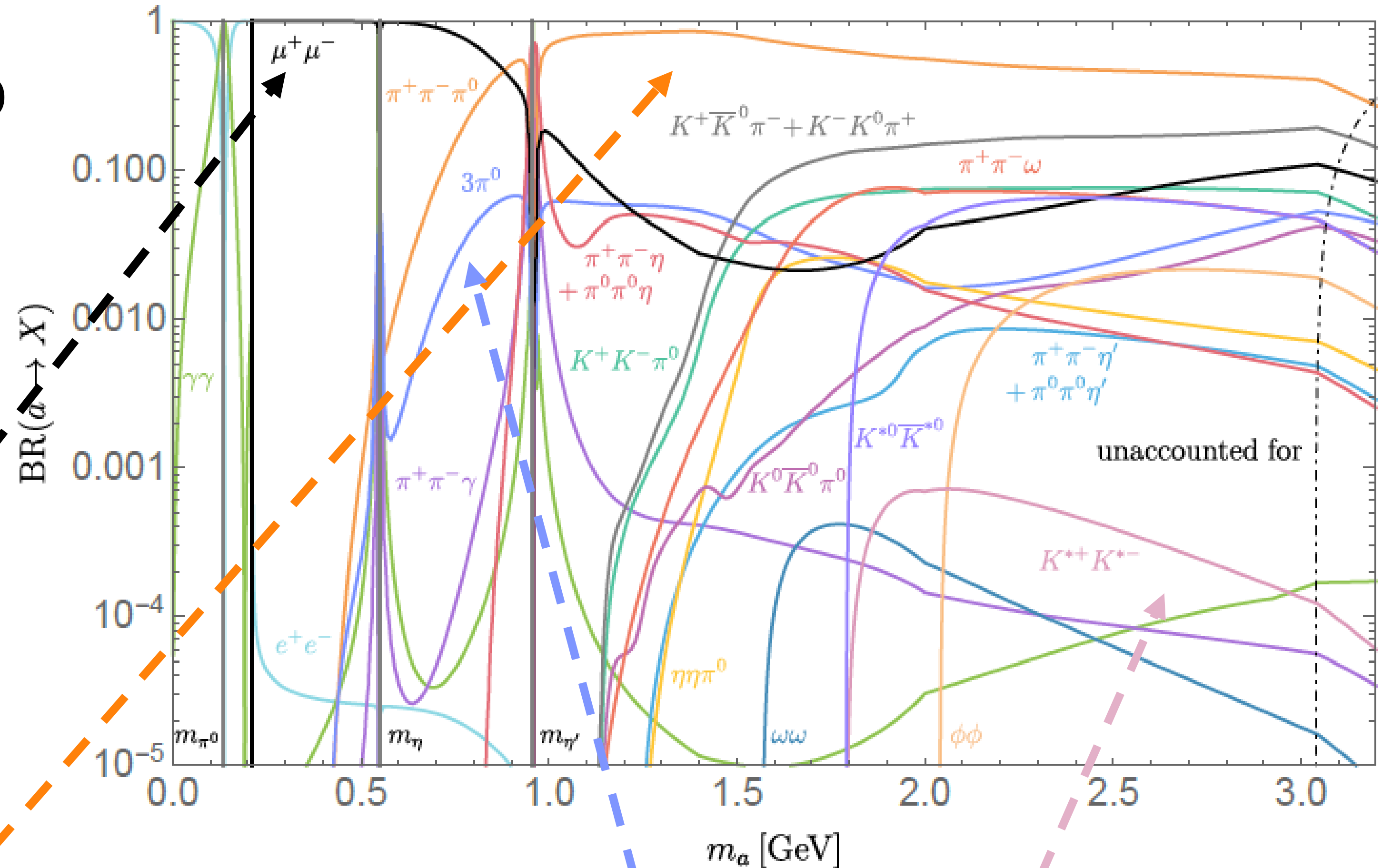


Dark Pion Decays (ALP-Like)

Result applies to generic flavor diagonal ALP couplings

See also [D. Aloni, Y. Soreq and M. Williams, 1811.03474],

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



SM isospin suppressed modes

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

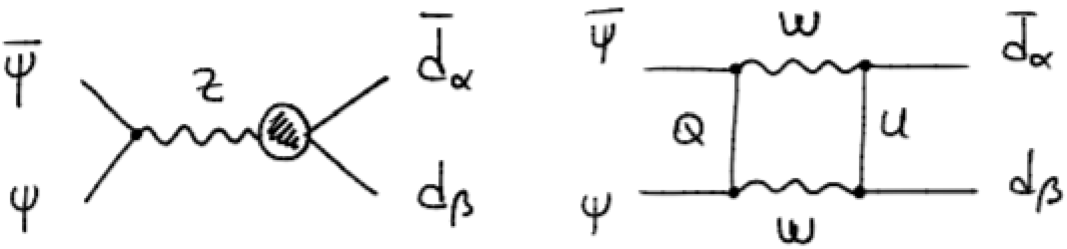
Elaborate discussions on indirect and ALP-type constraints in backup slides and the paper, e.g. flavor probes. See also Jure Zupan's talk.

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

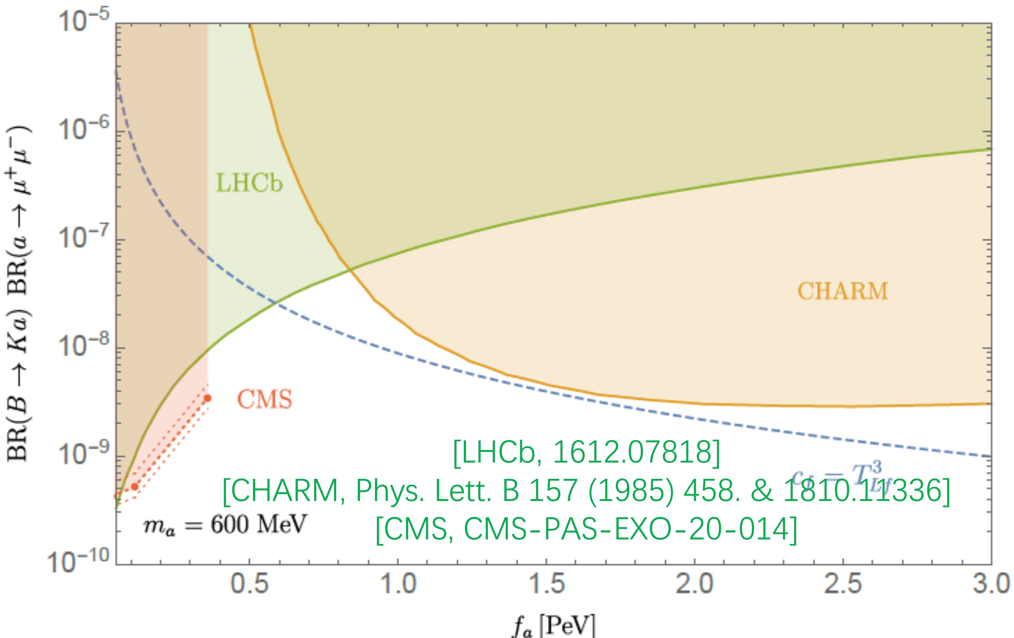
$$\langle \hat{\pi}_a X | \mathcal{H}_{\rm eff} | B \rangle = \langle \hat{\pi}_a | \langle X | \mathcal{H}_{\rm eff} | 0 \rangle | B \rangle = \frac{i g^2}{64\pi^2} V_{ts}^* V_{tb} \langle X | \bar{s}_L \gamma_\mu b_L | B \rangle \frac{p^\mu_{\hat{\pi}}}{f_a^{(a)}} \left[\frac{m_t^2}{m_W^2} \left(\log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

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

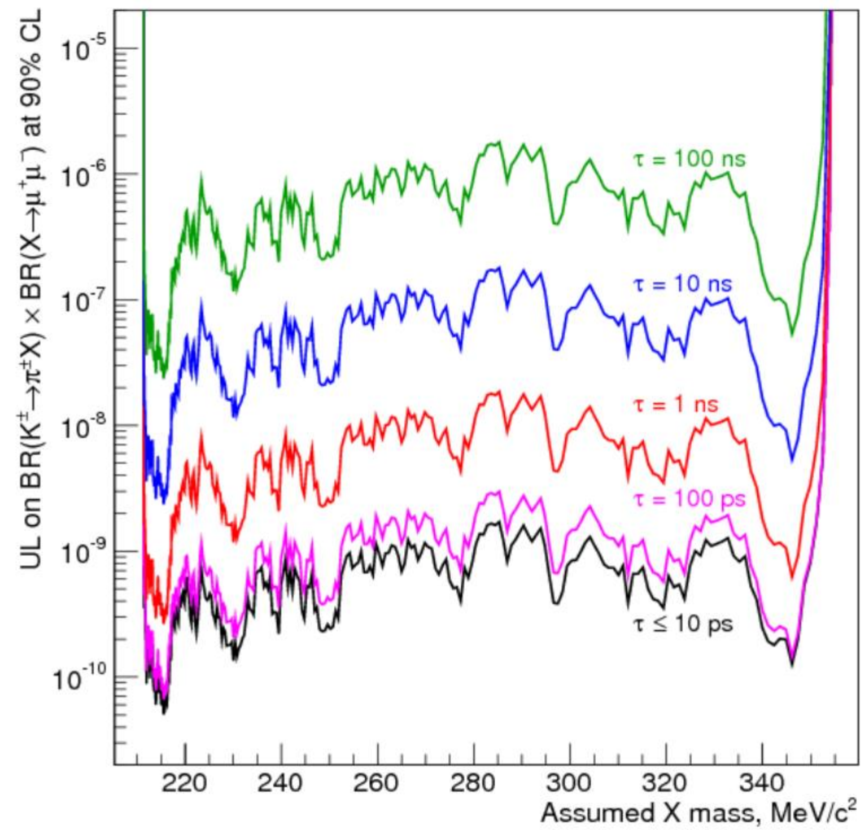
Experimentally achievable if dark pions are LLP

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



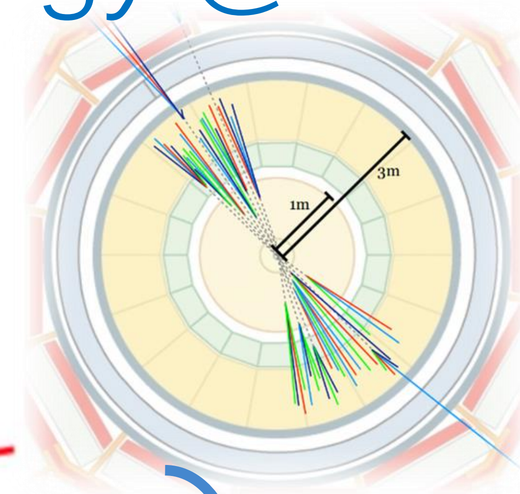
$$\mathrm{BR}(K^+ \to \pi^+ \hat{\pi}^{(b)}) \approx 3.9 \times 10^{-11} \left(\frac{10^3\ \mathrm{TeV}}{f_a^{(b)}} \right)^2 \lambda_{\pi\hat{\pi}}^{1/2}$$

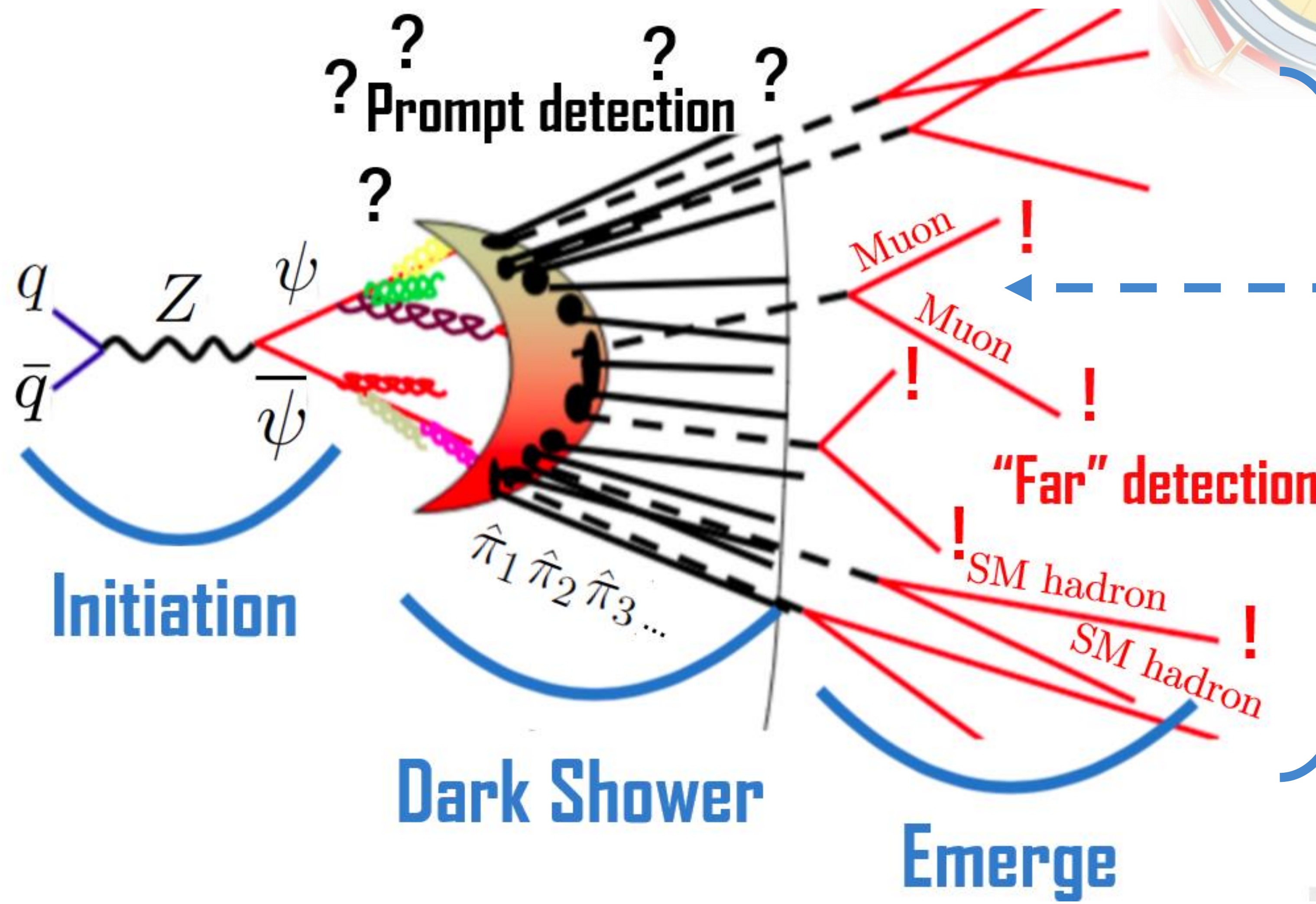
Kaon FCNC + LLP mode probes f_a ~ PeV also. [NA48/2 1612.04723]

EW Scale Phenomenology @ LHC

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

[P. Schwaller, D. Stolarski and A. Weiler, 1502.05409]
[CMS, 1810.10069]



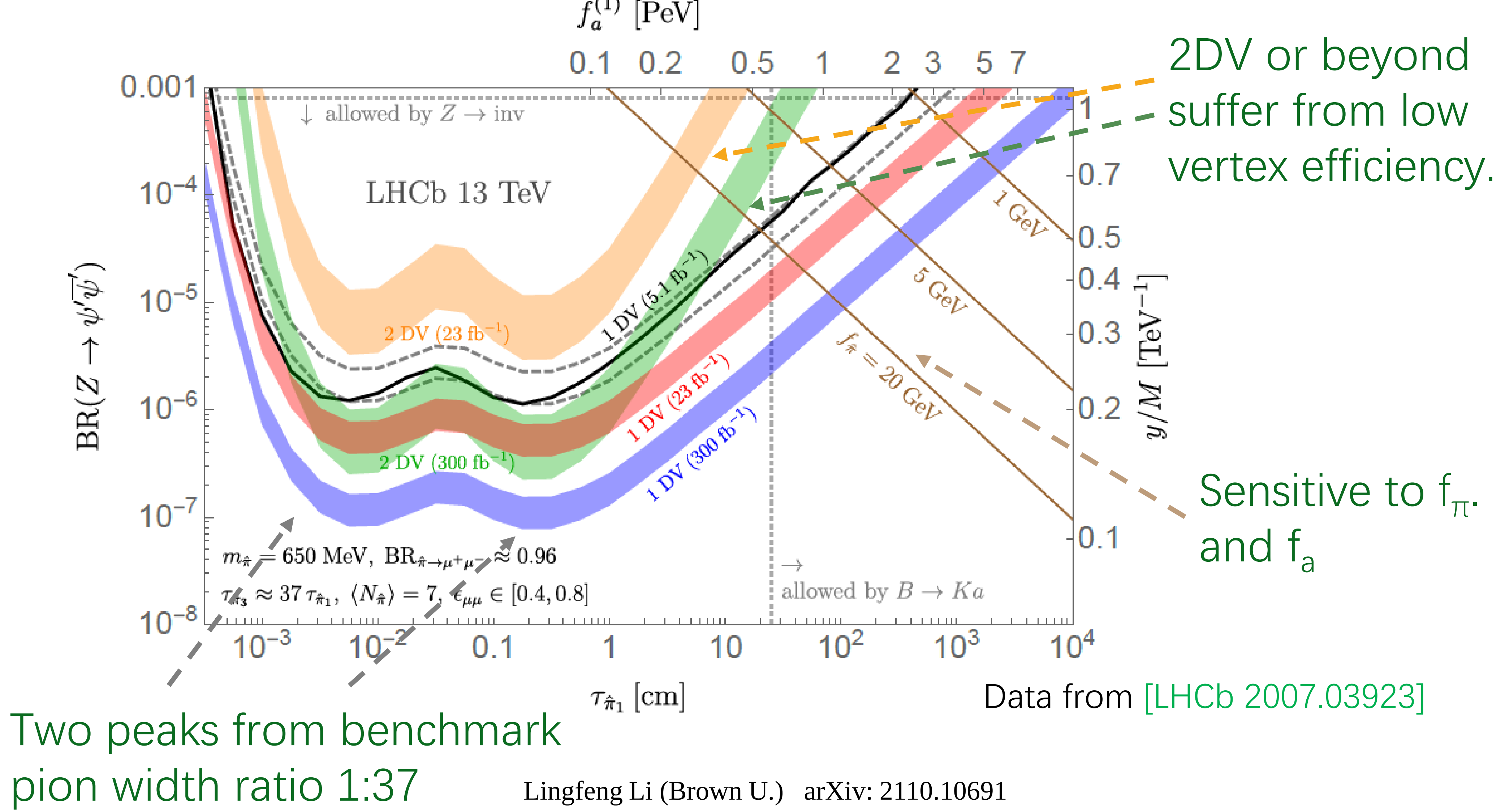


Dimuon displaced vertexes (DV) are sharp signals

Fully inclusive searches rely on multiplicity of LLP tracks.

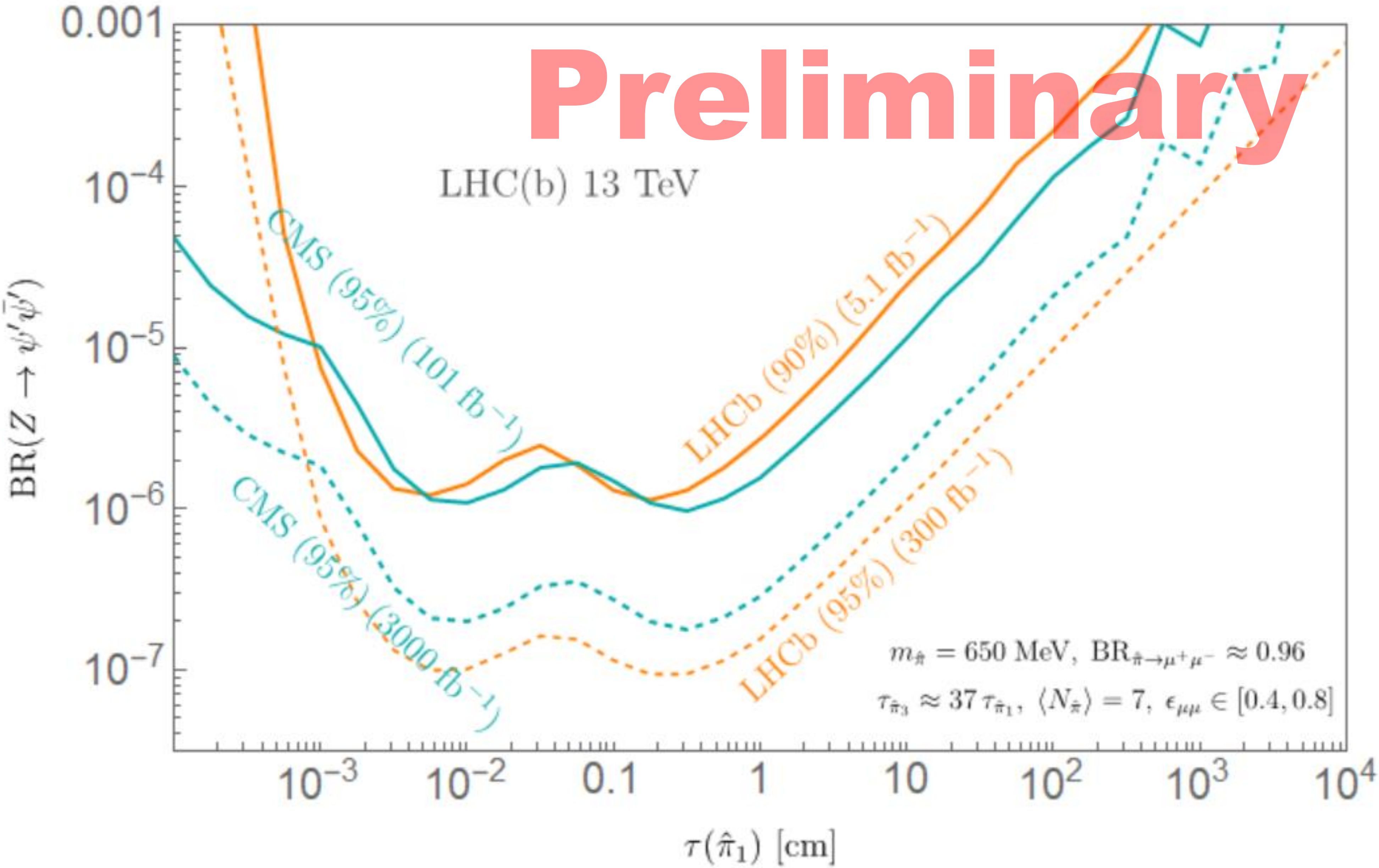
Example: Dimuon Search @ LHCb

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



Data from [LHCb 2007.03923]

Lingfeng Li (Brown U.) arXiv: 2110.10691



Limits from the CMS data scouting [CMS, CMS-PAS-EXO-20-014]

Summary

- Dark mesons are common and well motivated. From simple UV structures, there will be rich phenomenology.
- Easily long-lived. Dedicated calculations below the cc threshold.
- Phenomenology from current data shows that an M ~ a few TeV is achievable. Bright future prospects.
- Open fields (alternative portals, cosmology···) remain to be fully explored.

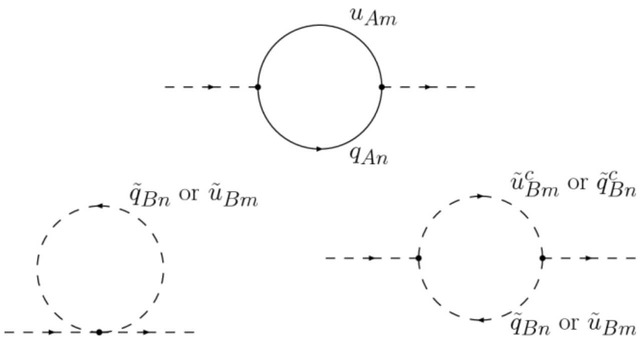
Backup Slides

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]

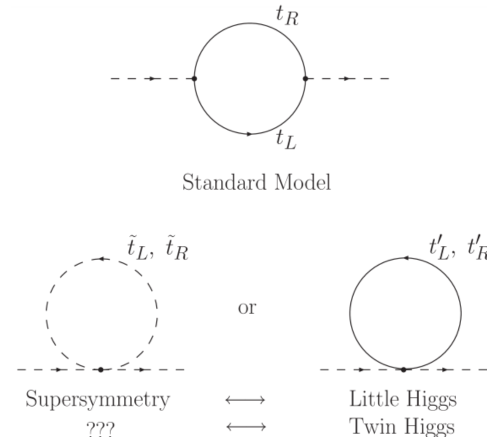


See also Tripled Top (TT) model

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

Twin Higgs

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



Motivating Scenario II: Relaxion

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

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

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

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

Motivating Scenario III: Asymmetric Dark Matter

The (mirror) baryon number stabilizes the dark matter

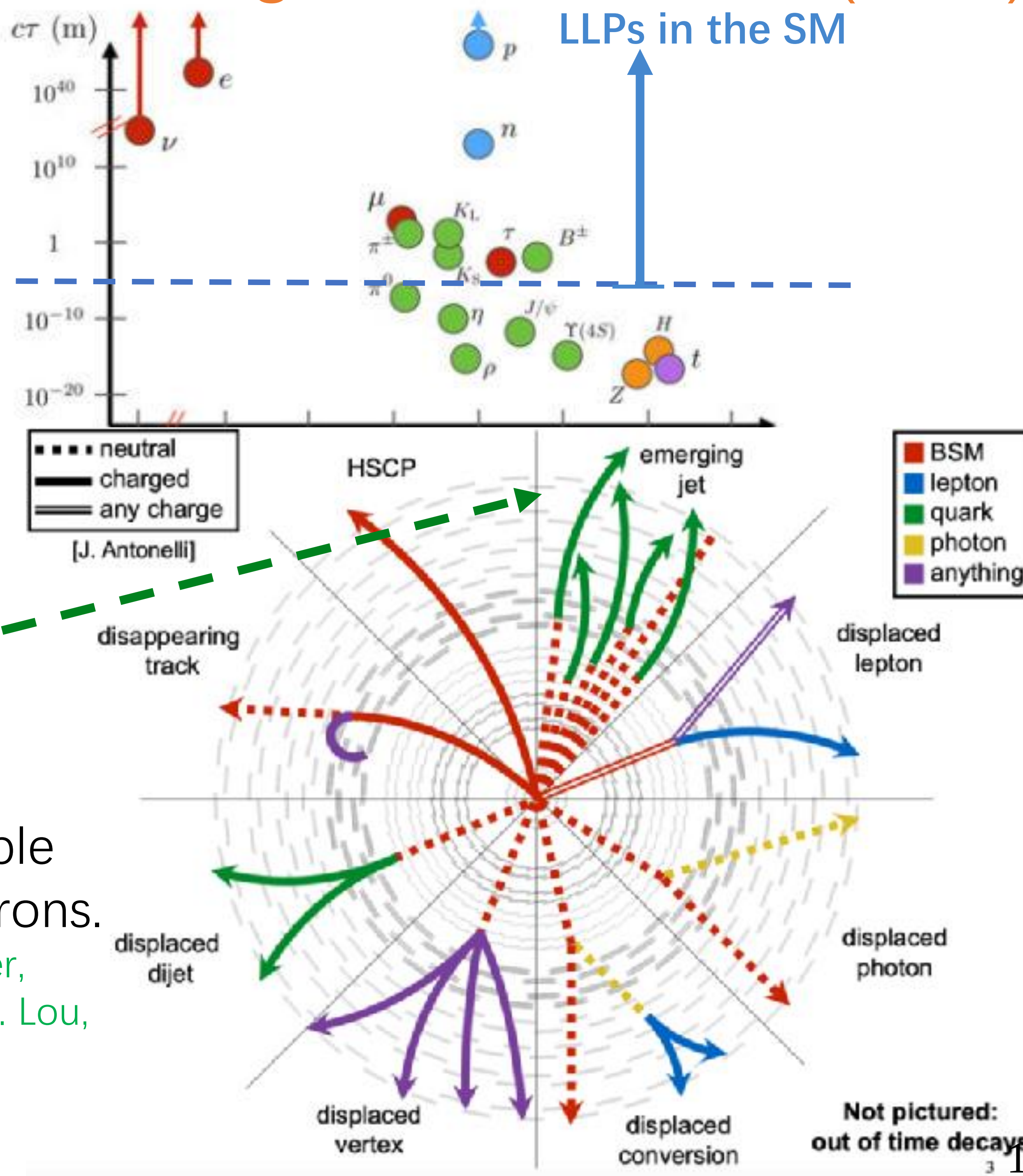
[D. E. Kaplan, M. Luty and K. M. Zurek, 0901.4117]

The large elastic Xsec allowed between dark matter particles may help solve the so called small scale crisis in cosmology.

[X. Chu, C. Garcia-Cely, H. Murayama, 1901.00075] [J. Terning, C. Verhaaren, K. Zora, 1902.08211]

HEP-ph/ex Motivation: Long-Lived Particles (LLPs)

Many recent efforts/ proposals to search for LLPs e.g. [J. Alimena et al, 2203.05502] [J. L. Feng et al, 2203.05090]



One of the perhaps most interesting and challenging scenario: Emerging/semivisible jets made of many dark hadrons. [P. Schwaller, D. Stolarski and A. Weiler, 1502.05409] [T. Cohen, M. Lisanti, H.K. Lou, 1503.00009]

Alternative Tripled Top (TT) Model

Arbitrarily light

A few TeV

The superpotential :

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

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

The soft breaking term:

A few TeV (≈M)

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

A Folded SUSY-like spectrum realized in 4D

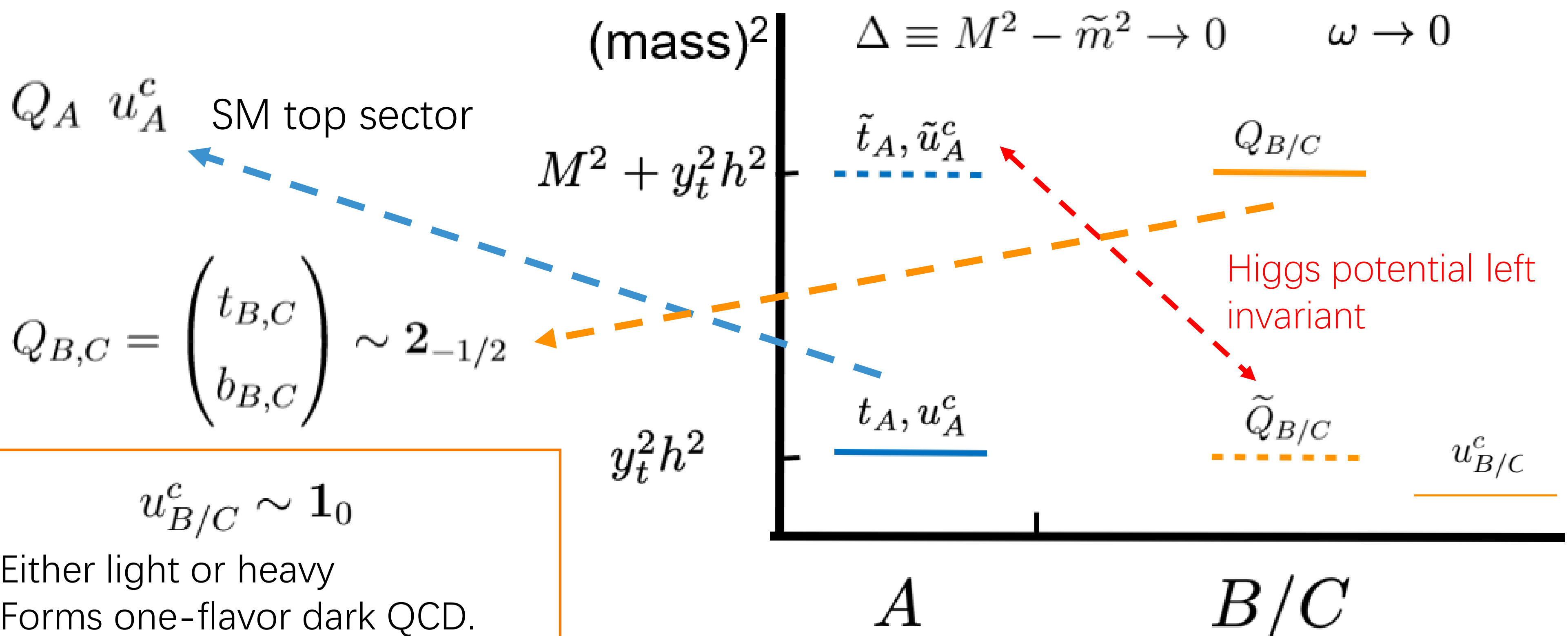
For details of the original model, see [H-C.Cheng, LL, E.Salvioni and C. Verhaareen 1803.03561]

1803.03651 1905.03772 20xy.ijklm

Alternate Tripled Top (TT) Model & Accidental SUSY

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

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



$u^c_{B/C} \sim \mathbf{1}_0$

Either light or heavy

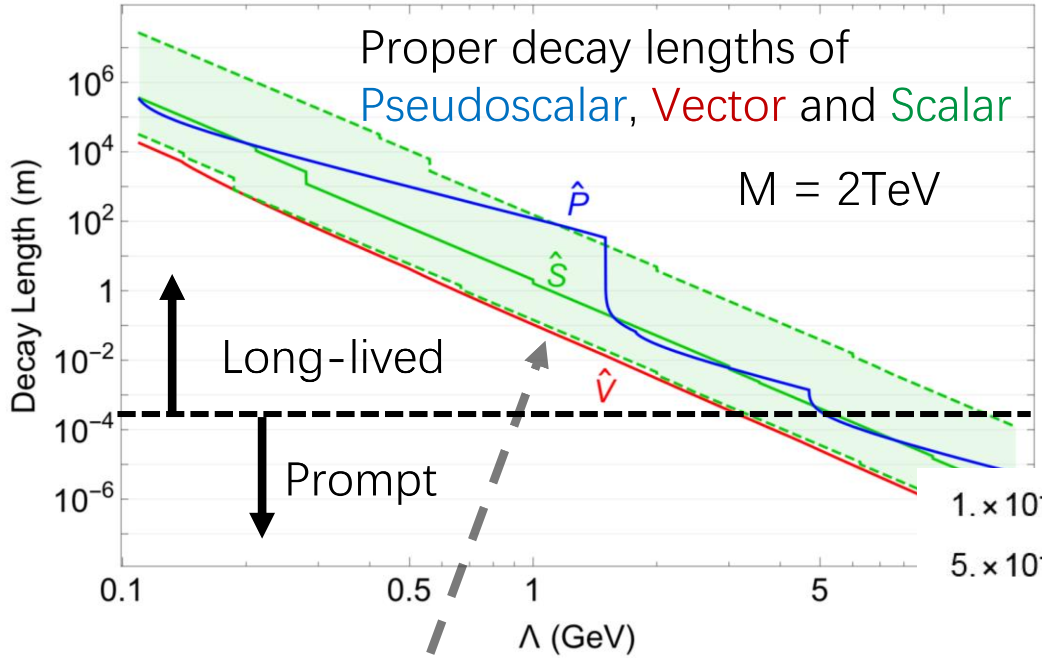
Forms one-flavor dark QCD.

Dark hadrons:

Pseudoscalar, Vector and Scalar

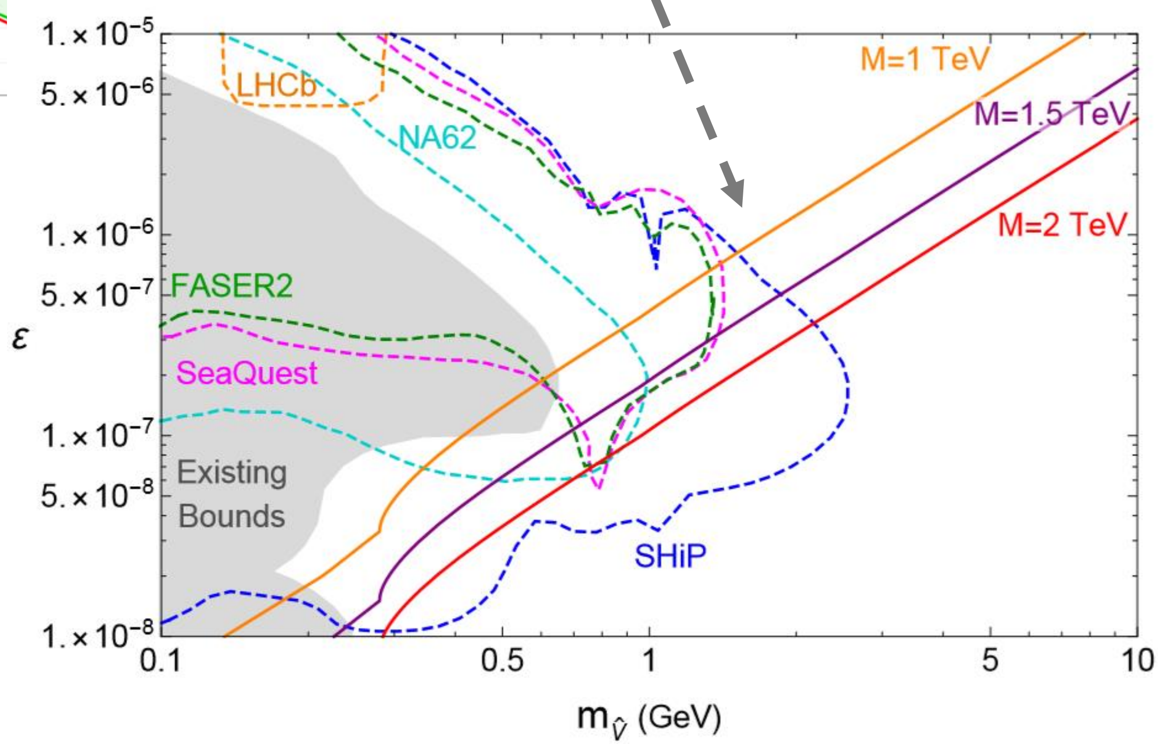
1803.03651 1905.03772 20xy.ijklm

One flavor Dark QCD- No Dark Pions



Dark vector meson picks up an effective mixing parameter, similar to a dark photon in the forward/ intensity frontier searches.

$$\varepsilon_{\rm eff} \sim \frac{1}{2}\sqrt{\frac{\alpha_Z}{\alpha}}\,\varepsilon_Z \approx 3.8\times10^{-7}\left(\frac{\Lambda}{1\,{\rm GeV}}\right)^{3/2}\left(\frac{m_{\hat V}}{2\,{\rm GeV}}\right)^{1/2}\left(\frac{2\,{\rm TeV}}{M}\right)^{2}$$



Without flavor symmetry, pseudo scalar width scales as: $Y^4\Lambda^3 m f^2/M^4$, $Y^4\Lambda^5/M^4$ for vector.

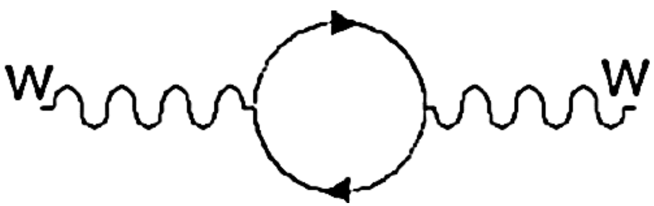
Easily and naturally become long-lived

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

Indirect/Precision Constraints

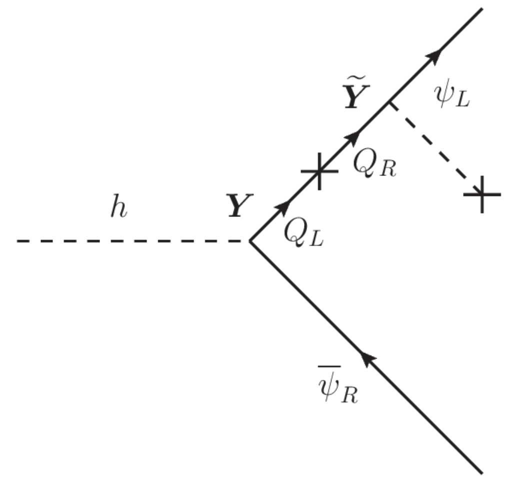
$$M \gtrsim 0.9\,\text{TeV}\; Y^2 \left(\frac{N_d N}{6}\right)^{1/2}$$

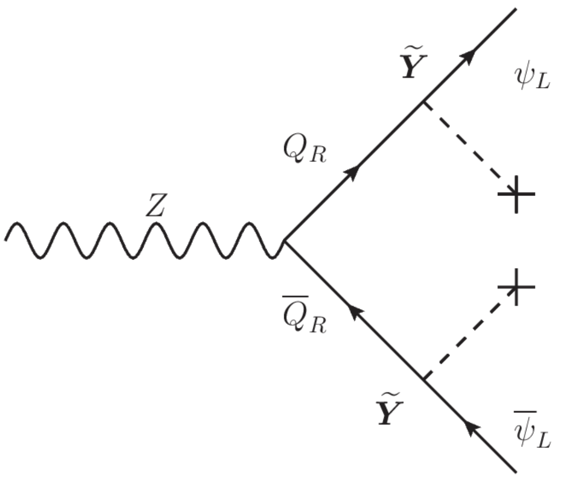
From EW oblique parameter T < O(10^{-3})



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

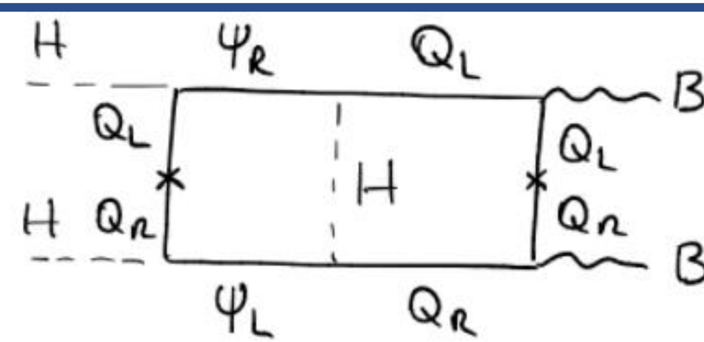
From Higgs invisible decay BR < 13%





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

From Z invisible decay width <~2 MeV

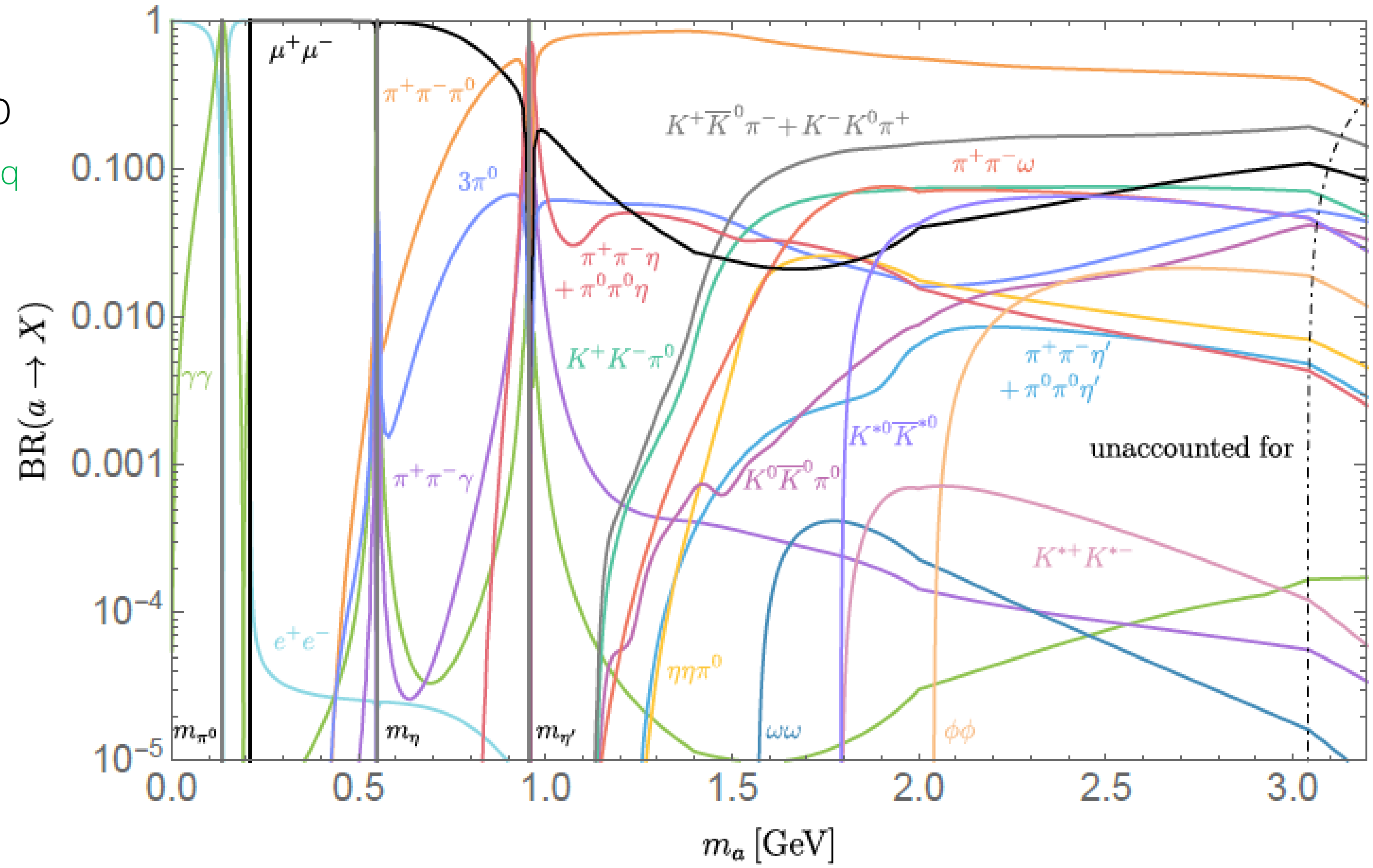


$$M \gtrsim 1.5\ \text{TeV}\ \ Y\widetilde{Y}$$

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 $a \to K^0\overline{K}^0\pi^0$

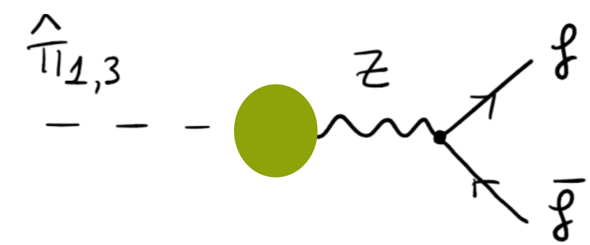
A.9 $a \to K^+K^-\pi^0$

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

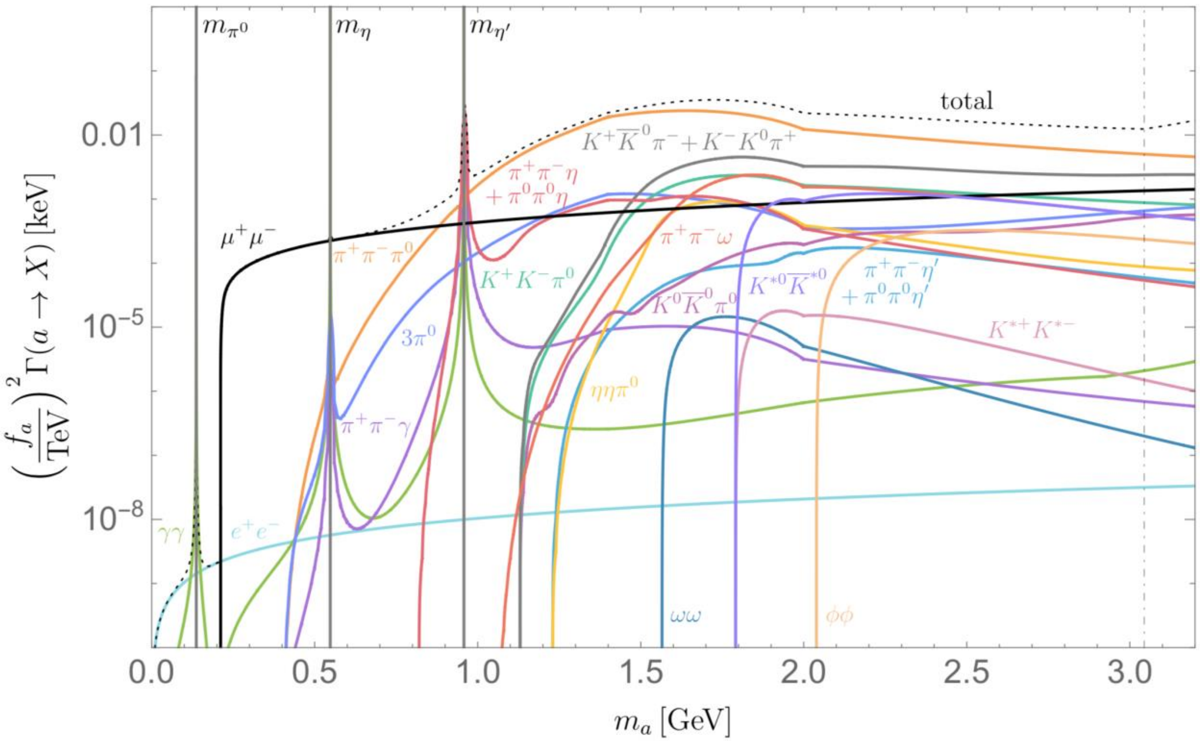
A.11 $a \to \omega\omega, \phi\phi, K^{*+}K^{*-}, K^{*0}\overline{K}^{*0}$

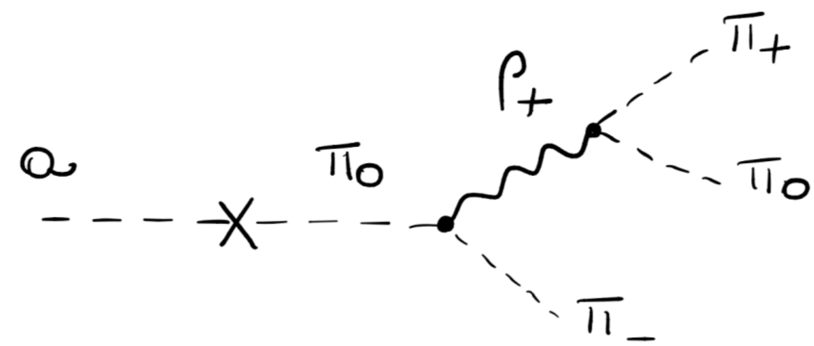
A.12 $a \to \pi^+\pi^-\omega$

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



Dark Pion Decays (ALP-Like, III)





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

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

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

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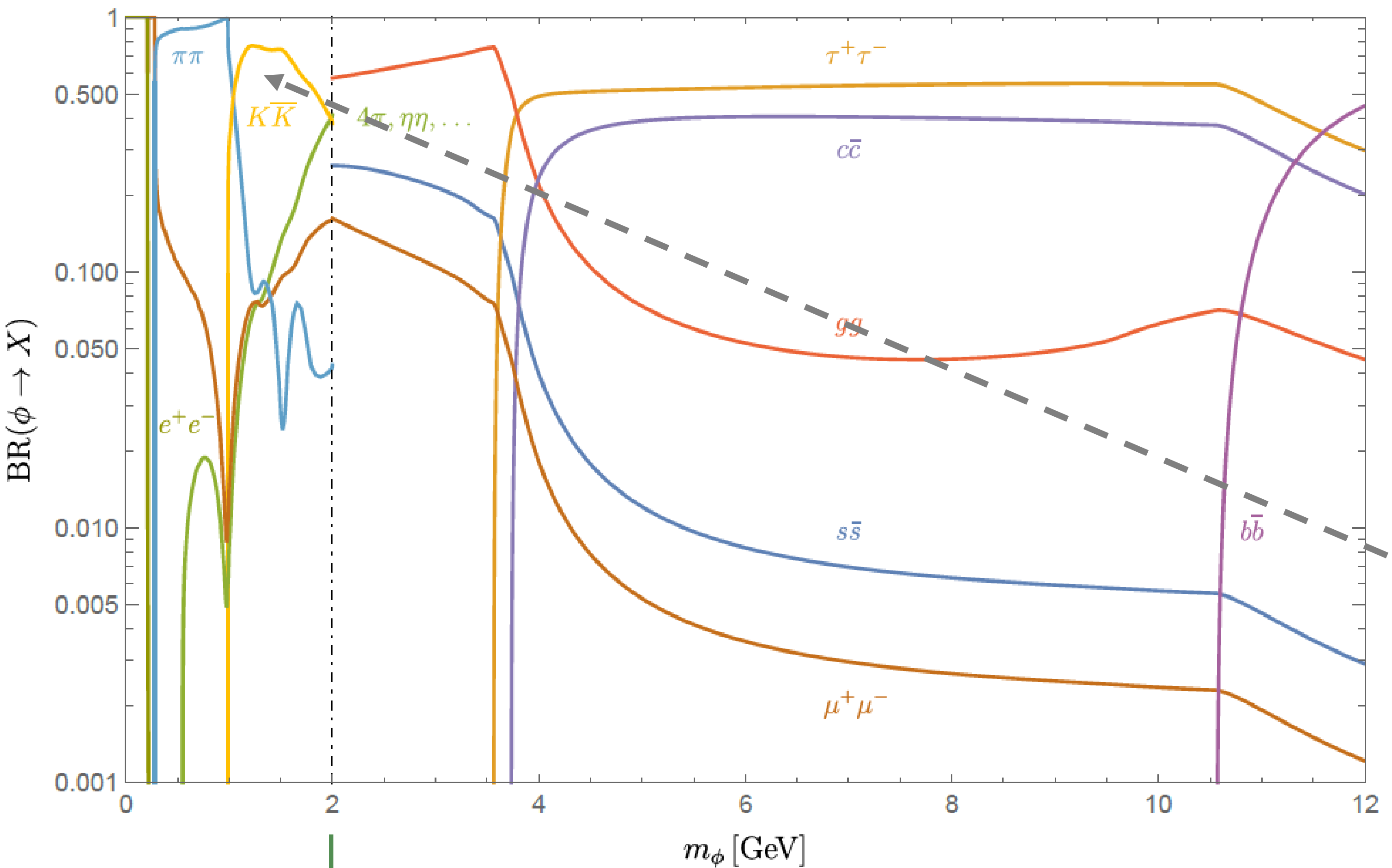
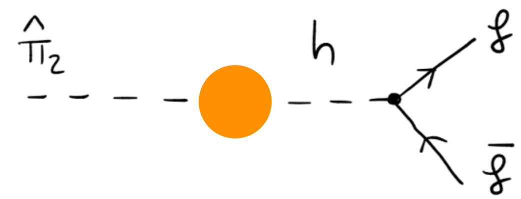
Higgs Portal Decays

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



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



ππ or KK dominate low mass region

Perturbative QCD results

Hadronic Exclusives

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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

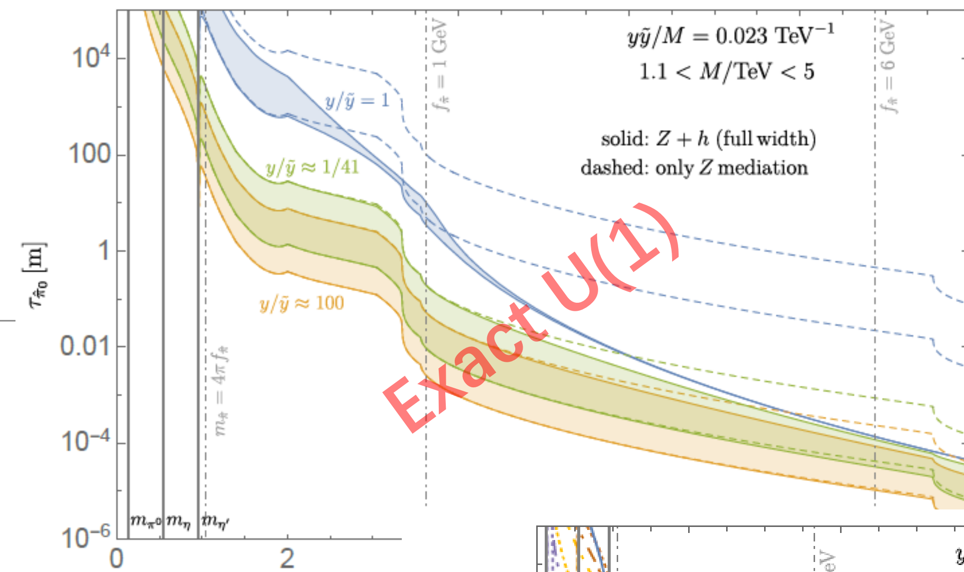
The U(1) subgroup of the SU(2) isospin is exact if everything is diagonal

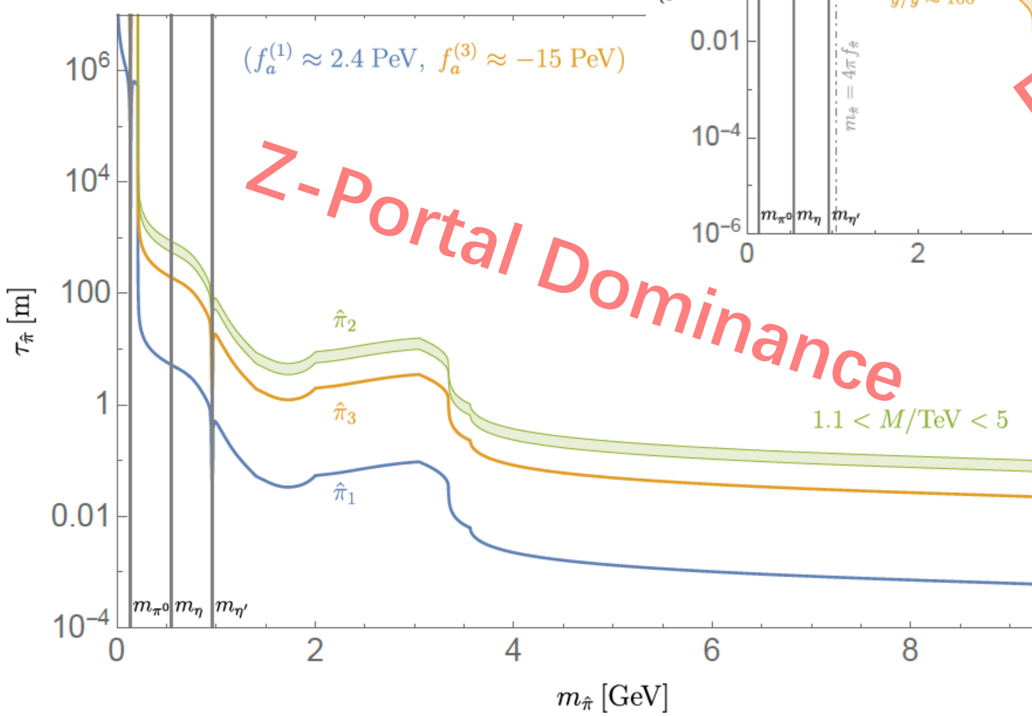
The Higgs portal is suppressed if either $\boldsymbol{Y}$ or $\widetilde{\boldsymbol{Y}}$ =0

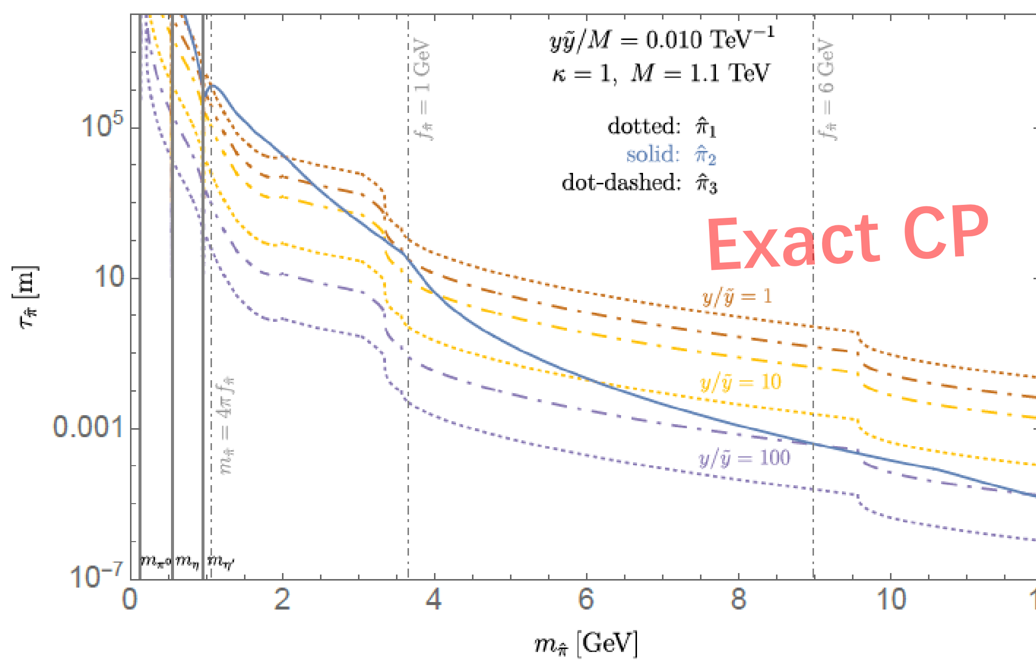
The CP is conserved in the dark sector if all couplings are real.

Dark Pion as Long-lived Particles

Lifetime between 1mm to >10m

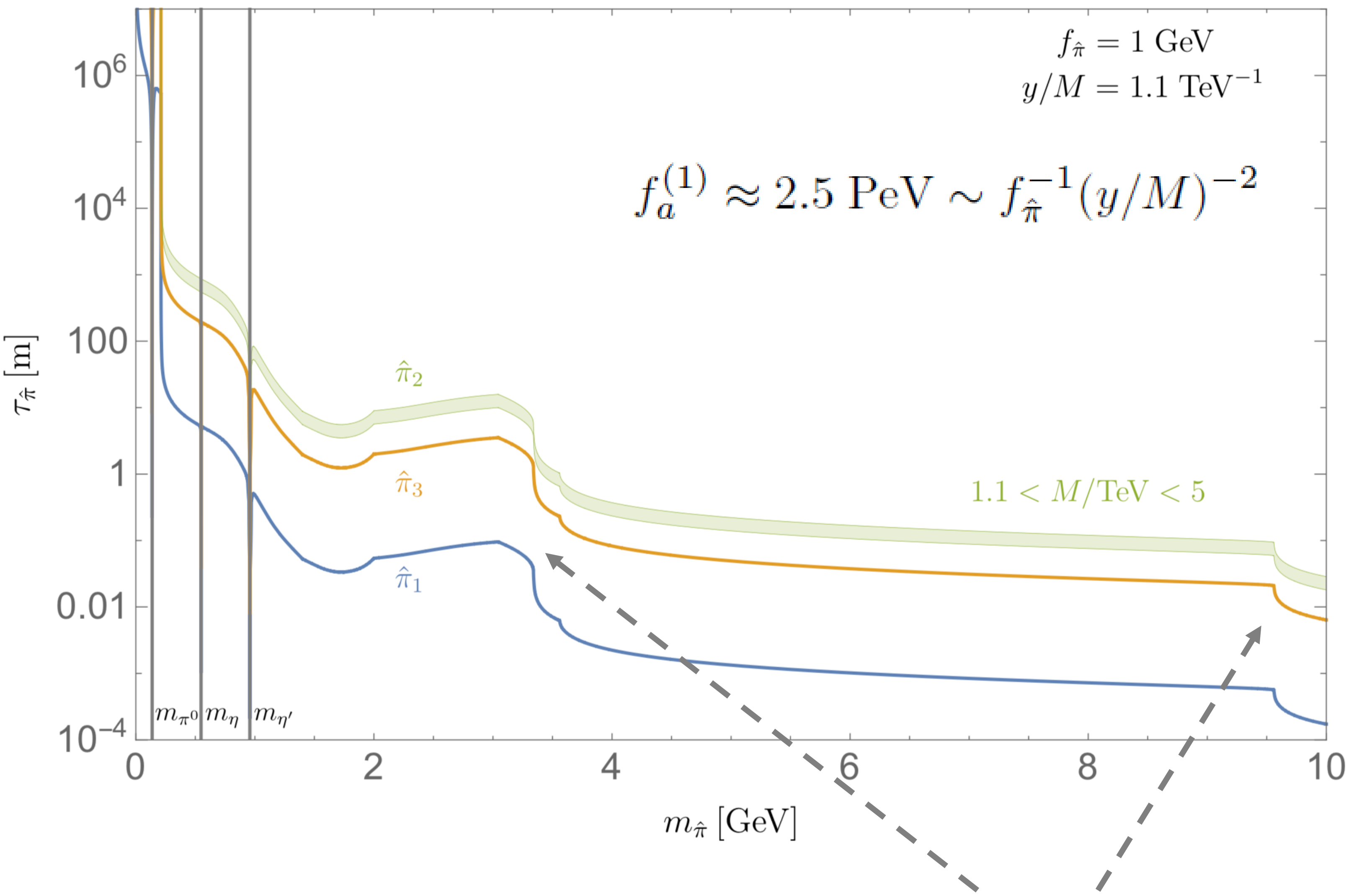






Easy LLP with strong parameter dependence

LLP in the Z Portal Dominance



cc, ττ, and bb thresholds

Lingfeng Li (Brown U.) arXiv: 2110.10691

Dark Chiral perturbation Theory

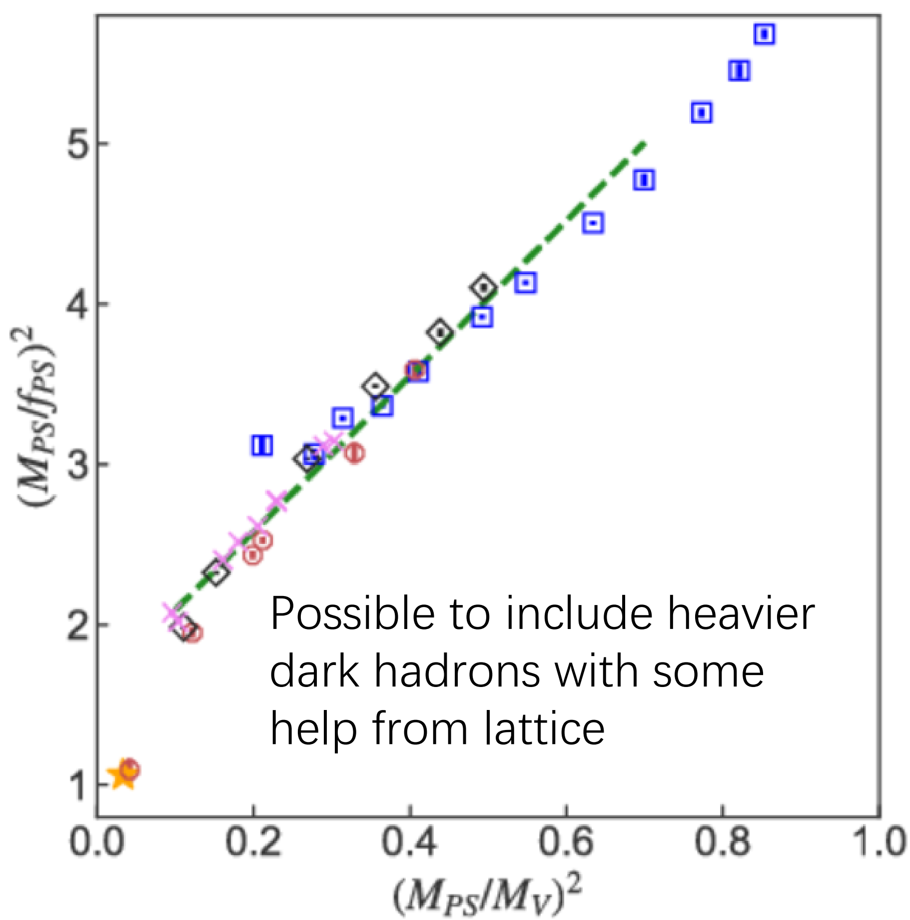
Dark ChpT describe more complicated interaction patterns and dark isospin breaking. Useful at E<<m_Z

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

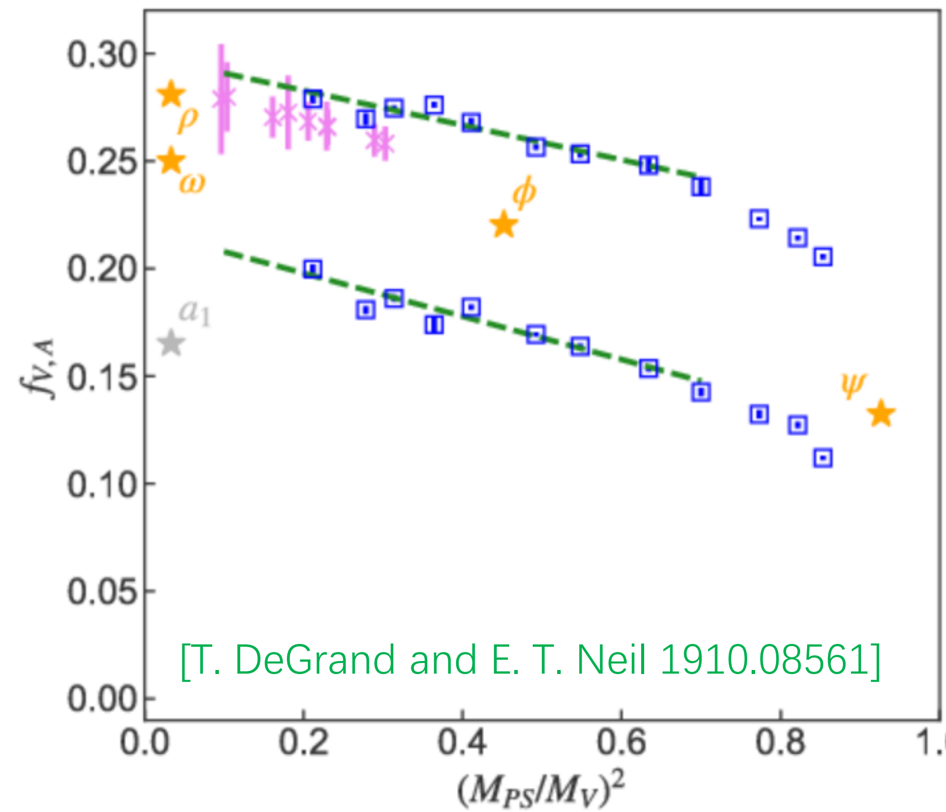
$$\mathcal{L}_{\hat{\pi}}^{(2)} \supset \frac{f_{\hat{\pi}}^2}{4}\mathrm{Tr}[(D^\mu U)^\dagger D_\mu U] + \frac{\hat{B}_0 f_{\hat{\pi}}^2}{2}\mathrm{Tr}[U\widehat{\boldsymbol{m}}_{\psi'}^\dagger + \widehat{\boldsymbol{m}}_{\psi'}U^\dagger]$$

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

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



Possible to include heavier dark hadrons with some help from lattice

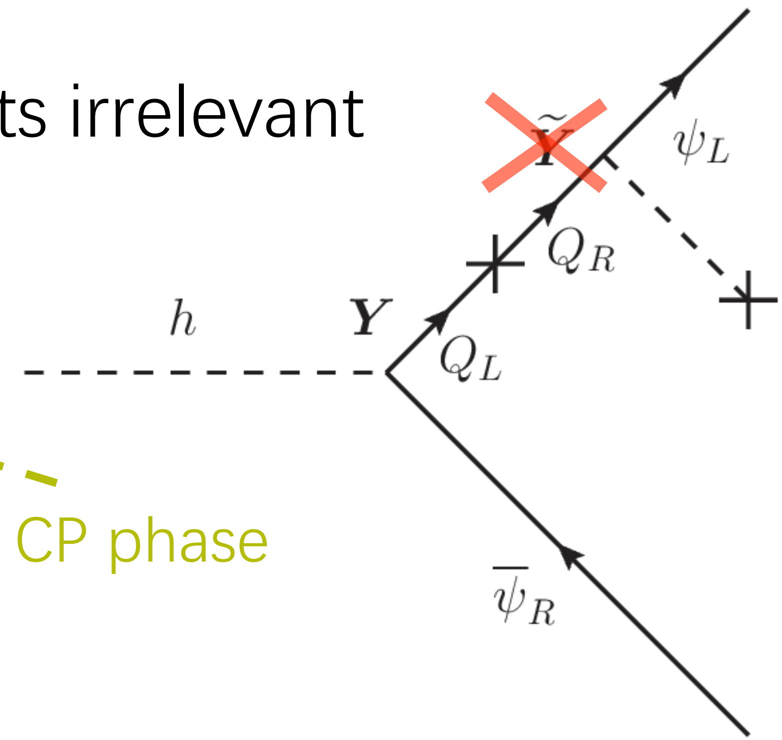


[T. DeGrand and E. T. Neil 1910.08561]

Case Study: Z Portal Dominance

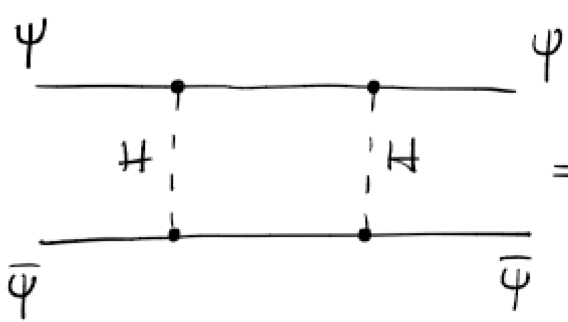
$$-\mathcal{L}_{\rm UV} = \overline{Q}_L \boldsymbol{Y} \psi_R H + \overline{Q}_R \widetilde{\boldsymbol{Y}} \psi_L H + \overline{Q}_L \boldsymbol{M} Q_R + \overline{\psi}_L \boldsymbol{\omega} \psi_R + \text{h.c.},$$

Higgs invisible decay width constraints irrelevant



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

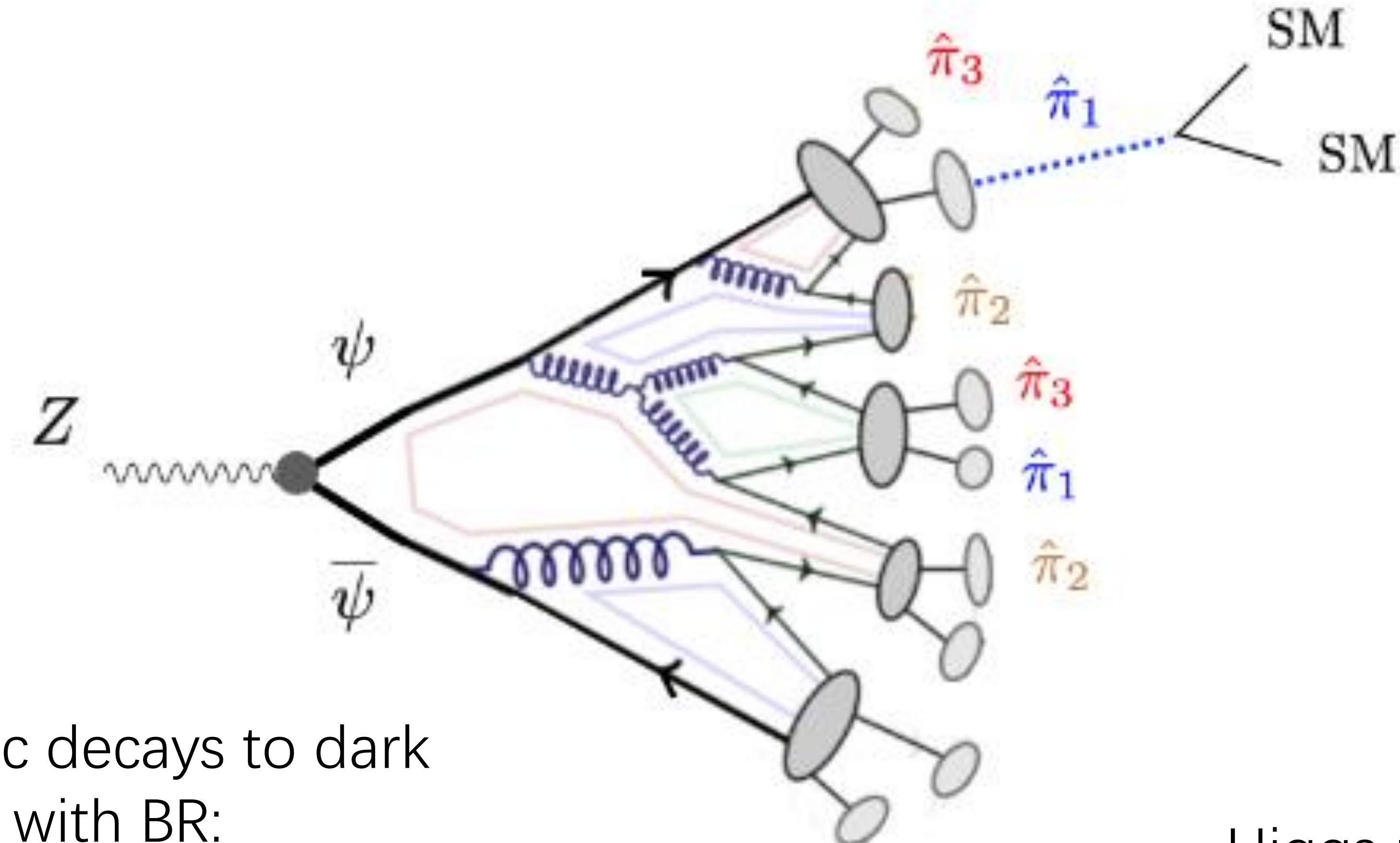
For N=2 case, contains a free CP phase



⇒ π_2 decays via the CP-violating mixing with π_1

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

Phenomenology @ the EW Scale



Z exotic decays to dark quarks with BR:

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

Usually dominates the phenomenology because of large stastics:

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

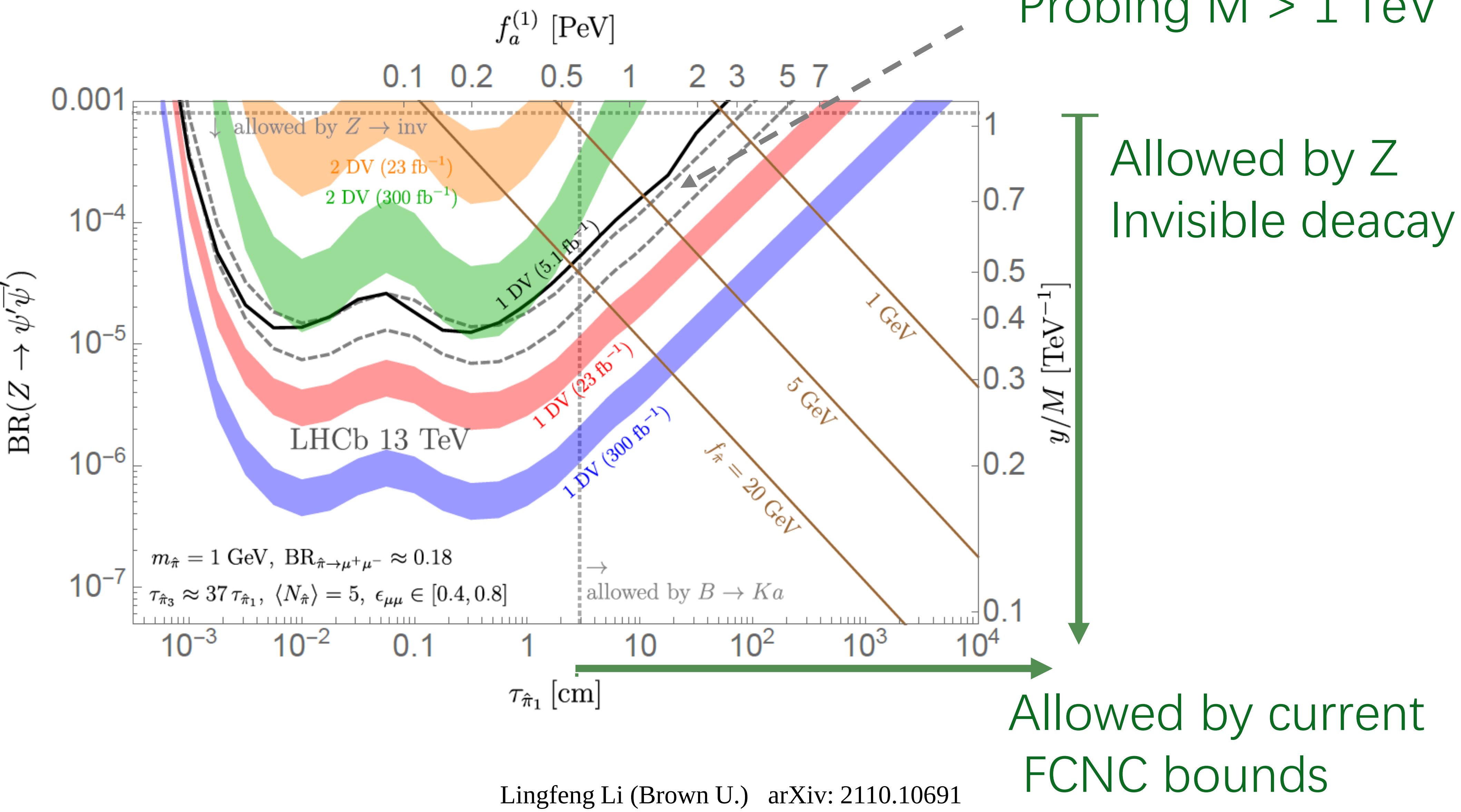
Higgs portal only relevant when both $\mathbf{Y}$, $\widetilde{\mathbf{Y}}$ are large

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

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

Example: Dimuon Search @ LHCb

Another benchmark with 1 GeV dark pions

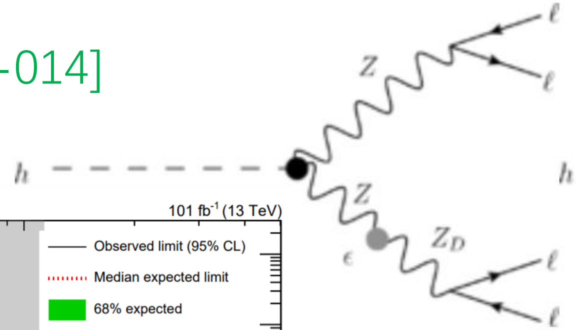


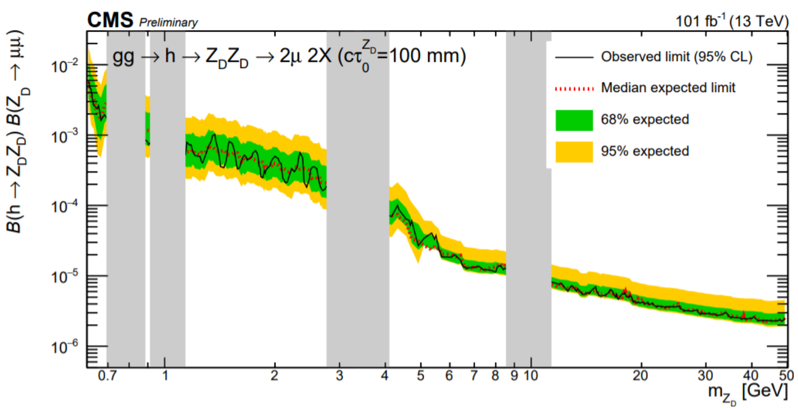
Lingfeng Li (Brown U.) arXiv: 2110.10691

Further Opportunities @ LHC

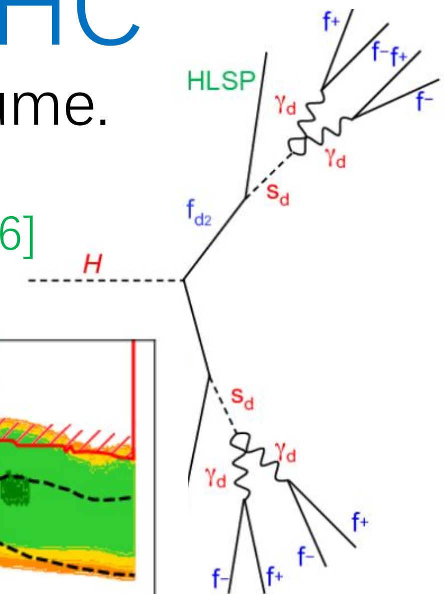
ATLAS/CMS benefit from larger luminosities and decay volume.

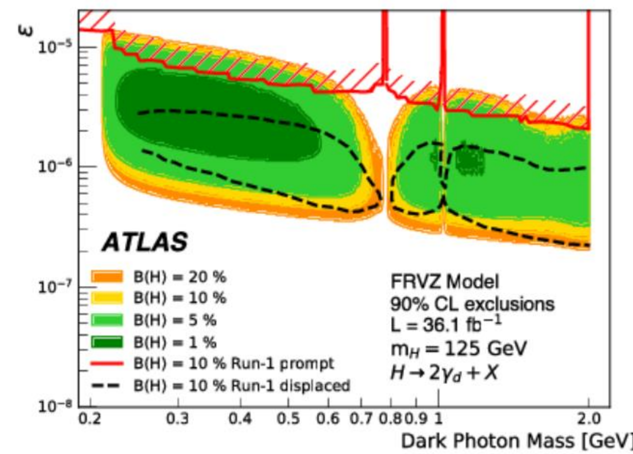
[CMS: CMS-PAS-EXO-20-014]



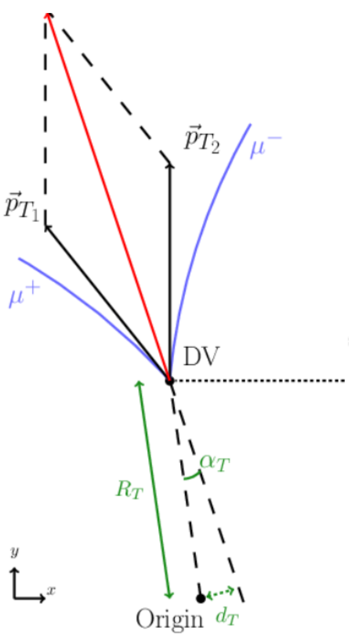


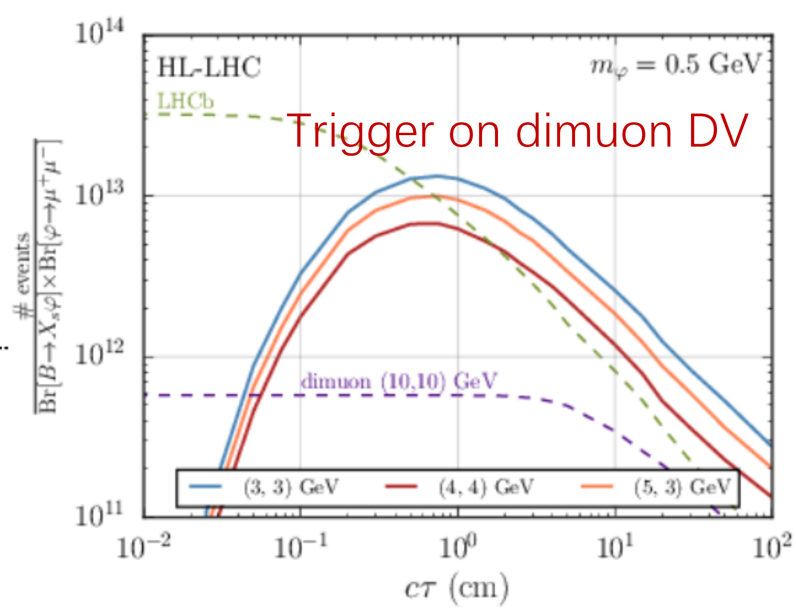
[ATLAS: 1909.01246]

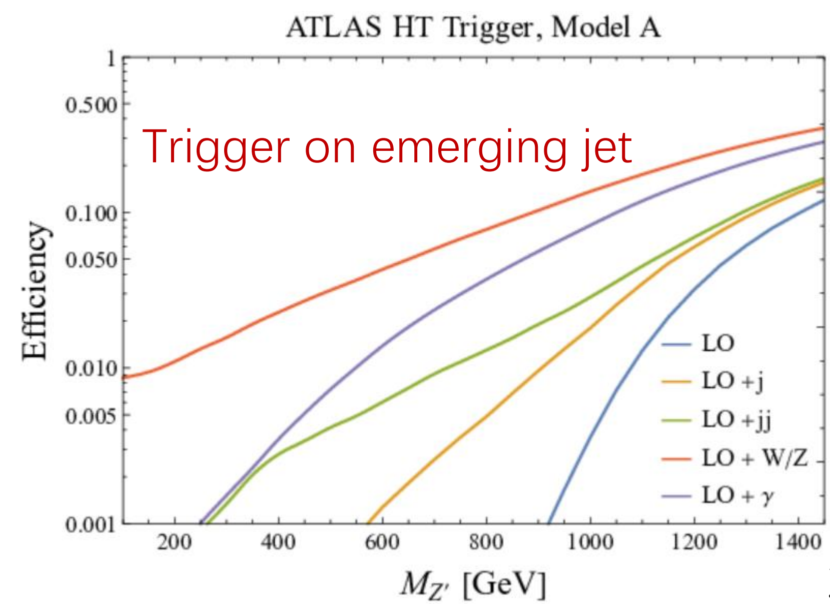




LLP oriented triggers? [Y. Gershtein and S. Knapen, 1907.00007, D. Linthrone and D. Stolarski, 2103.08620]







TeV Scale Phenomenology @ LHC

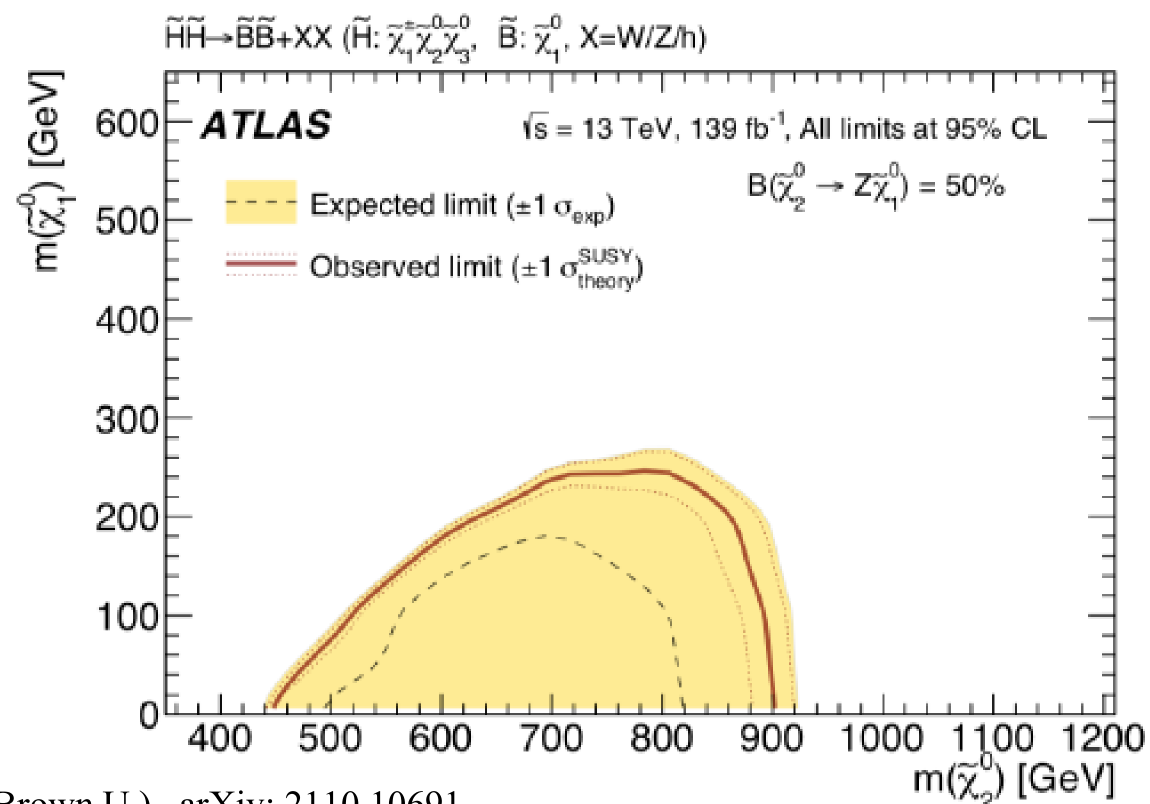
Direct production of heavy EW doublets:

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

⇒Diboson + emerging jet signals

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

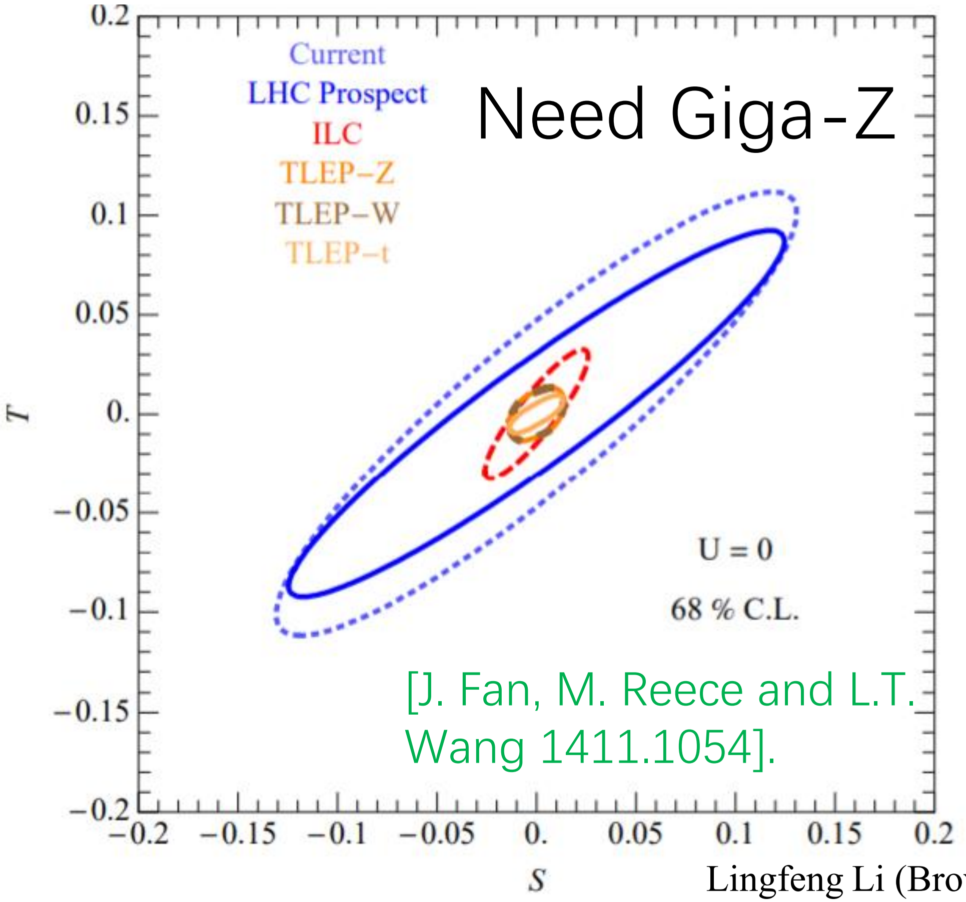
Estimated limit: M>1.3 TeV @ HL-LHC



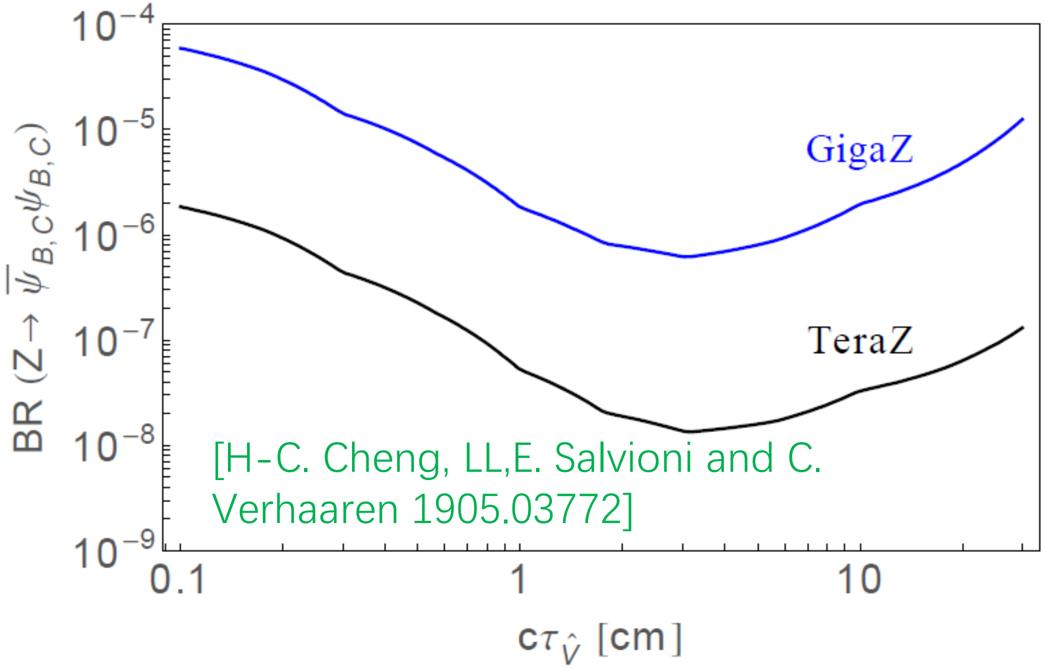
Prospect at Future Colliders

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

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

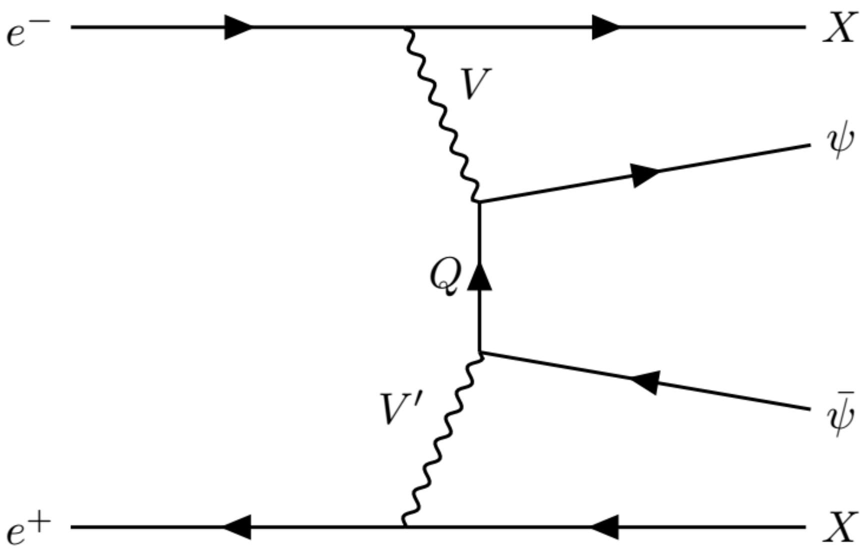


Direct search in H/Z decays:



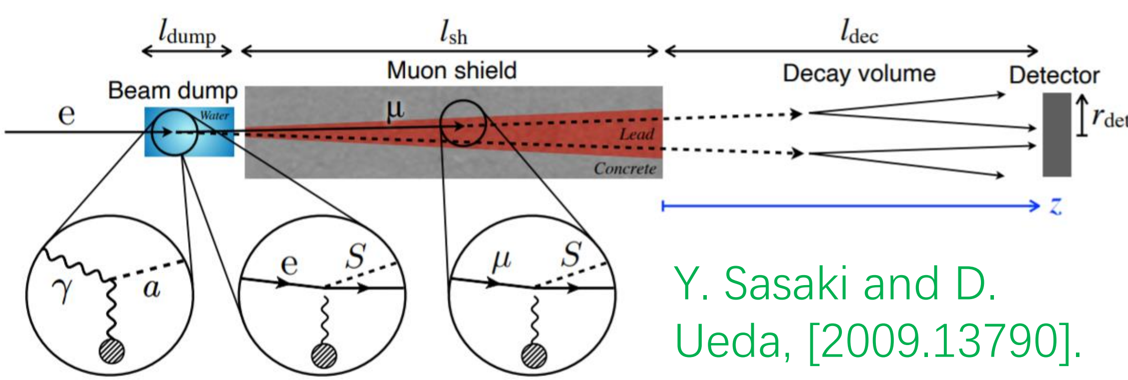
(VERY conservative) limits on exotic Z → dark shower decays but with a DIFFERENT model.

Prospect at Future Colliders (II)



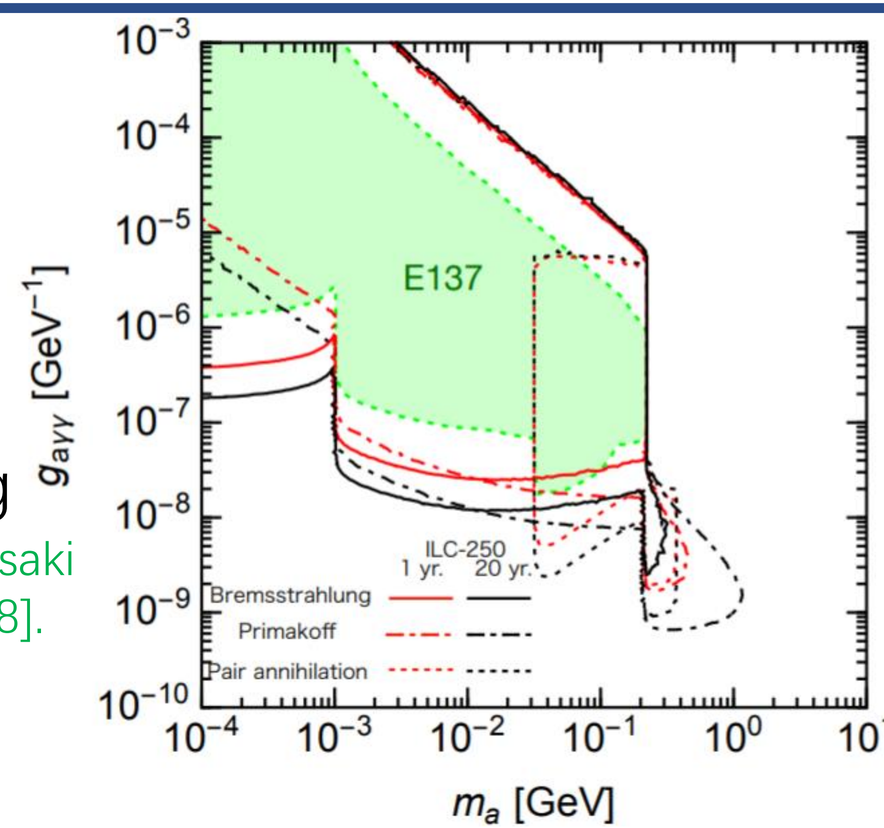
Energy-frontier searches:

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



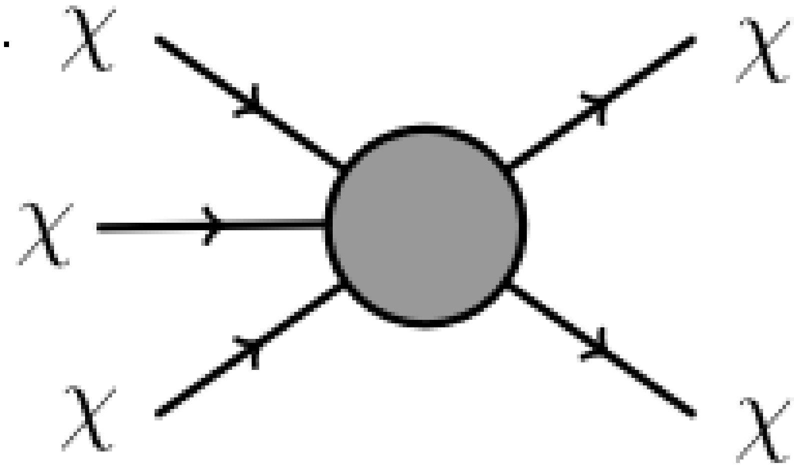
Y. Sasaki and D. Ueda, [2009.13790].

Intensity-frontier approach: searching in the beam dump: K. Asai, S. Iwamoto, Y. Sasaki and D. Ueda, [2105.13768].



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.