



Long-Lived Dark Pions

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LLP XI, CERN in Cyberspace

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

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

Energy
 ???
 Energy Frontier

h/Z
 (HL-)LHC and ...
 Intensity Frontier
 Displaced
 Inaccessibility

A general form

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

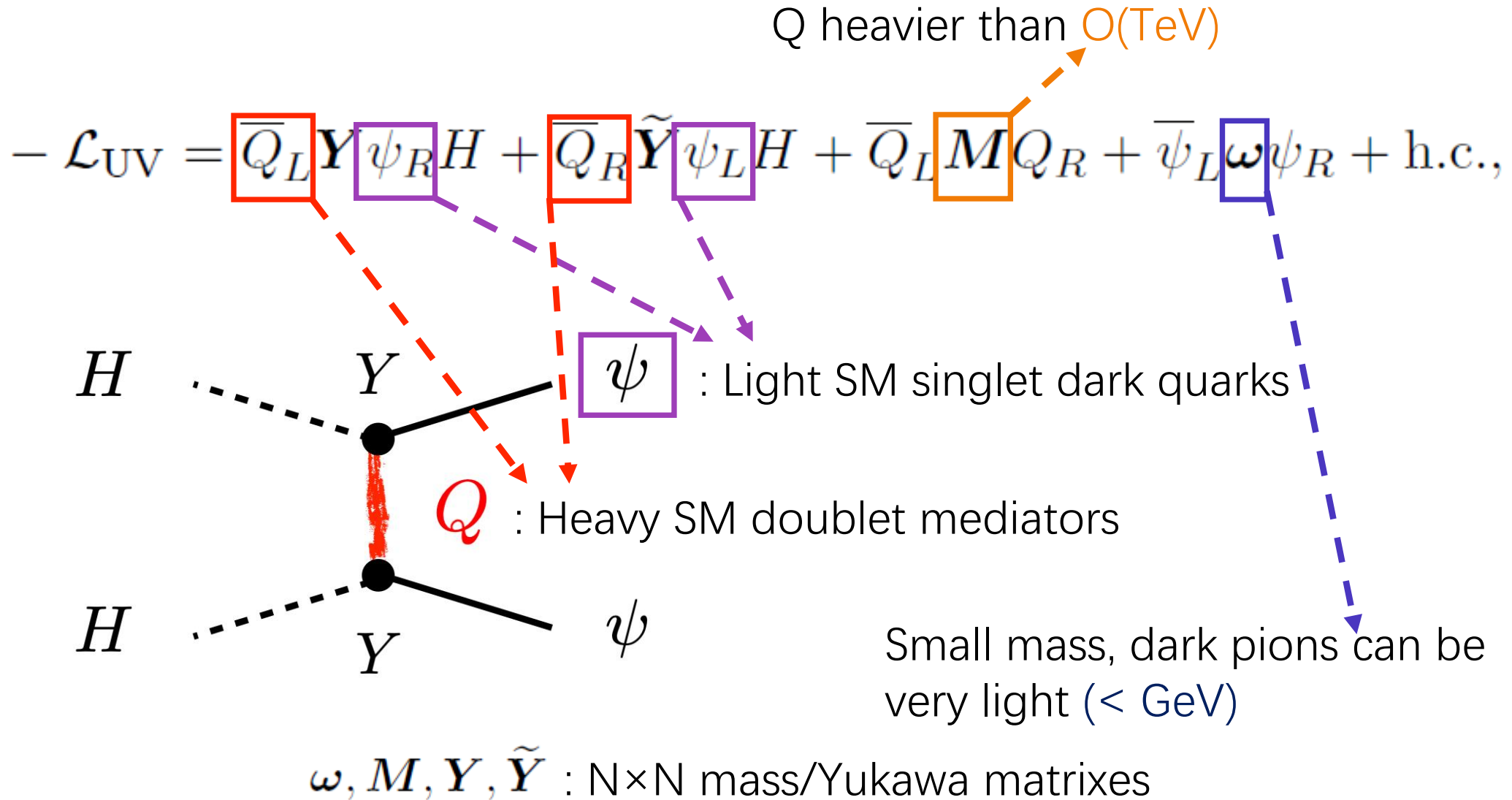
Suppressed HV-SM coupling from the ~TeV scale

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

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

[G. Albouy et al, 2203.09503]

Irrelevant Portal Dark Pions



Irrelevant Portal Dark Pions (II)

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

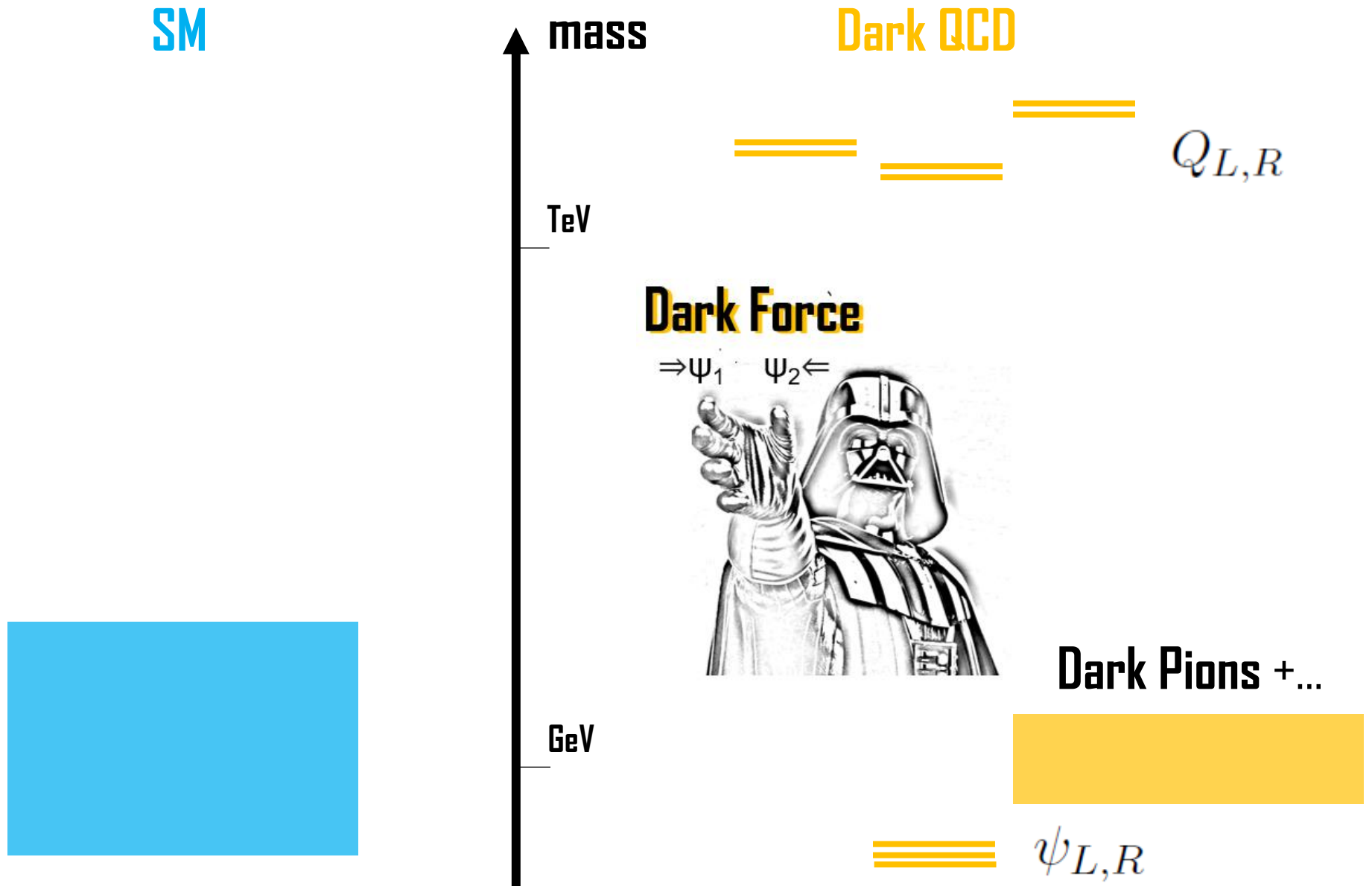
Dimension-6 Z portal couplings

Dimension-5 Higgs portal coupling

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

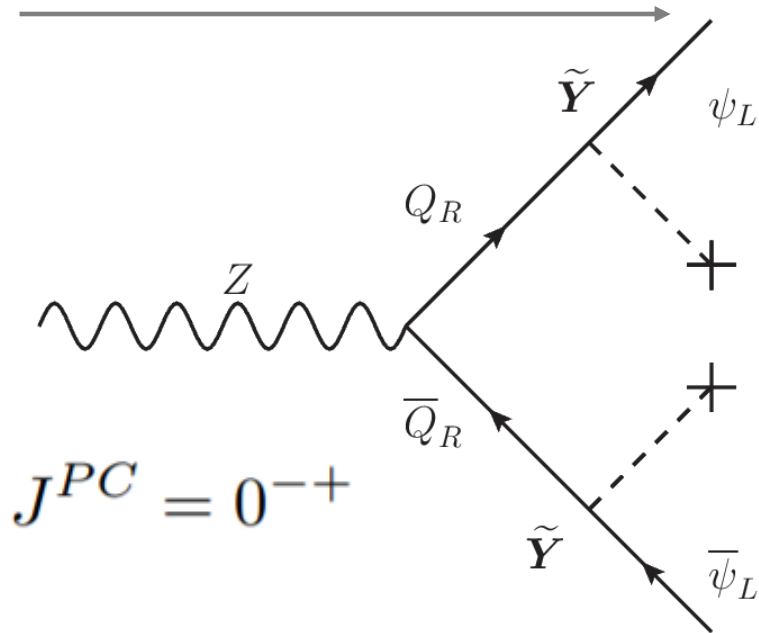
In the special case $N_{\text{flavor}} = 1$, no isospin symmetry, thus no pNGBs, the dark sector has a heavy pseudoscalar (P), a vector (V) and a scalar (S) as ground states with comparable masses.

The Cartoon of Dark Spectrum



Two Flavor, Three Dark Pions

Z portal dark pion production



$$J^{PC} = 0^{-+}$$

Z portal dark pion decay

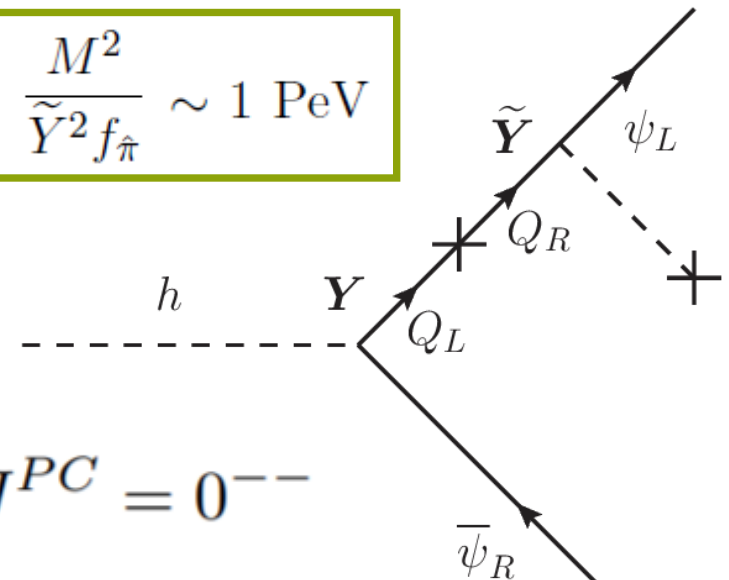
Dark pions rearrange into **CP eigenstates** (like K_S and K_L in the SM)

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

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

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

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



$$J^{PC} = 0^{--}$$

Higgs portal dark pion production

Higgs portal dark pion decays

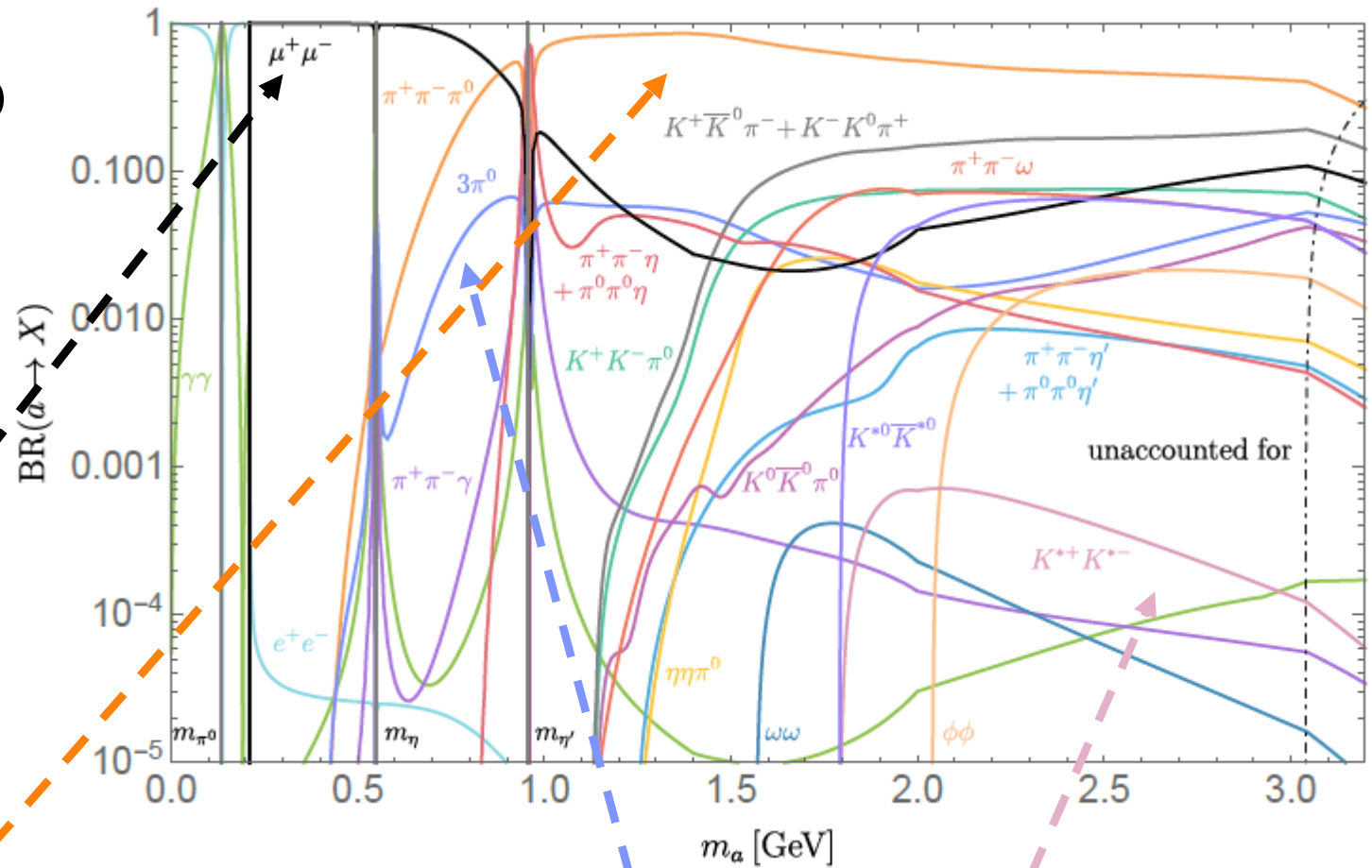
Dark Pion Decays (ALP-Like)

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

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



SM isospin suppressed modes

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.

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

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 ~ 3

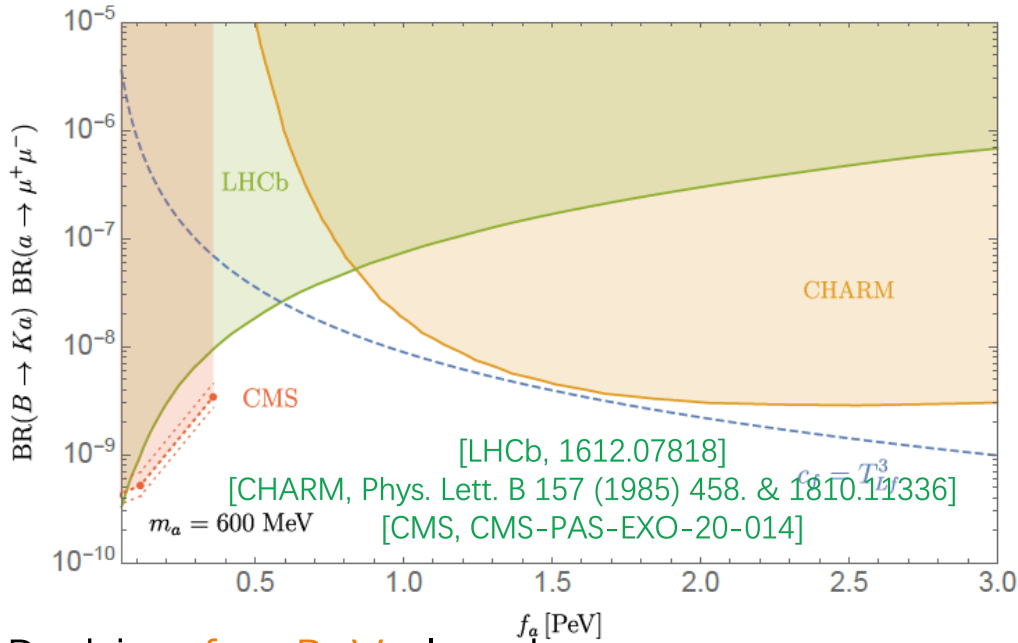
$$\langle \hat{\pi}_a X | \mathcal{H}_{\text{eff}} | B \rangle = \langle \hat{\pi}_a | \langle X | \mathcal{H}_{\text{eff}} | 0 \rangle | B \rangle = \frac{ig^2}{64\pi^2} V_{ts}^* V_{tb} \langle X | \bar{s}_L \gamma_\mu b_L | B \rangle \frac{p_{\hat{\pi}}^\mu}{f_a^{(a)}} \left[\frac{m_t^2}{m_W^2} \left(\log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

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

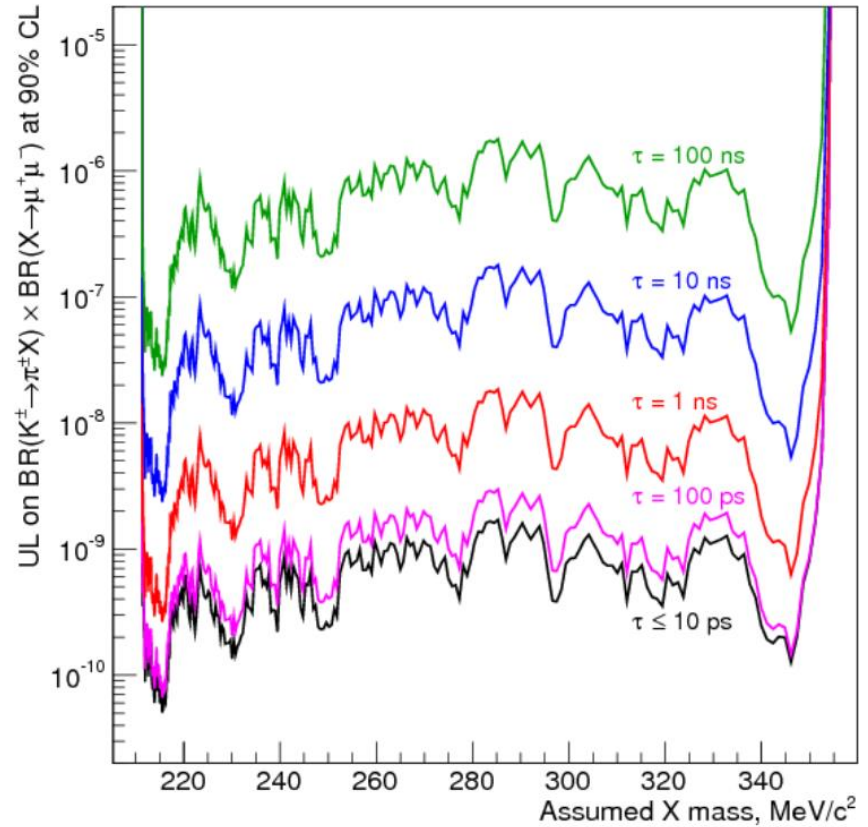
Experimentally achievable if dark pions are LLP

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 $f_a \sim$ PeV already
 Reaching $O(8-60)$ PeV for future experiments



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

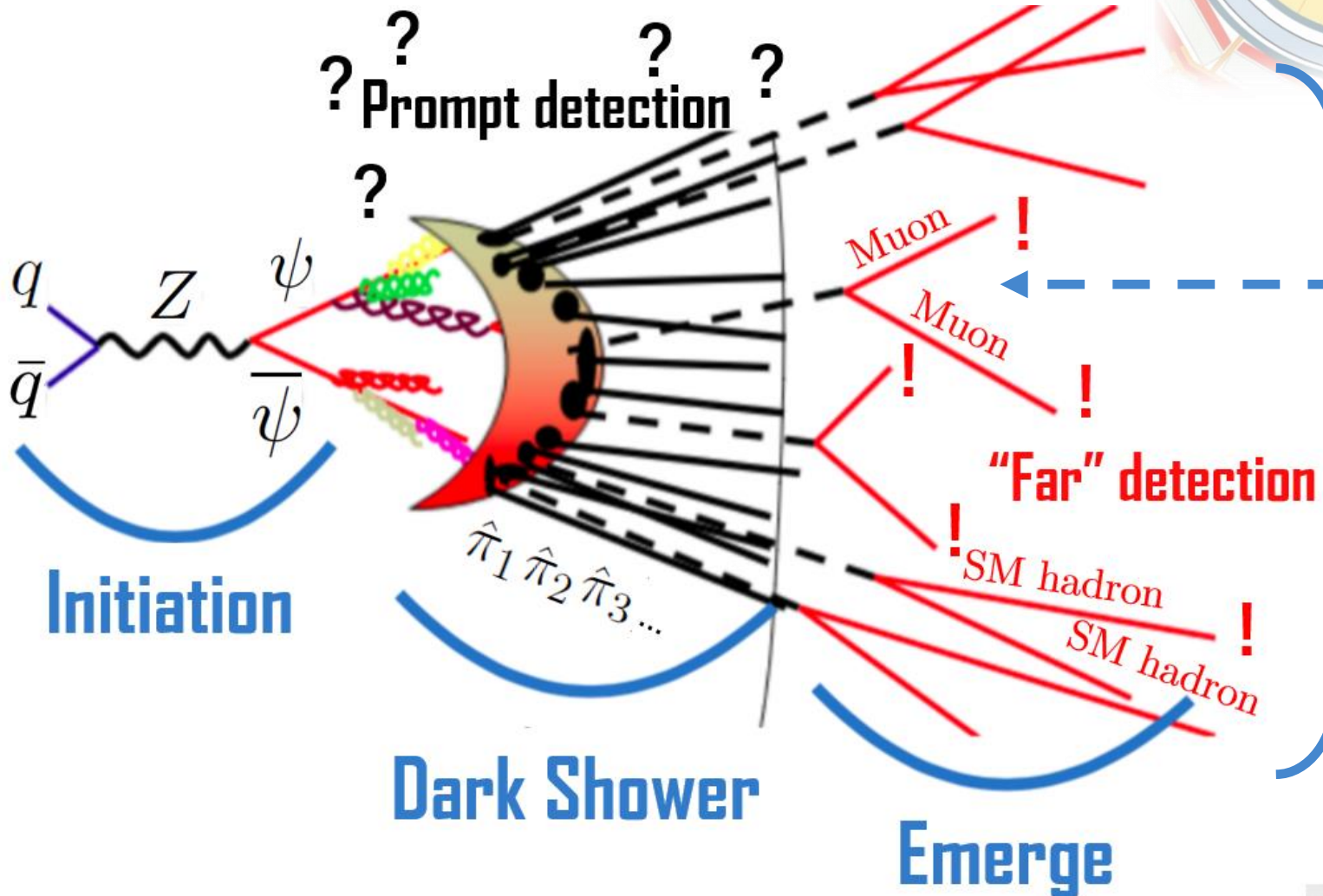
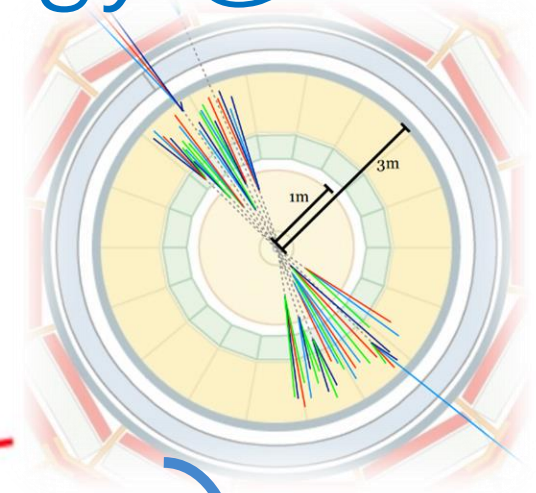
$$BR(K^+ \rightarrow \pi^+ \hat{\pi}^{(b)}) \approx 3.9 \times 10^{-11} \left(\frac{10^3 \text{ TeV}}{f_a^{(b)}} \right)^2 \lambda_{\pi\hat{\pi}}^{1/2}$$

EW Scale Phenomenology @ LHC

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

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

[CMS, 1810.10069]

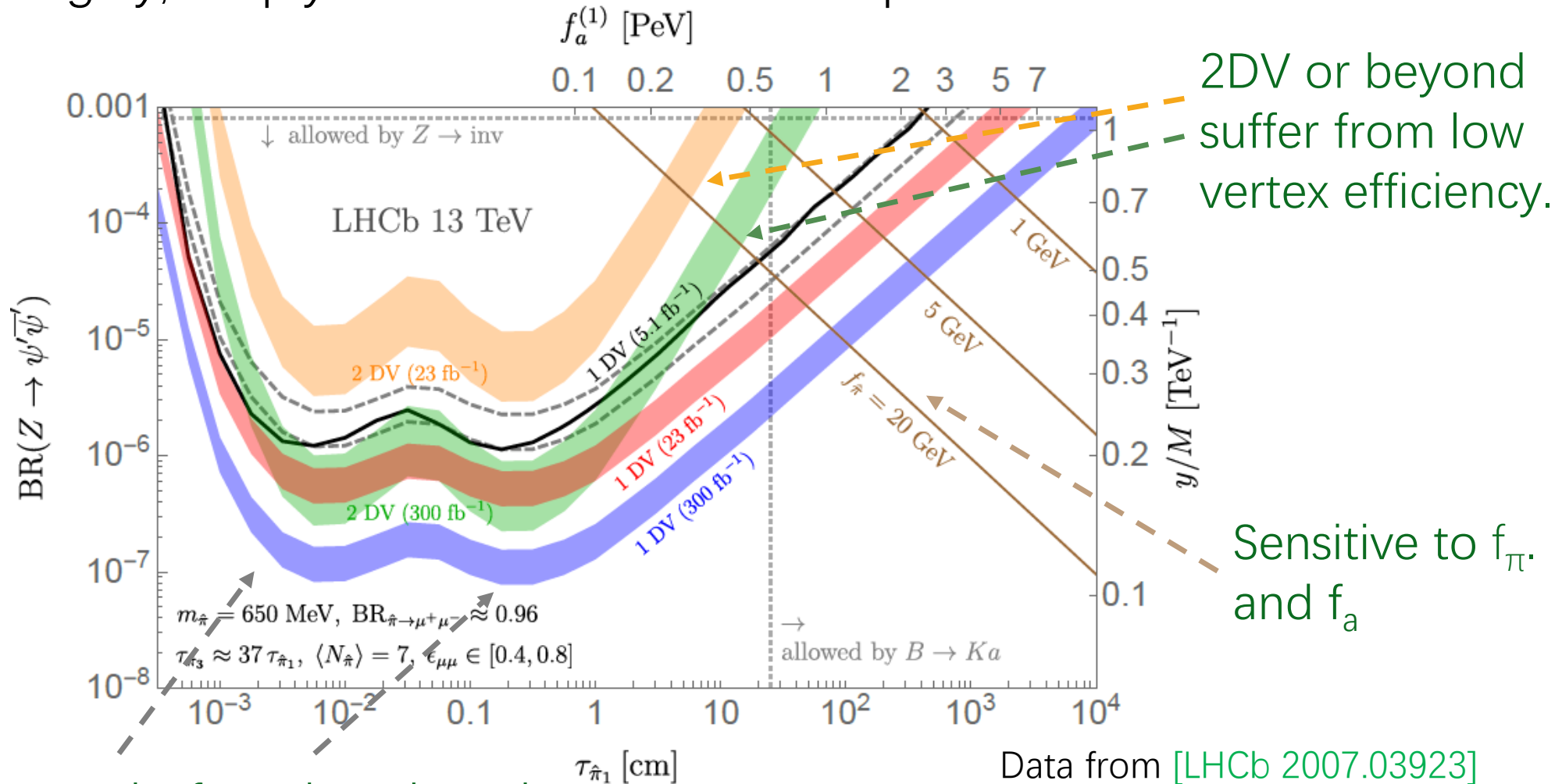


Dimuon displaced vertexes (DV) are sharp signals

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.



2DV or beyond suffer from low vertex efficiency.

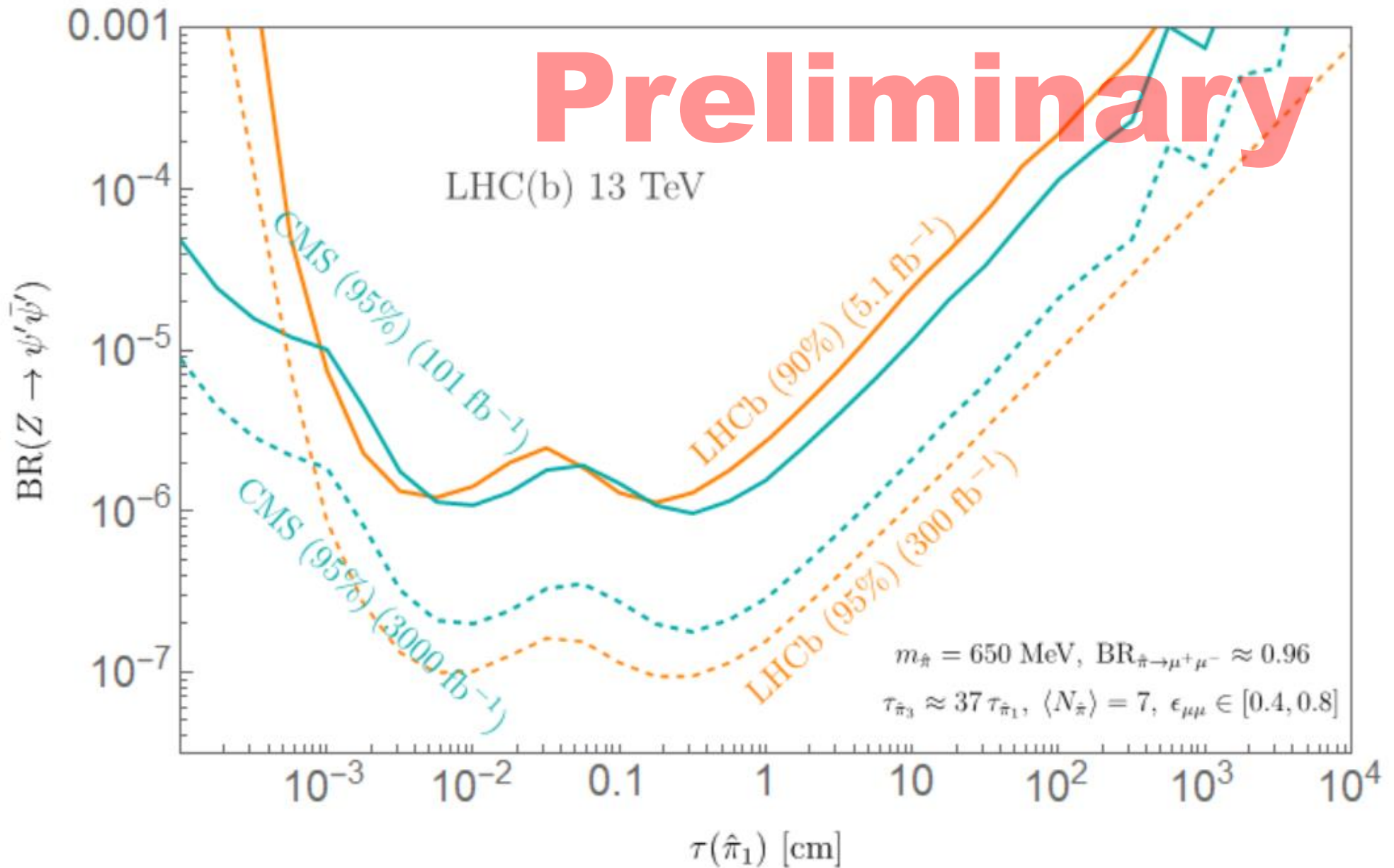
Sensitive to f_{π} and f_a

Data from [LHCb 2007.03923]

Two peaks from benchmark pion width ratio 1:37

Lingfeng Li (Brown U.) arXiv: 2110.10691

Preliminary



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 $M \sim$ a few TeV is achievable. Bright future prospects.
- Open fields (alternative portals, cosmology...) remain to be fully explored.

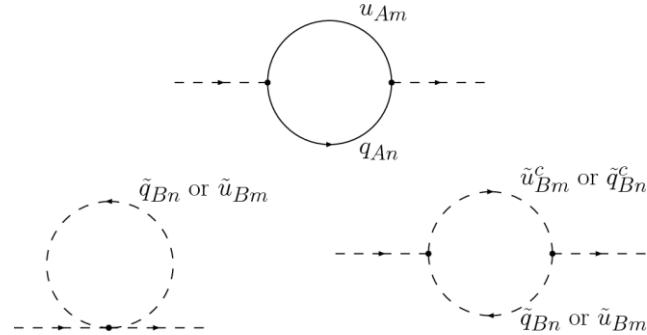
Backup Slides

Motivating Scenario I: Neutral Naturalness

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

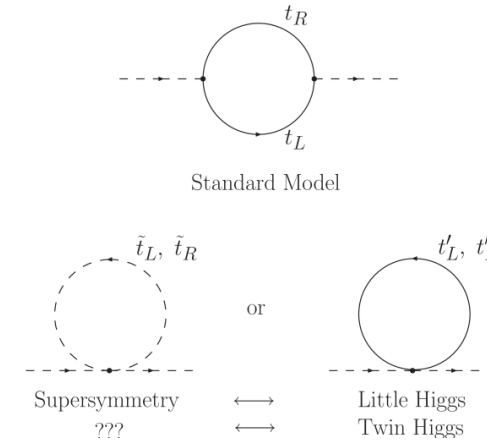
Folded SUSY

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



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

[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]

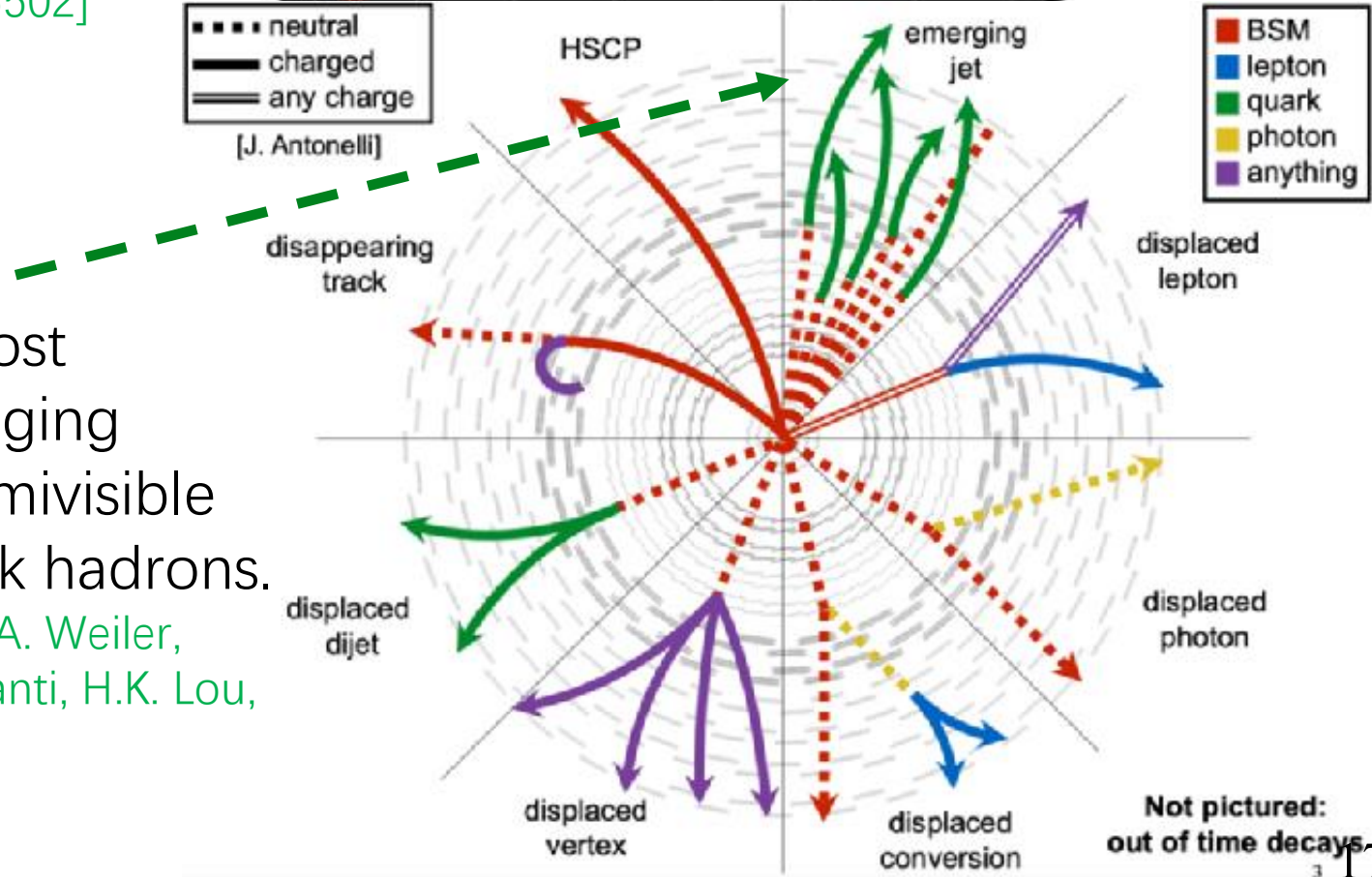
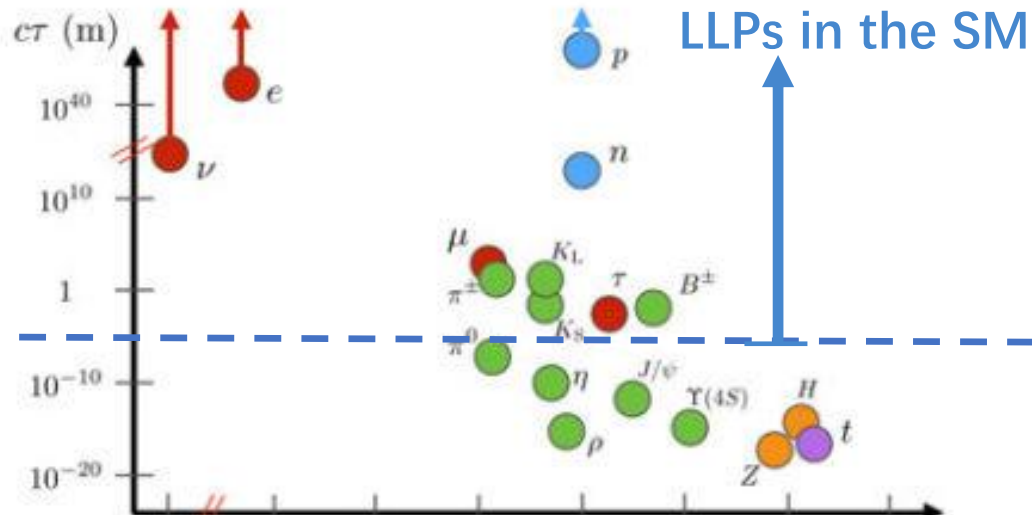
The large elastic Xsec allowed between dark matter particles may help solve the so called small scale crisis in cosmology.

[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

The superpotential :

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

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

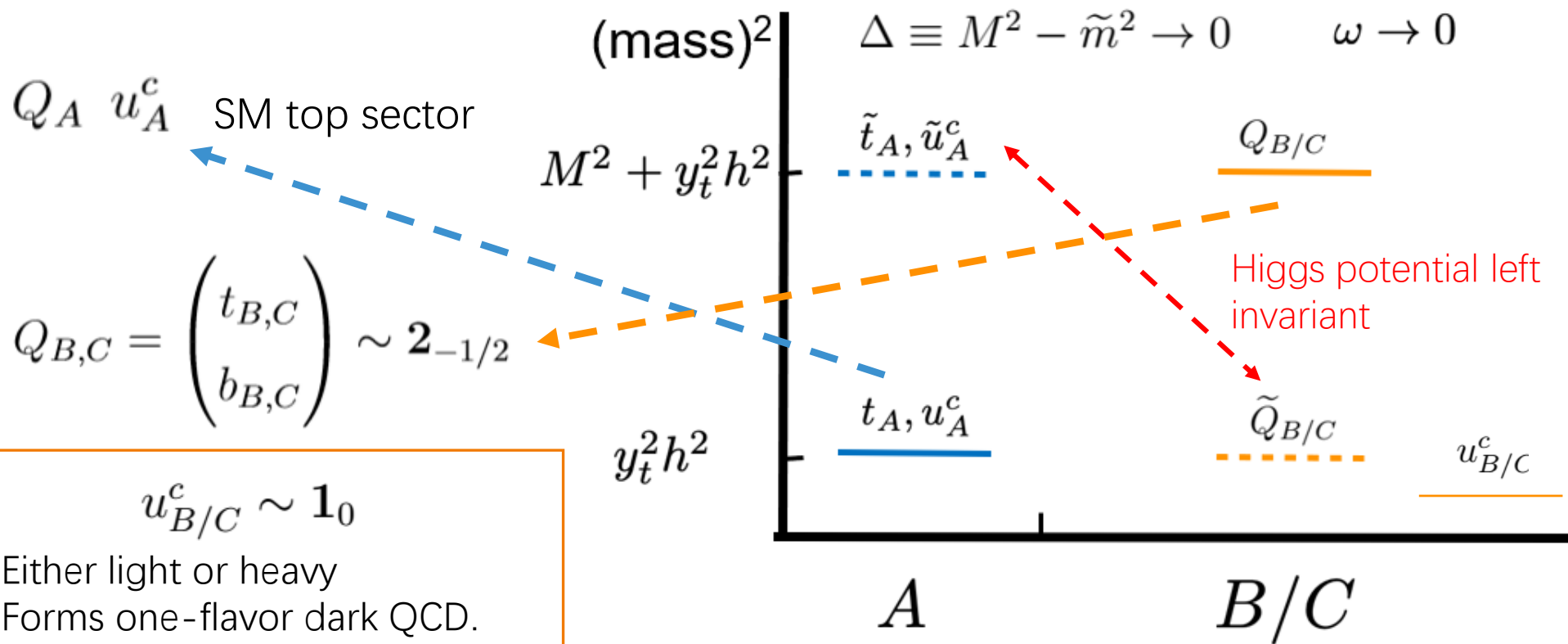
For details of the original model, see [H-C.Cheng, LL, E.Salvioni and C. Verhaareen 1803.03561]

1803.03651 1905.03772 20xy.ijklm

Alternate Tripled Top (TT) Model & Accidental SUSY

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

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



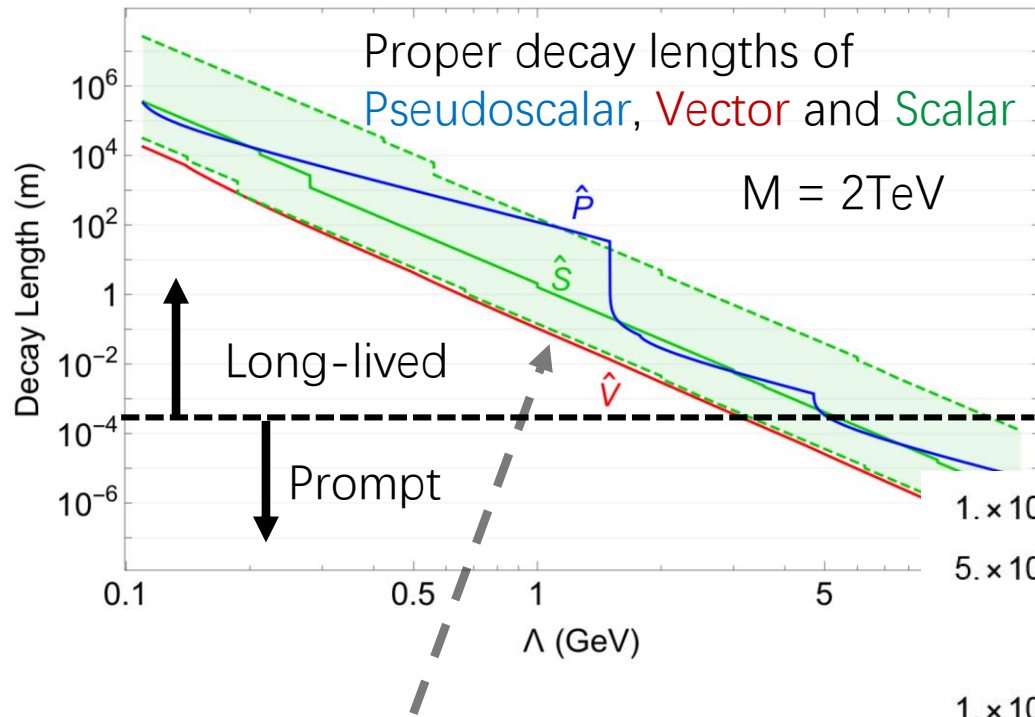
$$u_{B/C}^c \sim 10$$

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

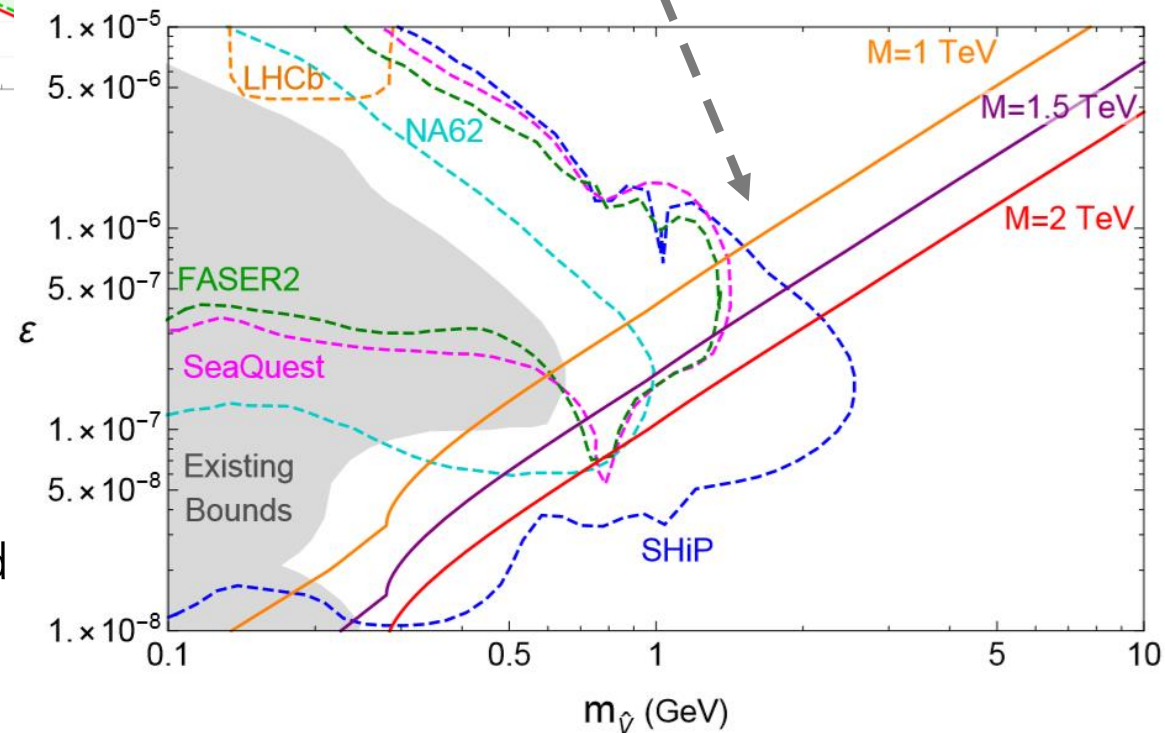


Dark vector meson picks up an effective mixing parameter, similar to a dark photon in the forward/ intensity frontier searches.

$$\epsilon_{\text{eff}} \sim \frac{1}{2} \sqrt{\frac{\alpha_Z}{\alpha}} \epsilon_Z \approx 3.8 \times 10^{-7} \left(\frac{\Lambda}{1 \text{ GeV}} \right)^{3/2} \left(\frac{m_{\hat{V}}}{2 \text{ GeV}} \right)^{1/2} \left(\frac{2 \text{ TeV}}{M} \right)^2$$

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

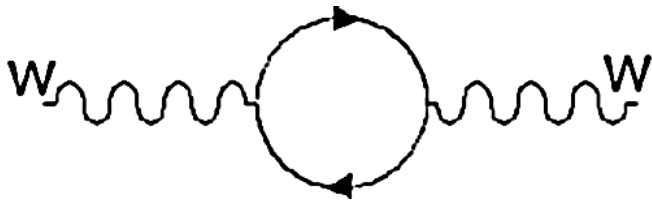


Details of phenomenology : [H-C.Cheng, LL, E.Salvioni and C. Verhaaren 1905.03772]

Indirect/Precision Constraints

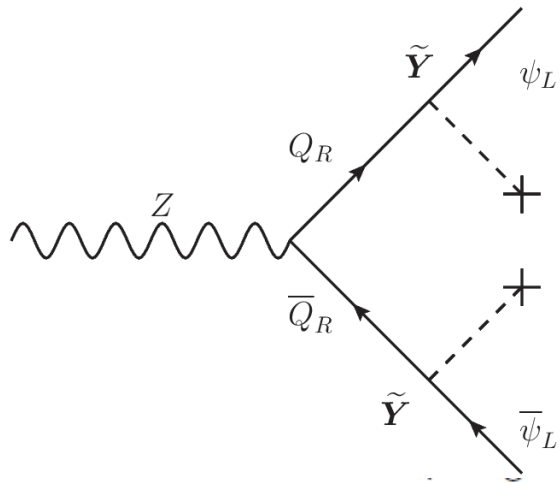
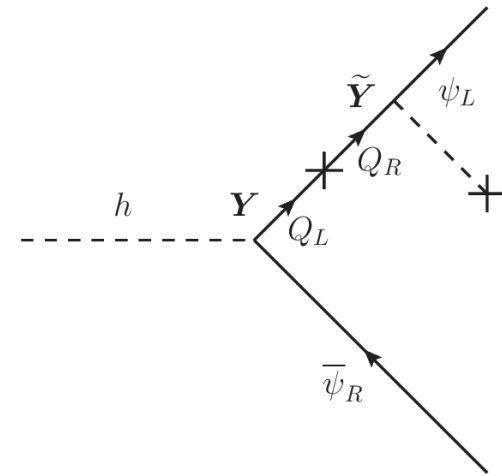
$$M \gtrsim 0.9 \text{ TeV } Y^2 \left(\frac{N_d N}{6} \right)^{1/2}$$

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



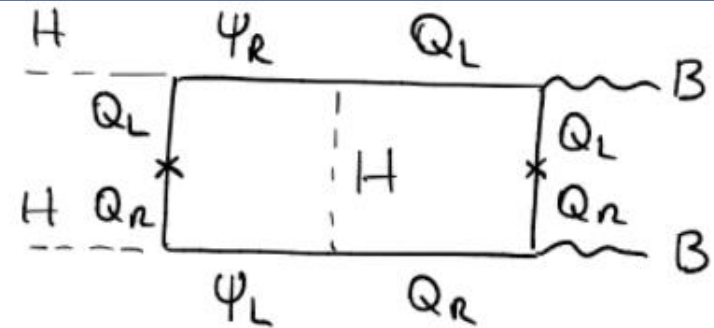
$$M \gtrsim 0.4 \text{ TeV} \left(\frac{N_d \text{Tr}(\mathbf{Y}\mathbf{Y}^\dagger \tilde{\mathbf{Y}}\tilde{\mathbf{Y}}^\dagger)}{3 \times 10^{-4}} \right)^{1/2}$$

From Higgs invisible decay BR < 13%



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

From Z invisible decay width < ~2 MeV

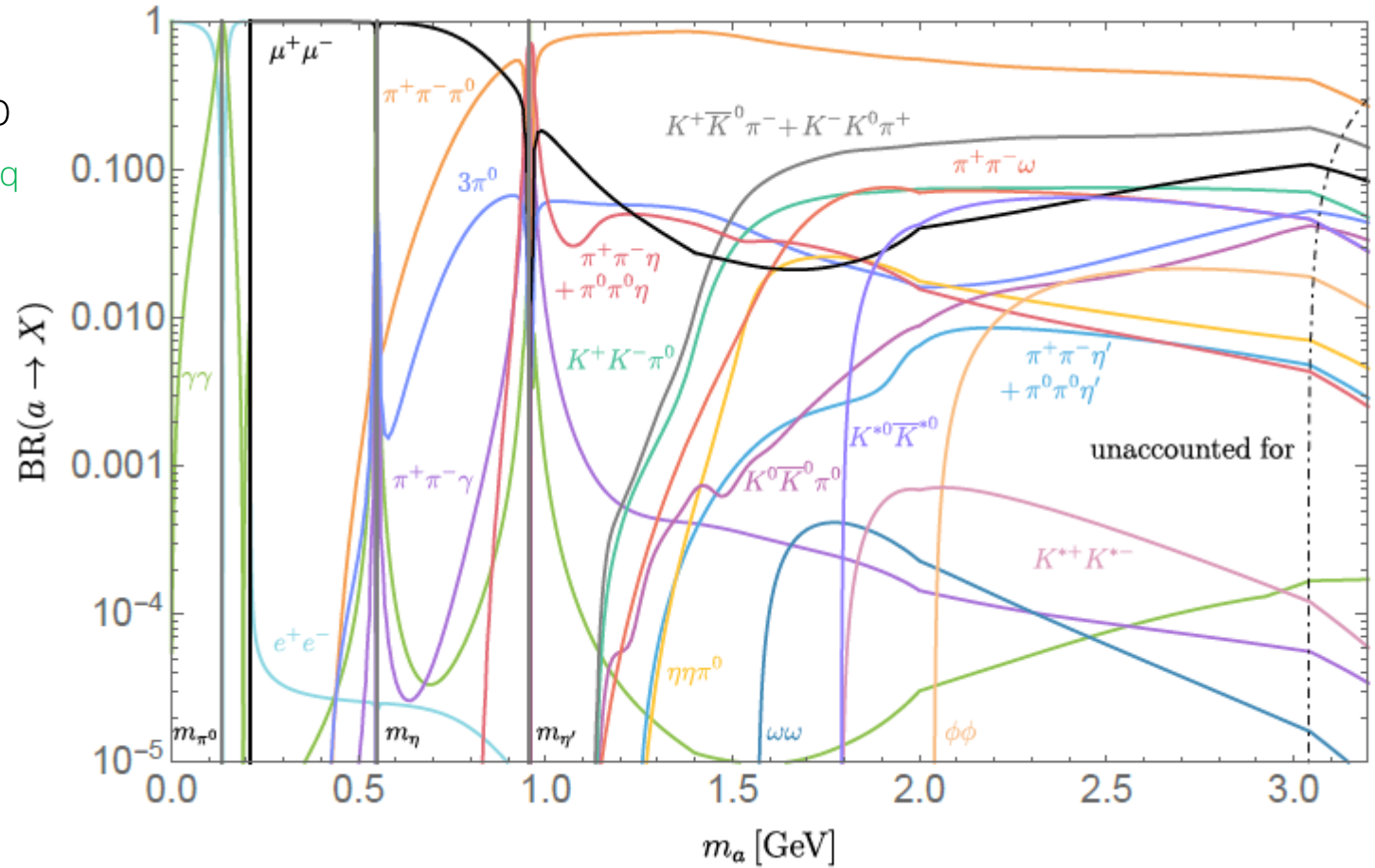


$$M \gtrsim 1.5 \text{ TeV } Y \tilde{Y}$$

From electron EDM
if CP is violated maximally

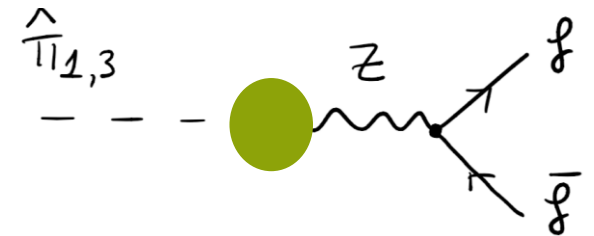
Dark Pion Decays (ALP-Like)

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

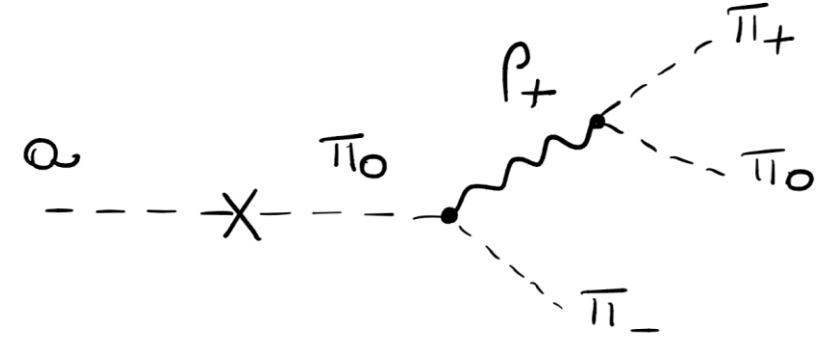
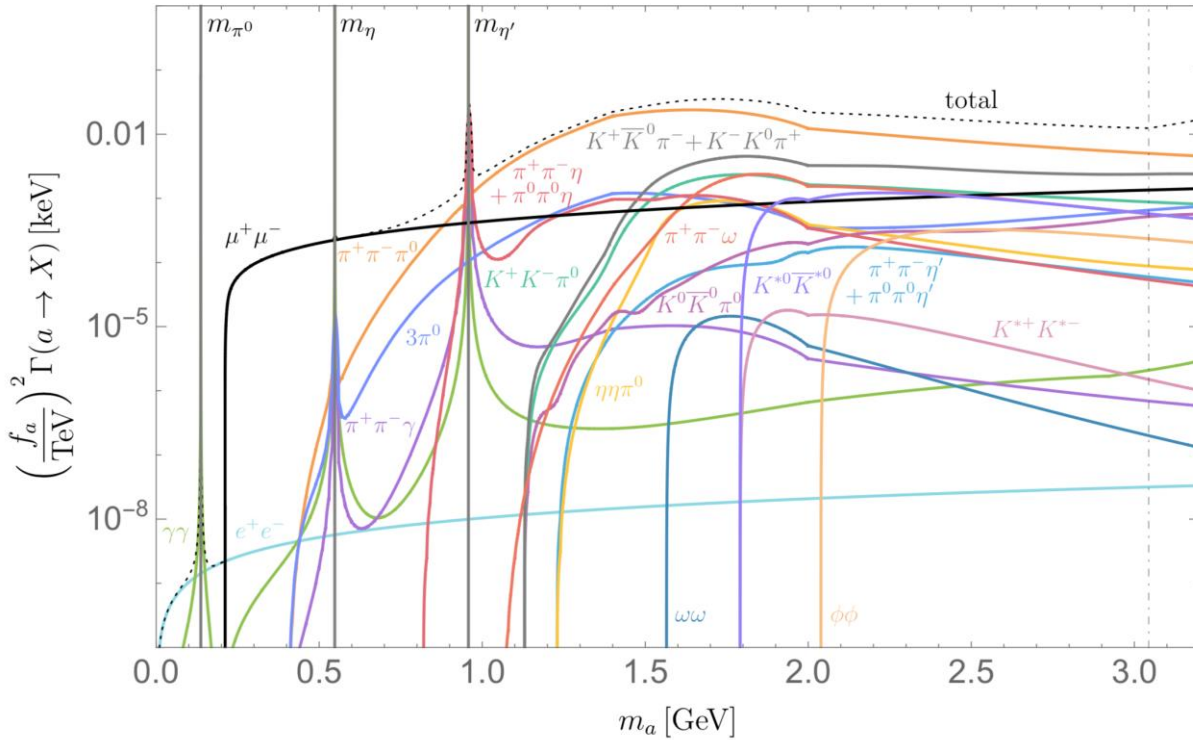


- A.1 $a \rightarrow \gamma\gamma$
- A.2 $a \rightarrow \pi^+\pi^-\gamma$
- A.3 $a \rightarrow \pi^+\pi^-\pi^0$
- A.4 $a \rightarrow 3\pi^0$
- A.5 $a \rightarrow \pi^0\pi^0\eta, \pi^+\pi^-$
- A.6 $a \rightarrow \pi^0\pi^0\eta', \pi^+\pi^-$
- A.7 $a \rightarrow \eta\eta\pi^0$
- A.8 $a \rightarrow K^0\bar{K}^0\pi^0$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

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



Dark Pion Decays (ALP-Like, III)



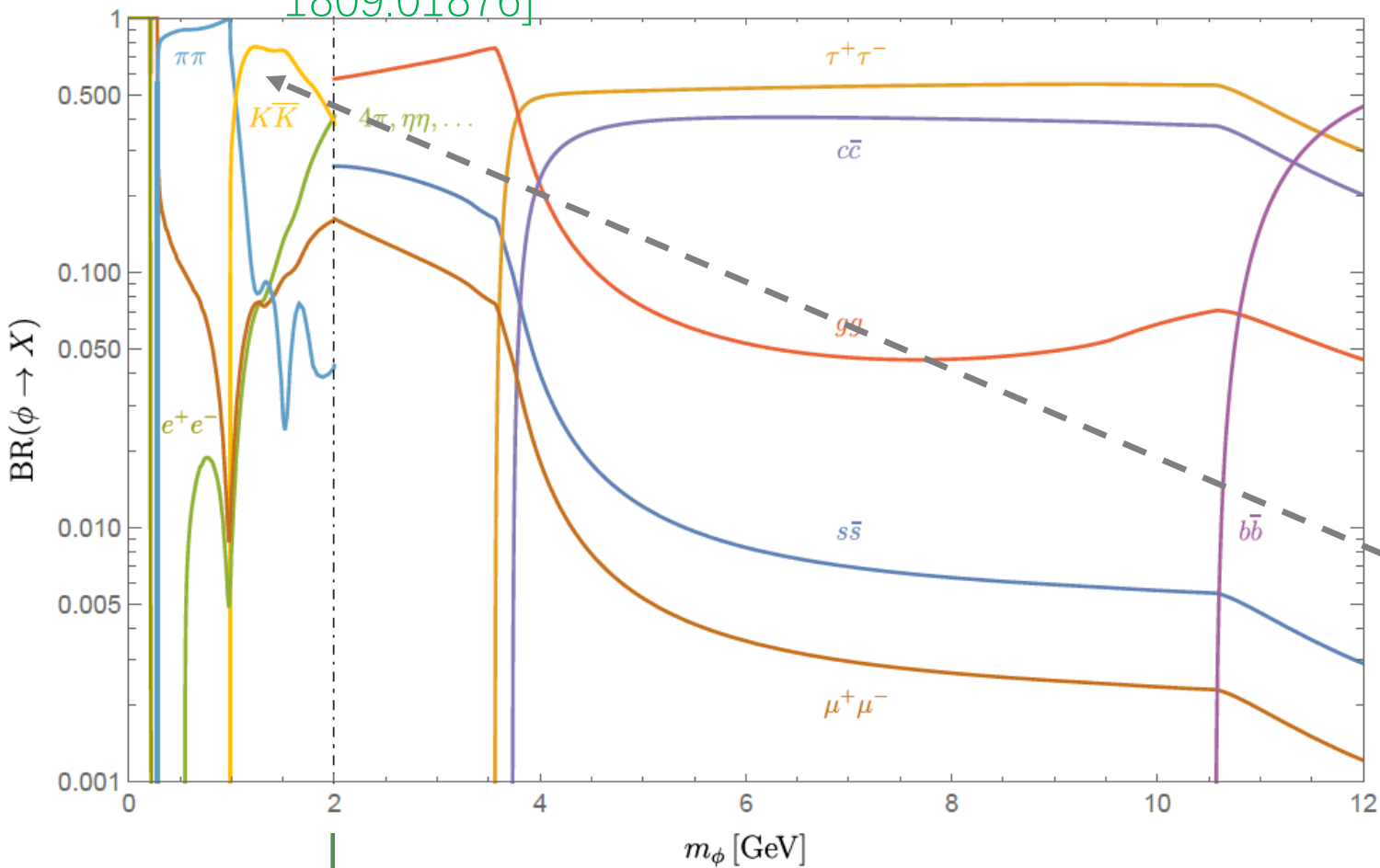
The dominant mode $\pi^+\pi^-\pi^0$ comes from the $\rho\pi\pi$ coupling

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

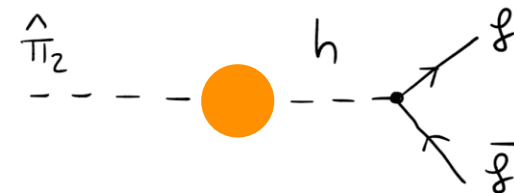
$$\begin{aligned} \mathcal{M}_{\text{VMD}} = & \frac{\langle a\pi_0 \rangle}{f_a} \left\{ g^2 f_\pi \left[(2m_{12}^2 + m_{23}^2 - m_a^2 - 3m_\pi^2) \text{BW}_\rho(m_{23}^2) \right. \right. \\ & \left. \left. + (2m_{12}^2 + m_{13}^2 - m_a^2 - 3m_\pi^2) \text{BW}_\rho(m_{13}^2) \right] \mathcal{F}_V(m_a)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

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

Lingfeng Li (Brown U.) arXiv: 2110.10691

Hadronic Exclusives

Symmetries of the Dark Pion Model

Depending on forms of ω, 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

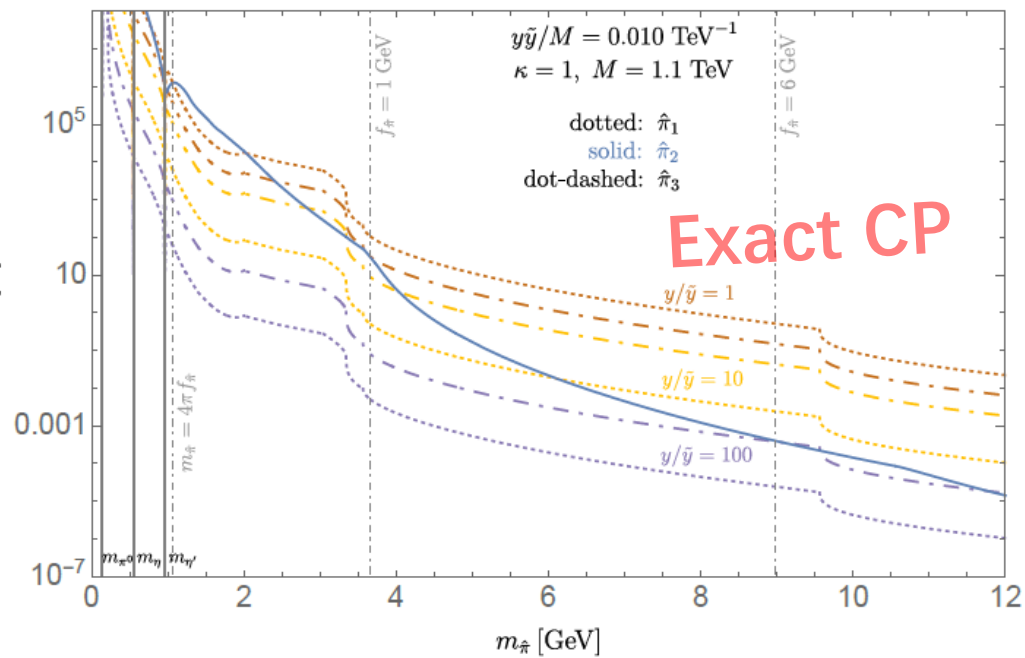
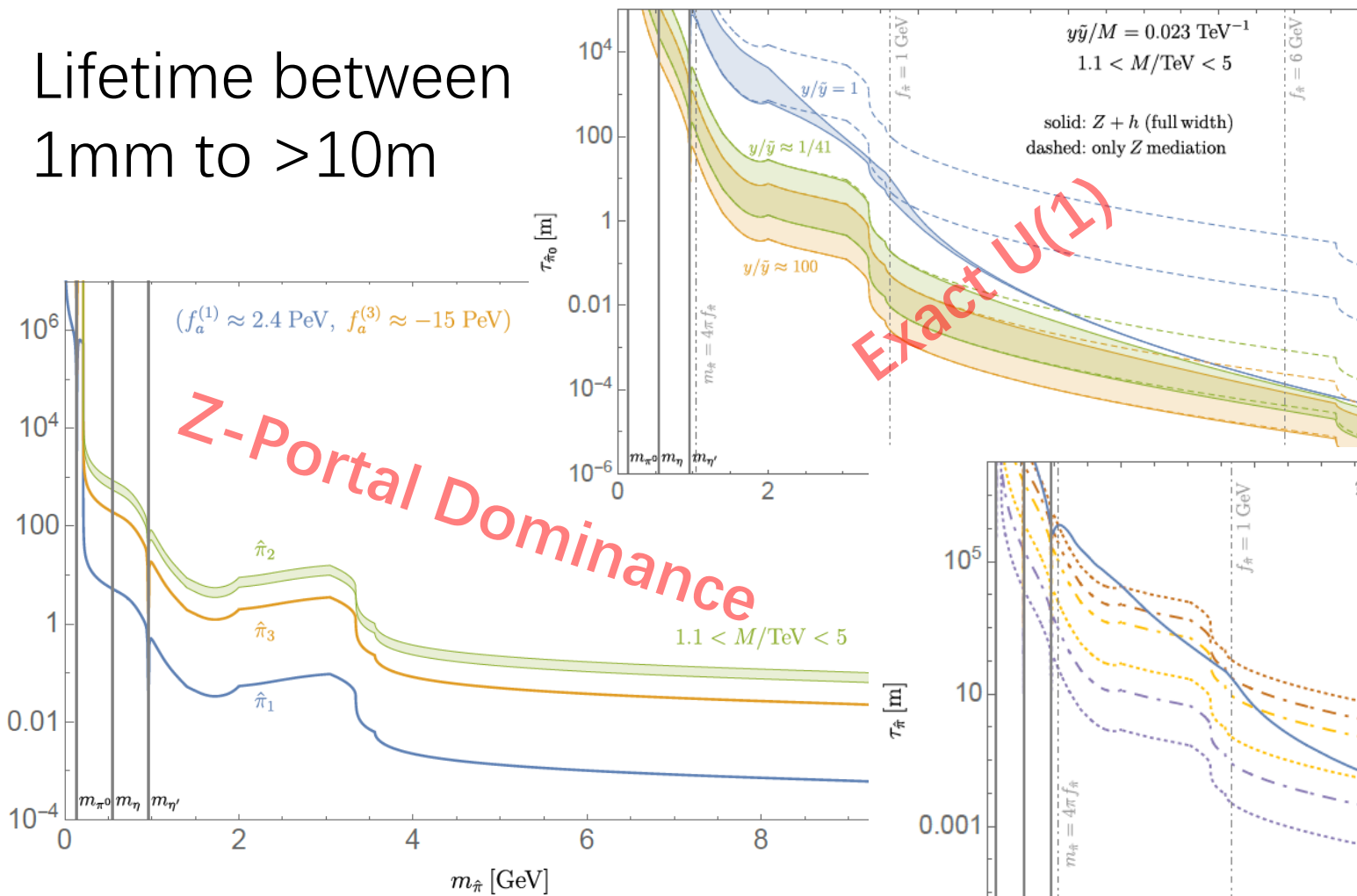
The $U(1)$ subgroup of the $SU(2)$ isospin is exact if everything is diagonal

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.

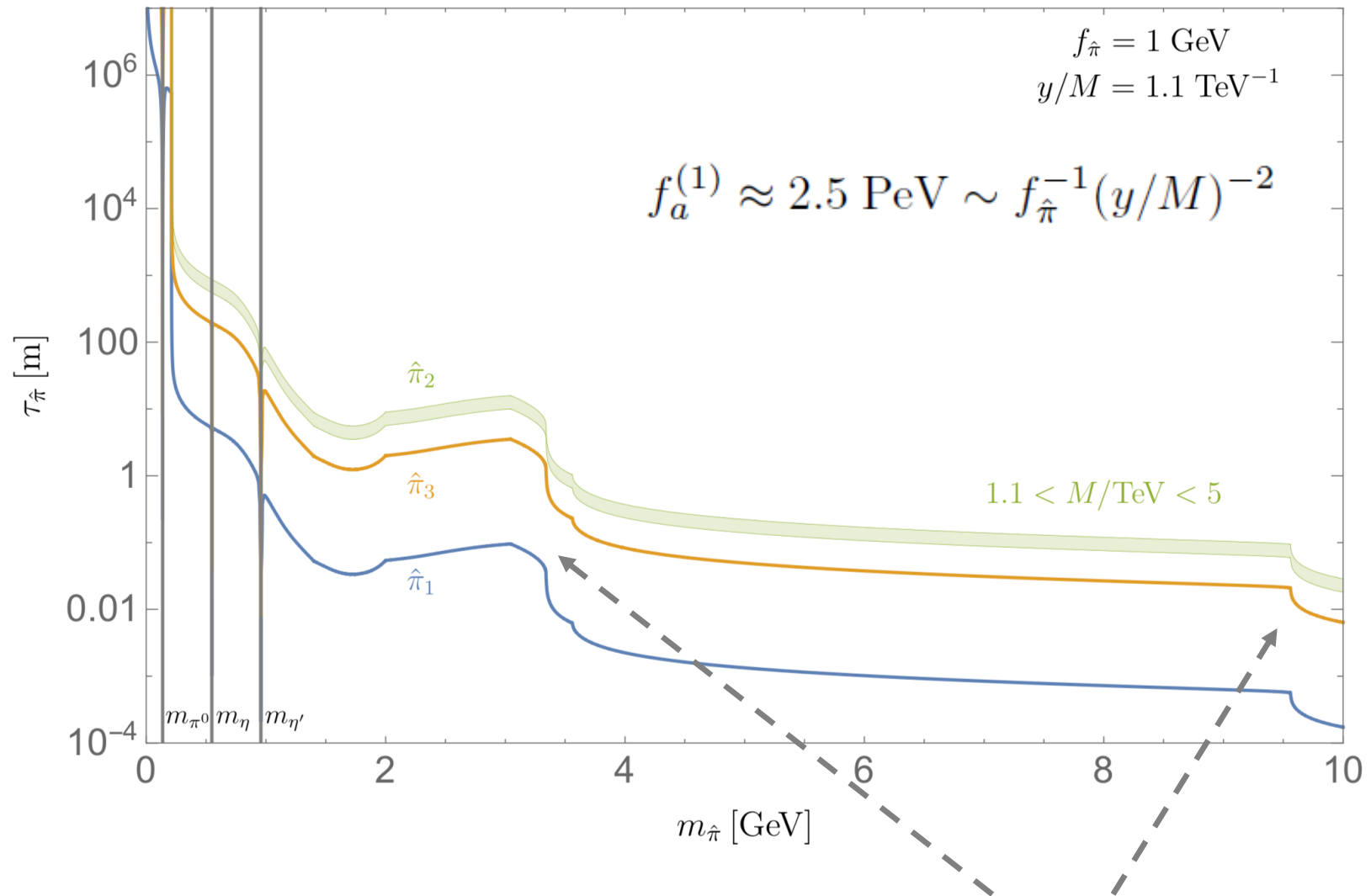
Dark Pion as Long-lived Particles

Lifetime between 1mm to >10m



Easy LLP with strong parameter dependence

LLP in the Z Portal Dominance



Dark Chiral perturbation Theory

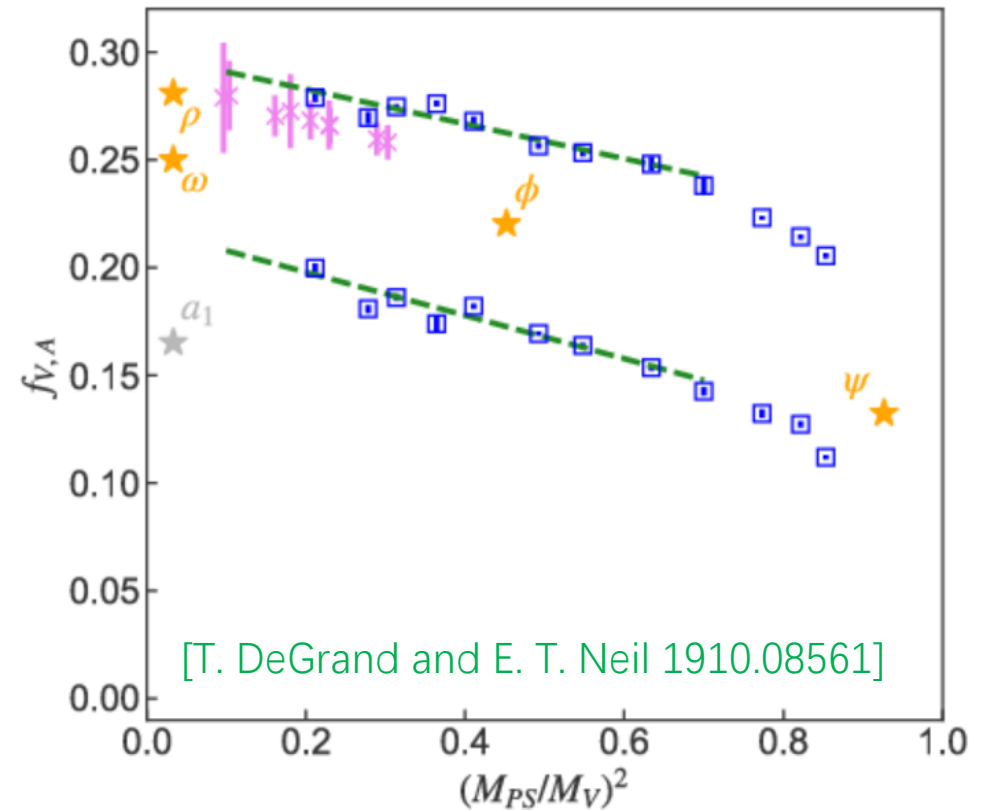
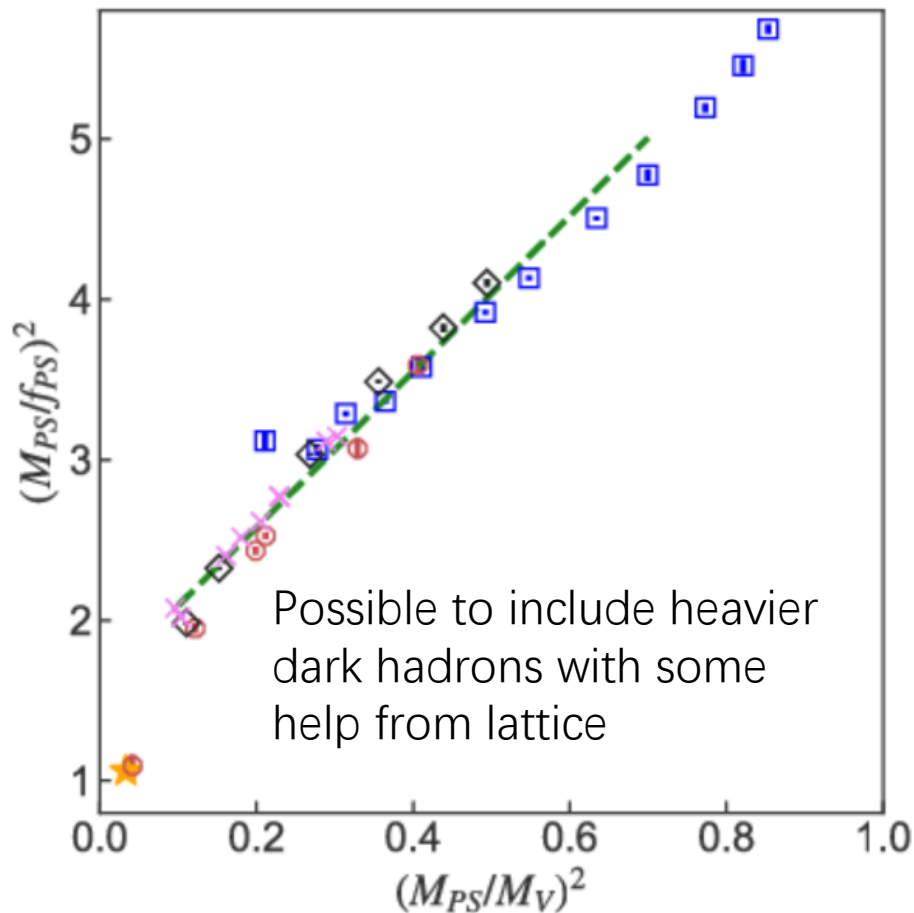
Dark ChpT describe more complicated interaction patterns and dark isospin breaking. Useful at $E \ll m_Z$

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

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

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

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



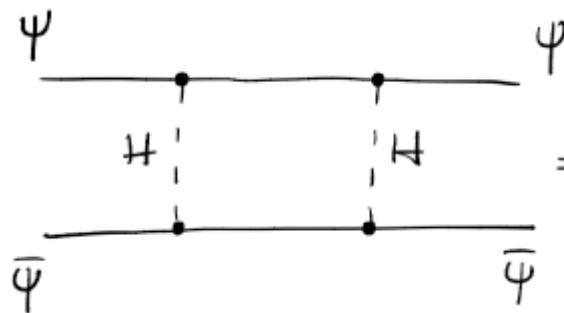
Case Study: Z Portal Dominance

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

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

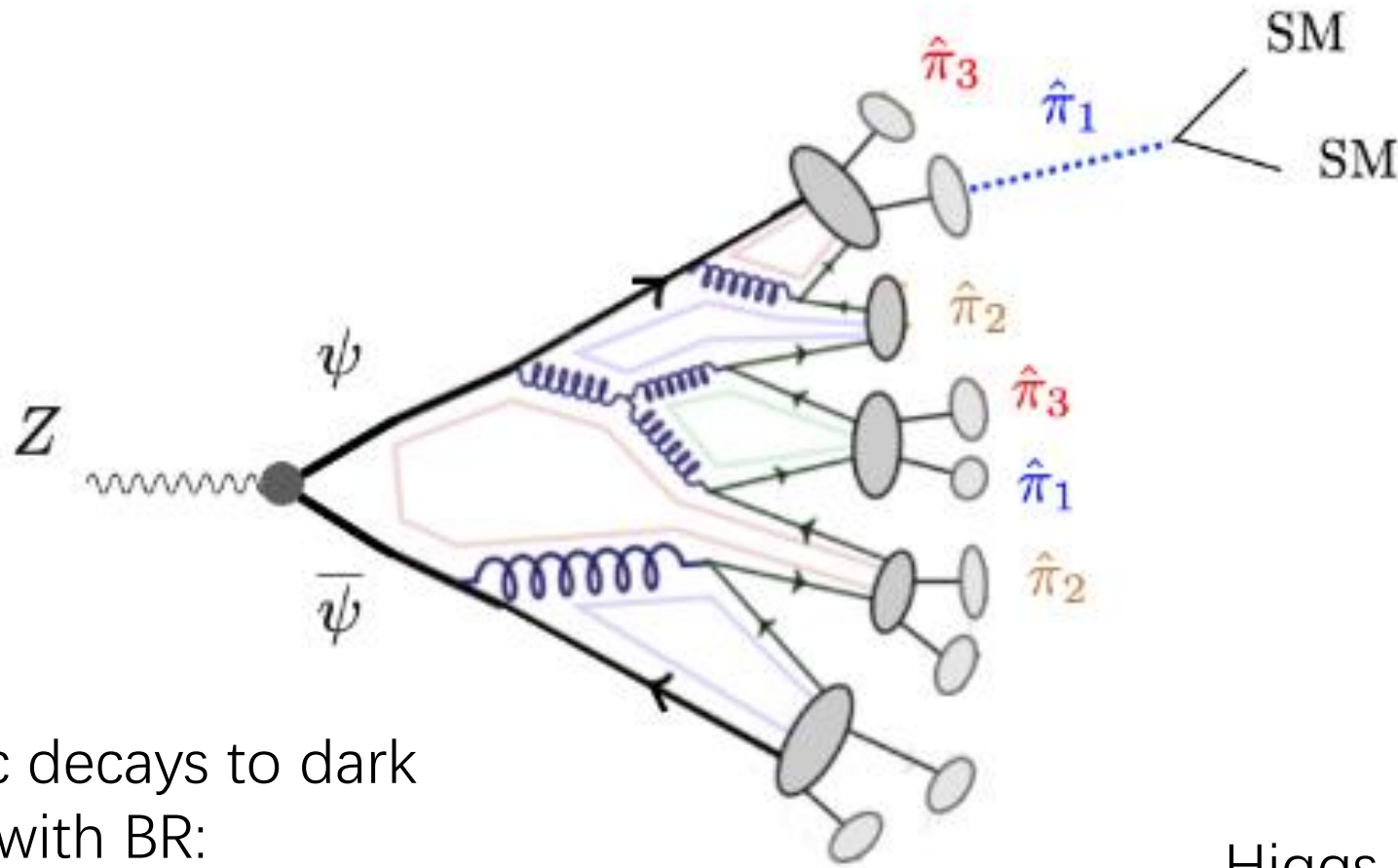


$\Rightarrow \pi_2$ decays via the CP-violating mixing with π_1

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

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

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

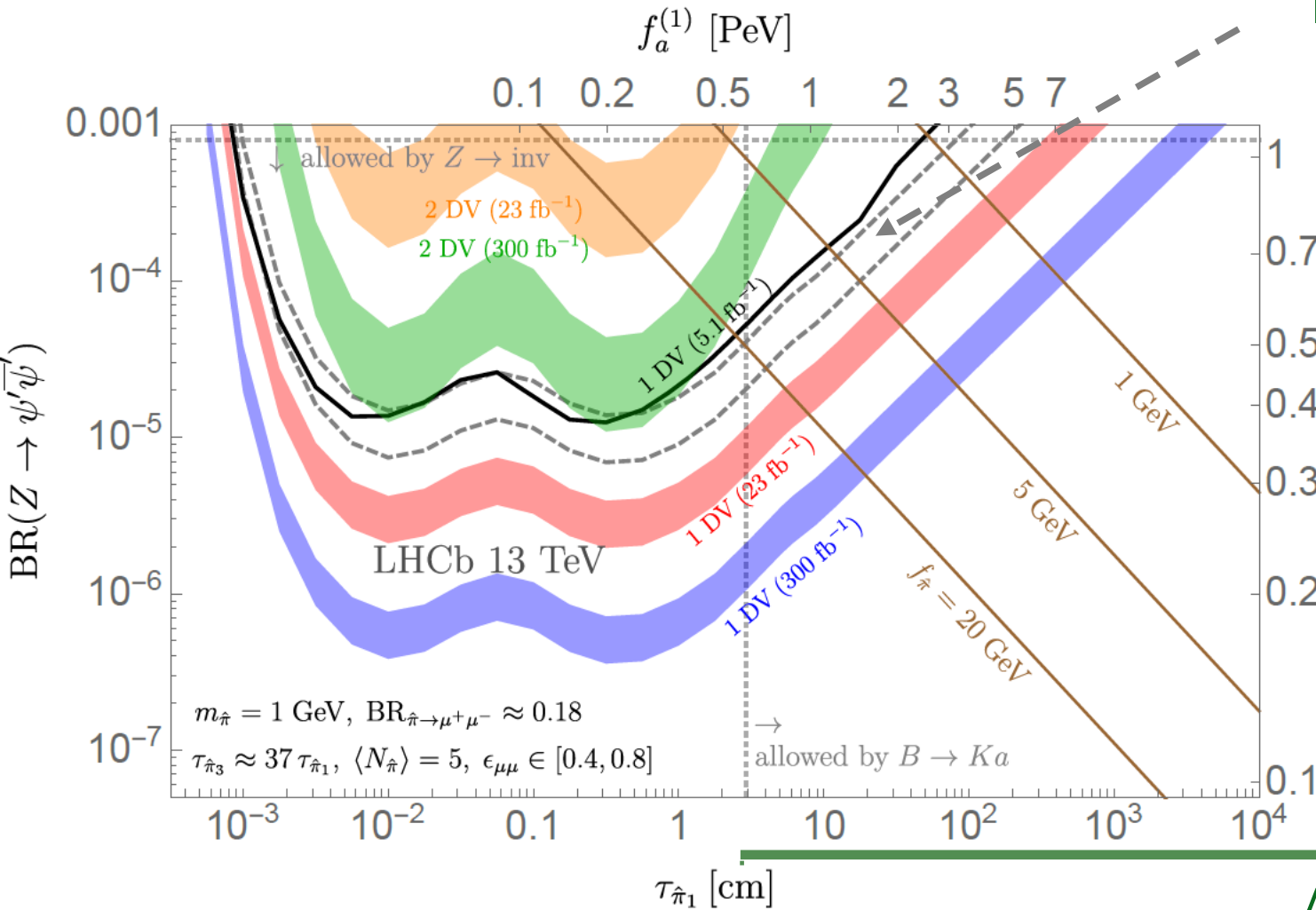
$$\sigma_Z \approx 55 \text{ nb}$$

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

Example: Dimuon Search @ LHCb

Another benchmark with 1 GeV dark pions

Probing $M > 1$ TeV



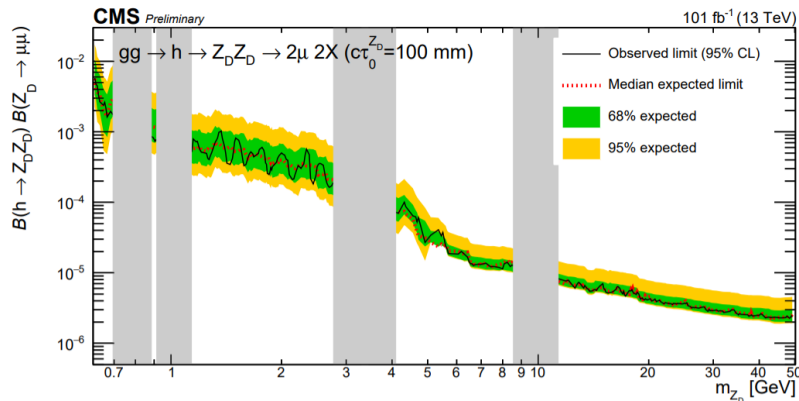
Allowed by Z
Invisible decay

Allowed by current
FCNC bounds

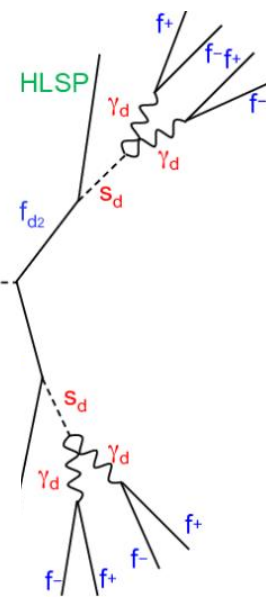
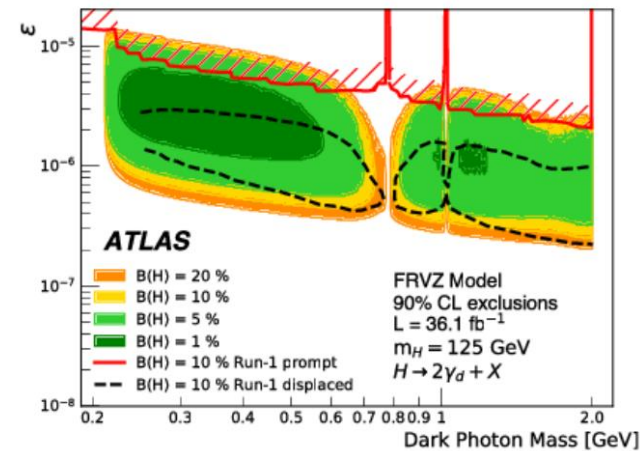
Further Opportunities @ LHC

ATLAS/CMS benefit from larger luminosities and decay volume.

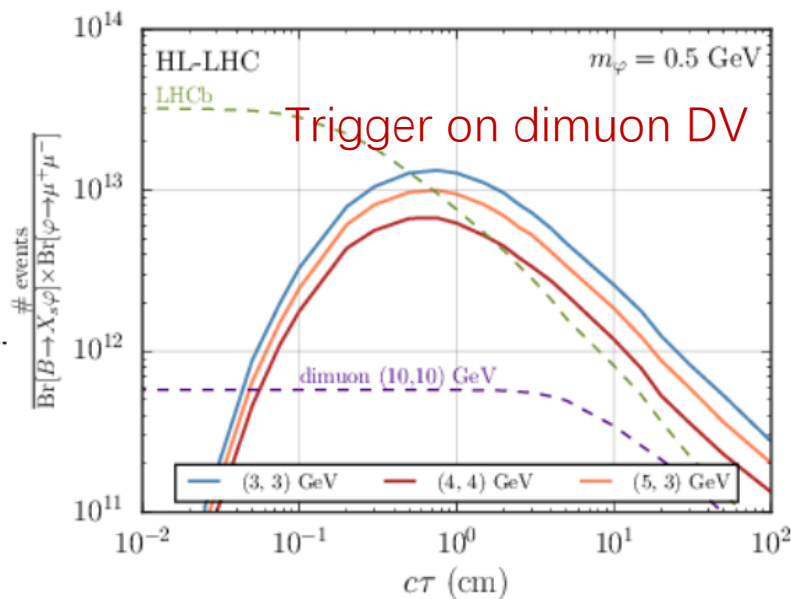
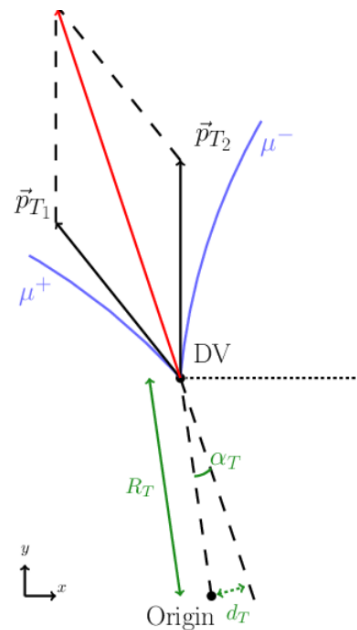
[CMS: CMS-PAS-EXO-20-014]



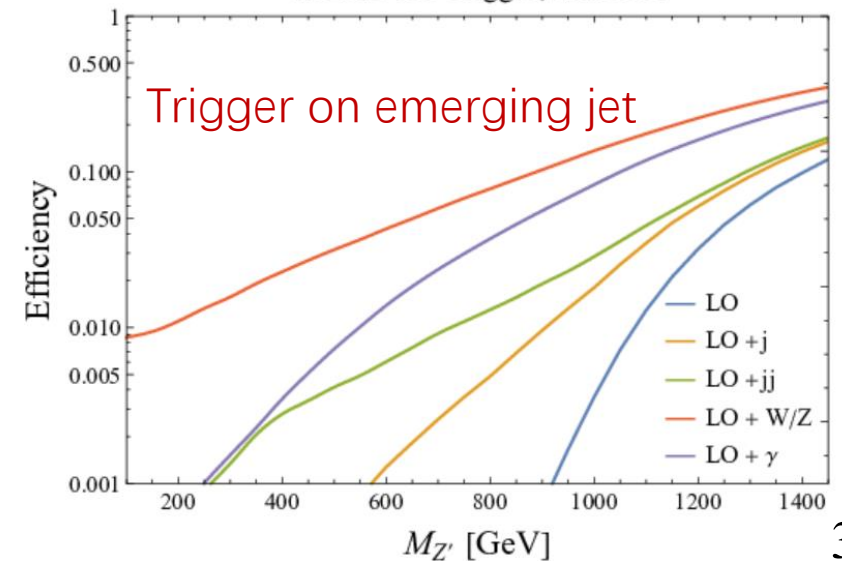
[ATLAS: 1909.01246]



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



ATLAS HT Trigger, Model A



TeV Scale Phenomenology @ LHC

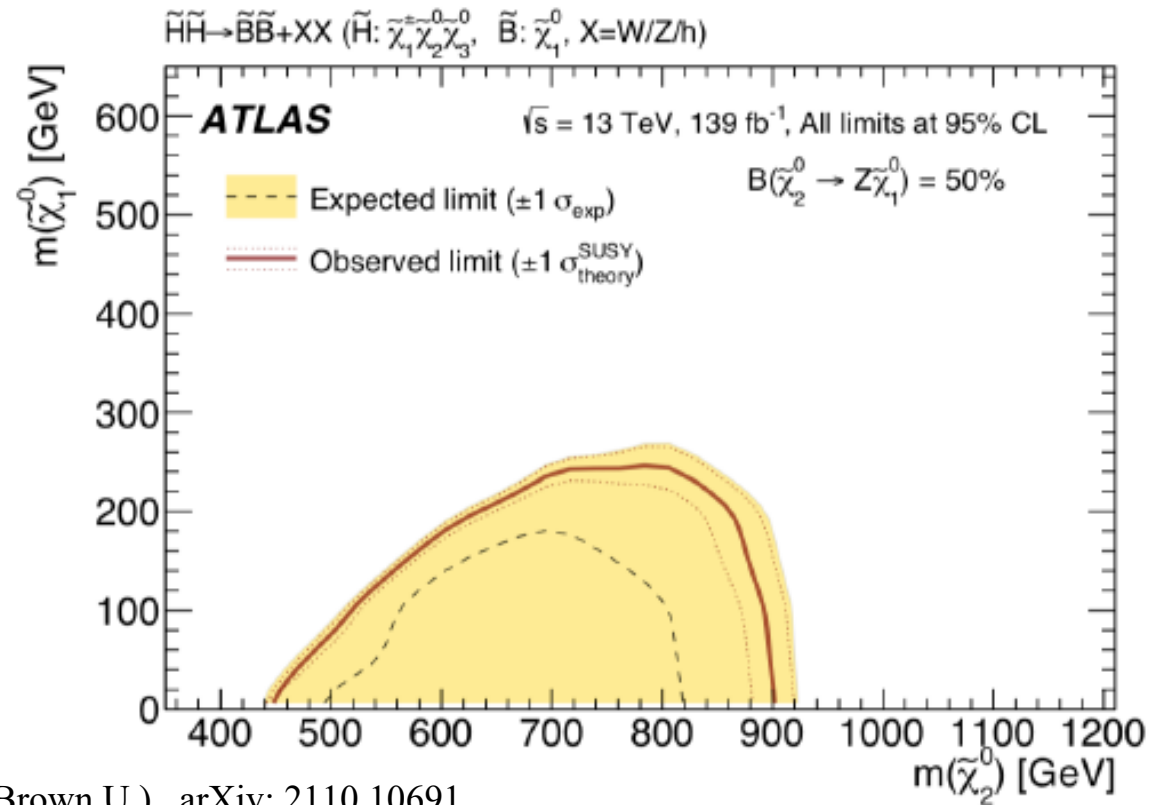
Direct production of heavy EW doublets:

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

⇒ Diboson + emerging jet signals

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

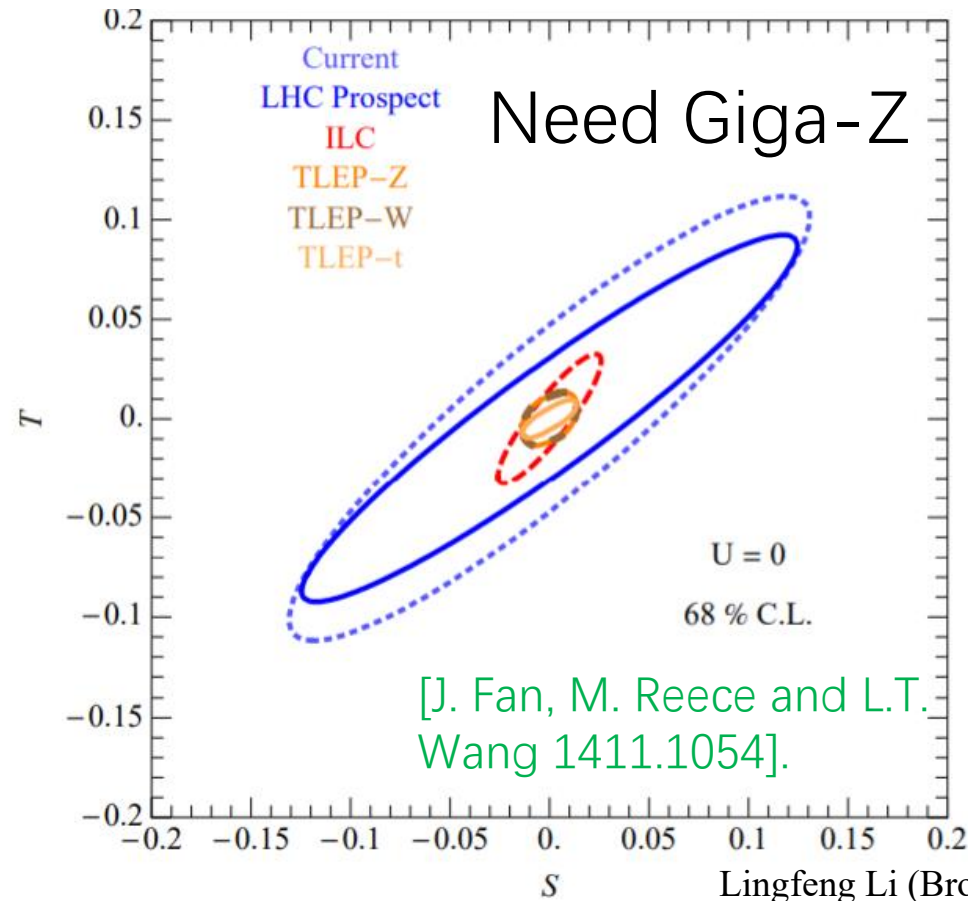
Estimated limit: $M > 1.3$ TeV @ HL-LHC



Prospect at Future Colliders

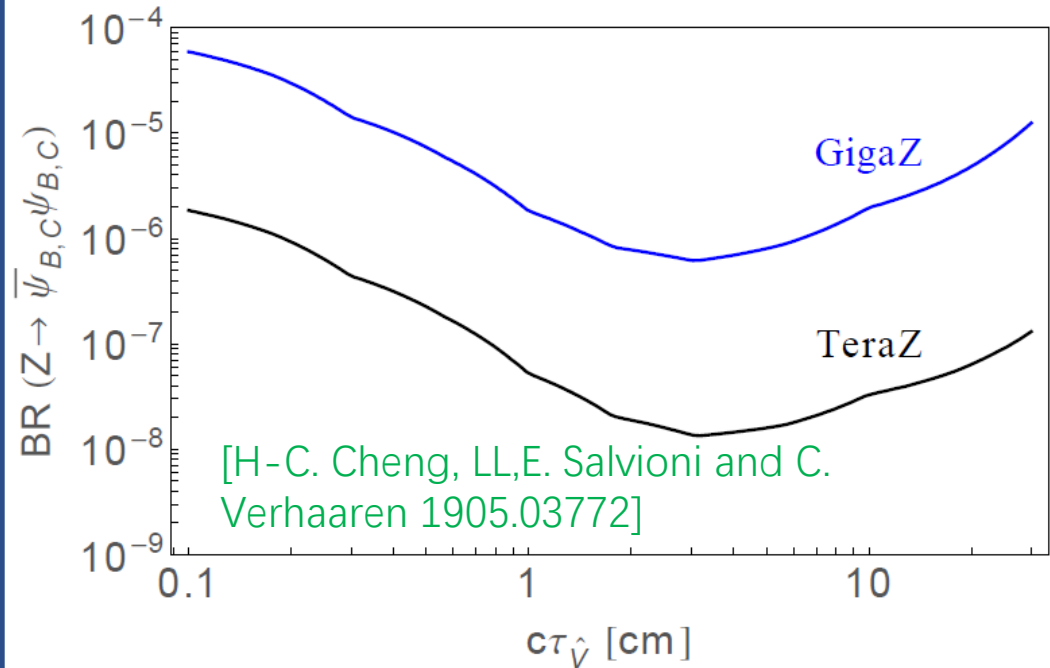
Indirect/Intensity (EWPT),
Shifting the T parameter:

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



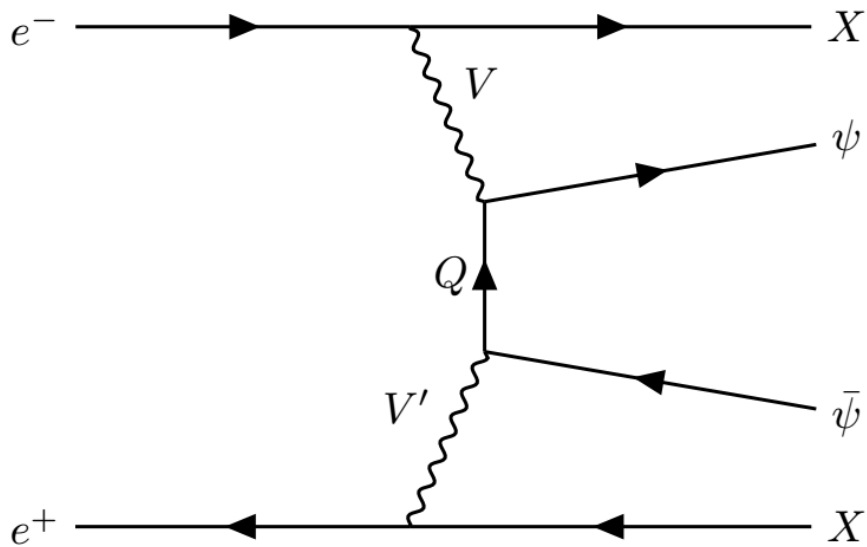
Lingfeng Li (Brown U.) arXiv: 2110.10691

Direct search in H/Z decays:



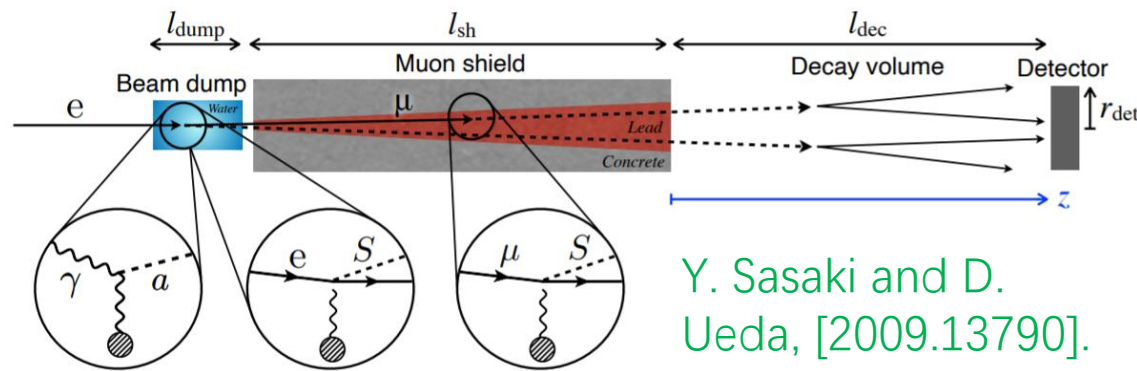
(VERY conservative) limits on exotic $Z \rightarrow$
dark shower decays but with a
DIFFERENT model.

Prospect at Future Colliders (II)

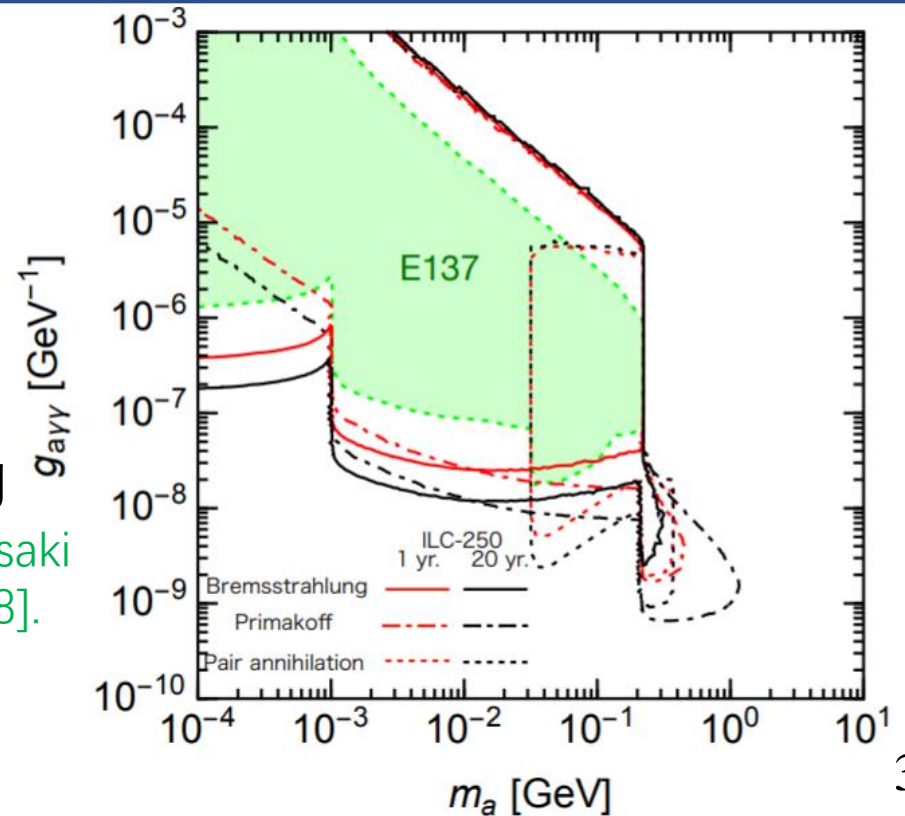


Energy-frontier searches:

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



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



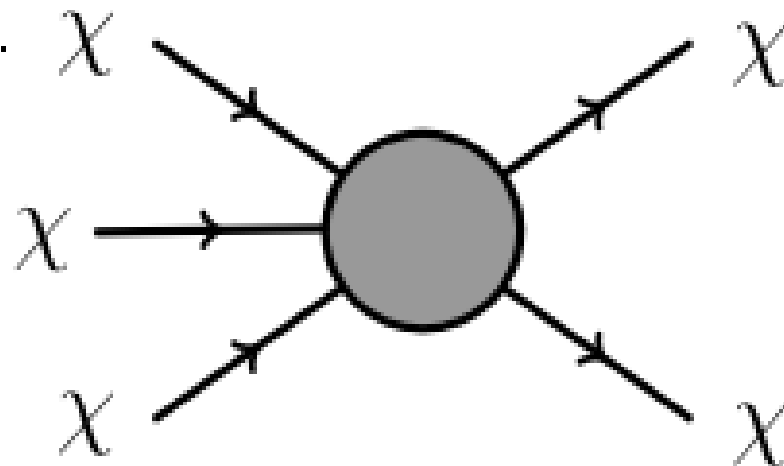
Comments on Cosmology

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.