Hadronic decays of GeV-scale axion-like particles

2308.xxxxx + 2110.10691

with Hsin-Chia Cheng (Davis) and Lingfeng Li (Brown)

Ennio Salvioni

Advanced Calculus for Fundamental Interactions, July 10, 2023

Theory motivation: why GeV-scale ALPs?

ALP = axion-like particle = light pseudo-Nambu-Goldstone boson a,

with interactions to Standard Model particles suppressed by a large scale f_a

Masses $m_a \sim \Lambda_{\mathrm{QCD}} \sim \mathrm{GeV}$ motivated by many new physics scenarios:

(1) Models addressing the strong *CP* problem

Minimal QCD axion needs to be far lighter than GeV…

[Grilli di Cortona, Hardy, Pardo Vega, Villadoro 2015]

$$m_a^2 f_a^2 \sim m_\pi^2 f_\pi^2 \qquad \rightarrow \qquad m_a = 5.7\ \mu\mathrm{eV} \left(\frac{10^{12}\ \mathrm{GeV}}{f_a} \right)$$

$$(f_a)_{\mathrm{astrophysics}} \gtrsim 10^8\ \mathrm{GeV} \qquad \rightarrow \qquad m_a \lesssim 0.1\ \mathrm{eV}$$

… but many variations exist that produce heavier axions.

Key feature is coupling to gluons, other couplings more model dependent

$$\mathcal{L}_{\mathrm{eff}} \supset c_g \frac{\alpha_s}{4\pi} \frac{a}{f_a} G^a_{\mu\nu} \widetilde{G}^{\mu\nu\, a}$$

Introduction: why GeV-scale ALPs?

Masses $m_a \sim \Lambda_{\rm QCD} \sim {\rm GeV}$ motivated by many new physics scenarios:

(2) Models addressing hierarchy problem by making Higgs a composite Goldstone:
ALP is "sibling" of the Higgs, arising from global symmetry breaking at TeV

[Gripaios, Pomarol, Riva, Serra 2009]

(3) Models with extra elementary scalars, SUSY hidden sectors, …

(4) ALPs as composite mesons from a dark QCD at GeV scale
Key feature is (non-universal) coupling to fermions,

$$\mathcal{L}_{\rm eff} \supset -\frac{\partial_\mu a}{f_a} \sum_f c_f \bar{f} \gamma^\mu \gamma_5 f$$

[Cheng, Li, Salvioni 2021]

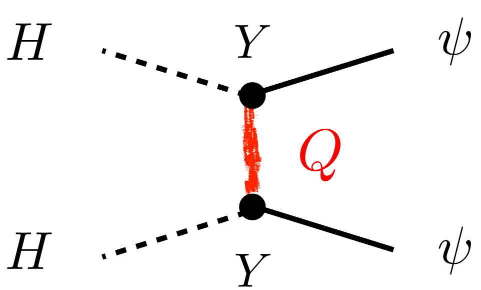
Example dark sector

- Dark QCD with confinement scale Λ
- N light dark quarks ψ, SM singlets
- N heavy dark quarks Q, with SM electroweak charges

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

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

"dark pions"



$$M \gtrsim \text{TeV}$$

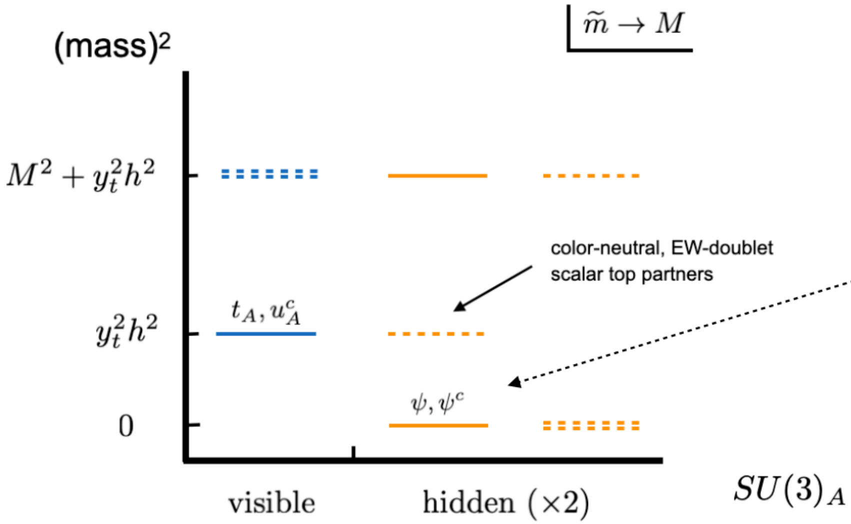
heavy mediators

[Cheng, Li, Salvioni, 2110.10691]

Ultraviolet motivations

"Tripled Top" framework for neutral naturalness: accidental SUSY of the spectrum

[Cheng, Li, Salvioni, Verhaaren 2018]
[Burdman, Chacko, Goh, Harnik 2006]



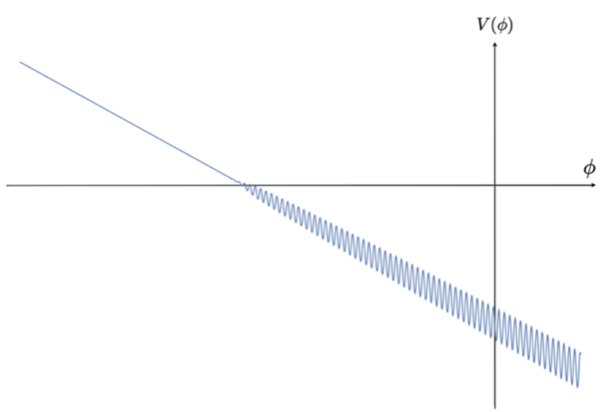
light Dirac fermions

This model, with $Y = y_t$ and $\widetilde{Y} = 0$

$$SU(3)_A \times SU(3)_B \times SU(3)_C \times SU(2) \times U(1)$$

Non-QCD version of the relaxion: new fermions generate backreaction potential

[Graham, Kaplan, Rajendran 2015]

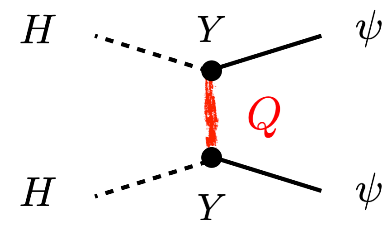


$$\frac{1}{32\pi^2} \frac{\phi}{f} \widetilde{G}_{\mu\nu} G^{\mu\nu}$$

$$V_b = \Lambda^4 \cos(\phi/f)$$

with $\quad \Lambda^4 \sim 4\pi f_{\hat{\pi}}^3 \dfrac{Y\widetilde{Y}\langle h \rangle^2}{M}$

Dark pions



- Integrate out heavy fermions Q

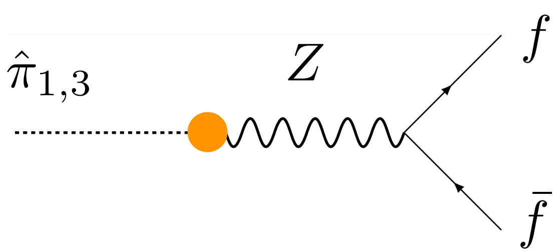
$$\mathcal{L}_{\rm EFT} \sim \underbrace{(\overline{\psi}_R \boldsymbol{Y}^\dagger \boldsymbol{M}^{-2} \boldsymbol{Y} \gamma^\mu \psi_R)\,(iH^\dagger D_\mu H) + (\overline{\psi}_L \widetilde{\boldsymbol{Y}}^\dagger \boldsymbol{M}^{-2} \widetilde{\boldsymbol{Y}} \gamma^\mu \psi_L)\,(iH^\dagger D_\mu H)}_{Z\text{ portal (dim-6)}}$$

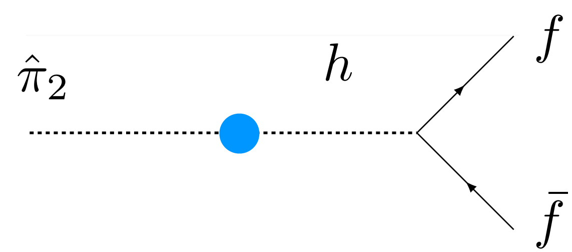
$$- \overline{\psi}_L \boldsymbol{\omega} \psi_R + \underbrace{\overline{\psi}_L \widetilde{\boldsymbol{Y}}^\dagger \boldsymbol{M}^{-1} \boldsymbol{Y} \psi_R |H|^2}_{\text{Higgs portal (dim-5)}}$$

Z portal (dim-6)

Higgs portal (dim-5)

- $N = 2$ flavors: dark pions $\hat{\pi}_a \sim \overline{\psi} i \sigma_a \gamma_5 \psi$

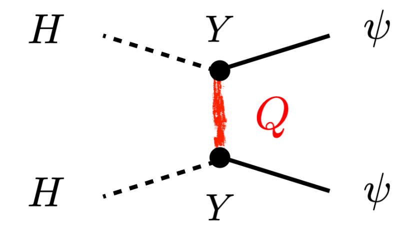




$J^{PC} = 0^{-+}$ $J^{PC} = 0^{--}$

composite ALP   composite Higgs-mixed scalar

Dark pions



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$$-\,\overline{\psi}_L \boldsymbol{\omega} \psi_R + \overline{\psi}_L \widetilde{\boldsymbol{Y}}^\dagger \boldsymbol{M}^{-1} \boldsymbol{Y} \psi_R |H|^2$$

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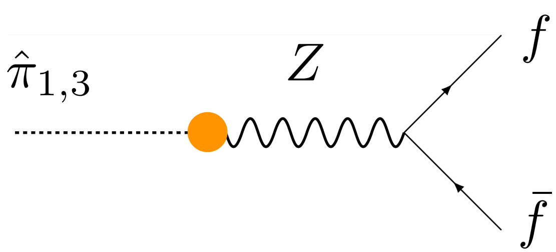
$$\mathcal{L}_{\rm eff} \supset -\frac{\partial_\mu a}{f_a} \sum_f c_f \bar{f} \gamma^\mu \gamma_5 f$$



$$c_f = T_L^3(f)$$

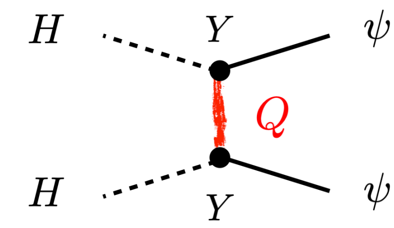
isospin-violating couplings to SM fermions

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

composite ALP

$$f_a \sim \frac{M^2}{Y^2 f_{\hat{\pi}}} = 1\ \text{PeV} \left(\frac{M/Y}{\text{TeV}}\right)^2 \left(\frac{1\ \text{GeV}}{f_{\hat{\pi}}}\right)$$

Dark pions



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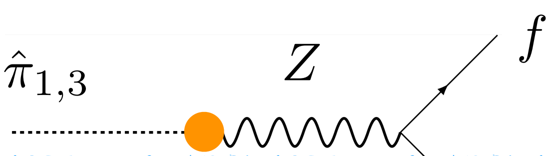

$c_f = T_L^3(f)$

isospin-violating couplings

In summary:

- Many models predict GeV-scale ALPs, with many different coupling patterns
- Important to consider a general EFT

Experimental motivation

Many current or planned experiments have sensitivity to GeV-scale ALPs:

- ✓ Existing collider detectors: ATLAS, CMS, LHCb, Belle II, dedicated detectors for long-lived particles (e.g. FASER), …
- ✓ Fixed-target experiments, such as proton beam dumps; neutrino detectors (DUNE)
- ✓ Proposed detectors @ High-Luminosity LHC + future colliders

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For all of them, modelling production and decay accurately is important to correctly assess sensitivity and compare to other probes

For $m_a \sim \Lambda_{\rm QCD} \sim {\rm GeV}$, non-perturbativity of SM QCD is a challenge: need to calculate decays to exclusive hadronic final states

Snapshot

$$\mathcal{L}_a = \frac{1}{2}(\partial_\mu a)^2 - \frac{1}{2}m_a^2 a^2 - \frac{\partial_\mu a}{f_a}\sum_f c_f \bar{f}\gamma^\mu\gamma_5 f \qquad \text{with} \qquad c_f = T_L^3(f)$$

[Cheng, Li, Salvioni, 2021]

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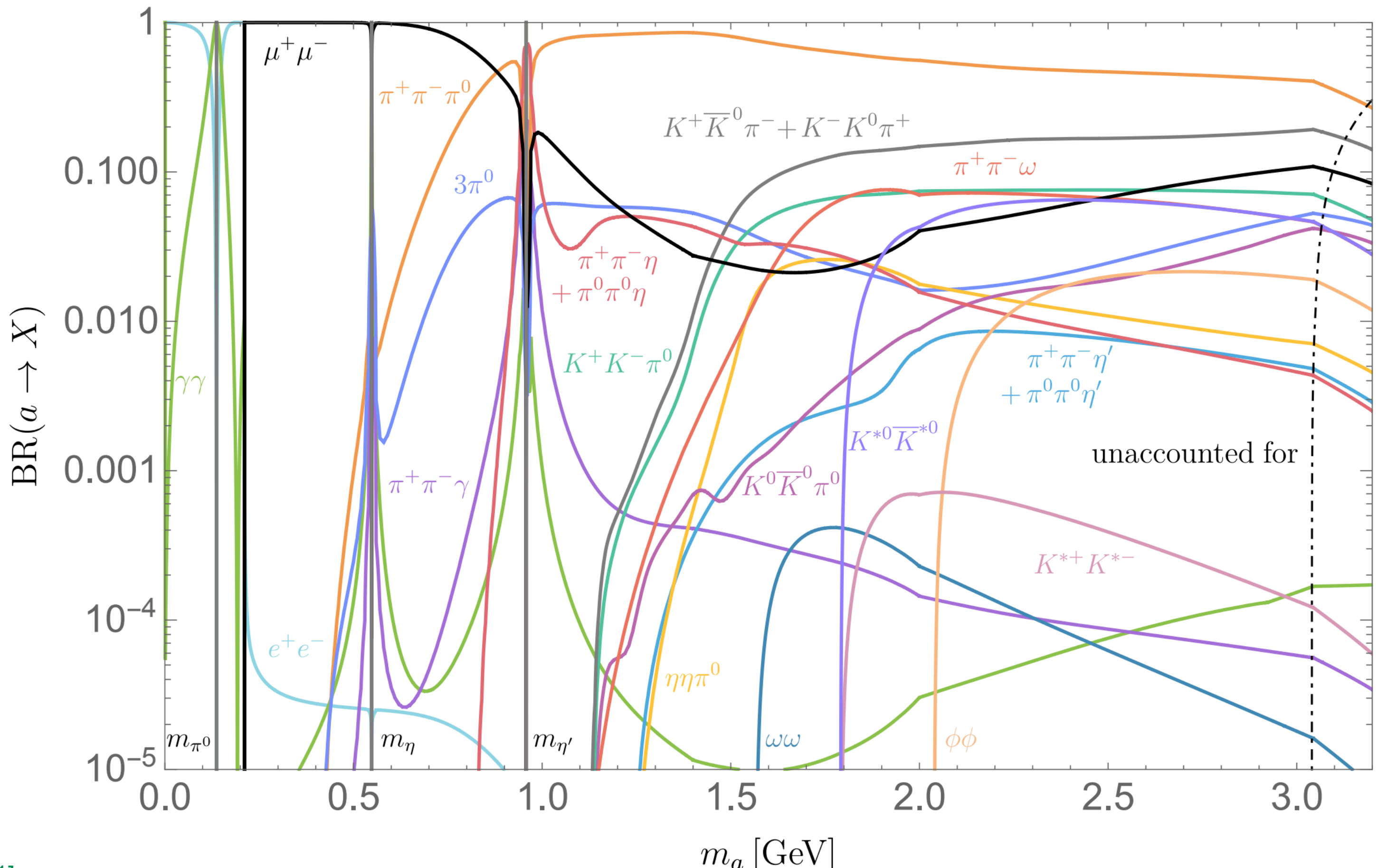
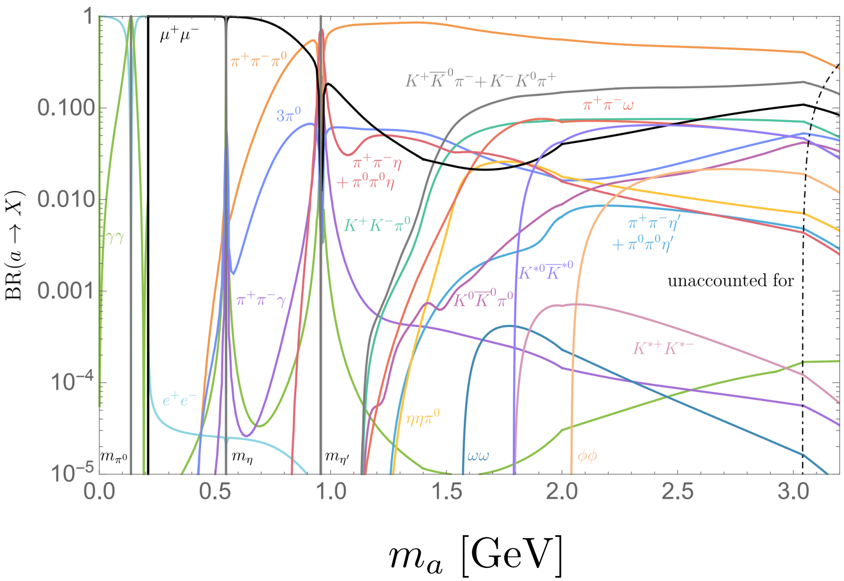
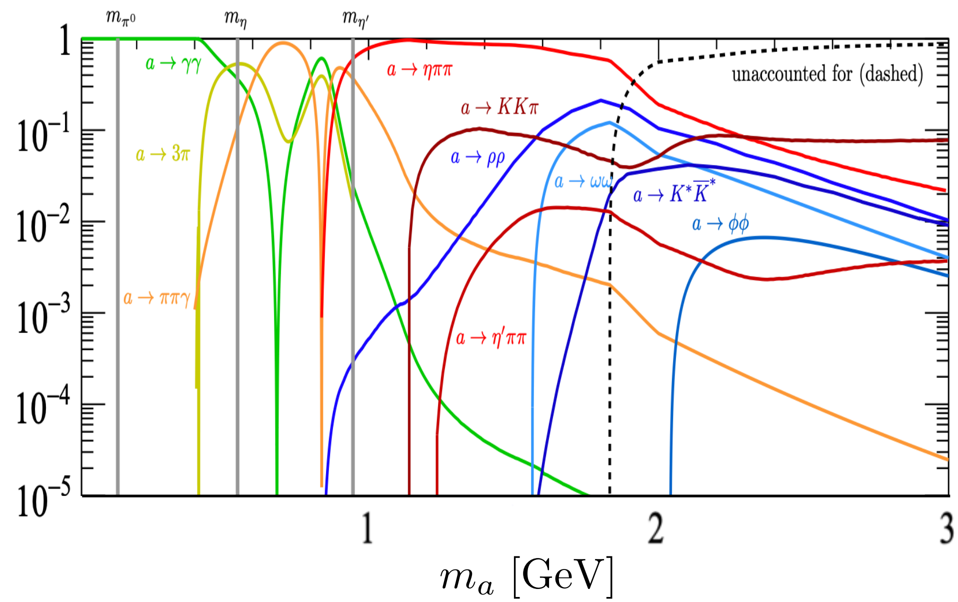


[Cheng, Li, Salvioni, 2021]

Big differences between models





$$\mathcal{L}_{\text{eff}} \supset -\frac{\partial_\mu a}{f_a} \sum_f c_f \bar{f} \gamma^\mu \gamma_5 f$$

$$c_f = T_L^3(f)$$

$$\mathcal{L}_{\text{eff}} \supset c_g \frac{\alpha_s}{4\pi} \frac{a}{f_a} G^a_{\mu\nu} \widetilde{G}^{\mu\nu\, a}$$

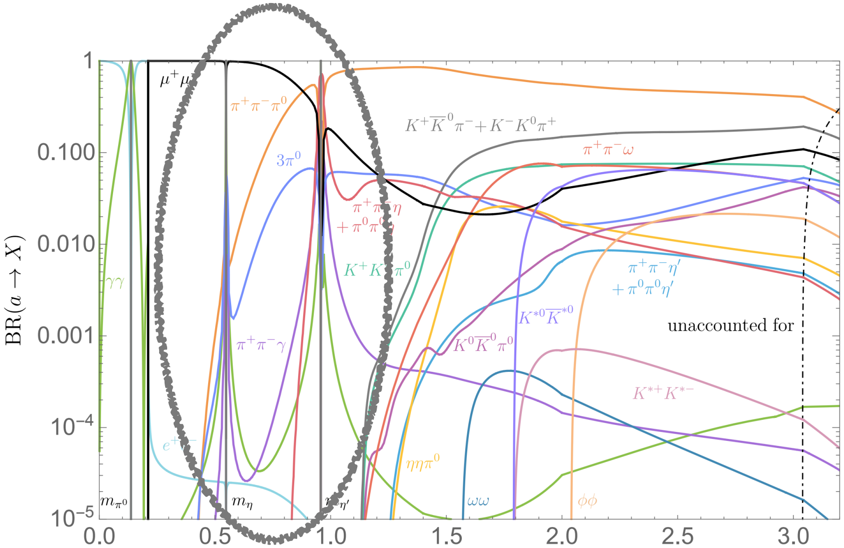
isospin-breaking coupling to fermions

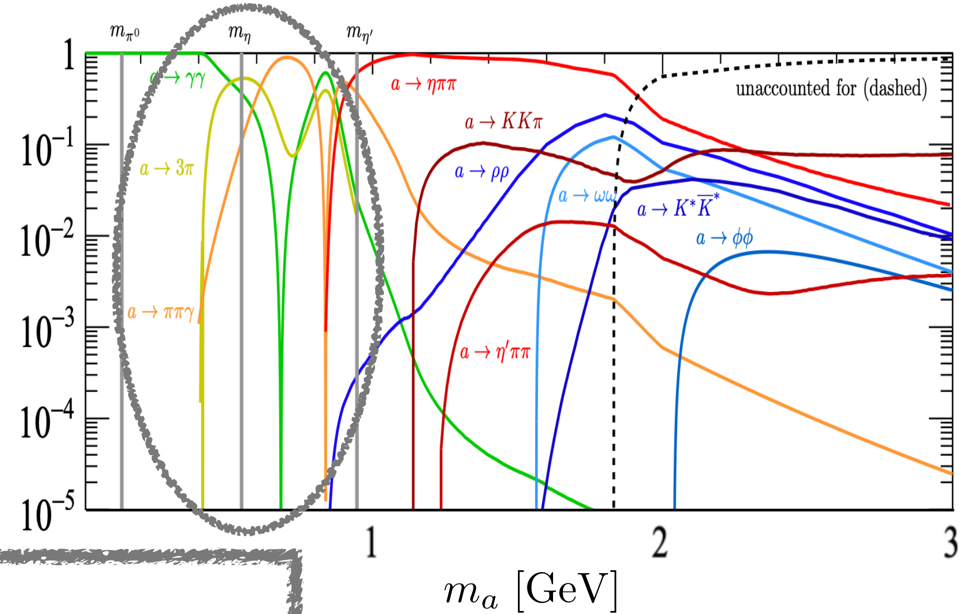
coupling to gluons

[Cheng, Li, Salvioni, 2021]

[Aloni, Soreq, Williams 2018]

Big differences between models





$a \to \pi^+\pi^-\gamma$: negligible vs dominant

$\mathcal{L}$

$$\mathcal{L}_{\text{eff}} \supset c_g \frac{\alpha_s}{4\pi} \frac{a}{f_a} G^a_{\mu\nu} \widetilde{G}^{\mu\nu\, a}$$

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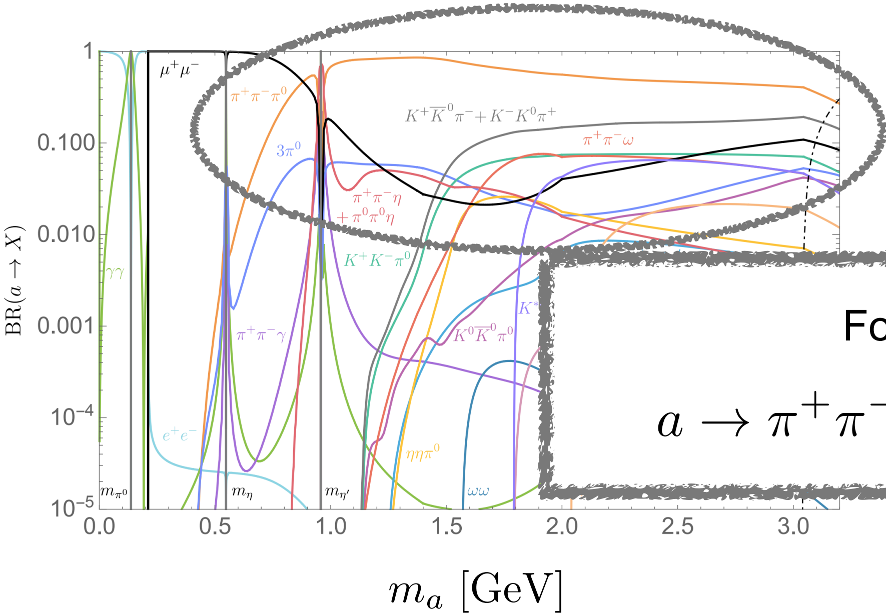
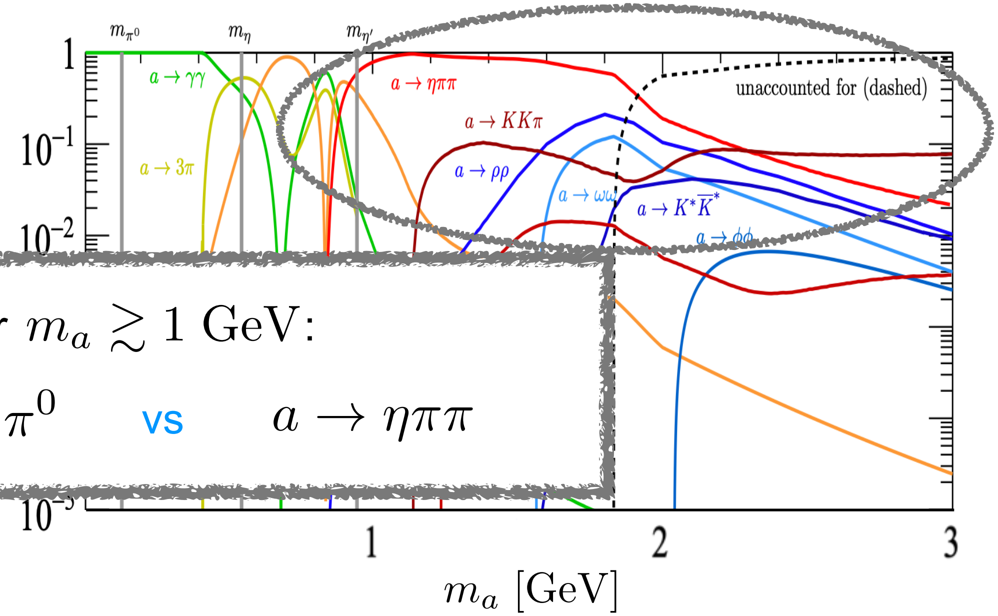




For $m_a \gtrsim 1$ GeV:

$a \to \pi^+\pi^-\pi^0$ vs $a \to \eta\pi\pi$

$$\mathcal{L}_{\rm eff} \supset -\frac{\partial_\mu a}{f_a} \sum_f c_f \bar{f} \gamma^\mu \gamma_5 f$$

$$c_f = T_L^3(f)$$

$$\mathcal{L}_{\rm eff} \supset c_g \frac{\alpha_s}{4\pi} \frac{a}{f_a} G^a_{\mu\nu} \widetilde{G}^{\mu\nu\, a}$$

isospin-breaking coupling to fermions

coupling to gluons

[Cheng, Li, Salvioni, 2021]

[Aloni, Soreq, Williams 2018]

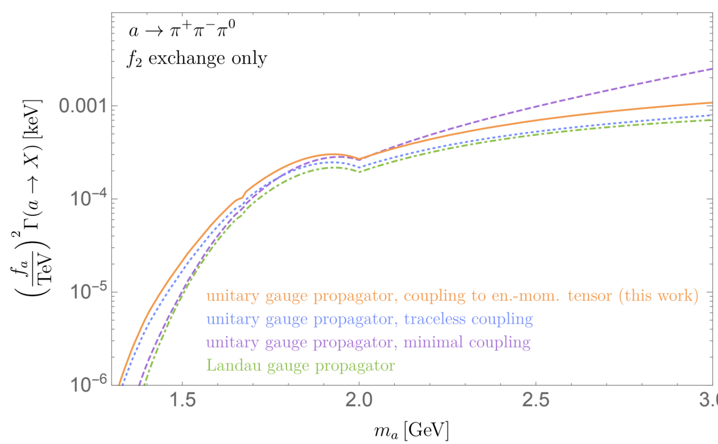
Methods

Three mass regimes, following [Aloni, Soreq, Williams 2018]

- For $m_a < m_{\eta'} \approx 1\ \mathrm{GeV}$, match ALP effective field theory to Chiral Perturbation Theory (leading order + corrections)
- For $m_{\eta'} < m_a \lesssim 3\ \mathrm{GeV}$: include exchange of scalar, vector, tensor resonances, using as much input from data as possible
- For $m_a \gtrsim 3\ \mathrm{GeV}$, perturbative QCD

Some differences in treatment, for instance [Cheng, Li, Salvioni 2021]

- Implementation of vector meson dominance (impacts e.g. $a \to \pi^+\pi^-\gamma$)
- Couplings and propagator of f_2 tensor meson



General analysis

Take ALP effective field theory

hermitian matrix

$$\mathcal{L}_{\text{eff}}^{D\leq 5} = \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{m_{a,0}^2}{2}a^2 - \frac{\partial^\mu a}{f}\sum_F \bar{\psi}_F \boldsymbol{c}_F \gamma_\mu \psi_F$$

chiral

$$+ c_{GG}\frac{\alpha_s}{4\pi}\frac{a}{f}G_{\mu\nu}^a \tilde{G}^{\mu\nu,a} + c_{WW}\frac{\alpha_2}{4\pi}\frac{a}{f}W_{\mu\nu}^A \tilde{W}^{\mu\nu,A} + c_{BB}\frac{\alpha_1}{4\pi}\frac{a}{f}B_{\mu\nu}\tilde{B}^{\mu\nu}$$

Write code that evaluates ALP decay widths into all SM hadronic final states, for arbitrary values of coupling coefficients

Speed up by calculating just once and storing as many numerical integrals (typically over amplitudes extracted from data) as possible

Needs extensive testing against previous results
+ ironing out differences in existing implementations of ChPT and resonance exchange

[Cheng, Li, Salvioni, in progress]

Outlook

- Writing code that evaluates decay widths of GeV-scale ALPs into any SM hadronic final states, for arbitrary values of coupling coefficients [Cheng, Li, Salvioni, in progress]

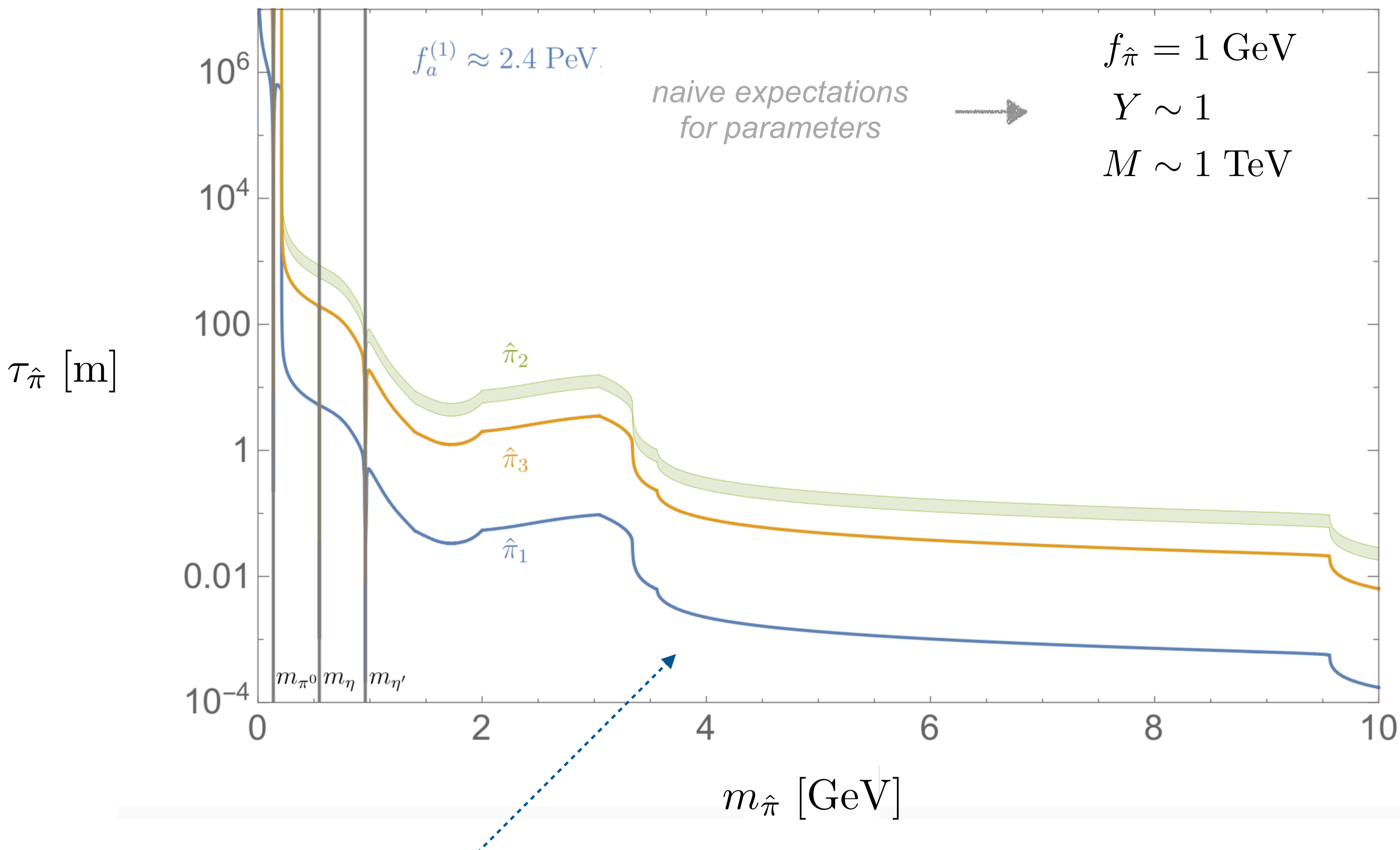
- Relevant for many theoretical scenarios
  + very valuable for interpretations of wealth of experimental searches

- Several extensions would be useful and can be envisaged:
  - integration with RG running of couplings from high to low scales
  - extension to include production mechanisms
  - extension to scalar (vs pseudoscalar) particles

- ALPINIST code https://github.com/jjerhot/ALPINIST [Jerhot, Döbrich, Ertas, Kahlhöfer, Spadaro 2201.05170]
  does part of the above, but only includes a few decay modes
  and cannot handle general coupling structure

Supplementary material

Light dark pions are long lived

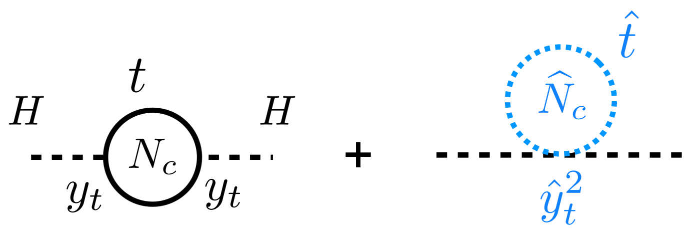


$c\tau$ between 10 meters and 1 millimeter ➡ natural long-lived particle target

Light dark sectors

- Neutral naturalness: natural electroweak breaking without new QCD-charged particles. Instead, the "top partners" are charged under a dark color symmetry:

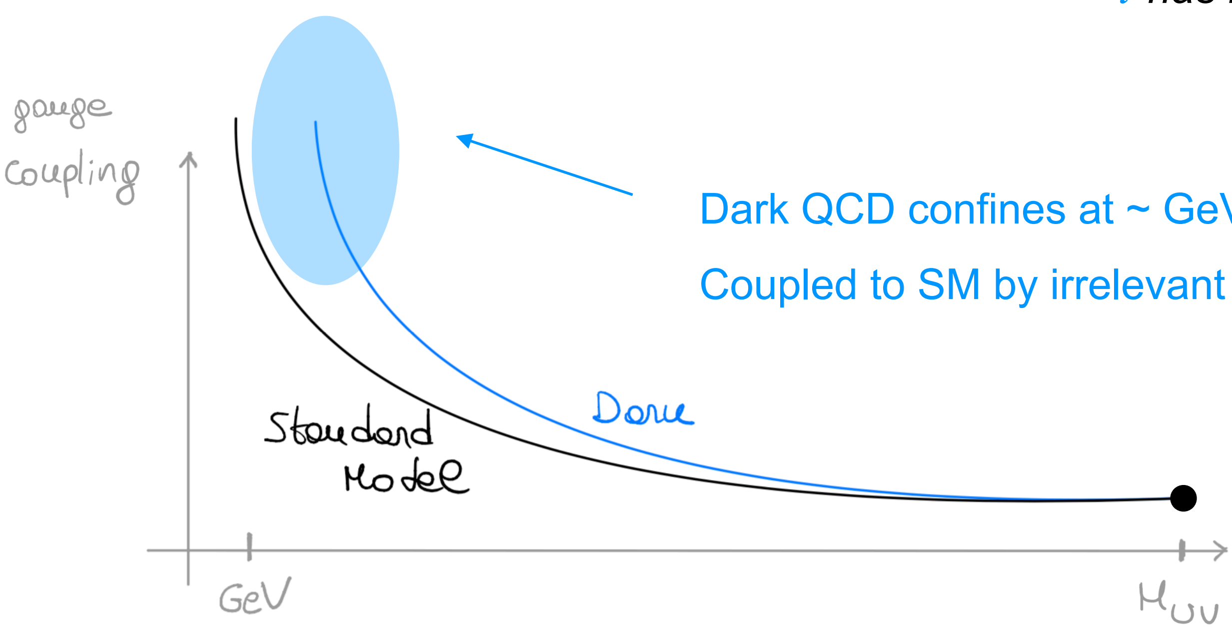
[Chacko, Goh, Harnik 2004]



$$y_t \overset{\mathbb{Z}_2}{\longleftrightarrow} \hat{y}_t$$

$\hat{t}$ has no Standard Model charges

[Cheng, Li, Salvioni, Verhaaren 2018]
[Cohen, Craig, Giudice, McCullough 2018]



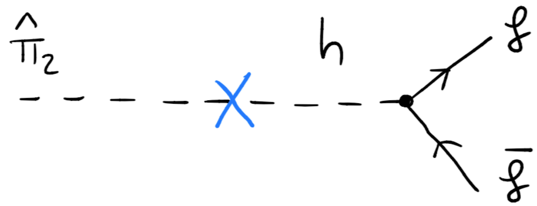
Dark QCD confines at ~ GeV

Coupled to SM by irrelevant operators $\sim \dfrac{\mathcal{O}_{\rm dark}\mathcal{O}_{\rm SM}}{M^2}$

$$g_s \overset{\mathbb{Z}_2}{\longleftrightarrow} \hat{g}_s$$

CP-even dark pion: mixing with the Higgs

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



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

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

- Light *CP*-even scalar mixed with Higgs $\rightarrow$ apply results of [Winkler, 1809.01876]

- Non-trivial interplay with dark quark mass matrix $$\boldsymbol{m}_\psi = \boldsymbol{\omega} - \frac{v^2}{2} \widetilde{\boldsymbol{Y}}^\dagger \boldsymbol{M}^{-1} \boldsymbol{Y}$$

$$\langle 0 | \overline{\psi}' \frac{i\sigma_a}{2} \gamma_5 \psi'(0) | \hat{\pi}_b(p) \rangle = -\delta_{ab} f_{\hat{\pi}} \frac{m_{\hat{\pi}_a}^2}{\text{Tr}(\boldsymbol{m}_{\psi'})}$$

$$\langle 0 | j_{5a}^\mu(0) | \hat{\pi}_b(p) \rangle = -i\delta_{ab} f_{\hat{\pi}}\, p^\mu$$

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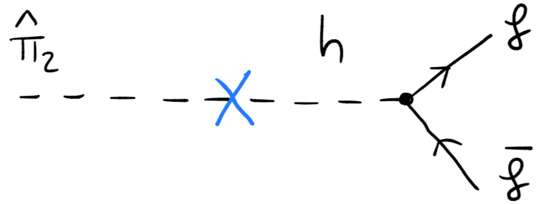

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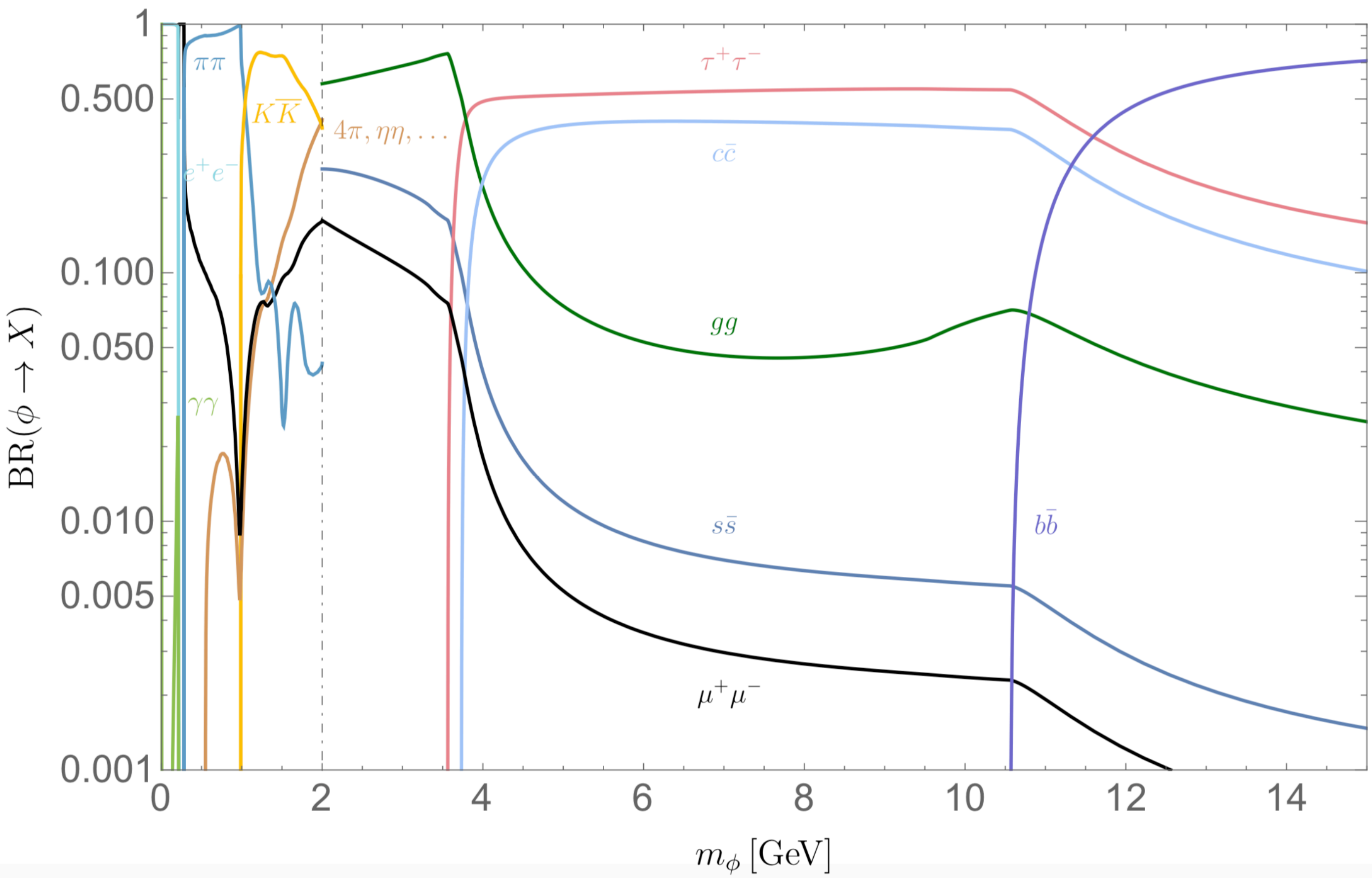
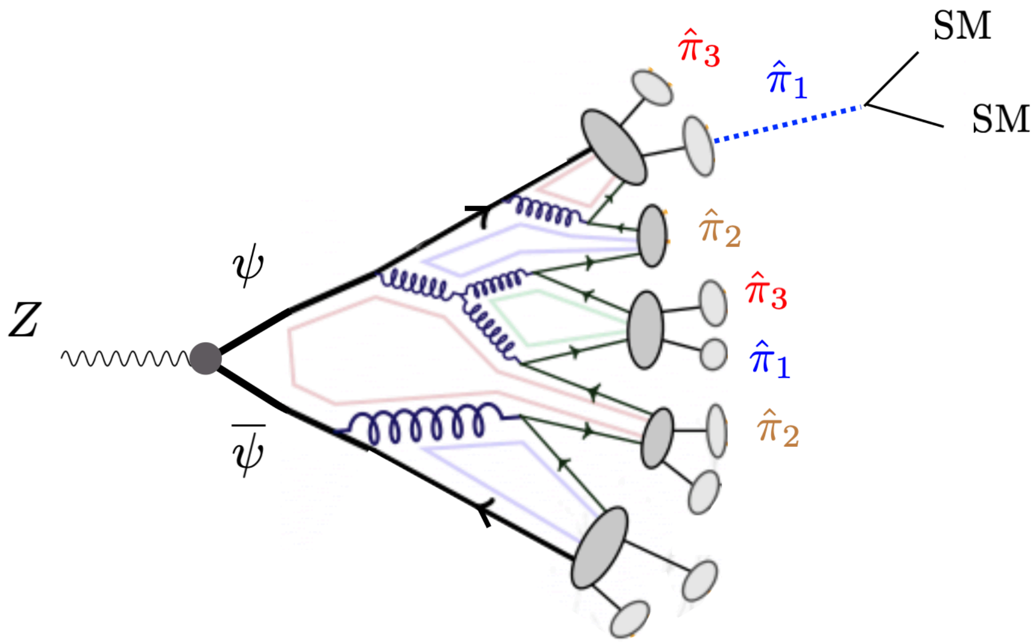


Dark showers at the LHC

$$\mathrm{BR}(Z \to \psi'\overline{\psi}') \sim 2 \times 10^{-4}\, y^4 \left(\frac{\mathrm{TeV}}{M}\right)^4$$



$> 10^{11}$ Z bosons @ HL-LHC: strong discovery potential, still mostly unexplored

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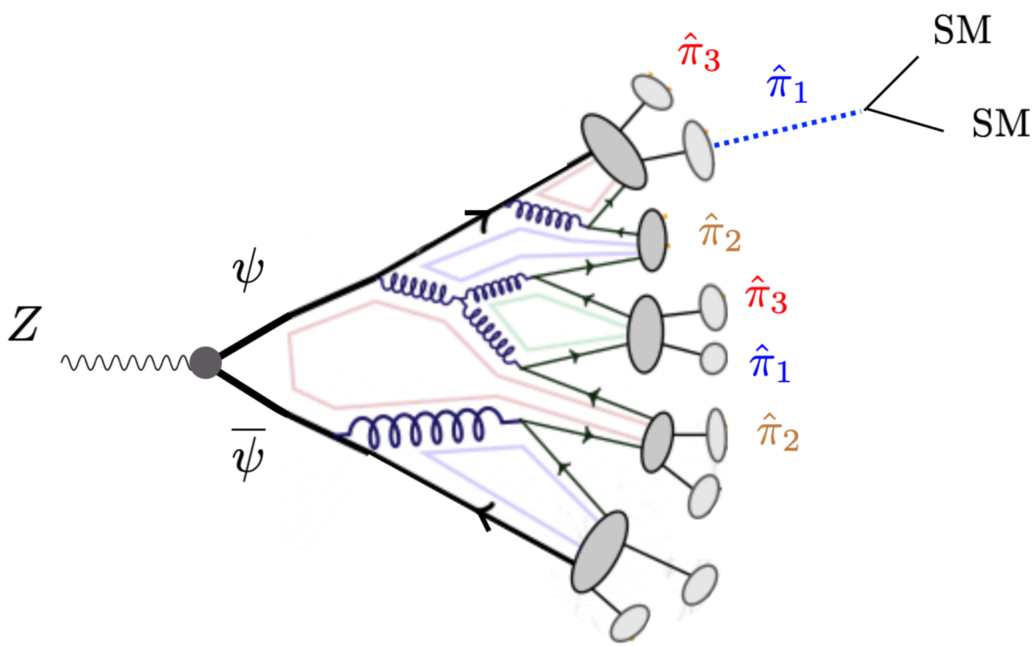


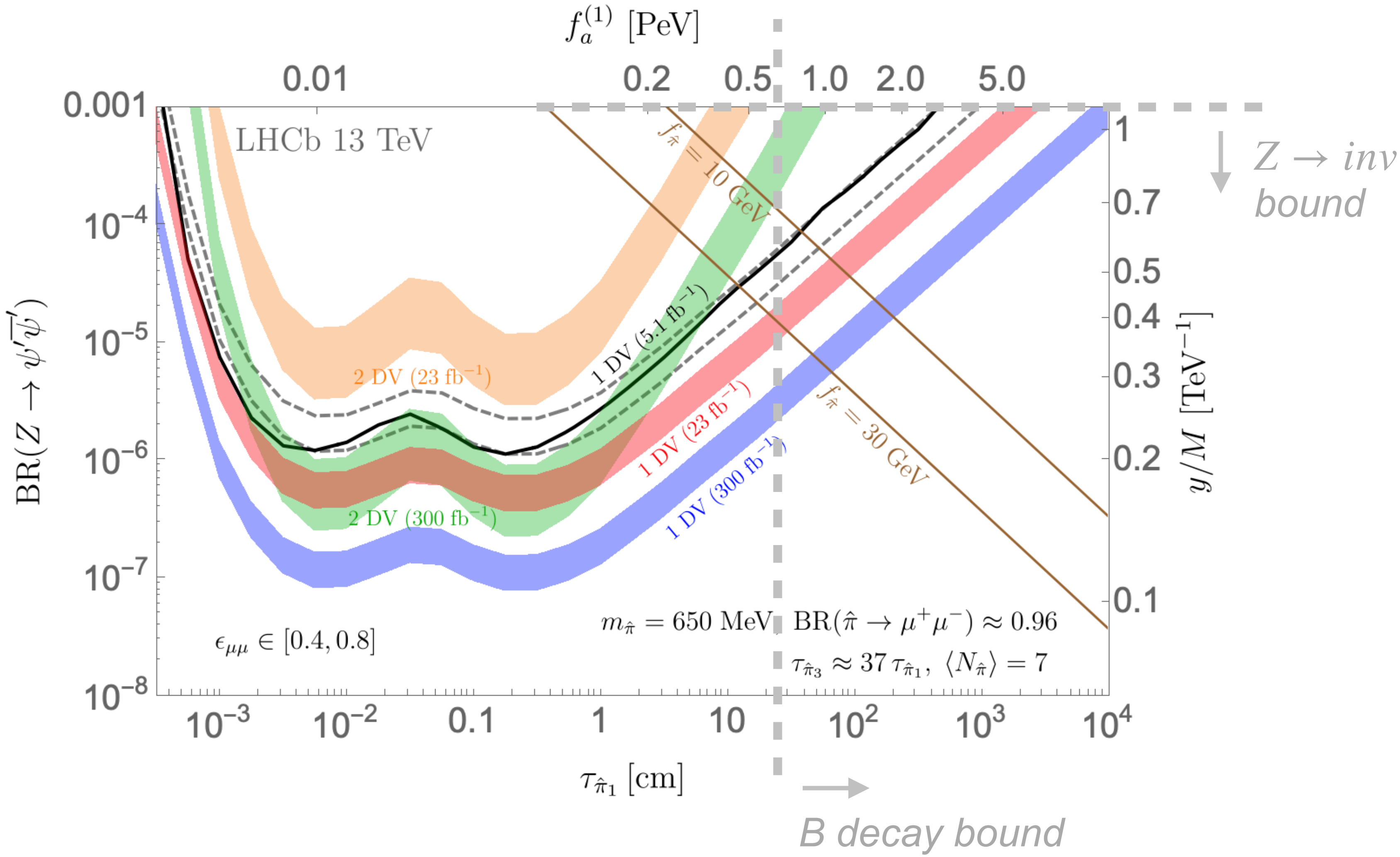
No hard SM activity automatically present (contrast to emerging jets)

To begin, focus on trigger-friendly $\hat{\pi} \to \mu^+\mu^-$

[Schwaller, Stolarski, Weiler 2015]
[CMS 2018]

Dark showers @ LHCb

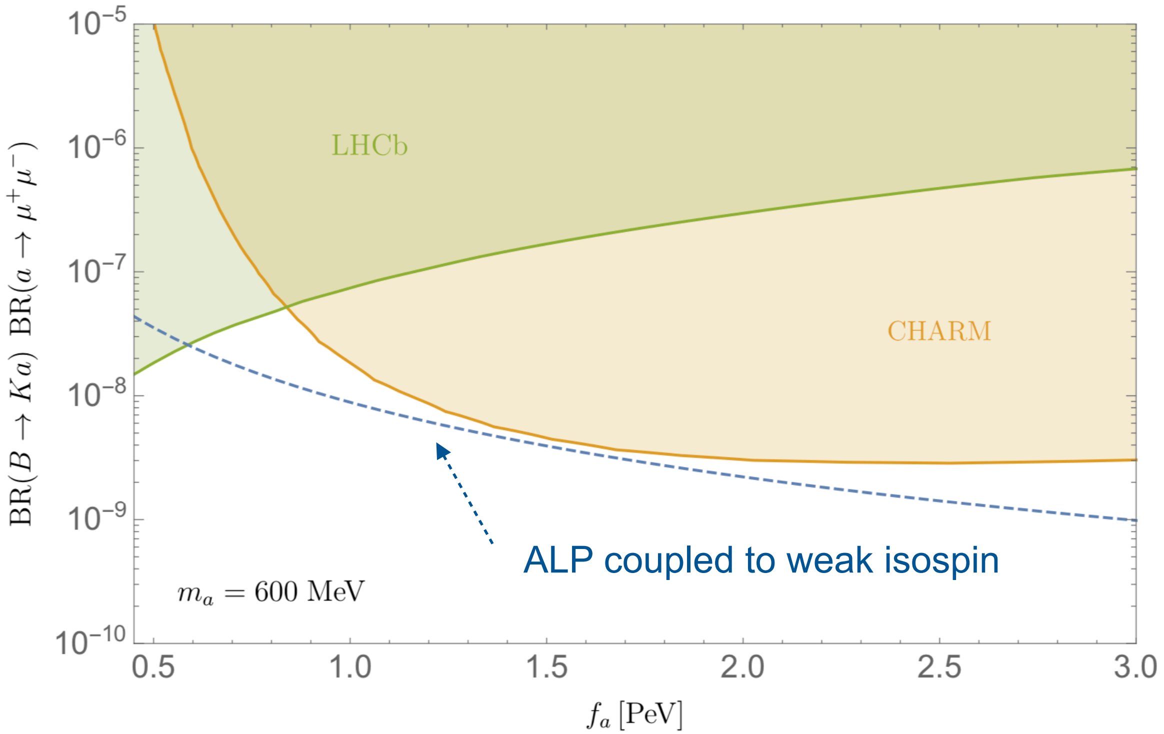
For LHCb, apply latest search for displaced $X \to \mu^+\mu^-$ [LHCb 2007.03923], including backgrounds, to project to Run 3 and high luminosity



Meson FCNC decays

- $m_a > 2m_\mu$: bounds from $B \to K^{(*)}(a \to \mu\mu)$ @ LHCb and @ CHARM beam dump

bounds from [Döbrich, Ertas, Kahlhöfer, Spadaro 2018]



$f_a \gtrsim 0.6$ PeV

Proposed LLP experiments can extend reach strongly: CODEX-b, FASER 2, MATHUSLA

$$f_a \gtrsim 8 \text{ to } 60 \text{ PeV}$$

[CODEX-b Expression of Interest 2019]