A theory of dark pions

Ennio Salvioni

University of Padua
and CERN

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2109.xxxxx
with Hsin-Chia Cheng (Davis) and Lingfeng Li (Brown)

symmetry

Theory motivation

- **Hidden sectors: light, confining,** feebly coupled to the Standard Model

  Can be part of answer to key questions:

  Little hierarchy through Neutral Naturalness, hidden hadrons as Dark Matter *

- Very relevant given current experimental status.

  Dark Sector theory motivations sharpen aim & chart progress

- **Irrelevant portals** are well motivated, yet have not received much attention

  compared to renormalizable Higgs / kinetic / ν

* see talk by Michele Redi

Experiment/pheno motivation

- Hidden valley signatures are diverse, many opportunities for progress

  LHC plays critical role, but need dedicated strategies for selection & analysis

Targets:

- maximise coverage of existing detectors, especially for “dark jet”-type signals
- assess interplay with LLP-specific proposals, and intensity frontier

- Having a **theory of dark pions** helps: coherent description
  - ✓ Dark pions are CP-odd (*composite ALPs*) or CP-even (*composite scalars*)
  - ✓ Direct link with *Z* boson decays to dark sector, strong potential

[Cheng, Li, Salvioni, 2109.xxxxx]

[Freytsis, Knapen, Robinson, Tsai 2016]
[Renner, Schwaller 2018]
[Cheng, Li, Salvioni, Verhaaren 2019]
[Contino, Max, Mishra 2020]

A theory of dark pions

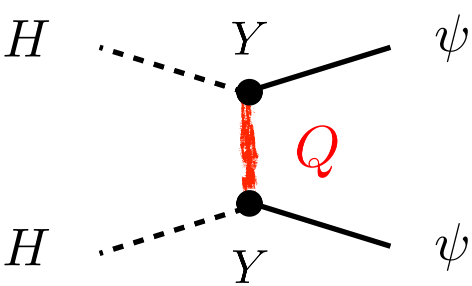
[Cheng, Li, Salvioni, 2109.xxxxx]

- $SU(N_d)$ dark QCD, confining at Λ
- N light dark quarks ψ_i , SM singlets
- N heavy dark quarks $Q_i \sim \mathbf{2}_{1/2}$ under $SU(2)_L \times U(1)_Y$

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

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

"dark pions"

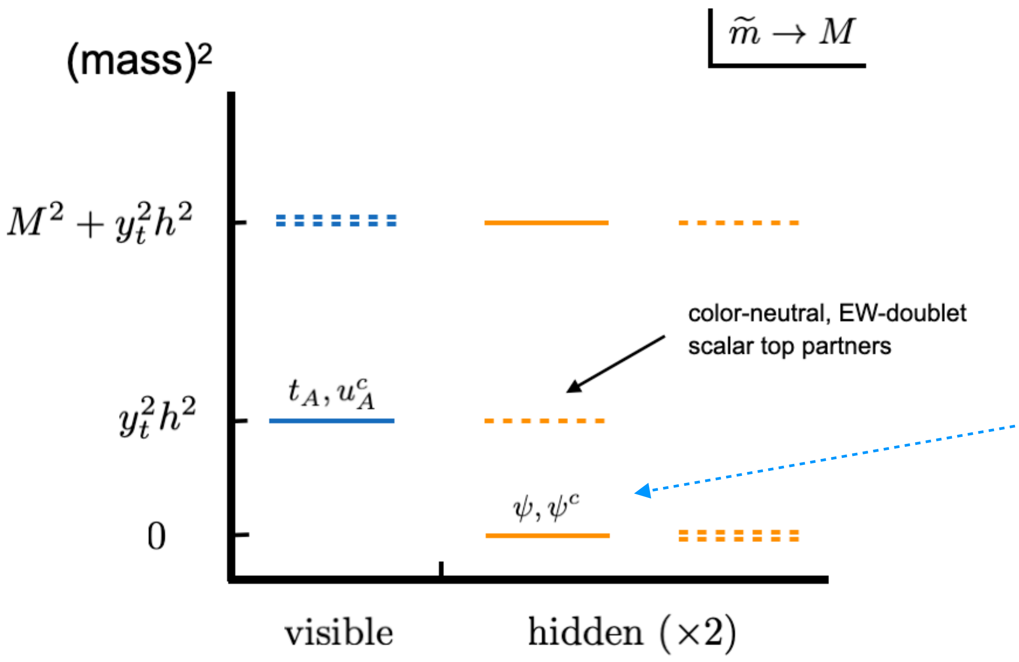


$$M \gtrsim \text{TeV}$$

heavy mediators

Ultraviolet motivation/1

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



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

light Dirac fermions

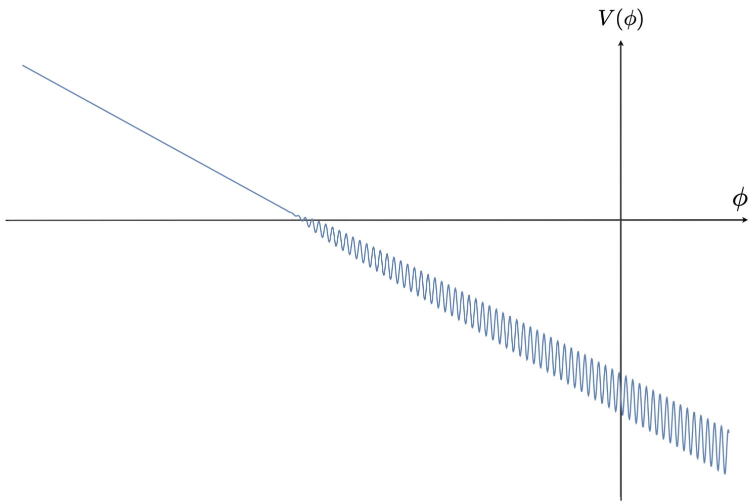
This model, with $Y = y_t$ and $\widetilde{Y} = 0$

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

Ultraviolet motivation/2

- 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 $$\Lambda^4 \sim 4\pi f_{\hat{\pi}}^3 \frac{Y\widetilde{Y}\langle h\rangle^2}{M}$$

- $N=1$ out of minimality. $N=1$ QCD is peculiar:

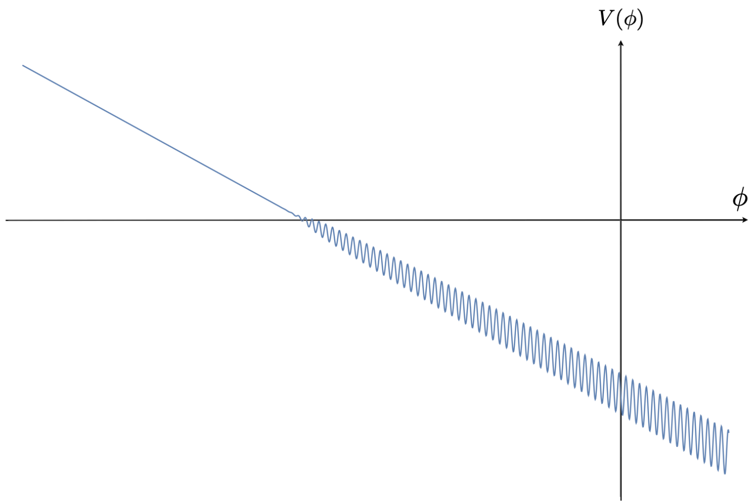
- no Goldstone bosons, spectrum fully computable (in principle) on lattice, given strong scale Λ

- vector meson decays to SM, $\rho_D \to f_{\rm SM}\bar{f}_{\rm SM}$

[Cheng, Li, Salvioni, Verhaaren 2019]

Ultraviolet motivation/2

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



[Graham, Kaplan, Rajendran, 2015]

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

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

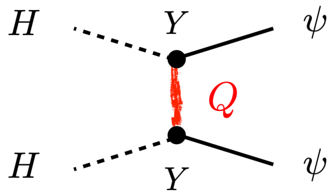
with $\quad \Lambda^4 \sim 4\pi f_{\hat{\pi}}^3 \frac{Y\widetilde{Y}\langle h\rangle^2}{M}$

- Setup is common to different approaches to Higgs naturalness

➡ compelling choice to study theory of dark pions ($N > 1$)

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

Tree-level quark EFT



- Integrate out heavy fermions Q

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

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

Z portal @ dim-6, Higgs portal @ dim-5:

$\widetilde{Y} \sim 0$ and $\widetilde{Y} \sim Y$ give very different parametrics

(when $\widetilde{Y} \sim Y,$ important correction to light quark masses, too)

Tree-level quark EFT

- Integrate out heavy fermions Q

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

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

$$\Gamma(Z \to \psi\overline{\psi}) < 2\ \text{MeV} \quad \Rightarrow \quad M \gtrsim 0.7\ \text{TeV} \left(\frac{N_d \text{Tr}(\boldsymbol{Y}\boldsymbol{Y}^\dagger \boldsymbol{Y}\boldsymbol{Y}^\dagger) + (\boldsymbol{Y} \to \widetilde{\boldsymbol{Y}})}{3} \right)^{1/4}$$

(LEP+SLD)

$$\text{BR}(h \to \psi\overline{\psi}) < 0.13 \quad \Rightarrow \quad M \gtrsim 0.4\ \text{TeV} \left(\frac{N_d \text{Tr}(\boldsymbol{Y}\boldsymbol{Y}^\dagger \widetilde{\boldsymbol{Y}}\widetilde{\boldsymbol{Y}}^\dagger)}{3 \times 10^{-4}} \right)^{1/2}$$

(ATLAS 2020)

$M \sim \text{TeV}$:

Z bound allows Y or $\widetilde{Y} \sim 1$

h bound allows $Y \sim \widetilde{Y} \sim 0.1$

Dark pion decays

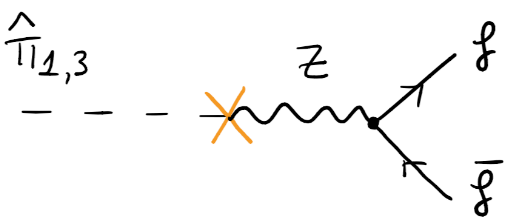
[Cheng, Li, Salvioni, 2109.xxxxx]

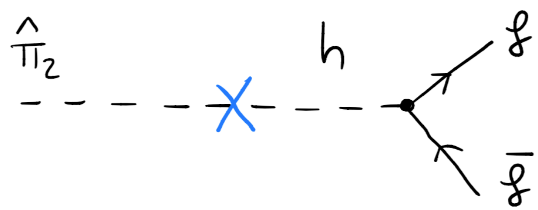
- Integrate out heavy fermions Q

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

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

- $N = 2$ flavors, $\hat{\pi}_a \sim \overline{\psi}' i \sigma_a \gamma_5 \psi'$



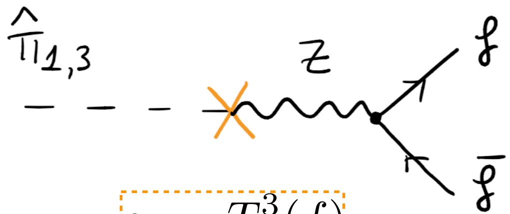


$J^{PC} = 0^{-+}$ $\qquad\qquad$ $J^{PC} = 0^{--}$

(in general, no dark $U(1)$ $\rightarrow$ $\hat{\pi}_{1,2}$ are distinct states)

Dark pions as composite ALPs

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



$$c_f = T^3_L(f)$$

$$\mathcal{L}_{\rm eff} \sim \frac{\partial_\mu \hat{\pi}}{f_a} \sum_f c_f \bar{f} \gamma^\mu \gamma_5 f$$

$$f_a^{(1)} \sim f_a^{(3)} \sim \frac{M}{Y}\frac{M}{Y f_{\hat{\pi}}} \sim 10^3 \text{ TeV} \left(\frac{M/Y}{\text{TeV}}\right)^2 \left(\frac{\text{GeV}}{f_{\hat{\pi}}}\right)$$

decay constant = not a physical scale, combination of underlying parameters

- Light ALPs coupled to SM fermions

  Need detailed description of hadronic decays for $m_a \lesssim 3$ GeV

- Extend data-driven methods of [Aloni, Soreq, Williams 1811.03474]

  Match to ChPT below 1 GeV; include scalar, vector, tensor resonances for 1-3 GeV

  Arbitrary couplings to SM fermions

Exclusive decays of light ALPs: calculation

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

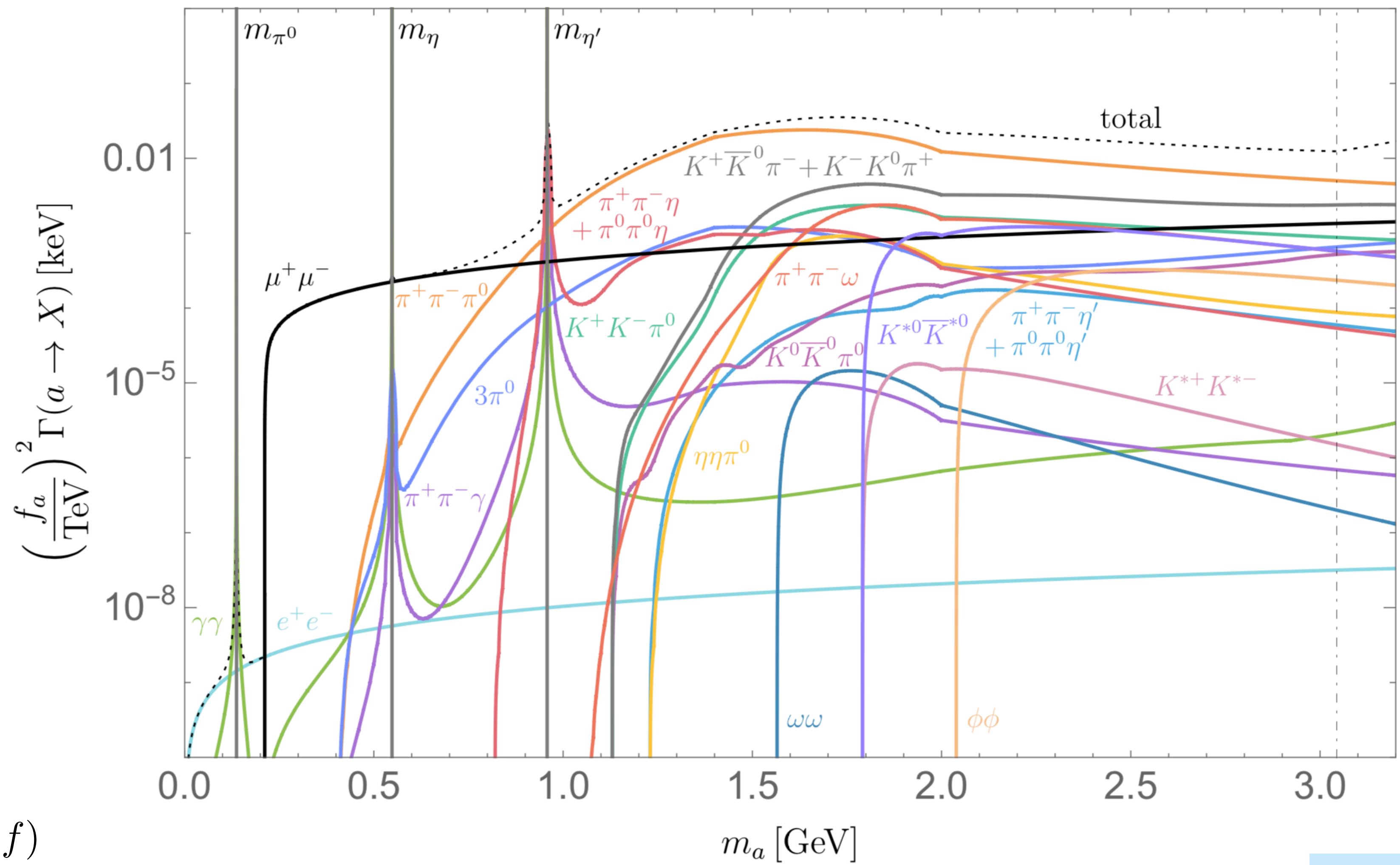
Appendix with easy-to-use, general results

[Cheng, Li, Salvioni, 2109.xxxxx]

Exclusive decays of light ALPs: results

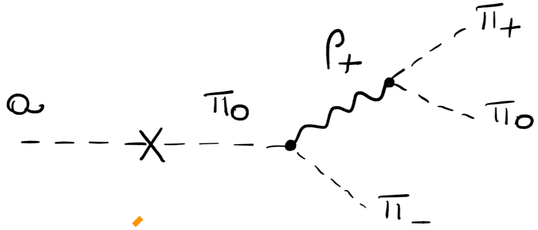
$$\mathcal{L}_a = \frac{1}{2}(\partial_\mu a)^2 - \frac{1}{2}m_a^2 a^2 - \frac{\partial_\mu a}{f_a}\sum_f c_f \bar{f}\gamma^\mu\gamma_5 f$$

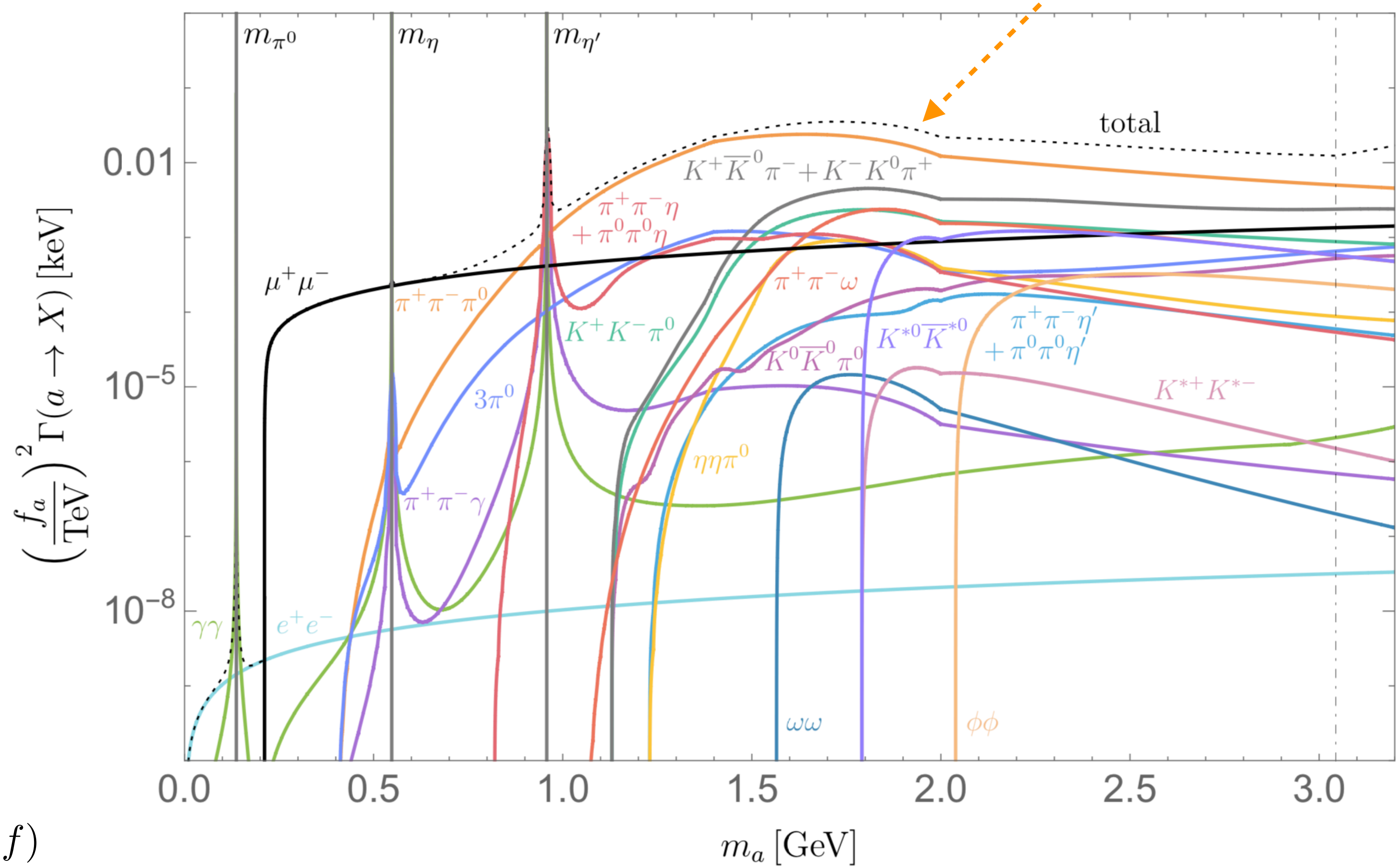
[Cheng, Li, Salvioni, 2109.xxxxx]



$c_f = T_L^3(f)$

Exclusive decays of light ALPs: results

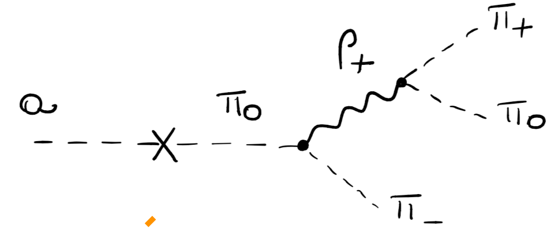


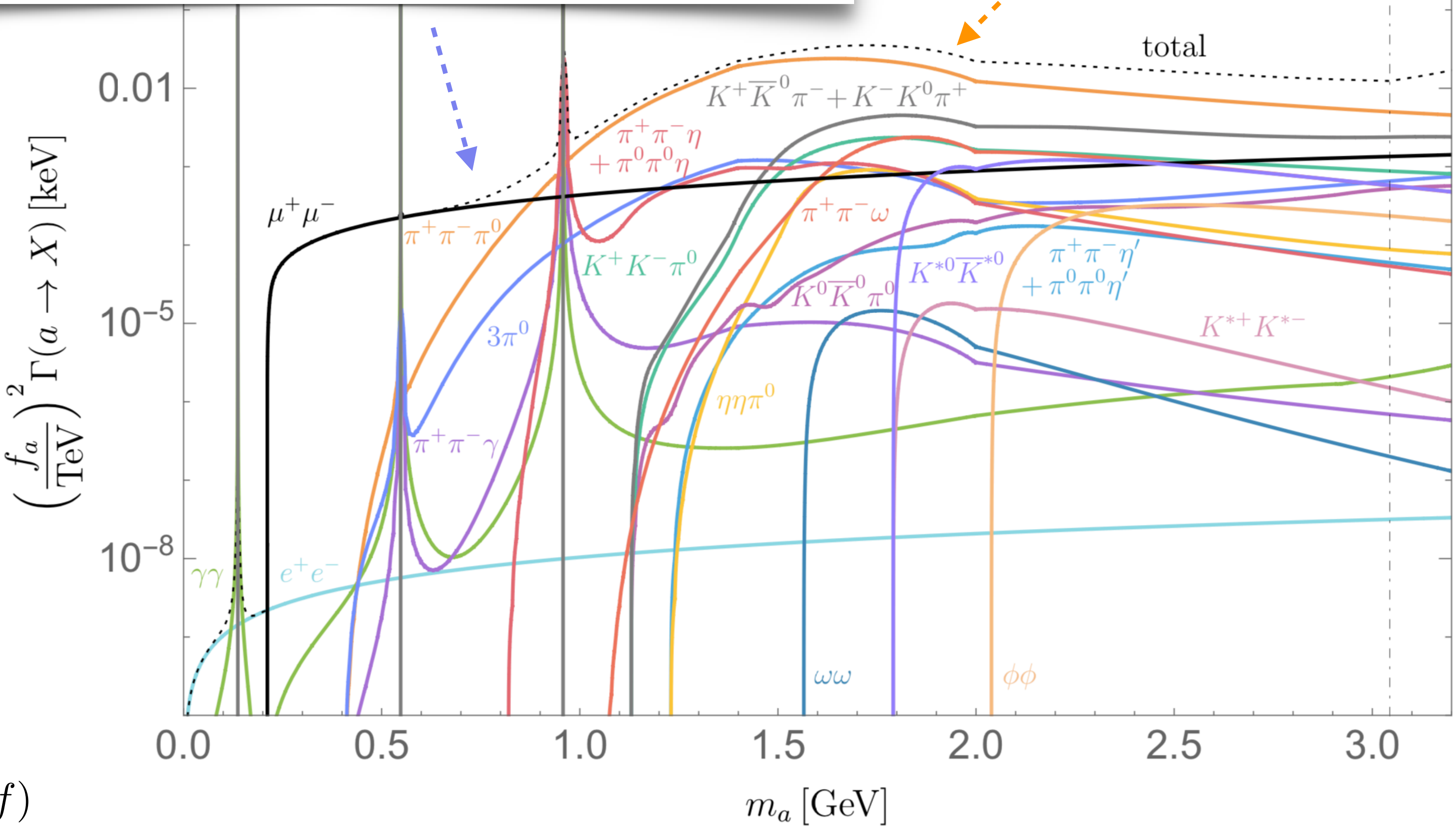


$c_f = T_L^3(f)$

Exclusive decays of light ALPs: results

- ALP has nontrivial $U(3)$ representation up to 3 GeV, $a \to P(V \to PP)$ dominates
- No $\rho_0\pi_0\pi_0$ coupling $\to$ $\Gamma(a \to 3\pi_0) \ll \Gamma(a \to \pi_+\pi_-\pi_0)$
- Very different pattern from other known models





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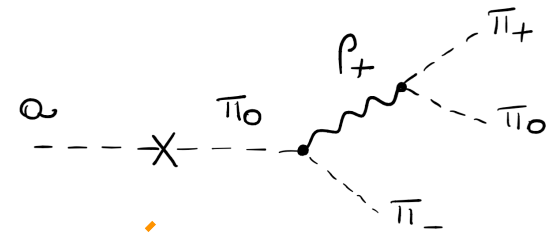
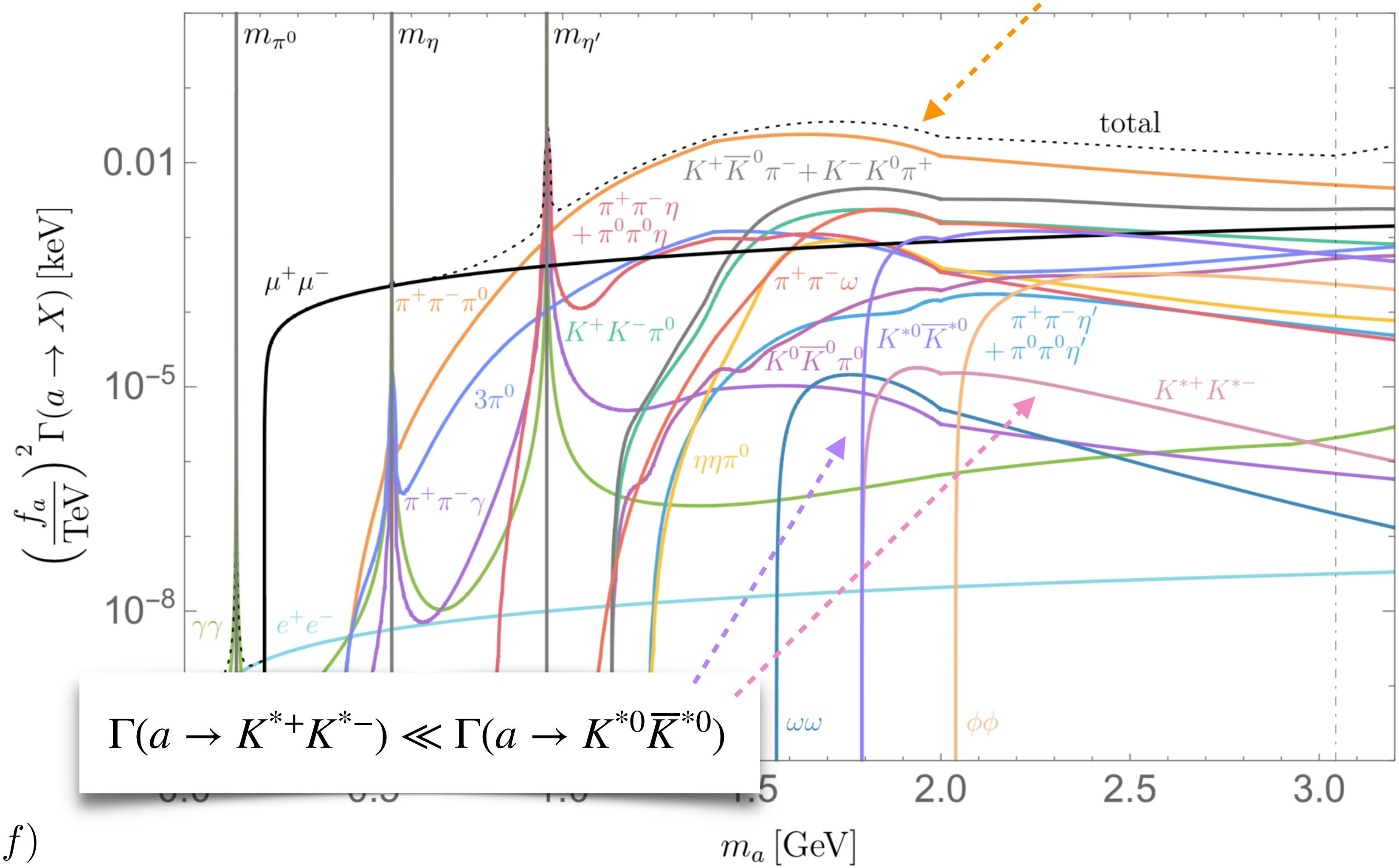
Exclusive decays of light ALPs: results



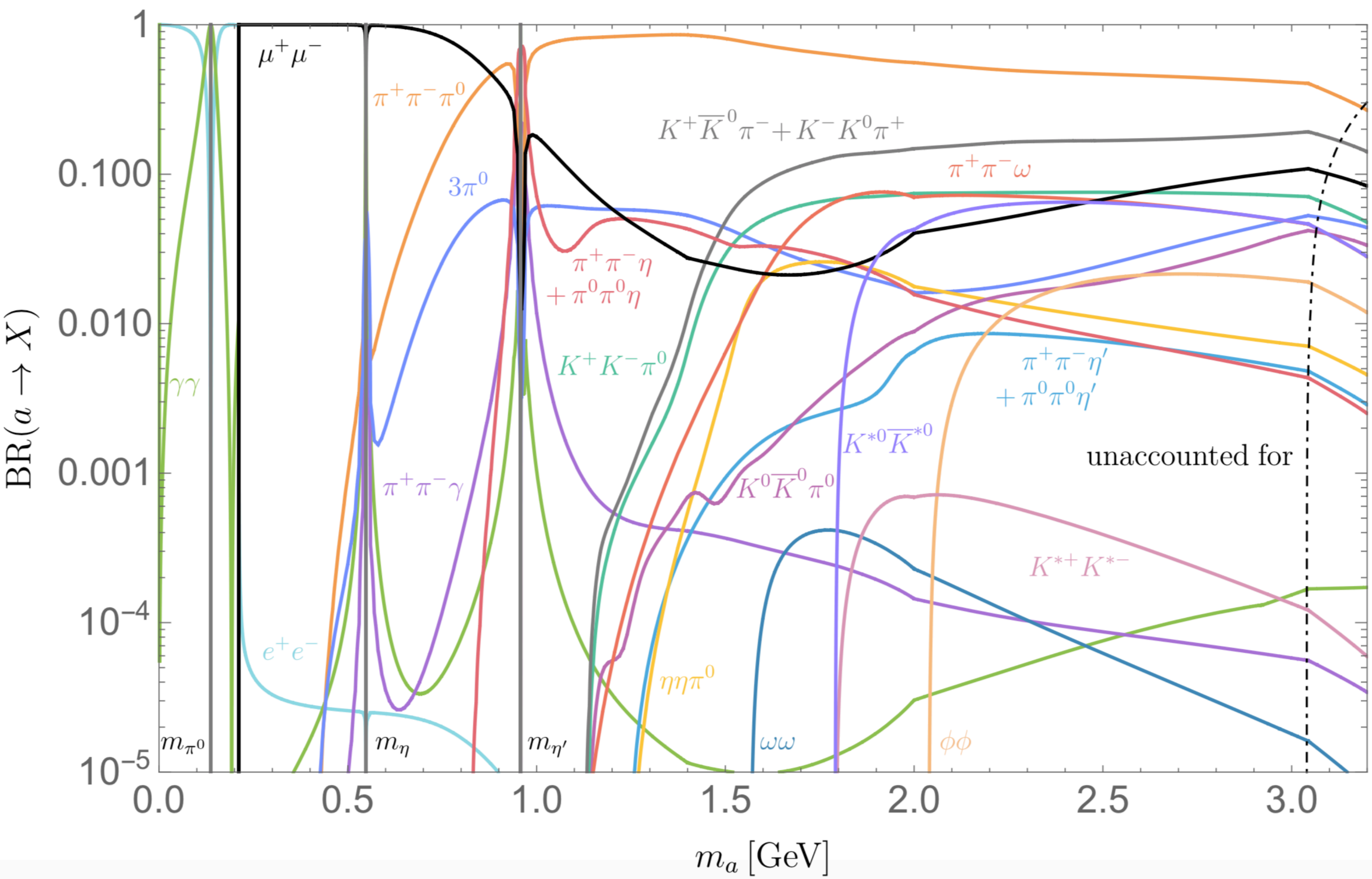


$$\Gamma(a \to K^{*+}K^{*-}) \ll \Gamma(a \to K^{*0}\overline{K}^{*0})$$

$c_f = T_L^3(f)$

Branching ratios

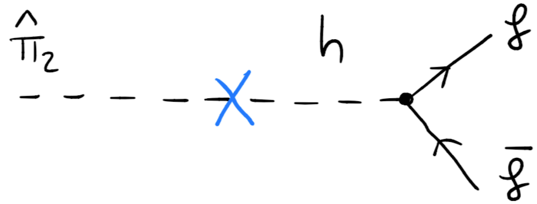
$$\mathcal{L}_a = \frac{1}{2}(\partial_\mu a)^2 - \frac{1}{2}m_a^2 a^2 - \frac{\partial_\mu a}{f_a}\sum_f c_f \bar{f}\gamma^\mu\gamma_5 f$$



$c_f = T_L^3(f)$

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 $\quad \boldsymbol{m}_\psi = \boldsymbol{\omega} - \frac{v^2}{2} \widetilde{\boldsymbol{Y}}^\dagger \boldsymbol{M}^{-1} \boldsymbol{Y}$

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

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

CP-even dark pion: mixing with the Higgs

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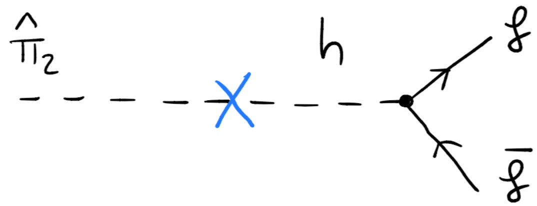

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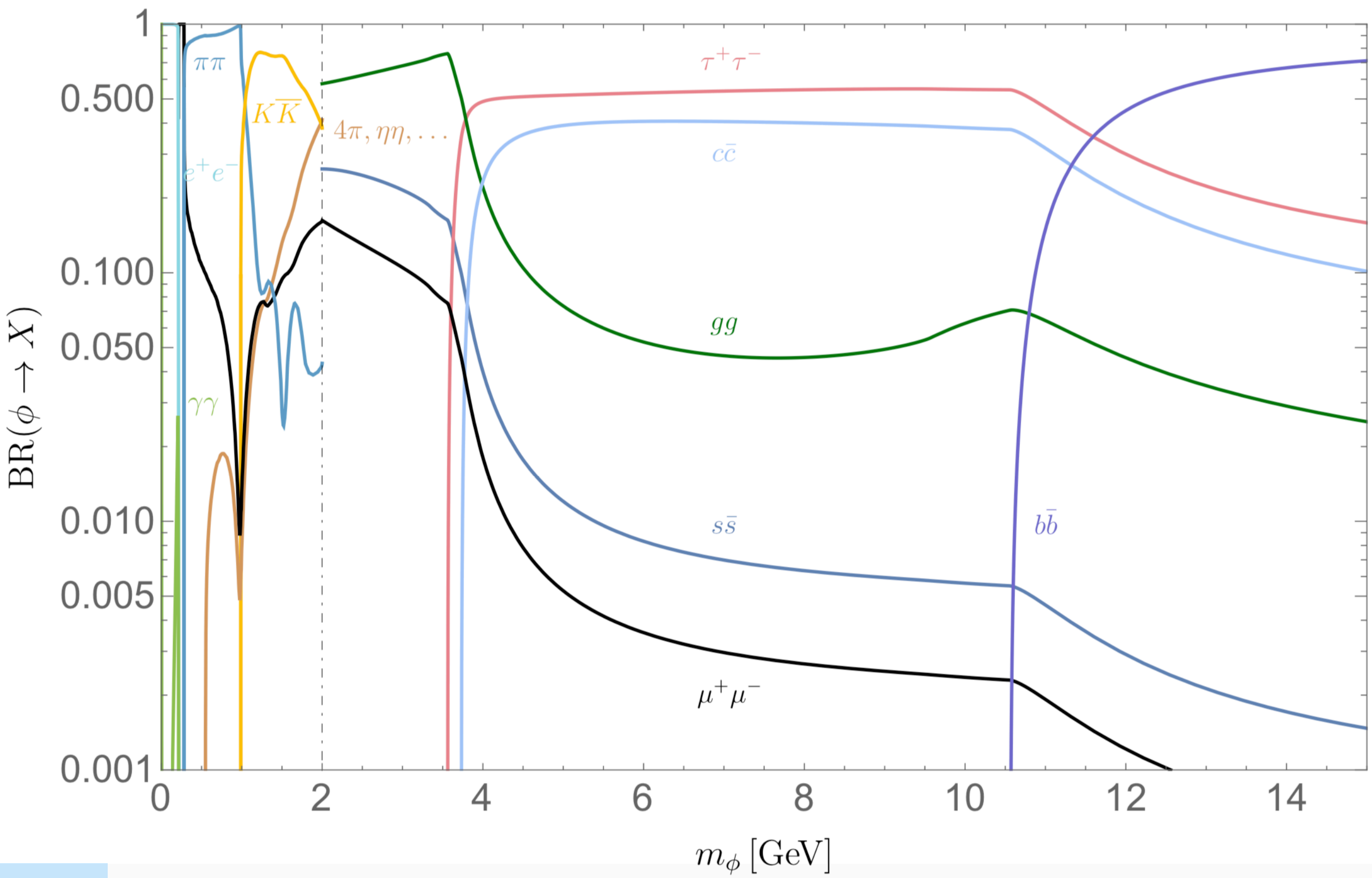

Case study: model with $\widetilde{Y} = 0$

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

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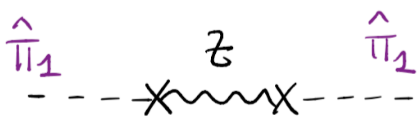
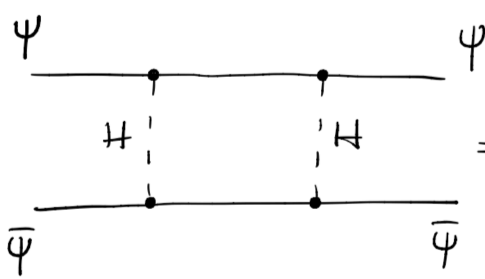
- No constraints from Higgs invisible decays
- $(N-1)^2$ phases $\rightarrow$ for $N = 2$, $\quad \boldsymbol{Y} = \begin{pmatrix} y_{11} & y_{12} e^{i\alpha} \\ y_{21} & y_{22} \end{pmatrix}$
- All pions decay through Z portal; $\hat{\pi}_2$ via *CP*-violating mixing with $\hat{\pi}_1$



$$\Rightarrow -\frac{f_{\hat\pi}^2 v^2}{32}\left(\mathrm{Tr}\left[\sigma_1 Y^\dagger M^{-2} Y\right]\partial_\mu \hat\pi_1\right)^2$$



$$\Rightarrow -\frac{f_{\hat\pi}^2}{32\pi^2}\mathrm{Tr}\left[\sigma_1 Y^\dagger M^{-2} Y\right]\mathrm{Tr}\left[\sigma_2 Y^\dagger Y\right]\partial_\mu \hat\pi_1 \partial^\mu \hat\pi_2$$

Case study: model with $\widetilde{Y} = 0$

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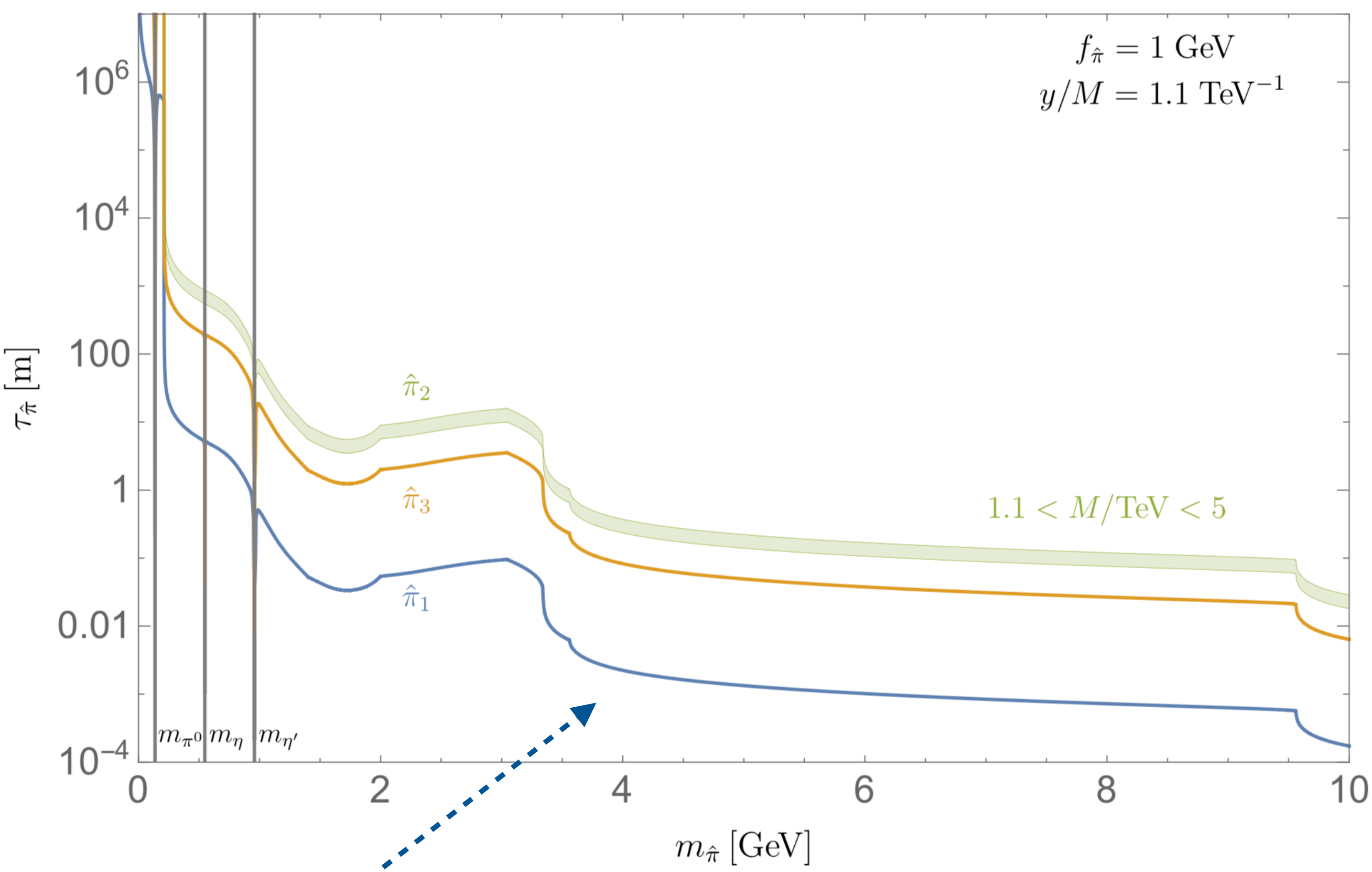
- All pions decay through *Z* portal; $\hat{\pi}_2$ via *CP*-violating mixing with $\hat{\pi}_1$

For generic texture:

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

3 free parameters: $y/M, \quad f_{\hat{\pi}}, \quad m_{\hat{\pi}}$

Case study: model with $\widetilde{Y} = 0$

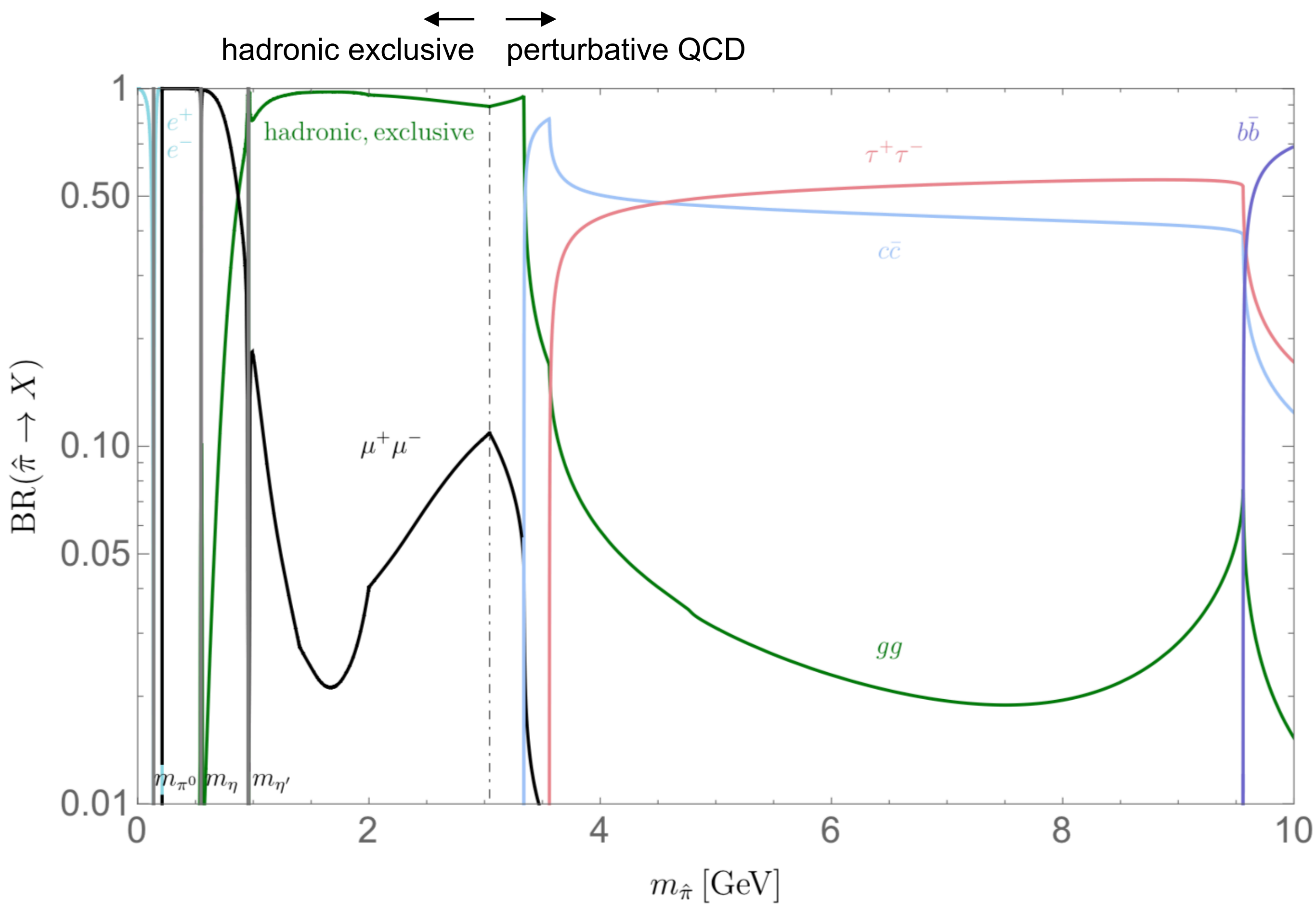


$$f_a^{(1)} \approx 2.5 \text{ PeV} \sim f_{\hat\pi}^{-1}(y/M)^{-2}$$

$c\tau$ between 10 meters and 1 millimeter

Excellent LLP target

Case study: model with $\widetilde{Y} = 0$



Focus on $\hat{\pi} \to \mu^+\mu^-$ here, but much more to do

$\pi^+\pi^-\pi^0$

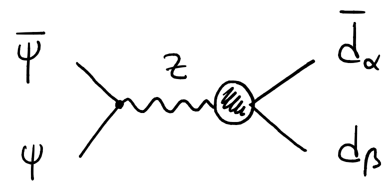
$K^{*0}\overline{K}^{*0} \to (K^+\pi^-)(K^-\pi^+)$

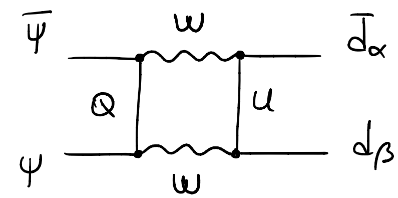
$KK\pi$

...

Meson FCNC decays

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





- Amplitude can be fully adapted from $d\bar{s} \to \nu\bar{\nu}$ results in [Inami, Lim 1980]

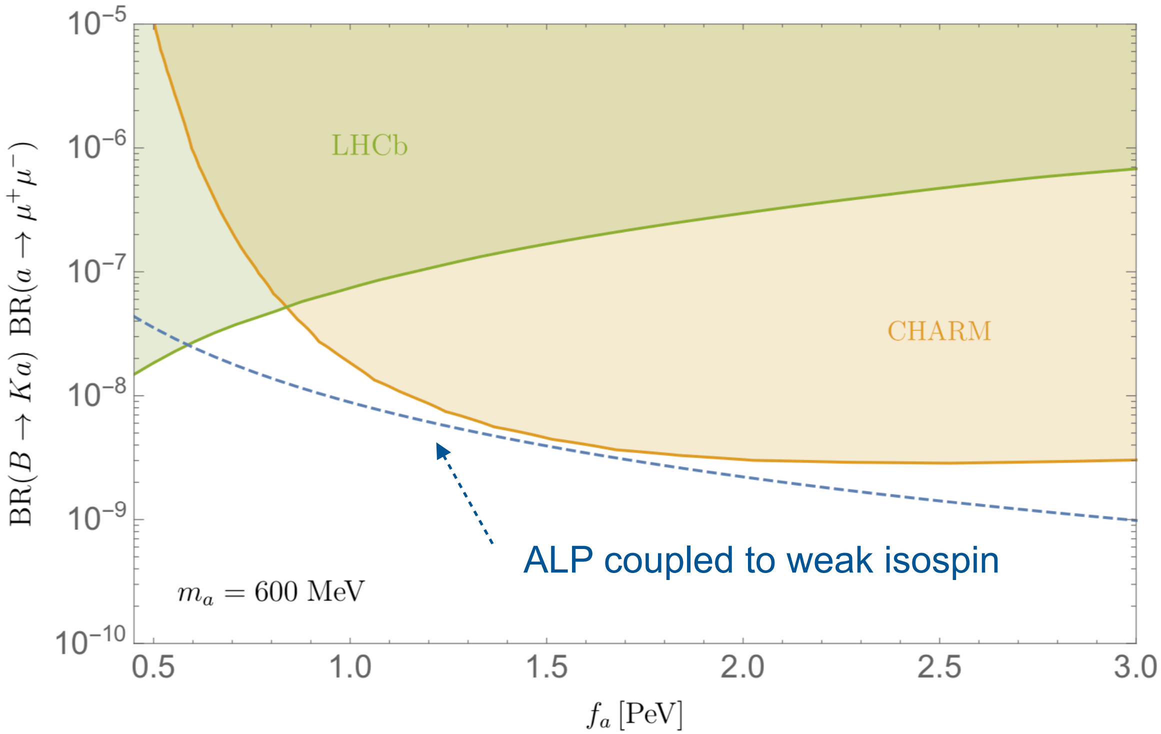
$$\Gamma(B \to K\hat{\pi}_a) = \frac{m_B^3}{64\pi} f_0(m_{\hat{\pi}}^2)^2 \left| \frac{g^2 V_{ts}^* V_{tb}}{64\pi^2 f_a^{(a)}} \left[\frac{m_t^2}{m_W^2} \left(\log \frac{M^2}{m_t^2} - 2 \right) + 3 \right] \right|^2 \left(1 - \frac{m_K^2}{m_B^2} \right)^2 \lambda_{K\hat{\pi}}^{1/2}$$

small hierarchy of scales, finite terms important (factor ~ 3 in rate)

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

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]

$$f_a \gtrsim 0.6 \text{ PeV}$$

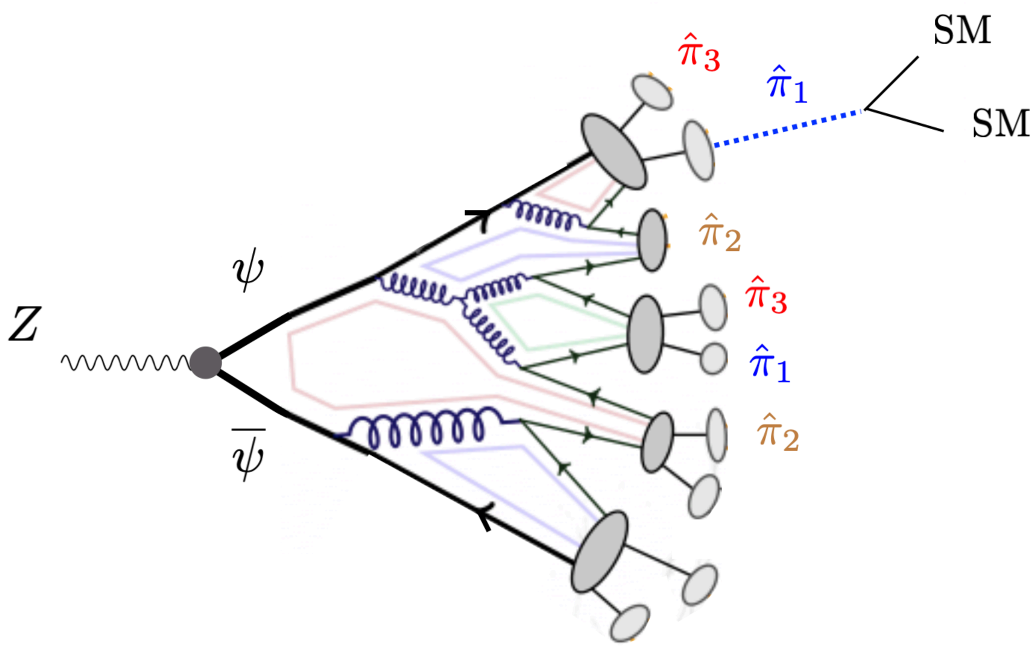
Proposed LLP experiments can extend reach strongly: CODEX-b, FASER 2, MATHUSLA

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

[CODEX-b Expression of Interest 2019]

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

Dark showers at the LHC

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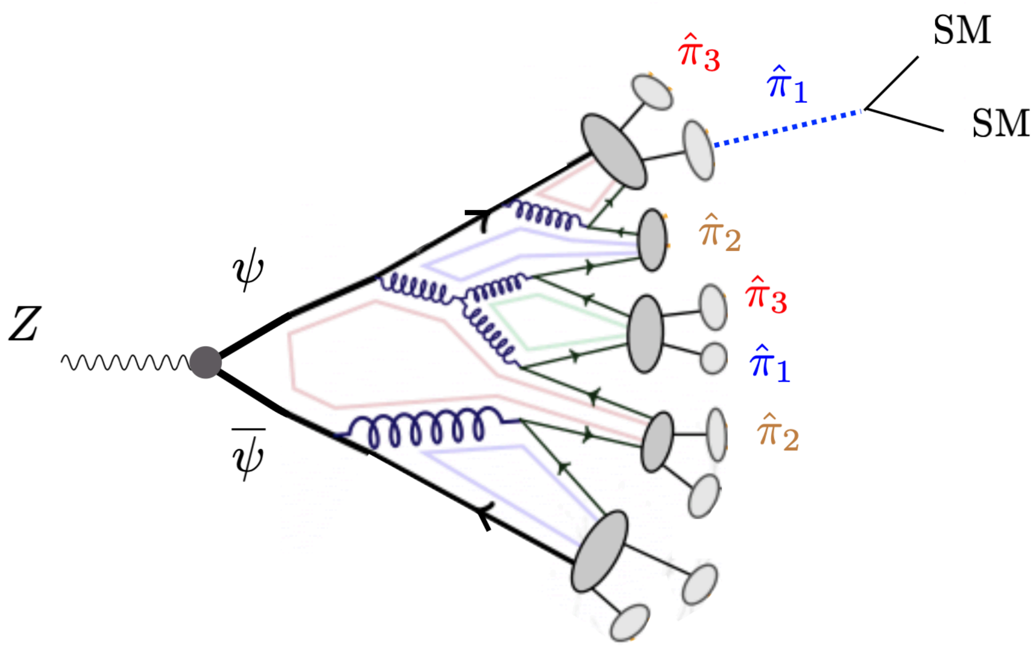


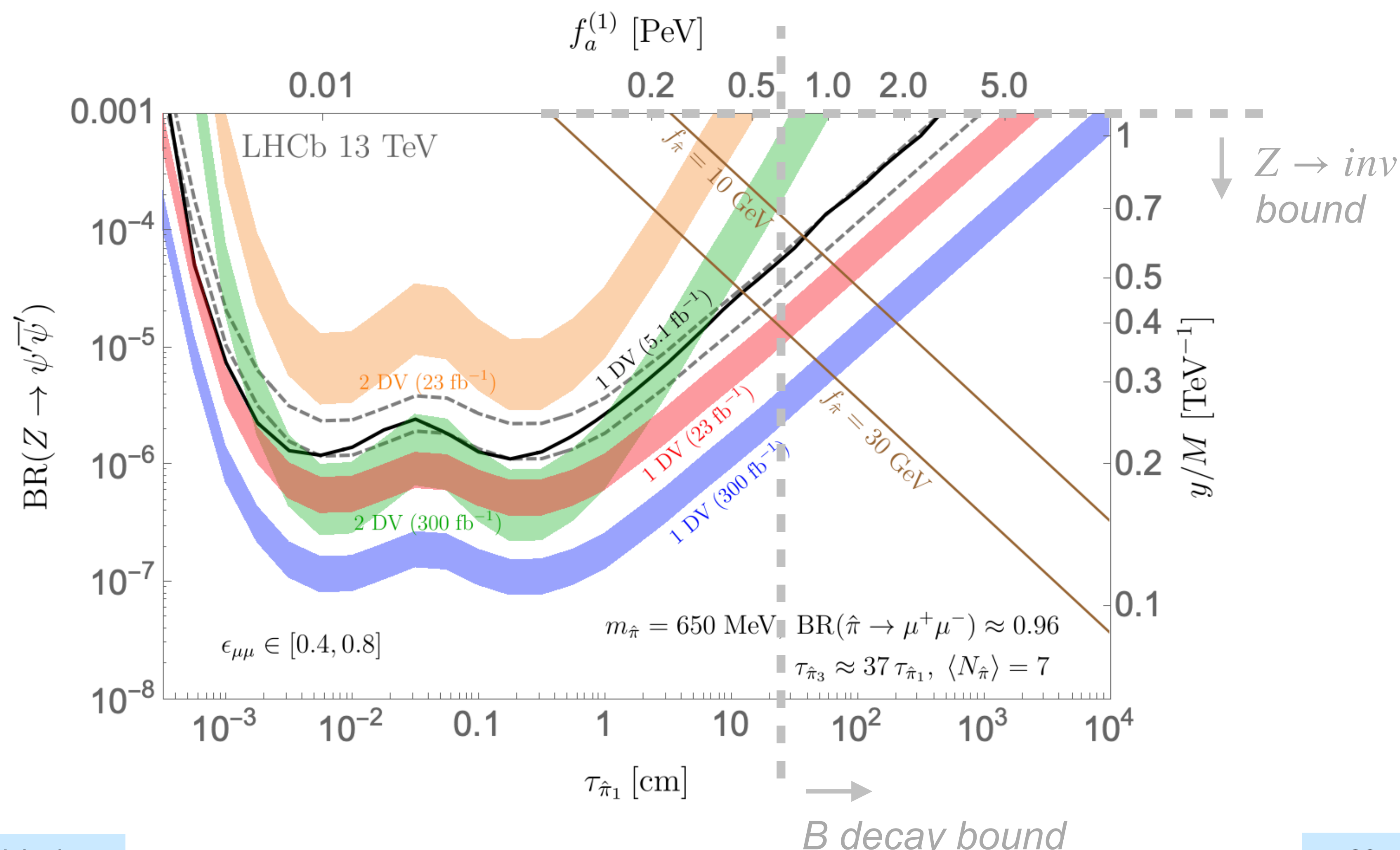
No hard SM activity automatically present (contrast to emerging jets)

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

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

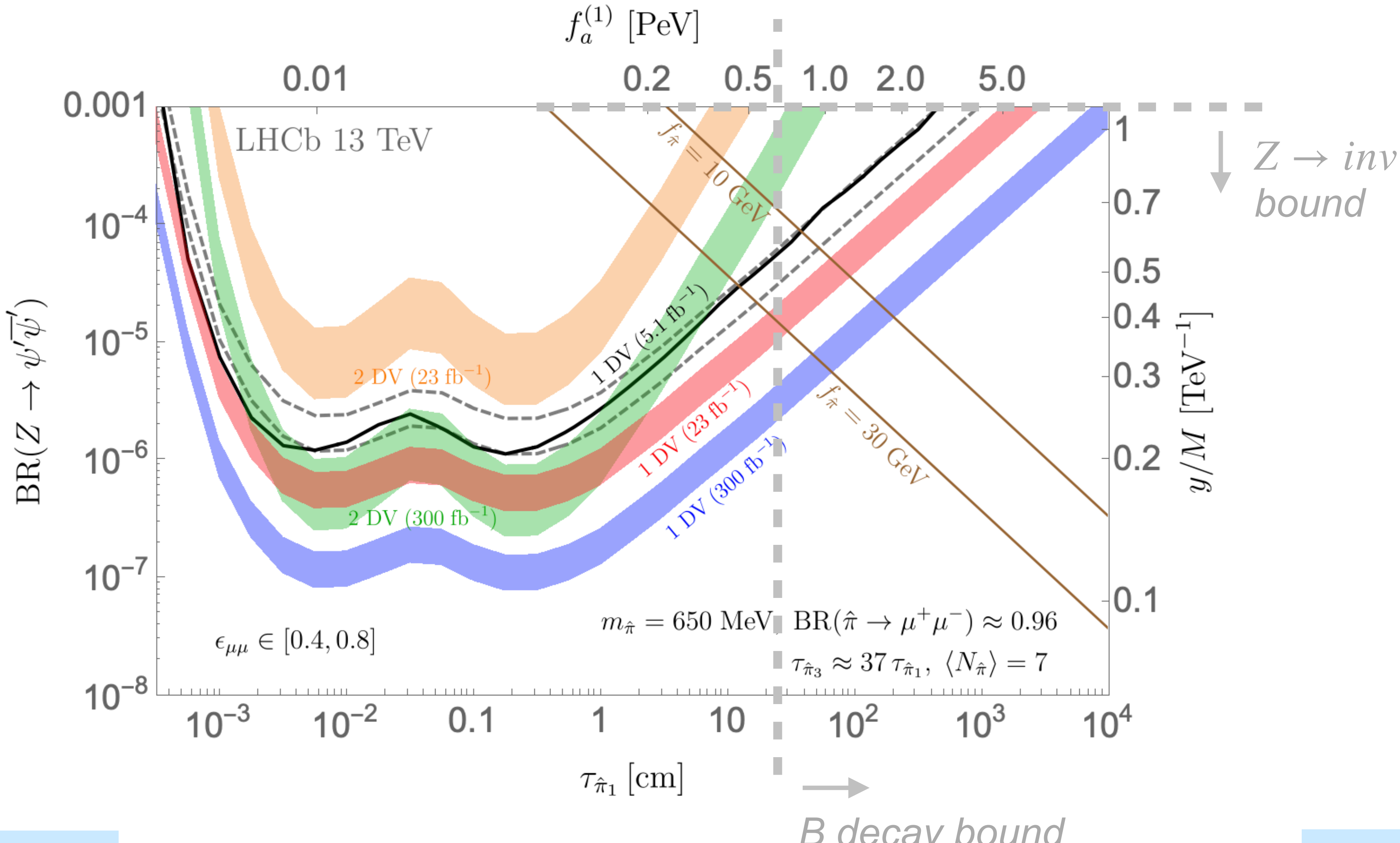
Dark showers @ LHCb

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



Dark showers @ LHCb

$Z \to$ dark jets probes new direction in parameter space



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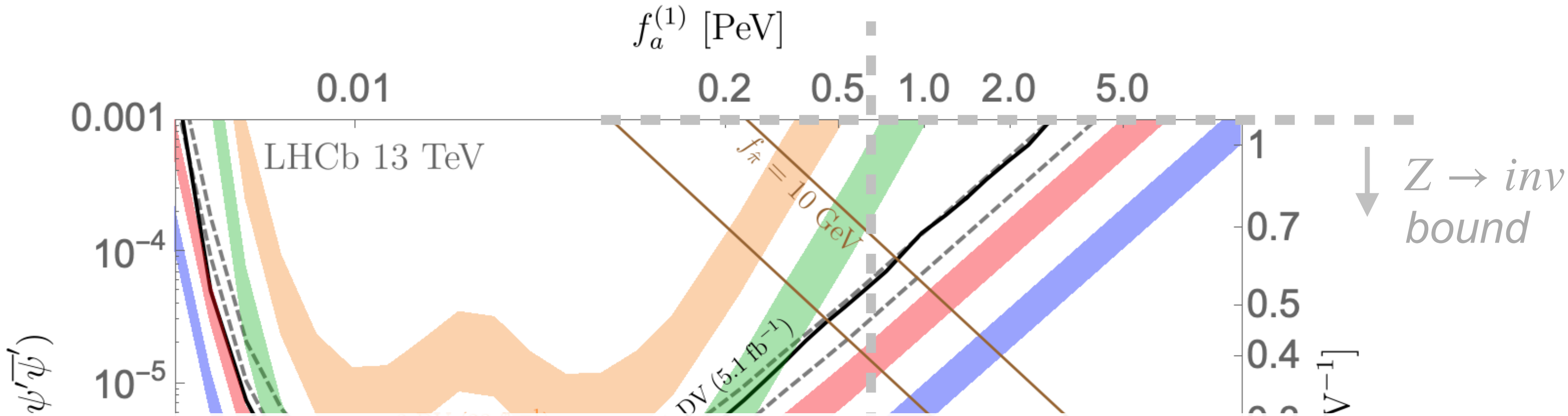


- For ATLAS and CMS, sensitivity studies are more complex (separate paper)

@ CMS, data scouting for displaced dimuons is qualitative change [CMS PAS EXO-20-014]

Very low p_T and $m_{\mu\mu}$ become accessible, exploit volume and luminosity

($l_{xy} < 11$ cm at trigger level)

Summary and plans

- Theory of dark pions, coherent framework motivated by naturalness ideas.
  Integrate out heavy fermion mediators $\rightarrow$ irrelevant Z and h portals

- Dark pions are automatically LLPs in testable parameter range

- Just scratched the pheno: dark showers @ ATLAS and CMS,
  hadronic dark pion decays, intensity frontier signatures … all to be done

- Most advanced calculation to date of exclusive ALP decays in $m_a \lesssim 3\ \mathrm{GeV}$ range,
  (arbitrary couplings to SM fermions)

Supplementary material

Theory motivation

- Irrelevant portals: less exotic than one may think

Interesting analogy with **neutrinos:**

"Hidden sector" coupled feebly to already-known particles.

W and *Z* are "heavy mediators" giving higher-dim operators at low energies

$$\mathcal{L}_6 \sim \frac{g_Z^2}{m_Z^2} \bar{\nu}\gamma^\mu \nu \bar{e}\gamma_\mu e$$

Theoretical proposal 1930 (Pauli)

Experimental discovery 1956 (Cowan & Reines)

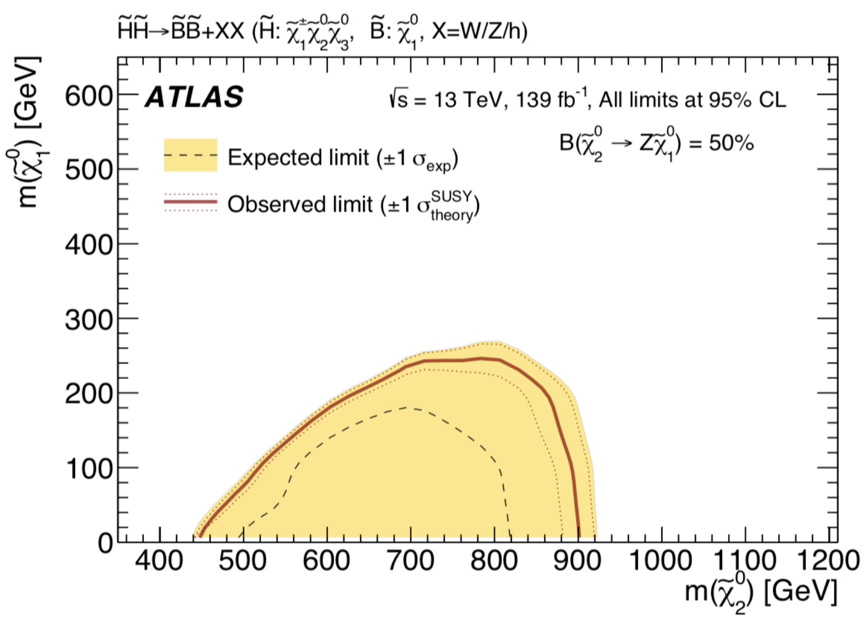
Mediators produced on shell 1983 (UA1 & UA2) $\ldots$

[Contino, Max, Mishra 2012.08537]

Direct searches for heavy mediators?

$$u\bar{d} \to W^* \to Q_u \overline{Q}_d \to (W^+\psi)(Z\psi) \quad \text{or} \quad (W^+\psi)(Z\psi)$$

If dark jets are invisible: ~ Higgsino bounds for very light neutralino LSP



(d) $(\widetilde{H}, \widetilde{B})$ with $\mathcal{B}(\tilde\chi_2^0 \to Z\tilde\chi_1^0) = 50\%$

All-hadronic + MET at ATLAS:

$$M \gtrsim 1.1\ \text{TeV}$$

[ATLAS 2108.07586]

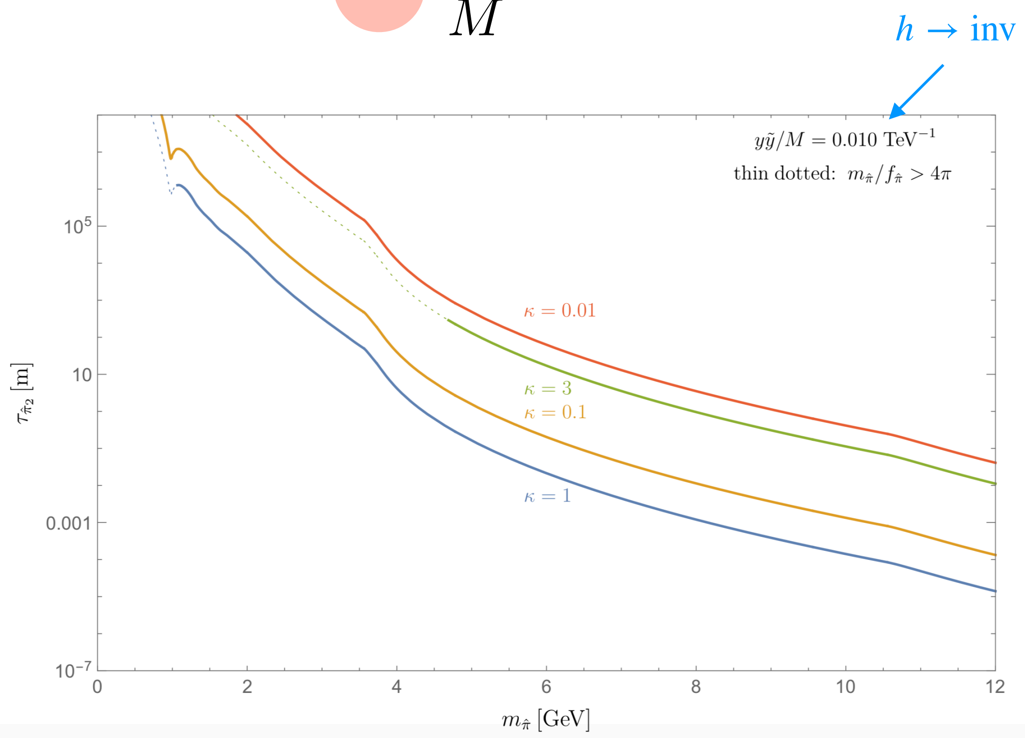
(HL-LHC estimate: $M \gtrsim 1.3$ TeV)

CP-even dark pion

- In most general setup with $Y, \widetilde{Y} \neq 0$, nontrivial interplay with quark mass matrix

$$\boldsymbol{m}_\psi = \boldsymbol{\omega} - \frac{v^2}{2}\widetilde{\boldsymbol{Y}}^\dagger \boldsymbol{M}^{-1}\boldsymbol{Y}$$

- Define $\omega \sim \kappa \dfrac{Y\widetilde{Y}v^2}{M}$



For CP-even $\hat{\pi}_2$, shortest lifetime

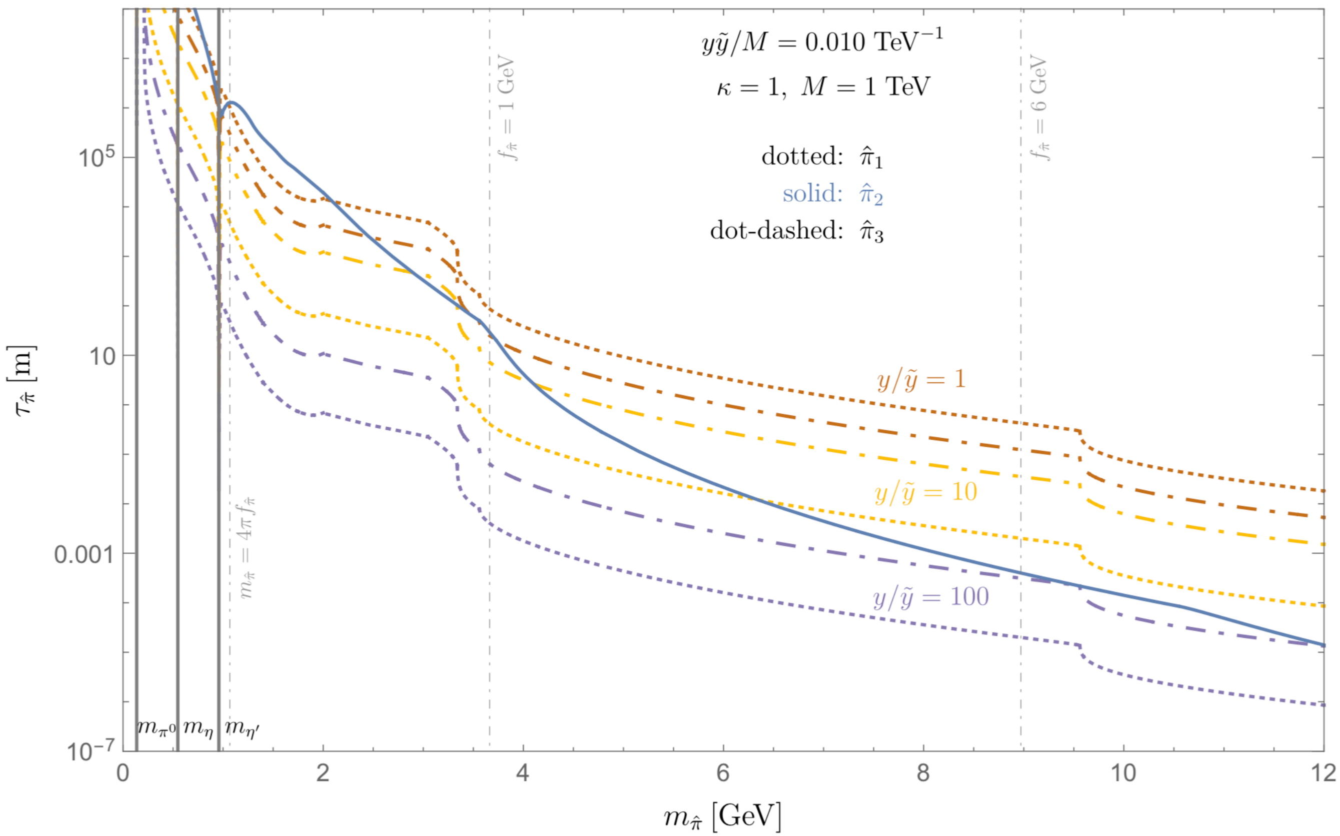
is obtained for $\kappa \sim 1$

(mild coincidence of scales)

$$m_{\hat{\pi}} = \left(4\pi c(\kappa) f_{\hat{\pi}} \frac{y\tilde{y}v^2}{M}\right)^{1/2}$$

$$s_\theta^{(2)} = 2\pi d(\kappa) f_{\hat{\pi}}^2 \frac{y\widetilde{y}}{M}\frac{v}{m_h^2}$$

CP-even vs CP-odd pions



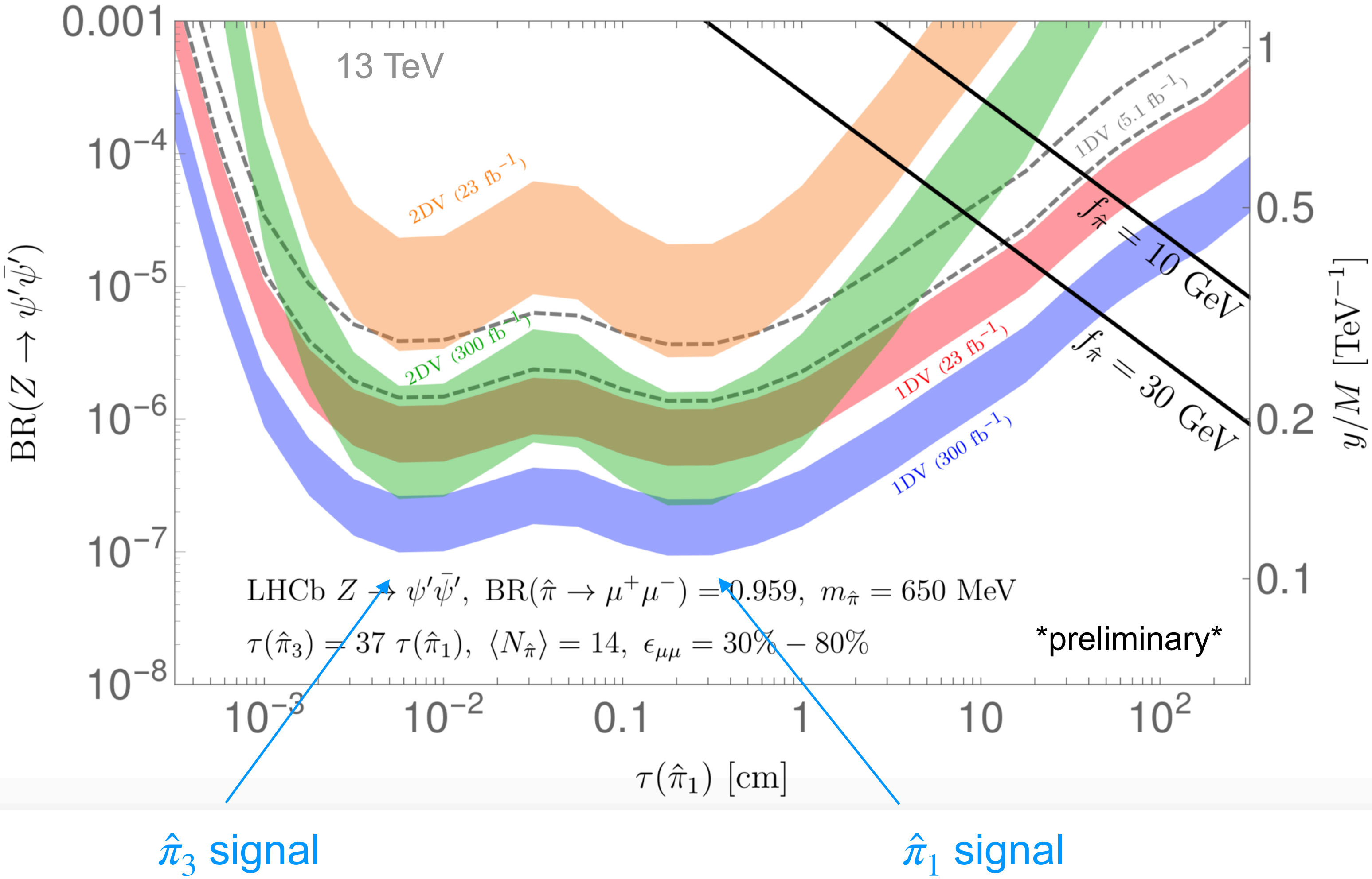
- Strong mass dependence of dark shower decay features
- For $m_{\hat{\pi}} \gtrsim 4$ GeV, *CP*-even pion can be the shortest-lived one

$$m_{\hat{\pi}} = \left(4\pi c(\kappa) f_{\hat{\pi}} \frac{y\tilde{y}v^2}{M}\right)^{1/2}$$

$$s_\theta^{(2)} = 2\pi d(\kappa) f_{\hat{\pi}}^2 \frac{y\tilde{y}}{M} \frac{v}{m_h^2}$$

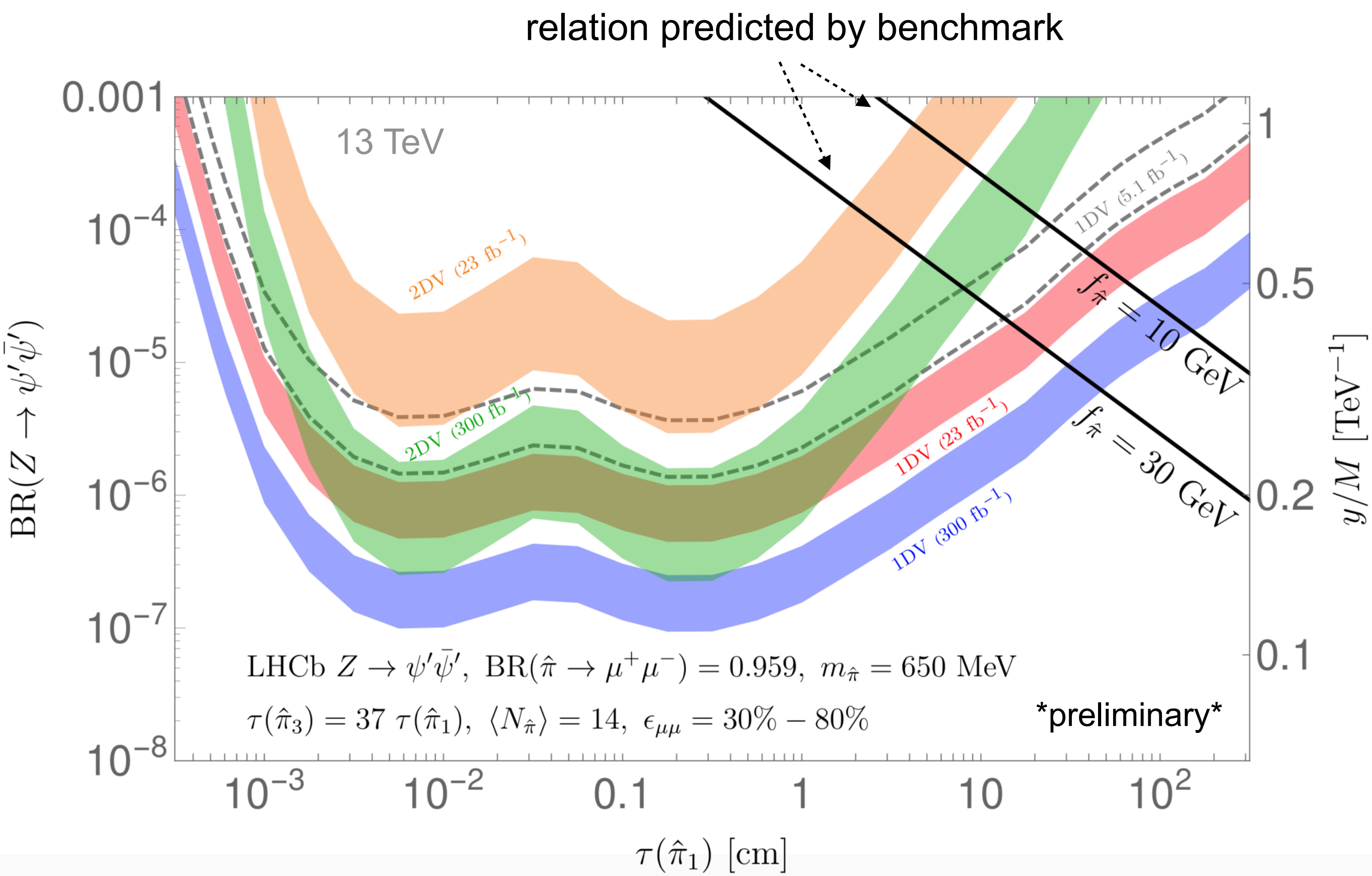
$$f_a^{(b)} = p^{(b)}(\kappa) \frac{M^2}{y\tilde{y} f_{\hat{\pi}}} \left(r + q^{(b)}(\kappa) r^{-1}\right)^{-1}$$

Muon-rich dark showers @ LHCb



$$\rho_T(\mathrm{DV}) \in [1.2, 3.0]\ \mathrm{cm}$$

Muon-rich dark showers @ LHCb



$$\mathrm{BR}(Z \to \psi'\overline{\psi}') \propto (y/M)^4$$

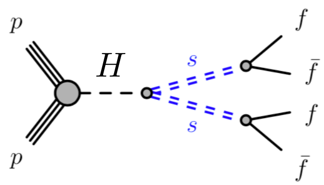
$$\tau_{1,3} \propto f_{\hat\pi}^{-2}(y/M)^{-4}$$

Dark Sectors @ ATLAS

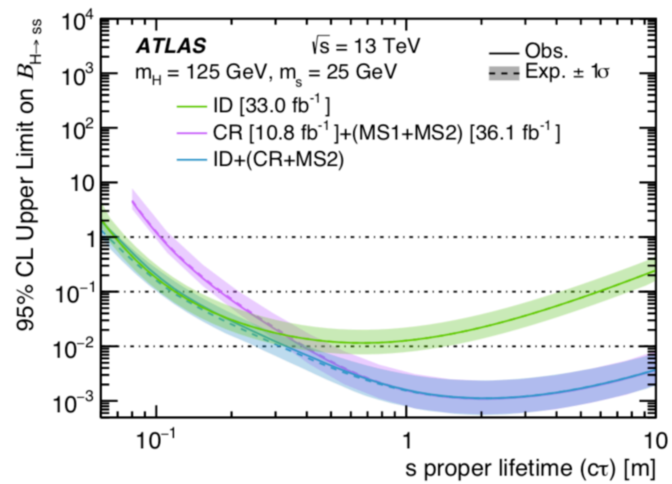
- Impressive array of Run 2 dark sector searches. Important focus on exotic Higgs decays

✓ Displaced jets in MS, calorimeter, and ID + MS

[**ATLAS** 1811.07370, 1902.03094, 1911.12575]

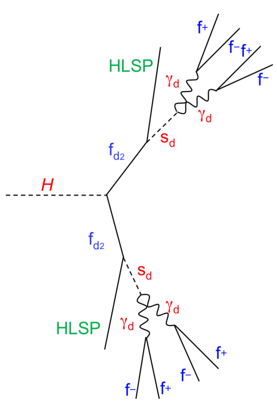


$\mathrm{BR}(s \to b\bar{b}) \approx 90\%$

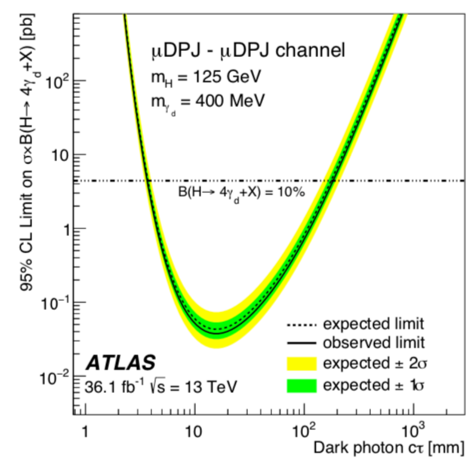


✓ Two displaced "dark-photon jets" (muonic or hadronic)

[**ATLAS** 1909.01246]



$\mathrm{BR}(\gamma_d \to \ell\ell) \approx 45\%$



- All of these rely on LLP-specific triggers

Higgs *vs* *Z* portal

(*take* $Y = y_t \approx 1$)

$$\mathcal{L}_6 \sim \frac{Y^2}{M^2}\left(H^\dagger D_\mu H \overline{\psi}\gamma^\mu\psi + \frac{\hat{\alpha}_s}{12\pi}|H|^2\hat{G}_{\mu\nu}\hat{G}^{\mu\nu}\right)$$

Z portal

$$\mathrm{BR}(Z \to \psi\overline{\psi}) \approx 1.8 \times 10^{-4}\left(\frac{1\ \mathrm{TeV}}{M}\right)^4$$

Higgs portal

$$\mathrm{BR}(h \to \hat{g}\hat{g}) \approx 1.3 \times 10^{-4}\left(\frac{1\ \mathrm{TeV}}{M}\right)^4\left(\frac{\hat{\alpha}_s}{0.2}\right)^2$$

- @ LHC, 13 TeV: $\sigma_Z \approx 55$ nb, $\sigma_h \approx 49$ pb → ***Z* decays to hidden sector** dominate

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

- LEP sensitivity ($Z \to$ invisible, $\widehat{T}$ parameter, visible signatures) limited to ~ 0.7 - 1 TeV

$\sim 2 \times 10^7$ Z @ LEP

➡ $M \gtrsim 1$ TeV is wide open for the LHC

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

- How many flavors of hidden quarks?

$N_f = 1$

- no light "pions," spectrum (in principle) fully computable on lattice
- vector meson decays to SM

[Cheng, Li, Salvioni, Verhaaren 1906.02198]

$N_f \geq 2$

- light "pions" are present, dominate the dark parton showers
- vector meson can decay to $\pi\pi$
- much larger freedom as to symmetry pattern

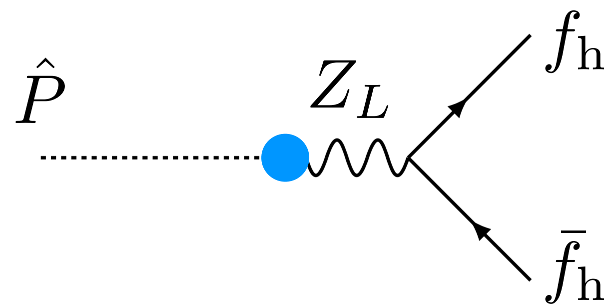
[Cheng, Li, Salvioni, Verhaaren in progress]

Hidden meson decays

[Cheng, Li, Salvioni, Verhaaren 1906.02198]

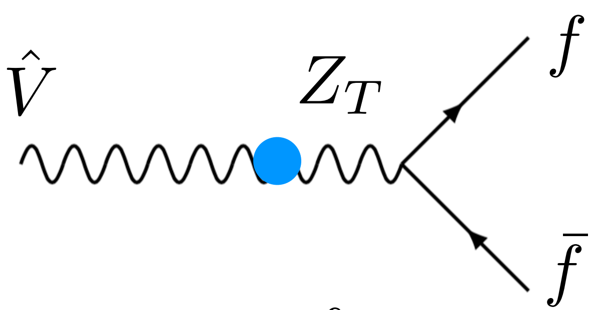
It turns out, all lightest mesons decay back to SM via Z portal

- Pseudoscalar



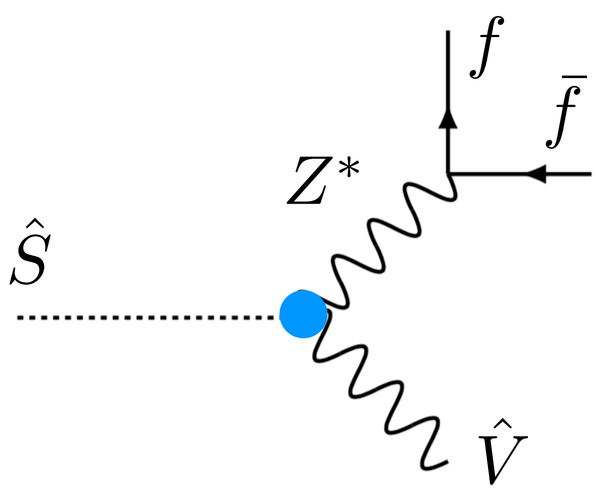
helicity-suppressed

- Vector



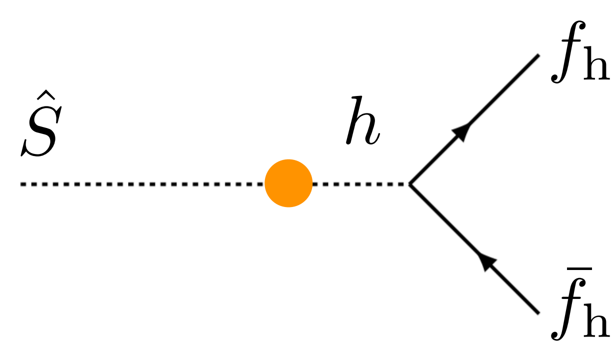
"democratic"

- Scalar

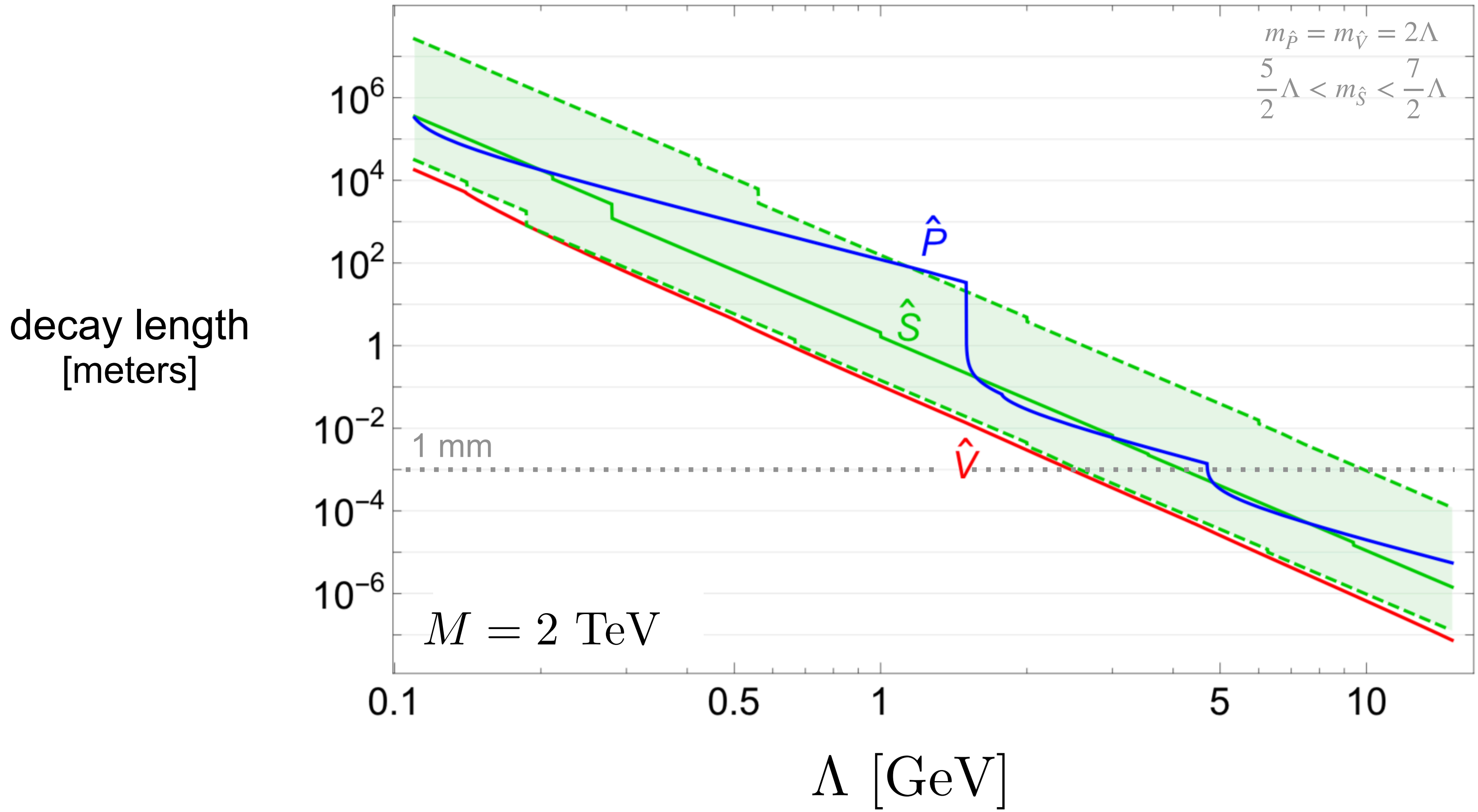


$\gg$

dominates



Hidden meson lifetimes



Two main parameters determine signatures:

- Hidden strong scale Λ
- Mediation scale M