A Z-portal to the dark sector at FCC-ee

Ennio Salvioni

University of Padua

3rd FCC France
December 1, 2021

2110.10691 + in progress
with Hsin-Chia Cheng (UC Davis) and Lingfeng Li (Brown)

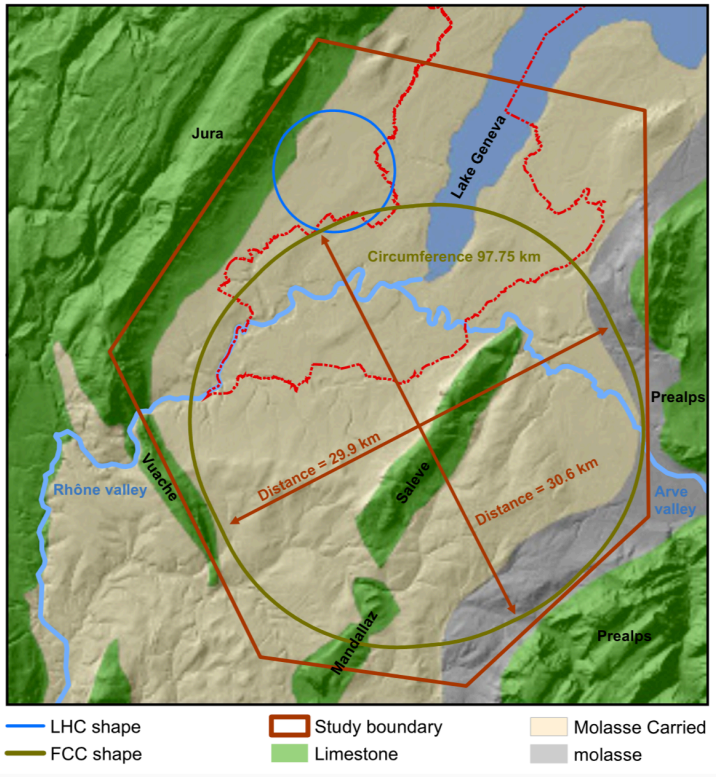
Introduction

- **FCC-ee:** electroweak, Higgs, top factory

  $Z, WW, hZ, t\bar{t}$ runs

  5×10^{12} Z boson decays (Tera-Z)

[FCC layout, from CDR]



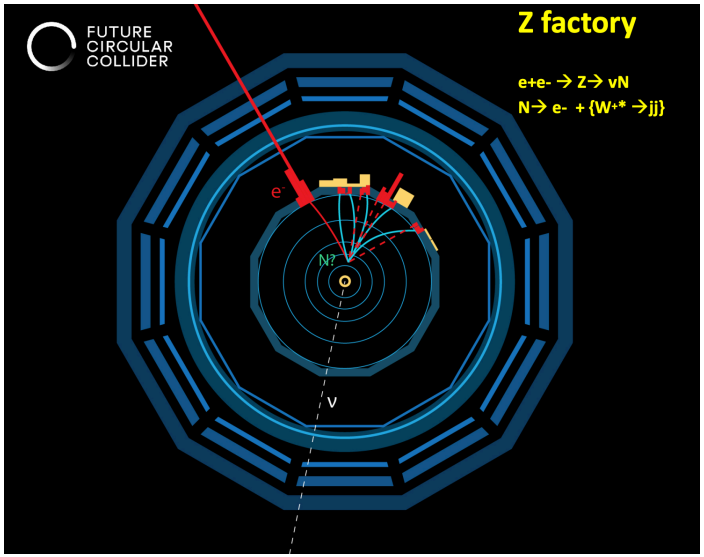
- **Much more than (exquisite) precision measurements:**

  unique opportunity to probe light new particles in the 1 to 100 GeV range

- A few existing studies but much remains to be explored, to strengthen physics case

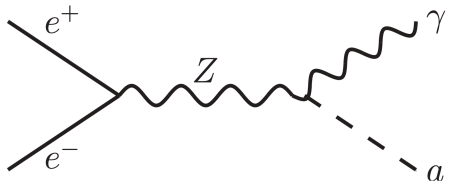
New light particles at Tera-Z: examples

Heavy neutral leptons



[J. Alimena @ Snowmass EF09, https://indico.fnal.gov/event/51673/]
[Blondel, Graverini, Serra, Shaposhnikov 1411.5230]

Axion-like particles



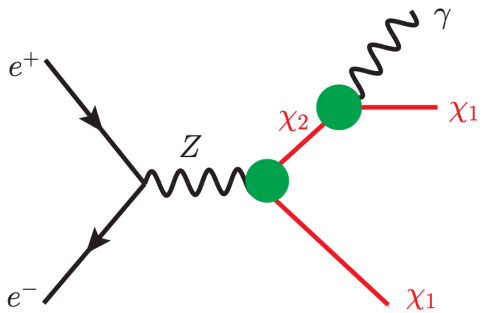
$$a \to \gamma\gamma,\ \mu^+\mu^-,\ b\bar{b},\ \text{invisible}$$

[Bauer, Heiles, Neubert, Thamm 1808.10323]
[Cacciapaglia, Deandrea, Iyer, Sridhar 2104.11064]
also invisible dark photon: [Cobal et al. 2006.15945]

Light dark matter

Magnetic inelastic DM

$$\frac{1}{\Lambda_{\rm MIDM}}\bar{\chi}_2\sigma^{\mu\nu}\chi_1 B_{\mu\nu}$$



[Liu, Wang, Wang, Xue 1712.07237]

recent essays with more refs:
[Chrzaszcz, Gonzalez Suarez, Monteil 2106.15459]
[Knapen, Thamm 2108.08949]

This talk

- Z-pole run of FCC-ee as portal to dark sector

- Dark QCD with non-renormalizable couplings to Standard Model (“hidden valley”)

[Strassler, Zurek 2006]

- A variety of potential signatures: from prompt to **long-lived decays**, from few-body final states to **“dark-jet" topologies**

This talk

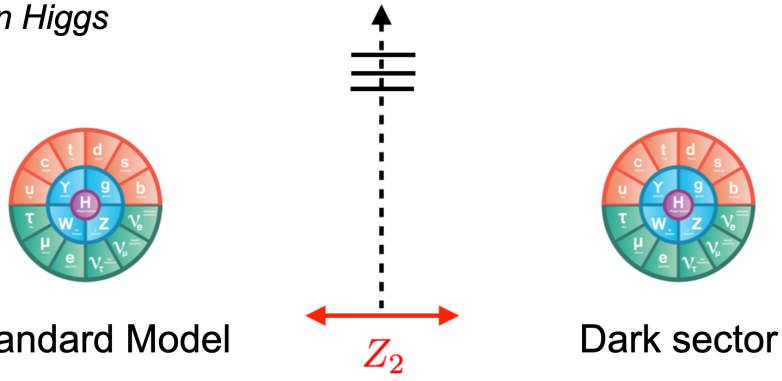
- Z-pole run of FCC-ee as portal to dark sector
- Dark QCD with non-renormalizable couplings to Standard Model ("hidden valley")

[Strassler, Zurek 2006]

- Specific motivations from approaches to hierarchy problem:

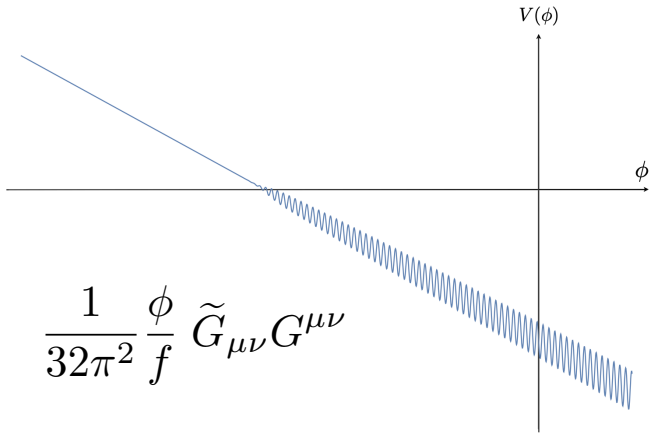
Neutral Naturalness

Twin Higgs



[Chacko, Goh, Harnik 2005]

Relaxion



[Graham, Kaplan, Rajendran 2015]

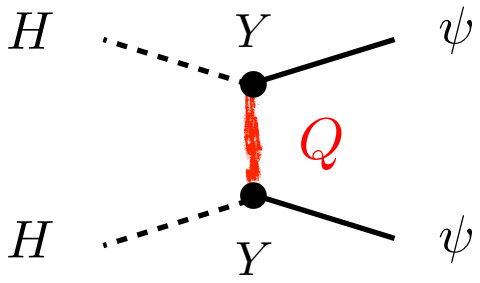
The dark sector

- 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"

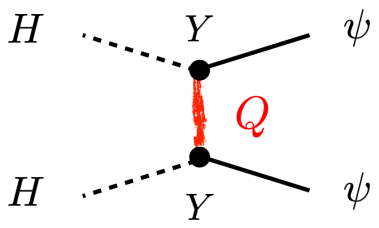


$$M \gtrsim \text{TeV}$$

heavy mediators

[Cheng, Li, Salvioni, 2110.10691]

Dark pions



- Integrate out heavy fermions Q

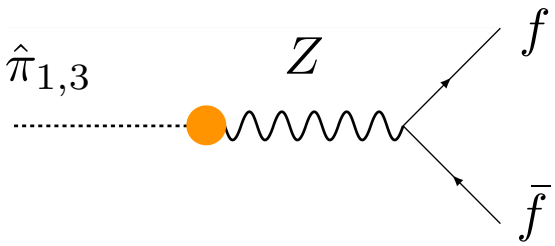
$$\mathcal{L}_{\rm EFT} \sim (\overline{\psi}_R \boldsymbol{Y}^\dagger \boldsymbol{M}^{-2} \boldsymbol{Y} \gamma^\mu \psi_R)\,(iH^\dagger D_\mu H) + (\overline{\psi}_L \widetilde{\boldsymbol{Y}}^\dagger \boldsymbol{M}^{-2} \widetilde{\boldsymbol{Y}} \gamma^\mu \psi_L)\,(iH^\dagger D_\mu H)$$

Z portal (dim-6)

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

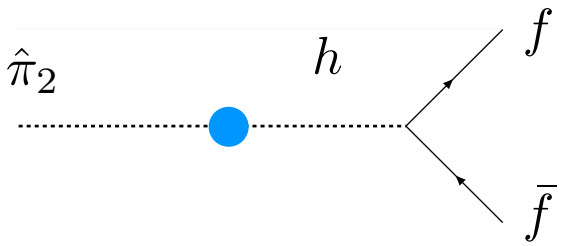
Higgs portal (dim-5)

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



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

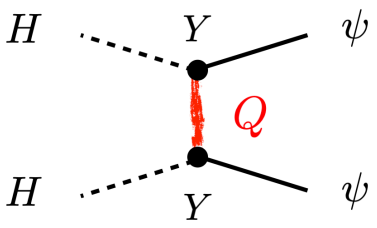
composite ALP



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

composite “scalar”

Dark pions



- Integrate out heavy fermions Q

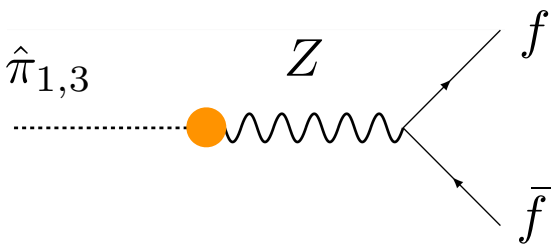
$$\mathcal{L}_{\rm EFT} \sim (\overline{\psi}_R \boldsymbol{Y}^\dagger \boldsymbol{M}^{-2} \boldsymbol{Y} \gamma^\mu \psi_R)\,(iH^\dagger D_\mu H) + (\overline{\psi}_L \widetilde{\boldsymbol{Y}}^\dagger \boldsymbol{M}^{-2} \widetilde{\boldsymbol{Y}} \gamma^\mu \psi_L)\,(iH^\dagger D_\mu H)$$

Z portal (dim-6)

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

Higgs portal (dim-5)

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



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

composite ALP

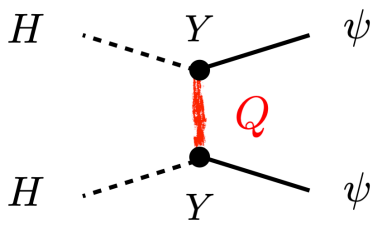
Neutral naturalness models prefer chiral structure

$$Y \sim y_t \sim 1, \quad \widetilde{Y} \sim 0, \quad M \sim \text{TeV}$$

Z portal dominates

[Cheng, Li, Salvioni, Verhaaren 2018+2019]

Dark pions



- Integrate out heavy fermions Q

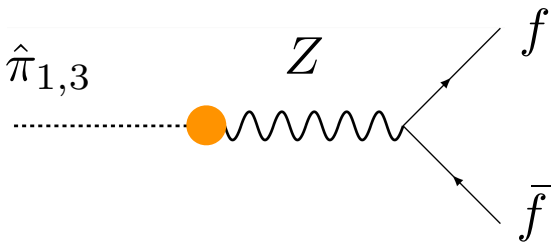
$$\mathcal{L}_{\rm EFT} \sim (\overline{\psi}_R \boldsymbol{Y}^\dagger \boldsymbol{M}^{-2} \boldsymbol{Y} \gamma^\mu \psi_R)\,(iH^\dagger D_\mu H) + (\overline{\psi}_L \widetilde{\boldsymbol{Y}}^\dagger \boldsymbol{M}^{-2} \widetilde{\boldsymbol{Y}} \gamma^\mu \psi_L)\,(iH^\dagger D_\mu H)$$

Z portal (dim-6)

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

Higgs portal (dim-5)

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



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

composite ALP

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

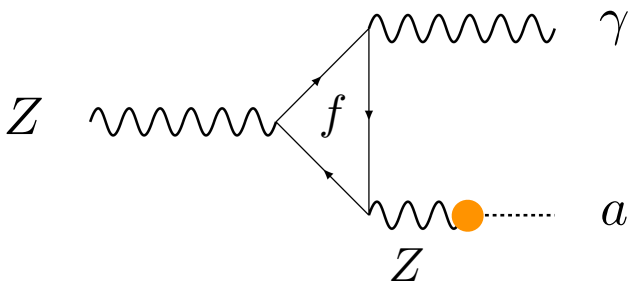
$c_f = T_L^3(f)$ *isospin-violating couplings*

$$f_a \sim \frac{M^2}{Y^2 f_{\hat{\pi}}} > 10\ \text{TeV} \left(\frac{M/Y}{\text{TeV}}\right)^2 \left(\frac{100\ \text{GeV}}{f_{\hat{\pi}}}\right)$$

smallest possible effective decay constant

Composite ALP at FCC-ee

preliminary



$$\mathcal{L}_{\rm eff} = \frac{2e^2}{s_w c_w} C_{\gamma Z} \frac{a}{f_a} F_{\mu\nu} \widetilde{Z}^{\mu\nu}$$

$$C_{\gamma Z} = -\sum_f \frac{N_c^f Q_f v_f T_L^3(f)}{8\pi^2} B_3(\tau_f, \tau_{f/Z}) \approx \frac{N_c Q_t v_t T_L^3(f)}{8\pi^2}$$

SM is anomaly free, only top contribution survives

~ 5 times smaller than for universal c_f

[Bauer, Neubert, Thamm 1708.00443]

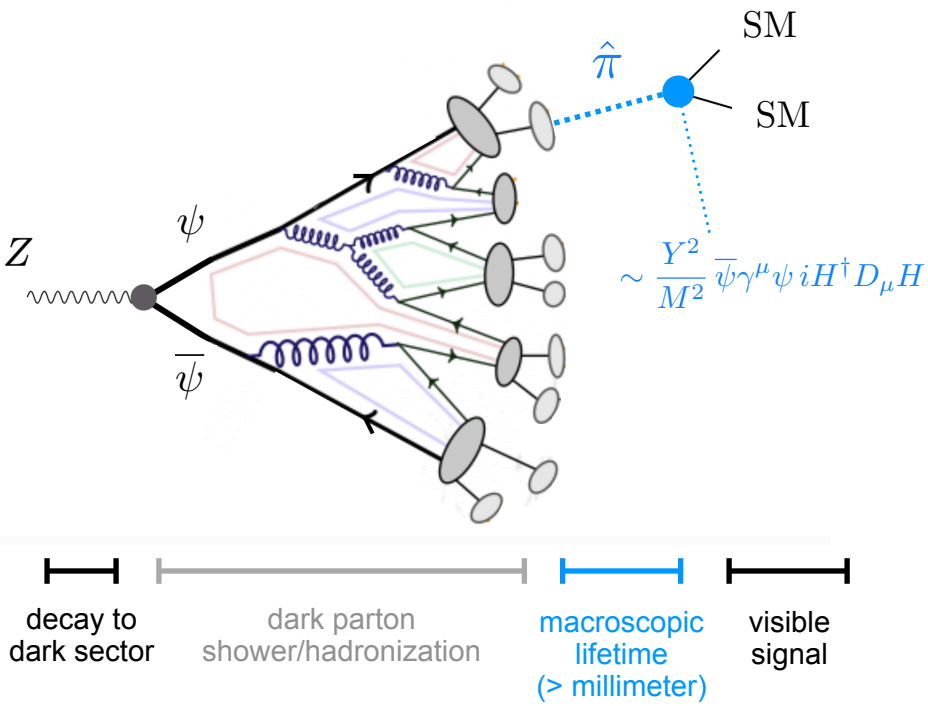
$$\mathrm{BR}(Z \to \gamma a) \approx 10^{-11} \left(\frac{10\ \mathrm{TeV}}{f_a}\right)^2 \left(1 - \frac{m_a^2}{m_Z^2}\right)^3$$

Ex.: for $a \to$ invisible, sensitivity 2×10^{-11} [Cobal et al. 2006.15945]

Suppression of the effective coupling makes it challenging, even for smallest values of f_a

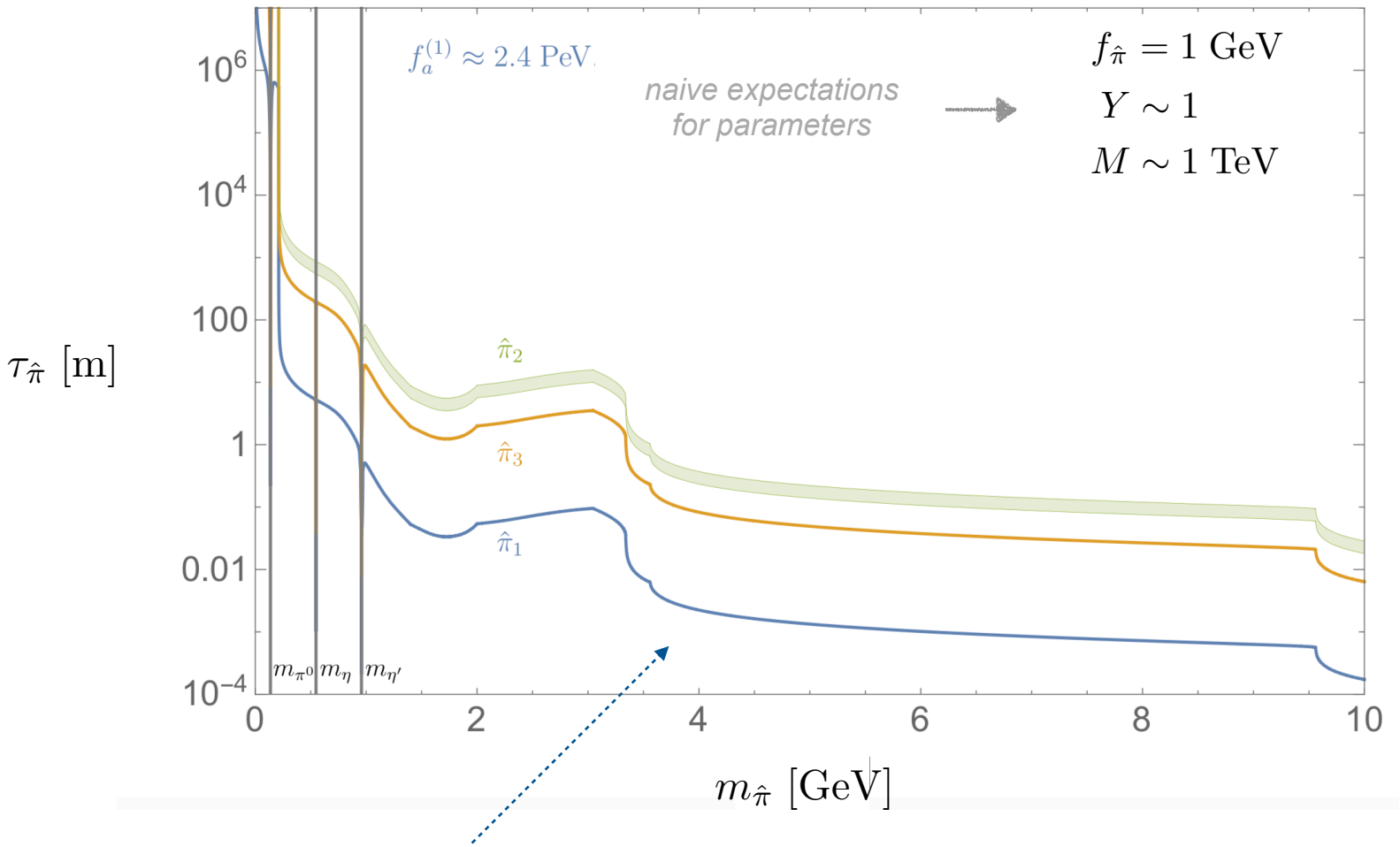
Dark jets at FCC-ee

- But for GeV-scale dark sector, typical event results in dark jets:



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

Light dark pions are long lived



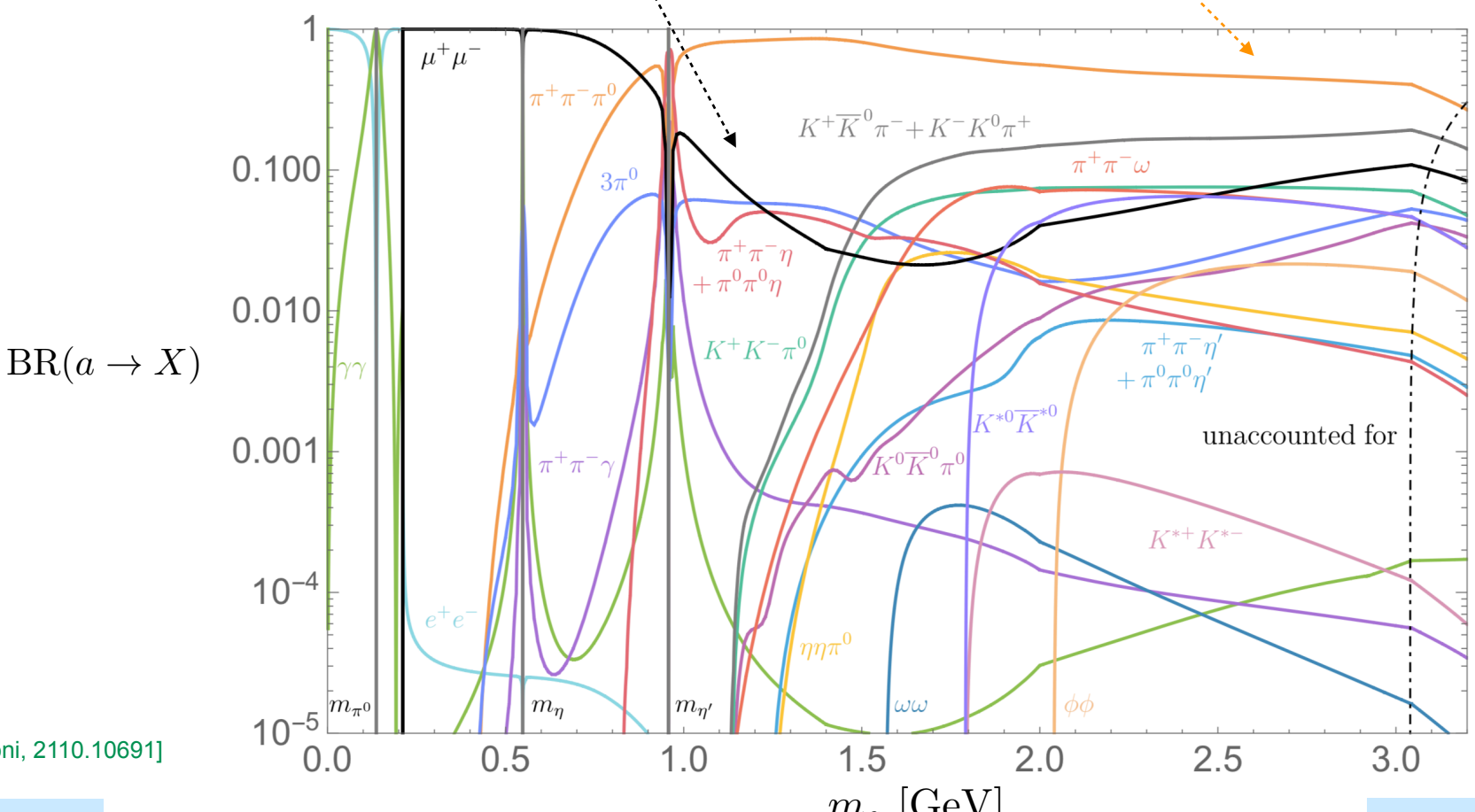
$c\tau$ between 10 meters and 1 millimeter ➡ natural long-lived particle target

Which signatures?

$c_f = T_L^3(f)$ *isospin-violating couplings*

$a \to \mu^+\mu^-$ always > few %

$a \to \pi^+\pi^-\pi^0$ dominates



[Cheng, Li, Salvioni, 2110.10691]

Dark jets at FCC-ee

- No studies are available yet for “dark pion jets”
- $a \to \mu^+\mu^-$ signal has similarities with $N = 1$ flavor dark QCD [Cheng, Li, Salvioni, Verhaaren 2019]

$N = 1$: no Goldstone bosons, lightest mesons are

$\hat{P}$ pseudoscalar, very long-lived

$\hat{V}$ vector, mixes with (transverse) Z

$$Z \to \psi\overline{\psi} \to j_{\rm dark}\, j_{\rm dark} \to (\hat{V} \to \ell^+\ell^-)_{\rm DV} + X$$

- Projection based on LHC tracker performance [CMS 1810.10069]
- Require ≥ 2 lepton tracks per dark jet, main background is $Z \to b\bar{b}$

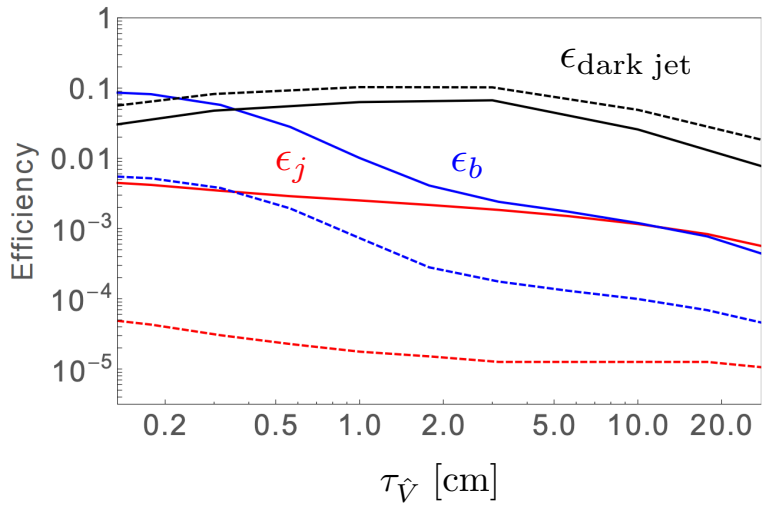
Dark jets at FCC-ee

- No studies are available yet for “dark pion jets”
- $a \to \mu^+\mu^-$ signal has similarities with $N = 1$ flavor dark QCD [Cheng, Li, Salvioni, Verhaaren 2019]

$N = 1$: no Goldstone bosons, lightest mesons are

- $\hat{P}$ pseudoscalar, very long-lived
- $\hat{V}$ vector, mixes with (transverse) Z

$$Z \to \psi\overline{\psi} \to j_{\rm dark}\, j_{\rm dark} \to (\hat{V} \to \ell^+\ell^-)_{\rm DV} + X$$



Benchmark: $m_{\hat{P}} = m_{\hat{V}} = 1$ GeV

$$\frac{\langle N_{\hat{P}} \rangle}{\langle N_{\hat{V}} \rangle} = \frac{1}{3}$$

≈ 7 mesons per jet

solid: $N_{\rm track} \geq 5, \quad N_{{\rm track},\,\ell} = 0, 1$

dashed: $N_{\rm track} \geq 3, \quad N_{{\rm track},\,\ell} \geq 2$

Dark jets at FCC-ee

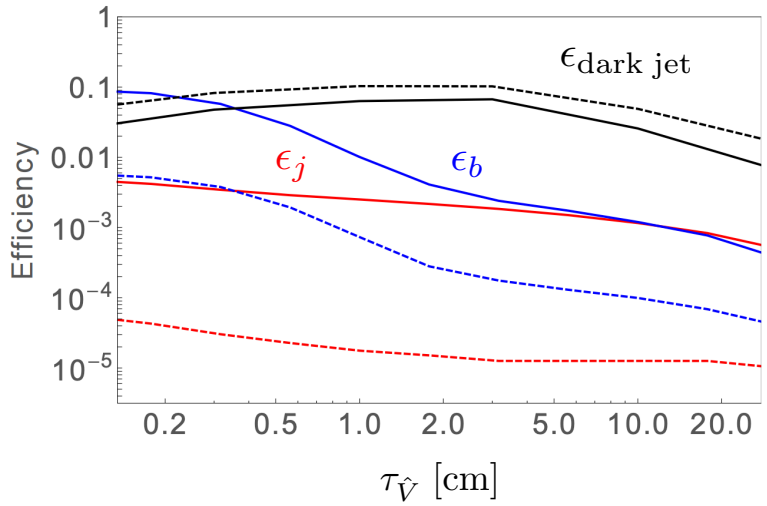
- No studies are available yet for “dark pion jets”
- $a \to \mu^+\mu^-$ signal has similarities with $N = 1$ flavor dark QCD [Cheng, Li, Salvioni, Verhaaren 2019]

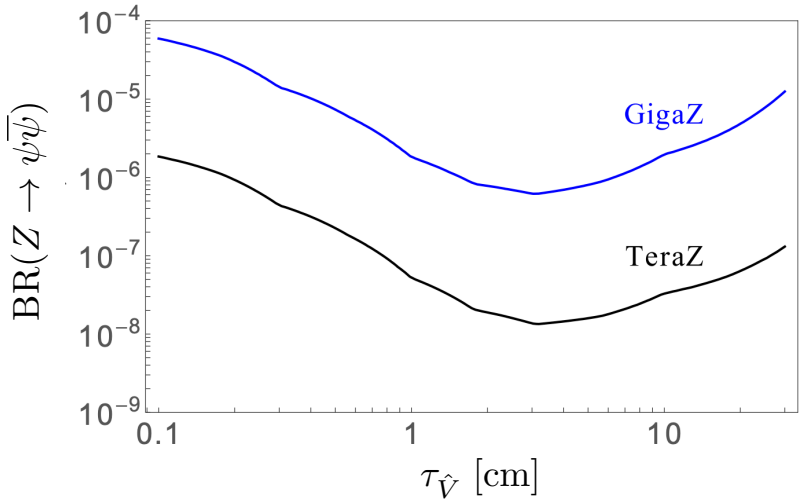
$N = 1$: no Goldstone bosons, lightest mesons are

$\hat{P}$ pseudoscalar, very long-lived

$\hat{V}$ vector, mixes with (transverse) Z

$$Z \to \psi\overline{\psi} \to j_{\rm dark}\, j_{\rm dark} \to (\hat{V} \to \ell^+\ell^-)_{\rm DV} + X$$





Dark jets at FCC-ee

- No studies are available yet for “dark pion jets”
- $a \to \mu^+\mu^-$ signal has similarities with $N = 1$ flavor dark QCD [Cheng, Li, Salvioni, Verhaaren 2019]

$N = 1$: no Goldstone bosons, lightest mesons are

$\hat{P}$ pseudoscalar, very long-lived

$\hat{V}$ vector, mixes with (transverse) Z

$$Z \to \psi\overline{\psi} \to j_{\rm dark}\, j_{\rm dark} \to (\hat{V} \to \ell^+\ell^-)_{\rm DV} + X$$

- Are hadronic modes feasible, possibly requiring 2 displaced vertices per event?

$$\mathrm{BR}(a \to \pi^+\pi^-\pi^0) \sim O(1)$$

Outlook

- Direct production of light BSM particles is key target for FCC-ee Z-pole program.
  However, much of the physics potential is yet to be explored

- Decays to dark QCD sectors predict a host of possible signatures.
  Here, focused on dark jets made of long-lived dark hadrons

To do:

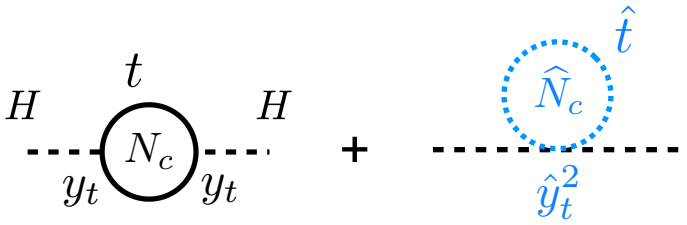
- Signal characterization and phenomenological/experimental analyses
- Comparison with other probes:
  - electroweak precision @ FCC-ee
  - proposals for LLP-specific experiments @ LHC and beyond
  - direct reach on mediators @ FCC-hh (from EWino-like to emerging-jet like)

Supplementary material

Light dark sectors

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

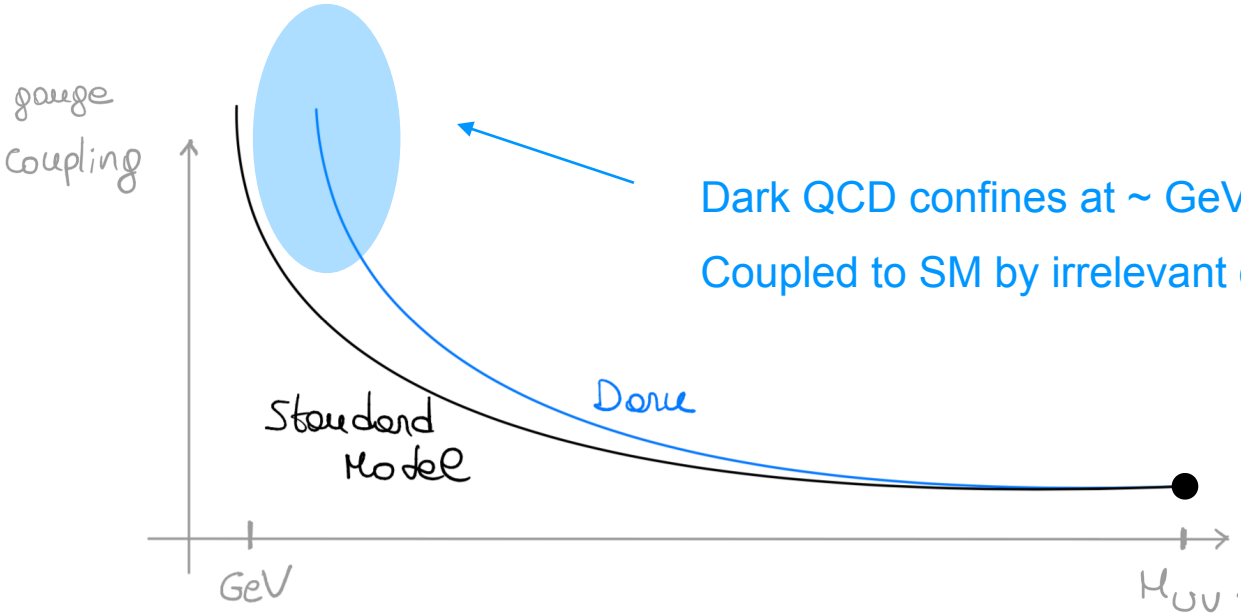
[Chacko, Goh, Harnik 2004]



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

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

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



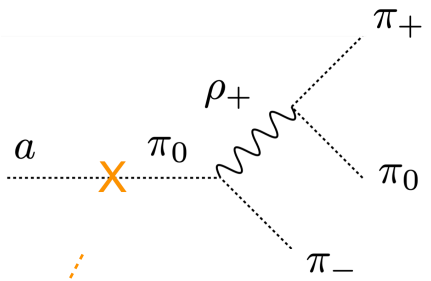
Dark QCD confines at ~ GeV

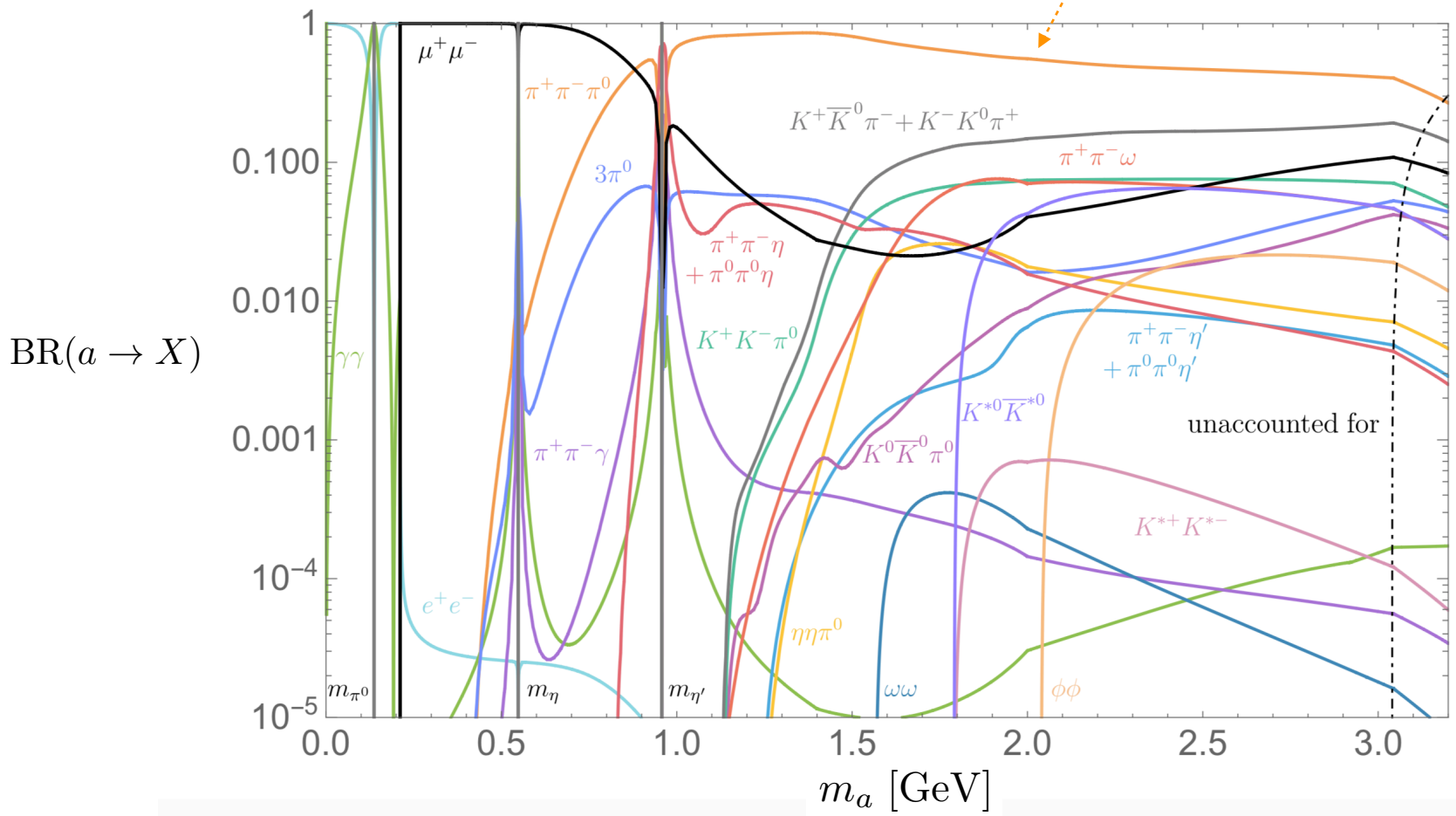
Coupled to SM by irrelevant operators $\sim \dfrac{\mathcal{O}_{\rm dark}\mathcal{O}_{\rm SM}}{M^2}$

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

Hadronic decays of light ALPs

- ALP has non-trivial U(3) representation up to 3 GeV, $a \to P(V \to PP)$ dominates
- No $\rho_0\pi_0\pi_0$ coupling $\rightarrow$ $\Gamma(a \to 3\pi_0) \ll \Gamma(a \to \pi_+\pi_-\pi_0)$
- Distinctive pattern compared to other scenarios





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)

$M \sim \text{TeV}$:

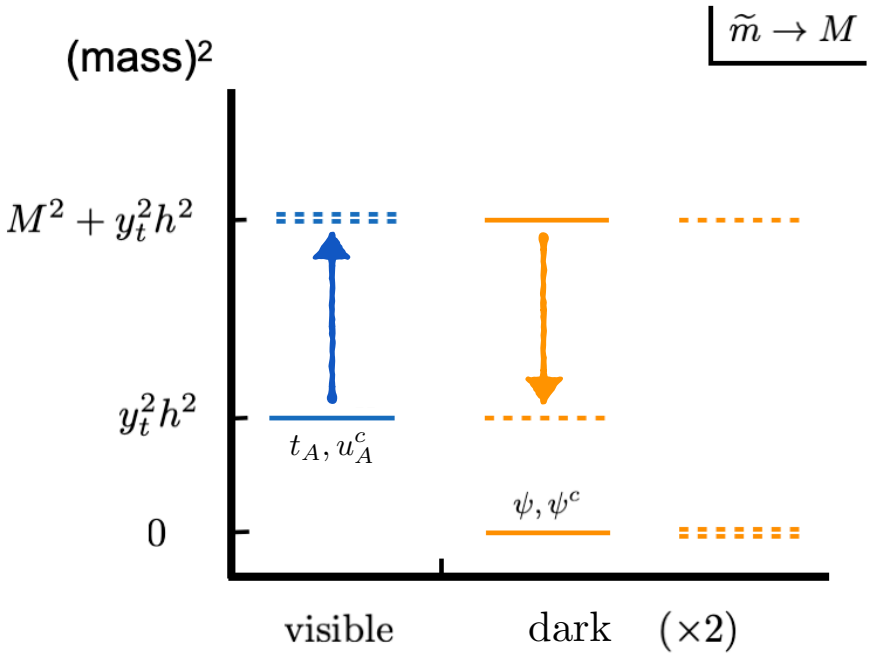
Z bound allows Y or $\widetilde{Y} \sim 1$

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

Ultraviolet motivation/1

- *Tripled Top* neutral naturalness: accidental SUSY of the spectrum

[Cheng, Li, Salvioni, Verhaaren 2018]



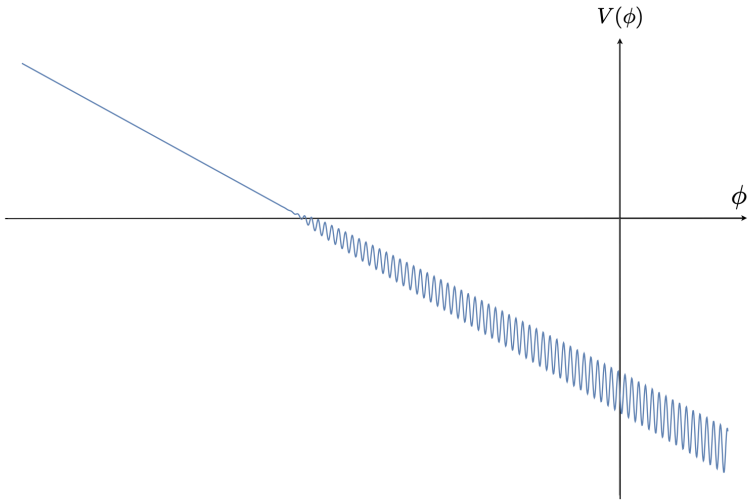
$$SU(3)_A \times SU(3)_B \times SU(3)_C \times SU(2) \times U(1)$$

$$Y = y_t\,, \quad \widetilde{Y} = 0\,, \quad M \sim \mathrm{TeV}$$

Z portal dominates

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

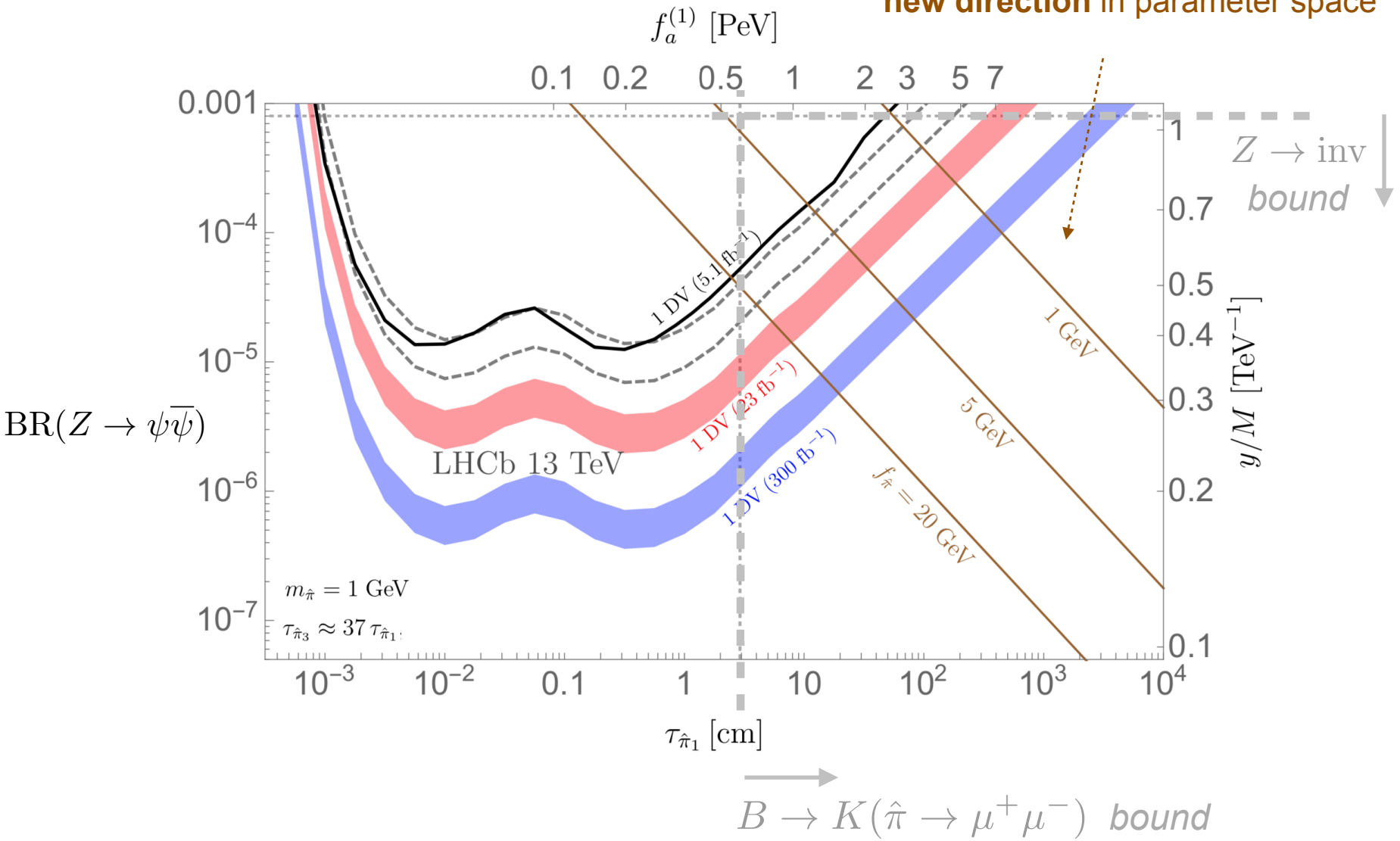
- Setup is common to different approaches to Higgs naturalness

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

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

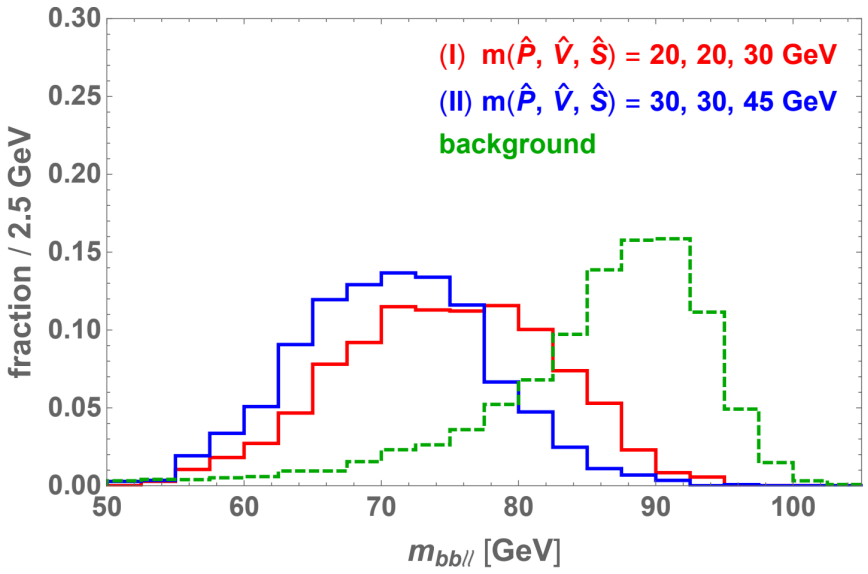
Dark jets at LHCb

Dark jet searches access
new direction in parameter space



Few-body final states at FCC-ee: prompt

$$Z \to (\hat{P} \to b\bar{b})(\hat{S} \to \hat{V} f\bar{f} \to \ell\ell f\bar{f})$$

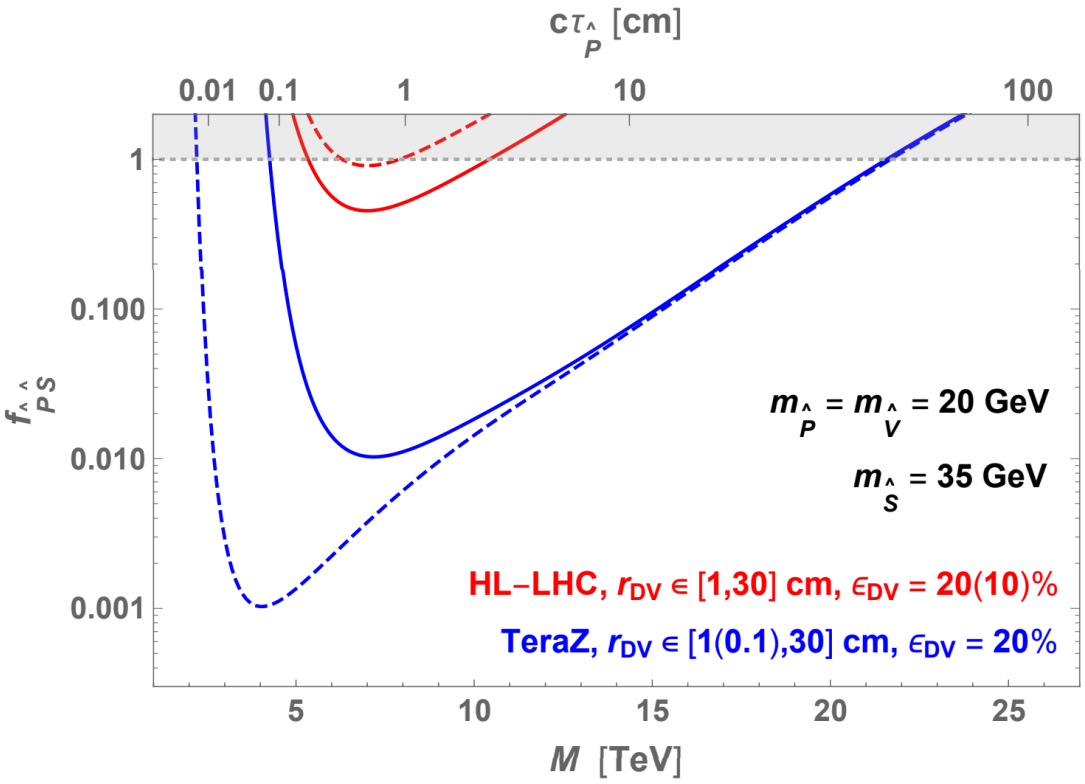


$$|m_{\ell\ell} - m_{\hat{V}}| < 0.5 \text{ GeV}, \qquad m_{bb} \in [m_{\hat{P}} - 10 \text{ GeV}, m_{\hat{P}} + 5 \text{ GeV}], \qquad m_{bb\ell\ell} < 85 \text{ GeV}$$

$$\text{(I)} \quad M \gtrsim 5.4 \text{ TeV} \left(\frac{f_{\hat{P}\hat{S}}}{1}\right)^{1/4}, \qquad \text{(II)} \quad M \gtrsim 5.2 \text{ TeV} \left(\frac{f_{\hat{P}\hat{S}}}{1}\right)^{1/4}, \qquad \text{(GigaZ)}$$

Few-body final states at FCC-ee: long-lived

$$Z \to (\hat{P} \to b\bar{b})_{\rm DV}(\hat{S} \to \hat{V} f\bar{f} \to \ell\ell f\bar{f})$$



[Cheng, Li, Salvioni, Verhaaren 2019]

$$M \gtrsim 20 \text{ TeV} \ @ \ \text{Tera-Z}$$