Composite ALPs through the Z portal

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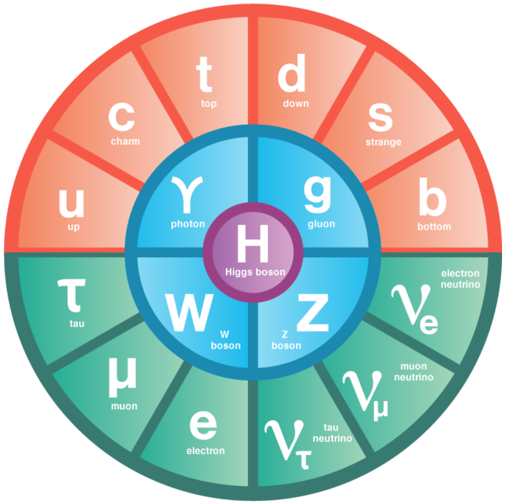
Light Dark World 2023
Karlsruhe, September 19

2310.xxxxx [hep-ph]

with Hsin-Chia Cheng (Davis), Xu-Hui Jiang (HKUST)
and Lingfeng Li (Brown)

symmetry

Introduction



$$\psi, G_D^{a\,\mu\nu}$$

Dark QCD

(neutral under the Standard Model)

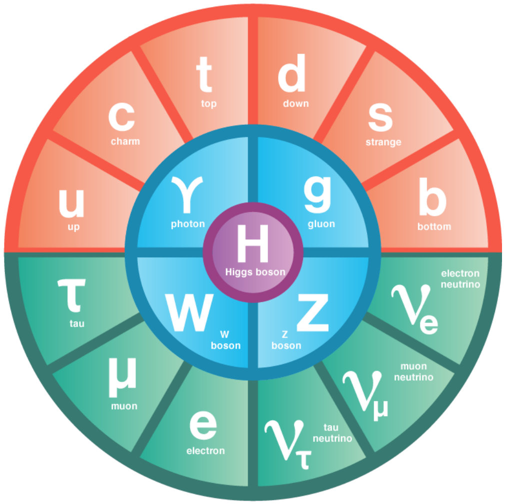
- Motivated by big questions: dark matter (e.g. SIMPs), naturalness (neutral naturalness, relaxion models), …

[Hochberg et al. 2014]
[Chacko, Goh, Harnik 2005]
[Graham, Kaplan, Rajendran 2015]

- "Dark shower" - type signatures at the LHC: challenging, but major progress recently, with room for further improvement

[Born et al. 2023]
[Cohen et al. 2023]
[Bernreuther et al. 2022]
[Knapen, Shelton, Xu 2021]
…

Introduction



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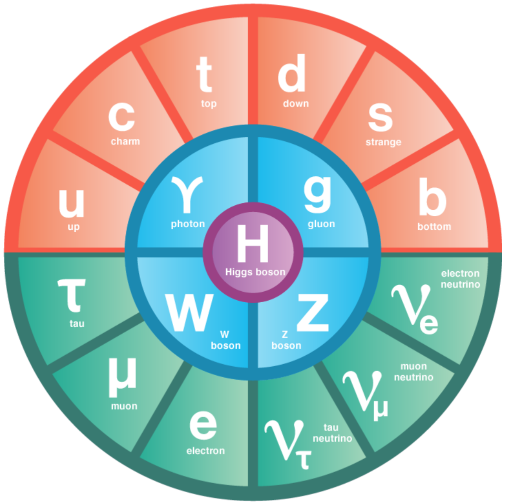
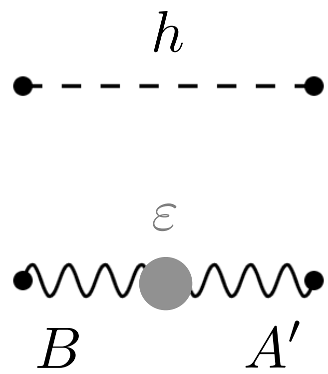
Which portal?

Introduction





$\psi, G_D^{a\,\mu\nu}$

Dark QCD

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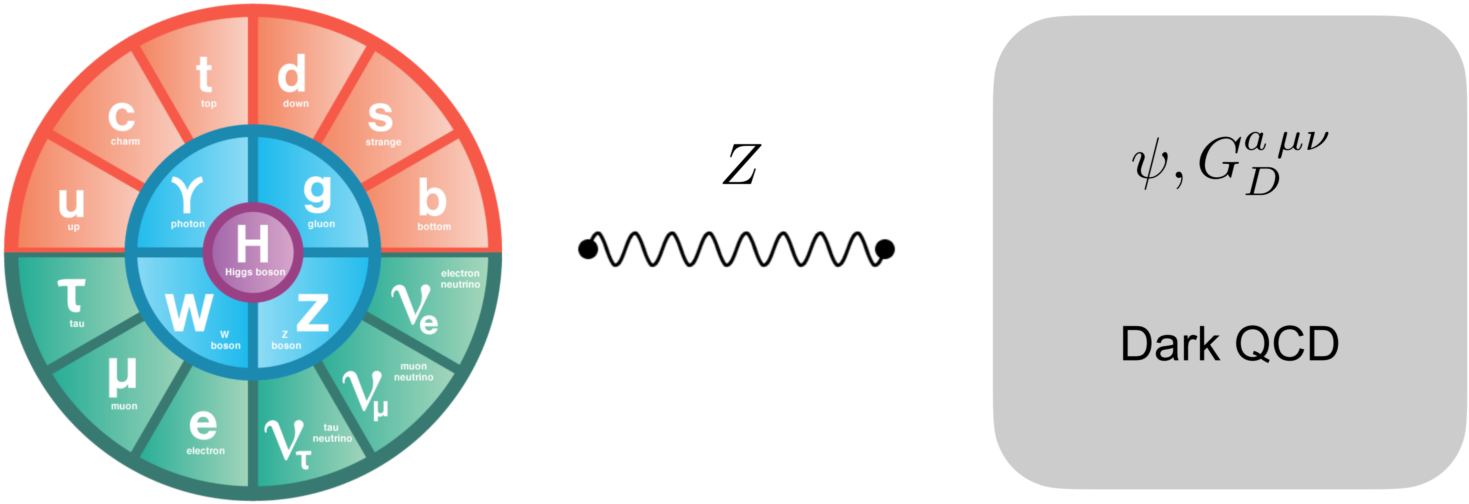
Which portal?

Some interactions are very well studied: Higgs, dark photon

Introduction



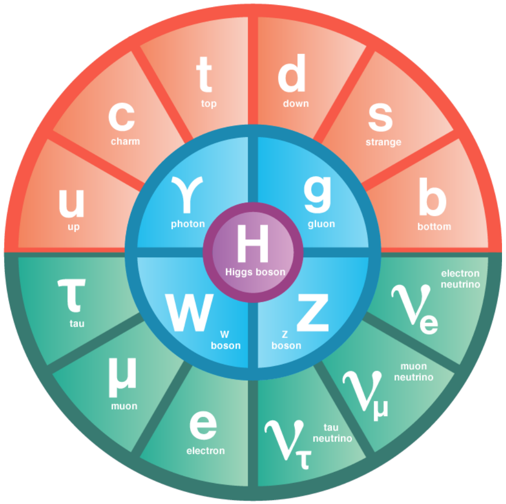
(neutral under the Standard Model)

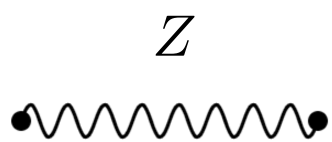
Z portal is far less explored, yet the LHC is collecting a huge sample:

$> 10^{11}\ Z$ bosons @ High-Luminosity phase

(one thousand times more than for Higgs)

Introduction



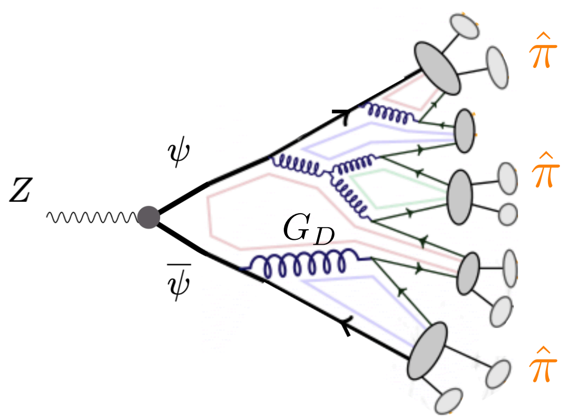


electroweak
invariant op.

$\psi, G_D^{a\,\mu\nu}$

Dark QCD

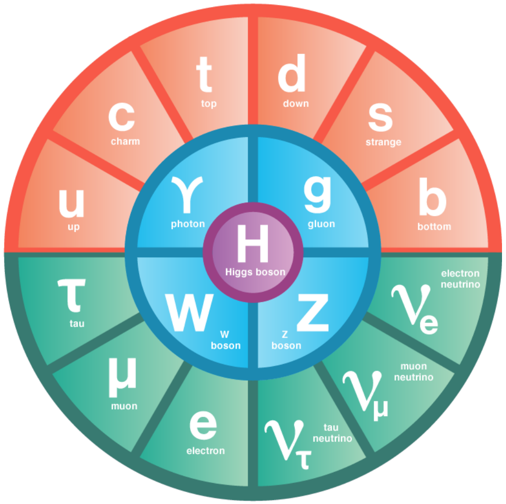
$$\frac{c}{M^2}(iH^\dagger \overleftrightarrow{D}_\mu H)(\overline{\psi}\gamma^\mu\psi)$$

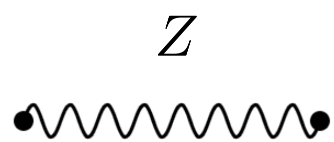


"Dark shower" events generated by *Z* decays at LHC

Mostly produce lightest dark hadrons, the dark pions

Introduction





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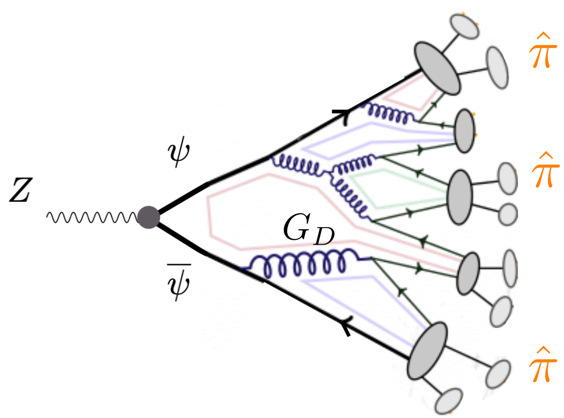
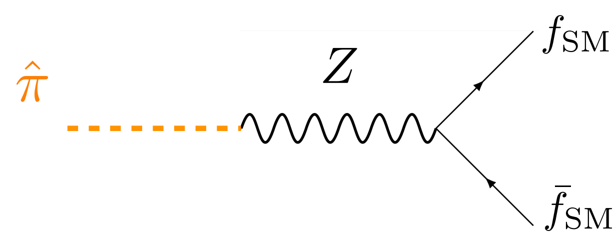
Dark QCD

$$\frac{c}{M^2}(iH^\dagger \overleftrightarrow{D}_\mu H)(\overline{\psi}\gamma^\mu\psi)$$

$$\frac{1}{f_a}(iH^\dagger \overleftrightarrow{D}_\mu H)(\partial^\mu \hat{\pi})$$





dark pions behave as composite ALPs

ALP through the *Z* portal

Distinctive feature of *Z* portal is coupling of ALPs (dark pions) to Higgs current,

$$\frac{1}{f_a}(iH^\dagger \overleftrightarrow{D}_\mu H)(\partial^\mu a) \quad \xrightarrow{\text{EOM}} \quad -\frac{\partial_\mu a}{f_a}\sum_f c_f \bar{f}\gamma^\mu\gamma_5 f\,, \quad c_f = T_L^3(f)$$

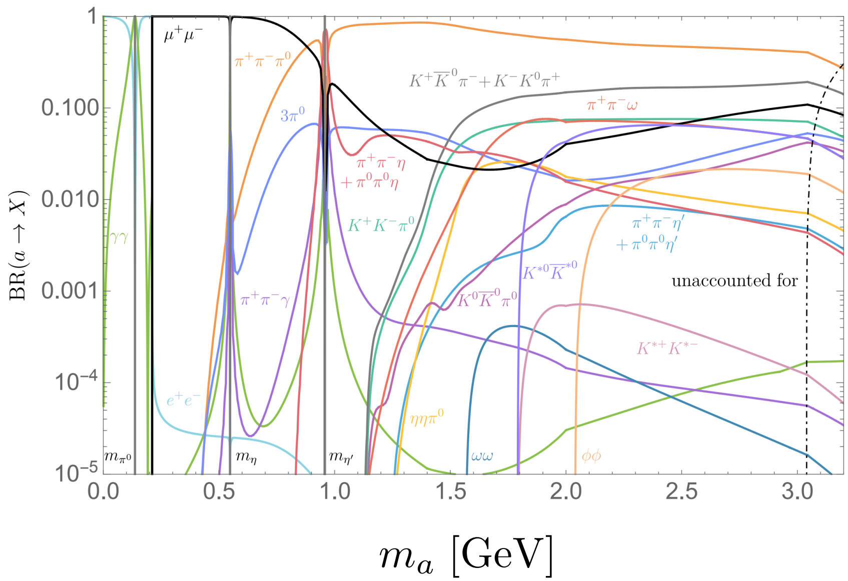
For $m_a \sim \mathrm{GeV}$, must consider decays to exclusive final states containing SM hadrons

Apply data-driven methods, 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 feasible

Isospin-violating couplings lead to important differences with universal scenarios

Big differences with gluon-coupled ALP



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

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isospin-breaking coupling to fermions

[Cheng, Li, Salvioni, 2021]

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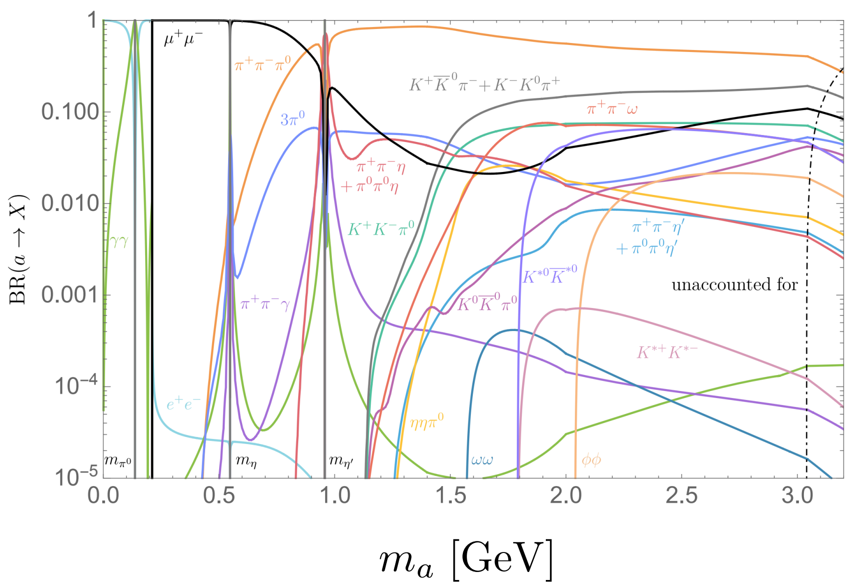

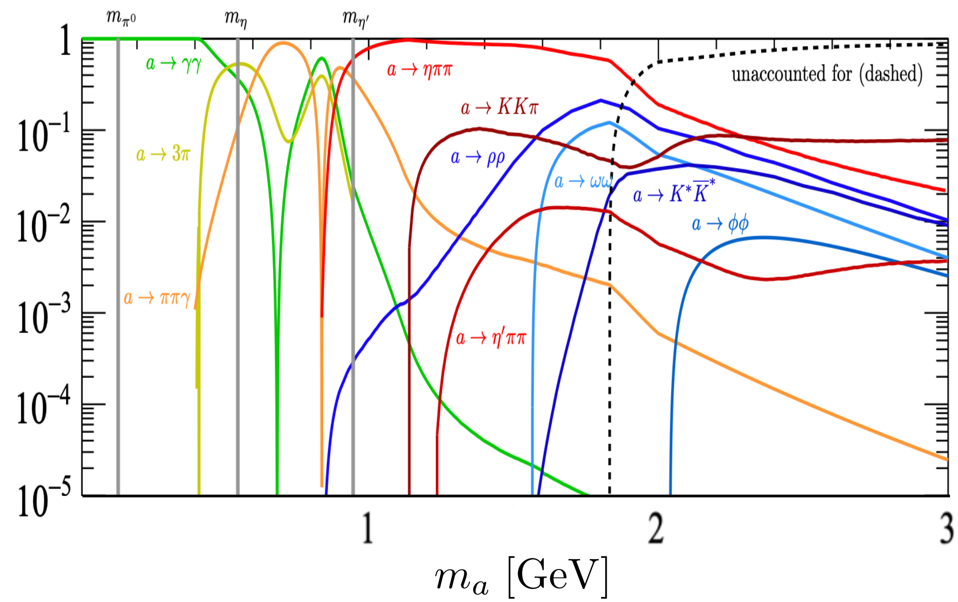

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isospin-breaking coupling to fermions

coupling to gluons

[Cheng, Li, Salvioni, 2021]

[Aloni, Soreq, Williams 2018]

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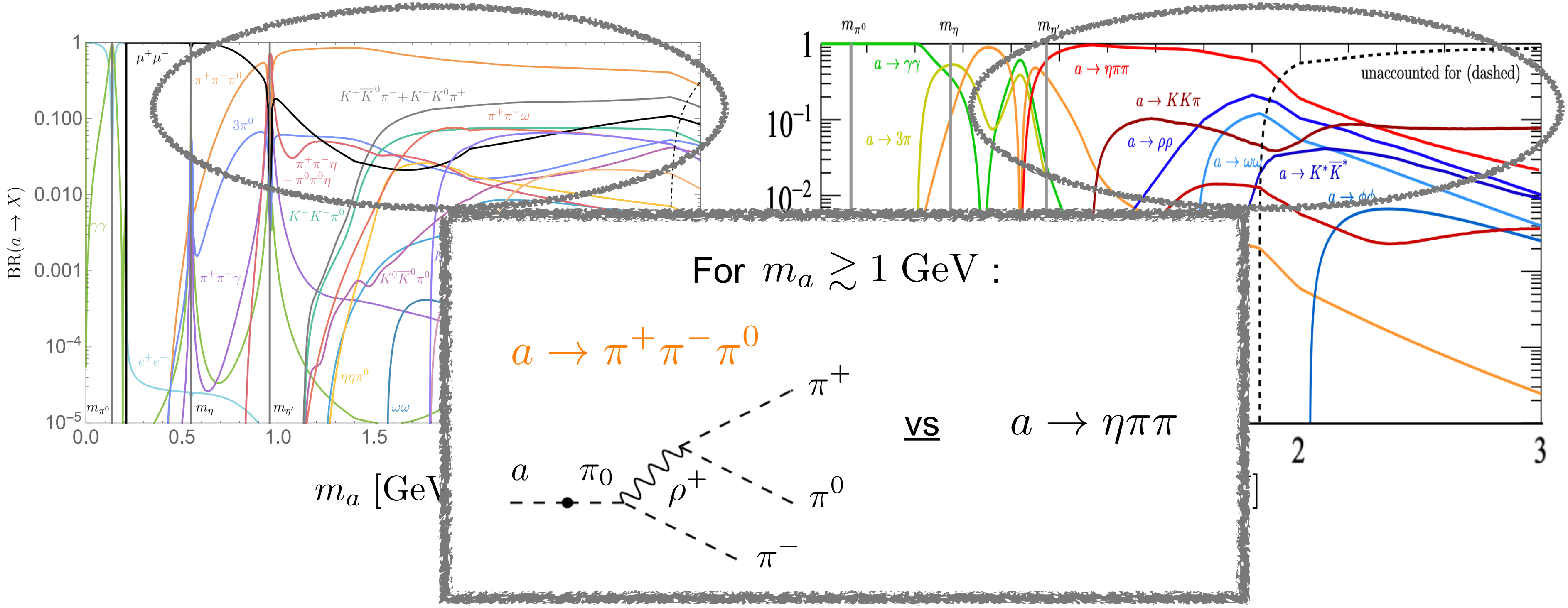

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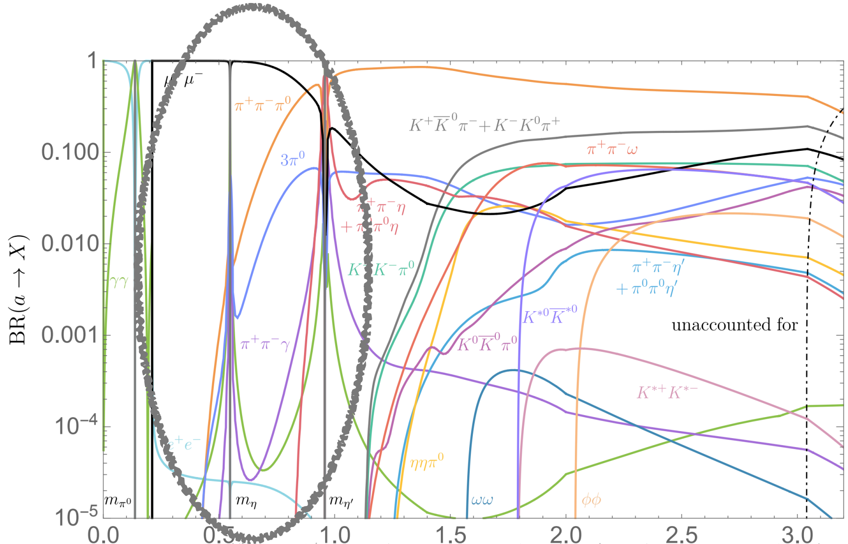

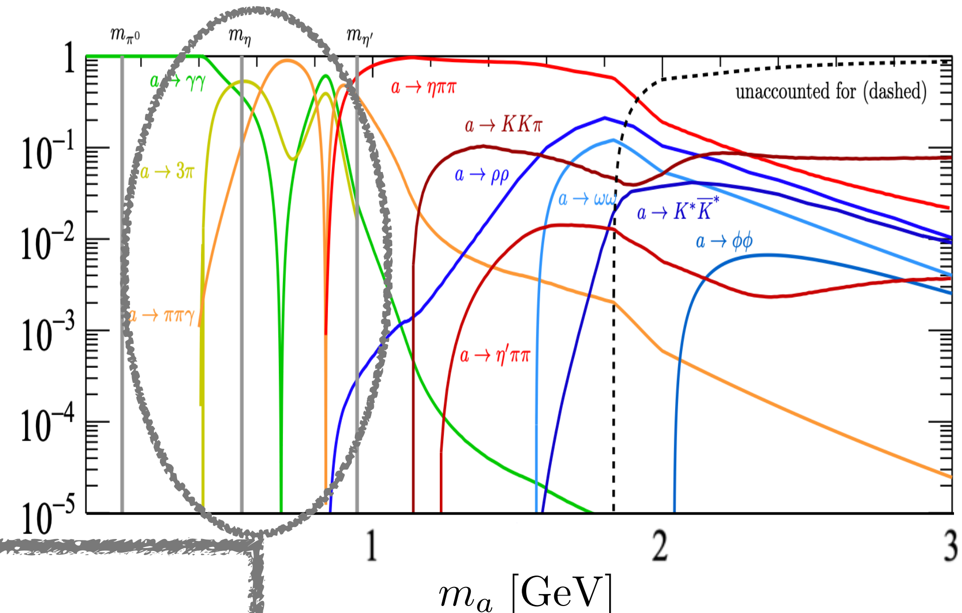

$a \to \pi^+\pi^-\gamma$: negligible vs dominant

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

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

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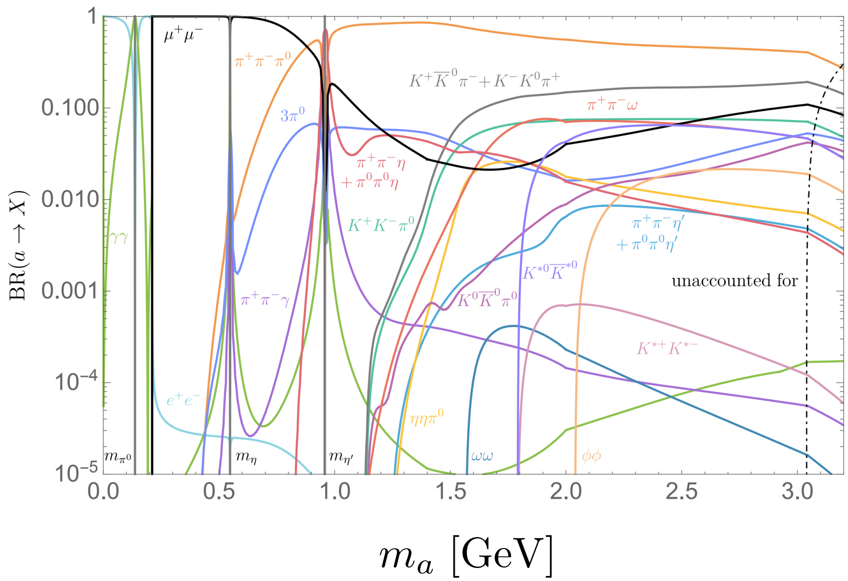
ALP couplings to SM hadrons



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

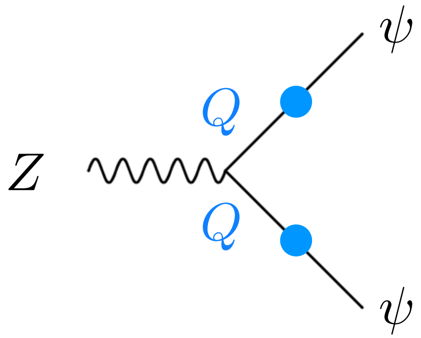
[Cheng, Li, Salvioni, 2021]

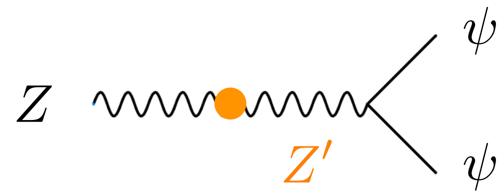
Our calculations apply to arbitrary (flavour-diagonal) couplings to fermions

Use it for your next ALP model!

Models

$$\frac{c}{M^2}(iH^\dagger \overleftrightarrow{D}_\mu H)(\overline{\psi}\gamma^\mu\psi)$$





$$\mathcal{L}_{\rm UV} \supset \overline{Q} Y \psi H \quad \rightarrow \quad \frac{c}{M^2} \sim \frac{Y^2}{M_Q^2}$$

$$\mathcal{L}_{\rm UV} \supset \delta \hat{M}^2 Z^\mu Z'_\mu \quad \rightarrow \quad \frac{c}{M^2} \sim \frac{g_D^2}{M_{Z'}^2}$$

Dark quarks Q with SM electroweak charges

Need to be heavier than ~ 1 TeV

[Cheng, Li, Salvioni, 2021]

Dark gauge boson Z'

Can even be lighter than the Z

[Cheng, Jiang, Li, Salvioni, 2310.xxxxxx]

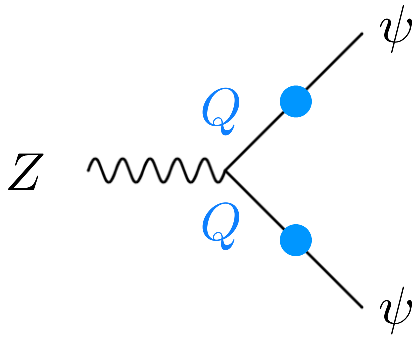
In both models, there are corrections to electroweak precision observables

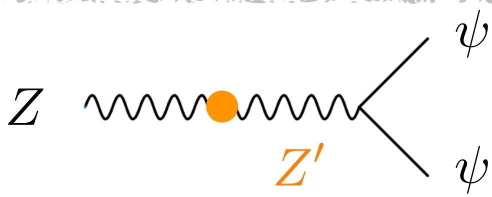
What dark pion signatures can we expect, after taking the bounds into account?

Models

$$\frac{c}{M^2}(iH^\dagger \overleftrightarrow{D}_\mu H)(\overline{\psi}\gamma^\mu\psi)$$

today





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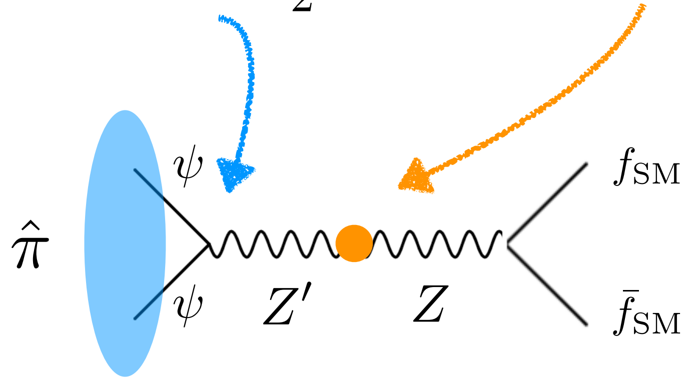
Mass-mixed Z'

Gauge boson of dark $U(1)_D$ symmetry

$$\mathcal{L}_{\rm BSM} \supset g_D \overline{\psi}\gamma^\mu \boldsymbol{X}\psi + \frac{1}{2}\hat{M}^2_{Z'} Z'^\mu Z'_\mu + \delta \hat{M}^2 Z^\mu Z'_\mu$$



$$-\frac{\varepsilon}{2} Z'_{\mu\nu} B^{\mu\nu}$$

[Essig, Schuster, Toro 2009]

Kinetic mixing does not mediate decay of dark pions

ε affects transverse modes, while dark pion mixes with longitudinal modes

Need mass mixing (assumed to originate from second doublet with $U(1)_D$ charge)

[Babu, Kolda, March-Russell 1997]

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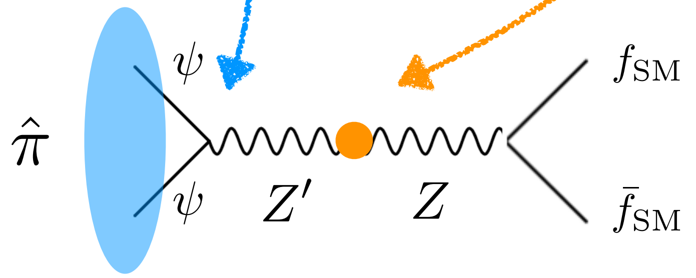

Integrating out Z and Z', find effective decay constant $\mathcal{L}_{\rm eff} \supset -\frac{\partial_\mu \hat{\pi}_i}{f_a^{(i)}} T^3_L(f)\bar{f}\gamma^\mu\gamma_5 f$

$$f_a^{(i)} = \frac{2M_Z^2 M_{Z'}^2}{\mathrm{Tr}(\sigma_i \boldsymbol{X}'_A) g_D g_Z f_{\hat{\pi}} \delta\hat{M}^2} \approx 1\ \mathrm{PeV}\ \frac{1}{\mathrm{Tr}(\sigma_i \boldsymbol{X}'_A) g_D} \left(\frac{1\ \mathrm{GeV}}{f_{\hat{\pi}}}\right)\left(\frac{10^{-2}}{\delta\hat{M}^2/M_Z^2}\right)\left(\frac{M_{Z'}}{60\ \mathrm{GeV}}\right)^2$$

focus on light Z', below M_Z

assume $N_f = 2$ dark flavors
$\rightarrow N_f^2 - 1 = 3$ dark pions

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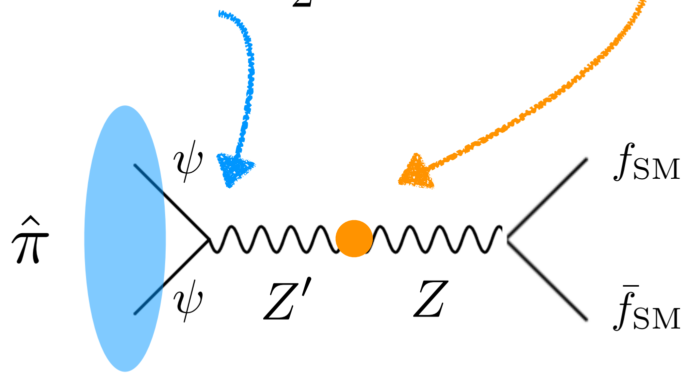

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upper bound on Z - Z' mixing

from electroweak precision

assume $N_f = 2$ dark flavors

$\rightarrow N_f^2 - 1 = 3$ dark pions

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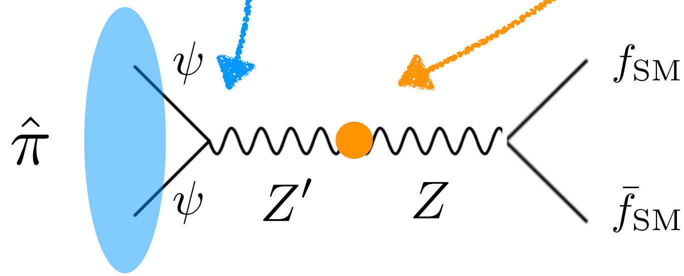

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decay constant of dark pions

assume $N_f = 2$ dark flavors

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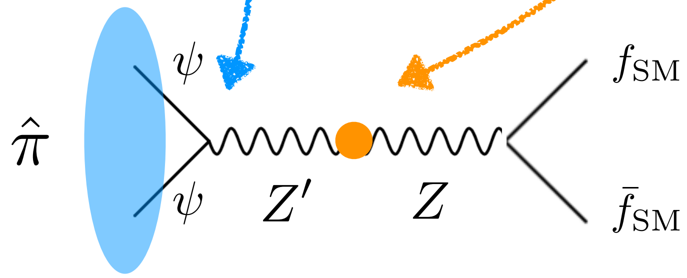

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axial-vector coupling of Z' to physical dark quarks

(generated by dark Yukawas $y_{ij}\overline{\psi}_i\Phi\psi_j$)

assume $N_f = 2$ dark flavors
$\rightarrow N_f^2 - 1 = 3$ dark pions

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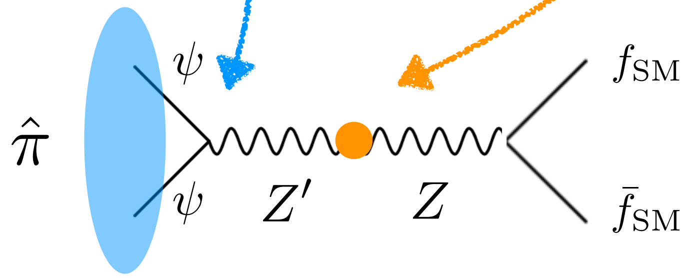

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typical decay constant is at ~ PeV: dark pions are

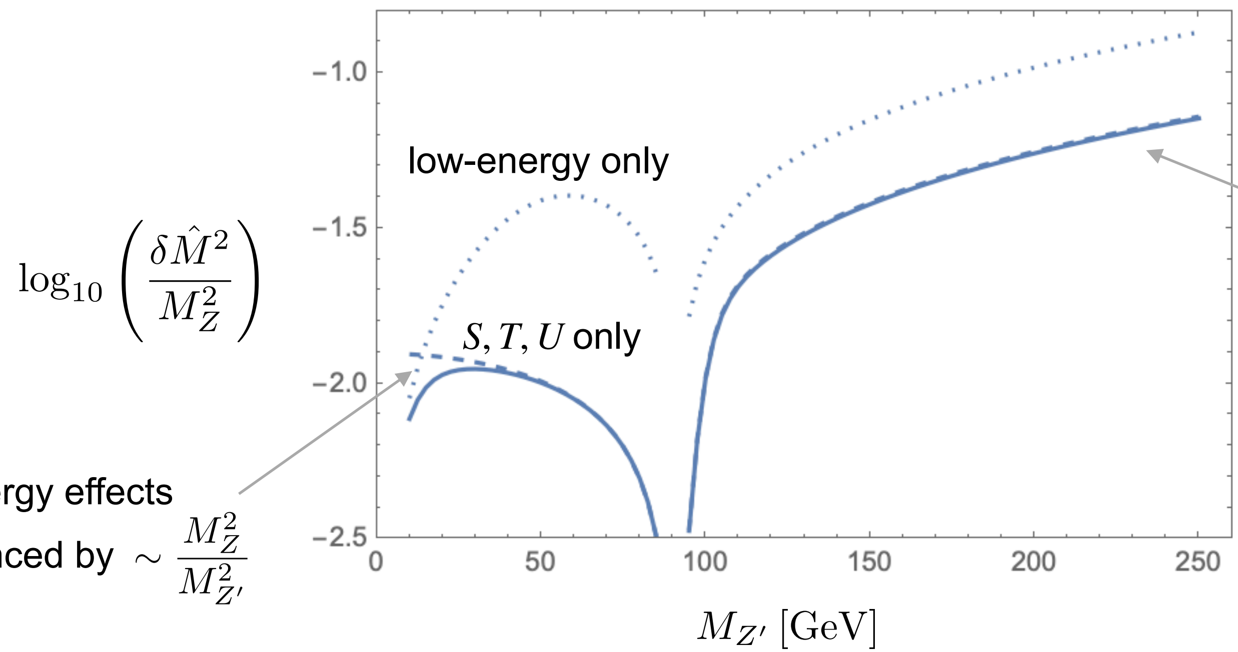
interesting target for present & future LHC experiments

assume $N_f = 2$ dark flavors

$\rightarrow N_f^2 - 1 = 3$ dark pions

Electroweak precision constraints

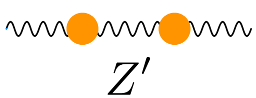
- Z pole couplings and W mass $\rightarrow$ S, T, U parameters [Peskin, Takeuchi 1992]
- Add low-energy data (atomic parity violation, ee, ep scattering) [Altarelli et al. 1991]



Low-energy effects enhanced by $\sim \frac{M_Z^2}{M_{Z'}^2}$

$$\frac{(\delta\hat{M}^2)^2}{M_{Z'}^2} = \text{constant}$$

EFT regime



[Barbieri et al. 2004]

[Here results for zero kinetic mixing, complete analysis in paper.

S, T, U fit has flat direction for $\varepsilon \approx -\delta\hat{M}^2/(s_W M_Z^2)$, lifted by low-energy data]

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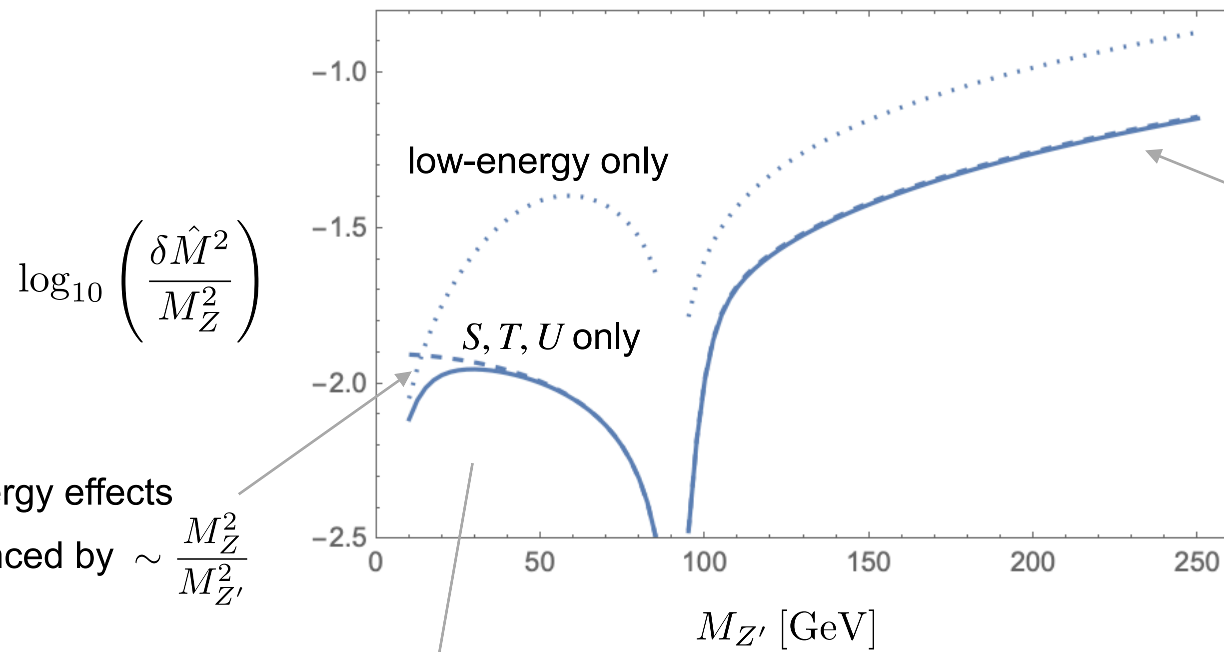

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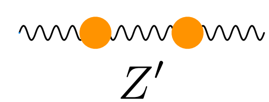


[Barbieri et al. 2004]

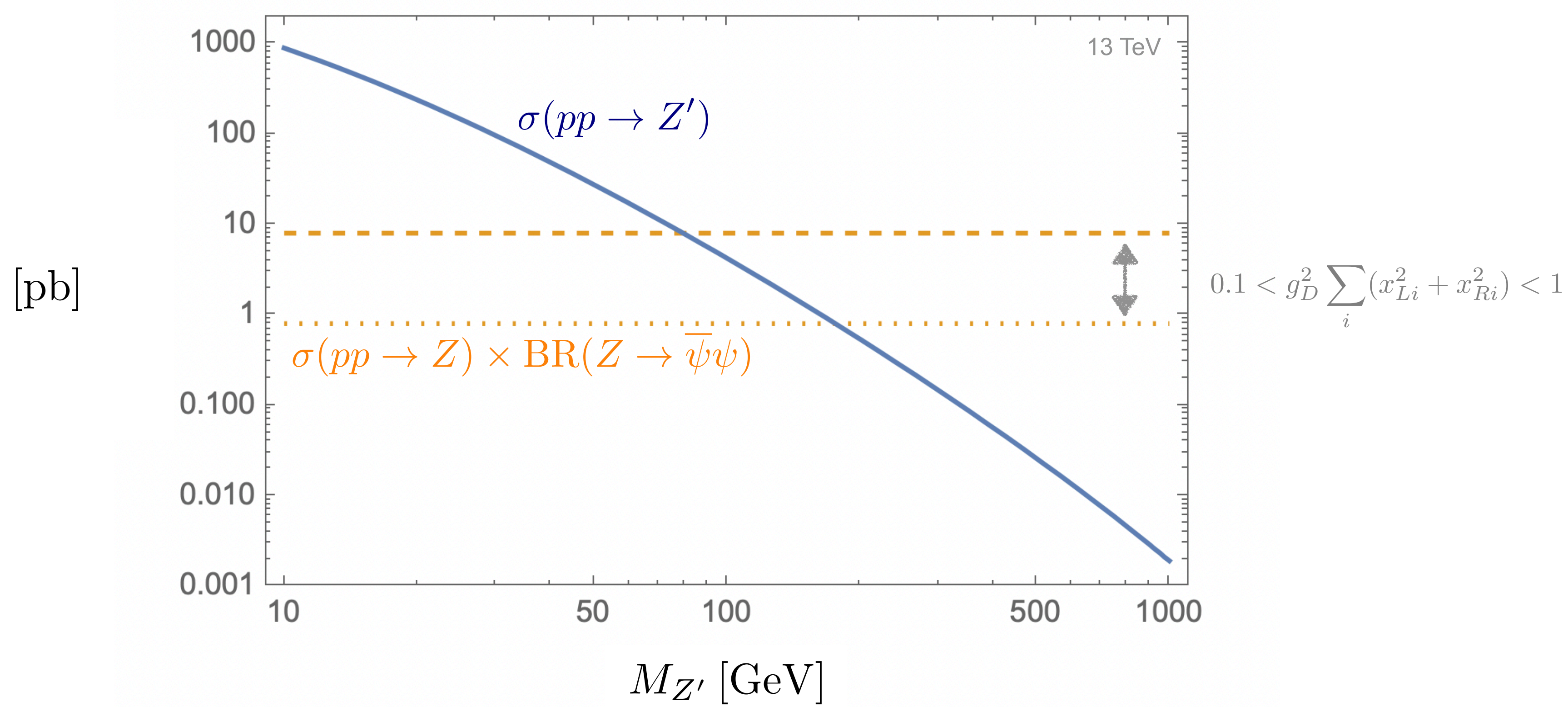
For light Z', bound is approximately $\frac{\delta \hat{M}^2}{M_Z^2} \approx \xi \lesssim 10^{-2}$

mixing angle between Z and Z'

Phenomenology

Dark sector production at the LHC: Z' versus Z

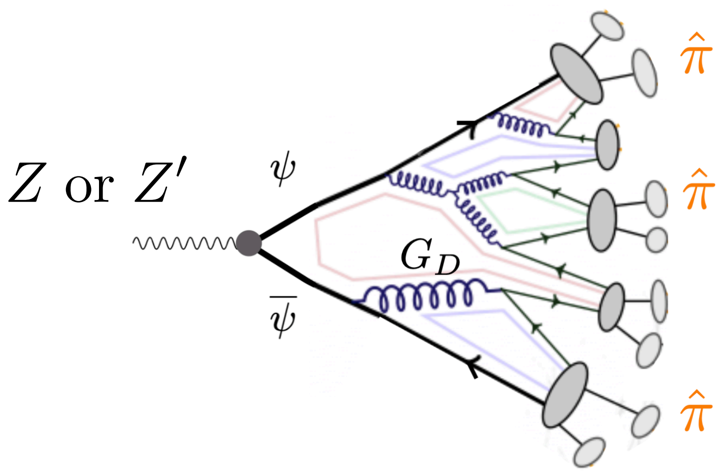
(mixing angle $\xi = 0.01$)



A light Z' gives a large rate of dark sector events, consistently with EW precision

Phenomenology

Signals: dark shower events versus FCNC decays of SM mesons



$$B \to K\,\hat{\pi}$$

loop function

$$\mathrm{BR} \approx 10^{-8} \left(\frac{1\ \mathrm{PeV}}{f_a}\right)^2 \left(\frac{\mathcal{K}_t}{10}\right)^2$$

Emerging jets (mix of macroscopic lifetimes)

No hard SM objects automatically associated

→ trigger is key issue, focus on $\hat{\pi} \to \mu^+\mu^-$

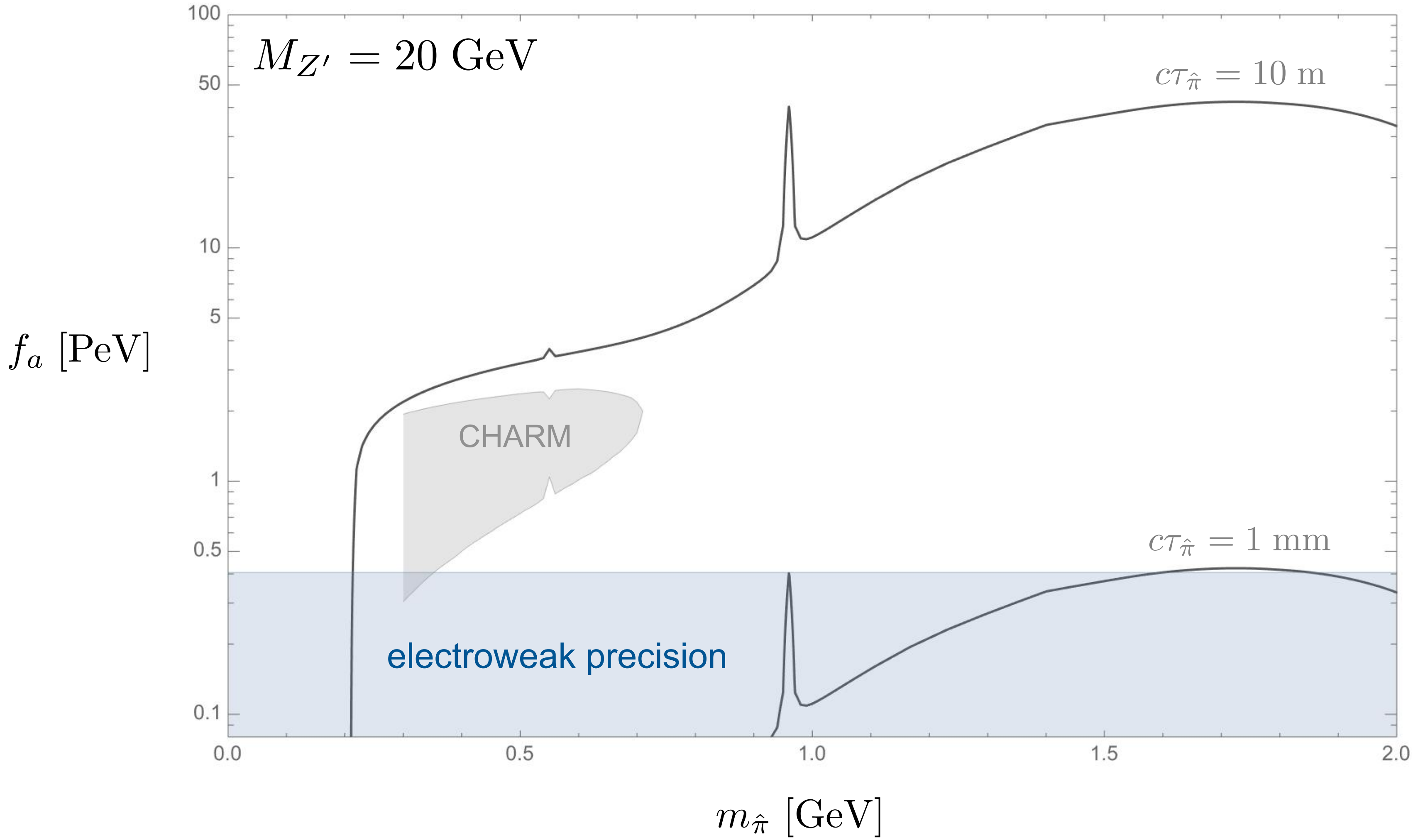
Distinctive feature of confining dark sector

General probe of light new particles

Only sensitive to f_a

[Schwaller, Stolarski, Weiler 2015]

Constraints: pre-LHC



$\mathrm{Tr}(\sigma_{1,3} \boldsymbol{X}'_A) = 1$

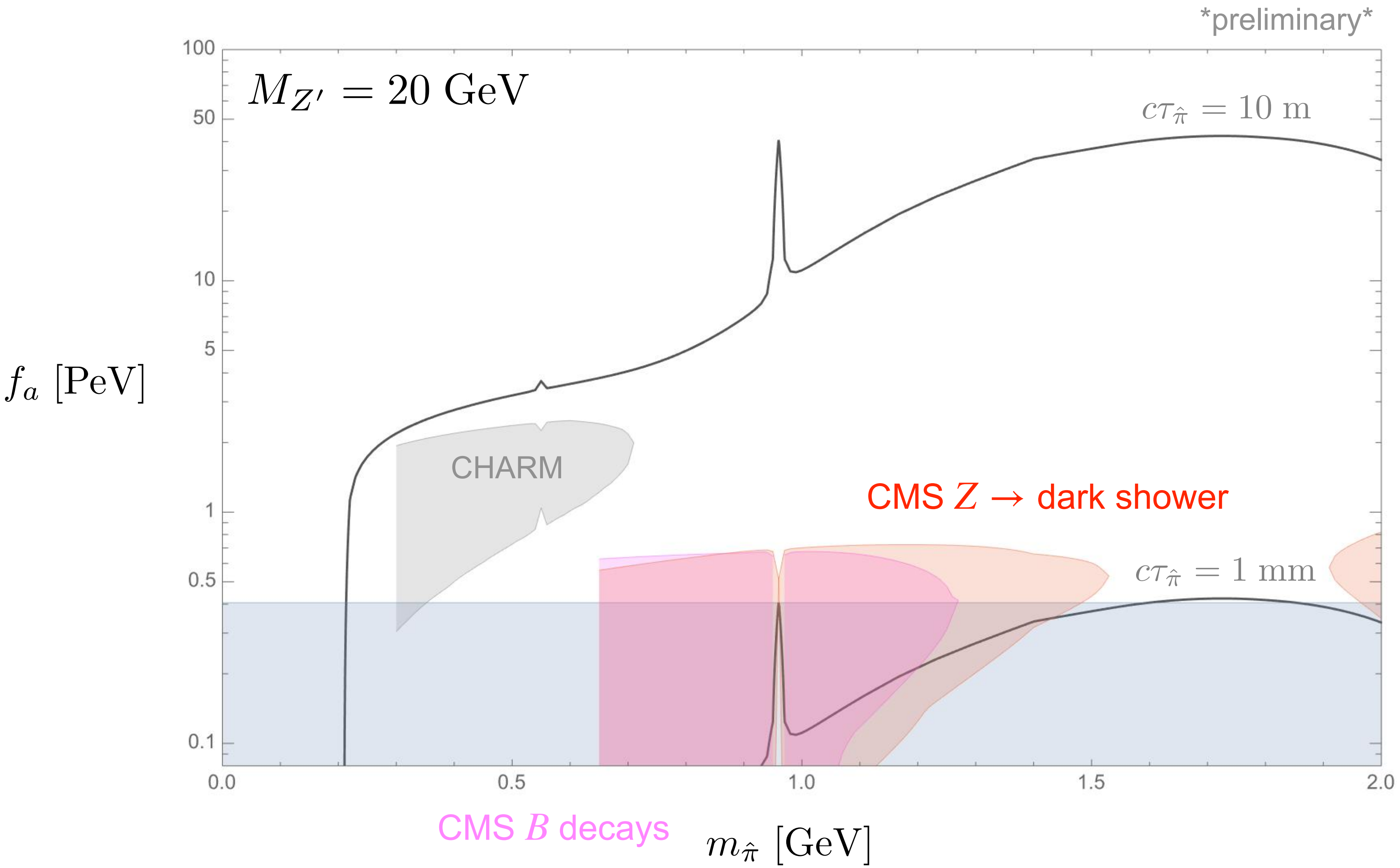
$\hat{\pi}_2$ collider stable

$g_D = 0.25,\ f_{\hat{\pi}} = 1$ GeV

(traded Z - Z' mixing for f_a)

CHARM: [Döbrich, Ertas, Kahlhöfer, Spadaro 2018]

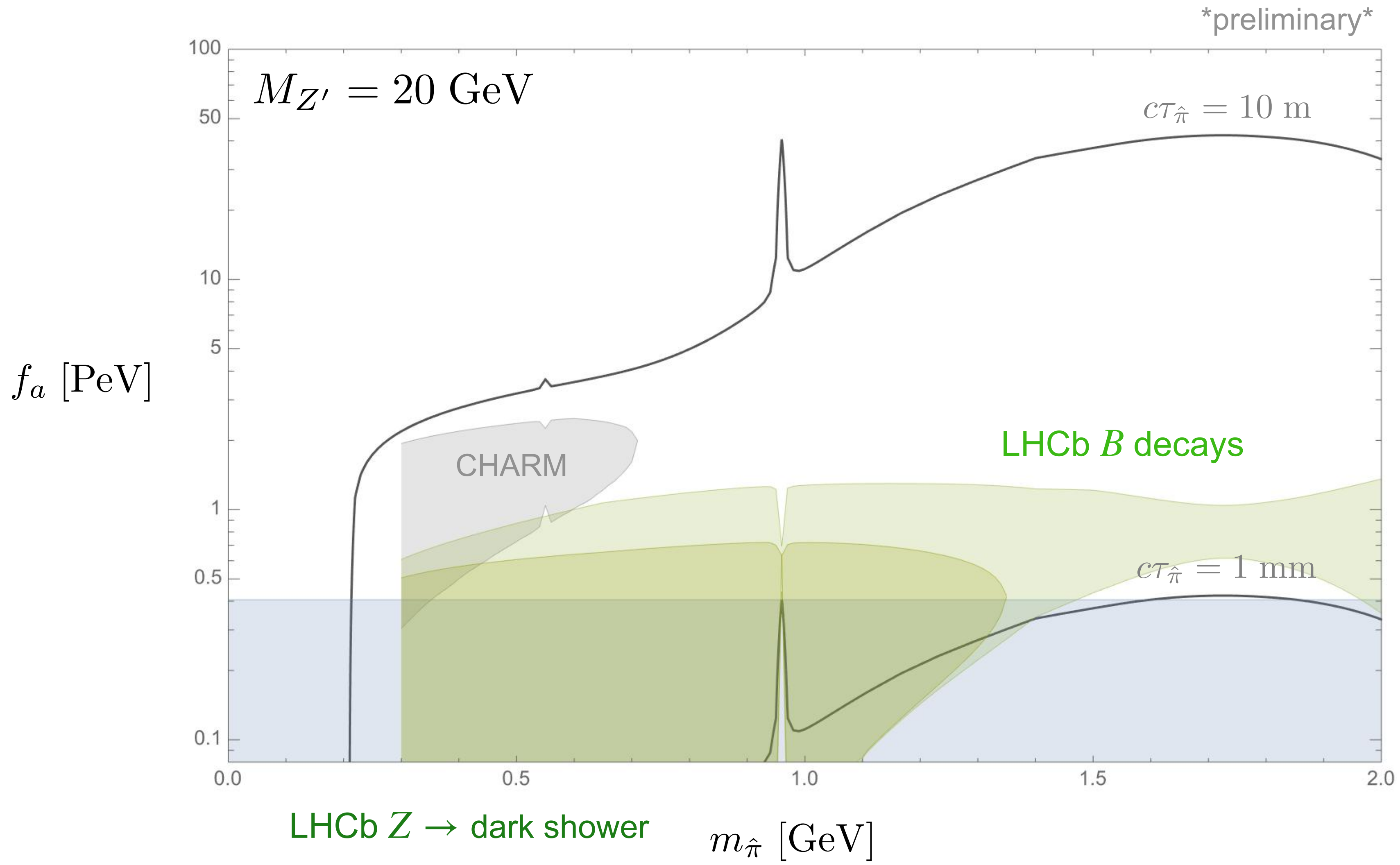
Constraints: CMS



We recast the CMS scouting search for displaced dimuons to dark shower signal

[CMS 2112.13769]

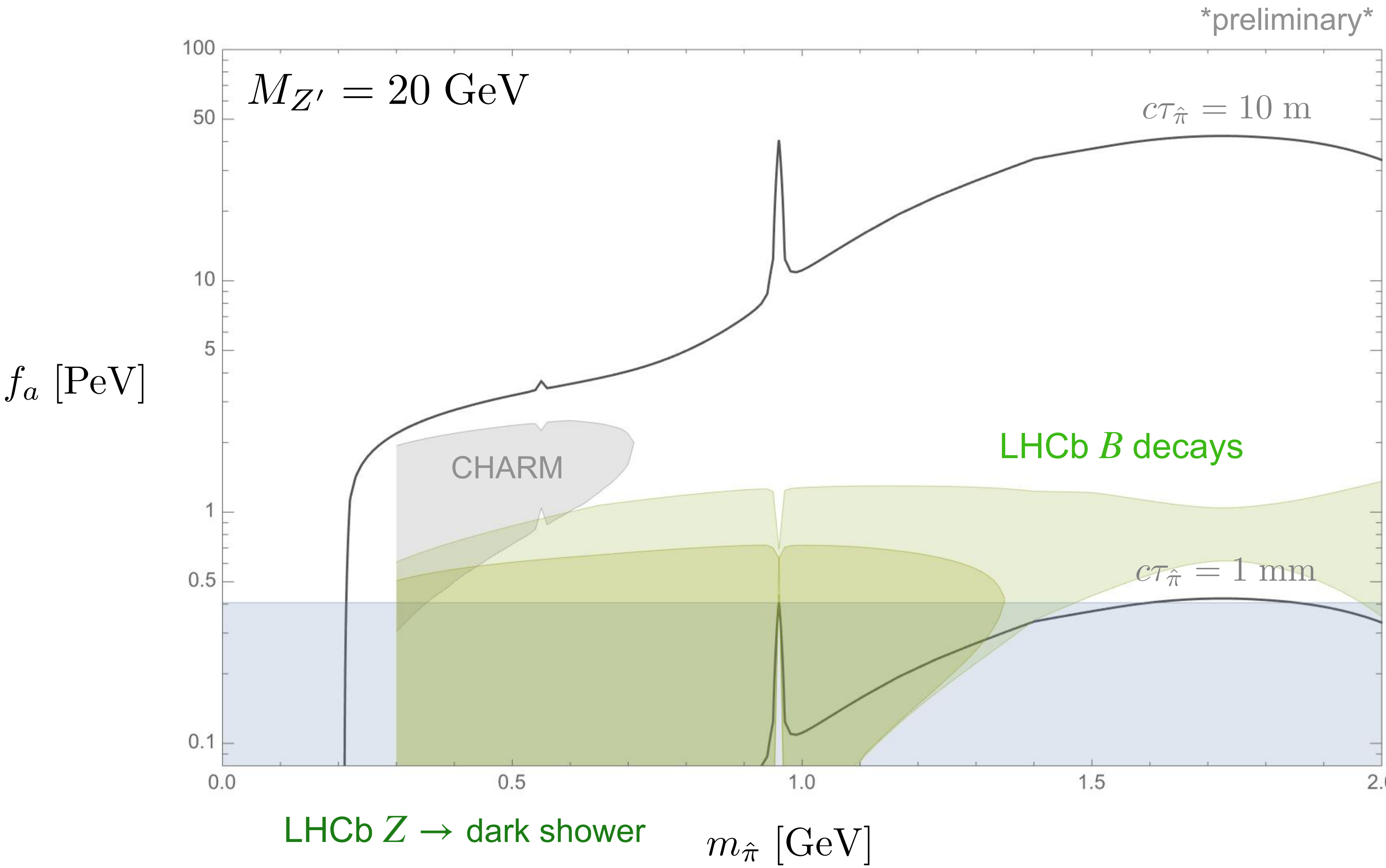
Constraints: LHCb



We recast the LHCb search for low-mass dimuon resonances to dark shower signal

[LHCb 2007.03923]

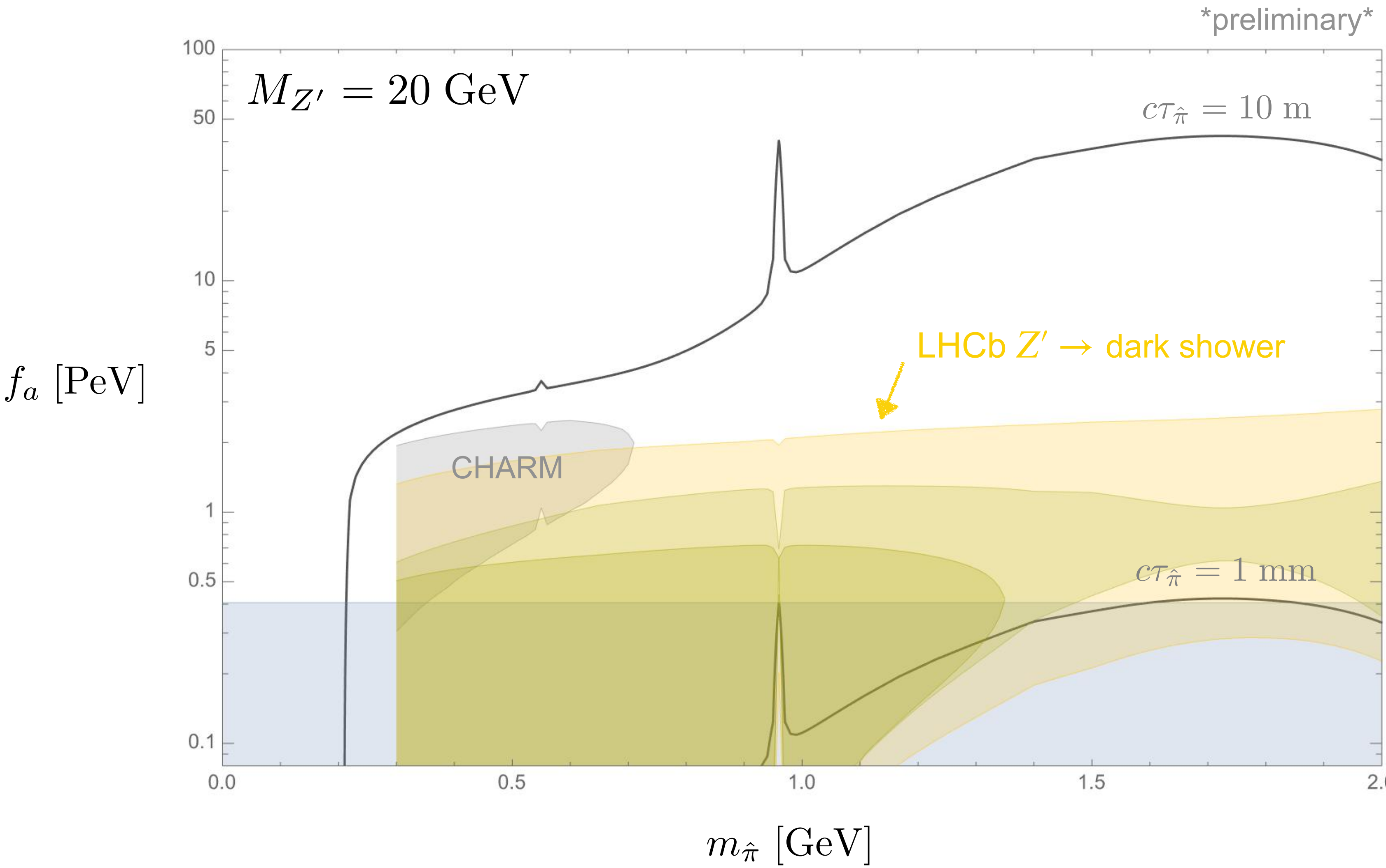
Constraints: LHCb



Z decay exclusions depend on underlying parameters (e.g. $f_{\hat{\pi}}$)

B decay exclusions do not

Constraints: LHCb



Dark shower signal initiated by light Z' can be powerfully tested by LHCb

Summary

- More than 10^{11} Z bosons @ LHC: can it be the portal to a confining dark sector?

- Dark pions behave as composite ALPs. Electroweak precision constraints automatically make them LLPs, leading to dark shower signatures

- Two classes of models. Here focused on completion by (light) Z' with mass mixing

- Presented recasts of CMS and LHCb searches for light dimuon resonances: dark shower sensitivity competes with FCNC B meson decays

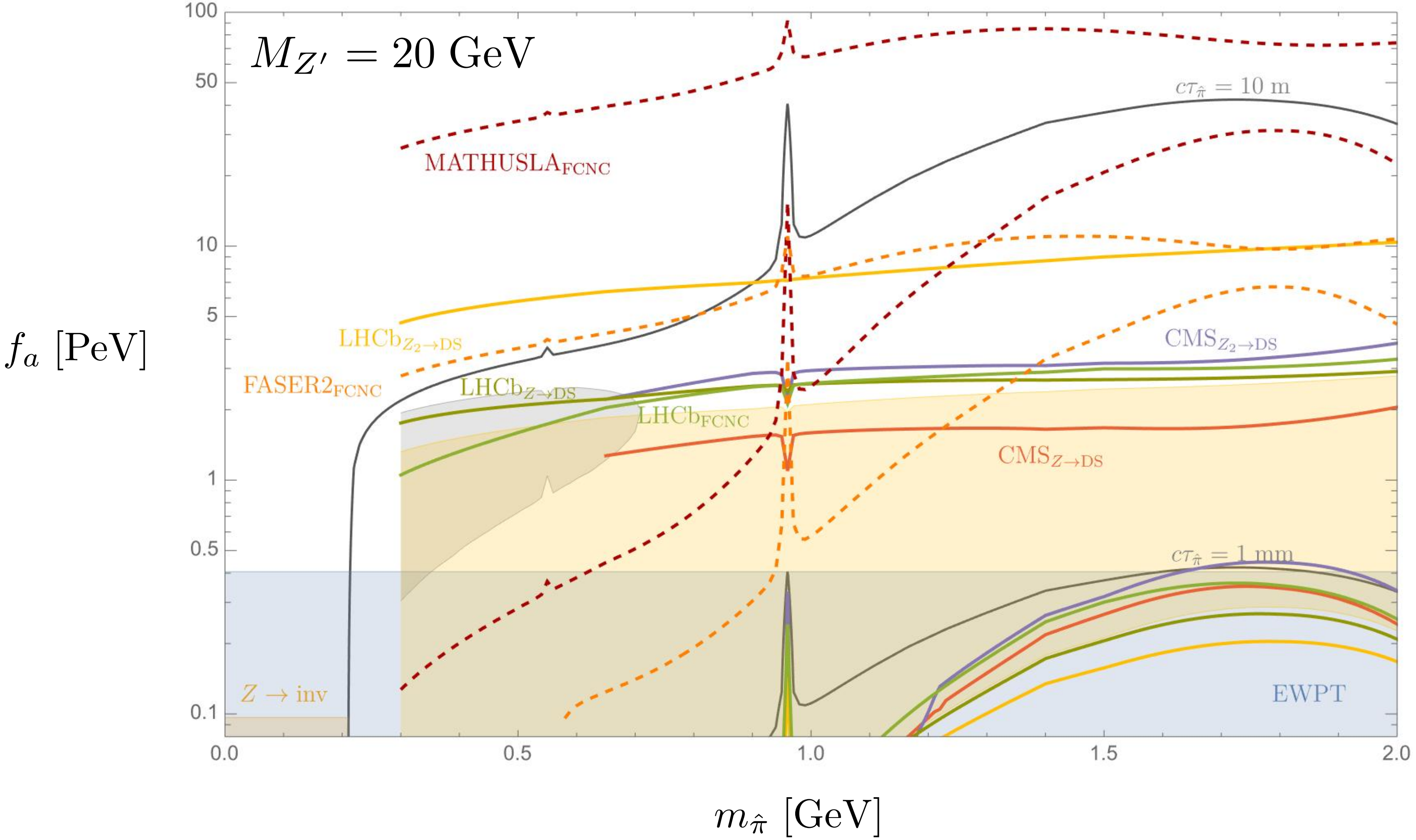
- Much left to do, starting with hadronic ALP decays. For instance, we find $a \to \pi^+\pi^-\pi^0$ dominates for $m_a \gtrsim 1\ \mathrm{GeV}$

[Cheng, Jiang, Li, Salvioni to appear]

Extra slides

Partial set of projections

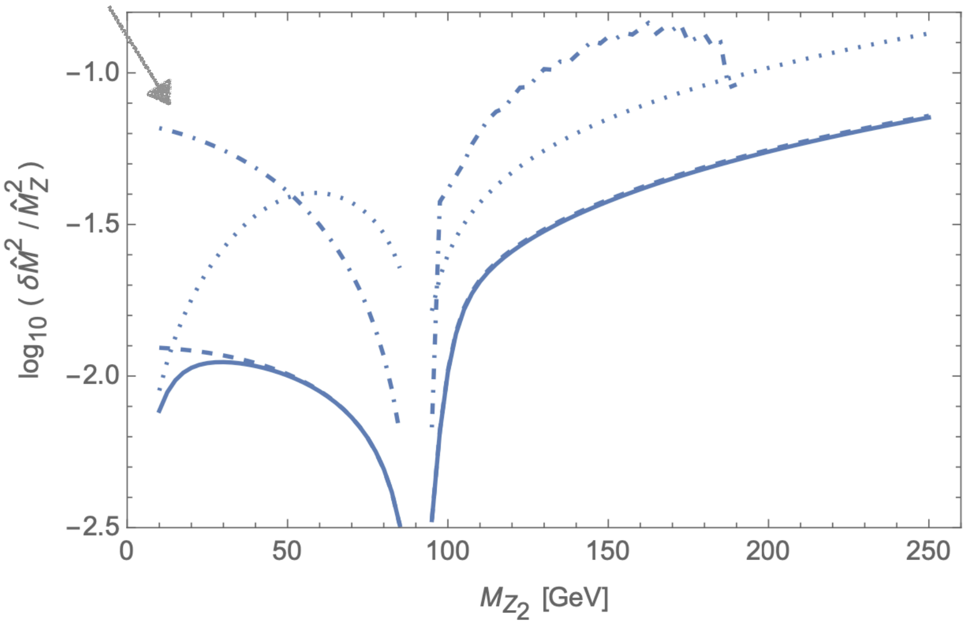
preliminary



(here the Z' is called Z_2)

More on EW precision

DELPHI $e^+e^- \to \gamma(Z_2 \to \text{inv})$



$$S = \frac{4s_W^2}{\alpha}\left(\frac{c_W^2}{s_W}\xi t_\chi - c_W^2\xi^2\right), \quad T = \frac{1}{\alpha}\left(2s_W\xi t_\chi + \xi^2\left(\frac{M_{Z_2}^2}{M_{Z_1}^2} - 2\right)\right), \quad U = \frac{4s_W^2}{\alpha}c_W^2\xi^2,$$

$$\left(\begin{array}{c} \mathcal{L}_{Z_1 f\bar{f}} = -\frac{\bar{Z}e}{s_W c_W}\bar{f}\gamma^\mu(T_{Lf}^3 - s_*^2 Q_f)fZ_{1\mu}, \\ \bar{Z} = 1 + \frac{\alpha T}{2}, \qquad s_*^2 = s_W^2 + \frac{\alpha}{c_W^2 - s_W^2}\left(\frac{S}{4} - s_W^2 c_W^2 T\right), \\ \frac{M_W^2}{M_Z^2} = c_W^2 + \frac{\alpha c_W^2}{c_W^2 - s_W^2}\left(-\frac{S}{2} + c_W^2 T + \frac{c_W^2 - s_W^2}{4s_W^2}U\right). \end{array}\right)$$

(here the Z is called Z_1 and $\varepsilon \equiv \sin\chi$)

More on EW precision/2

B.1 Oblique parameters for heavy dark Z'

For $M_{Z_2} \gg M_{Z_1}$, the dark Z' can be integrated out to obtain an effective Lagrangian at the weak scale. In the parametrization of Ref. [10], Eqs. (3.5) and (3.6) are replaced by expressions that depend on W, Y, V, X in addition to $\widehat{S}, \widehat{T}$ and $\widehat{U}$,

$$\bar{Z} = 1 + \frac{1}{2}\left[\widehat{T} - W - \frac{s_W^2}{c_W^2} Y + 2\frac{s_W}{c_W} X\right], \tag{B.11}$$

$$s_*^2(M_Z^2) - s_W^2 = \frac{1}{c_W^2 - s_W^2}\left[s_W^2 \widehat{S} - s_W^2 c_W^2 \widehat{T} - s_W^4 W + \frac{s_W}{c_W}(1 - 2 s_W^2 c_W^2) X - s_W^2 c_W^2 Y\right],$$

$$\frac{M_W^2}{M_Z^2} - c_W^2 = \frac{c_W^2}{c_W^2 - s_W^2}\left[-2 s_W^2 \widehat{S} + c_W^2 \widehat{T} - (c_W^2 - s_W^2)(\widehat{U} - V) - 2 s_W c_W X + s_W^2 (W + Y)\right].$$

Integrating out the $\hat{Z}'$ at tree level from Eqs. (2.3) and (2.4), we obtain

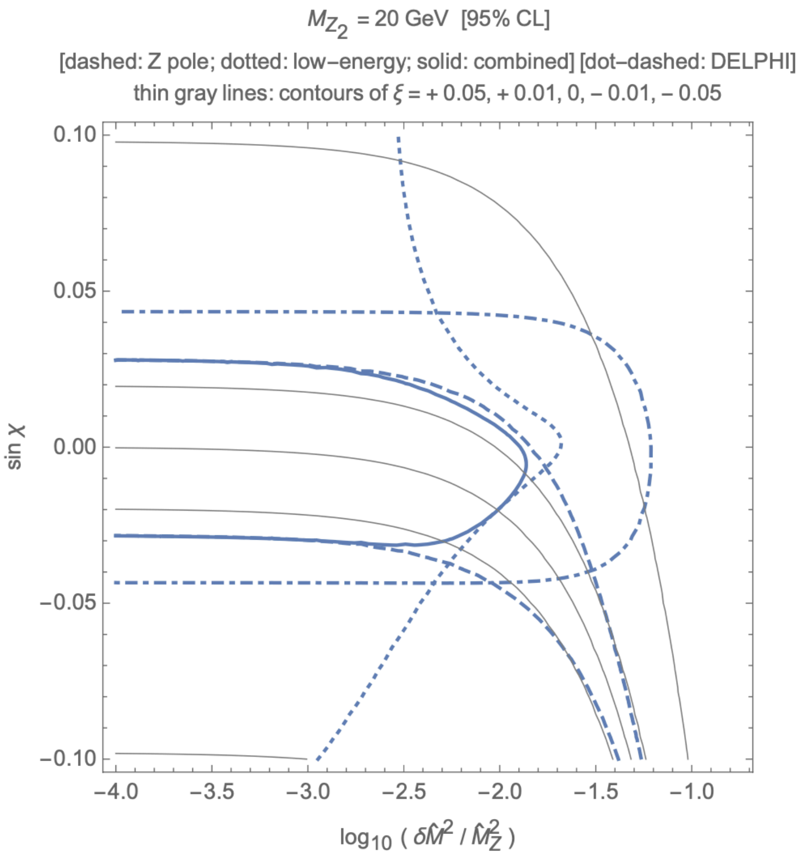
$$\widehat{S} = -\frac{\hat{c}_W^2}{\hat{s}_W}\frac{\delta \hat{M}^2}{\hat{M}_{Z'}^2}\left(\sin\chi + \hat{s}_W \frac{\delta \hat{M}^2}{\hat{M}_{Z'}^2}\right), \qquad \widehat{T} = \hat{c}_W^2 \frac{(\delta \hat{M}^2)^2}{M_W^2 \hat{M}_{Z'}^2},$$

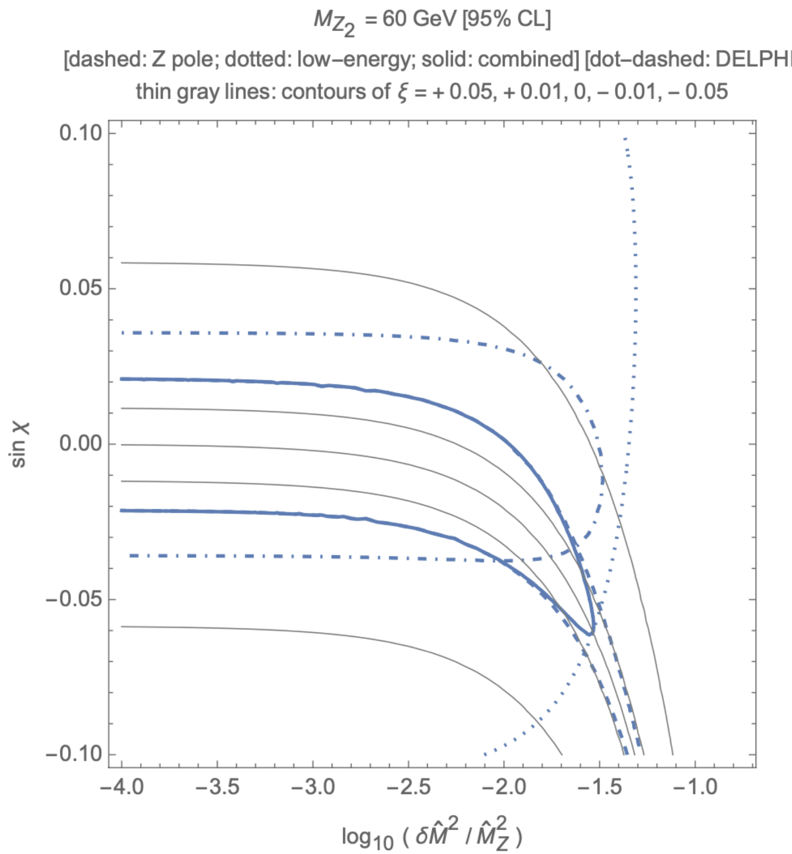
$$\widehat{U} = -\hat{c}_W^2 \frac{(\delta \hat{M}^2)^2}{\hat{M}_{Z'}^4}, \quad W = V = \hat{c}_W^2 \frac{M_W^2 (\delta \hat{M}^2)^2}{\hat{M}_{Z'}^6}, \quad Y = \frac{M_W^2}{\hat{M}_{Z'}^2}\left(\sin\chi + \hat{s}_W \frac{\delta \hat{M}^2}{\hat{M}_{Z'}^2}\right)^2,$$

$$X = -\hat{c}_W \frac{M_W^2 \delta \hat{M}^2}{\hat{M}_{Z'}^4}\left(\sin\chi + \hat{s}_W \frac{\delta \hat{M}^2}{\hat{M}_{Z'}^2}\right). \tag{B.12}$$

We observe that $\widehat{S} = (\hat{c}_W/\hat{s}_W)(\hat{M}_{Z'}^2/M_W^2)X$ and $\widehat{T} = -(\hat{M}_{Z'}^2/M_W^2)\widehat{U} = (\hat{M}_{Z'}^4/M_W^4)V$, explicitly illustrating the well-known fact that $\widehat{S}, \widehat{T}, W, Y$ are sufficient to descrive heavy universal new physics [10].

More on EW precision/3





FCNC B meson decays

$$\mathcal{L}_{\text{eff}}^{\text{FCNC}} = -\, g_D \hat{g}_Z \frac{\delta \hat{M}^2}{M_{Z_1}^2 M_{Z_2}^2 \cos^2\chi} \frac{\hat{g}^2}{128\pi^2} J_D^\mu \bar{d}_j \gamma_\mu P_L d_i \sum_{q\,\in\, u,c,t} V_{qj}^* V_{qi} \mathcal{K}_q + \text{h.c.}\ , \tag{6.1}$$

where

$$\mathcal{K}_q \equiv x_q \log \frac{\Lambda_{\text{UV}}^2}{M_W^2} + \frac{-7x_q + x_q^2}{2(1-x_q)} - \frac{4x_q - 2x_q^2 + x_q^3}{(1-x_q)^2} \log x_q\,, \tag{6.2}$$

with the definition $x_q \equiv m_q^2/M_W^2$. The contribution from $q = t$ dominates. The residual divergence appears because our treatment of the Z-Z' mixing is not UV complete. The divergence will be removed in a complete model where the new fields inducing $\delta \hat{M}^2$, such as a second Higgs doublet, are included dynamically. In that case Λ_{UV} would be set by the mass of the charged Higgs scalar, possibly up to $O(1)$ factors. Numerically, the dimensionless quantity $\mathcal{K}_t$ varies from 5.0 to 16 as Λ_{UV} is increased from 300 GeV to 1 TeV, signaling an important theoretical uncertainty.

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

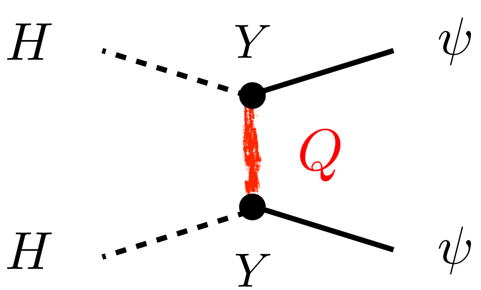
Model with heavy fermions Q

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

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

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

"dark pions"

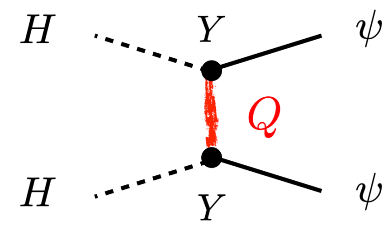


$$M \gtrsim \text{TeV}$$

heavy mediators

[Cheng, Li, Salvioni, 2110.10691]

Dark pions



- Integrate out heavy fermions Q

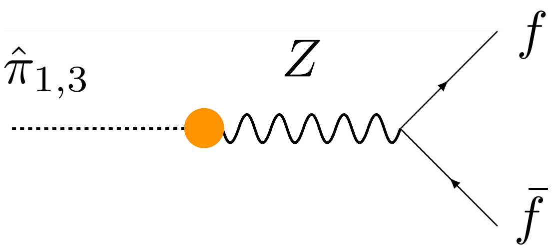
$$\mathcal{L}_{\rm EFT} \sim (\overline{\psi}_R \boldsymbol{Y}^\dagger \boldsymbol{M}^{-2} \boldsymbol{Y} \gamma^\mu \psi_R)\,(iH^\dagger D_\mu H) + (\overline{\psi}_L \widetilde{\boldsymbol{Y}}^\dagger \boldsymbol{M}^{-2} \widetilde{\boldsymbol{Y}} \gamma^\mu \psi_L)\,(iH^\dagger D_\mu H)$$

Z portal (dim-6)

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

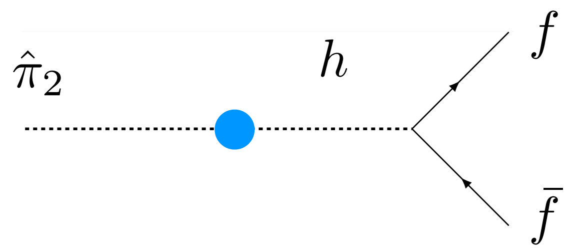
Higgs portal (dim-5)

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



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

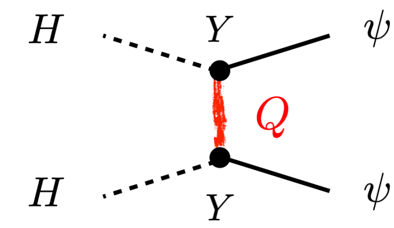
composite ALP



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

composite Higgs-mixed scalar

Dark pions



- Integrate out heavy fermions Q

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

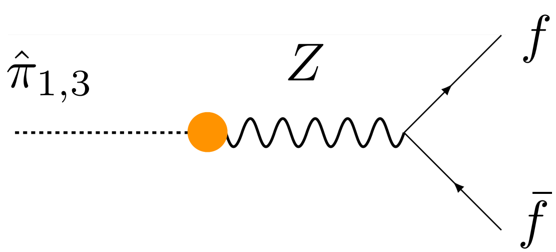
Z portal (dim-6)

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

Higgs portal (dim-5)

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

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



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

isospin-violating couplings to SM fermions

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

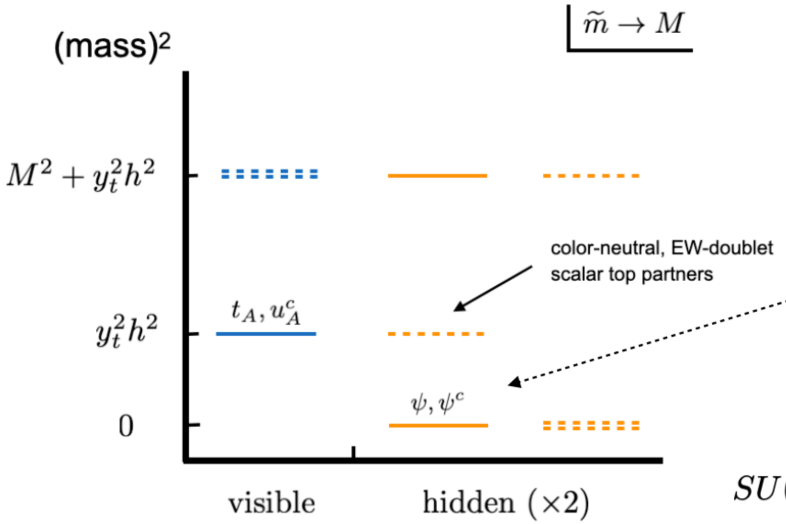
composite ALP

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

Ultraviolet motivations

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

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



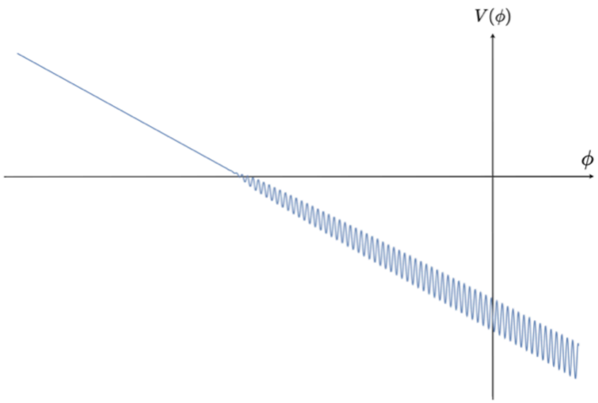
light Dirac fermions

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

Dark showers @ LHCb

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