Charming dark pions

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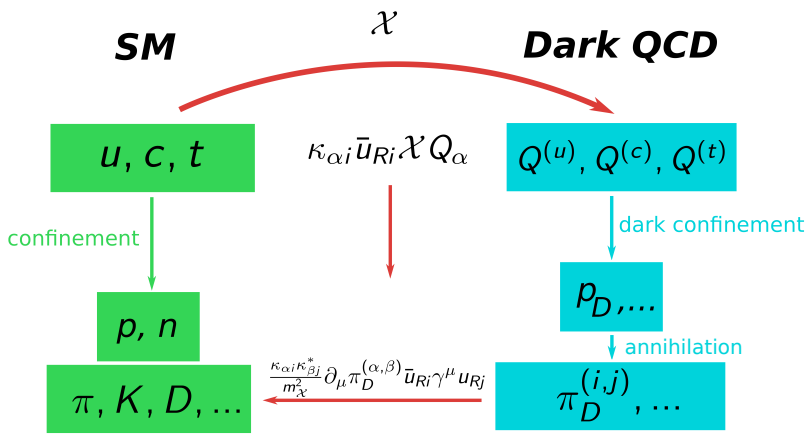
Framework

- ALP pNGB of global U(1)

$$\mathcal{L}_{eff} = \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{m_a^2}{2}a^2 + \frac{\partial_\mu a}{f_a}\left[(c_{u_R})_{ij}\bar{u}_{Ri}\gamma^\mu u_{Rj} + c_H H^\dagger i\overleftrightarrow{D_\mu}H\right]$$
$$- \frac{a}{f_a}\left[c_{gg}\frac{g_3^2}{32\pi^2}G^a_{\mu\nu}\tilde{G}^{\mu\nu a} + c_{WW}\frac{g_2^2}{32\pi^2}W^I_{\mu\nu}\tilde{W}^{\mu\nu I} + c_{BB}\frac{g_1^2}{32\pi^2}B_{\mu\nu}\tilde{B}^{\mu\nu}\right]$$

- no coupling to Q_L, d_R, leptons
- $\mathcal{O}_H = (\partial_\mu a/f_a)\, H^\dagger i\overleftrightarrow{D_\mu}H$ and $\mathcal{O}_W = (a/f_a)\, g_2^2/(32\pi^2) W^I_{\mu\nu}\tilde{W}^{\mu\nu I}$ induce FCNCs
  $\Rightarrow$ assume small WCs
- flavour-violating effects from $\frac{\partial_\mu a}{f_a}\left(c_{u_R}\right)_{ij}\bar{u}_{R_i}\gamma^\mu u_{R_j}$

Benchmark 1: 'Dark QCD' UV completion



Dark Pions	Dark quark content
$\pi_D^{(1,2)}$	$\bar{Q}_2 Q_1$
$\pi_D^{(1,3)}$	$\bar{Q}_3 Q_1$
$\pi_D^{(2,3)}$	$\bar{Q}_3 Q_2$
π_{D_3}	$\frac{1}{\sqrt{2}}\left[\bar{Q}_1 Q_1 - \bar{Q}_2 Q_2\right]$
π_{D_8}	$\frac{1}{\sqrt{6}}\left[\bar{Q}_1 Q_1 + \bar{Q}_2 Q_2 - 2\bar{Q}_3 Q_3\right]$

- $SU(3)_D$ dark sector with neutral dark quarks
- heavy mediator $\chi \sim (3, \bar{3}, 1, -2/3)$ under $SU(3) \otimes SU(3)_D \otimes SU(2)_L \otimes U(1)_Y$
- confinement at $\Lambda_{darkQCD}$
- lightest dark baryon DM candidate
- various π_D lifetimes possible
- identify ALP with π_{D_3} and π_{D_8}

Benchmark 1: 'Dark QCD' UV completion

- non-trivial flavour interplay from coupling $\kappa_{\alpha i}\bar{u}_{R_i}\mathcal{X}Q_\alpha$
- parameterise the coupling $\kappa = UDV$
- degenerate dark quark masses $\rightarrow$ V absorbed from dark flavour symmetry
- $D = diag\left(\kappa_0 + \kappa_1, \kappa_0 + \kappa_2, \kappa_0 - \kappa_1 - \kappa_2\right)$
- U in analogy to V_{CKM}: $U = U_{23}U_{13}U_{12}$, with U_{ij} 3×3 rotation matrices
- benchmark: $\kappa_1 = \kappa_0/2$, $\kappa_2 = \theta_{13} = \theta_{23} = 0$, $\theta_{12} = 0.022$

$$-\sum_{\alpha,\beta}\kappa_{\alpha i}\kappa^*_{\beta j}(\lambda^a)_{\alpha,\beta}\frac{f_{\pi_D}}{m^2_{\mathcal{X}}}\partial_\mu\pi_D^{(\alpha,\beta)}\bar{u}_{R_i}\gamma^\mu u_{R_j} \rightarrow (c_{u_R})_{ij}\frac{1}{f_a}\partial_\mu a\bar{u}_{R_i}\gamma^\mu u_{R_j}$$

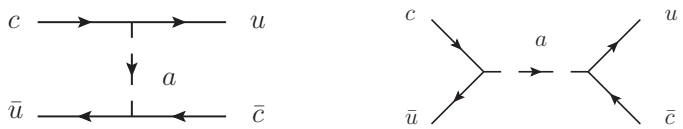
Benchmark 2: Froggatt-Nielsen UV completion

- global flavor $U(1)$ broken by vev $\langle S \rangle = f_a$ with $S = \frac{1}{\sqrt{2}} (f_a + s) e^{ia/f_a}$
- S has charge -1 under new $U(1)$
- here: only u_R charged under new $U(1)$
- new Yukawa term: $-y_{u_{ij}} \left(\frac{S}{\Lambda}\right)^{n_j^u} \bar{q}_{L_i} \tilde{H} u_{R_j} + h.c.$

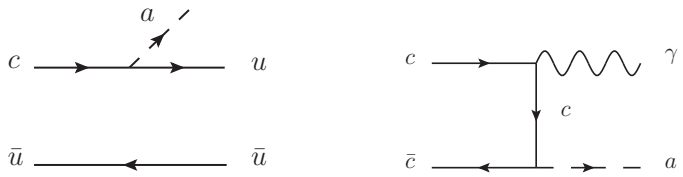
  $\Rightarrow -\frac{ia}{f_a} \bar{q}_{L_i} \tilde{H} u_{R_j} Y_{u_{ij}} n_j^u$ with $Y_{u_{ij}} = y_{u_{ij}} \left(\frac{f_a}{\Lambda}\right)^{n_j^u}$
- with $f_a/\Lambda = \epsilon \sim m_c/m_t$, right quark masses from $n_j = diag(2, 1, 0)$
- after diagonalising $Y_{u_{ij}}$: $c_{u_R} = \begin{pmatrix} 2 & 3\epsilon & 3\epsilon^2 \\ 3\epsilon & 1 & \epsilon \\ 3\epsilon^2 & \epsilon & \epsilon^2 \end{pmatrix}$

Constraints on the model: Flavour constraints

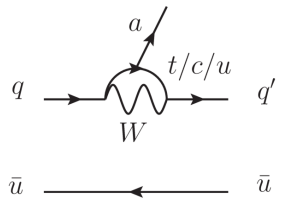
- $\Delta F = 2$: $D^0 - \bar{D}^0$ mixing



- $\Delta F = 1$:
  - tree-level: $D^{\pm} \to \pi^{\pm}$ *invisible*, $J/\psi \to \gamma$ *invisible*

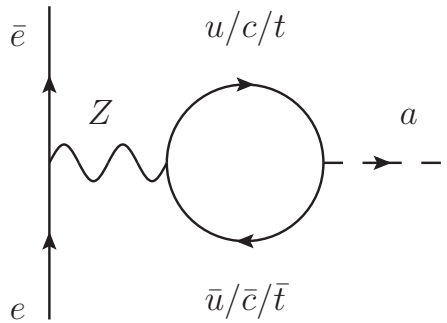


  - 1-loop: $K^{\pm} \to \pi^{\pm}$ *invisible*, $B^{\pm} \to \pi^{\pm}/K^{\pm}$ *invisible*



Constraints on the model: cosmology and astrophysic

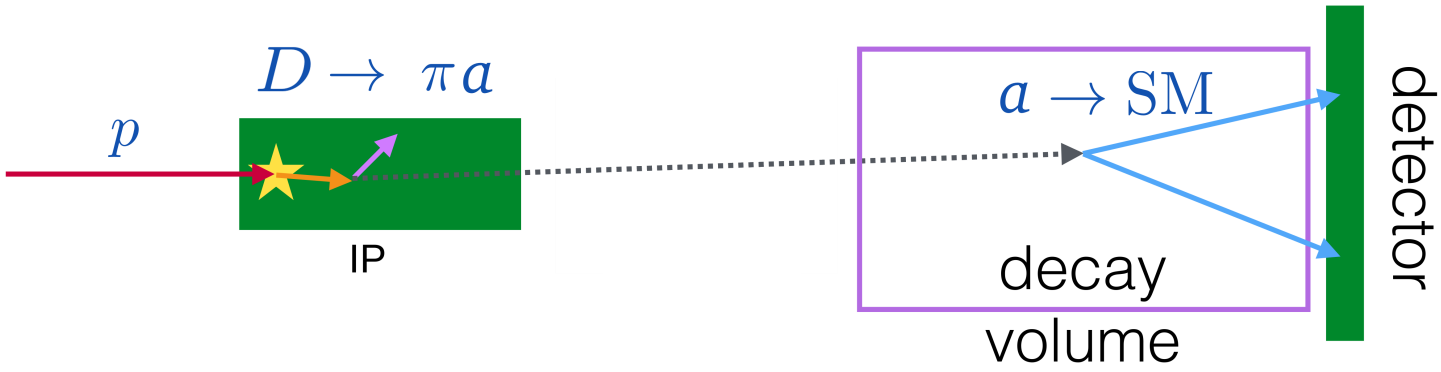
- cosmological constraints from *Cadamuro, Redondo 2012*; *Millea, Knox 2015* (includes # effective dof, distortion of CMB spectrum, red giant bursts, . . .)
- astrophysics: red giant burst



$\Rightarrow$ constraint on effective coupling to electrons

Experimental prospects

- consider production in D meson decays
- possible testing grounds: NA62, SHiP, FASER, MATHUSLA, ...

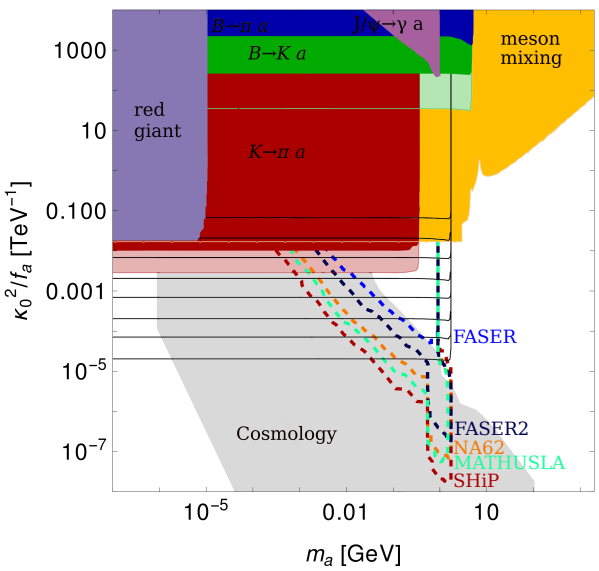


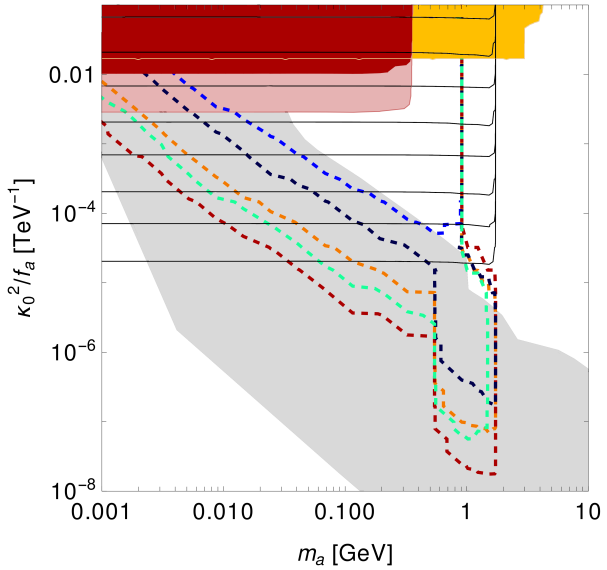
- number of ALPs:

$$N_a = N_D \cdot Br(D \to \pi a) \cdot \epsilon_{geom} \cdot F_{decay}$$

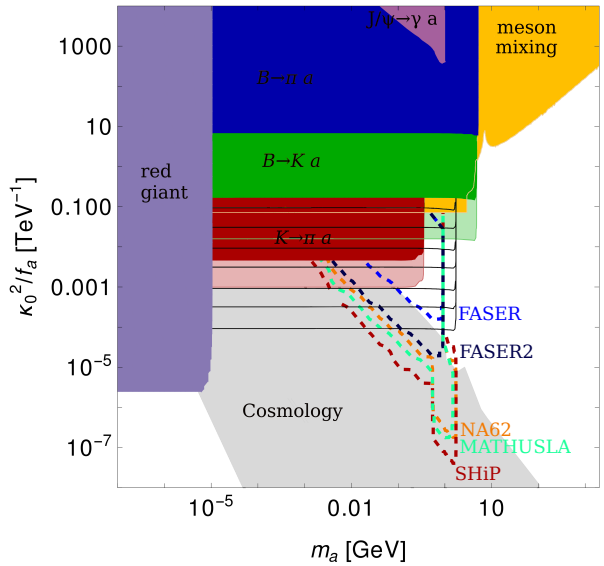
- 3 events for detection

Results: 'dark QCD' UV completion



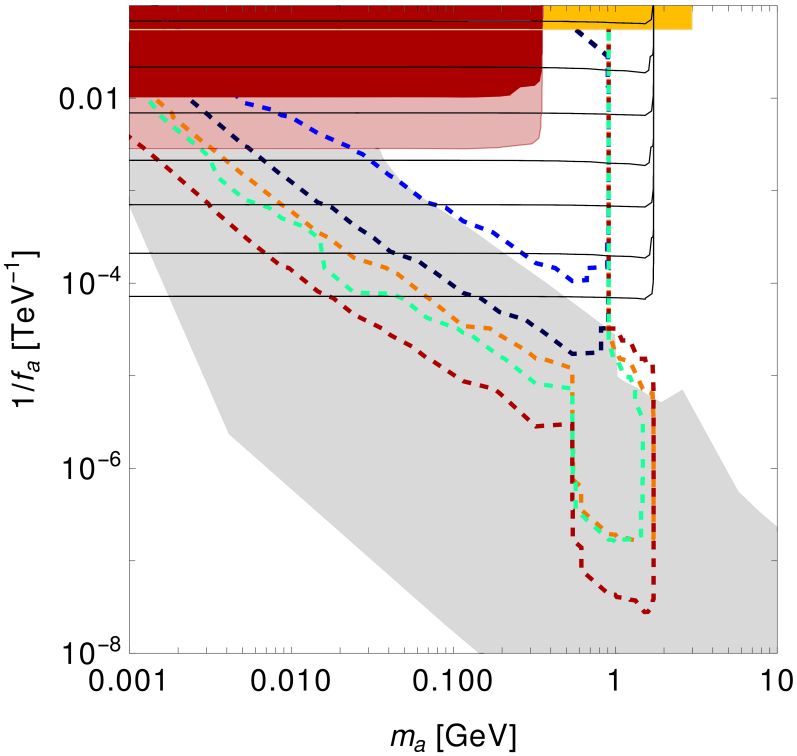


$a \equiv \pi_{D_3}$

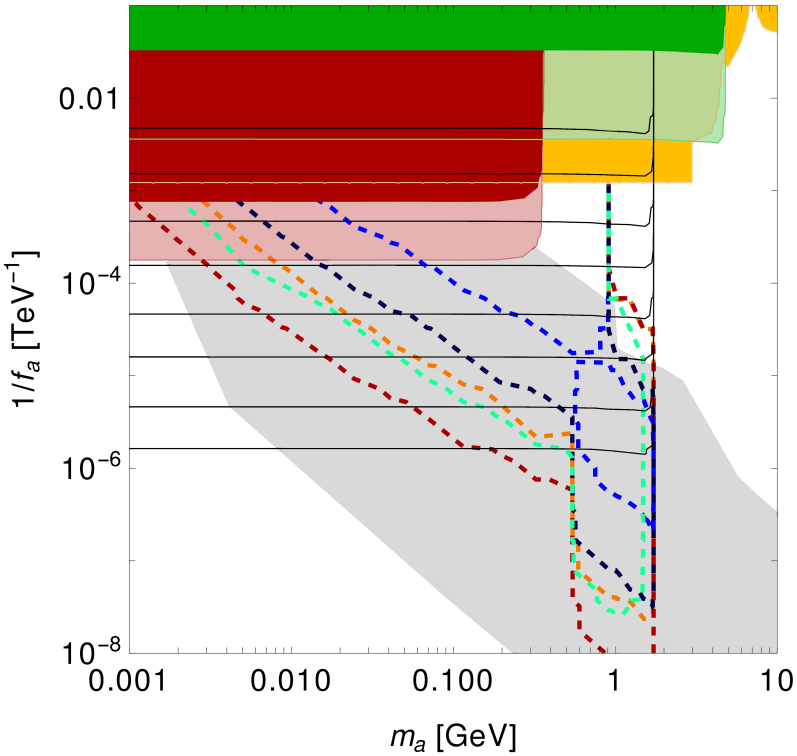


$a \equiv \pi_{D_8}$

Results: FN UV completion and anarchic benchmark



FN



$(c_{u_R})_{ij} = 1$

Summary and Outlook

- search for NP in charm physics
- $m_a \sim$ *few GeV* can be probed with upcoming experiments
- higher mass region ideas:
  - additional production modes, e.g. top decays
  - charming emerging jets, prompt decay searches
  - in dark QCD: DM direct detection

Thank you

Back-up slides

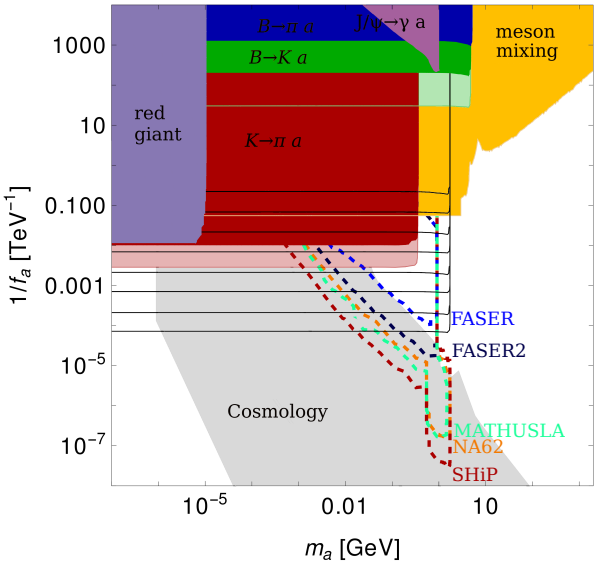
Couplings with numerical values

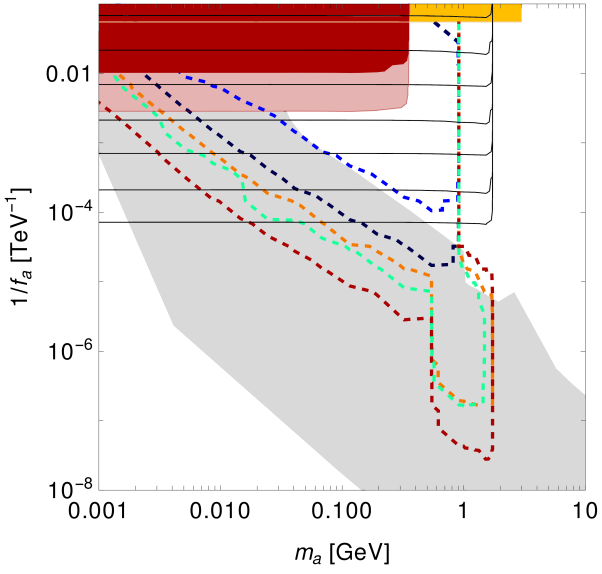
$$\pi_{D_3} : c_{u_R} \simeq \begin{pmatrix} -2.248\kappa_0^2 & -0.071\kappa_0^2 & 0 \\ -0.071\kappa_0^2 & 0.998\kappa_0^2 & 0 \\ 0 & 0 & 0 \end{pmatrix};$$

$$\pi_{D_8} : c_{u_R} \simeq \begin{pmatrix} -1.299\kappa_0^2 & -0.016\kappa_0^2 & 0 \\ -0.016\kappa_0^2 & -0.578\kappa_0^2 & 0 \\ 0 & 0 & 0.289\kappa_0^2 \end{pmatrix}$$

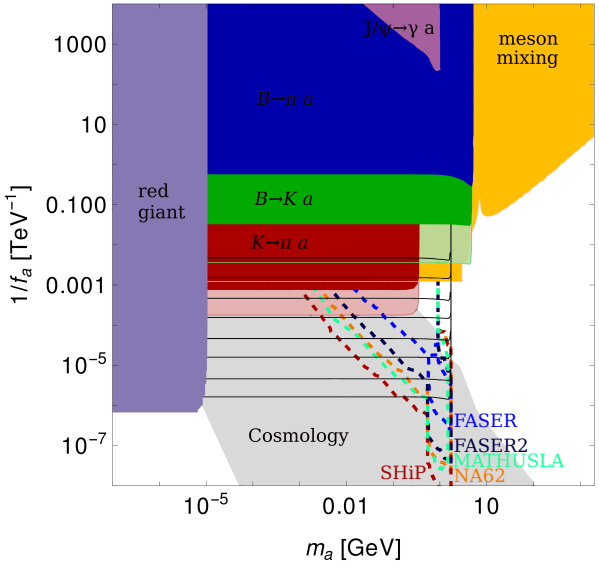
$$FN : c_{u_R} \simeq \begin{pmatrix} 2.0001 & 0.0220 & 0.0002 \\ 0.0220 & 1.0001 & 0.0073 \\ 0.0002 & 0.0073 & 0.0001 \end{pmatrix}$$

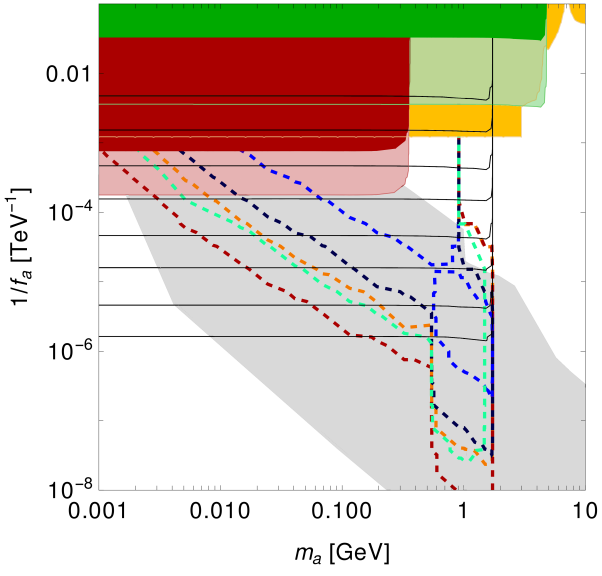
all dark QCD UV completion plots





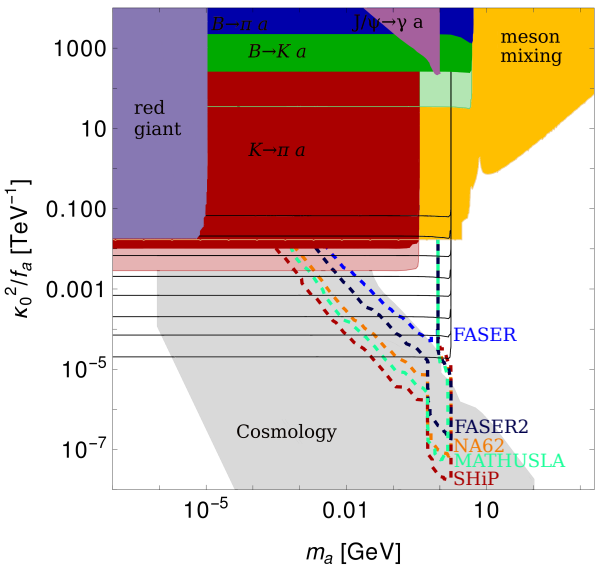
$a \equiv \pi_{D_3}$

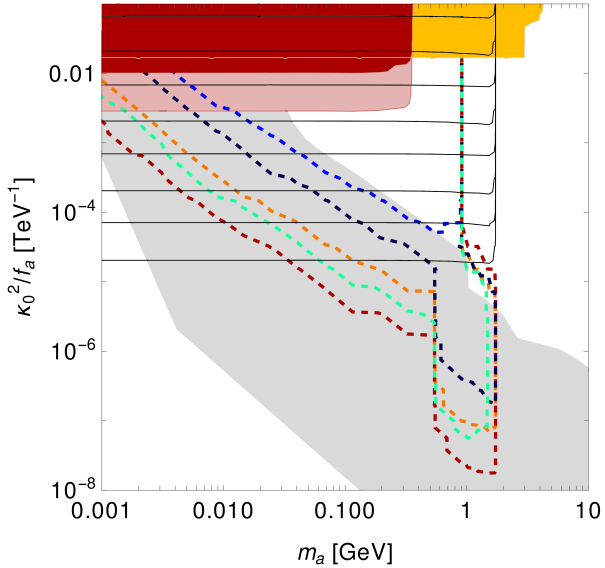




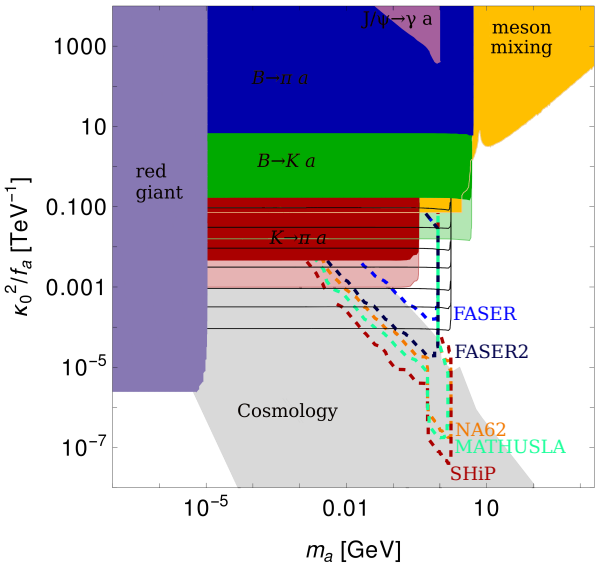
$a \equiv \pi_{D_8}$

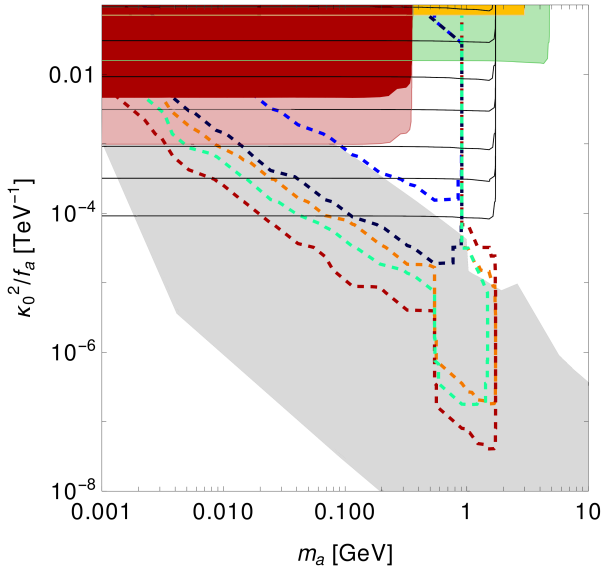
all Fn and anarchic benchmark point plots





FN





$(c_{u_R})_{ij} = 1$