

Charming ALPs

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Cluster of Excellence
PRISMA⁺

Precision Physics,
Fundamental Interactions
and Structure of Matter

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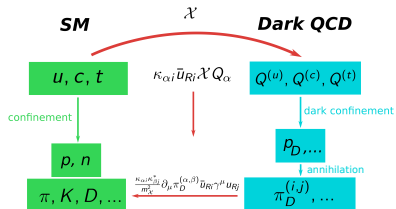
Motivation/Framework

- ALPs are ubiquitous in BSM models
- can have non-trivial interaction with flavour & forward physics phenomenology
- focus on up-sector:

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

- FCNCs from $\mathcal{O}_u = \frac{\delta_\mu a}{f_a} (c_{u_R})_{ij} \bar{u}_{Ri} \gamma^\mu u_{Rj}$,
 $\mathcal{O}_H = (\partial_\mu a / f_a) H^\dagger i \overleftrightarrow{D}_\mu H$, $\mathcal{O}_W = (a / f_a) g_2^2 / (32\pi^2) W_{\mu\nu}^I \tilde{W}^{\mu\nu I}$
 \Rightarrow here: c_H, c_W small
- flavour-violating effects from $\frac{\partial_\mu a}{f_a} (c_{u_R})_{ij} \bar{u}_{Ri} \gamma^\mu u_{Rj}$

Benchmark 1: 'Dark QCD' UV completion



- $SU(3)_D$ 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} (difference: coupling to tops)

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}	$\frac{1}{\sqrt{2}} [\bar{Q}_1 Q_1 - \bar{Q}_2 Q_2]$
π_{D_8}	$\frac{1}{\sqrt{6}} [\bar{Q}_1 Q_1 + \bar{Q}_2 Q_2 - 2\bar{Q}_3 Q_3]$

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
- $D = \text{diag}(\kappa_0 + \kappa_1, \kappa_0 + \kappa_2, \kappa_0 - \kappa_1 - \kappa_2)$
- U in analogy to V_{CKM} : $U = U_{23}U_{13}U_{12}$, with U_{ij} 3×3 rotation matrices
- benchmark: $\kappa_1 = \kappa_0/2$, $\kappa_2 = \theta_{13} = \theta_{23} = 0$, $\theta_{12} = 0.022$

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

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 $n_j = \text{diag}(2, 1, 0)$
- after diagonalising $Y_{u_{ij}}$: $c_{uR} = \begin{pmatrix} 2 & 3\epsilon & 3\epsilon^2 \\ 3\epsilon & 1 & \epsilon \\ 3\epsilon^2 & \epsilon & \epsilon^2 \end{pmatrix}$

Constraints on the model: Flavour constraints

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

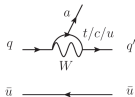


- $\Delta F = 1$:

- tree-level: $D^\pm \rightarrow \pi^\pm$ *invisible*, $J/\psi \rightarrow \gamma$ *invisible*

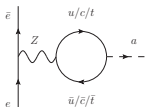


- 1-loop: $K^\pm \rightarrow \pi^\pm$ *invisible*, $B^\pm \rightarrow \pi^\pm / K^\pm$ *invisible*



Constraints on the model: cosmology and astrophysic

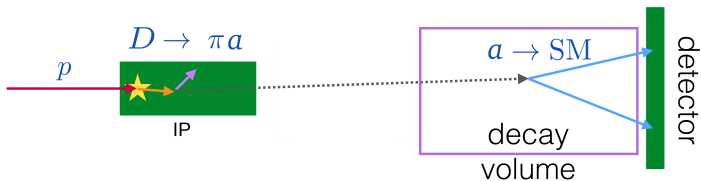
- cosmological constraints include \neq effective dof, distortion of CMB spectrum, modifications of the predicted BBN, ... (c.f. *Cadamuro, Redondo 2012; Millea, Knox 2015; Depta, Hufnagel, Schmidt-Hoberg 2020*)
- astrophysics:
 - red giant burst through effective coupling to electrons:



- SN1987a cooling through bremsstrahlung process
 $N + N \rightarrow N + N + a$

Forward physics prospects

- consider production in D meson decays
- possible testing grounds: NA62, SHiP, FASER, FASER 2, MATHUSLA, ...

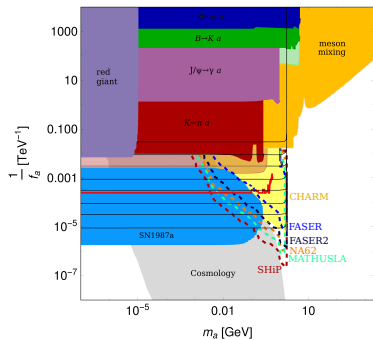


- number of ALPs:

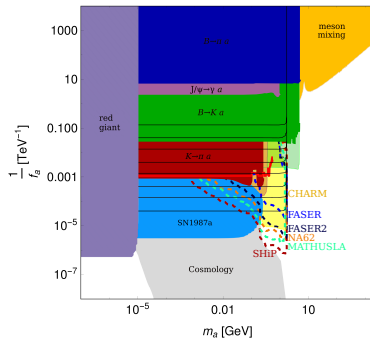
$$N_a = N_D \cdot Br(D \rightarrow \pi a) \cdot \epsilon_{geom} \cdot F_{decay}$$

- 3 events for detection

Results: 'dark QCD' UV completion

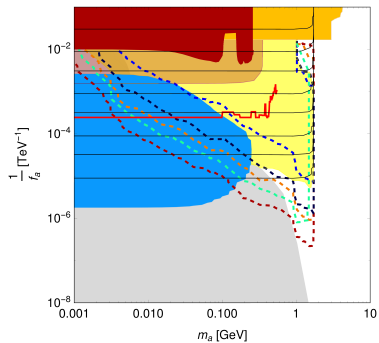


$$a \equiv \pi D_3$$

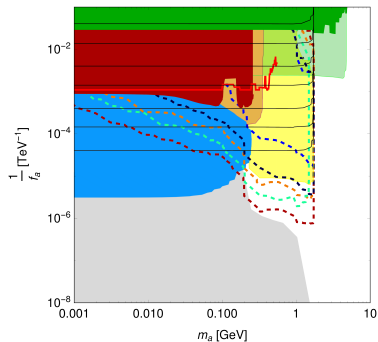


$$a \equiv \pi D_8$$

Results: 'dark QCD' UV completion

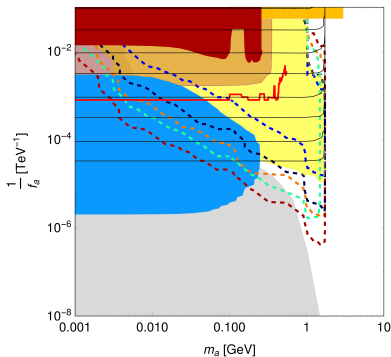


$$a \equiv \pi D_3$$

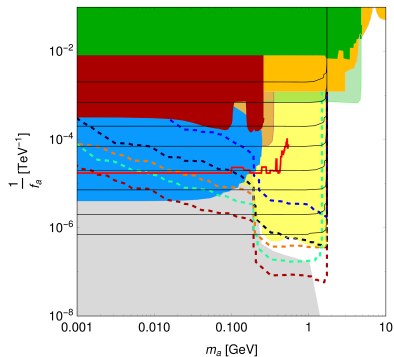


$$a \equiv \pi D_8$$

Results: FN UV completion and anarchic benchmark



FN



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

Summary and Outlook

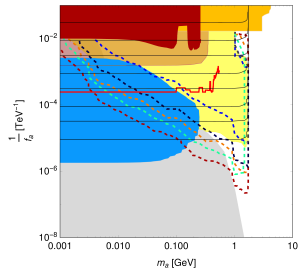
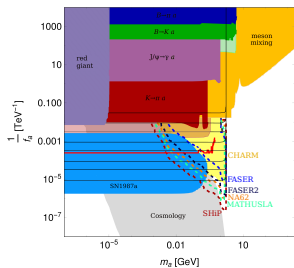
- search for NP in charm physics
- parameters space with forward physics phenomenology unconstrained
- $m_a \sim \text{few GeV}$ can be probed at forward physics facilities
- higher mass region ideas:
 - additional production modes, e.g. top decays
 - charming emerging jets, prompt decay searches
 - in dark QCD: DM direct detection

Back-up slides

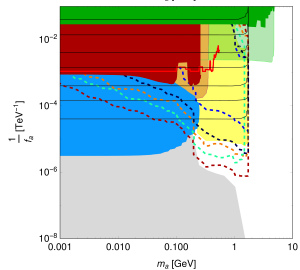
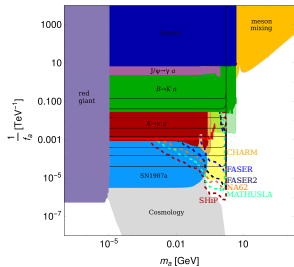
Couplings with numerical values

$$\begin{aligned}\pi_{D_3} : c_{UR} &\simeq \begin{pmatrix} -2.248\kappa_0^2 & -0.071\kappa_0^2 & 0 \\ -0.071\kappa_0^2 & 0.998\kappa_0^2 & 0 \\ 0 & 0 & 0 \end{pmatrix}; \\ \pi_{D_8} : c_{UR} &\simeq \begin{pmatrix} -1.299\kappa_0^2 & -0.016\kappa_0^2 & 0 \\ -0.016\kappa_0^2 & -0.578\kappa_0^2 & 0 \\ 0 & 0 & 0.289\kappa_0^2 \end{pmatrix} \\ FN : c_{UR} &\simeq \begin{pmatrix} 2.0001 & 0.0220 & 0.0002 \\ 0.0220 & 1.0001 & 0.0073 \\ 0.0002 & 0.0073 & 0.0001 \end{pmatrix}\end{aligned}$$

all dark QCD UV completion plots

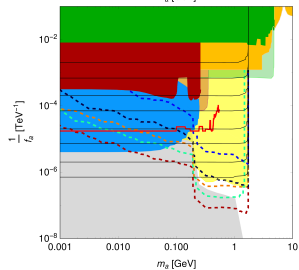
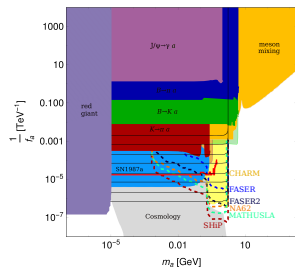
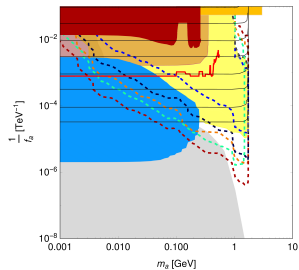
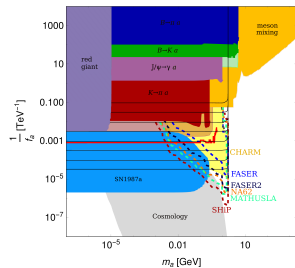


$$a \equiv \pi D_3$$



$$a \equiv \pi D_8$$

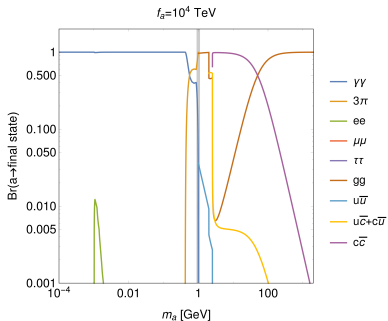
all FN and anarchic benchmark point plots



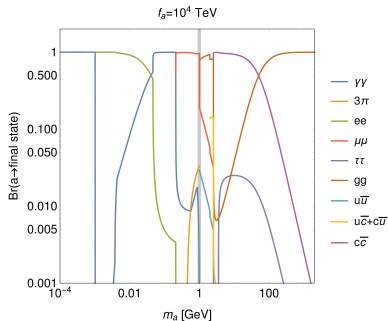
FN

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

ALP decays (dark-QCD)

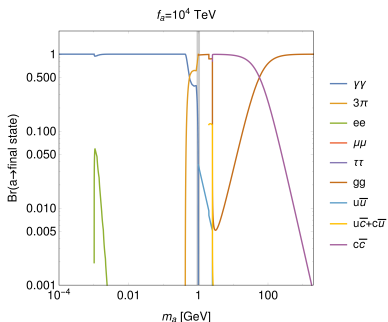


π_{D_3}

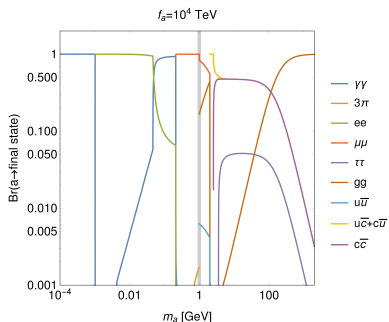


π_{D_8}

ALP decays (FN and anarchical scenario)



FN



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