Charming ALPs

Christiane Scherb

THEP JGU Mainz

(2101.07803: Adrian Carmona, CS and Pedro Schwaller, and ongoing work)
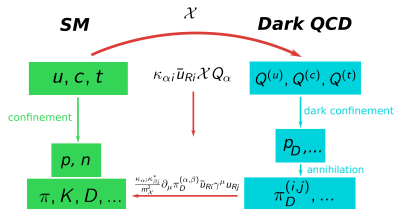
- ALPs are ubiquitous in BSM models
- can have non-trivial interaction with flavor & various lifetimes
- focus on up-sector:

$$\mathcal{L}_{eff} = \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{m_a^2}{2}a^2 + \frac{\partial_\mu a}{f_a}\left[(c_{u_R})_{ij}\bar{u}_{Ri}\gamma^\mu u_{Rj} + c_H H^\dagger i\overleftrightarrow{D}_\mu H\right]$$

$$- \frac{a}{f_a}\left[c_{gg}\frac{g_3^2}{32\pi^2}G_{\mu\nu}^a\tilde{G}^{\mu\nu a} + c_{WW}\frac{g_2^2}{32\pi^2}W_{\mu\nu}^I\tilde{W}^{\mu\nu I} + c_{BB}\frac{g_1^2}{32\pi^2}B_{\mu\nu}\tilde{B}^{\mu\nu}\right]$$

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

SM χ **Dark QCD**

u, c, t $\kappa_{\alpha i} \bar{u}_{Ri} \chi Q_\alpha$ $Q^{(u)}, Q^{(c)}, Q^{(t)}$

confinement   dark confinement

p, n $P_D, ...$

annihilation

$\pi, K, D, ...$ $\frac{\kappa_{\alpha i} \kappa^*_{\beta i}}{m_\chi^2} \partial_\mu \pi_D^{(\alpha,\beta)} \bar{u}_{Ri} \gamma^\mu u_{Rj}$ $\pi_D^{(i,j)}, ...$

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} (difference: coupling to tops)

- non-trivial flavor 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 flavor 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: $\kappa_1 = \kappa_0/2$, $\kappa_2 = \theta_{13} = \theta_{23} = 0$, $\theta_{12} = 0.022$

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

- 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 $Y_{u_{ij}}$: $c_{u_R} = \begin{pmatrix} 2 & 3\epsilon & 3\epsilon^2 \\ 3\epsilon & 1 & \epsilon \\ 3\epsilon^2 & \epsilon & \epsilon^2 \end{pmatrix}$

- $\Delta F = 2$: $D^0 - \bar{D}^0$ 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*
- cosmological constraints including # 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 bremstrahlung process $N + N \to N + N + a$

- ALP production from D mesons: $D \to \pi a$
  - $\to$ possible if $\kappa_{12} \neq 0$ (true for all our benchmark points)
  - $\to$ collider and fixed target experiments
  - $\to$ mostly for long-lived ALPs

- production from flavor violating top decays (ongoing work): $t \to aq \ (q = c, u)$
  - $\to$ possible if $\kappa_{31} \neq 0$ or $\kappa_{32} \neq 0$ (for FN and anarchical benchmark)
  - $\to$ collider experiments
  - $\to$ different search strategies for different lifetimes

Searches via D meson decays

- possible testing grounds: NA62, SHiP, FASER, FASER 2, MATHUSLA, . . .
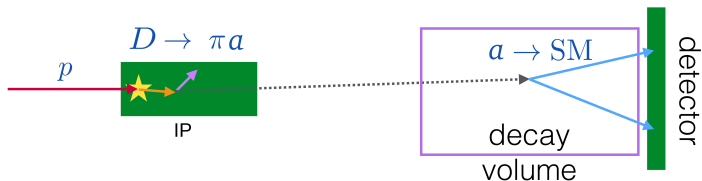
- number of ALPs:

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

- 3 events for detection
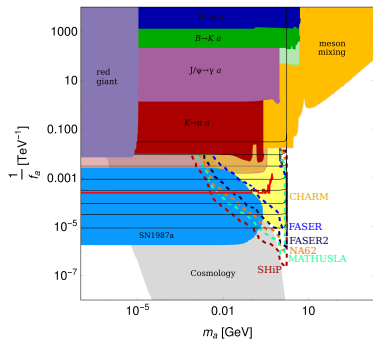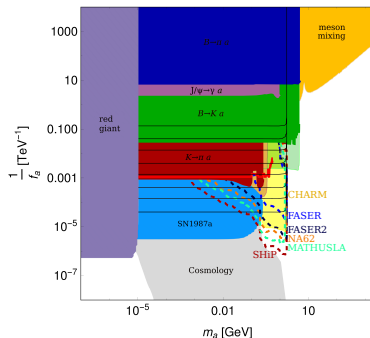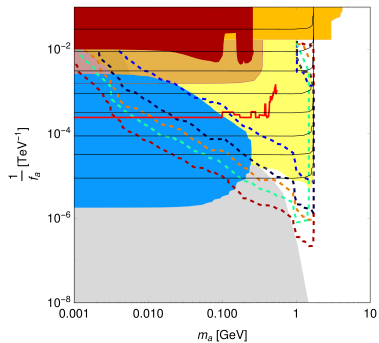
$$a \equiv \pi_{D_3}$$

$$a \equiv \pi_{D_8}$$

$$a \equiv \pi_{D_3}$$

$$a \equiv \pi_{D_8}$$

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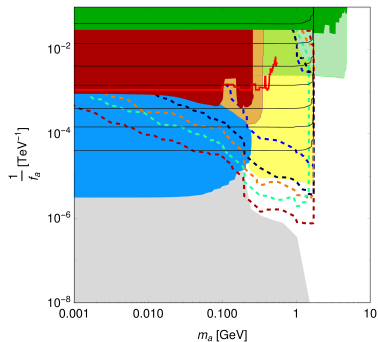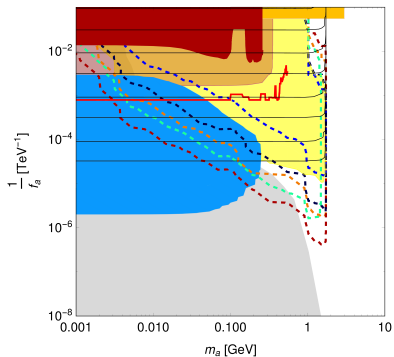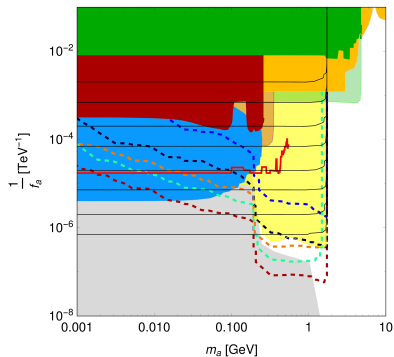
$(c_{u_R})_{ij} = 1$

- prompt ALPs: $t \to hq$ can be recasted, if $m_a \sim m_h$
- current bounds:
  - $BR(t \to hc) < 1.2 \times 10^{-3}$, $BR(t \to hu) = 0$,
  - $BR(t \to hu) < 1.1 \times 10^{-3}$, $BR(t \to hu) = 0$,
  - both channels open $BR(t \to hq) \lesssim 5 \times 10^{-4}$
- prospects:
  - HL-LHC $BR(t \to hq) \lesssim 10^{-4}$,
  - FCC-hh: $BR(t \to hq) \lesssim 10^{-5}$
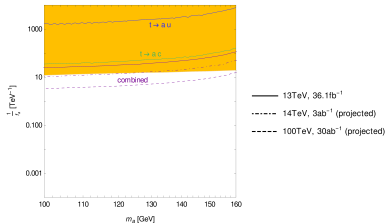
FN
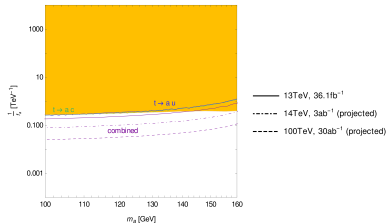
$(c_{u_R})_{ij} = 1$

Prospect: top and long-lived ALP

- vary $c\tau$ and $Br(t \to aq)$ independently
- use energy deposit in calorimeters for displaced jets:
  $\log_{10}\left(\frac{E_{had}}{E_{em}}\right) > 1.2$
- background: here only $t\bar{t}$ considered
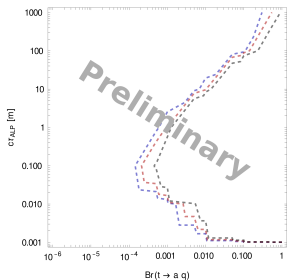
$m_a = 2$ GeV $m_a = 10$ GeV
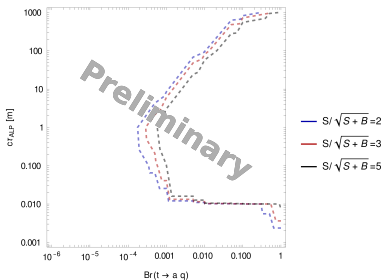
- search for NP in charm physics
- $m_a \sim$ *few GeV* can be probed at forward physics facilities
- large part of parameters space unconstrained for
  $m_a \gtrsim$ *few GeV*
- searches with associated top:
  - flavor violating top decay beyond Higgs mass region
  - top and displaced jet
  - top with associated light jet and missing energy

Back-up slides

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

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

$$FN : c_{u_R} \simeq \begin{pmatrix} 2.0001 & 0.0220 & 0.0002 \\ 0.0220 & 1.0001 & 0.0073 \\ 0.0002 & 0.0073 & 0.0001 \end{pmatrix}$$
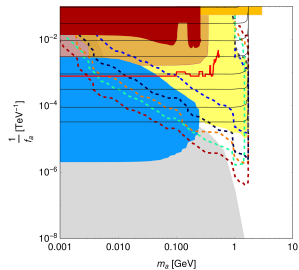
$a \equiv \pi_{D_3}$

$a \equiv \pi_{D_8}$
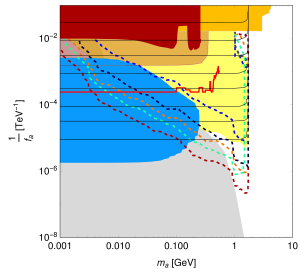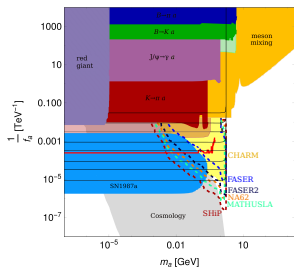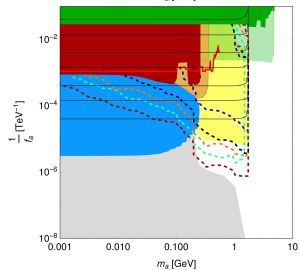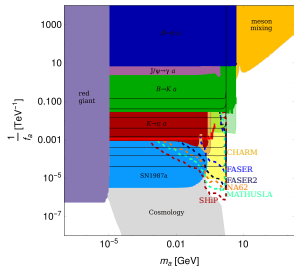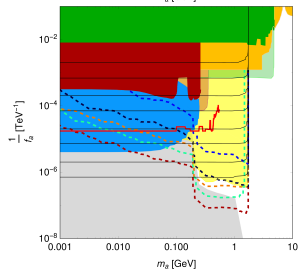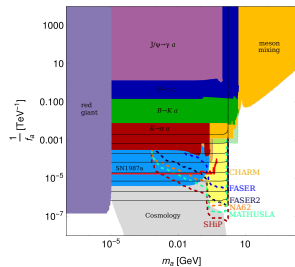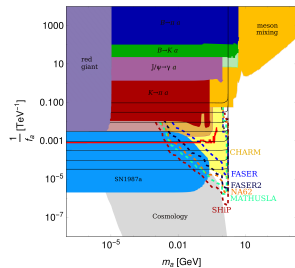
FN

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

ALP decays (dark-QCD)

π_{D_3}

π_{D_8}

FN

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

$m_a = 2$ GeV

$m_a = 2$ GeV