Charming ALPs from the TOP

La Thuile 2022 – Les Rencontres de Physique de la Vallée d'Aoste

UNIVERSIDAD DE GRANADA

OFPI Oficina de Proyectos Internacionales

athenea 3i

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Charming ALPs from the Top

Based on

* "Charming ALPs", A.C., Christiane Scherb, Pedro Schwaller
  JHEP 08 (2021) 121 , arxiv: 2101.07803

* "The ALPs from the Top: Searching for long-lived axion-like particles from exotic top decays", A.C. Fatemeh Elahi, Christiane Scherb, Pedro Schwaller , arxiv: 2202.09731

Motivation

- Axion-like particles (ALPs) are ubiquitous in BSM models
- ALPs can show a non-trivial flavor structure
- In general,

$$\mathcal{L}_{eff} = \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{M_a^2 a^2}{2} + \frac{\partial_\mu a}{f_a}\Big[(C_{uR})_{ij}\,\bar{u}_{Ri}\gamma^\mu u_{Rj} + (C_{qL})_{ij}\,\bar{q}_{Li}\gamma^\mu q_{Lj}$$

$$+ (C_{dR})_{ij}\,\bar{d}_{Ri}\gamma^\mu d_{Rj} + (C_\ell)_{ij}\,\bar{\ell}_{Li}\gamma^\mu \ell_{Lj} + (C_e)_{ij}\,\bar{e}_{Ri}\gamma^\mu e_{Rj}\Big]$$

$$-\frac{a}{f_a}\Big[C_{GG}\frac{g_3^2}{32\pi^2}G^a_{\mu\nu}\tilde{G}^{a\,\mu\nu} + C_{WW}\frac{g_2^2}{32\pi^2}W^I_{\mu\nu}\tilde{W}^{I\,\mu\nu} + C_{BB}\frac{g_1^2}{32\pi^2}B_{\mu\nu}\tilde{B}^{\mu\nu}\Big]$$

Some UV theories will just generate C_{uR} at tree-level

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$$+ (C_{d_R})_{ij}\,\bar{d}_{R i}\gamma^\mu d_{R j} + (C_{\ell})_{ij}\,\bar{\ell}_{L i}\gamma^\mu \ell_{L j} + (C_e)_{ij}\,\bar{e}_{R i}\gamma^\mu e_{R j}\Big]$$

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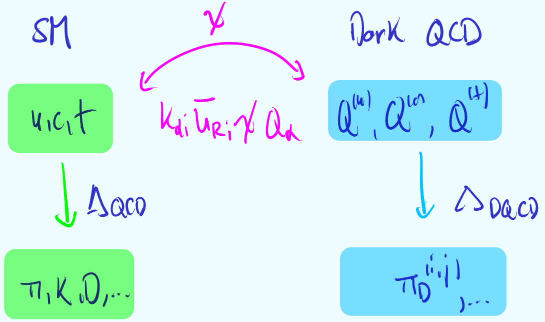
Some UV theories will just generate C_{u_R} at tree-level

A QCD-like dark sector

[Bai, Schwaller '14]



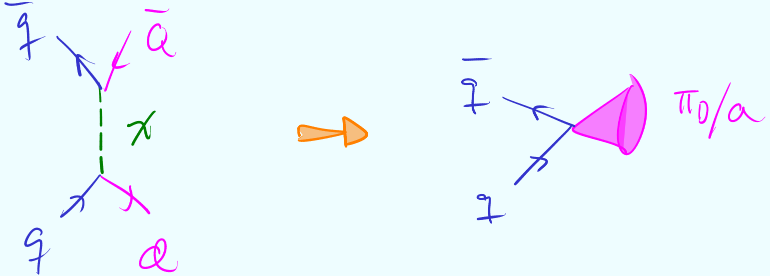
$$\mathcal{L}_{eff} \supset \frac{f_D}{m_\chi^2} \kappa_{\alpha i} \kappa^*_{\beta j} \partial_\mu \pi_D^{(\alpha,\beta)} \bar{u}_{Ri} \gamma^\mu u_{Rj}$$

- A dark $SU(N)_D$ with n_D flavors $(N = n_D = 3)$
- A heavy scalar mediator $\chi \sim (3, \bar{3}, 1, -2/3)$ under $SU(3) \otimes SU(3)_D \otimes SU(2)_L \otimes U(1)_Y$
- $M_Q \ll \Lambda_{DQCD}$

A QCD-like dark sector

see also [Renner, Schwaller '18]

- SM couplings fixed by χ quantum numbers
  - → Only couplings to RH up-quarks



- Lightest dark baryon DM candidate

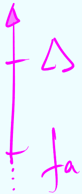
Flavons

- pNGBs of horizontal symmetries [Feng et al '98]

  e.g. $\frac{1}{f_a} \partial_\mu a_K \bar{\psi}_R^i \gamma^\mu T^K \psi_R^j$

- U(1) symmetry for RH up-quarks

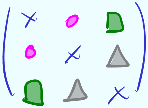
  $S = \frac{1}{\sqrt{2}}(f_a + s)\, e^{ia/f_a}$ $\langle S \rangle = f_a$



	S	H	q_L^i	d_R^i	u_R	c_R	t_R
U(1)	-1	0	0	0	2	1	0

$$\mathcal{L}_{eff} \supset -\lambda_u^{ij} \left(\frac{S}{\Delta}\right)^{n_j} \bar{q}_{L_i} \tilde{H} u_{R_j}$$

At the end of the day ...

* $\mathcal{L}_{eff} \supset \frac{\partial_\mu a}{f_a} (C_{u_R})_{ij} \, \bar{u}_{R_i} \gamma^\mu u_{R_j}$ $\qquad C_{u_R} =$ 

* RGEs will generate [Chala et al, '21; Bauer et al '21; Bonilla et al, '21]

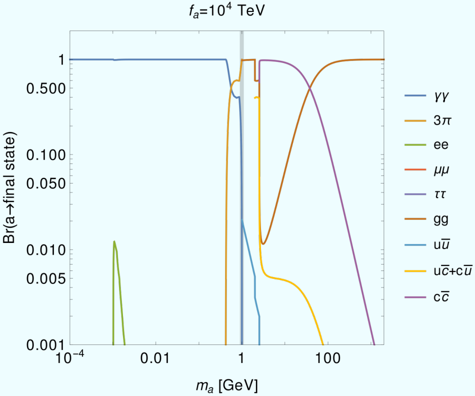
$$C_{q_L} = \frac{Y_u C_{u_R} Y_u}{32\pi^2} \ln\left(\frac{f_a^2}{\mu^2}\right) \qquad C_H = \frac{3}{8\pi^2} \mathrm{Tr}\left(Y_u C_{u_R} Y_u\right) \ln\left(\frac{f_a^2}{\mu^2}\right)$$

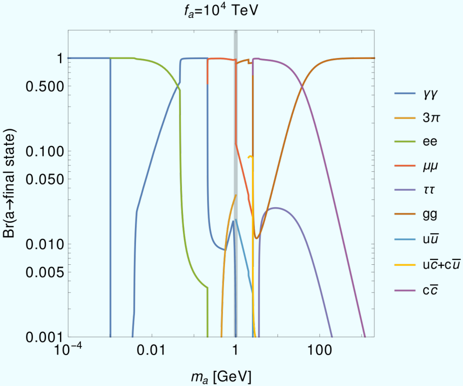
$\xrightarrow{\text{E.O.M}}$ $a \to l^+ l^-$, $a \to \bar{d}_i d_j$, ...

* Heavy-quarks loop induced processes will also lead to

$\longrightarrow$ $a \to \gamma\gamma, gg$

Charming ALPs





$a = \pi_{D3}$

without $a\bar{t}t$ coupling

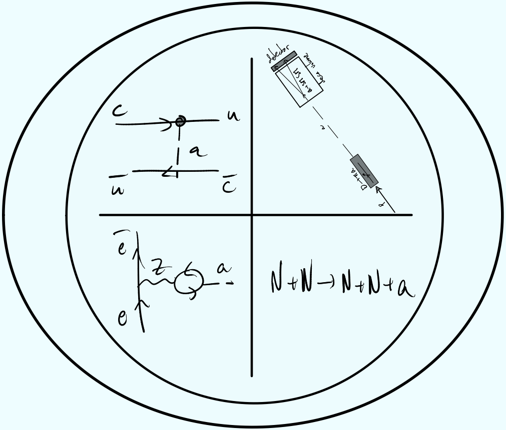
$(C_{uR})_{33} = 0$

$a = \pi_{D8}$

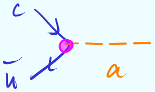
with $a\bar{t}t$ coupling

$(C_{uR})_{33} \neq 0$

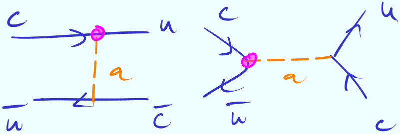
PHENϕ



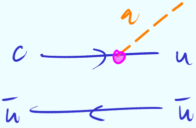
Pheno: Flavor



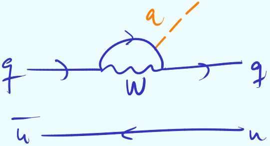
* Neutral meson mixing



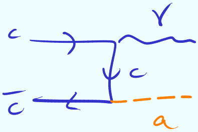
* Rare decays



$D \to \pi a$



$B \to K a, B \to \pi a, K \to \pi a$



$J/\psi \to a \gamma$

Pheno: Flavor

- $D^+ \to (\tau^+ \to \pi^+ \nu)\bar{\nu}$ RECASTED WITH M^2_{MISS} FOR $D^+ \to \pi^+ a$
- $B^+ \to K^+ \bar{\nu}\nu$ & $B^0 \to K^0 \bar{\nu}\nu$ RECASTED WITH $S_B = k^2/M_B^2$ FOR $B \to K a$
- $B^+ \to \pi^+ \bar{\nu}\nu$ RECASTED WITH $\sqrt{\vec{p}_\pi^{\,2}}$ FOR $B \to \pi a$
- $K^+ \to \pi^+ a$ for $m_a > 0$
- $B^\pm \to K^\pm \bar{\nu}\nu$ expected at Belle II with $50\ ab^{-1}$
  and $K^\pm \to \pi^\pm \bar{\nu}\nu$ at NA62

Pheno: Cosmo & Astro

* Astrophysical bounds
  - ✓ SN1987a through the process $N+N \to N+N+a$
  - ✓ Red Giant bursts via the coupling to electrons

* Cosmological bounds

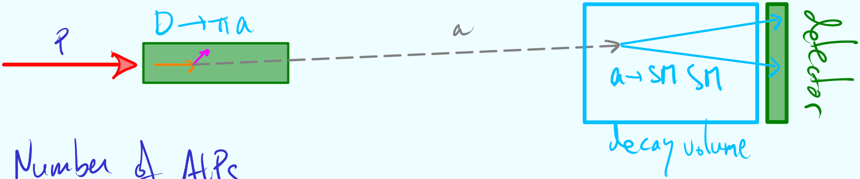
  N_{eff}, distortion of CMB spectrum, BBN, ...

  [Cadamuro, Redondo '12, Millea, Knox '15, Depta et al '20]

  Most of bounds derived assume just couplings to photons but they can be still recasted

Pheno: Colliders and fixed target exp

* Fixed target experiments: NA62, SHiP, CHARM



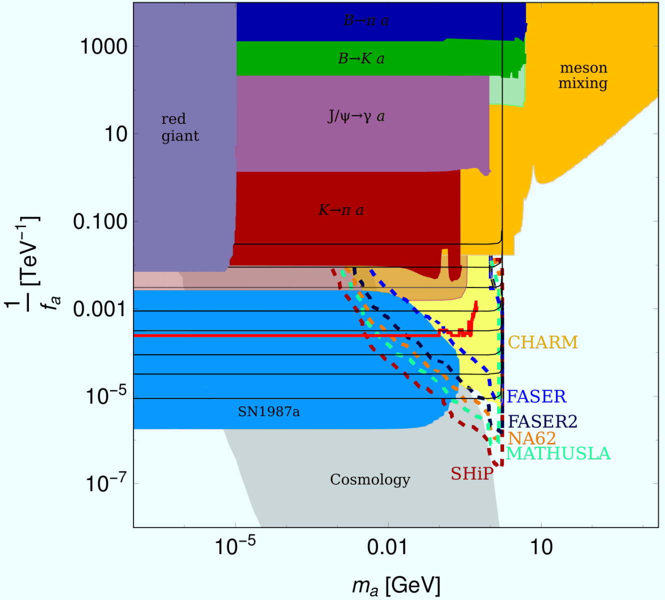
Number of ALPs

$$N_a = N_D \cdot Br(D \to \pi a)\, \varepsilon_{GEOM} \cdot F_{decay}$$

* LHC forward detectors: FASER, FASER II, MATHUSLA

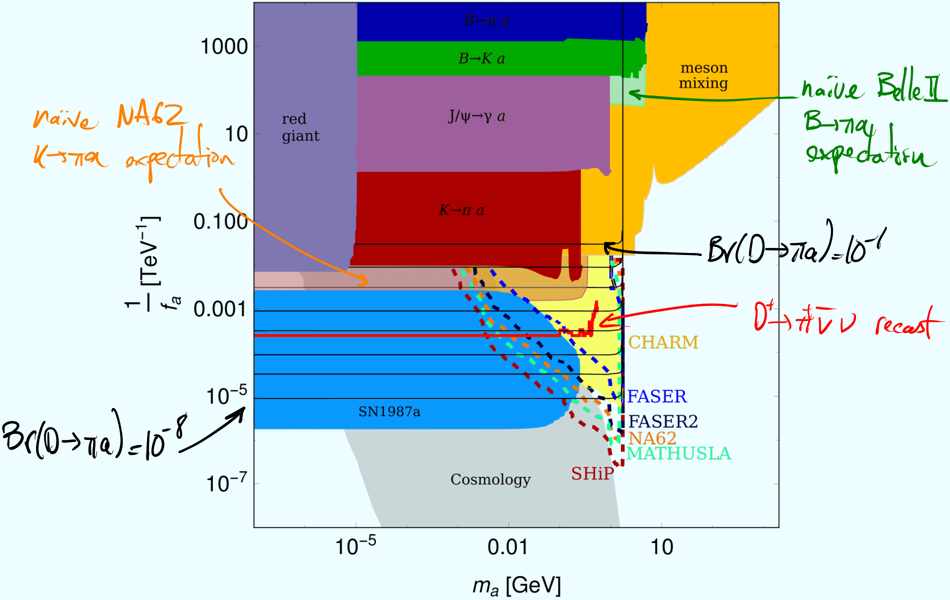
Pheno: bounds

π_{U3}, $(C_{uR})_{33} = 0$



Pheno: bounds

π_{D3}, $(C_{uR})_{33} = 0$



Pheno: bounds

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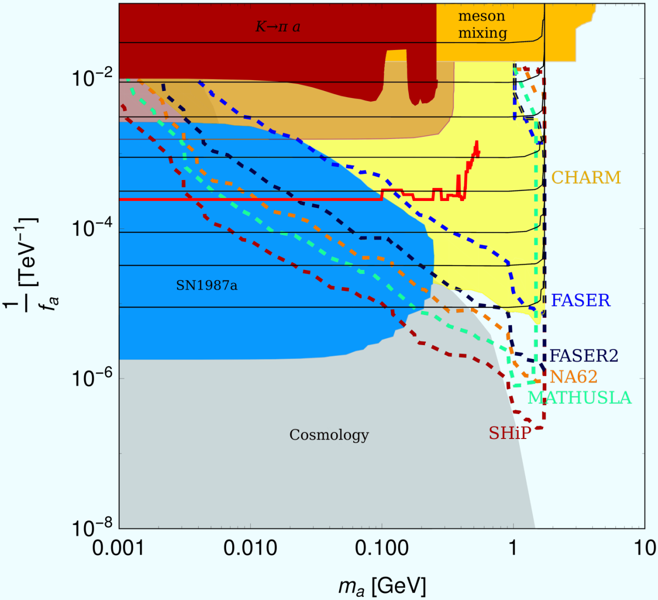
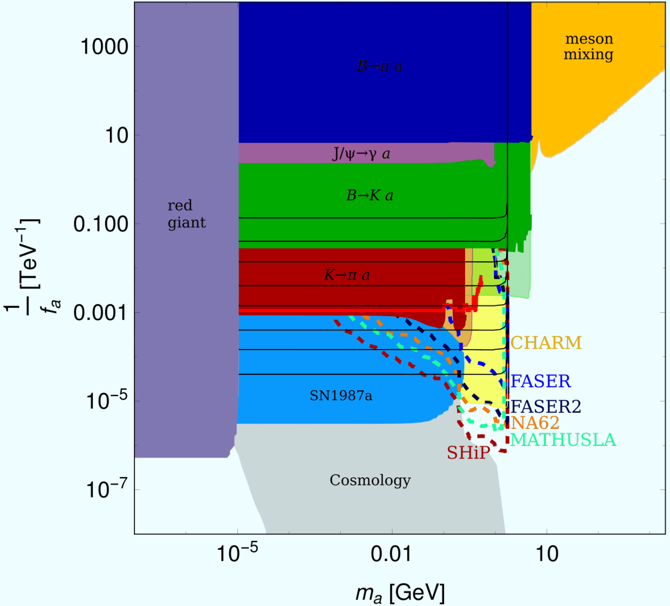


Pheno: bounds

$\pi_{03}, (C_{uR})_{33} \neq 0$



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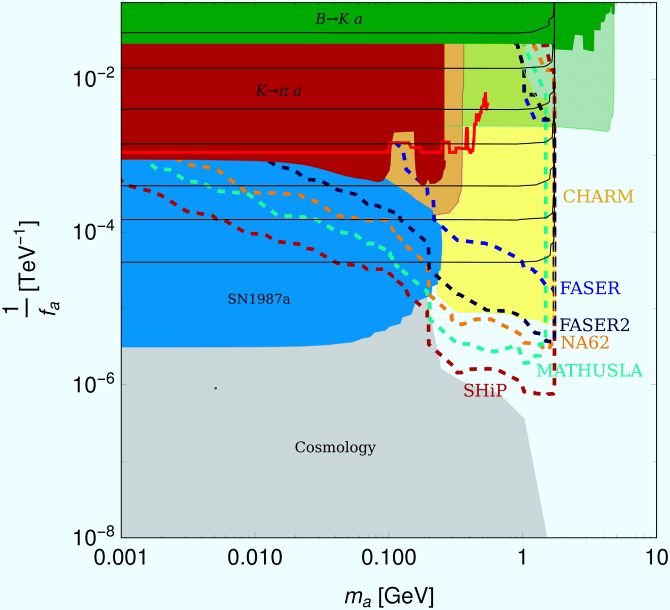
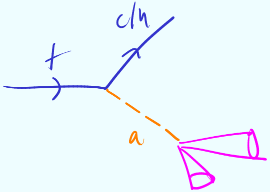


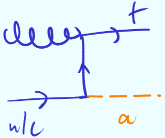
ALPs from the Top

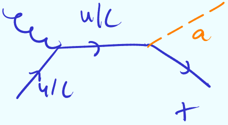
* Probe charming ALP above charm threshold



For $m_a \gtrsim$ GeV ALP will decay hadronically

* We recast searches for exotic tops decays

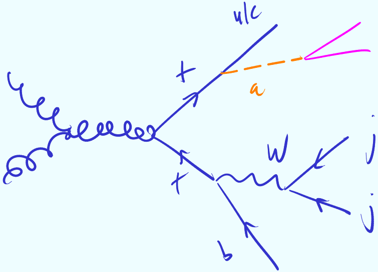




✓ prompt ALP decay

✓ "stable" ALP

ALPs from the Top: signal & background

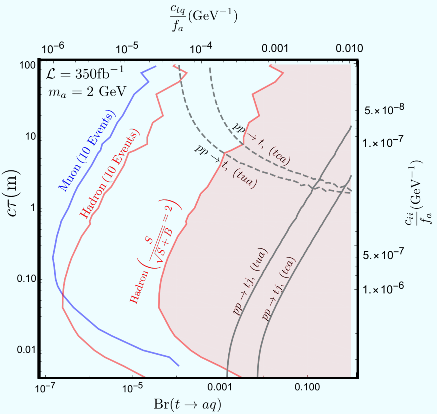


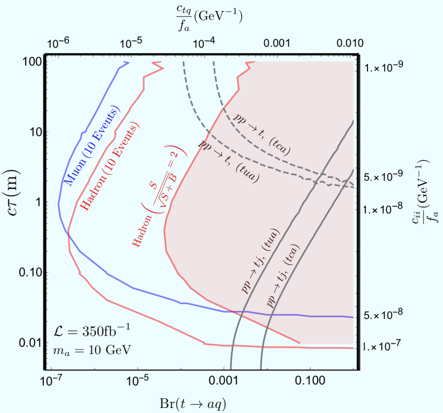
low mass displaced jet

see also Castro et al '20 for heavier ALPs

	$\mathbf{m_a = 2}$ **GeV**	$\mathbf{m_a = 10}$ **GeV**	$\mathbf{t\bar{t}}$
total	$(1)\ 2.79 \times 10^5$	$(1)\ 2.79 \times 10^5$	$(1)\ 2.91 \times 10^8$
3 – 6 jets with $\mathbf{p_T > 40}$ **GeV &** $\mathbf{\|\eta\| < 2.5}$	$(0.8439)\ 2.35 \times 10^5$	$(0.8414)\ 2.35 \times 10^5$	$(0.71801)\ 2.09 \times 10^8$
1 jet with $\mathbf{\log_{10}\left(\frac{E_{had}}{E_{em}}\right) > 1.2}$	$(0.1436)\ 4.00 \times 10^4$	$(0.0775)\ 2.16 \times 10^4$	$(0.01244)\ 3.61 \times 10^6$
displaced jet has $\mathbf{\leq 2}$ **tracks with** $\mathbf{p_T > 2}$ **GeV**	$(0.1436)\ 4.00 \times 10^4$	$(0.0775)\ 2.16 \times 10^4$	$(0.00022)\ 6.39 \times 10^4$

ALPs from the Top: signal & background



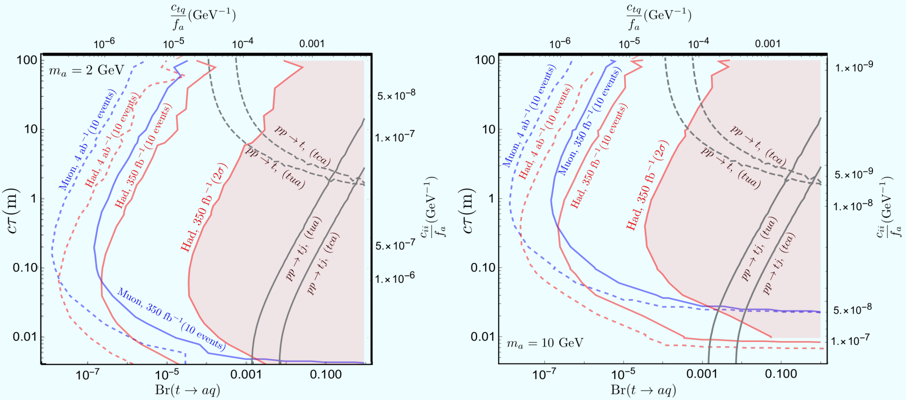


Conclusions

- Charming ALPs are good example of flavored ALP
- Very different ways of probing the model
  - FLAVOR
  - ASTROPHYSICS
  - COSMOLOGY
  - FIXED TARGED EXP
- We can probe top BRs of 10^{-4} and below
- Room for improvement!

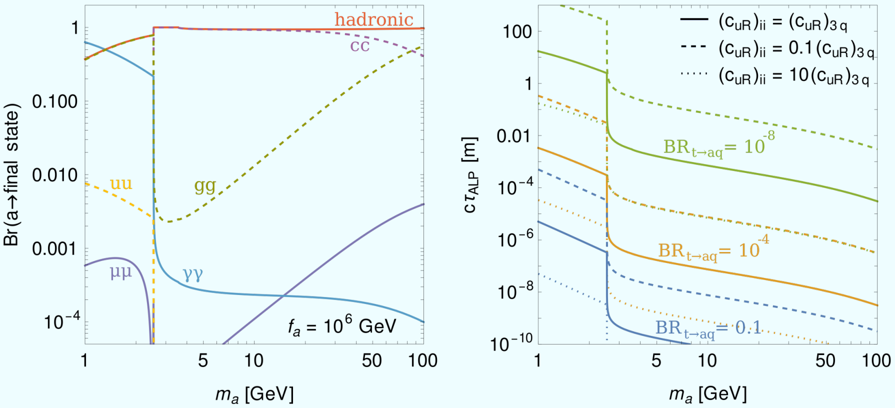
BACK-UP

LHC-HL

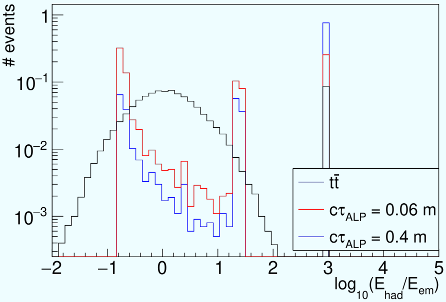


$\frac{c_{tq}}{f_a}(\mathrm{GeV}^{-1})$
$m_a = 2$ GeV
Muon, 4 ab^{-1}(10 events)
Had, 4 ab^{-1}(10 events)
Had, 350 fb^{-1}(10 events)
Had, 350 fb^{-1}(2σ)
Muon, 350 fb^{-1}(10 events)
$pp \to t$, (tca)
$pp \to t$, (tua)
$pp \to tj$, (tua)
$pp \to tj$, (tca)
$c\tau$(m)
Br$(t \to aq)$
$\frac{c_{ii}}{f_a}(\mathrm{GeV}^{-1})$
$m_a = 10$ GeV

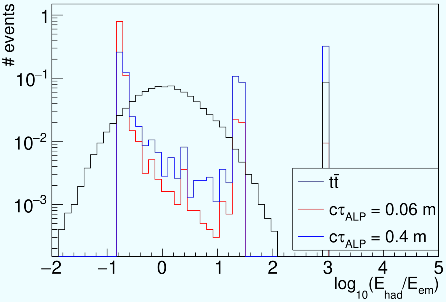
BRs & lifetime



Calorimater Energy deposit ratio

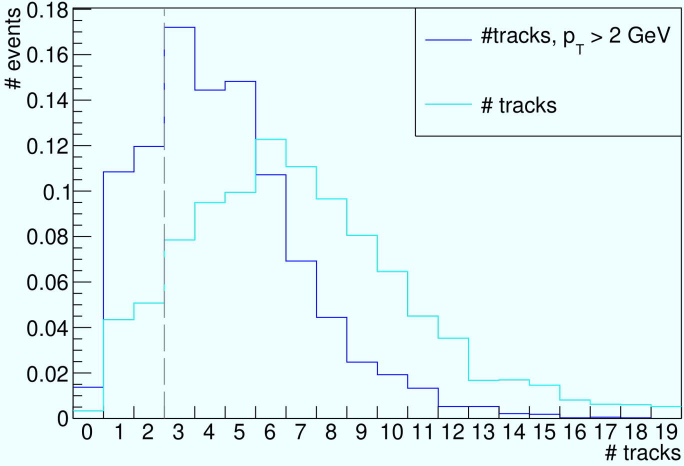


$M_a = 2$ GeV



$M_a = 10$ GeV

Track Veto



events
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19
tracks
#tracks, p_T > 2 GeV
tracks

A QCD-like dark sector

$$\mathcal{L}_D = -\frac{1}{4} G_D^{\mu\nu a} G^a_{D\mu\nu} + \bar{Q}_\alpha i \not{D} Q_\alpha - m_Q \bar{Q}_\alpha Q_\alpha$$
$$+ |D_\mu \chi|^2 - m_\chi^2 |\chi|^2 - \left[\kappa_{\alpha i} \bar{u}_{Ri} \chi Q_\alpha + h.c. \right]$$

We assume that $\kappa = V \cdot D \cdot U$ with $V = \mathbb{1}$, $U = U_{23} \cdot U_{13} \cdot U_{12}$

$D = \mathrm{diag}(\kappa_0 + \kappa_1, \kappa_0 + \kappa_2, \kappa_0 - (\kappa_1 + \kappa_2))$

$$U_{12} = \begin{pmatrix} c_{12} & s_{12} e^{-i\delta_{12}} & 0 \\ -s_{12} e^{-i\delta_{12}} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

For simplicity, we take $\kappa_1 = \kappa_0/2$ $\kappa_2 = 0$ $\theta_{13} = \theta_{23} = 0$ $\delta_{ij} = 0$

$\theta_{12} = 0'022$

A QCD-like dark sector

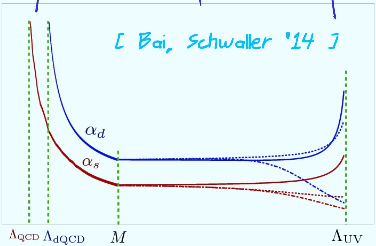
$M_\chi \gg M_Q$

$$\mathcal{L}_{eff} = -\frac{1}{4} G_D^{\mu\nu a} G^a_{D\mu\nu} + \bar{Q}_\alpha i \not{D} Q_\alpha - M_Q \bar{Q}_\alpha Q_\alpha$$

$$- \frac{\kappa_{\alpha i} \kappa^*_{\beta j}}{2 M_\chi^2} \left(\bar{Q}_\beta \gamma^\mu P_L Q_\alpha\right)\left(\bar{u}_{Ri} \gamma_\mu u_{Rj}\right)$$

In the limit $M_Q \to 0$, $M_\chi \to \infty$ $SU(3)_{DL} \otimes SU(3)_{DR} \to SU(3)_{DV}$

by $\langle \bar{Q}_\alpha Q_\beta \rangle \sim \delta_{\alpha\beta} \Lambda^3_{DQCD}$ delivering 8 pNGB



$\Lambda_{DQCD} \approx$ few Λ_{QCD}

A QCD-like dark sector

$$\mathcal{L}_{eff} \supset -\frac{1}{4} G_D^{\mu\nu a} G^a_{D\mu\nu} + \bar{Q}_\alpha i \not{D} Q_\alpha - M_Q \bar{Q}_\alpha Q_\alpha$$

$$- \frac{f_D}{2M_\chi^2} \kappa_{\alpha i}\kappa^*_{\beta j} (\lambda^a)_{\alpha\beta} \partial_\mu \pi_{Da} (\bar{u}_{Ri}\gamma_\mu u_{Rj})$$

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_{D3}	$1/\sqrt{2}\,[\bar{Q}_1 Q_1 - \bar{Q}_2 Q_2]$
π_{D8}	$1/\sqrt{6}\,[\bar{Q}_1 Q_1 + \bar{Q}_2 Q_2 - 2\bar{Q}_3 Q_3]$

$$(C_{uR})_{ij} \frac{1}{f_a} \partial_\mu a\, \bar{u}_{Ri}\gamma^\mu u_{Rj}$$

A QCD-like dark sector

$$\mathcal{L}_{eff} \supset (C_{uR})_{ij} \frac{1}{f_a} \partial_\mu a \, \bar{u}_{Ri} \gamma^\mu u_{Rj}$$

π_{D3} $$C_{uR} \approx \kappa_0^2 \begin{pmatrix} -2'248 & -0'071 & 0 \\ -0'071 & 0'998 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

π_{D8} $$C_{uR} \approx \kappa_8^2 \begin{pmatrix} -1'299 & -0'016 & 0 \\ -0'016 & -0'578 & 0 \\ 0 & 0 & 0'289 \end{pmatrix}$$