OFFSHELL 2021

THE VIRTUAL HEP CONFERENCE

RUN 4 HL LHC

6-9 July 2021

Exploring new possibilities to discover a light pseudo-scalar at LHCb

D. Buarque Franzosi, G. Cacciapaglia , **X. Cid Vidal**,
G. Ferretti, T. Flacke, C. Vázquez Sierra

July 6th 2021

[arXiv:2106.12615]

Outline

- Motivation
- Benchmark models
  [Axion-like particles in Composite Higgs models]
- Existing bounds and projections
- LHCb prospects for $a \rightarrow \tau\tau$ [NEW]
- LHCb prospects for $a \rightarrow cc$ [NEW]
- Conclusions and Outlook

Motivation

- Many well-motivated Standard Model extensions contain scalars beyond the Higgs boson (2HDM, SUSY, composite Higgs, ALPs, relaxions, etc., etc.) which in part of the parameter space could be light (e.g. lighter than the Z boson).
- LEP puts important constraints (direct production, Z-decays, ...), but only if couplings to electrons and/or EW gauge bosons are not small.
- Rare meson decays put important constraints, but only if the BSM scalar is lighter than the mesons.
- Most LHC resonance searches focus on either the Higgs mass region, or higher masses.

➡ **There is a bit of a blind spot in searches for (neutral colorless) BSM resonances in the mass regime O(5-10 GeV) - O(100 GeV).**

➡ **Backgrounds at the LHC for such light resonance searches are huge.**

➡ **But LHCb is great, and we should explore every decay channel we can!**

An axion-like particle (ALP): The Lagrangian

The ALP effective Lagrangian:

$$\mathcal{L}_{\text{eff}} \supset \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{1}{2}m_a^2 a^2 - i\sum_\psi C_\psi \frac{m_\psi}{f} a\bar{\psi}\gamma^5\psi$$
$$+ \frac{a}{16\pi^2 f}\left(g_s^2 K_g G^a_{\mu\nu}\tilde{G}^{a\mu\nu} + g^2 K_W W^i_{\mu\nu}\tilde{W}^{i\mu\nu} + g'^2 K_B B_{\mu\nu}\tilde{B}^{\mu\nu}\right)$$

- *f* is the ALP decay constant (we will consider TeV scale *f*).
- If all couplings are *O*(1), *a* is produced via gluon-fusion.
- The EFT has many free parameters which dictate the *a* branching ratios
  ⇒ to **compare prospects of searches** for different ALP decays we need to **choose a benchmark model**.

Underlying models with an ALP: UV embeddings of a composite Higgs

Composite Higgs models address the **SM hierarchy problem** by assuming the Higgs to be a **bound state of underlying elementary particles** (alike pions in QCD).

Models with an underlying confining gauge group, fermionic Higgs constituents and partial top-compositeness have been proposed [Gherghetta et al (2014)] and classified [Ferretti etal (2014)]. The models require two types of underlying fermions.
[for the model list, see backup slides]

All models contain additional light composite scalars beyond the Higgs. **In particular all models contain an ALP.**

UV embeddings of a composite Higgs

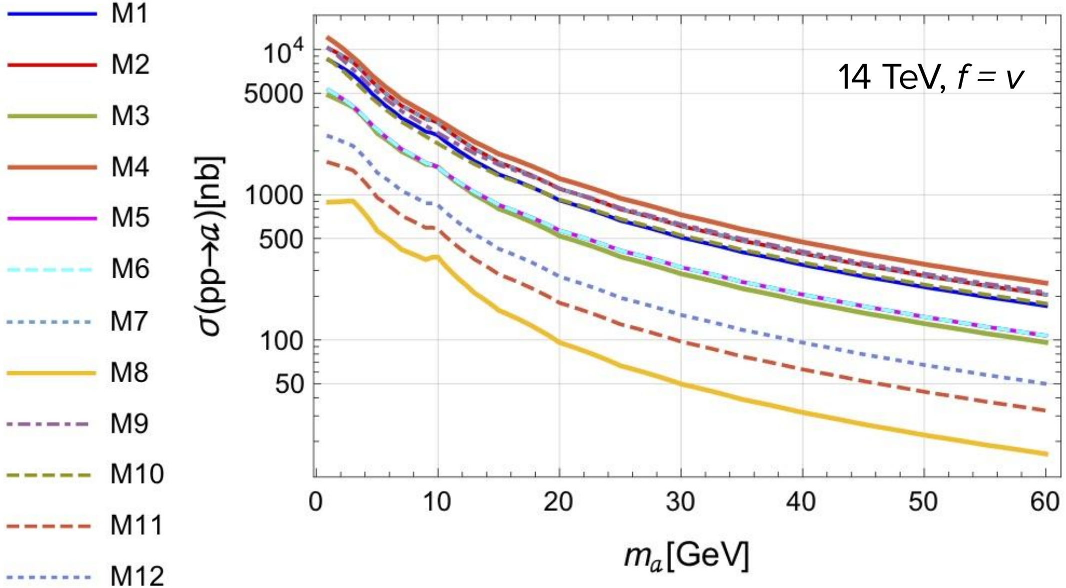
Key-points (for our study):

- The models are theoretically **well motivated**.
- The models are **very predictive**: Within a model, all ALP coupling constants are fixed, the scale *f* is linked to the composite Higgs scale, and the only free parameter is m_a .
- Couplings to all fermions apart from the top are **uniform**: $C_\psi = C$.
  Thus, branching ratios to different fermion pairs are just $m^2_{\psi i} / m^2_{\psi j}$.

UV embeddings of a composite Higgs

couplings & production cross sections

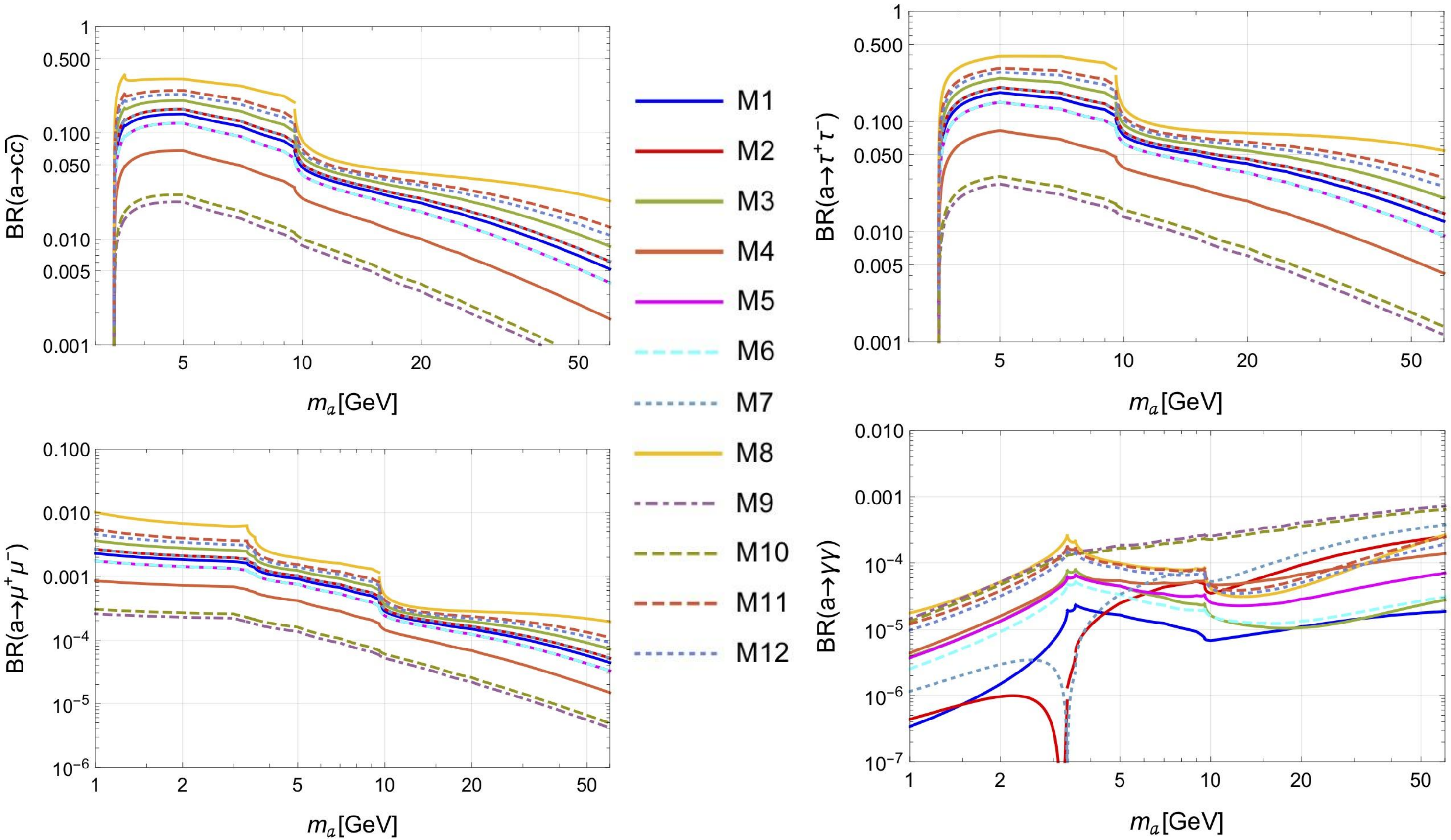
	$C_{\psi\neq t}$	C_t	K_g	$K_\gamma = K_W + K_B$
M1	2.17	5.79	−7.24	10.4
M2	2.61	4.79	−8.70	17.7
M3	2.17	2.54	−6.34	0.483
M4	1.46	2.43	−10.9	−5.82
M5	1.46	6.31	−4.85	4.04
M6	1.46	6.31	−4.85	5.50
M7	2.61	4.79	−8.70	20.3
M8	1.90	3.16	−1.58	−0.422
M9	0.702	1.87	−10.3	−16.2
M10	0.702	1.87	−9.36	−13.7
M11	1.66	2.22	−3.33	−2.22
M12	1.83	2.84	−4.06	−1.69



$$\sigma \propto (v/f)^2$$

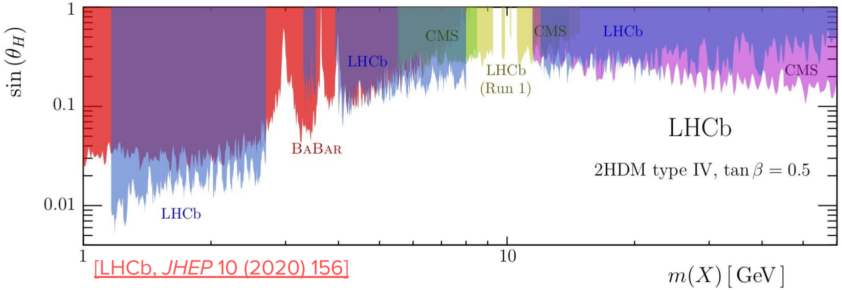
footnote: Each model comes with 4 possible values for C_t.
Shown here are only results for one.

UV embeddings: ALP branching ratios



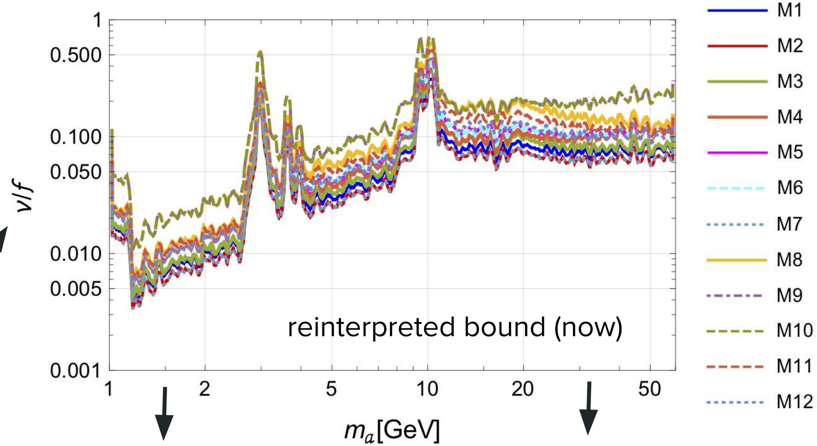
Bounds and projections for the di-muon channel

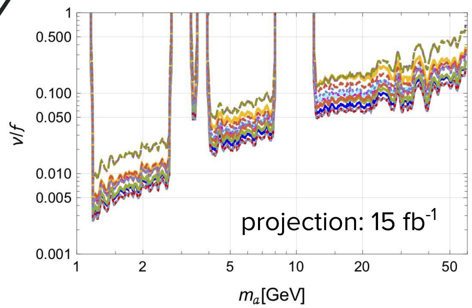
Searches for *a*➔*μμ* @ 13 TeV are already available, and bounds can be reinterpreted for our benchmark model.

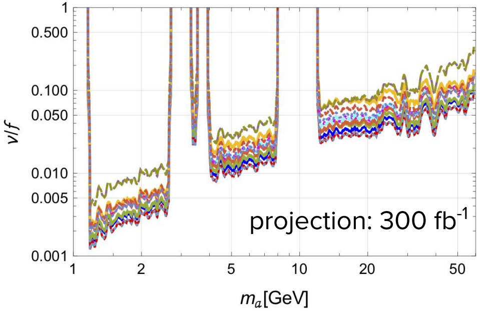


[LHCb, *JHEP* 10 (2020) 156]

$$\left.\frac{v}{f}\right|_{\text{bound}} = \sqrt{\frac{\hat{\sigma}(pp\to a)}{\tilde{\sigma}(pp\to a)}\frac{\hat{\mathscr{B}}(a\to\mu^+\mu^-)}{\tilde{\mathscr{B}}(a\to\mu^+\mu^-)}}\left.\sin\theta_H\right|_{\text{bound}}$$

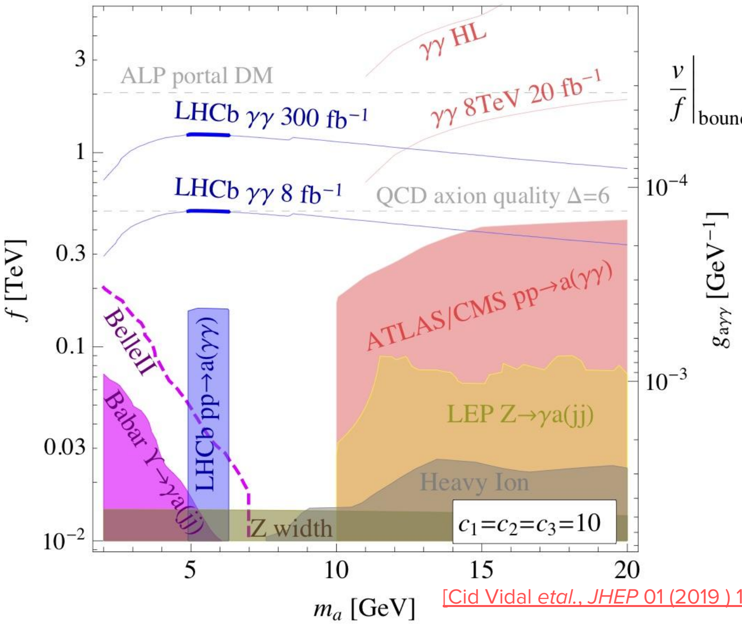






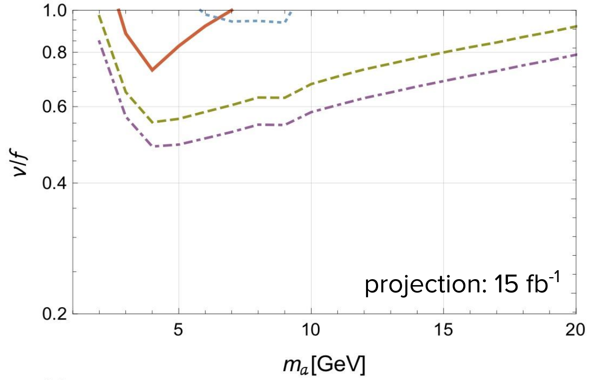
Bounds and projections for the di-photon channel

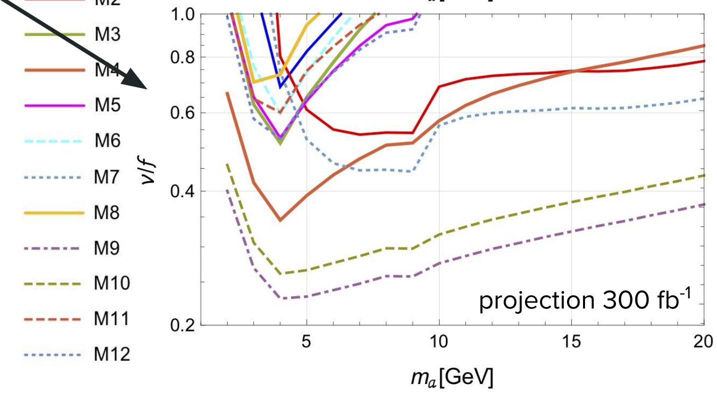
Bounds on and prospects for $a \to \gamma\gamma$ have been studied and can reinterpreted for our benchmark model.



[Cid Vidal *etal.*, *JHEP* 01 (2019) 113]

$$\left.\frac{v}{f}\right|_{\text{bound}} = \sqrt{\frac{\hat{\sigma}(pp \to a)\,\hat{\mathscr{B}}(a \to \gamma\gamma)}{\tilde{\sigma}(pp \to a)\,\tilde{\mathscr{B}}(a \to \gamma\gamma)}}\;\left.\frac{v}{f}\right|_{\text{fermiophobic}}$$





New search in $a \rightarrow \tau^+\tau^-$: Intro

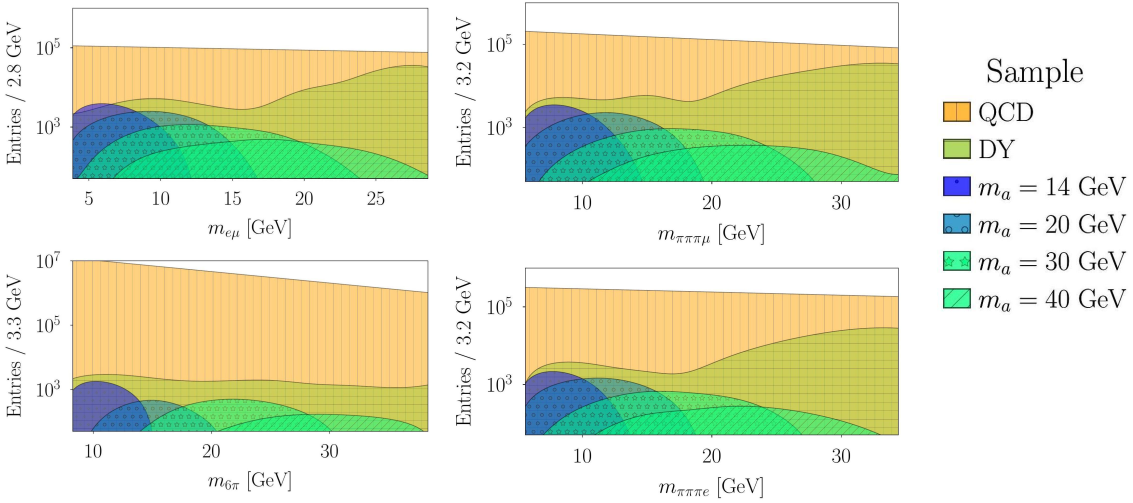
Reconstruction of τ leptons is hard at LHCb: computation of $\not{E}_T$ not possible

- However, examples exist of analyses with only τs at LHCb (Z→ττ, B→ττ)
- Coupling of ALPs to τ enhanced compared to that of μ
- Strategy considered involves reconstruction of τ as:
  - τ→πππν (τ_{3h}), τ→eνν (τ_e), τ→μνν (τ_μ) and pair combinations of these: $\tau_{3h}\tau_{3h}$, $\tau_{3h}\tau_e$, $\tau_{3h}\tau_\mu$ and $\tau_e\tau_\mu$
  - Tight (realistic) selection designed to cope with the usual trigger rates at LHCb. Includes cuts in kinematic variables, isolations and displacements
  - Simulation of all signal and backgrounds using Pythia, efficiency corrected with specific ALP model @NLO

New search in $a \to \tau^+\tau^-$: Backgrounds

Main background determined to be arising from heavy QCD production and Drell Yan ττ production. Others (DY➔μμ or Υ) negligible

- Only consider ALP mass region 14-40 GeV
- QCD found to be dominant for all modes
- $\tau_e\tau_\mu(\tau_{3h}\tau_{3h})$ seen to be (sub)dominant already from these yields
- Invariant mass not peaking due to neutrinos



New search in $a \to \tau^+\tau^-$: Efficiencies

Computation of yields based on efficiencies as determined from simulation, measured τ BRs and cross-sections for the background [see refs at the paper]. Obtained per mode (j) and ALP mass!

$$S_j = \mathcal{L} \times \sigma(pp \to a) \times \mathcal{B}(a \to \tau^+\tau^-) \times \varepsilon_j^{\mathrm{ALP}} \times (\mathcal{B}(\tau_1) \times \mathcal{B}(\tau_2))_j$$

$$B_j = \mathcal{L} \times (\sigma(pp \to Z/\gamma* \to \tau^+\tau^-) \times \varepsilon_j^{\mathrm{DY}} \times (\mathcal{B}(\tau_1) \times \mathcal{B}(\tau_2))_j + \sigma(pp \to b\bar{b}) \times \varepsilon_j^{\mathrm{QCD}})$$

Backgrounds

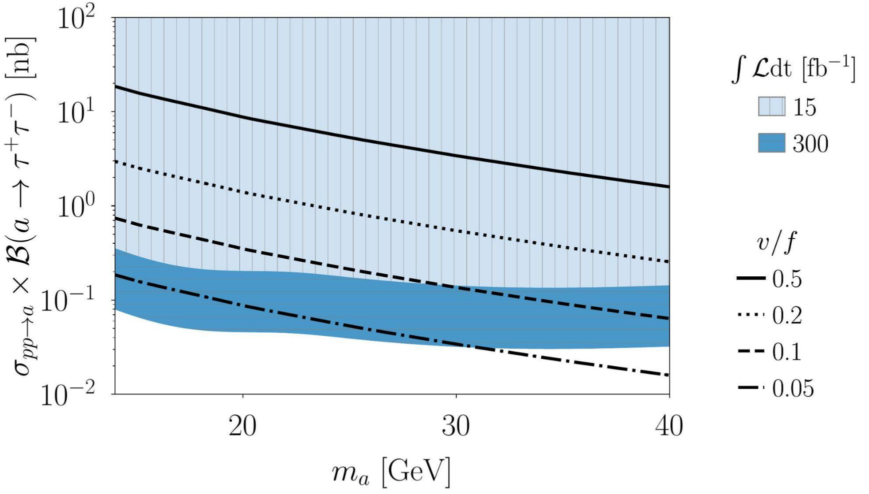
Mass range (GeV)	Category	$\varepsilon^{\mathrm{DY}}$ (%)	$\varepsilon^{\mathrm{QCD}}$ (%)
(6.6, 13.6) | 14	h_3h_3	0.0208	1.32×10^{-5}
(4.0, 12.2) | 14	$h_3\mu$	0.0112	2.90×10^{-7}
(4.0, 12.2) | 14	h_3e	0.00680	4.61×10^{-7}
(2.5, 10.0) | 14	$e\mu$	0.00520	1.75×10^{-7}

Signal

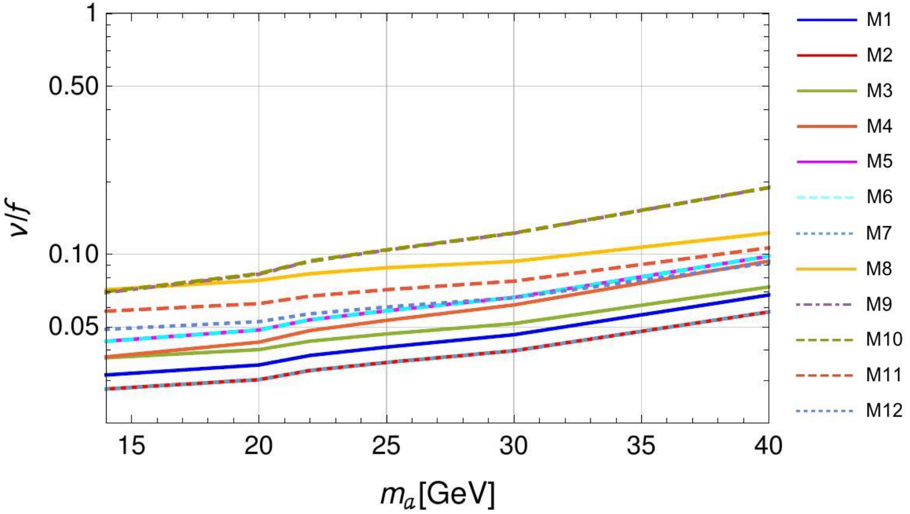
Mass (GeV)	$\varepsilon_{h_3h_3}$ (%)	$\varepsilon_{h_3\mu}$ (%)	ε_{h_3e} (%)	$\varepsilon_{e\mu}$ (%)
14	0.130	0.0817	0.0465	0.0523
20	0.102	0.173	0.109	0.108
22	0.271	0.177	0.111	0.109
25	0.315	0.221	0.142	0.139

New search in $a \to \tau^+\tau^-$: Limits

Limits computed with the CLs method, for all models under consideration. Combine 4 modes for every mass



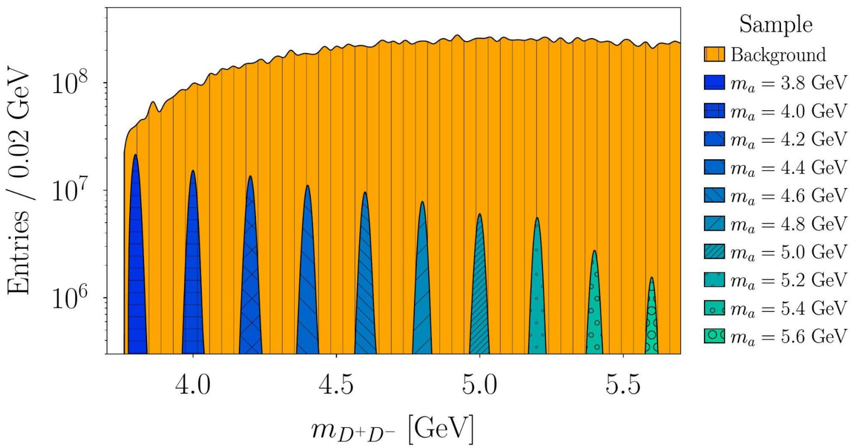
Limits in v/f at 300 fb^{-1}



New search in $a \rightarrow c\bar{c}$: Intro

Coupling of ALPs to quarks usually addressed through jets. Alternative at LHCb: exclusive charm reconstruction, provides great mass resolution (~9 GeV)

- For a small mass range (3.8-6 GeV), the ALP might be fully reconstructed through a D^+D^- final state (with $D^+ \rightarrow K\pi\pi$). Proof of principle, other modes, e.g., $D^0\bar{D}^0$ also possible
- Full simulation developed also in Pythia, D hadronization taken from there
- Main background from QCD production of cc.



New search in $a \to c\bar{c}$: Efficiencies

Computation of yields again based on efficiencies as determined from simulation, measured D BRs and cross-sections for the background. Depends on ALP mass!

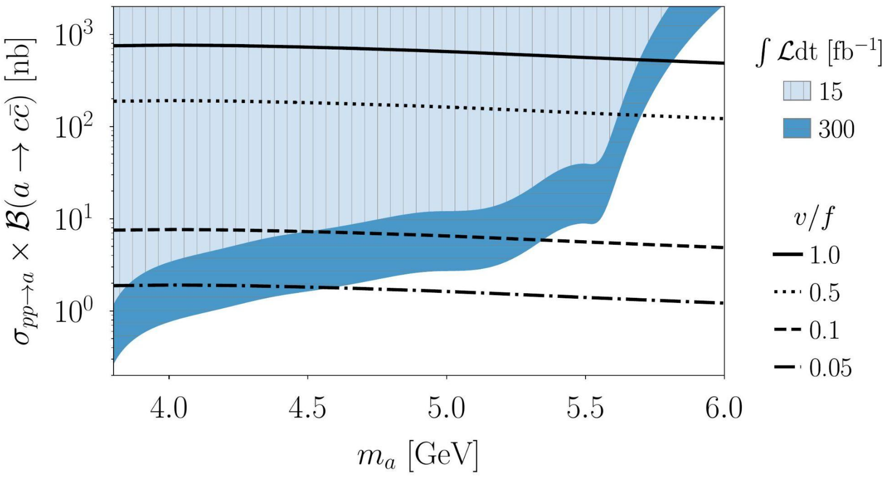
- Determine both efficiency to have all 6 daughters in acceptance and to have both charm hadronizing to a D. Selection with usual LHCb cuts (acceptance + kinematics)!

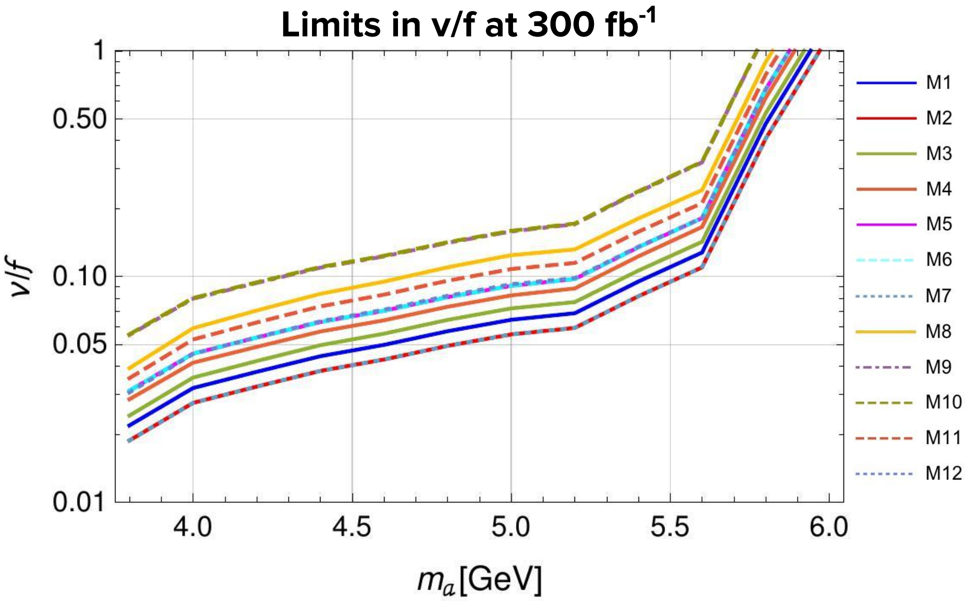
$$\epsilon_{S,B} = f^{S,B}_{c\bar{c}\to D^+D^-} \times f^{S,B}_{Acc} \times f^{S,B}_{mass}$$

	Signal (in %)			Background (in %)
m_a[GeV]	$f^S_{c\bar{c}\to D^+D^-}$	$f^S_{c\bar{c}\to D^+D^-} \times f^S_{Acc}$	ε_S	ε_B
3.8	22.0	1.71	1.62	0.000390
4.0	17.7	1.27	1.16	0.000768
4.2	14.9	1.12	1.04	0.00101
4.4	14.1	1.02	0.891	0.00122

New search in $a \to c\bar{c}$: Results

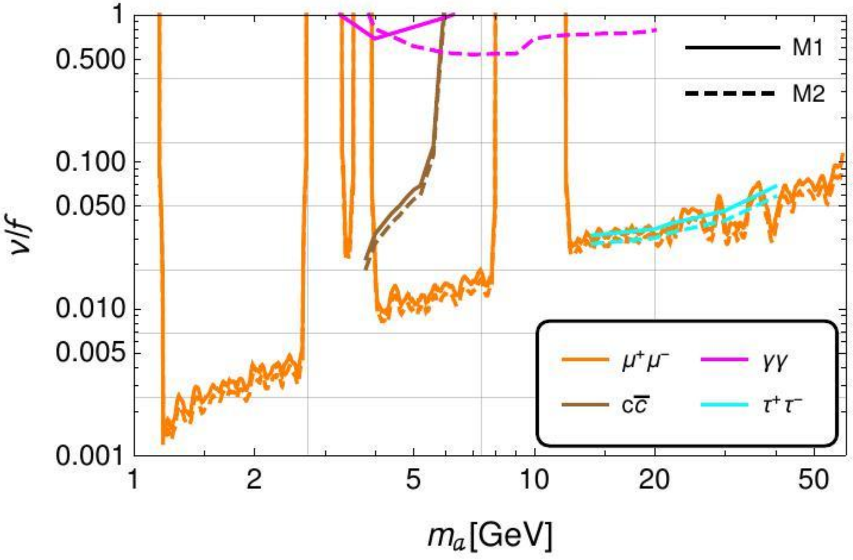
Limits computed again with the CLs method

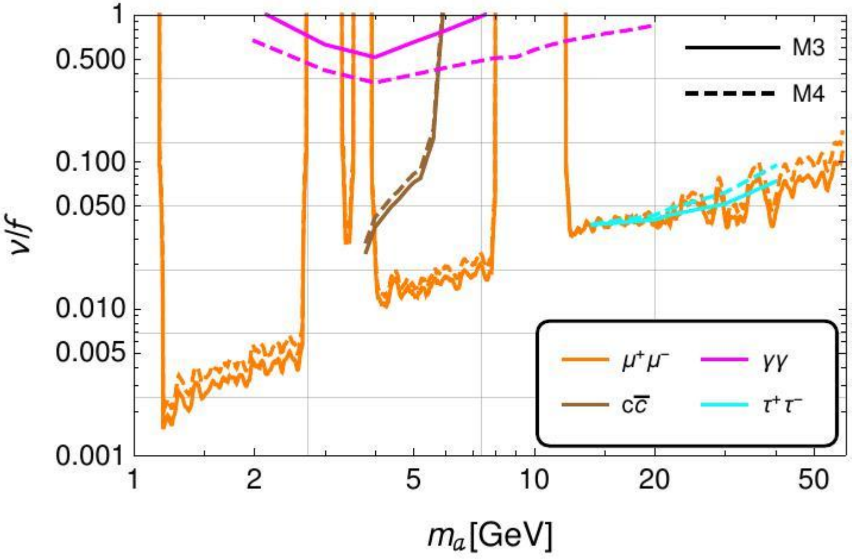




Summary results

Limits in v/f for all modes we have studied (more in backup). μμ dominates, but others interesting under certain conditions/masses



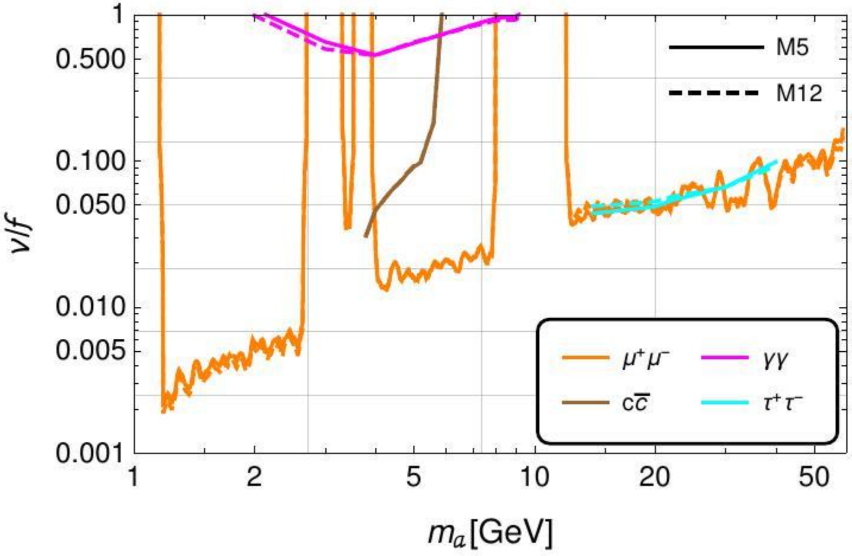


Conclusions and Outlook

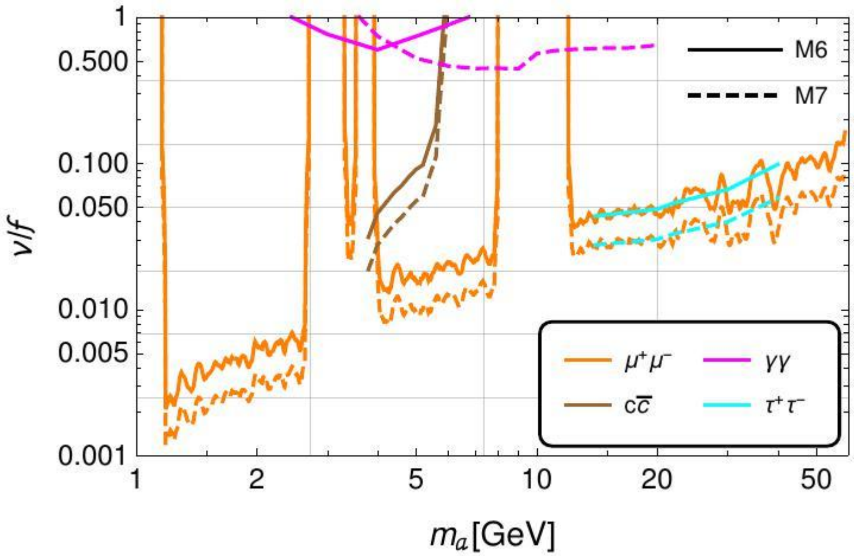
- Prospects for discovering an ALP at LHCb are really good.
- Results were presented for composite Higgs benchmark models, but also more model independently, in terms of bounds on $\sigma x \mathcal{B}$!
- Assuming universal fermion coupling, muons yield dominant bound, but other modes are important too. (Important to control S/B and systematic effects!)
- below 40 GeV, $\tau\tau$ is competitive. Precise studies including all detector, trigger, etc. effects are still required though.
- Not impossible to conceive models with fermion non-universal couplings (e.g. leptophobic or lepton non-universal). Then hadrons become more relevant, or the relative relevance of the di-muon and di-tau channels is altered.

Thank you!

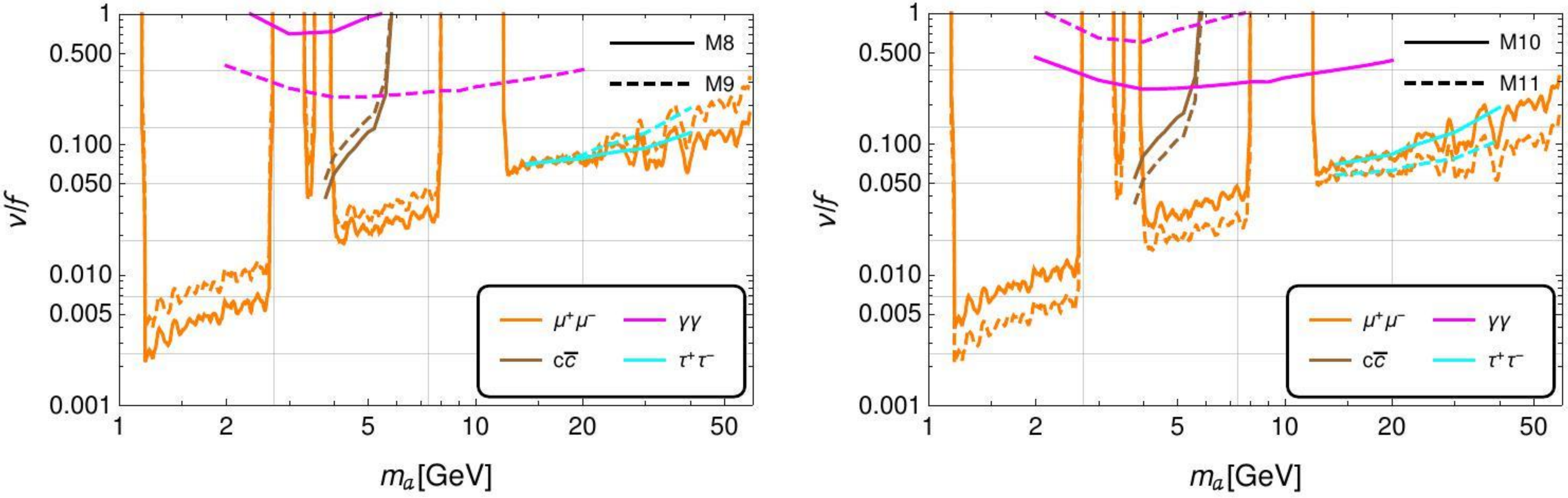
Backup slides



M5
M12
$\mu^+\mu^-$
$\gamma\gamma$
$c\bar{c}$
$\tau^+\tau^-$
v/f
m_a[GeV]



M6
M7
$\mu^+\mu^-$
$\gamma\gamma$
$c\bar{c}$
$\tau^+\tau^-$
v/f
m_a[GeV]



M8
M9
M10
M11
$\mu^+\mu^-$
$\gamma\gamma$
$c\bar{c}$
$\tau^+\tau^-$
v/f
m_a[GeV]
1
0.500
0.100
0.050
0.010
0.005
0.001
1
2
5
10
20
50

Coset	HC	ψ	χ	$-q_\chi/q_\psi$	Baryon	Name	Lattice
$\frac{SU(5)}{SO(5)} \times \frac{SU(6)}{SO(6)}$	SO(7)	$5 \times \mathbf{F}$	$6 \times \mathbf{Sp}$	5/6	$\psi\chi\chi$	M1	
	SO(9)	$5 \times \mathbf{F}$	$6 \times \mathbf{Sp}$	5/12	$\psi\chi\chi$	M2	
	SO(7)	$5 \times \mathbf{Sp}$	$6 \times \mathrm{F}$	5/6	$\psi\psi\chi$	M3	
	SO(9)	$5 \times \mathbf{Sp}$	$6 \times \mathrm{F}$	5/3	$\psi\psi\chi$	M4	
$\frac{SU(5)}{SO(5)} \times \frac{SU(6)}{Sp(6)}$	Sp(4)	$5 \times \mathbf{A}_2$	$6 \times \mathbf{F}$	5/3	$\psi\chi\chi$	M5	√
$\frac{SU(5)}{SO(5)} \times \frac{SU(3)^2}{SU(3)}$	SU(4)	$5 \times \mathbf{A}_2$	$3 \times (\mathbf{F}, \overline{\mathbf{F}})$	5/3	$\psi\chi\chi$	M6	√
	SO(10)	$5 \times \mathbf{F}$	$3 \times (\mathbf{Sp}, \overline{\mathbf{Sp}})$	5/12	$\psi\chi\chi$	M7	
$\frac{SU(4)}{Sp(4)} \times \frac{SU(6)}{SO(6)}$	Sp(4)	$4 \times \mathbf{F}$	$6 \times \mathbf{A}_2$	1/3	$\psi\psi\chi$	M8	√
	SO(11)	$4 \times \mathbf{Sp}$	$6 \times \mathbf{F}$	8/3	$\psi\psi\chi$	M9	
$\frac{SU(4)^2}{SU(4)} \times \frac{SU(6)}{SO(6)}$	SO(10)	$4 \times (\mathbf{Sp}, \overline{\mathbf{Sp}})$	$6 \times \mathbf{F}$	8/3	$\psi\psi\chi$	M10	
	SU(4)	$4 \times (\mathbf{F}, \overline{\mathbf{F}})$	$6 \times \mathbf{A}_2$	2/3	$\psi\psi\chi$	M11	√
$\frac{SU(4)^2}{SU(4)} \times \frac{SU(3)^2}{SU(3)}$	SU(5)	$4 \times (\mathbf{F}, \overline{\mathbf{F}})$	$3 \times (\mathbf{A}_2, \overline{\mathbf{A}_2})$	4/9	$\psi\psi\chi$	M12	

[Front.in Phys. 7 (2019) 22]

TABLE I. Model details. The first column shows the EW and QCD colour cosets, respectively, followed by the representations under the confining hypercolour (HC) gauge group of the EW sector fermions ψ and the QCD coloured ones χ. The $-q_\chi/q_\psi$ column indicates the ratio of charges of the fermions under the non-anomalous $U(1)$ combination, while "Baryon" indicate the typical top partner structure.