Phenomenology of an elusive top-philic ALP at the LHC

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Based on arXiv:2311.16048

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LHCTopWG

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ALP effective action

★**Axion like particles are motivated (light) new physics particles**

★***They appear in many UV completions of the Standard Model***

Strong CP problem and beyond

ALP: Pseudo-Nambu Goldstone Boson of a spontaneously broken symmetry

✳ ***Dimension 5 Effective action suppressed by Axion decay constant***

✳ ***Coupling structure dictated by symmetry***

Only subset of these coupling is actually independent, once we consider allowed re-parametrizations

Shift symmetric

$$\mathcal{L}_a = \frac{1}{2}(\partial_\mu a)^2 - \frac{1}{2}m_a^2 a^2 + \frac{\partial^\mu a}{f_a}\sum_f \bar{\psi}_f c_f \gamma_\mu \psi_f + c_H \frac{\partial^\mu a}{f_a} H^\dagger i D_\mu H$$

$$+ c_{GG}\frac{\alpha_S}{4\pi}\frac{a}{f_a}G\tilde{G} + c_{WW}\frac{\alpha_2}{4\pi}\frac{a}{f_a}W\tilde{W} + c_{BB}\frac{\alpha_1}{4\pi}\frac{a}{f_a}B\tilde{B},$$

Mass term
(shift symmetry breaking)

Anomaly induced

Top-Philic ALP

We consider ALP coupled only (derivatively) to RH top

★***E.g.: UV models where ALP top coupling derives from top-mixing with new sector***

$$\mathcal{L}_{\text{int.}} = c_t \frac{\partial^\mu a}{f_a} \bar{t}_R \gamma_\mu t_R .$$

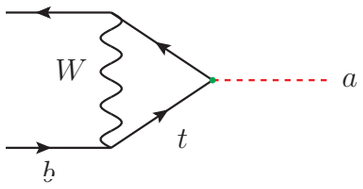
Recent works

arXiv:2303.17634
arXiv:2306.08686
arXiv:2308.11703
arXiv:2307.10372

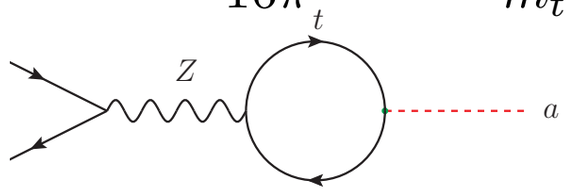
Shift symmetry of the tree-level interaction implies rules on induced ALP interactions

✓ **Top-Philic ALP: tree level top-coupling induces coupling to all SM fermions**

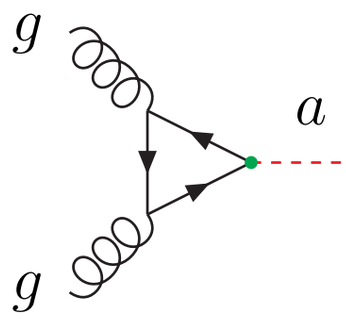
$$c_b \simeq 5 c_t \frac{y_t^2}{16\pi^2} \log \frac{\Lambda}{m_t}$$



$$c_f \simeq -12 c_t \frac{y_t^2}{16\pi^2} T_3^f \log \frac{\Lambda}{m_t}$$



✓ **Top-philic ALP: what about couplings to gauge bosons? Gluons?**



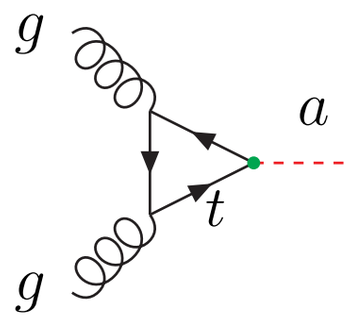
Important for LHC signatures

Details on Gluons - ALP interaction

★*How does the top-philic ALP interacts with gluons?*

Amplitude a - G - G generated by top loop

$$i\mathcal{A}^{\mu\nu}\left(a(k) \to g(p)g(q)\right) = i\frac{\alpha_S}{\pi}\frac{c_t}{f_a}\delta^{ab}p_\alpha q_\beta \epsilon^{\mu\nu\alpha\beta}\left[1 + 2m_t^2 C_0(p,q;m_t^2)\right]$$



Low energy regime (q^2 << m_t^2)

$$\mathcal{A}(a \to gg) \sim \frac{\alpha_S}{\pi}\frac{c_t}{f_a}\frac{m_a^2}{24m_t^2}$$

Suppressed as m_a^2/m_t^2

High energy regime (q^2 >> m_t^2)

$$\mathcal{A}(a \to gg) \sim \frac{\alpha_S}{\pi}\frac{c_t}{f_a}$$

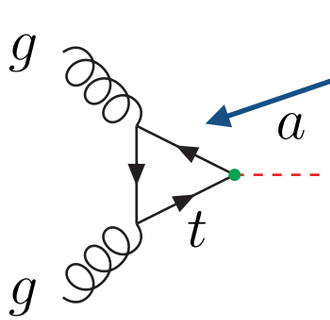
As gluon contact term interaction

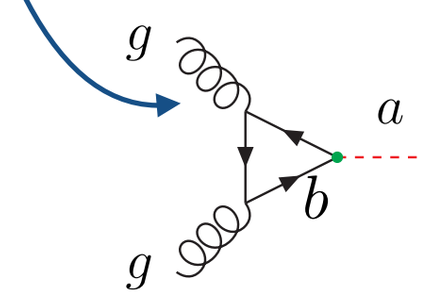
Relevant for production with jet at high pT

★In low energy regime, contributions from other fermions (higher loop order) is relevant

Relevant for resonant production and ALP decay

$$\mathcal{A}(a \to gg) \sim \frac{\alpha_S}{\pi}\frac{c_t}{f_a}\left[-\frac{m_a^2}{24m_t^2} + \frac{5}{2}\frac{y_t^2}{16\pi^2}\log\frac{\Lambda}{m_t}\right]$$





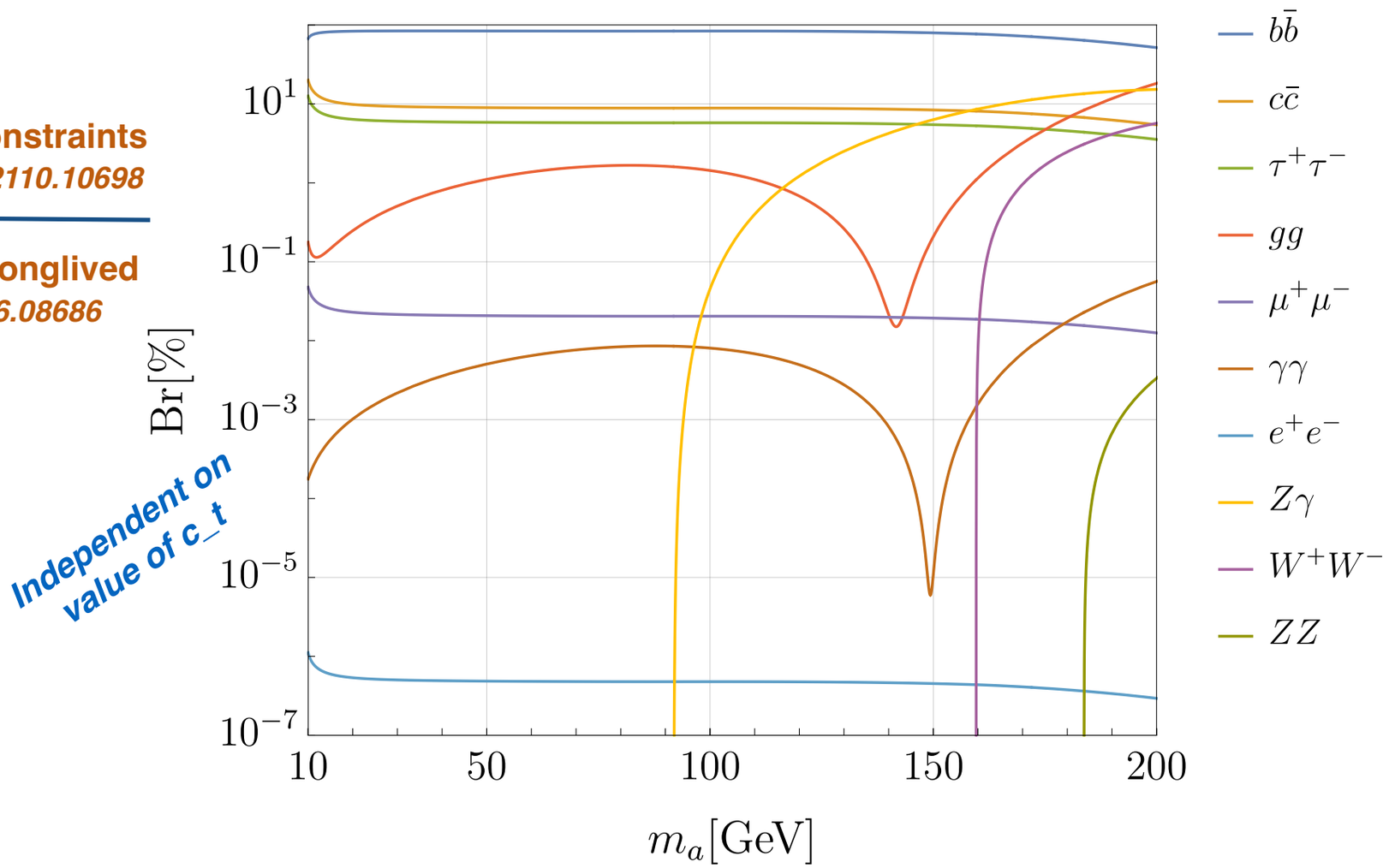
BR of a Top-Philic ALP

★**We consider top-philic ALP with mass scale GeV — O(100) GeV**

★***Rich spectrum of decay channels, in this mass range bb dominates***

Flavour constraints
e.g.: arXiv:2110.10698

Possible longlived
arXiv:2306.08686



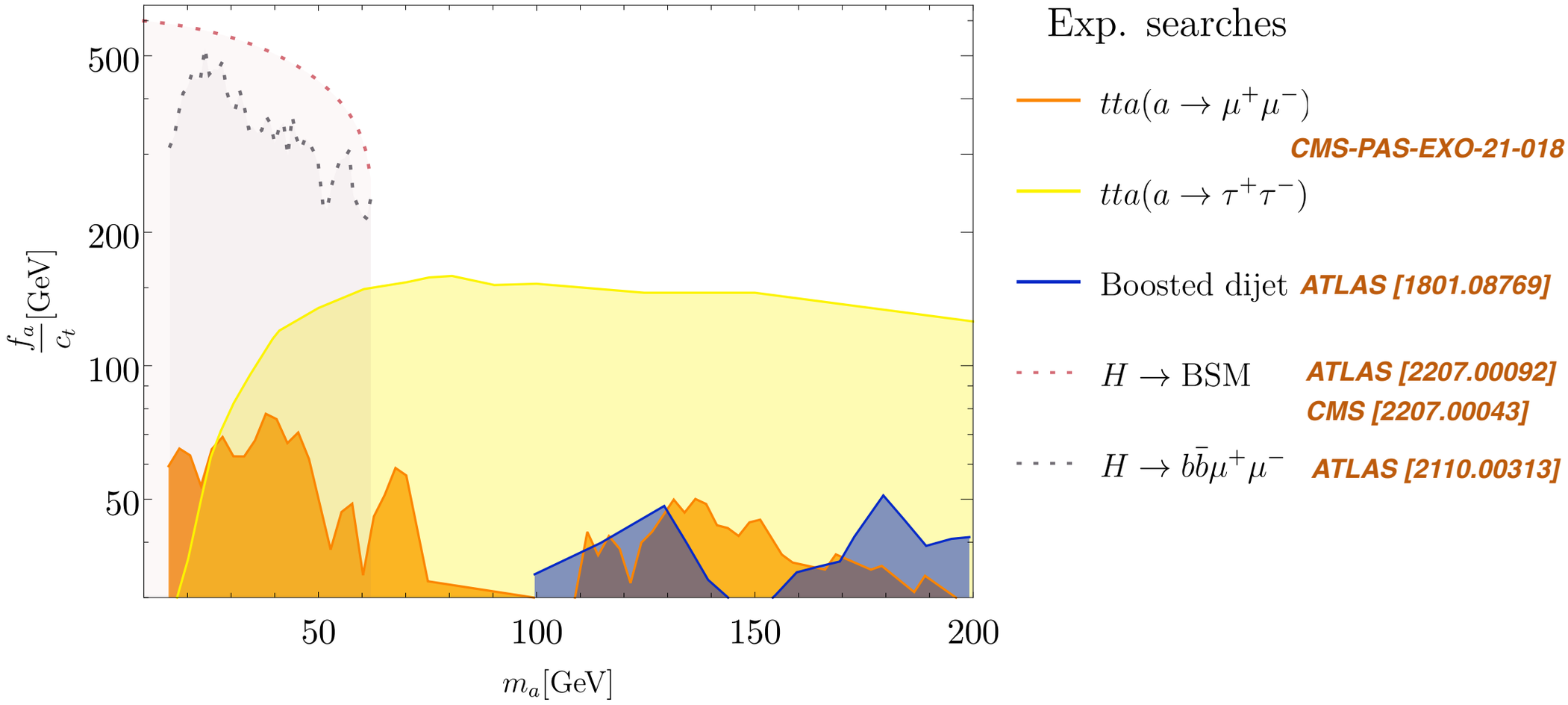
Independent on value of c_t

ALP shift symmetry is broken
Di-photon and di-tops

What is LHC reach in this mass range?

Where do we stand

★*Elusive particle strongly coupled with the top*



- Moderate cross section because suppressed aGG interaction
- Main decay mode is into b quarks

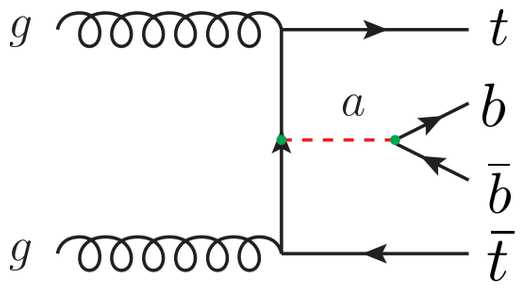
$$\sigma_{\rm tot}^{13\rm TeV} \sim 10^{-2} \left(\frac{c_t/f_a}{\rm TeV^{-1}} \right)^2 \rm pb$$

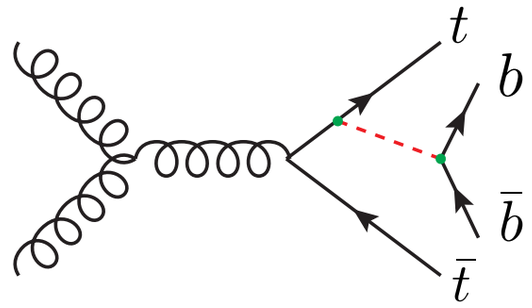
Several strategies in top-rich final states explored

Top-philic ALP in ttbb

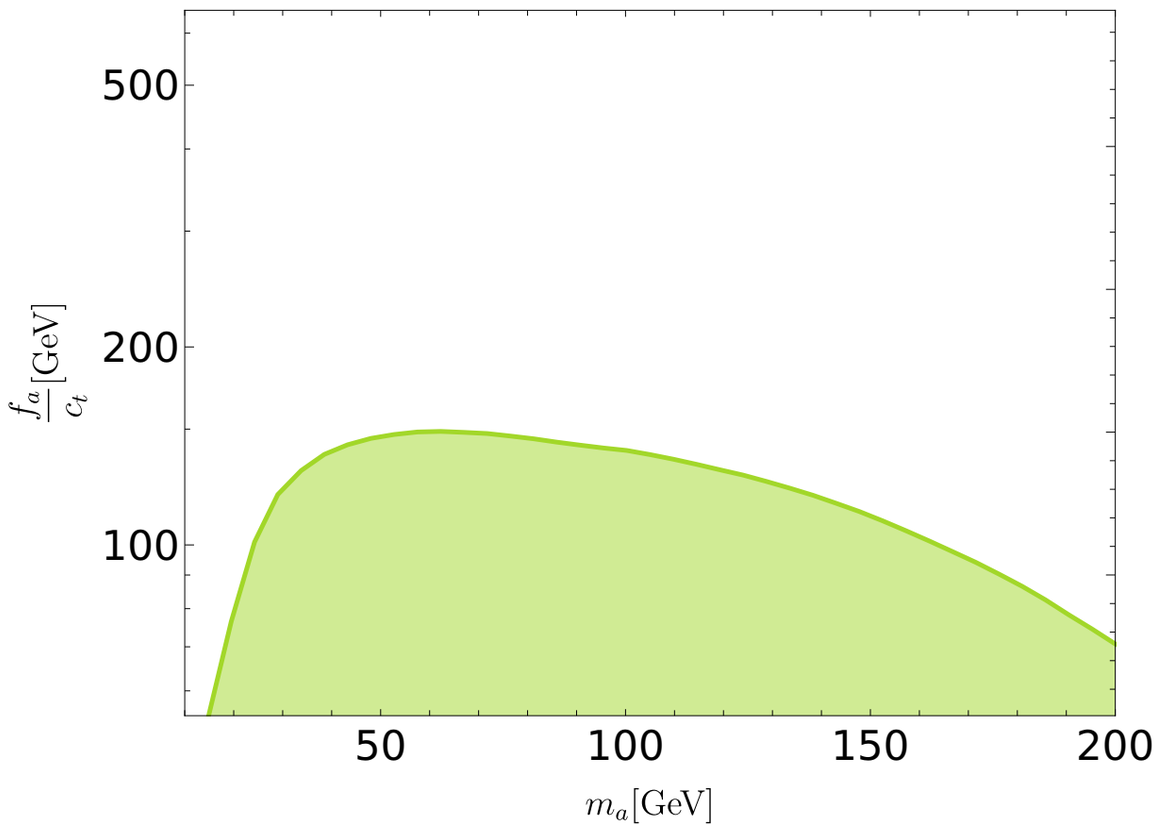
★Top-philic ALP BR is mainly into b quark pairs

★Production in association with tops leads to $pp \to t\bar{t}a \to t\bar{t}\bar{b}b$





$$\sigma(pp \to t\bar{t}a) \propto (c_t/f_a)^2$$



Exp.	Channel	$\mu_{t\bar{t}b\bar{b}} \pm$ stat. $\pm$ syst.	Ref.
CMS	dilepton	$1.36 \pm 0.10 \pm 0.34$	[63]
CMS	lepton+jets	$1.26 \pm 0.04 \pm 0.31$	[63]
ATLAS	dilepton ($e\mu$, 4b)	$1.75 \pm 0.05 \pm 0.56$	[61]
ATLAS	lepton+jets (4b)	$1.57 \pm 0.09 \pm 0.49$	[61]

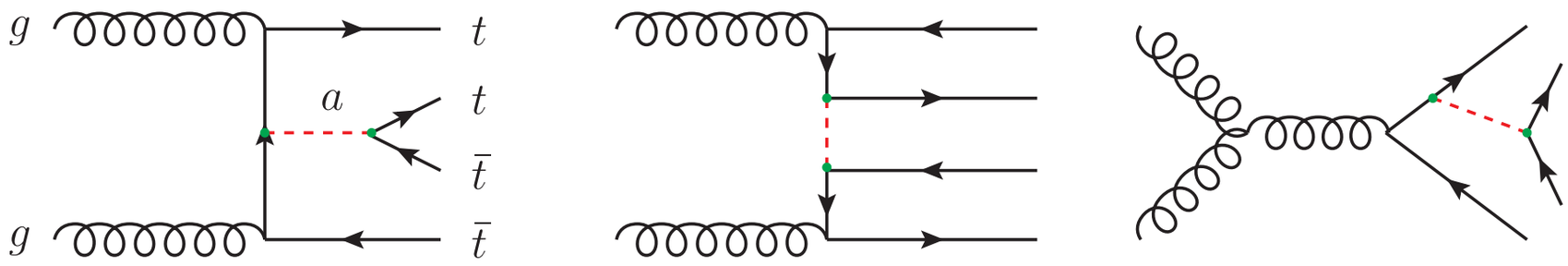
arXiv:2003.06467

arXiv:1811.12113

- ✳ Resonant channels dominate
- ✳ Signal strength measures ALP contribution wrt SM one
- ✳ Compared with CMS and ATLAS xsec measurements
- ✳ This final state would benefit from a resonant search

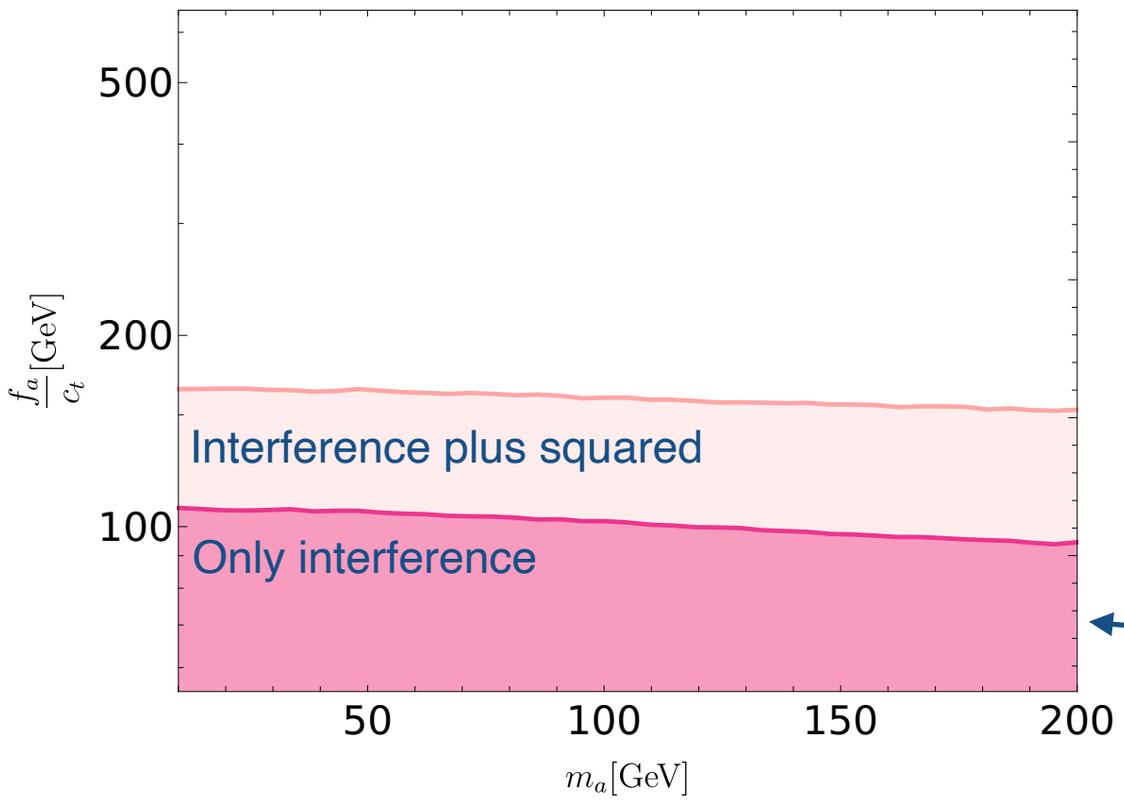
Top-philic ALP in 4 tops

★Top-philic ALP corrections to 4 top total cross section



✳ Considered interference (+ squared) effects

$\sim (c_t/f_a)^2$ $\sim (c_t/f_a)^4$



Exp.	Channel	$\mu_{t\bar{t}t\bar{t}} \pm$ stat. $\pm$ syst.	Ref.	
ATLAS	SSDL+ML	$1.70 \pm 0.40^{+0.7}_{-0.4}$	[68]	*arXiv:2303.15061*
ATLAS	OSDL+1L	$2.00 \pm 0.70^{+1.5}_{-1.0}$	[71]	*arXiv:2106.11683*
CMS	SSDL+ML	$1.32 \pm 0.27^{+0.2}_{-0.23}$	[69]	*arXiv:2305.13439*
CMS	OSDL+1L	$2.20 \pm 0.50 \pm 0.50$	[70]	*arXiv:2303.03864*

✳ Included QCD and mixed QCD–EW processes

✳ Considered most recent 4-top theory prediction *arXiv:2212.03259*

✳ Compared with CMS and ATLAS measurements

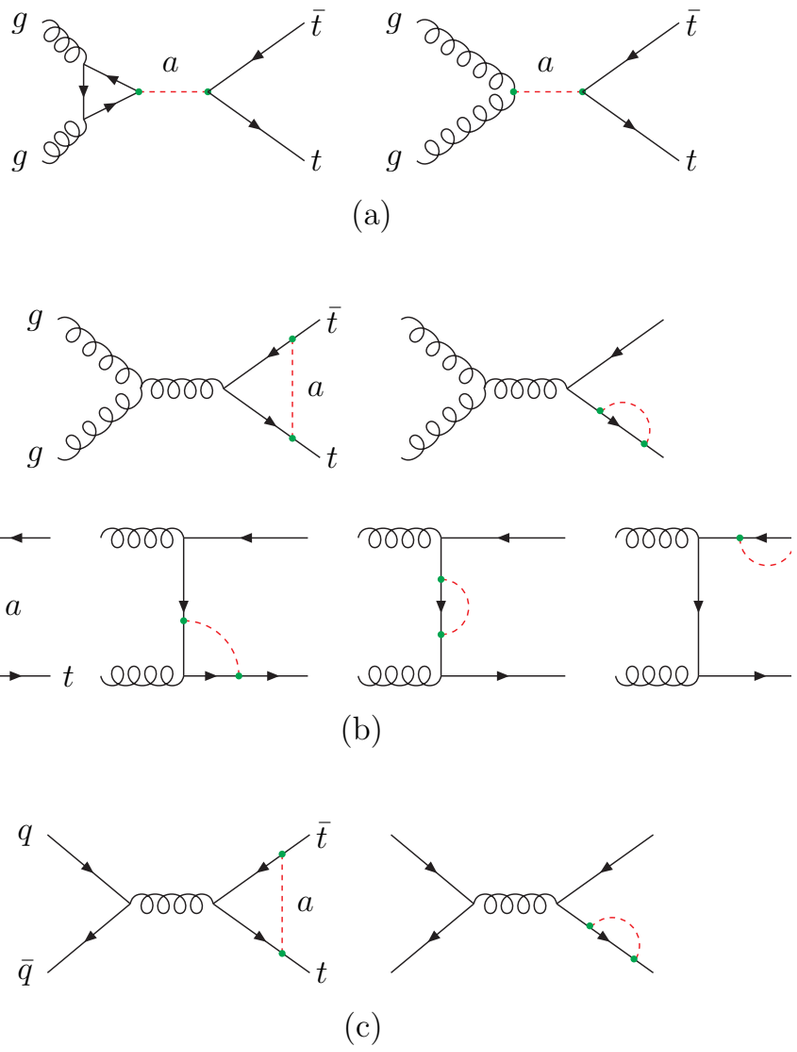
✳ Limits obtained combining the four analysis

Top-philic ALP in t tbar

★Top-philic ALP corrections to t tbar differential distributions

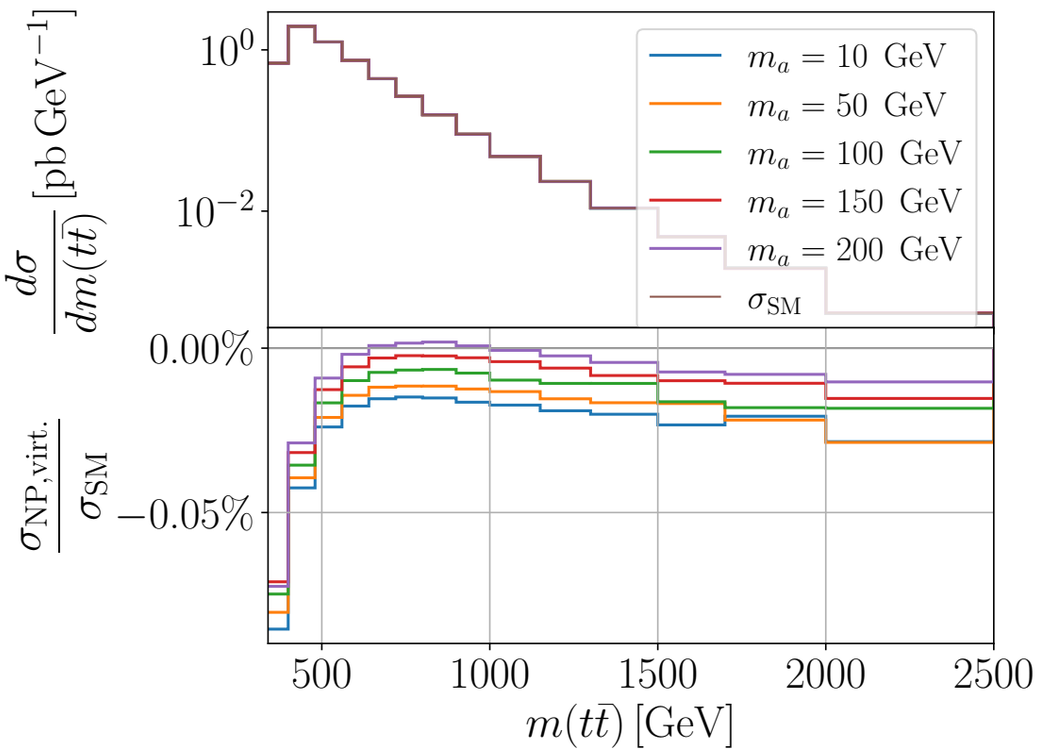
$$\sigma = \sigma_{\mathrm{SM}} + \sigma_{\mathrm{NP,\,virt}} + \sigma_{\mathrm{NP,\,real}}$$

Complete one-loop computation performed



One-loop diagrams with ALP exchange (non derivative basis)

- ✳ Real contribution negligible
- ✳ Virtual contribution is interference $\sim (c_t/f_a)^2$
- ✳ Mild dependence on value of ALP mass
- ✳ Compared with exp distribution of mtt and pT
- ✳ Larger deviations in region close to threshold



arXiv:2311.16048 S.Blasi, F. Maltoni, AM, K. Mimasu, D. Pagani, S. Tentori

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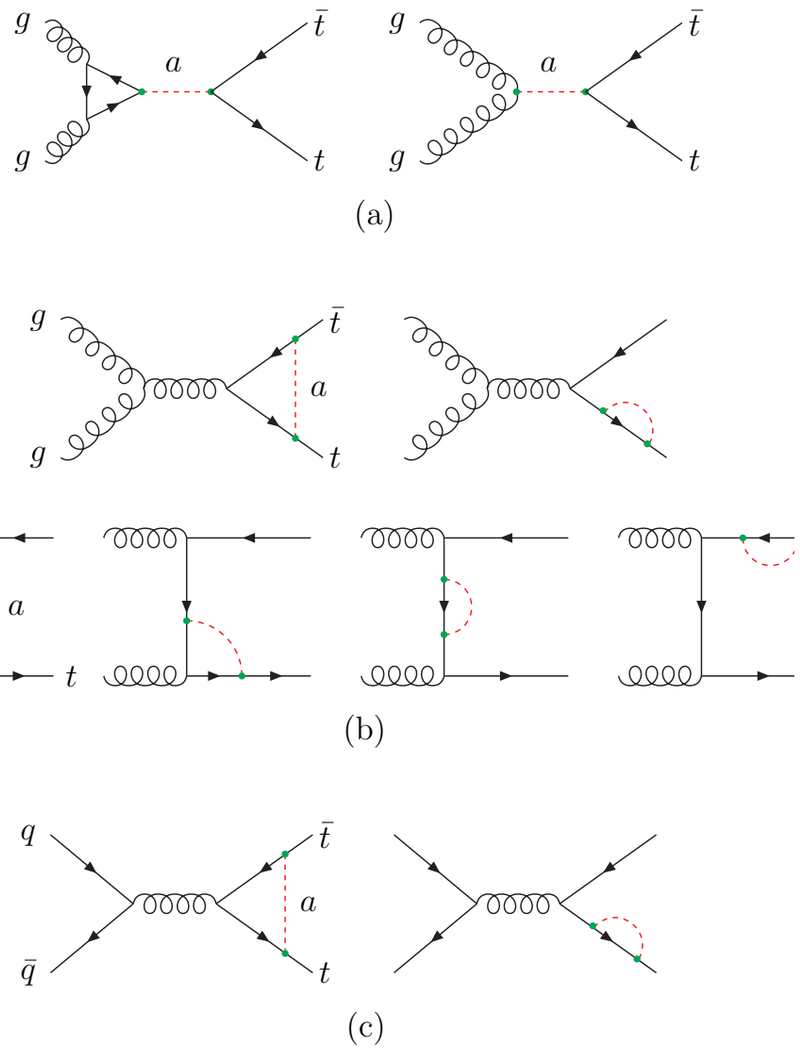
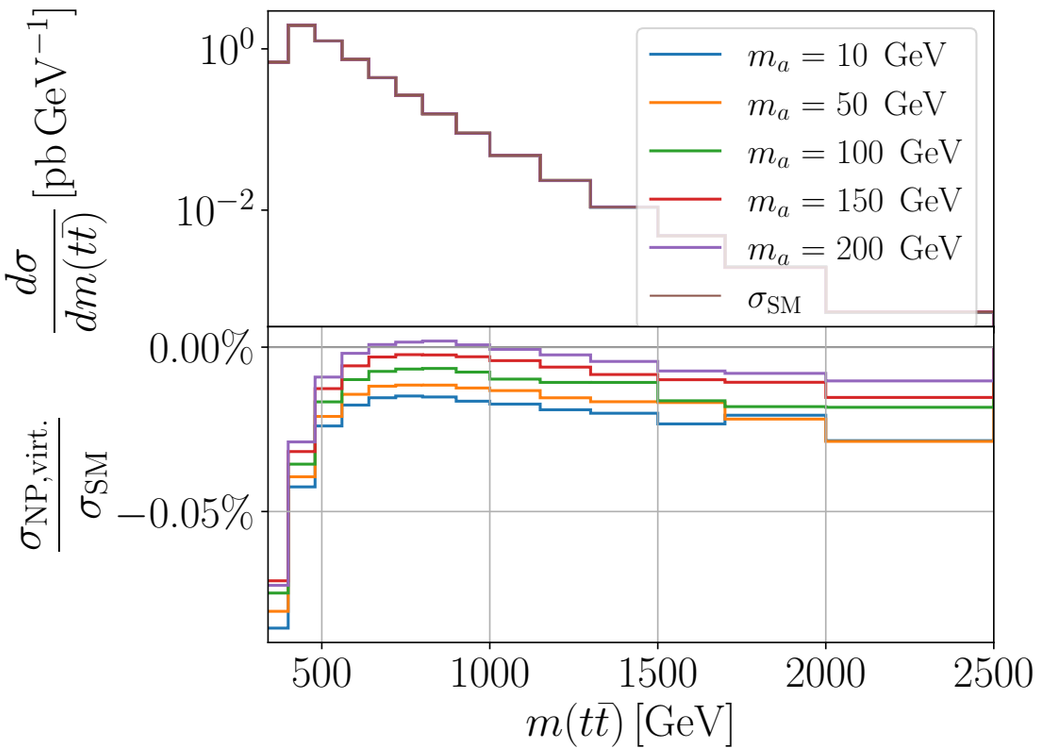


One-loop diagrams with ALP exchange (non derivative basis)

Limits obtained

m_a [GeV]	10	50	100	150	200
$\frac{f_a}{c_t}$ [GeV]	201	206	212	221	234

See paper for ATLAS and CMS analysis used



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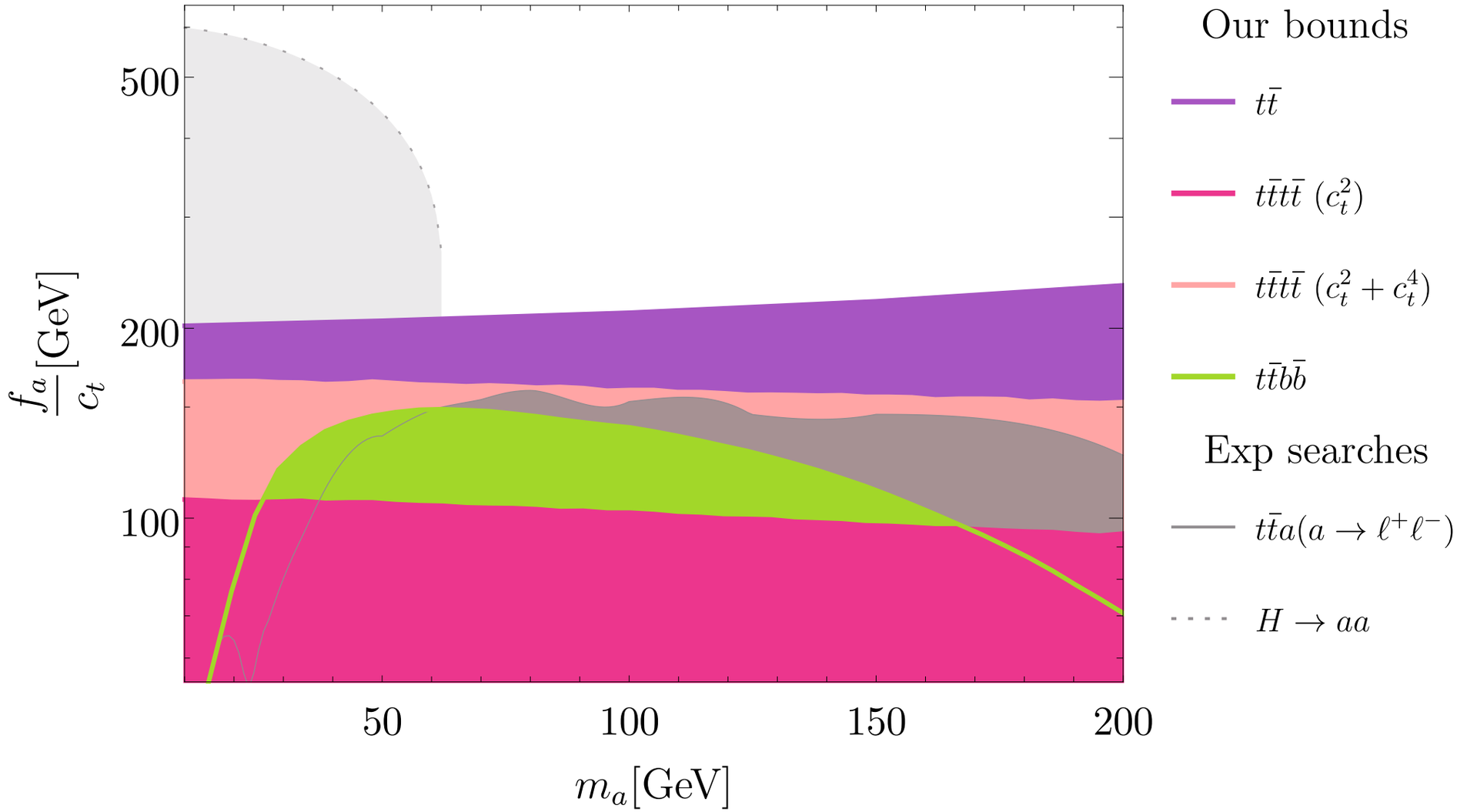
Where do we get to

Many top(s) final states explored



!!! Top-philic ALP may be hiding in top rich final states !!!

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Conclusions

★Axion Like Particles arise in many BSM extensions

★ALP effective action is dictated by symmetries

★Top-philic ALP interesting possibility to be searched for at the LHC

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Top-philic ALP in the GeV to hundreds GeV mass window

✦Elusive at LHC because suppressed aGG interaction

✦Showed that it can be revealed in top-rich final states

$t\bar{t}$ $t\bar{t}b\bar{b}$ $t\bar{t}t\bar{t}$

★We also explored invisible top-philic ALP

If ALP is mediator to dark matter sector

✓*See the paper for details*