Axions and top-quark physics

TOP2023

[Bonilla, Brivio, Gavela, Sanz, 2107.11392]
[Esser. Madigan, Sanz, Ubiali, 2303.17634]
[Rygaard, Niedziela, Schäfer, Bruggisser, Alimena, Westhoff, Blekman, 2306.08686]
[Blasi, Maltoni, Mariotti, Mimasu, Pagani, **ST** 23XX.XXXX]

Simone Tentori

UCLouvain

ALP: Why do we care?

- Strong CP Problem
- Composite Higgs models
- Neutrino mass generation
- Even more exotic stuff

What is an ALP?

- Generalization of QCD axion with arbitrary relation between m_a and f_a
- pNGB arising from a spontaneously broken global U(1)
- Original shift-symmetry broken by mass → $m_a < f_a$

UV MODEL

- Additional BSM states charged
- New U(1) chiral symmetry
- New scalar Φ

→ Symmetry breaks at scale f_a →

Shift-symmetric Lagrangian with ALP

→ Introducing m_a breaks the shift-symmetry →

Soft-breaking requires m_a<f_a

Generic ALP Lagrangian

$$\mathcal{L}_a = \frac{1}{2}(\partial_\mu a)^2 - \frac{1}{2}m_a^2 a^2 + \frac{\partial^\mu a}{f_a}\sum_F \bar{\psi}_F c_F \gamma_\mu \psi_F + c_H \frac{\partial^\mu a}{f_a} H^\dagger i D_\mu H$$
$$+ c_{GG}\frac{\alpha_S}{4\pi}\frac{a}{f_a}G\tilde{G} + c_{WW}\frac{\alpha_2}{4\pi}\frac{a}{f_a}W\tilde{W} + c_{BB}\frac{\alpha_1}{4\pi}\frac{a}{f_a}B\tilde{B}$$

- Shift-symmetry preserving terms
- Shift-symmetry violating terms

What is a top-philic ALP?

$$\mathcal{L} = \frac{c_t}{2}\frac{\partial_\mu a}{f_a}\bar{t}\gamma^\mu\gamma^5 t$$

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Equations of motion

$$\mathcal{L}_{\text{equiv.}} = -ic_t\frac{m_t}{f_a}a\bar{t}\gamma_5 t + c_t\frac{\alpha_S}{8\pi}\frac{a}{f_a}G\tilde{G} + \text{E.W.terms}$$

What is a top-philic ALP?

$$\mathcal{L} = \frac{c_t}{2}\frac{\partial_\mu a}{f_a}\bar{t}\gamma^\mu\gamma^5 t$$

Equations of motion

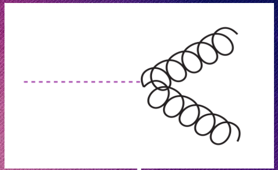
ALP = Pseudoscalar term + Contact term

$$\mathcal{L}_{\text{equiv.}} = -ic_t\frac{m_t}{f_a}a\bar{t}\gamma_5 t + c_t\frac{\alpha_S}{8\pi}\frac{a}{f_a}G\tilde{G} + \text{E.W.terms}$$

TOP-ALP vs Pseudoscalar

$$a \to gg(\gamma\gamma)$$

Blasi, Maltoni, Mariotti, Mimasu, Pagani, **ST** [23XX.XXXX]
Bauer, Neubert, Thamm [1708.00443]



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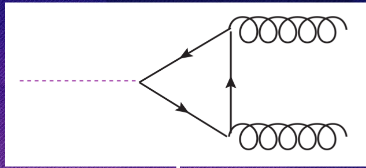


$$\Gamma \propto \left[1 + 2m_t^2 C(p,q,m_t)\right]^2$$

Only contact interaction

Only Pseudoscalar

$2m_t > m_a$

$$\Gamma \propto \left[\cancel{1} + 2m_t^2\left(\cancel{-\frac{1}{2m_t^2}} - \frac{m_a^2}{24m_t^4}\right)\right]^2$$

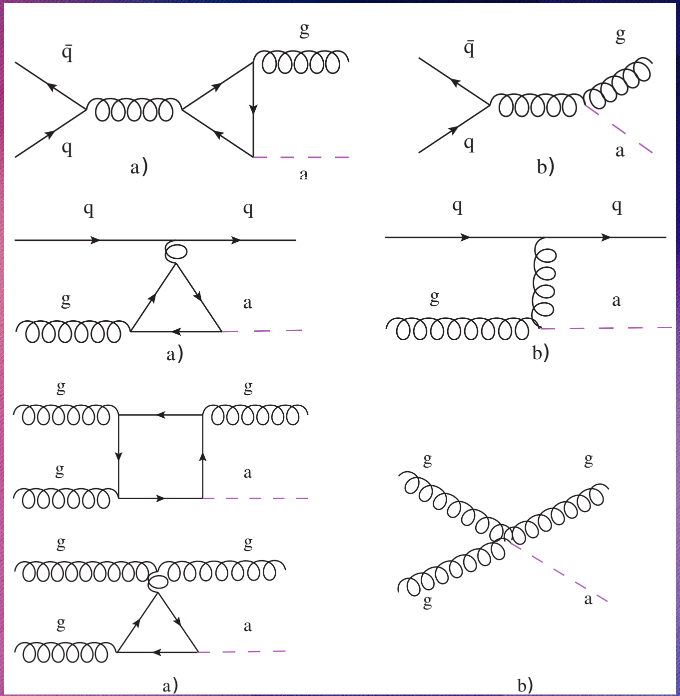
Cancellation between contact interaction and pseudoscalar!

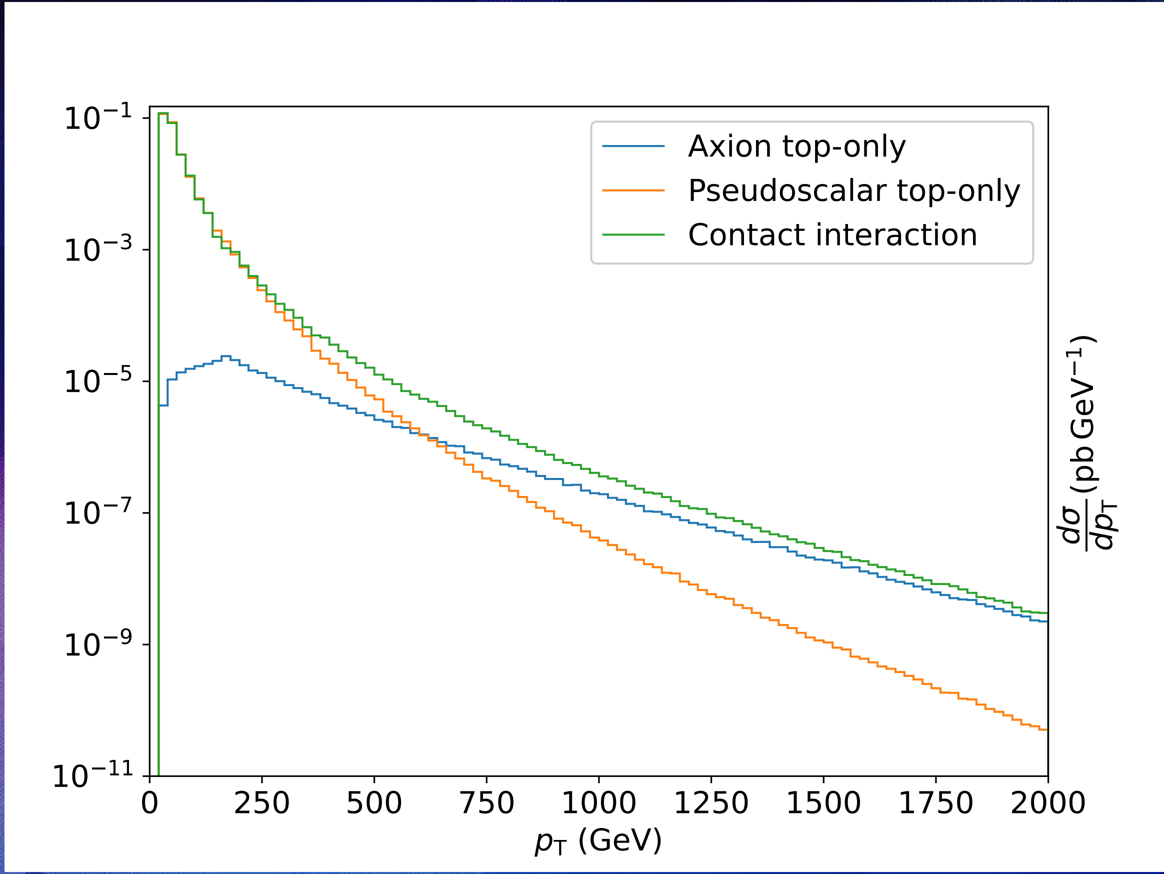
$$\Gamma \propto \frac{m_a^4}{144m_t^4}$$

Super-suppressed w.r.t. single terms

TOP-ALP vs Pseudoscalar

$$pp \to a + \text{jet}$$





About top-philic ALP monogamy

Can we have an ALP coupling only to top-quark?

- Tree level: YES [Esser. Madigan, Sanz, Ubiali, 2303.17634] [Blasi, Maltoni, Mariotti, Mimasu, Pagani, **ST** [23XX.XXXX]]
- Loop level: NO, effective coupling generated for all fermions

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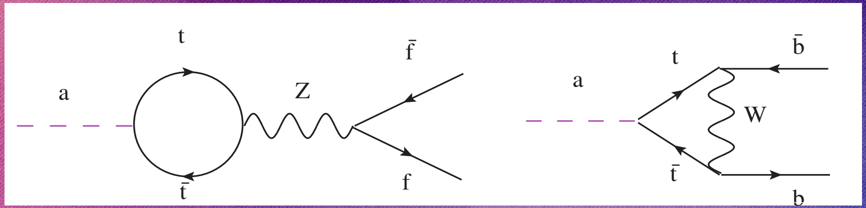
[Bauer, Neubert, Renner, Schnubel Thamm, 2012.12272, 2110.10698]
[Bonilla, Brivio, Gavela, Sanz, 2107.11392]

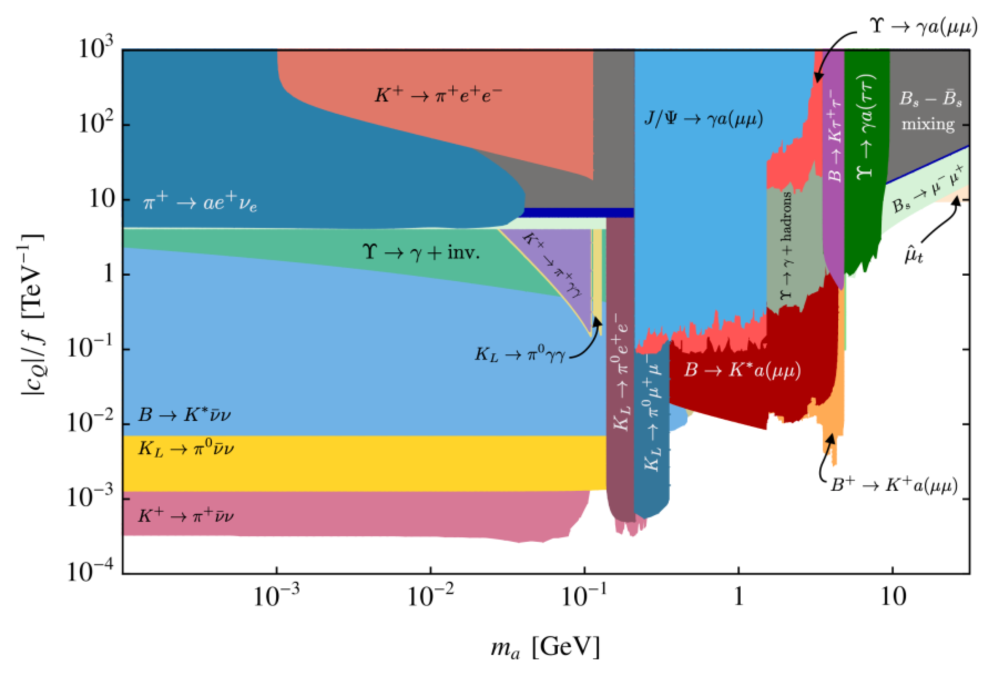


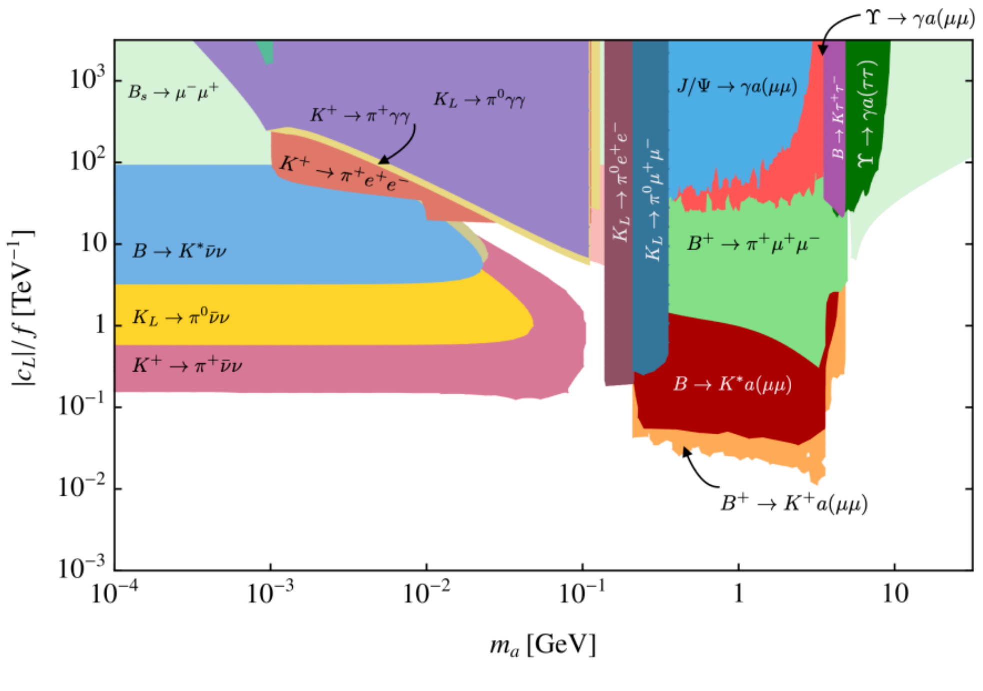
- Coupling sign depends on T_3^f
- UV scale Λ (Λ≈1TeV-4πTeV)
- Correction up to $c_f \sim 5 - 10\%\, c_t$

$$\mathcal{L}_{a,\mathrm{int}} = \sum_f -ic_f \frac{m_f}{f_a} a\bar{\psi}_f \gamma_5 \psi_f + \sum_f \frac{c_f}{2}\frac{\alpha_S}{4\pi}\frac{a}{f_a} G\tilde{G} + \mathrm{E.W.terms}$$

$$\begin{cases} c_t(m_t) & = c_t(\Lambda)\left(1 - 9\frac{y_t^2}{16\pi^2}\log\frac{\Lambda}{m_t}\right) \\ c_b(m_t) & = 5c_t(\Lambda)\frac{y_t^2}{16\pi^2}\log\frac{\Lambda}{m_t} \\ c_f(m_t) & = -12\, c_t(\Lambda)\frac{y_t^2}{16\pi^2}T_3^f\log\frac{\Lambda}{m_t} \end{cases}$$

Below 10 GeV: Flavour Bounds

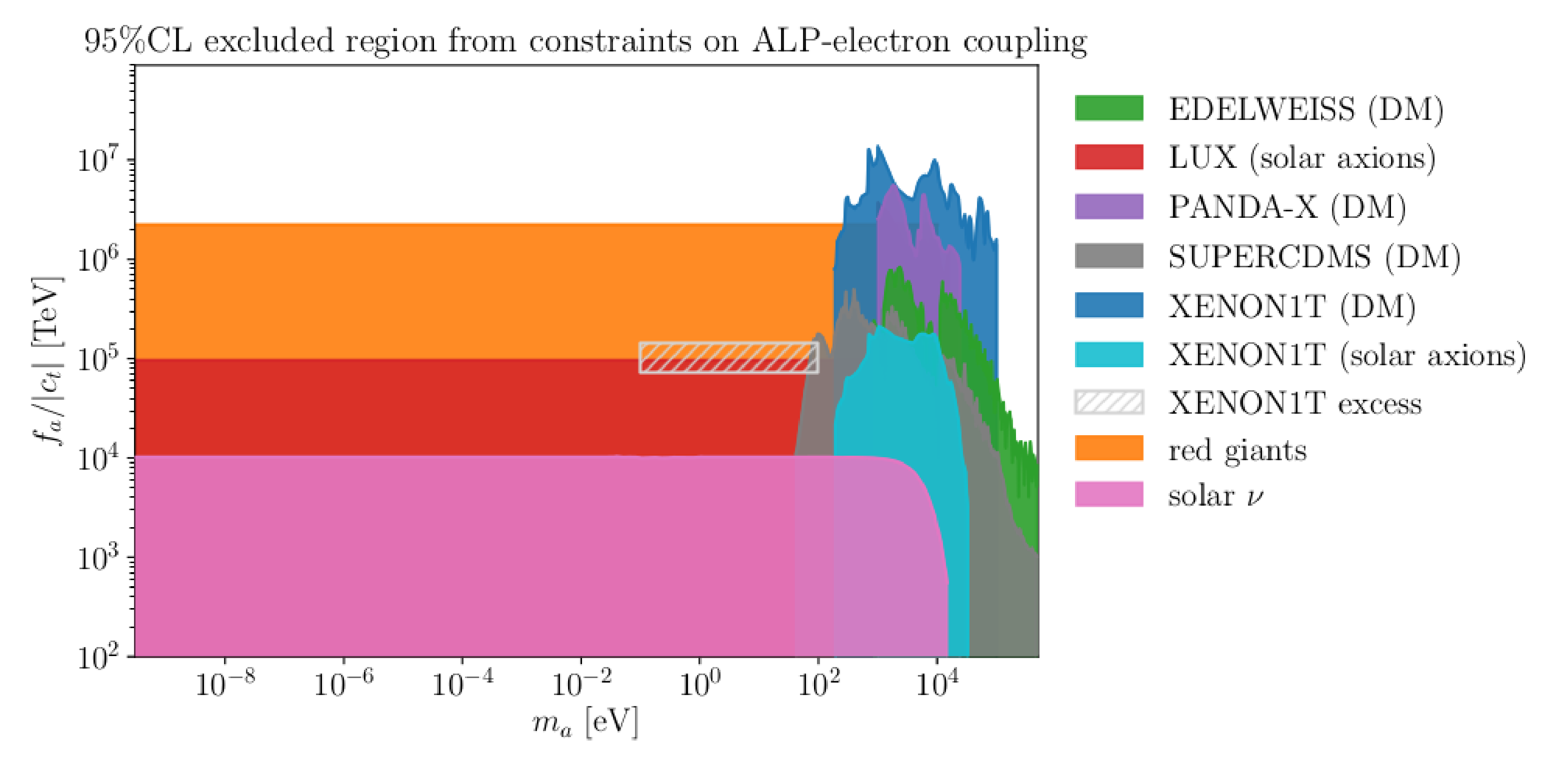




[Bauer, Neubert, Renner, Schnubel Thamm, 2110.10698]

For the 1-10 GeV region and $\mu^+\mu^-$ searches look at [Rygaard, Niedziela, Schäfer, Bruggisser, Alimena, Westhoff, Blekman, 2306.08686]

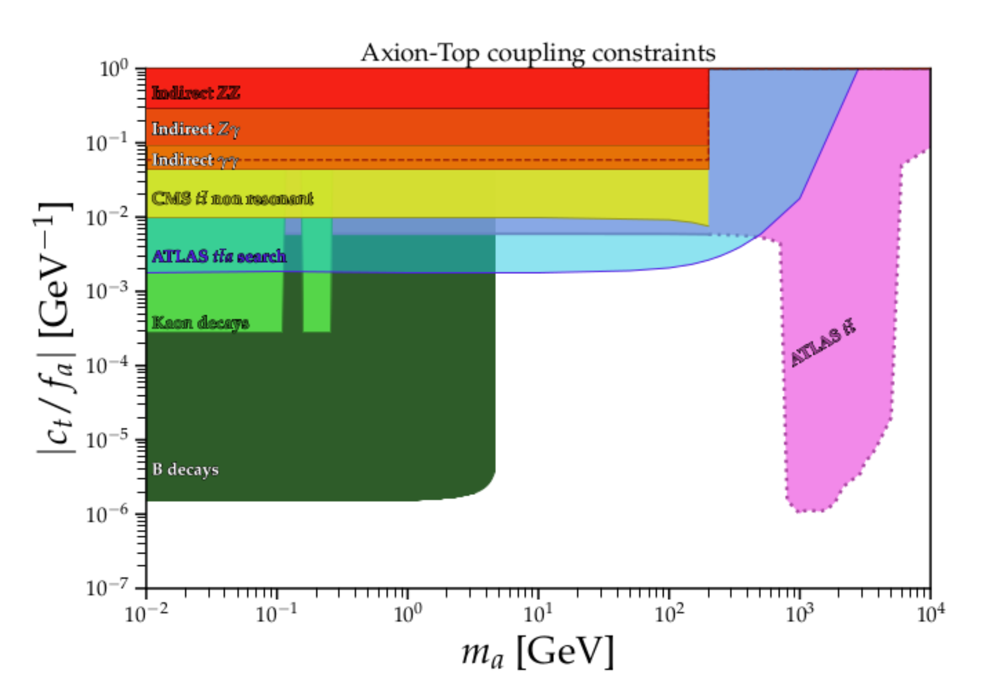
Below 1 MeV: Astro-Cosmological Bounds



[Bonilla, Brivio, Gavela, Sanz, 2107.11392]

Above 200GeV axion mass

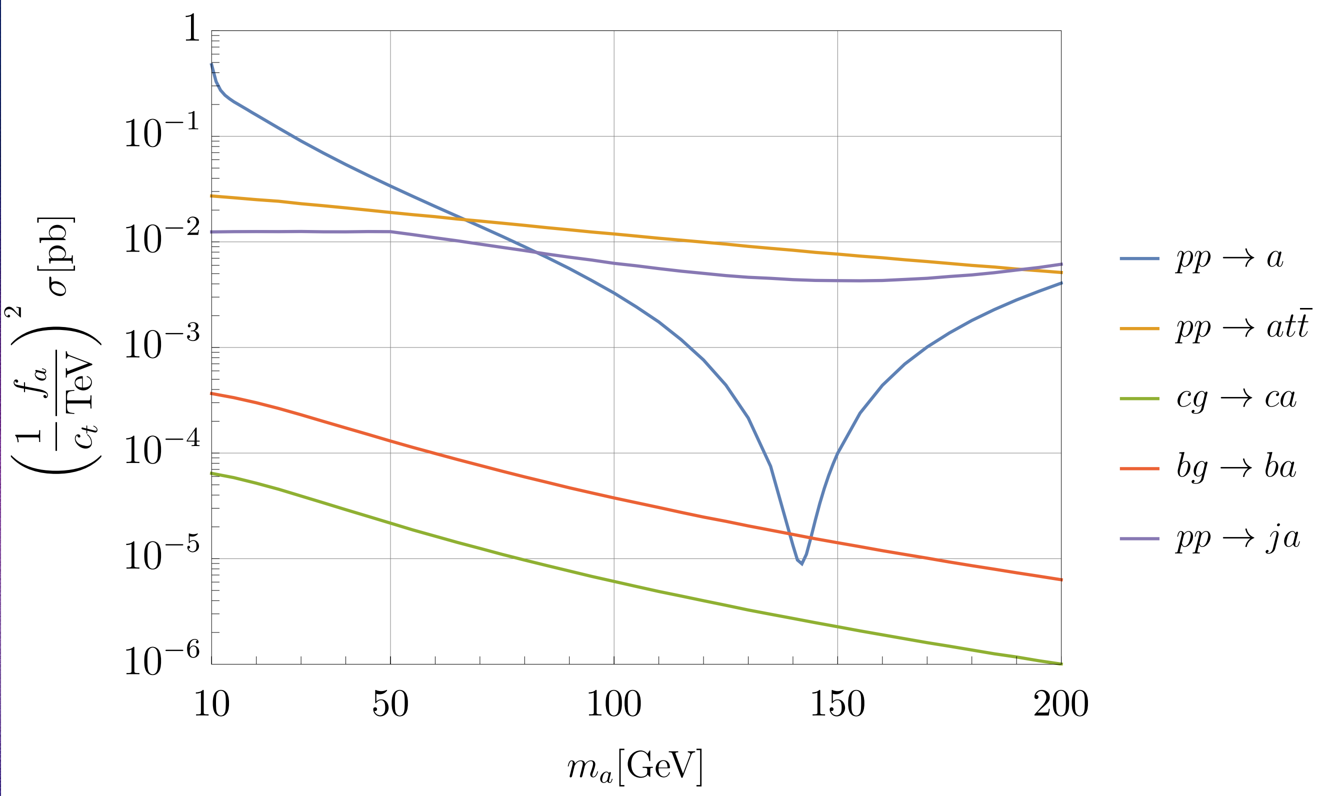
- Supression into di-photon decay is not-effective anymore
- $t\bar{t}$ resonant searches



[Esser. Madigan, Sanz, Ubiali, 2303.17634]

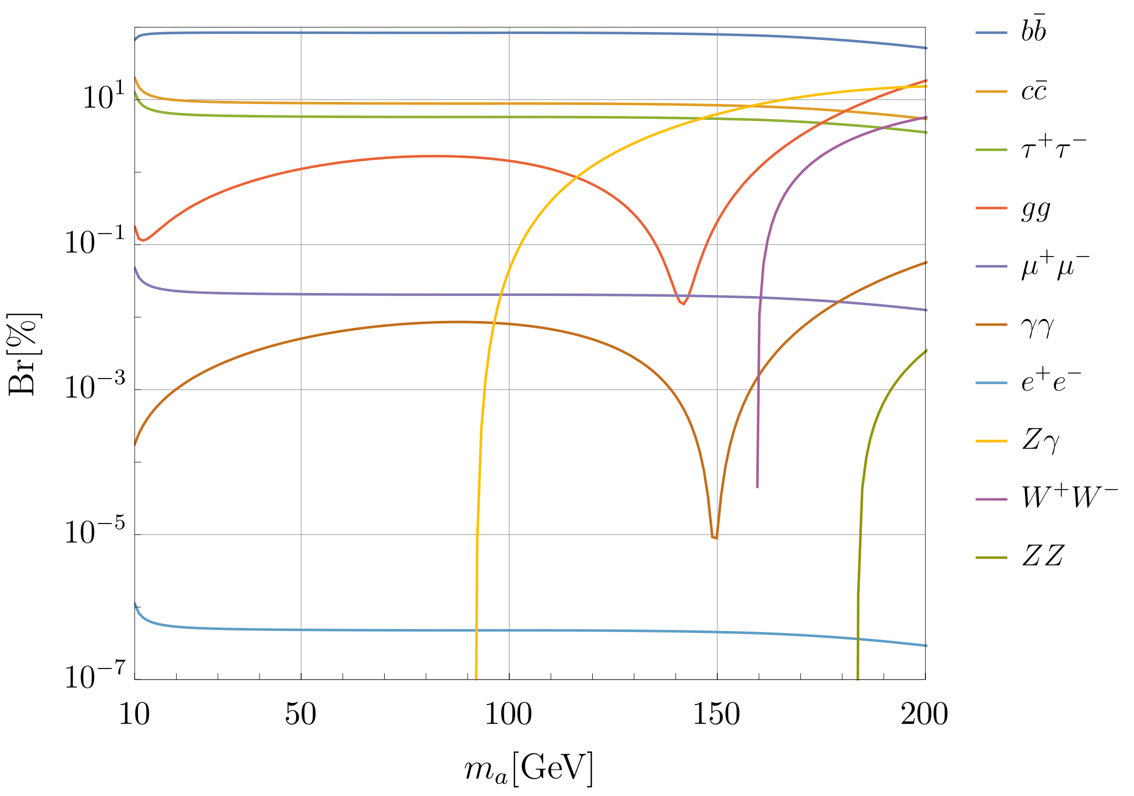
The Golden Region: 10-200 GeV

Production



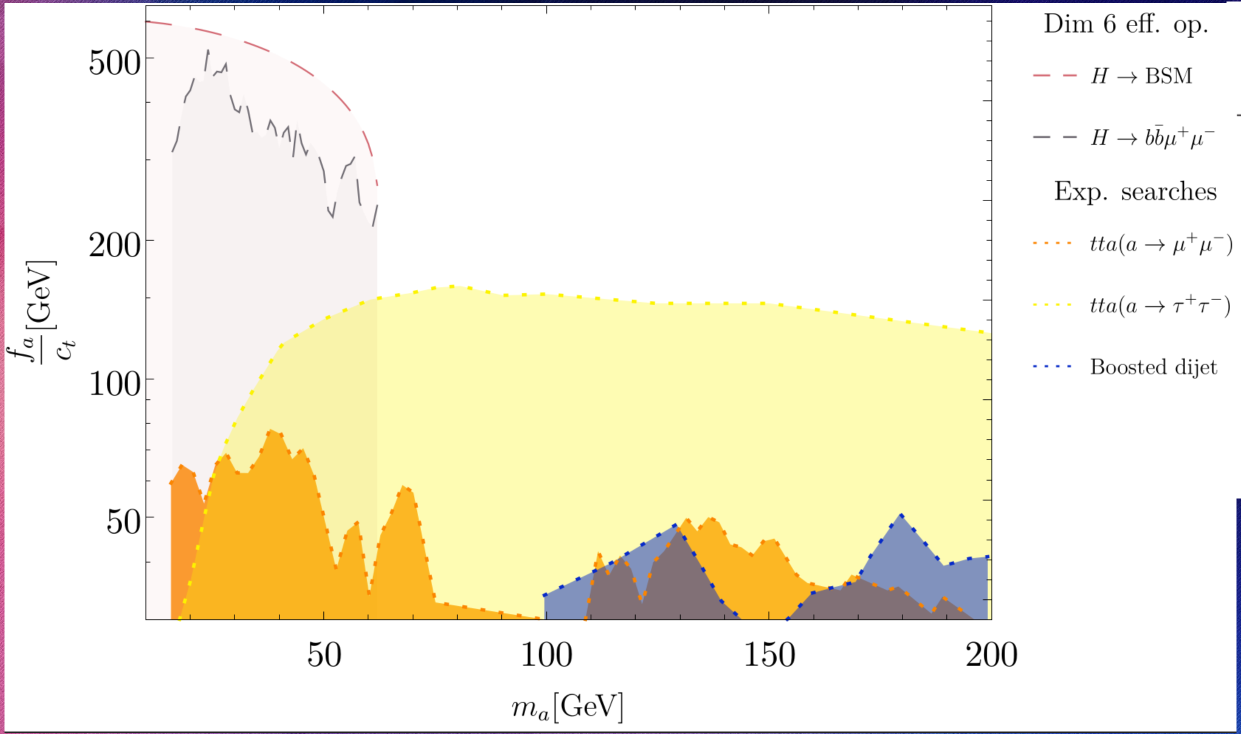
The Golden Region: 10-200 GeV

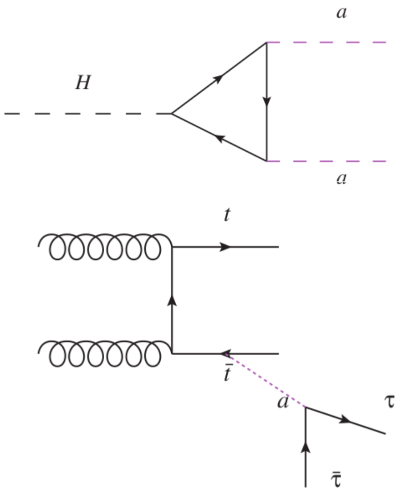
Branching Ratios



The Golden Region: where do we stand

[ATLAS, 2207.00092], [CMS,2207.00043], [ATLAS, 2110.00313],[CMS-PAS-EXO-21-018],[ATLAS, 1801.08769]



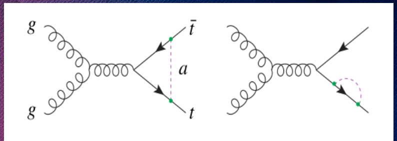


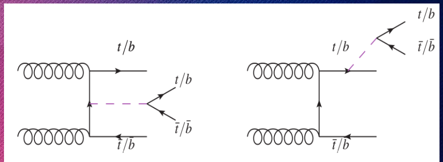
Other non-relevant searches:

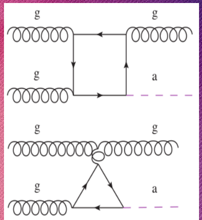
- Diphoton boosted and not [ATLAS, 2211.04172, 2102.13405, ATLAS-CONF-2023-035]
- Resonant boosted $b\bar{b}$ [CMS, 1810.11822]
- $Z \to$ BSM, $Z \to \gamma a(\tau\tau)$, $Z \to \gamma a(jj)$ LEP

Assuming no dim. 6 operator $C_{ah}\partial_\mu a \partial^\mu a \phi^\dagger \phi$

Where to look for Top-philic-ALP?







Where to look at?

2 benchmark scenarios

Visible ALP
(ALP decay into SM particles)

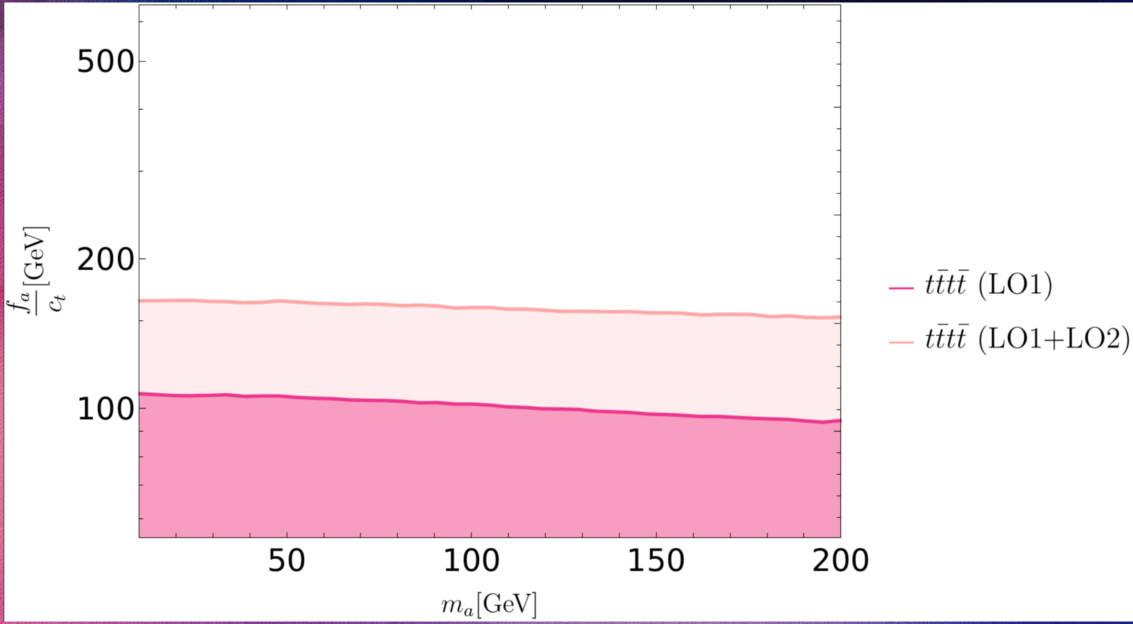
→ $t\bar{t}b\bar{b}$ total cross section

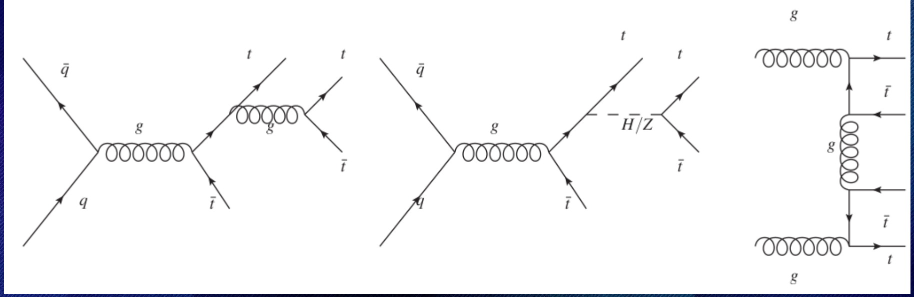
Invisible ALP
(ALP decay into BSM particles or long-lived)

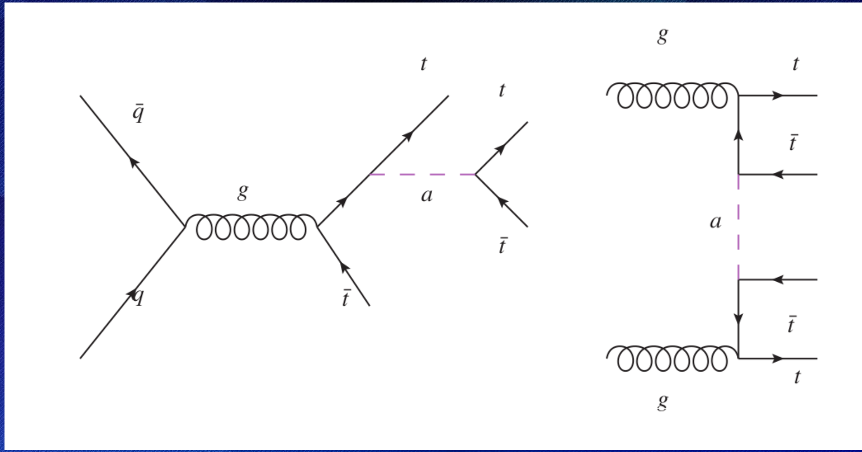
→
- Monojet + missing energy
- $t\bar{t}$ + missing energy

Benchmark-independent: $t\bar{t}$ differential distributions, 4 top total cross section

Four-top total cross section





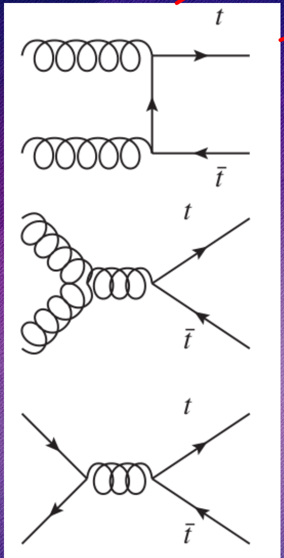


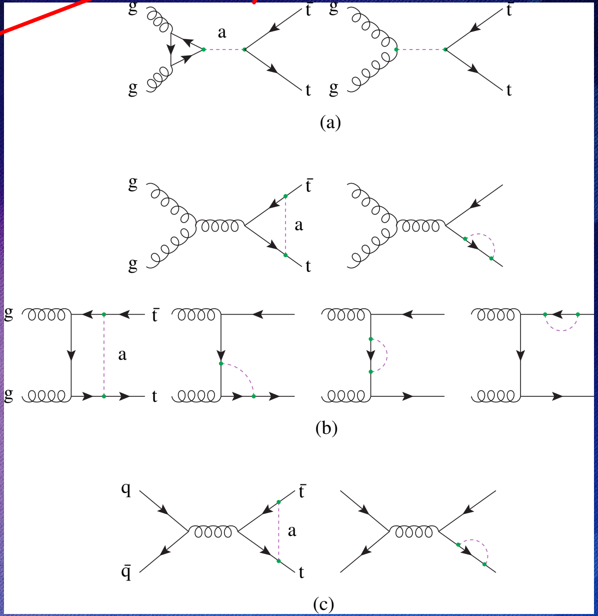
Exp.	Channel	$\mu_{t\bar{t}t\bar{t}}$ ± stat. ± syst.
ATLAS	SSDL+ML	$1.70 \pm 0.40^{+0.7}_{-0.4}$
ATLAS	OSDL+1L	$2.00 \pm 0.70^{+1.5}_{-1.0}$
CMS	SSDL+ML	$1.32 \pm 0.27^{+0.2}_{-0.23}$
CMS	OSDL+1L	$2.20 \pm 0.50 \pm 0.50$

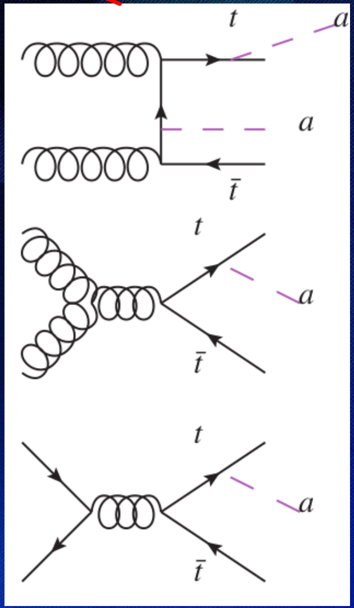
[ATLAS, 2303.15061]
[ATLAS, 2106.11683]
[CMS, 2305.13439]
[CMS, 2303.03864]

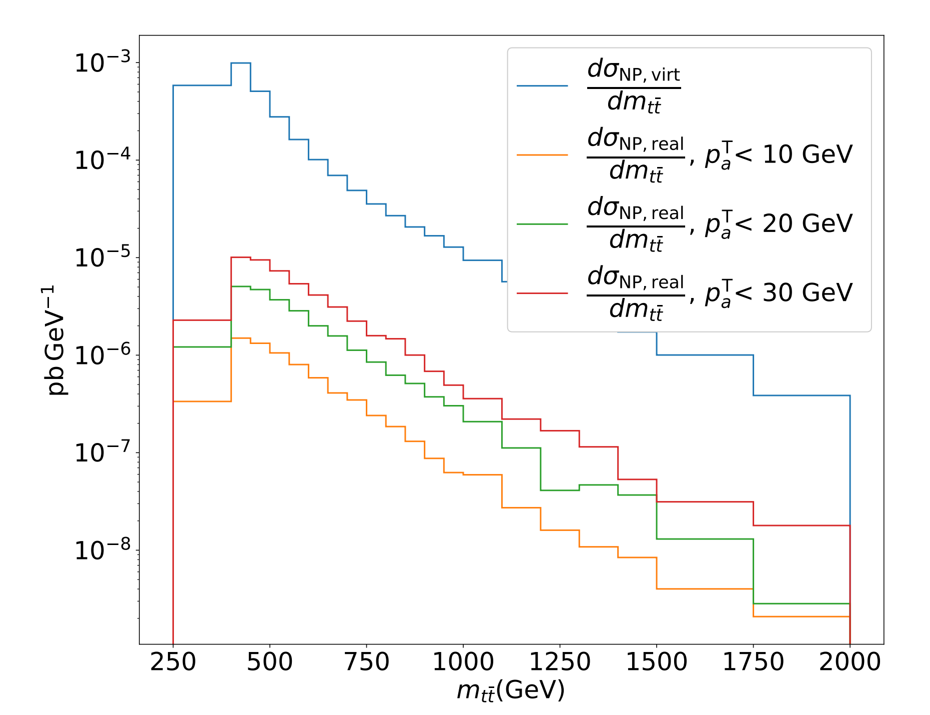
$t\bar{t}$ differential distributions

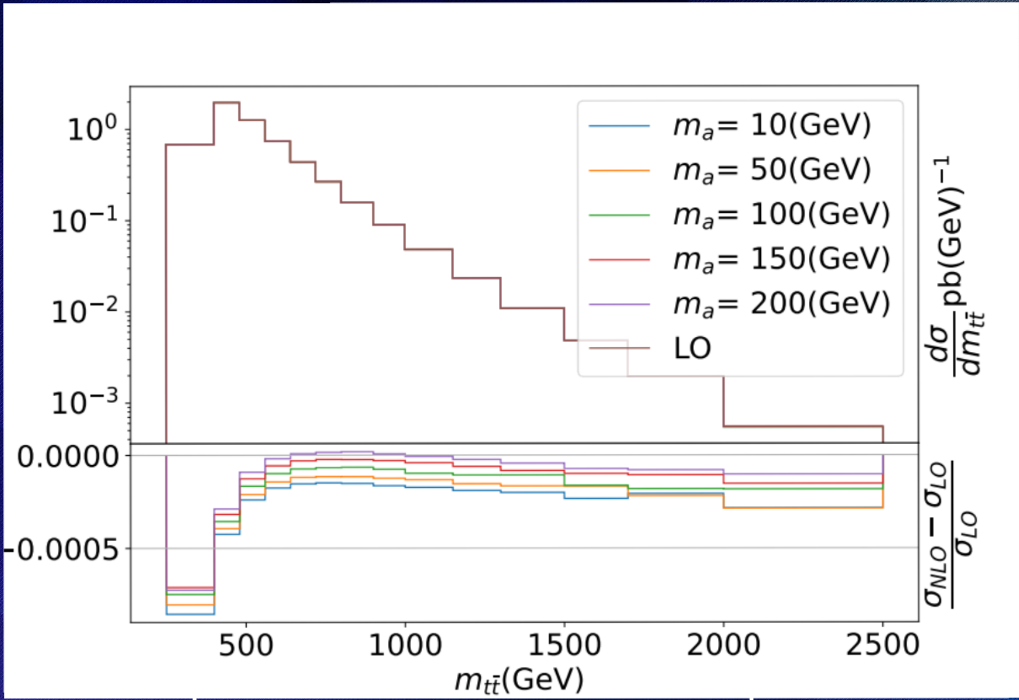
$$\sigma_{\text{tot}} = \sigma_{\text{SM,LO}} + \sigma_{\text{NP,virt}} + \sigma_{\text{NP,real}}$$











Real emission is negligible w.r.t. virtual corrections

Big corrections near the threshold

Corrections weakly dependent on ALP mass

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$m_{t\bar{t}}$ distributions

$\sqrt{s}$	Collab.	Channel	bins	
8 TeV	ATLAS	Dilepton	6	[1607.07281]
8 TeV	ATLAS	ℓ-jets	7	[1511.04716]
8 TeV	CMS	Dilepton	6	[1505.04480]
8 TeV	CMS	ℓ-jets	7	[1505.04480]
13 TeV	ATLAS	ℓ-jets	9	[1908.07305]
13 TeV	CMS	Dilepton	7	[1811.06625]
13 TeV	CMS	ℓ-jets	10	[1803.08856]
13 TeV	CMS	ℓ-jets	15	[2108.02803]

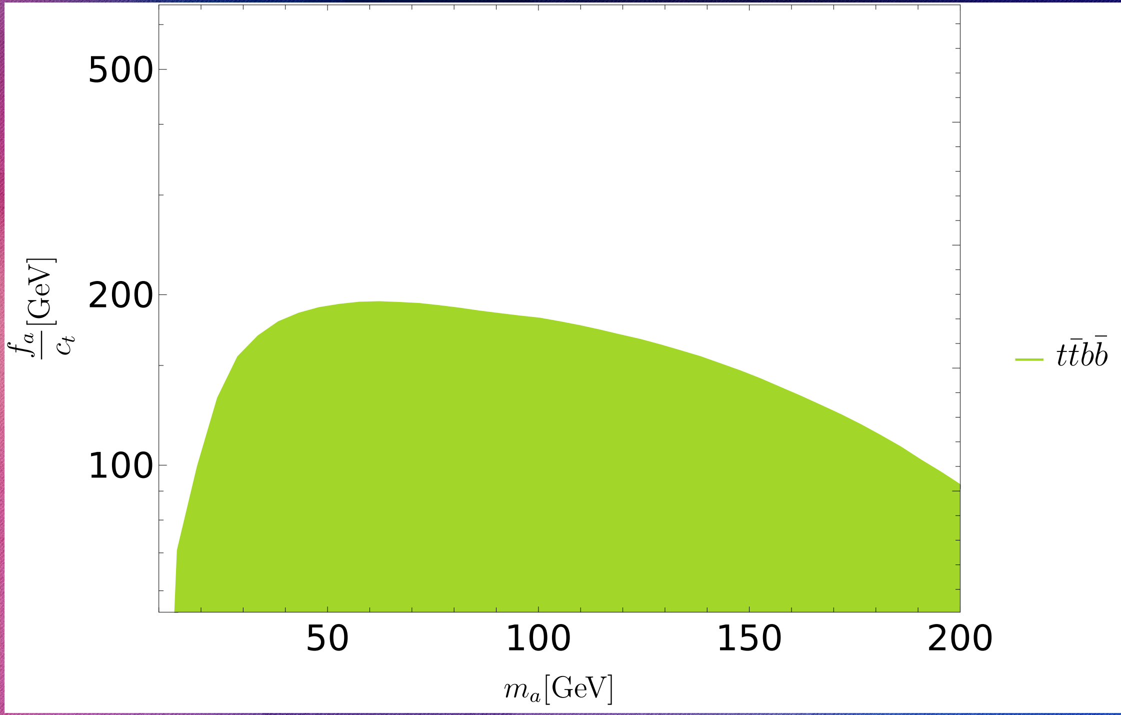
p_t distributions

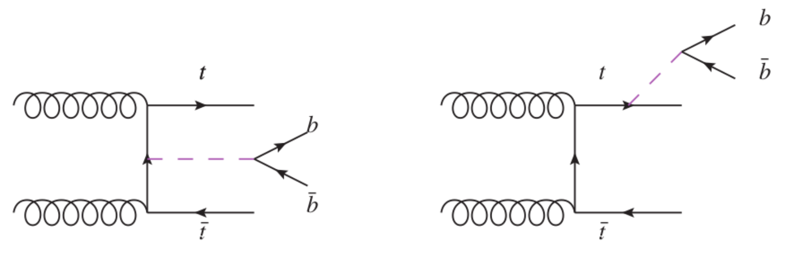
$\sqrt{s}$	Collab.	channel	bins	
8 TeV	ATLAS	ℓ-jets	8	[1511.04716]
8 TeV	CMS	Dilepton	5	[1505.04480]
8 TeV	CMS	ℓ-jets	8	[1505.04480]
13 TeV	ATLAS	ℓ-jets	8	[1908.07305]
13 TeV	CMS	Dilepton	6	[1811.06625]
13 TeV	CMS	ℓ-jets	17	[2108.02803]

Limit combining independent measurements

m_a (GeV)	$\frac{f_a}{c_t}$ (GeV)
10	201.765
50	205.515
100	211.619
150	220.606
200	233.856

Visible ALP: $t\bar{t}b\bar{b}$ total cross section





[CMS, 2003.06467, 1909.05306], [ATLAS, 1811.12113]

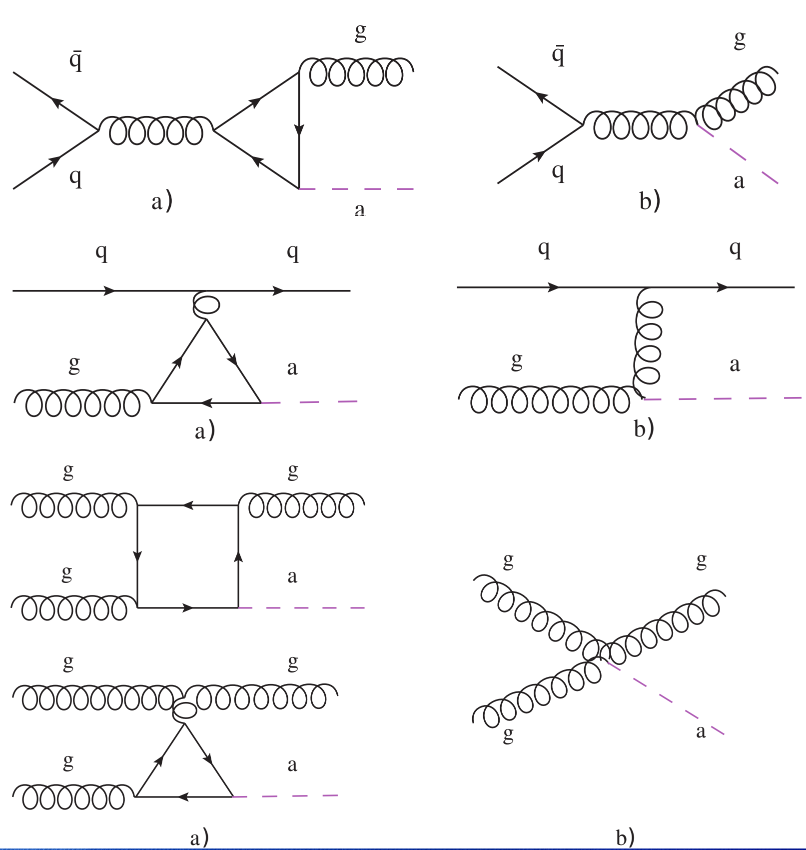
Exp.	Channel	$\mu_{t\bar{t}b\bar{b}} \pm$ stat. $\pm$ syst.	Nominal theory prediction
CMS	dilepton	$1.36 \pm 0.10 \pm 0.34$	POWHEG+PY8
CMS	lepton+jets	$1.26 \pm 0.04 \pm 0.31$	POWHEG+PY8
CMS	hadronic	$1.21 \pm 0.05 \pm 0.20$	MadGraph5_aMC@NLO+FxFx (5FS)
ATLAS	dilepton ($e\mu$, 3b)	$1.33 \pm 0.04 \pm 0.41$	SHERPA 2.2 (4FS)
ATLAS	dilepton ($e\mu$, 4b)	$1.75 \pm 0.05 \pm 0.56$	SHERPA 2.2 (4FS)
ATLAS	lepton+jets (3b)	$1.25 \pm 0.19 \pm 0.44$	SHERPA 2.2 (4FS)
ATLAS	lepton+jets (4b)	$1.57 \pm 0.09 \pm 0.49$	SHERPA 2.2 (4FS)

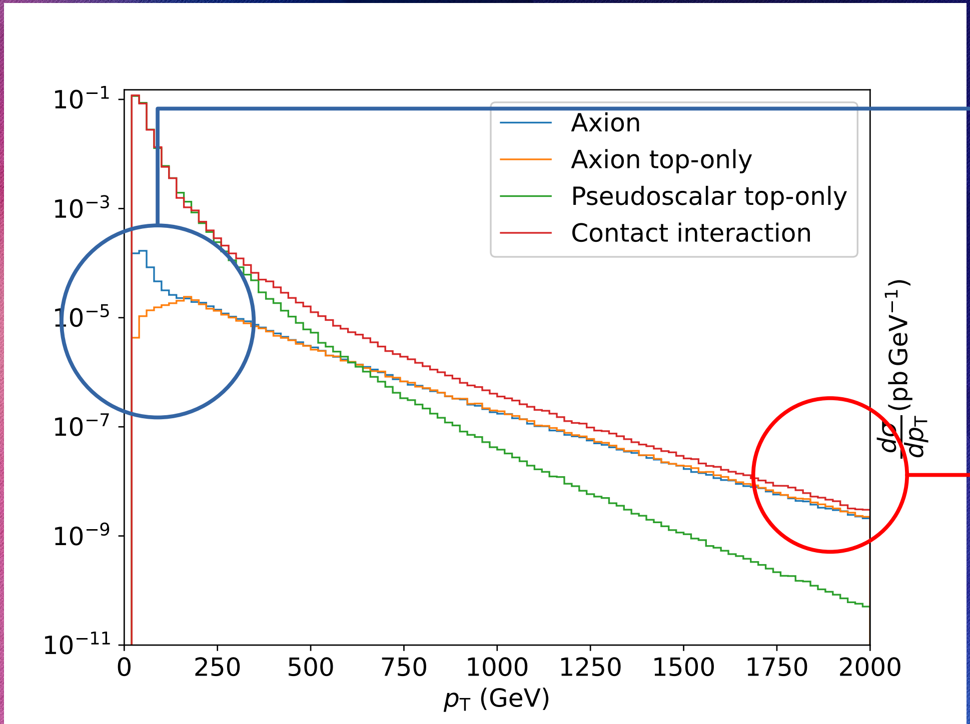
Invisible ALP: monojet

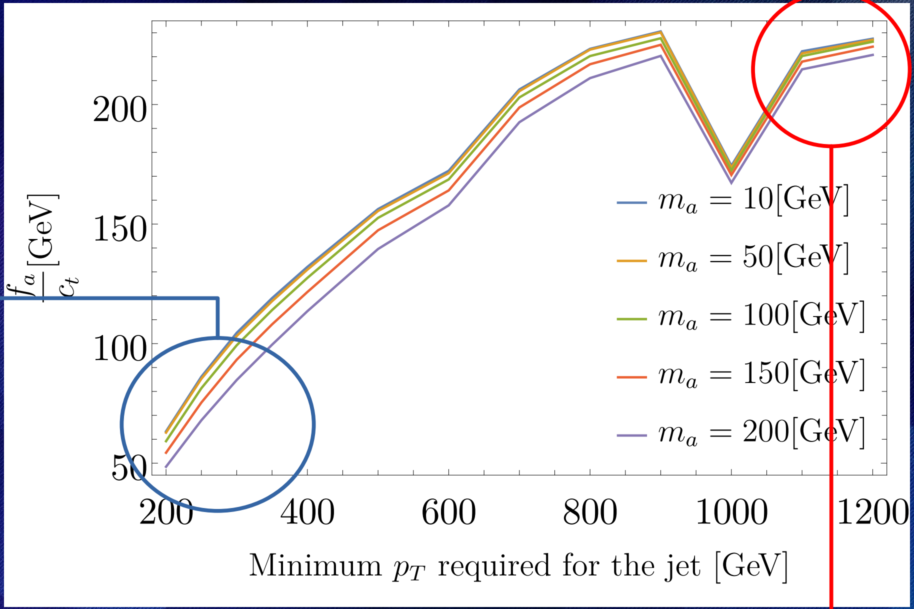
ALP can be invisible:

- Long lived ALP is not possible in this mass interval
- We can consider the ALP as a portal to DM (s-channel simplified model)

$$\mathcal{L}_\chi \supset i\bar{\chi}\partial_\mu\gamma^\mu\chi - m_{\rm DM}\bar{\chi}\chi - ic_{\rm DM}\frac{m_\chi}{f_a}a\bar{\chi}\gamma^5\chi$$



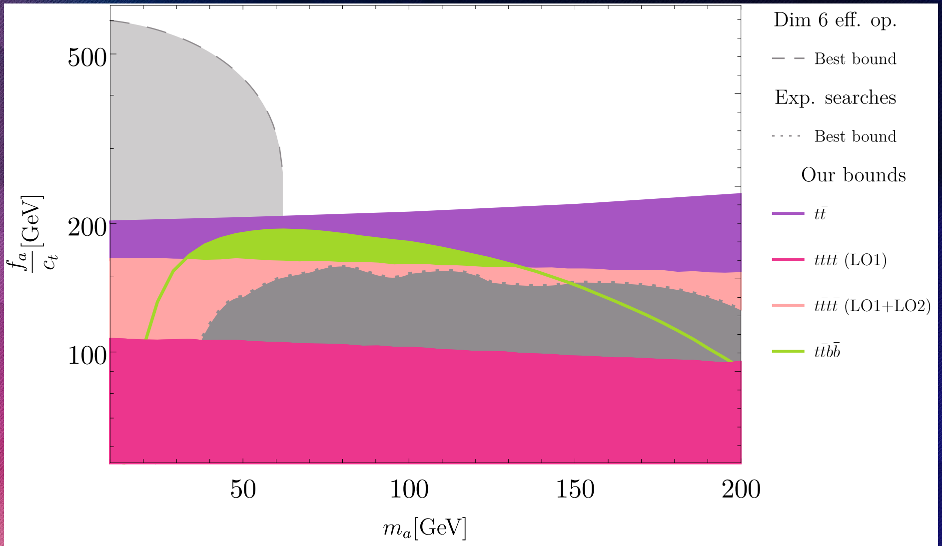




m_a(GeV)	$\frac{f_a}{c_t}$(GeV)	Cut(GeV)
10	230.58	$p_T > 900$
50	230.20	$p_T > 900$
100	227.72	$p_T > 900$
150	224.98	$p_T > 900$
200	220.75	$p_T > 1200$

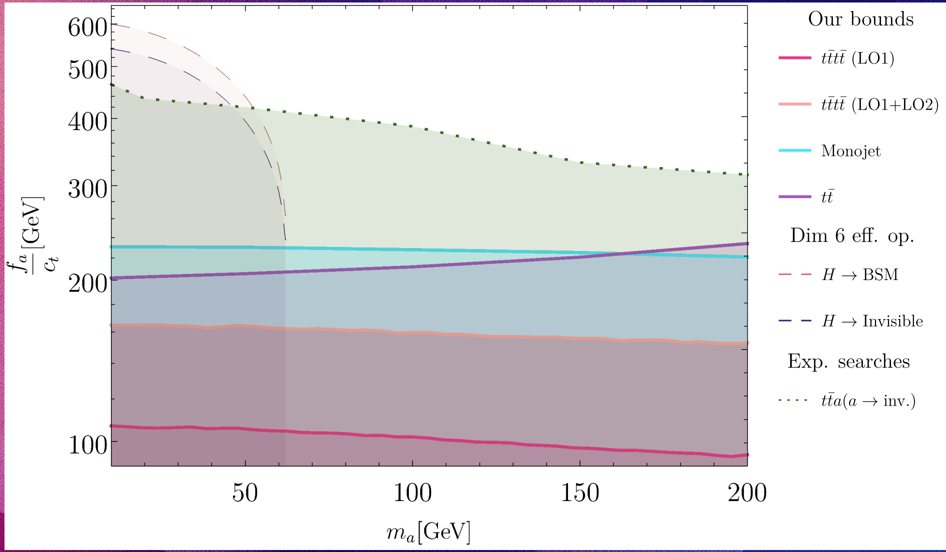
Using [ATLAS, 2102.10874]

Summary



Visible Axion:

- At low masses Higgs decay gives strong bounds
- $t\bar{t}$ gives best bound



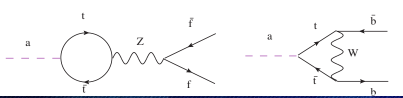
Invisible Axion:

- At low masses Higgs decay gives strong bounds
- Monojet and $t\bar{t}$ are strong and same order
- $t\bar{t}$ + missing energy provides the best bound

[CMS,2107.10892]

Final Remarks

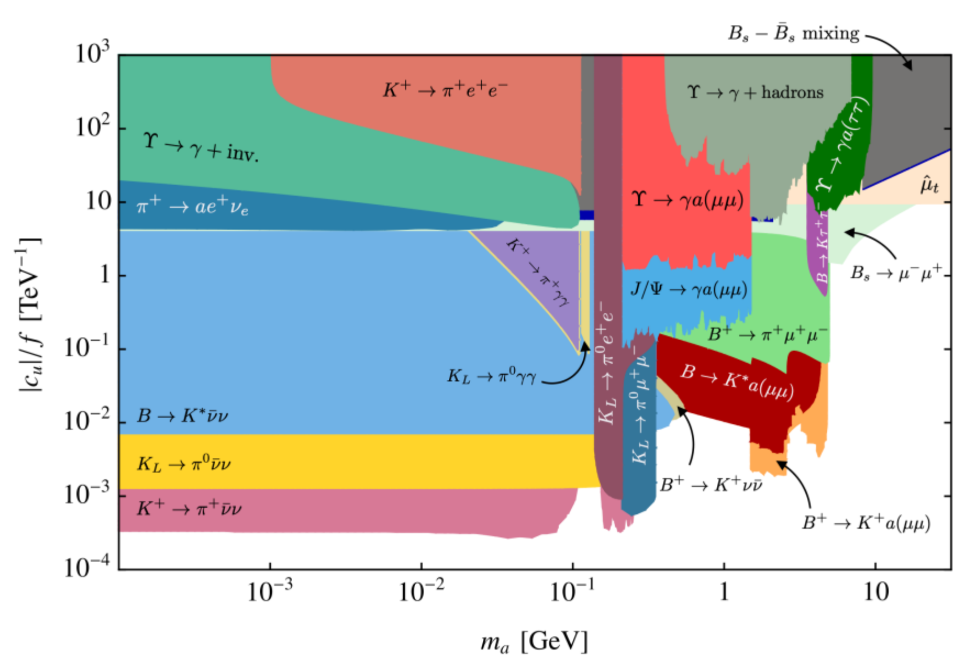
- ALP arise in plenty of theoretical frameworks
- Many recent work started focusing on Top-Philic ALP
    - Coupling to other fermions are anyway generated
    - Different type of searches complement each other

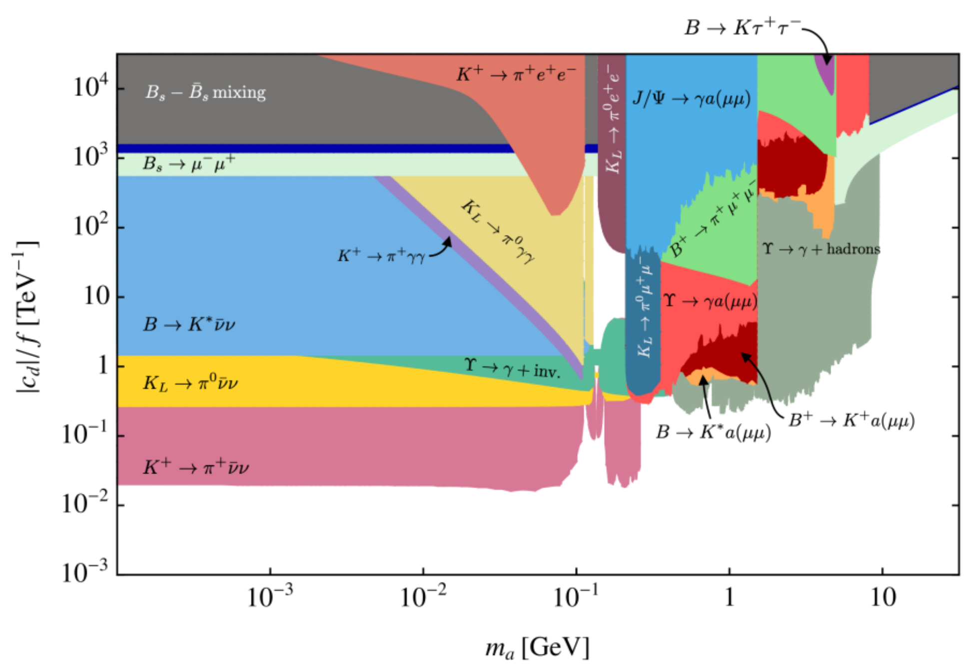


- The 10-200GeV region is challenging, bounds are difficult to put
    - All channel involving top are competitive with each other
    - Missing energy channel are also competitive
- Should we start designating ALP-dedicated experimental searches?

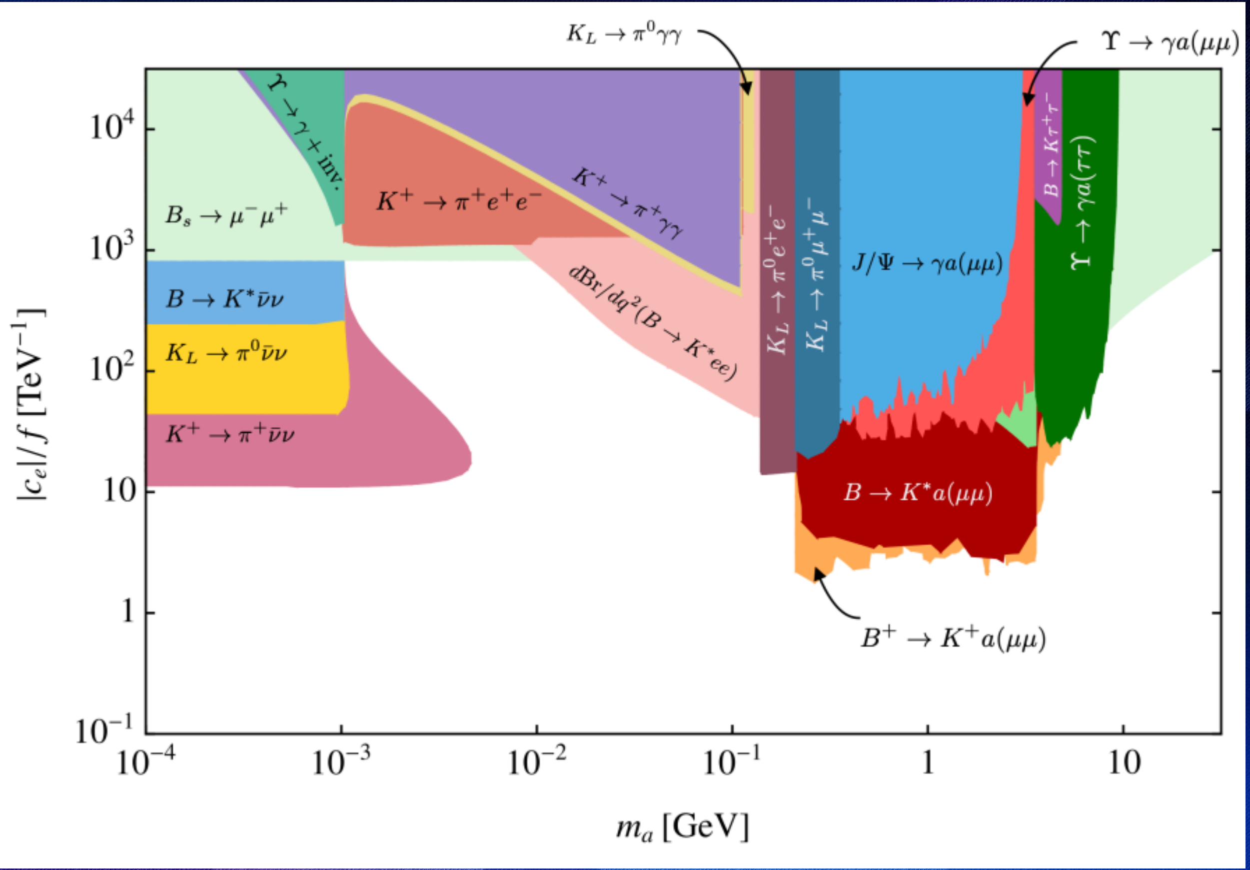
Extra

Up-like and Down-like Flavour bounds





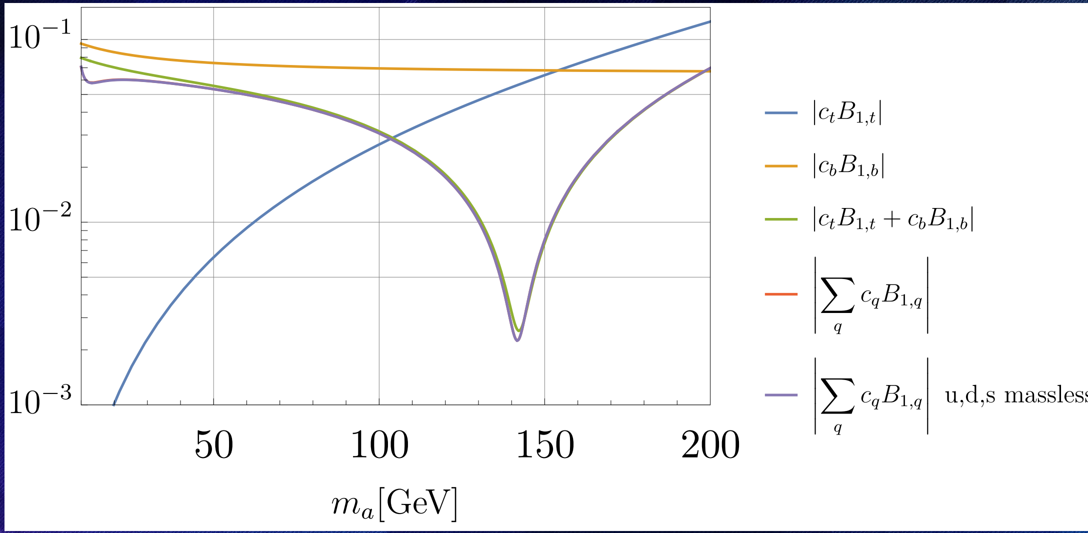
Down-like Leptons Flavour bounds

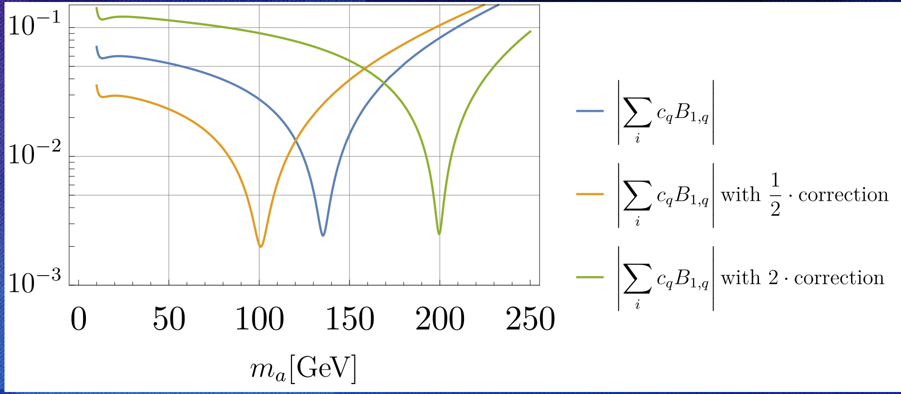


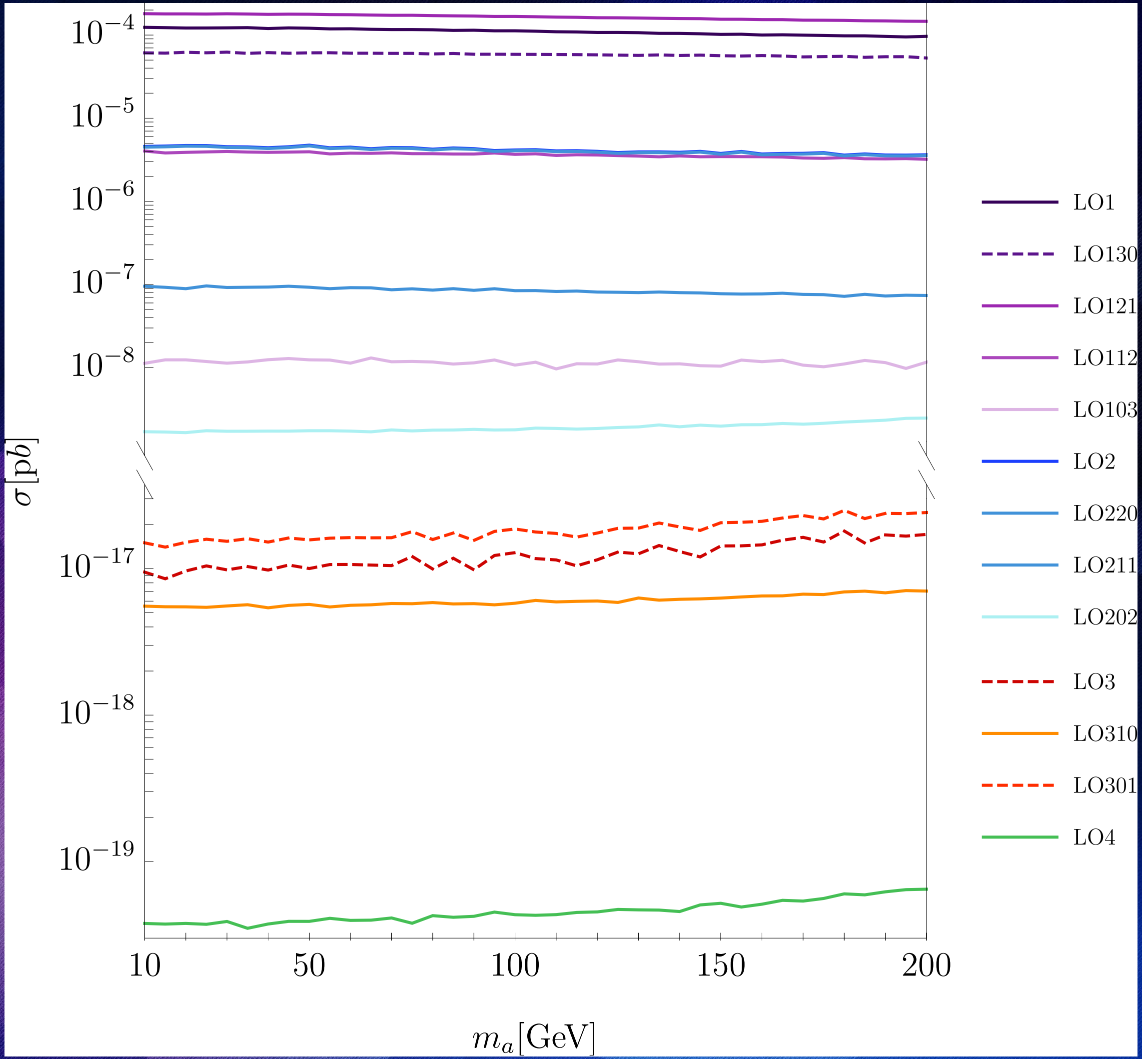
FULL QUARKS CONTRIBUTION TO DI-GLUON(PHOTON) DECAY

$$\Gamma[a \to gg(\gamma\gamma)] \propto \left| \frac{1}{2} \sum_{f=\text{quarks}} B_1\left(\frac{4m_f^2}{m_a^2}\right) c_f \right|^2$$

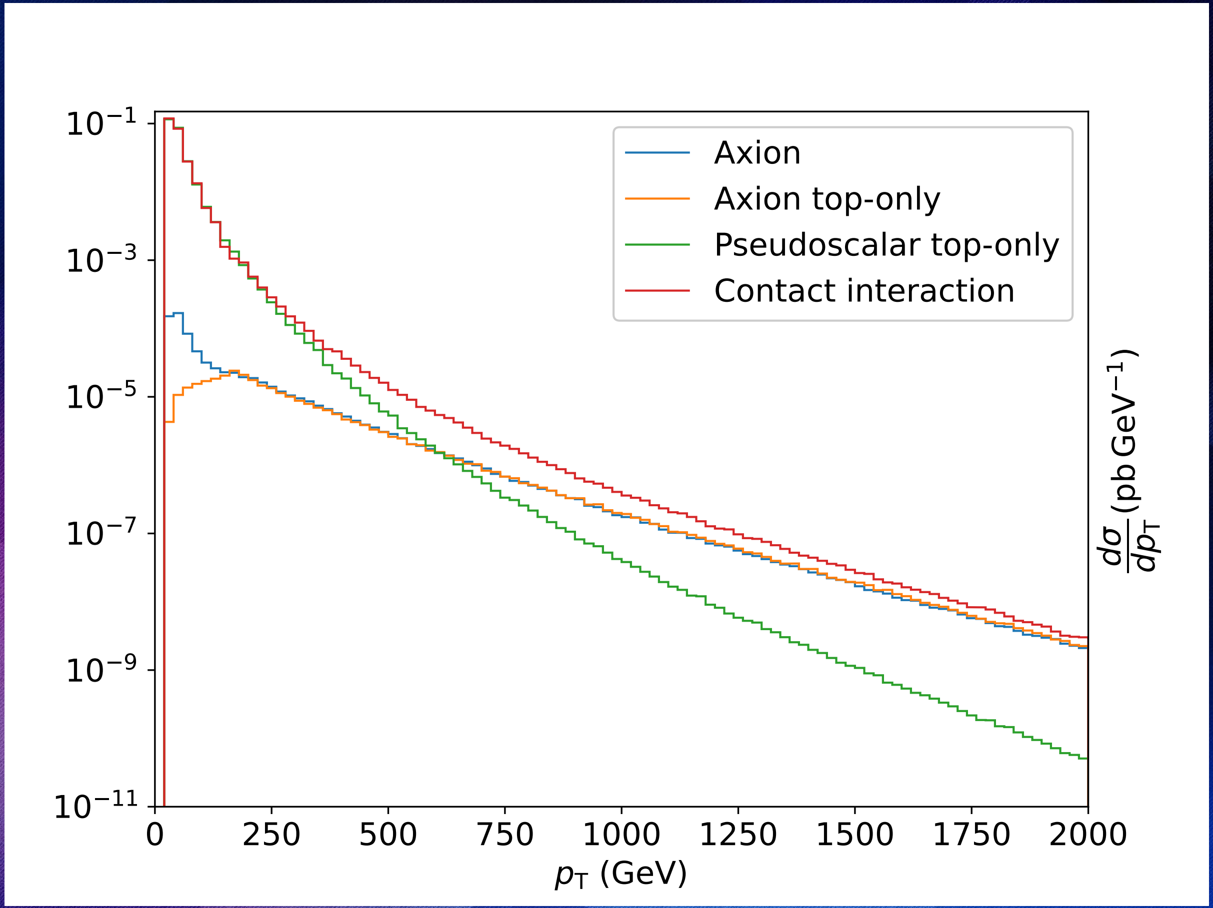
$$\begin{cases} c_t(m_t) &= c_t(\Lambda)\left(1 - 9\frac{y_t^2}{16\pi^2}\log\frac{\Lambda}{m_t}\right) \\ c_b(m_t) &= 5c_t(\Lambda)\frac{y_t^2}{16\pi^2}\log\frac{\Lambda}{m_t} \\ c_f(m_t) &= -12\,c_t(\Lambda)\frac{y_t^2}{16\pi^2}T_3^f\log\frac{\Lambda}{m_t} \end{cases}$$






10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-17}
10^{-18}
10^{-19}
$\sigma[\mathrm{pb}]$
10
50
100
150
200
$m_a[\mathrm{GeV}]$
LO1
LO130
LO121
LO112
LO103
LO2
LO220
LO211
LO202
LO3
LO310
LO301
LO4

Top-only vs full couplings



INVISIBLE ALP: DM SCENARIO